Formation of Gravitational Wave Sources Originating From Globular Clusters:

Lessons from Monte Carlo *N*-body Simulations

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Abbas Askar
POLONEZ and Marie Skłodowska-Curie Fellow
Nicolaus Copernicus Astronomical Center
Warsaw, Poland

askar@camk.edu.pl

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NATIONAL SCIENCE CENTRE POLAND

MARIE CURIE ACTIONS

CAMK PAN

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

MOCCA
https://moccacode.net/

Gravitational wave mergers of compact object binaries by LVK

- 83 merging binary black holes detected by LIGO-Virgo-KAGRA (LVK) since 2015
  - Observed merger rate: $17.9 - 44\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (Abbott et al. 2021)
- 2 merging binary neutron stars and 6 black hole-neutron stars

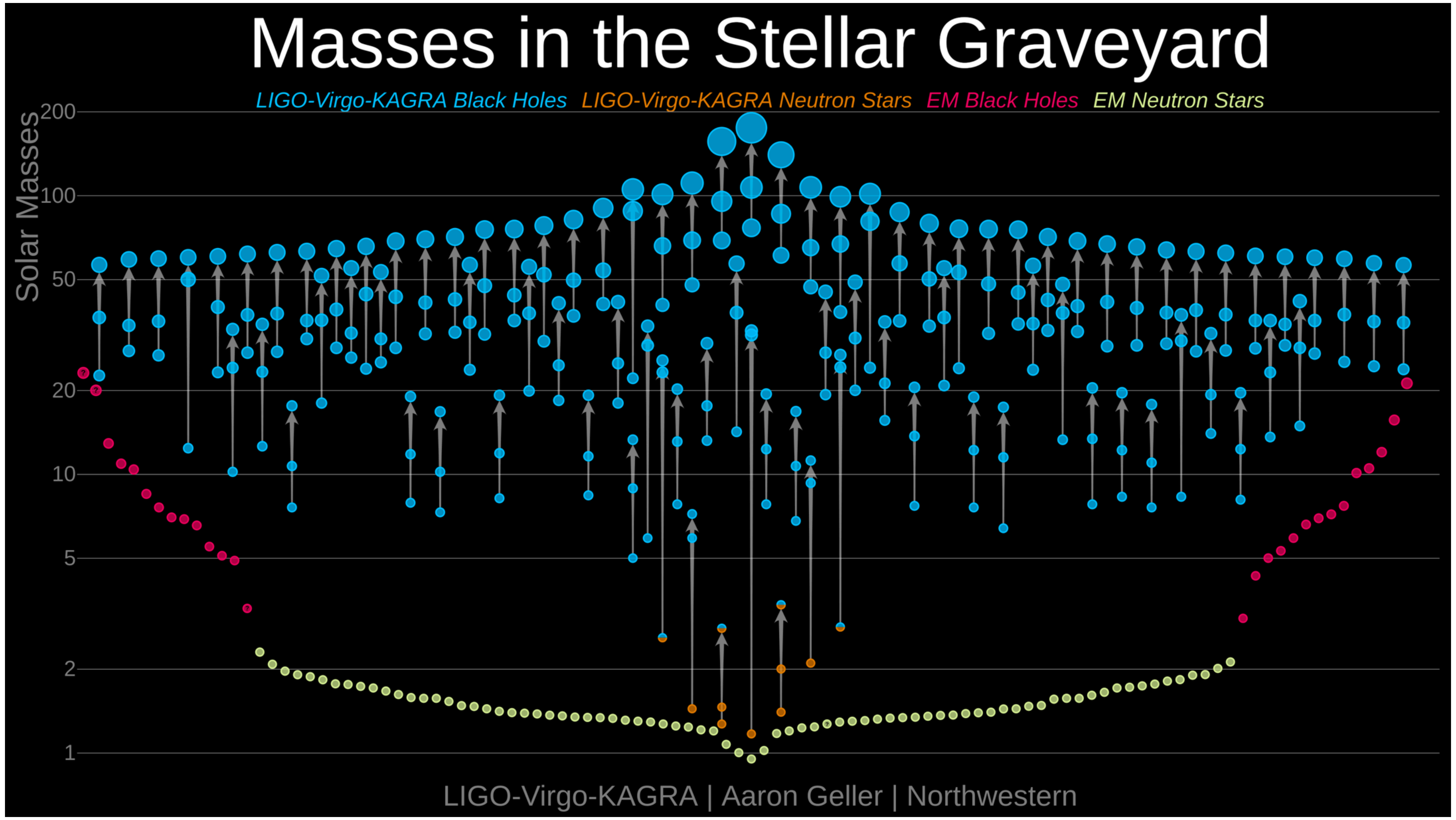

Image Credit: Visualization: LIGO-Virgo-KAGRA / Aaron Geller / Northwestern Geller

Key Question:

- **What is the astrophysical origin of these merging black holes?**

Possible Answers:

- Isolated binary evolution
- **Dynamical formation in dense stellar environments**
- Other scenarios: Mergers in field triples, black holes trapped in accretion disks of active galactic nuclei
- Non-stellar origin black holes: Primordial black holes

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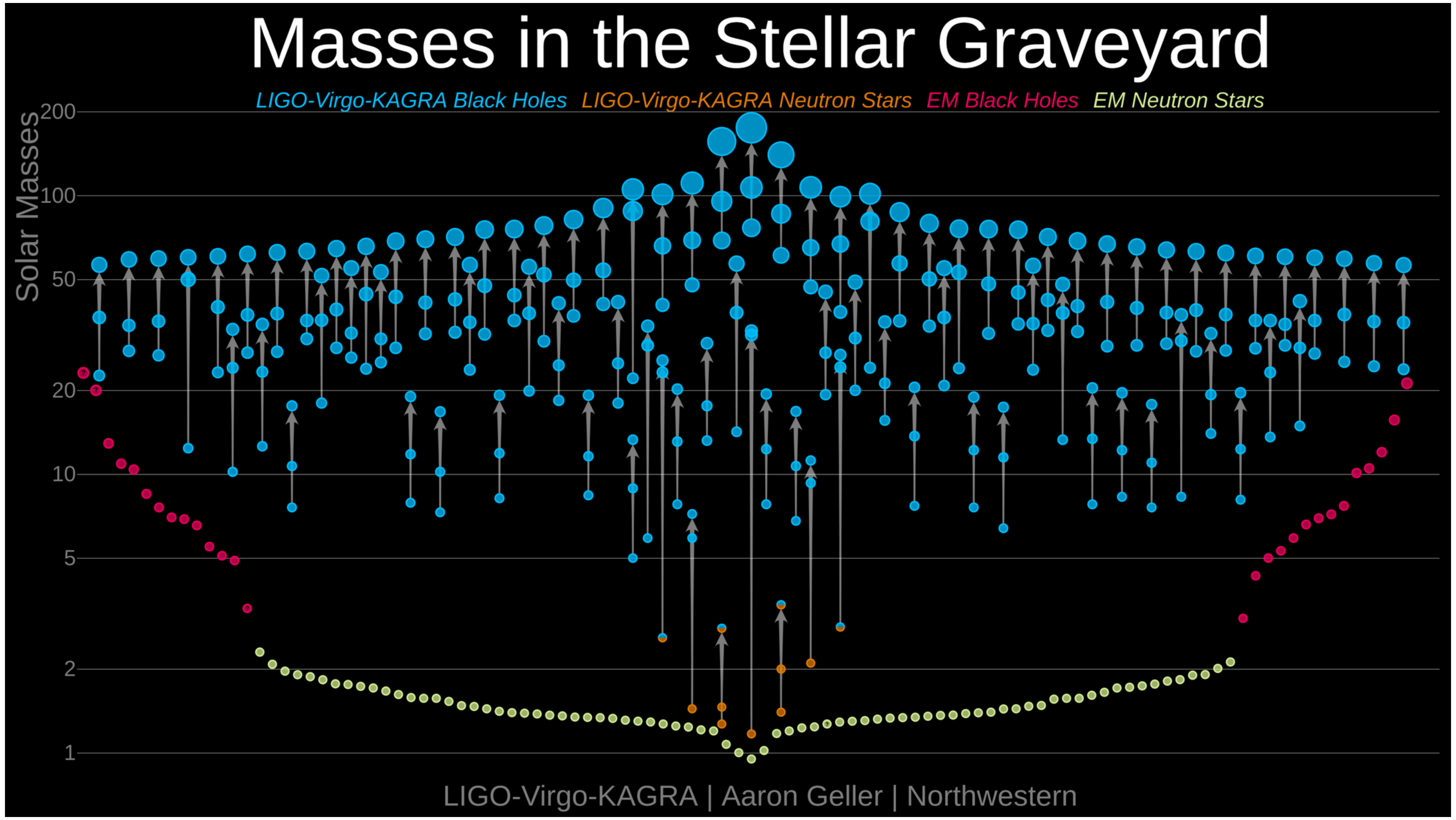

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Globular Clusters

- Spherical collection of stars that orbits a galactic core as a satellite.
- Comprise 100,000 to millions of stars.
- Globular clusters in the Milky Way are estimated to be at least 10 billion years old
- Most of these stars are old Population II (metal-poor) stars.
- Stars are clumped closely together, especially near the centre of the cluster → high central densities $\gtrsim 10^4 - 10^5\ \mathrm{M_\odot\ pc^{-3}}$
- **Interplay between dynamical encounters and stellar/binary evolution in globular clusters makes them efficient factories for producing exotic astrophysical objects →** ***blue straggler stars, gravitational wave sources, compact object binaries, and high-energy transients***

NGC 104 aka 47 Tucanae

Mass $\sim 7 \times 10^5 \mathrm{M_\odot}$

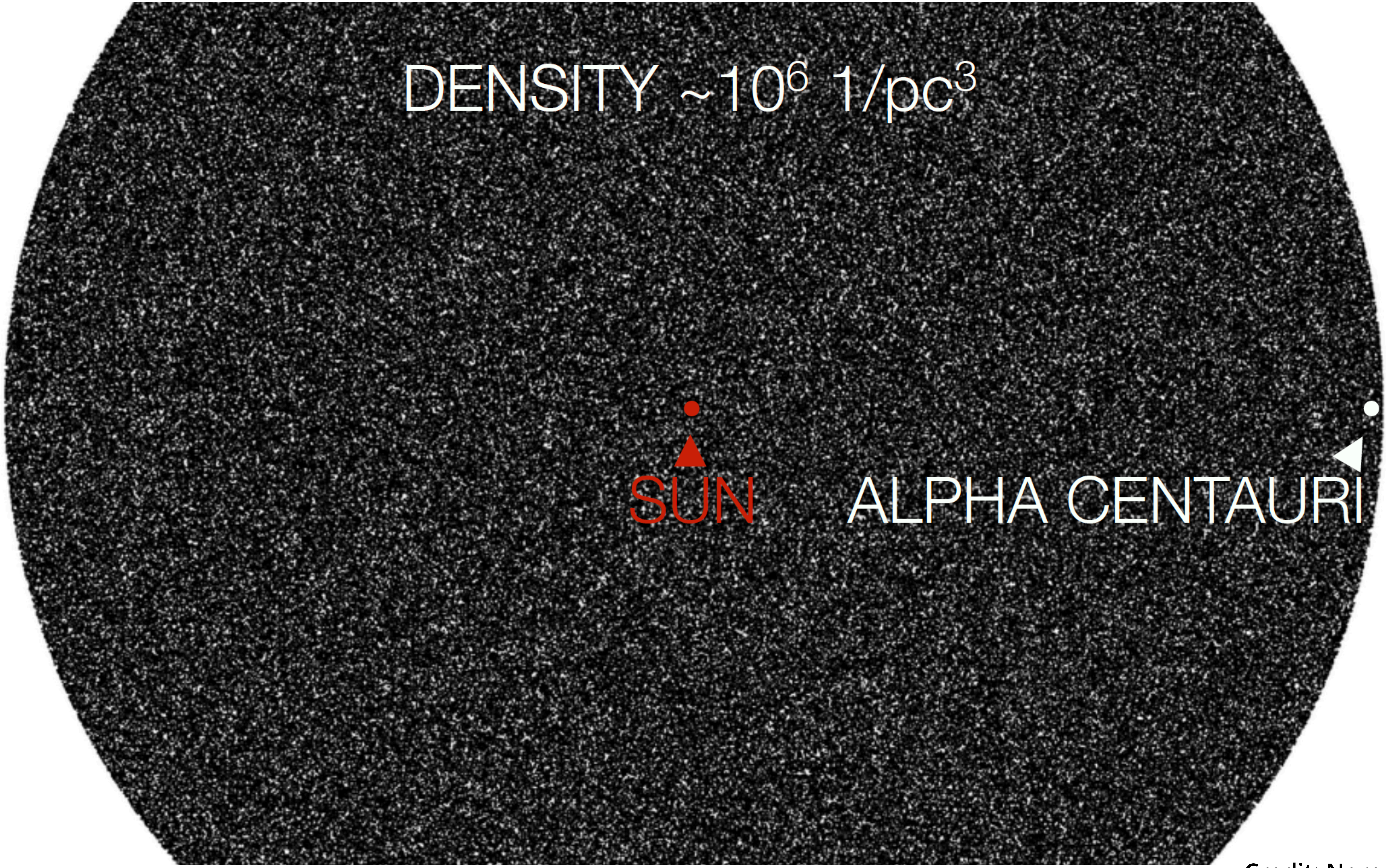
$r_\mathrm{c} \sim 0.6$ pc $\quad r_\mathrm{hl} \sim 4$ pc

$\rho_\mathrm{c} \sim 10^5\ \mathrm{M_\odot\ pc^{-3}}$

Age $\sim 12 - 13$ Gyr

$[\mathrm{Fe/H}] \sim -0.78$

Stellar density in the densest star clusters



D = 4.34 lyrs

or

1.33 pc

Credit: Nora Lüetzgendorf

Observing the sky inside a globular cluster

NGC 104 aka 47 Tucanae

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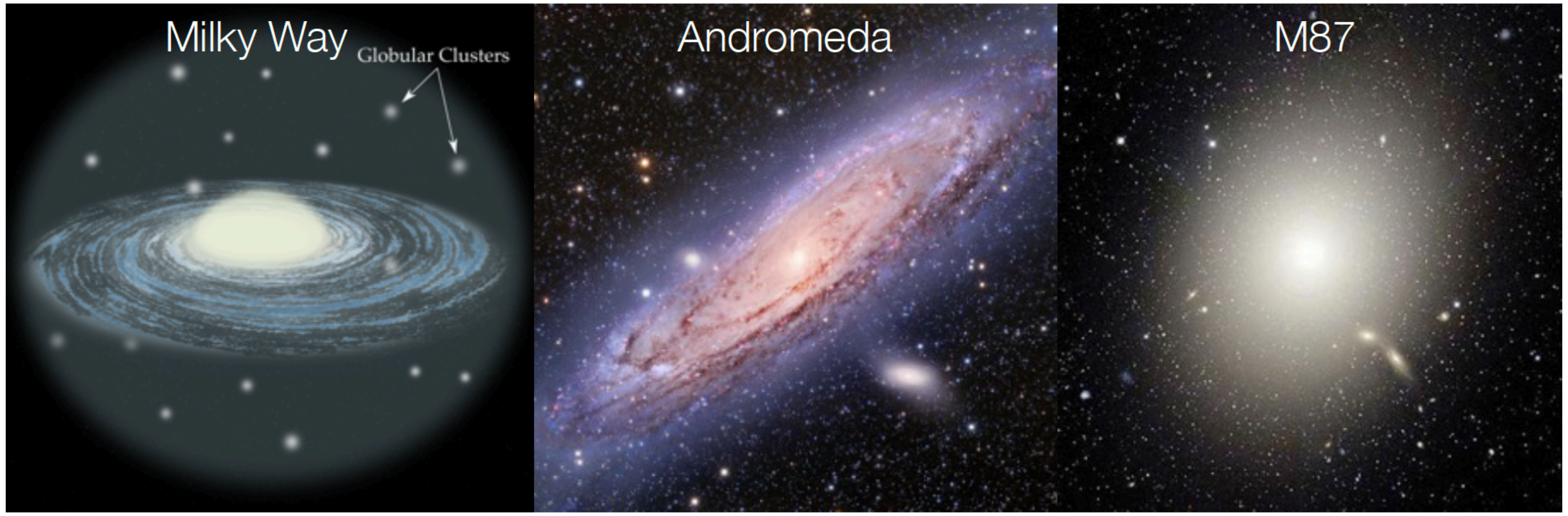
From the core of 47 Tuc

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

Specific frequencies of globular clusters

Credit: N. Lüetzgendorf

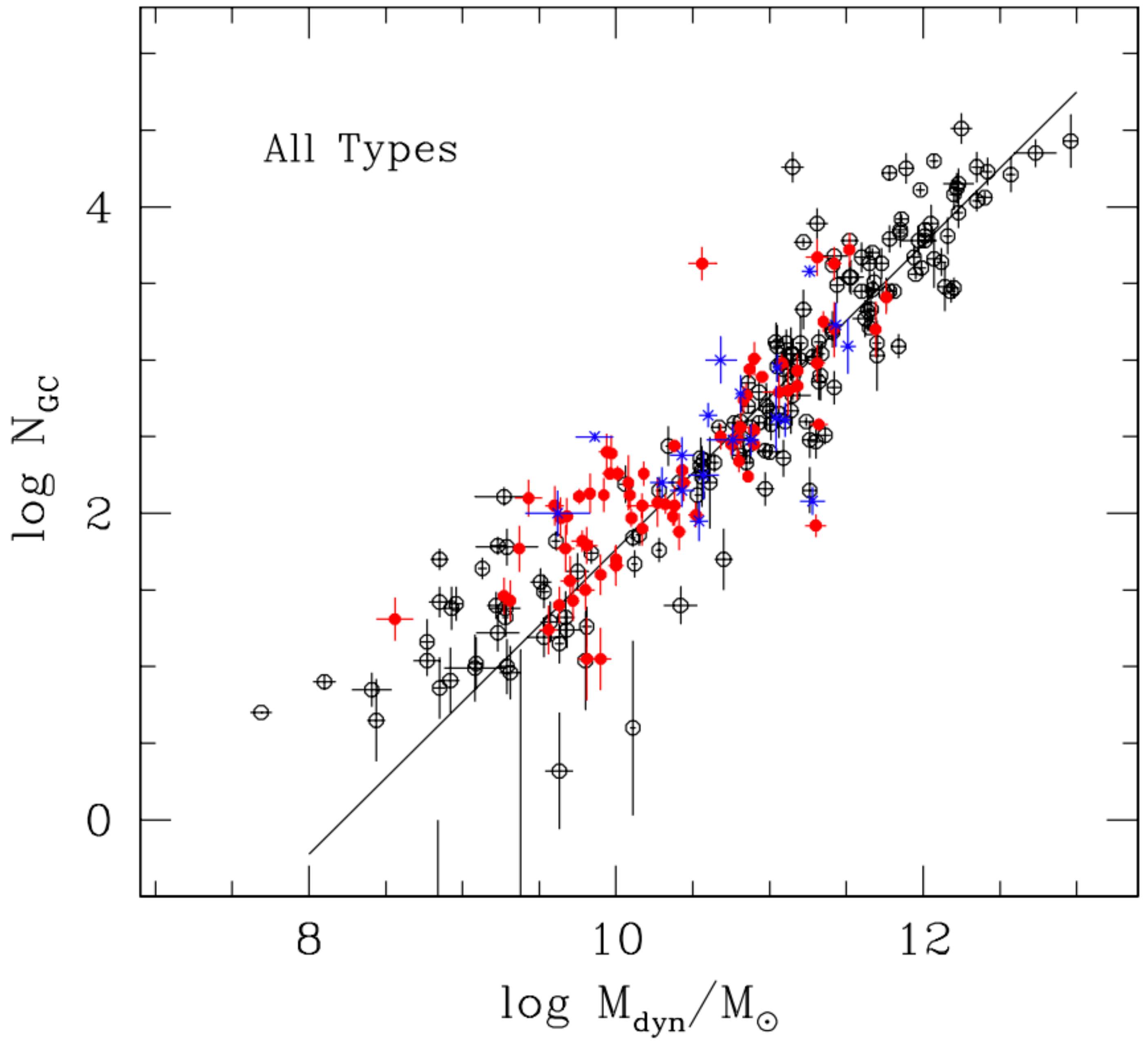


~150 GCs

~460 GCs

~15000 GCs

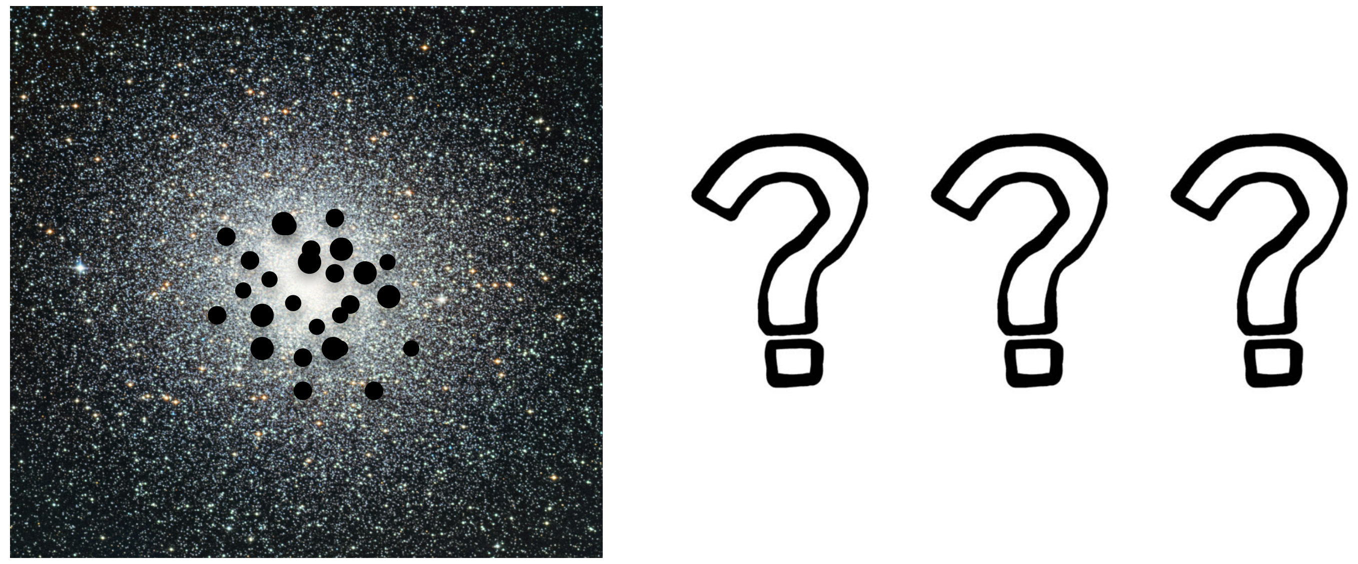
- Specific frequency of globular clusters correlates with dynamical mass of the host galaxy
- Currently $\sim 0.1 - 1\,\%$ of galaxy stellar mass is in globular clusters (Harris et al. 2014)

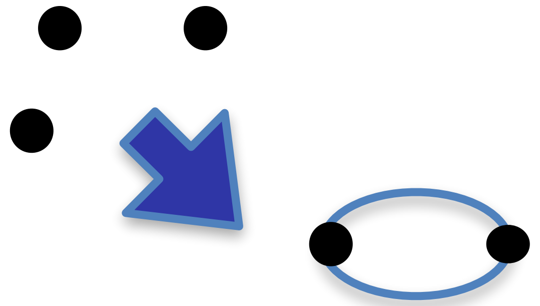


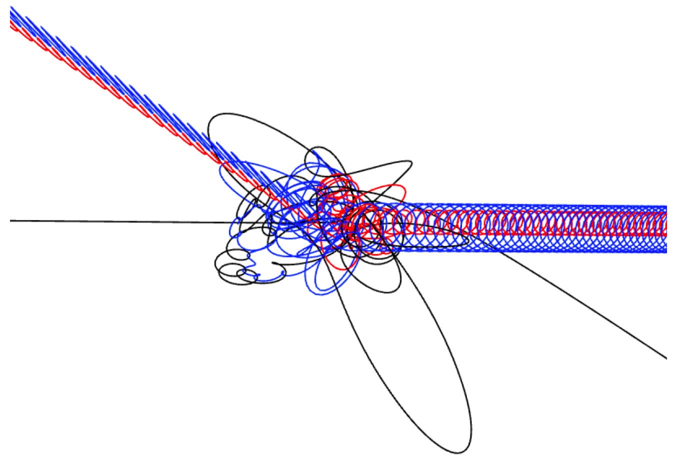
Harris, Harris, & Alessi (2013)

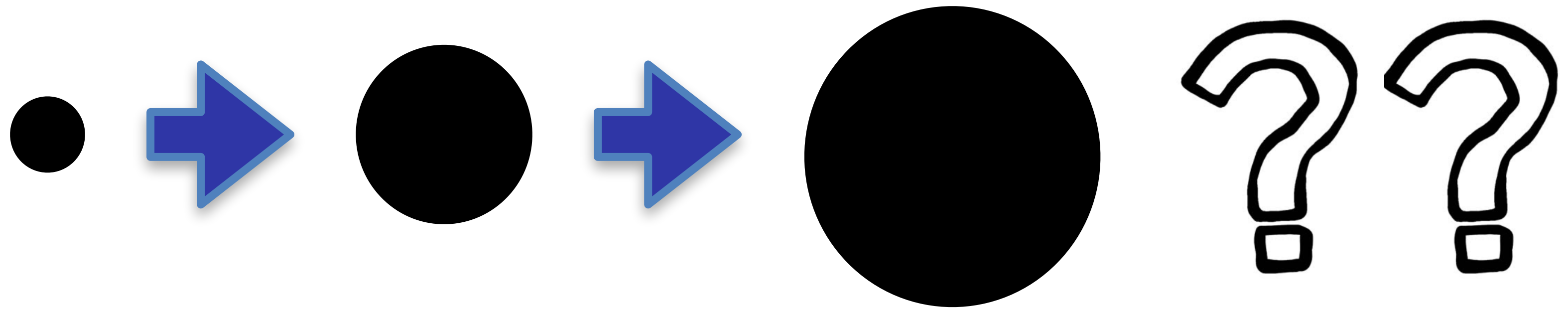
Key Questions

- What happens to black holes in globular clusters?
  - Do black holes receive large kicks when they are formed in core-collapse supernovae?
  - What fraction of black holes can be retained in stellar clusters?
- What are the dynamical processes that lead to the formation of binary black holes?
- What is the contribution of dynamically formed binary black holes to the merger rate?
- Could intermediate-mass black holes be created in dense stellar clusters? Can these grow by merging with other black holes?







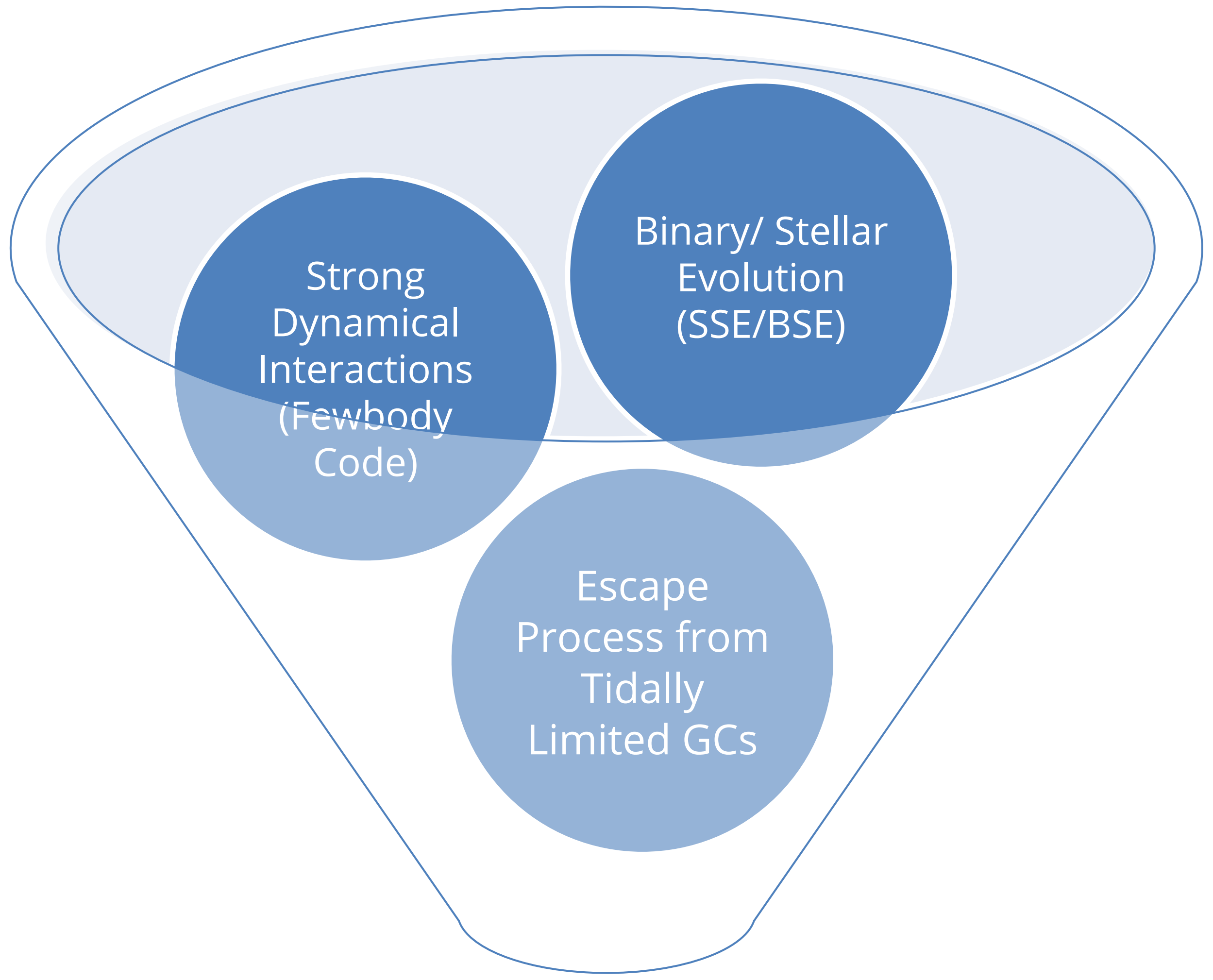


The MOCCA code and large database of simulated star cluster models

- **MO**nte **C**arlo **C**luster simul**A**tor: code to evolve realistic star clusters (Giersz et al. 2013; Hypki & Giersz 2013)
  - Based on Hénon (1971, 1973) MC method and improvements to it by Stodolkiewicz (1982, 1985; 1986) and Giersz (1998, 2001, 2006) → Combines the particle based approach of the direct *N*-body method with the statistical treatment for 2-body relaxation
  - Stellar/binary evolution based on ***SSE/BSE*** code (Hurley et al. 2000; 2002) with several upgrades (Kamlah et al. 2022)
  - Direct integration for binary-single and binary-binary interactions: ***Fewbody*** code (Fregeau et al. 2004)
  - Good agreement with direct *N*-body simulations: (Giersz et al. 2013; Wang et al. 2016; Madrid et al. 2017; Kamlah et al. 2022)
- **Can simulate the evolution of a realistic cluster on the timescale of days to weeks**
- **Advantage: Useful for carrying out large survey of simulated models that probe the initial parameter space: initial masses, size, densities, initial binary fraction, metallicity, BH kicks → MOCCA-Survey Database I, II, III (Belloni et al. 2016; Askar et al. 2017; Hypki et al. 2022; 2024; Maliszewski et al. 2022; Giersz et al. 2024)**

MOCCA

https://moccacode.net/



Strong Dynamical Interactions (Fewbody Code)

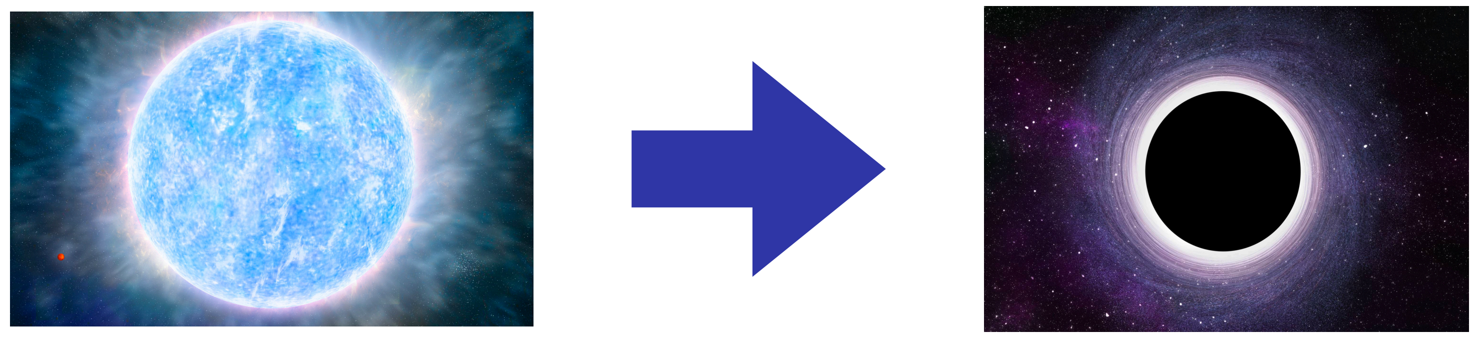
Binary/ Stellar Evolution (SSE/BSE)

Escape Process from Tidally Limited GCs

MOCCA

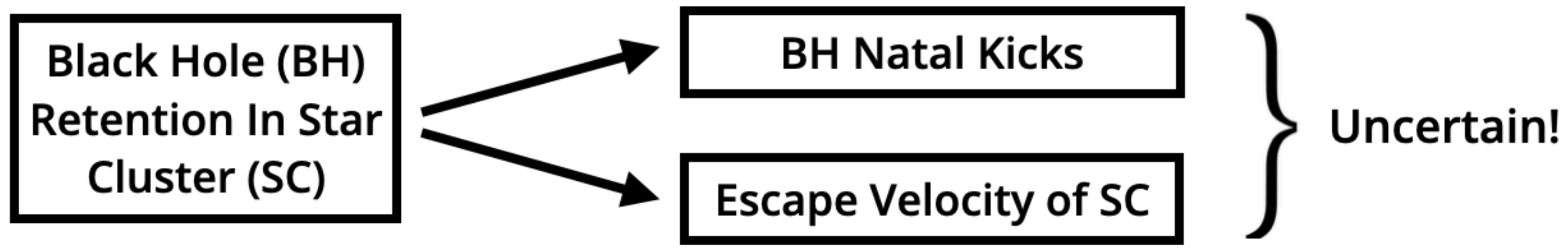
Black hole retention in star clusters

- **Stellar-mass black holes (~ 10 to $50\ \mathrm{M}_\odot$) form when massive stars end their lives**
  - Black hole progenitors evolve within few to 30 Myr
  - **Retention: natal kick of the black hole needs to be less than the escape speed of the host cluster**
    - Natal kick depends on the final evolution of the progenitor star: its mass and metallicity
      Fryer et al. (2012), Janka (2013) Belczynski et al. (2002; 2008; 2016), Spera & Mapelli (2017), Kamlah et al. (2022)



$\mathrm{M_{ZAMS}} \gtrsim 18 - 20\mathrm{M}_\odot$

~ 2 black hole for every 1000 stars



Black Hole (BH) Retention In Star Cluster (SC)

BH Natal Kicks

Escape Velocity of SC

Uncertain!

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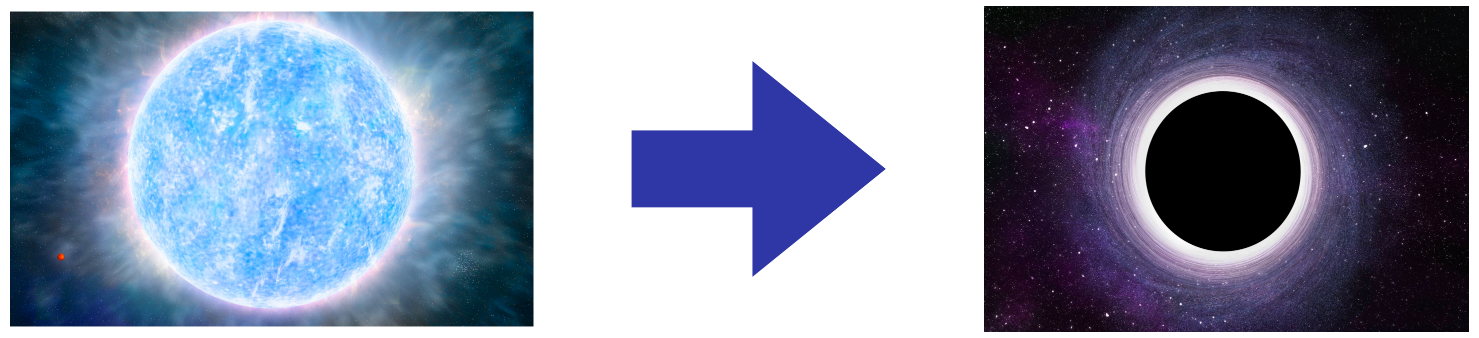

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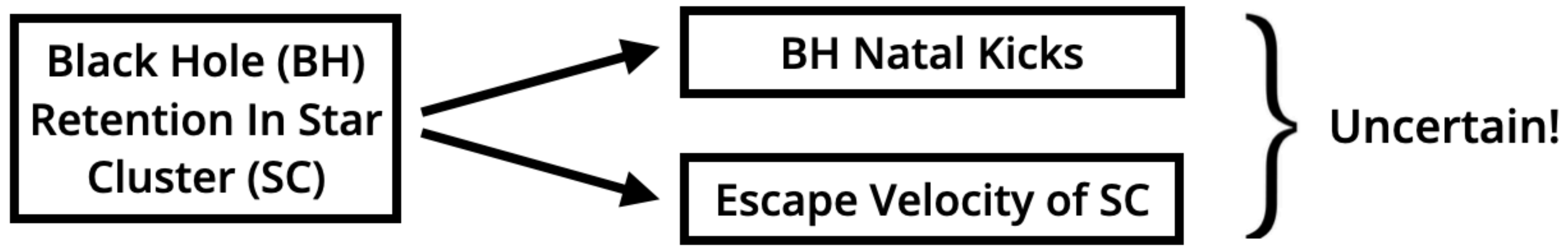

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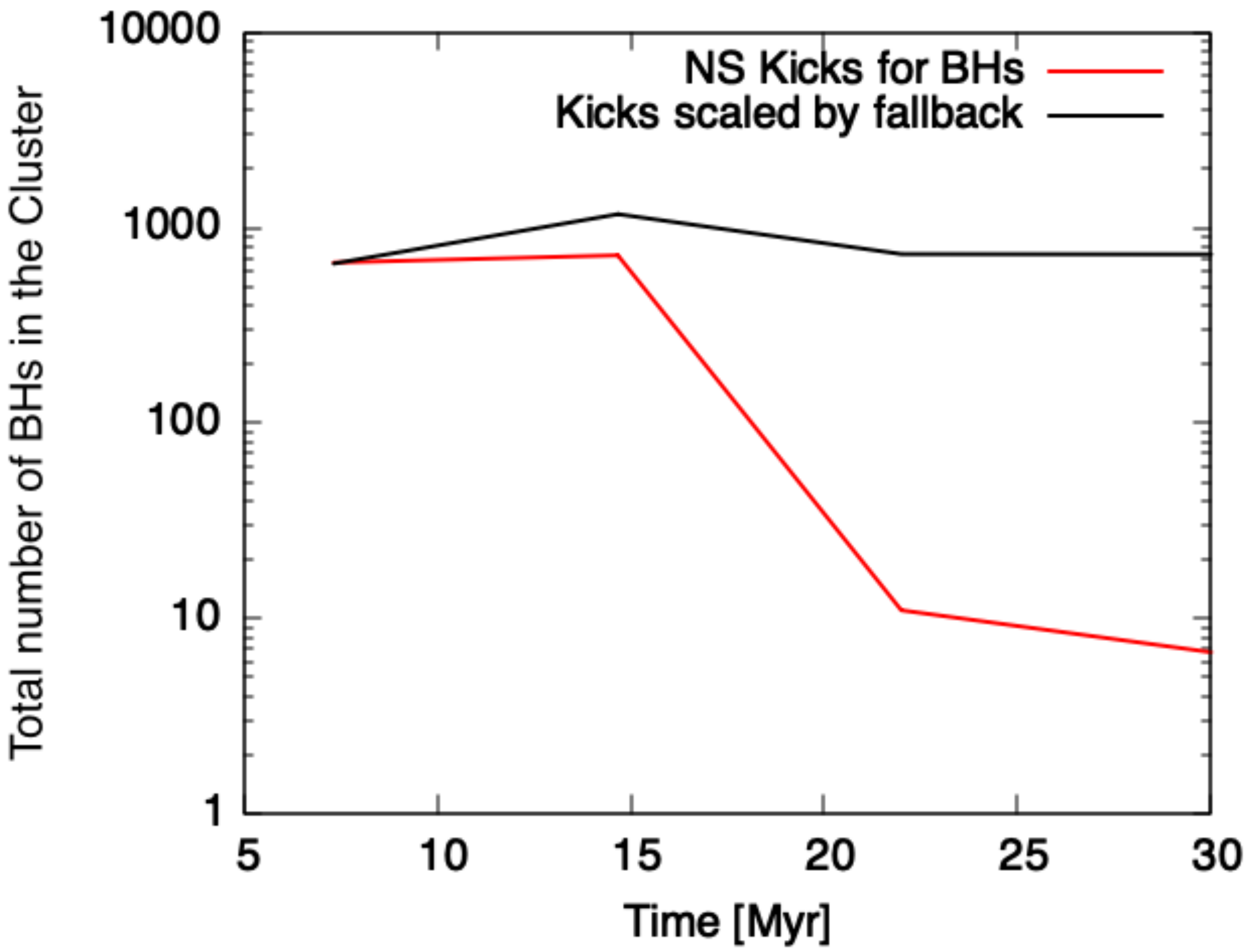
N = 700,000, Initial binary fraction (IBF) = 10%
$Z = 0.05\ Z_\odot$, r_h = 4.8 pc, r_t = 120 pc, V_{esc} = 33 km/s
$0.08\ \mathrm{M}_\odot \leq \mathrm{M}_{\mathrm{ZAMS}} \leq 100\ \mathrm{M}_\odot$ (Kroupa 2001 IMF)
Number of black hole progenitors ~ 1900

2 cases (N = 700,000):

- Neutron star kicks (Hobbs et al. 2005) for black holes
- Black hole kicks scaled by fallback (Belczynski et al. 2002) and momentum conservation



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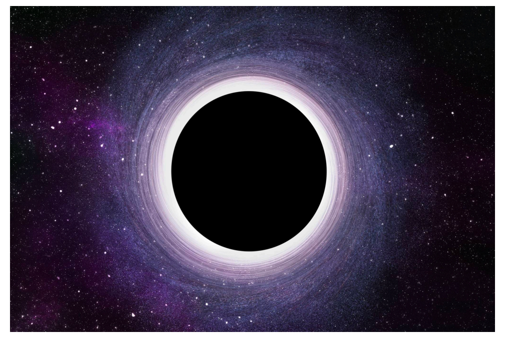

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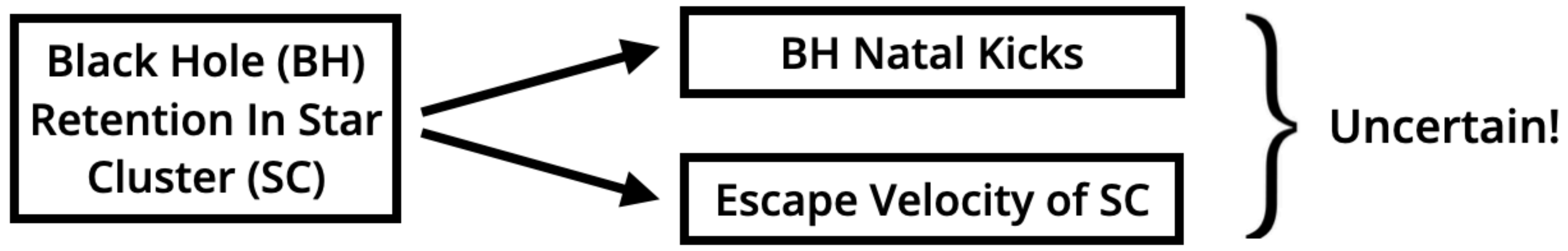

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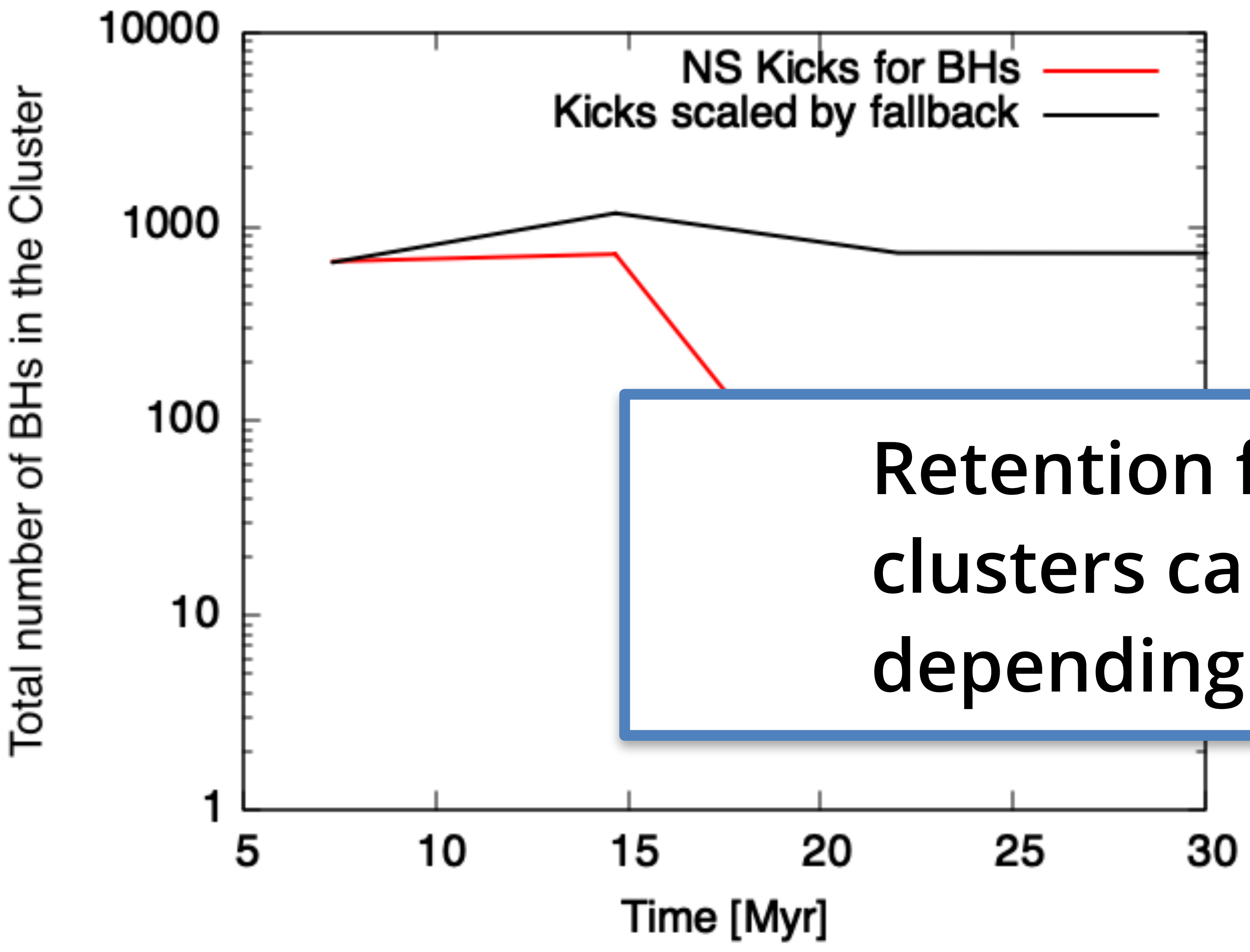
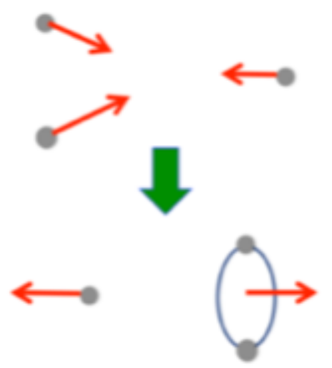


Retention fraction of black holes in globular clusters can be as high as 55% or lower than 1% depending on how you compute natal kicks!

Black hole dynamics in star clusters

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

- 3 body binary formation



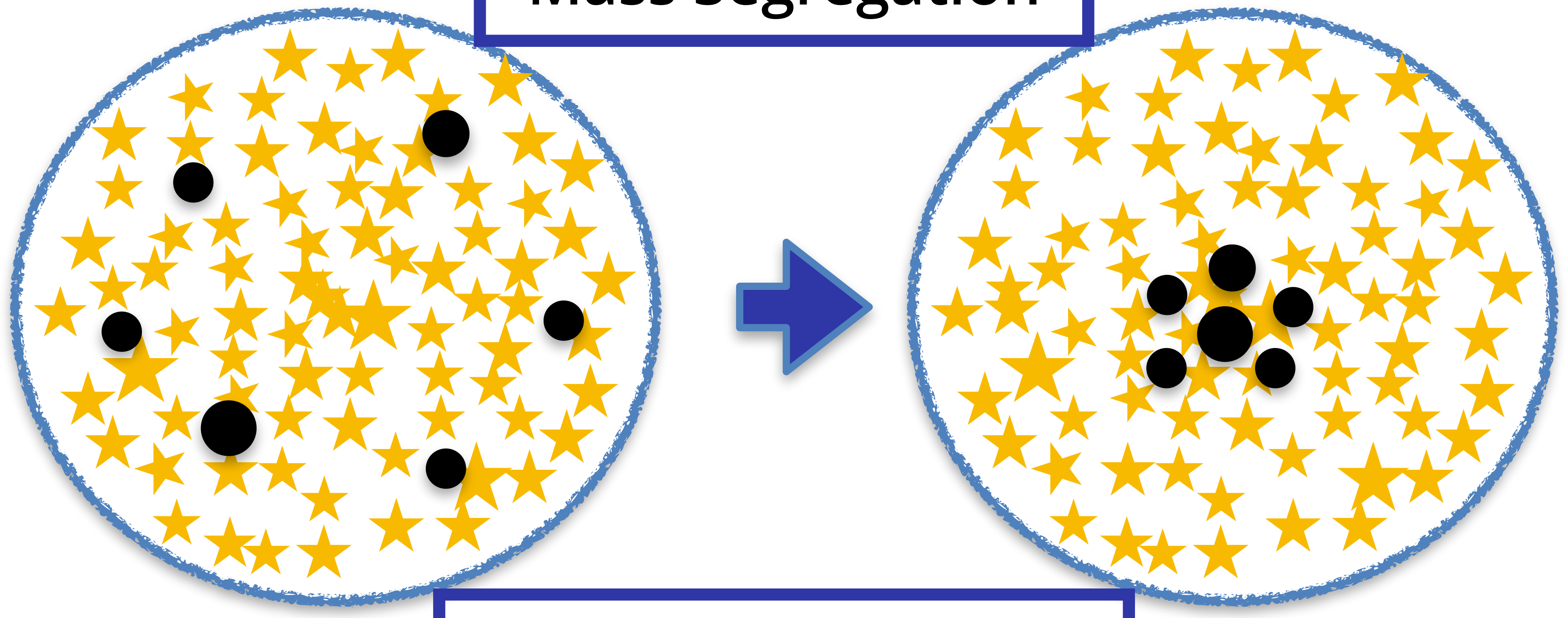
- Chaotic binary-single and binary-binary interactions involving black holes
  - Formation of binary black holes through exchange encounters (Portegies Zwart & McMillan 2002)
  - Mergers may also occur during these interactions (Samsing 2018, Samsing, Askar, Giersz 2018, Rodriguez et al. 2018 a,b)

- Hardening of binary black holes through interactions → binary becomes ‘useful’ → can merge due to gravitational wave radiation within a Hubble time

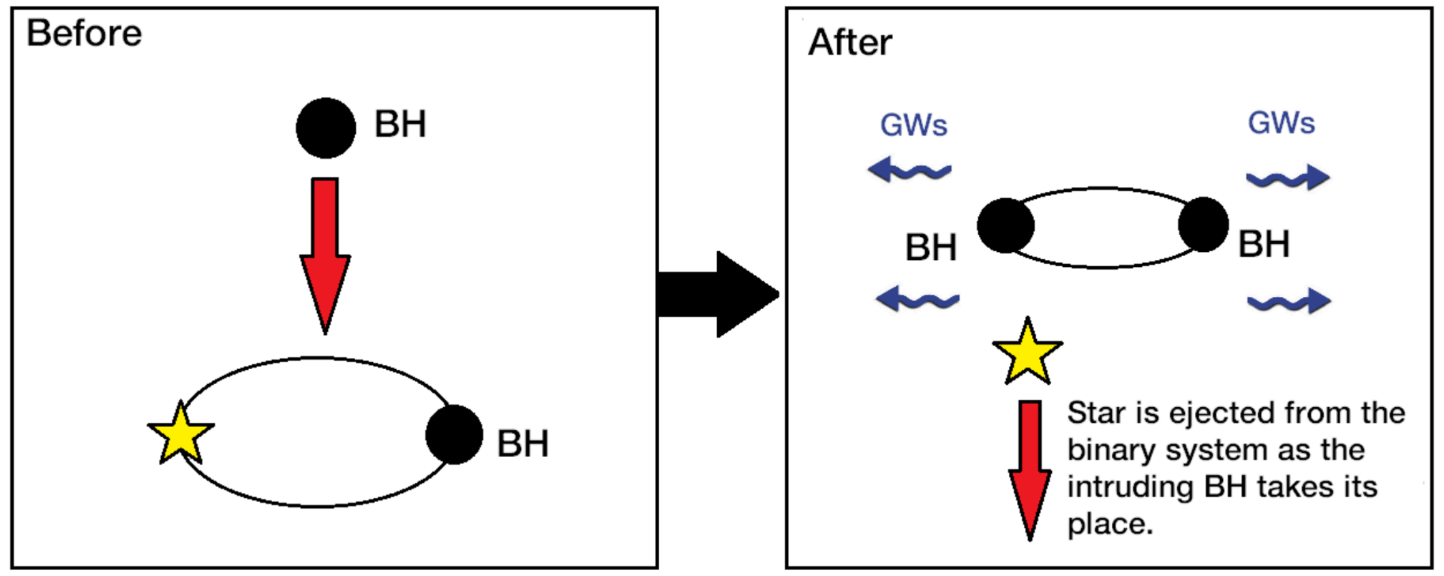
$$\tau_{\rm gr} \simeq 10^{10} yr \left(\frac{a_{\rm bin}}{3.3R_\odot}\right)^4 \frac{1}{(m_1+m_2)m_1m_2} \cdot \left(1-e^2\right)^{7/2}$$

(Peters 1964)

Mass Segregation

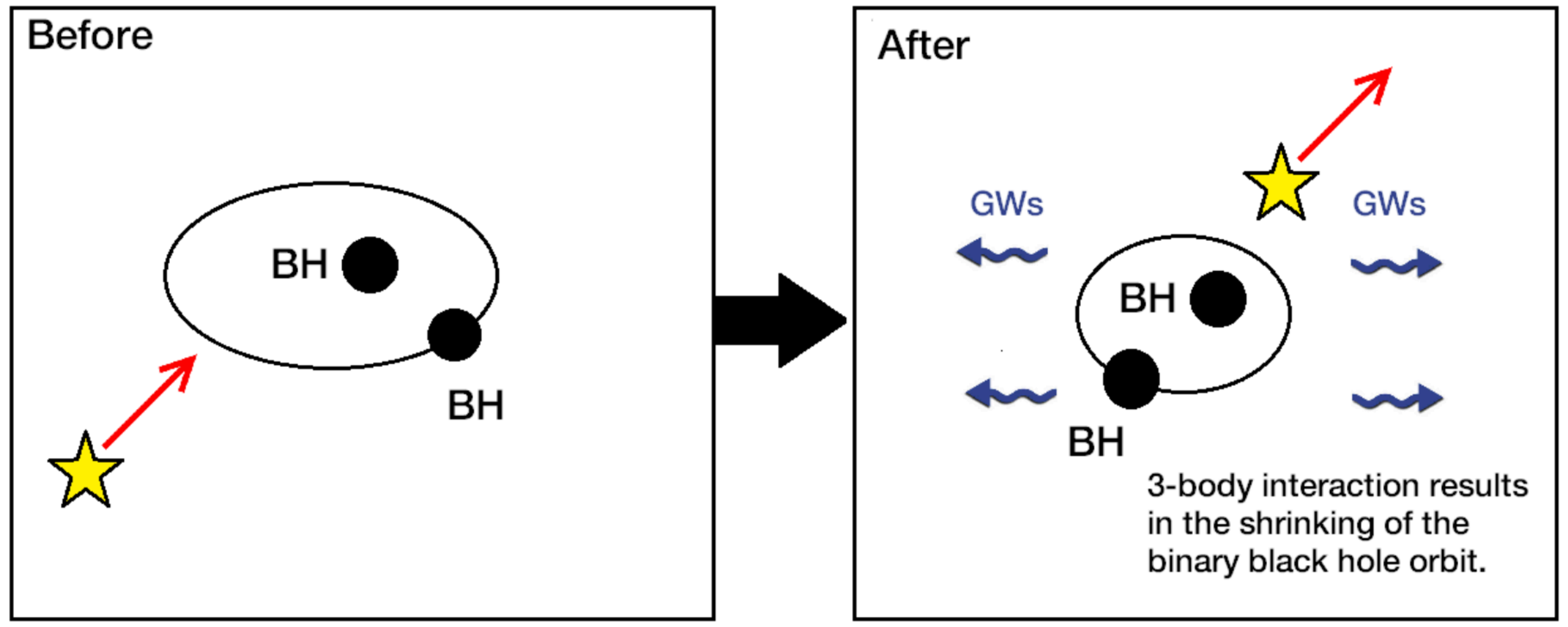


Exchange Encounters



Star is ejected from the binary system as the intruding BH takes its place.

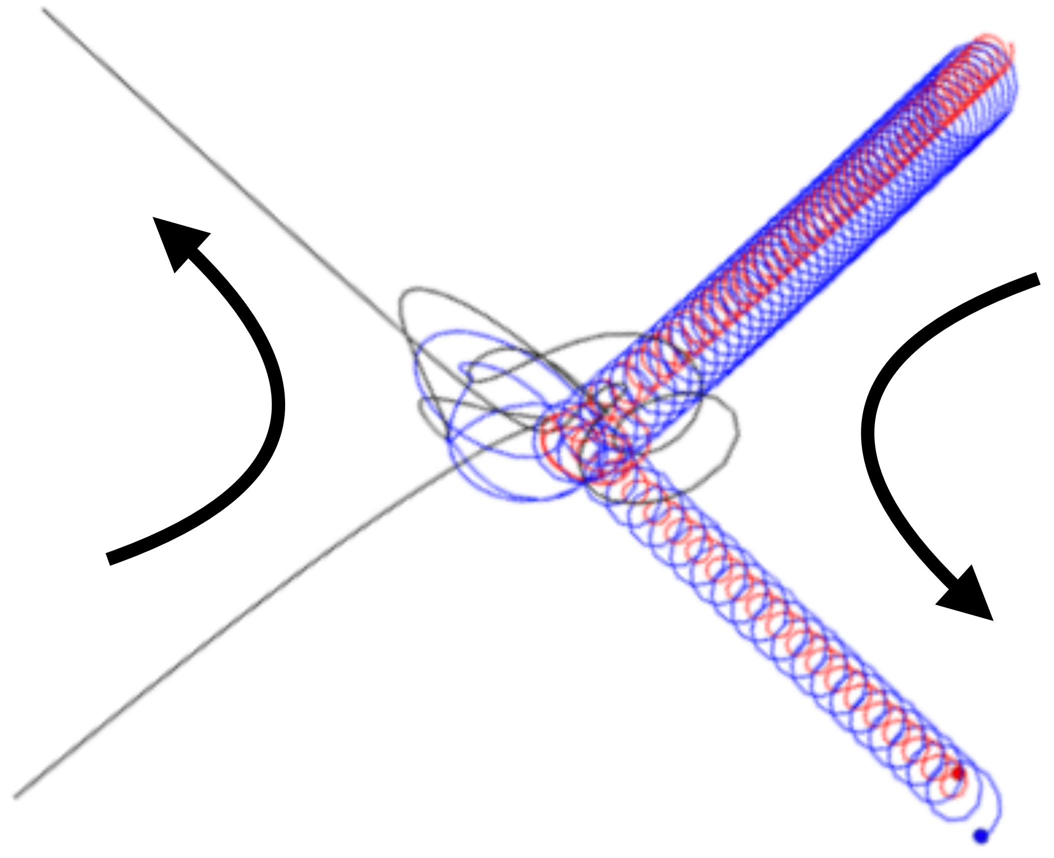
Binary Hardening in Fly-by Encounters



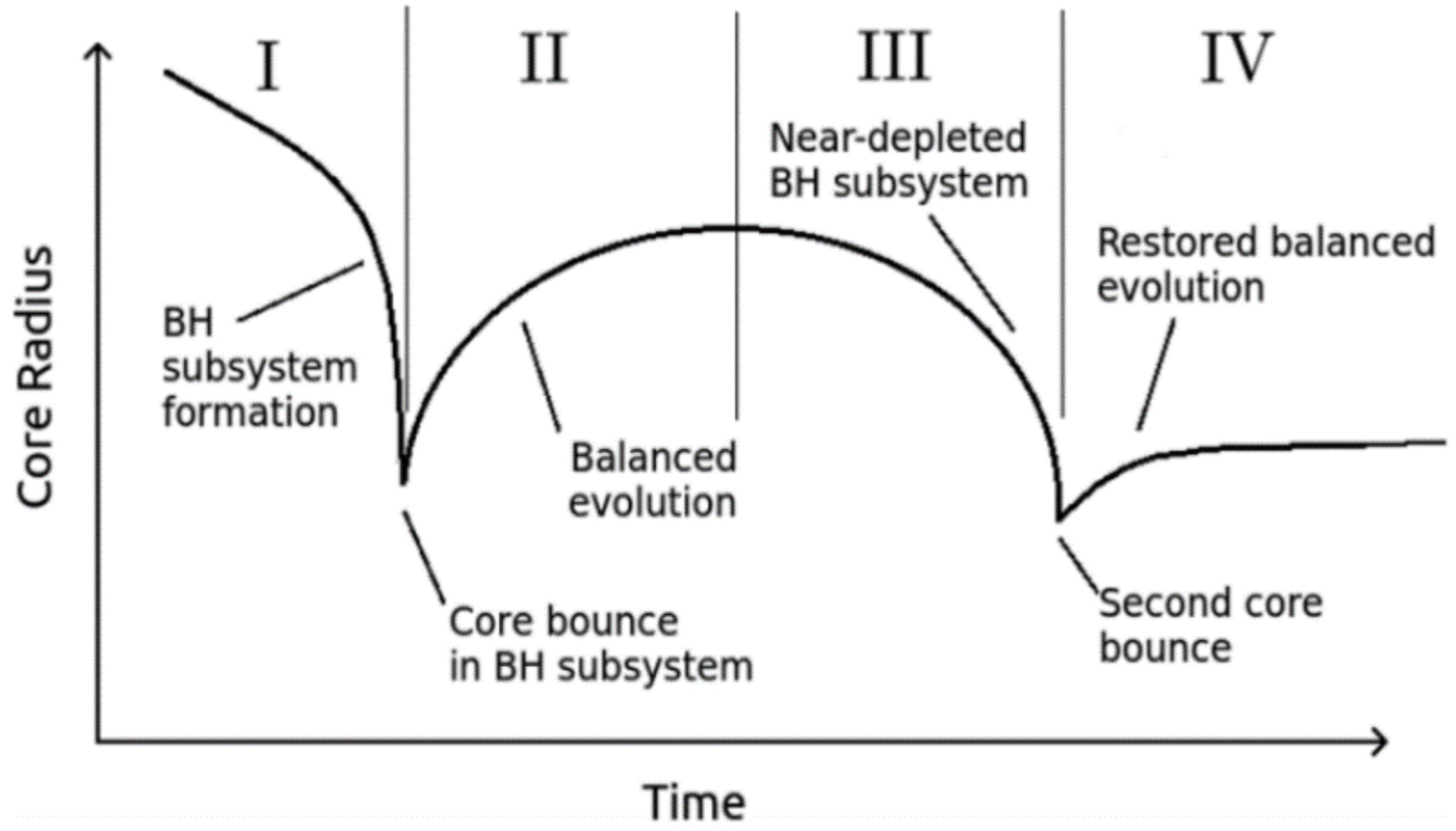
3-body interaction results in the shrinking of the binary black hole orbit.

Dynamical processes leading to binary black hole formation

- Dynamical interactions also eject tight binary black holes out of the cluster due to dynamical recoil (scattering kick)
  - Can merge due to gravitational wave emission outside the cluster



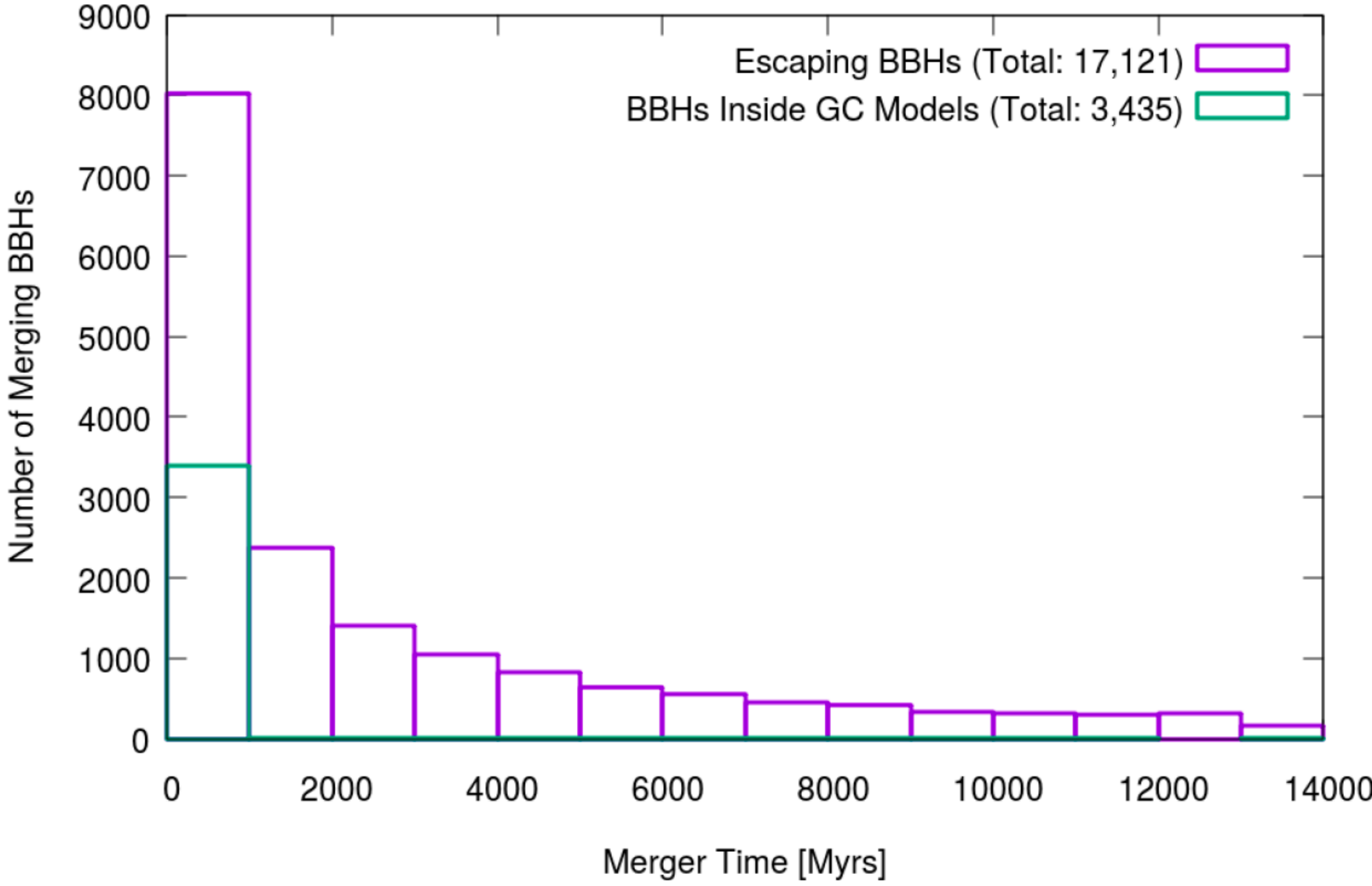
- Black hole population in clusters depletes with time → depletion time depends on cluster initial properties
  - Black holes heat surrounding stars (Mackey et al. 2007;2008, Breen & Heggie 2013)
  - Initially dense clusters → more interactions → faster depletion of black holes
  - Less dense clusters → fewer interactions → slower depletion of black holes
- Initially dense clusters that are dynamically older produce more ‘useful’ binary black holes



Credit: Breen & Heggie (2013)

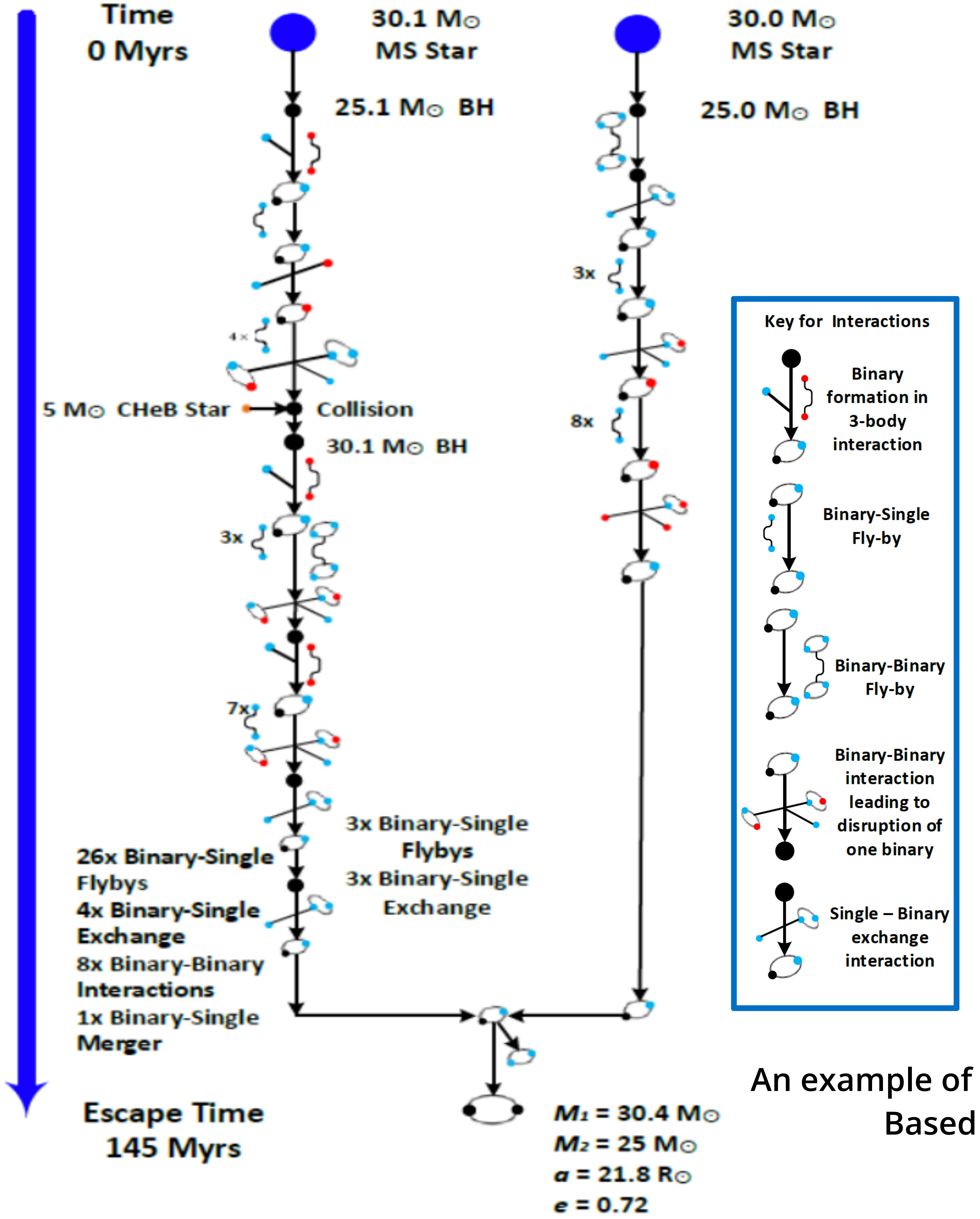
Producing binary black holes in globular clusters

- Simulated 2000 GC models with different initial parameters as part of the MOCCA-Survey Database I (Askar et al. 2017)
  - Black hole natal kicks computed according to the mass fallback prescription given by Belczynski et al. (2002) → **1007 GC models**
  - Systematically search for merging binary black holes that escape of merge inside the cluster
- 17,121 'useful' BBHs escaped the cluster
- 3,435 BBHs merged inside the cluster within a Hubble time
- Most mergers inside the cluster occur within the first 500 Myr of cluster evolution
- Dynamically formed escapers contribute to binary black hole mergers at later times
  - Mostly formed in exchange encounters during 3 or 4-body encounters



Models from MOCCA Survey Database I (Askar et al. 2017)

Dynamical formation of a binary black hole



An example of a dynamically formed BBH from Askar et al. (2017)
Based on interaction diagrams first presented in
Rodriguez et al. (2016)

- 2 single black holes form in the cluster from the evolution of massive stars
- Both end up in 2 different binaries following numerous dynamical interactions
- Form a binary after a binary-binary exchange interaction and are ejected from the cluster
- Will merge outside the cluster after 208 Myr since the beginning of cluster evolution

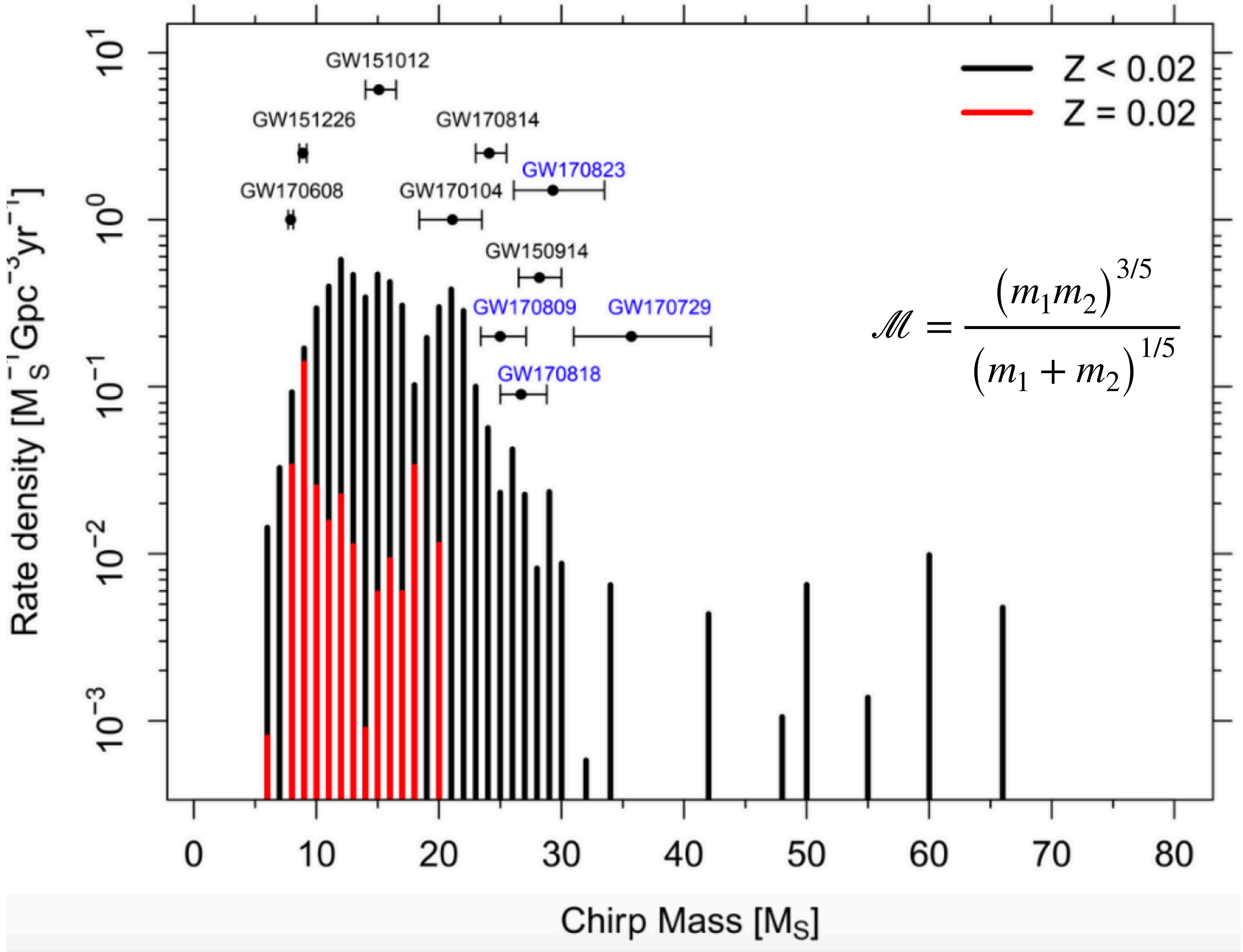
$$t_{\rm merg} = t_{\rm esc} + t_{\rm GW}$$ Peters (1964)

$$t_{\rm merg} = 145 + 63$$

$$t_{\rm merg} = 208 \text{ Myr}$$

Merger rates for binary black holes originating from globular clusters

- Estimated local merger rate density as done for isolated field BHs (Bulik, Belczynski & Rudak 2004).
  - GC star formation rate as a function of redshift (Katz & Ricotti 2013)
    - Peak in GC Formation at about redshift (z) of 3
- Local merger rate density of BBHs originating from GCs: $5.5 – 25\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (Askar et al. 2017)
  - Consistent with independently calculated rates by Rodriguez et al. (2016), Park et al. (2017), Hong et al. (2018; 2020), Mapelli et al. 2022 and also other recent studies
  - Rodriguez & Loeb (2018) → $15\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$



Differential rate density per unit chirp mass
Updated Fig. 4 from Askar et al. (2017)
Credit: Magdalena Szkudlarek

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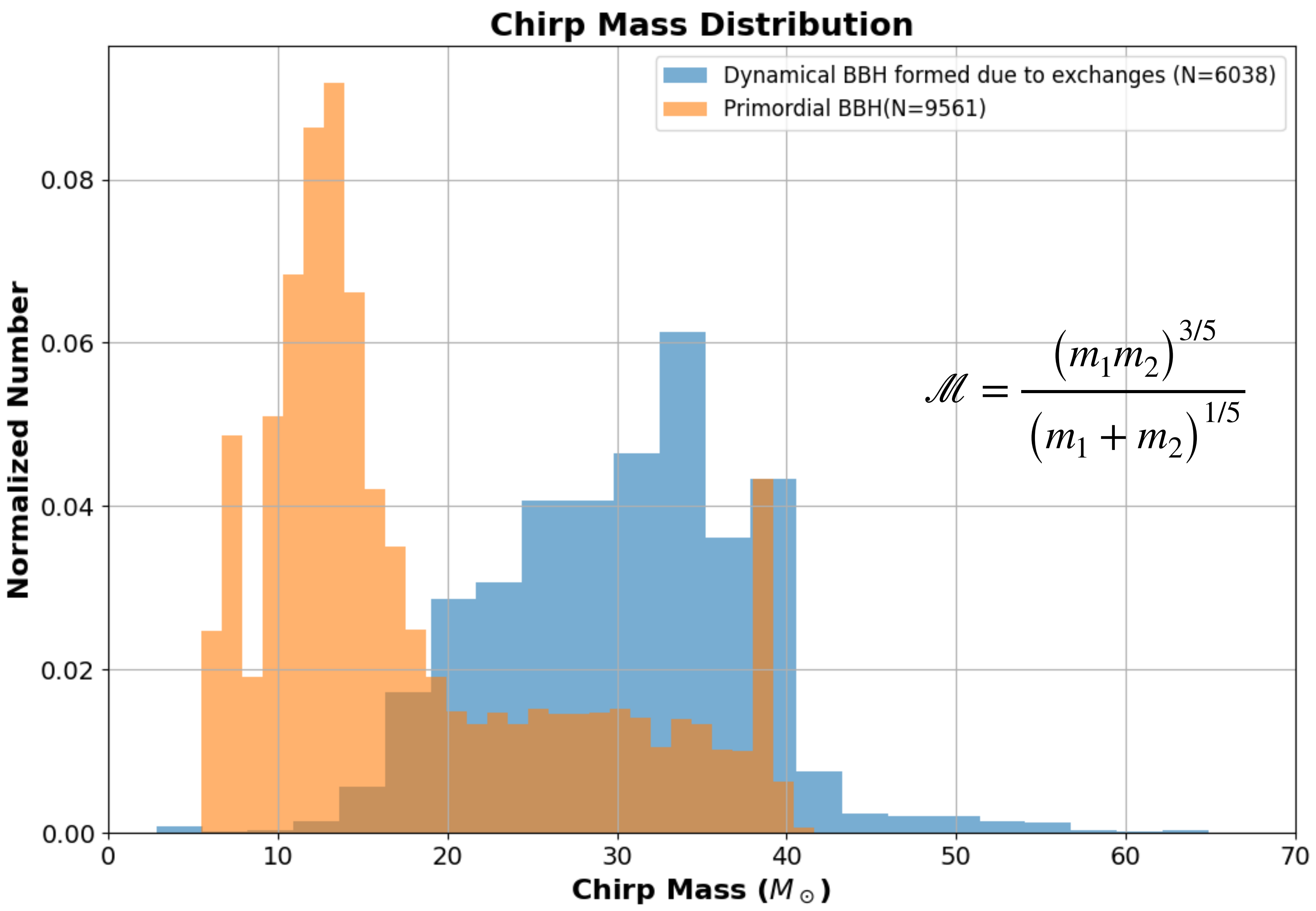

$$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

New MOCCA Models from 2024 (~320 star cluster models)

- **Improved treatment for progenitor winds (Vink et al. 2001; 2008)**
- **BH masses depend on 'Rapid' supernova prescription from Fryer et al. 2012**

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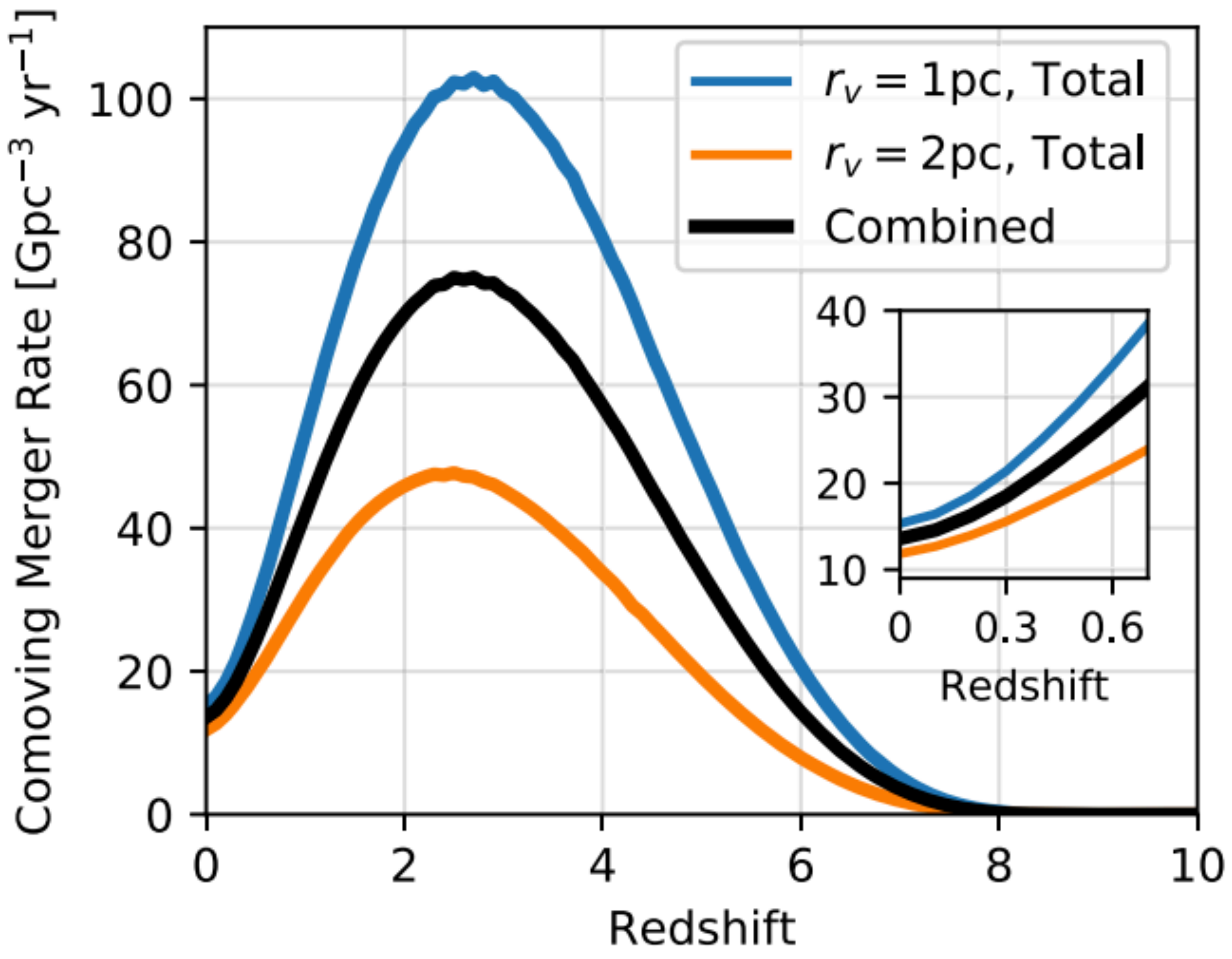
- Open question: How much star formation took place in globular clusters?
  - Currently $\sim 0.1 - 1\,\%$ of galaxy stellar mass is in globular clusters (Harris et al. 2014)
  - May have been $\gtrsim 10\,\%$ at $z > 3$ (Muratov & Gnedin 2010)



Rodriguez & Loeb (2018)

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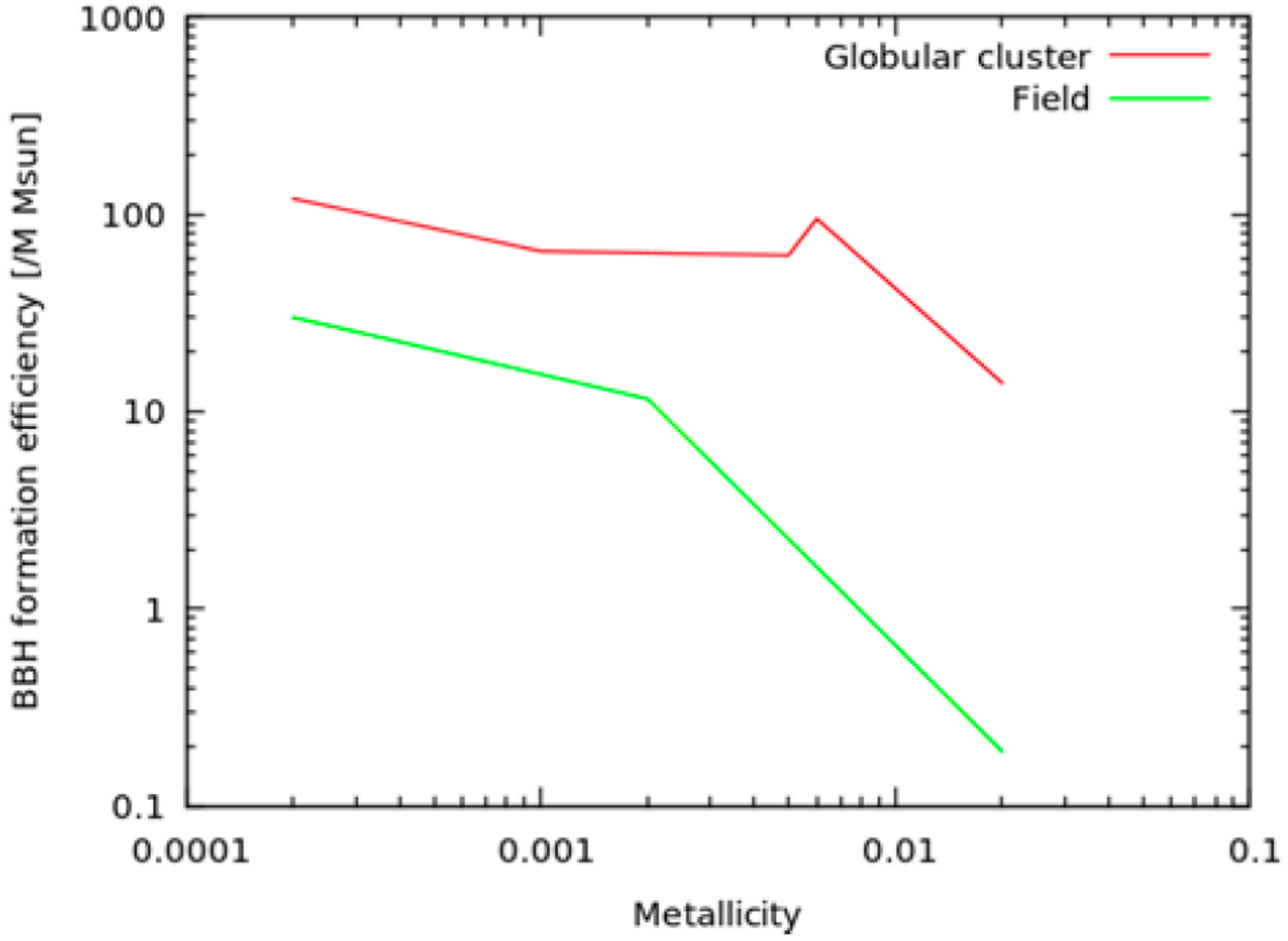
So which dominates, field or cluster?

$\boxed{\text{Common} \times \text{Rare} \gtrless \text{Rare} \times \text{Common?}}$

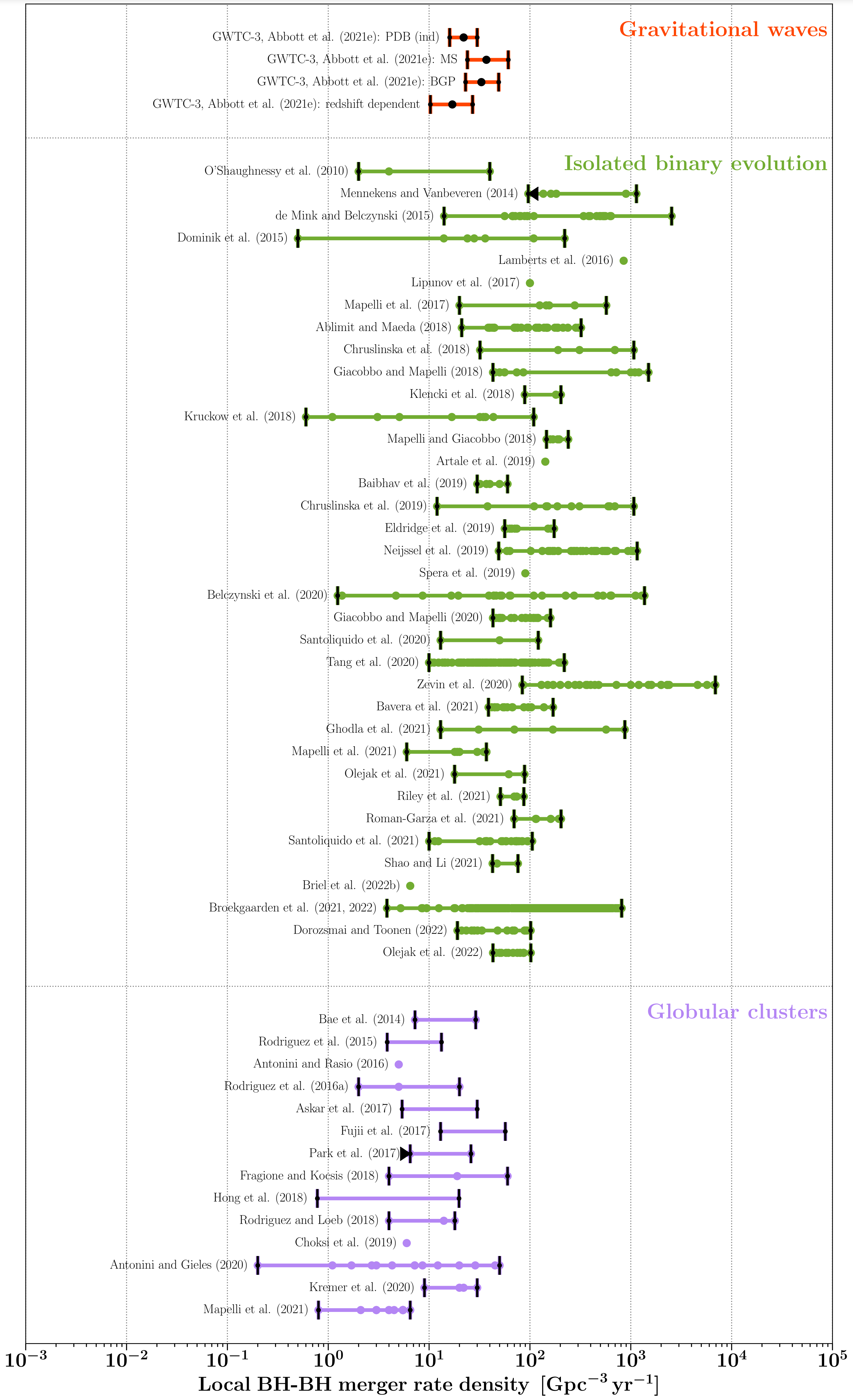
Askar-Davies Inequality



Efficiency: Number of merging BBH binaries per
(Figure Credit: Tomasz Bulik)

Field data from Belczynski et al. 2016

Merger rates for binary black holes from globular clusters



Credit: Mandel & Broekgaarden (2021)
Open Data: DOI 10.5281/zenodo.5072400

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Common × Rare ≳ Rare × Common?

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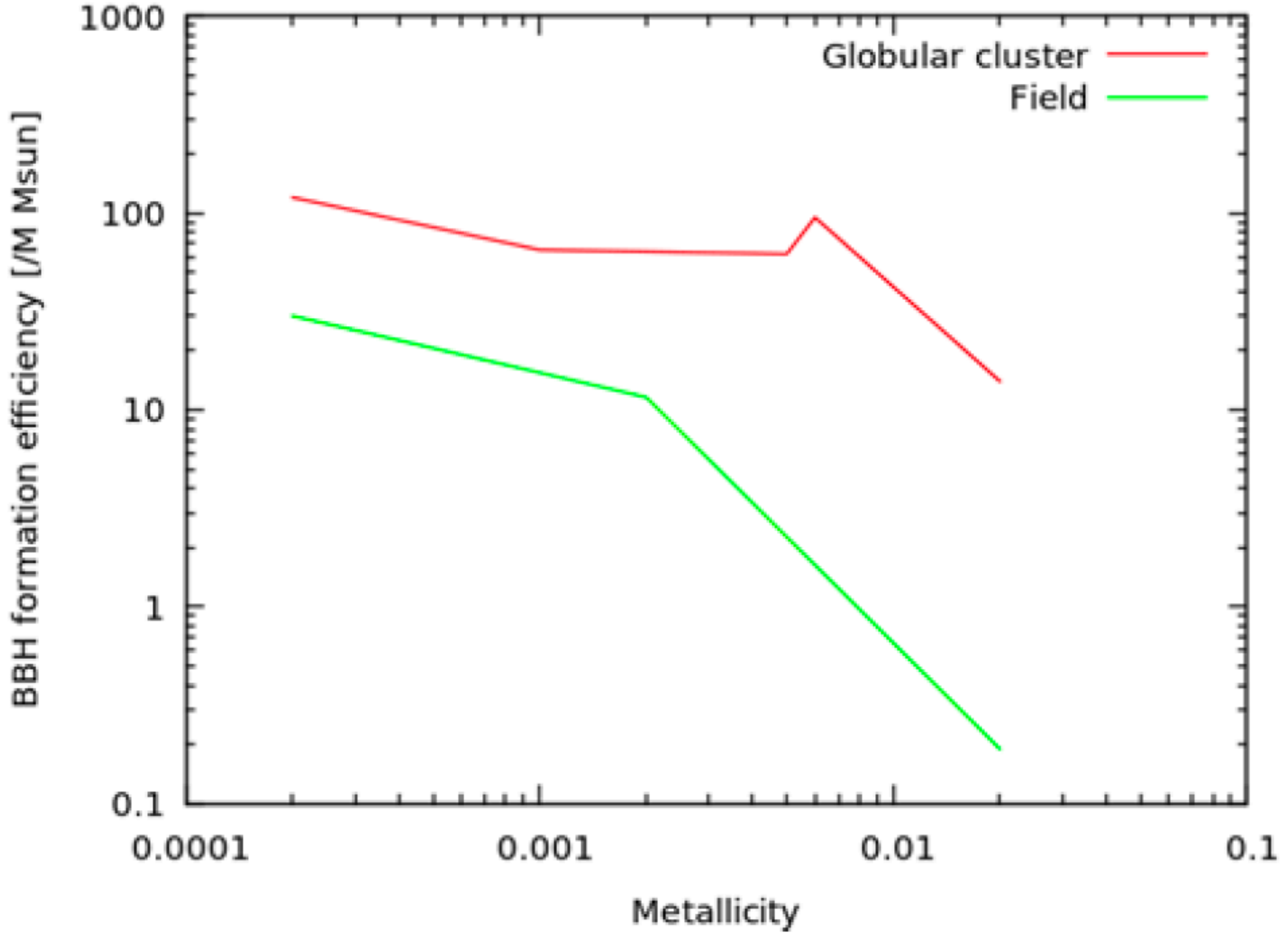
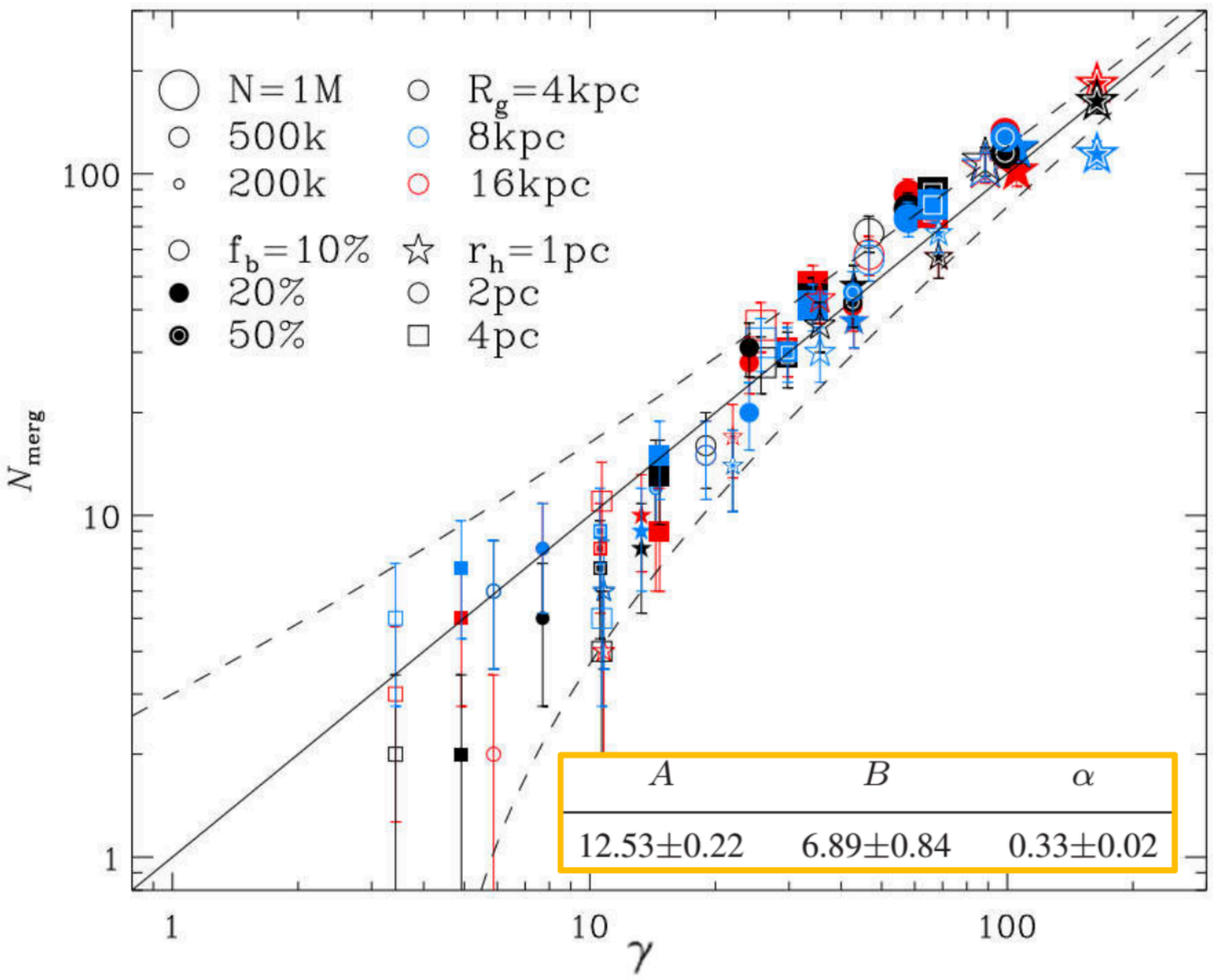


Efficiency: Number of merging BBH binaries per
(Figure Credit: Tomasz Bulik)

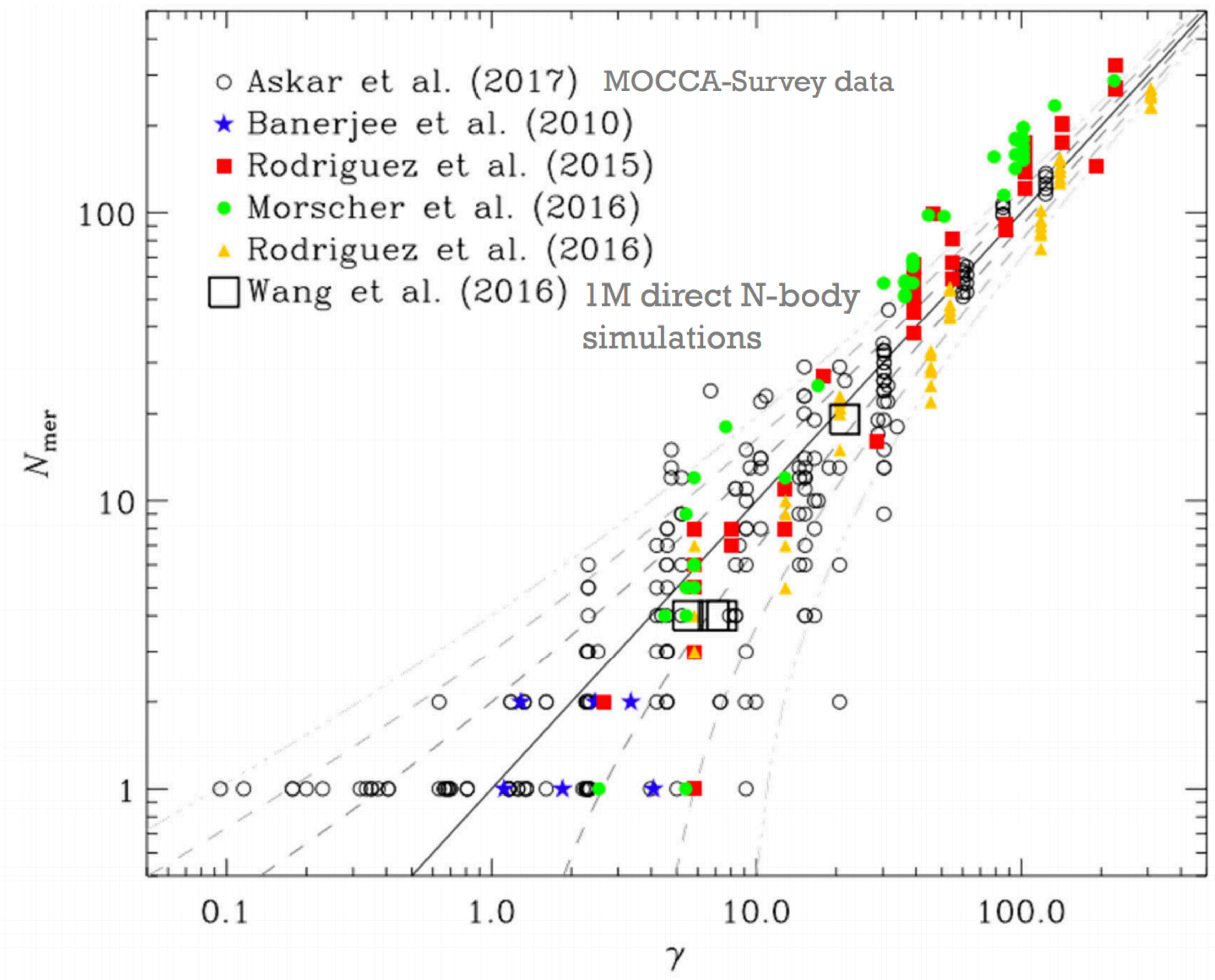
Field data from Belczynski et al. 2016

Binary black hole production and globular cluster properties



A	B	α
12.53±0.22	6.89±0.84	0.33±0.02

Number of merging binary black holes 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)



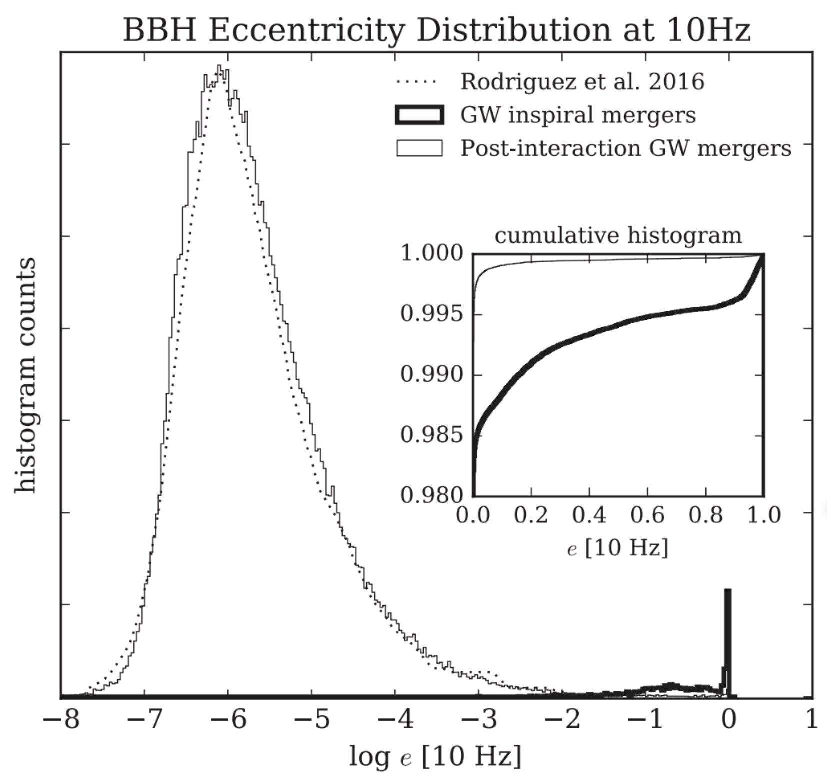
$$\gamma \equiv \underbrace{\boxed{A}\,\frac{M_0}{10^5\mathrm{M}_\odot}\times\left(\frac{\rho_\mathrm{h}}{10^5\mathrm{M}_\odot\mathrm{pc}^{-3}}\right)^{\boxed{\alpha}}}_{\text{dynamical channel}} + \underbrace{\boxed{B}\,\frac{M_0}{10^5\mathrm{M}_\odot}\times f_{\mathrm{b},0}}_{\text{primordial channel}}$$

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

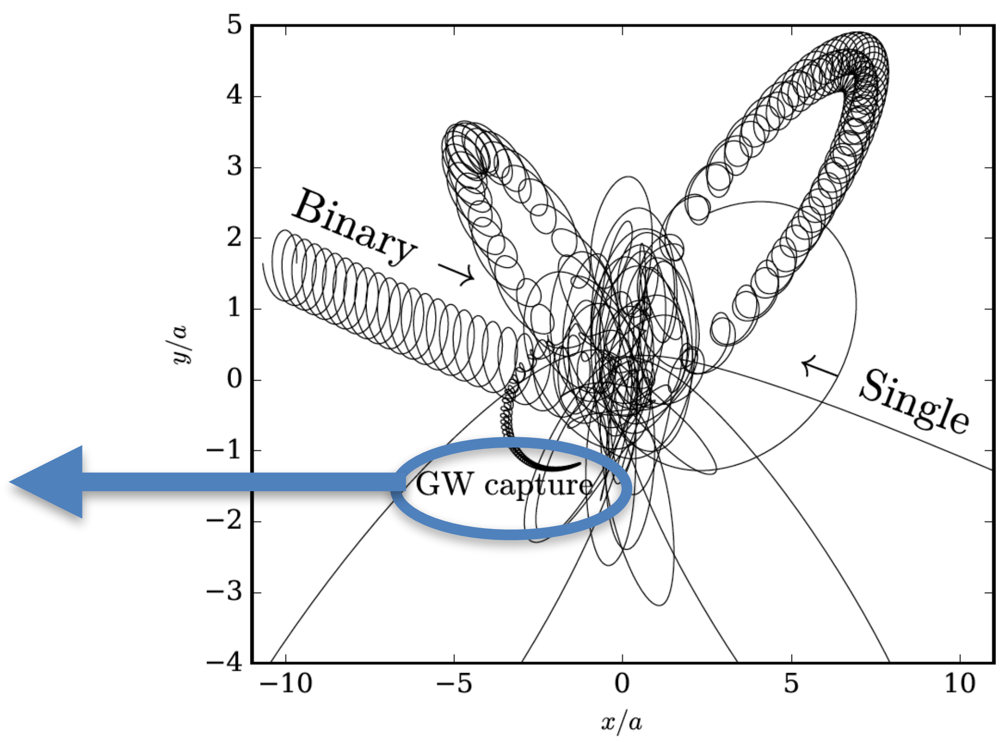
Eccentric binary black holes mergers in clusters

- Non-negligible probability of experiencing a very close passage during a resonant encounter
- Significant orbital energy and angular momentum are carried away from the system by gravitational wave radiation → can result in rapid, highly-eccentric black hole mergers ($e > 0.1$)
- Rate of such capture mergers: $0.5 - 2\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

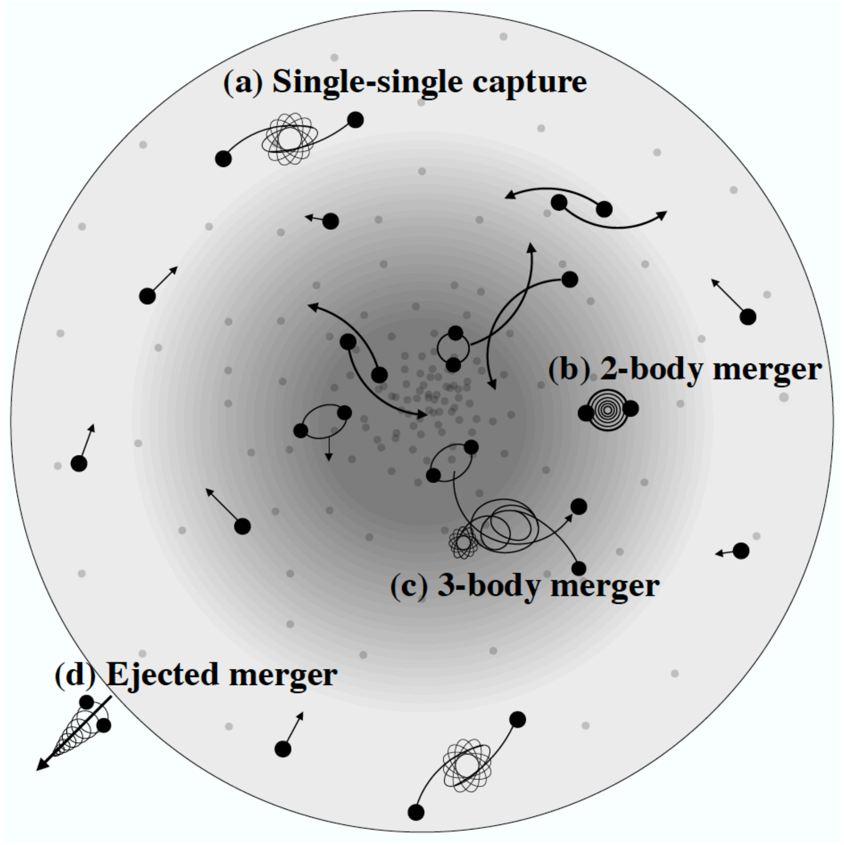
  see Samsing (2018), Samsing, Askar, Giersz (2018), Rodriguez et al. (2018 a,b)
- Very rarely single black holes may also capture each other and merge (Samsing et al. 2020)
- Hierarchical three-body mergers (Samsing & Ilan 2018, Veske et al. 2020)
- For eccentric mergers during binary-binary interactions, see Zevin et al. (2018)
- See also contribution from triple systems (Antonini, Toonen & Hamers 2017)



Samsing & Ramirez-Ruiz (2017)



Samsing (2018)



Credit: Samsing et al. (2020)

GW190521 and LVK observations of black holes in the upper-mass gap

- Pair and pulsational pair instability supernovae prevent formation of black holes with masses in the range: $\sim 50^{+20}_{-10} - 120\ \mathrm{M}_\odot$ → **upper mass gap of black holes**
- LVK Observations of massive stellar-mass black holes:

LVK Merger Event	Primary Mass $[M_\odot]$	Secondary Mass $[M_\odot]$	Effective Spin χ_{eff}	Luminosity Distance (Gpc)	Redshift (z)
GW190521_030229	$95.3^{+28.7}_{-18.9}$	$69^{+22.7}_{-23.1}$	$0.03^{+0.32}_{-0.39}$	$6.1^{+4.9}_{-3.1}$	$0.64^{+0.28}_{-0.28}$
GW190403_051519	$88^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$	$0.70^{+0.15}_{-0.27}$	$8.00^{+5.99}_{-3.99}$	$1.14^{+0.64}_{-0.49}$
GW190426_190642	$106.9^{+41.6}_{-25.2}$	$76.6^{+26.2}_{-33.6}$	$0.19^{+0.43}_{-0.40}$	$4.35^{+3.35}_{-2.15}$	$0.70^{+0.41}_{-0.30}$
GW200220_061928	87^{+40}_{-23}	61^{+26}_{-25}	$0.06^{+0.40}_{-0.38}$	$6.1^{+4.9}_{-3.1}$	$1.14^{+0.64}_{-0.49}$

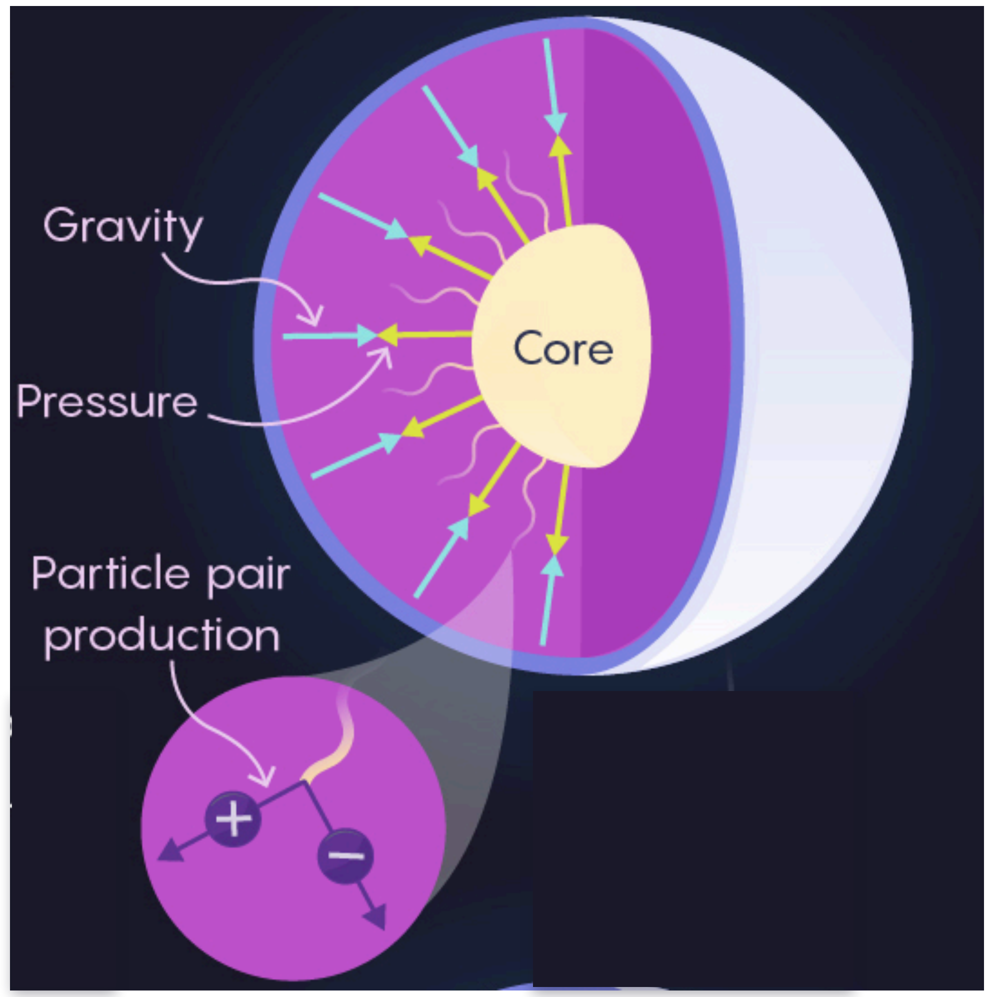


Image Credit: Lucy Reading-Ikkanda/Quanta Magazine

Data from GWTC-2.1 and 3 (Abbot et al. 2020; 2021) https://www.gw-openscience.org/

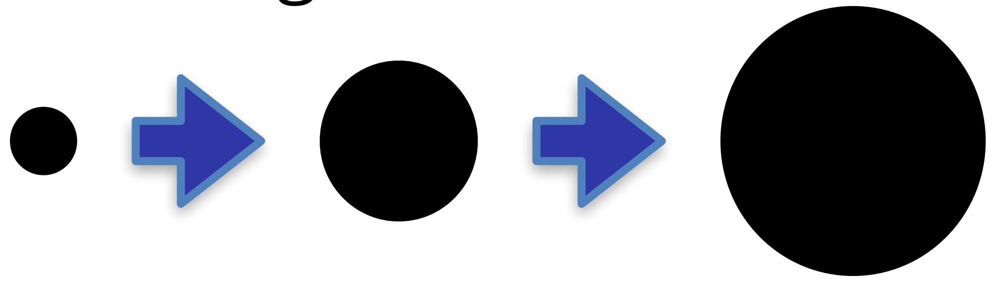
Repeated or hierarchal mergers of black holes in dense star clusters

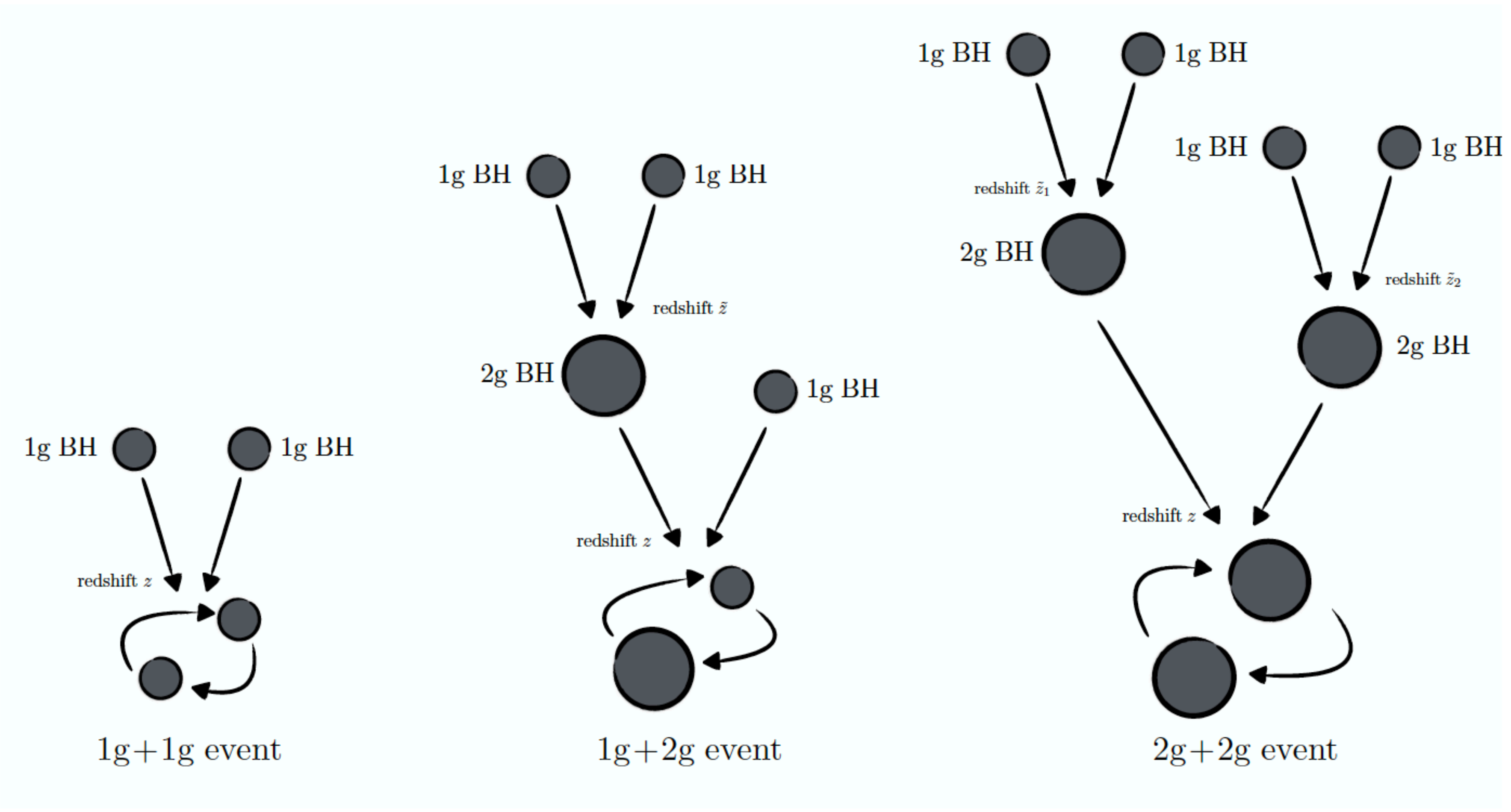
- Two sBHs (1G) merge due to gravitational wave (GW) emission and form a more massive BH (2G)
- In a dense star cluster, this merged BH (2G) can pair up and merge with another BH (1G or 2G)
- Most straightforward way for growing BHs and one of the proposed formation channels for GW events like GW190521

  Rodriguez et al. (2019; 2020), Arca Sedda et al. (2020; 2021), Fragione et al. (2020) Kremer et al. (2020), Samsing & Hotokezaka (2020), di Carlo et al. (2020), Dall'Amico et al. (2021), Mapelli et al. (2021), Banerjee (2022)
- Repeated BH could lead to the runaway growth of an IMBH

  $\sim 10^2 - 10^4\ M_\odot$

  Miller & Hamilton (2002); Mouri & Taniguchi (2002); Portegies Zwart & McMillan (2002)





Gerosa & Berti (2017)

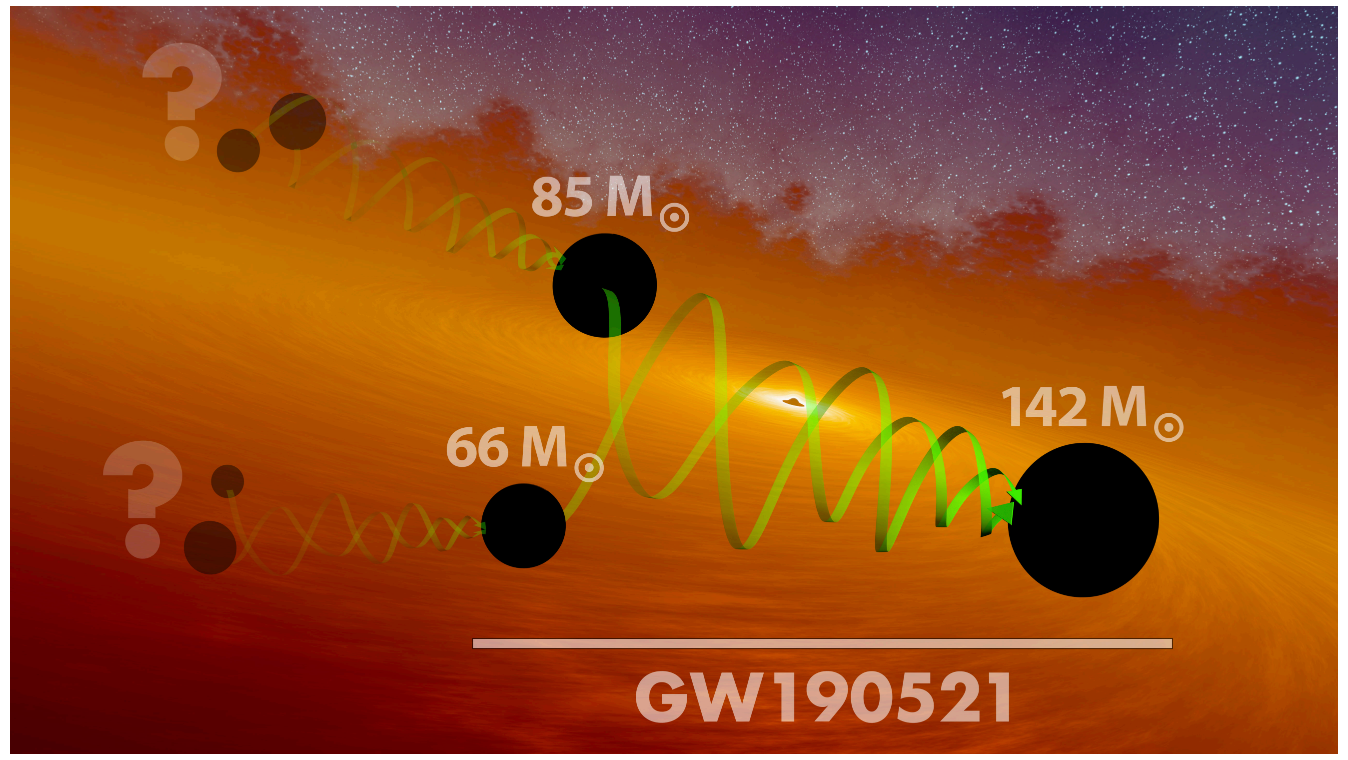


Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

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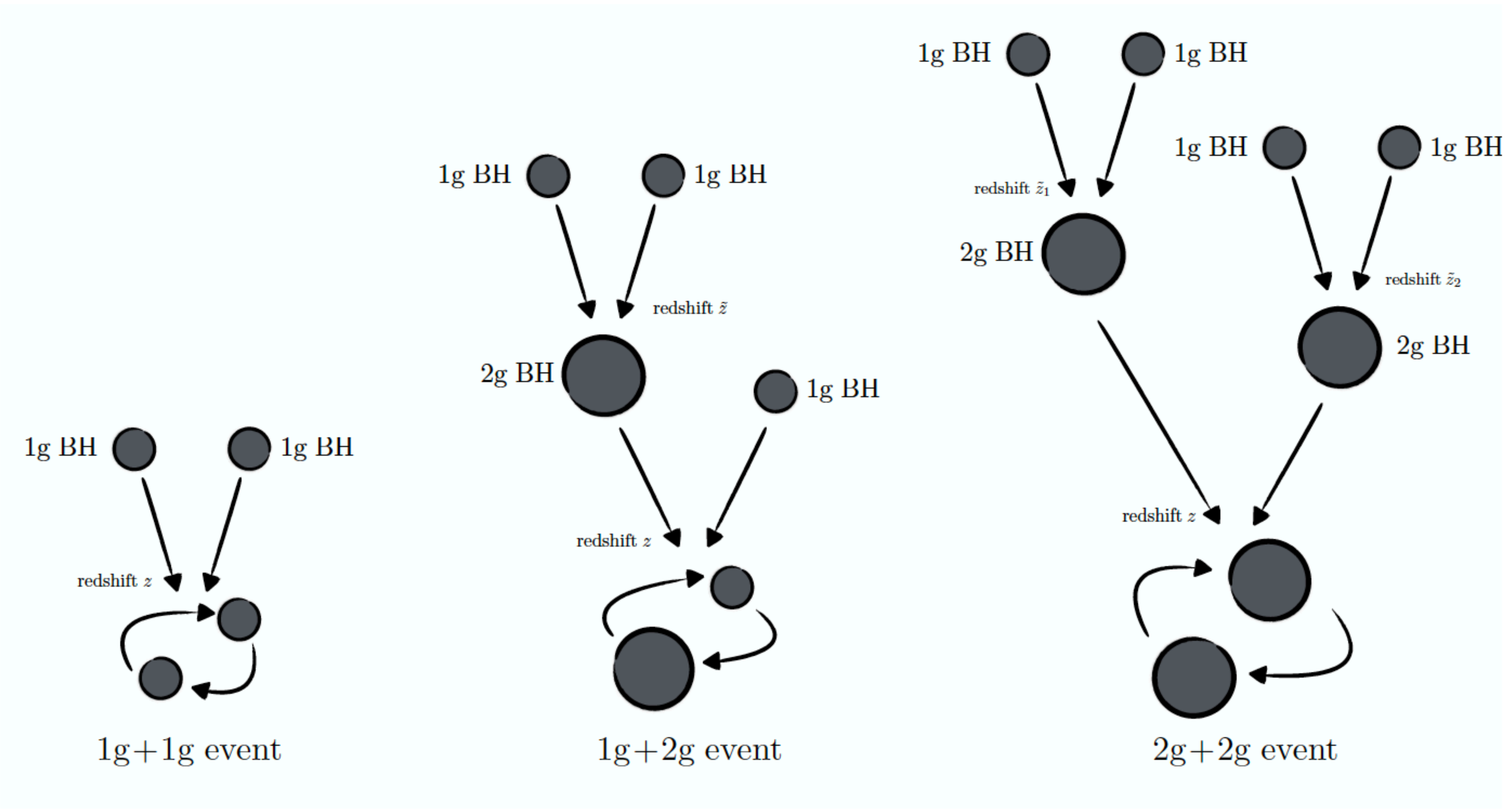
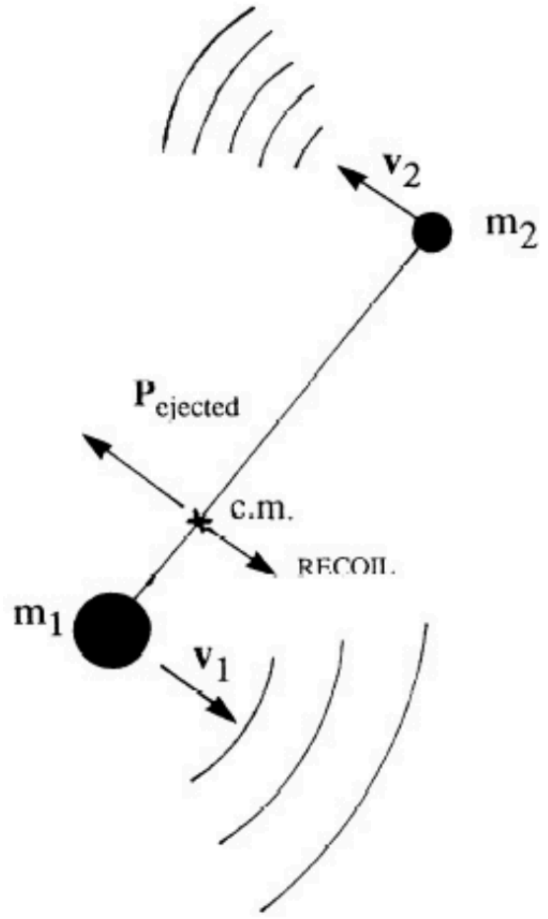
- In a dense star cluster, this merged BH (2G) can pair up and merge with another BH (1G or 2G)
- Most straightforward way for growing BHs
- Problem: Can be difficult to retain a merged BH in a dense environment due to GW recoil kicks

(e.g., Merritt et al. 2004; Holley-Bockelmann et al. 2008)

  - If GW recoil kick magnitude is larger than the escape speed of the cluster then merged BH will escape
  - Magnitude of GW depends on mass ratio of merging BH and the magnitude and orientation of their spins



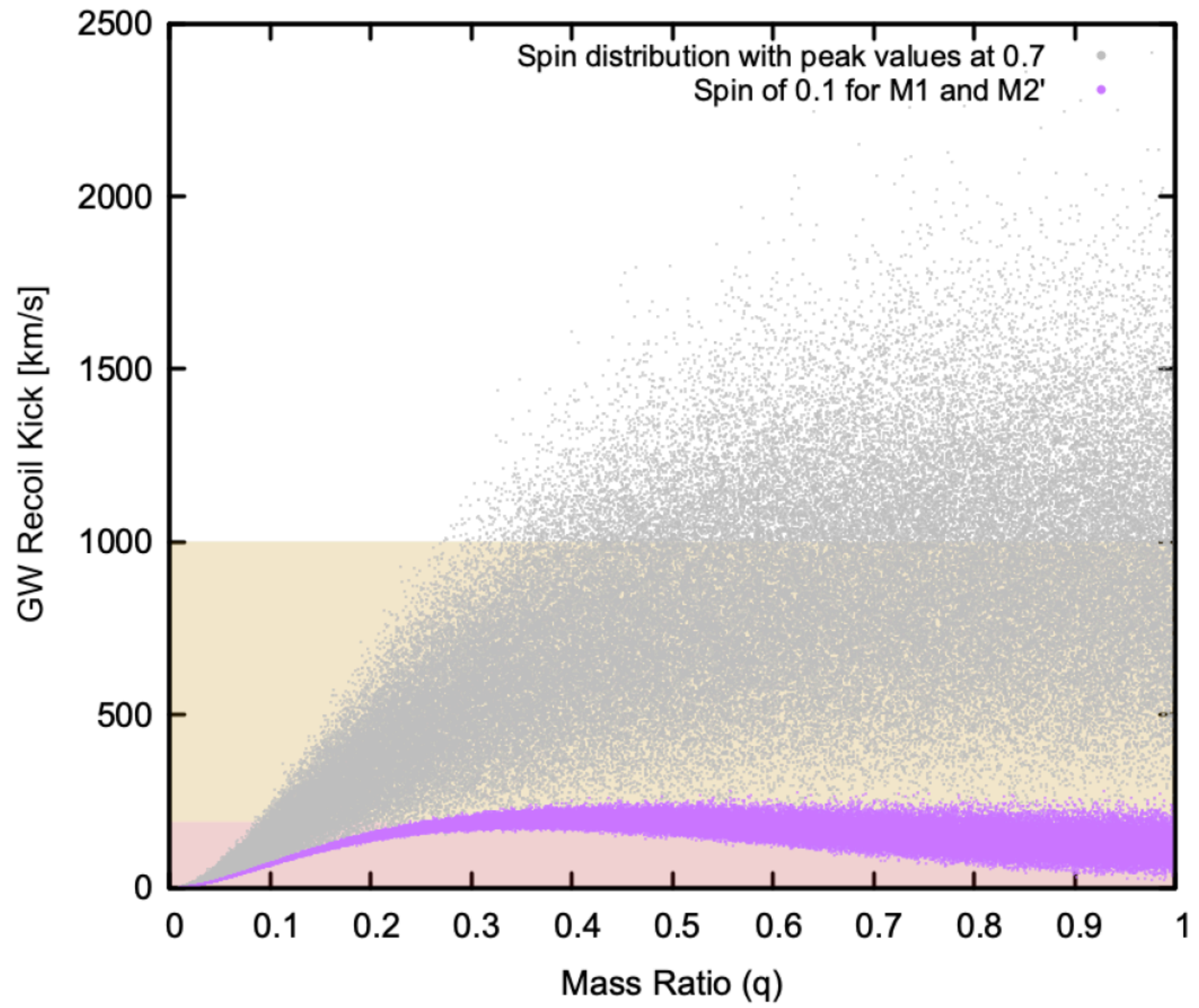
Gerosa & Berti (2017)



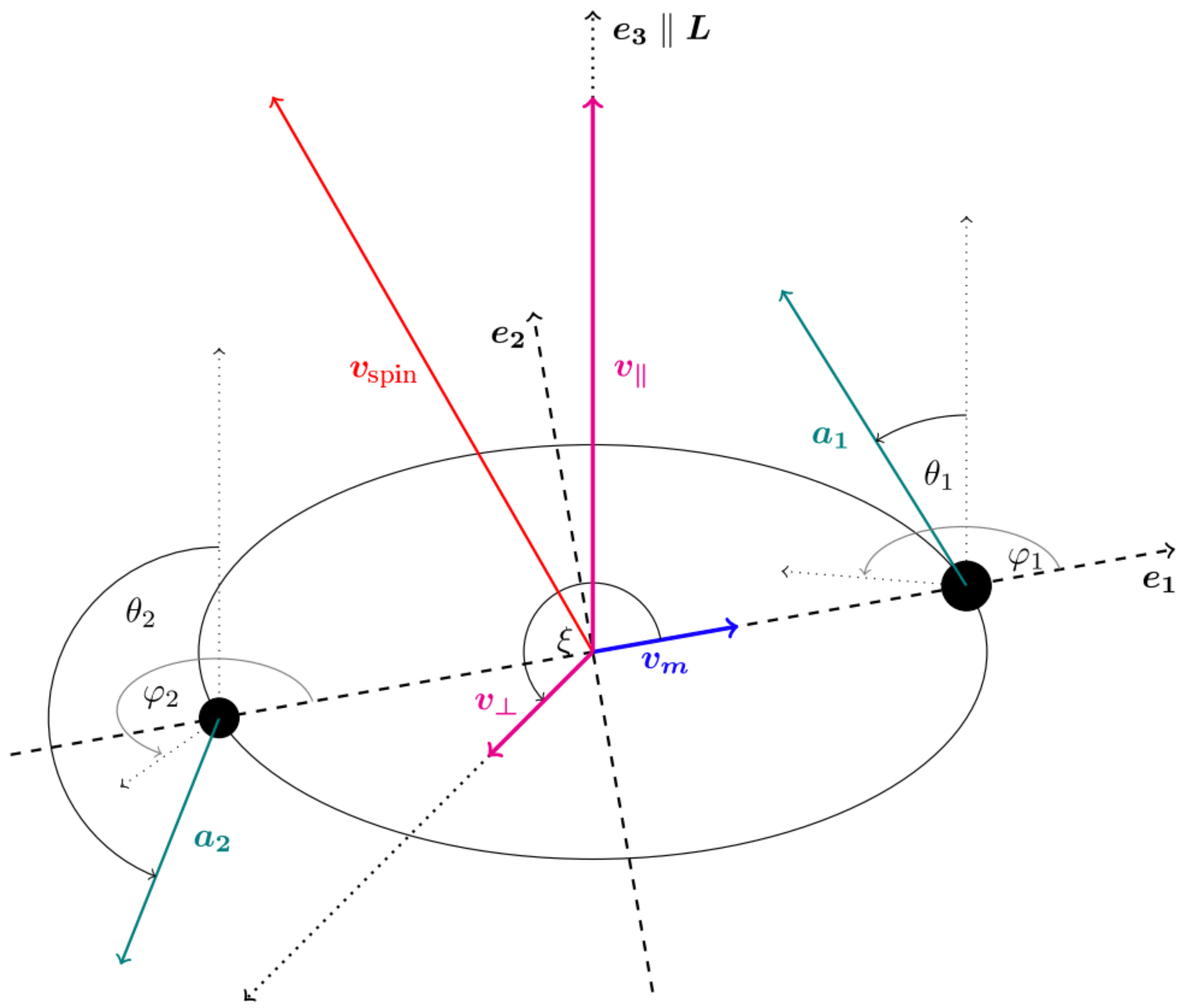
Wiseman (1992)

Repeated or hierarchal mergers of black holes in dense star clusters

- Magnitude of GW recoil kick depends on mass ratio of merging BHs and the magnitude and orientation of their spins



Assuming isotropic spin directions
GW recoil kicks calculated using van Meter (2010)

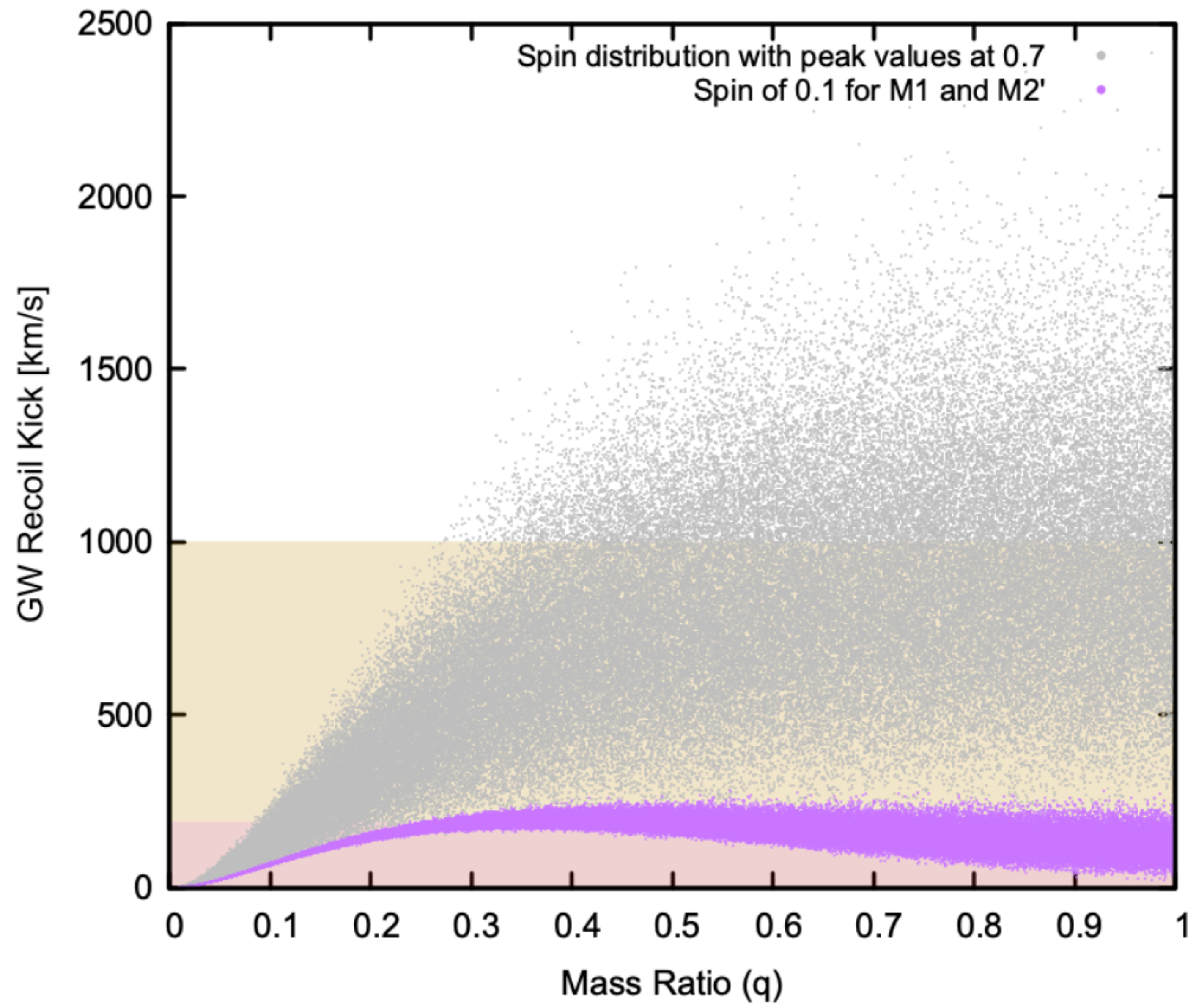


Morawski et al. (2018)

- If sBH birth spins are low then 2G BHs can potentially be retained in environments like globular clusters
  - 2G BHs are likely to have to have large spins values (close to 0.7) → 2G+1G and 2G+2G merger products will receive large recoil kicks → harder to retain 3G and 4G BHs
- Better chances for retaining merged BHs in NSCs due to higher escape velocities (Gerosa & Berti 2019; Antonini et al. 2020; Fragione et al. 2022)

Repeated or hierarchal mergers of black holes in dense star clusters

- Magnitude of GW recoil kick depends on mass ratio of merging BHs and the magnitude and orientation of their spins



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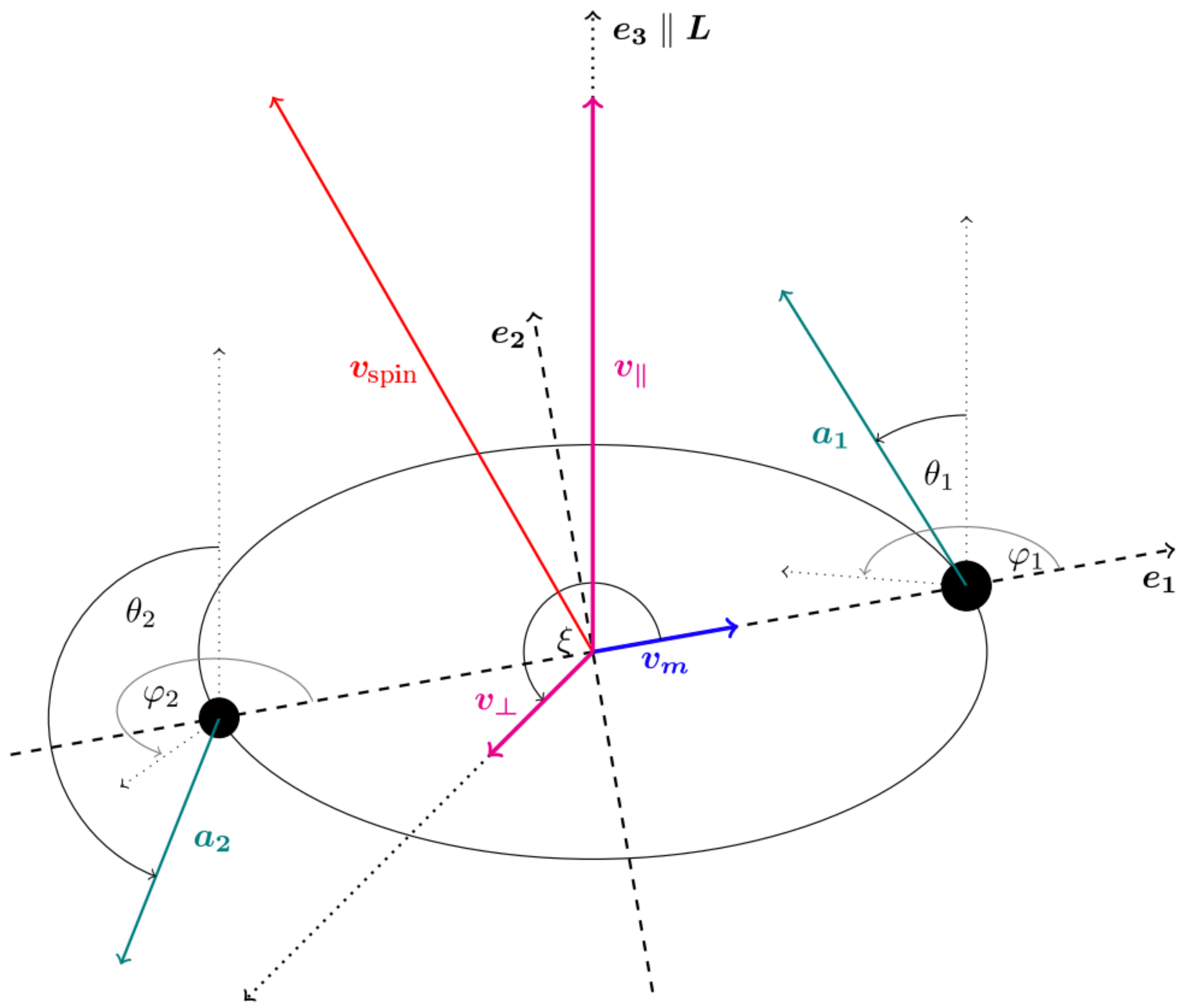

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2020; Fragione et al. 2022)

Birth spins of BHs are highly uncertain!

Upper-mass gap BH Mergers: Results from MOCCA simulations

- Mergers in the mass gap

$N = 2.5$ million stars ($1.4 \times 10^6\, M_\odot$) between $0.08\, M_\odot \leq M_{ZAMS} \leq 150\, M_\odot$

$Z = 0.05\, Z_\odot$ (1 model with $Z = 0.01\, Z_\odot$)

$R_h = 0.8$ pc ($\rho_0 = 4 \times 10^6\, M_\odot\, pc^{-3}$) and 2 pc ($\rho_0 = 2.5 \times 10^5\, M_\odot\, pc^{-3}$)

Initial binary fraction 5% and 25%

Updated treatment for stellar winds, natal kicks and remnant masses (Kamlah et al. 2022)

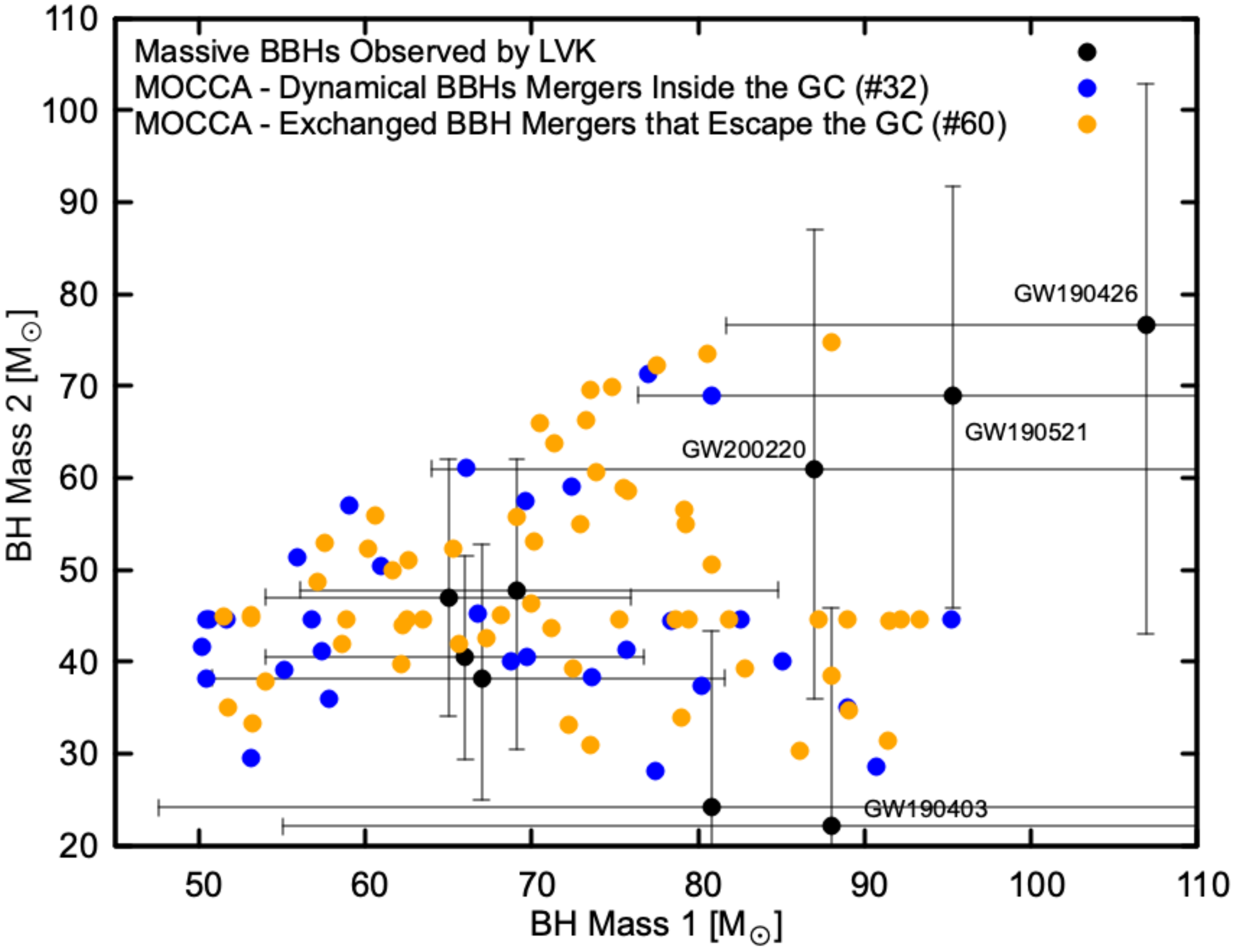
Birth Spins of Black Holes = 0.1 (Fuller & Ma 2019)

GW Recoil Kicks Included

BHs in the mass gap are mostly 1G+2G Mergers
Few 2G+2G mergers

Maximum black hole mass from stellar evolution depends on metallicity and prescriptions for progenitor evolution → up to 45 $M_\odot$

(Belczynski et al. 2016 ; Banerjee et al. 2020)



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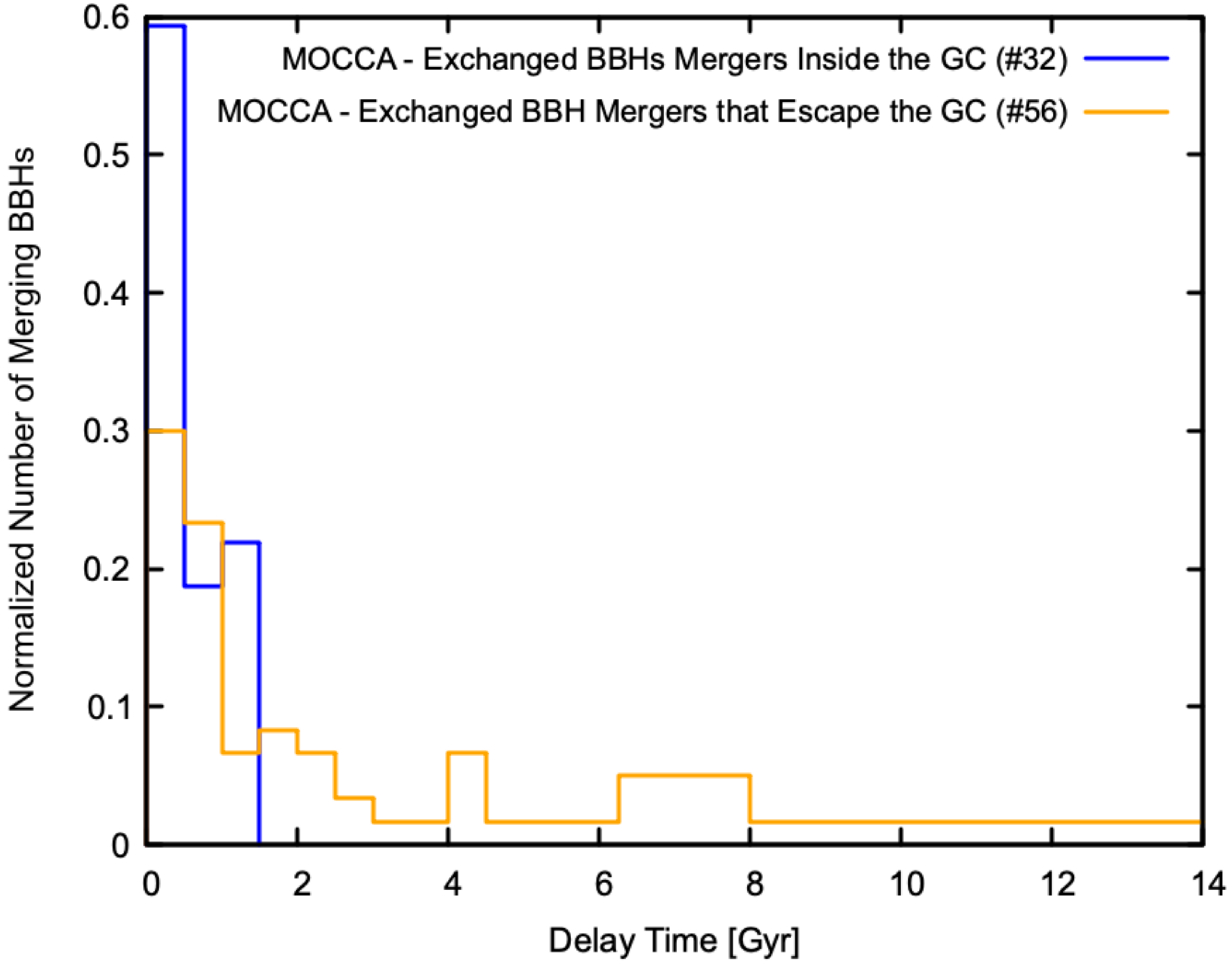

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Other pathways for growing black holes in dense star clusters

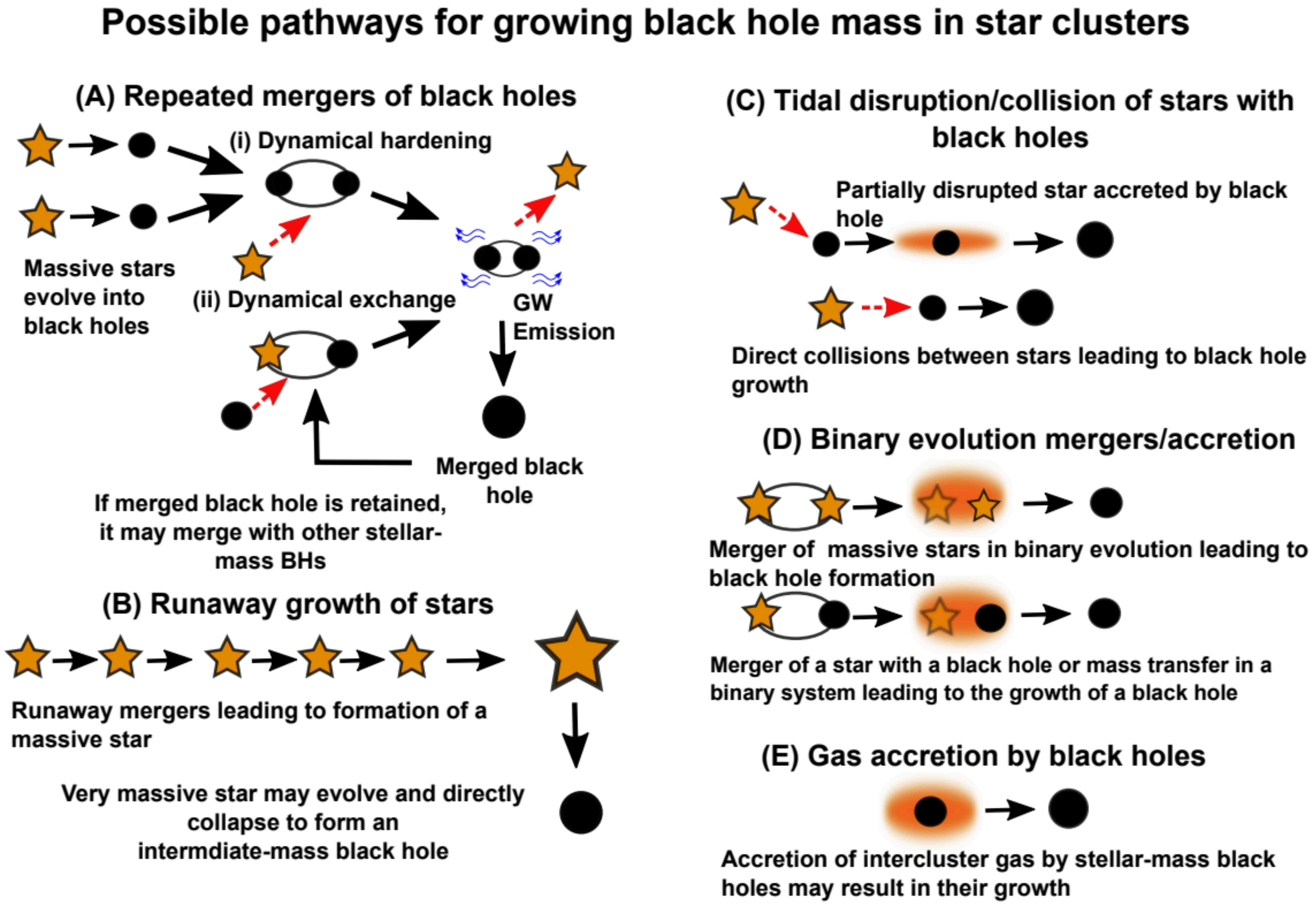
(A) Repeated or hierarchical mergers of stellar-mass BHs

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

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

(D) Binary mergers leading to IMBH formation

(E) Gas accretion by stellar-mass BHs



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

Conclusions

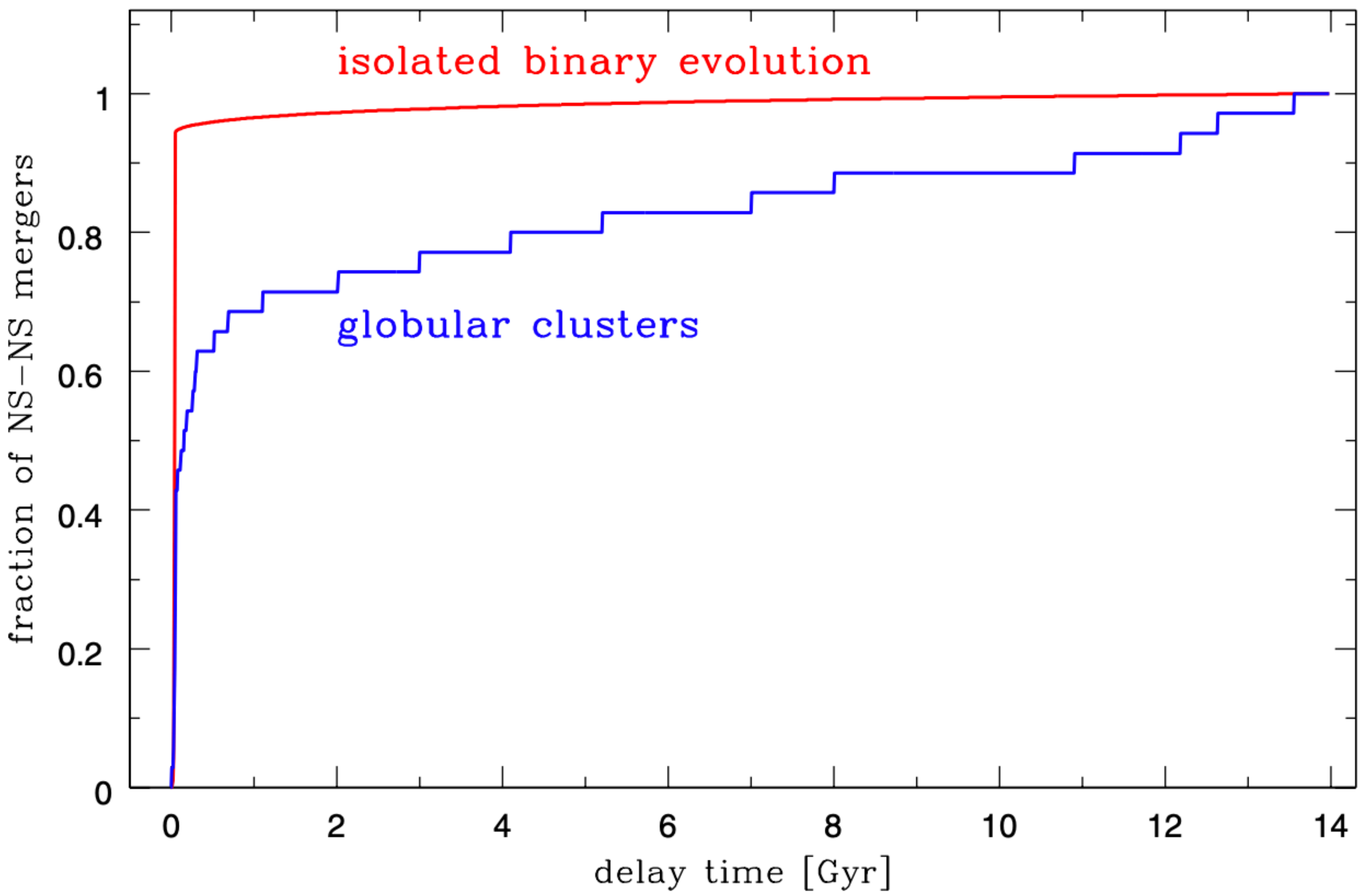
- Initial black hole retention in stellar clusters depends on the natal kicks that they receive
- Dense clusters can efficiently form ‘useful’ binary black holes through dynamical interactions:
  - Major channel: Exchange during binary-single encounters
  - Binary black holes can be hardened and made ‘useful’ due to encounters
- Maximum local merger rate contribution from globular clusters is $\sim 25\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (consistent with the observed merger rate from LVK)
- Binary black holes with component masses in the upper mass gap ($\sim 50^{+20}_{-10}$ to $120\ \mathrm{M}_{\odot}$) can be made in stellar clusters through:

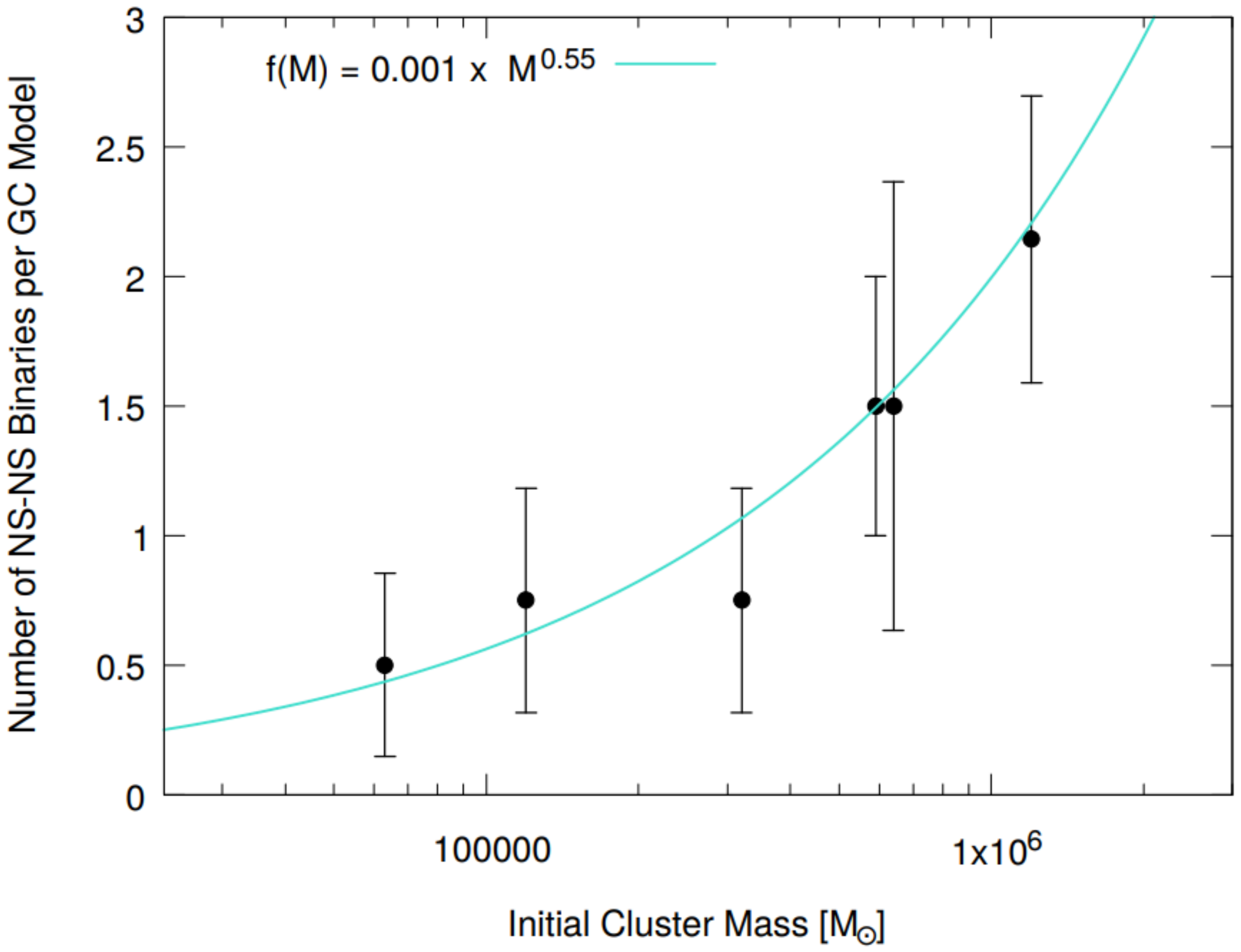
  Hierarchical mergers of black holes → *need low birth spins to avoid ejection of 2G black holes due to gravitational recoil kicks* or *2G black holes can only be retained in the densest nuclear stellar clusters*

  - ***GW190521 and similar detections are consistent with dynamical formation!***

Binary neutron star mergers from globular clusters

- Results from 27 GC models simulated with MOCCA the code (Belczynski et al. 2018)
  - Reduced neutron star natal kicks: 0 km/s and 100 km/s
  - 21 ‘useful’ neutron stars escape the cluster and 13 merge inside the cluster
  - Local merge rate densities of $0.05\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$



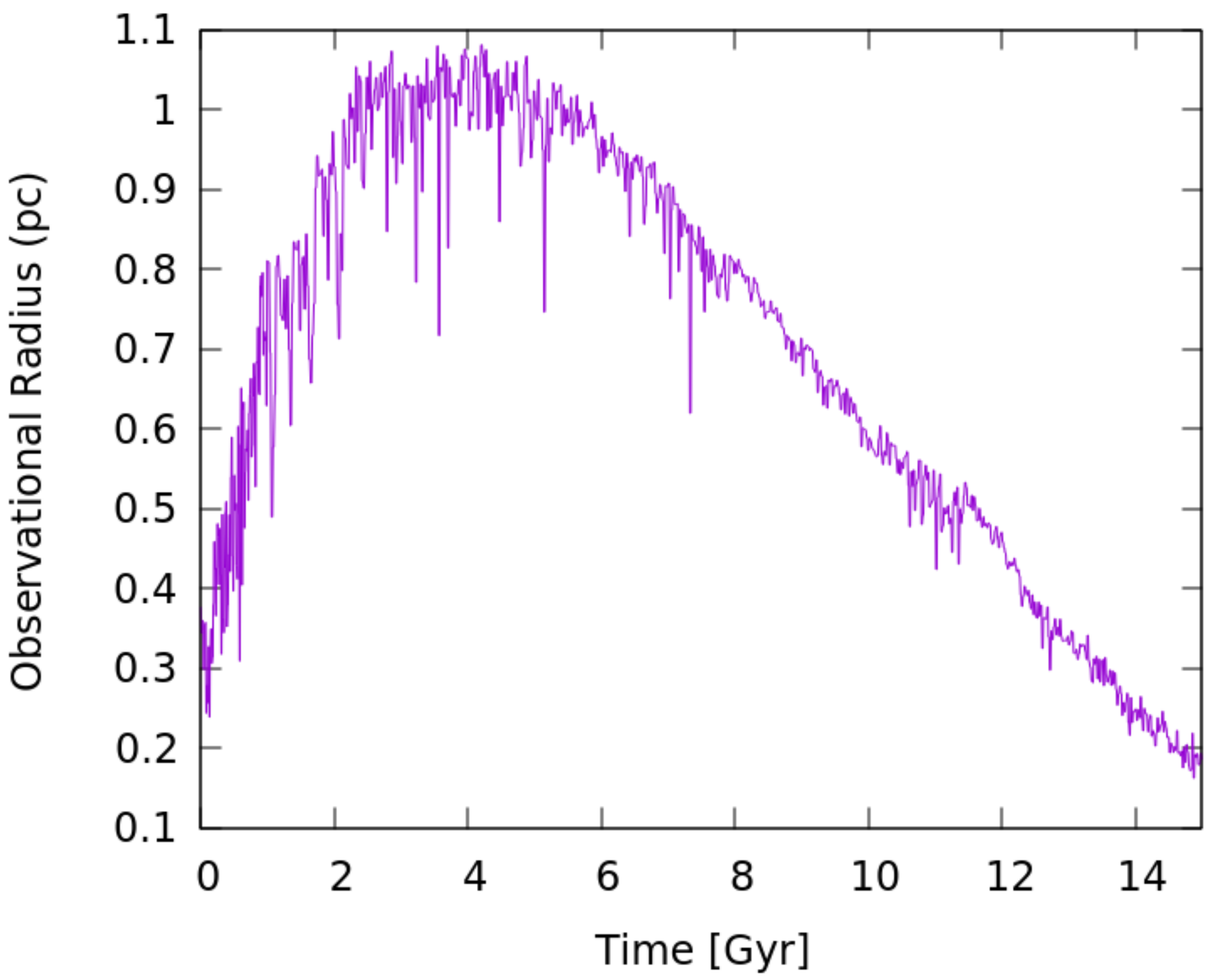


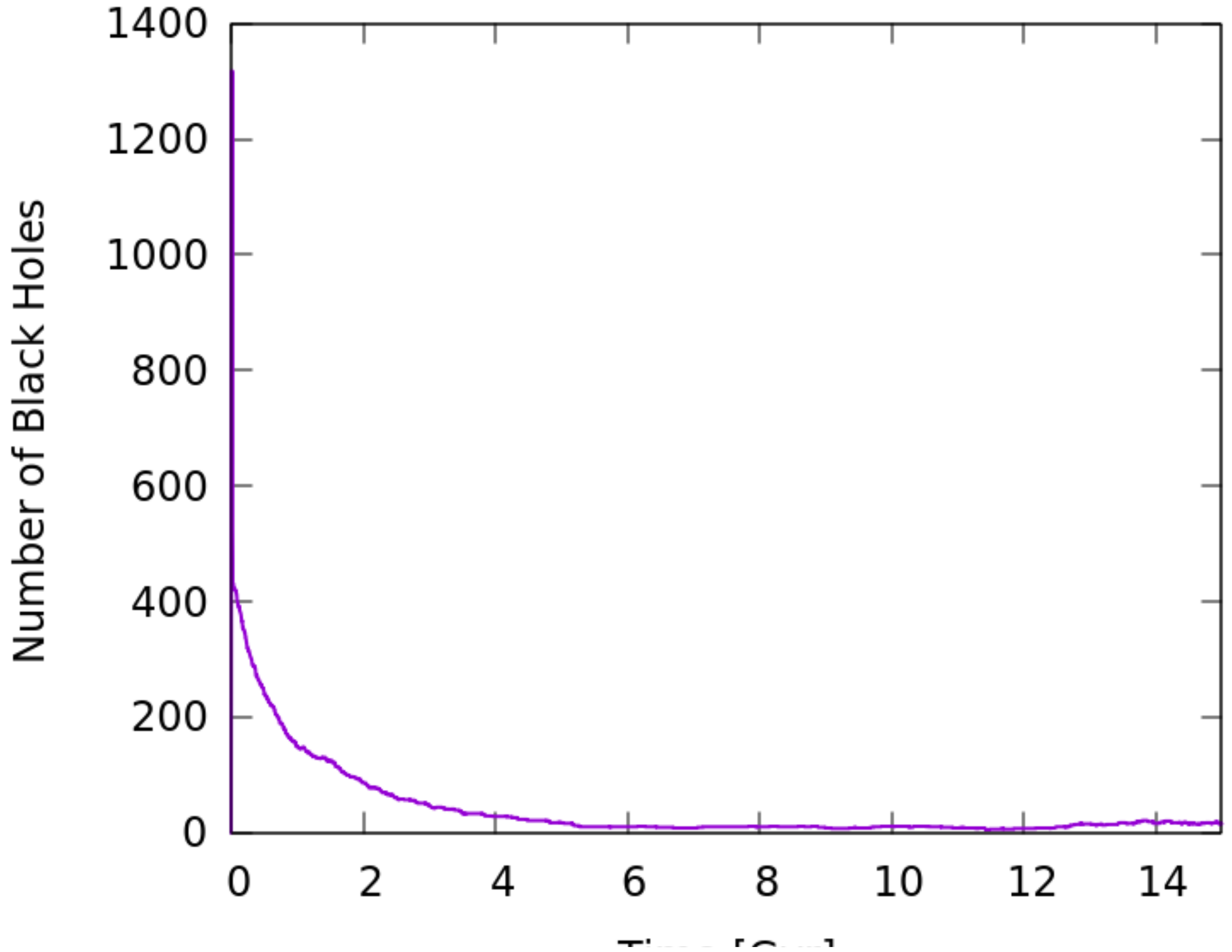
Figures from Belczynski, Askar et al. 2018

Binary neutron star mergers from globular clusters: black holes delay BNS formation

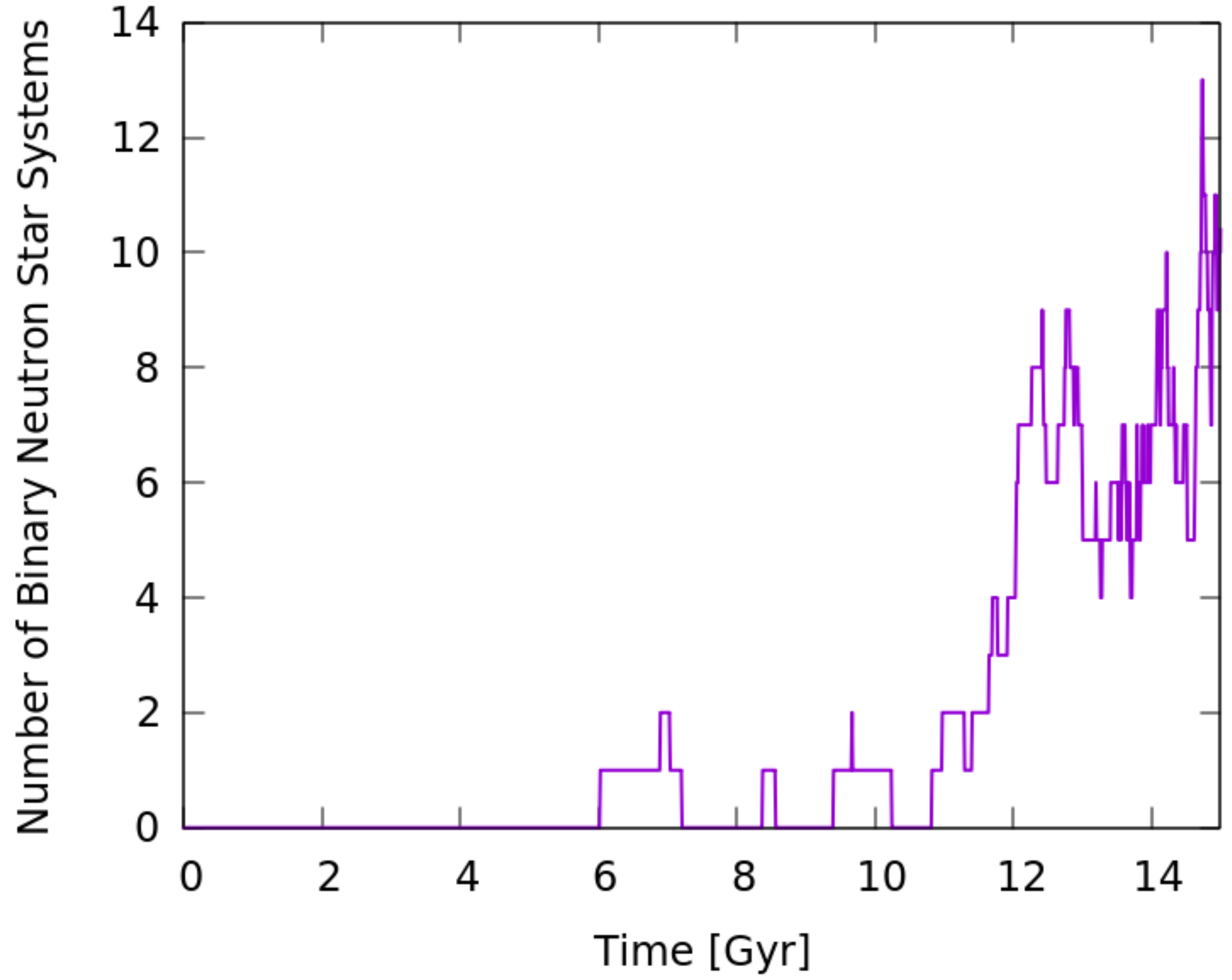
- Binary NS systems only begin to dynamically form in GCs once BHs have been depleted and cluster is evolving towards core collapse

- BHs in the GC center ‘heat’ stars around them, preventing segregation of lower mass stars

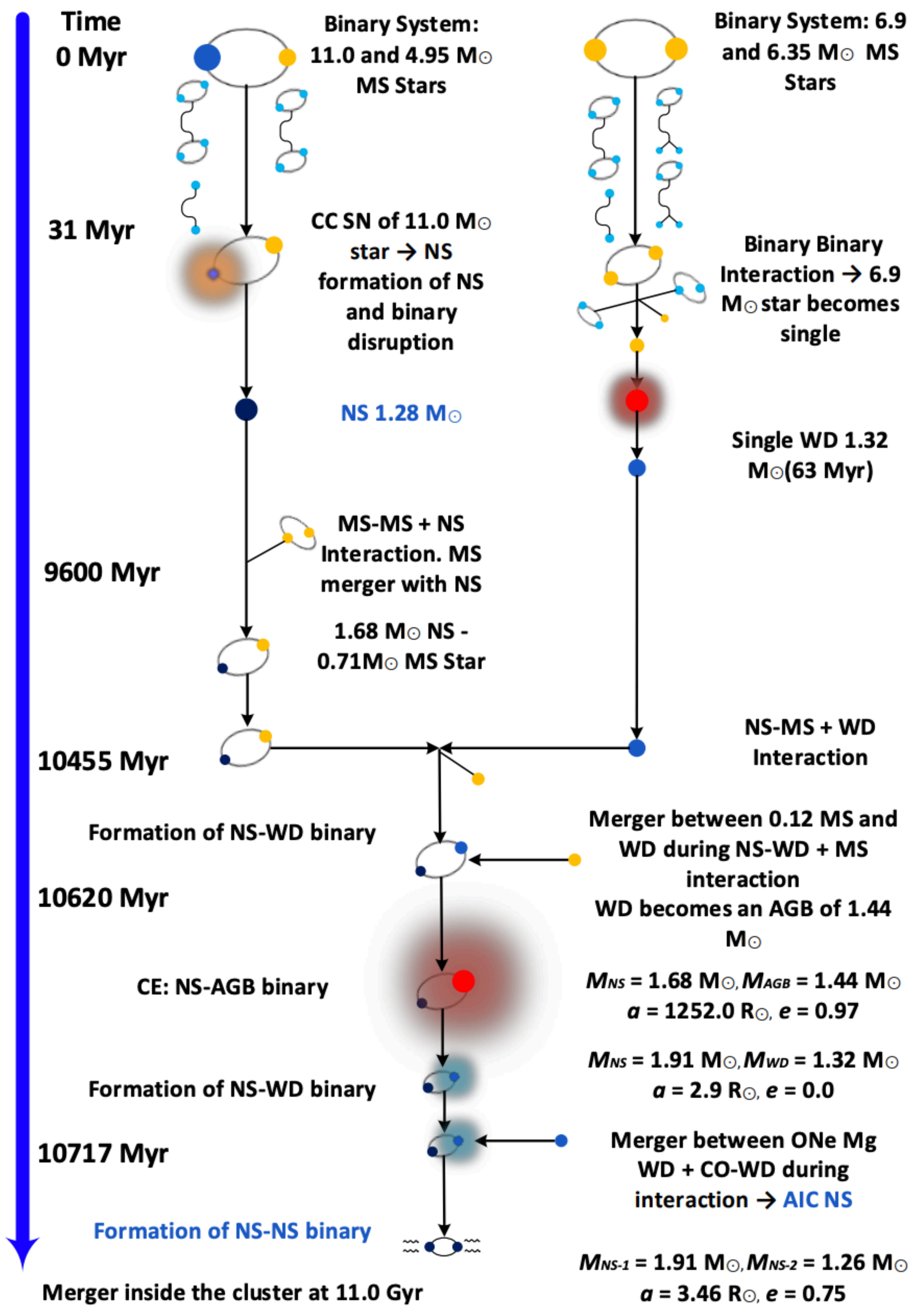




- B2127+11C in M15 (NGC 7078), core radius: 0.42 pc half-light radius: 3.02 pc
- J1807−2500 in NGC 6544: core radius 0.04 pc and 1.06 pc



Binary neutron star mergers from globular clusters



Time

0 Myr

Binary System: 11.0 and 4.95 $M_\odot$ MS Stars

Binary System: 6.9 and 6.35 $M_\odot$ MS Stars

31 Myr

CC SN of 11.0 $M_\odot$ star → NS formation of NS and binary disruption

Binary Binary Interaction → 6.9 $M_\odot$ star becomes single

NS 1.28 $M_\odot$

Single WD 1.32 $M_\odot$ (63 Myr)

9600 Myr

MS-MS + NS Interaction. MS merger with NS

1.68 $M_\odot$ NS - 0.71 $M_\odot$ MS Star

10455 Myr

NS-MS + WD Interaction

Formation of NS-WD binary

Merger between 0.12 MS and WD during NS-WD + MS interaction

WD becomes an AGB of 1.44 $M_\odot$

10620 Myr

CE: NS-AGB binary

$M_{NS} = 1.68\ M_\odot, M_{AGB} = 1.44\ M_\odot$
$a = 1252.0\ R_\odot,\ e = 0.97$

Formation of NS-WD binary

$M_{NS} = 1.91\ M_\odot, M_{WD} = 1.32\ M_\odot$
$a = 2.9\ R_\odot,\ e = 0.0$

10717 Myr

Merger between ONe Mg WD + CO-WD during interaction → AIC NS

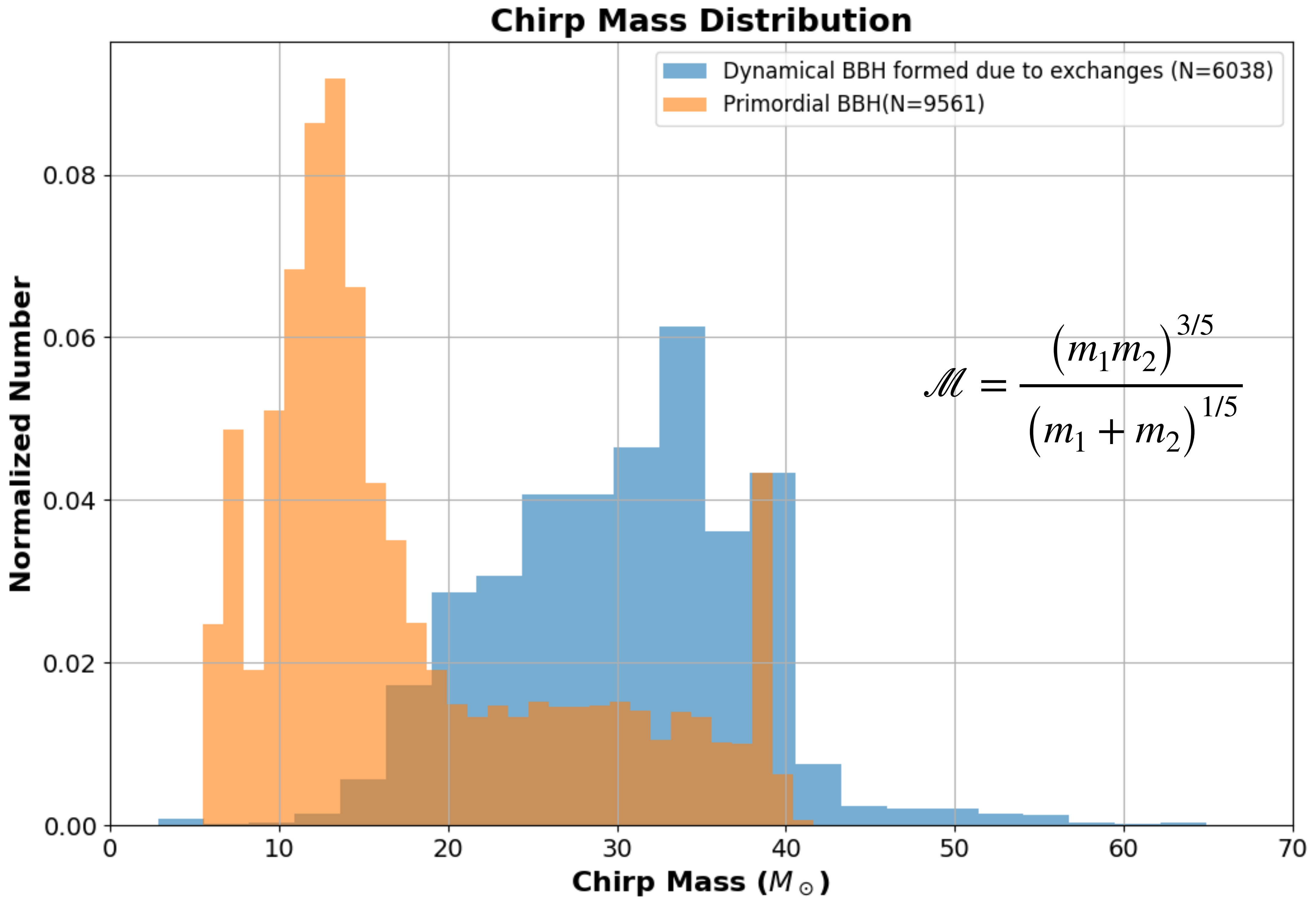
Formation of NS-NS binary

$M_{NS\text{-}1} = 1.91\ M_\odot, M_{NS\text{-}2} = 1.26\ M_\odot$
$a = 3.46\ R_\odot,\ e = 0.75$

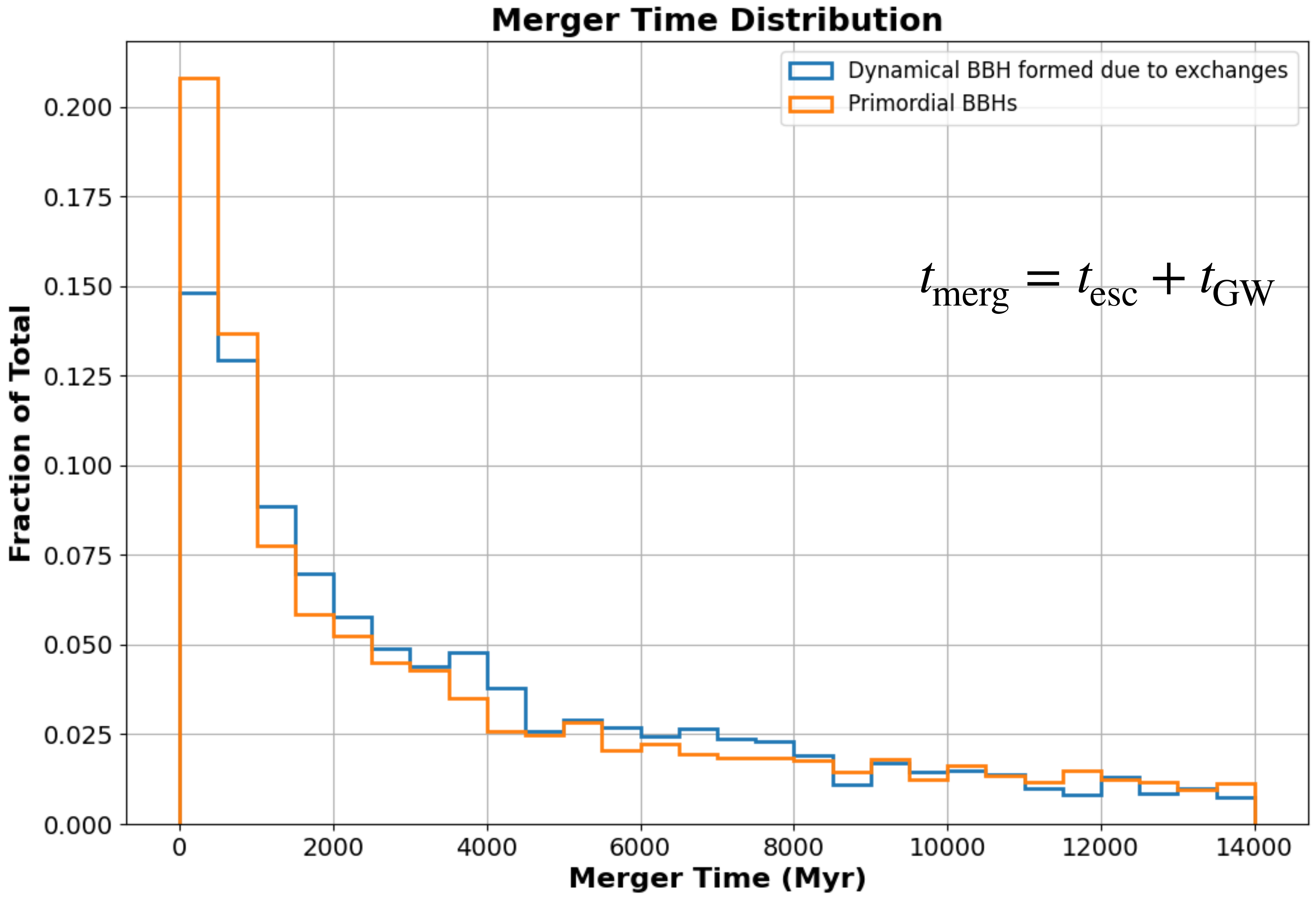
Merger inside the cluster at 11.0 Gyr

From Belczynski, Askar, Arca Sedda et al. 2018

Producing binary black holes in globular clusters



$$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

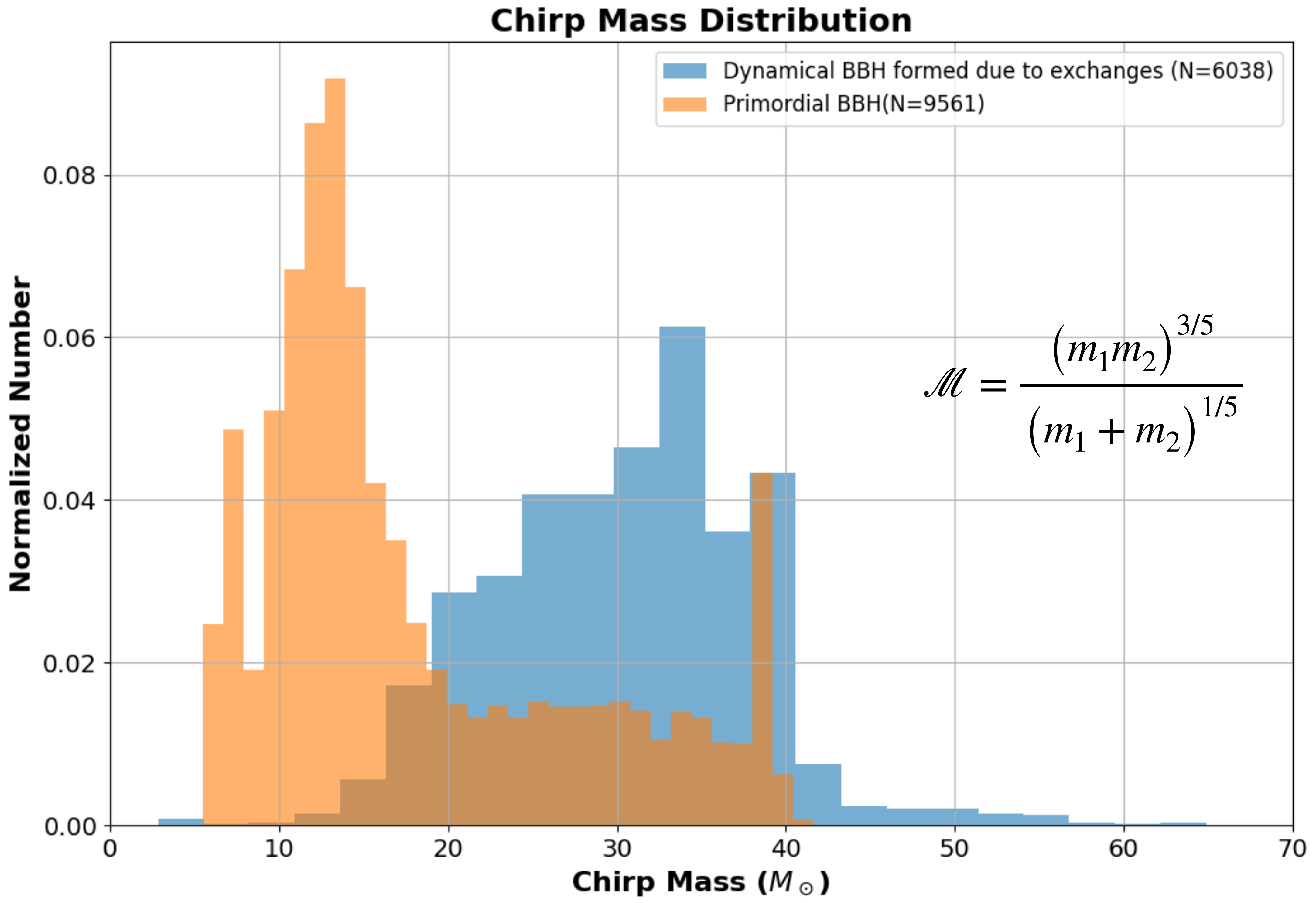


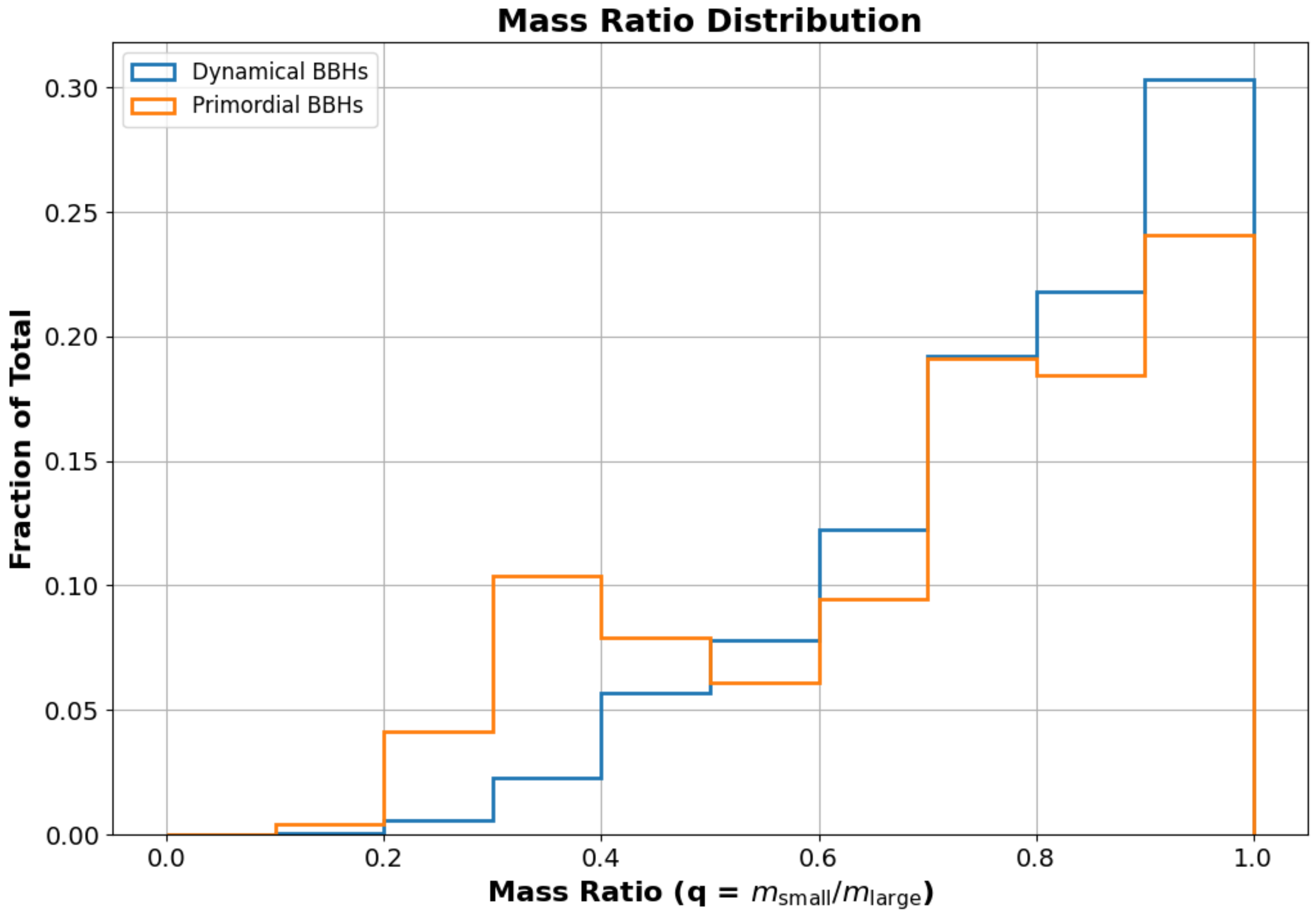
$$t_{\rm merg} = t_{\rm esc} + t_{\rm GW}$$

Consequence of using Sana et al. (2012) distribution for initial binary parameters

New MOCCA Models from 2024

Producing binary black holes in globular clusters





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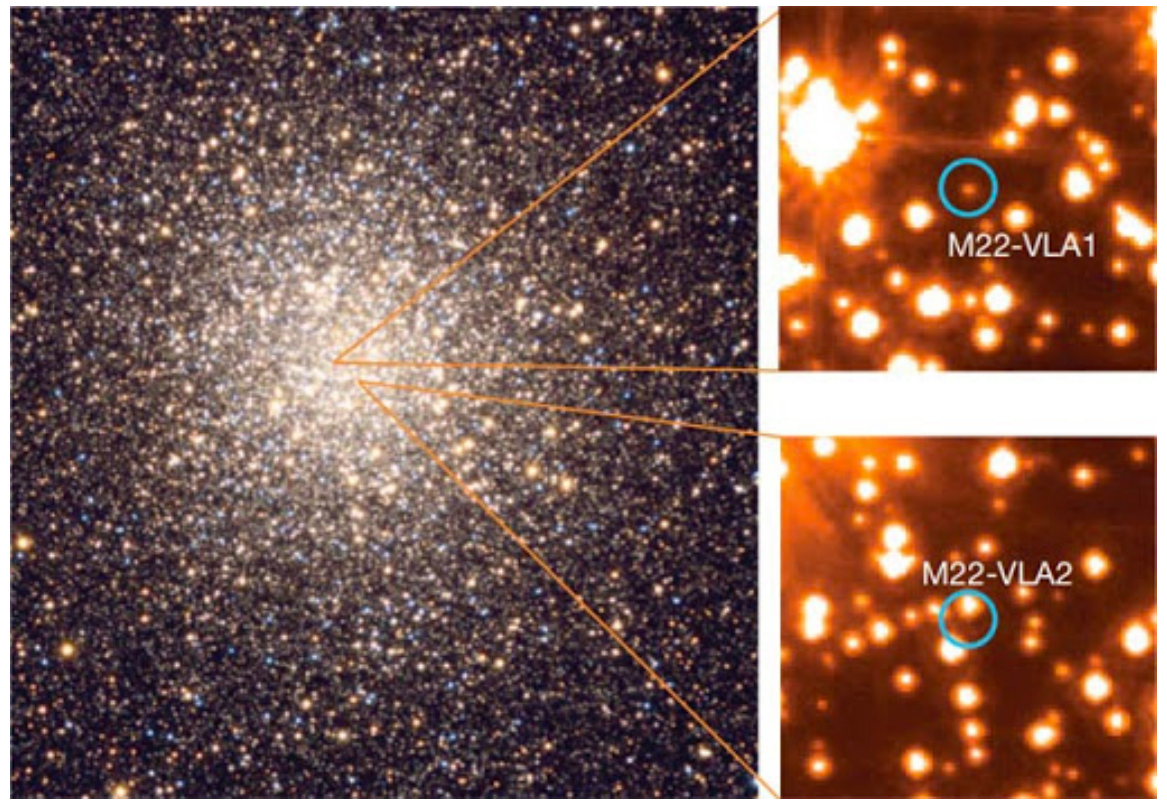
New MOCCA Models from 2024

Observations of stellar-mass black holes in globular clusters

Type of Black Holes (BHs)	Observational Method	Observations
Accreting BHs in Binary Systems	**X-ray/Radio Observations**	• 2 candidates in M22 (Strader et al. 2012) • 1 candidate in M62 (Chomiuk et al. 2013) • Ultracompact BH-WD binary in 47 Tuc (Bahramian et al. 2017) • BH-Red Straggler binary in M10 (Shishkovsky et al. 2018) • ULXs observed in a GC in the elliptical galaxy NGC 4472 (Maccarone et al. 2007)
Detached BHs in Binaries with a Luminous Companion	**Radial Velocity Measurement**	• 3 detected using MUSE in NGC 3201 (Giesers et al. 2018; 2019) $M \sin i = 7.68 \pm 0.50\ \mathrm{M}_\odot,\ 4.40 \pm 2.8\ \mathrm{M}_\odot$ and $4.531 \pm 0.21\ \mathrm{M}_\odot$



2 BH candidates in M22 (Strader et al. 2012)

NGC 3201