Simulating Star Cluster Evolution:
From Black Hole Nurseries to Synthetic Observations

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CAMK PAN

BH GROWTH
Growing Black Holes in Star Clusters
https://bhg.camk.edu.pl/

MOCCA
https://camk.pl/moccacode/

Introduction Star Clusters

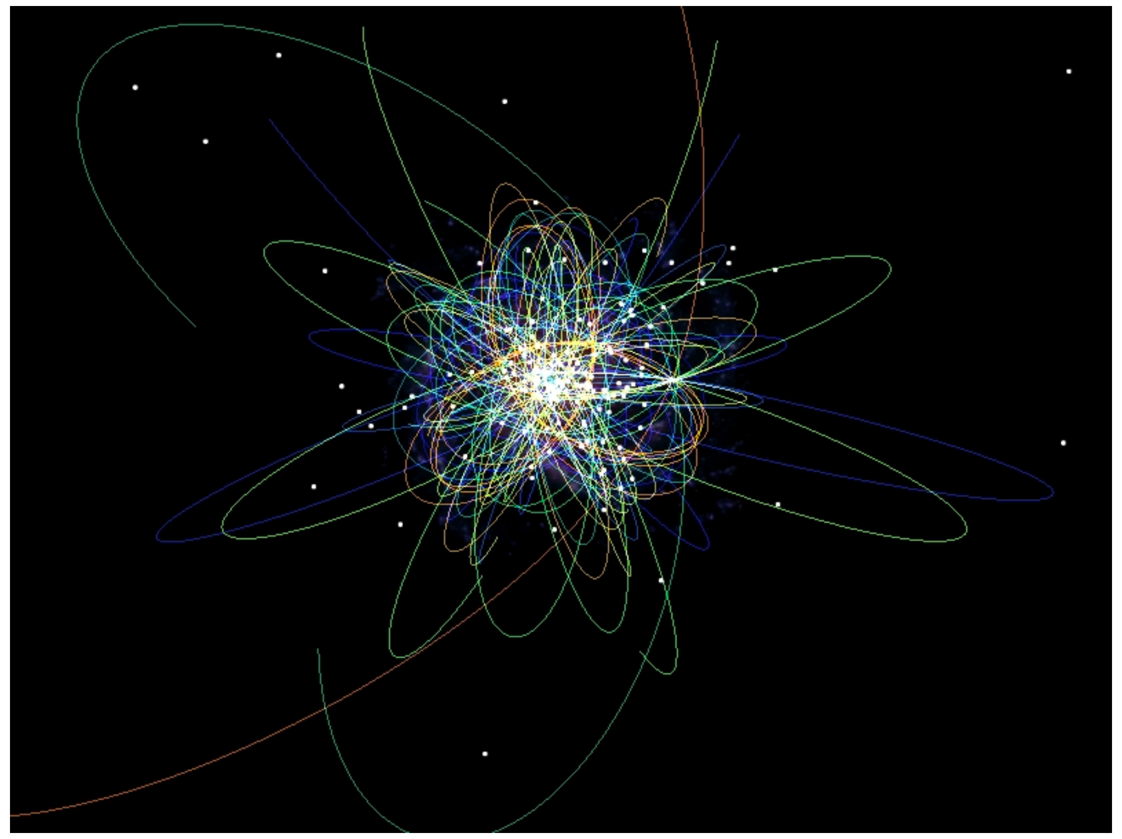
Pleiades star cluster (M45)
Credit: NASA, ESA, and AURA/Caltech

M15 Globular Cluster (Credit: *HST)*

What is a Star Cluster?

- Stars that formed at roughly the same time

- Stars that are gravitationally bound to each other



Star Cluster Formation

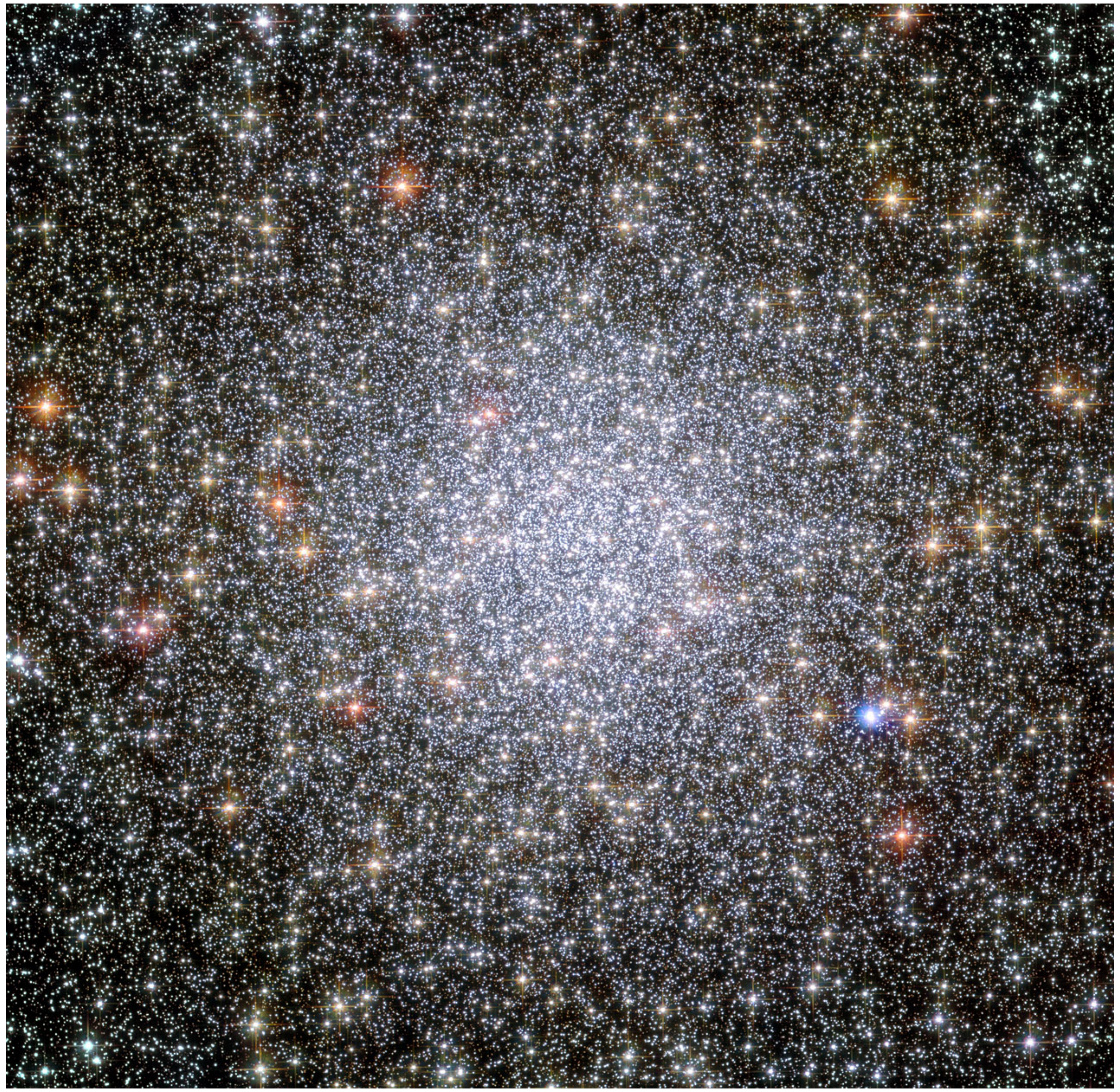
- Stars are born in large clouds of molecular gas
- These clouds (hundreds to millions of solar masses) fragment and collapse, forming many stars at roughly the same time

Pillars of Creation within the Eagle Nebula
Credit: *JWST*

R136, Tarantula Nebula, Large Magellanic Cloud
Credit: *HST*

Dense Star Clusters

- Stars in dense clusters are packed extremely closely
- Stellar densities can be millions of times higher than in the Solar neighbourhood
- Close encounters between stars become common
- Encounters drive cluster evolution → clusters are dynamically evolving systems



47 Tuc (NGC 104)
Credit: *HST*

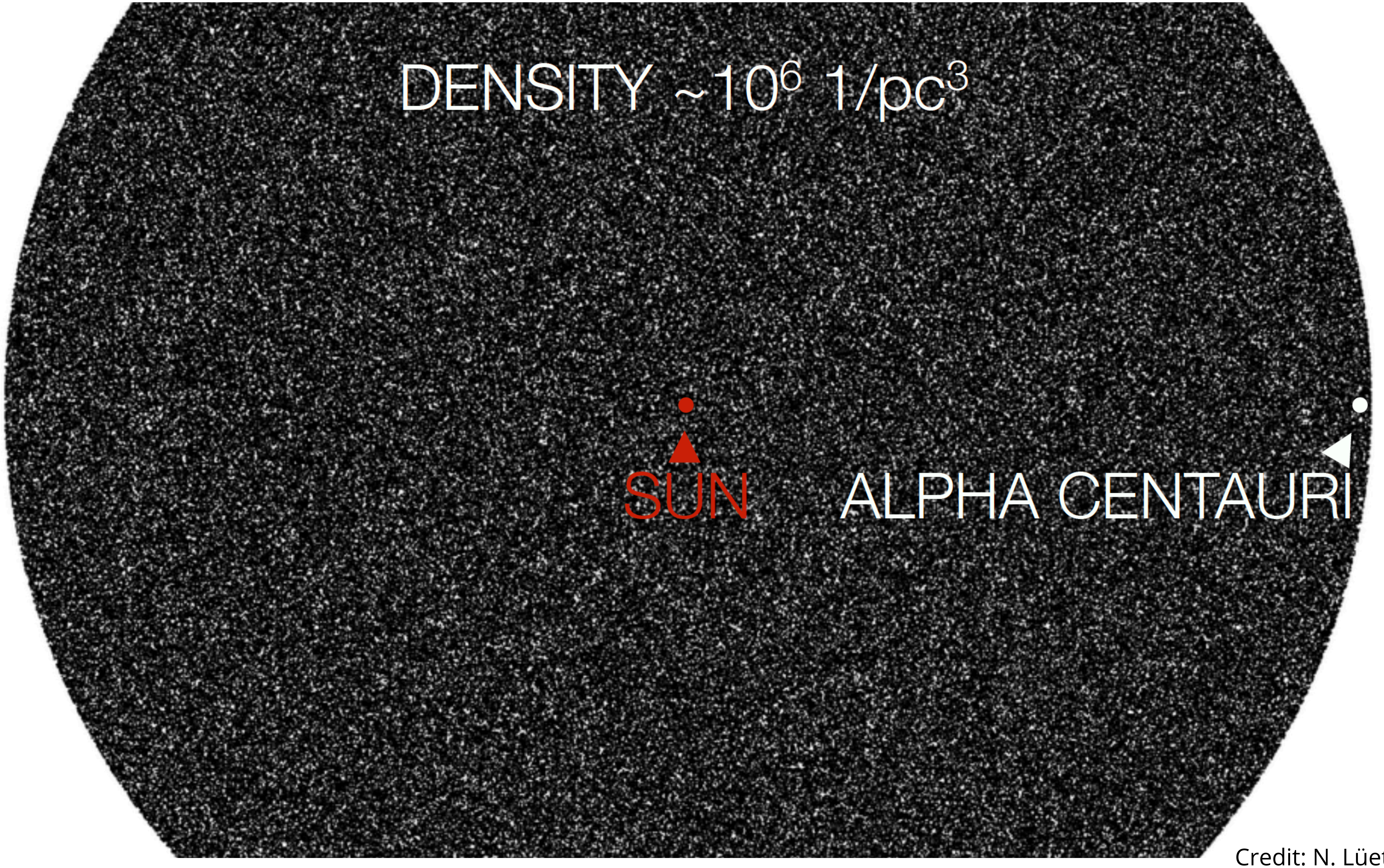
Mass $= 8.5 \times 10^5\,\mathrm{M}_\odot$

Age $= 12 - 13\,\mathrm{Gyr}$

$r_{hl} = 4.02\,\mathrm{pc}$

$\rho_c = 10^5\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$

Dense Star Clusters



D = 4.34 lyrs

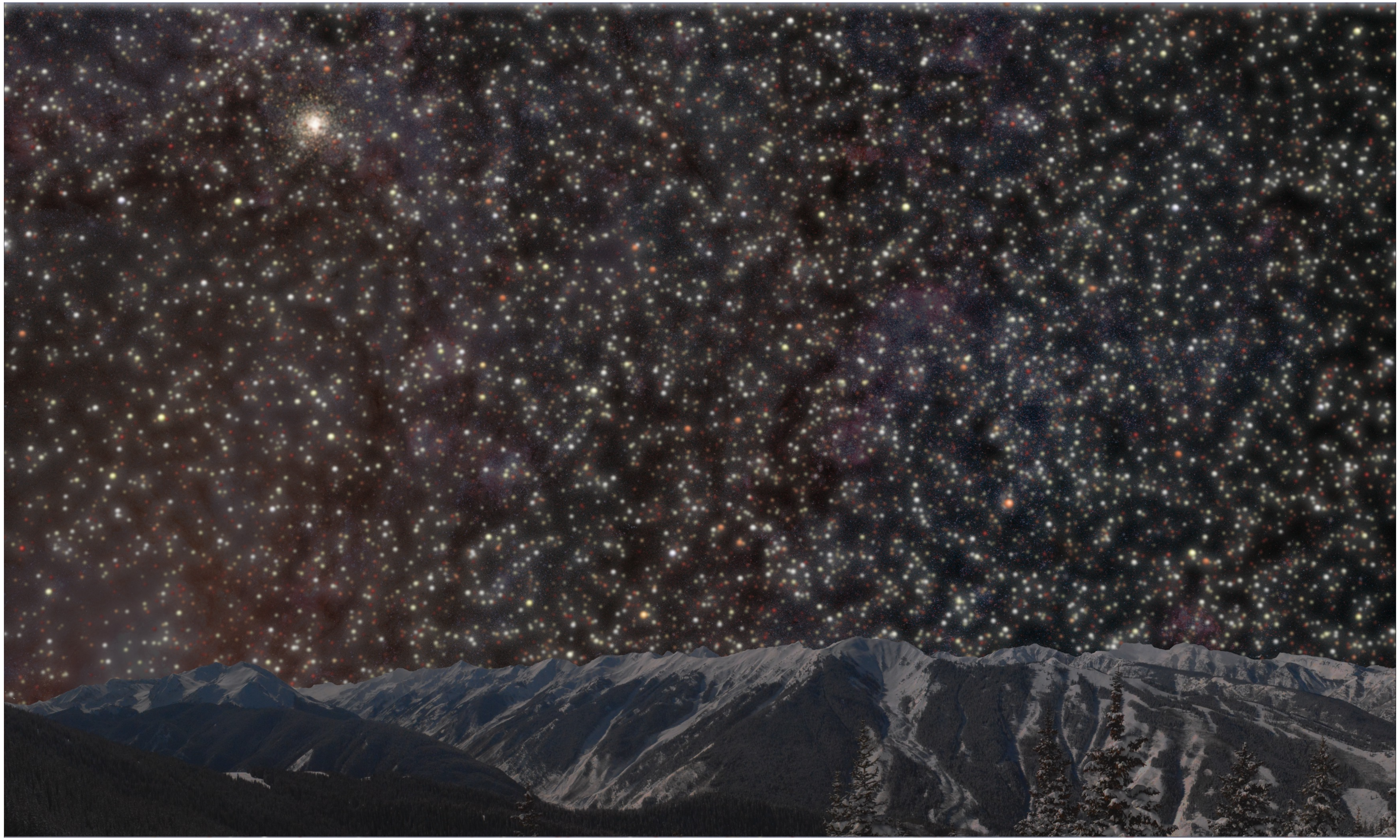
or

1.33 pc

Credit: N. Lüetzgendorf

Observing the Sky Inside a Globular Cluster

From the core of 47 Tuc



What The Night Sky Would Look Like From Inside A Globular Cluster
Credit: William Harris and Jeremy Webb (2014)

Observing the Sky Inside a Globular Cluster

From 2.5 pc from the center of 47 Tuc

What The Night Sky Would Look Like From Inside A Globular Cluster
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Observing the Sky Inside a Globular Cluster

From 10 pc from the center of 47 Tuc

What The Night Sky Would Look Like From Inside A Globular Cluster

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Astrophysical Importance of Globular Clusters

Witnesses of the early Galactic evolution

- First to form
- Mostly metal poor/Chemically uncontaminated

Stellar Evolution Laboratories

- 'Simple' stellar populations
- Test of the 'stellar clock'

Distance and Age Indicators

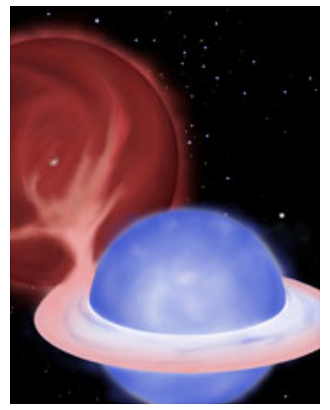
- Standard candles: the RR Lyrae stars
- GC system integrated luminosity function
- The turn-off luminosity = 'the clock'

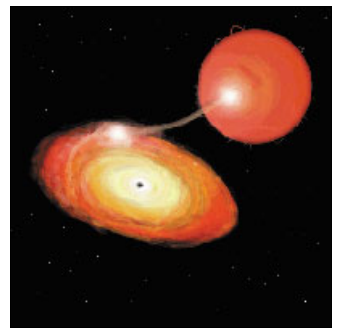
Stellar/Galactic Dynamics

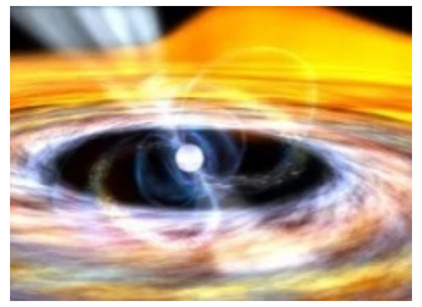
- **Dense environments (laboratories for stellar dynamics):**
- evaporation, mass segregation, core collapse, strong interactions, collisions, mergers
- Test particle of the galactic gravitational field

Populations of Peculiar Objects/ Stellar Exotica

- X-ray Sources (strong–weak–diffuse)/LMXBs
- Blue Stragglers
- Eclipsing Binaries
- White Dwarfs, Planetary Nebulae
- Cataclysmic Variables
- Millisecond Pulsars and Neutron Stars
- Stellar-mass Black Holes
- Binary black holes
- Intermediate-mass Black Hole?







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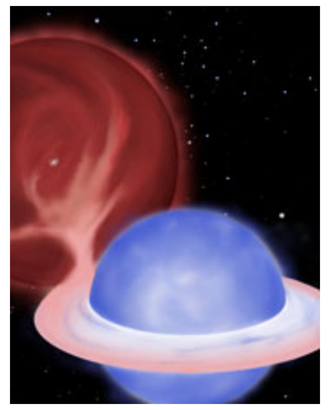
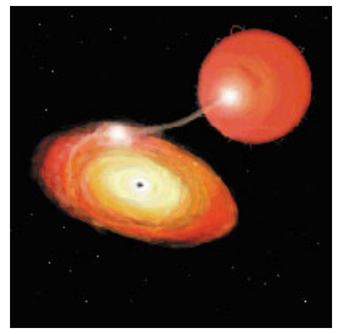
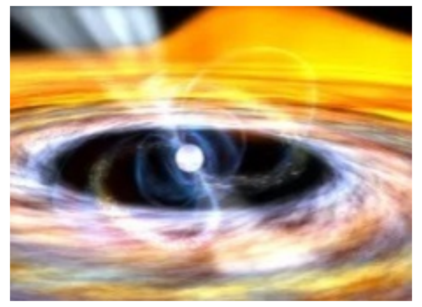
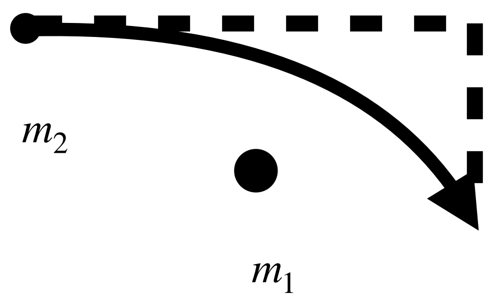






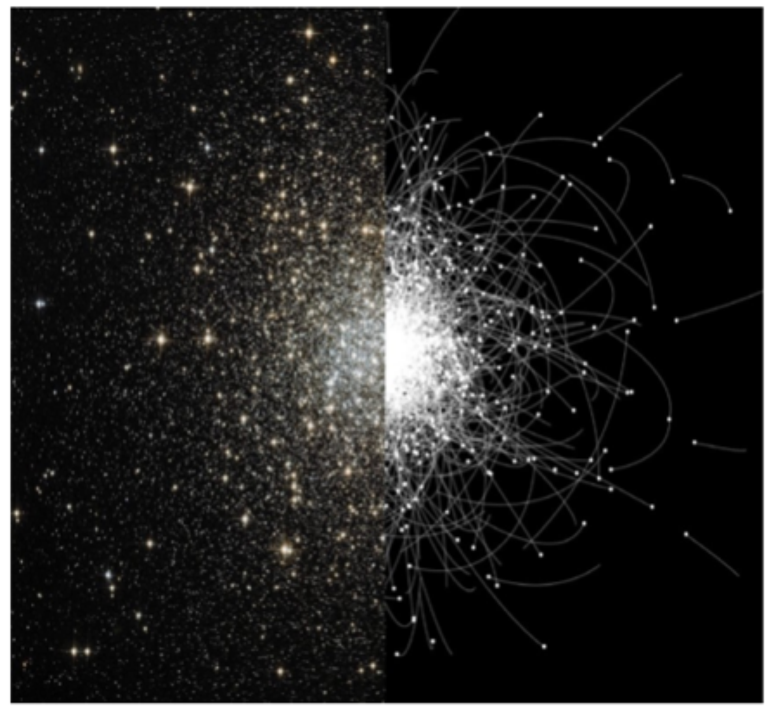
Dynamics in Dense Star Clusters

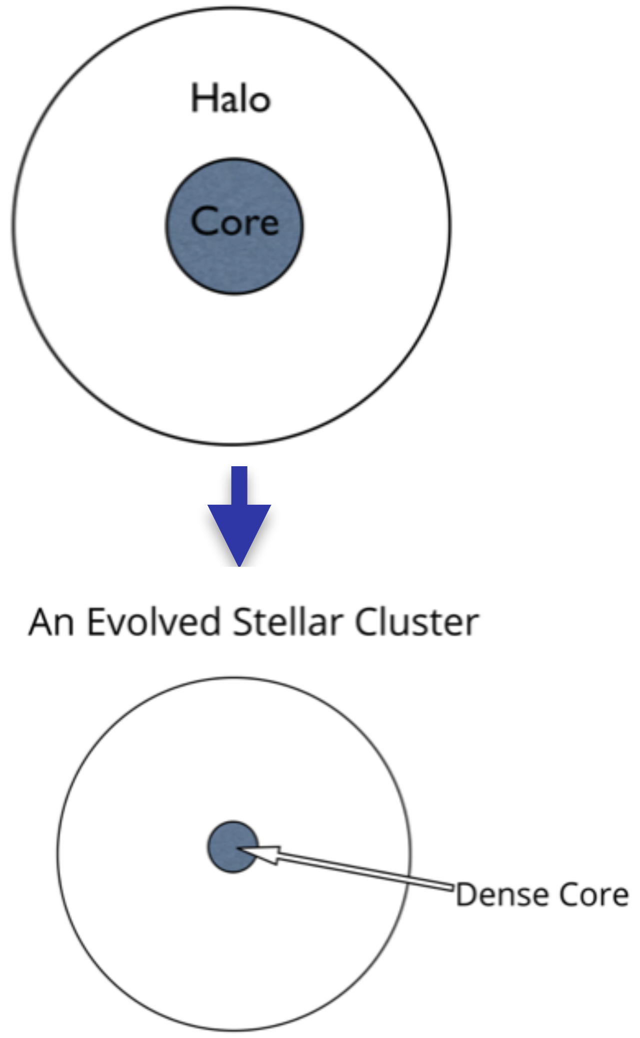
- Gravitational encounters between stars drive the evolution of star clusters

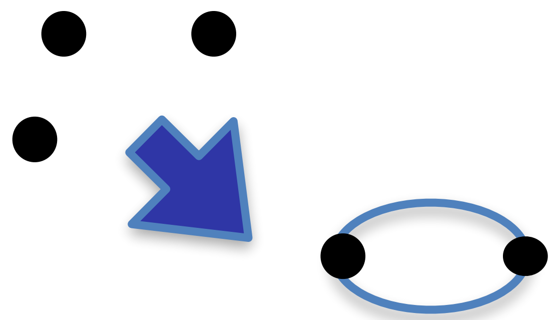


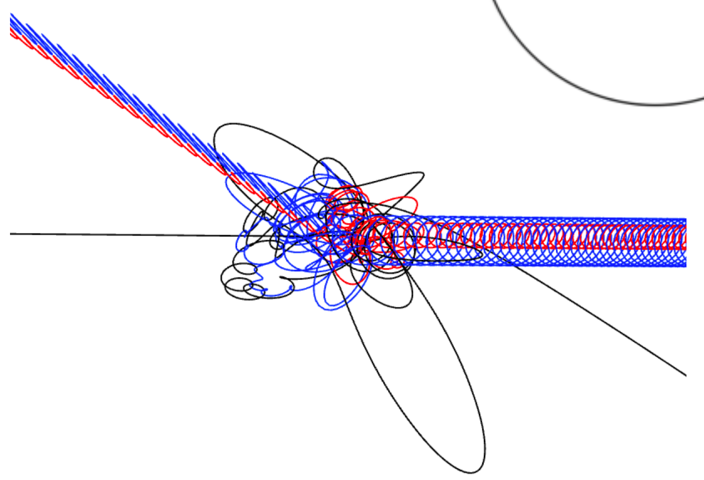
  - Many weak interactions cumulatively modify stellar orbits → **two-body relaxation** → transports energy within a star cluster

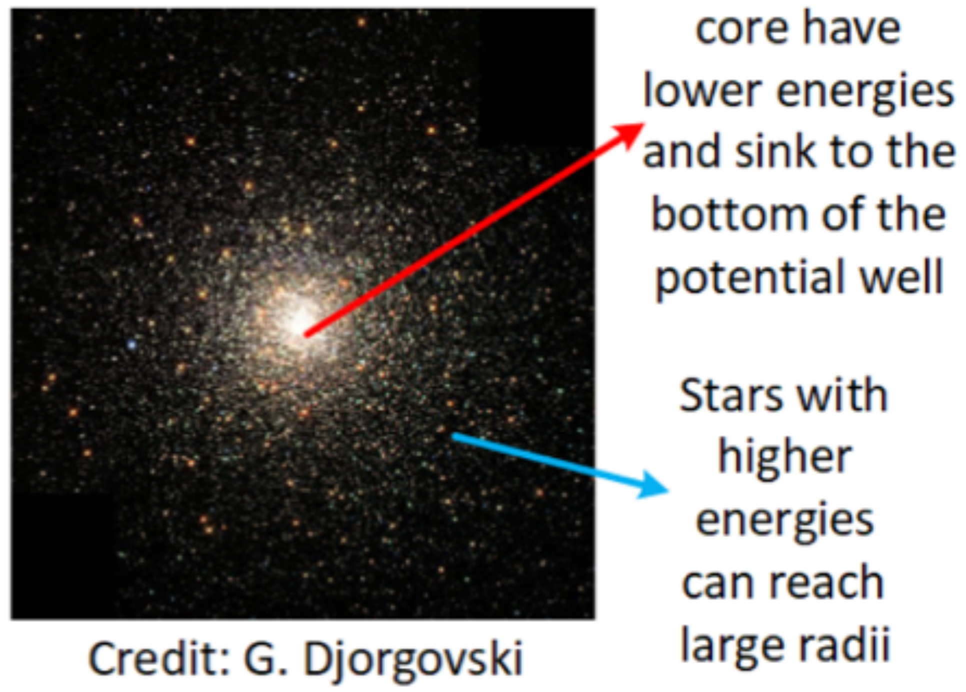
- **Consequences:**
  - **Mass segregation** (massive stars sink to the center)
  - **Core Collapse:** Energy loss from the core via relaxation leads to collapse
  - Frequent close encounters in dense cores → formation and **dynamical interactions of binaries**
  - **Evaporation:** stars gain energy and escape the cluster into the host galaxy







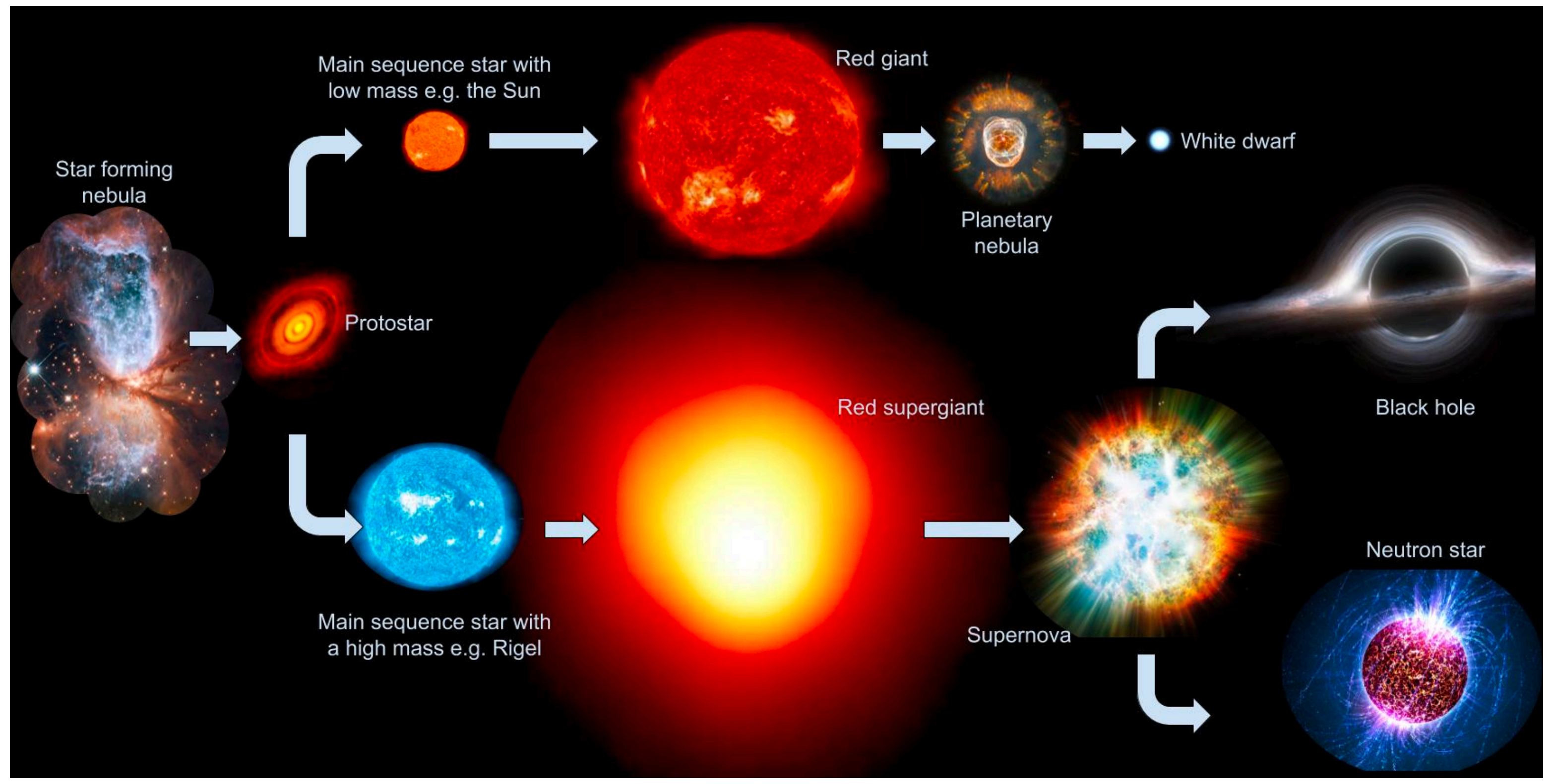


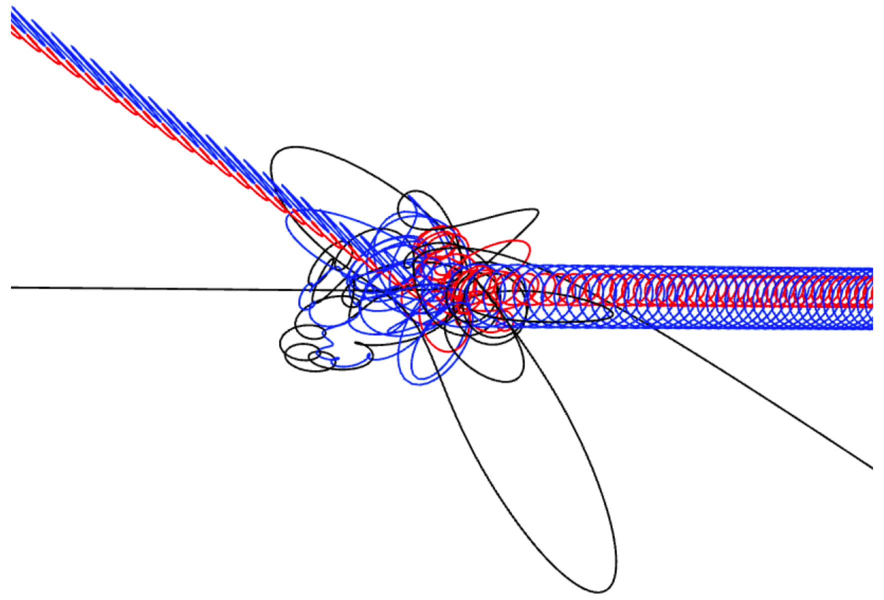


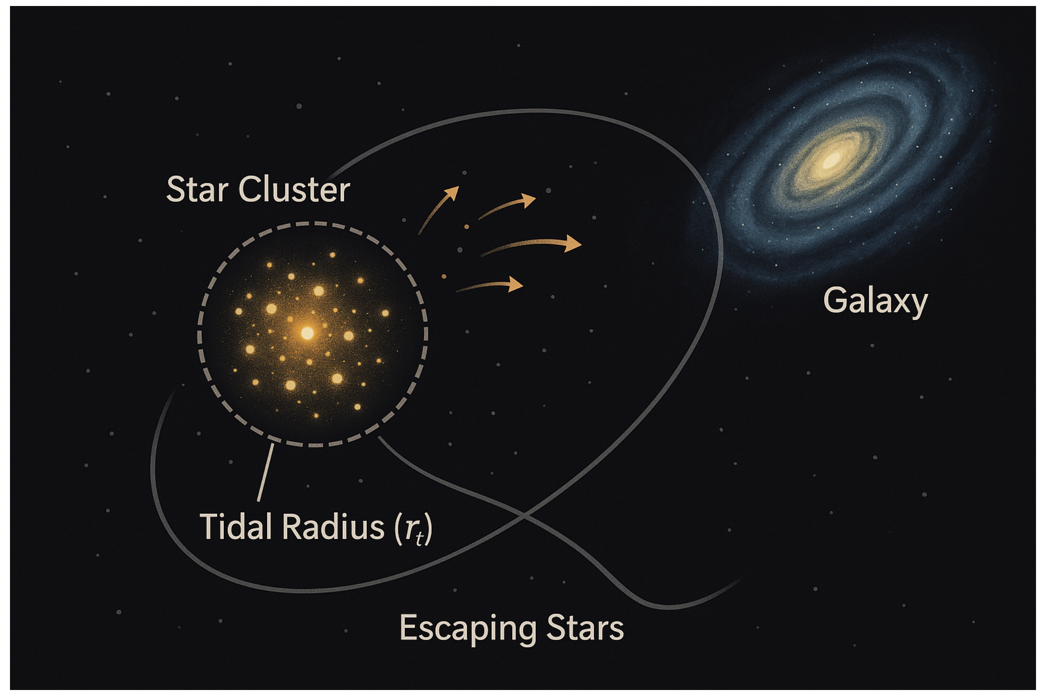
Credit: G. Djorgovski

How Do We Simulate Star Cluster Evolution?

- Star clusters contain up to millions of stars evolving over billions of years
- Their evolution is governed by several coupled processes:
  - Gravitational interactions between stars (two-body relaxation, close encounters)
  - Formation and evolution of binaries (strong interactions, energy exchange)
  - Stellar evolution and mass loss
  - Influence of the host galaxy (tidal field and escape of stars)
- **Challenges**
  - These processes act on very different length and time scales → requires dedicated **numerical simulations**



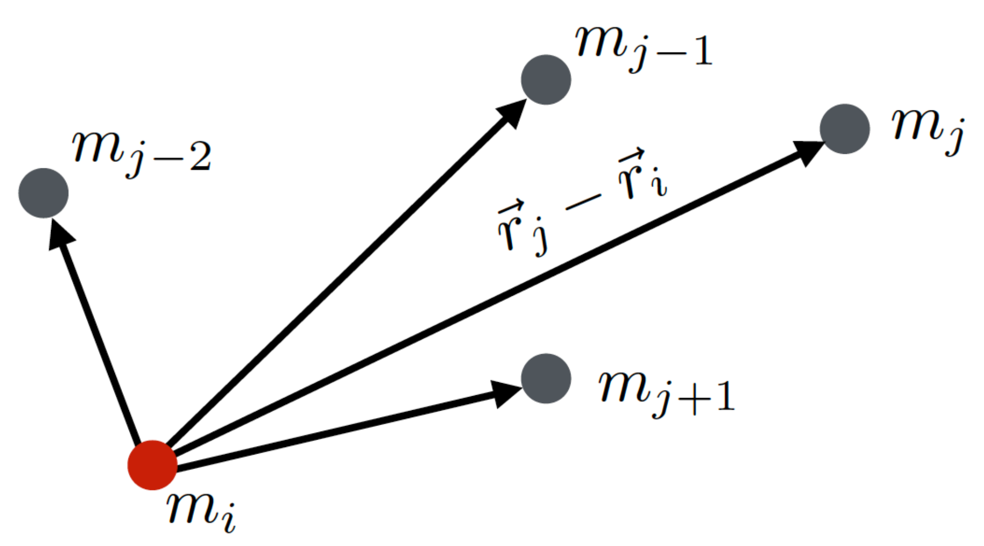


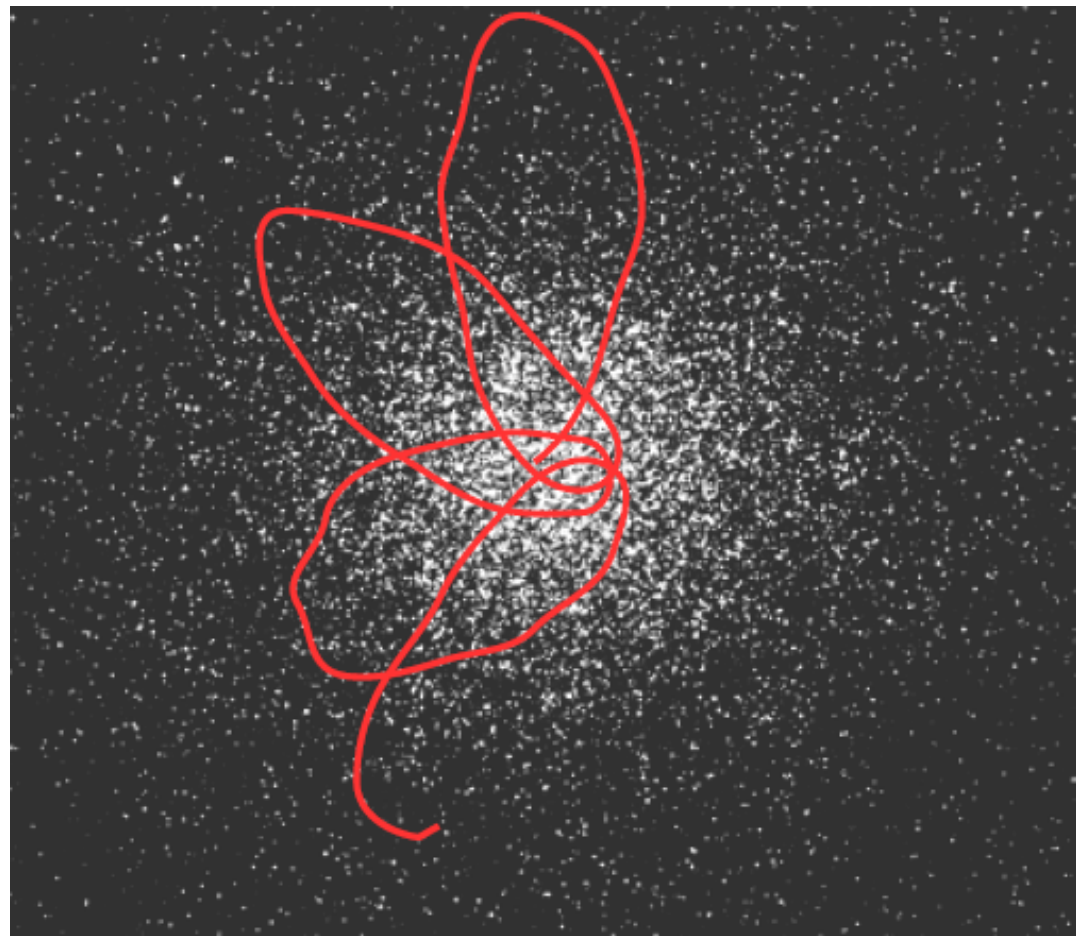


Numerical Approaches to Star Cluster Simulation

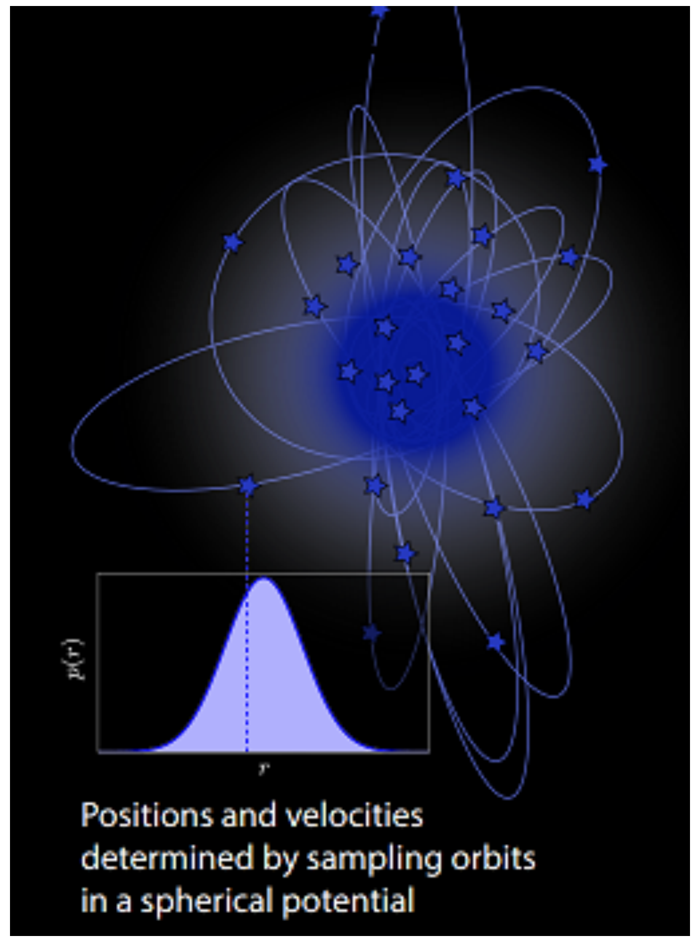
- Direct *N*-body simulations: e.g., NBODYX codes (Aarseth 2010; Wang et al. 2015): PeTar (Wang et al. 2000)
  - Follow the gravitational force between all stars directly
  - High accuracy but computationally expensive → $O\left(N^2\right)$
- Monte Carlo *N*-body codes: e.g., CMC (Rodriguez et al. 2022) and MOCCA (Giersz et al. 2013; 2025)
  - Model relaxation statistically → Follow evolution ***of*** orbits not motion ***on*** orbits
  - Use small *N*-integrator for computing the outcome of 3-body and 4-body interactions
  - Can simulate a realistic star cluster within a few days to weeks
  - Limitations: Spherically symmetric systems → $O\left(N \ln N\right)$

$$\vec{F}_i = \sum_{j=1, j\neq i}^{N} G m_i m_j \frac{\vec{r}_j - \vec{r}_i}{|\vec{r}_j - \vec{r}_i|^3}$$





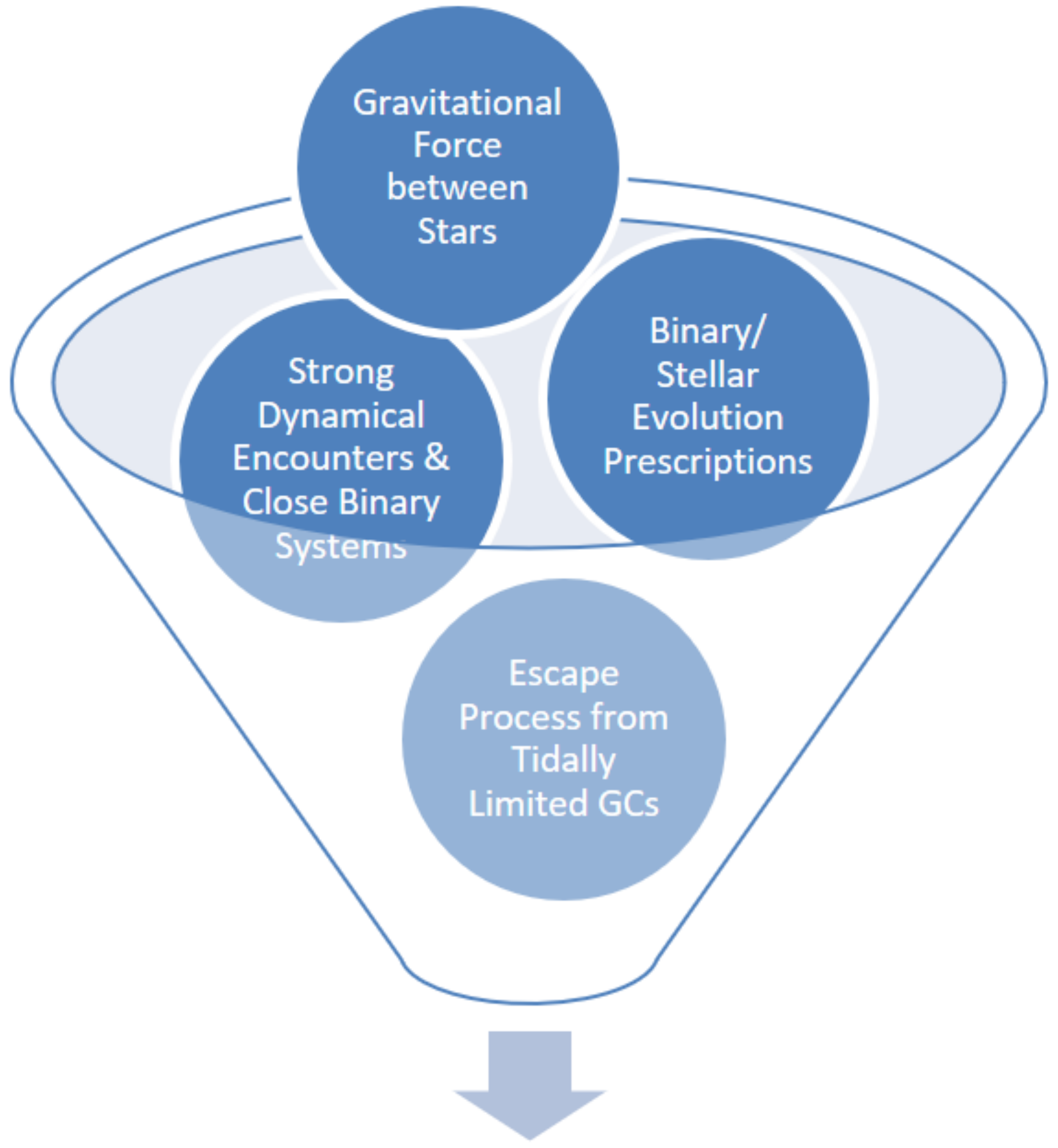
Credit: D. Heggie



Credit: F. Rasio

The MOCCA Code

- **MO**nte **C**arlo **C**luster simul**A**tor: code to evolve realistic star clusters
  - Developed at CAMK
  - Based on a Hénon's Monte Carlo method → further improved by Stodółkiewicz and Giersz
- Includes key physics:
  - Stellar & binary evolution (SSE/BSE + updates)
  - Few-body integrator for close encounters
  - Realistic treatment for escapers in a tidal field
  - Validated against direct *N*-body simulations
- **Can simulate realistic clusters in days to weeks → enabling large grids of models exploring the initial parameter space**
  - MOCCA-Survey Database I, II, III (Askar et al. 2017; Hypki et al. 2022; Maliszewski et al. 2022; Giersz et al. 2025; Wiktorowicz et al. 2025)



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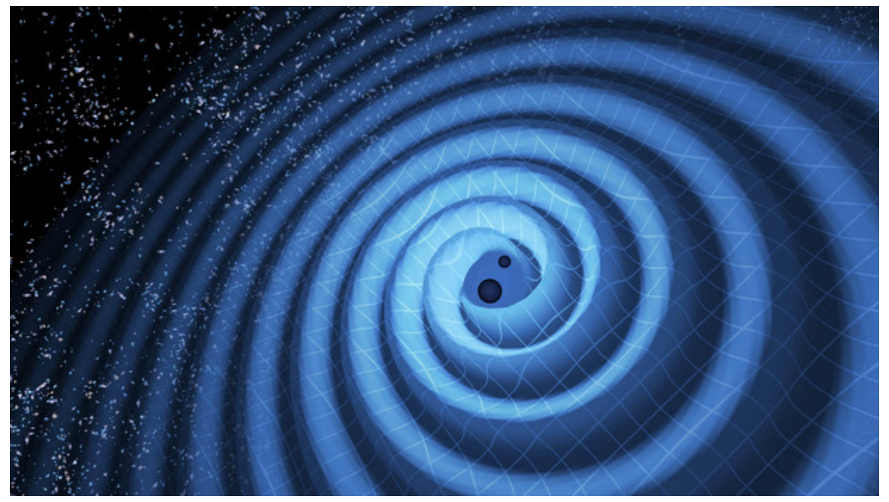
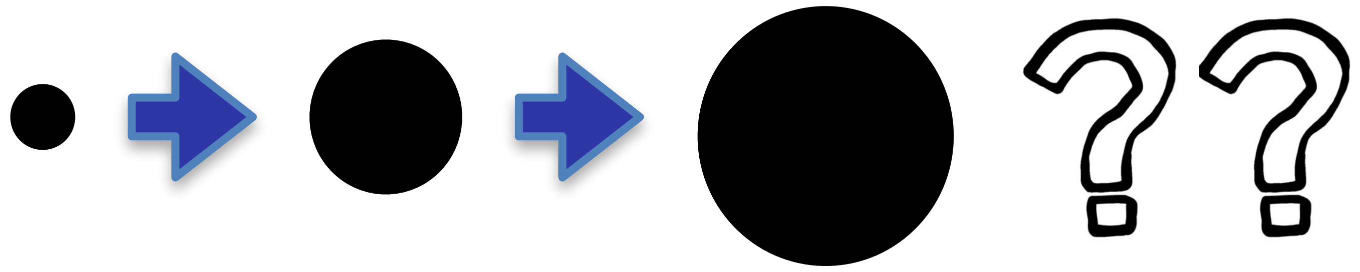
MOCCA

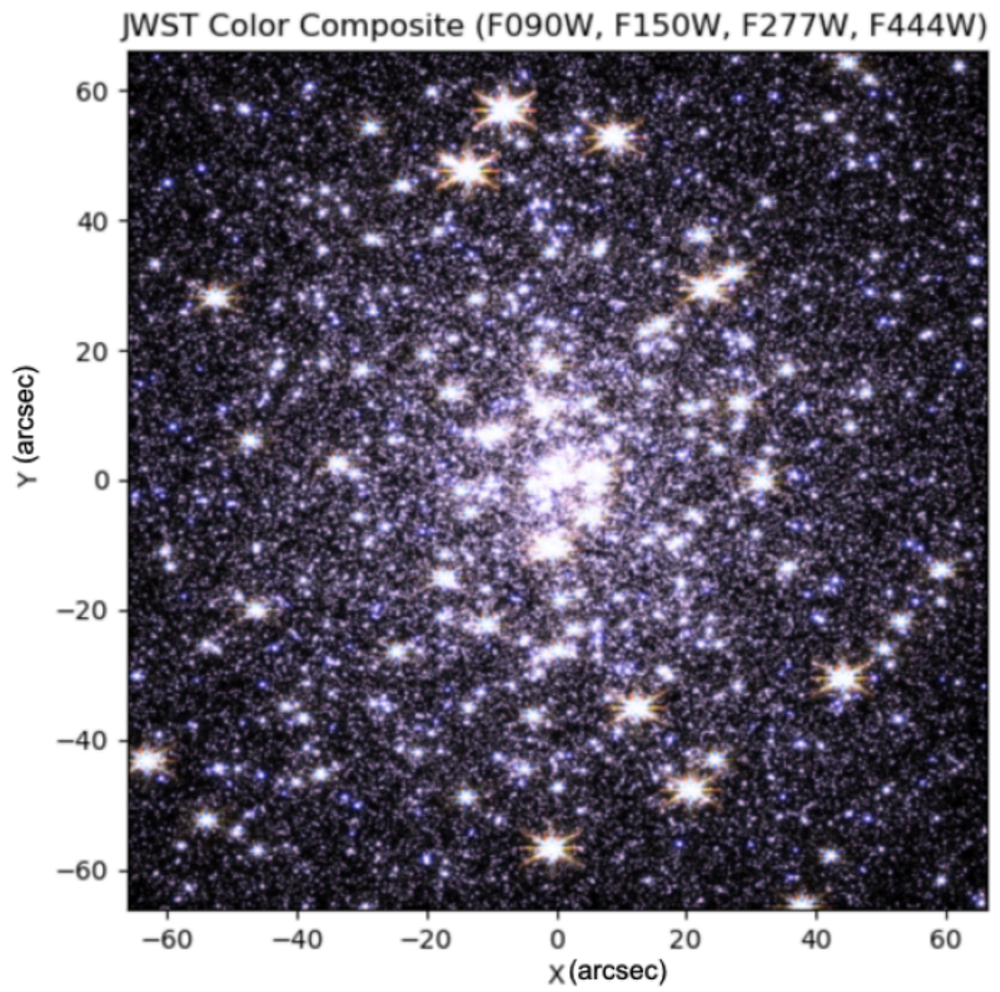
https://camk.pl/moccacode/

The MOCCA Code: Science Applications

- **Binary black holes (BBHs) & gravitational wave (GW) sources**
  (Askar et al. 2017; Belczynski et al. 2018; Hong et al. 2018; Zhao et al. 2026)
- **Black hole subsystems in clusters**
  (Arca Sedda et al. 2018; Askar et al. 2018; Giersz et al. 2019; Leveque et al. 2023)
- **Intermediate-mass black holes (IMBHs)**
  (Giersz et al. 2015; Askar et al 2017; 2023 Maliszewski et al. 2022; Vergara, Askar et al. 2025, 2026)
- **Mock observations**
  (Wang et al. 2016; Askar et al. 2017; Belloni et al. 2017; Askar et al. 2018)
- Multiple stellar populations (Hypki et al. 2022,2025; Giersz et al. 2025a,b)
- X-ray binaries / ULXs (Wiktorowicz et al. 2025)
- Double white dwarf binaries (Hellström et al. 2024, 2025)
- Blue stragglers & stellar exotica (Hypki et al. 2013, 2017)
- Cataclysmic variables (Belloni et al. 2016, 2017, 2019)







Mock JWST Image of a MOCCA Snapshot
Credit: Sohaib Ali, Paolo Bianchini, FSPS, Agostino Leveque and Lucas Hellström

Producing Binary Black Holes in Globular Clusters

- Black holes segregate to the center of the cluster → interact with each other and surrounding stars

↓

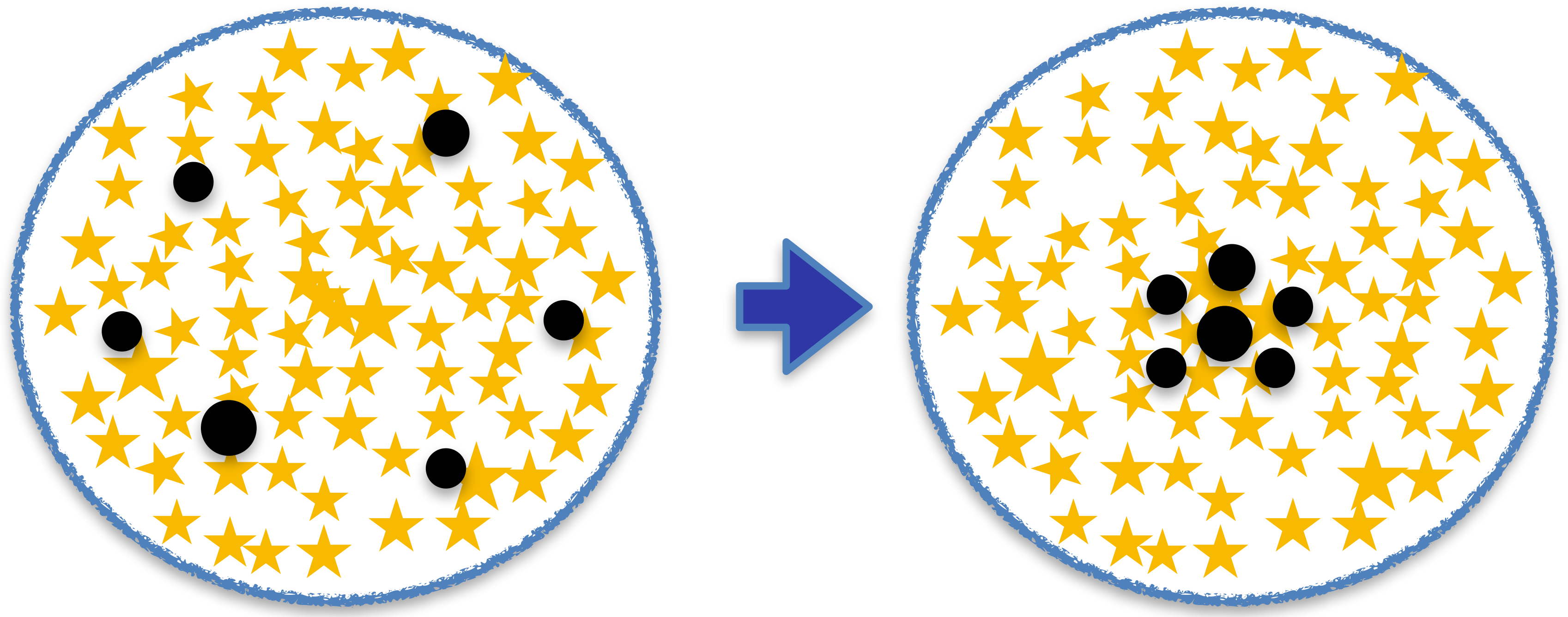
- 3 and 4-body close dynamical interactions involving black holes
  - **Formation of BBH through exchange encounters**
  - Mergers can also occur during these interactions (Samsing 2018, Samsing, Askar, Giersz 2018, Rodriguez et al. 2018 a,b, Zevin 2018)

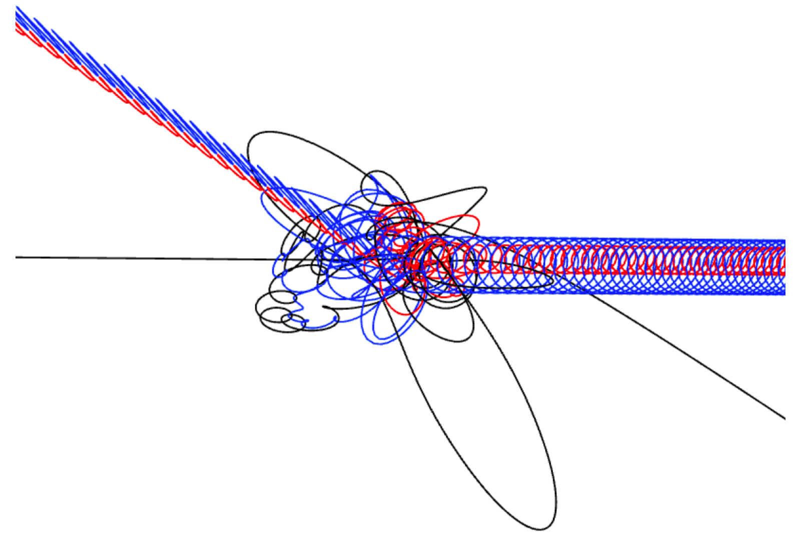
↓

- Hardening of BBH through interactions → binary becomes ‘useful’ → can merge due to gravitational wave radiation within a Hubble time → interactions can also eject binary from the cluster

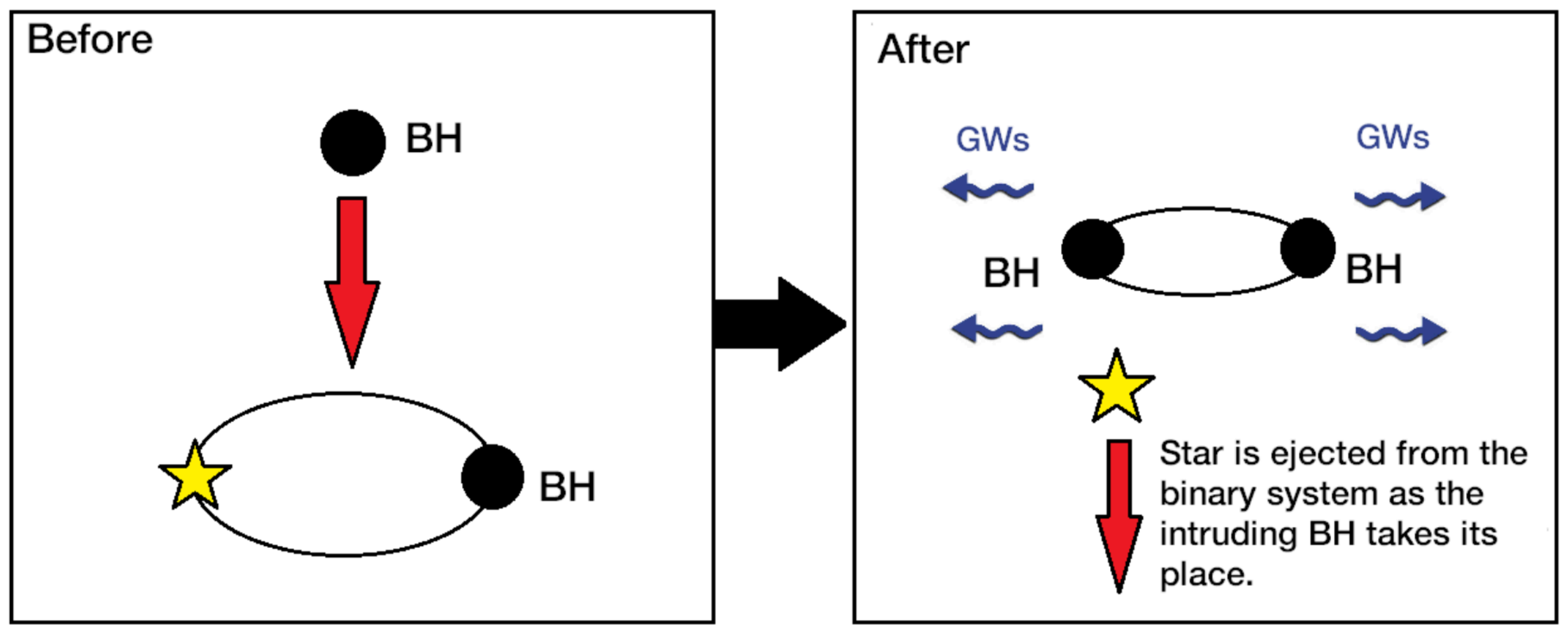
$$\tau_{gr} \simeq 10^{10} yr \left(\frac{a_{bin}}{3.3 R_{\odot}}\right)^4 \frac{1}{(m_1+m_2)m_1 m_2} \cdot \left(1-e^2\right)^{7/2}$$ (Peters 1964)

Mass Segregation





Exchange Encounters



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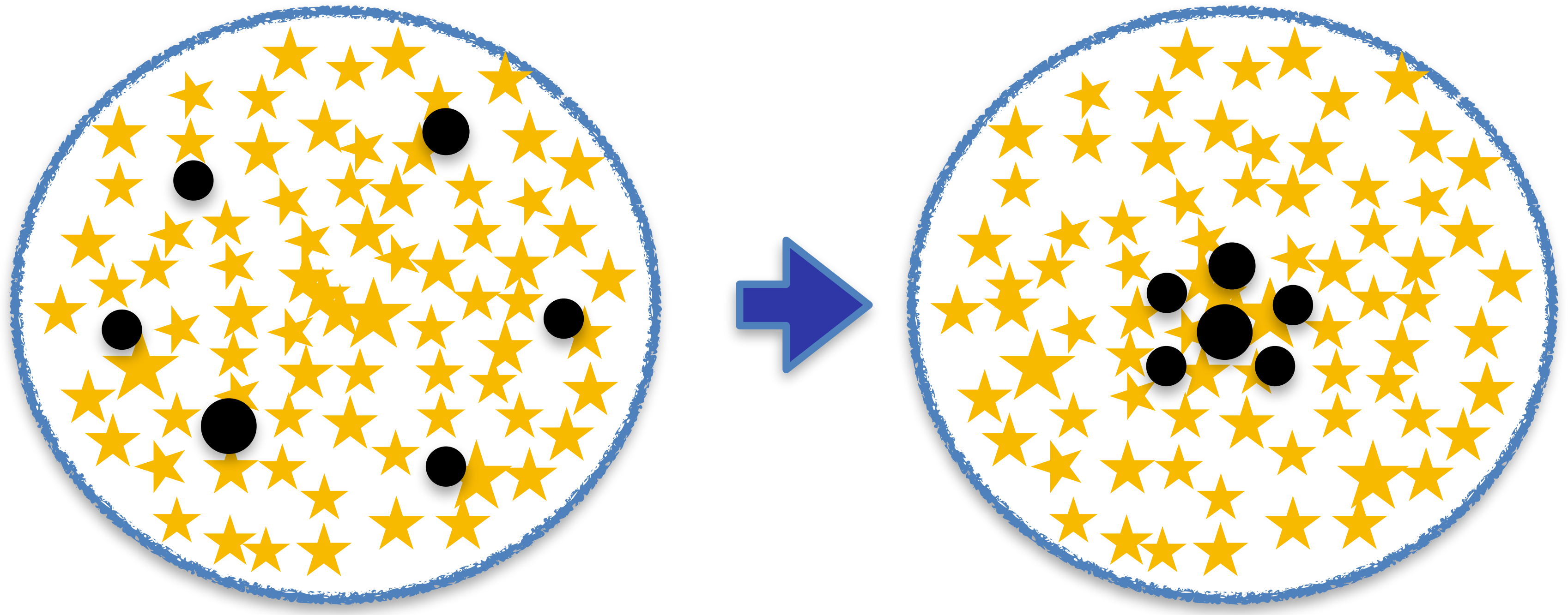
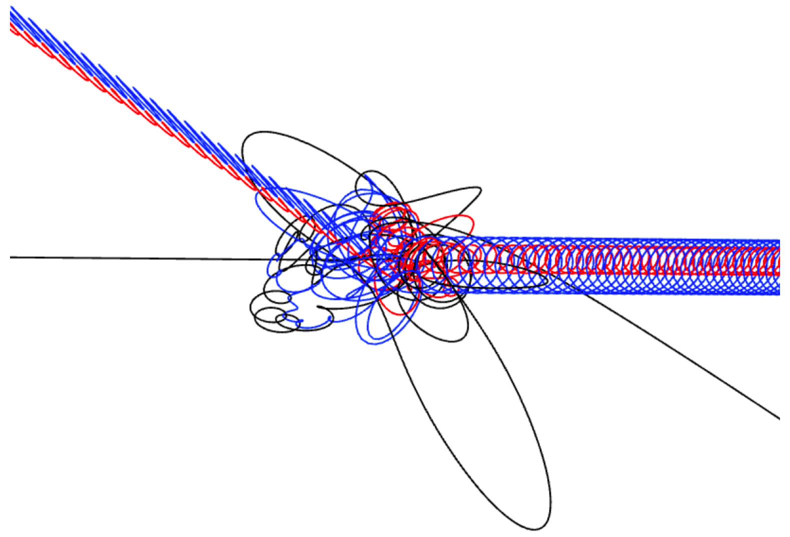
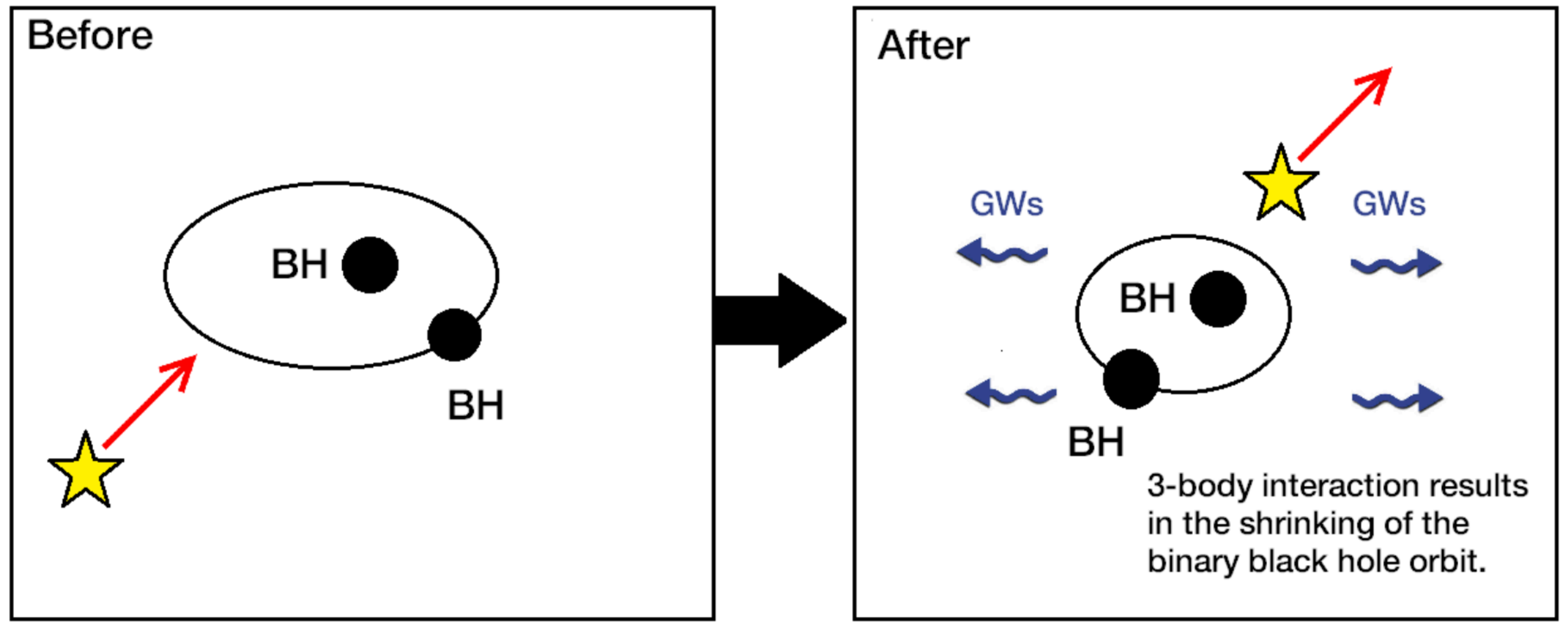




Binary Hardening in Fly-by Encounters



Binary Hardening in Action

$m_1 = 30\,M_\odot$

$m_2 = 30\,M_\odot$

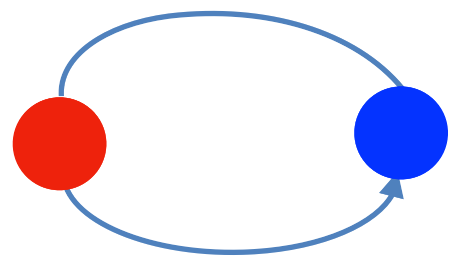
$a_{bin} = 0.5$ AU

$e_{bin} = 0.33$

$m_{single} = 30\,M_\odot$

$v_\infty = 30\,\mathrm{km/s}$

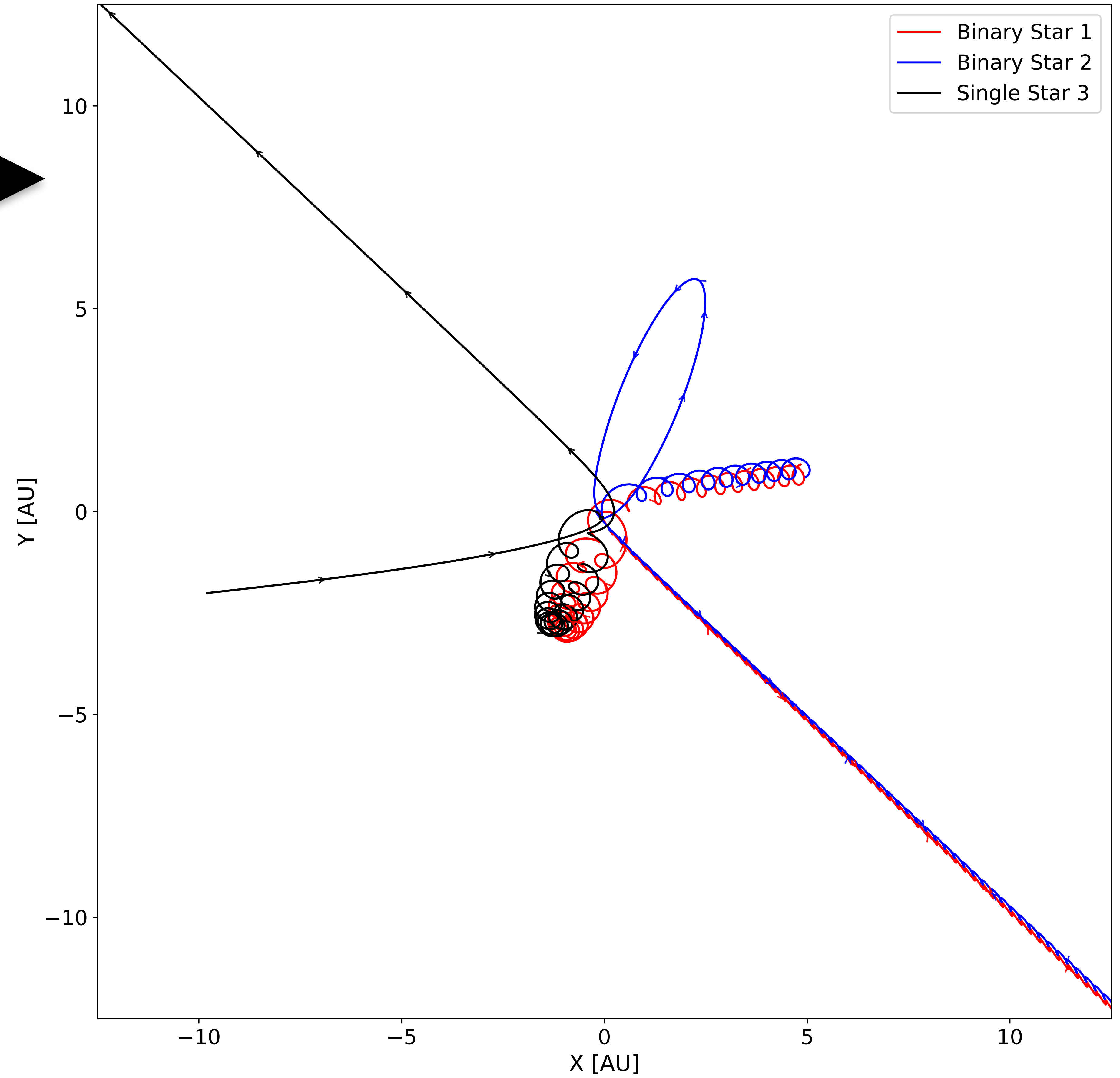
$b = 5.0$ AU



$\tau_{gr} \simeq 246613$ Myr

$$\tau_{gr} \propto a^4 \frac{1}{(m_1 + m_2) m_1 m_2} \cdot \left(1 - e^2\right)^{7/2}$$

Resonant fly-by interaction simulated with Tsunami



$m_1 = 30\,M_\odot$

$m_2 = 30\,M_\odot$

$a_{bin} = 0.235$ AU

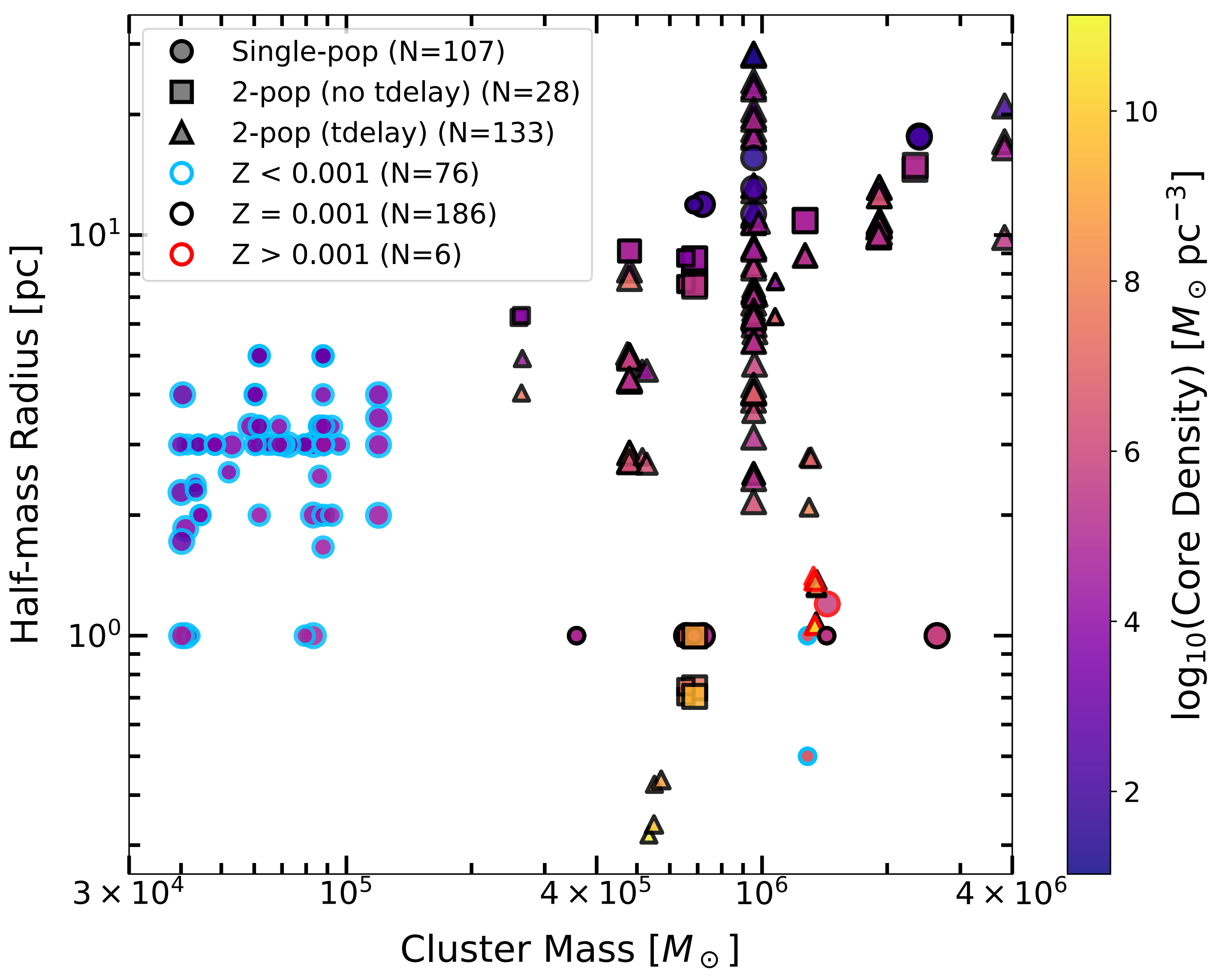
$e_{bin} = 0.994$

$\tau_{gr} \simeq 0.005$ Myr

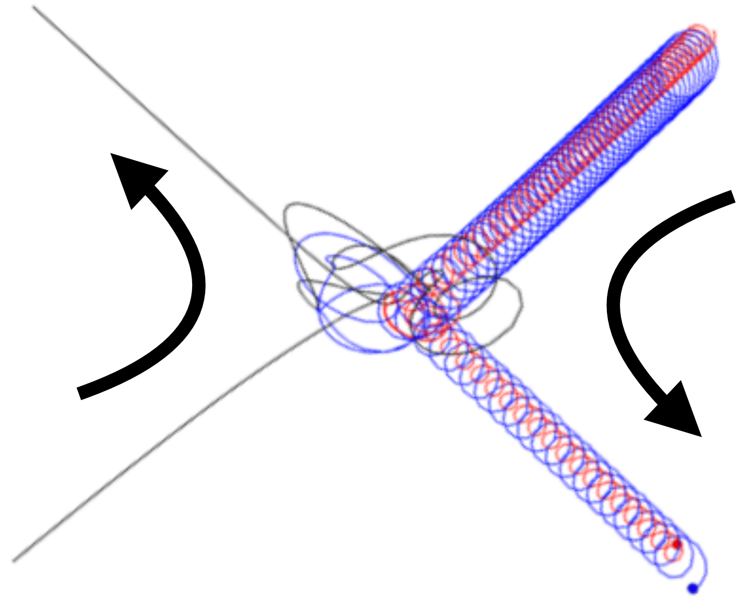
TSUNAMI code is a direct few-body code with algorithmic regularization, tidal forces and post-Newtonian corrections (Trani et al. 2022, 2023; Trani & Spera 2023; Hellström et al. 2022)

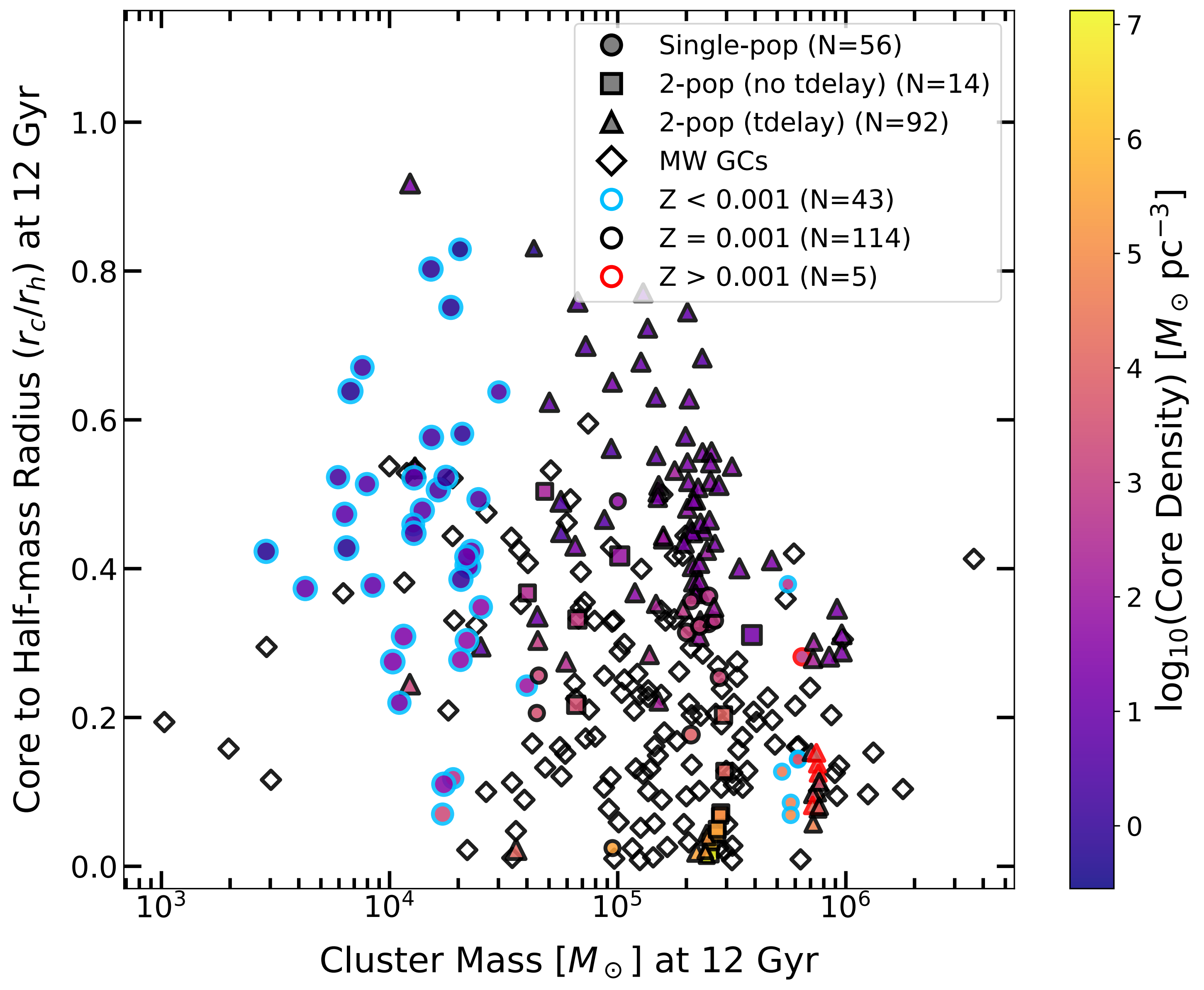
Binary Black Hole Production in MOCCA Simulations

- 268 MOCCA cluster models (2024–2025 update)
  - Wide range of initial masses, densities, initial binary fraction, Galactocentric radii and metallicity
  - Updated stellar winds & remnant mass prescriptions
  - Gravitational wave recoil kicks included
  - Also includes initial models with two distinct populations
- **Investigate BBHs that escape the clusters**



Initial Conditions of MOCCA Star Cluster Simulations (Zhao, Askar et al. 2026)



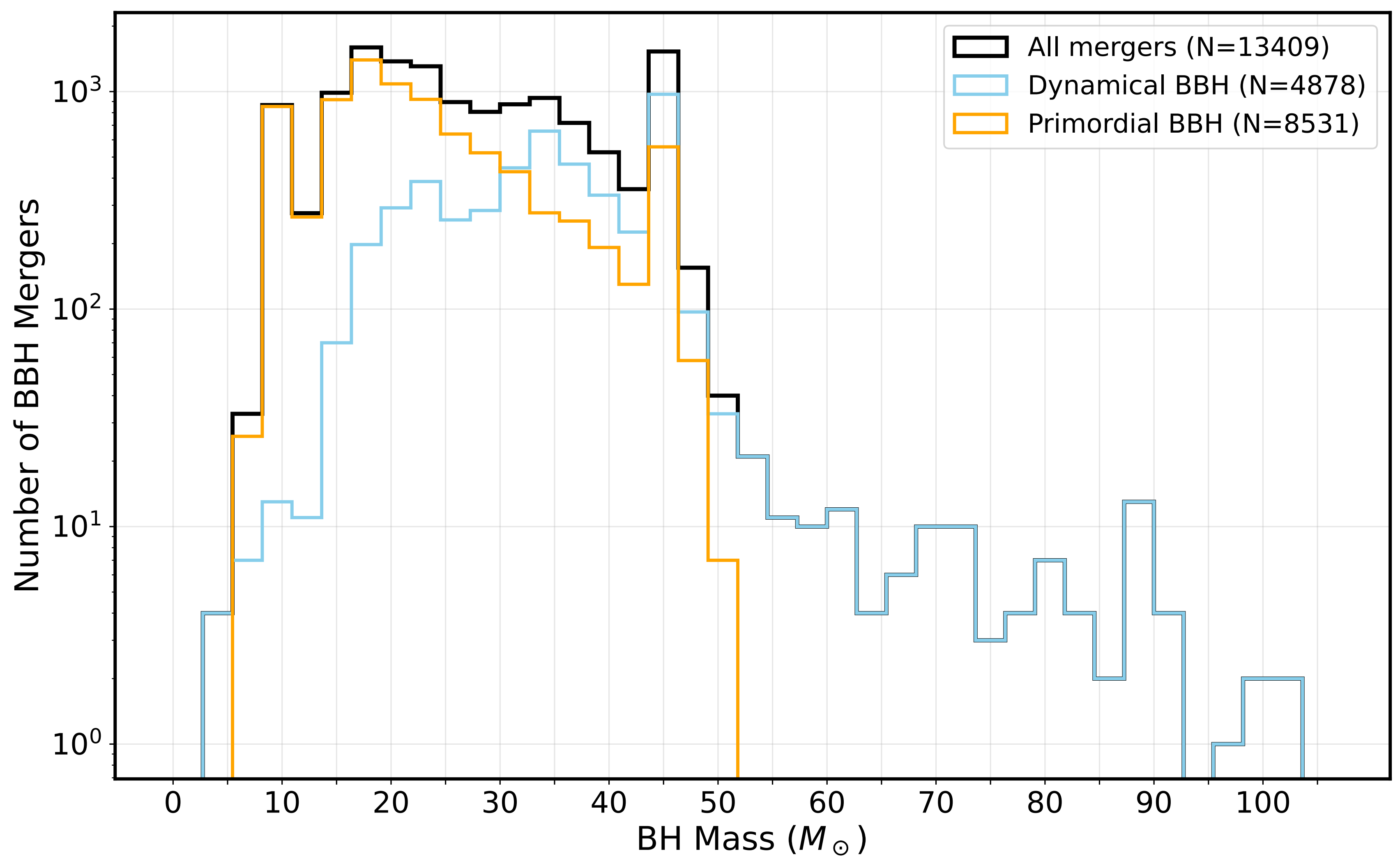


12 Gyr Properties of Surviving Clusters (Zhao, Askar et al. 2026)

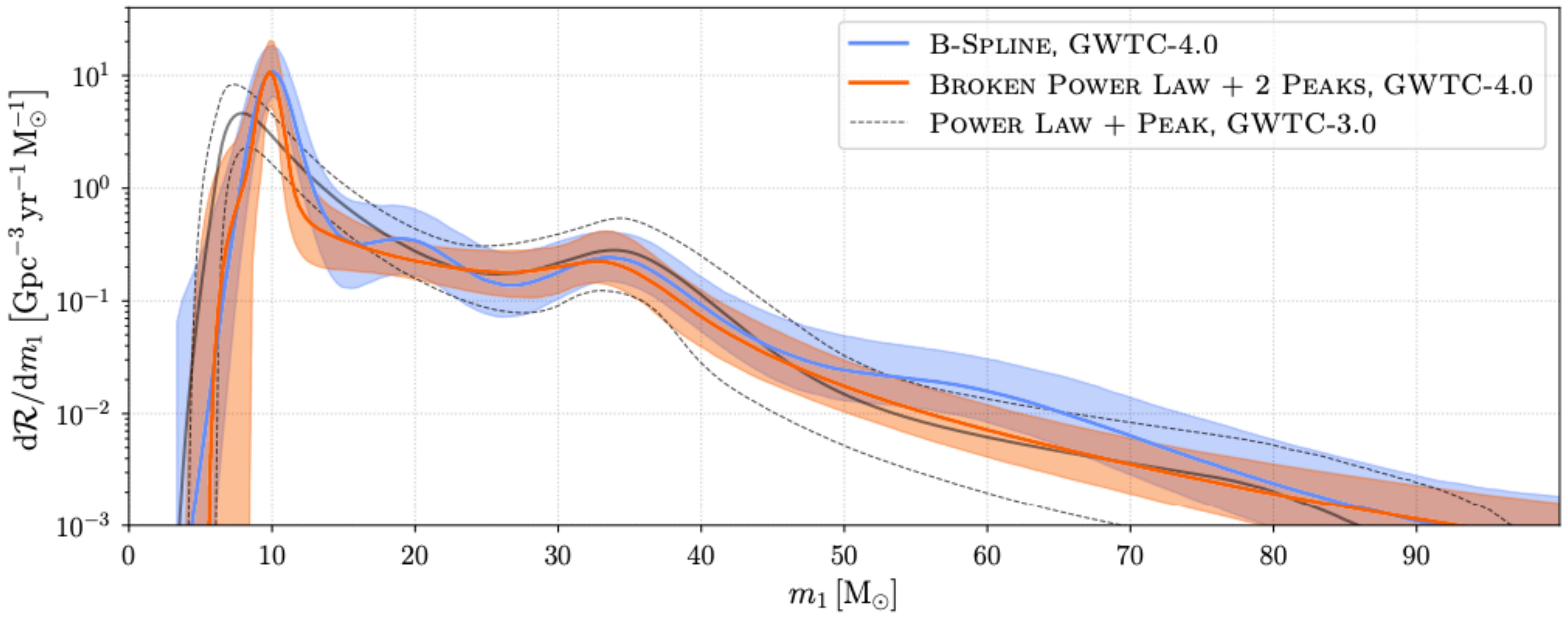
Binary Black Hole Production in MOCCA Simulations

- Total BBH mergers produced: ~13,409
  - Dynamical exchanges: ~4,878
  - Initial binaries (primordial) driven to merger: ~8,531
- Dynamical interactions help produce high-mass BBHs ($> 50\,\mathrm{M}_{\odot}$)
  - Repeated mergers of BHs or BH-star collisions
  - Naturally populate the upper mass range seen by LVK collaboration
- Mass distribution is channel dependent
  - Initial (Primordial) Binaries: peaks at lower masses
  - Dynamical: dominates the high-mass tail

Distribution of Primary BH Masses for Merging BBHs

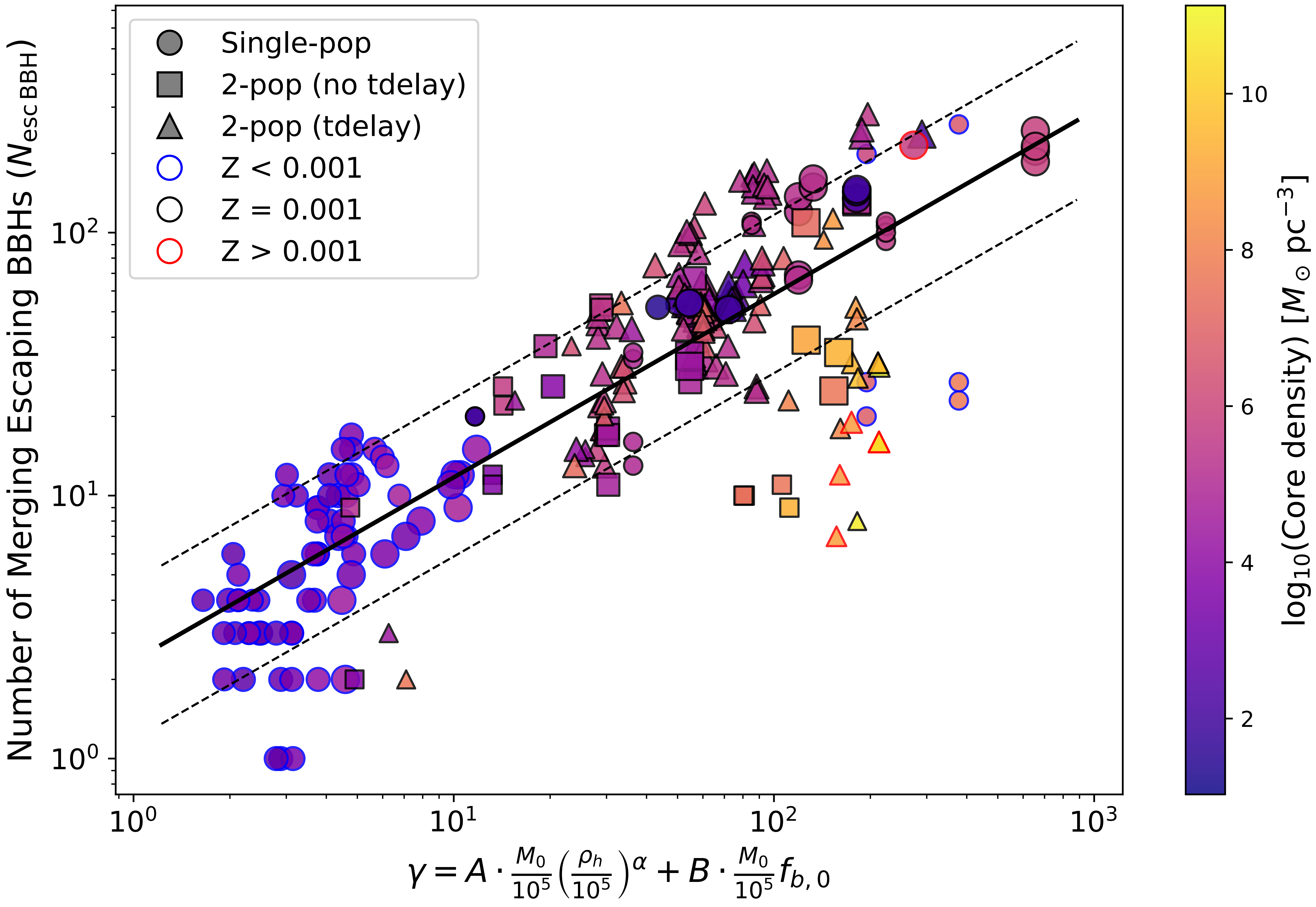


Distribution of Primary BH Masses in Escaping BBHs from MOCCA Models



Differential merger rate as a function of primary mass
LVK Collaboration (2025): https://arxiv.org/pdf/2508.18083v2

Binary Black Hole Production and Globular Cluster Properties



$$\equiv A \frac{M_0}{10^5 \mathrm{M}_\odot} \times \left(\frac{\rho_\mathrm{h}}{10^5 \mathrm{M}_\odot \mathrm{pc}^{-3}}\right)^{\alpha} + B \frac{M_0}{10^5 \mathrm{M}_\odot} \times f_{\mathrm{b},0}$$

dynamical channel — primordial channel

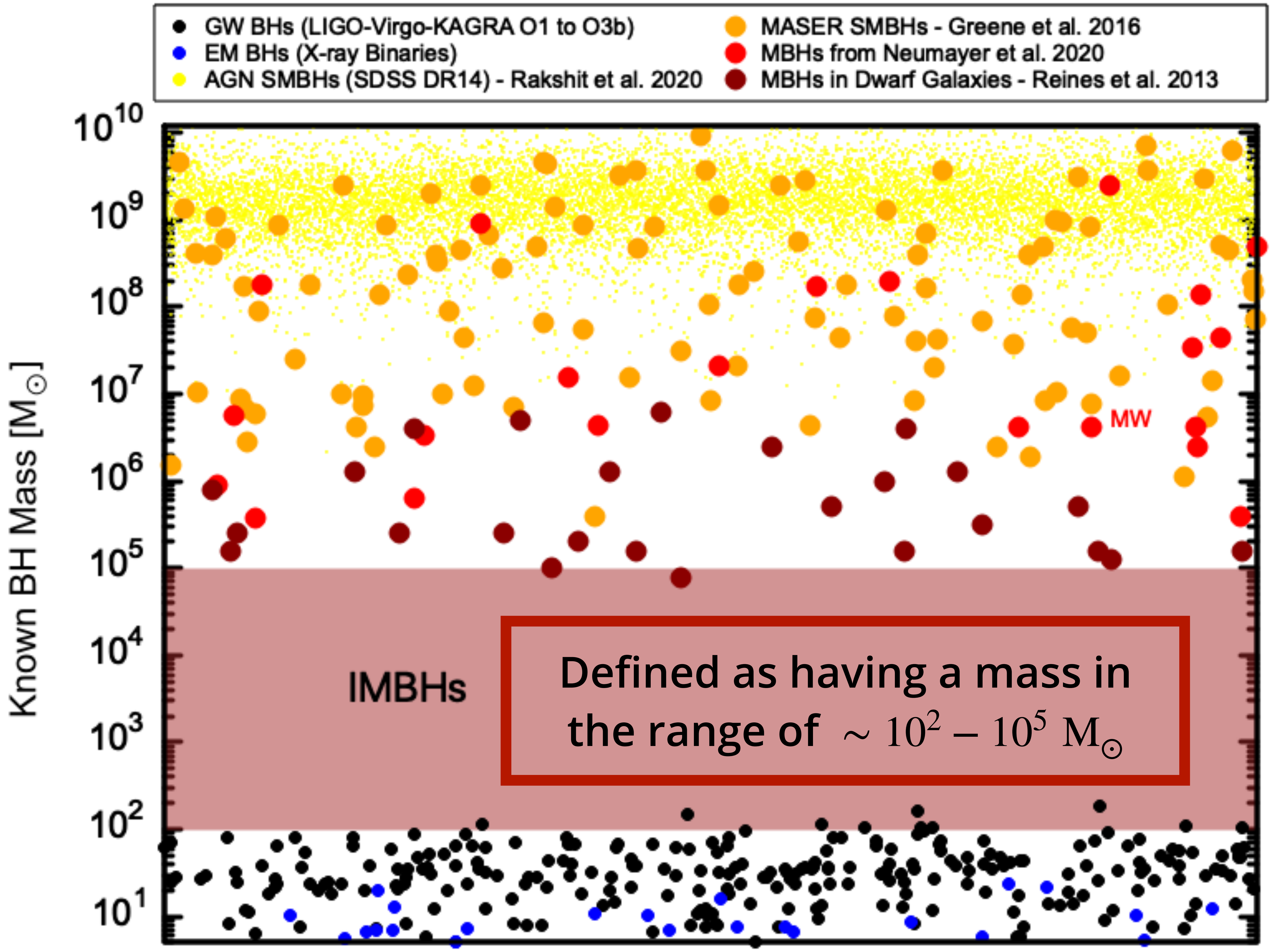
Number of merging BBHs as a function of initial cluster mass (M_0), average density (ρ_h) and binary fraction ($f_{b,0}$) (Hong, Vesperini, Askar et al. 2018)

Hong, Vesperini, Askar et al. (2018)
Hong, Askar et al. (2020)

A Quick Introduction: Intermediate-Mass black holes (IMBHs)

- 2 *well-observed* classes of black holes:

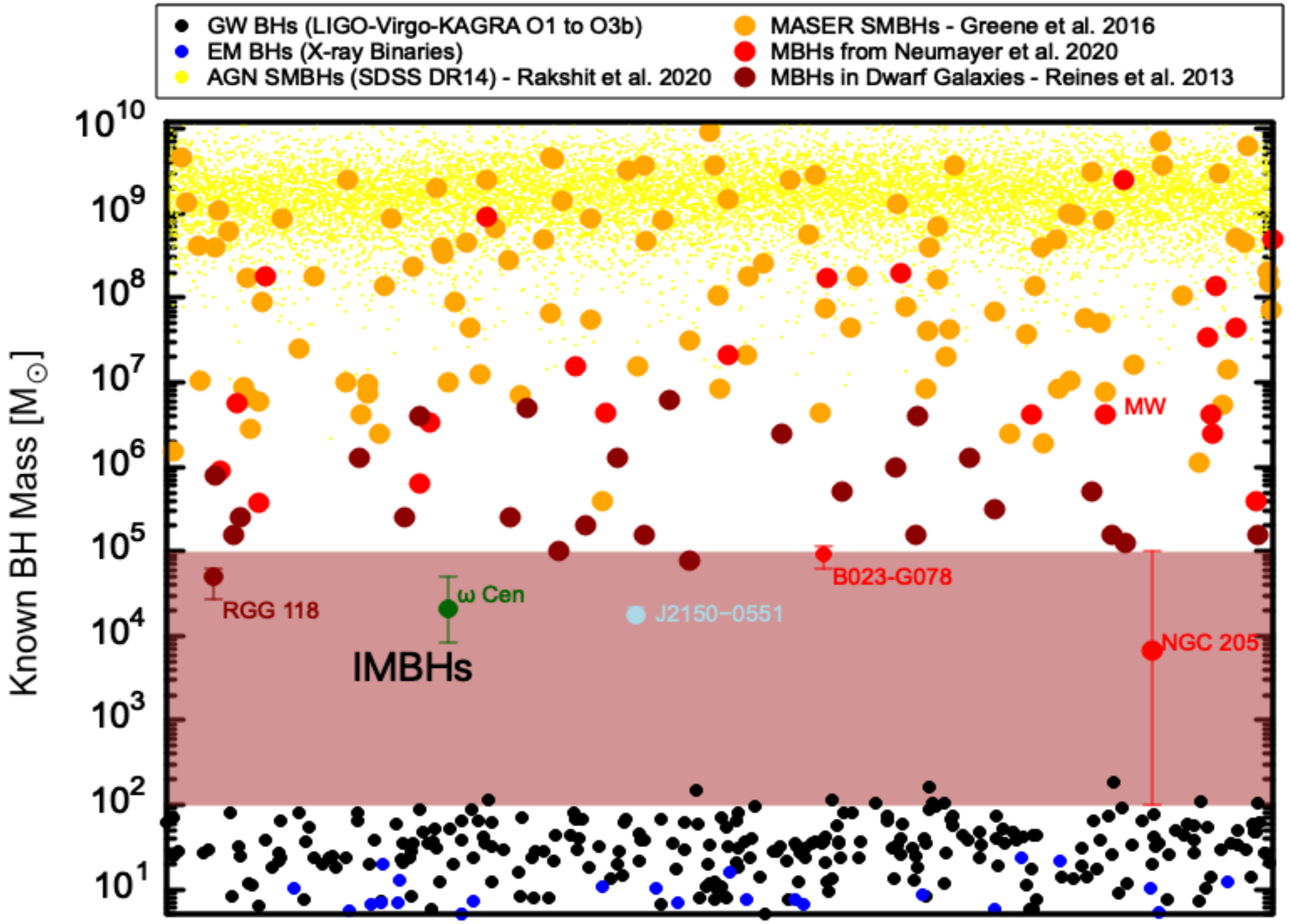
1. **Stellar-mass black holes (sBH):** $\lesssim 100\,M_\odot$
   - **Formation:** End products of evolution of massive stars ($M_{ZAMS} \gtrsim 20\,M_\odot$)
   - **Growth:**
     - Accretion: close binary systems or gas-rich environments
     - Mergers with other sBHs → close binary systems that emit gravitational waves → LVK GW190521: $\sim 150\,M_\odot$
2. **SMBHs:** $\gtrsim 10^6\,M_\odot$
   - Observed in galactic nuclei
   - **Formation?**
   - **Growth:**
     - Accretion of gas/dust
     - Mergers with BHs and disruption of stars



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

A Few Promising IMBH Candidates

Object	Estimated Mass (M☉)	Detection Method	Host Type	Reference
RGG 118	~50,000	Optical spectroscopy and X-ray observations	Dwarf galaxy nucleus	Baldassare et al. (2015)
NGC 205	~6,800	Dynamical modeling using HST/STIS spectroscopy	Dwarf elliptical galaxy nucleus	Nguyen et al. (2019)
B023-G078 (M31 GC)	~100,000	Stellar dynamics (integral-field spectroscopic kinematics from Gemini/NIFS) and photometry (*HST*)	Star Cluster in M31	Pechetti et al. (2022)
Omega Centauri (ω Cen; MW GC)	≥8,200	Proper motion studies with *HST*	Star Cluster in MW)	Häberle et al. (2024)
3XMM J215022.4−055108	~17,500	X-ray spectral modeling of tidal disruption event	Extragalactic Star Cluster	Lin et al. (2019) Wen et al. (2021)



Forming and Growing IMBHs in Dense Stellar Environments

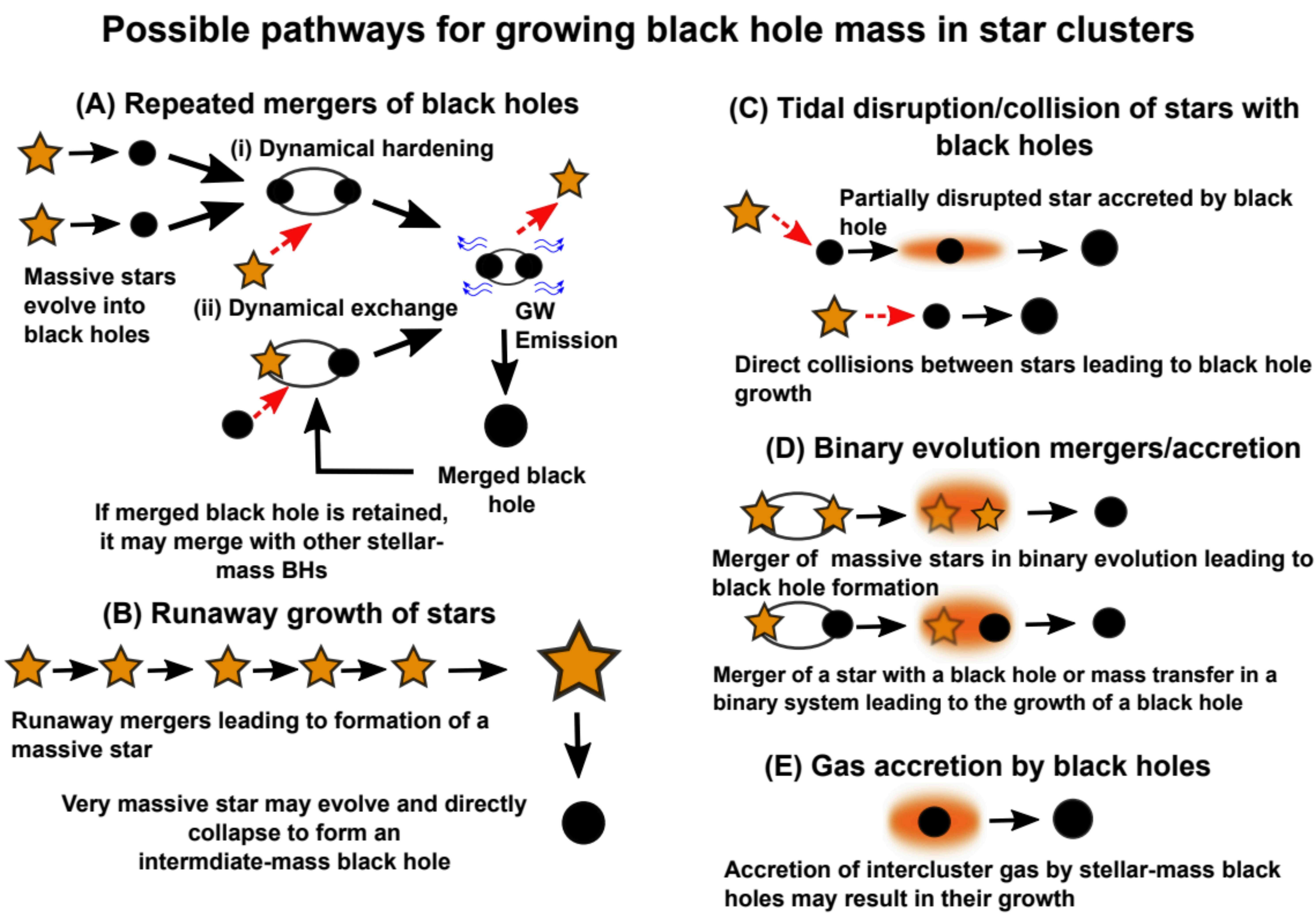
(A) Repeated or hierarchical mergers of stellar-mass BHs

(B) Fast runaway: Stellar collisions resulting in IMBH formation

(C) Slow runaway: Gradual growth of a stellar-mass BH

(D) Binary evolution mergers leading to IMBH formation

(E) Gas accretion by stellar-mass BHs

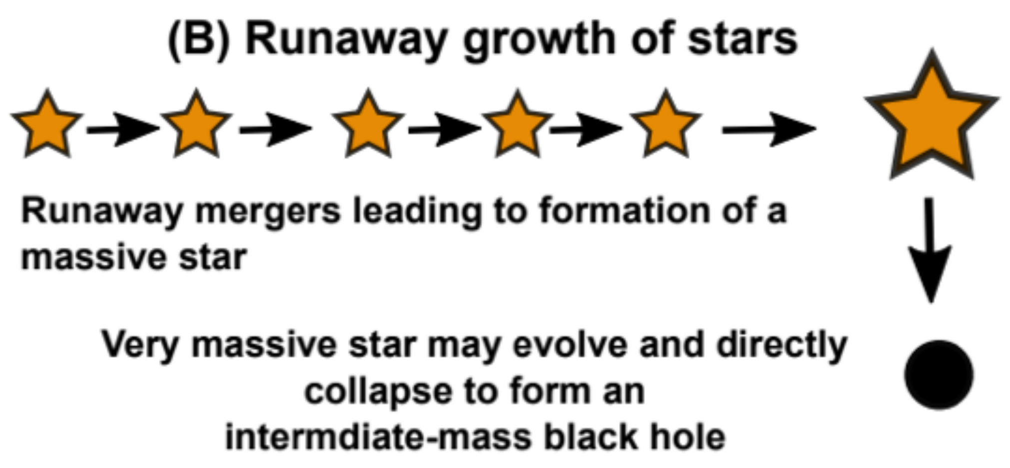


Askar, Baldassare & Mezcua (2024); https://arxiv.org/abs/2311.12118

IMBH Formation in MOCCA Simulations

Initial Conditions of Star Cluster Models

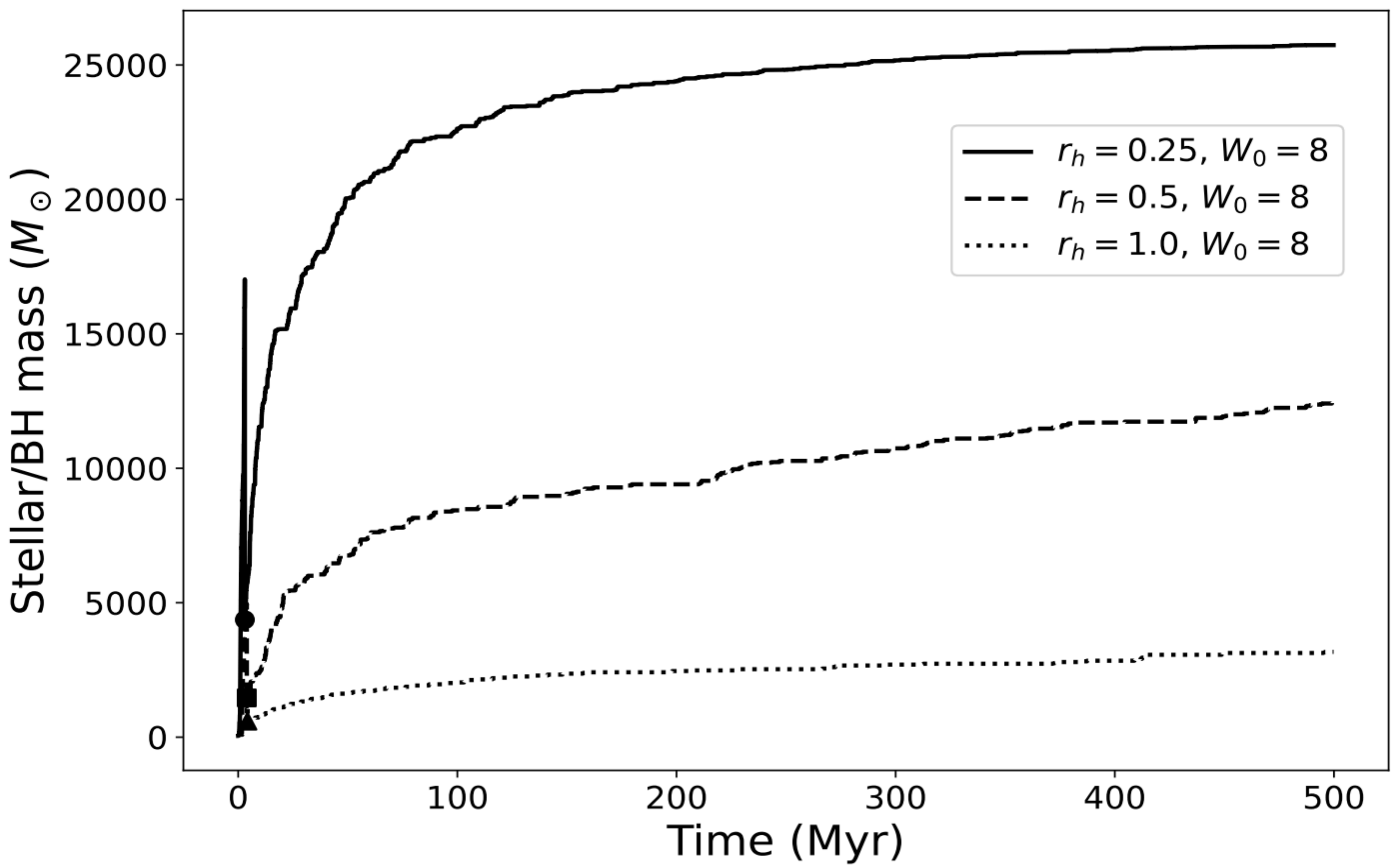
- $N = 2 \times 10^6$ objects → $1.29 \times 10^6\,\mathrm{M_\odot}$
- 10% binary fraction
- $Z = 0.0005 \approx 2.5\,\%$ of $\mathrm{Z_\odot}$
- Galactocentric radius = 10 kpc



Model	$\mathrm{r_h}$ (pc)	$\mathrm{W_0}$	ρ_{core} ($\mathrm{M_\odot\,pc^{-3}}$)	T_{rh} (Myr)	IMBH? ($\mathrm{M_{BH}}$ at 12 Gyr)
rh0.25–W08	0.25	8	4.38×10^8	42.7	✓($2.762 \times 10^4\,M_\odot$)
rh0.5–W08	0.50	8	5.86×10^7	121.0	✓($1.537 \times 10^4\,M_\odot$)
rh0.5–W05	0.50	5	4.34×10^6	121.0	×
rh1.0–W08	1.00	8	7.36×10^6	342.3	✓($6.244 \times 10^3\,M_\odot$)
rh2.0–W08	2.00	8	8.67×10^5	965.6	×

Askar, Vergara & Ali (2025); https://arxiv.org/abs/2510.03766

MOCCA BH GROWTH Growing Black Holes in Star Clusters



Early very massive star (VMS) formation (~3 Myr) → merges with sBH → seeds IMBH → rapid growth (≤500 Myr) via BH mergers and tidal disruption of stars and white dwarfs

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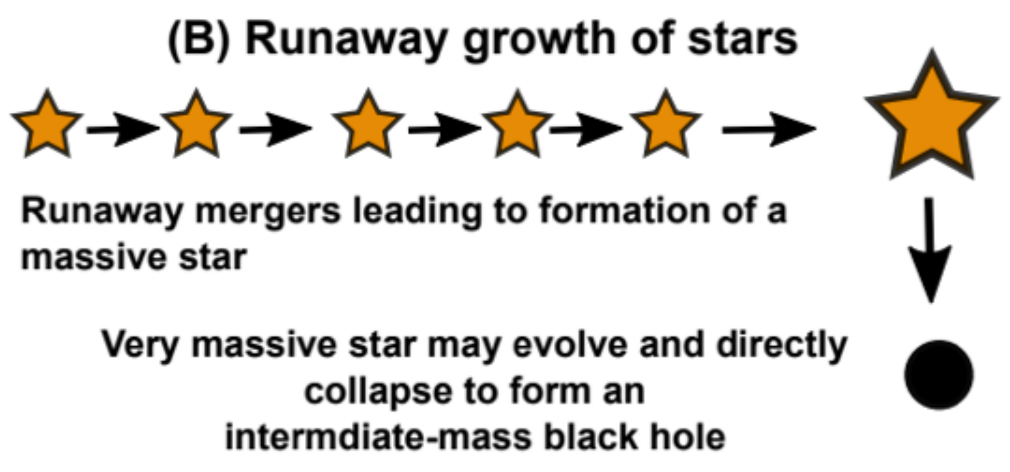

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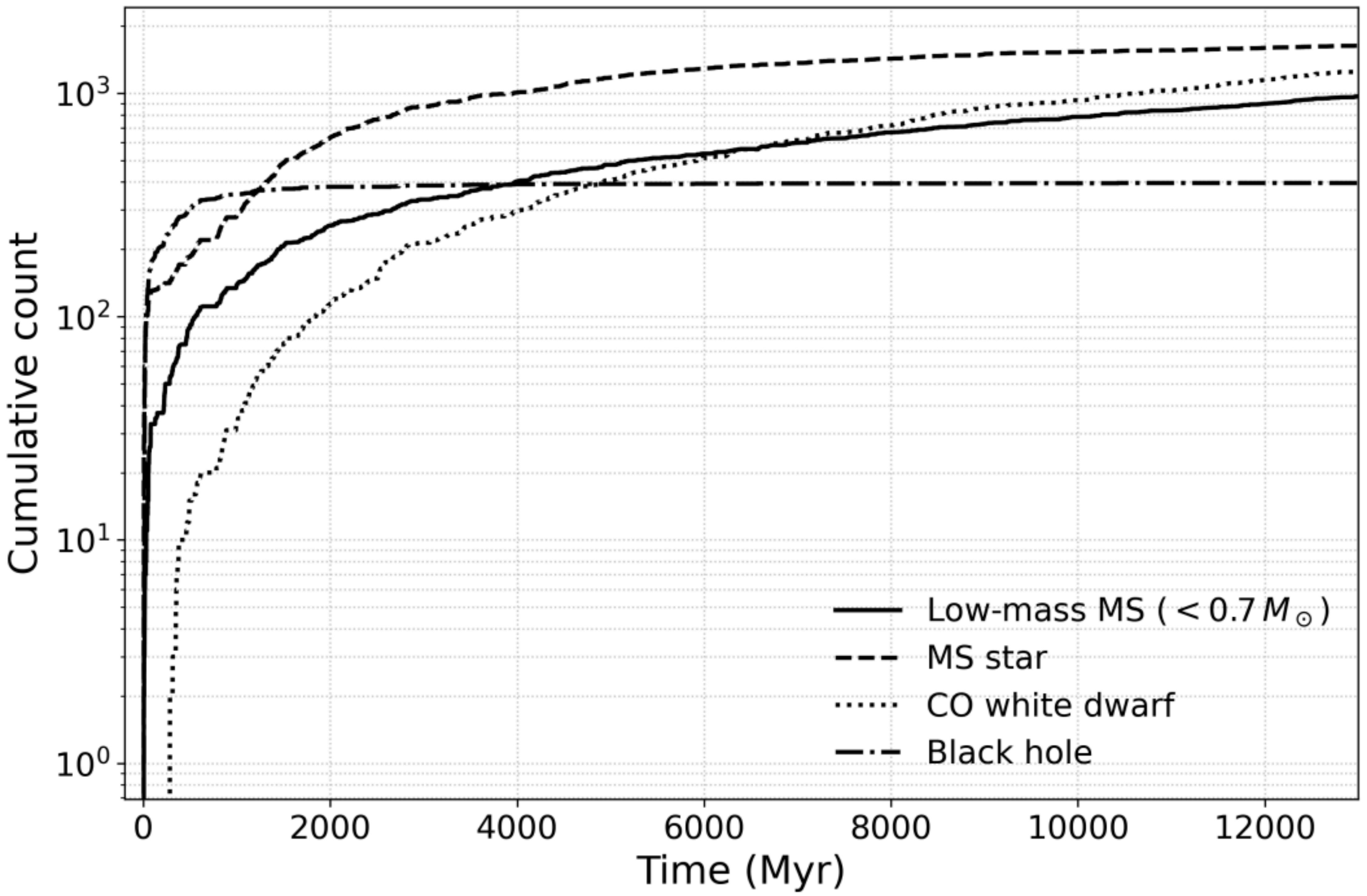
MOCCA

BH GROWTH — Growing Black Holes in Star Clusters



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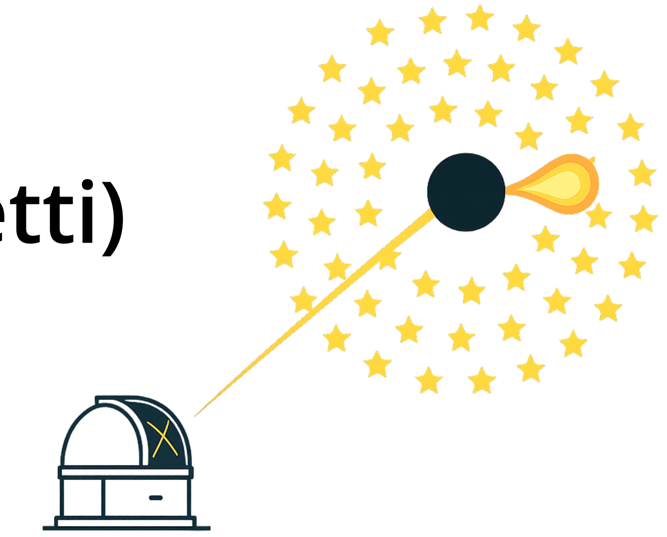
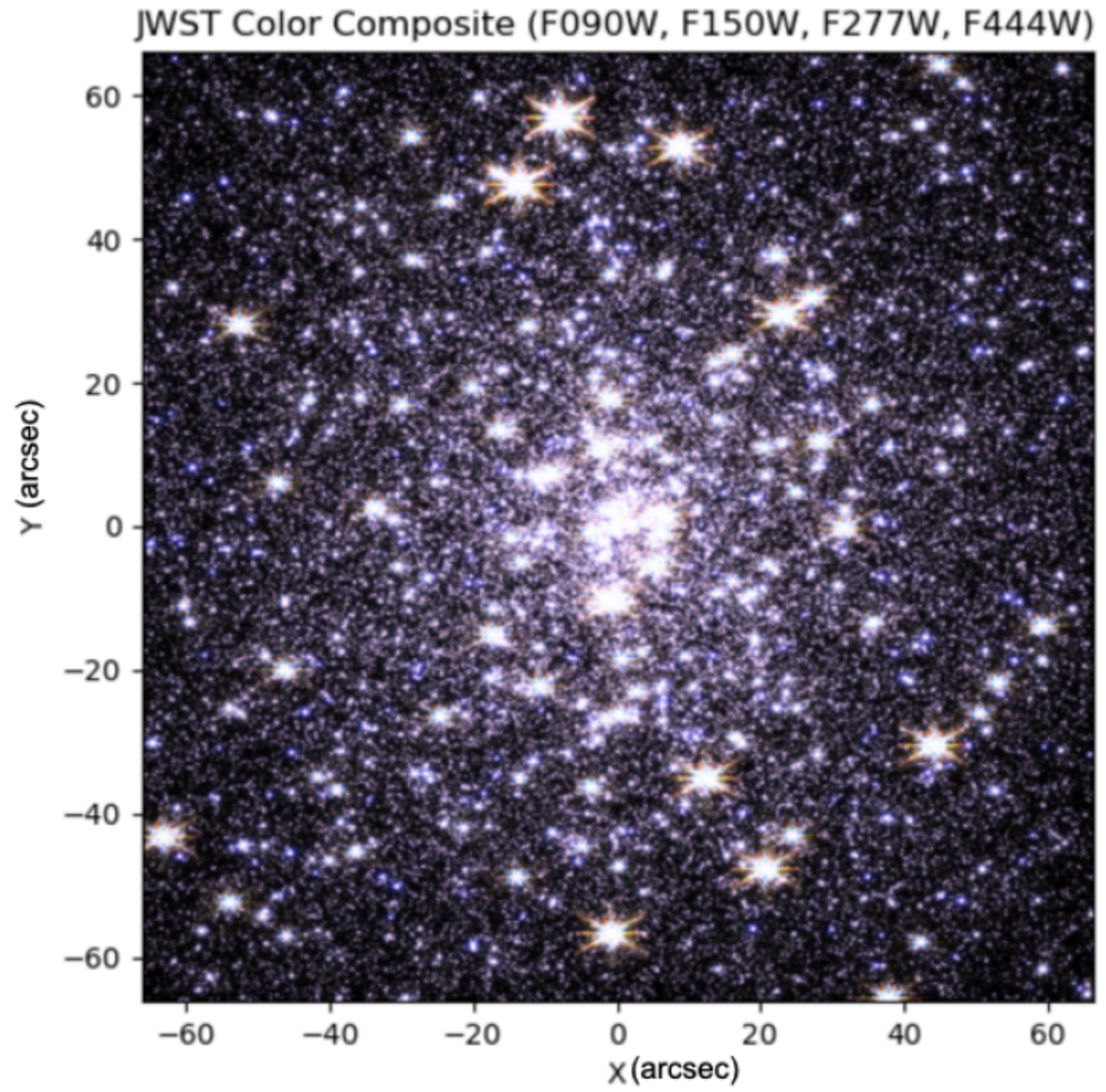
NCN SONATA Project: Bridge theory ↔ Observations

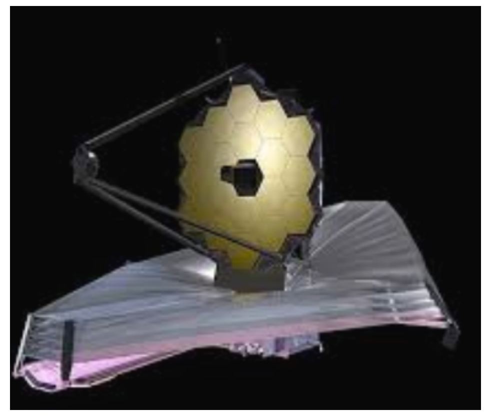
NATIONAL SCIENCE CENTRE

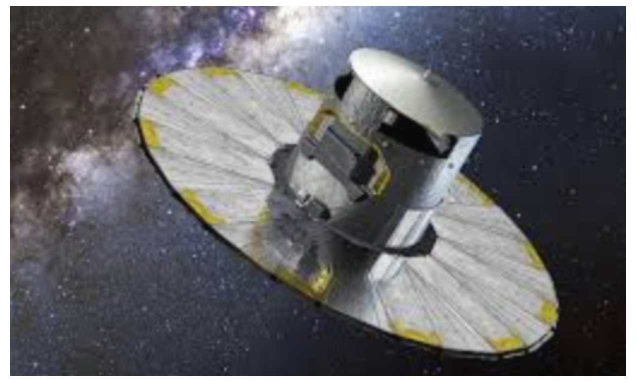
- ***"Bridging Observations and Theory: Synthetic Star Cluster Observations from Numerical Simulations" (2025-2029)***
- Main Goals:
  - Develop SYNOBS: simulations → realistic observations (images & spectra)
  - Use synthetic observations to:
    - Infer the presence of IMBHs & stellar-mass BHs in clusters
    - **IMBH detection & mock IFU observations (Postdoc: Dr. Renuka Pechetti)**
    - Binaries containing compact objects
    - Binary stars (including astrometric & eclipsing)
    - Multiple stellar populations & stellar exotica
  - Direct comparison with HST, JWST, VLT/MUSE, Gaia & ELT data





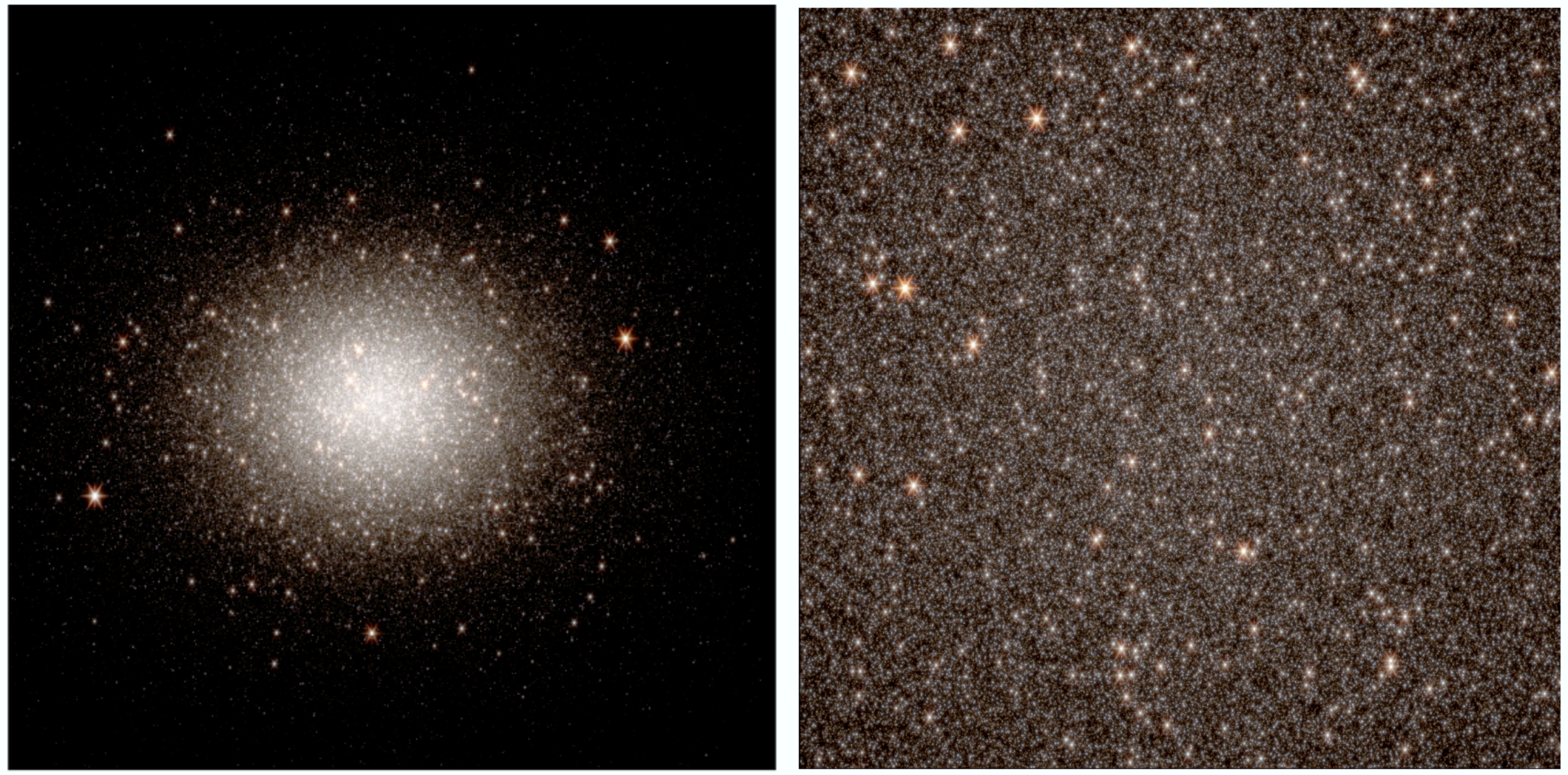
Mock JWST Image of a MOCCA Snapshot
Credit: Sohaib Ali, Paolo Bianchini, FSPS, Agostino Leveque and Lucas Hellström

PhD Project: Bridge theory ↔ Observations

- **Join our team at CAMK: Fully funded PhD position (4 years)**
- Main tasks:
  - Simulations (MOCCA & direct *N*-body) → realistic observations (images, photometry, astrometry)
  - Simulate time-resolved observations: orbital motion of binaries and eclipses
  - Build synthetic observables: colour-magnitude diagrams, light curves, surface brightness profiles, mass segregation profiles → Compare with observations
- Scientific Applications:
  - Study binary stars and compact objects
  - Probe blue stragglers & multiple stellar populations
  - Detect stellar-mass BH subsystems & IMBHs



JWST Mock Images from the "ROLLIN': Rotating Globular Clusters Simulations" Project (Bianchini, Varri, Askar et al. submitted 2025)

- Training in simulations, data analysis & observational techniques (within an international network of collaborators)
- Grant-funded conference travel, research visits, summer schools & access to computing resources

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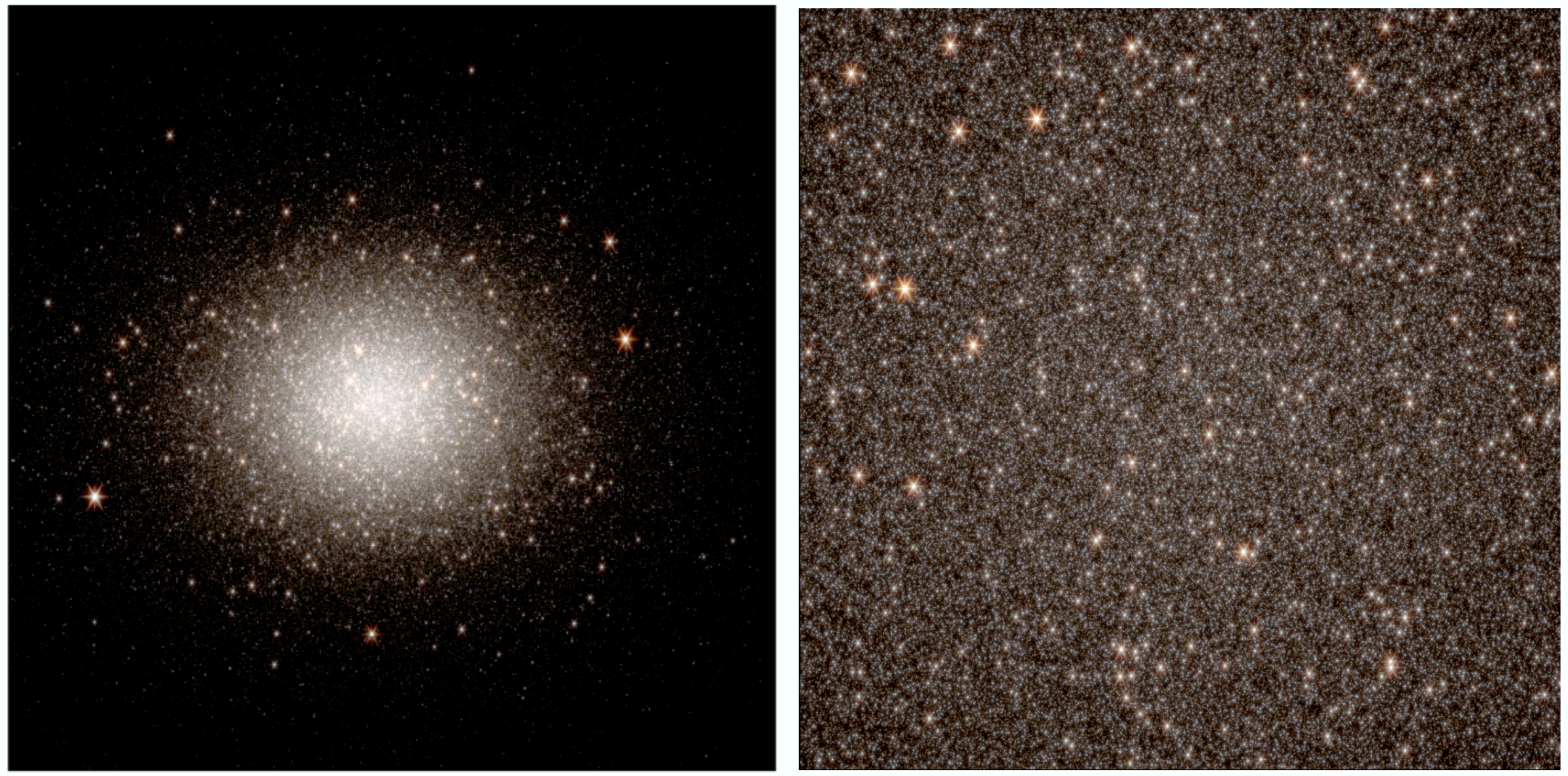

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If you have any questions about the project, please contact me at: askar@camk.edu.pl

Call for Applications is Open: https://www.camk.edu.pl/en/archiwum/2026/03/04/recruitment-20262027/