MODEST-18

Dense Stellar Systems in the Era of Gaia, LIGO & LISA

June 25 - 29, 2018
Santorini, Greece

Northwestern
CIERA

sites.northwestern.edu/modest18ciera/

Tuesday

MORNING SESSION – Star Cluster Observations [Chair: Eva Noyola]

Andrea Dieball (Bonn): *Hunting for the Coolest and Faintest Objects in M4*

Silvia Raso (Bologna): *Observational Properties of Blue Straggler Stars in GCs*

Arash Bahramian (MSU): *The MAVERIC Survey – Finding Stellar Mass BH Candidates in Galactic GCs*

Eugene Vasiliev (Cambridge IoA): *Using Gaia for Studying Milky Way Star Clusters*

Craig Heinke (Alberta): *Understanding the X-ray Emissivity of Old Stellar Populations*

Sara Saracino (Bologna): *GEMINI/GeMS Observations of GCs in the Galactic Bulge*

Benjamin Giesers (Göttingen): *Resolving the Central Dynamics of GCs with MUSE*

Peter Zeidler (STScI): *The Primordial Binary Fraction in Westerlund 2*

Andrea Dieball (Bonn): *Hunting for the Coolest and Faintest Objects in M4*

In a first deep near-infrared (NIR) study of the globular cluster M4 we presented the NIR deepest color-magnitude diagram (CMD) of a globular cluster to date. The NIR data were deep enough to reach the end of the H-burning sequence and the bottom of the white dwarf (WD) cooling sequence, and to potentially push into the brown dwarf (BD) regime. We used the deepest archival optical data to proper motion clean the NIR data, and detected four sources fainter than the H-burning limit but without an optical counterpart, which made all these source potential BDs. In this talk, we present an analysis of the second epoch HST WFC3 NIR data of M 4. All four BD candidates were recovered, and one source is indeed a likely cluster member. We discuss the nature of this source based on its position in all CMDs and colour-colour diagrams. It is, at its magnitude, the reddest source in the optical-near CMDs and appears redder than the WD cooling sequence, but still bluer than an extension of the MS. This source might indeed be a BD – and as such, the first BD detected in a globular cluster. However, we cannot exclude that this source might be a very cool (approx. 4000 K) WD (and thus one of the coolest WDs reported in M4, although its color appears to be somewhat too red for a WD), or possibly a very cool and thus very low-mass MS star (and thus the lowest-mass MS source detected in M\,4), or a WD-BD binary.

Silvia Raso (Bologna): *Observational Properties of Blue Straggler Stars in GCs*
Blue Straggler Stars (BSS) are core hydrogen-burning objects that appear brighter and bluer than the main sequence turn-off in the color-magnitude diagram. Their position suggests that they are more massive than main sequence stars, as it has also been confirmed by a few mass measurements. Due to their mass, they are ideal test particles to study the dynamical evolution of the parent stellar system. In this talk I will present the last observational results on this topic, based on data from the HST UV Legacy Survey of Galactic Globular Clusters (GGCs). By using a parameter that measures the level of the radial segregation of BSS, we traced the internal dynamical evolution of 48 GGCs (about 30% of the total population in the Milky Way). I will also present the Spectral Energy Distribution (SED) for a sample of BSS in the core of 47Tuc, taking advantage of the large set of high resolution images available in the HST archive, ranging from UV to the near-IR.

Arash Bahramian (MSU): *The MAVERIC Survey – Finding Stellar Mass BH Candidates in Galactic GCs*

The survival and presence of stellar mass black holes in globular clusters remains a hot topic for observations and simulations. Recent discoveries of black hole candidates in globular clusters indicate that black holes remain in star clusters today, supported by recent simulations. Joint radio and X-ray observations provide a crucial path to search for accreting black holes, as black holes tend to have stronger flat-spectrum radio emission (due to a stronger jet) for a given X-ray luminosity, compared to other source classes. We have been conducting a deep radio (VLA and ATCA) survey of Galactic globular clusters to search for candidate black holes in globular clusters. In this talk I will present some of the recent results from our survey, including 47 Tuc X9 (the first ultracompact binary with a candidate black hole, M10-VLA1 (a possibly face-on black hole system), our limits on intermediate-mass black holes in globular clusters and what they mean in an evolutionary picture of globular clusters.

Eugene Vasiliev (Cambridge IoA): *Using Gaia for Studying Milky Way Star Clusters*

I review the implications of the Gaia data for studying the star clusters. Starting with an overview of the content and the properties of the Data release 2, I discuss the various caveats in analyzing the data and possible approaches for mitigating them. To illustrate the scientific impact of this dataset, I consider the determination of internal kinematic properties (velocity dispersion, anisotropy, and rotation) for several globular clusters. Finally, I discuss the synergy with other instruments and surveys, and the prospects from further Gaia data releases.

Craig Heinke (Alberta): *Understanding the X-ray Emissivity of Old Stellar Populations*

We investigate what factors affect the X-ray emissivity (luminosity per unit stellar mass) of old stellar populations. Previous work has shown that dense globular clusters have higher X-ray emissivity than less-dense globular clusters, that old open clusters have higher X-ray emissivity than typical globular clusters, and that typical galactic field populations have similar X-ray emissivities. We collect data from the literature, and investigate several intriguing claims of odd X-ray sources in low-density populations (X-ray binaries in the Sculptor Dwarf Galaxy, a quiescent neutron star in an open cluster, and a diffuse X-ray shell around a CV in a sparse globular cluster), showing that each are due to fore- or background sources. We then compare the X-ray emissivities of globular clusters, open clusters, and galactic field populations. Above a density of 10^4 Msun/pc^3, XRBs appear to be dominated by dynamically formed systems. The X-ray emissivity of lower-density populations varies dramatically with binary fraction and metallicity. Future work may resolve the ambiguity between these two parameters.

Sara Saracino (Bologna): *GEMINI/GeMS Observations of GCs in the Galactic Bulge*

The Galactic bulge is one of the most inaccessible region of the Galaxy and its structure, formation and evolution are still subject of intense debate within the international community.

Bulge globular clusters are key tools to constrain the properties of the bulge, as they share kinematics, spatial distribution and composition with bulge field stars. However, these systems have been widely excluded from large surveys due to observational limitations, and they remained poorly investigated so far. By exploiting the superb capabilities offered by the the near-infrared GSAOI imager in tandem with the Multi-Coniugate Adaptive Optics system GeMS at the Gemini South Telescope, we started an observational campaign aimed at characterizing the stellar population content and the structural and physical properties of a sample of GCs orbiting the innermost part of the Milky Way bulge. In this talk I will give an overview of the results recently achieved in this field, starting from the low-reddening cluster NGC 6624, passing through the moderately-reddened (E(B-V)=0.2) cluster NGC 6569, to end with the highly obscured (E(B-V) = 3.1) cluster Liller 1. This approach promises to open a new line of investigation for all of those systems in the Galaxy for which optical observations are almost totally useless.

Benjamin Giesers (Göttingen): *Resolving the Central Dynamics of GCs with MUSE*
We are currently realising a massive spectroscopic survey of 25 Galactic globular clusters with MUSE at the VLT. MUSE gives us the possibility to extract spectra of some thousand stars per exposure. Our survey is the first blind spectroscopic investigation of globular clusters and has provided us with 1,000,000 spectra of 200,000 stars so far. Dedicated multi-epoch observations allow us to find binary stars and have already resulted in the discovery of a quiescent stellar-mass black hole in the core of NGC 3201. Our survey promises to constrain the population of stellar remnants in dense stellar clusters and hence will help in the interpretation of future gravitational wave events. Other science cases cover the cluster kinematics or chemistry of the cluster stars. As such, we supplement the GAIA survey for the inner parts of the globular clusters.

Peter Zeidler (STScI): *The Primordial Binary Fraction in Westerlund 2*

We present preliminary results of an HST photometric and astrometric campaign aimed at probing the unexplored population of low and intermediate-mass binaries (periods of ~2 days to several hundred years) in the young, massive cluster Westerlund 2 (WD2). Over a 3 year span, we have a total of 45 orbits using the HST WFC3 instrument. We will be able to measure, for the first time, the separation, flux ratio and the angle of barely resolved short, intermediate and long period binaries in WD2. Our sample closely represents the properties of the primordial binary population in star clusters. To date, we have found 2061 cluster members a surprisingly high fraction (~30%) of low and intermediate mass short period binaries (12 days) within the cluster. The large amount of binary systems have implications for the dynamics of the cluster and suggests that the binaries may not be randomly oriented but have a preferential alignment in young star forming regions.

Tuesday

EVENING SESSION – N-body Dynamics and Codes [Chair: Douglas Heggie]

Long Wang (AIA): *New Hybrid N-body Code for Million-body Simulations*

Tjarda Boekholt (Aveiro): *Accurate and Precise N-body Simulations*

Silvia Toonen (Amsterdam): *The Evolution of Triple-star Systems*

Phil Breen (Edinburgh): *Unveiling the Kinematic Richness of Star Clusters*

Alison Sills (McMaster): *Multiple Populations in GCs: Dynamics and Collisions?*

Sourav Chatterjee (TIFR): *Monte Carlo Models of Dense Star Clusters*

Mirek Giersz (Copernicus Center): *MOCCA Survey Database I. – What Next?*

Jeremy Webb (Toronto): *A Direct N-body Simulation of Pal5 and its Tidal Tails*

Arkadiusz Hypki (Adam Mickiewicz): *BEANS — Interactive, Distributed Data Analysis of Huge Data Sets* [C]

Long Wang (AIA): *New Hybrid N-body Code for Million-body Simulations*

Although the million-body direction N-body modelling of globular clusters (GCs) can be performed now (Wang et al. 2016), it is still not practical to simulation dense GCs with initial half-mass radius of 1-2pc and large fraction of binaries. Even the loose GC in Wang et al. (2016) require half-a-year computational times on GPU clusters. In this work, we have developed a new hybrid N-body code, which combines the Particle-tree and particle-particle integrators (P3T) and time-transformed symplectic integrator (Algorithmic regularization). We have benchmark tests on K-computer with different processors and particle numbers. The results indicates that this new code can be used to simulate a N=10^6 star cluster with 100% primordial binaries based on the period distribution from Kroupa (1995). With the new code, it is possible to perform long-term dense GC simulations or even larger N collisional gravitational dynamical systems like nuclear star clusters and ultra-compacted dwarf galaxies.

Tjarda Boekholt (Aveiro): *Accurate and Precise N-body Simulations*

Numerical solutions to Newton's equations of motion for chaotic self gravitating systems of more than 2 bodies are often regarded to be irreversible. This is due to the exponential growth of errors introduced by the integration scheme and the numerical round-off in the least significant figure. This secular growth of error is sometimes attributed to the increase in entropy of the system even though Newton's equations of motion are strictly time reversible. We demonstrate that when numerical errors are reduced to below the physical perturbation and its exponential growth during integration the microscopic reversibility is retrieved. Time reversibility itself is not a guarantee for a definitive solution to the chaotic N-body problem. However, time reversible algorithms may be used to find initial conditions for which perturbed trajectories converge rather than diverge. The ability to calculate such a converging pair of solutions is a striking illustration which shows that it is possible to compute a definitive solution to a highly unstable problem. This works as follows: If you (i) use a code which is capable of producing a definitive solution (and which will therefore handle converging pairs of solutions correctly), (ii) use it to study the statistical result of some other problem, and then (iii) find that some other code produces a solution S with statistical properties which are indistinguishable from those of the definitive solution, then solution S may be deemed veracious.

Silvia Toonen (Amsterdam): *The Evolution of Triple-star Systems*

While the principles of stellar and binary evolution theory have been accepted for a long time, our understanding of triple-star evolution is lagging behind. It is important to understand these systems, as triples are common in the field. About 15% of low-mass stellar systems are triples, but for high-mass stars the fraction increases to over 50%. At the same time, triple evolution is often invoked to explain exotic systems which cannot be explained easily by binary evolution. Examples are low-mass X-ray binaries, supernova type Ia progenitors and blue stragglers. Modeling triple evolution, however, is challenging as it is a combination of three-body dynamics and stellar evolution. In the past, most studies of three-body systems have focused on purely dynamical aspects without taking stellar evolution into account. However, in recent years, the first interdisciplinary studies have taken place which demonstrate the richness of the interacting regime. Here, I will show the first results of our recent code TRES for simulating the evolution of stellar triples, which combines stellar evolution and interactions with three-body dynamics. In this talk, I will give an overview of the evolution of realistic (stellar) triples and I will discuss how triple evolution differs from binary evolution. What are the common evolutionary pathways that triple systems evolve through? I will show how triple evolution can lead effectively to mergers and collisions of compact objects, and show the consequences for gravitational wave sources and supernova type Ia progenitors.

Phil Breen (Edinburgh): *Unveiling the Kinematic Richness of Star Clusters*

Thanks to new-generation astrometric data from Gaia, coupled with decades-long observational campaigns with the Hubble Space Telescope and forthcoming large spectroscopic surveys, we are about to enter a new ”golden age” for the study of dense stellar systems, as the full phase space of several Galactic globular clusters will be soon unlocked for the first time. The mounting empirical evidence that their three-dimensional velocity space is much more complex than usually expected encourages us to use them as refreshingly novel phase space laboratories for some long-forgotten aspects of collisional gravitational dynamics. In this context, I will present some new theoretical insight resulting from a comprehensive investigation of the role played by angular momentum and primordial velocity anisotropy in the long-term evolution of collisional stellar systems, with particular attention to implications on the moment of core collapse.

Alison Sills (McMaster): *Multiple Populations in GCs: Dynamics and Collisions?*

The presence of multiple populations in globular clusters is now well-established, but a self-consistent explanation still eludes us. In this talk, I will move discuss a number of aspects of the multiple population problem that could be addressed through an understanding of their impact on stellar dynamics, and the impact of dynamical effects on the multiple populations. I will touch on the effect of the tidal field of the galaxy on the radial distribution of stars in each population, the possible effects of helium on the stellar masses, and spend some time discussing the possible contributions of stellar collisions and the conditions under which they could be important.

Sourav Chatterjee (TIFR): *Monte Carlo Models of Dense Star Clusters*

I will briefly describe the Hénon-type Monte Carlo technique for modeling of dense star clusters. I will describe our highly successful Monte Carlo code CMC with a focus on how different physical processes are treated in the code. I will highlight our latest results obtained from models using CMC and planned updates to CMC.

Mirek Giersz (Copernicus Center): *MOCCA Survey Database I. – What Next?*

I will briefly describe the project MOCCA Server Database and its set-up. Then I will list and shortly describe most of projects connected with analysis of the Database. Projects which deal, among others, with: BH and NS populations in star clusters and their interactions, IMBHs and their observational signatures, and many more. Finally, I will discuss recent developments of the MOCCA code and planed simulations for the MOCCA Survey Database II.

Jeremy Webb (Toronto): *A Direct N-body Simulation of Pal5 and its Tidal Tails*

We present a direct N-body simulation of the globular cluster Pal 5, allowing the cluster to evolve for a Hubble time while also following the evolution of stars which escape the cluster. The evolution of key cluster properties will be discussed, with a particular emphases on mass segregation and the mass functions of both the cluster and its tidal tails. Motivated by previous observations that find the cluster and tails to be devoid of low mass stars, we examine how and when low-mass stars escape Pal 5. We also explore methods for locating escaped Pal 5 stars as streams in the Milky Way and discuss preliminary work using the newest Gaia catalogue.

Arkadiusz Hypki (Adam Mickiewicz): *BEANS — Interactive, Distributed Data Analysis of Huge Data Sets* [C]

BEANS is a web-based software for interactive distributed data analysis with a clear interface for querying, filtering, aggregating, and plotting data from an arbitrary number of data sets and tables. During the talk I would like to present a number of interesting, easy to understand but yet very powerful examples of data analysis made in the BEANS software. The example data sets are based on the data from MOCCA simulations which is one of the most powerful codes to simulate real-size star clusters. The example queries will be made against the data coming from over 2000 MOCCA simulations, where every simulation takes on average 20 GBs and contains around 10 different files. The BEANS software will be shown how one can manage the data sets which are large and contain also large number of files.

Wednesday

MORNING SESSION – Stellar Remnants in Star Clusters [Chair: Michela Mapelli]

Abbas Askar (Copernicus Center): *Black Hole Subsystems in Galactic GCs*

Sara Rastello (Rome): *Stellar BH Binary Mergers in Open Clusters*

Sambaran Banerjee (Bonn): *Stellar-mass BHs in Young Massive and Open Clusters and Their Role in GW Generation*

Vaclav Pavlik (Prague): *The BH Retention Fraction in Star Clusters*

Kyle Kremer (CIERA): *How BHs Shape the Dynamical Evolution and Observable Properties of GCs*

Vincent Henault-Brunet (Herzberg): *Weighing Populations of Dark Remnants in GCs with Multimass Models*

Natasha Ivanova (Alberta): *Formation of BH X-Ray Binaries with Non-degenerate Donors in GCs*

Ross Church (Lund): *47 Tux X9: A UCXB with a BH Accretor*

Abbas Askar (Copernicus Center): *Black Hole Subsystems in Galactic GCs*

There have been increasing theoretical speculations and observational indications that certain globular clusters (GCs) could contain a sizeable population of stellar mass black holes (BHs). In this talk, I will discuss results from simulations of GC models that contain a sizeable population of BHs up to a Hubble time. A large fraction of BHs in these GCs can form a subsystem that is mixed with other stars. The presence this subsystem of BHs can significantly influence the observed properties of the GC. By comparing the observed properties of such GC models with available observational properties of Galactic GCs, I will identify Galactic GCs that are most likely to be hosting a large population of BHs.

Sara Rastello (Rome): *Stellar BH Binary Mergers in Open Clusters*

The recent detection of gravitational waves by the LIGO/VIRGO collaboration, produced by the merging of two massive (M25 Solar masses) black holes, provides the first confirmation that such massive systems exist and may merge in a Hubble time. In order to shed light on this intriguing phenomenon, we investigate the dynamical evolution of a massive stellar black hole binary (BHB) evolving in a typical Galactic open clusters (Moc ~0.3-4 × 10^3 M⊙). Our study is done by means of high precision, direct, N-body simulations carried out with the NBODY7 code. Exploring the dynamical evolution of such massive BHBs in four different cluster models we found as a general result that in 95% of the cases the dynamical interactions induce a shrink of the BHB semi-major axis and contemporary increase its eccentricity. We also found that in such young, low-density and dynamically active stellar systems, repeated stellar encounters can drive the BHB coalescence, in a fraction of the investigated cases (2%), depending on the host cluster properties.

Sambaran Banerjee (Bonn): *Stellar-mass BHs in Young Massive and Open Clusters and Their Role in GW Generation*

The study of stellar-mass black holes (BHs) in dense stellar clusters is in the spotlight, in the era of the LIGO's detections and the identifications of BH candidates in globular clusters (GCs). This ongoing series of study presents sets of evolutionary models of compact open- or young massive-type stellar clusters of varying size and metallicity. Adopting state-of-the-art schemes for stellar wind and remnant formation, such model clusters are evolved ab initio with state-of-the-art, relativistic, direct N-body approach for at least 10 Gyr or until dissolution. The binary-black hole (BBH) mergers obtained in these models show prominence in in-cluster, dynamically formed triple-mediated mergers compared to those occurring among the dynamically-ejected BBHs. This effect, which stems from the elevated tendency to form compact subsystems in such lower-mass clusters and their self-consistent relativistic treatment, remains to be true in the presence of a realistic primordial-binary population which, in fact, tends to boost such in-situ mergers. These dynamical BBH mergers from young massive- and open-type clusters are inherently consistent with the to-date LIGO-observed BBH events and would add up to BBH merger rates comparable to those from GCs and nuclear clusters. In the latest set of such simulations [Banerjee, S., in prep.], the nature of the subsystems, hosting the relativistic coalescences, are tracked in detail. Such studies also suggest that ~Gyr-old open clusters would be potential hosts for tight (detached) BH-main sequence binaries (of size ~1-10 AU) as recently discovered in the GC NGC 3201. [References: Banerjee, S., 2017, MNRAS, 467, 524; Banerjee, S., 2018, MNRAS, 473, 909]

Vaclav Pavlik (Prague): *The BH Retention Fraction in Star Clusters*

Recent research has been constraining the retention fraction of black holes (BHs) in globular clusters by comparing the degree of mass segregation with N-body simulations. They are consistent with an upper limit of the retention fraction being 50 % or less. In this work, we focus on direct simulations of the dynamics of BHs in star clusters. We aim to constrain the effective distribution of natal kicks that BHs receive during supernova explosions and to estimate the BH retention fraction. We used the collisional N-body code “nbody6” to measure the retention fraction of BHs for a given set of parameters which are: the initial mass of a star cluster, the initial half-mass radius and σ, which sets the effective Maxwellian BH velocity kick distribution. We compare these direct N-body models with our analytic estimates and newest observational constraints. The numerical simulations show that for the 1D velocity kick dispersion σ < 50 km/s, clusters with radii of 2 pc and initially more massive than 5×10^3 Msun retain more than 20 % of BHs within their half-mass radii. Our simple analytic model yields the number of retained BHs in a good agreement with the N-body models. Furthermore, the analytic estimates show that ultra-compact dwarf galaxies (UCDs) should have retained more than 80 % of their BHs for σ < 190 km/s. Although our models do not contain primordial binaries, in the most compact clusters with 10^3 stars, we have found evidence of delayed SN explosions producing BHs due to dynamically formed binary stars. These cases do not occur in the more populous or expanded clusters.

Kyle Kremer (CIERA): *How BHs Shape the Dynamical Evolution and Observable Properties of GCs*

Numerical simulations have shown that black holes (BHs) can strongly influence the evolution and present-day observational properties of globular clusters (GCs). Over the past decade, stellar-mass BH candidates have been identified in several Milky Way (MW) GCs. Using a Monte Carlo code, we construct GC models that match several MW clusters including NGC 3201, the first cluster in which a stellar-mass BH was identified through radial-velocity measurements. We predict that NGC 3201 contains 200 stellar-mass BHs. Furthermore, we explore the dynamical formation of main sequence-BH binaries and demonstrate that systems similar to the observed BH binary in NGC 3201 are produced naturally.

Vincent Henault-Brunet (Herzberg): *Weighing Populations of Dark Remnants in GCs with Multimass Models*

The growing number of candidate stellar-mass black holes (BHs) observed in globular clusters (GCs) may represent the tip of the iceberg of a larger population of BHs in these systems. To fully understand the evolution of BHs in clusters and the importance of dynamical formation of BH-BH binaries for recent gravitational wave detections, we must constrain the actual size of these BH populations in GCs at the present day. In this talk, I will describe applications of equilibrium distribution function based multimass models (that properly account for mass segregation) to infer the content of dark stellar remnants in GCs, a fast and flexible alternative/complement to the more computationally intensive Monte Carlo and N-body evolutionary models. I will first demonstrate the ability of these multimass models to recover the mass distribution of remnants by applying them to mock data, and then show model fits to the observed properties of selected Milky Way GCs.

Natasha Ivanova (Alberta): *Formation of BH X-Ray Binaries with Non-degenerate Donors in GCs*

We discuss a formation channel for low-mass X-ray binaries with black hole accretors and non-degenerate donors via grazing tidal encounters with subgiants. The donors—stripped subgiants—will be strongly underluminous when compared to subgiant or giant branch stars of the same colors. As the underluminous stripped strugglers can only be formed by grazing encounters with black holes, their detections could provide strong constraints on the number density of the retained black holes in Milky Way globular clusters.

Ross Church (Lund): *47 Tux X9: A UCXB with a BH Accretor*

47 Tuc X9 is an unusual ultra-compact X-ray binary located in the core of the globular cluster 47 Tucanae. I will explain why observations in the radio and X-ray suggest a black hole accretor, and show that our SPH simulations of mass transfer from white dwarfs to compact objects imply the accretor must be a black hole. Finally I will discuss how dynamical processes in globular clusters can lead to the formation of close WD-BH binaries at a rate comparable with the observation of 47 Tuc X9.

Wednesday

EVENING SESSION – GW Sources [Chair: Steve McMillan]

Michela Mapelli (Innsbruck): *Merging Compact Objects in a Cosmological Context*

Carl Rodriguez (MIT): *Creating a New Generation of (highly spinning and very massive) Binary BH Mergers*

Johan Samsing (Princeton): *Formation of Eccentric BH Mergers*

Mike Zevin (CIERA): *The Role of Binary–Binary Encounters in Inducing Highly Eccentric GW Inspirals*

Bence Kocsis (Eotvos): *Distinguishing Source Populations with LIGO/VIRGO*

Katelyn Breivik (CIERA): *LISA Sources in GCs*

Elisa Bortolas (Padova): *EMRIs Triggered by Supernova Kicks in the Galactic Center*

Bao-Minh Hoang (UCLA): *Black Hole Mergers in Galactic Nuclei*

Michela Mapelli (Innsbruck): *Merging Compact Objects in a Cosmological Context*

The cosmological framework of merging black hole and neutron star binaries has often been overlooked in the past, but is crucial for our understanding of LIGO and Virgo events, because binaries which merge in the backyard of the Milky Way (at redshift 0.1) might have formed at much larger redshift (z~4 or more). In this talk, I present a new model to describe the cosmic merger rate of black holes and neutron stars, accounting for both isolated and dynamically formed binaries. I show that most GW150914, GW170104 and GW170814-like events come from metal-poor stellar binaries which formed at high redshift. Finally, I discuss the properties of the host galaxies of merging binaries.

Carl Rodriguez (MIT): *Creating a New Generation of (highly spinning and very massive) Binary BH Mergers*

Since the first detection two years ago, gravitational waves have promised to revolutionize the physics and astrophysics of compact objects. But to understand what these gravitational waves are telling us, we need to understand how these relativistic binary systems formed in the first place. In this talk, I will describe how the inclusion of post-Newtonian physics in models of dense star clusters can radically change the predicted masses, spins, and eccentricities of dynamically-formed binary black hole mergers. In particular, I will discuss how black holes can undergo multiple mergers in globular clusters, creating a second generation of black holes more massive (and with potentially greater spins) than those formed through stellar collapse.

Johan Samsing (Princeton): *Formation of Eccentric BH Mergers*

I will show that a non negligible fraction of black hole binary mergers forming in stellar clusters will appear in the LIGO band with an eccentricity 0.1. Recent (Newtonian) studies have argued that eccentric GW sources are unlikely to form, however, with a consistent implementation of post-Newtonian terms in the N-body equation of motion, the fraction is about 100 times higher than previously thought. This brings the fraction of eccentric GW mergers up to about 5%, which could have profound implications for mapping out the dynamical universe through the detection of GW black hole mergers.

Mike Zevin (CIERA): *The Role of Binary–Binary Encounters in Inducing Highly Eccentric GW Inspirals*

The multiple discoveries of coalescing binary black hole systems have enticed exploration into mechanisms responsible for their formation and subsequent merger. In this study, we perform scattering experiments of binary-single and binary-binary black hole interactions from realistic cluster models with post-Newtonian dynamics included. By including post-Newtonian effects in the equations of motion, the dissipation of orbital energy from the emission of gravitational radiation can lead to inspirals and mergers during resonant interactions, oftentimes with measurable eccentricities when entering the LIGO sensitive frequency range. Though less frequent, we find that binary-binary interactions are much more efficient at inducing inspirals than their binary-single counterparts, accounting for ~20-30% of in-cluster mergers, depending on the properties of the cluster environment. Binary-binary interactions also readily form stable, hierarchical triple systems that undergo Lidov-Kozai oscillations which over periods of time will impart orbital eccentricity into the inner binary. The gravitational waveforms of eccentric inspirals are distinct from those generated by merging binaries which have circularized, and observations of such systems would highly constrain their formation scenario.

Bence Kocsis (Eotvos): *Distinguishing Source Populations with LIGO/VIRGO*

The detections of gravitational waves from LIGO/VIRGO have opened a window to study astrophysics. I will discuss ways to distinguish between different BH/BH merger source populations including mergers in galactic nuclei and globular clusters, using the distributions of masses, mass ratios, and eccentricities. I will also highlight some smoking gun signatures which may help identify the host environment.

Katelyn Breivik (CIERA): *LISA Sources in GCs*

We explore the formation of double-compact-object binaries in Milky Way (MW) globular clusters (GCs) which may be detectable by the Laser Interferometer Space Antenna (LISA). We use a set of 137 fully-evolved GC models that, overall, effectively match the properties of the observed GCs in the MW. We estimate that, in total, the MW GCs contain ~21 sources which will be detectable by LISA. These detectable sources contain all combinations of black hole (BH), neutron star (NS), and white dwarf (WD) components. We also show that some of the BH-BH binaries produced in globular clusters can have signal-to-noise ratios large enough to be detectable at the distance of the Andromeda galaxy or even the Virgo cluster.

Elisa Bortolas (Padova): *EMRIs Triggered by Supernova Kicks in the Galactic Center*

One of the most promising gravitational wave (GW) sources detectable by the forthcoming LISA observatory are the so-called EMRIs, i.e. GW-driven inspirals of stellar mass compact objects (COs) onto supermassive black holes (SMBHs). In the standard picture, an EMRI may be generated if a CO is scattered in the vicinity of an SMBH by means of relaxation processes. In this talk, I will propose a novel mechanism to produce EMRIs in star-forming nuclei: in these regions, supernova kicks may scatter newborn stellar black holes and neutron stars on extremely eccentric orbits; thus, the timescale over which they are expected to inspiral onto the central SMBH via GW emission may become shorter than the timescale for other orbital perturbations to occur. By applying this argument to our Galactic Center, I will show that up to 0.1 per cent of the COs born in the innermost pc of our Galaxy may become EMRIs as a result of their natal kicks. I will elaborate on the fraction of COs experiencing a proper GW-inspiral versus the ones directly plunging onto the SMBH; finally, I will speculate on the possibility of observing supernova-driven EMRI events occurring in star-forming nuclei other than our Galactic Center.

Bao-Minh Hoang (UCLA): *Black Hole Mergers in Galactic Nuclei*

Almost every galaxy, our own Milky Way included, has a supermassive black hole in its heart. Around these supermassive black holes are the densest stellar structures in the Universe, called nuclear star clusters. These nuclear star clusters are expected to be abundant in stellar-mass black holes (BHs) and BH-BH binaries. Gravitational perturbations from the central supermassive black hole can have significant effects on the BH-BH binary (via the so-called Eccentric Kozai-Lidov Mechanism). In particular, the eccentricity may approach unity, and the pericenter distance may become sufficiently small that gravitational-wave emission drives the BH-BH binary to merge. We construct a proof-of-concept model for this process and, specifically, we study the eccentric Kozai-Lidov mechanism in unequal-mass, soft BH-BH binaries. We find that this mechanism leads to enhanced merger rate and could potentially compete with other dynamical formation processes for merging BH–BH binaries, such as interactions of stellar BHs in globular clusters, or in nuclear star clusters without a central supermassive black hole.

Thursday

MORNING SESSION – GW Sources and Stellar Remnants in Star Clusters – continued [Chair: Vicky Kalogera]

Debatri Chattopadhyay (Swinburne): *Compact Binary Coalescences – Astrophysical Sources of GWs*

Jongsuk Hong (KIAA): *Binary BH Mergers from GCs – The Impact of Host Cluster Properties*

Mario Spera (Innsbruck): *Formation and Evolution of BHs in Star Clusters*

Claire Ye (CIERA): *Modeling Millisecond Pulsars in GCs*

Mario Cadelano (Bologna): *A Secondary View on Millisecond Pulsars in GCs*

Mark Morris (UCLA): *The Distribution of Stellar Remnants in the Central Parsecs of the Galaxy*

Aleksey Generozov (Columbia): *Formation of X-ray Binaries via Tidal Capture in the Galactic Center*

Lucy McNeill (Monash): *Gravitational Radiation from Tidally Interacting Compact Binaries*

Nicola Giacobbo (Padova): *A Critical Look at Progenitors of Merging Black Hole Binaries* [C]

Debatri Chattopadhyay (Swinburne): *Compact Binary Coalescences – Astrophysical Sources of GWs*

Star Clusters are efficient environments for formation of compact binaries. The dense environment also gives plenty of opportunity for these objects to go through dynamical interactions and even subsequent mergers. Doing NBODY simulations of star clusters with various initial conditions and noting these effect on the production of compact binaries can tell us about gravitational wave events aLIGO will be observing. Comparing compact binary mergers in dense cluster environments to isolated galactic disk compact binary mergers will help us to figure out how efficient dense environments are for producing gravitational wave events.

Jongsuk Hong (KIAA): *Binary BH Mergers from GCs – The Impact of Host Cluster Properties*

Globular clusters (GCs) provide a good environment for the formation of black hole binaries (BBHs), some of which can merge with gravitational waves (GW) within the age of the Universe. We have performed a survey of Monte-Carlo simulations to explore the impact of host GC properties on the formation and detection of BBH mergers originating from GCs. We find that the number of BBH mergers from GCs is influenced by not only the initial mass but also the initial half-mass radius and primordial binary fraction of GCs. BBH mergers can be identified by their origins, primordial and dynamical BBH mergers, significantly affecting their properties such as the mass and merging time distributions. In this talk we will provide some empirical relations like the expected number of BBH mergers from individual GCs and the time evolution of merger rates of these BBHs, which can be used to estimate the detection rates.

Mario Spera (Innsbruck): *Formation and Evolution of BHs in Star Clusters*

The first confirmation of the existence of merging stellar-mass black holes (BHs) came on September 14 2015, when the LIGO interferometers observed the gravitational-wave signal from two BHs with mass larger than 25 Msun (GW150914). Since then, four additional BH mergers were observed, and two of them have BHs with mass larger than 30 Msun. From the theoretical point of view, the models that predict the formation and evolution of binary BHs are still uncertain. In this talk, I will present the BH mass spectrum and the statistics of binary BHs obtained with the SEVN code. SEVN is our new population synthesis code that implements up-to-date stellar evolution prescriptions for both isolated and binary stars and up-to-date supernova explosion models, including pulsational pair-instability and pair-instability supernovae. I will also discuss the implications of our predictions for the expected number and merger rates of binary BHs in dense star clusters, as a function of metallicity.

Claire Ye (CIERA): *Modeling Millisecond Pulsars in GCs*

Over a hundred millisecond pulsars (MSPs) have been observed in globular clusters (GCs), motivating theoretical studies of the formation and evolution of these objects. We study the formation and dynamical evolution of MSPs in GCs using our Cluster Monte Carlo code. We show that neutron stars formed in core-collapse supernova or accretion-induced/merger-induced collapse can be spun up through mass transfer to form MSPs. Furthermore, we show that the number of MSPs is anti-correlated with the total number of black holes (BHs) retained in the host cluster. This is consistent with theoretical studies showing that BHs have strong influence on the evolution of GCs and their exotic stellar populations. As a result, MSPs could be used as an observational constraint on the BH populations in GCs.

Mario Cadelano (Bologna): *A Secondary View on Millisecond Pulsars in GCs*

Millisecond pulsars are rapidly rotating neutron stars formed in binary systems through mass accretion from evolving companion stars. Due to their collisional environments, globular clusters host 40% of the entire millisecond pulsar population known in the Galaxy and since this population is mainly composed by compact binary systems, they are ideal sources of gravitational waves to be investigated with the next generation of interferometers. I will present the main properties of this population as seen from the optical analysis of their secondary stars, i.e. the pulsar companion stars. The different properties of the companion stars are a key ingredient to perform a proper classification of millisecond pulsars, as well as to shed light on their accretion history and evolution, to date still obscure. I will go through the characterization of the companion stars from the very early stages of the evolution, where mass accretion is still on-going, to the very latest stages, where the secondary stars appear as heavily stripped and perturbed low-mass remnants.

Mark Morris (UCLA): *The Distribution of Stellar Remnants in the Central Parsecs of the Galaxy*

X-ray Observations with the Chandra X-ray Observatory are providing the best information presently possible on the radial distribution of binary systems containing white dwarfs, neutron stars, and black holes in the nuclear stellar cluster of our Galaxy. These distributions constrain a variety of processes, including binary formation and disruption, stellar mergers, the survival of primordial binaries, and mass segregation. In this talk, I will present the results of the most complete and reliable catalog yet compiled of point X-ray sources in the inner ~20 pc of the Galactic center, based on a total of 4.5 Ms of observations made over a 15-year period with Chandra. Dynamical implications of the distributions of the various classes of X-ray sources will be discussed.

Aleksey Generozov (Columbia): *Formation of X-ray Binaries via Tidal Capture in the Galactic Center*

Observations have revealed the presence of a large population of X-ray binaries (XRBs) in the central parsec of the Galactic Center, including ~10 black hole XRBs discovered recently by Hailey et al. 2018. This population is likely just the tip of the iceberg, signifying the presence of hundreds of less luminous XRBs. I will describe how tidal capture of low mass stars by black holes can account for this population.

Lucy McNeill (Monash): *Gravitational Radiation from Tidally Interacting Compact Binaries*

The Laser Interferometer Space Antenna (LISA) is expected to detect hundreds of galactic white-dwarf binaries in the first weeks of operation alone. These detections will rely on accurate waveform templates to compare with the signal. Pairs of compact objects formed from binary-binary interactions in dense stellar systems are expected to be highly eccentric and close at periastron. If eccentric and close enough, these binaries (involving stars with finite structure) can undergo significant energy and angular momentum exchange between the stellar tides and the orbit. Binaries in this scheme will emit gravitational waves in the LISA band, and some of these pairs may be detectable before they circularize. Due to the variation of the orbital frequency from tidal interactions, they produce significantly different waveforms compared to eccentric binaries where tides have not been considered in the waveform. This talk will discuss the normal mode analysis used to model such systems, and the qualitative features of the gravitational waves emitted by these systems.

Nicola Giacobbo (Padova): *A Critical Look at Progenitors of Merging Black Hole Binaries* [C]

The recent detection of gravitational waves has proven the existence of massive stellar black hole binaries (BHBs), but the formation channels of BHBs are still an open question. One of the most powerful tools to investigate the origin of BHBs are the population-synthesis codes. In this talk, I describe my new code MOBSE, which is an updated version of the widely used binary population synthesis code, BSE (Hurley et al. 2002). In MOBSE, I have included the most recent models of star evolution, wind mass-loss and core-collapse supernovae, which are the key ingredients to determine the fate of massive stars. Based on the results of MOBSE, I show that only massive metal-poor stars (Z 0.002) can be the progenitors of gravitational-wave events like GW150914. Finally, I show that most of the binary systems leading to the formation of BHBs pass through the common envelope phase.

Thursday

EVENING SESSION – Star and Star Cluster Formation [Chair: Simon Portegies Zwart]

Kenji Bekki (UWA): *Formation of GCs with Abundance Spreads in R-process Elements – Evidence of Neutron Star Mergers*

Francisca Concha-Ramirez (Leiden): *Viscous Evolution of Circumstellar Disks in Young Star Clusters*

Michael Fellhauer (Concepcion): *A New Formation Channel for Compact Ellipticals*

Aleksandra Kuznetsova (Michigan): *Signatures of Star Cluster Formation by Global Gravitational Collapse*

Giampaolo Piotto (Padova): *Multiple Stellar Populations in Star Clusters*

Florent Renaud (Lund): *Forming the first GCs*

Christina Schoettler (Sheffield): *Kinematics of Stars Ejected from Young Clusters in N-body Simulations*

Joshua Wall (Drexel): *Effects of Combined Stellar Feedback on Star Formation in Stellar Clusters*

Kenji Bekki (UWA): *Formation of GCs with Abundance Spreads in R-process Elements – Evidence of Neutron Star Mergers*

Recent observations have revealed that a number of the Galactic globular clusters (GCs) show star-to-star abundance spreads in r-process elements (e.g., Eu and Ba). In my talk, I discuss these observations in the context of chemical enrichment by gaseous ejecta from neutron star mergers (NSMs) in the early formation histories of these GCs. Our new simulations of GC formation demonstrate that such high-speed gaseous ejecta from NSMs can be trapped by intra-cluster medium, if ejecta from AGB stars can be accumulated within GCs ~ 10^8 yr after GC formation. Our simulations therefore suggest that stars with enhanced r-process abundances can also have Na-enhanced abundance patterns, which is consistent with observations. Based on these results, we discuss the key roles of NSMs in chemical and dynamical histories of GCs.

Francisca Concha-Ramirez (Leiden): *Viscous Evolution of Circumstellar Disks in Young Star Clusters*

Stars with circumstellar disks may form in environments with high stellar and gas densities which affects the disks through processes like truncation from dynamical encounters, ram pressure stripping, and external photoevaporation. Circumstellar disks also undergo viscous evolution which leads to disk expansion. Previous work indicates that dynamical truncation and viscous evolution play a major role in determining circumstellar disk size and mass distributions. However, it remains unclear under what circumstances each of these two processes dominates. Here we present results of simulations of young stellar clusters taking viscous evolution and dynamical truncations into account. We model the embedded phase of the clusters by adding leftover gas as a background potential which can be present through the whole evolution of the cluster, or expelled after $\SI{1}{Myr}$. We compare our simulation results to actual observations of disk sizes, disk masses, and accretion rates in star forming regions. We argue that the relative importance of dynamical truncations and the viscous evolution of the disks changes with time and cluster density. Viscous evolution causes the importance of dynamial encounters to increase in time, but the encounters cease soon after the expulsion of the leftover gas. For the clusters simulated in this work, viscous growth dominates the evolution of the disks. Our model overestimates the observed values for disk mass, size, and accretion rates.

Michael Fellhauer (Concepcion): *A New Formation Channel for Compact Ellipticals*

The formation of compact elliptical (cE) galaxies like M32 is still under debate. We propose a new formation channel making them the high mass extension of massive star clusters and UCDs rather than the low mass extension of elliptical galaxies. Our models show that we can reproduce all structural and dynamical properties of cEs in the merging star cluster scenario, i.e. the formation out of a dense and massive cluster of star clusters.

Aleksandra Kuznetsova (Michigan): *Signatures of Star Cluster Formation by Global Gravitational Collapse*

Our recent models of star cluster formation have shown that the global gravitational collapse (also called cold collapse) of molecular clouds can adequately reproduce the morphological and broad kinematic features of young embedded star clusters. I will discuss the results of several numerical simulations that model the formation of realistic young star clusters, using the Orion Nebula Cluster as a test case. We find that star formation by cold collapse creates a rapidly changing landscape during cluster assembly, creating both primordial and dynamical mass segregation during a relatively short period of time. However, there is evidence for kinematic and morphological substructure that can survive to later times, an imprint of the importance of the local gravitational potential in building clusters and associations. Our models can replicate a range of kinematic signatures seen in kinematic studies of the gas in the OMC-1 region and in radial velocity surveys of the stars in Orion A. Finally, I will detail the predicted range of observational signatures that can be seen with GAIA for young clusters that have formed by global gravitational collapse.

Giampaolo Piotto (Padova): *Multiple Stellar Populations in Star Clusters*

The presence of multiple sequences lin the color-magnitude diagrams of old stellar clusters, associated to a complex chemestry mainly involving light elements is now fully demonstrated and widely accepted. Still, we lack of a formation scenario able to repreduce all observational facts. In my talk, I will review the present photometric, spectroscopic, and kinematical results and the possible future observations that we can undertake to gather new data useful for better understanding this puzzling phenomenon.

Florent Renaud (Lund): *Forming the first GCs*

As one of the densest stellar environments, globular clusters are thought to play an important role on the formation, growth and merger of black holes. To constrain this formation history, in terms of epochs, timescales and frequency, one needs to understand how and when globular clusters are formed. Such studies are also of prime importance in galaxy evolution, as globulars represent a unique way to probe the physics of their host(s) at very high redshift. Yet, it remains unclear what physical process(es) drives the formation of globular clusters, if they all formed the same way, or through multiple channels, and how all this evolves with cosmic time and with galactic environment. In this talk, I will introduce a cosmological simulation resolving, for the first time, the formation sites of the first globular clusters at parsec resolution. I will use it to illustrate how the (inter)galactic environment influences the formation of massive stellar systems at specific times and locations and to explore which physical mechanisms convey this influence from the large scales down to the star formation scales.

Christina Schoettler (Sheffield): *Kinematics of Stars Ejected from Young Clusters in N-body Simulations*

Using N-body simulations with 1000 stars probing the early phases of star cluster evolution, we investigate the mass and velocity distributions of stars that become unbound from these clusters or are ejected. 'Runaway stars' that are found at large distances from star-forming regions moving at high velocities, are generally higher mass stars, e.g. O or B stars. Due to observational limitations, it is still difficult to find lower mass stars that have been ejected from young clusters. It is unclear if high-mass stars are more, less or equally likely to be ejected than low-mass stars. Few-body dynamics suggests that in an interaction the least massive object is ejected, so we should find many more ejected low-mass stars than high-mass stars. However in high N-body systems, this relation does not always apply. In our parameter space study, we used a broad set of differing initial conditions from subvirial to supervirial, sub-structured to roughly uniform. Preliminary results suggest that the fraction of ejected/unbound high-mass stars compared to the fraction of ejected/unbound low-mass stars differs considerably with initial conditions. In initially smooth, virialised clusters, only a small percentage of stars are ejected at all. In 19 of 20 simulations all of those were low-mass stars, with high-mass star ejection an absolute exception. In initially sub-structured, supervirial clusters, 50% to 95% of all stars are ejected/become unbound, however high-mass stars are always less likely to be ejected than low-mass stars. On the opposite end of the initial conditions, for very subvirial, smooth clusters, at most 30% of stars become unbound, with massive stars on average more likely to be ejected than low-mass stars. In velocity space, our preliminary results suggest that ejection velocities of high-mass stars are on average not higher than those of lower-mass stars.

Joshua Wall (Drexel): *Effects of Combined Stellar Feedback on Star Formation in Stellar Clusters*

We present results of hybrid MHD+N-body simulations of star cluster formation and evolution including self consistent feedback from the stars in the form of radiation, winds, and supernovae from all stars more massive than 7 solar masses. The MHD is modeled with the adaptive mesh refinement code FLASH, while the N-body computations are done with a direct algorithm. Radiation is modeled using ray tracing along long characteristics in directions distributed using the HEALPIX algorithm, and causes ionization and momentum deposition, while winds and supernova conserve momentum and energy during injection. Stellar evolution is followed using power-law fits to evolution models in SeBa. We use a gravity bridge within the AMUSE framework to couple the N-body dynamics of the stars to the gas dynamics in FLASH. Feedback from the massive stars alters the structure of young clusters as gas ejection occurs. We diagnose this behavior by distinguishing between fractal distribution and central clustering using a Q parameter computed from the minimum spanning tree of each model cluster. Global effects of feedback in our simulations will also be discussed.

Friday

MORNING SESSION – Nuclear Star Clusters [Chair: Fred Rasio]

Mayte Alfaro-Cuello (MPIA): *A Deep View into the Nucleus of the Sagittarius Dwarf Spheroidal Galaxy*

Rainer Schödel (IAA-CSIC): *The Stellar Cusp around the Milky Way's Central MBH*

Andrea Ghez (UCLA): *Chemical-Dynamical Modeling of the Milky Way Nuclear Star Cluster*

Alessandro Trani (Tokyo): *Scatterings on a Sphere – Insights on the Origin of the S-stars*

Ákos Szölgyén (Eotvos): *Disks of BHs in Galactic Nuclei*

Yasna Ordenes Briceño (Heidelberg): *Nuclear Star Clusters and their Link to Compact Stellar Systems*

Alexander Rasskazov (Eotvos): *The Rate of GW Capture of Stellar-mass BHs in Nuclear Star Clusters*

Nick Stone (Columbia): *Understanding Elevated Rates of Tidal Disruption in Post-Starburst Galaxies*

Francisco Nogueras-Lara (IAA/CSIC): *GALACTICNUCLEUS: A High Angular Resolution Survey of the Galactic Center* [C]

Mayte Alfaro-Cuello (MPIA): *A Deep View into the Nucleus of the Sagittarius Dwarf Spheroidal Galaxy*

The origin of some of the most massive and complex Galactic globular clusters (GCs)is still unclear and one of the proposed explanations is that they are former nuclear star clusters (NSCs) of dwarf galaxies accreted and disrupted by the Milky Way. In this context, the nucleus of the Sagittarius dwarf spheroidal galaxy (Sgr dSph) offers a privileged view of a nucleus in a stage before the complete stripping of the host galaxy. As part of this complex nucleus the massive GC M54 provides a link between high-mass metal complex GCs and NSCs. In this talk I will show the results of the analysis of ~6600 member stars extracted from MUSE observations of this nucleus. This wealth of chemo-dynamical information allowed the study of a galactic nucleus at an unprecedented detail, unveiling the presence of at least three stellar sub-populations with clear differences in age and metallicity. I will illustrate how these populations can be explained by a combination of events in the nucleus of the Sgr dSph galaxy. Our data show evidences that the build-up of this nucleus could be the result of the interplay between infall and accretion of GCs by dynamical friction effects and of in-situ star formation from gas inflows.

Rainer Schödel (IAA-CSIC): *The Stellar Cusp around the Milky Way's Central MBH*

A stellar cusp in a dense stellar system around a massive black hole is a firm prediction of stellar dynamics. Nevertheless, observational evidence from the nuclear cluster of the Milky Way appeared to contradict the theoretical expectations. In this talk we will review the topic and present the latest observational evidence that provides evidence, from multiple tracers, that the cusp exists, albeit with a flatter slope than predicted by simple models. We show how observations and theory can be reconciled. We confirm that the cusp is not observed in the bright giants and discuss possible explanations.

Andrea Ghez (UCLA): *Chemical-Dynamical Modeling of the Milky Way Nuclear Star Cluster*

Due to its proximity, the Milky Way nuclear star cluster provides us with a wealth of data not available in other galactic nuclei. In particular, we can observe the properties of individual stars. These properties include their positions in two dimension and their velocity in three dimensions. With the rapid advances integral field and multi-object spectroscopy, we can also derive the physical properties of individual stars, such as their metallicity. The combination of dynamics and metallicity can be used to search for kinematic substructures as signatures of the formation of the nuclear star cluster. I will discuss the first chemical-dynamical model of the nuclear star cluster using a mixture model to search for kinematically distinct populations based on metallicity and velocity. In addition, I will also discuss these results in the context of formation models of the cluster.

Alessandro Trani (Tokyo): *Scatterings on a Sphere – Insights on the Origin of the S-stars*

Long-term spectroscopy monitoring has recently set an upper limit to the age of the S-stars, the ~30 stars that lie close (0.04 pc) to the supermassive black hole (SMBH) in the Galactic center. The inferred age is about 6 Myr, which is compatible with the age of the stellar disk that lies at a farther distance from the SMBH (0.04-0.1 pc). This is in tension with one of the leading formation scenarios, according to which the S-stars formed in the tidal breakup of binaries migrated from outside the central parsec. In my talk, I will present a new formation channel that can accommodate the latest observational constraints. I have investigated the outcome of three-body encounters between binary stars (from the young stellar disk) and stellar mass black holes (from the stellar cusp around the SMBH), by means of simulations exploiting Mikkola's regularization scheme. I will show how these Keplerian three-body encounters, in which all encountering bodies orbit around the SMBH, can produce stars with the typical eccentricity of the S-stars. To conclude, I will highlight the role that these encounters can have in enhancing black hole binary mergers in galactic nuclei.

Ákos Szölgyén (Eotvos): *Disks of BHs in Galactic Nuclei*

Gravitational torques among objects orbiting a supermassive black hole drive the rapid reorientation of orbital planes in nuclear star clusters (NSCs), a process known as vector resonant relaxation. In my talk, I discuss the statistical equilibrium of NSCs with a distribution of masses, semi-major axes, and eccentricities (Szolgyen & Kocsis, arxiv:1803.07090). We examined the case of NSCs formed by episodes of star formation or globular cluster infall and constructed a Monte Carlo Markov Chain method to sample the microcanonical ensemble of the NSC and which drive the system to equilibrium. Results show that massive stars and stellar mass black holes form a warped disk, while low mass stars resemble a spherical distribution with a possible net rotation. This explains the origin of the clockwise disk in the Galactic center and predicts a population of black holes (BHs) embedded within this structure. The rate of mergers among massive stars, tidal disruption events among BHs and massive stars, and BH–BH mergers are highly increased in such disks. The first two may explain the origin of the observed G1 and G2 clouds, the latter may be important for gravitational wave detections with LIGO and VIRGO. More generally, black holes are expected to settle in disks in all spherical dense stellar systems including globular clusters.

Yasna Ordenes Briceño (Heidelberg): *Nuclear Star Clusters and their Link to Compact Stellar Systems*

The Next Generation Fornax Survey (NGFS) recently uncovered a surprising bimodal mass distribution of nuclear star clusters (NSCs) with peaks located at log(M_star/Msun)~5.4 and ~6.3. These two NSC sub-populations show also different stellar population properties. The sub-population with more massive nuclei are older than 2 Gyr and have metal-poor stellar populations (Z0.02Zsun), while the less massive nuclei are younger than ~2 Gyr with metallicities in the range 0.02Z/Zsun1. There is tentative evidence for a spatially coherent structure where younger NSCs are predominantly found. In addition, we found an anti-correlation between the nucleus-to-galaxy mass ratio (Mass_nuc/Mass_gal) as a function of the galaxy mass. This relation is opposite to the one found for massive galaxies and is reaching values up to 10% in the mass ratio for the lowest dwarf galaxy masses. In light of these results, I will discuss the challenges that these findings imply for modern NSC formation scenarios and show how the NSC properties are correlated with those of its neighborhood.

Alexander Rasskazov (Eotvos): *The Rate of GW Capture of Stellar-mass BHs in Nuclear Star Clusters*

One of the possible origins of black hole (BH) mergers is the direct capture when two single BHs have a close encounter and form a binary due to gravitational wave emission. In this project I calculate the rate of such events in galactic nuclei focusing on the effect of dynamical friction which brings a large number of heavy BHs inside the nuclear star cluster. The total event rates turn out to be rather small (~0.02-0.1 yr^-1 Gpc^-3) although that estimate is highly uncertain given the uncertainty in BH mass distribution and other parameters.

Nick Stone (Columbia): *Understanding Elevated Rates of Tidal Disruption in Post-Starburst Galaxies*

Tidal Disruption Events (TDEs) occur when stars pass too close to supermassive black holes in galactic nuclei. Statistical samples of these luminous flares offer information on the parsec-scale stellar dynamics of distant galaxies. One puzzling observational discovery is the peculiar host galaxy preference of TDEs: an order unity fraction of observed flares originate in “E+A” or post-starburst galaxies, which make up only ~0.1% of all low-redshift galaxies. Several dynamical mechanisms have been proposed to explain this overproduction of tidal disruption events, from unusually dense nuclear star clusters to radially anisotropic stellar systems to binary supermassive black holes. We show how delay time distributions (DTDs) can break degeneracies between such hypotheses and help determine which exotic dynamical mechanism is responsible for the post-starburst preference. In the context of a single dynamical model, the DTD aids in constraining free parameters. We predict theoretical DTDs for overdense nuclear star clusters, radially biased galaxies, and a simplified version of the supermassive black hole binary scenario. By comparing to the observed DTD, we can preliminarily exclude the latter hypothesis. Both overdense nuclear star clusters and radial velocity biases appear compatible with the observed delay time distribution, though the radial anisotropy explanation is in tension with observed TDE host masses.

Francisco Nogueras-Lara (IAA/CSIC): *GALACTICNUCLEUS: A High Angular Resolution Survey of the Galactic Center* [C]

The GALACTICNUCLEUS survey is a high angular resolution, 0.2”, JHK_s survey of the central few thousand square parsecs of the Galactic centre (GC) that reaches a few magnitudes deeper than any existing, seeing-limited surveys (Nogueras-Lara et al, 2018). The centre of the Milky Way is of fundamental interest as it constitutes a unique laboratory to study the stellar nuclei and their role in the context of galaxy evolution. Our main goal is to obtain a far more global view of the GC’s stellar population, structure and history, overcoming the extreme crowding and extinction that characterize this very dense and extreme environment.

Friday

EVENING SESSION – Massive Black Holes [Chair: Natasha Ivanova]

Nora Lützgendorf (ESA/STScI): *An Upper Limit on the Mass of a Central BH in the LMC*
Eva Noyola (UT Austin): *Looking for Dark Matter and Finding a BH Instead*
Mario Pasquato (INAF): *Finding IMBHs in Star Clusters with Machine Learning*
Federico Abbate (Milano-Bicocca): *Limits on Central Black Holes from Pulsar Timing in GCs*
Dominik Schleicher (Concepcion): *The Importance of Collisions during the Formation of the First MBHs*
Giacomo Fragione (Jerusalem): *IMBHs in GCs – Retention, GWs and Tidal Disruption Events*
Karina Voggel (Utah): *A New Method to Estimate the Number of SMBHs Hiding in UCDs*
Alessandro Ballone (INAF Padova): *Weighing the IMBH candidate CO-0.40-0.22* in the Galactic Centre* [C]

Nora Lützgendorf (ESA/STScI): *An Upper Limit on the Mass of a Central BH in the LMC*

We constrain the possible presence of a central black hole (BH) in the center of the Large Magellanic Cloud (LMC). This requires spectroscopic measurements over an area of order a square degree, due to the poorly known position of the kinematic center. Such measurements are now possible with the impressive field of view of the Multi Unit Spectroscopic Explorer (MUSE) on the ESO Very Large Telescope. We used the Calcium Triplet (850 nm) spectral lines in many short-exposure MUSE pointings to create a two-dimensional integrated-light line-of-sight velocity map from the 108 individual spectra, taking care to identify and remove Galactic foreground populations. The data reveal a clear velocity gradient at an unprecedented spatial resolution of 1 arcmin2. We fit kinematic models to arrive at a 3sigma upper-mass-limit of ≈ 107M⊙ for any central BH – consistent with the known scaling relations for supermassive black holes and their host systems. With the new Gaia data release we hope to have a new center to refine our search.

Eva Noyola (UT Austin): *Looking for Dark Matter and Finding a BH Instead*

I will present a surprising result for a Milky Way dwarf spheroidal galaxy. As part of a large program trying to map the shape of dark matter haloes in dwarf galaxies and possible dark matter content in globular clusters, we encountered one case for which the kinematic profile appears to point to the presence of a central black hole. I will show the results of our ongoing dynamical models for this object.

Mario Pasquato (INAF): *Finding IMBHs in Star Clusters with Machine Learning*

I will present the first results of my machine-learning based approach at indirect intermediate-mass black hole detection in star clusters based on simulated optical and pulsar timing data. I use Montecarlo and Nbody simulations of clusters with or without an IMBH, generate mock data, and perform supervised classification on a set of variables manually generated from the data (features). I will discuss the performance of different machine learning algorithms measured via k-fold cross-validation in terms of the receiver operating characteristic curve, and its dependence on the way mock data is generated and translated into features.

Federico Abbate (Milano-Bicocca): *Limits on Central Black Holes from Pulsar Timing in GCs*

Globular clusters have been proposed to host intermediate mass black holes (IMBHs) in their center. Different methods have been proposed for their search as electromagnetic sources or through dynamical signatures. At present conclusive evidence has not been found. Here we suggest a new method based on precise measurements of the time derivatives of the acceleration made in pulsars present in the cluster. These measures can provide a wealth of information on the internal dynamics of the cluster. Using state-of-the-art N-body numerical simulations we find that measuring jerks and jounces of a large number of pulsars makes it possible to constrain the presence or set upper limits on the mass of the central black hole. This method has been tested on a number of Milky Way globular clusters.

Dominik Schleicher (Concepcion): *The Importance of Collisions during the Formation of the First MBHs*

For the formation of the first black holes, two main possibilities have been suggested: Direct collapse or the formation by collisions in dense stellar clusters. While the required conditions for direct collapse were shown to be rare in the early Universe, dense stellar clusters are expected as a frequent and generic outcome of gravitational collapse. In addition, the protostars of the new clusters are expected to have larger radii than main-sequence stars, enhancing the probability for collisions. In this talk, I will assess the possibility to produce massive objects via collisions using Nbody6, and outline the required conditions to produce massive black holes. Subsequently, I will discuss how the interaction between stellar-dynamical and gas-dynamical effects may further enhance the masses of the resulting objects.

The results I present are based on the following publications:

https://arxiv.org/abs/1801.05891

https://arxiv.org/abs/1801.05841

Giacomo Fragione (Jerusalem): *IMBHs in GCs – Retention, GWs and Tidal Disruption Events*

The recent discovery of gravitational waves has opened new horizons for physics. Current and upcoming missions, such as LIGO, VIRGO, KAGRA, and LISA, promise to shed light on black holes of every size from stellar mass (SBH) sizes up to supermassive black holes which reside in galactic nuclei. The intermediate mass black hole (IMBH) family has not been detected beyond any reasonable doubt neither directly nor indirectly. Recent analyses suggest observational evidence for the presence of IMBHs in the centers of two Galactic globular clusters. I investigate the possibility that globular clusters were born with a central IMBH, which undergo repeated merger events with stars and SBHs in the cluster core. By means of a semi-analytical method, I follow the evolution of the primordial cluster population in the galactic potential and the Gravitational Wave (GW) mergers of the binary IMBH-SBH systems. The models predict IMBHs within 1 kpc from the Galactic Center and show that the IMBH-SBH merger rate density changes from R~1000 Gpc^-3 yr^-1 beyond z~2 to R~1-10 Gpc^-3 yr^-1 at z~0. The rates at low redshifts may be significantly higher if young massive star clusters host IMBHs. The merger rates are dominated by IMBHs with masses between 10^3 and 10^4 solar masses. Currently there are no LIGO/VIRGO upper limits for GW sources in this mass range, but at design sensitivity these instruments may detect these IMBH-SBH mergers in the coming years. LISA and the Einstein Telescope will be best suited to detect these GW events. The inspirals of IMBH-SBH systems may also generate an unresolved GW background. Finally, I will discuss the predicted rate for the tidal disruption of stars by the central IMBH and its implications for future observations.

Karina Voggel (Utah): *A New Method to Estimate the Number of SMBHs Hiding in UCDs*

Central super-massive BHs (SMBHS) have been discovered in five high mass ultra-compact dwarfs (UCDs) that account for up to ~15% of their total mass (Seth et al. 2014, Ahn et al. 2017, 2018). This essentially confirms that many high-mass UCDs are the remaining nuclei of stripped galaxies. The existence of SMBHs in UCDs could significantly increase the total number of known SMBHs in the local universe. Having a measure of the total amount of stripped Nuclei in a Galaxy cluster would be a unique direct probe of its past merger history and yield an important census of this previously hidden population of SMBHs. Such a census of SMBHs in the local Universe are a crucial ingredient for models in which SMBHs grow through galaxy mergers. UCDs are the remnant nuclei that have not (yet) spiraled into the galaxy center and merged and thus provide a way to probe the frequency of this process. The low-frequency gravitational waves of such merging SMBH will be the prime targets for upcoming space-based gravitational wave detectors such as LISA. However a direct census of SMBHs in UCDs would require adaptive optics IFU observations of every individual UCD to measure its BH mass. This is both observationally too costly and simply not feasible for any faint or distant UCDs with current instrumentation.

Alessandro Ballone (INAF Padova): *Weighing the IMBH candidate CO-0.40-0.22* in the Galactic Centre* [C]

The high velocity gradient observed in the compact cloud CO-0.40-0.22, at a projected distance of 60 pc from the centre of the Milky Way, has led its discoverers to identify the closeby mm continuum emitter, CO-0.40-0.22*, with an intermediate mass black hole (IMBH) candidate. We describe the interaction between CO-0.40-0.22 and the IMBH, by means of a simple analytical model and of hydrodynamical simulations. Through such calculation, we obtain a lower limit to the mass of CO-0.40-0.22* of few 10^4 × M_sun. This result tends to exclude the formation of such massive black hole in the proximity of the Galactic Centre. On the other hand, CO-0.40-0.22* might have been brought to such distances in cosmological timescales, if it was born in a dark matter halo or globular cluster around the Milky Way.

[C] indicates a short contributed talk.