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

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Initial mass function (IMF) of stars

(Bastian 2010)
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?**

Images: 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)
  
  \[0.08 < m \leq 0.5 \, M_\odot \quad \alpha_1 = -1.3\]
  
  \[0.5 < m \leq 1M_\odot \quad \alpha_2 = -2.3\]
  
  \[1 < m < 150M_\odot \quad \alpha_3 = -2.3\]

• Vary \(\alpha_3\) to top-heavy IMFs
  \[\alpha = -(\Gamma + 1)\]

| \(\alpha_3\) | -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

Monte-Carlo (MOCCA) simulations (Giersz 2019)
Light clusters or dark clusters

BH escape
• Mass segregation time

Star escape
• Two-body relaxation time
• Galactic tidal field

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: $10 - 300 \ Gpc^{-3}yr^{-1}$
  - e.g., Belczynski 2016, Kruczkow 2018
- GCs: $5 - 15 \ Gpc^{-3}yr^{-1}$
  - e.g., Rodriguez 2016, 2017, Askar 2016, Fragione & Kocsis 2018
- Assume GCs have the same IMF as that of the field stars
• 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
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 |
|-------|------|------|------|------|
| $\alpha_3$ | -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

(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

$v_{esc}$ 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 < 30$M_\odot$ 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