Impact of initial mass functions on the dynamical channel of gravitational wave sources

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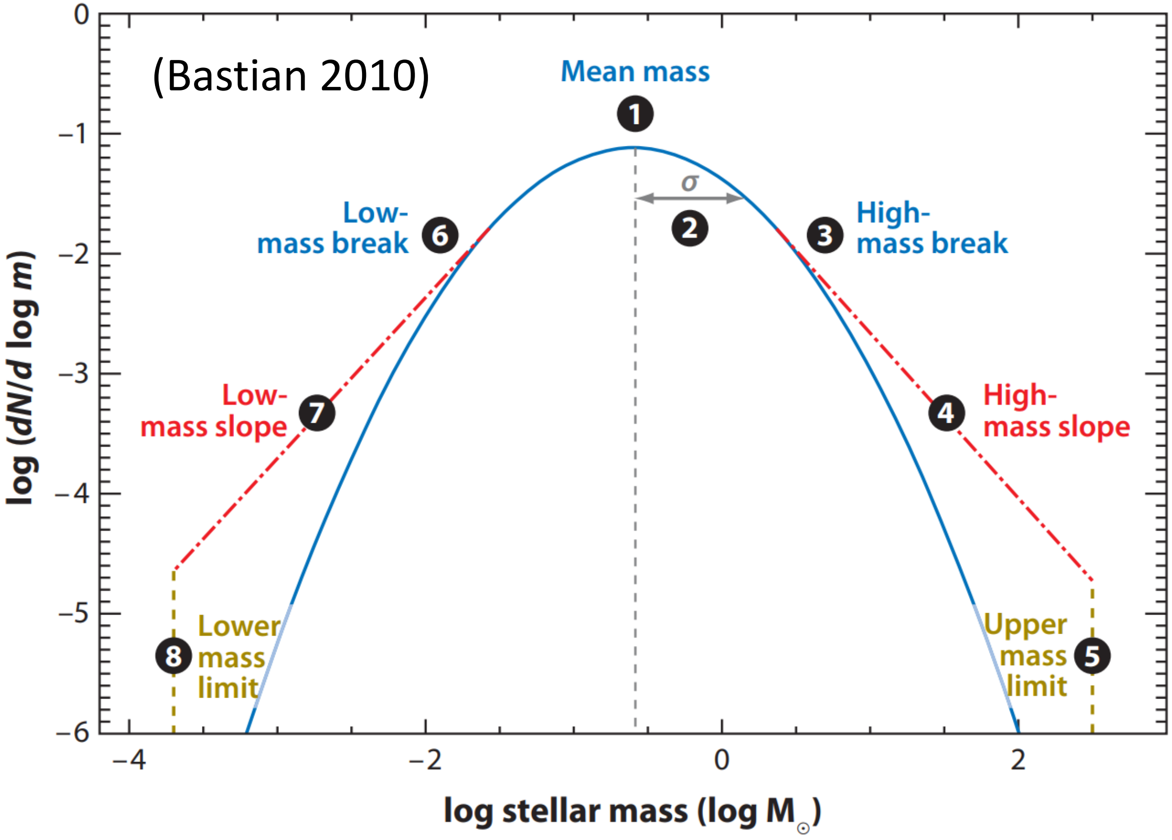
arXiv:1911.05077; 2101.09283

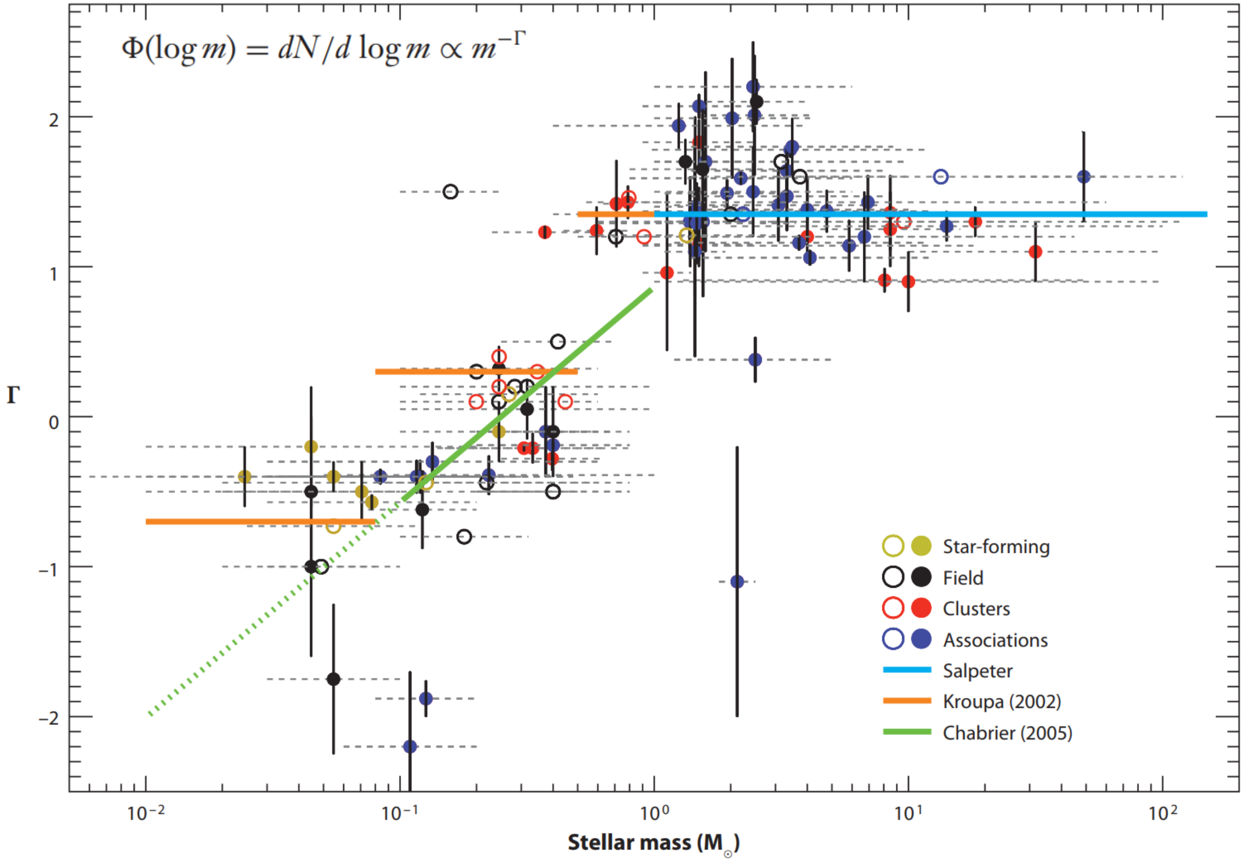
ChalCA-III 2021-6-18

Initial mass function (IMF) of stars



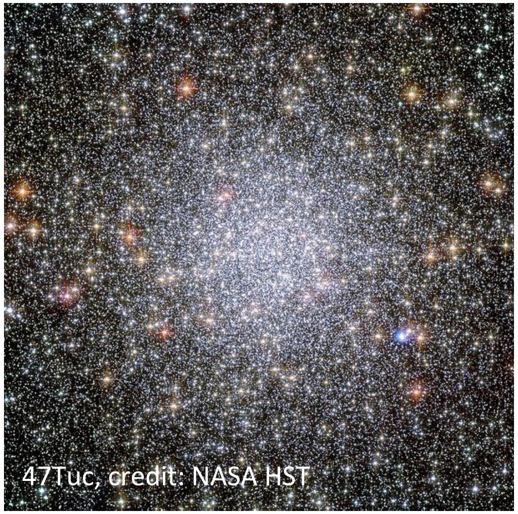
Is initial mass function universal?

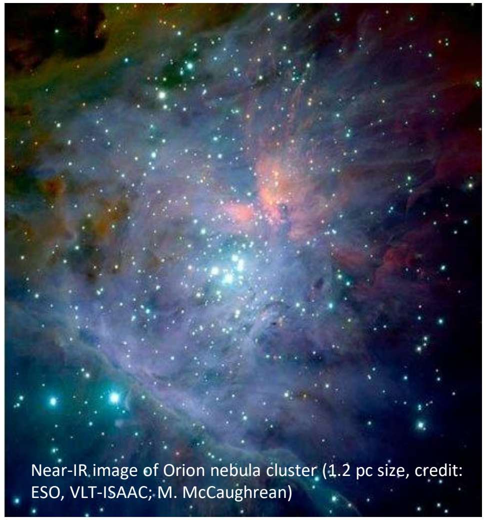
(Scalo 1998, Kroupa 2002, Bastian 2010)



Is IMF universal?

- **Top-heavy IMF**
  - Extreme dense clusters: Arches, Galactic center, R136 (e.g., $\Gamma \approx 0.7$; *Lu, 2013; Schneider, 2018, Hosek, 2019*)
  - Starburst galaxies ($\Gamma \approx 1.1$*; Zhang, 2018*)
  - Population III IMF from simulations (e.g., $\Gamma \sim 1.0 - 1.24$; Stacy, 2016)
- **Globular clusters?**


47Tuc, credit: NASA HST


Near-IR image of Orion nebula cluster (1.2 pc size, credit: ESO, VLT-ISAAC; M. McCaughrean)

How BH mass depends on IMF

- Multiple component IMF (Kroupa 2001)

$$0.08 < m \leq 0.5\, M_\odot \quad \alpha_1 = -1.3$$

$$0.5 < m \leq 1 M_\odot \quad \alpha_2 = -2.3$$

$$1 < m < 150 M_\odot \quad \alpha_3 = -2.3$$

- Vary α_3 to top-heavy IMFs

$$\alpha = -(\Gamma + 1)$$

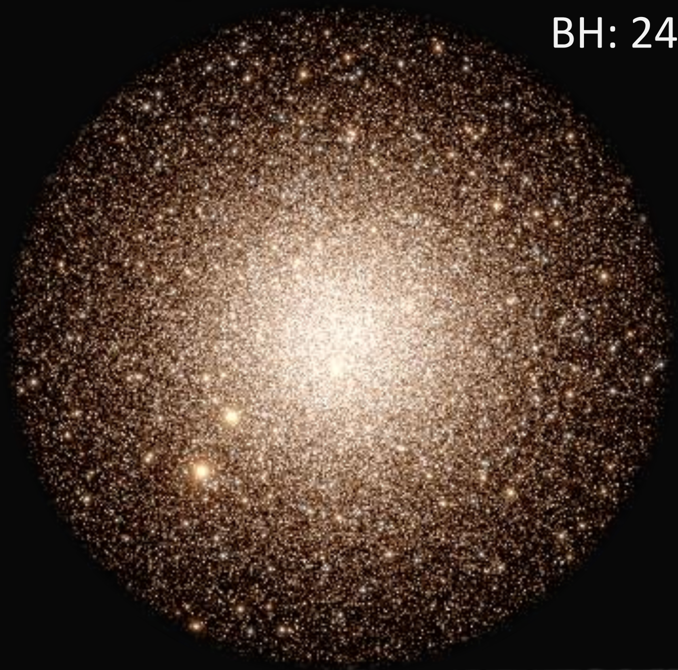
$\boldsymbol{a_3}$	**-1.5**	**-1.7**	**-2.0**	**-2.3**
M_{BH}/M	55%	38%	18%	7%

  - $Z = 0.001$; SSE *(Hurley 2000,2002; Belczynski 2010,2016a,b; Banerjee 2019)*

Strong impact of IMF on long-term evolution of GCs

Kroupa et al. (1993)

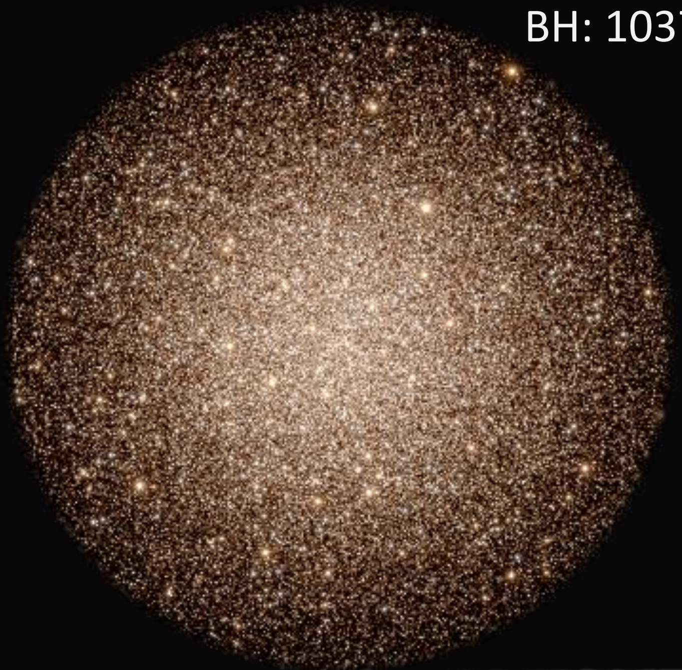
$\alpha_3 = -2.7$



BH: 245

Kroupa (2001)

$\alpha_3 = -2.3$

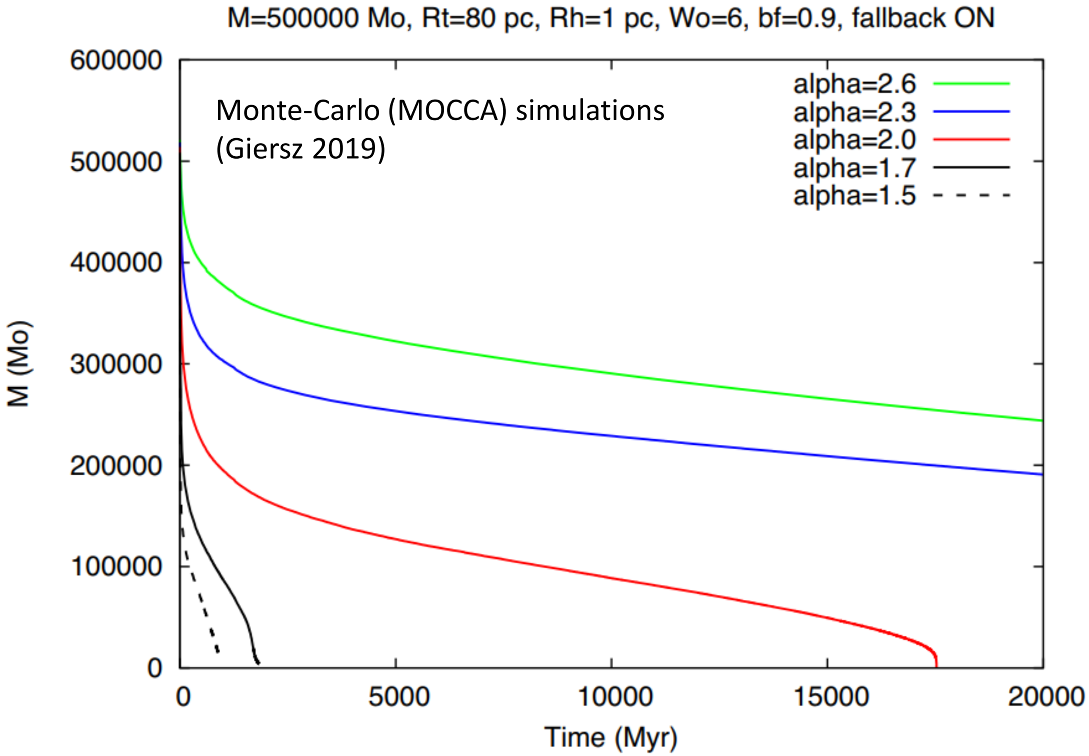


BH: 1037

DRAGON models (Wang, 2016)

Impact of IMFs on GC lifetime

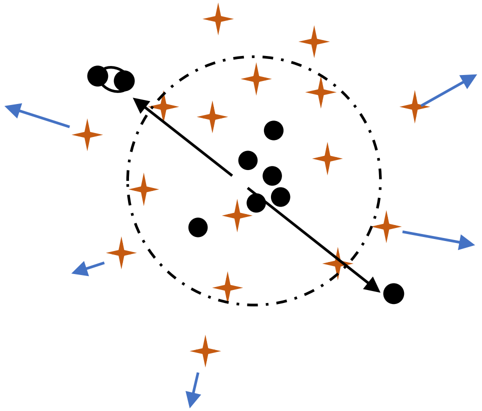
Many GCs with top-heavy IMF already disappear in the past



Light clusters or dark clusters

BH escape

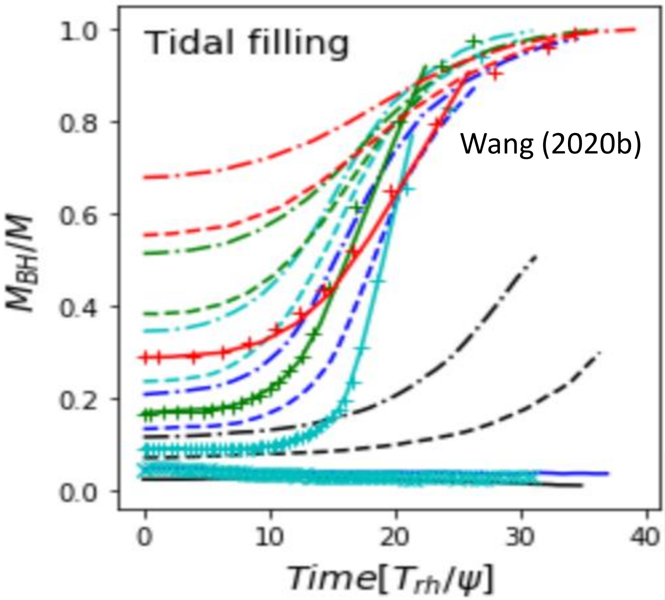
- Mass segregation time



Star escape

- Two-body relaxation time
- Galactic tidal field

Dark clusters (no stars)



Wang (2020b)

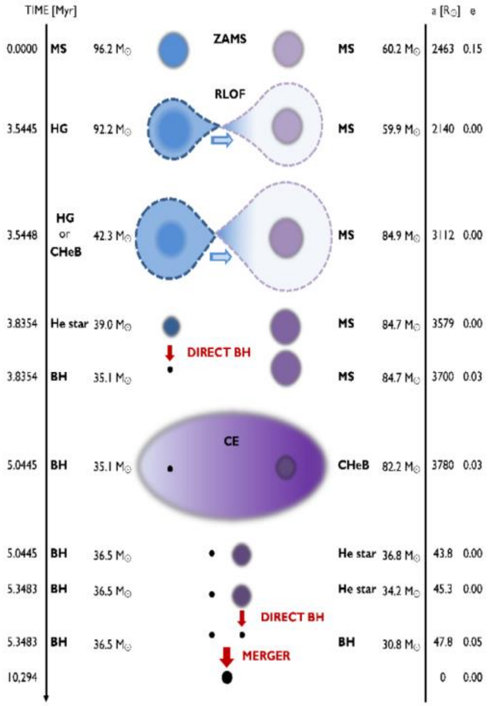
Light clusters (no BHs)

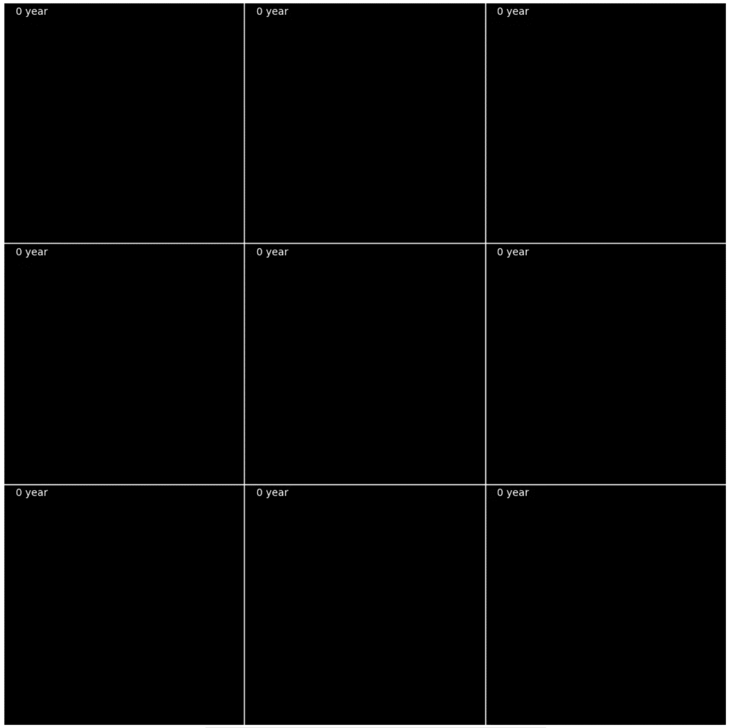
Top-heavy IMF tend to drive the GCs to become dark clusters (Banerjee 2011; Giersz 2019; Wang 2020b)

Two channels to form Gravitational wave progenitors

Stellar-evolution channel
- **common envelope**, *e.g., Giacobbo 2018; Belczynski, 2020*
- ***stable mass transfer***, *e.g., Kinugawa 2014, Tanikawa 2020*

Dynamical channel
- **globular clusters**, *e.g., Portegies Zwart 2020, Tanikawa 2013, Rodriguez 2016; Askar 2017; Fujii 2017*
- **open clusters**, *e.g., Di Carlo 2019; Kumamoto 2019*
- **galactic center**, *e.g., O'Leary 2009, Antonini 2019*





Highly uncertain, require fine tuning

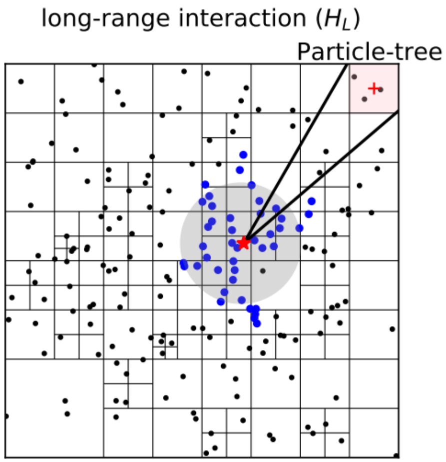
Purely dynamics

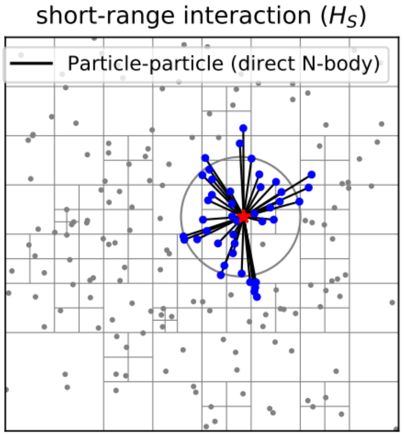
The contribution from GCs

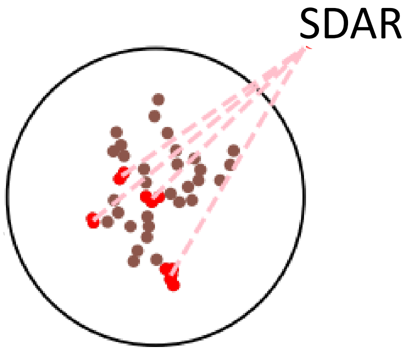
- The total masses of globular clusters (GCs) are small
  - Milky way stellar mass: $\sim 6 \times 10^{10}\ M_{\odot}$ (McMillian 2011)
  - Milky way GC total mass: $\sim 3.6 \times 10^{7} M_{\odot}$ (Baumgardt 2018)
- Field: $\mathbf{10 - 300}\ \boldsymbol{Gpc^{-3} yr^{-1}}$
  - e.g., Belczynski 2016, Kruczkow 2018
- GCs: $\mathbf{5 - 15}\ \boldsymbol{Gpc^{-3} yr^{-1}}$
  - e.g., Rodriguez 2016, 2017, Askar 2016, Fragione & Kocsis 2018
- Assume GCs have the same IMF as that of the field stars

PETAR

- Hybrid integrator
  - P^3T method (Oshino 2011)
    - Barnes-Hut tree (Barnes & Hut 1986)
    - 4th–order Hermite integrator (e.g., Aarseth 2003)
  - The slow-down algorithmic regularization method (SDAR; Wang, Nitadori & Makino 2020)
- High-performance
  - Parallelization: FDPS (MPI + OpenMP; Iwasawa 2016)
  - GPU (CUDA), AVX, AVX2, AVX512, A64FX
  - Fastest N-body code for collisional stellar systems
  - Support 100% binaries
- Single/binary stellar evolution
  - SSE/BSE (Hurley 2000,2002, Banerjee, 2020)
  - MOBSE (Giacobbo, 2018)
- External potential: Galpy (Bovy 2015)
- Open Source: https://github.com/lwang-astro/PeTar


long-range interaction (H_L)


short-range interaction (H_S)



BH binary mergers

N-body simulations using PeTar (Wang 2020)
$M = 5 \times 10^5 M_\odot$ Plummer model
$r_h = 2$ pc $Z = 0.001$

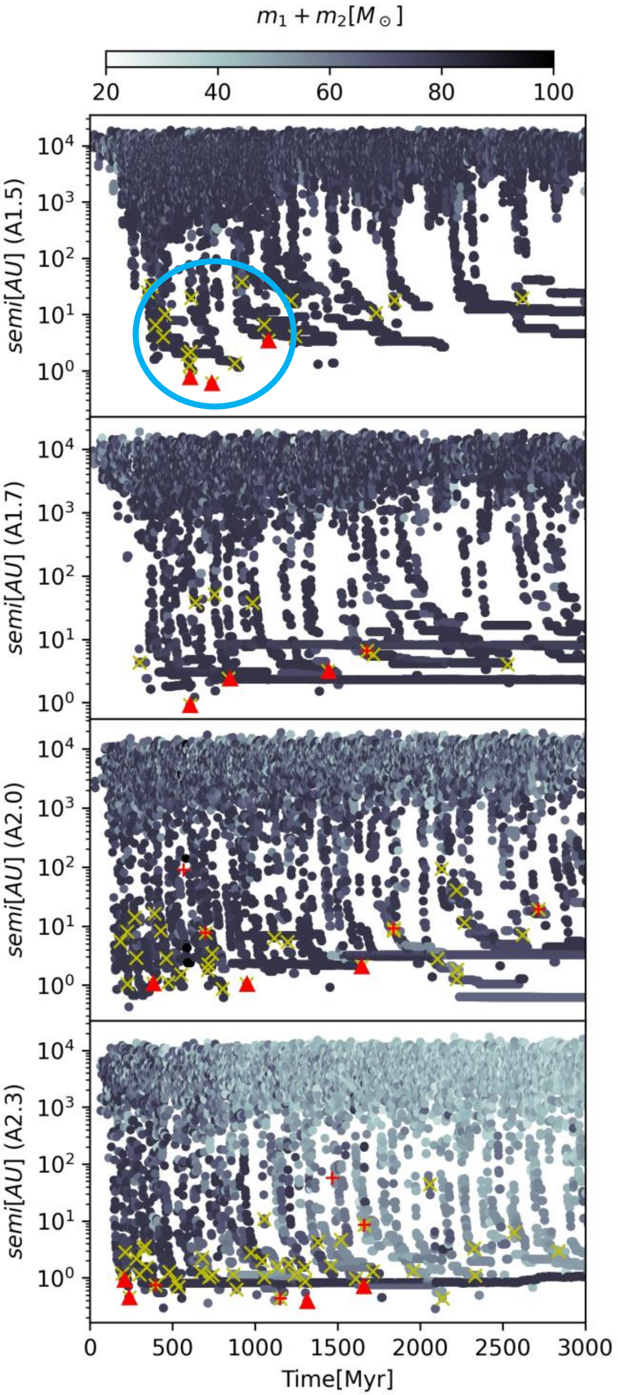
Model	A1.5	A1.7	A2.0	A2.3
α_3	-1.5	-1.7	-2.0	-2.3
N	182306	312605	581582	854625

Heggie-Hill law (1975): hard-> harder; soft->disrupt

Top-heavy IMF -> less efficiency of BH mergers

Model	A1.5	A1.7	A2.0	A2.3
N_{cand}	20	10	30	43
N_{in}	0	1	3	3
N_{out}	3	3	3	4

(Wang 2021, submitted)



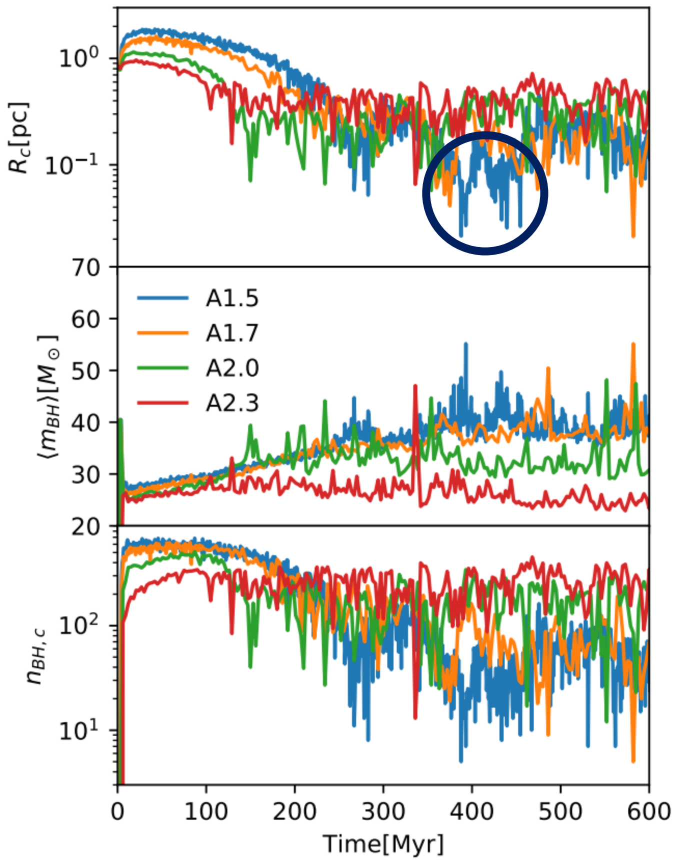
Core evolution

- Top-heavy IMF
  - Strong mass loss by winds
  - Larger core radius

Decrease density, reduce merger rate

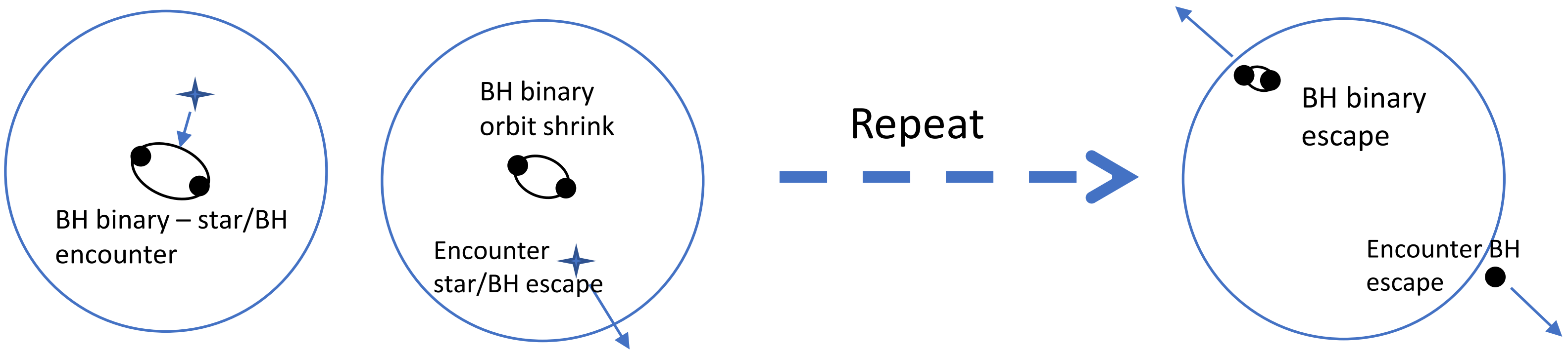
  - Deeper core collapse

Increase density, increase merger rate



Formation of tight BH binaries

BH escape due to few-body ejection, not directly affected by tidal field



BH binary – star/BH encounter

BH binary orbit shrink

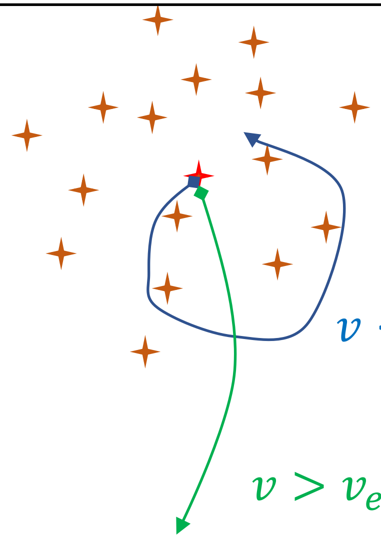
Encounter star/BH escape

Repeat

BH binary escape

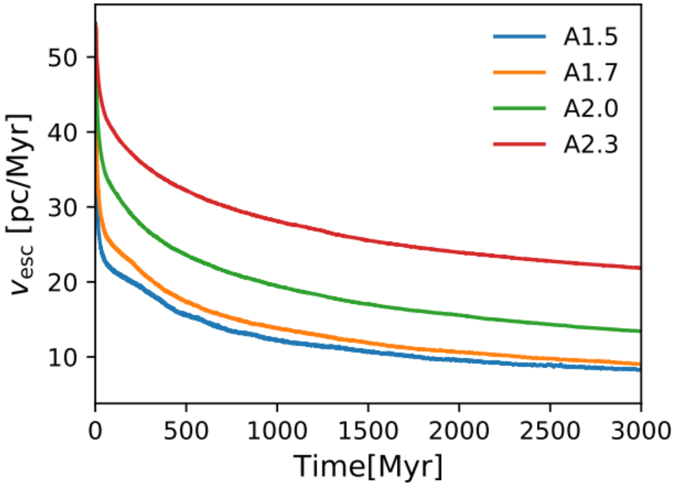
Encounter BH escape

v_{esc} determine how close BH binary can be

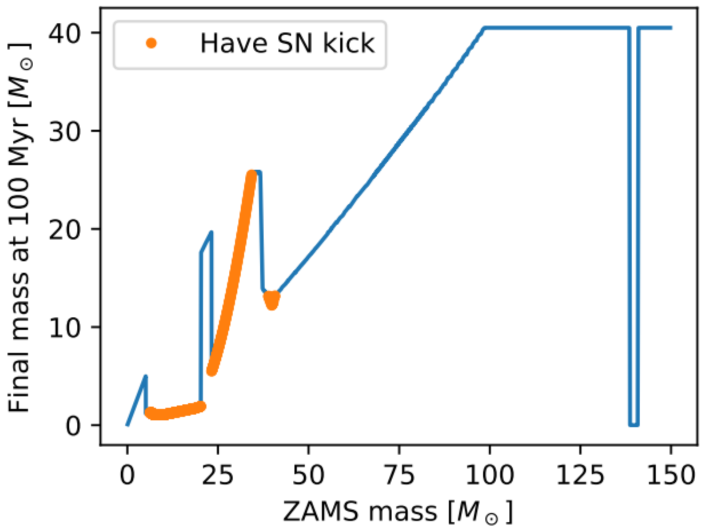


$v < v_{esc}$ bound again

$v > v_{esc}$ escape



Mass function of BHs

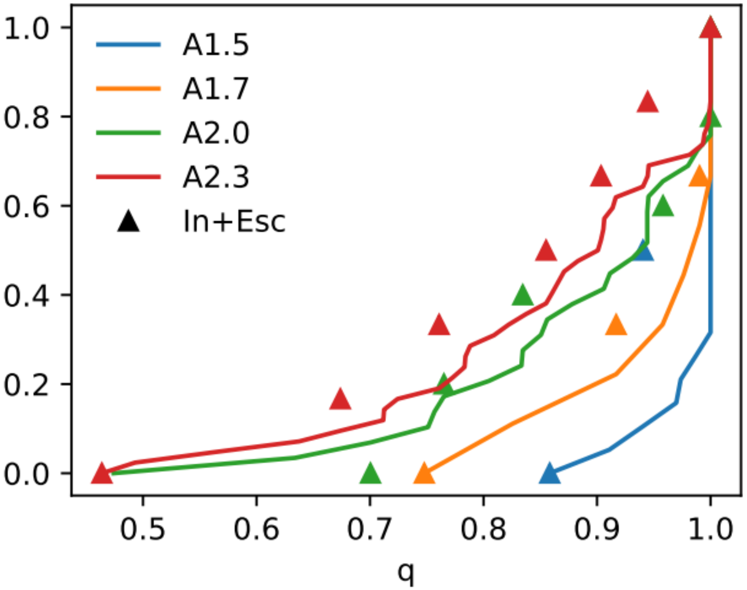


- Pulsation pair-instability supernova (PPSN; Belczynski, et al. 2016)
  - Massive stars → Equal mass BHs of $40.5\ M_\odot$
  - ZAMS mass $< 30M_\odot$ have natal kick after supernova

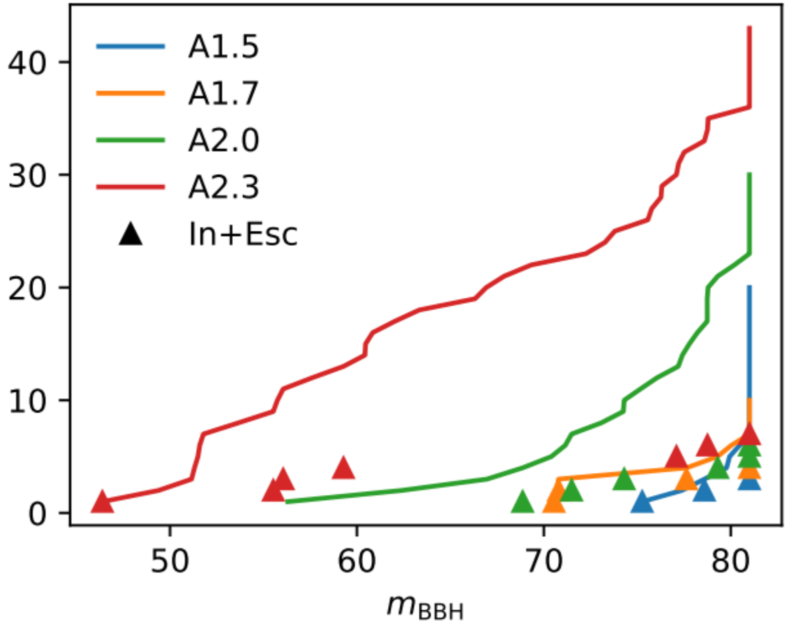
Mass distribution of BH mergers

- Top-heavy IMF tend to have massive BH mergers
  - Peak at (40.5 + 40.5) $M_\odot$

Mass ratio of BH binaries



Final mass of mergers



Summary

- Is IMF a universal function or environment-dependent?
  - GCs are ideal target to investigate high-redshift metal-poor IMF
- Impact of IMF on GCs is strong
  - $5 \times 10^5 M_\odot$ star-by-star N-body simulations of GCs using PeTar
  - https://github.com/lwang-astro/PeTar
  - Top-heavy IMF => Faster dissolution, Dark clusters