Star Clusters with MOCCA: Black Hole Growth, Multiple Stellar Populations, Gravitational Waves, and Mock Observations

Images generated by OpenAI ChatGPT 4.1

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

Abbas Askar

Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences
Warsaw, Poland

askar@camk.edu.pl

BH GROWTH
— Growing Black Holes in Star Clusters —

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

MOCCA

https://camk.pl/moccacode/

POLONEZ BIS

NATIONAL SCIENCE CENTRE POLAND

MARIE CURIE ACTIONS

CAMK PAN

Scientific Activities in 2025

Publication type	Published	Accepted / In Press	Submitted	Total
Peer-reviewed Journals *	8	4	3	15
Conference Proceedings ‡	0	3	0	3
White Papers †	1	0	0	1

* Peer-reviewed Journals: A&A (12), ApJ (1), Rep. Prog. Phys. (1), Acta Astronomica (1)

‡ IAUS 398 & MODEST-25: Compact Objects & Binaries in Dense Stellar Systems, Seoul, South Korea (June 2025)

† ESO Expanding Horizons

- MOCCA upgrades enabling large-N simulations ($N \sim 10^7 - 10^8$) with improved treatment of key physical processes

- Concluded the EU/EC + NCN POLONEZ BIS grant ("BHGrowth", Sept 2023–Aug 2025):

  - **21 publications** (17 peer-reviewed journal papers, 3 conference proceedings, 1 book chapter) **+** 2 manuscripts in preparation

- Started a 3-year NCN SONATA grant (from 1 Sept 2025; $\sim$ 1.75 million PLN) and a tenure-track position at CAMK

  - *"Bridging Observations and Theory: Synthetic Star Cluster Observations from Numerical Simulations"*

- NBODY6++GPU & MOCCA simulations of an extremely dense star cluster
$$\left(N = 10^6, r_h = 0.1\mathrm{pc}\right)$$

Astronomy & Astrophysics

Parameter	Value
Initial Mass (M_i)	$5.86 \times 10^5 \, \mathrm{M}_\odot$
Half-mass radius (r_{hm})	0.1 pc
Core density (ρ_c)	$4 \times 10^8 \, \mathrm{M}_\odot/\mathrm{pc}^3$
Kroupa IMF, min/max stellar mass	$0.08 - 150 \, \mathrm{M}_\odot$

Rapid formation of a very massive star (>50 000 $\mathrm{M}_\odot$), and subsequently, of an IMBH, from runaway collisions

Direct _N_-body and Monte Carlo simulations of dense star clusters

Marcelo C. Vergara[1,*], Abbas Askar[2,*], Albrecht W. H. Kamlah[3,1], Rainer Spurzem[1,4,5], Francesco Flammini Dotti[6,7,1,8], Dominik R. G. Schleicher[8,9], Manuel Arca Sedda[10,11,12,13], Arkadiusz Hypki[14,2], Mirek Giersz[2], Jarrod Hurley[15,16], Peter Berczik[2,17], Andres Escala[18], Nils Hoyer[3,19,20], Nadine Neumayer[3], Xiaoying Pang[21,22], Ataru Tanikawa[23,24], Renyue Cen[25,26], and Thorsten Naab[27]

- Runaway stellar collisions form a **very massive star (VMS)** → $\gtrsim 5 \times 10^4 \mathrm{M}_\odot$
  - Significant improvements to the treatment of VMS evolution and rejuvenation
- Pathway to **IMBH (intermediate-mass black hole)** formation on short timescales
- Computational Cost:
  - NBODY6++GPU: multi-GPU/CPU, 2 months → 5 Myr
  - MOCCA: single CPU, 10 hours → 7 Myr

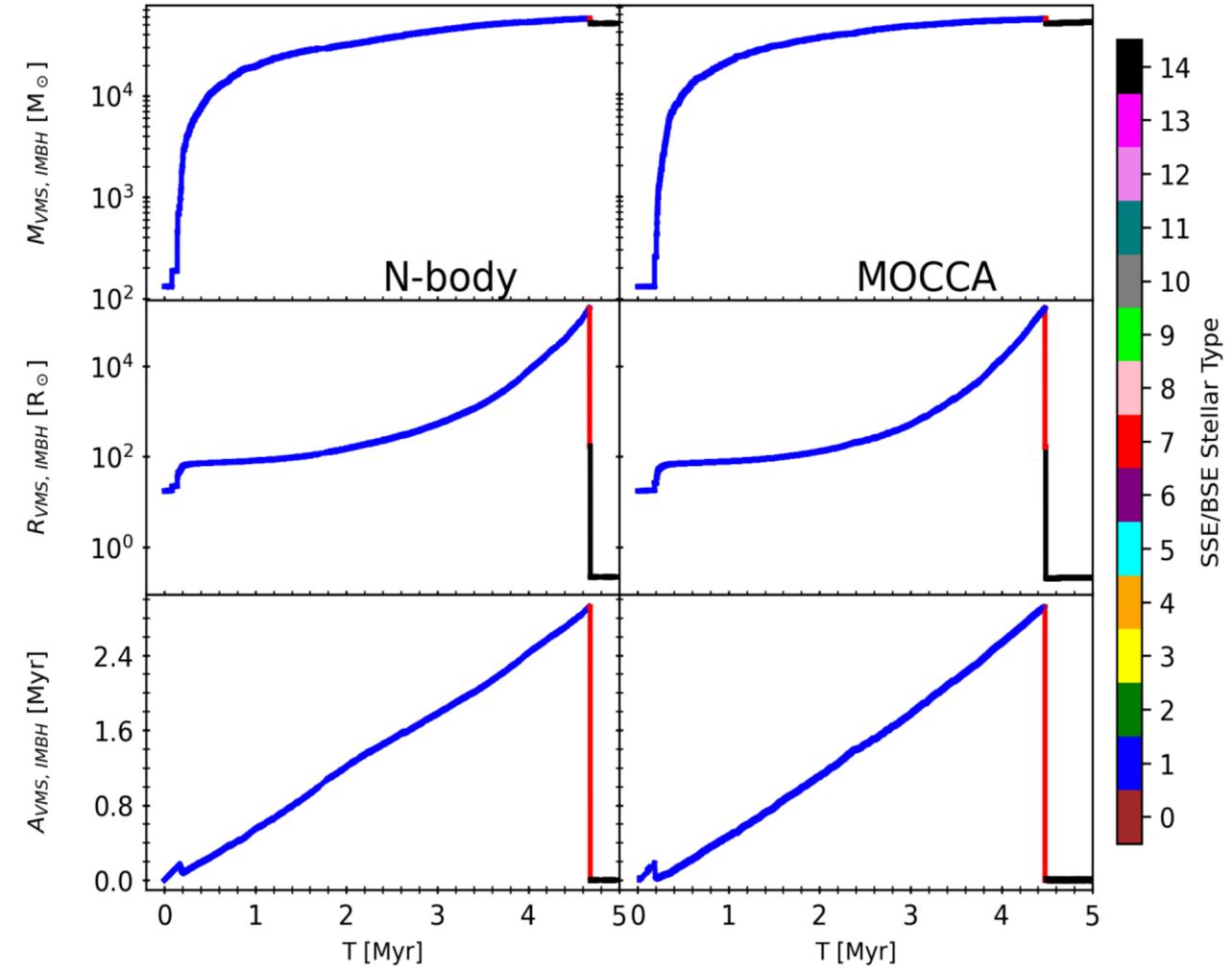- Extremely dense, low-metallicity star cluster models representative of young massive clusters observed with JWST

**Table 1.** Initial conditions of the cluster models.

Models	R_h [pc]	N 10^5	M $[10^5 M_\odot]$	ρ_h $[M_\odot \, pc^{-3}]$	Z
R005N750k	0.05	7.5	4.38	4.18×10^8	10^{-4}
R005N500k	0.05	5	2.93	2.79×10^8	10^{-4}
R001N250k	0.01	2.5	1.46	1.74×10^{10}	10^{-4}
R001N100k	0.01	1	0.58	6.92×10^9	10^{-4}
R0005N50k	0.005	0.5	0.28	2.67×10^{10}	10^{-4}

- Improved stellar collision prescriptions in MOCCA to achieve good agreement with direct N-body simulations

- A predictive mass–density threshold for efficient IMBH formation

- Up to $\sim 10\,\%$ of young massive clusters observed with JWST could potentially form IMBHs

Efficient black hole seed formation in low-metallicity and dense stellar clusters with implications for JWST sources

M.C. Vergara[1]⋆, A. Askar[2]⋆⋆, F. Flammini Dotti[3,4,1,5], D.R.G. Schleicher[5,6], A. Escala[7], R. Spurzem[1,8,9], M. Giersz[2], J. Hurley[10,11], M. Arca Sedda[12,13,14,15], and N. Neumayer[16]
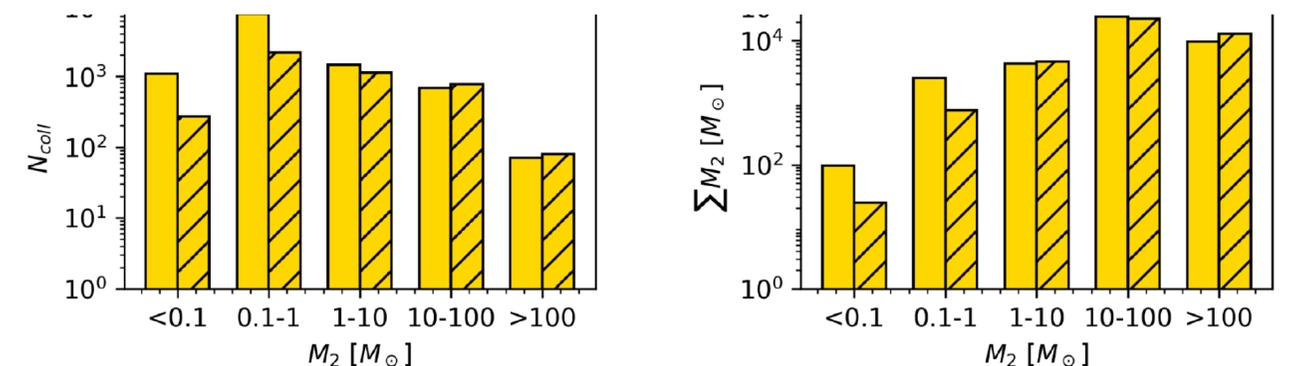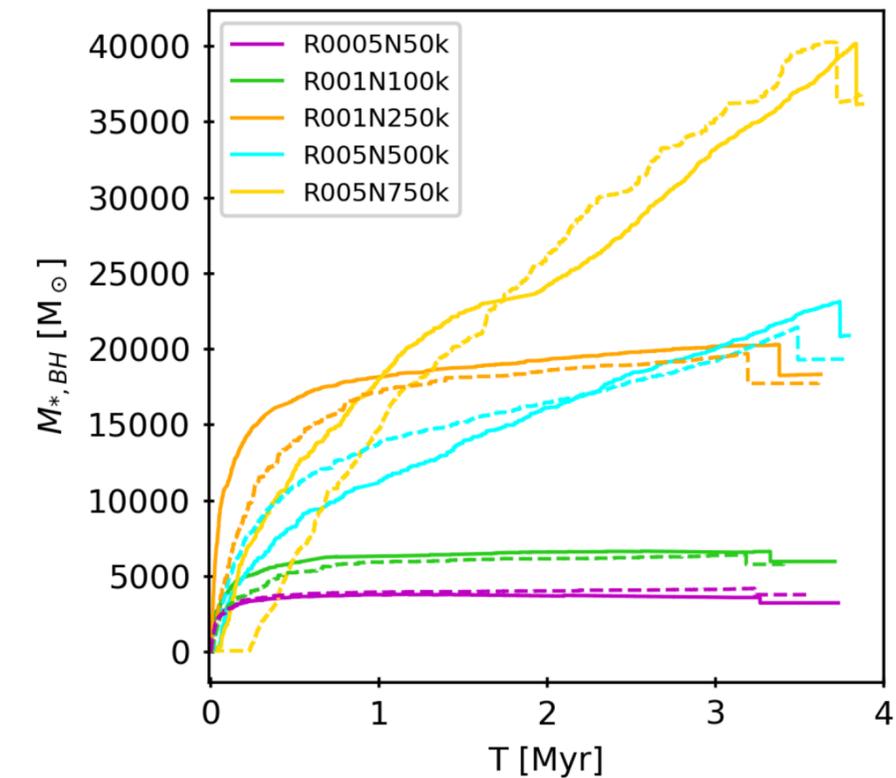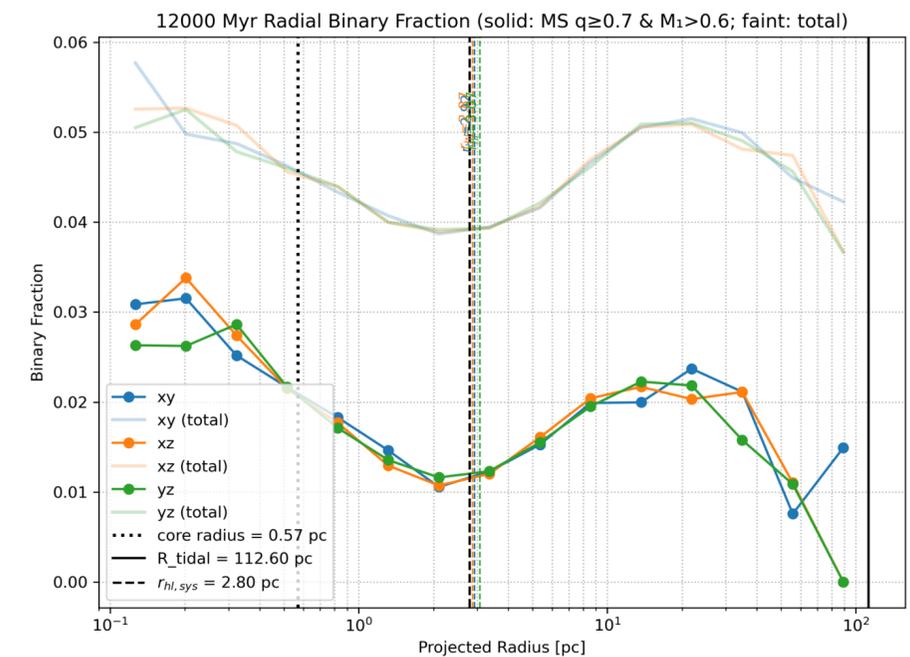
A Few Other Results and Ongoing Collaborations

- Gravitational-wave sources produced in star clusters:
  - with Yuetong Zhao & Youjun Lu (BNU and Chinese Academy of Sciences) & Verónica Vázquez-Aceves (Kavli Institute for Astronomy and Astrophysics, Peking University): Zhao, Askar et al. accepted in ApJ: https://arxiv.org/abs/2512.13151

- Omega Cen models with MOCCA:
  - Formation of an IMBH → $2 \times 10^4 - 4 \times 10^4 \, \mathrm{M_\odot}$
  - with Arshia Anjum & Holger Baumgardt (The University of Queensland)

- 50-million-body dense star clusters with MOCCA:
  - IMBH formation (seed supermassive BH?) through hierarchical BH mergers → $2 \times 10^5 \, \mathrm{M_\odot}$
  - with Dominik Schleicher & Matías Liempi (Sapienza University of Rome)

- POLONEZ BIS student project:
  - Jakub Szyndler (Warsaw Observatory): *Recovering IMBH mass using Jeans modeling with observational constraints* (manuscript in preparation)

- Binaries in 47 Tuc:
  - Inner regions (with Stefan Dreizler (Göttingen) & MUSE team)
 - Outskirts (with Giocomo Cordoni, Paolo Bianchini, Arn Marklund & Alessandra Mastrobuono Battisti)
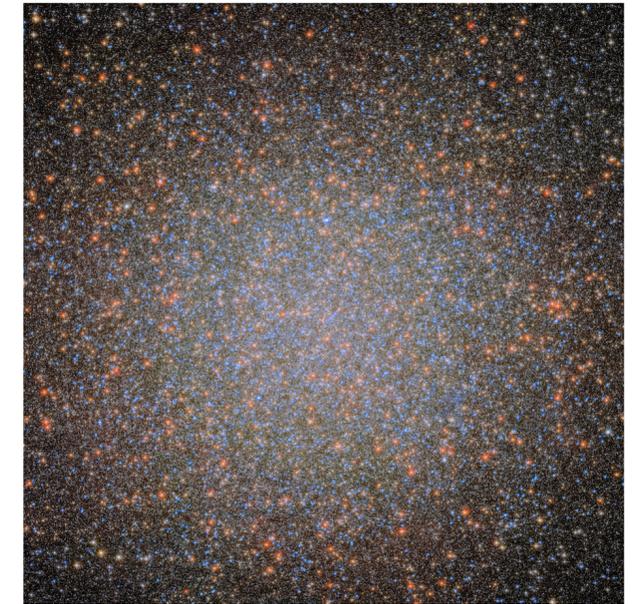
Omega Cen (Credit: *HST*)
IMBH in the Center $> 8200 \, \mathrm{M_\odot}$ **(Häberle et al. 2024)**


47 Tuc Model: Increasing binary fraction in the outskirts

A Few Other Results and Ongoing Collaborations

- Mock observations from Direct *N*-body and MOCCA simulations:
  - *Artificial intelligence based recovery of cluster mass distributions from images*
  - with Paolo Bianchini & Arn Marklund (Observatory of Strasbourg)
- Mass transfer in IMBH - star binaries:
  - with Aleksandra Olejak (MPA → CAMK)
- MOCCA zoom-in simulations with the *Tsunami* code:
  - Inclusion of post-Newtonian corrections, tidal dissipation, external potential
  - with Alessandro Trani (University of Concepción)
- Gravitational-wave lensing by globular clusters and IMBHs:
  - with CAMK colleagues: Sudhagar Suyamprakasam, Sreekanth Harikumar & Michał Bejger, et al.
- Accretion of AGB ejecta by stars in MOCCA simulations:
  - In collaboration with Alexey Bobrick (Monash University) & Melvyn Davies (Lund University)
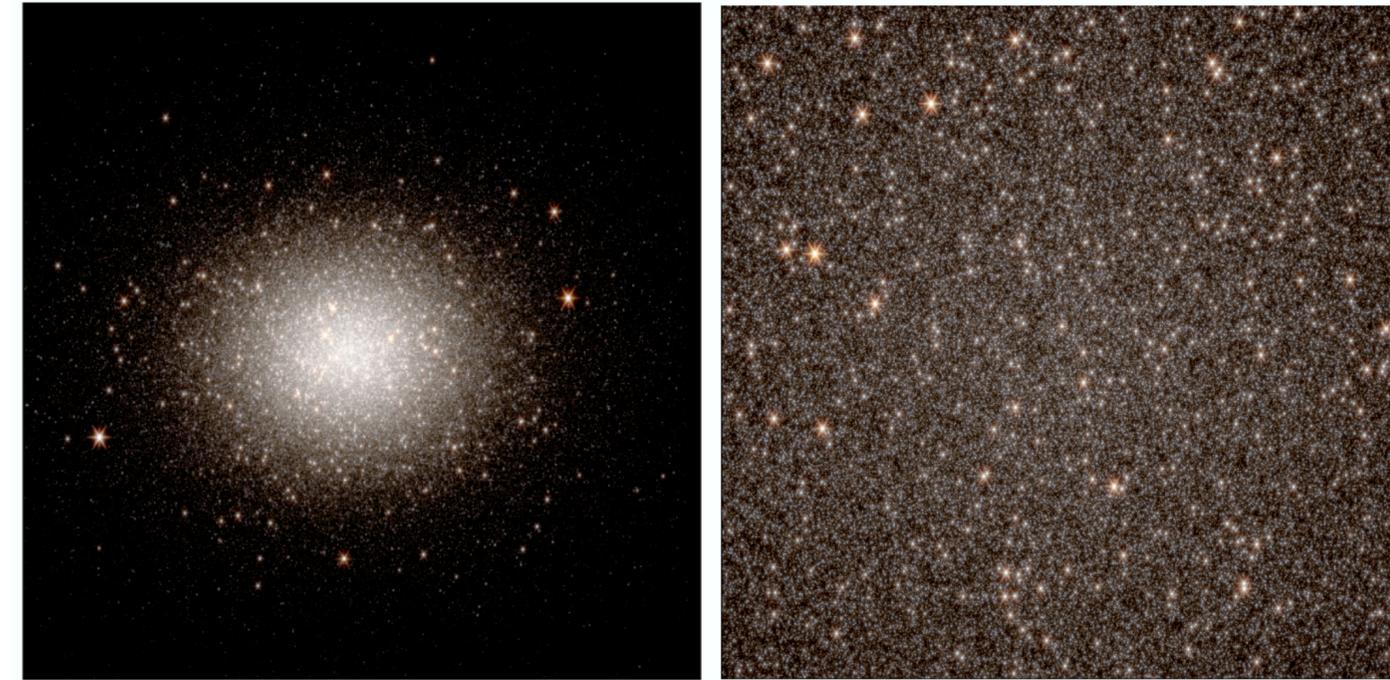
JWST Mock Images from the "ROLLIN': Rotating Globular Clusters Simulations" Project (Bianchini, Varri, Askar et al. submitted 2025)
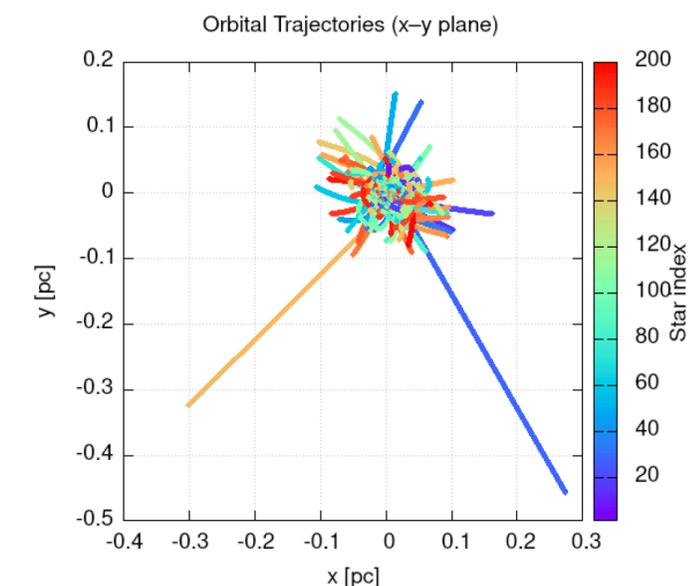
MOCCA Zoom-In Simulations with Tsunami: Dynamics around IMBH

Other Activities

- 15-day Industry Secondment (POLONEZ BIS requirement):
  - Telenor Sweden (HQ, Stockholm; Jul–Aug 2025) — analytics, automation, AI, and large-scale data systems

- Large scientific collaboration & meeting organization:
  - Core Member, LISA (*Laser Interferometer Space Antenna*) Astrophysics Working Group
  - Management & SOC, MODEST-26 Conference at ICISE, Quy Nhon, Vietnam (in Aug 2026)
  - SOC member of IAUS 411 in Bariloche, Argentina (in Nov 2026)

- Dissemination and outreach:
  - 5 conference talks, 3 seminars, 2 invited panels, and 1 popular science talk at CAMK
  - Collaboration with high-school students from *XXXIII LO Dwujęzyczne im. Mikołaja Kopernika* on 2-body encounters initiated after a CAMK popular talk; invited speaker at their *Kopernikalia 2026* festival in 2 weeks.

- CAMK Activities and Duties:
  - Helping organize journal club
  - **Doctoral Students' Ombudsman**