# Merging binary black holes in dense star clusters and in Pop. III environments

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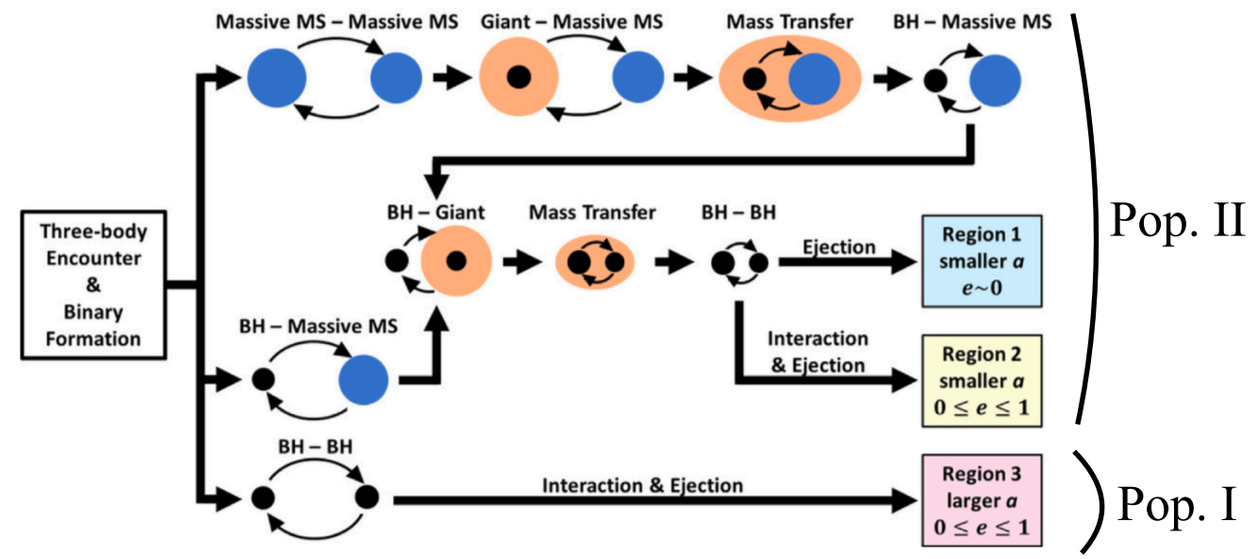
# Papers in 2020-2021

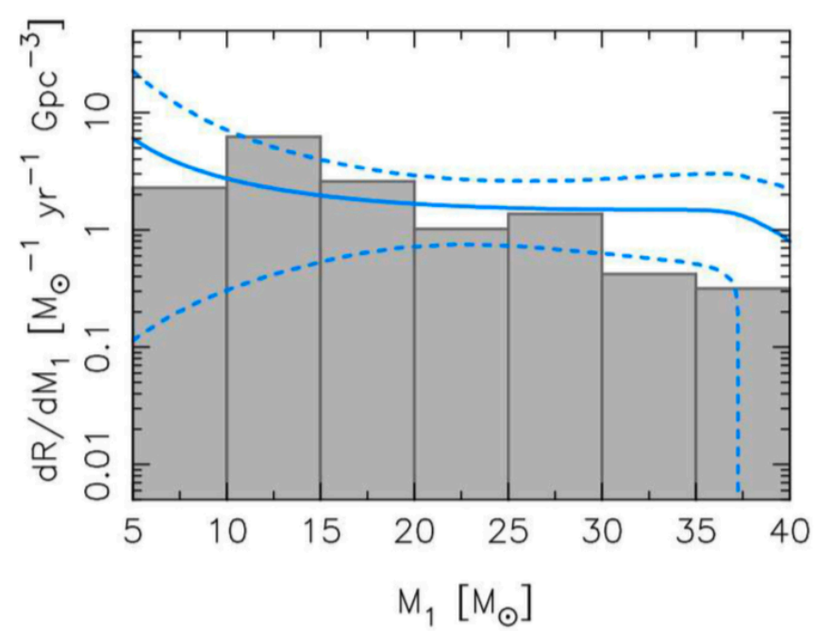
- Open clusters
  - **Kumamoto**, **Fujii**, **AT** (2020, MNRAS, 495, 4268) "Merger rate density of binary black holes formed in open clusters"
  - **Kumamoto**, **Fujii**, **Trani**, **AT** (2021, arXiv:2102.09323) "Spin distribution of binary black holes formed in open clusters"
  - **Trani**, **AT** , **Fujii**, Leigh, **Kumamoto** (2021, arXiv:2102.01689) "Spin misalignment of black hole binaries from young star clusters: comparison to GWTC-2 gravitational wave data" (see also Presentation No. 23)
  - **AT**, Kinugawa, **Kumamoto**, **Fujii** (2020, PASJ, 72, 39) "Formation rate of LB1-like systems through dynamical interactions"
  - Shikauchi, **Kumamoto**, **AT**, **Fujii** (2020, PASJ, 72, 45) "Gaia's detectability of black hole-main sequence star binaries formed in open clusters"
- Globular clusters
  - Wang, **Fujii**, **AT** (2021, arXiv:2101.09283, submitted) "Impact of initial mass functions on the dynamical channel of gravitational wave sources"
- Pop. III stars
  - **Kirihara**, **Susa**, **AT** (2021, submitted) "Merger conditions of a star-star interaction" (see also Presentation No. 22)
  - **AT**, Yoshida, Kinugawa, Takahashi, Umeda (2020, MNRAS, 495, 4170) "Fitting formulae for evolution tracks of massive stars under extreme metal-poor environments for population synthesis calculations and star cluster simulations"
  - **AT**, **Susa**, Yoshida, **Trani**, Kinugawa (2021, arXiv:2008.01890, ApJ accepted) "Merger rate density of Population III binary black holes below, above and in the pair-instability mass gap"
  - **AT**, Kinugawa, Yoshida, Hijikawa, Umeda (2020, arXiv:2010.07616, submitted) "Population III binary black holes: effects of convective overshooting on formation of GW190521"

# 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



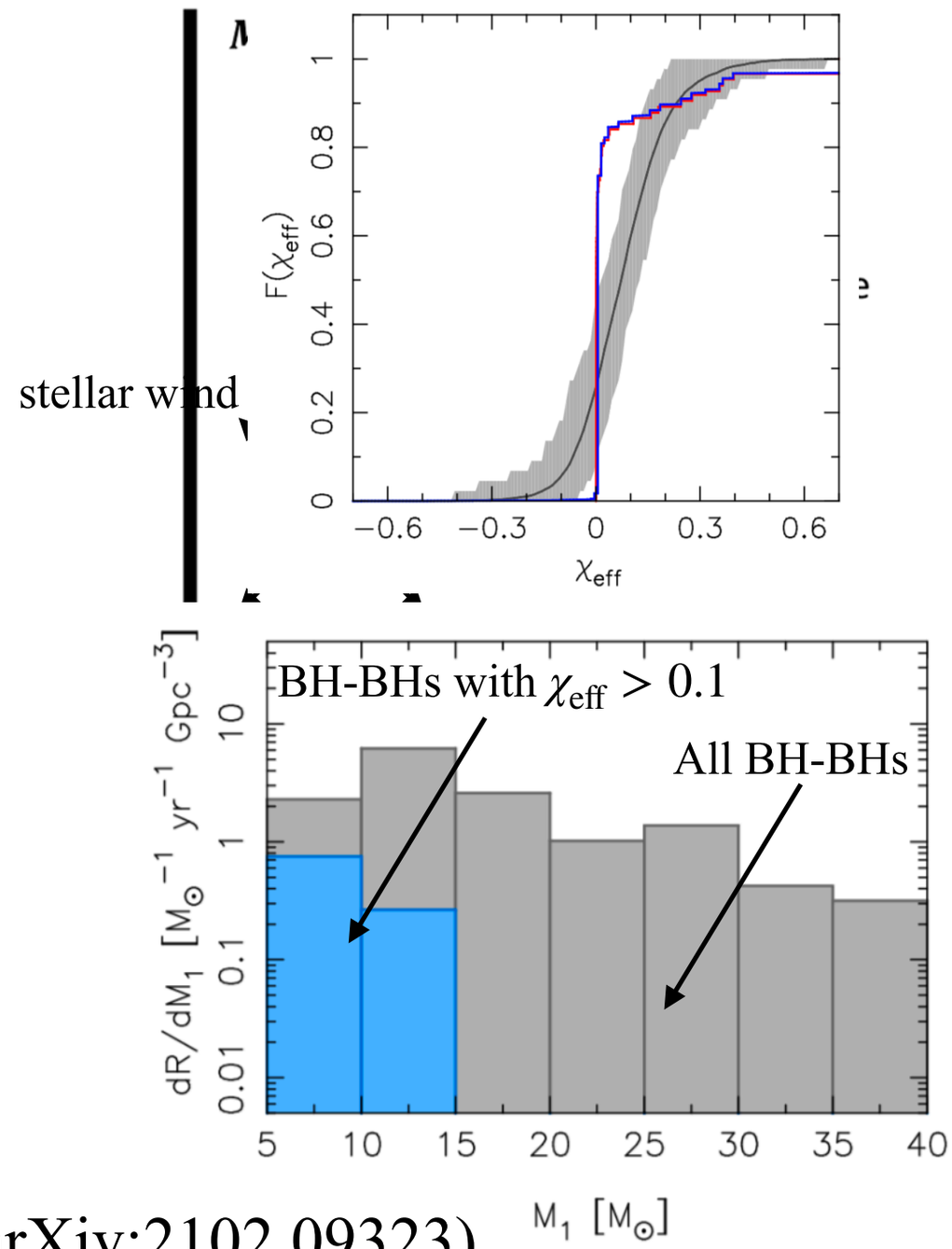

Kumamoto, Fujii, AT (2019, MNRAS, 486, 3942)




Kumamoto, Fujii, AT (2020, MNRAS, 495, 4268)

# BH-BH effective spins

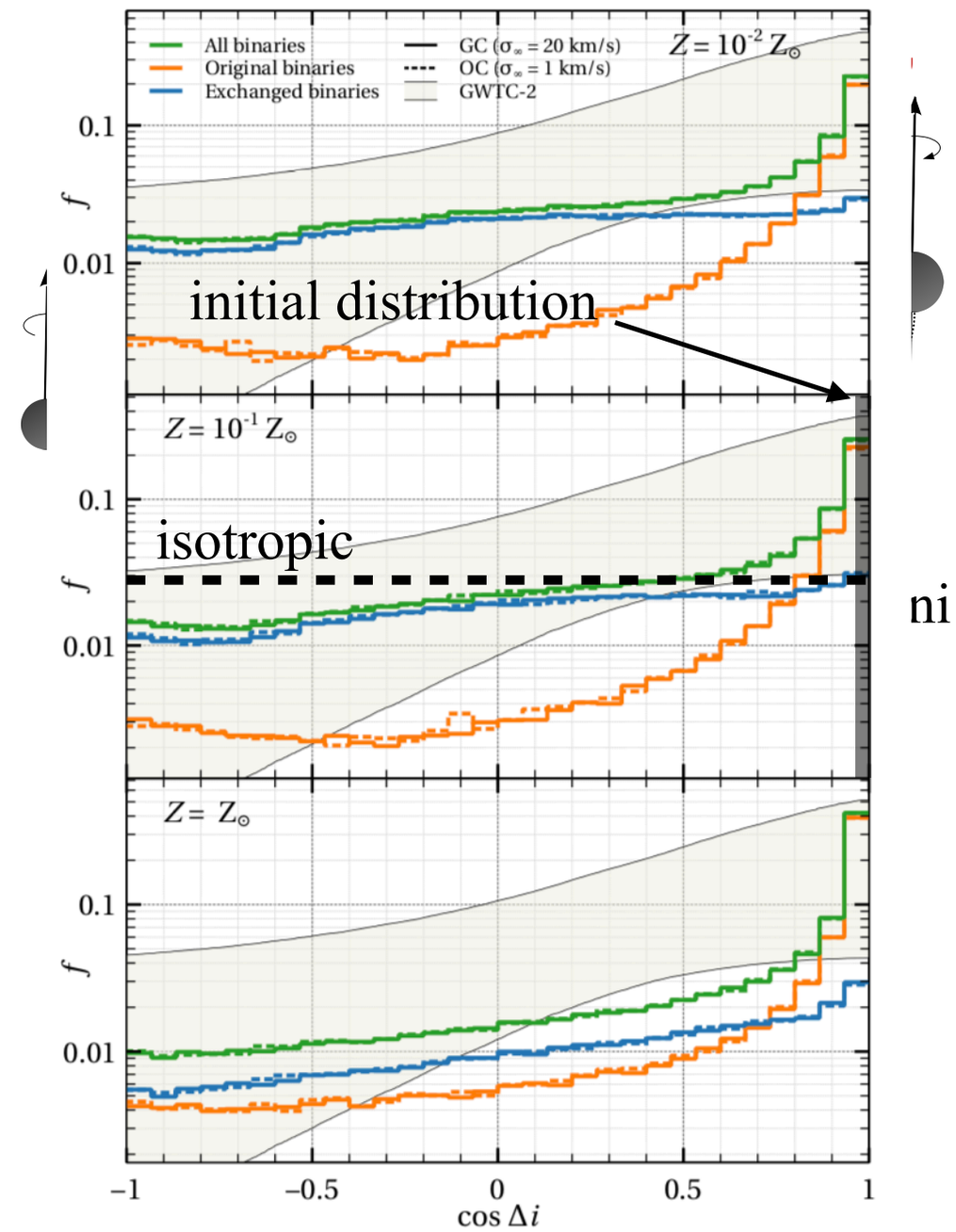
- Tidal spin up formulated by Hotokezaka & Piran (2017; see also Kushnir et al. 2016)
- ~ 20 % of BH-BHs have positive effective spins.
  - It may be consistent with GW observations if we take into account observational errors (Tanaka-san's talk).
- Lower-mass BH-BHs have higher effective spins.
  -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




Kumamoto, Fujii, Trani, AT (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 $\chi_p$.
- The misalignment doesn't attain the isotropic distribution.
- **See Presentation No. 23**

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Trani, AT et al. (2021, arXiv:2102.01689)

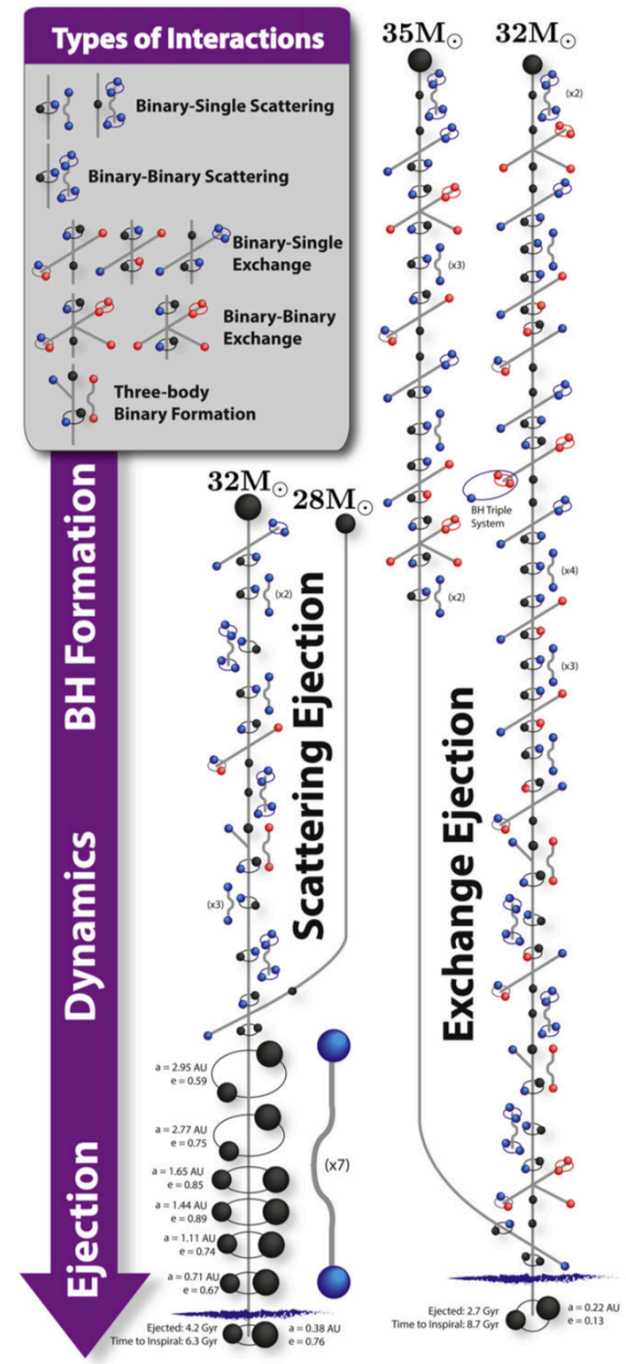
# Globular clusters

- 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)

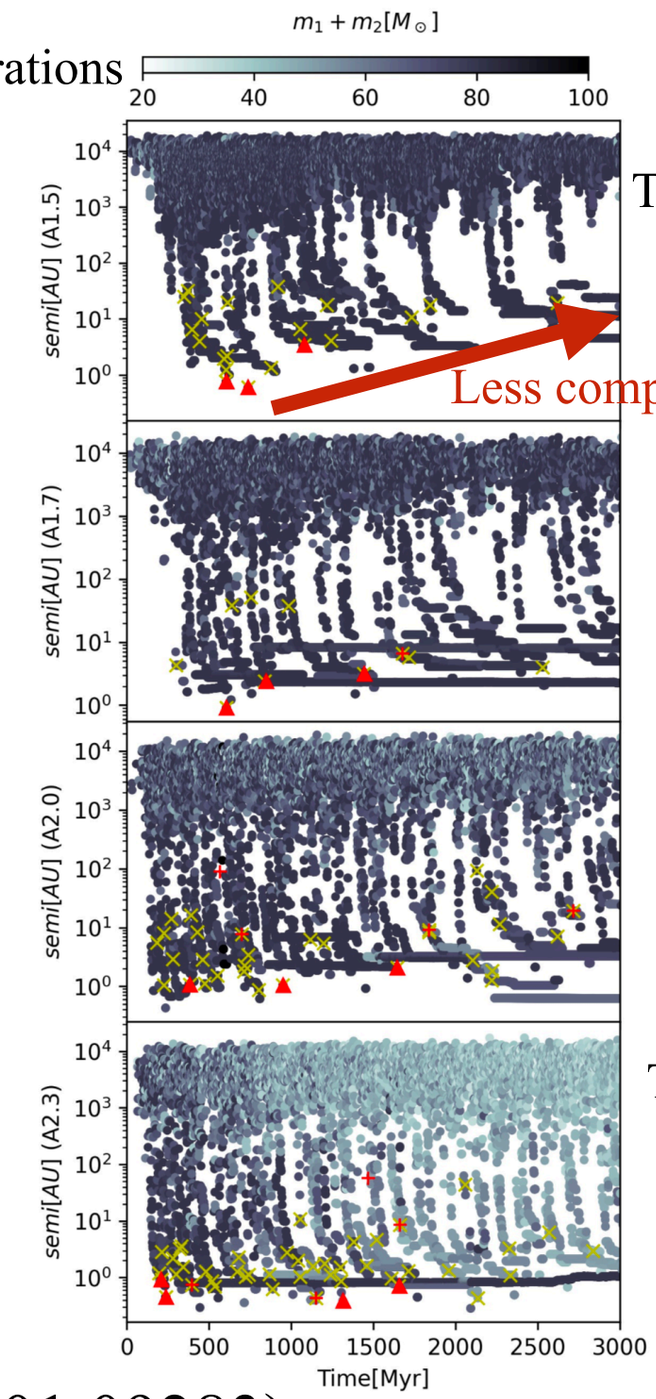



Rodrigeuz et al. (2016)

# 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

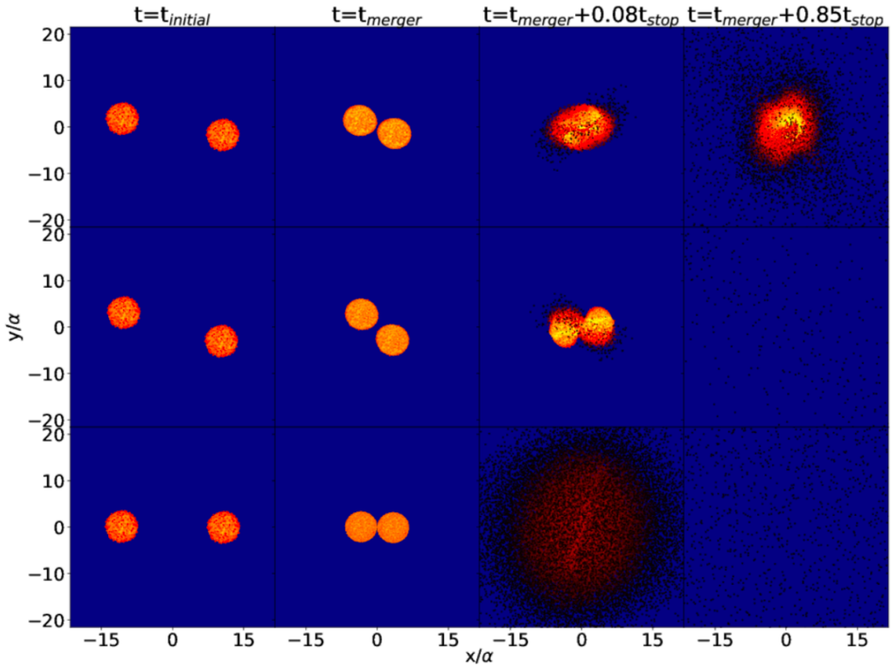
Less compact with time

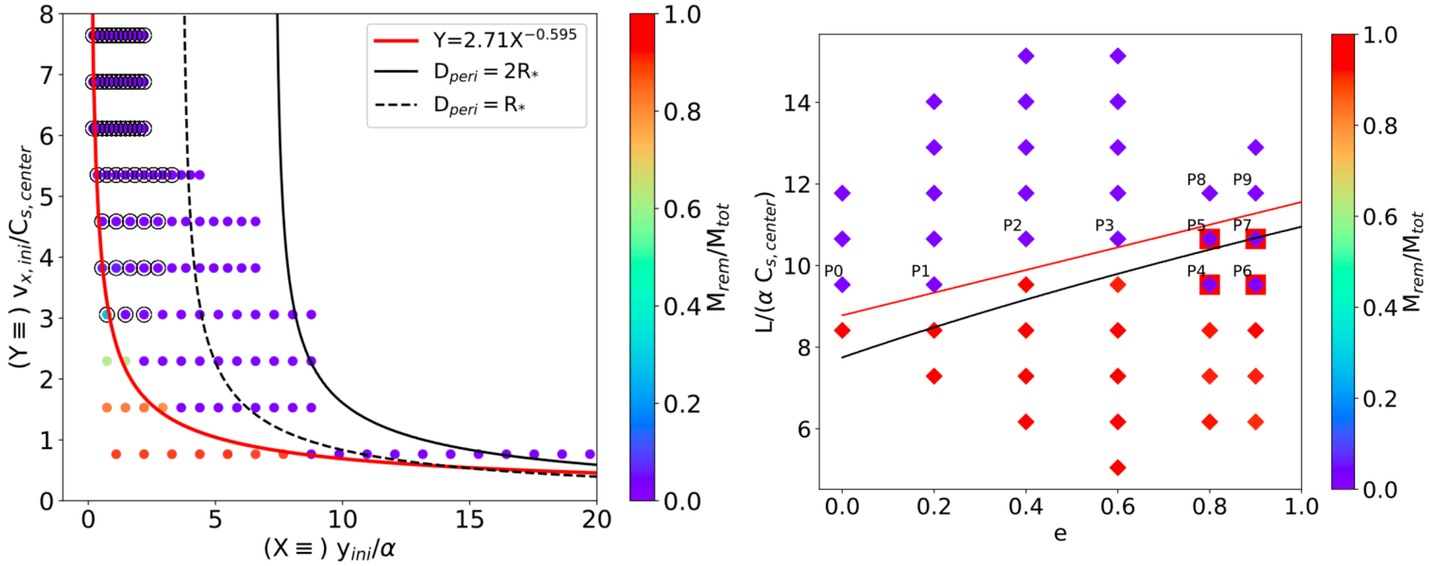
The standard IMF

Wang, Fujii, AT et al. (2021, arXiv:2101.09283)

# Stellar merger

- Importance
  - Pop. III clusters (Stacy et al. (2010; Clark et al. 2011; Greif et al. 2011; Smith et al. 2011; Susa 2019; Sugimura et al. 2020)
  - Formation of mass-gap BHs (Di Carlo et al. 2020)
  - Formation of IMBHs in GCs (Portegies Zwart et al. 2004; Sakurai et al. 2017)
- Accurate merger conditions required.
- **See Presentation No. 22**

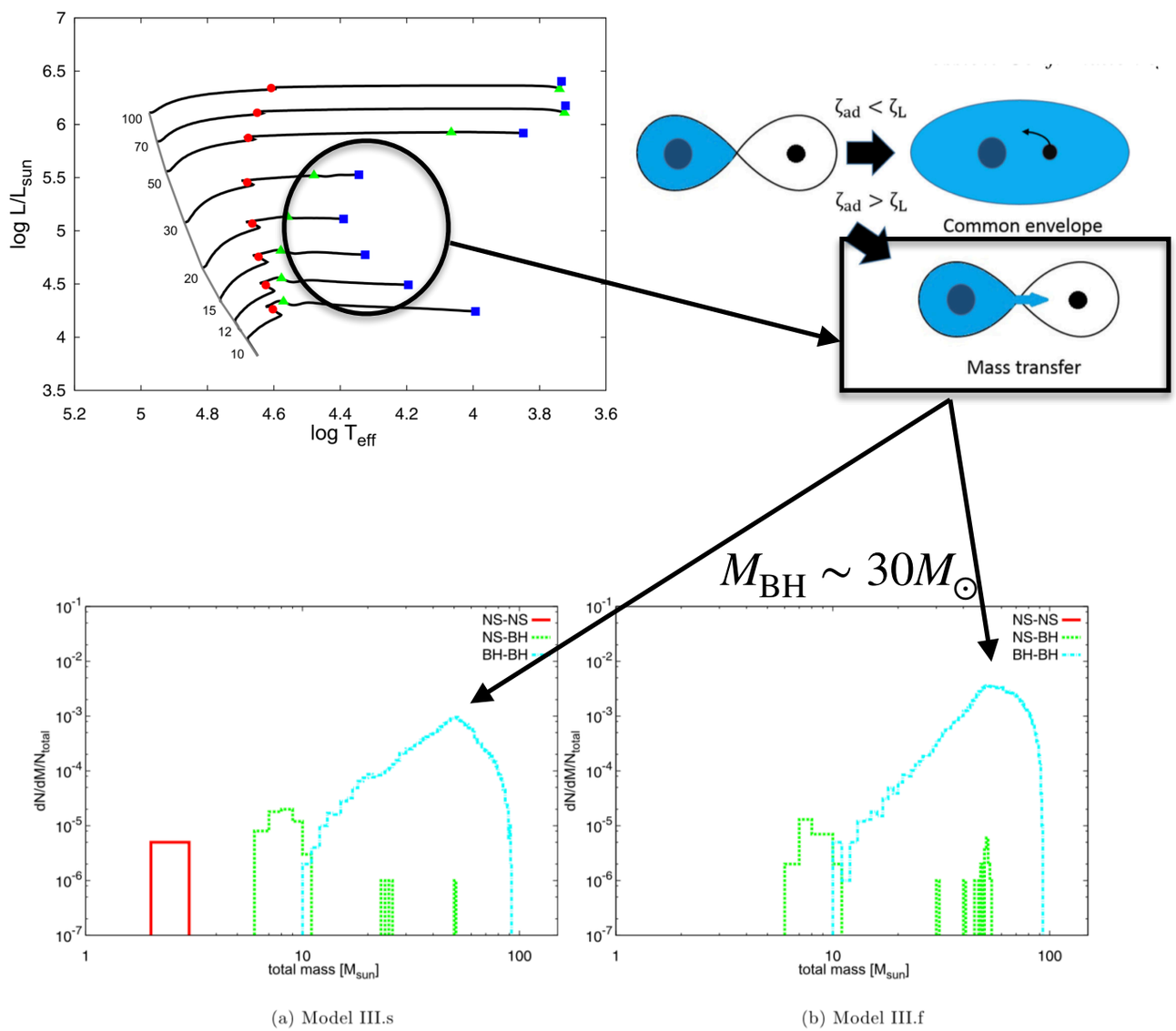



Kirihara, Susa, AT (2021, submitted)

# Pop. III BH-BHs

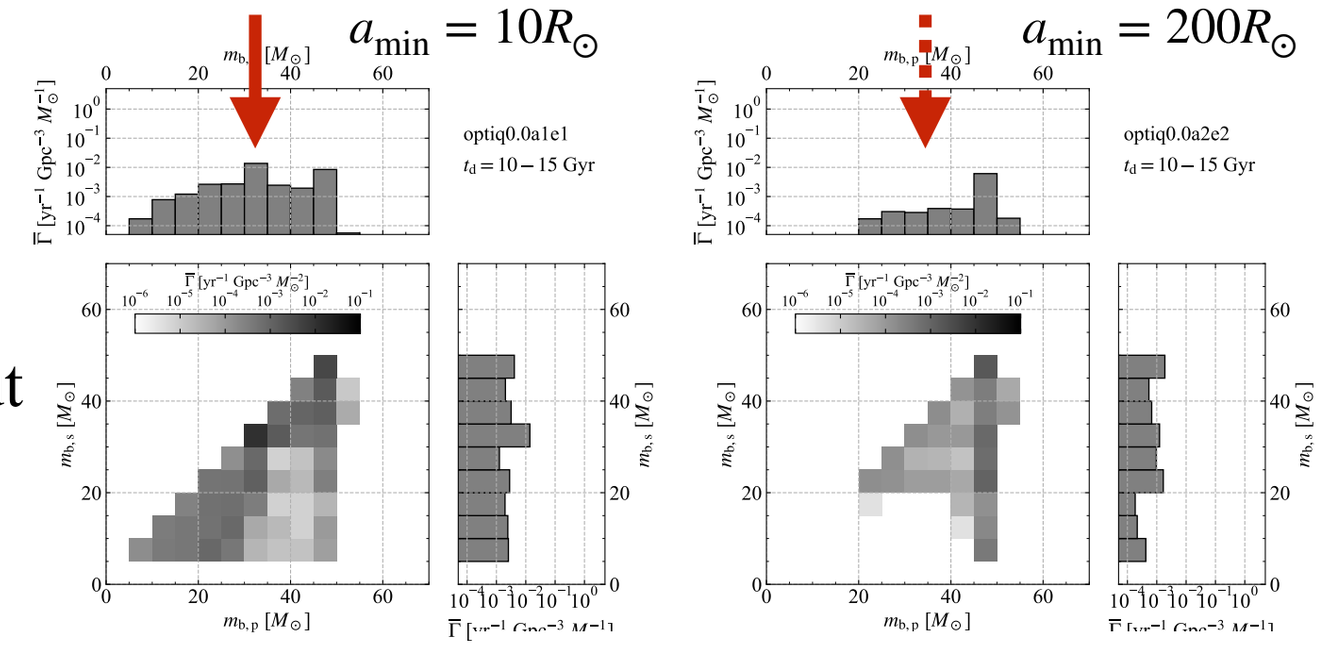
- Pop. III BH-BHs are one of promising origins of observed BH-BHs.
  - They typically have $M_{\rm BH} \sim 30 M_\odot$.
  - GW observations frequently find BH-BHs with $M_{\rm BH} \sim 30 M_\odot$.
- Uncertainties of Pop. III models?
- IMBHs $\sim 10^2 - 10^3 M_\odot$?
- The mass-gap event (GW190521)?

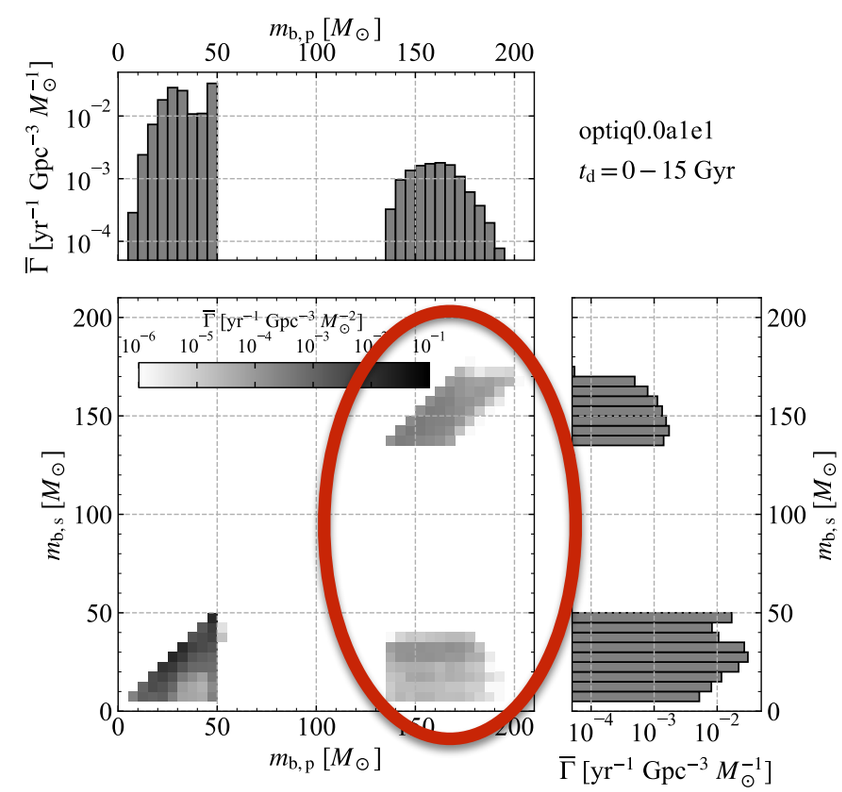



Kinugawa et al. (2014)

# Their mass distribution

- The merger rate density is insensitive to initial conditions, $\sim 10^{-14}\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}M_{\odot}^{-1}$.
- The $30M_{\odot}$ peak disappears without close ( $\sim 10R_{\odot}$) Pop. III binaries.
  - Pop. III binaries can be only $\gtrsim 100R_{\odot}$, since Pop. III stars expand to $\sim 100R_{\odot}$ at their proto-stellar phases (Omukai, Palla 2001; 2003)
- The sum of IMBH-BH and IMBH-IMBH merger rates is $\sim 1\ \mathrm{yr}^{-1}$ within $z \sim 0.82$ in a conservative Pop. III formation rate.



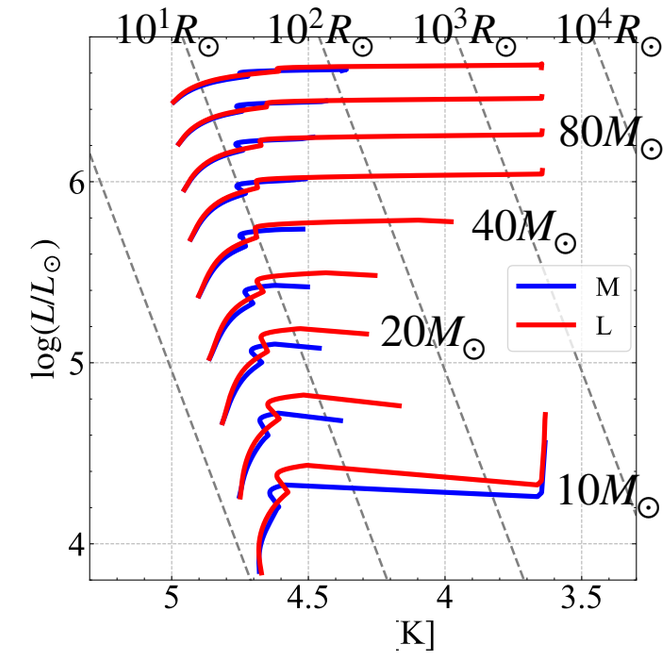



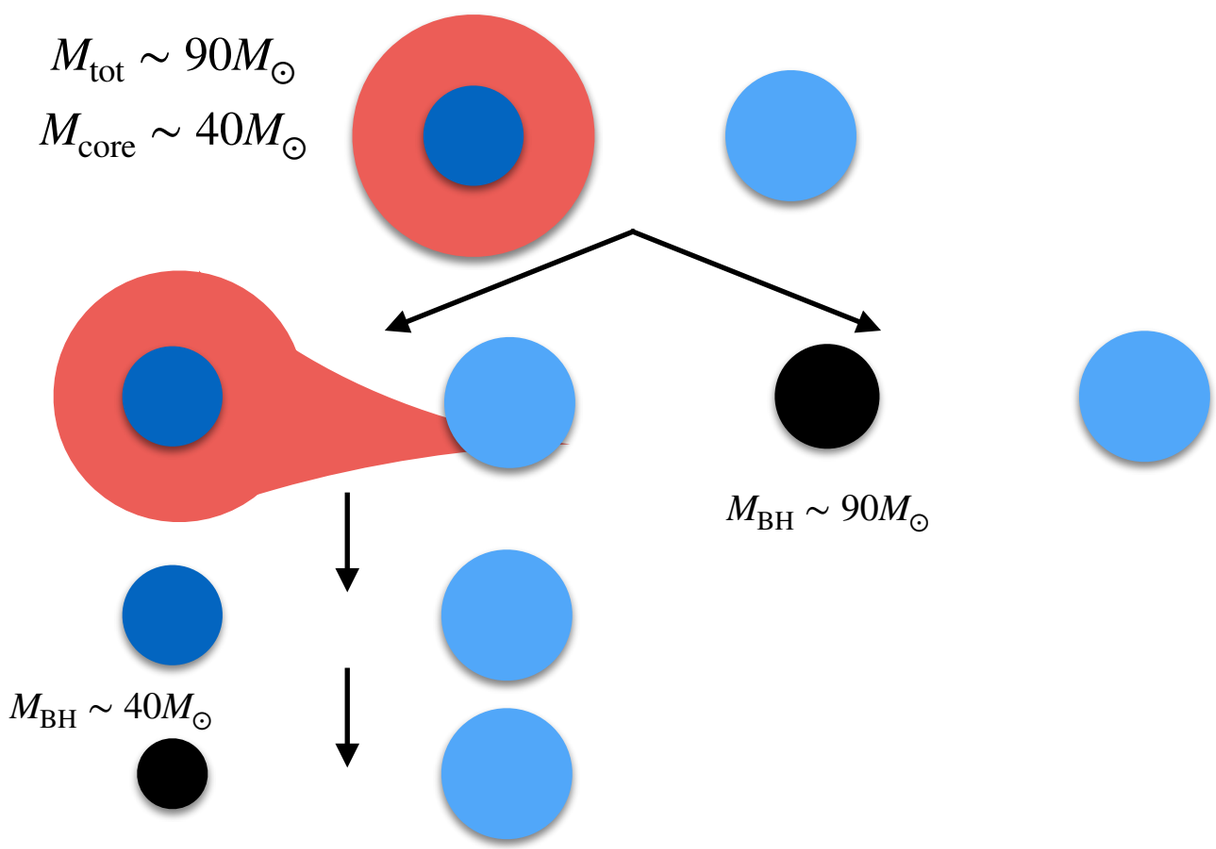

AT et al. (2021, arXiv:2008.01890)

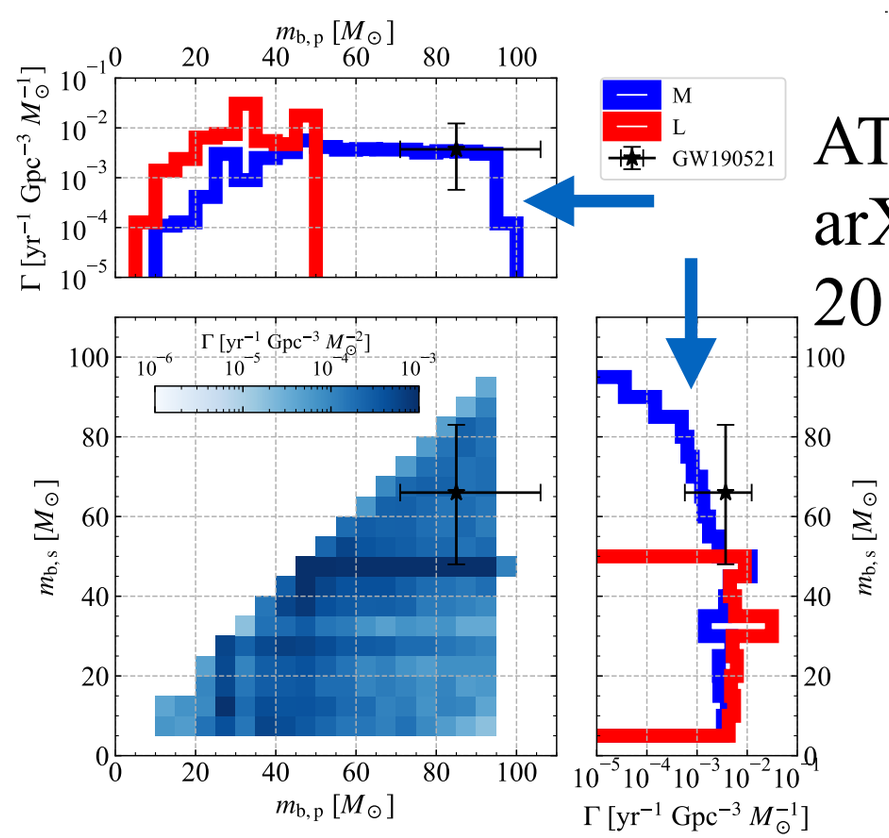
# Mass-gap event (GW190521)

- Pop. III binaries can form the mass-gap event if Pop. III stars with $\sim 90 M_\odot$ expand up to $\lesssim 100 R_\odot$.
- It can be attained if convective overshoot is not effective.

Pop. III models consistent with nearby star models




AT et al. (2020, arXiv: 2010.07616)

# Summary

- 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.
- Stellar merger conditions determined.
- Pop. III BH-BHs: unexpectedly large merger rate of IMBHs, and a possible solution for the mass-gap event.