Dynamical Formation of Compact Object Binaries

Image Credits: *HST (spacetelescope.org)* & LIGO *(ligo.caltech.edu)*

Abbas Askar

POLONEZ and Marie Skłodowska-Curie Fellow

Nicolaus Copernicus Astronomical Center

Warsaw, Poland

askar@camk.edu.pl

POLONEZ BIS

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/

Quick Recap: Gravitational wave mergers of compact object binaries by LVK

- 83 merging binary black holes detected by LIGO-Virgo-KAGRA (LVK) since 2015 up to O3b
  - Observed merger rate: $17.9 – 44\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (GWTC-3; Abbott et al. 2021; 2023)
- 2 merging binary neutron stars
  - Observed merger rate: $10 – 1700\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- ~ 6 black hole-neutron stars
  - Observed merger rate: $7.8 – 140\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Key Question:

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

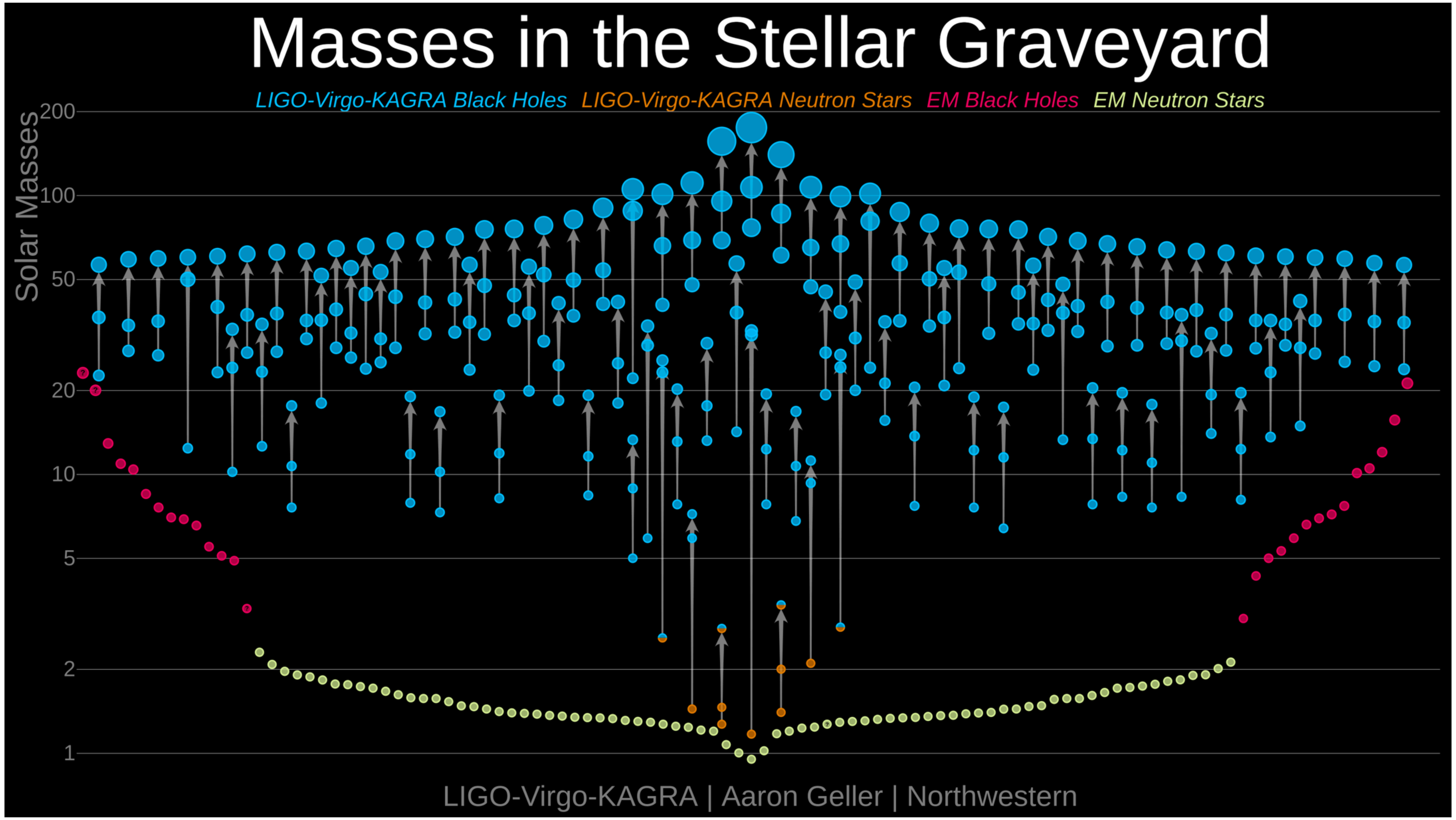

Image Credit: Visualization: LIGO-Virgo-KAGRA / Aaron Geller / Northwestern Geller

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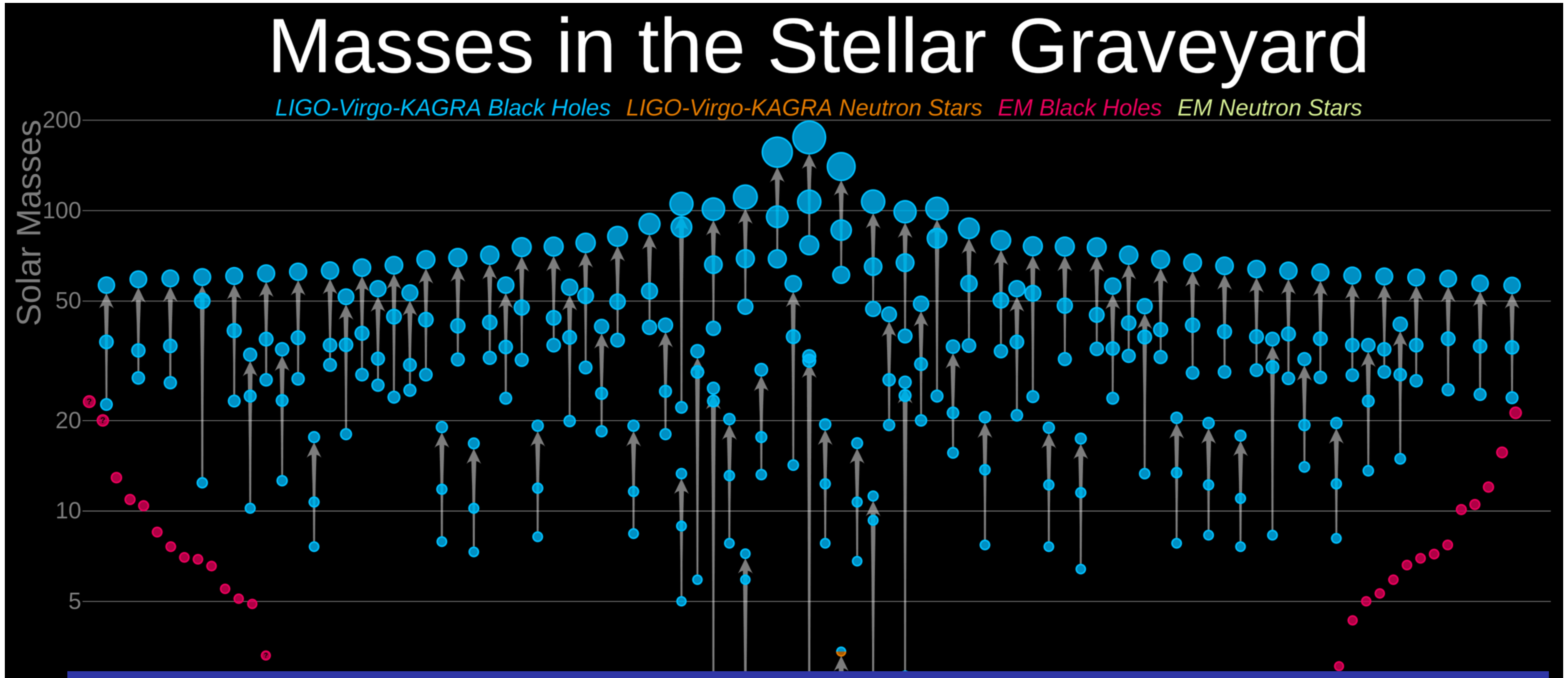

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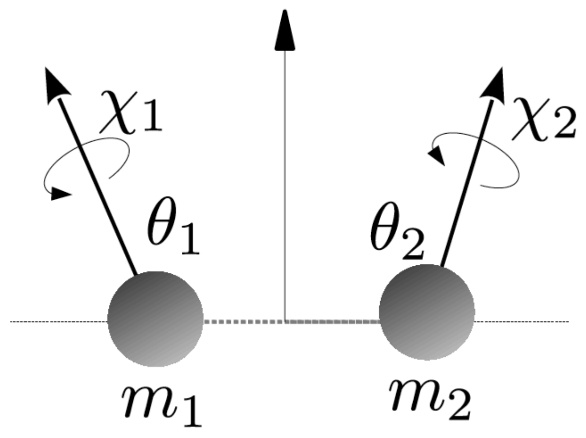
Main Observables:
- Chirp and component masses
- Effective spin (χ_{eff}): spins and their orientations
- Eccentricity: degenerate with spin-induced precession
- Merger rates
- Distance and localization



Proposed evolutionary pathways to merging binary black holes

Scheme adapted from Alessandro Trani, adapted from Maya Fishbach, adapted from Mike Zevin, adapted from Selma de Mink

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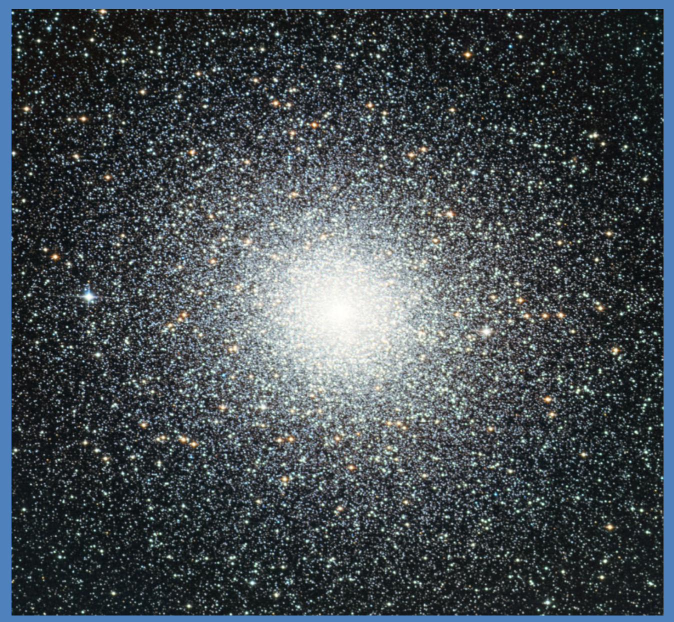
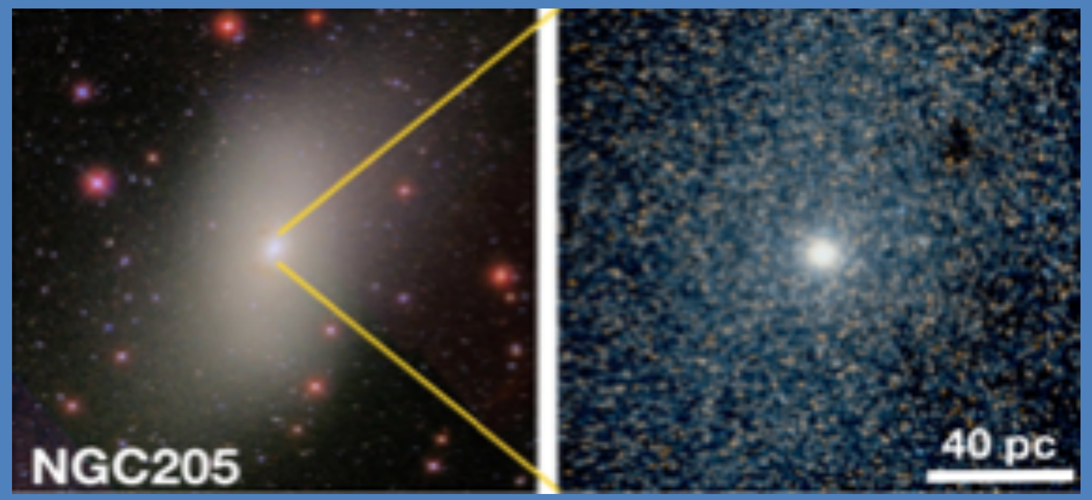
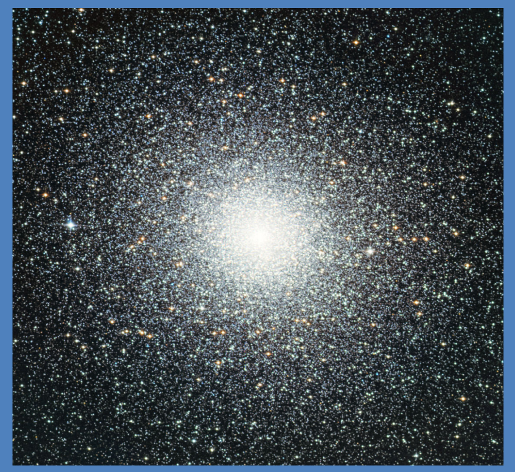
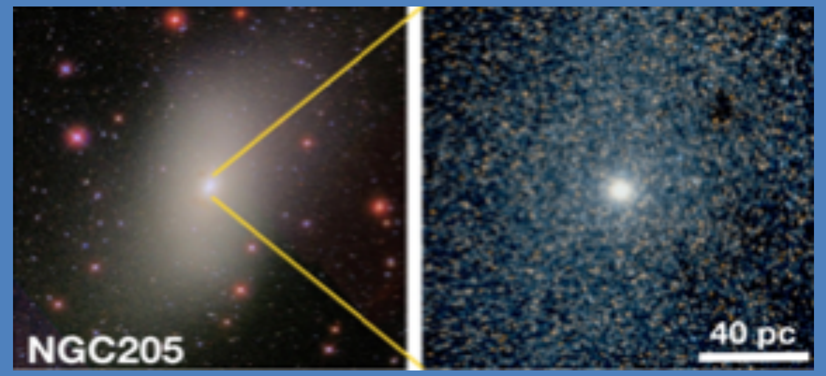
Star clusters and formation of binary black holes

	Open Clusters & Young Massive Clusters		Globular Clusters	Nuclear Star Clusters
				
Mass	$100 - \lesssim 10^4\ M_\odot$	$10^4 - 10^5\ M_\odot$	$10^4 - 10^6\ M_\odot$	$10^5 - 10^8\ M_\odot$
Radius	~ 1 – few pc	$\sim 1 - 10$ pc	$\sim 10 - 30$ pc	$\sim 1 - 10$ pc
Central Density	$\lesssim 10^3\ M_\odot\ pc^{-3}$	$\gtrsim 10^3\ M_\odot\ pc^{-3}$	$\gtrsim 10^4 - 10^5\ M_\odot\ pc^{-3}$	$10^5 - 10^7\ M_\odot\ pc^{-3}$
Ages	~ 1 Myr to few Gyr	a few to $\lesssim 100$ Myr	$\gtrsim 8 - 13$ Gyr	Age Spread
Local Merger Rates for Binary Black Holes	$\sim 50 - 100\ Gpc^{-3}\ yr^{-1}$		$\sim 5 - 25\ Gpc^{-3}\ yr^{-1}$	$\sim 1 - 10\ Gpc^{-3}\ yr^{-1}$

Star clusters and formation of binary black holes





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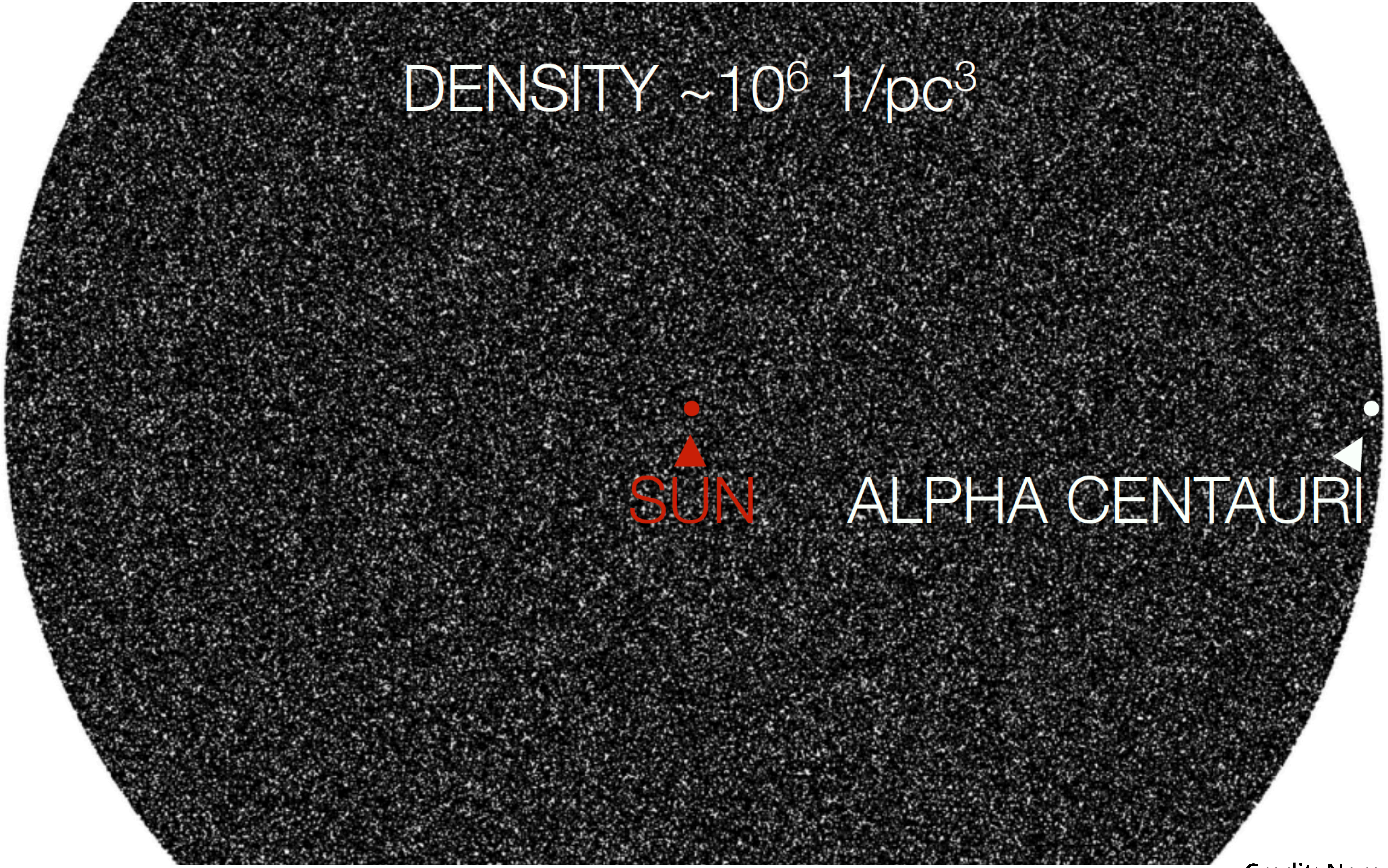
Useful Papers	Portegies Zwart & McMillan (2002), Banerjee et al. (2010), Mapelli et al. (2013), Ziosi et al. (2014), Goswami et al. (2014), Banerjee (2017; 2018; 2020; 2021), Fuji et al. (2017), Di Carlo et al. (2019; 2020;2021), Rastello et al. (2019; 2020; 2021), Kumamoto et al. (2019; 2020; 2021), Mapelli et al. (2020; 2021; 2022), Kremer et al. (2020), Martinez et al. (2020), Santoliquido et al. (2020), González et al. (2021), Rizzuto et al. (2021; 2022), Dall'Amico (2021), Fragione & Banerjee (2021); Bouffanais (2019), Britt et al. (2021), Trani et al. (2021; 2022)		Portegies Zwart & McMillan (2000), Miller & Hamilton (2002), M. Benacquista (2002), O'Leary et al. (2006; 2007), Sadowski et al. (2008), Moody & Sigurdsson (2009), Downing et al. (2010; 2011), Morscher et al. (2013), Bae et al. (2014), Rodriguez et al. (2016; 2017; 2018; 2019; 2020, 2021), Askar et al. (2017), Park et al. (2017), Chatterjee et al. (2017), Zevin et al. (2017; 2019), Samsing et al. (2017; 2018; 2019; 2020), Hong et al. (2018), Fragione & Kocsis (2018), Choksi et al. (2019), Arca Sedda et al. (2020), Antonini & Gieles (2020), Kremer et al. (2020), Samsing & Hotokezaka (2020); Mapelli et al. (2020; 2021; 2022)	Miller & Lauburg (2009), O'Leary et al. (2009), Miller & Davies (2012), McKernan (2012), Antonini et al. (2014;2016;2019), Antonini & Rasio (2016), Stone et al. (2017) Bartos et al (2017), Rodriguez & Antonini (2018), Arca Sedda et al. (2018;2020) Fragione et al. (2019), Hoang et al. (2018; 2019), Leigh et al. (2018), Arca-Sedda & Gualandris (2018), Yang et al. (2019), Rasskazov et al. (2019), Gerosa & Berti (2019), Arca Sedda (2020), Fragione & Silk (2020), Mapelli et al. (2022), Palmese & Conselice (2021), Fragione et al. (2022)

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

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

$r_c \sim 0.6$ pc $\qquad r_{hl} \sim 4$ pc

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

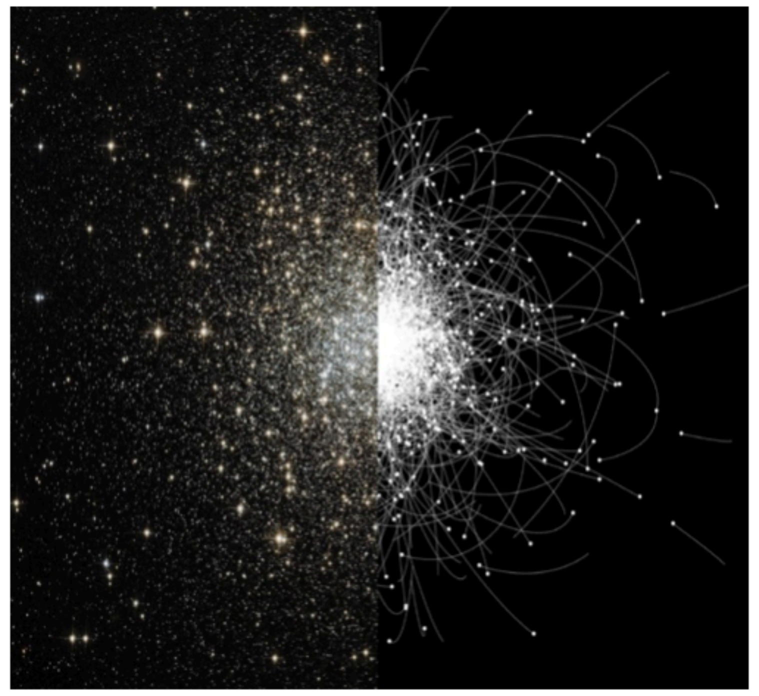
Age $\sim 12 - 13$ Gyr

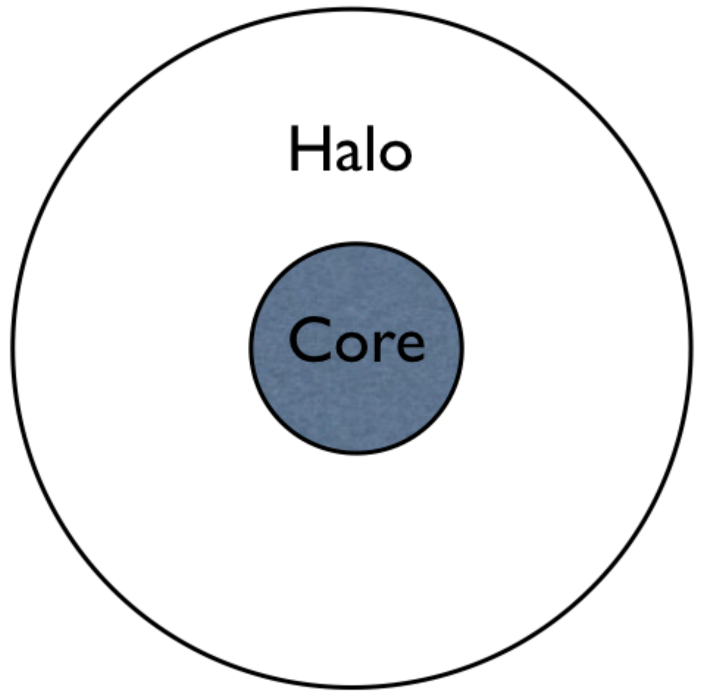
$[\mathrm{Fe/H}] \sim -0.78$

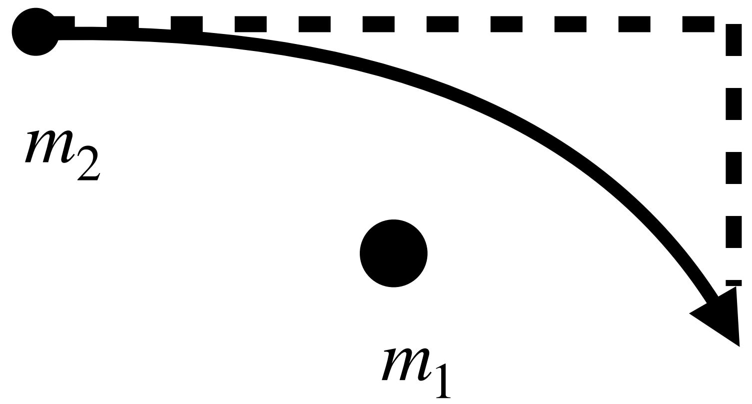
From the core of 47 Tuc

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

Dynamical evolution of star clusters: key points of stellar dynamics







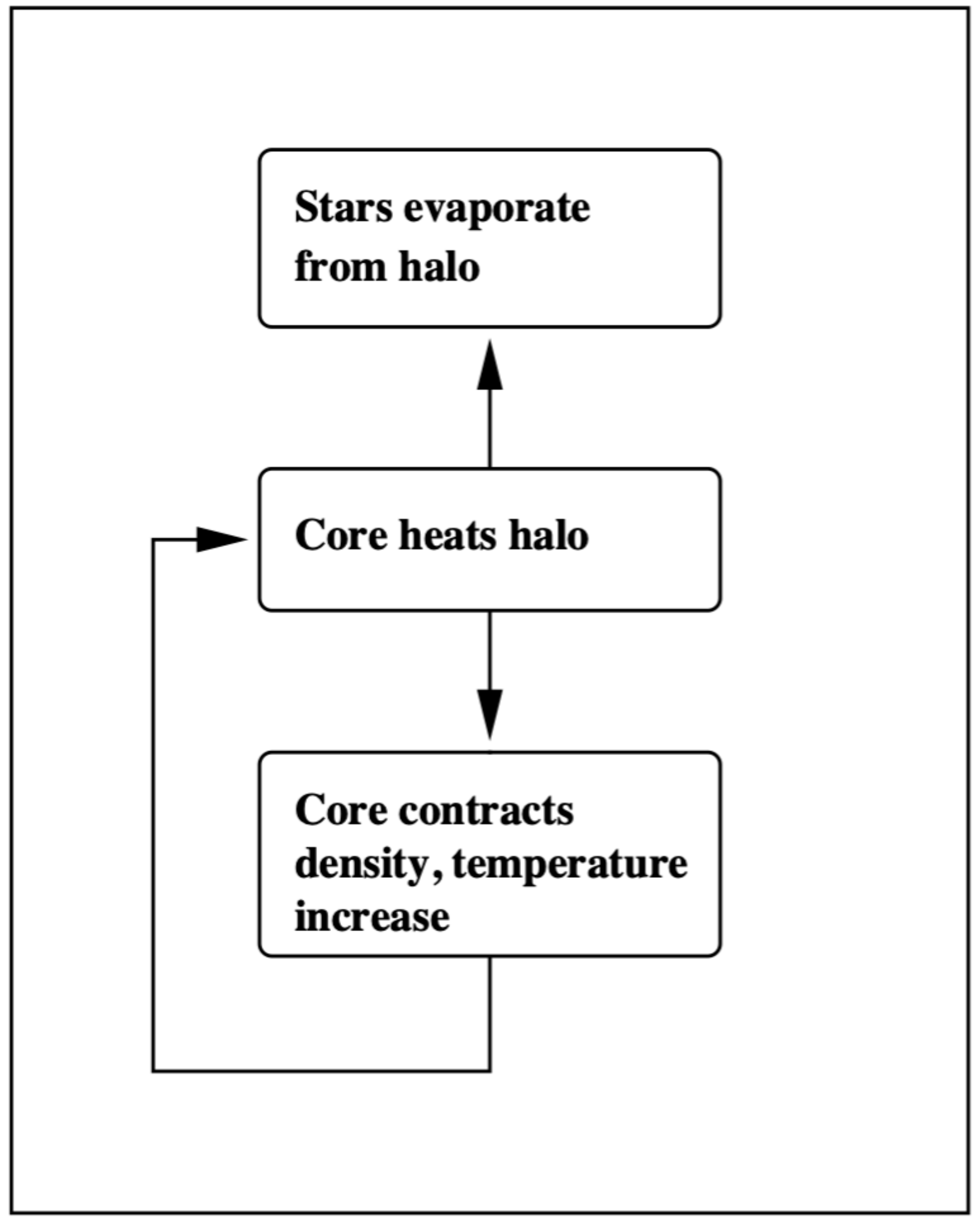
- System of many stars whose mutual gravity shapes their orbits and collective evolution

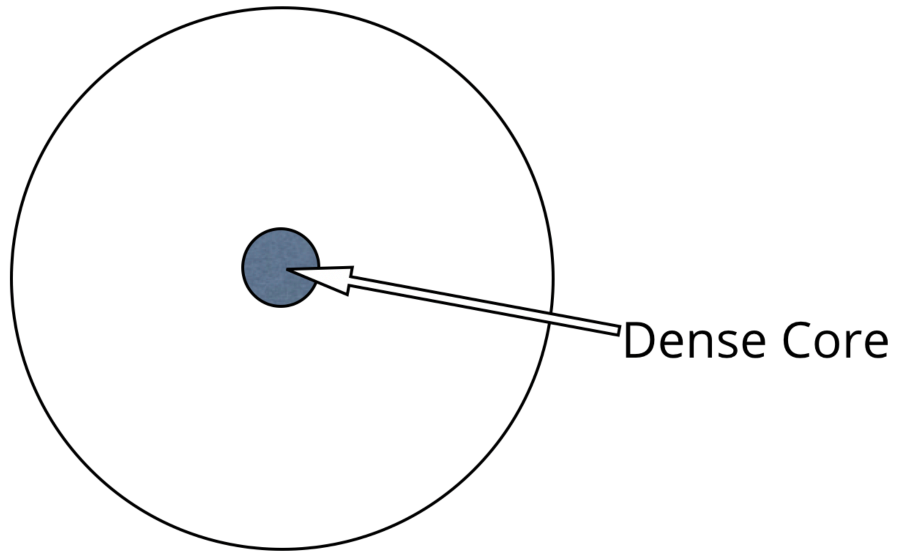
- **Scattering between stars transports energy within a star cluster (*two-body relaxation*):**
  - *Collisional systems* - Dynamical evolution driven by distant star-star interactions

$$t_{rel} \sim 15\ \text{Myr} \left(\frac{M_{\text{TOT}}}{10^4\ M_\odot}\right)^{1/2} \left(\frac{R}{1\text{pc}}\right)^{3/2} \left(\frac{1M_\odot}{m}\right)$$

$t_{rel} \sim 100$ Myr to few Gyr

$t_{rel} <$ Cluster age



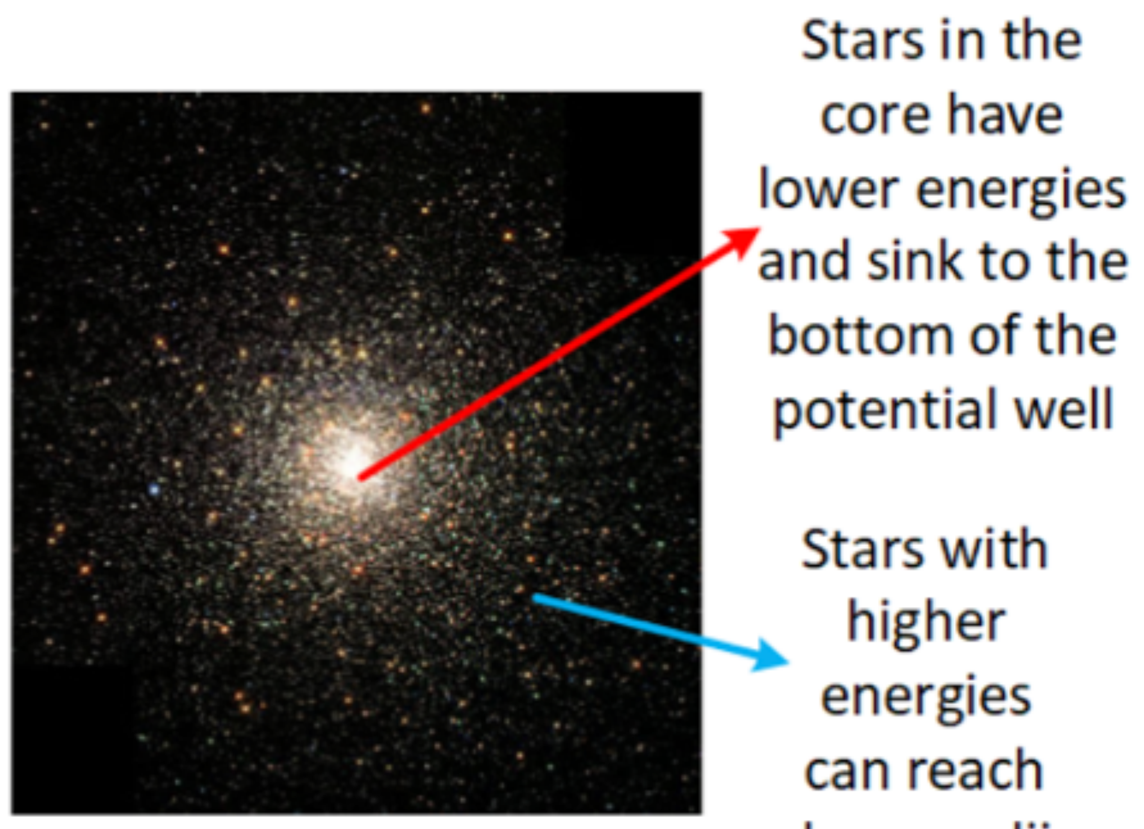


  - Variety of dynamical states are present

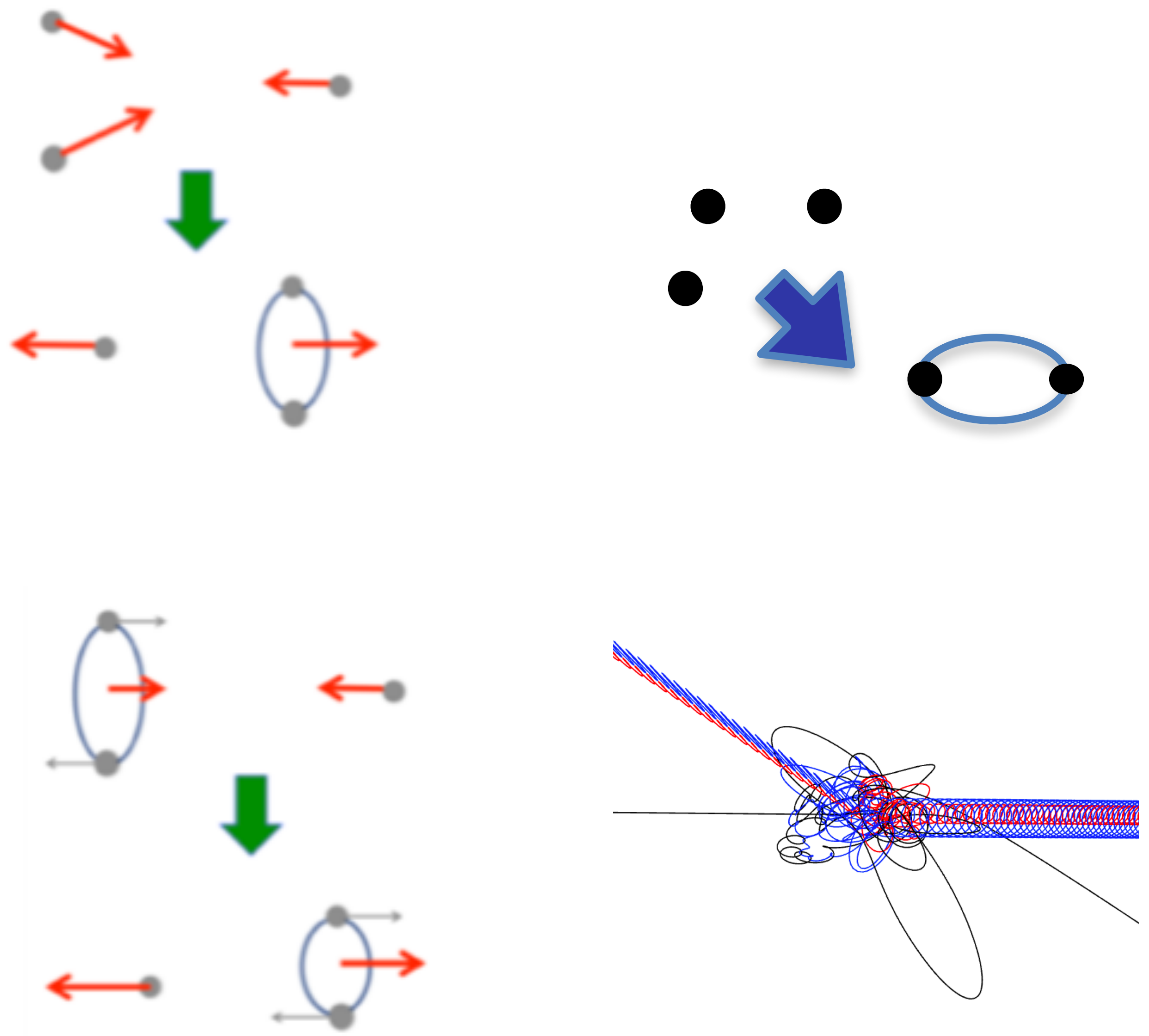
- **Self-gravitating systems have a *negative* heat capacity**

Consequences of dynamical evolution of star clusters

- **Evaporation:** Exchange of energy between stars can lead to stars becoming unbound
- **Mass Segregation:** Two-body relaxation tries to equalise kinetic energy of stars → massive stars sink to the cluster center
- **Core Collapse:** Energy loss via two-body scattering from cluster core leads to core collapse.
- **Binary Heating/Burning:** Heating via binary-single encounters can prevent or delay core collapse.
  - Interactions will process via encounters which can change membership and binary properties
  - If binary components are close enough they will spiral together and merge before they can heat the cluster.

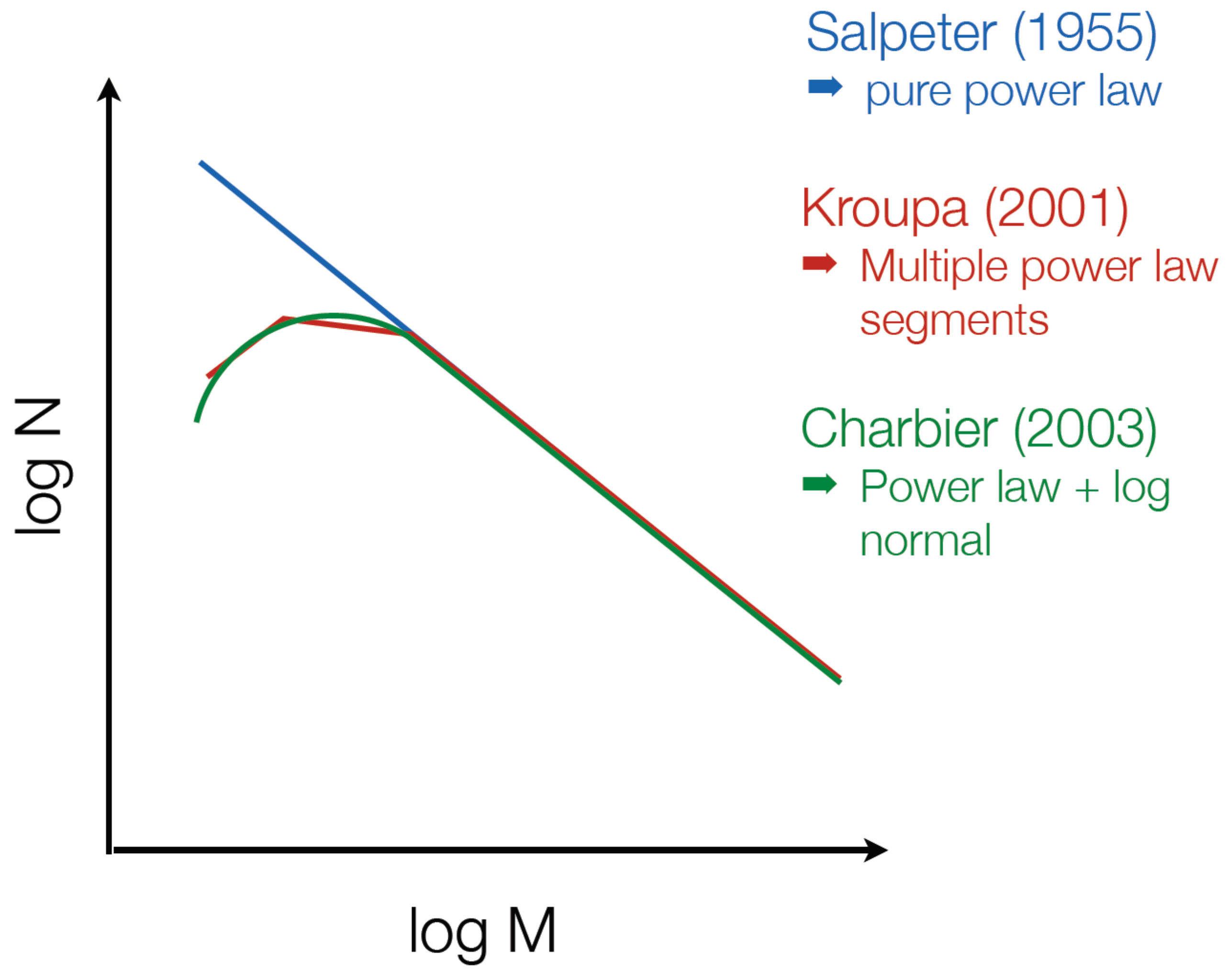


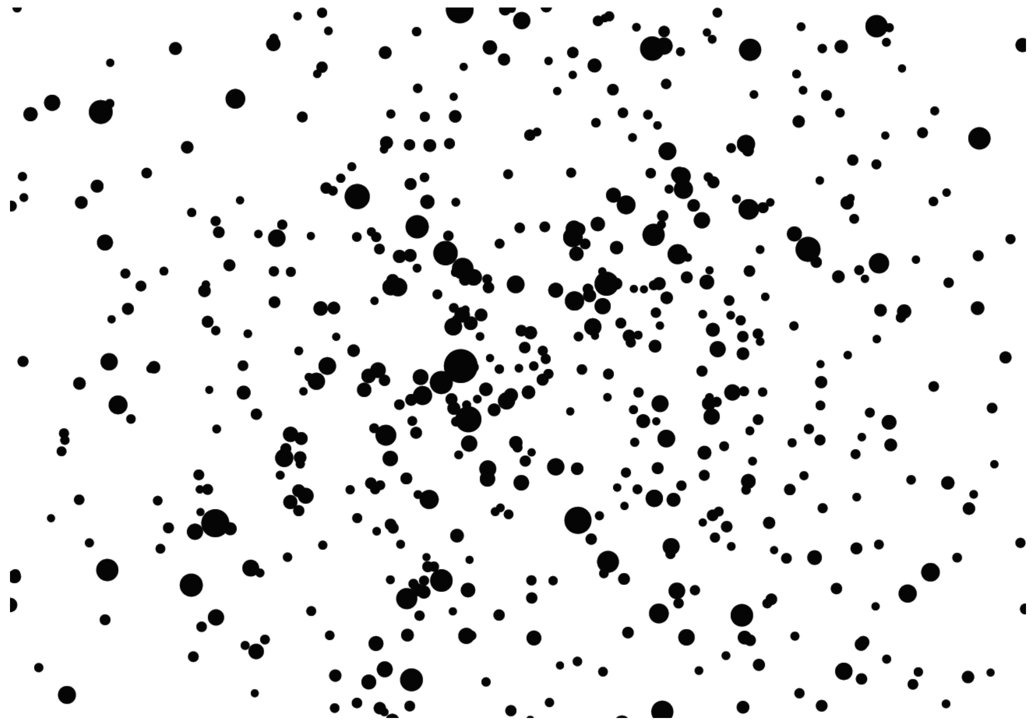
Credit: G. Djorgovski



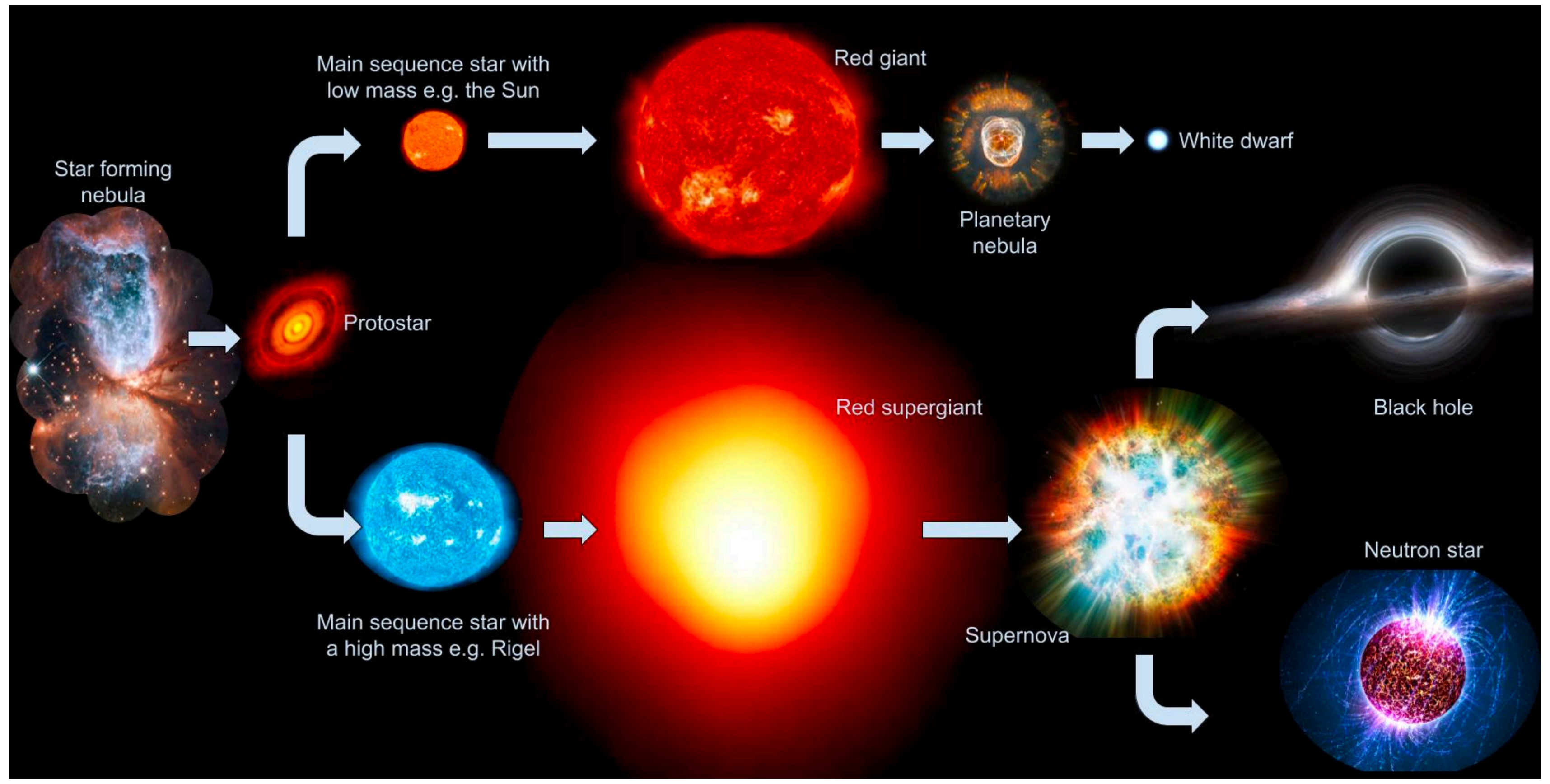
Simulating a realistic star cluster

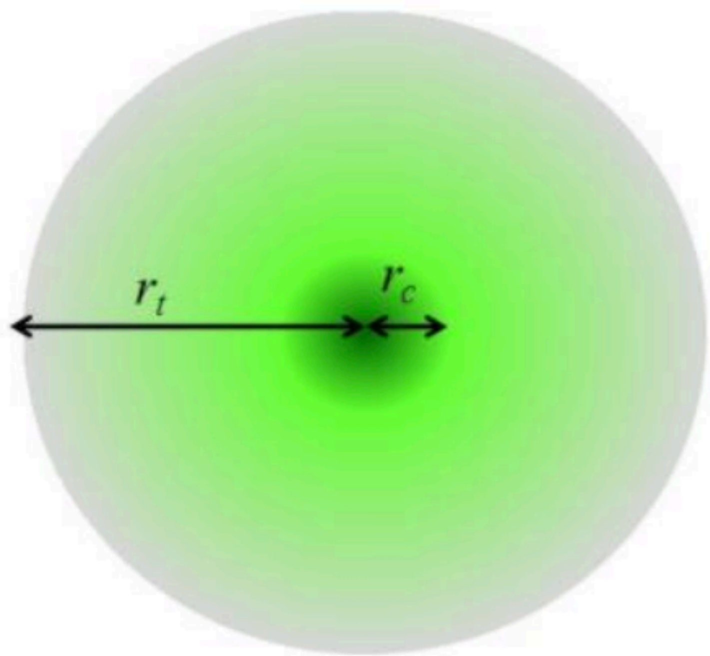
- Initial Model Ingredients:
  - Initial Distribution of Masses (Initial Mass Function)
    - Derived from observing young stellar clusters
  - Initial binary fraction?
    - Initial binaries can influence evolution of the stellar cluster
  - Position & Velocity Distribution
    - Equilibrium models (King 1962; 1966, Plummer 1915)





- Treatment of physical processes:
  - **Gravitational Dynamics**
  - **Stellar/Binary Evolution**
  - **Treatment of galactic field**
- Challenges:
  - ***Staggering discrepancies in length and time scales***
  - ***Multidisciplinary***

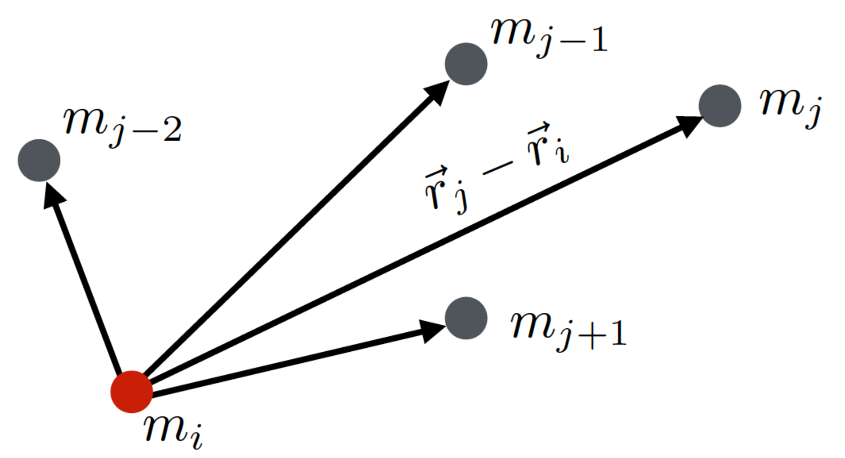




Star cluster evolution with numerical simulation codes

- **Direct summation *N*-body approach; "brute force"**
  - NBODYX series of codes: https://people.ast.cam.ac.uk/~sverre/web/pages/nbody.htm (Aarseth 2003) $T_{\mathrm{CPU}} \rightarrow \mathrm{O}\left(N^2\right)$
  - NBODY6++GPU (Wang, Spurzem et al. 2015; 2016): https://github.com/nbody6ppgpu
  - Hybrid codes (combine techniques from collisionless N-body codes): PeTar (Wang et al 2020): https://github.com/lwang-astro/PeTar

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

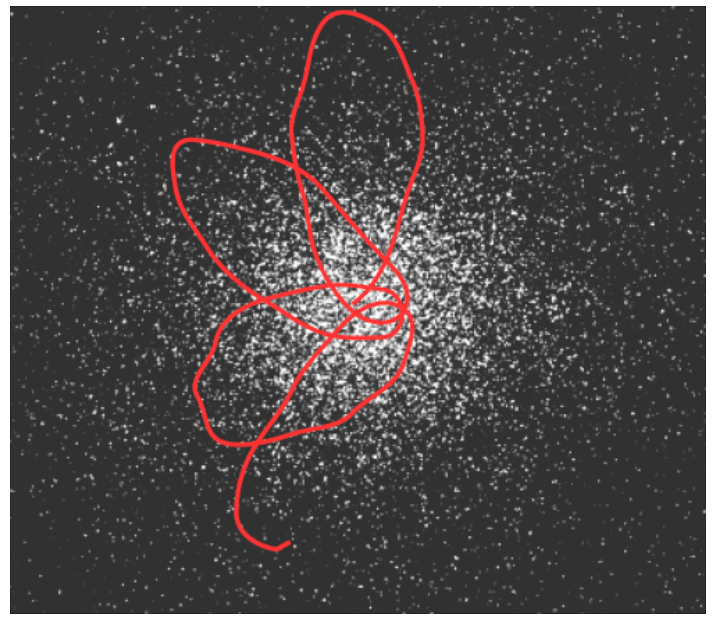


Sverre Aarseth
(1934 to 2024; passed away on 28/12/2024)

- **Monte Carlo method**
  - **CMC (Joshi et al 2000 → Rodriguez et al. 2022)** https://clustermontecarlo.github.io/CMC-COSMIC/
  - **MOCCA (Giersz 1998 → Hypki & Giersz 2013)** http://www.moccacode.net/

CMC Cluster Monte Carlo

MOCCA



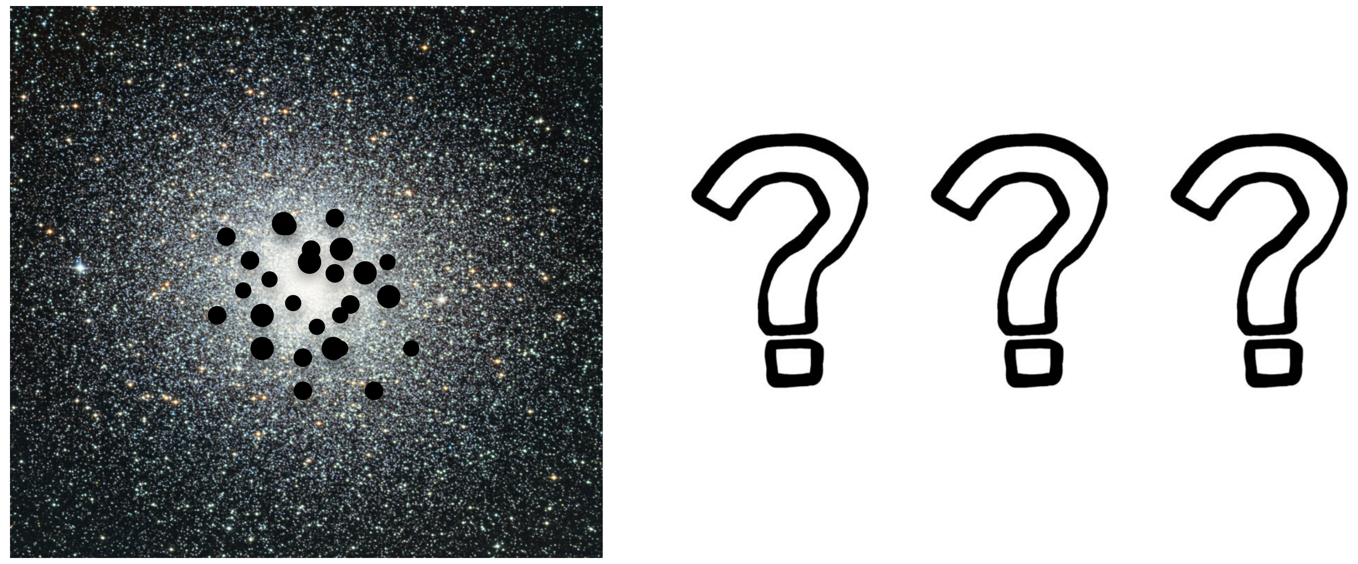
$T_{\mathrm{CPU}}/t_{\mathrm{rlx}} \propto N \ln N$

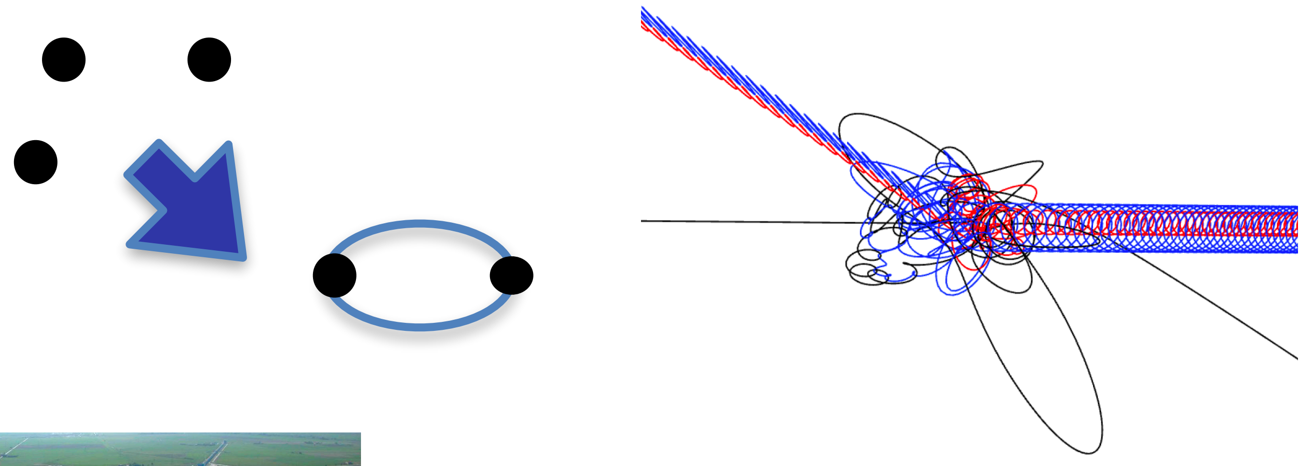
Michel Hénon
(!931-2013)

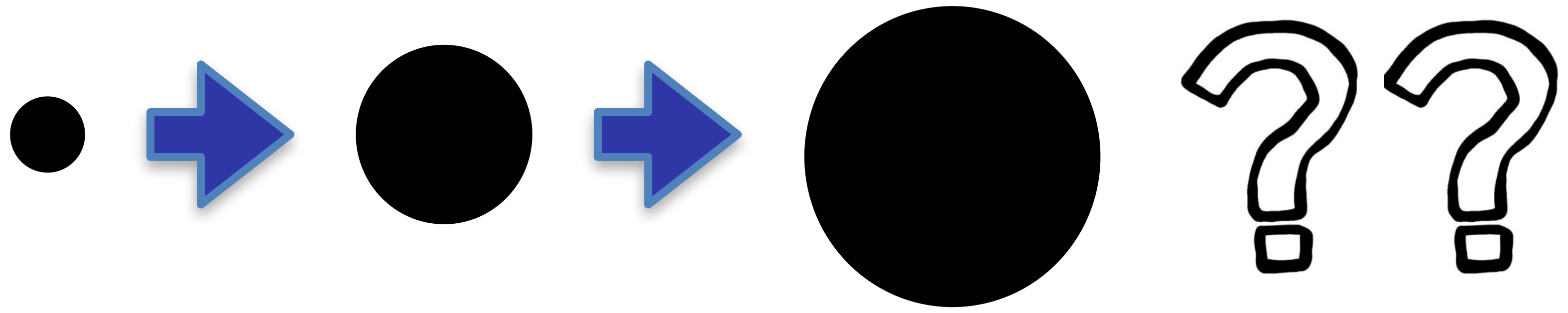
- **GW oriented semi-analytic/population synthesis codes:** clusterBH/BHBdynamics (Antonini & Gieles 2022), FASTCLUSTER (Mapelli et al. 2021; 2022), B-POP (Arca Sedda et al. 2023), RAPSTER (Kritos et al. 2024)

Key questions regarding binary black hole formation in star clusters

- 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?

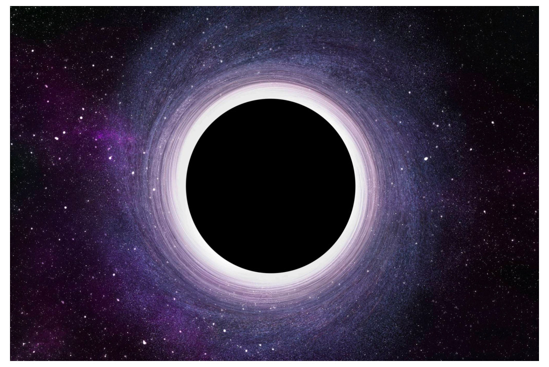






Black hole formation & retention in star clusters: natal kicks

$M_{ZAMS} \gtrsim 20 M_\odot$



- Evolution Time: 4 - 30 Myrs
- ~ 2.2 black holes for every 1000 stars (typical IMF)

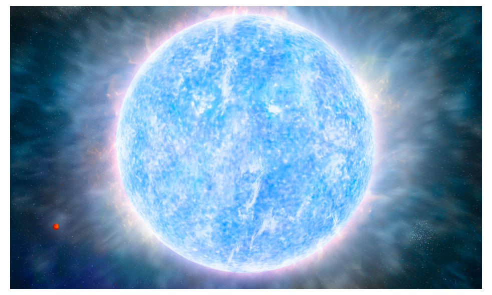
$\alpha = 2.3$

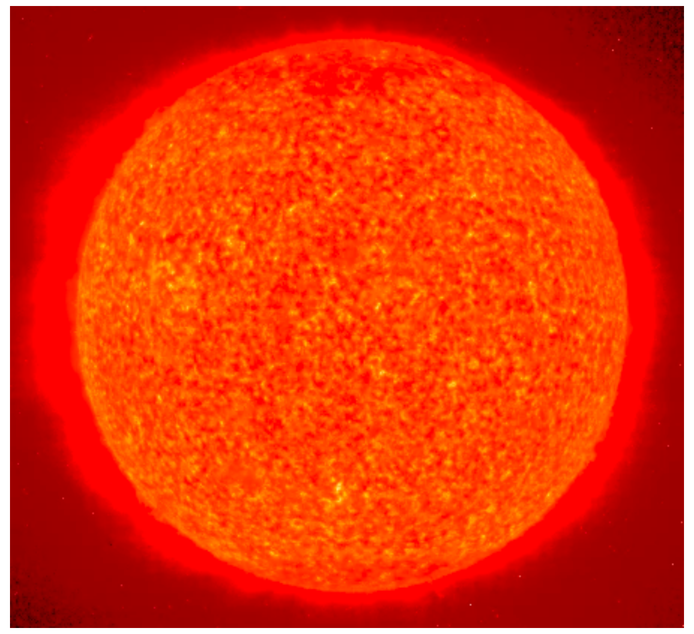
Black Hole (BH) Retention In Star Cluster (SC)

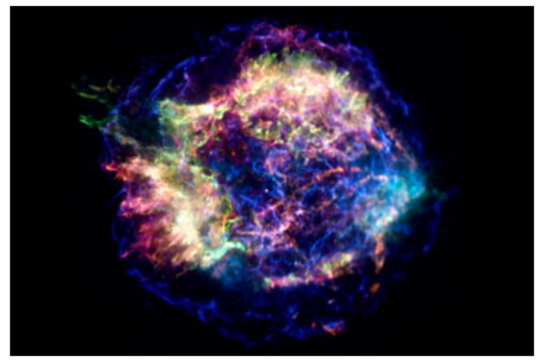
BH Natal Kicks

Escape Velocity of SC

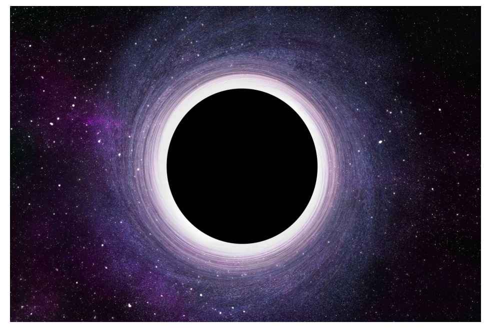
Uncertain!







Mass Fallback/
Direct Collapse



Black hole formation & retention in star clusters: natal kicks

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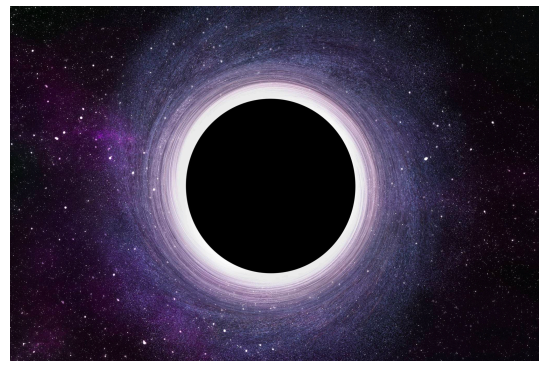

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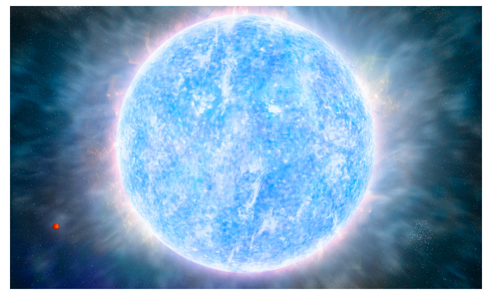
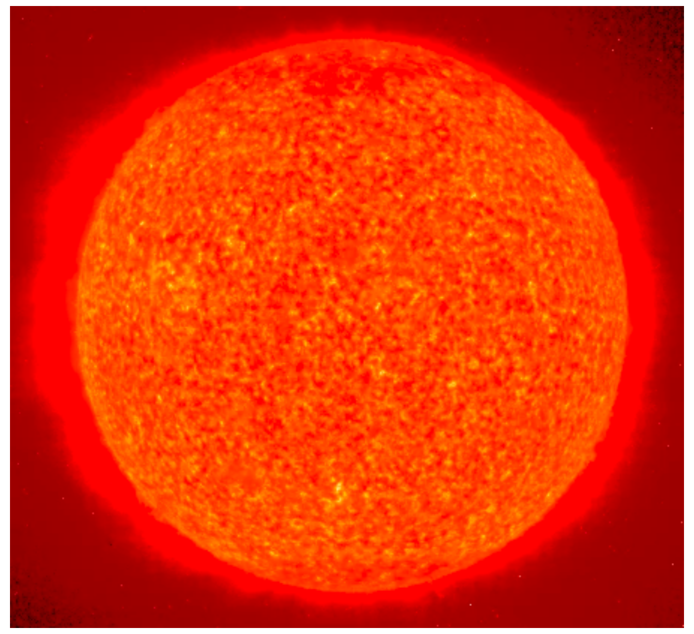
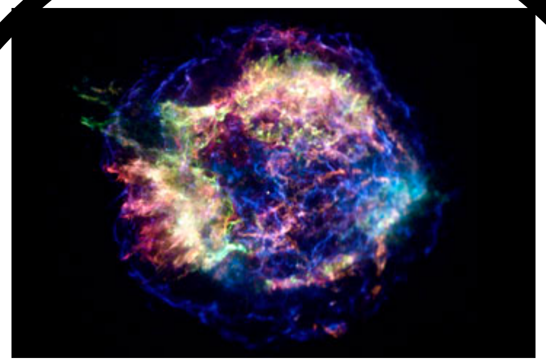
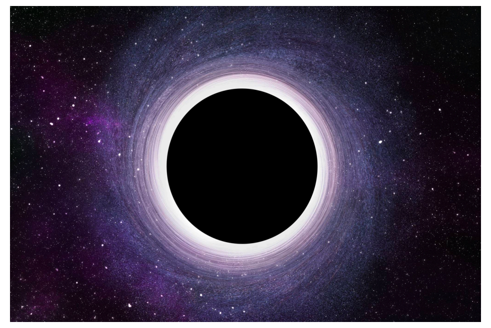




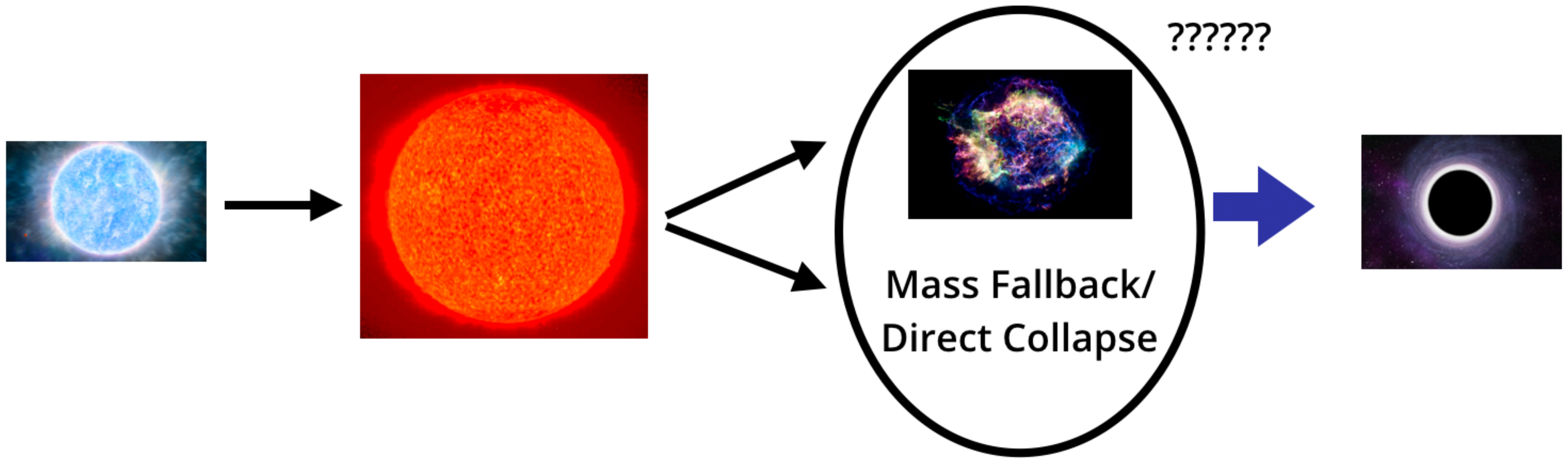


??????

Mass Fallback/ Direct Collapse



Black hole formation & retention in star clusters: natal kicks



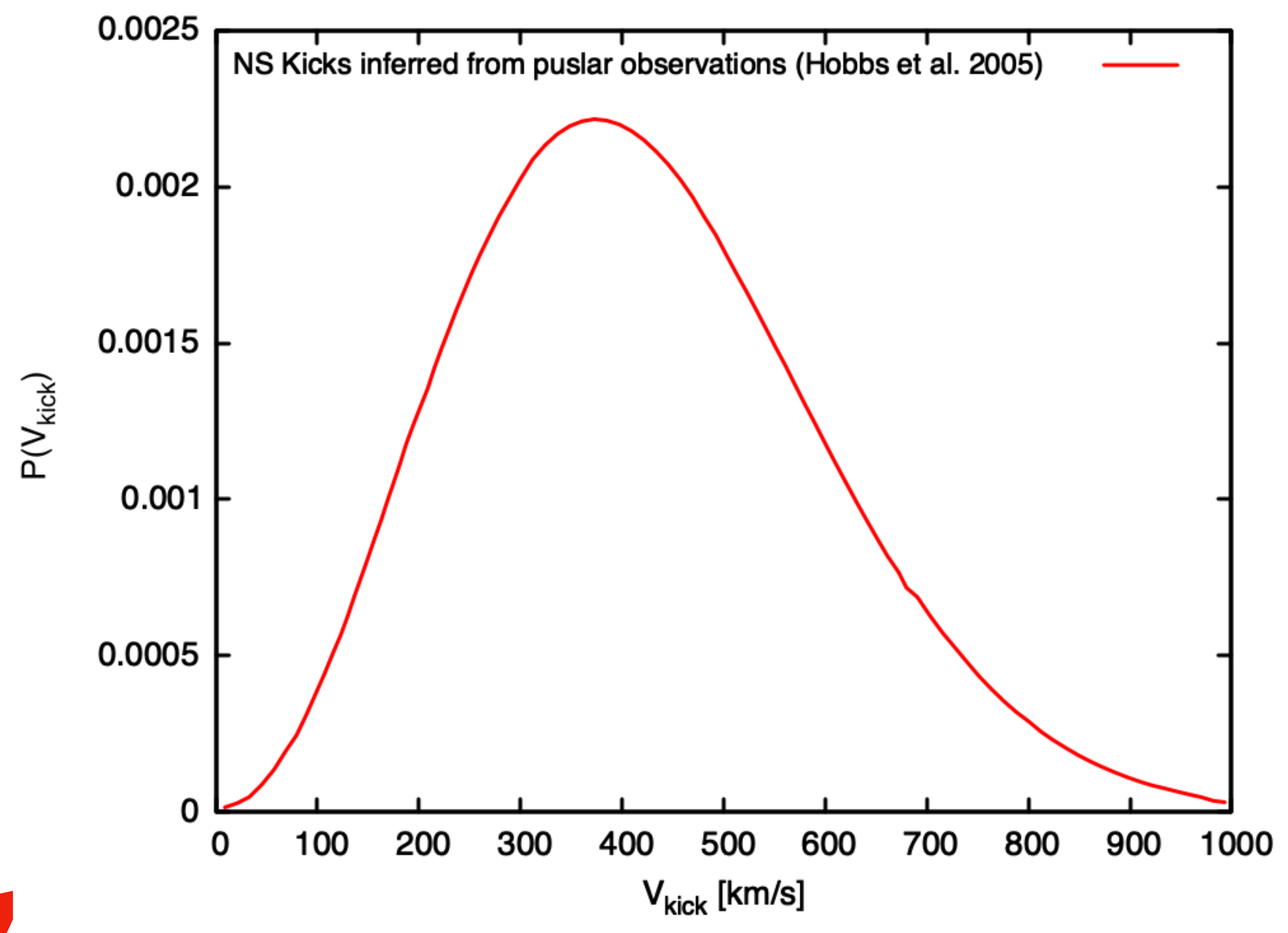
- **Core-collapse supernova (SN)** → asymmetric mass ejection and/or neutrino emission → Natal kicks as high as for neutron stars? → 200 – 500 km/s up to 1000 km/s
  (Repetto et al. 2012; Janka 2013, 2017, Observations: Mirabel et al. 2002, Hobbs et al. 2005)

- **Mass Fallback (Failed SN)/Direct Collapse** → Low natal kicks/no kicks? (Fryer 1999, Heger et al. 2002, Belczynski et al. 2002, 2010, Fryer et al. 2012, Mandel 2016, Amaro-Seoane & Chen 2015 **Observations**: Reynolds et al. 2015, Adams et al. 2016, Allan et al. 2020; Andrews & Kalogera 2022)

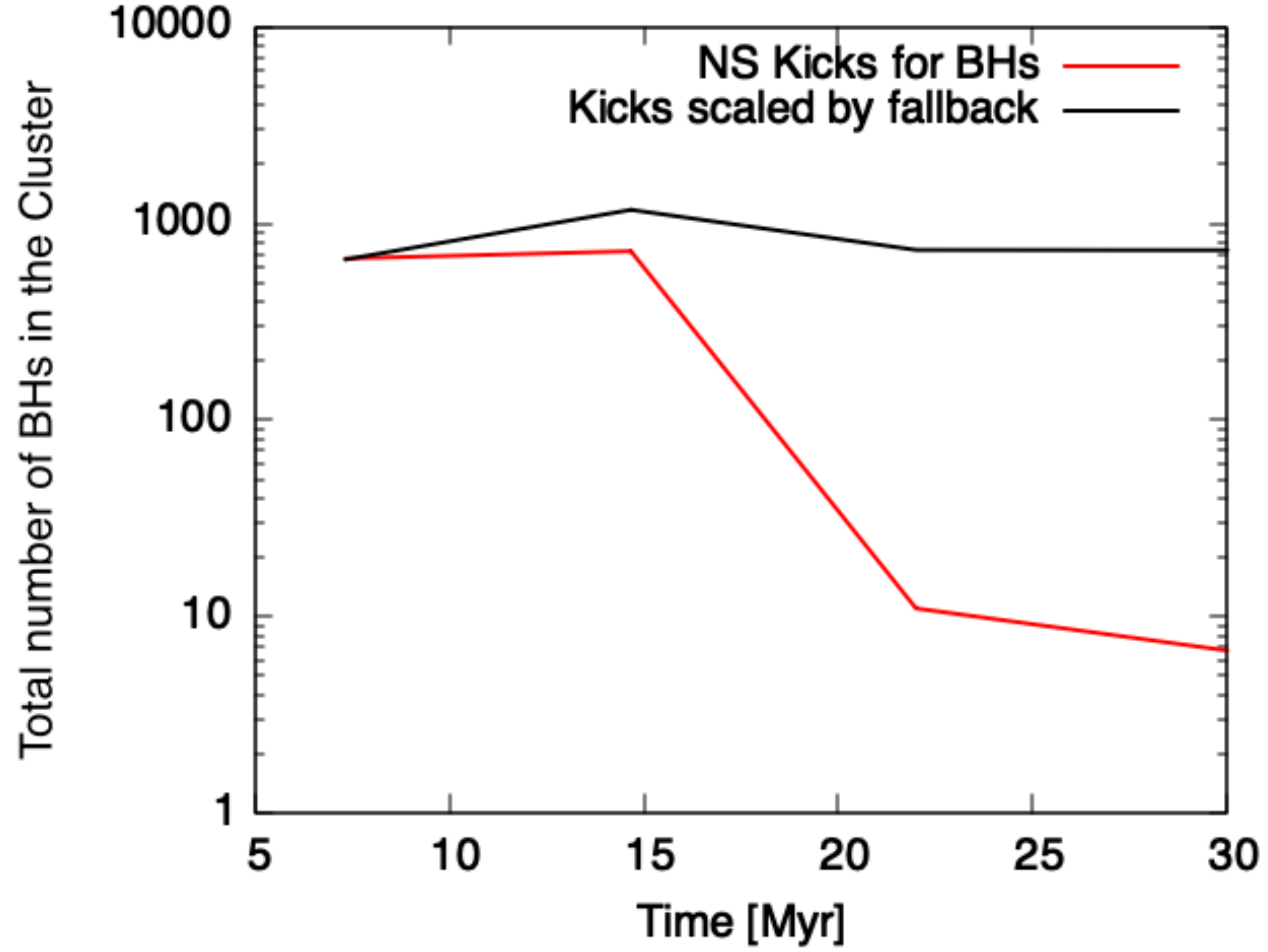
- **Momentum conservation and/or Fallback** → kicks scaled down linearly with black hole mass → Final black hole mass depends on the **mass of its progenitor, metallicity, winds, supernova model** (Belczynski et al. 2016, Spera & Mapelli 2017, Giacobbo et al. 2018) → metal-poor stars lose less mass during their evolution and are likely to evolve into more massive stellar-mass black holes.

Black hole retention in star clusters: natal kicks

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 $M_\odot \leq M_{ZAMS} \leq$ 100 $M_\odot$ (Kroupa 2001 IMF)
Belczynski et al. 2002 (for BH masses)
Number of BH progenitors ~ 1900



Retention after supernovae explosions



2 cases (N = 700,000):

1. Neutron star kicks (Hobbs et al. 2005) for black holes
2. Black hole kicks scaled by fallback (Belczynski et al. 2002)

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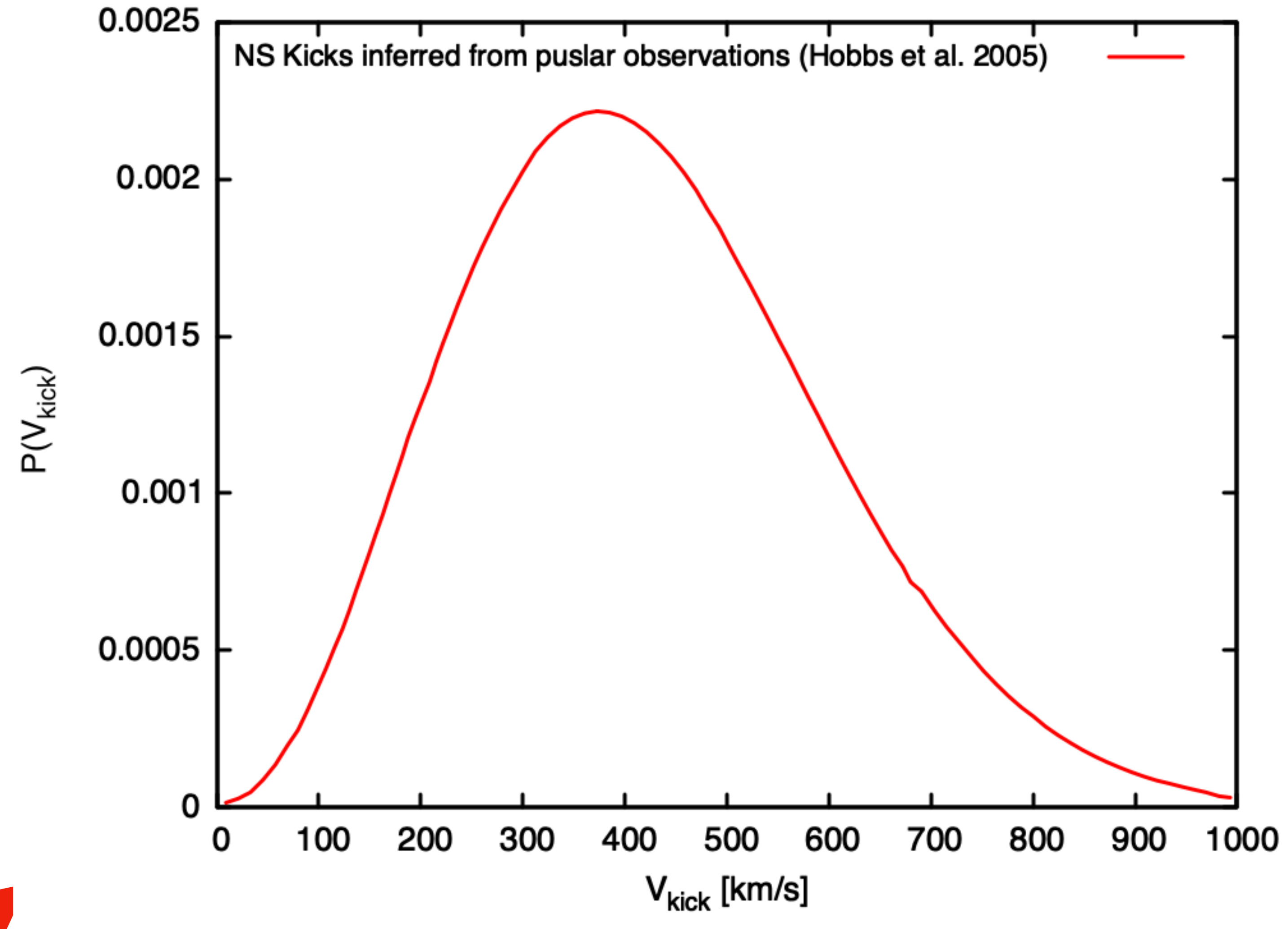

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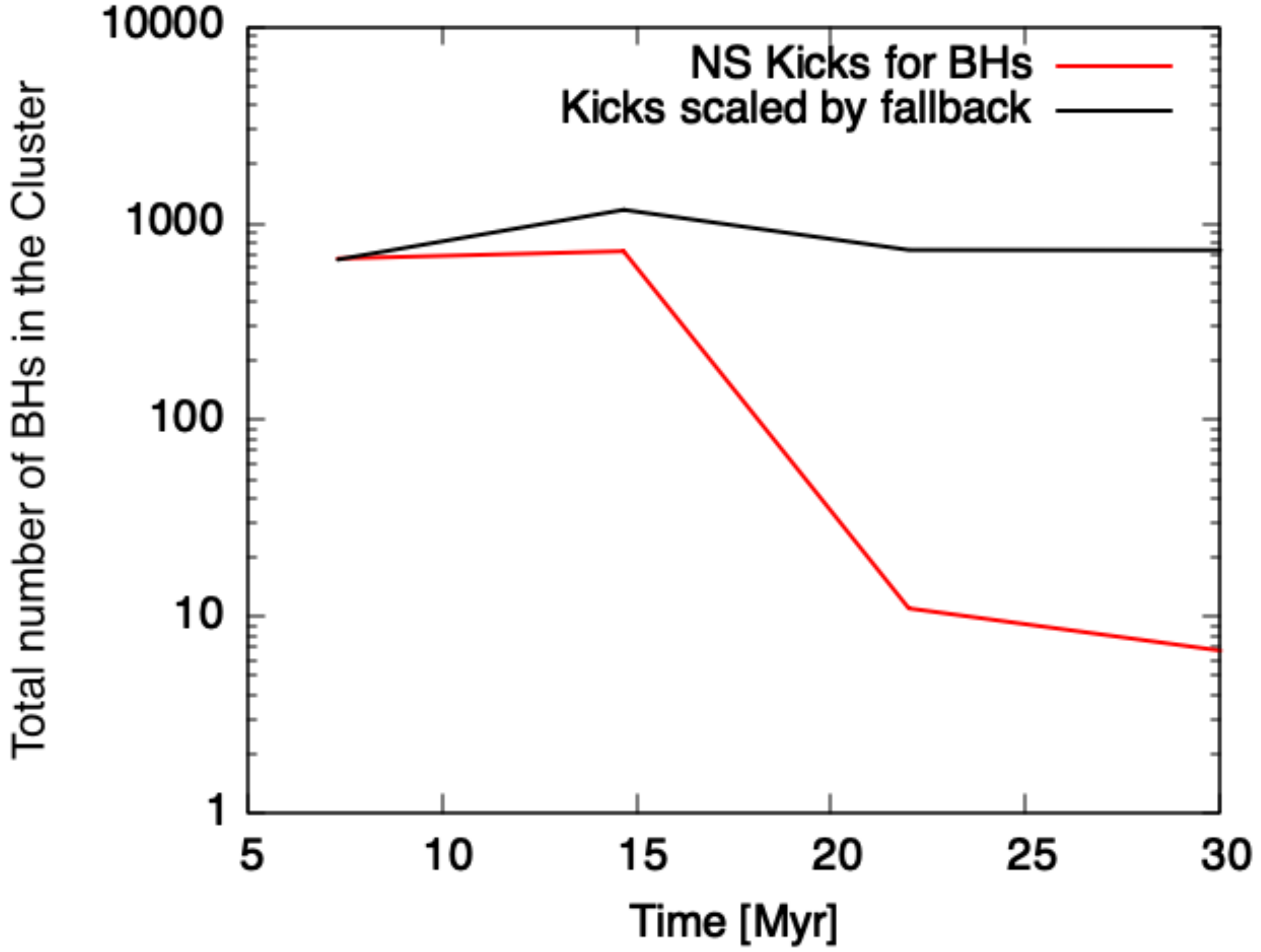
2. Black hole kicks scaled by fallback (Belczynski et al. 2002)

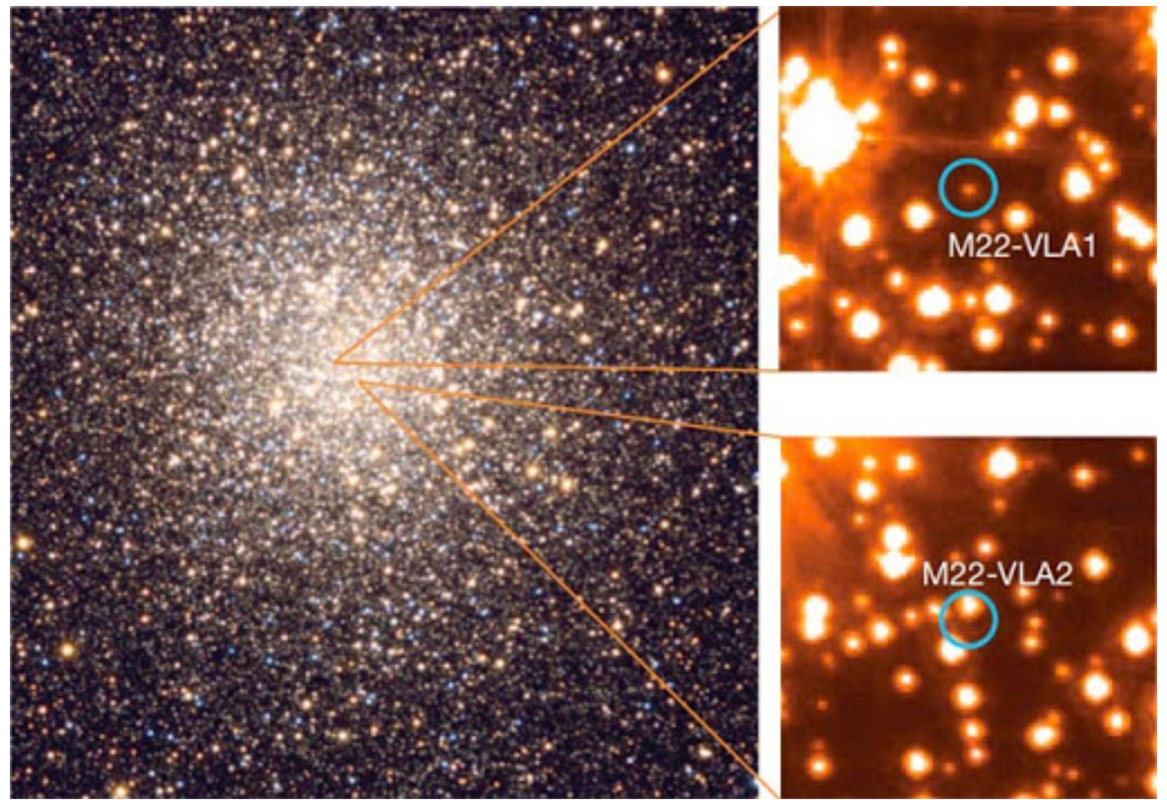
Retention after supernovae explosions



Retention fraction of black holes in globular clusters can be as high as 60% or lower than 1% depending on how you compute natal kicks!

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

Dynamical processes leading to binary black hole formation

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

↓

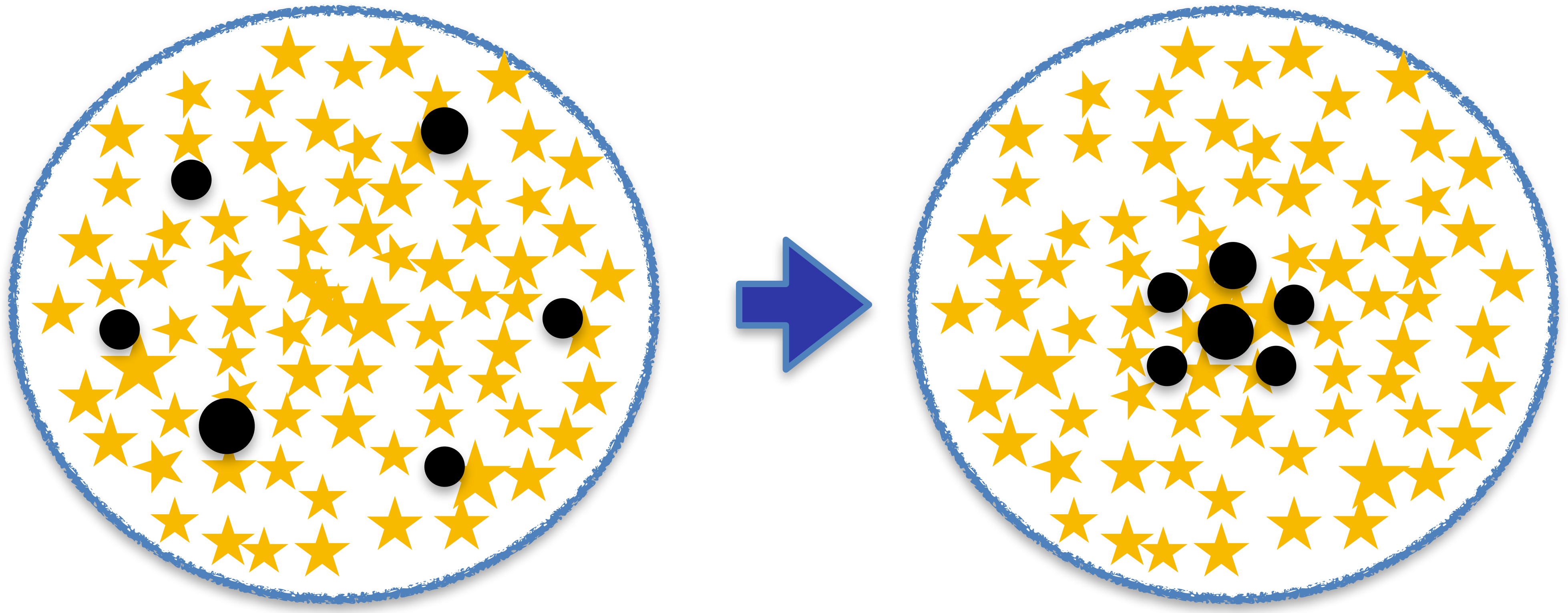
- 3 and 4-body close dynamical interactions involving black holes
  - **Formation of binary black holes through exchange encounters**
  - Mergers can also occur during these interactions (Samsing 2018, Samsing, Askar, Giersz 2018, Rodriguez et al. 2018 a,b, Zevin 2018)

↓

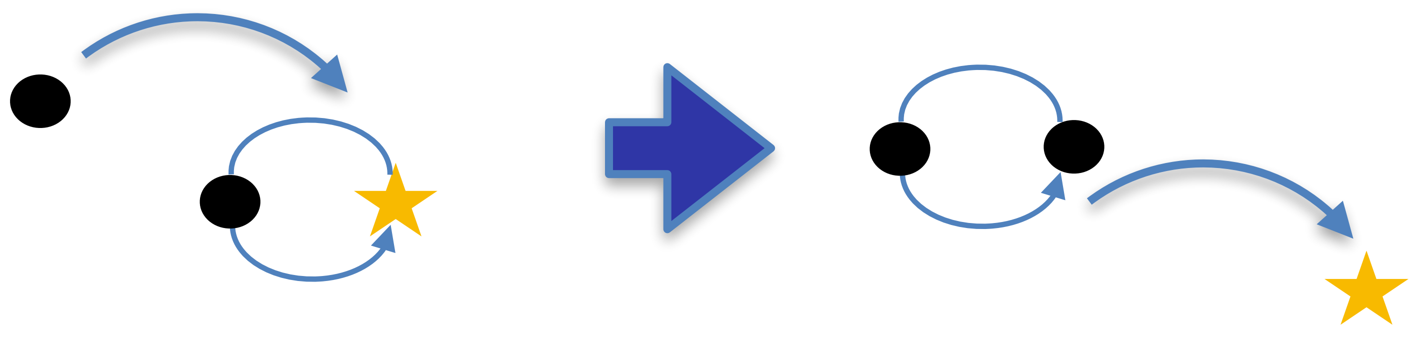
- Hardening of binary black holes through interactions → binary becomes 'useful' → can merge due to gravitational wave radiation within a Hubble time

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

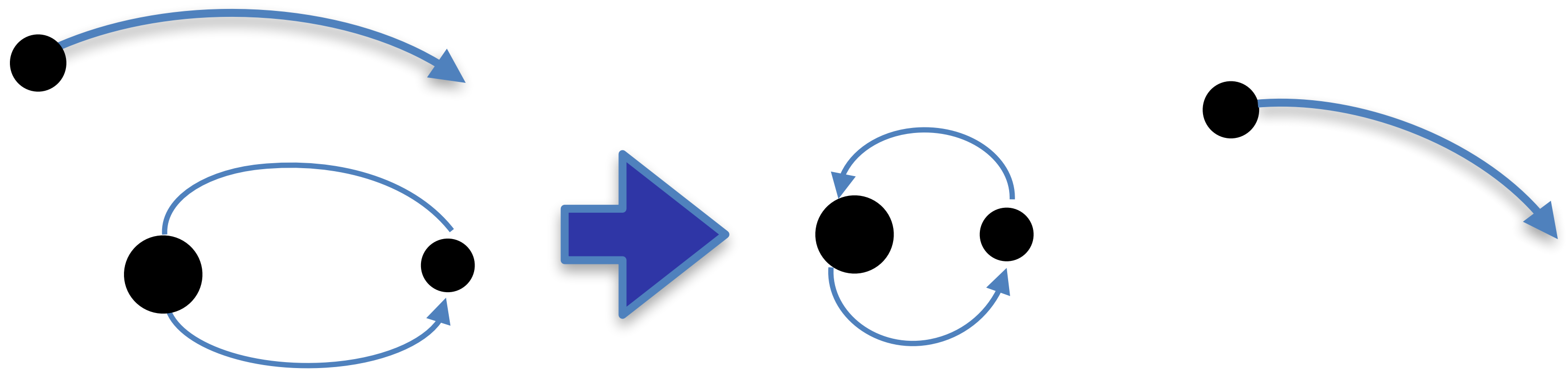
Mass Segregation



Exchange Encounters



Binary Hardening in Fly-by Encounters



Binary hardening in action

$m_1 = 30\,M_\odot$

$m_2 = 30\,M_\odot$

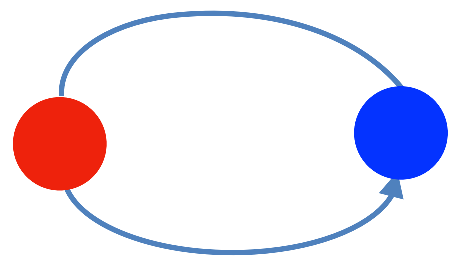
$a_{bin} = 0.5$ AU

$e_{bin} = 0.33$

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

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

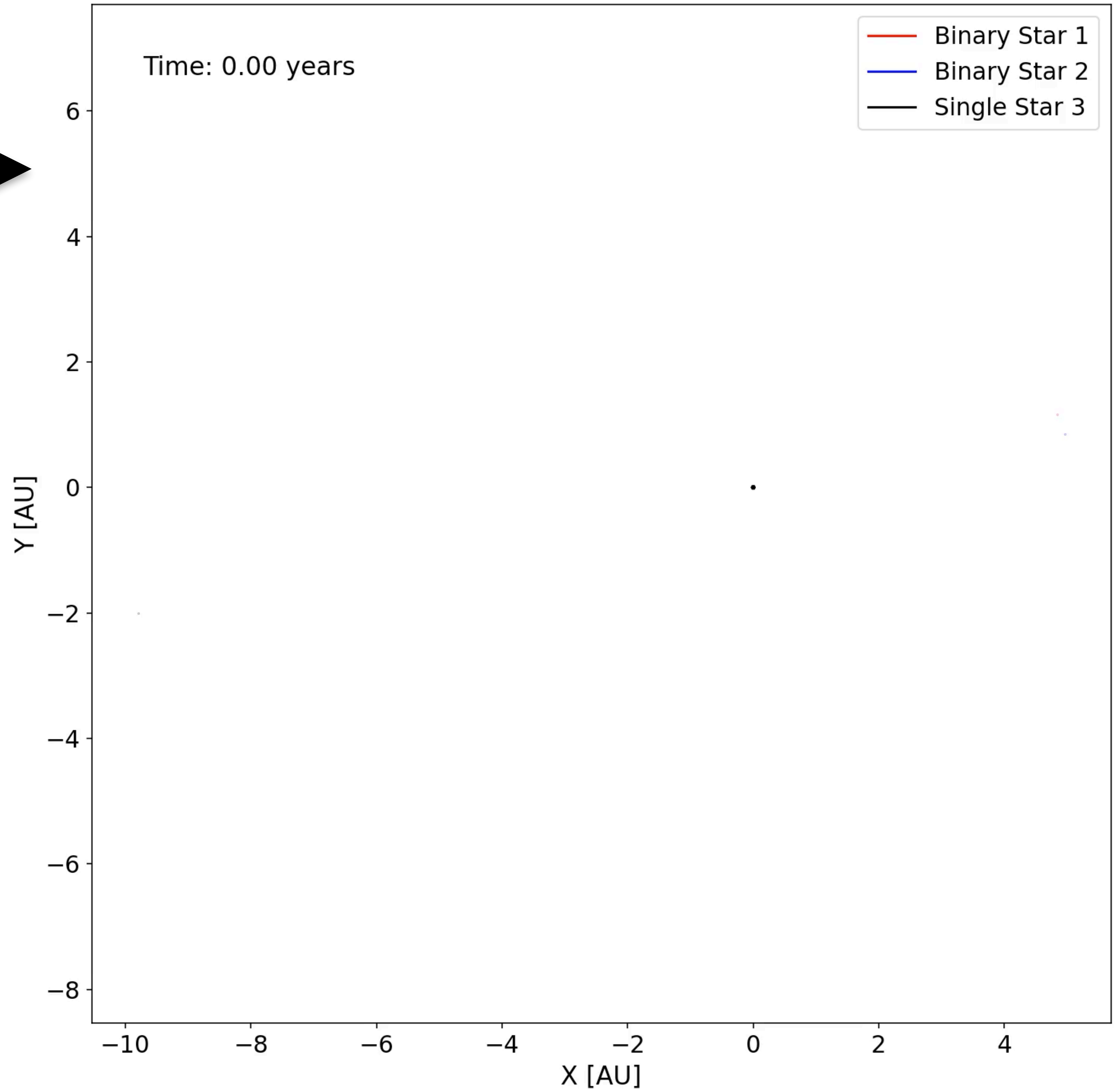
$b = 5.0$ AU



$$\tau_{gr} \simeq 246613\,\mathrm{Myr}$$

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

Resonant fly-by interaction simulated with Tsunami



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 hardening in action

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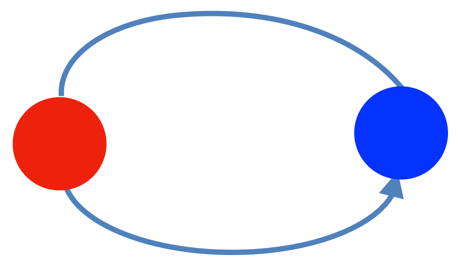

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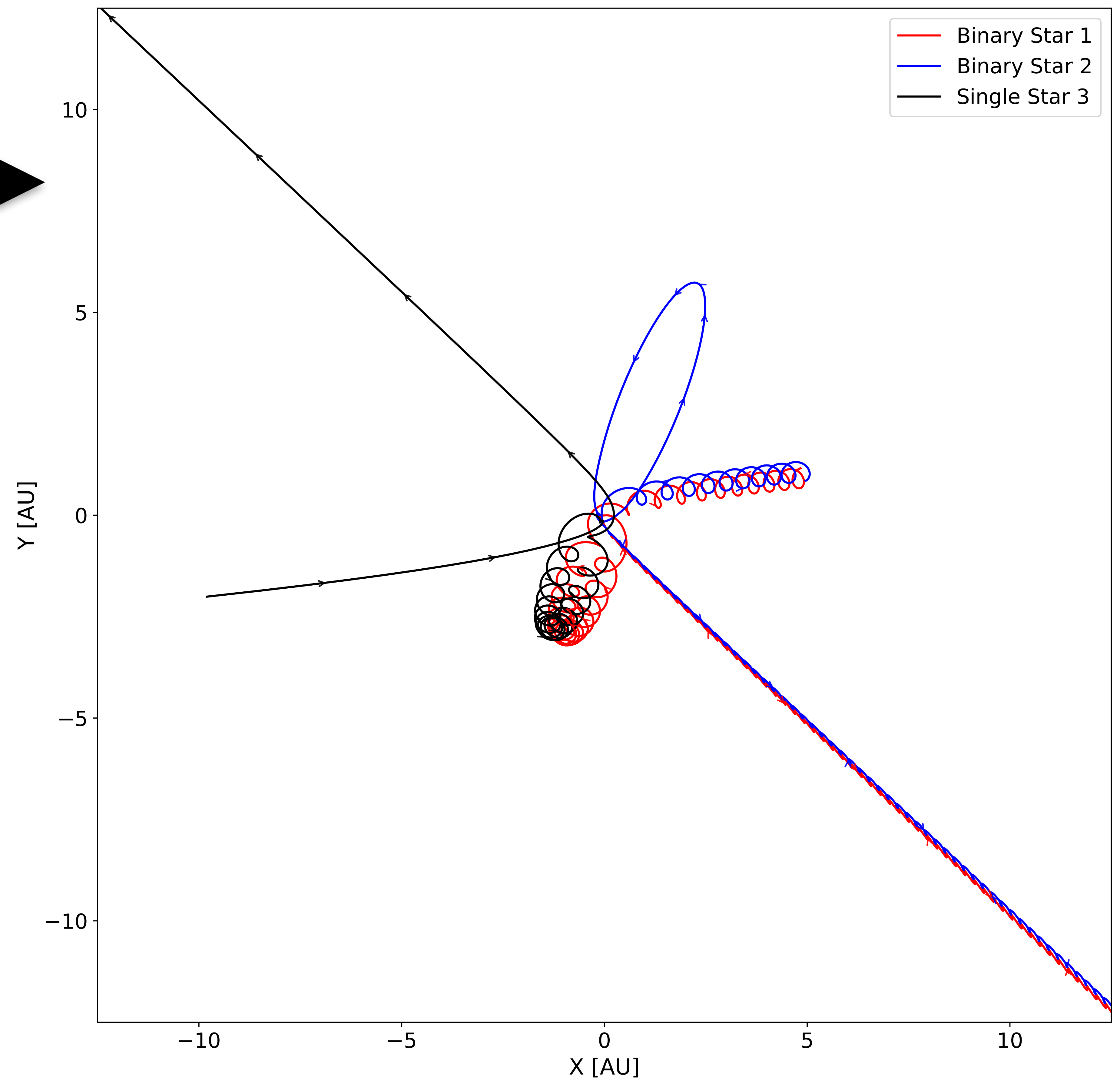


$\mathrm{m}_1 = 30\,\mathrm{M}_\odot$

$\mathrm{m}_2 = 30\,\mathrm{M}_\odot$

$a_{bin} = 0.235\ \mathrm{AU}$

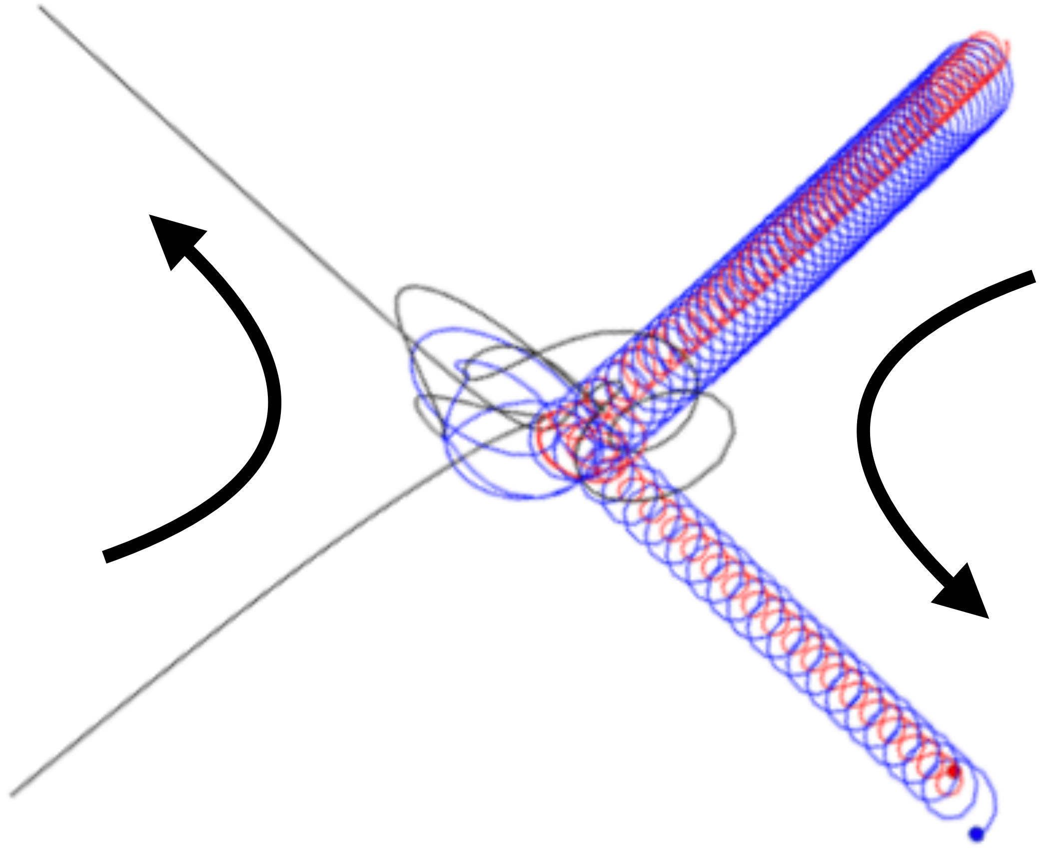
$e_{bin} = 0.994$

$$\boxed{\tau_{\mathrm{gr}} \simeq 0.005\,\mathrm{Myr}}$$

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)

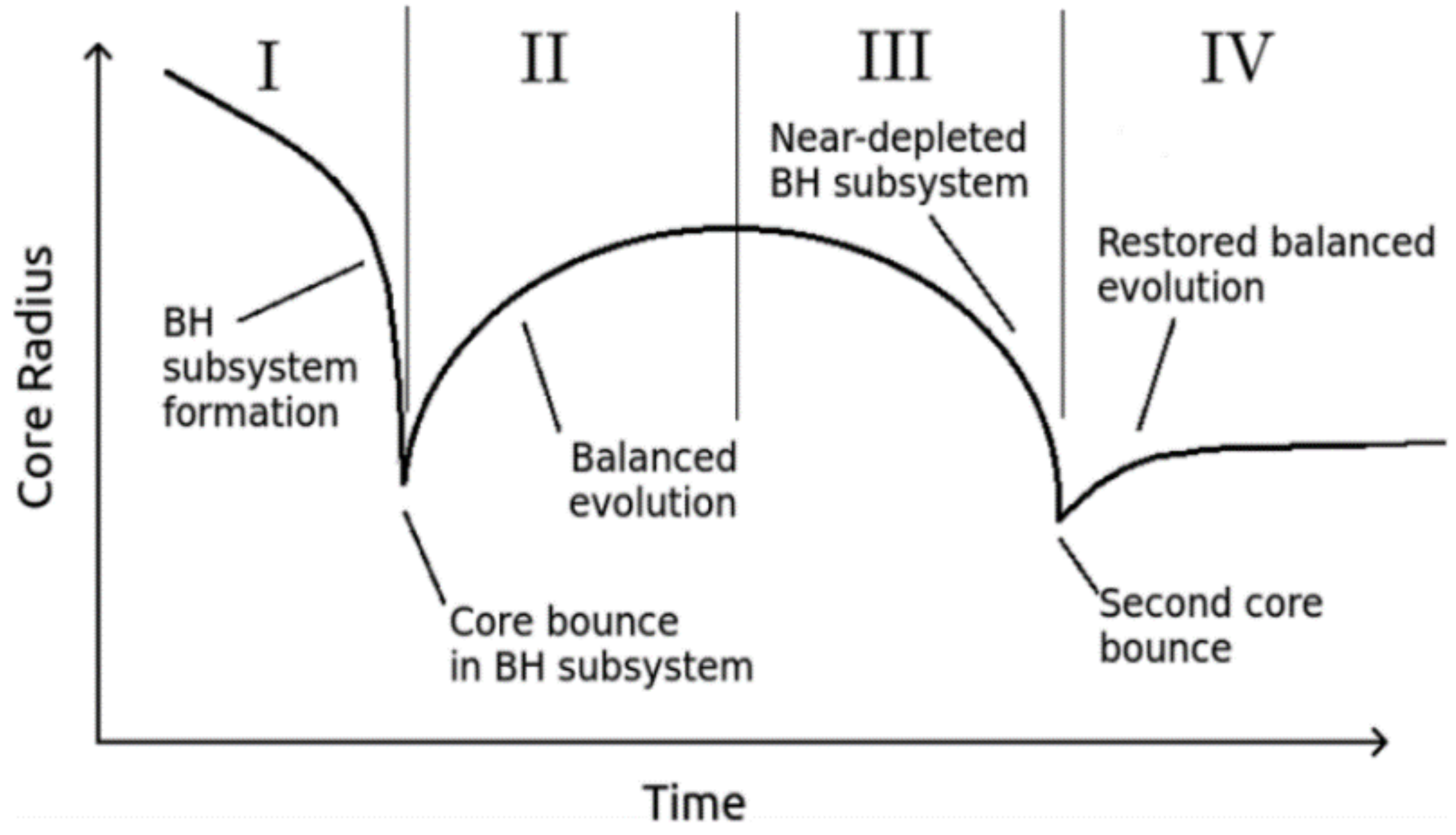
Dynamical processes leading to binary black hole formation

- 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



↓

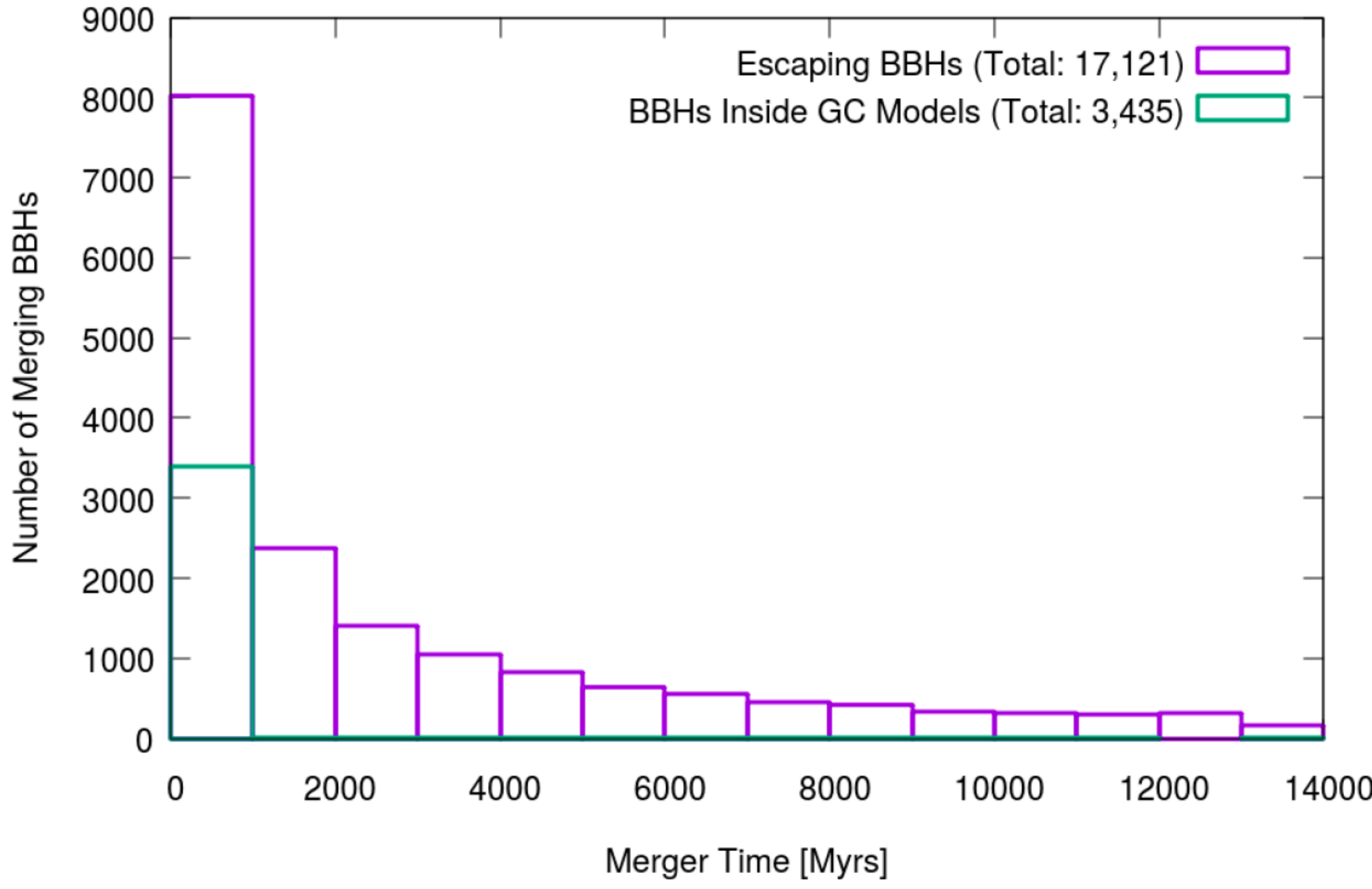
- Black hole population in clusters depletes with time → depletion time depends on cluster initial properties
  - Black holes heat surrounding stars (Mackey et al. 2007;2008, Breen & Heggie 2013)
  - Initially dense clusters → more interactions → faster depletion of black holes
  - Less dense clusters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



Credit: Breen & Heggie (2013)

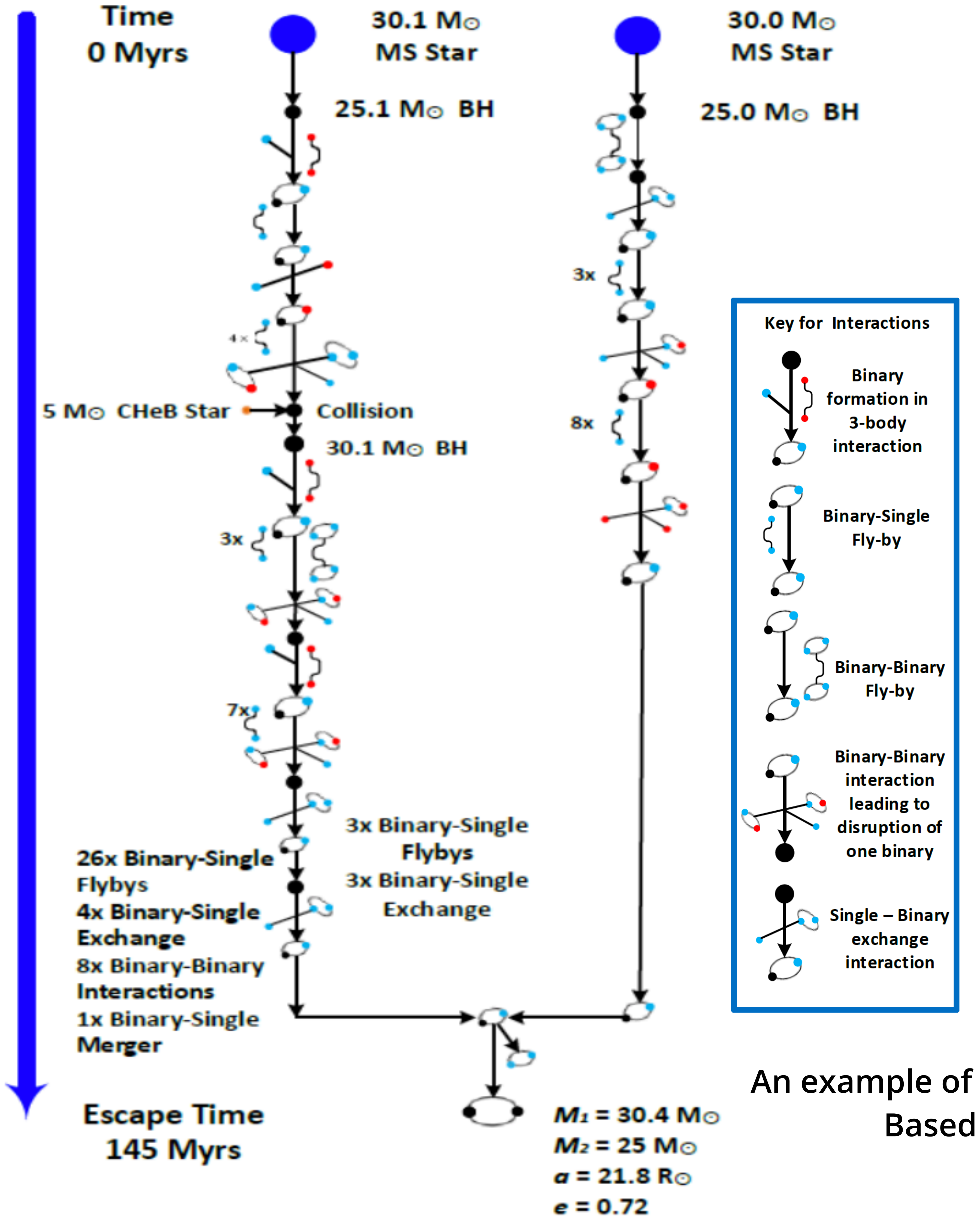
Producing binary black holes in globular clusters

- 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

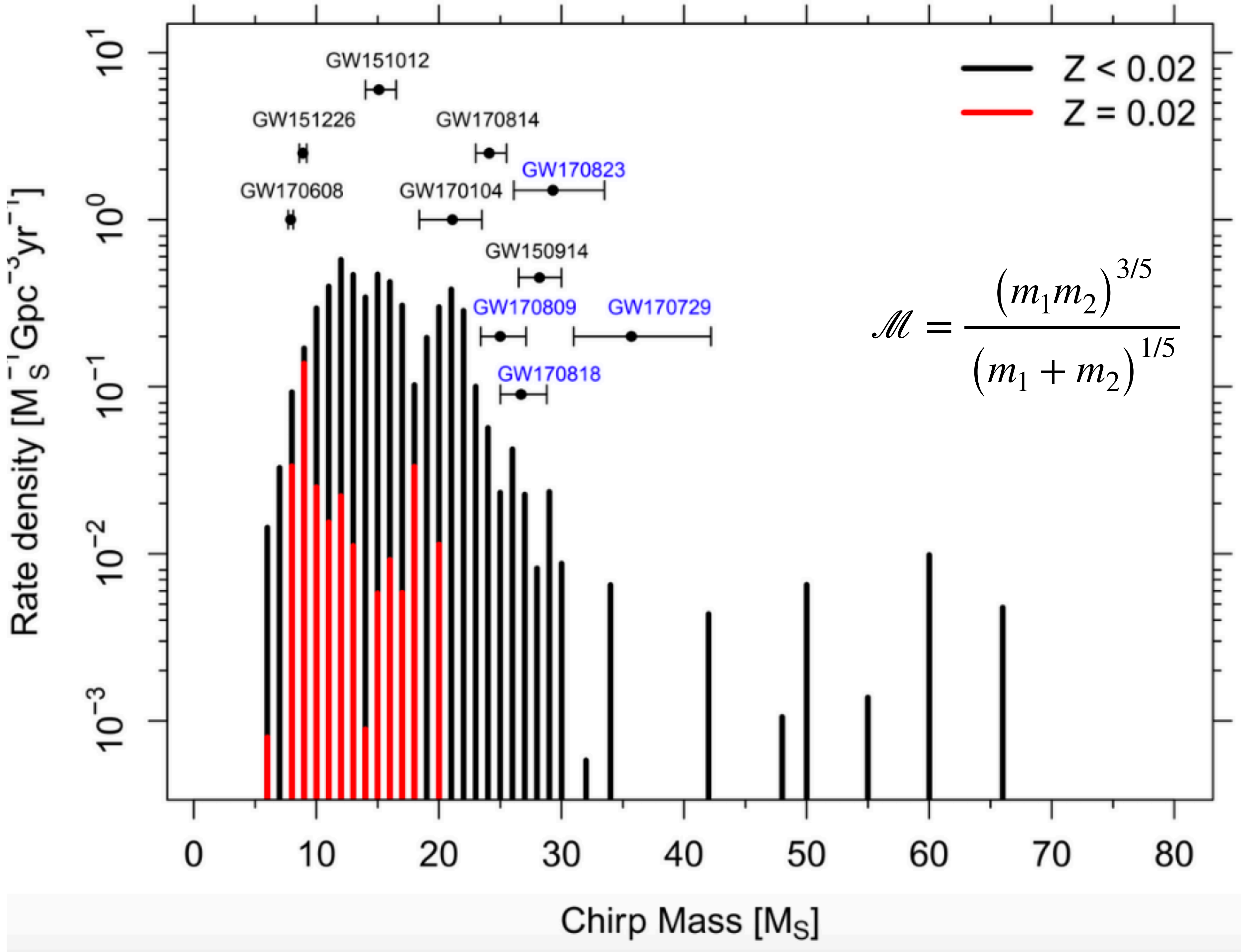
$$t_{\rm merg} = t_{\rm esc} + t_{\rm GW}$$ Peters (1964)

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

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

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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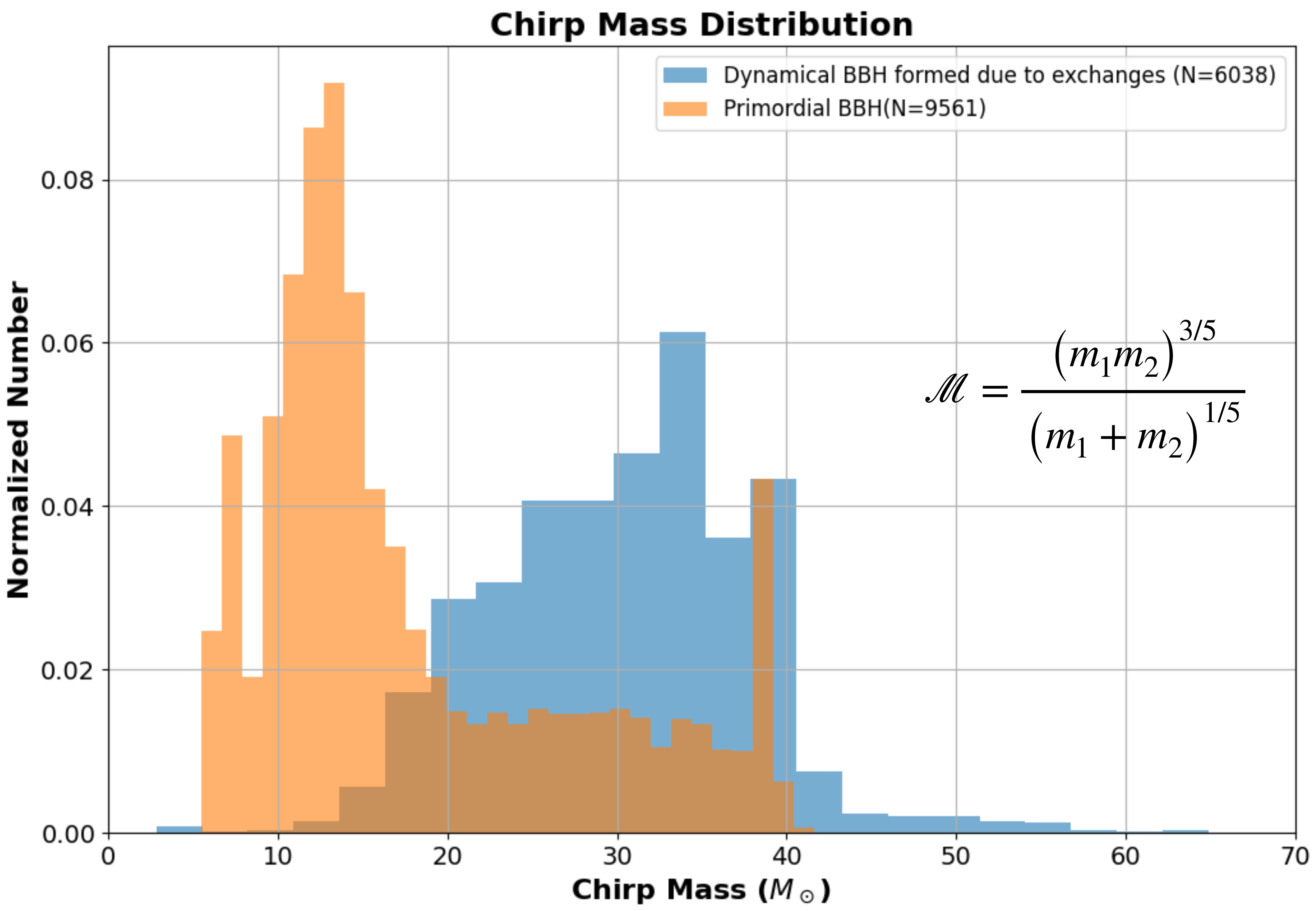

New MOCCA Models from 2024 (~320 star cluster models)
- Improved treatment for progenitor winds (Vink et al. 2001; 2008)
- BH masses depend on 'Rapid' supernova prescription from Fryer et al. 2012
- GW recoil kicks

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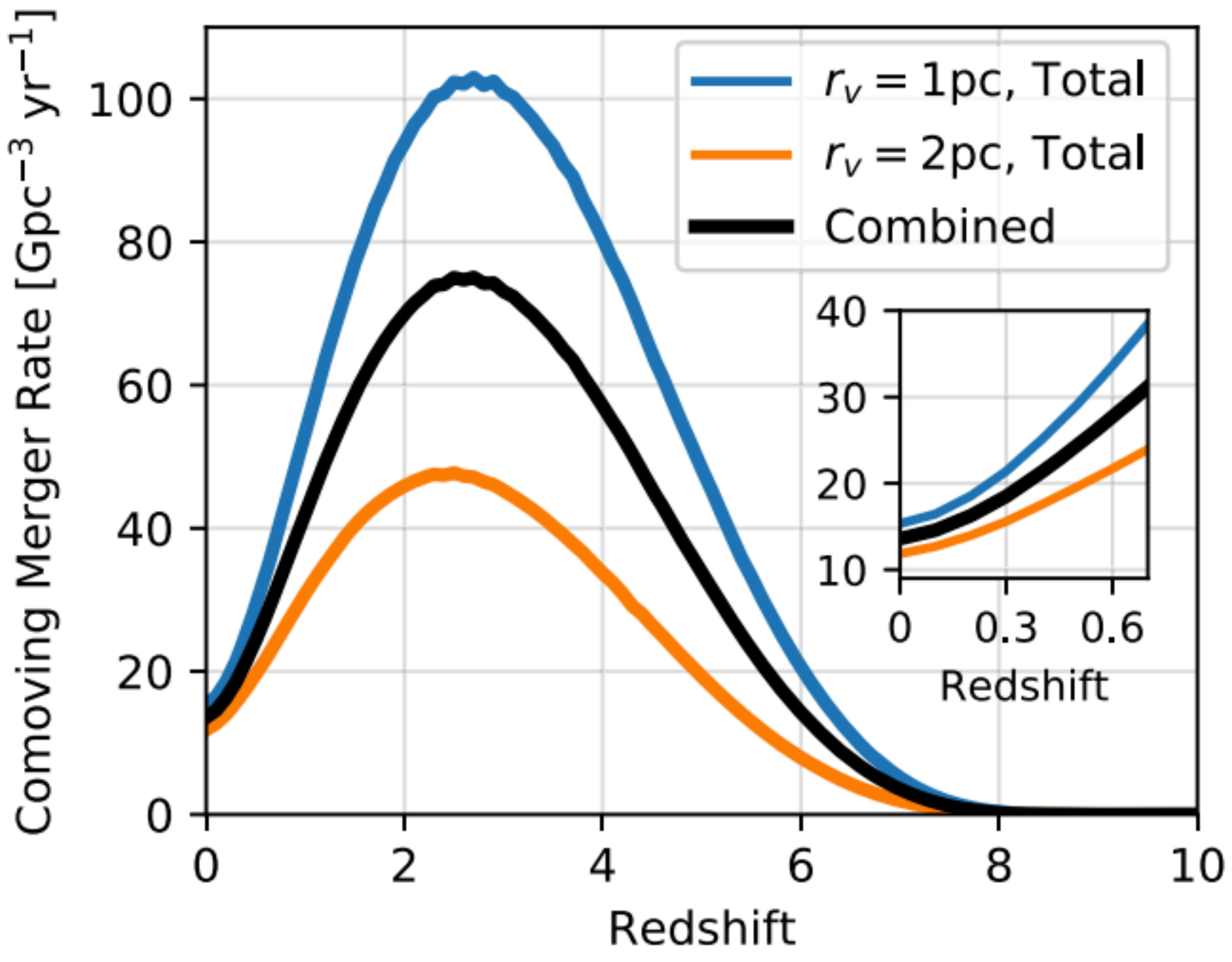
- Open question: How much star formation took place in globular clusters?
  - Currently $\sim 0.1 - 1\,\%$ of galaxy stellar mass is in globular clusters (Harris et al. 2014)
  - May have been $\gtrsim 10\,\%$ at $z > 3$ (Muratov & Gnedin 2010)



Rodriguez & Loeb (2018)

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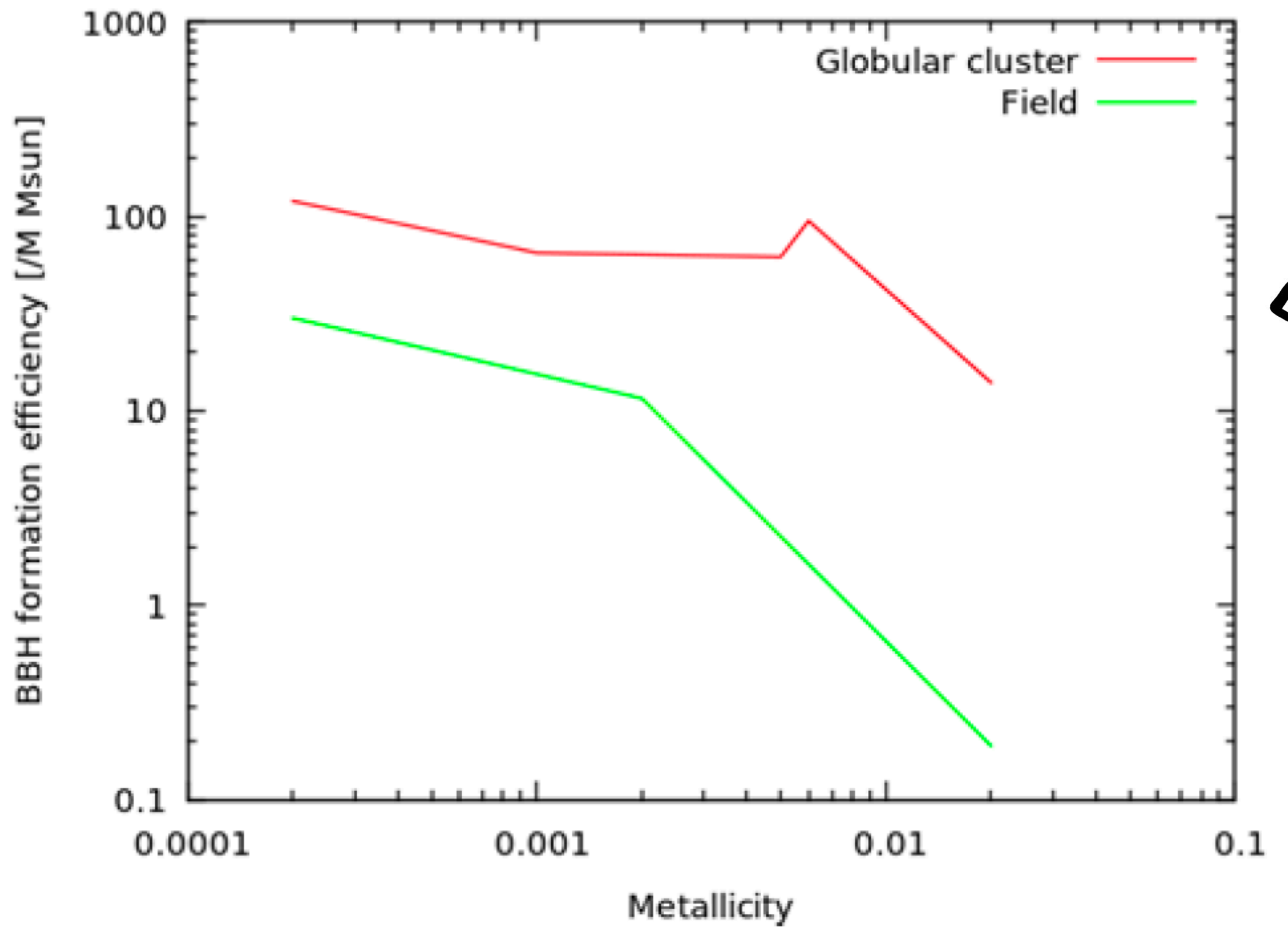
So which dominates, field or cluster?

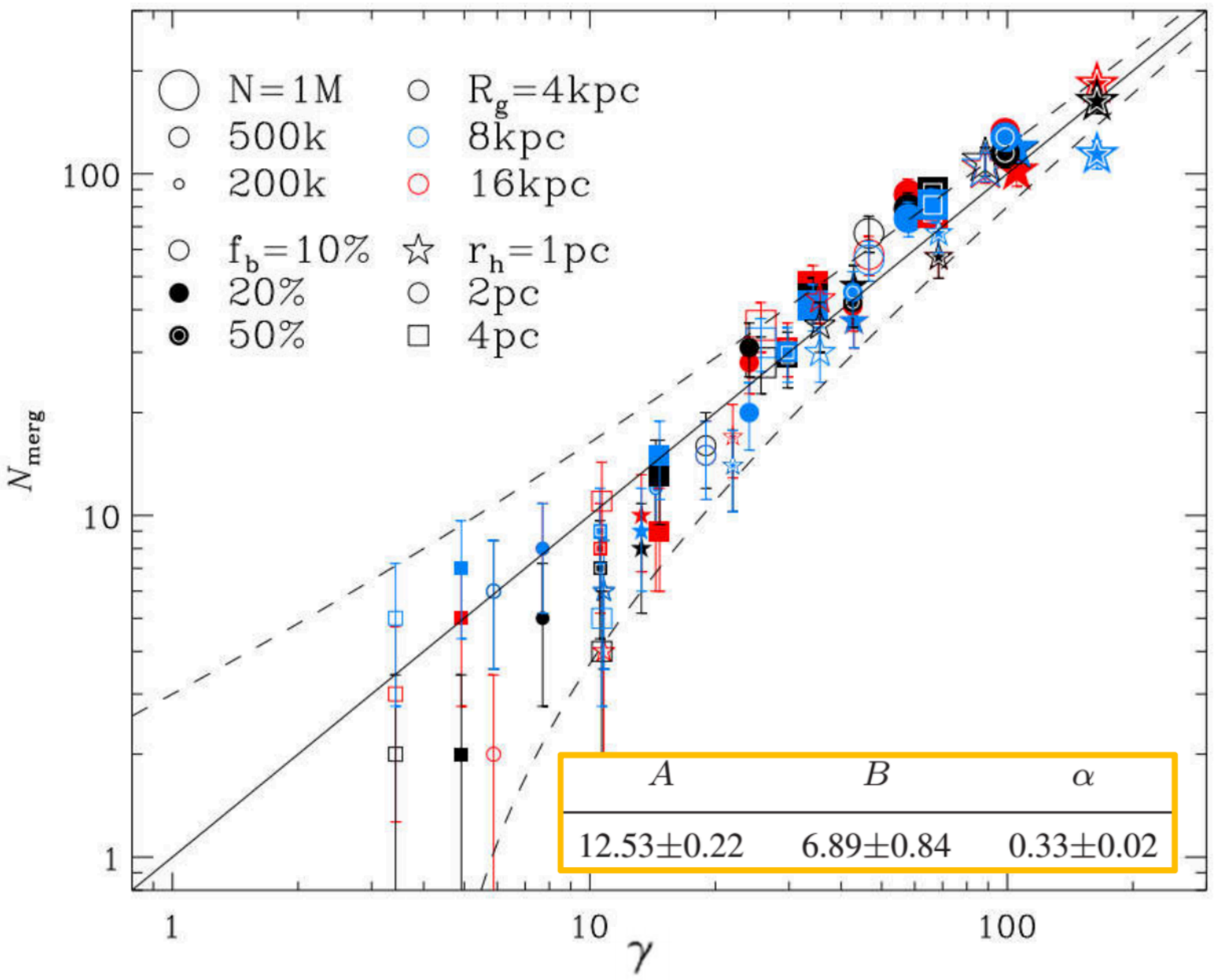
Common × Rare ≷ Rare × Common?



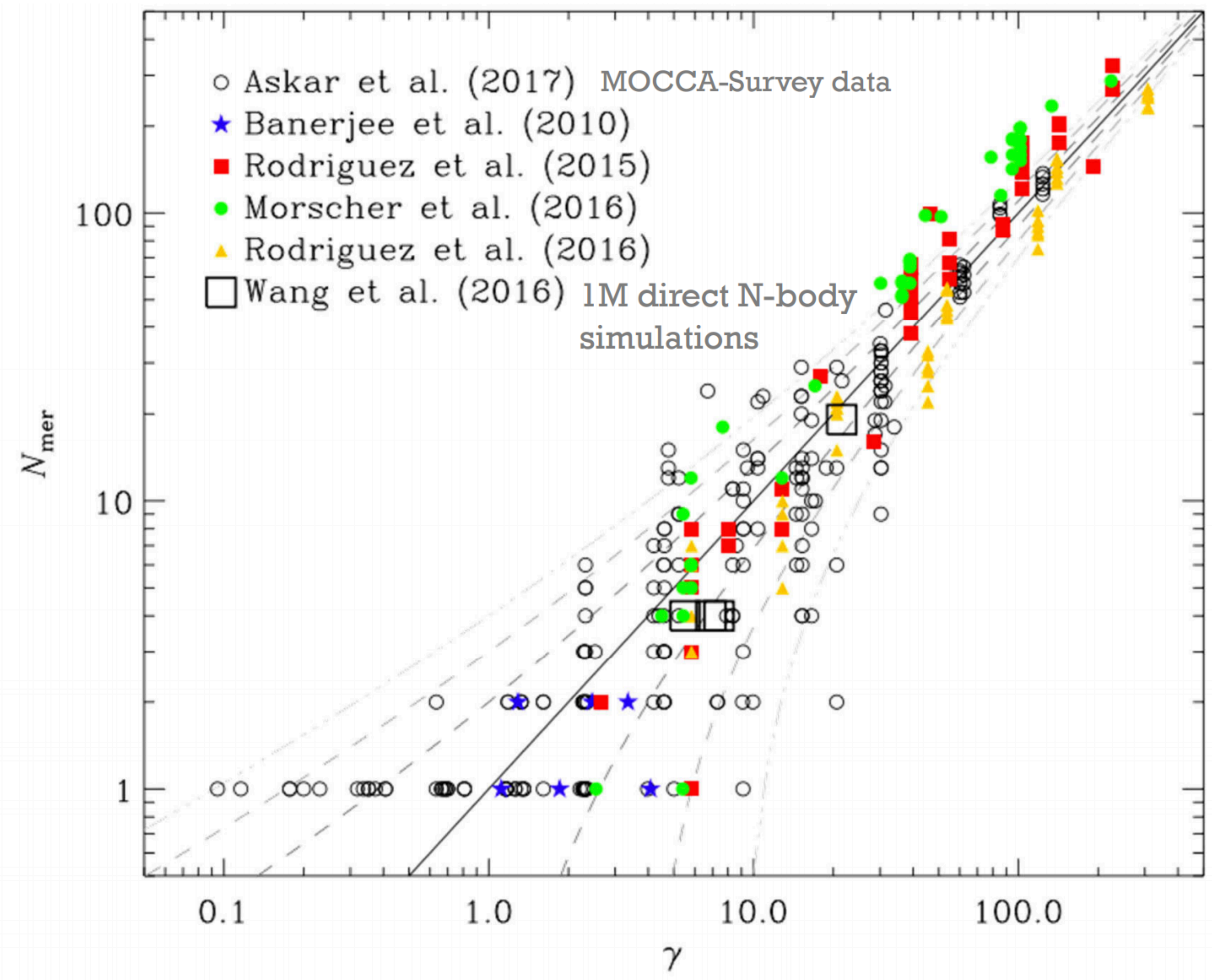
Efficiency: Number of merging BBH binaries per $10^6\ \mathrm{M}_\odot$
(Figure Credit: Tomasz Bulik)

Field data from Belczynski et al. 2016

Binary black hole production and globular cluster properties



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)

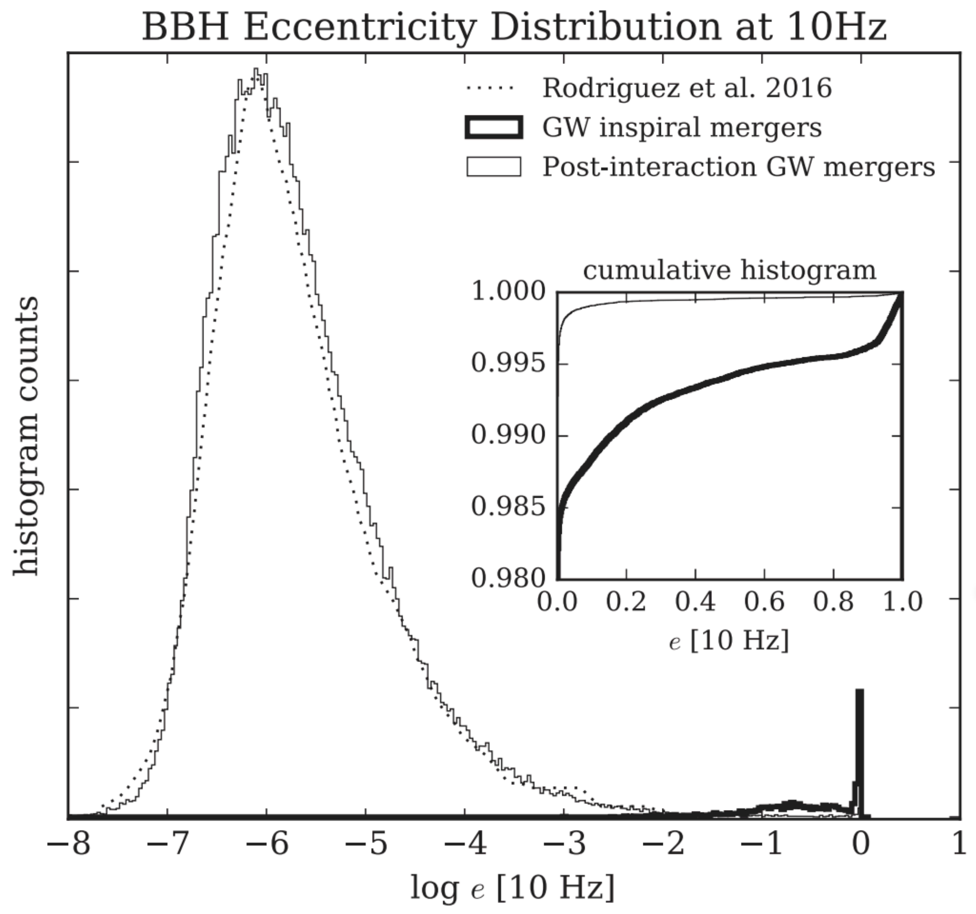


$$\gamma \equiv \underbrace{\boxed{A}\,\frac{M_0}{10^5 \mathrm{M}_\odot}\times\left(\frac{\rho_\mathrm{h}}{10^5 \mathrm{M}_\odot \mathrm{pc}^{-3}}\right)^{\boxed{\alpha}}}_{\text{dynamical channel}} + \underbrace{\boxed{B}\,\frac{M_0}{10^5 \mathrm{M}_\odot}\times f_{\mathrm{b},0}}_{\text{primordial channel}}$$

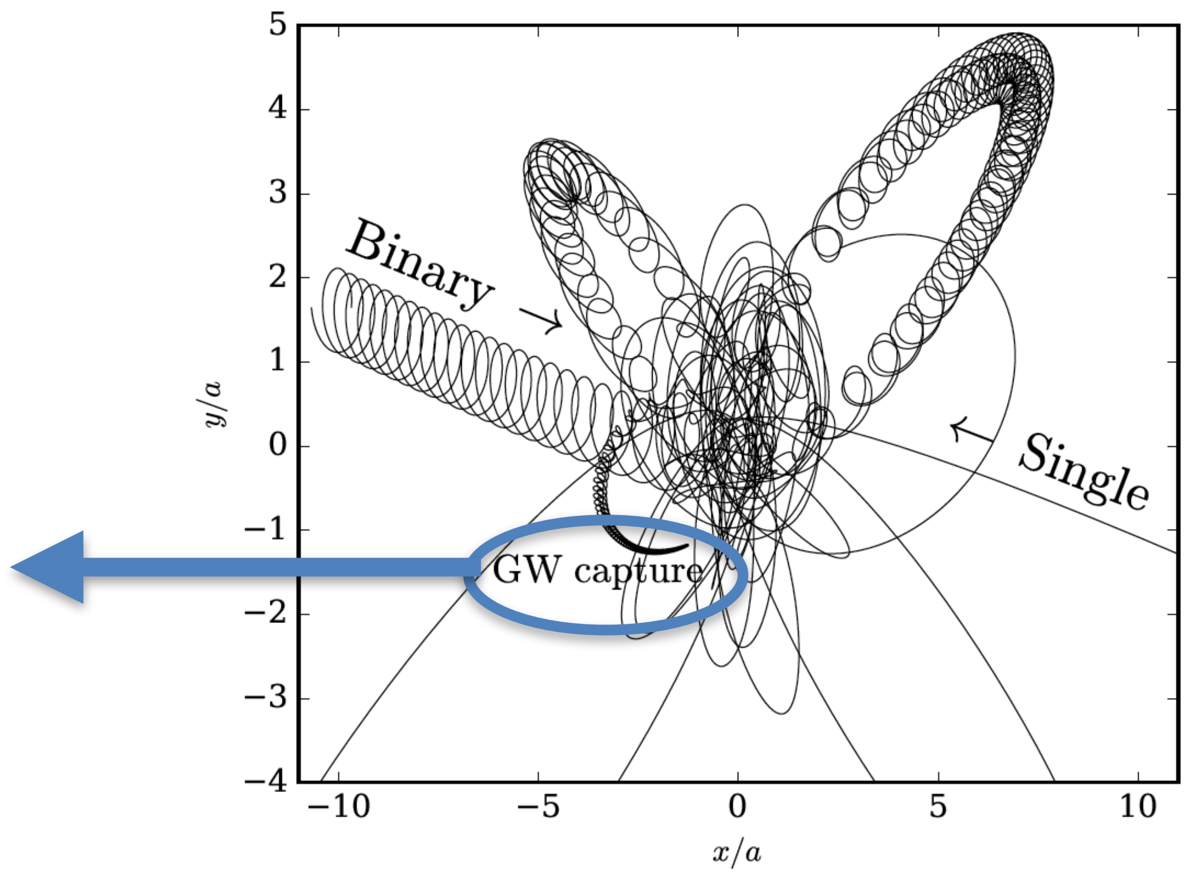
Hong, Vesperini, Askar et al. (2018)
Hong, Askar et al. (2020)

Eccentric binary black holes mergers in clusters

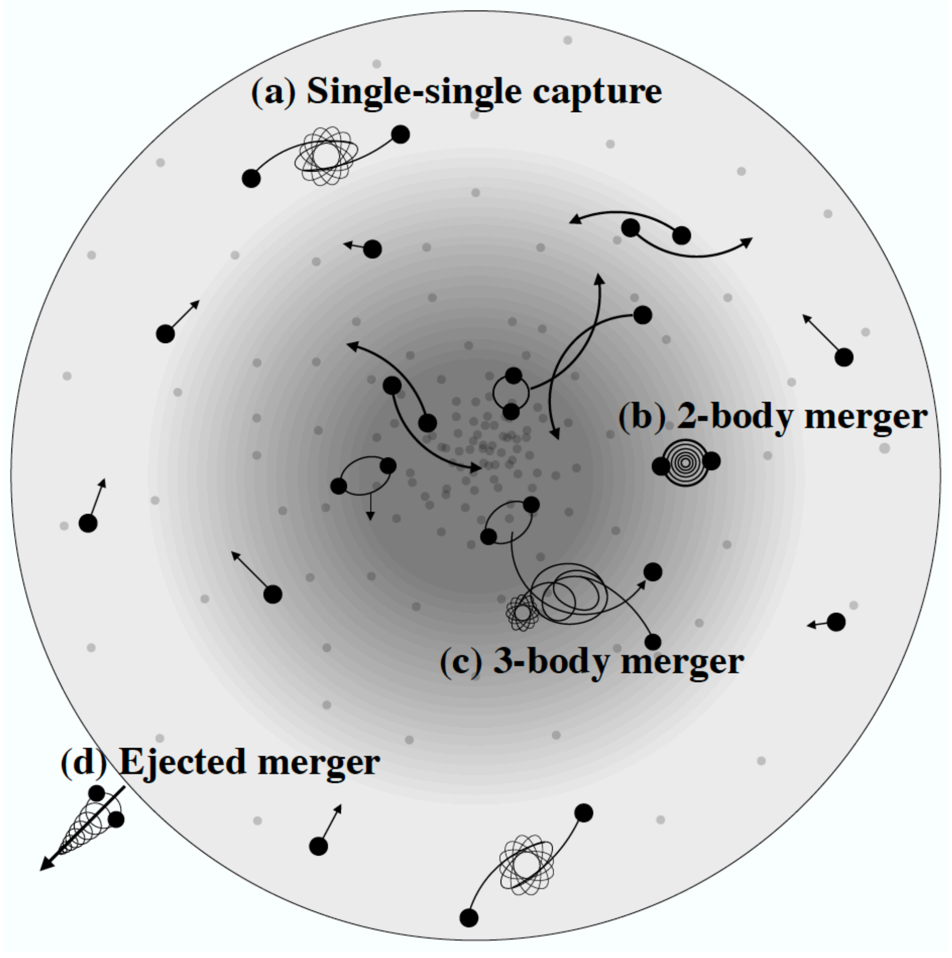
- Non-negligible probability of experiencing a very close passage during a resonant encounter
- Significant orbital energy and angular momentum are carried away from the system by gravitational wave radiation → can result in rapid, highly-eccentric black hole mergers (e > 0.1)
- Rate of such capture 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)



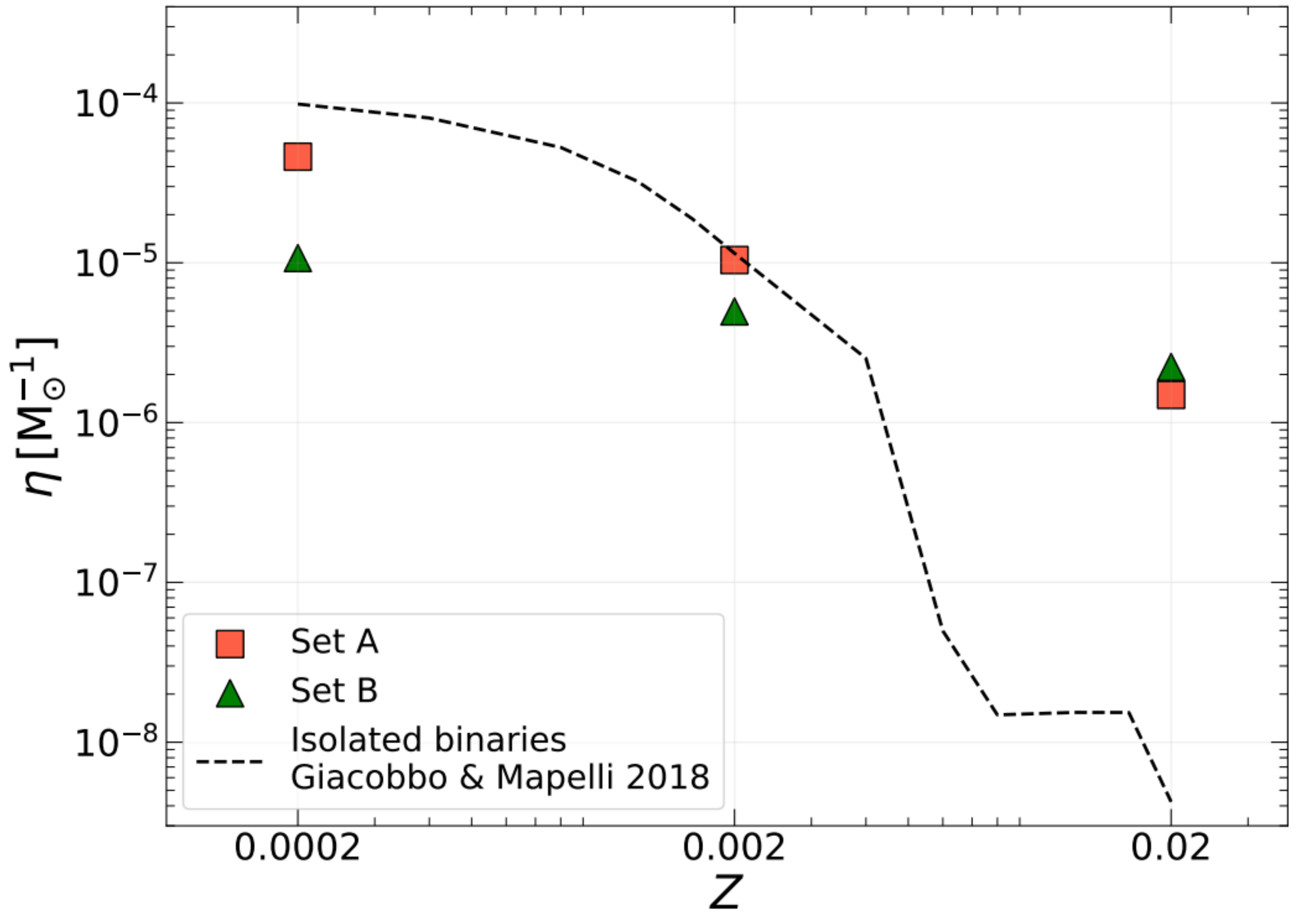
Samsing (2018)

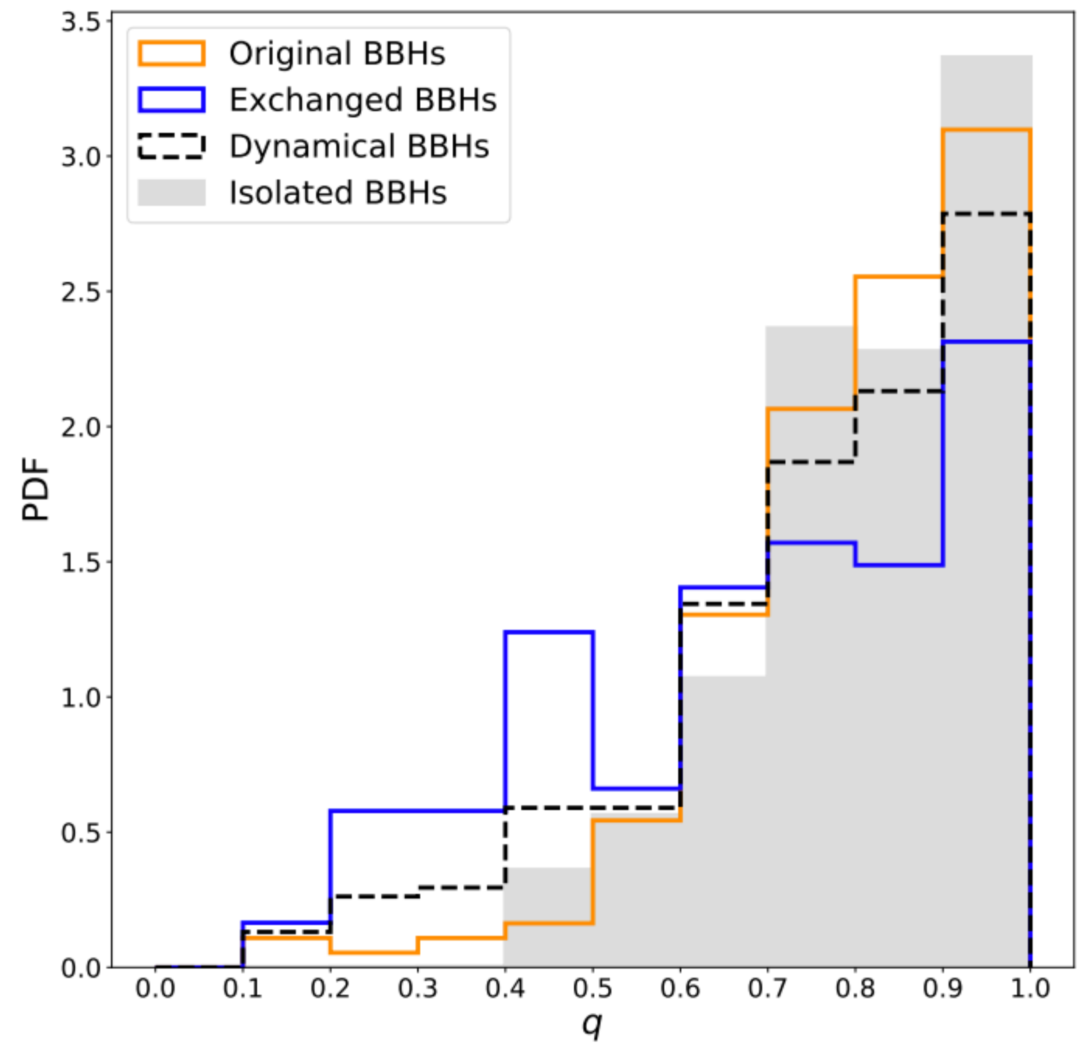


Credit: Samsing et al. (2020)

Binary black holes in open/young stellar clusters

- Higher fraction of star formation takes place in open and young clusters compared to globular clusters
  - Formation not limited to a given cosmic epoch
- More efficient at producing binary black holes at higher metallicities compared to isolated binary evolution
  - 90% of the mergers take place outside the cluster (Di Carlo et al. 2020)
  - Inclusion of post-Newtonian terms could lead to more in cluster mergers (Banerjee 2017; 2020)
- Produce more low mass ratio mergers
- Local merger rates of binary black holes originating in young stellar stellar: $50 - 100\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (Di Carlo et al. 2020)





Di Carlo 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}	$0.06^{+0.40}_{-0.38}$	$6.1^{+4.9}_{-3.1}$	$1.14^{+0.64}_{-0.49}$

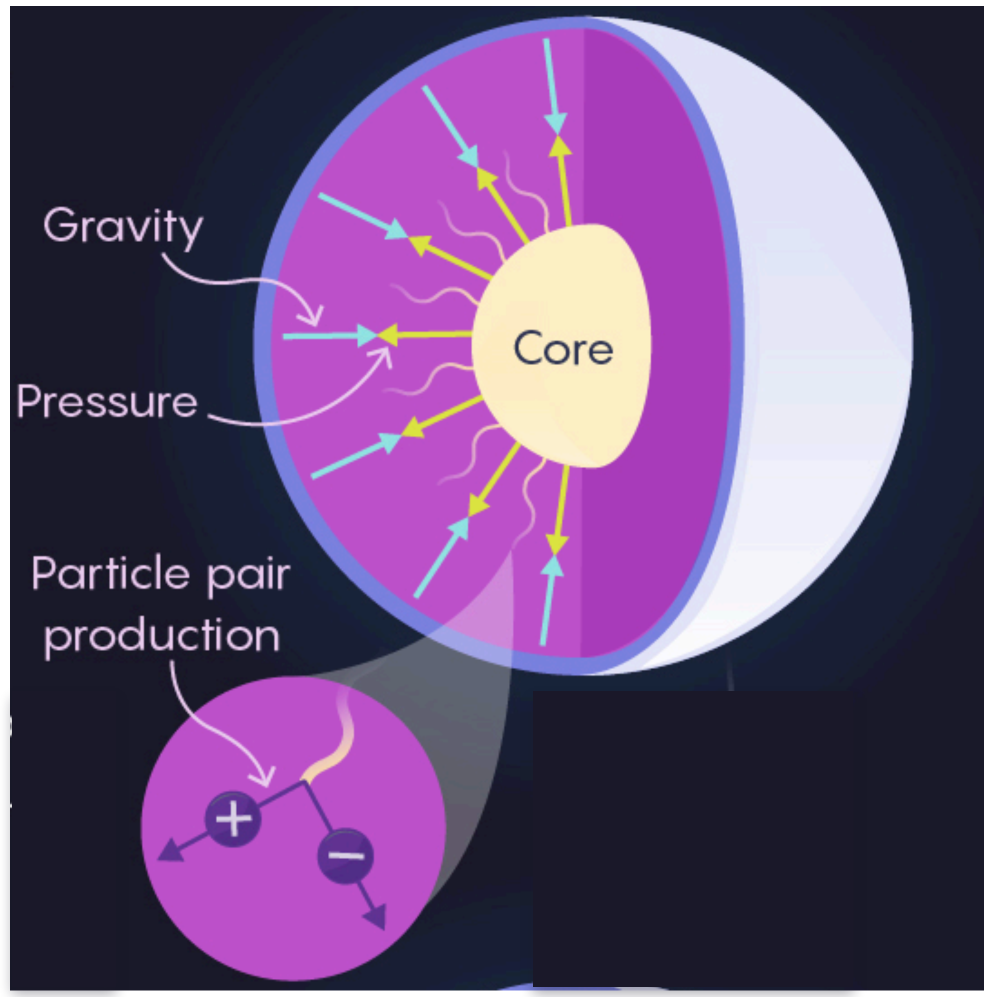


Image Credit: Lucy Reading-Ikkanda/Quanta Magazine

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

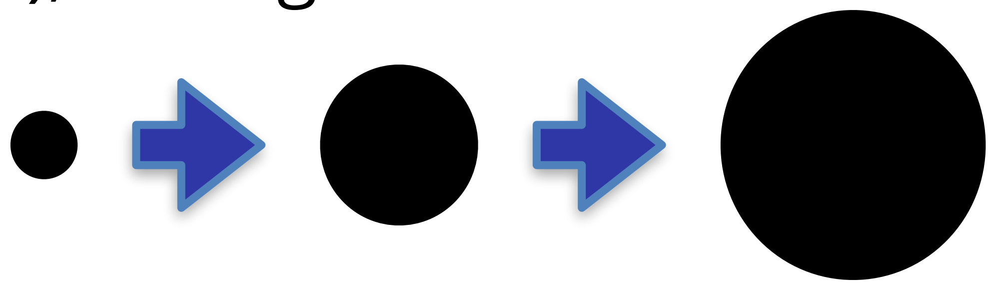
Repeated or hierarchal mergers of black holes in dense star clusters

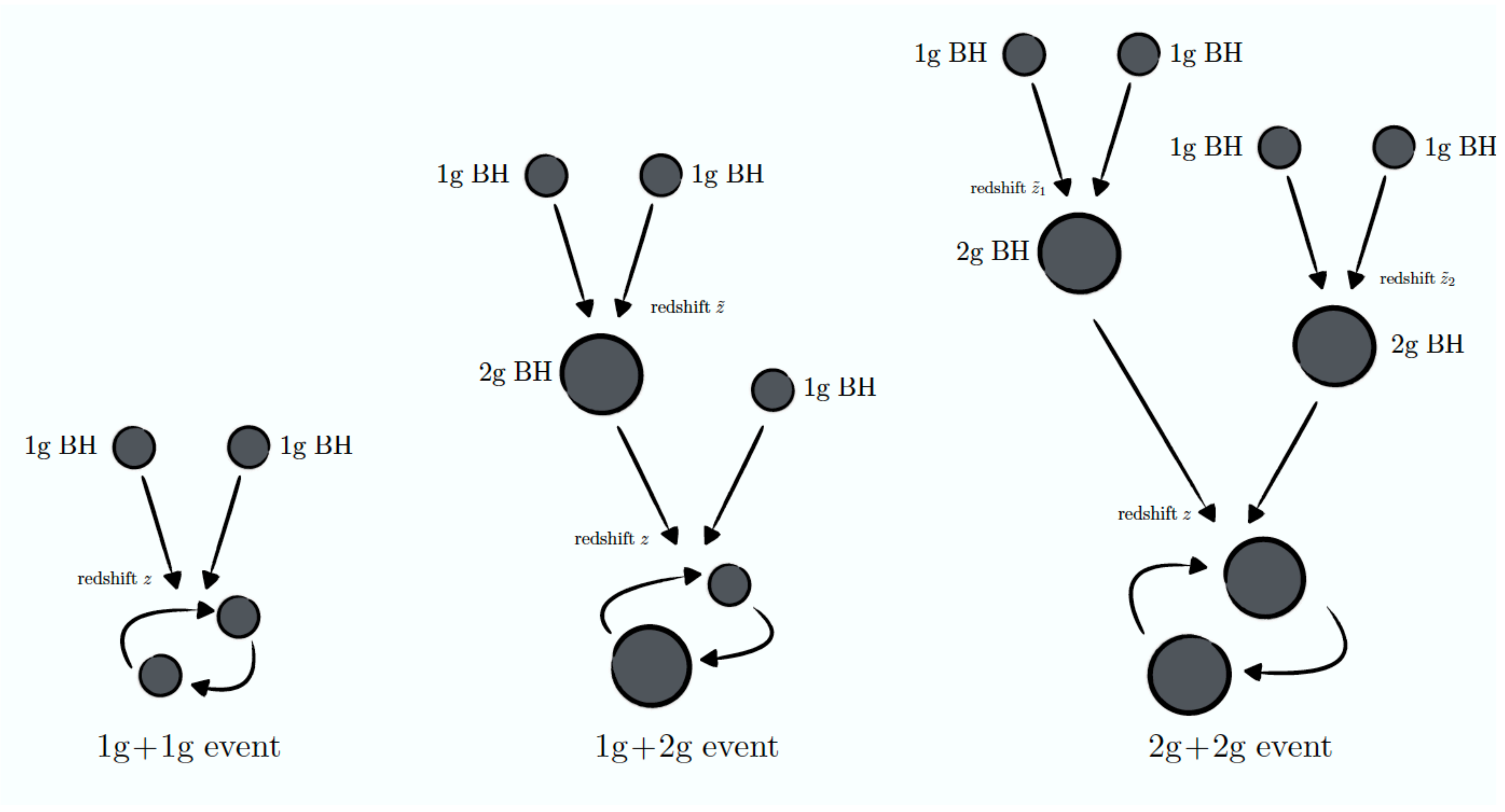
- Two sBHs (1G) merge due to gravitational wave (GW) emission and form a more massive BH (2G)
- In a dense star cluster, this merged BH (2G) can pair up and merge with another BH (1G or 2G)
- Most straightforward way for growing BHs and one of the proposed formation channels for GW events like GW190521

  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)

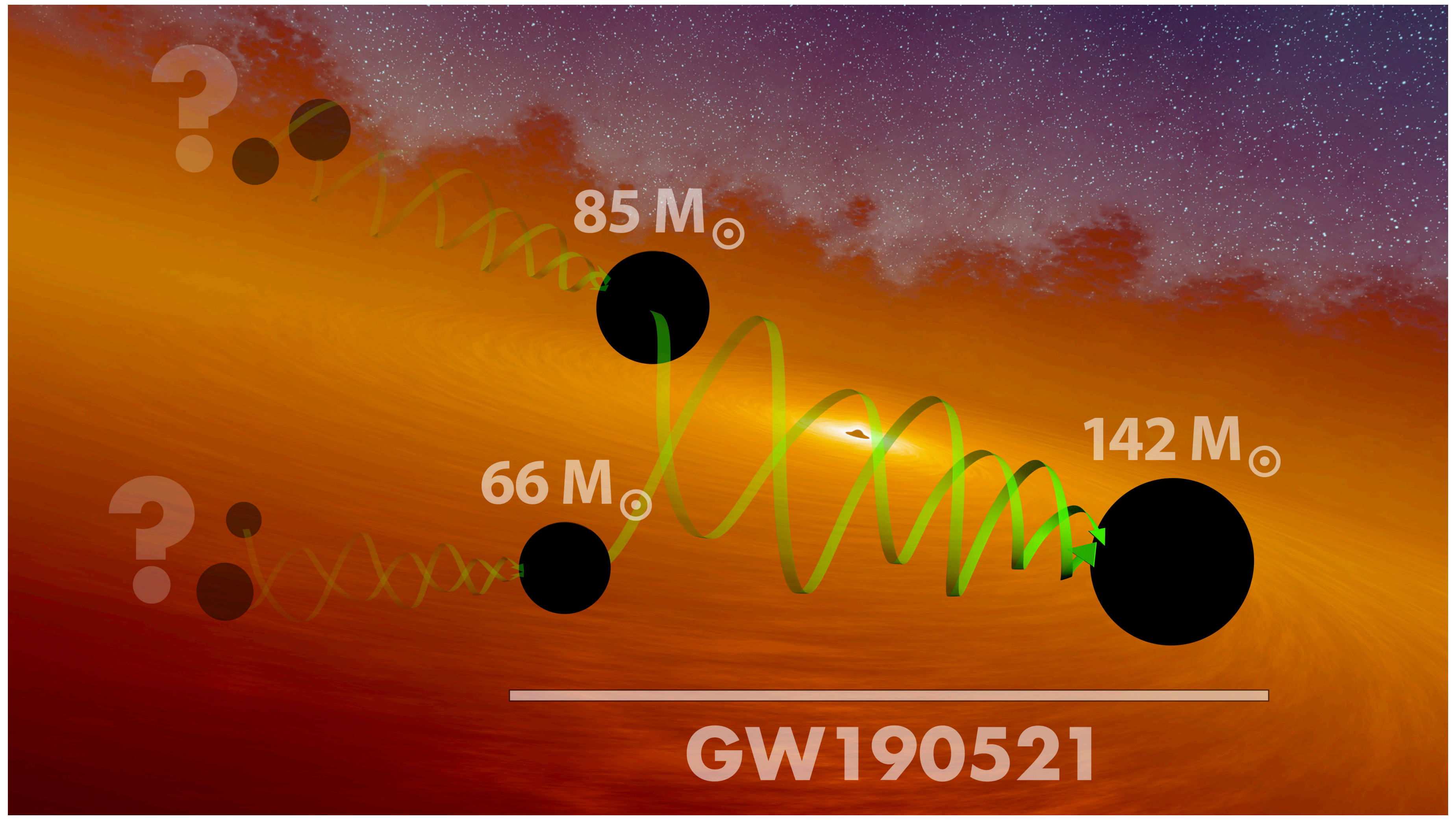


Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

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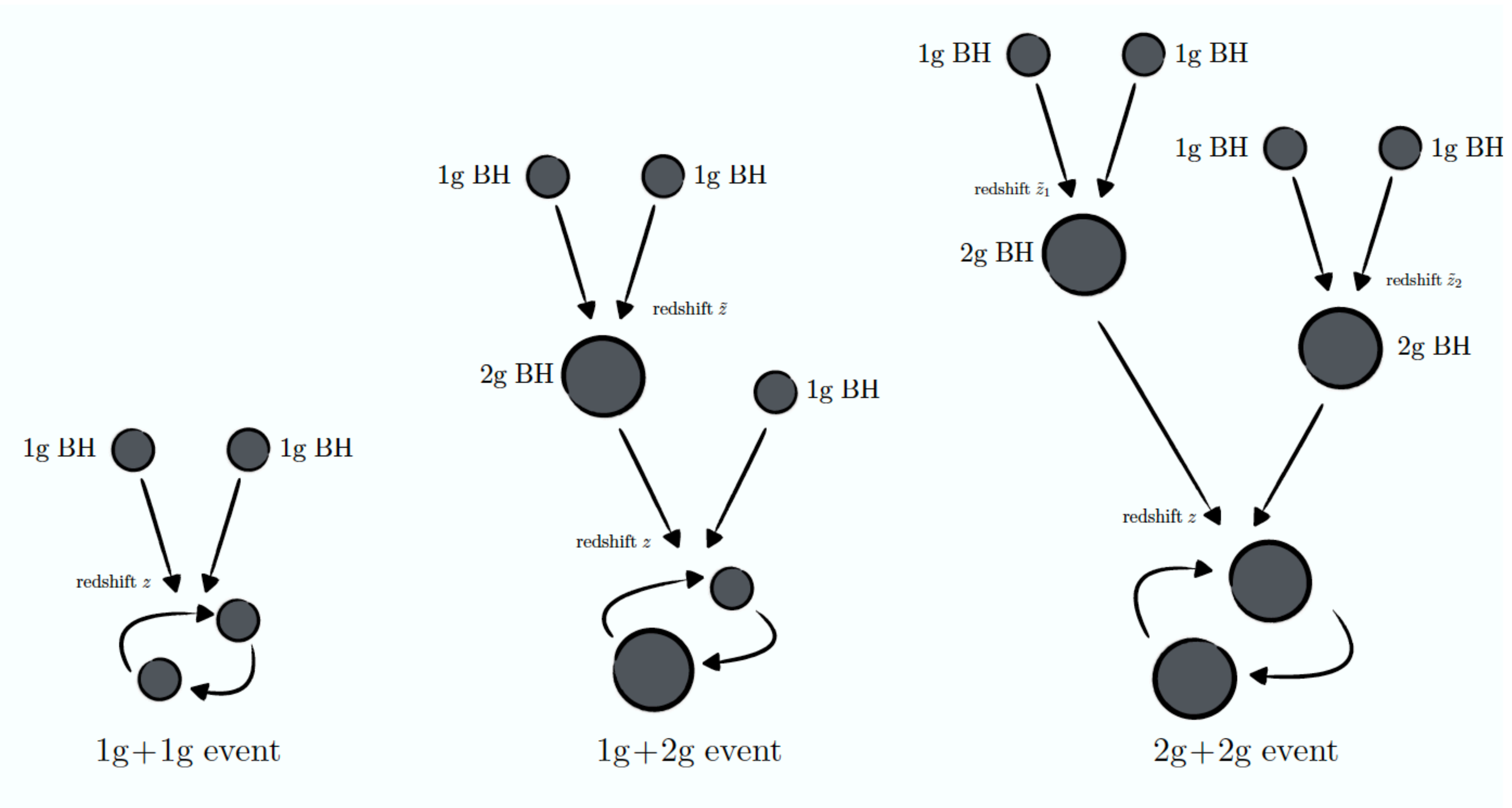
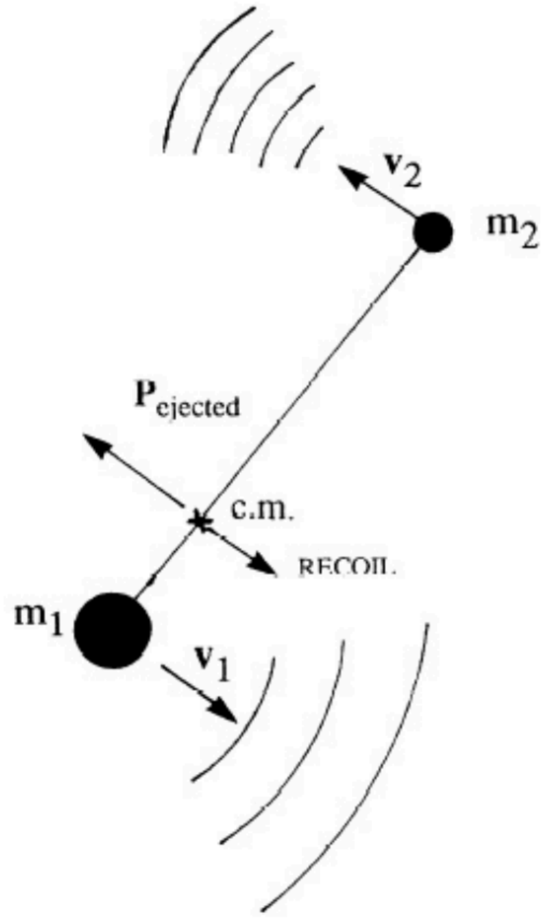
- In a dense star cluster, this merged BH (2G) can pair up and merge with another BH (1G or 2G)
- Most straightforward way for growing BHs
- Problem: Can be difficult to retain a merged BH in a dense environment due to GW recoil kicks

(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



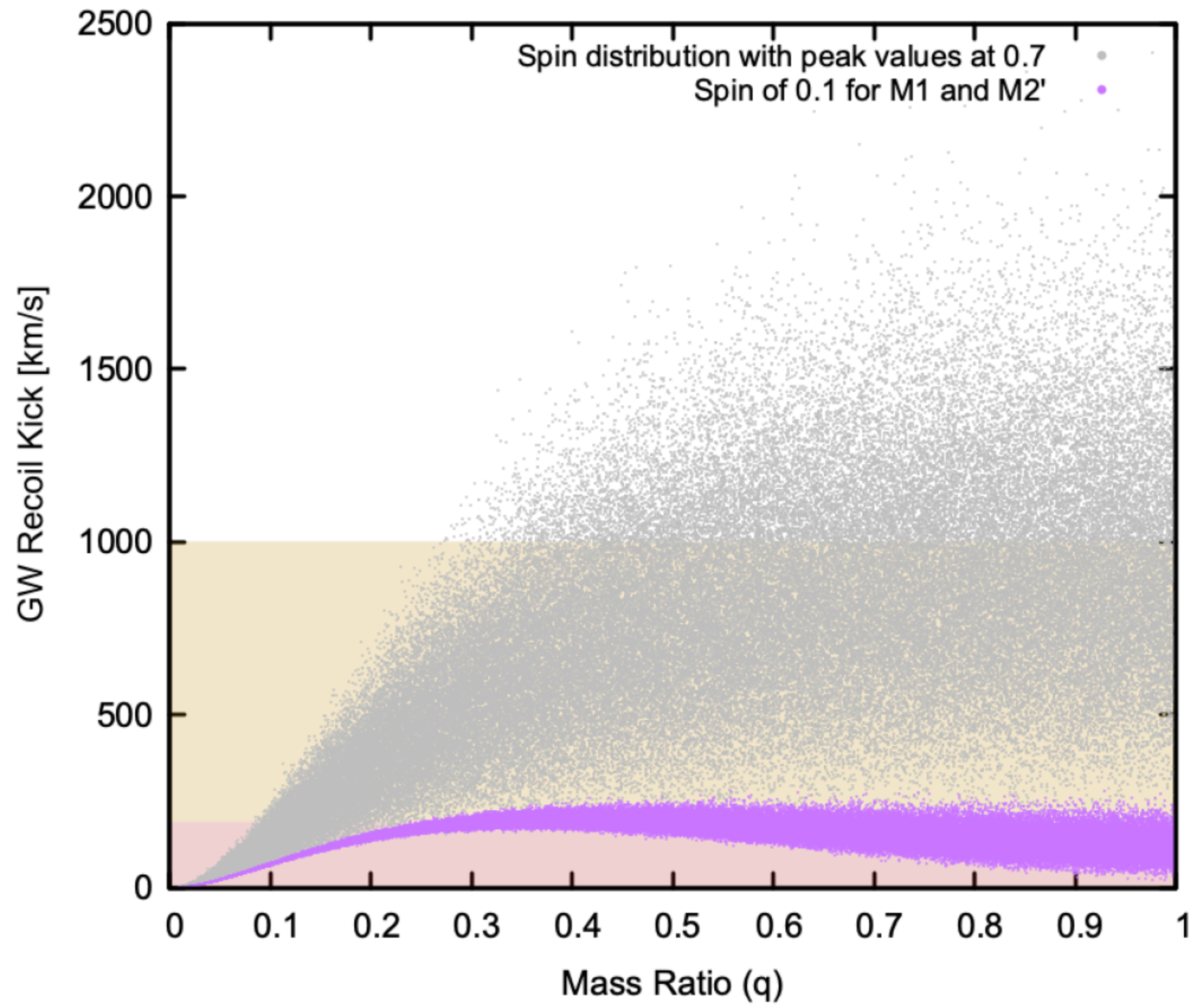
Gerosa & Berti (2017)



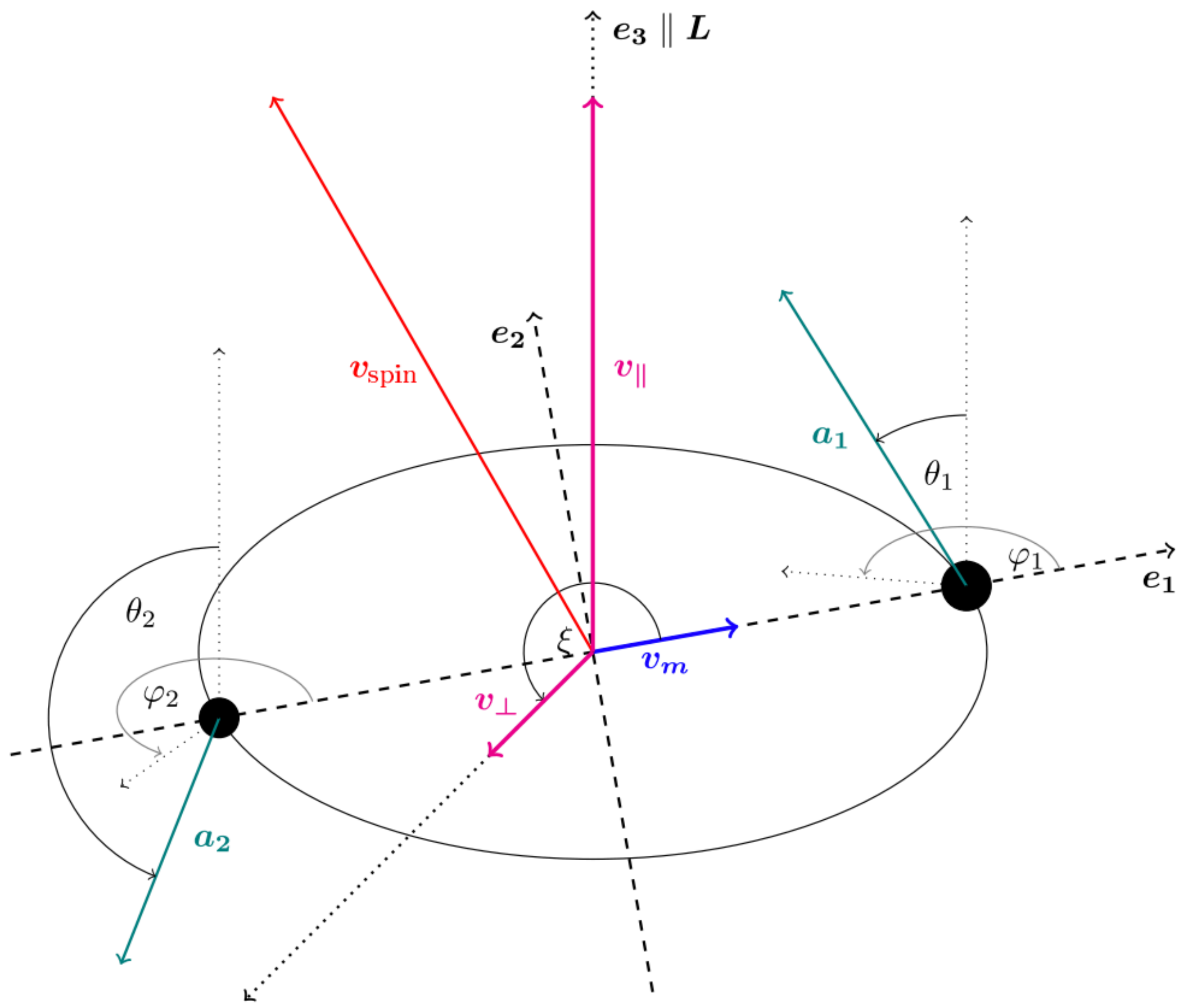
Wiseman (1992)

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)

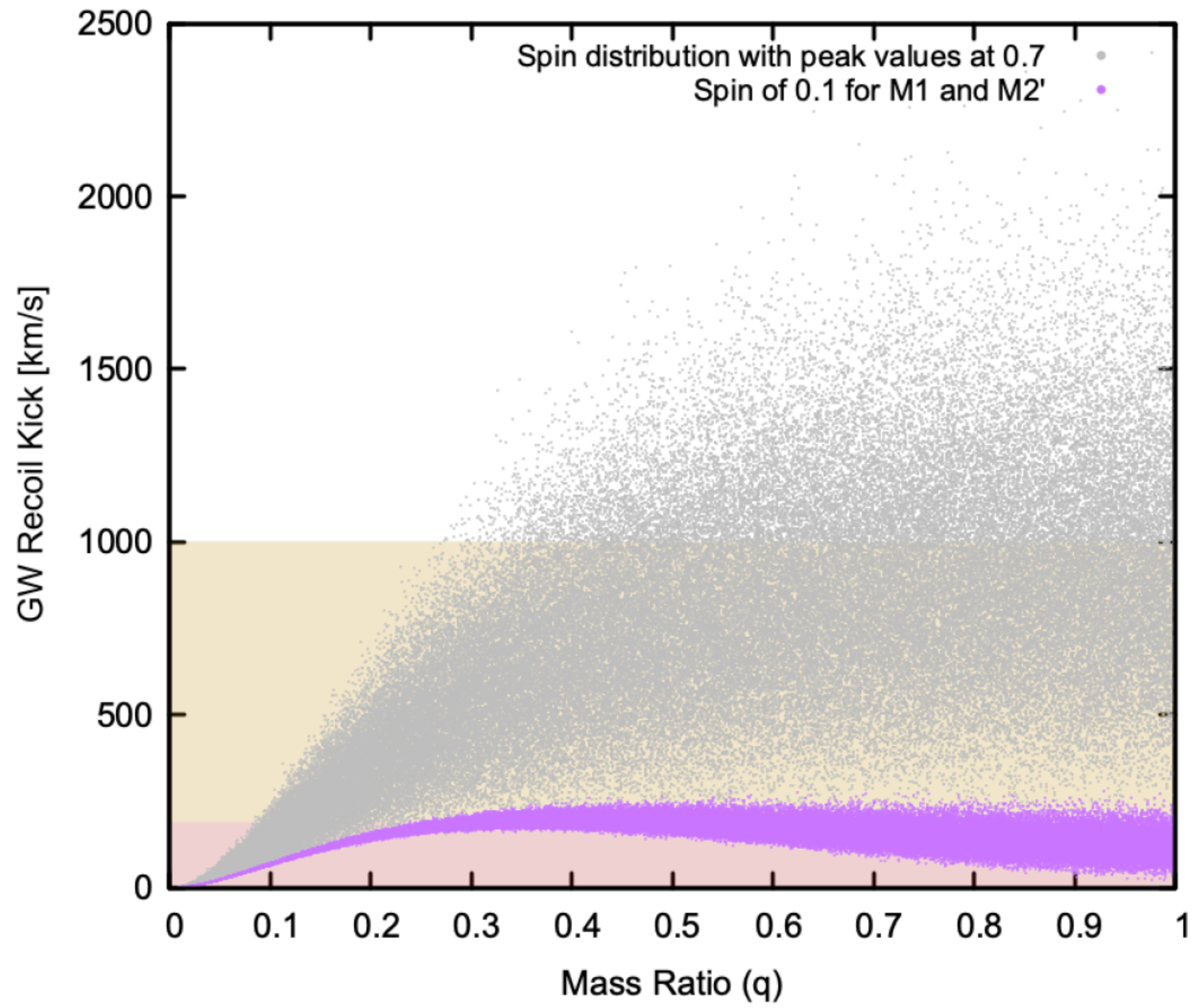


Morawski et al. (2018)

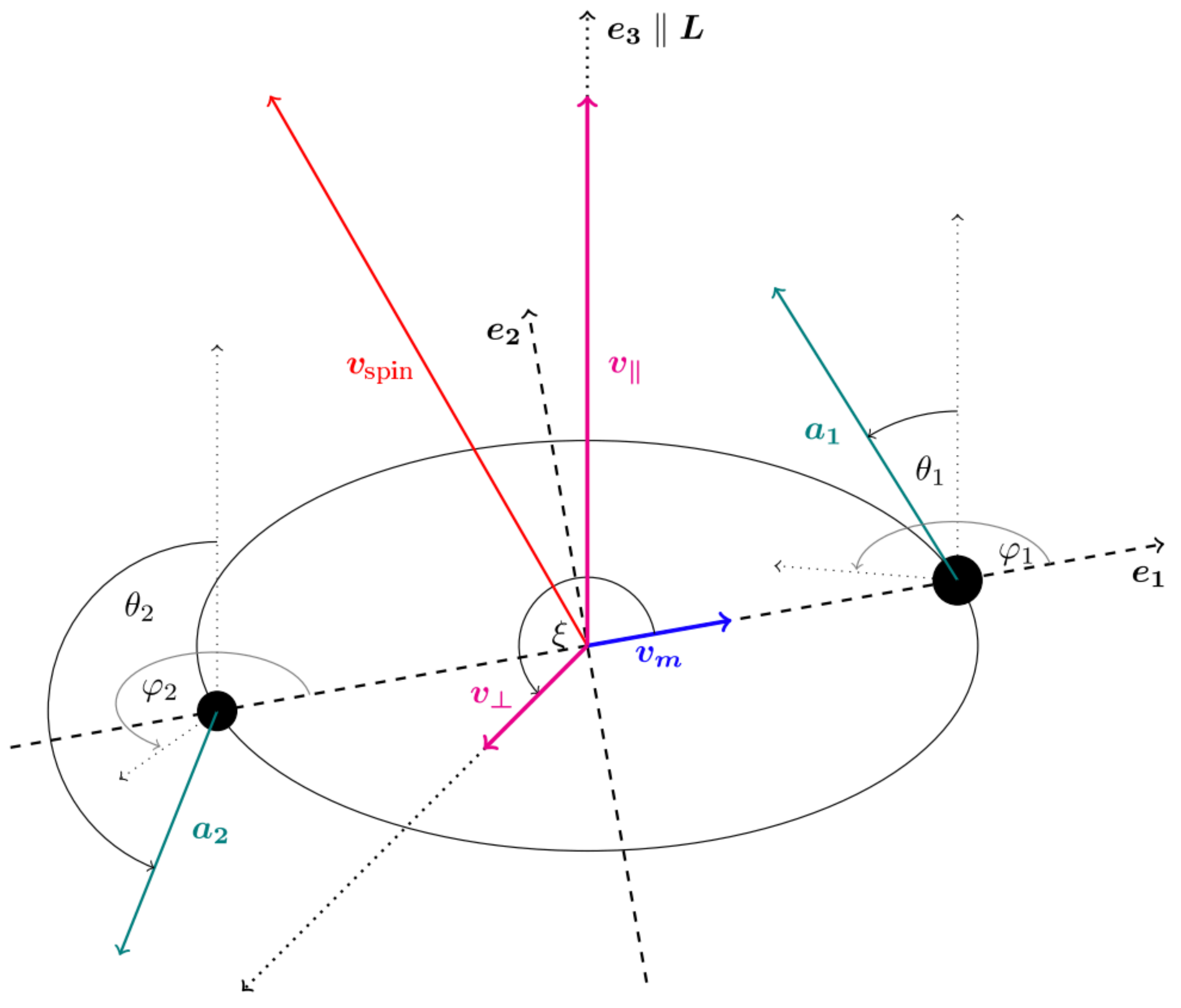
- If sBH birth spins are low then 2G BHs can potentially be retained in environments like globular clusters
  - 2G BHs are likely to have to have large spins values (close to 0.7) → 2G+1G and 2G+2G merger products will receive large recoil kicks → harder to retain 3G and 4G BHs
- Better chances for retaining 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



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 B

Birth spins of BHs are highly uncertain!

2020; Fragione et al. 2022)

Hierarchical mergers of black holes in star clusters: birth spins?

- Highly uncertain:
  - Depends on the efficiency of angular momentum transport during the evolution of the progenitor
  - Very efficient angular momentum transport from core to envelope → very low birth spins for black holes (Fuller & Ma 2019)

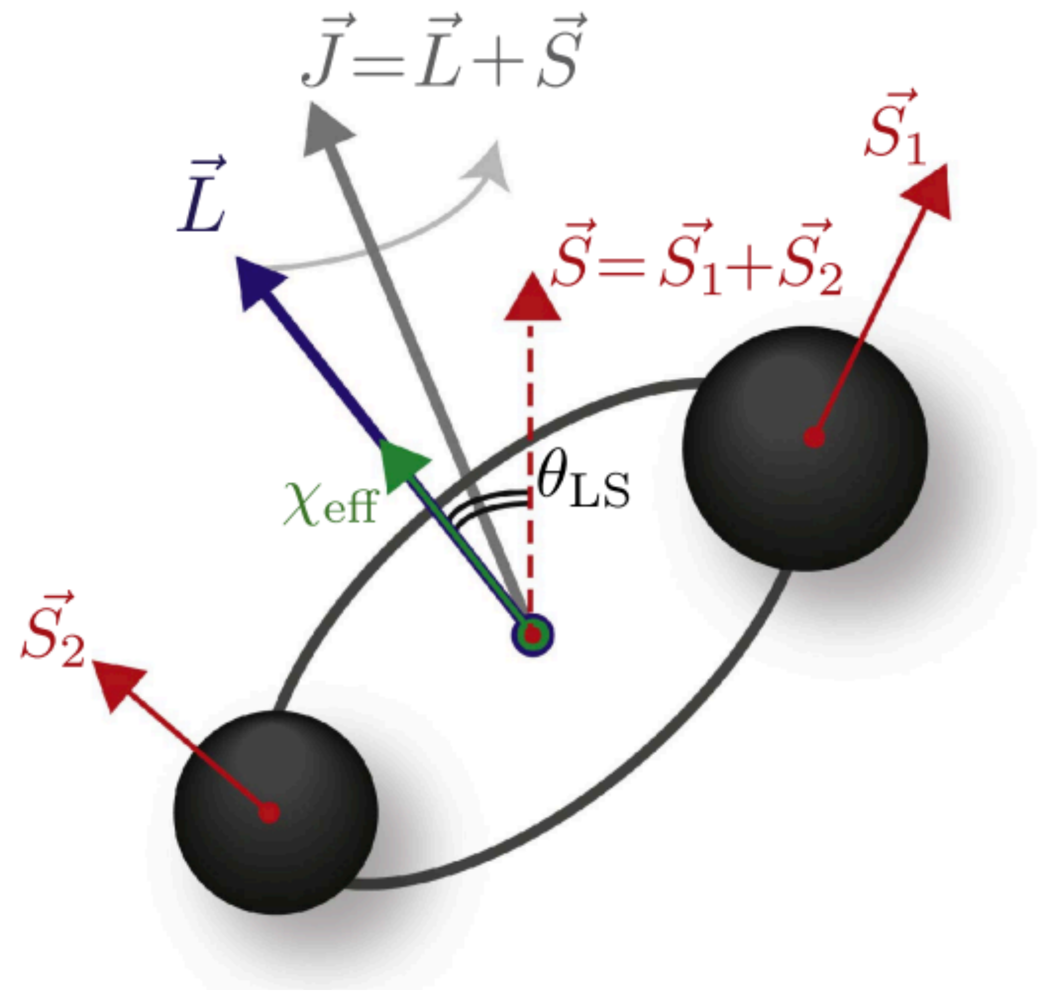
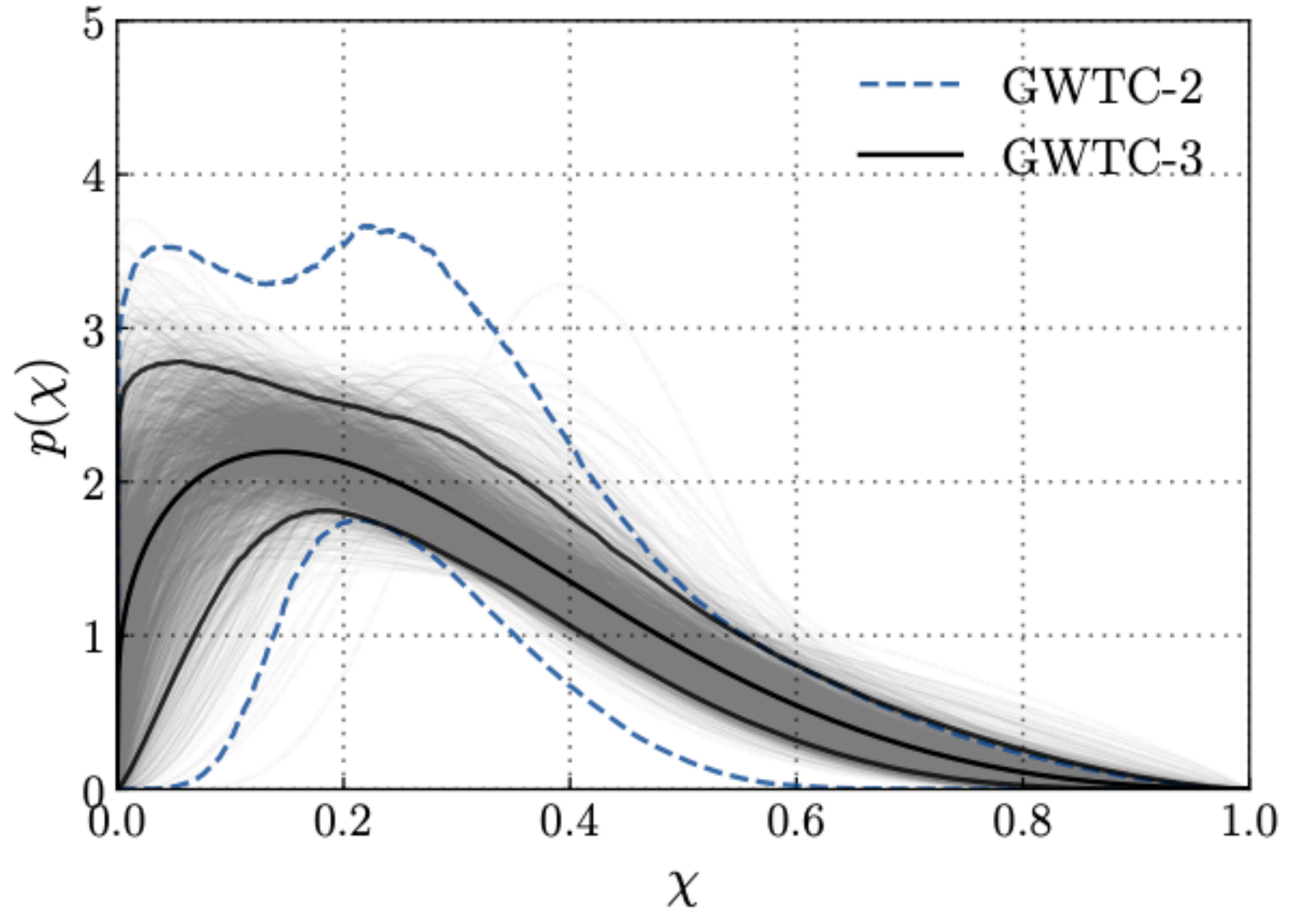
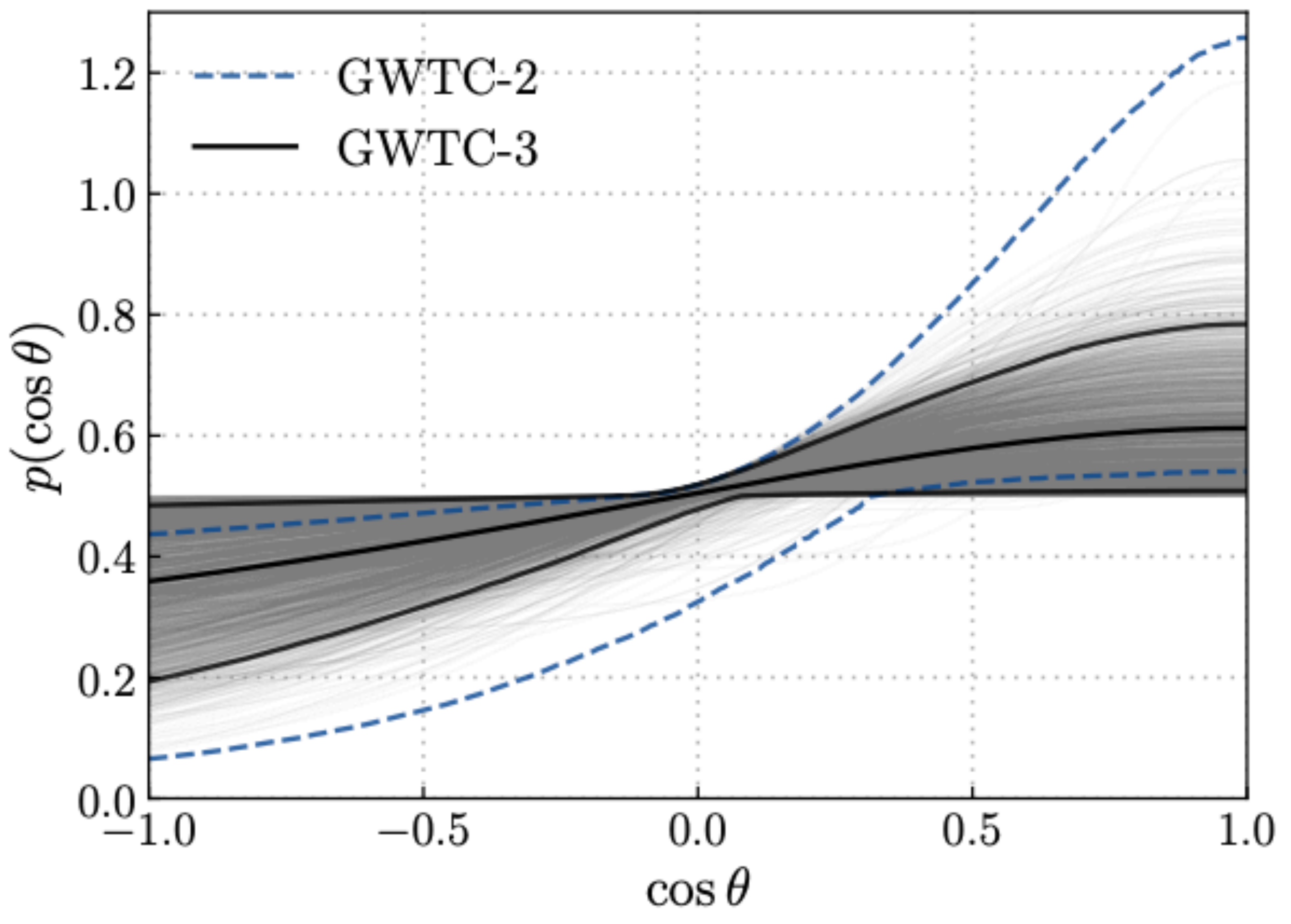


Fig.1 from Rodriguez et al. 2016



Inferred distribution of component spin magnitude

(Abbott et al. 2021; 2023)



Inferred distribution of spin-orbit misalignment

- LVK observations strongly suggest low spin magnitudes and isotropic distribution of spin-orbit misalignment angle
- Consistent with dynamical formation

Upper-mass gap BH Mergers: Results from MOCCA simulations

- Mergers in the mass gap

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

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

R_h = 0.8 pc (ρ_0 = 4 × 10^6 $M_\odot$ pc^{-3}) and 2 pc (ρ_0 = 2.5 × 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)

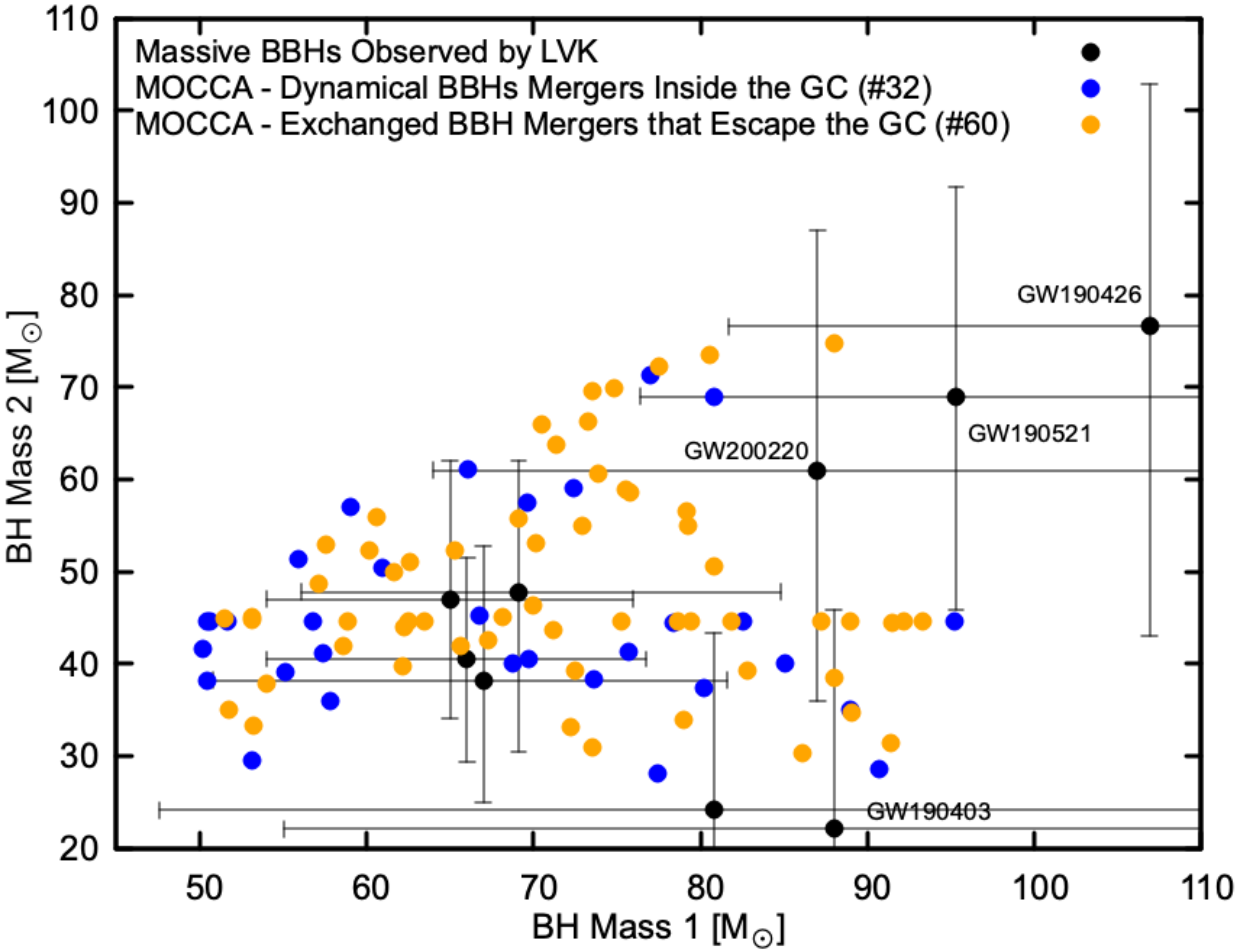
Birth Spins of Black Holes = 0.1 (Fuller & Ma 2019)

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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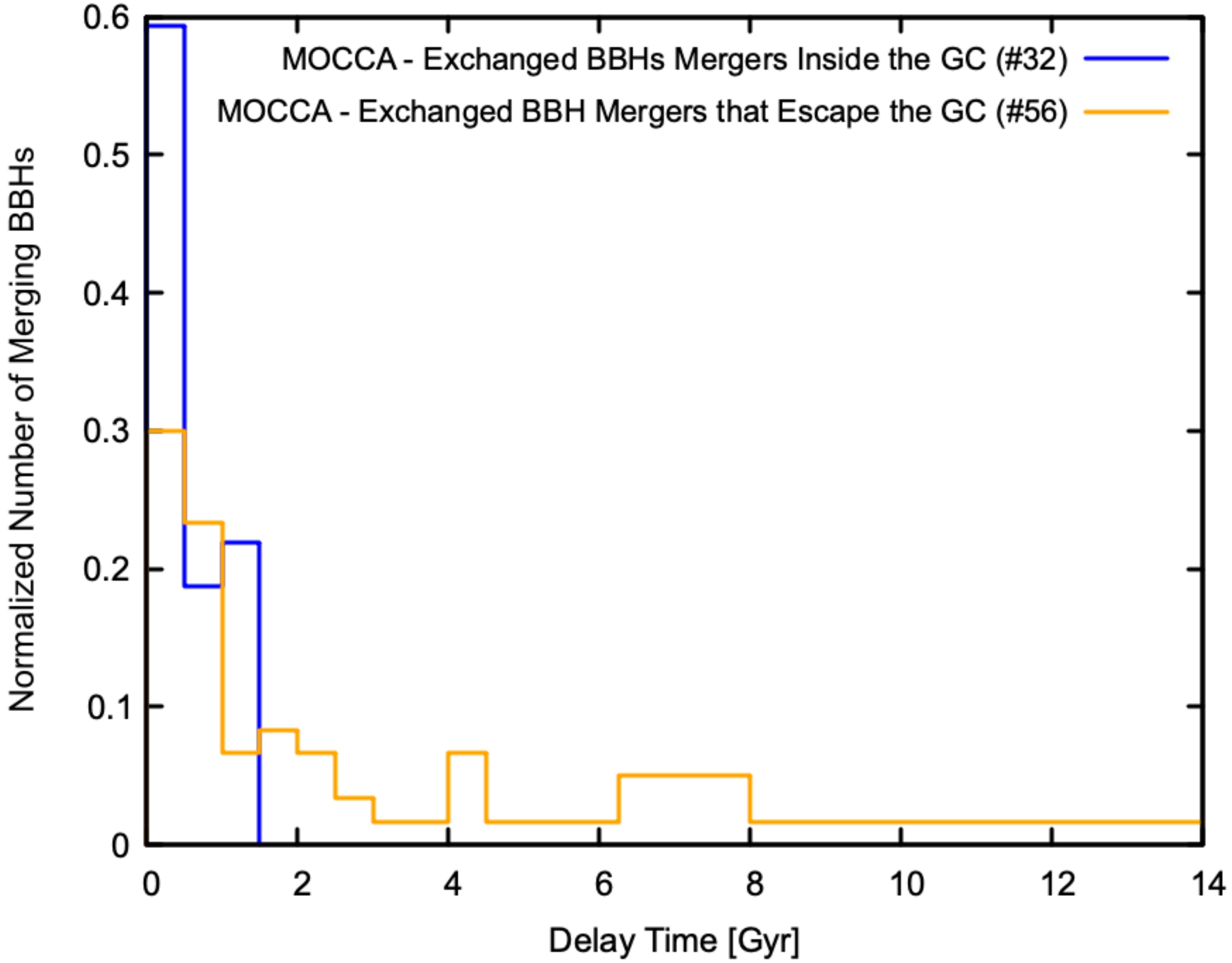


Other pathways for growing black holes in dense star clusters

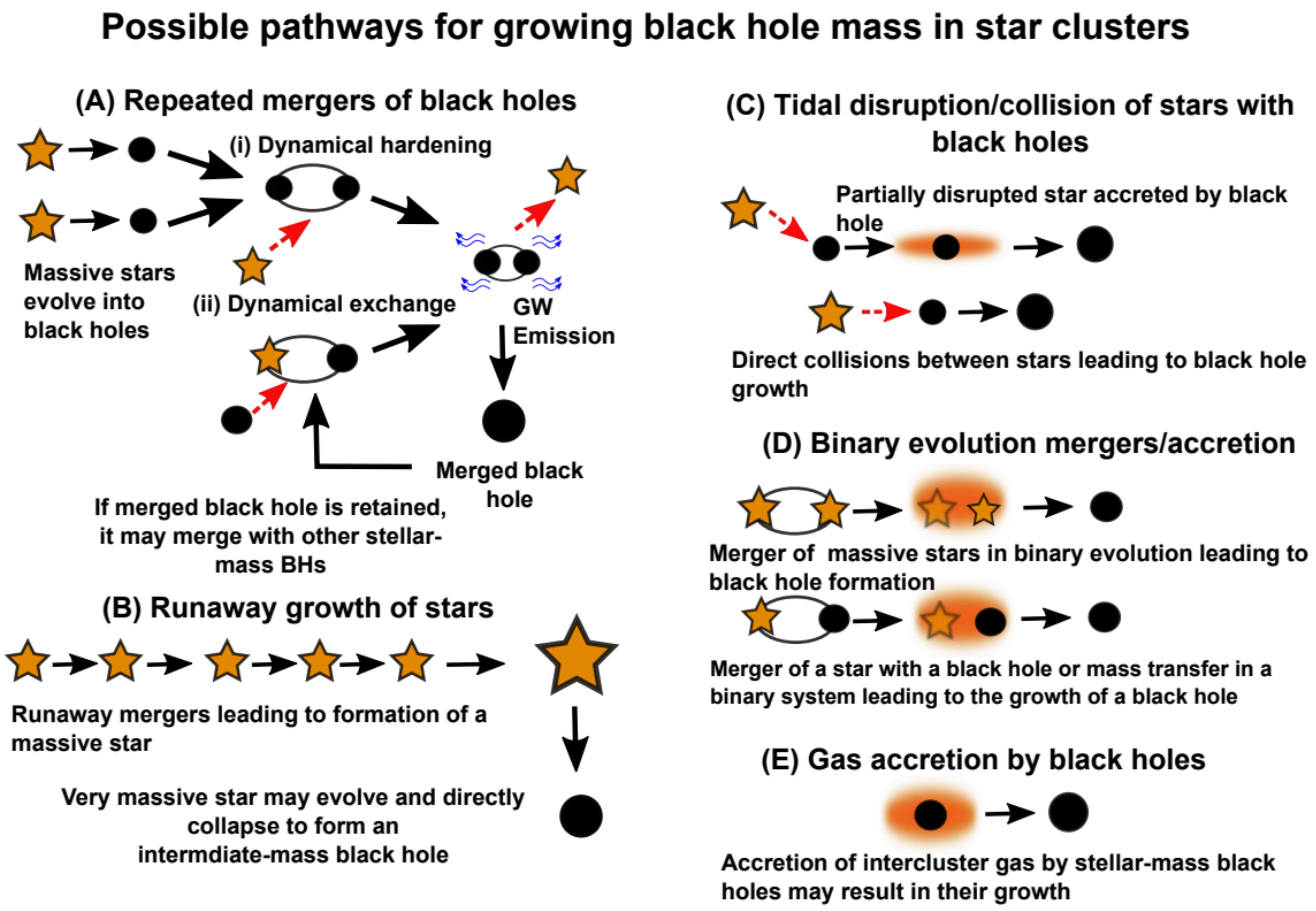
(A) Repeated or hierarchical mergers of stellar-mass BHs

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

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

(D) Binary evolution mergers leading to IMBH formation

(E) Gas accretion by stellar-mass BHs



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

Stellar mergers leading to black holes in the mass gap

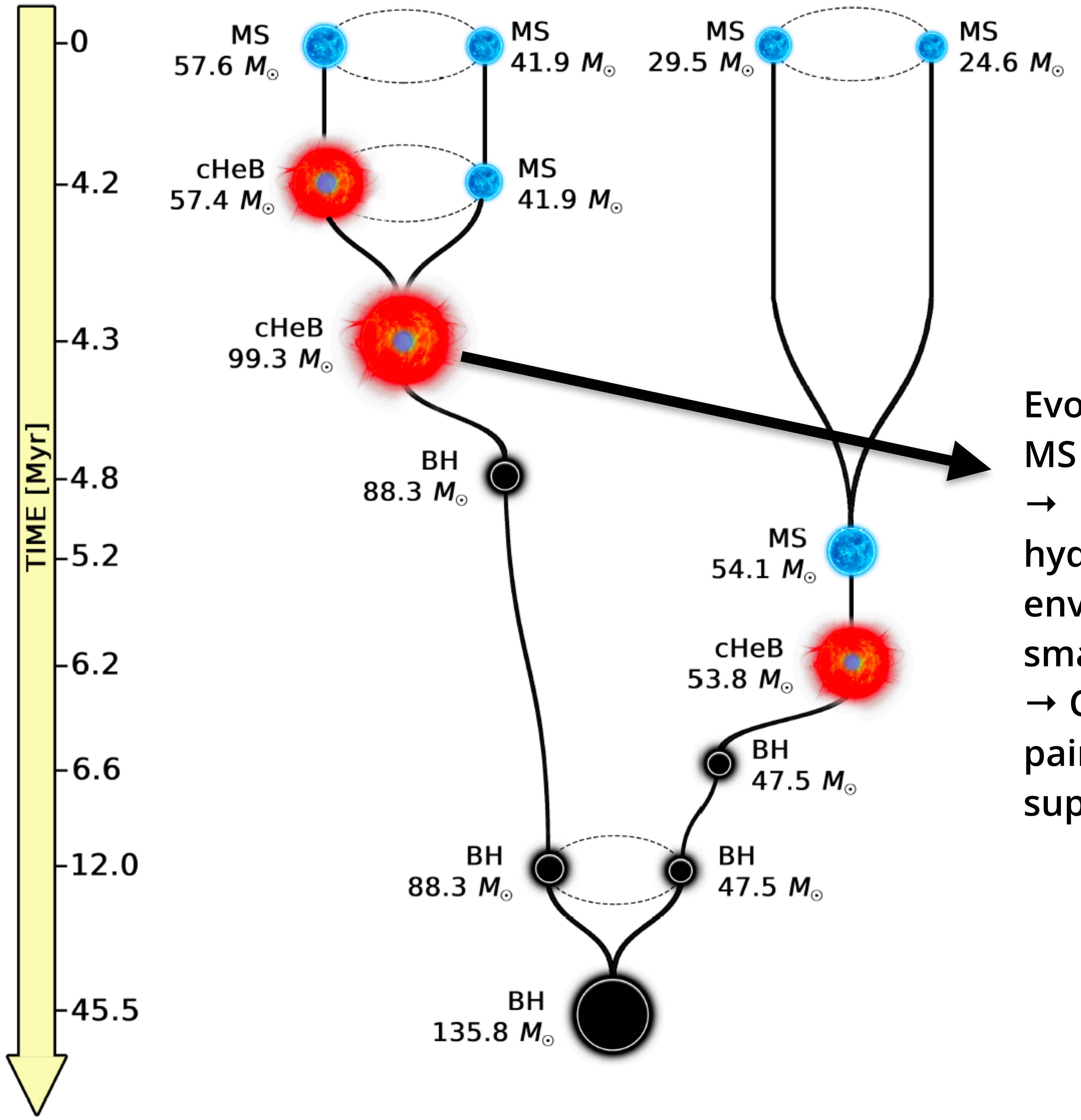


Fig. 7 in Di Carlo et al. 2020

Evolved Star + MS star merger → Massive hydrogen envelope and small He core → Circumvents pair instability supernova

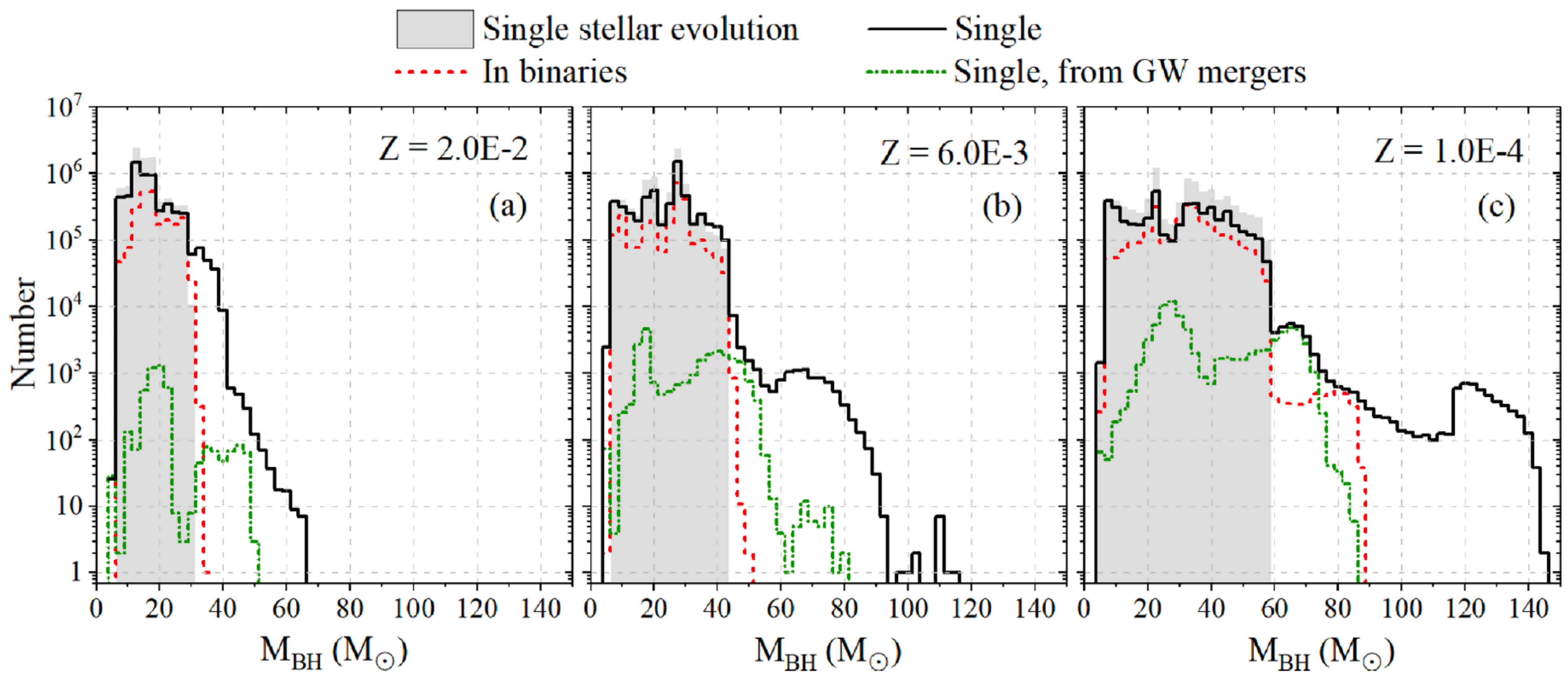


Fig. 4 in Spera et al. 2019 from SEVN population synthesis code

This effect is more pronounced at low metallicity where stellar winds are not strong enough to remove the massive Hydrogen envelope of the merger product. Since such massive BHs are single and very rare ($\lesssim 0.1$ per cent of the total number of BHs at $Z = 10^{-4}$) they do not play a major role in binary population-synthesis simulations. In contrast, they can be very important if they form in star clusters, where they have a high chance to acquire a companion through dynamical exchanges, so that they possibly become loud GW sources (Portegies Zwart & McMillan 2000; Mapelli 2016; Askar et al. 2017).

See also Ballone et al. 2022 and Costa et al. 2022: Hydrodynamical simulations of a stellar merger + stellar evolution of post-collision star with PARSEC and MESA → Circument pair-instability supernova → 87 $M_\odot$ black hole

Challenges and outlook

- **How accurate and representative are our star cluster models?**
  - **Initial Conditions:** Are we capturing the full diversity of dense stellar environments?
    - Poorly constrained at high redshift: initial mass, metallicity, tidal field evolution, primordial multiplicity fraction, and binary parameter distributions
  - **Input Physics:** Uncertainties in stellar/binary evolution, treatment of stellar mergers and tidal field of host galaxy
  - Major unknowns: stellar winds, remnant masses, natal kicks, common envelope efficiency, supernova models
  - Stellar mergers → runaway collisions and binary mergers → implications for very massive stars and IMBH formation
  - Evolving tidal field in which the star cluster evolves → cosmological evolution of host galaxy's
- Predictive power of numerical simulations requires stacked assumptions
  - Merger rate predictions rely on multiple assumptions holding simultaneously
    - Correct cosmological cluster formation history, accurate input physics and sampling of cluster types and properties
- Path Forward: Anchoring models in observations
  - Incorporate broader observational priors (e.g., input physics, cluster metallicities, binary fractions, galactic environments)
  - Need for better observations and models that can reproduce specific systems and global cluster properties

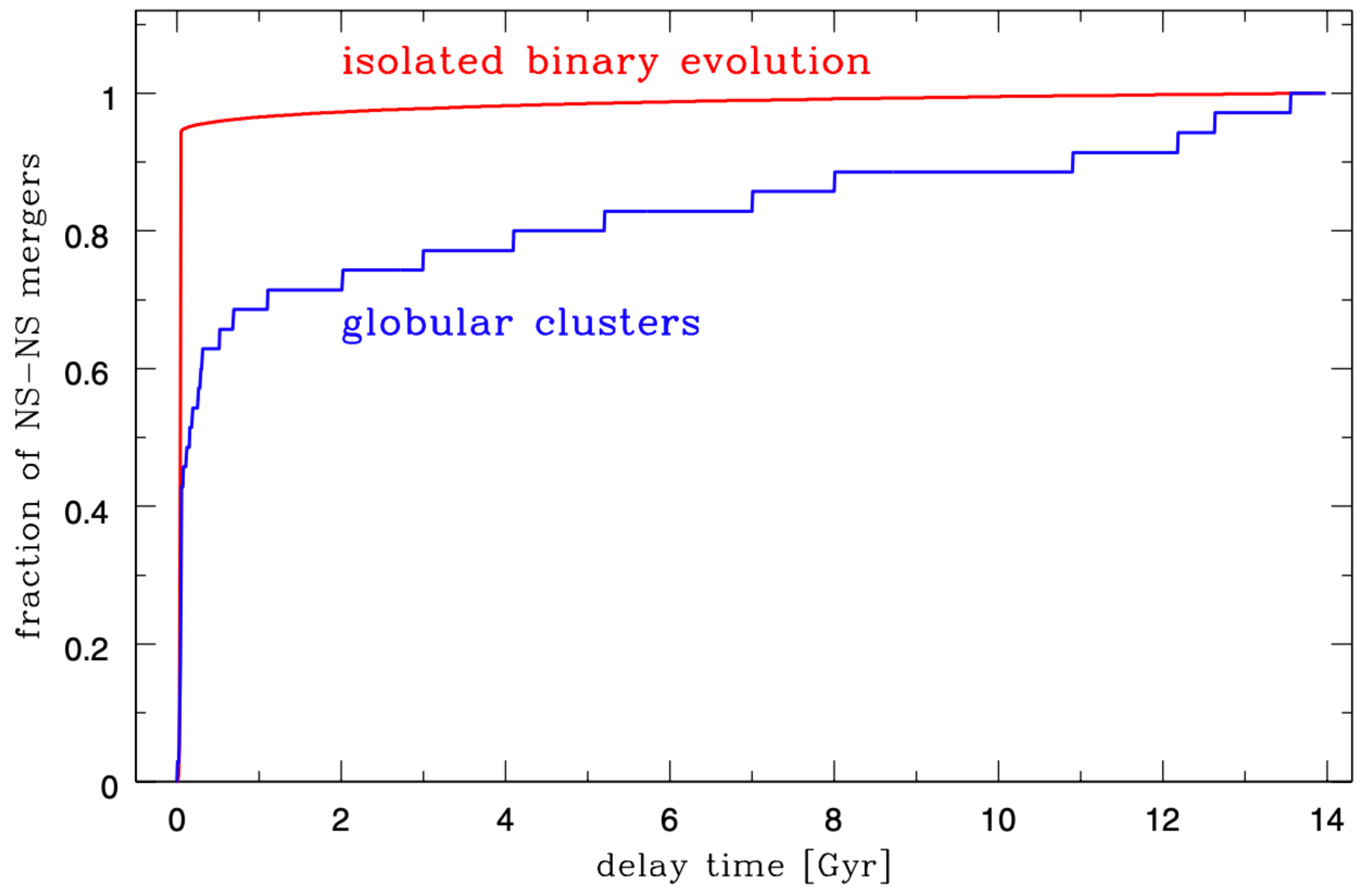
Conclusions

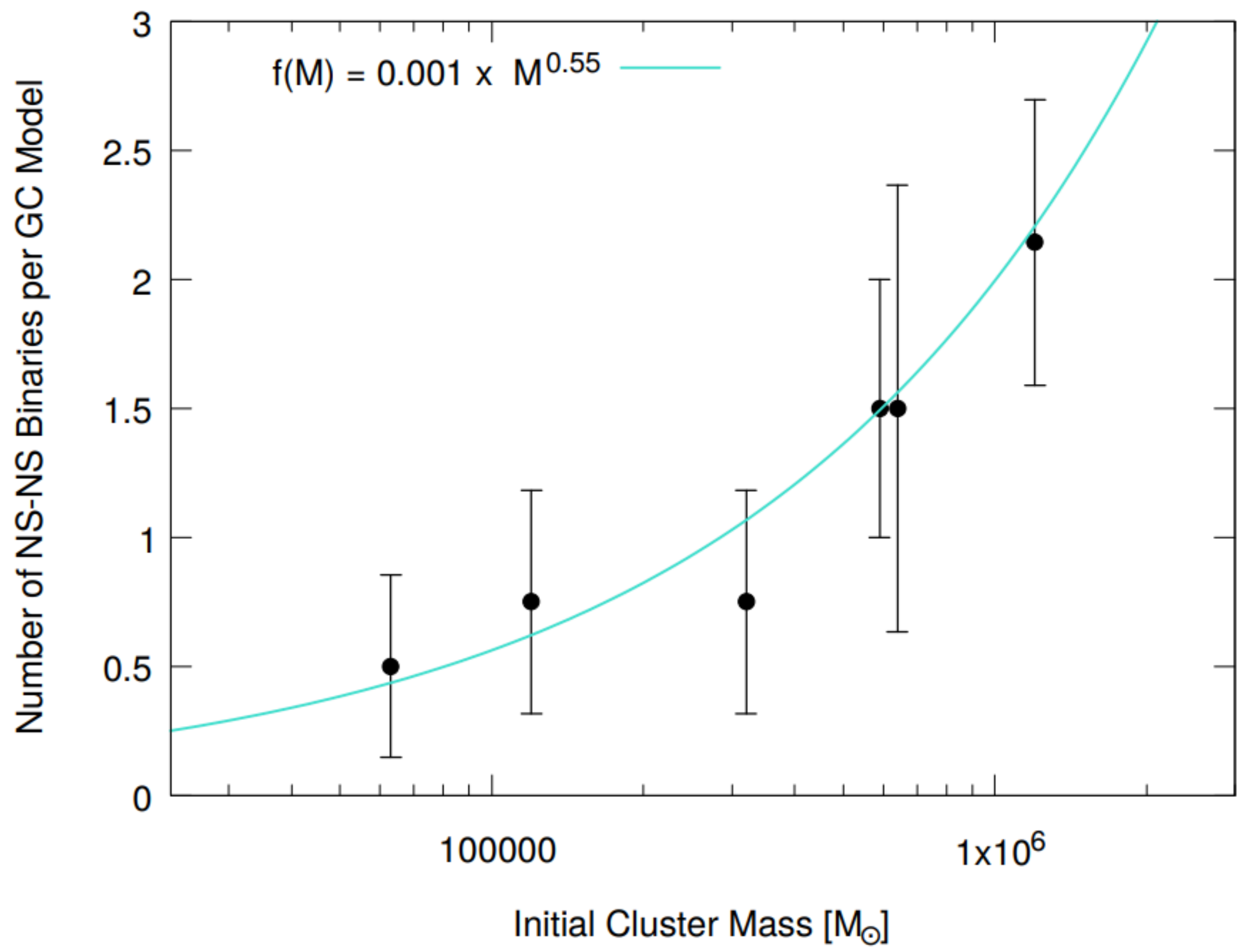
- Initial black hole retention in stellar clusters depends on the natal kicks that they receive
- Dense clusters can efficiently form 'useful' binary black holes through dynamical interactions:
  - Major channel: Exchange during binary-single encounters
  - Binary black holes can be hardened and made '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 (electron-capture supernovae kicks → few km/s)
  - 21 ‘useful’ neutron stars escape the cluster and 13 merge inside the cluster
  - Local merge rate densities of $0.05\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$



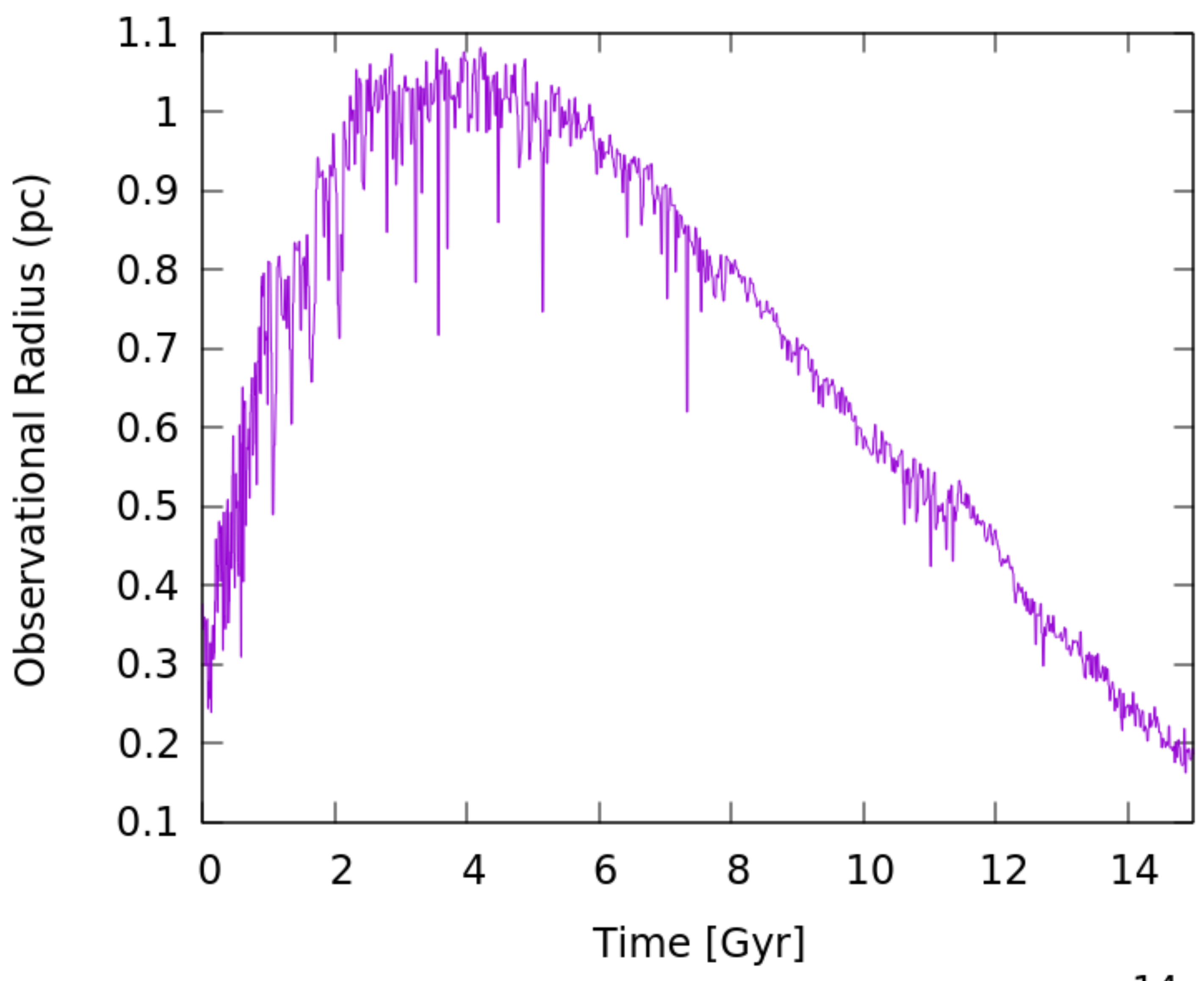


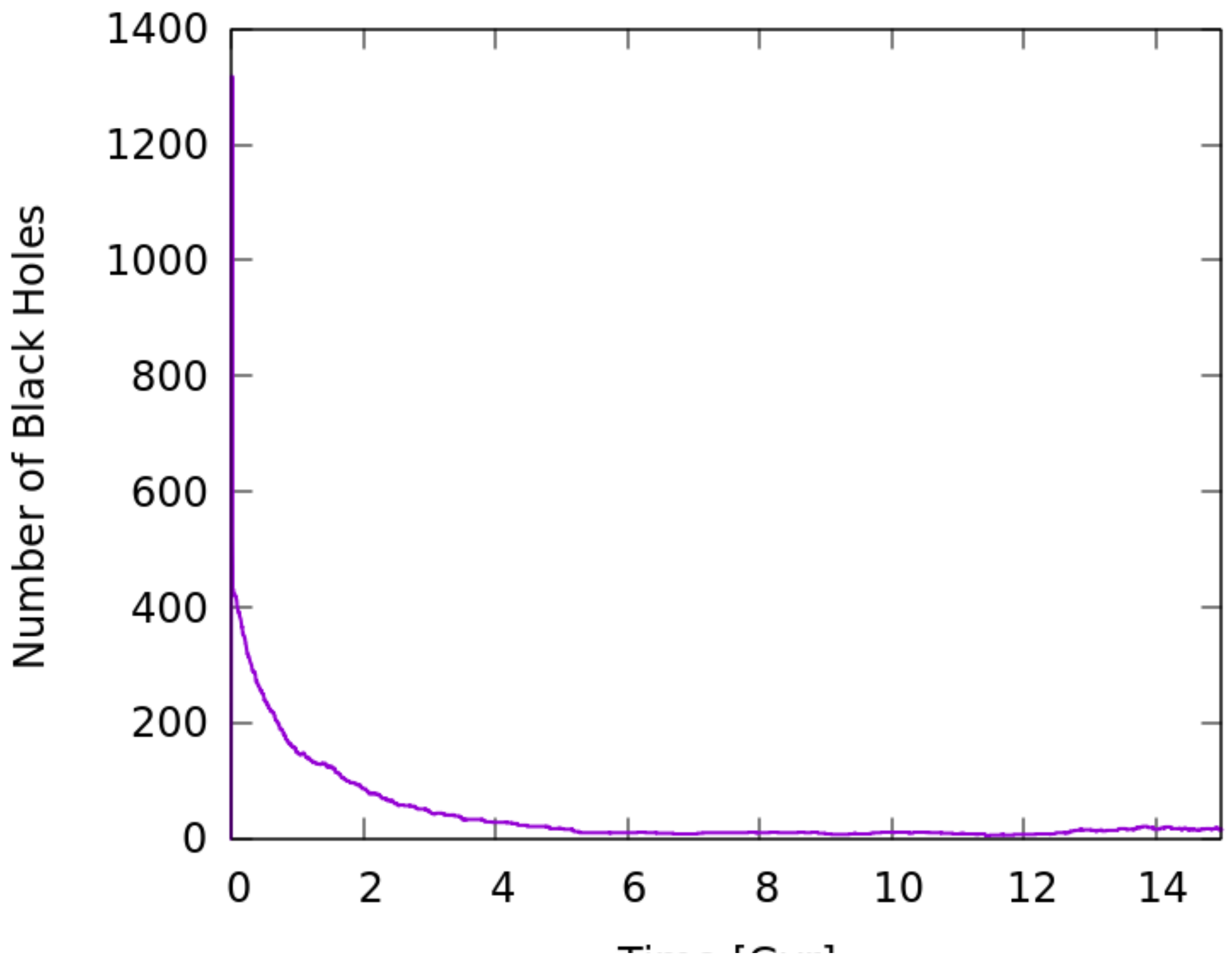
Figures from Belczynski, Askar et al. 2018

Back holes delay BNS formation in globular clusters

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

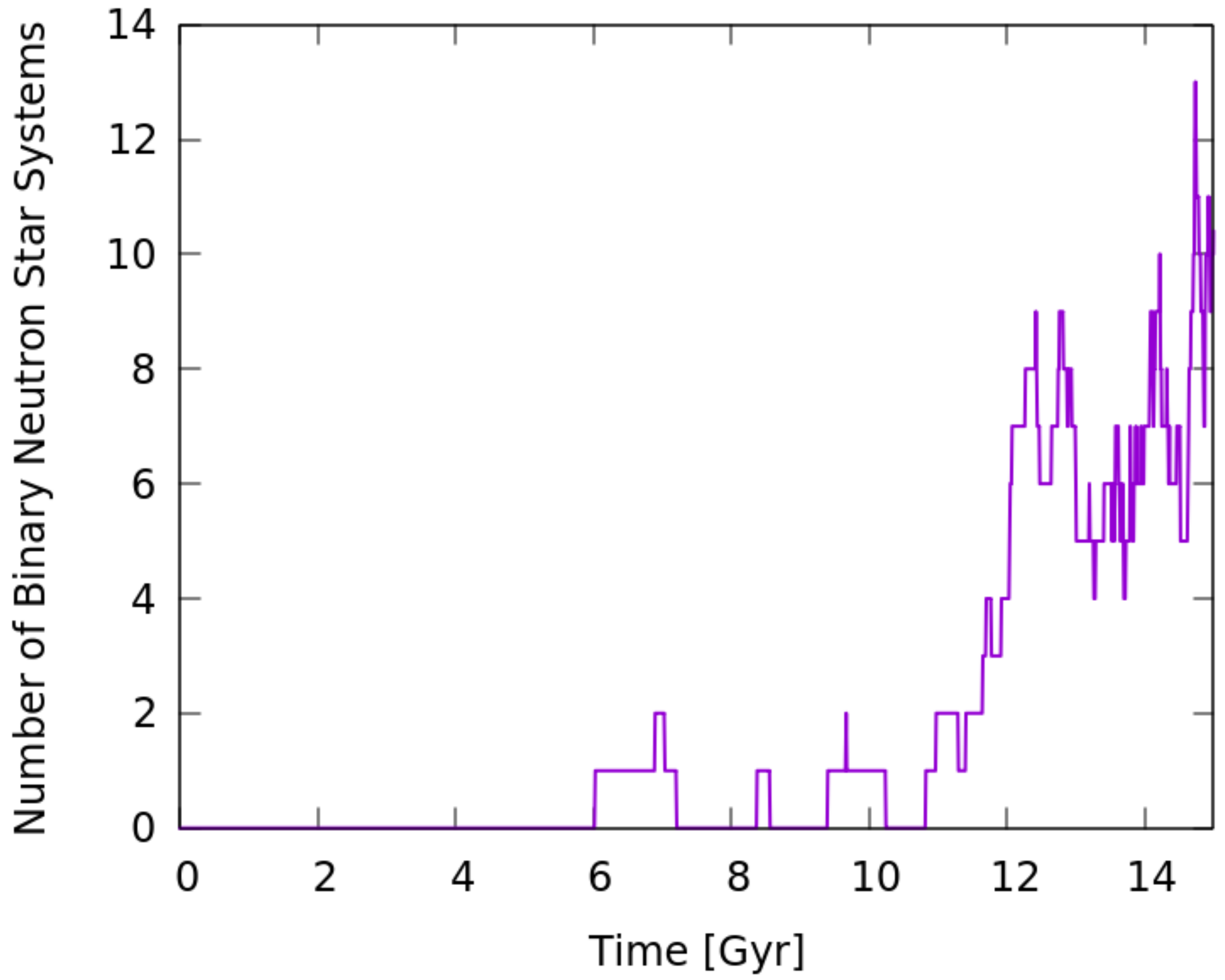
- BHs in the GC center 'heat' stars around them, preventing segregation of lower mass stars



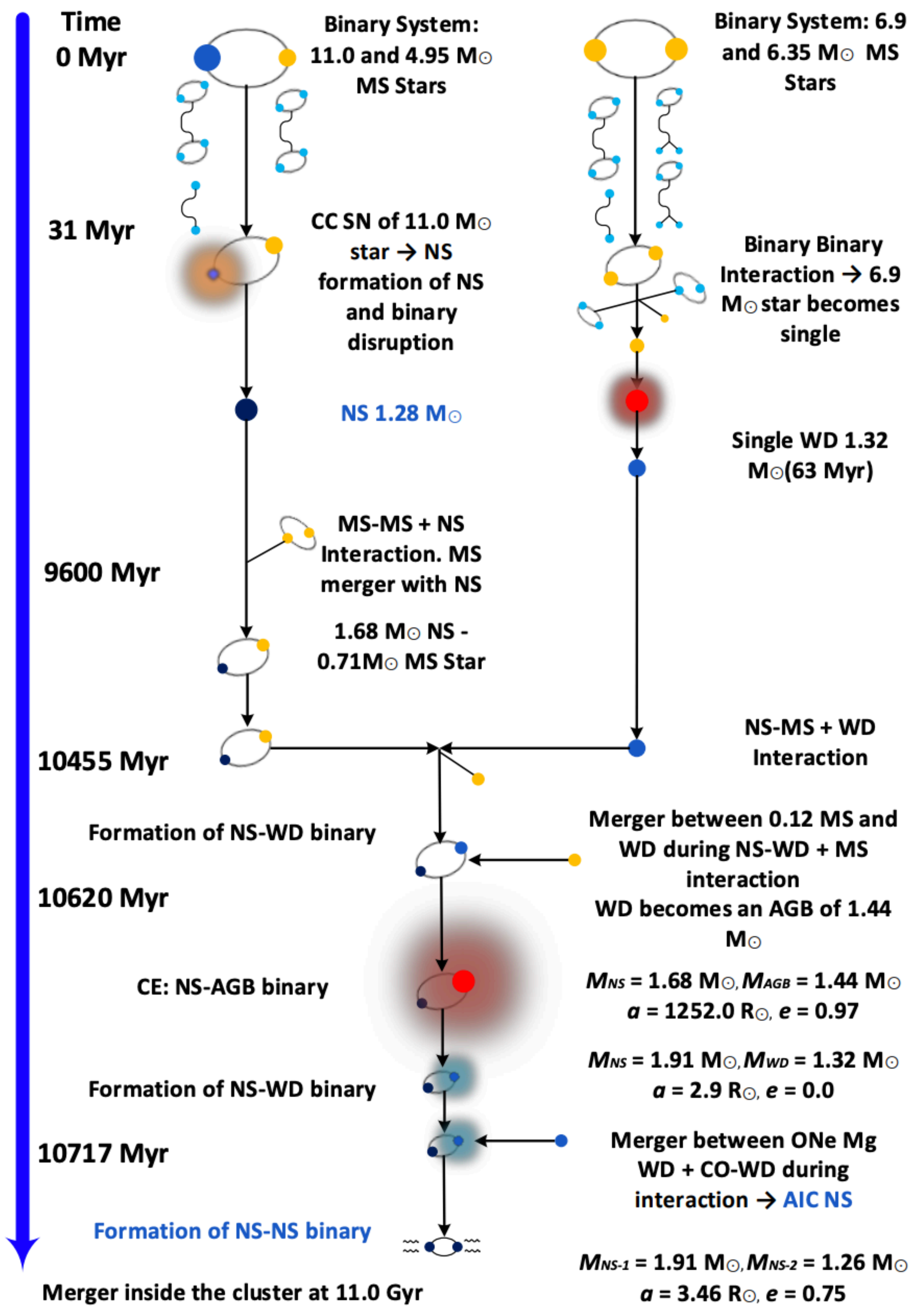


2 observed binary NS in Galactic globular clusters:

- 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

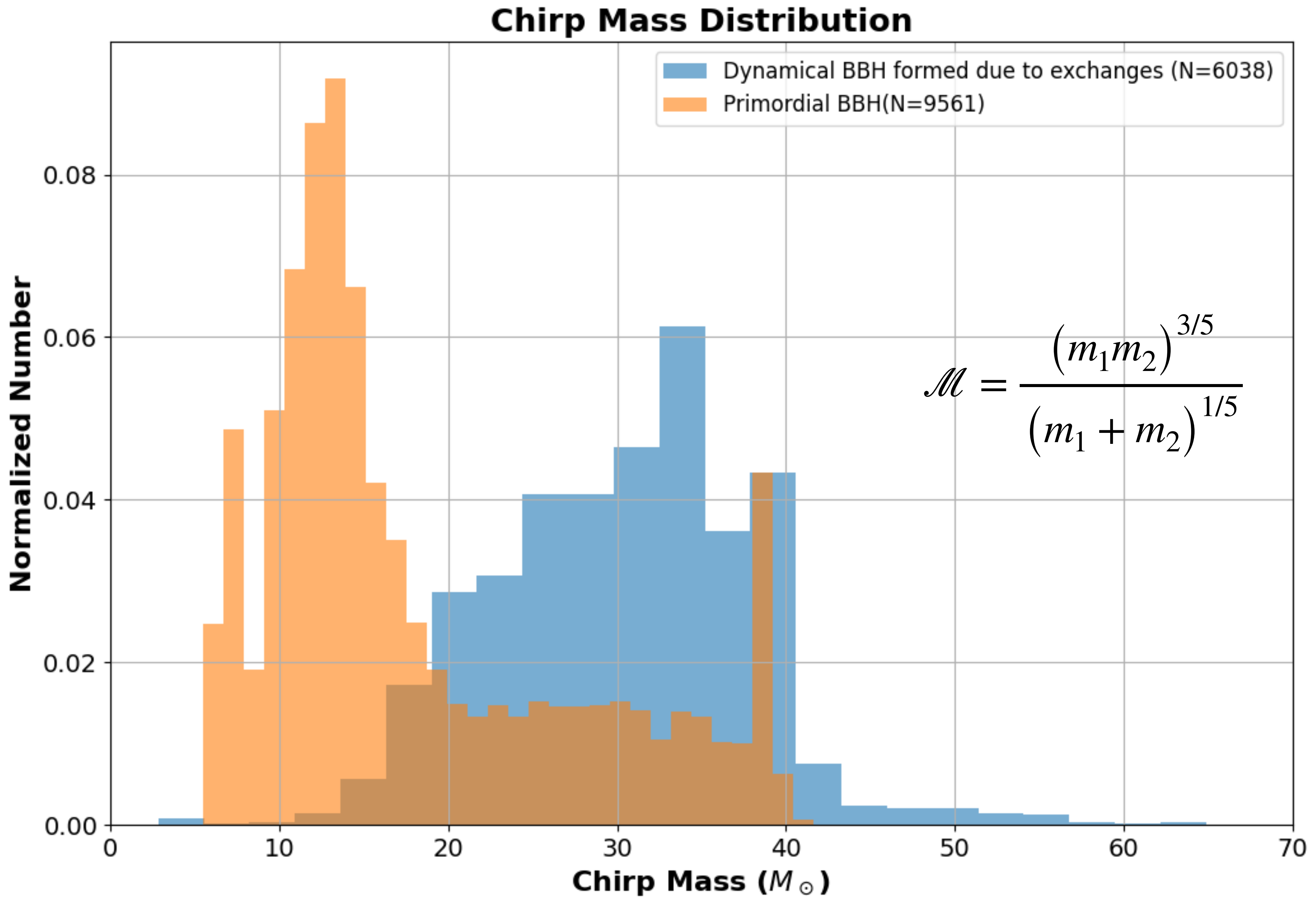


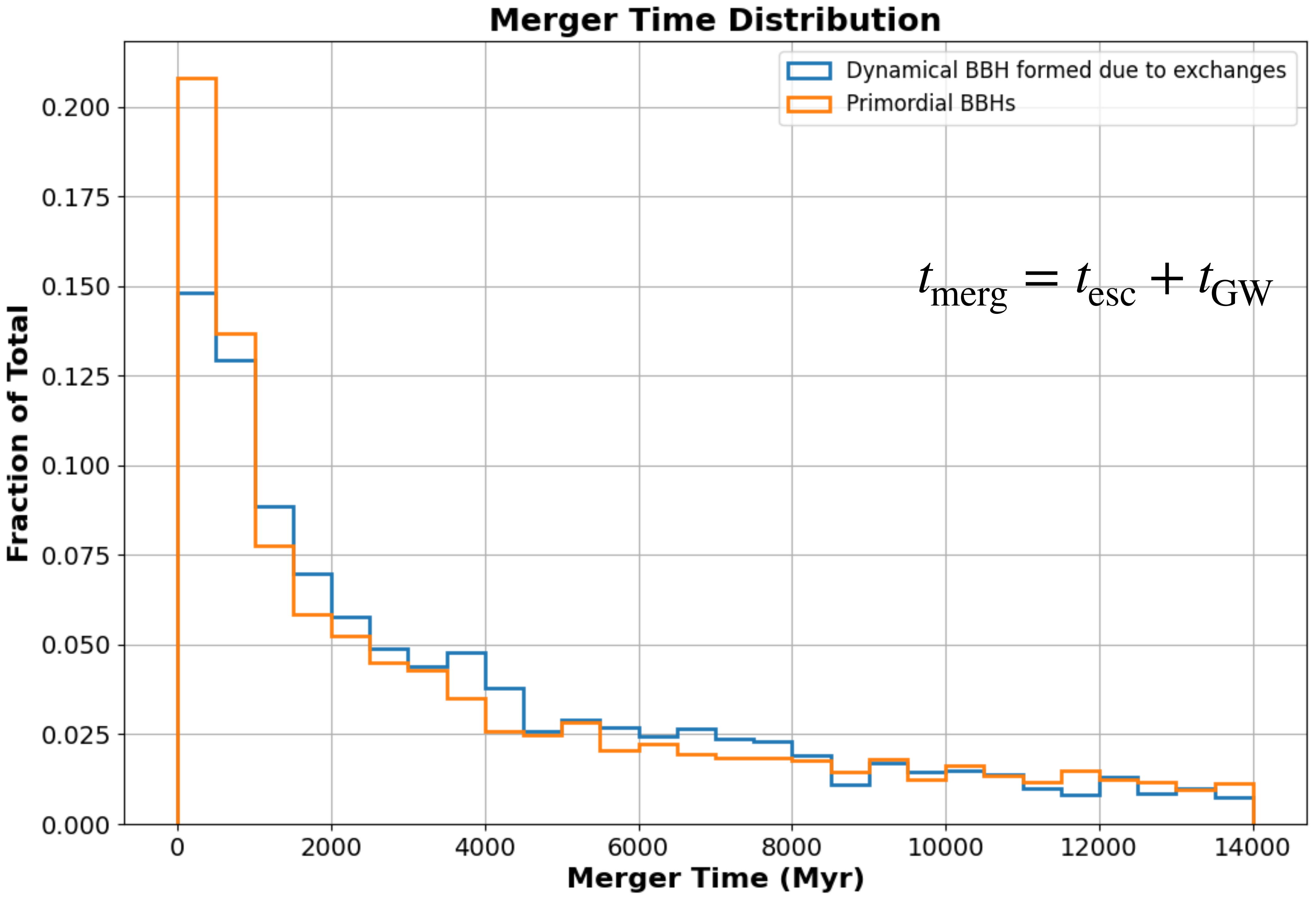
Binary neutron star mergers from globular clusters



From Belczynski, Askar, Arca Sedda et al. 2018

Producing binary black holes in globular clusters

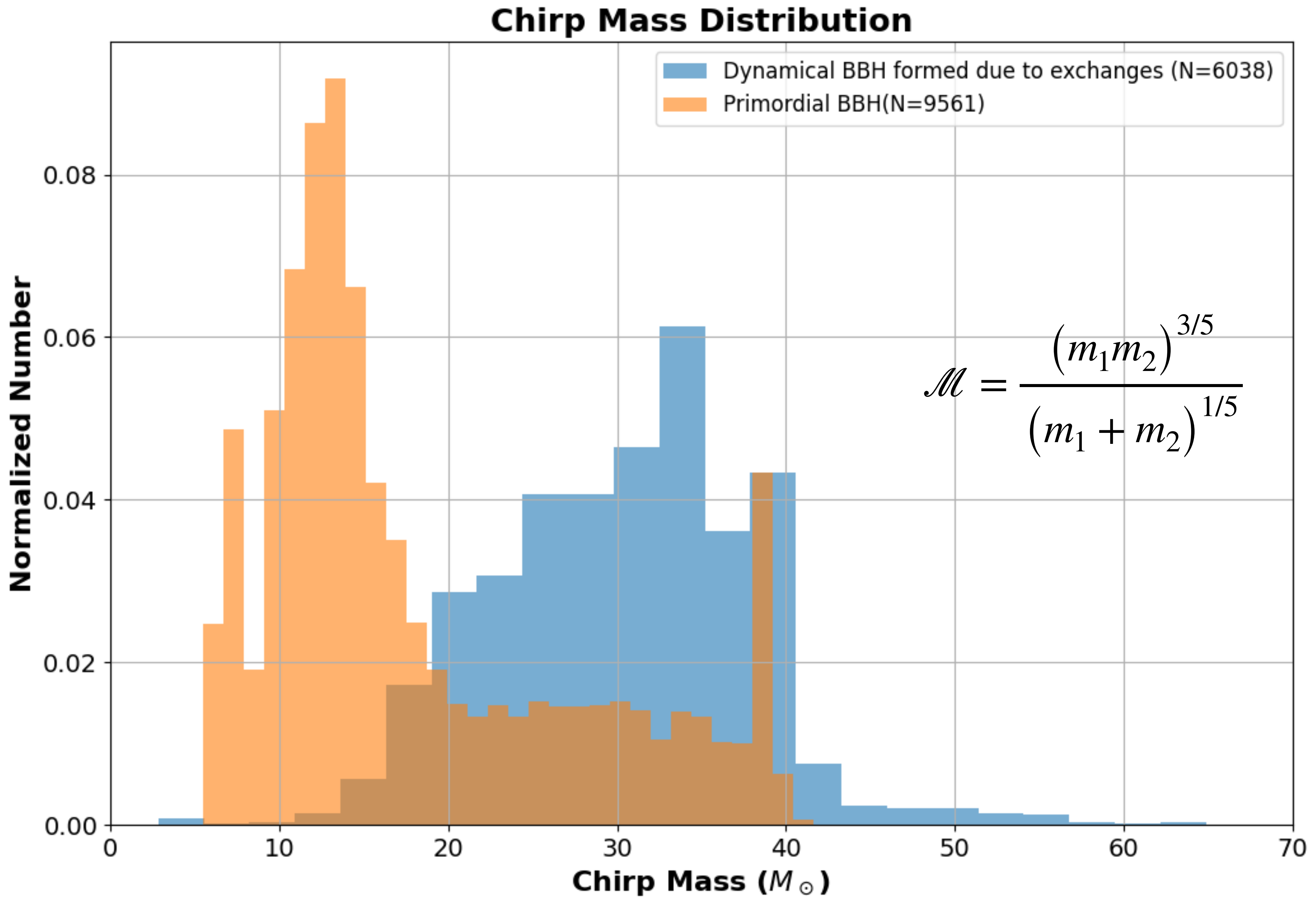


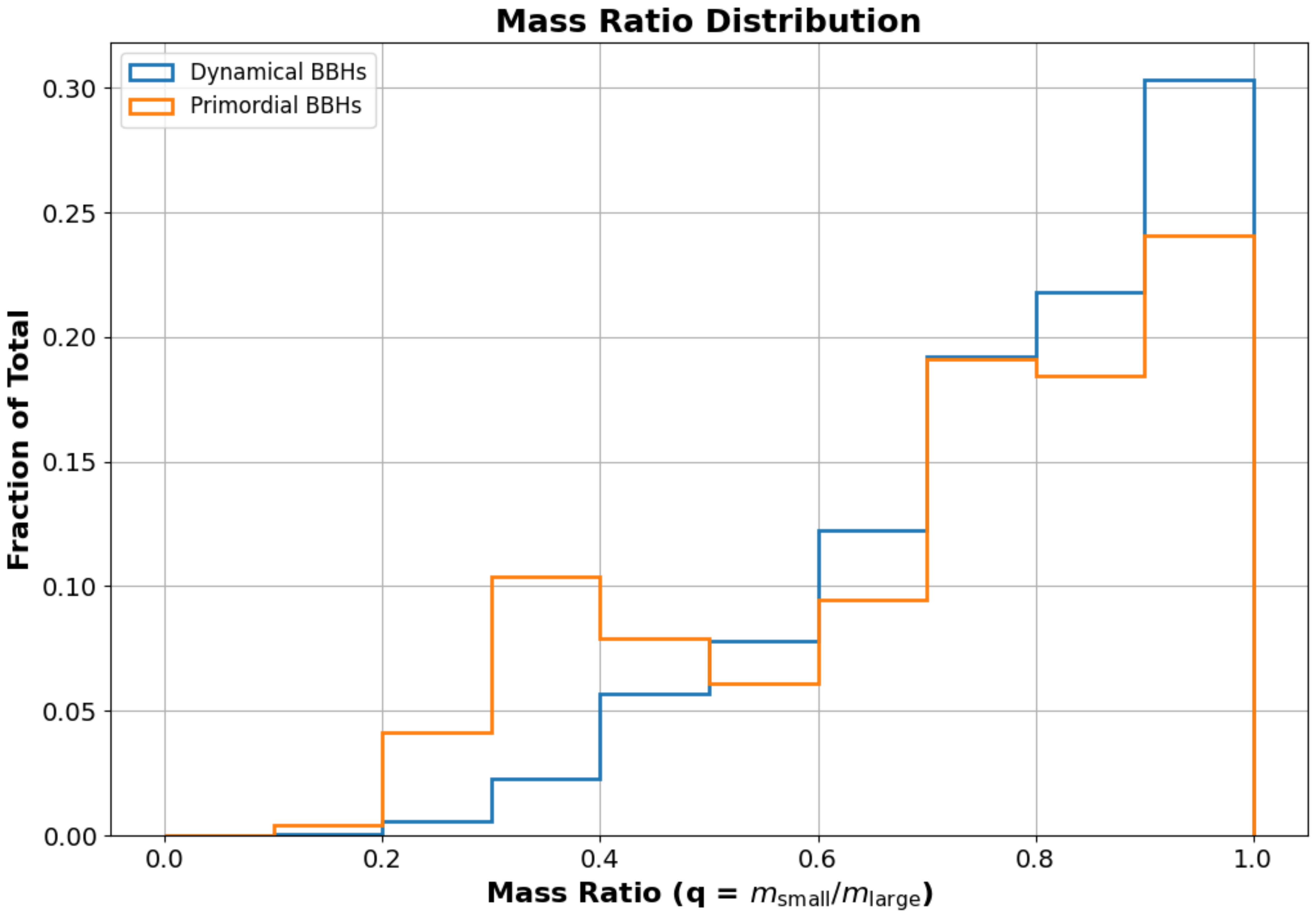


Consequence of using Sana et al. (2012) distribution for initial binary parameters

New MOCCA Models from 2024

Producing binary black holes in globular clusters





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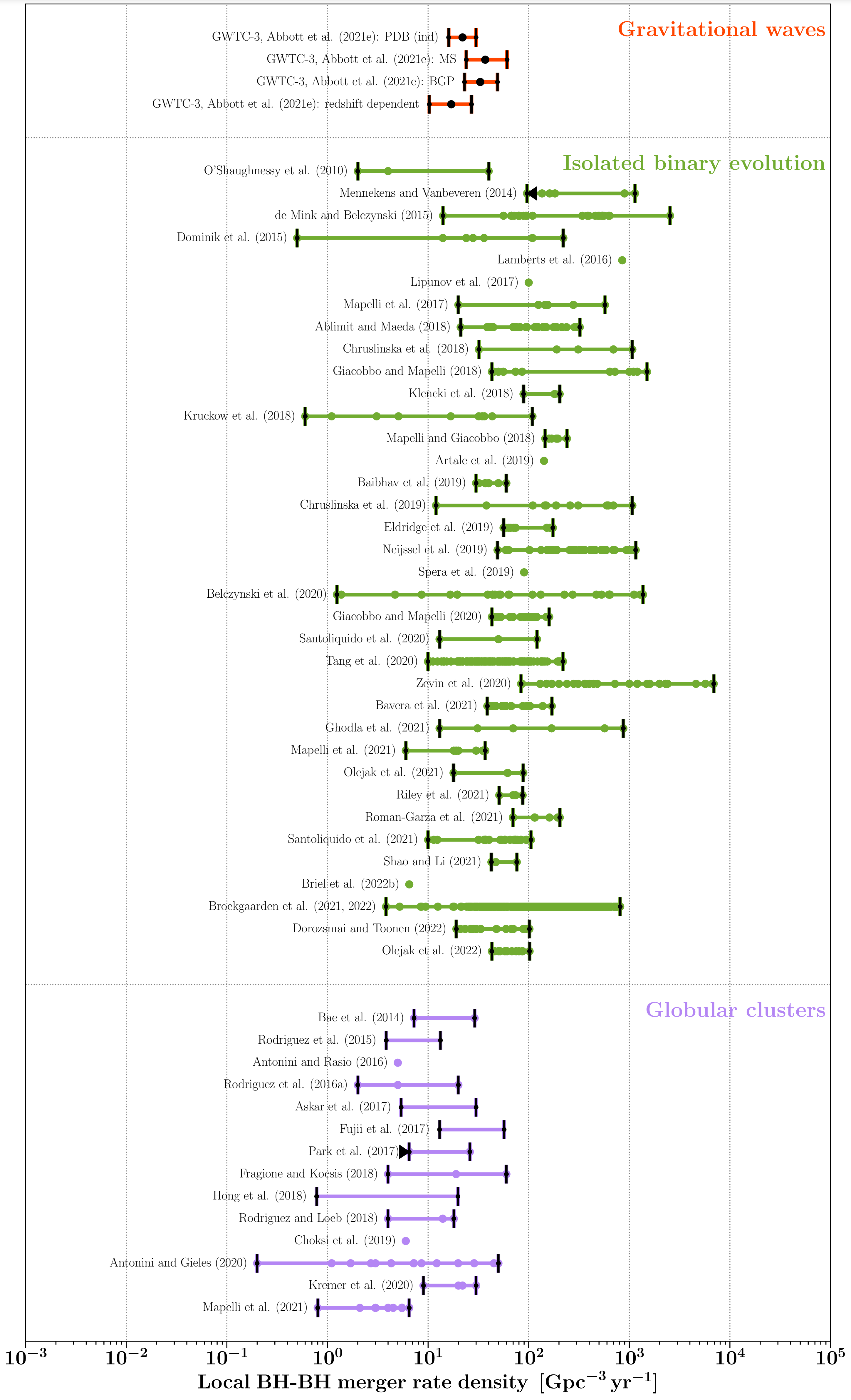
New MOCCA Models from 2024

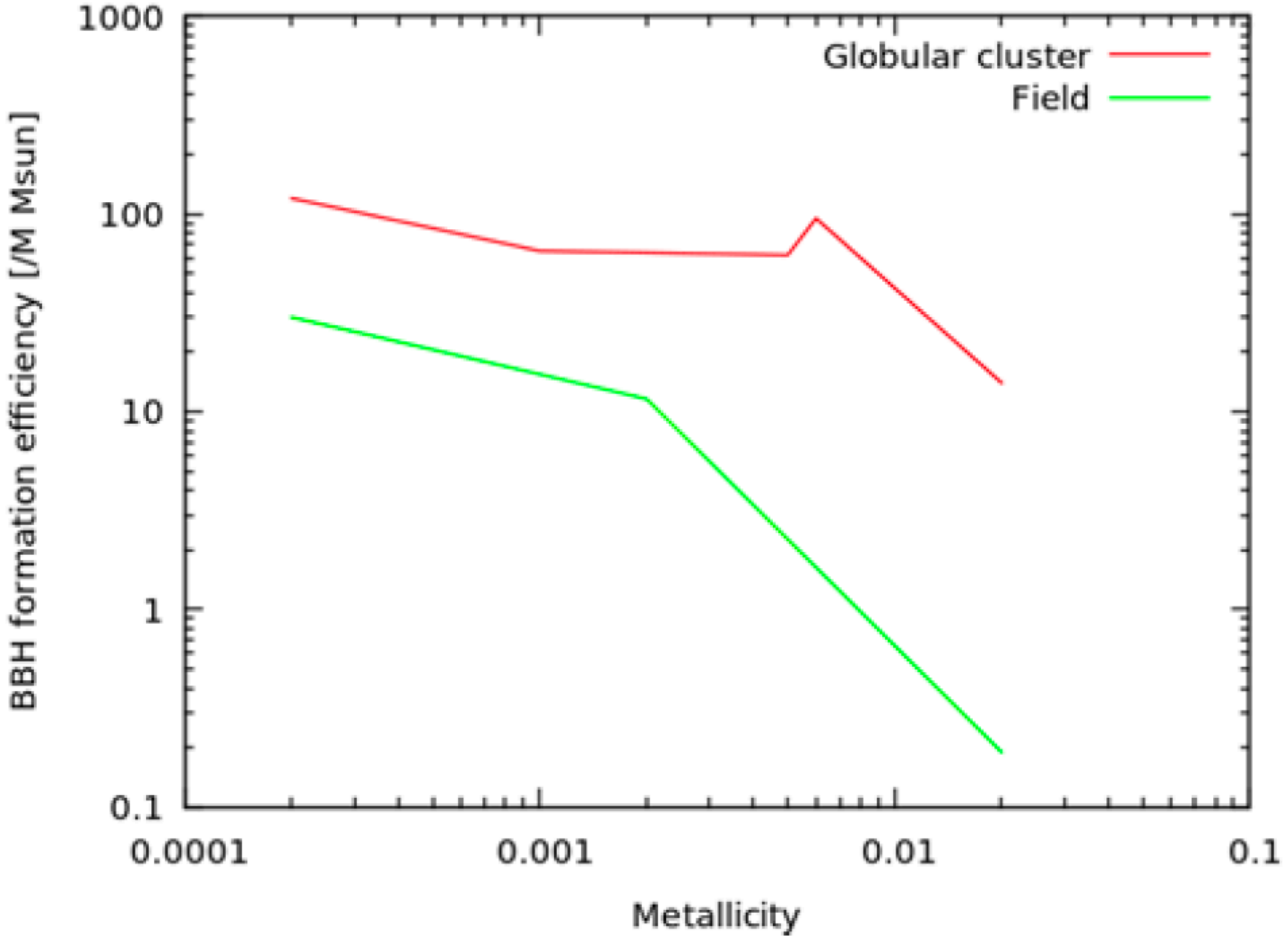
Merger rates for binary black holes from globular clusters



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

So which dominates, field or cluster?

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



Efficiency: Number of merging BBH binaries per $10^6\ \mathrm{M}_\odot$
(Figure Credit: Tomasz Bulik)

Field data from Belczynski et al. 2016

Hierarchical mergers of black holes in star clusters

- Retention of 2G black holes and birth spins of black holes

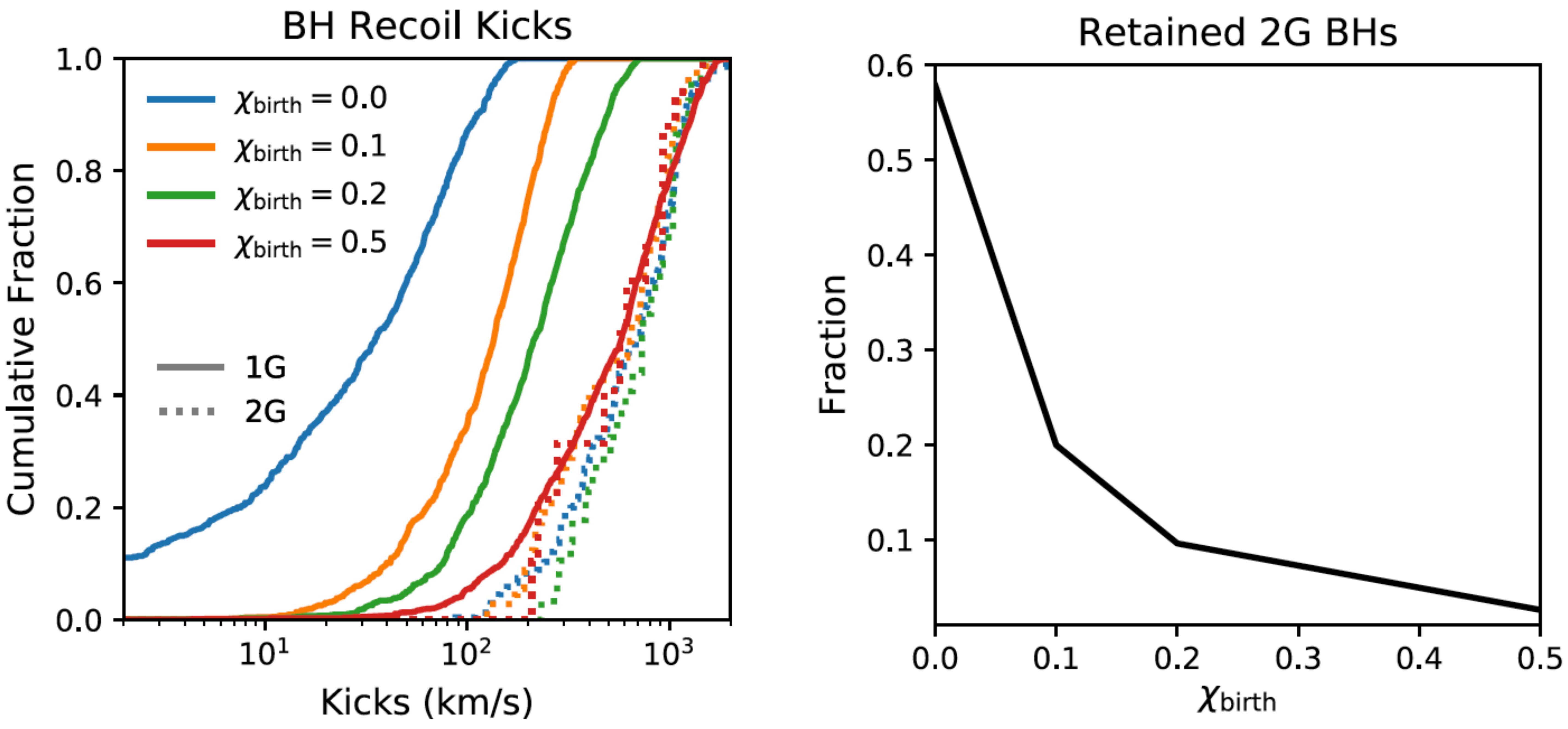
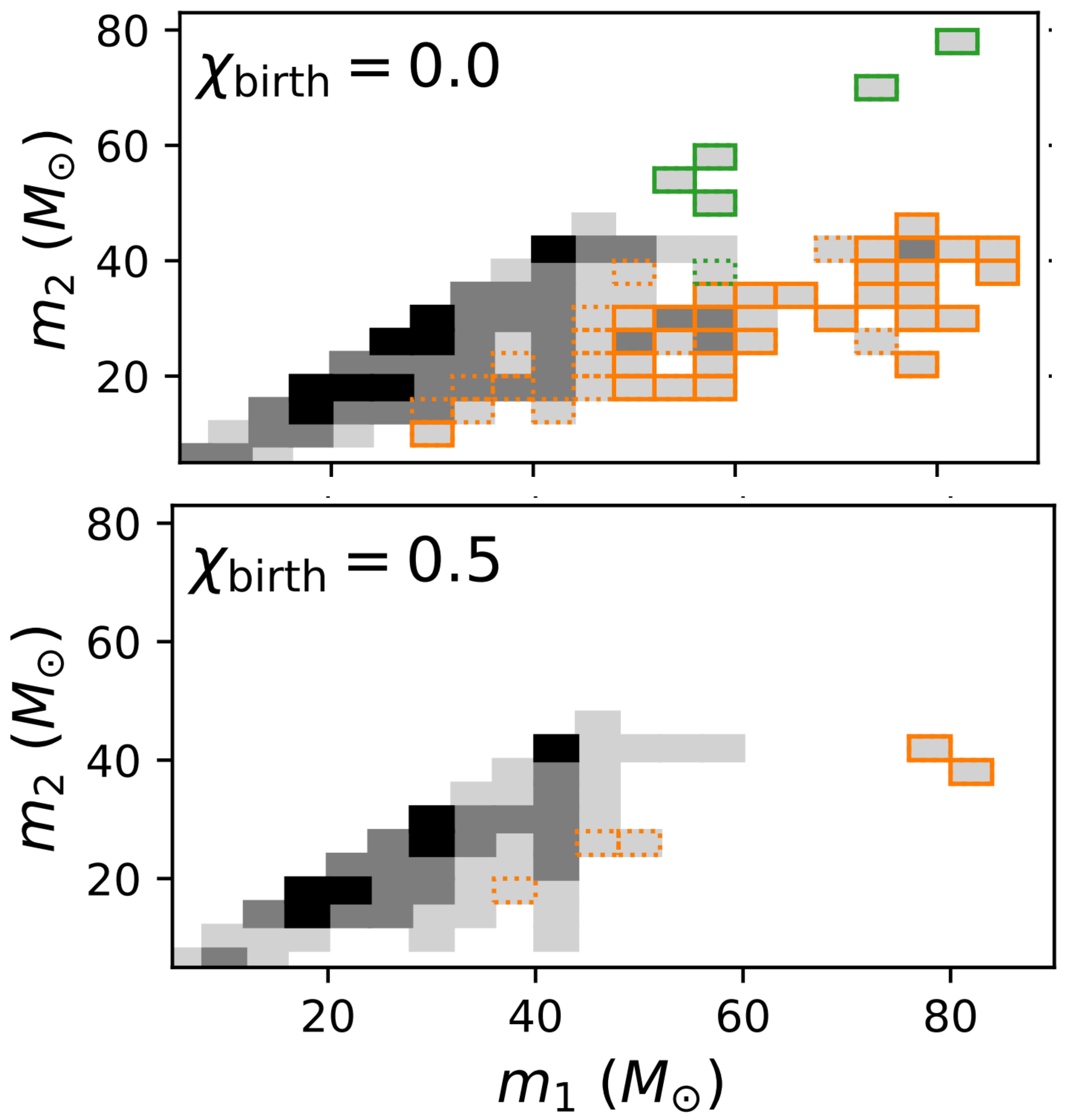


Fig. 1 from Rodriguez et al. 2019



Rodriguez et al. 2019

- For 1G birth spins close to 0 → 60% of second generation BHs will be retained in the cluster
- For 1G birth spins of 0.5→ 3% of second generation BHs will be retained in the cluster