Numerical study of the origin of merging binary black holes

JpGU 2021: M-GI135
計算科学が拓く宇宙の構造形成・進化から惑星表層環境変動まで

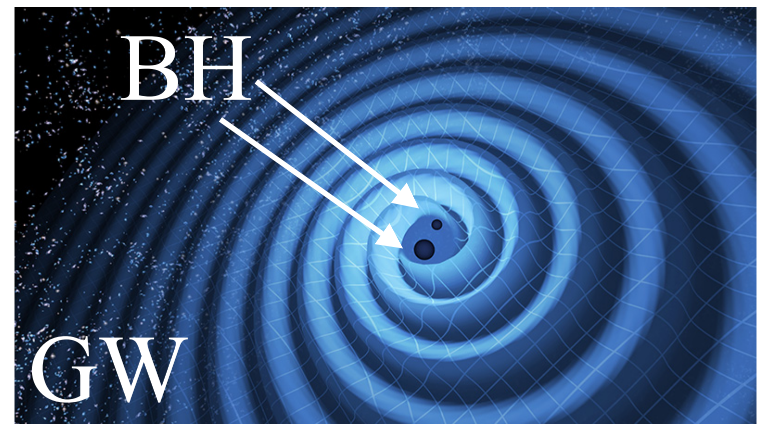
Speaker: <u>Ataru Tanikawa</u>[1]
Coauthors: Fujii M. S.[1], Kumamoto J.[1], Trani A. A.[1], Wang L.[1]
Other collaborators: Hijikawa K.[1], Kinugawa T.[1], Leigh N. W. C.[2], Susa H.[3], Takahashi K.[4], Umeda H.[1], Yoshida T.[5]
Institutes: [1]University of Tokyo, [2]University of Concepcion, [3]Konan University, [4]Max Planck Institute, [5]Kyoto University

Contents

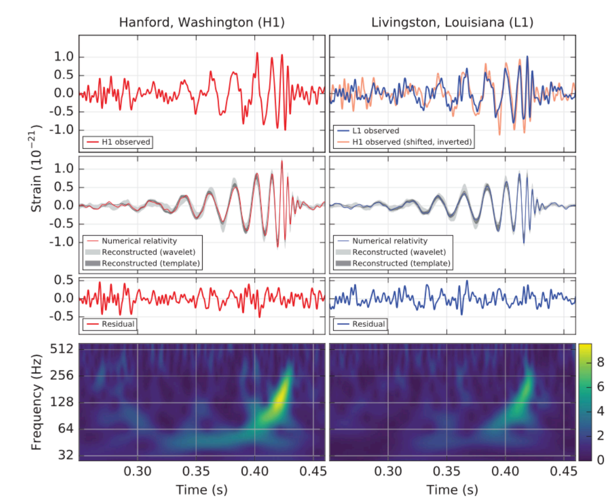
- Gravitational wave (GW) observations and binary black holes (BH-BHs)
- Isolated (Pop III) binary evolution
- Dynamical interactions in open clusters
- Dynamical interactions in globular clusters

GW observation and BH-BHs

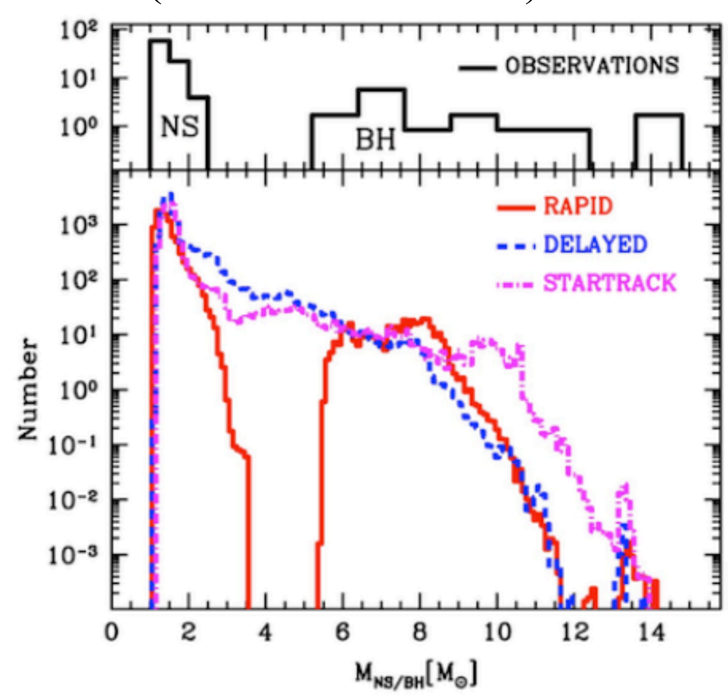
- The first detection of GWs is the first discovery of a BH-BH merger 2015.
- The number of BH-BHs grows to ~ 50 only during 5 years.
- Massive stellar-mass BHs: $\sim 30 M_{\odot}$
- Compact BH-BHs: $\sim 10 R_{\odot}$
- The origin of BH-BHs?
    - Isolated binary stars
    - Dense star clusters
    - Primordial BHs



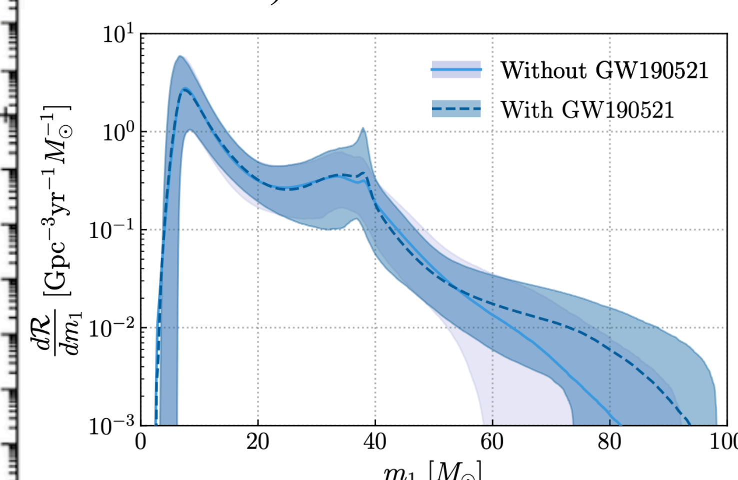
GW150914 (Abbott et al. 2016)



BHs in X-ray binaries (Casares et al. 2017)



The heavier BHs in BH-BHs (Abbott et al. 2020)



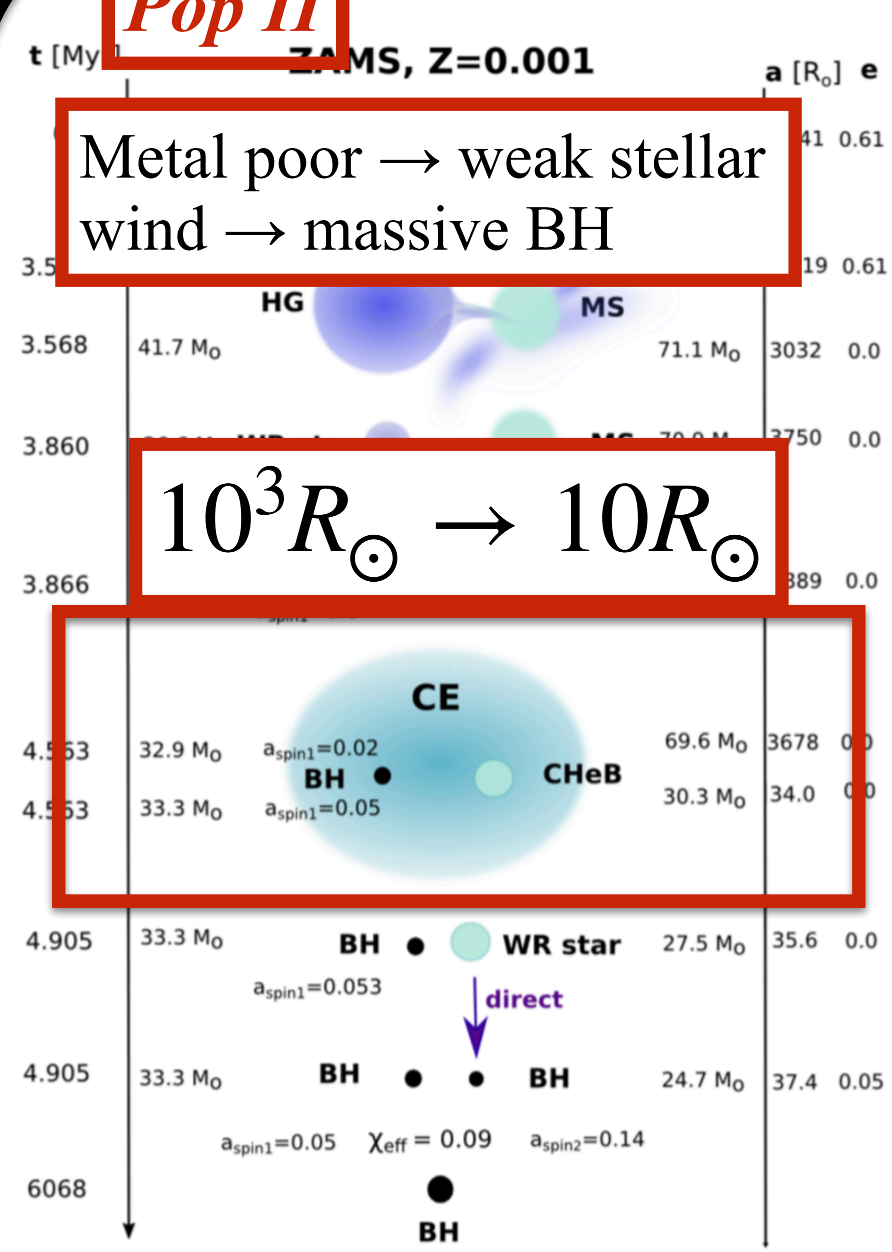
Formation scenarios

Isolated binary stars

Pop II

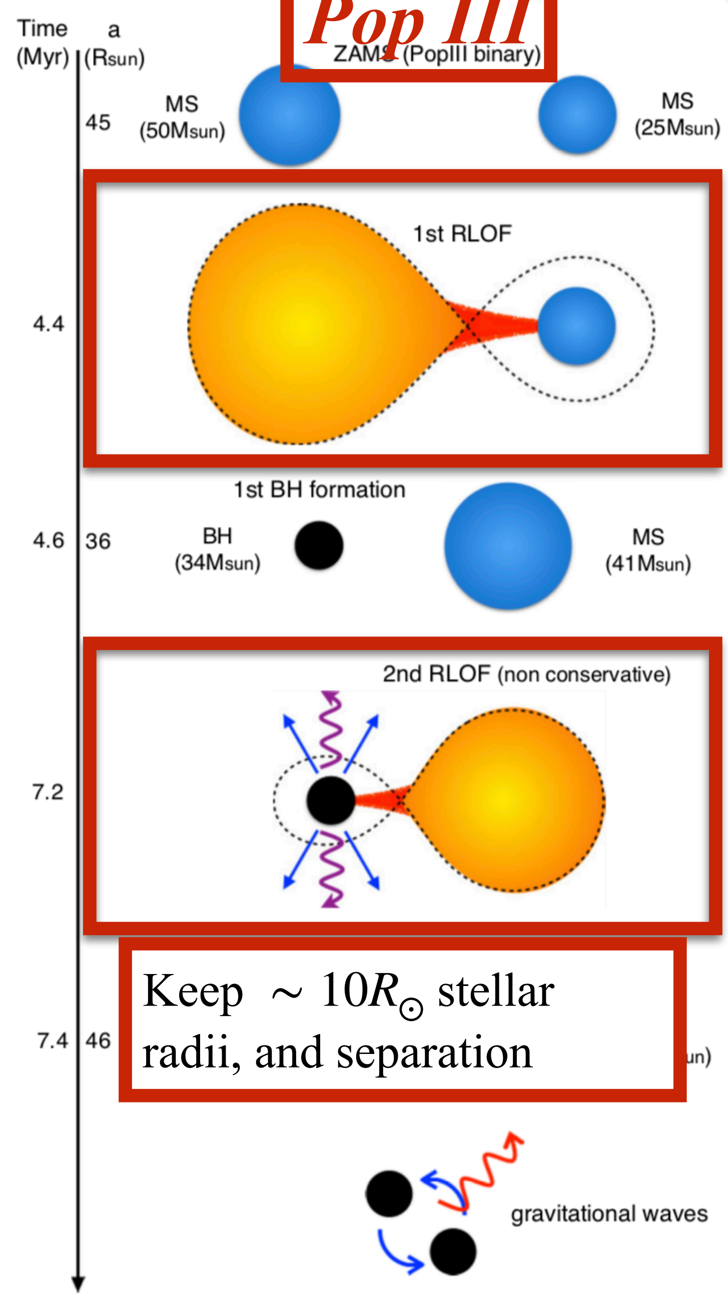
Metal poor → weak stellar wind → massive BH

$10^3 R_\odot \rightarrow 10 R_\odot$



Belczynski et al. (2020)

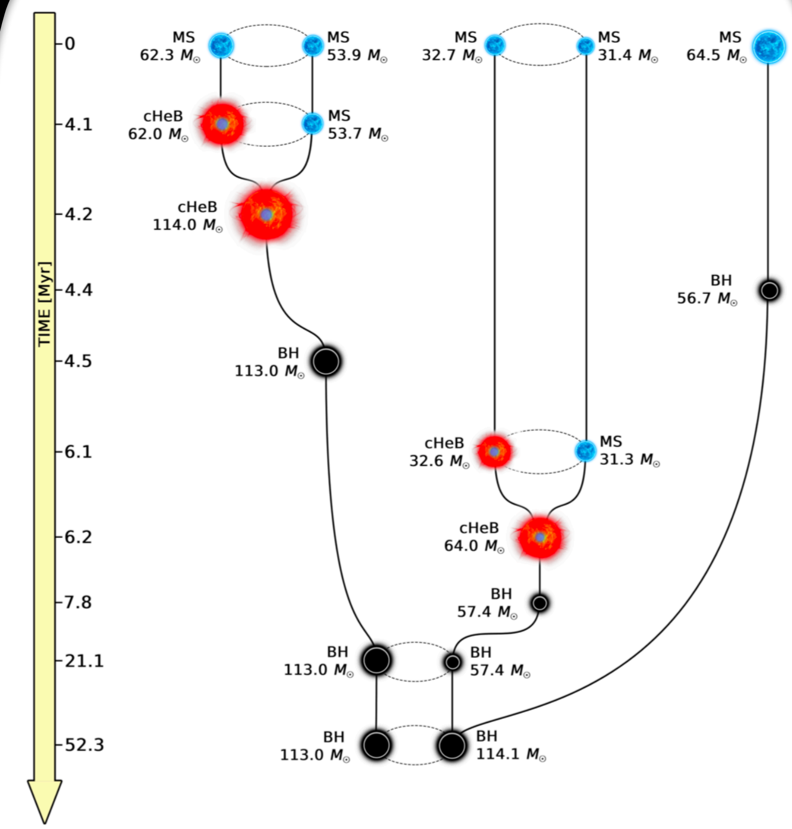
Pop III



Keep $\sim 10 R_\odot$ stellar radii, and separation

Inayoshi et al. (2017)

Star cluster

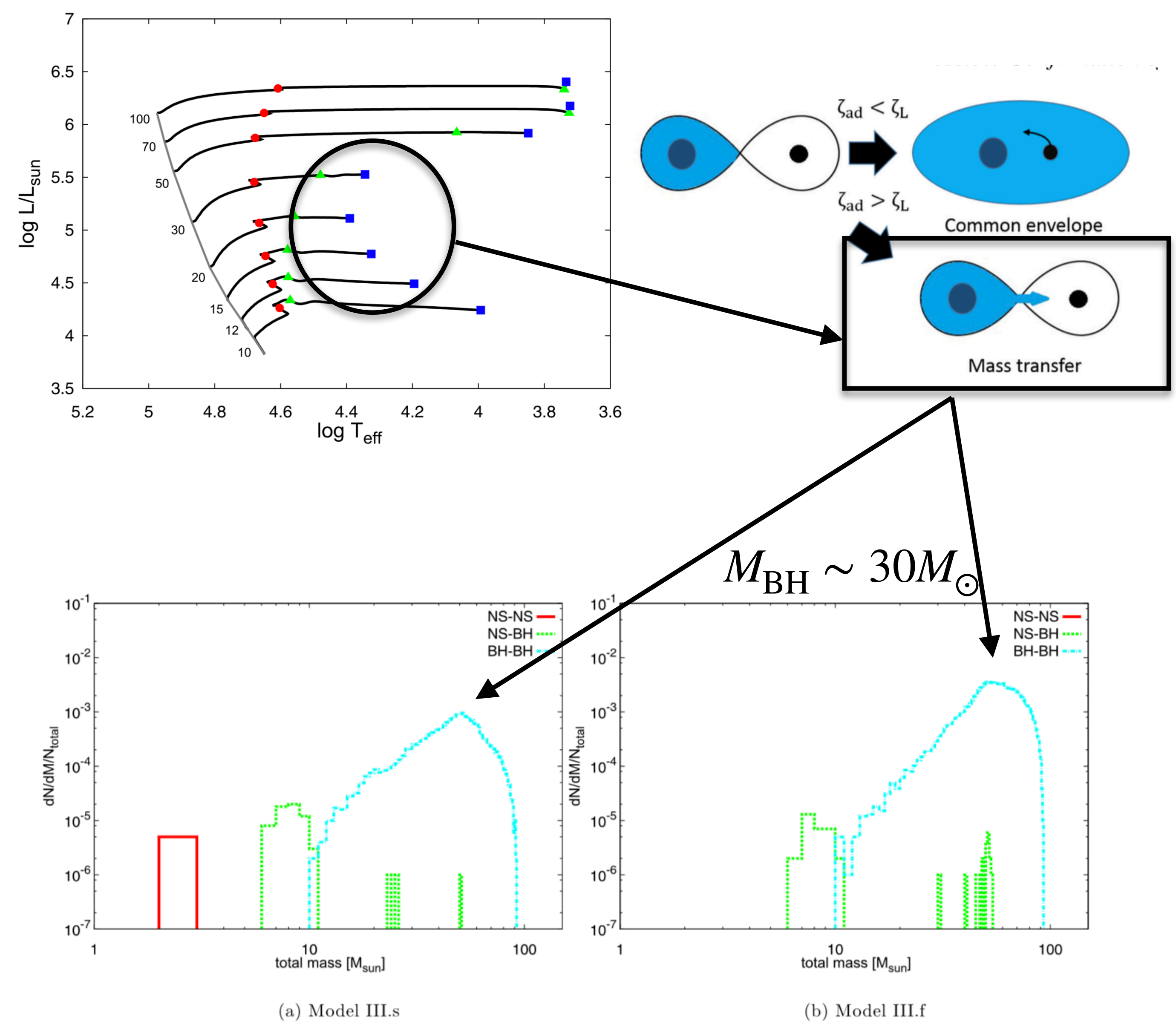


Di Carlo et al. (2021)

- Metal poor, and repeated BH mergers
- $\infty \rightarrow 10 R_\odot$ after BH formation

Pop. III BH-BHs

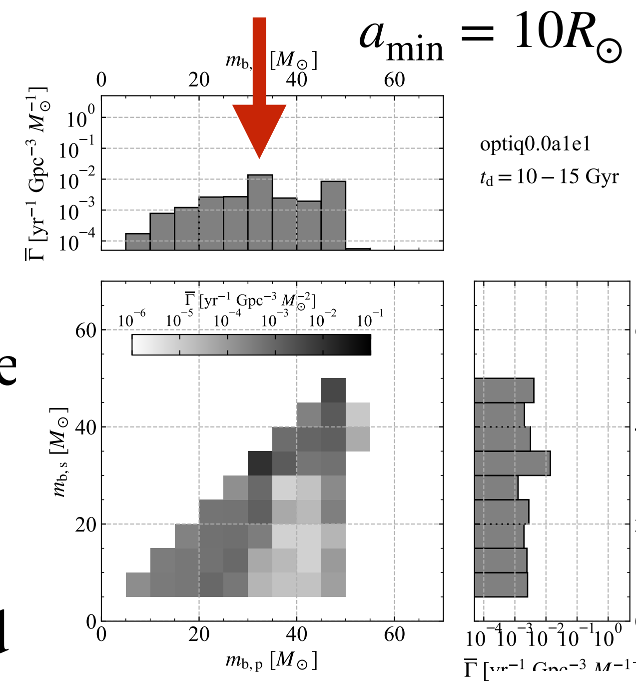
- Pop. III BH-BHs are one of promising origins of observed BH-BHs.
    - They typically have $M_{\rm BH} \sim 30 M_\odot$.
    - GW observations frequently find BH-BHs with $M_{\rm BH} \sim 30 M_\odot$.
- Uncertainties of Pop. III models?
- IMBHs $\sim 10^2 - 10^3 M_\odot$?
- The mass-gap event (GW190521)?

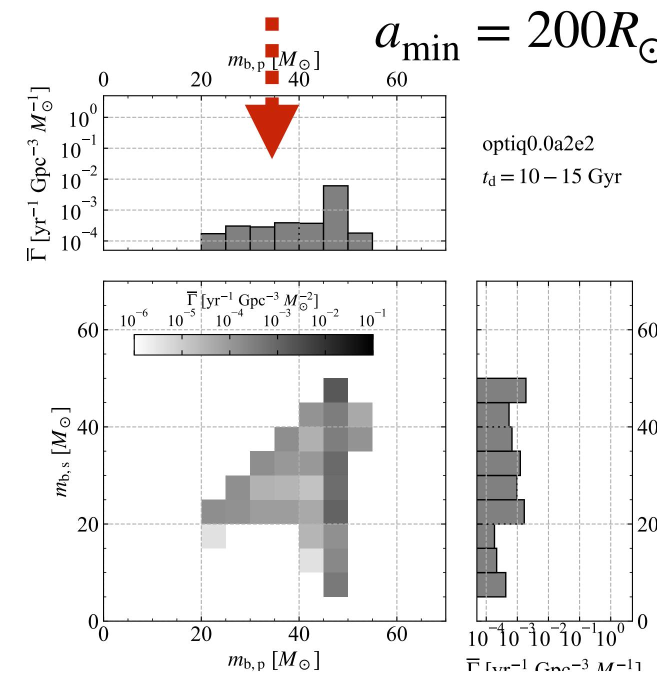


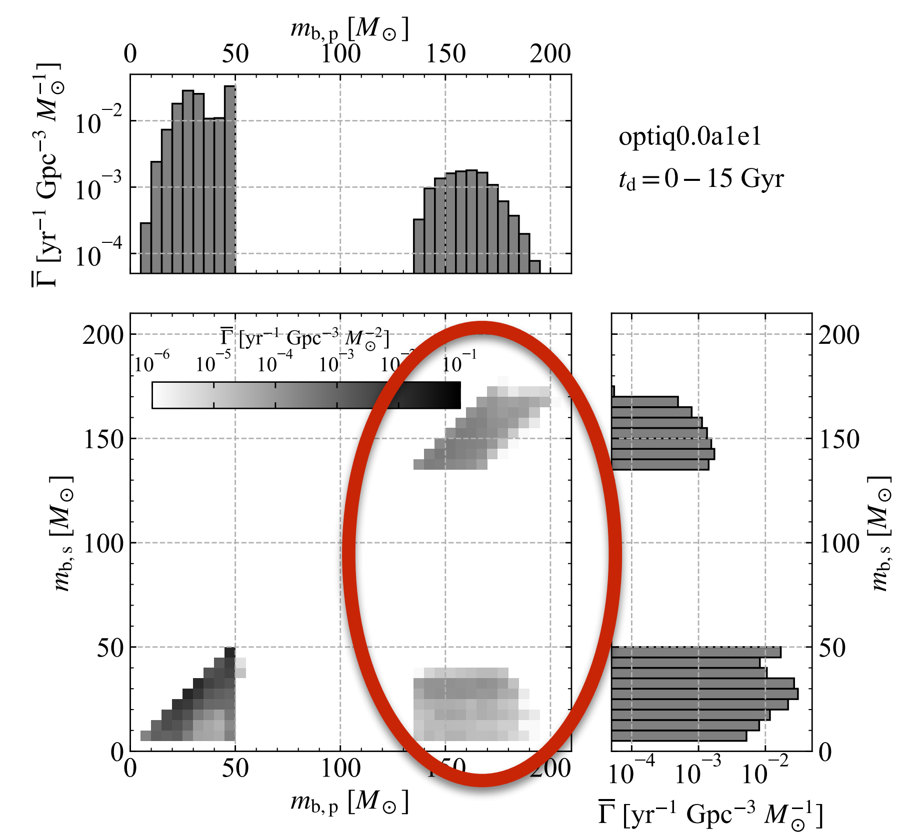
Kinugawa et al. (2014)

Their mass distribution

- The merger rate density is $\sim 0.1 \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$, smaller than the observed rate $\sim 10 \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$.
- The $30 M_{\odot}$ peak disappears without close ($\sim 10 R_{\odot}$) Pop. III binaries.
  - Pop. III binaries can be only $\gtrsim 100 R_{\odot}$, since Pop. III stars expand to $\sim 100 R_{\odot}$ at their proto-stellar phases (Omukai, Palla 2001; 2003)
- The sum of IMBH-BH and IMBH-IMBH merger rates is ~ 0.01 yr^{-1} Gpc^{-3}
  - Not violated the upper limit of 0.056 yr^{-1} Gpc^{-3} (LVK collab. 2021)
  - Detectable soon?







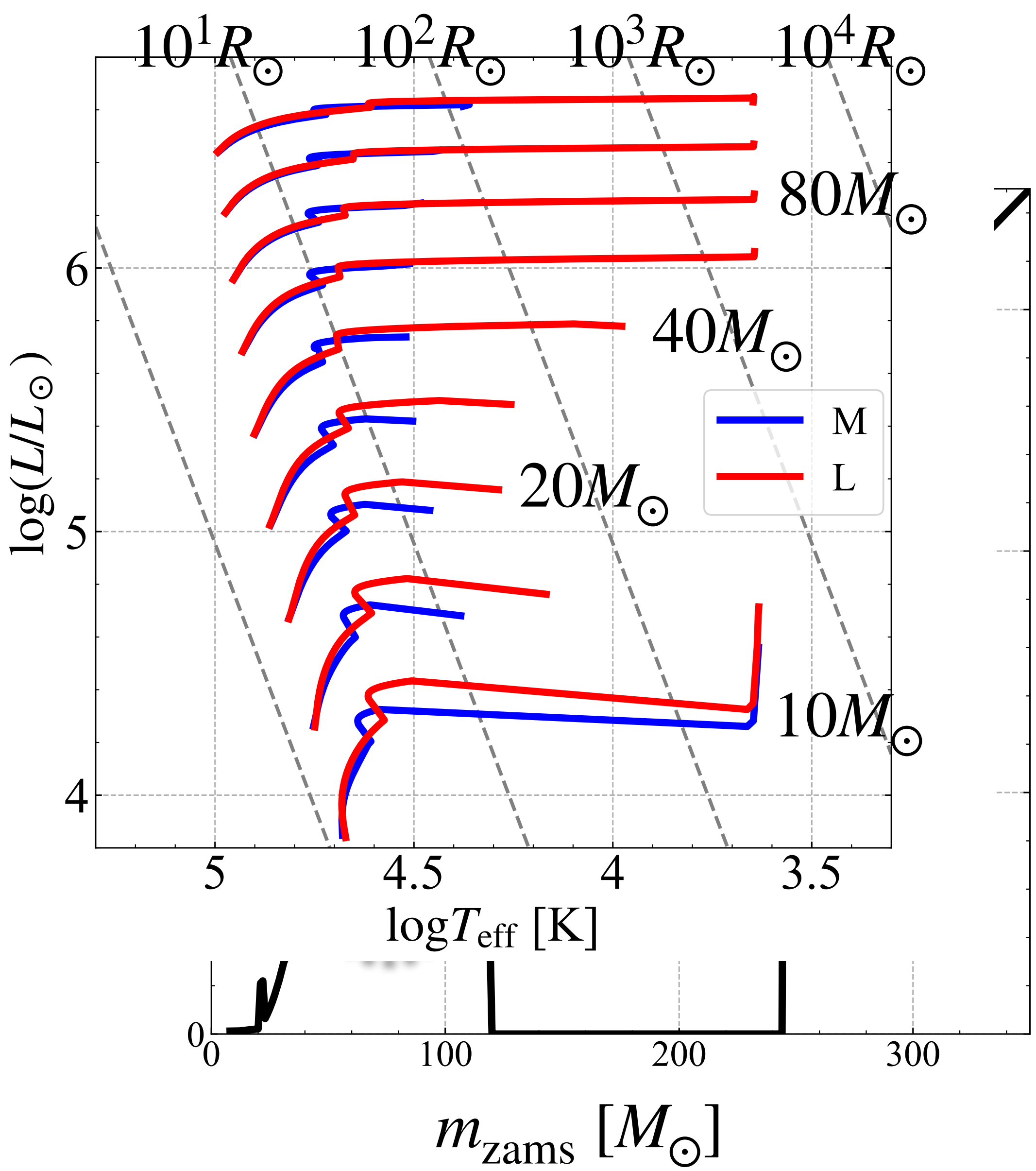
Tanikawa et al. (2021, ApJ, 910, 30)

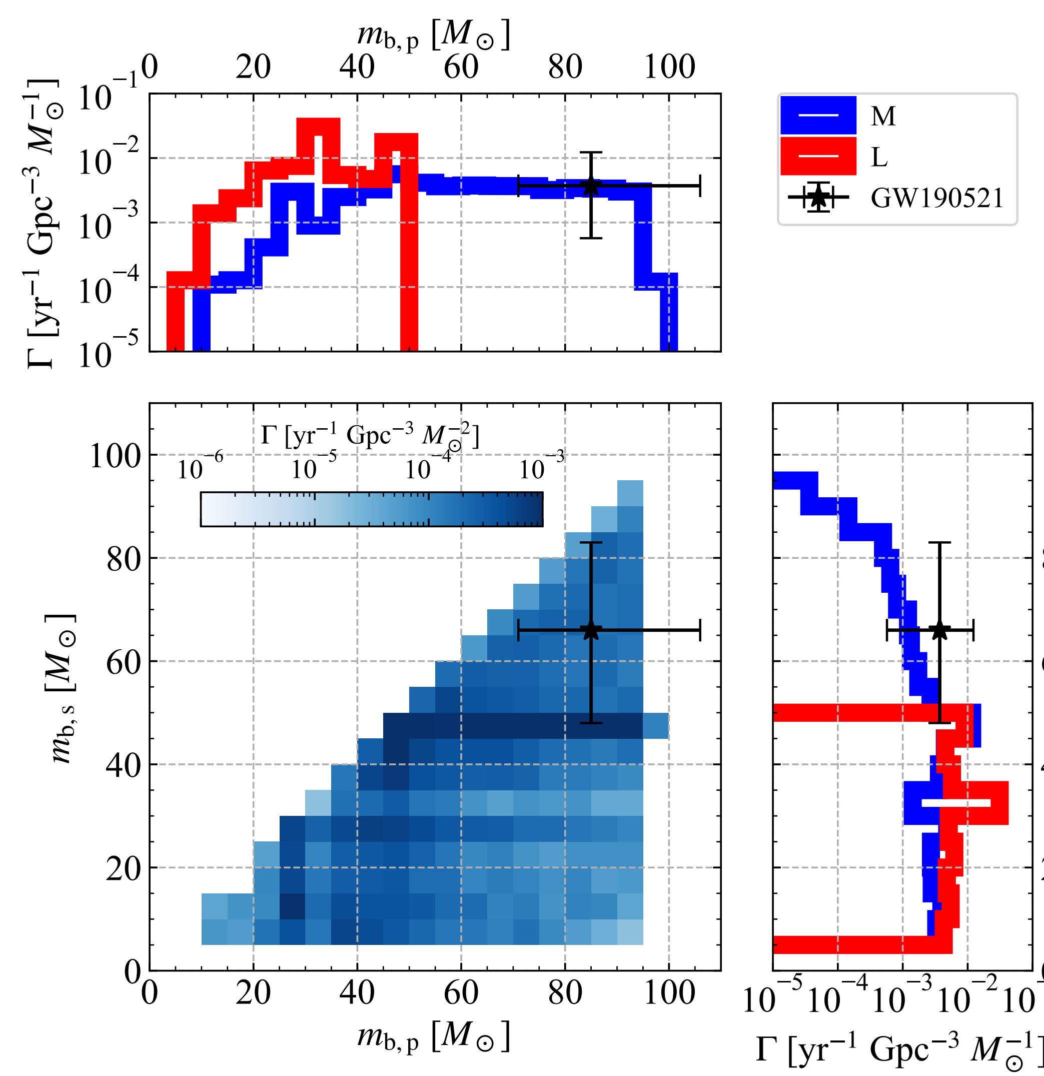
See also Hijikawa et al. (2021, MNRAS in press)

Mass-gap event GW190521

- Merger of $85^{+21} M_\odot$ and $66^{+17}_{18} M_\odot$

$M_{\rm tot} \sim 90 M_\odot$

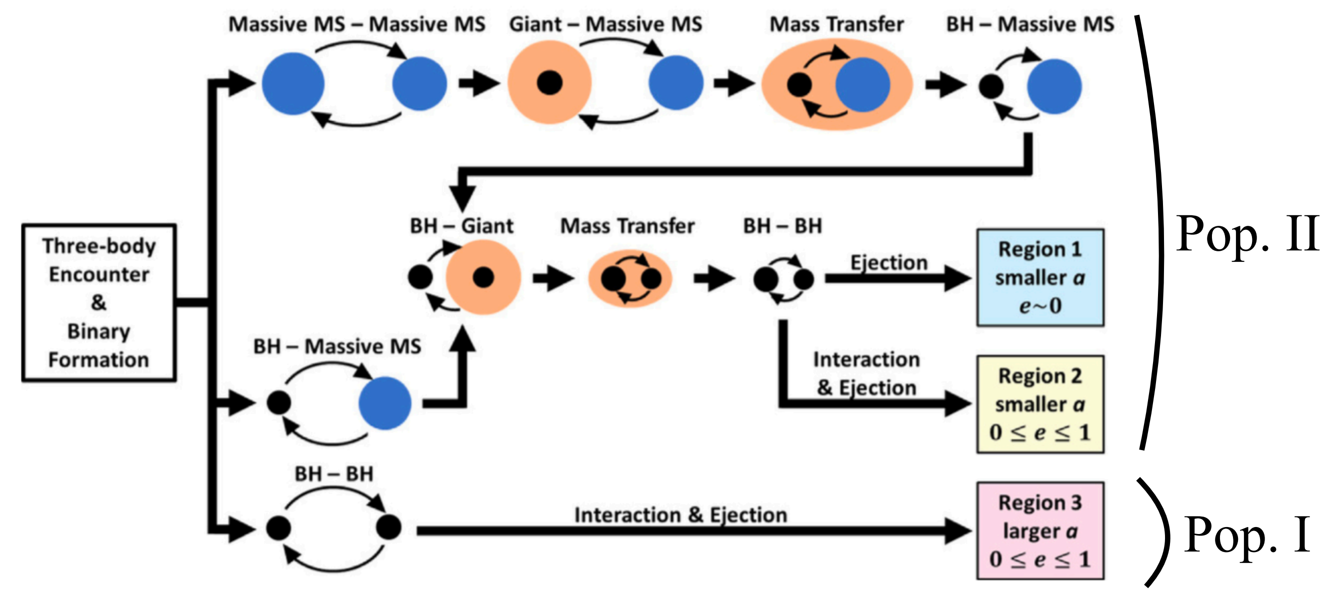




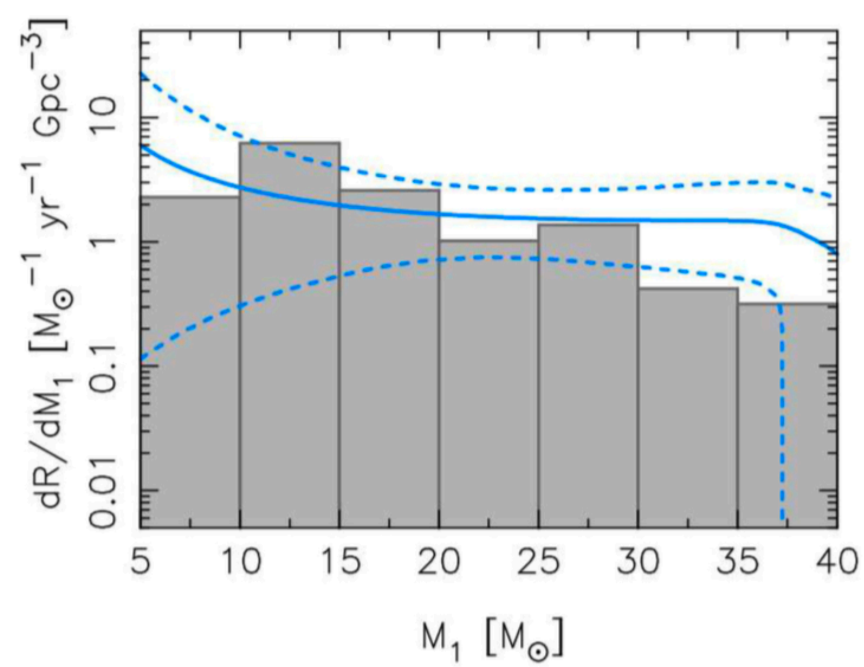
Tanikawa et al. (2021, MNRAS in press)

Open clusters

- Formation path to BH-BHs
  - Binary stars at the initial time (primordial binaries) are not needed.
  - If not, binary stars are always formed dynamically.
  - Primordial binary cases are discussed in Di Carlo et al. (2019; 2020)
- Formation mechanism
  - Pop. II: common envelope
  - Pop. I: dynamical capture
- Differential merger rate density consistent with GW observations
  - No BH-BHs with $M_1 > 40 M_\odot$ due to the absence of $Z < 0.1 Z_\odot$ simulations

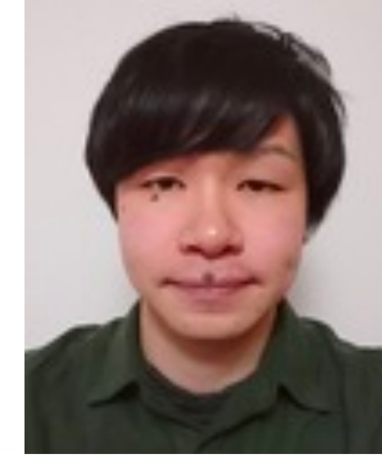


Kumamoto et al. (2019, MNRAS, 486, 3942)



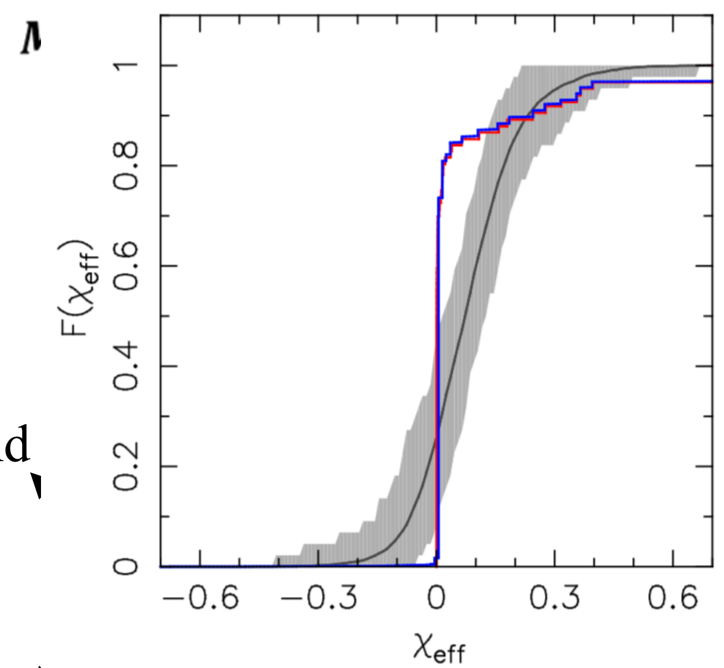
Kumamoto et al. (2020, MNRAS, 495, 4268)

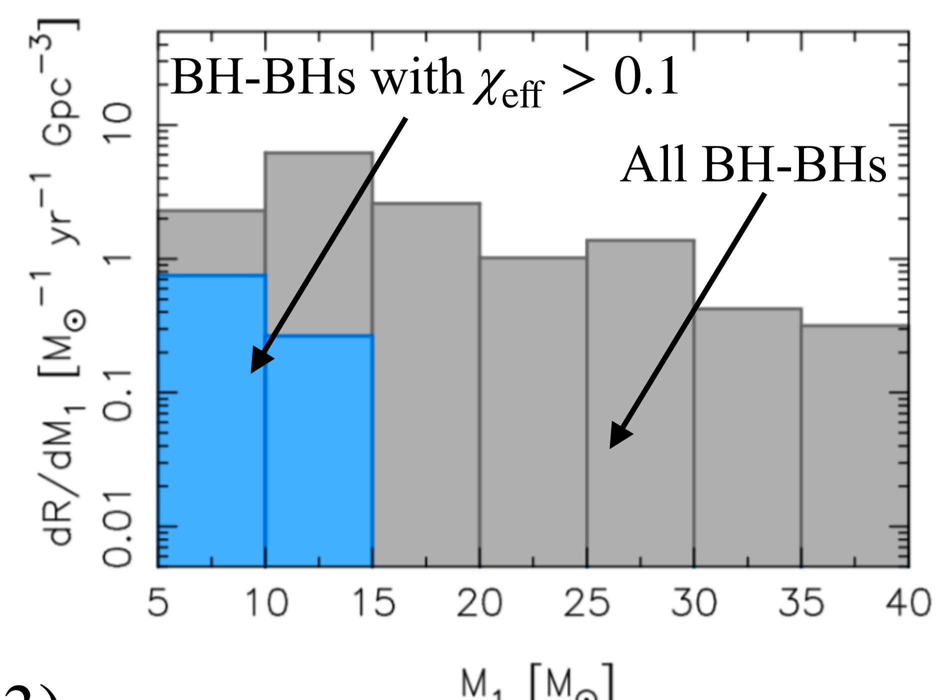
BH-BH effective spins



- Tidal spin up formulated by Hotokezaka & Piran (2017; see also Kushnir et al. 2016)
- $\sim 20\,\%$ of BH-BHs have positive effective spins.
  - It may be consistent with GW observations if we take into account observational errors (Tanaka-san's talk).
- Lower-mass BH-BHs have higher effective spins.
  - A possible clue to identify the BH-BH origin(s).
  - Consistent with Safarzadeh et al. (2020)'s argument.

stellar wind

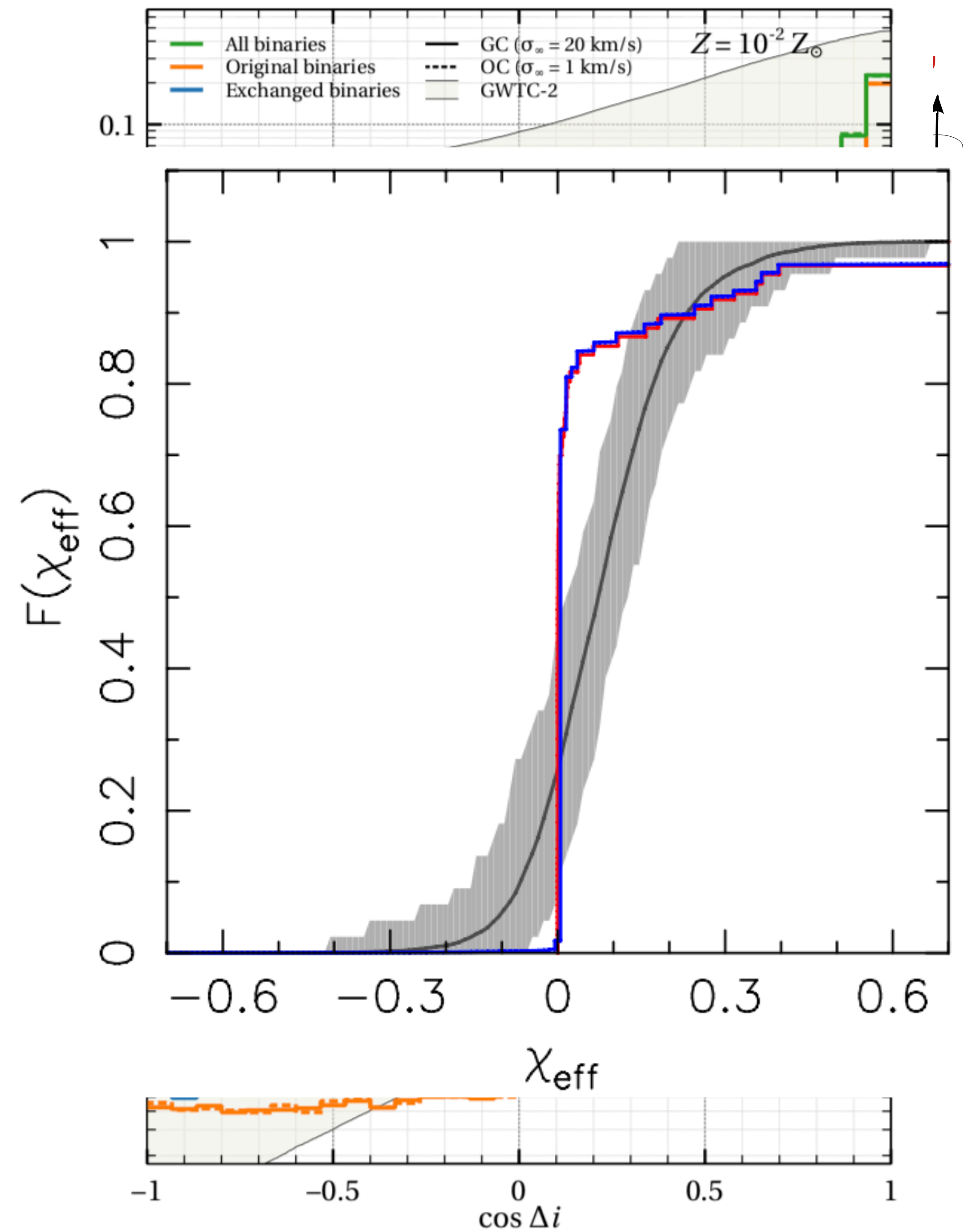




Kumamoto et al. (2021, arXiv:2102.09323)

Spin-orbit misalignment

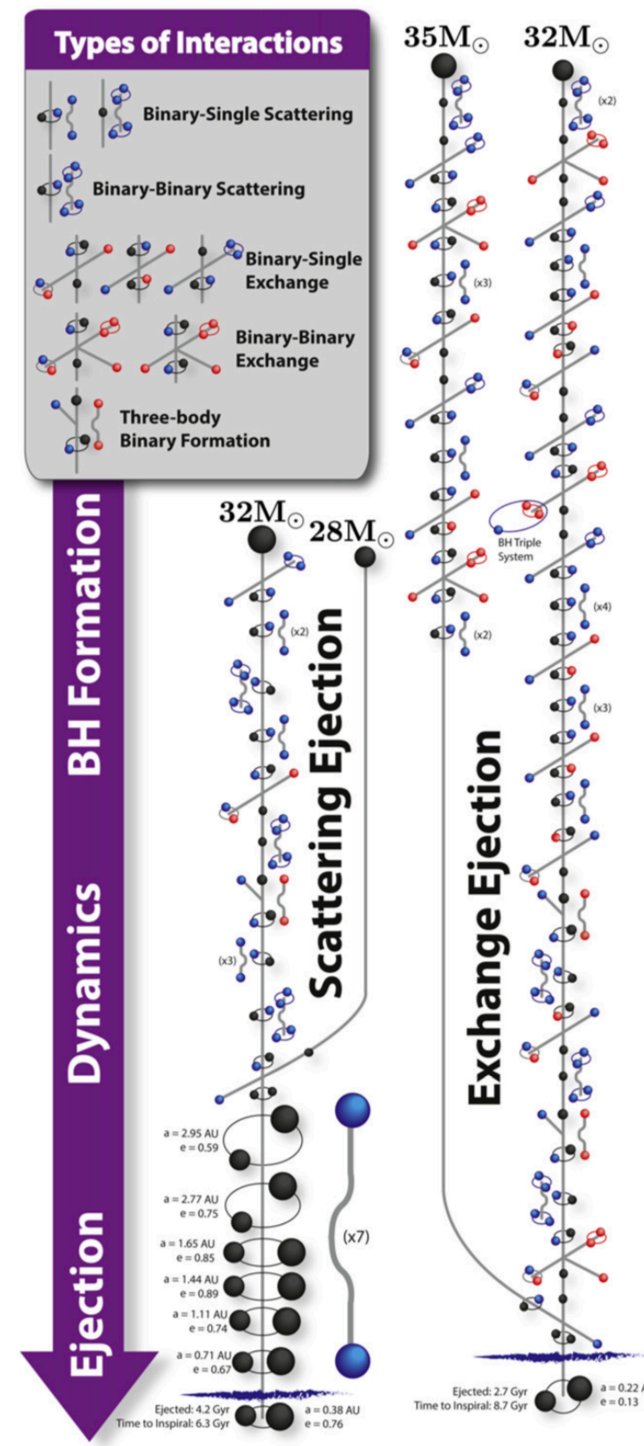
- $\sim 10\,\%$ of merging BH-BHs with spinning BHs experience a single encounter with another BH before they merge or are ejected.
- Such a single encounter makes spin-orbit misalignment, and produces non-zero $\chi_{\rm p}$.
- The misalignment doesn't attain the isotropic distribution.



Trani et al. (2021, MNRAS, 504, 910)

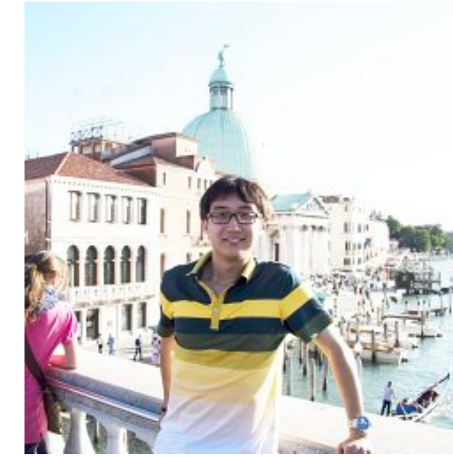
Globular clusters

- Globular cluster (GC) scenario (Portegies Zwart, McMillan 2000; Downing et al. 2010; Tanikawa 2013; Rodriguez et al. 2016; 2018; 2020; Fujii et al. 2017; Askar et al. 2017; Park et al. 2017; Samsing et al. 2018)
- It is unclear if GC-origin BH-BHs are numerous enough for the observed rate (but see Rodriguez et al. 2021)
    - The total cluster mass is 0.1-1% of the total stellar mass in the universe.
- Extra budget? (Weatherford et al. 2021)



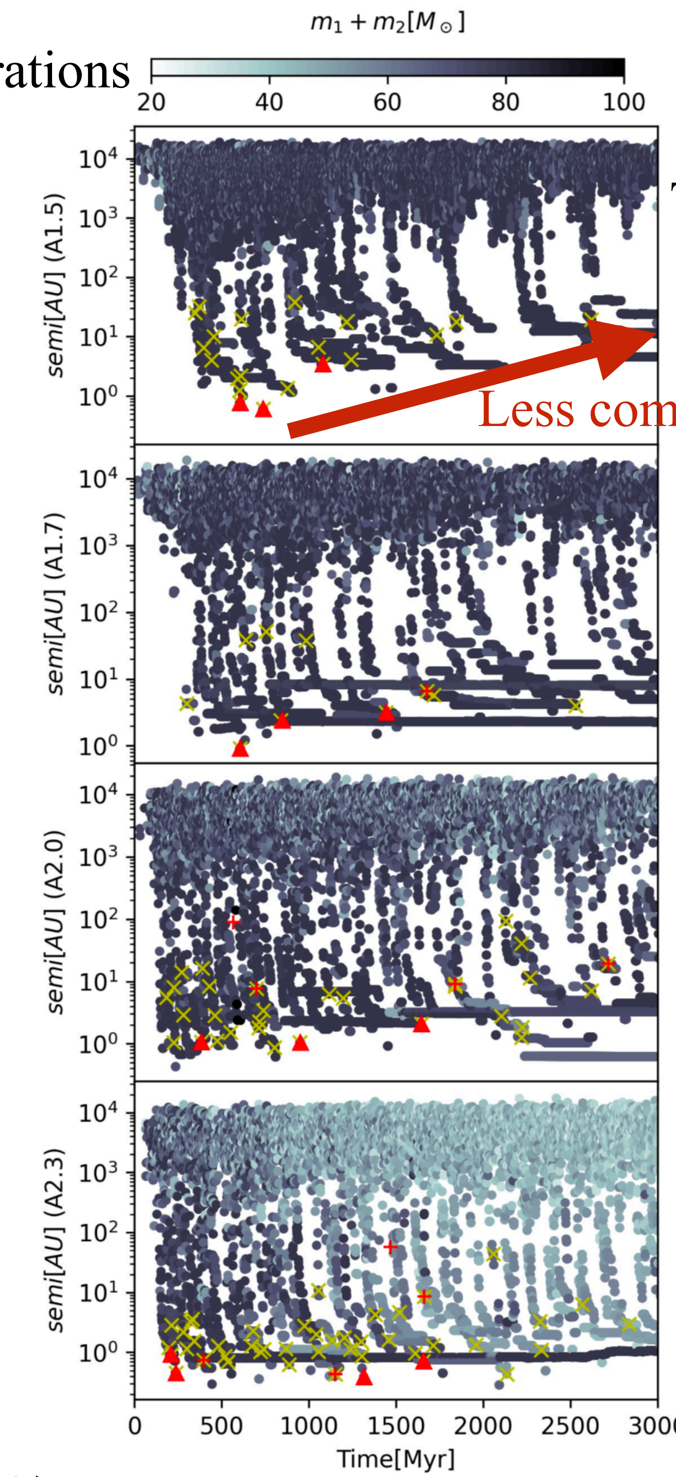
Rodrigeuz et al. (2016)

Top heavy IMF in GCs



- Top heavy IMF
  - Nearby dense star forming region (Lu et al. 2013; Schneider et al. 2018; Hosek et al. 2019)
  - Multiple stellar population in GCs (Milone et al. 2017; Bastian, Lardo 2018; Wang et al. 2020)
- Advantages for the GC-origin BH-BH scenario
  - More many BHs in each GC
  - Difficulty of EM observations
- Can they be the extra budget?
  - Not necessarily
  - They form many BH-BHs, but the BH-BHs are not enough compact to merge within the Hubble time.

BH-BH separations



The most top-heavy IMF

The standard IMF

Wang et al. (2021, MNRAS, 504, 5778)

Summary

- We have studied many formation scenarios of BH-BHs.
- Pop III BH-BHs have a smaller merger rate than observed. However,
  - $> 100 M_\odot$ BH mergers may be dominated by Pop III origins.
  - GW190521 can be formed from Pop III binary stars.
- BH-BHs formed in open clusters: their mass, effective spin, and tilt angle distributions, consistent with GW observations.
- GCs with top-heavy IMF which do not increase GC-origin BH-BHs as expected.