

# Star Clusters with MOCCA: Intermediate-Mass Black Holes, Gravitational Waves, and Synthetic Observations

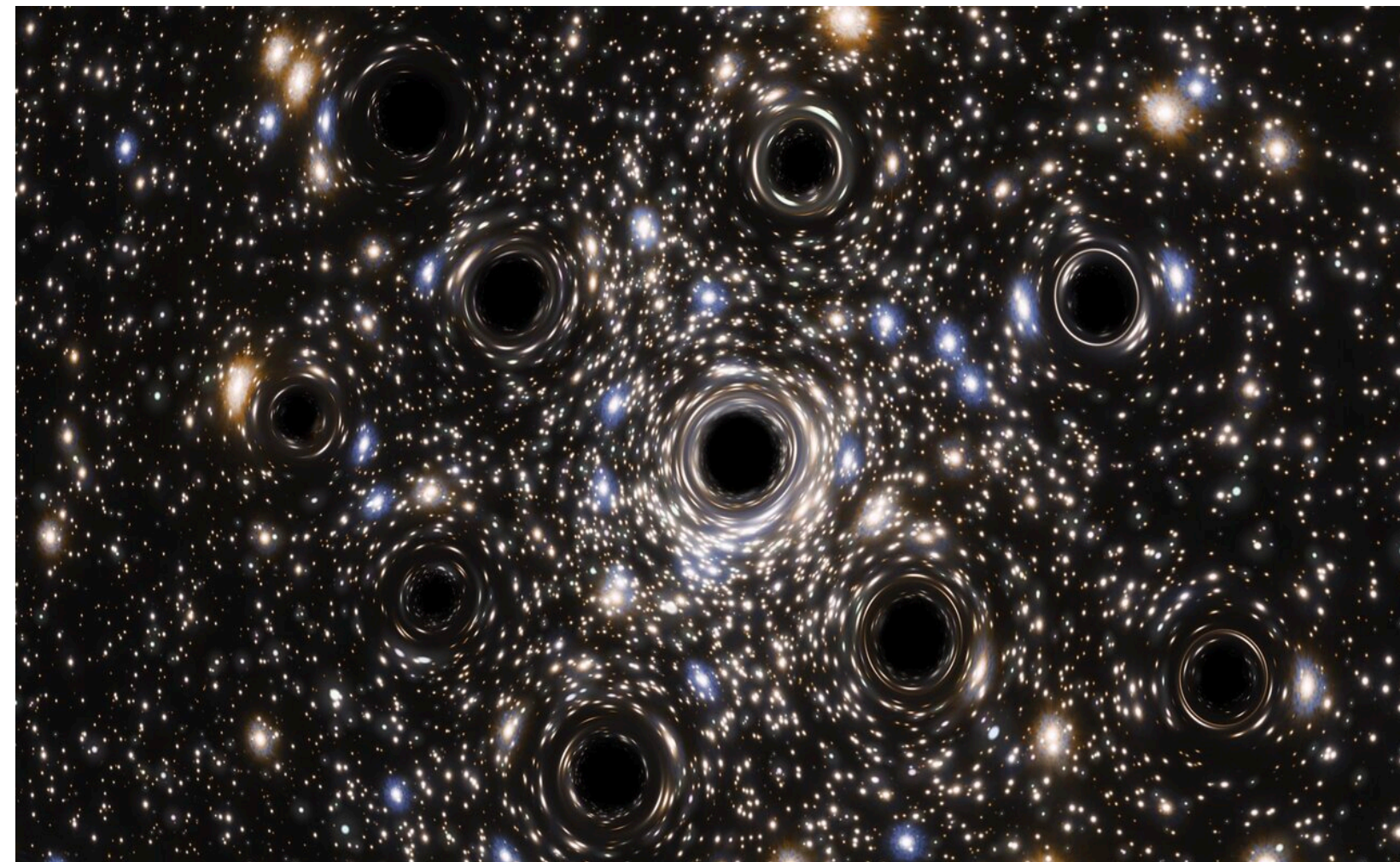


Image Credit: ESA/Hubble, N. Bartmann

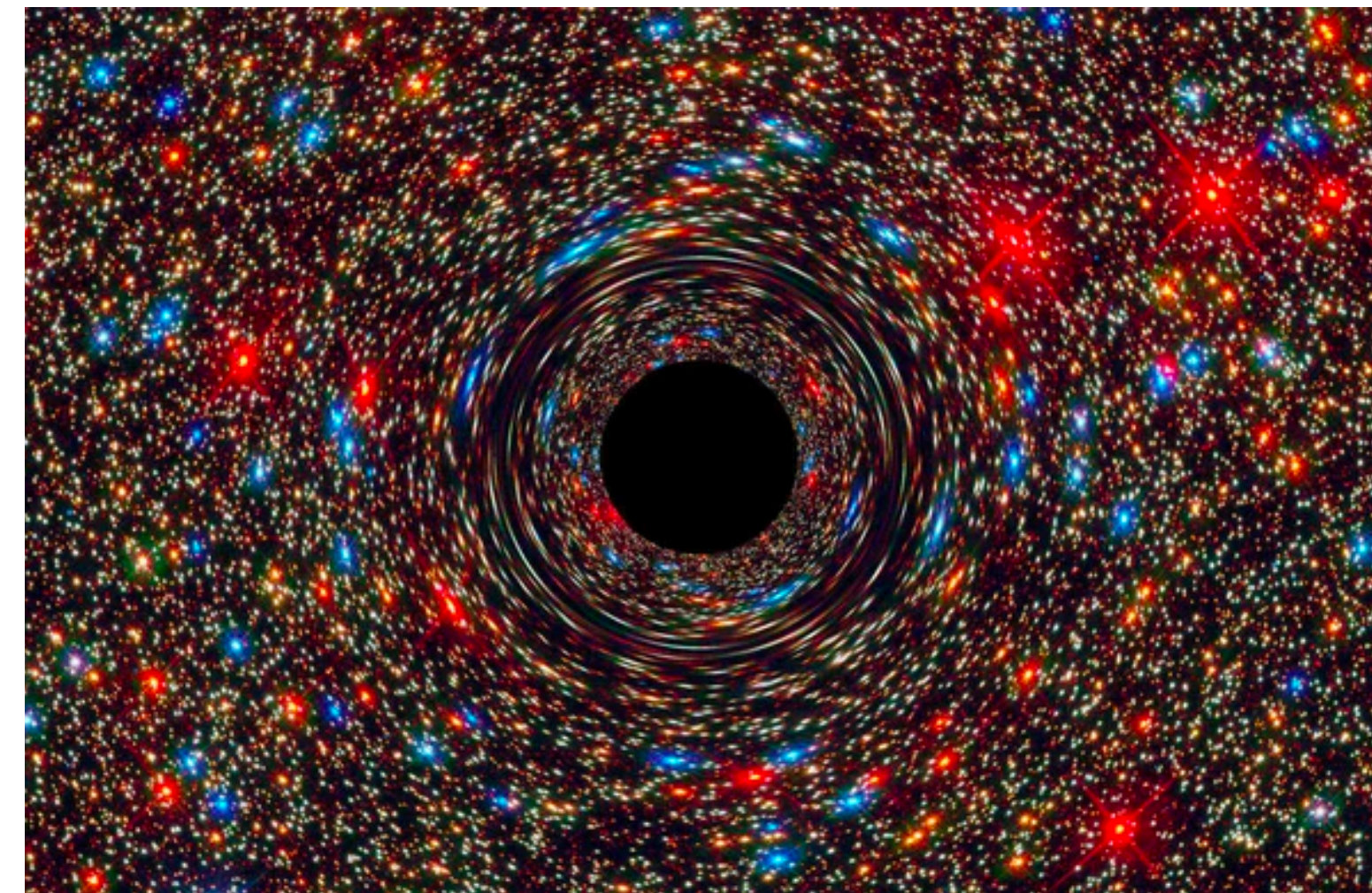
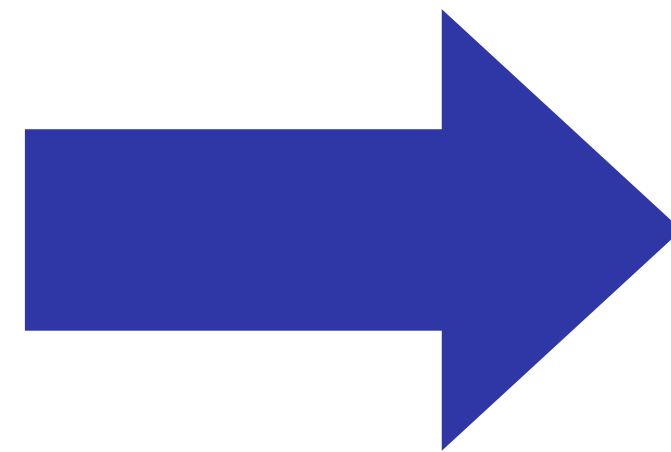


Image Credit: NASA, ESA, and D. Coe, J. Anderson, and R. van der Marel (STScI)

**Abbas Askar**

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Nicolaus Copernicus Astronomical Center  
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**BH GROWTH**  
★★★★ Growing Black Holes in Star Clusters ★★★★★

<https://bhg.camk.edu.pl/>

 **MOCCA**  
<https://moccacode.net/>





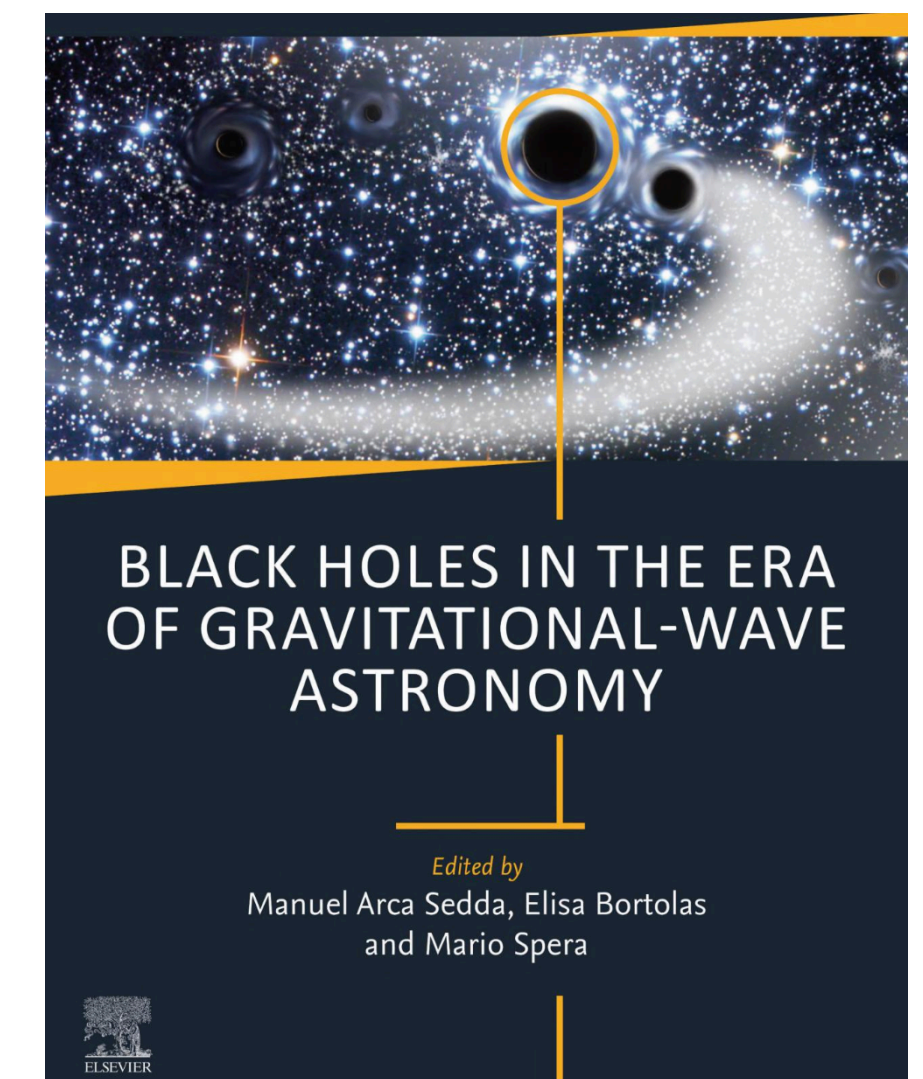
# Scientific activities in 2024

- Papers published in 2024:

- M. Pasquato, P. Trevisan, **A. Askar**, P. Lemos, G. Carenini, M. Mapelli, Y. Hezaveh: *"Interpretable machine learning for finding intermediate-mass black holes"* published in ApJ (2024): <https://arxiv.org/abs/2310.18560>
- B. Bhat, B. Lanzoni, E. Vesperini, F. R. Ferraro, F. I. Aros, **A. Askar**, A. Hypki: *"New Parameters for Star Cluster Dynamics: The Role of Clusters' Initial Conditions"* published in ApJ (2024): <https://arxiv.org/abs/2404.06992>
- L. Hellström, M. Giersz, A Hypki, D. Belloni, **A. Askar**, and G. Wiktorowicz: *"Double white dwarf binary population in MOCCA star clusters: Comparisons with observations of close and wide binaries"* published in A&A (2024): <https://arxiv.org/abs/2405.04314>
- A. R Livernois, F I Aros, E Vesperini, **A Askar**, A Bellini, M Giersz, J Hong, A Hypki, M Libralato, and T Ziliotto: *"Energy equipartition in multiple-population globular clusters"* published in MNRAS (2024): <https://arxiv.org/abs/2410.12968>

- Book chapter published in 2024:

- **A. Askar**, V.F. Baldassare, M. Mezcua: *"Intermediate-Mass Black Holes in Star Clusters and Dwarf Galaxies"* Chapter 2 in the book, *"Black Holes in the Era of Gravitational Wave Astronomy"*, ed. Arca Sedda, Bortolas, Spera, pub. Elsevier (May 2024): <https://arxiv.org/abs/2311.12118>
  - Author of Part I on Formation pathways of IMBHs and GWs from IMBH mergers with other BHs





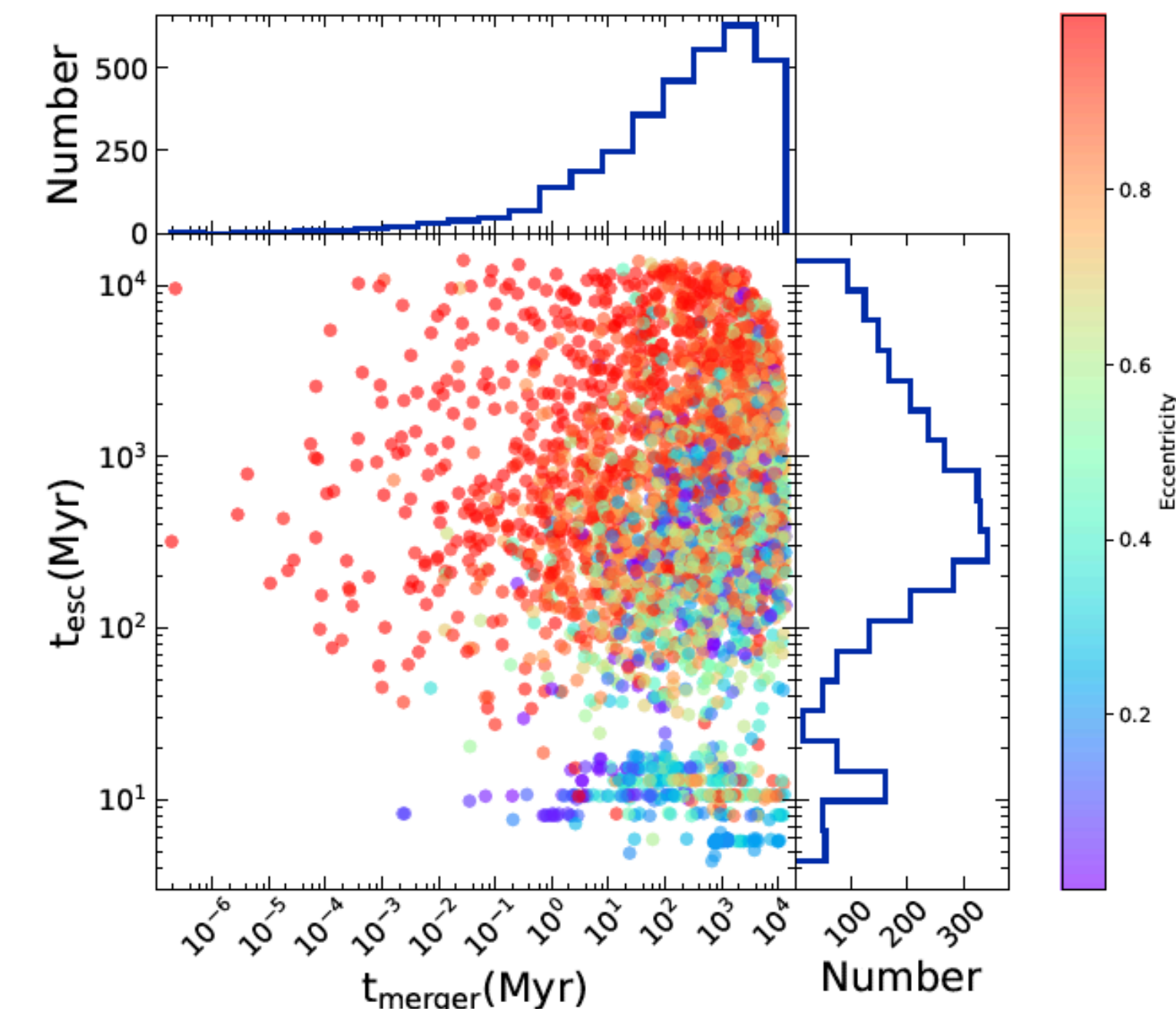
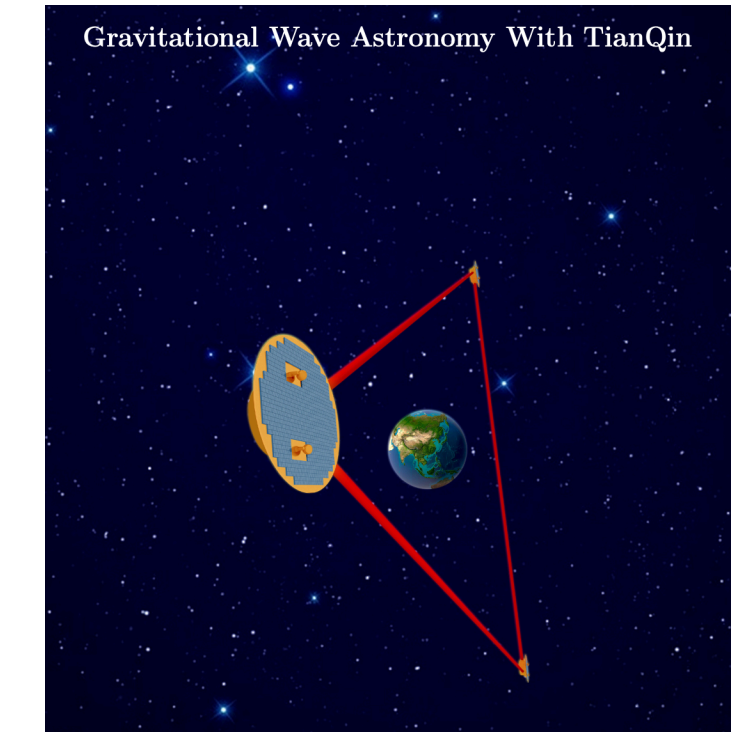
# Scientific activities in 2024

- Papers submitted in 2024 (undergoing review or published in 2025):

- Li E. K., Liu S., Torres-Orjuela A., Chen X., Inayoshi K., Wang L., Hu Y.-M., Amaro-Seoane P., **Askar A.**, Bambi C., and 43 co-authors: "*Gravitational Wave Astronomy With TianQin*" (Submitted to Reports on Progress in Physics 2024): <https://arxiv.org/abs/2409.19665>
  - Contributed to Section on 'light' intermediate-mass ratio inspirals (IMRIs): IMBH-compact object mergers
- M. Giersz, **A. Askar**, A. Hypki, J. Hong, G. Wiktorowicz, L. Hellström: "*MOCCA-III: Effects of pristine gas accretion and cluster migration on globular cluster evolution, global parameters and multiple stellar populations*" (Submitted to A&A 2024): <https://arxiv.org/abs/2411.06421>
- A. Hypki, E. Vesperini, M. Giersz, J. Hong, **A. Askar**, M. Otulakowska-Hypka, L. Hellström, G. Wiktorowicz: "*MOCCA: Global properties of tidally filling and underfilling globular star clusters with multiple stellar populations*" (Published in A&A 2025): <https://arxiv.org/abs/2406.08059>

- Papers completed during 2024 and submitted in January 2025:

- G. Wiktorowicz, M. Giersz, **A. Askar**, A. Hypki, L. Hellström: "*Ultraluminous X-ray sources in Globular Clusters*" (Submitted to A&A Jan 2025): <https://arxiv.org/abs/2501.06037>
- Y. Zhao, **A. Askar**, Y. Lu, Z. Cao, M. Giersz, G. Wiktorowicz, A. Hypki, L. Hellström, W. Ni: "*Multiband gravitational wave observations of eccentric escaping binary black holes from globular clusters*" (Submitted to A&A Jan 2025): preprint will be out soon + followup paper
  - We generate cosmic population of escaping sBBHs originating from GC models simulated with the MOCCA and estimate the detectable numbers of escaping sBBHs by low-frequency detectors



Zhao, Askar et al. submitted (2025)



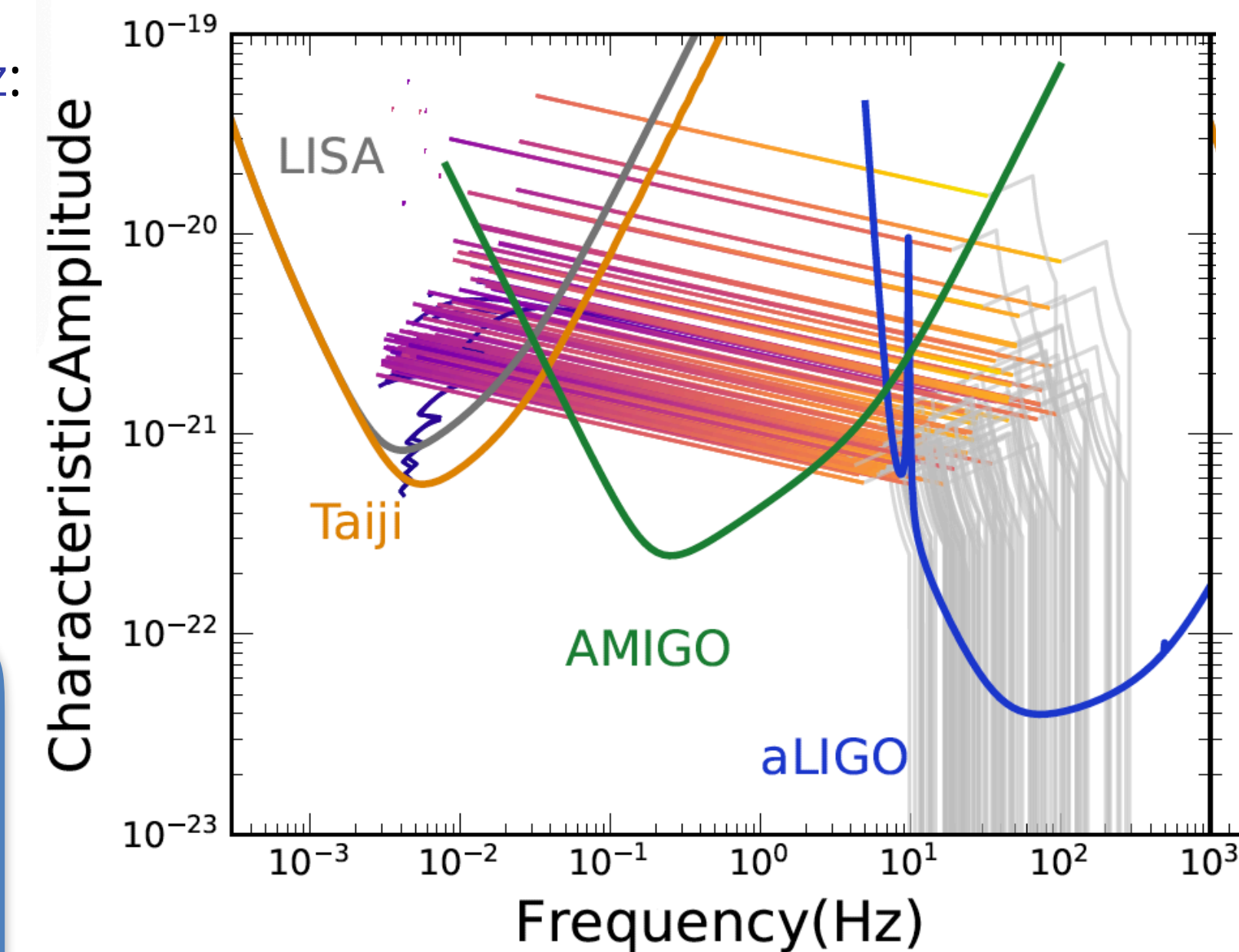
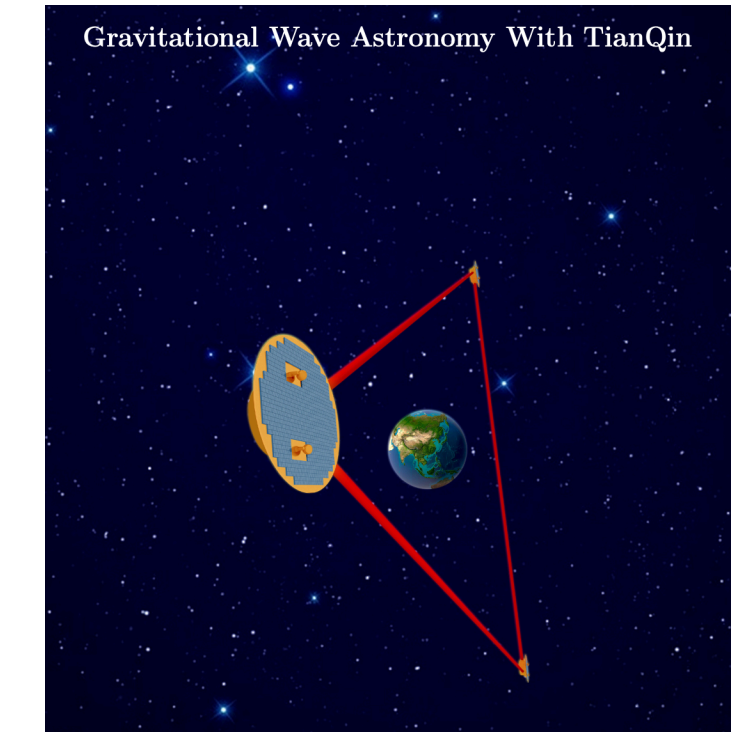
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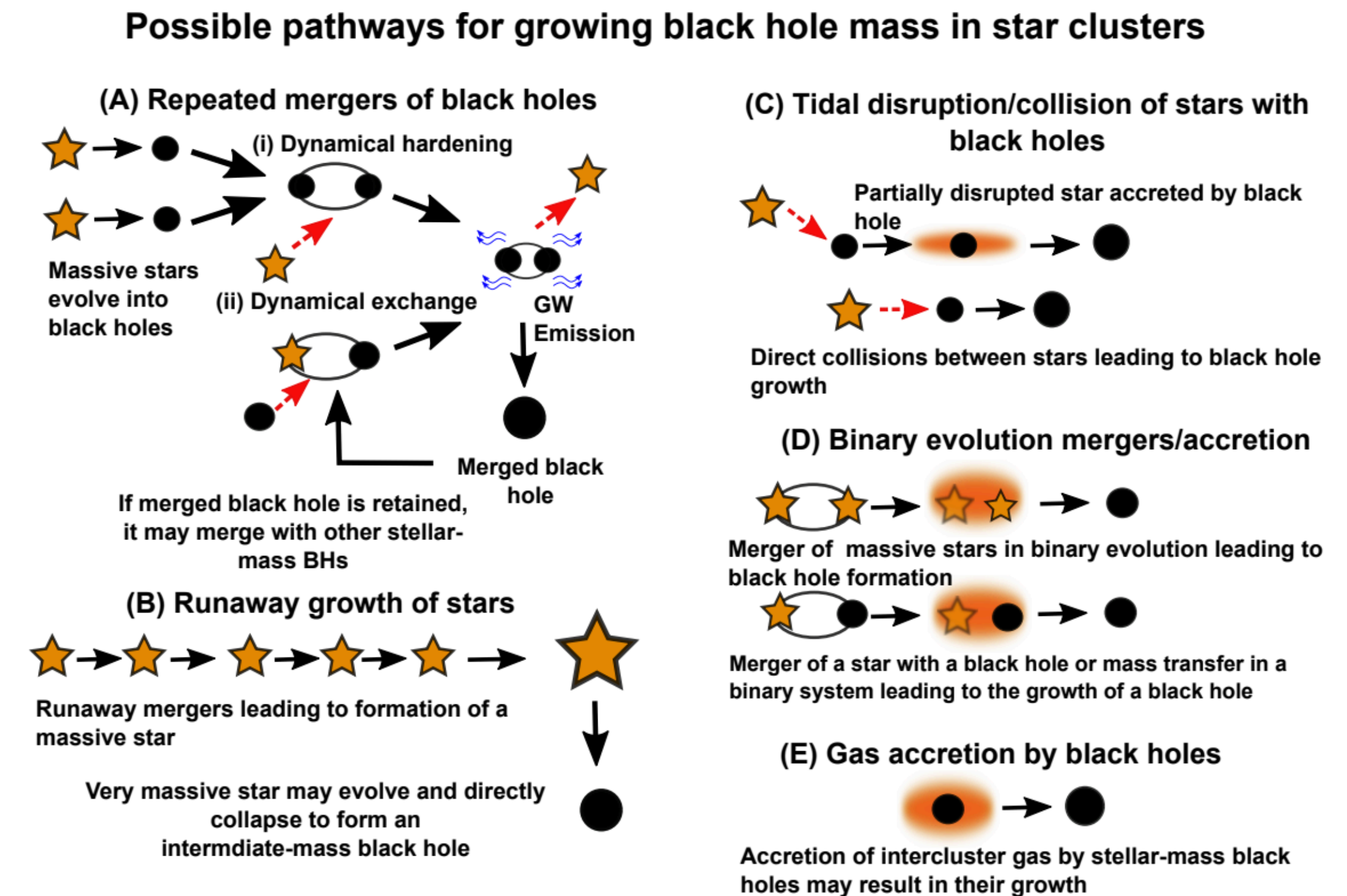
## Goals:

- *Identify predominant pathway for forming and growing intermediate-mass black holes (IMBHs) in star clusters*
- *Use simulations to provide observational constraints on the presence of IMBHs in stellar clusters*

## • Work done on project during 2024:

- Ongoing MOCCA code development: Several improvements and corrections
- Simulated few large-N GC Models with MOCCA:
  - $N = 2 \times 10^6$ , initial binary fraction = 10 %,  $R_{GC} = 10$  kpc,  $Z = 0.001$
  - Varied initial half-mass radius ( $r_h = 0.5$  & 1pc) and central concentration ( $\rho_c \sim 1.5 \times 10^7 \text{ M}_\odot \text{ pc}^{-3} \rightarrow 2 \times 10^8 \text{ M}_\odot \text{ pc}^{-3}$ )

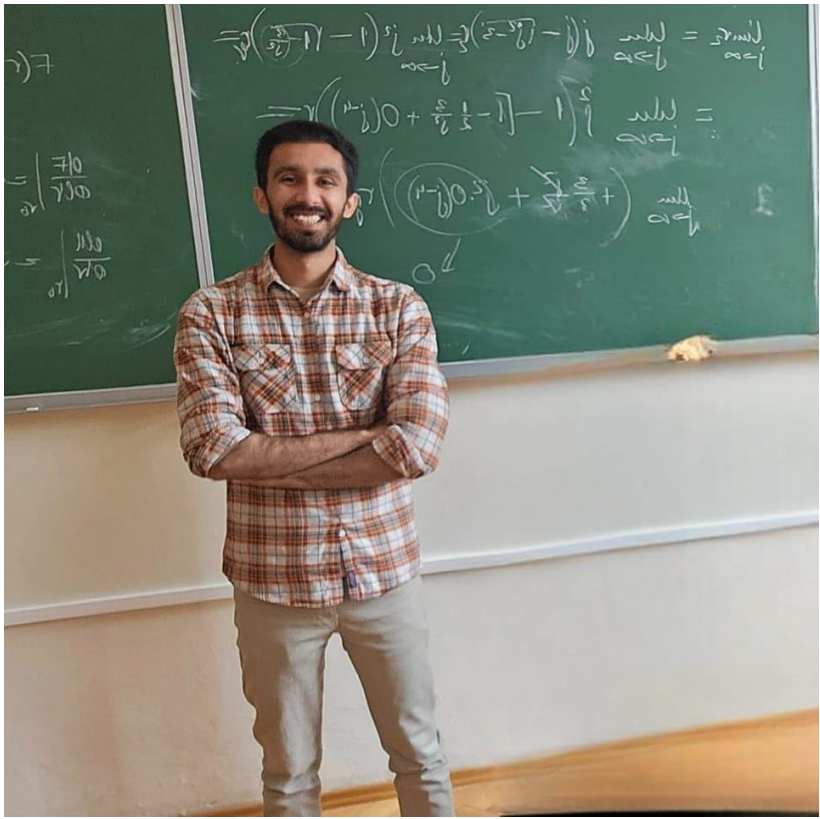
<https://bhg.camk.edu.pl/>



Askar, Baldassare & Mezcua (2024); <https://arxiv.org/abs/2311.12118>

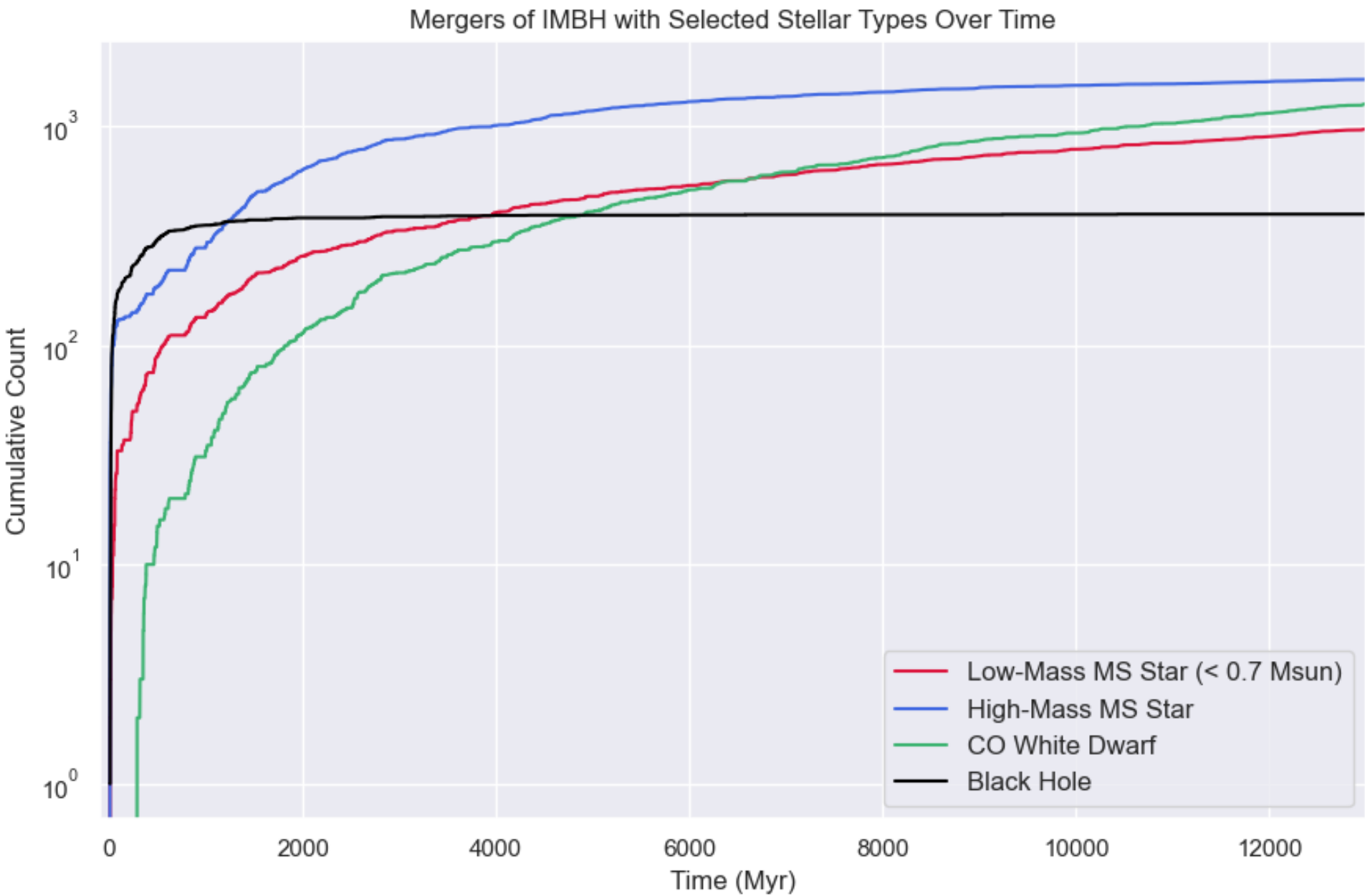
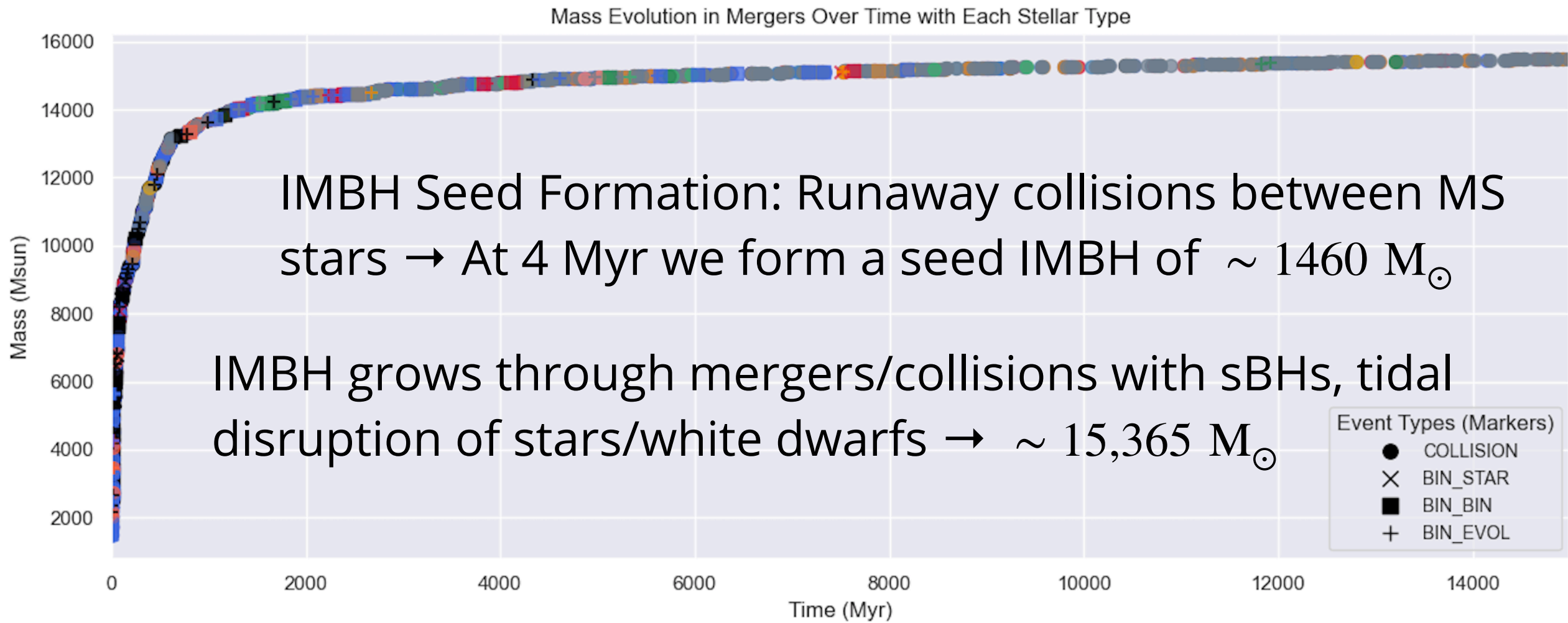


- Work done on project during 2024:
  - Hired a student (July 2024 to Nov 2024): **Sohaib Ali** (now a second year masters student in Physics & Astronomy at Nicolaus Copernicus University in Torún, Poland)
    - Help develop data analysis pipelines to obtain all IMBH growth events from MOCCA Simulations
    - Making synthetic observations of simulated GC models



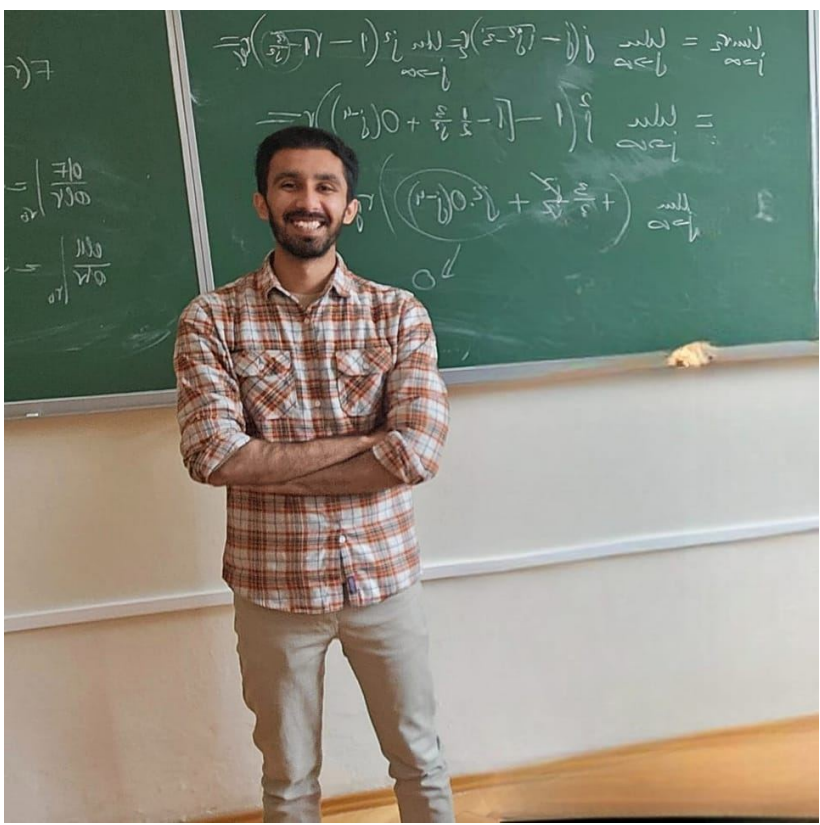
<https://nebula-navigator.github.io/>

$N = 2 \times 10^6$ , initial binary fraction = 10 %,  $R_{GC} = 10$  kpc,  $Z = 0.001$ ,  $r_h = 0.5$  pc



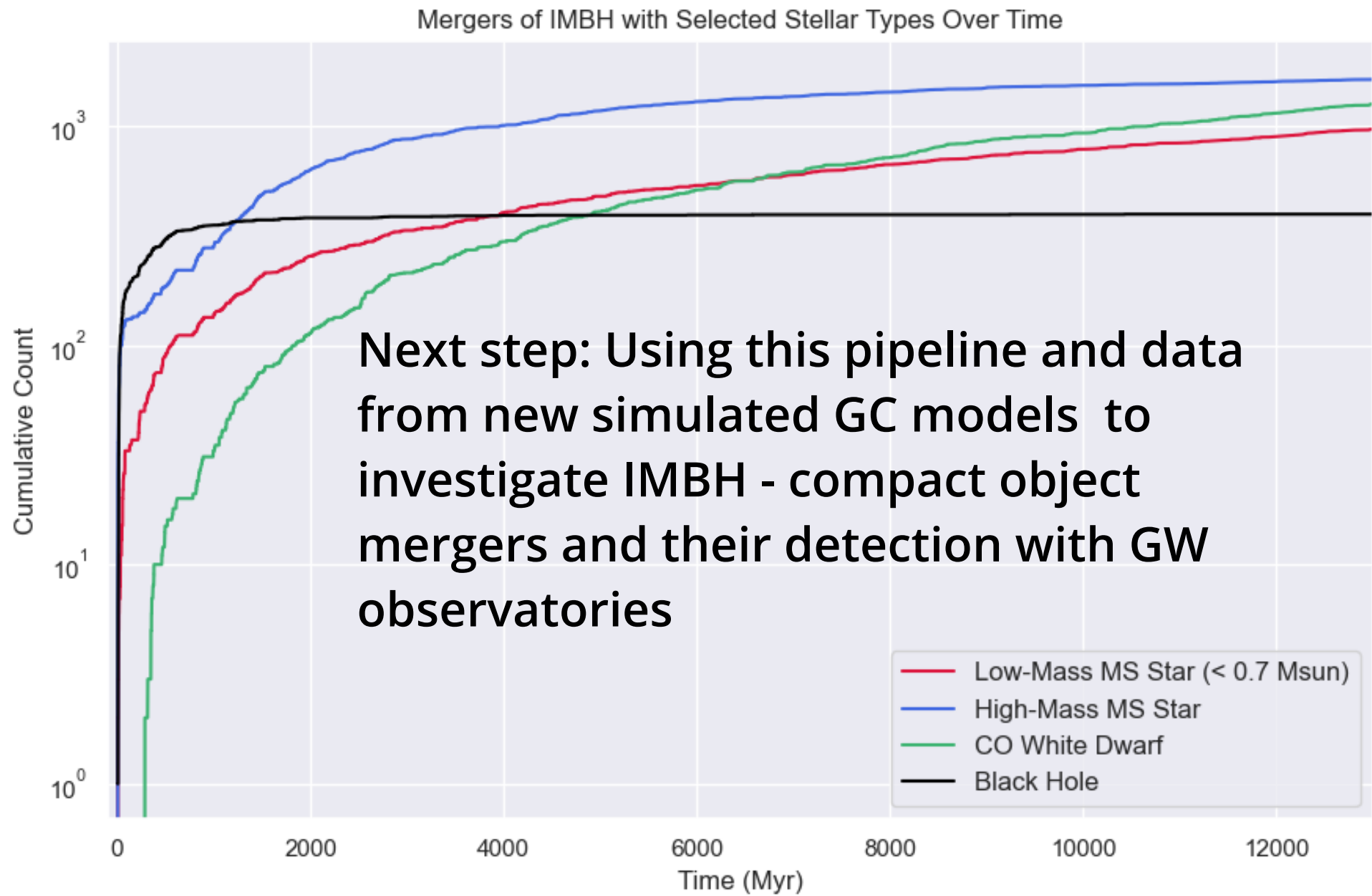
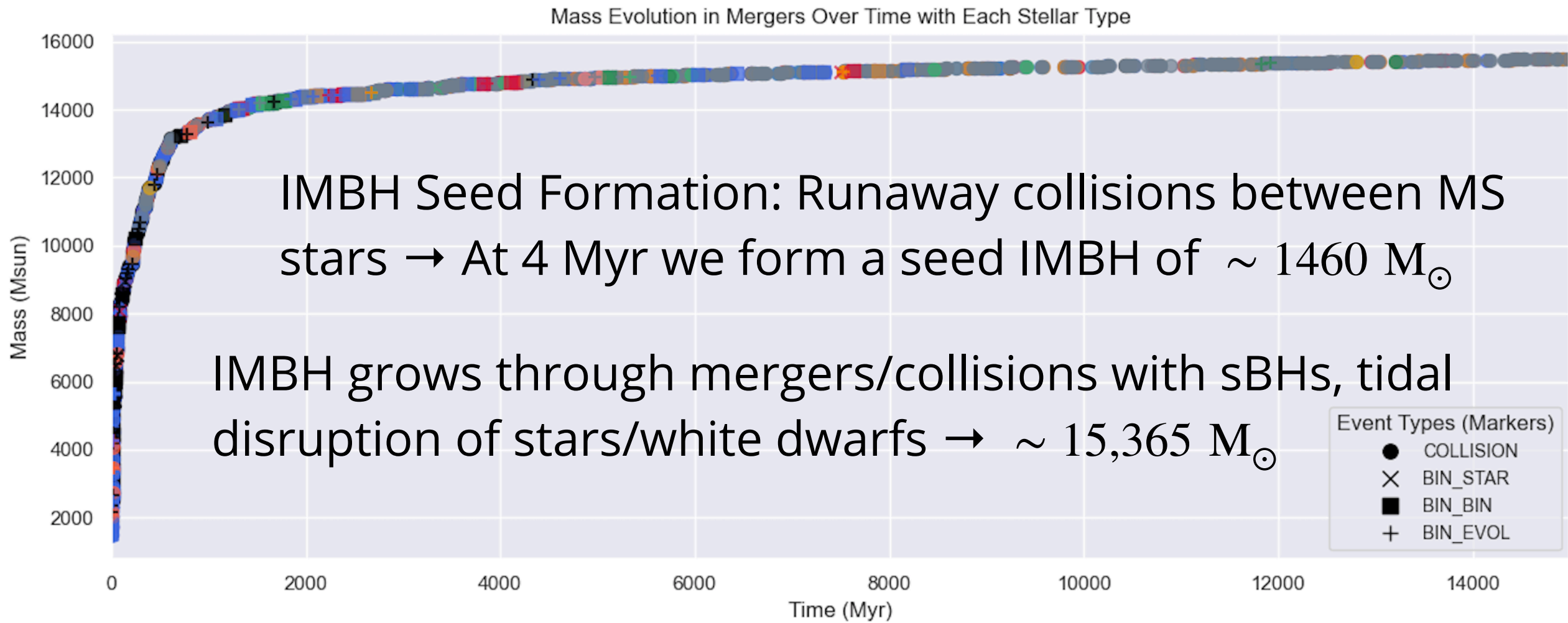


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# POLONEZ BIS Project: BHGrowth

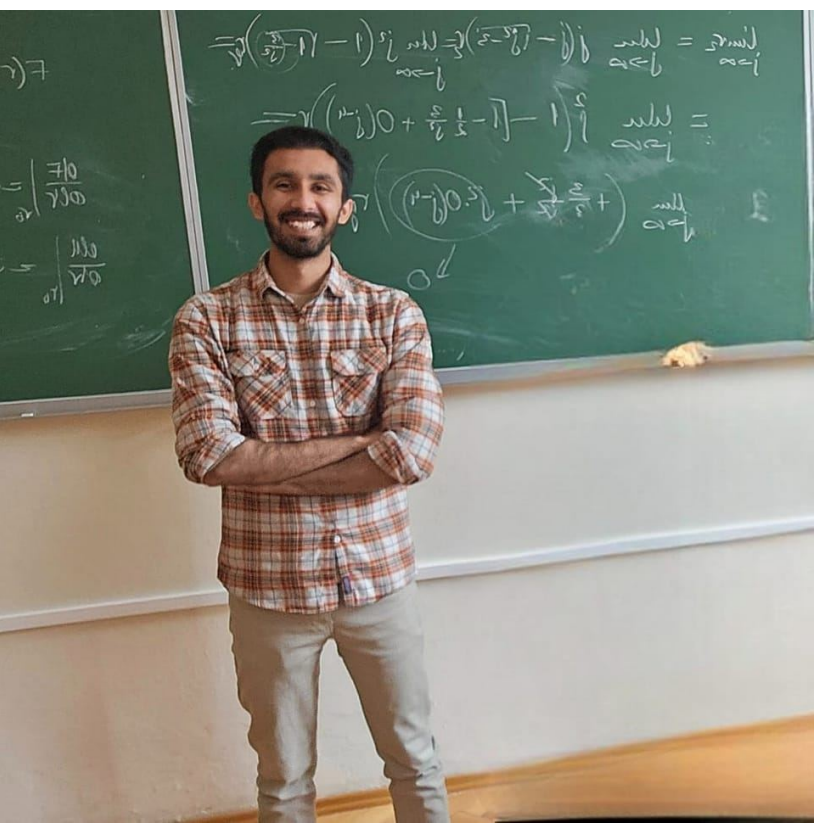


NATIONAL  
SCIENCE  
CENTRE  
POLAND

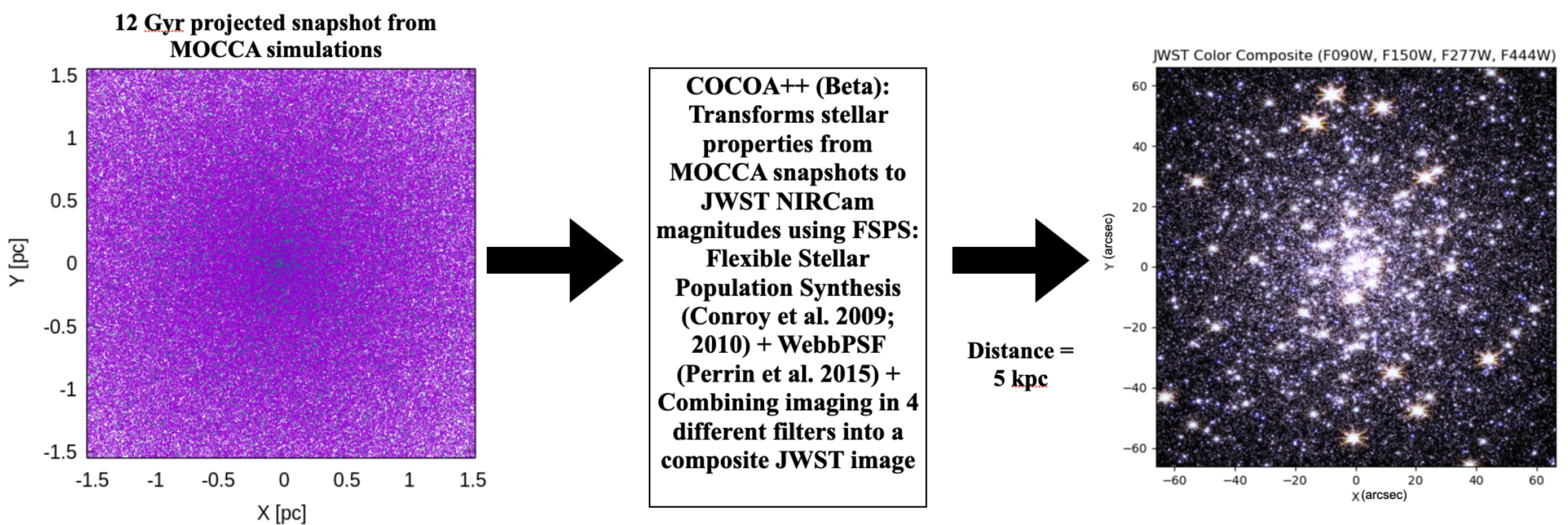


POLONEZ BIS

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    - Help develop data analysis pipelines to obtain all IMBH growth events from MOCCA Simulations
    - Making synthetic observations of simulated GC models



<https://nebula-navigator.github.io/>



Extension of the COCOA code (Askar et al. 2018): Cluster simulation Comparison with Observations): <https://github.com/abs2k12/COCOA>

In collaboration with Dr. Paolo Bianchini (Strasbourg Observatory)

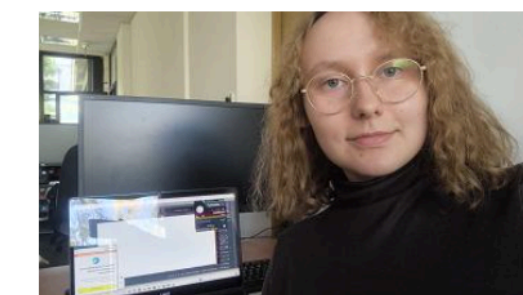


# Other activities

- Co-taught course on “Star Cluster Dynamics and Evolution” for GeoPlanet Doctoral School (Spring 2024), Lecture slides available at: <https://events.camk.edu.pl/event/98/>
- Co-chair of the SOC and LOC member for the MODEST-24: Exploring Dense Stellar Systems Across Cosmic Time conference hosted by CAMK, Warsaw in August 2024 (<https://events.camk.edu.pl/event/95/>)
  - 135 participants (105 in-person) with 118 contributions
- 2 talks at international conferences and one invited seminar talk
- More grant applications
- **Popularization and other teaching activities:**
  - Talk at CAMK Young Astronomers Meeting (2024)
  - Supervised the 2 week high school student project of Ismena Leśko (from Jarosław and studying at JDJ International Open Schools, Poznan) on numerical investigations of 2-body gravitational encounters with tidal dissipation (September 2024).
  - Supervised final high school research project for Amanda Skog, Aron Andrén & Alexander Andersson from Ystad Gymaniasium, Sweden working on 3-body gravitational scattering experiments: Merging stellar-mass binary black holes
  - Interviewed for a Hungarian popular science online news outlet (qubit.hu) regarding the possible discovery of an IMBH in Omega Centauri: <https://qubit.hu/2024/07/11/rejtelyes-fekete-lyukra-bukkantak-sajat-galaxisunkban-a-tejutrendszerben>



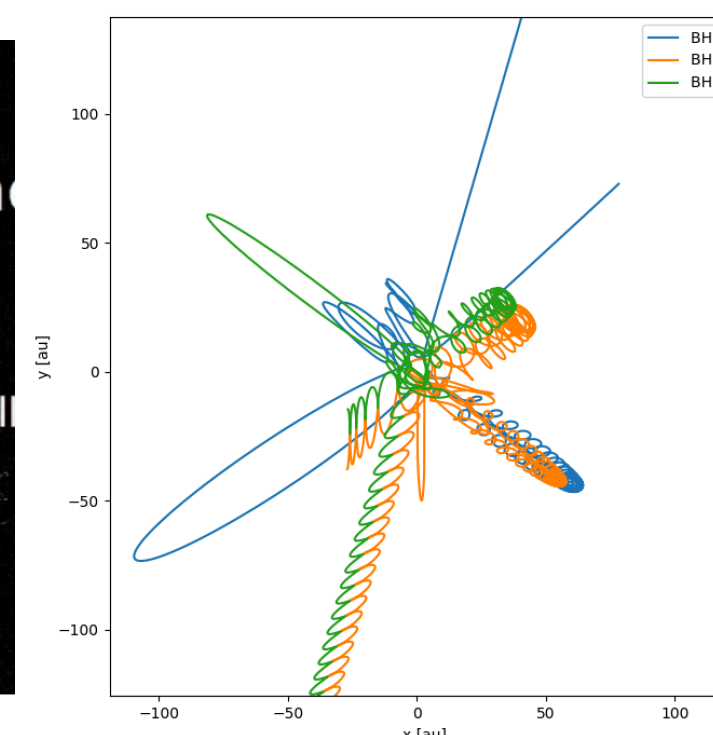
MODEST-24



## Najzdolniejsza młoda matematyczka w Polsce? Prawdopodobnie. "Na Harvardzie byliśmy jedyni z Europy"

Czy nasze szkoły mają pomysł na to, jak wspierać bardzo zdolne i ambitne dzieci? Co sprawia, że dziecko uczy się matematyki nie z przymusu, le...

harvard matematyka matura



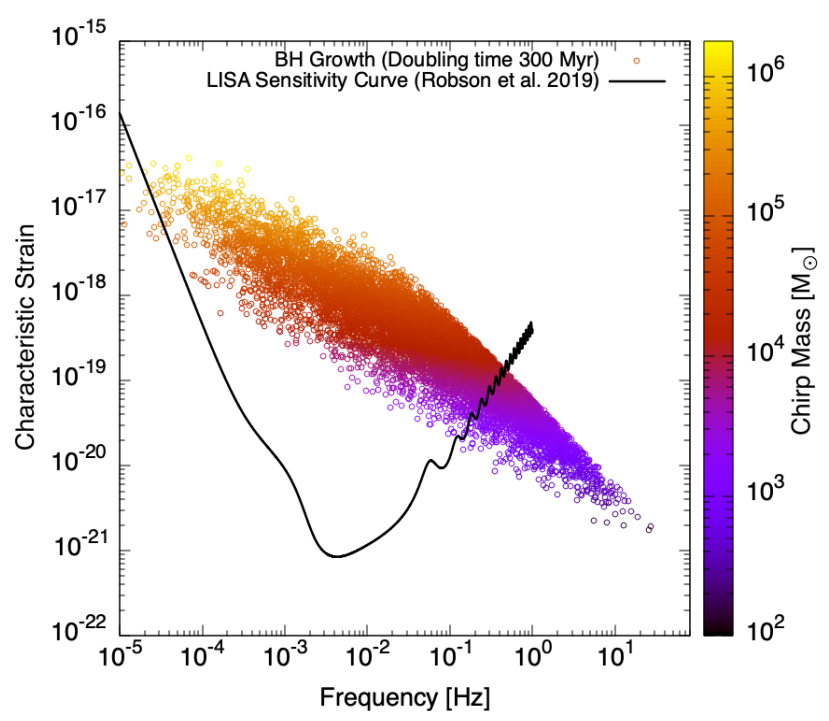


# Selected ongoing projects and things to do in 2025

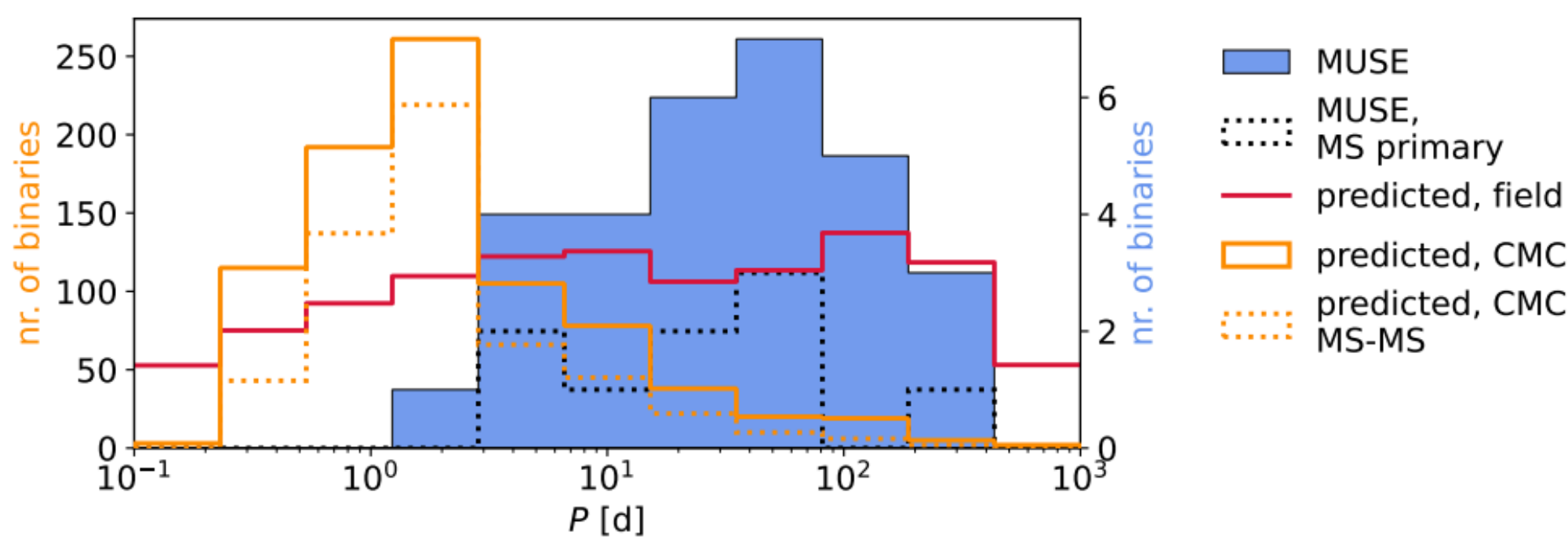
- *Formation of a VMS of 50,000  $M_{\odot}$  through runaway collisions in a direct N-body simulation (Vergrara, Askar et al. in prep)*  $N = 1 \times 10^6$ ,  $rh = 0.1$  pc
- *LISA sources originating in galactic nuclei: Mergers of SMBHs and IMBHs in galactic nuclei: binary properties and intermediate-mass ratio inspiral merger rates (based on Askar, Davies & Church 2021; 2022)*
- *Mass segregation in globular clusters harbouring an IMBH or a subsystem of stellar-mass BHs (led by former master student Markus Strickert)*
- *Growth of nuclear star cluster and SMBH in Milky Way and M31 (in collaboration with Agostino and Mirek using results from their previous papers)*
- *Comparison of properties of binaries in globular clusters (e.g., 47 Tuc) with MUSE with binaries from MOCCA simulations (in collaboration with Stefan Dreizler, Fabian Göttgens, Sebastian Kamann et al.)*
- *Multi-messenger study for the evolution of binary populations in the Milky Way star clusters (project led by Xiaoying Pang)*

Rapid formation of a massive black hole of  $>27000 M_{\odot}$  from a very massive star produced by thousands of stellar mergers in direct N-body simulations of dense star clusters

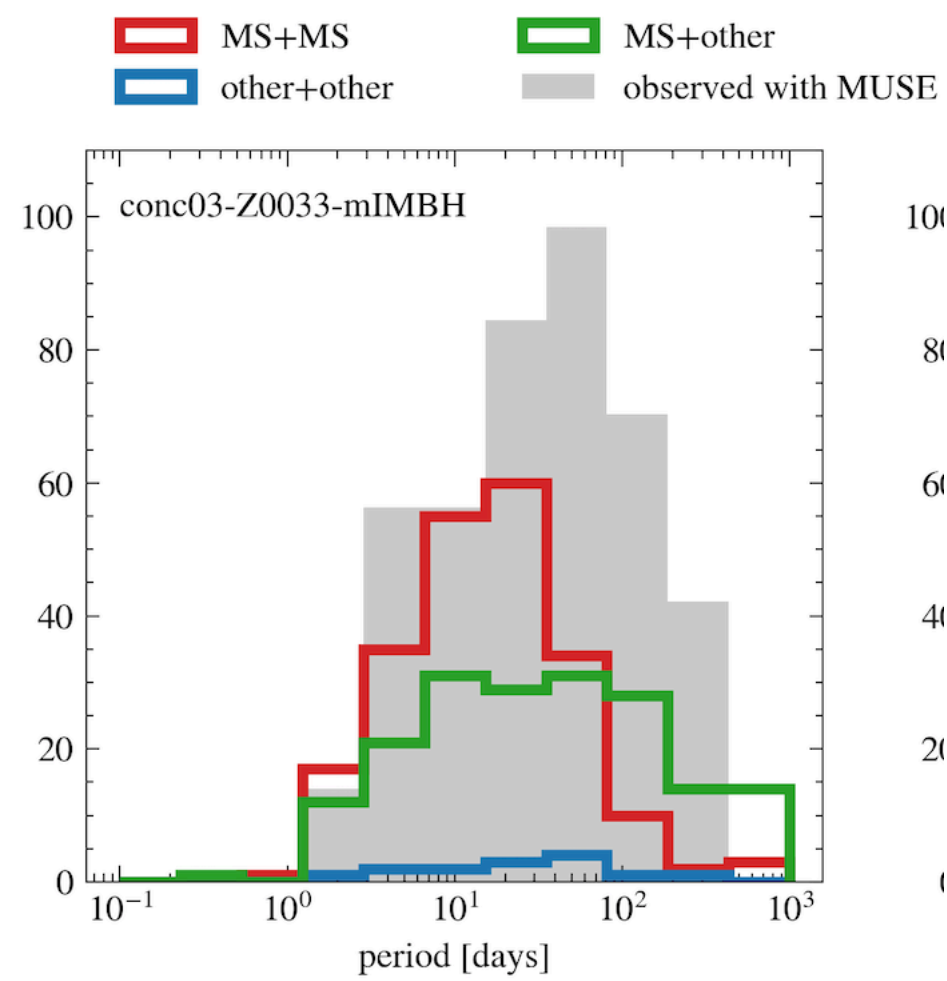
MARCELO C. VERGARA,<sup>1</sup> ABBAS ASKAR,<sup>2</sup> ALBRECHT W. H. KAMLAH,<sup>3,1</sup> RAINER SPURZEM,<sup>1,4,5</sup> FRANCESCO FLAMMINI DOTTI,<sup>1</sup> DOMINIK R.G. SCHLEICHER,<sup>6</sup> MANUEL ARCA SEDDA,<sup>7,8,9,10</sup> ARKADIUSZ HYPKI,<sup>11,2</sup> MIREK GIERSZ,<sup>2</sup> ATARU TANIKAWA,<sup>12,13</sup> JARROD HURLEY,<sup>14,15</sup> ANDRES ESCALA,<sup>16</sup> NILS HOYER,<sup>17,3,18,19</sup> NADINE NEUMAYER,<sup>3</sup> RENYUE CEN,<sup>20,21</sup> PETER BERCZIK,<sup>22,23,24</sup> THORSTEN NAAB,<sup>25</sup> AND XIAOYING PANG<sup>26,27</sup>



Askar in prep.



From Müller-Horn, Göttgens et al. 2024



Binaries in 47 Tuc: CMC vs MOCCA: Preliminary Results