Theoretical study of the origins of merging binary black holes

Colloquium 2021/06/14
Astronomical Institute, Tohoku University

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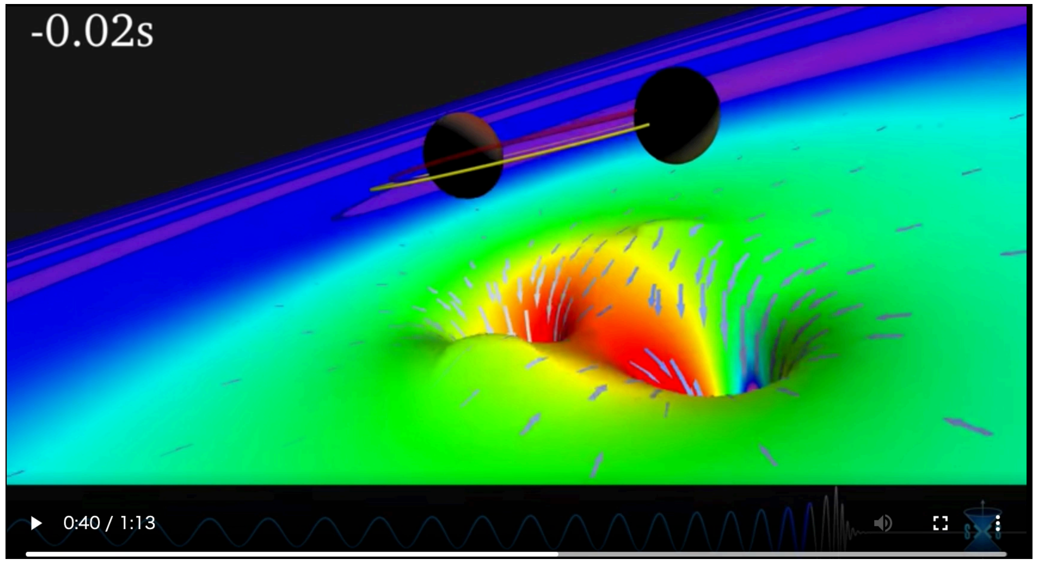
Contents

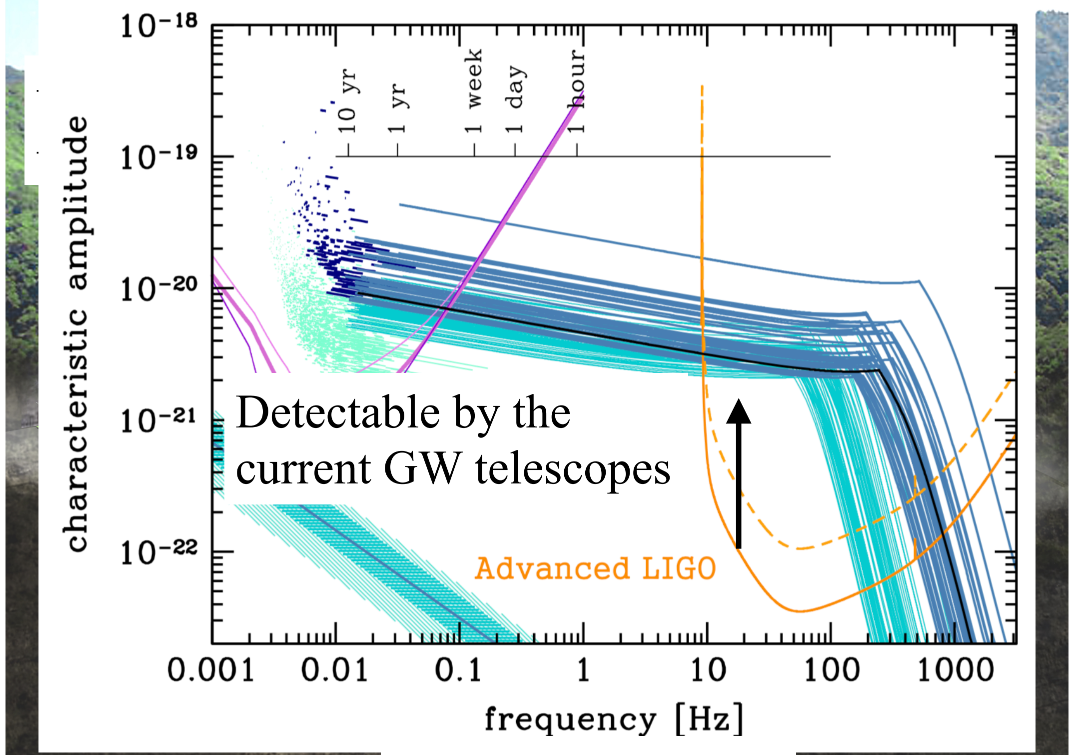
- Gravitational wave (GW) observations and stellar-mass black hole (BH) mergers
- Merging binary BHs formed in open clusters
- Formation scenario of the pair instability (PI) mass gap event GW190521

GWs from BH mergers

- A life of a merging binary BH
  - Born as BH-BH with masses of $\sim 10M_\odot$ and separation of $\lesssim 100R_\odot$ $\lesssim 10$ Gyr ago
  - Shrink the separation through GW radiation, not detectable
  - Large GW emission $\lesssim 1$ sec before their merger, detected by GW telescopes
- GW telescopes sensitive to 10-1000Hz
  - $f_{\rm gw} \sim \frac{1}{P(r_{\rm sch})} \sim 10^2\ {\rm Hz} \left(\frac{M_{\rm BH-BH}}{10^2 M_\odot}\right)^{-1}$



SXS project

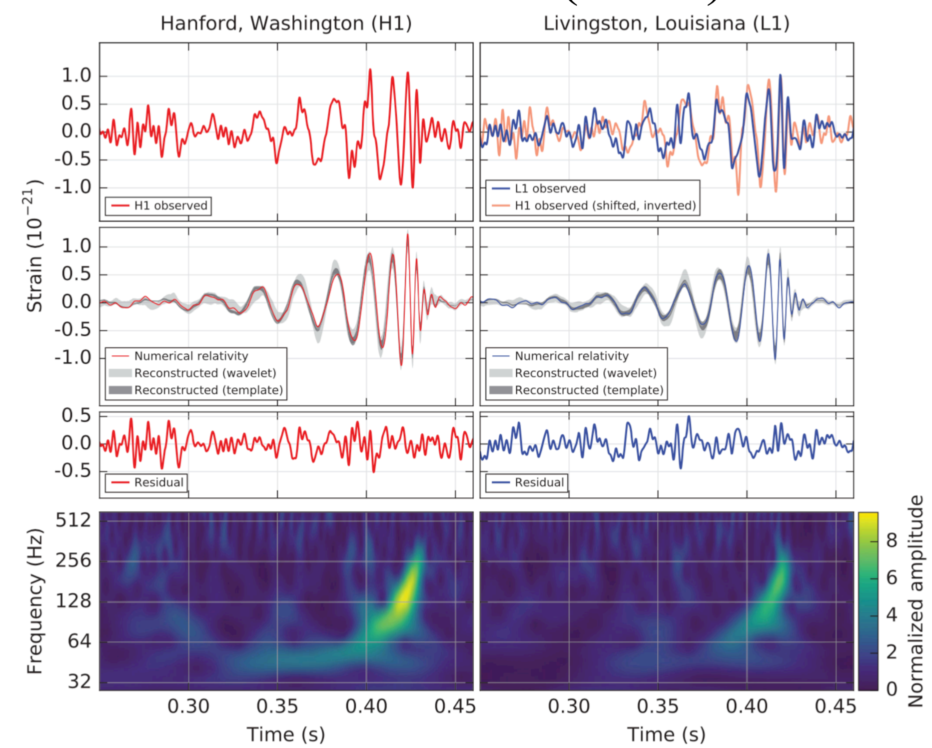


Sesana (2016)

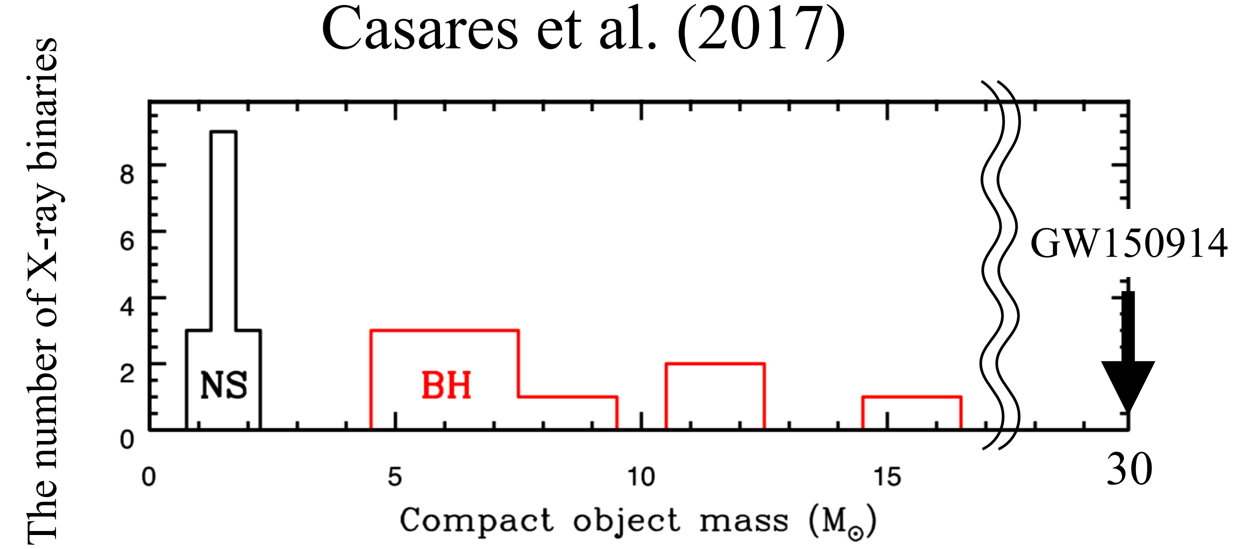
The first detection: GW150914

- Detected on 14 September 2015
- Merger of $36M_\odot$ and $29M_\odot$ BHs
- BHs heavier than observed before
  - Metal-poor star?
  - Star clusters?
  - Primordial BH?
- Compact binary BH
  - Merger time: $\lesssim 10^{10}$ yr
  - Separation: $\lesssim 10^{2}R_\odot$ at the formation of the binary BH.
  - Red supergiants: $\gtrsim 10^{3}R_\odot$

Abbott et al. (2016)



Casares et al. (2017)



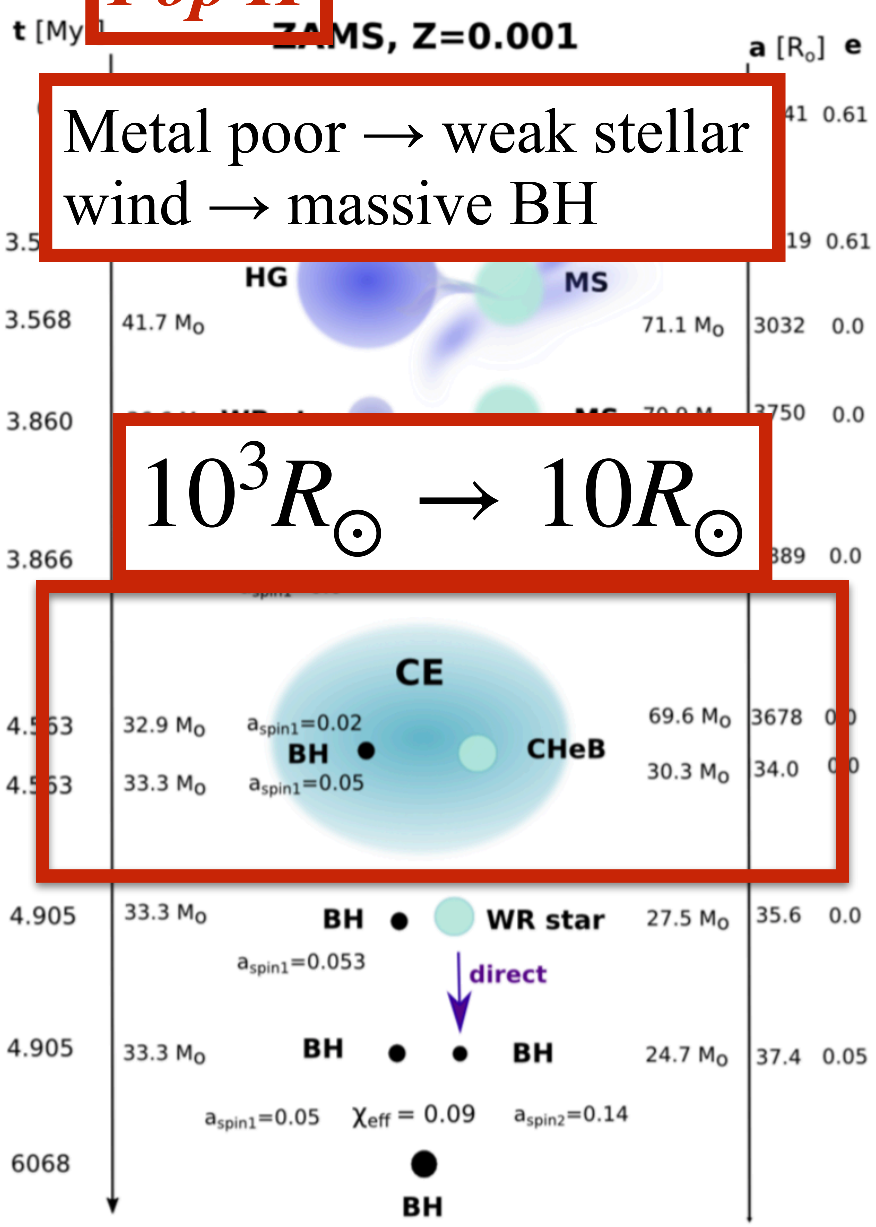
Many formation scenarios

Isolated binary stars

Pop II

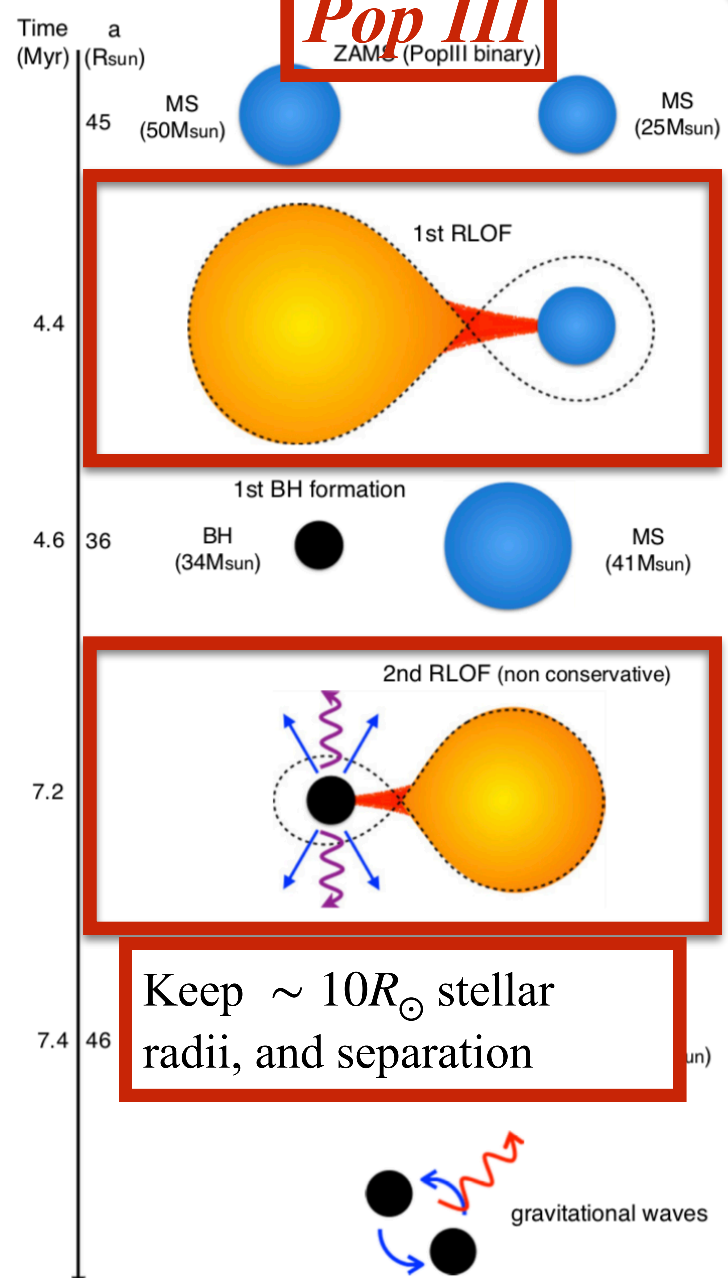
Metal poor → weak stellar wind → massive BH

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



Belczynski et al. (2020)

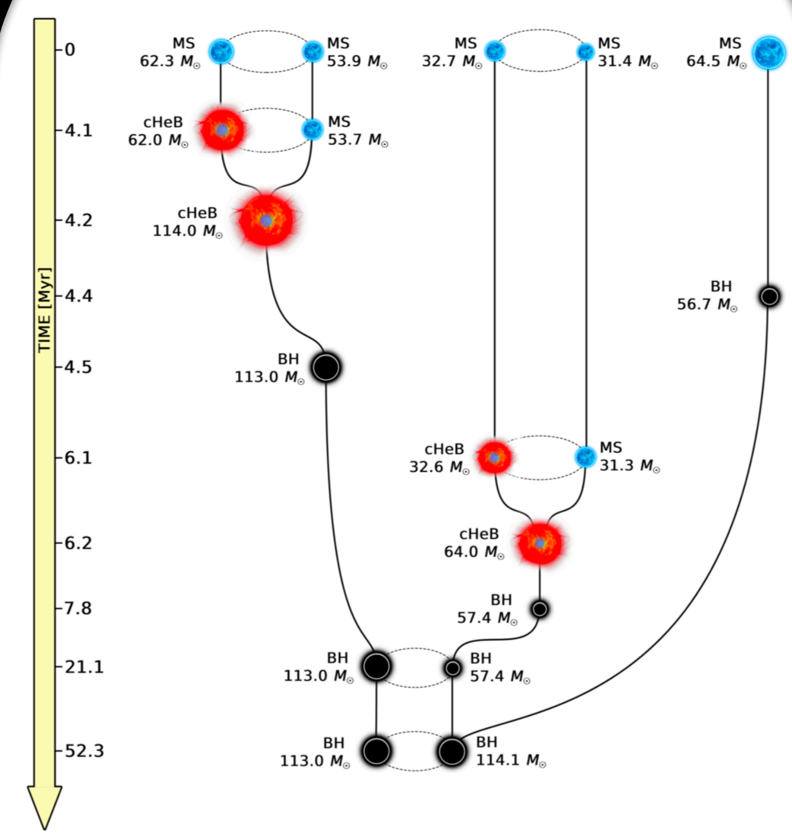
Pop III



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

Kinugawa et al. (2014); Inayoshi et al. (2017)

Star cluster



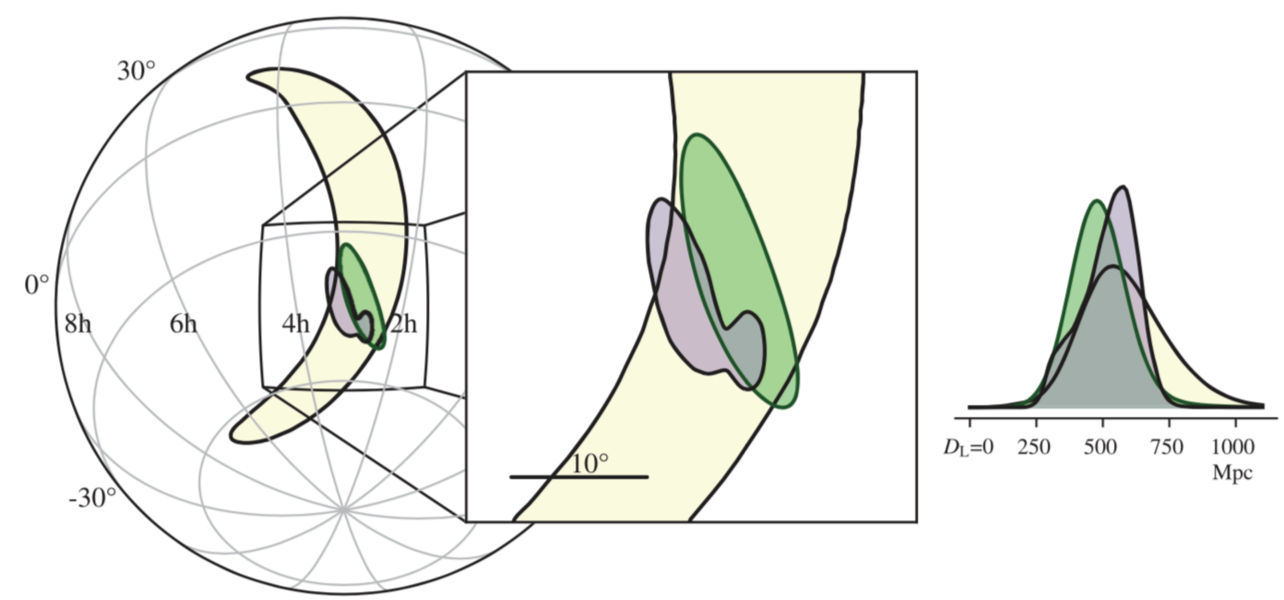
Di Carlo et al. (2021)

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

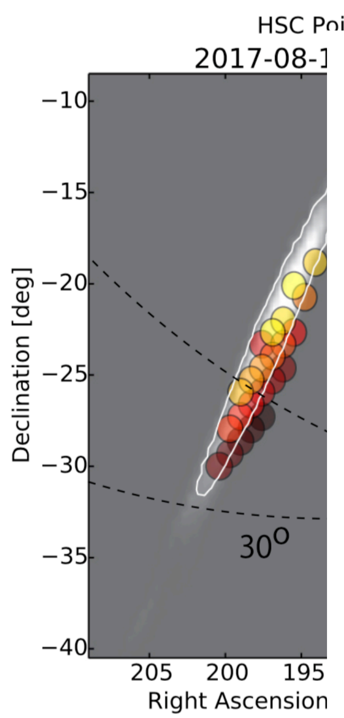
Difficulty of identification

- Large sky localization
- Impossible to find the host galaxy
- No conclusive electromagnetic counterpart unlike NS mergers

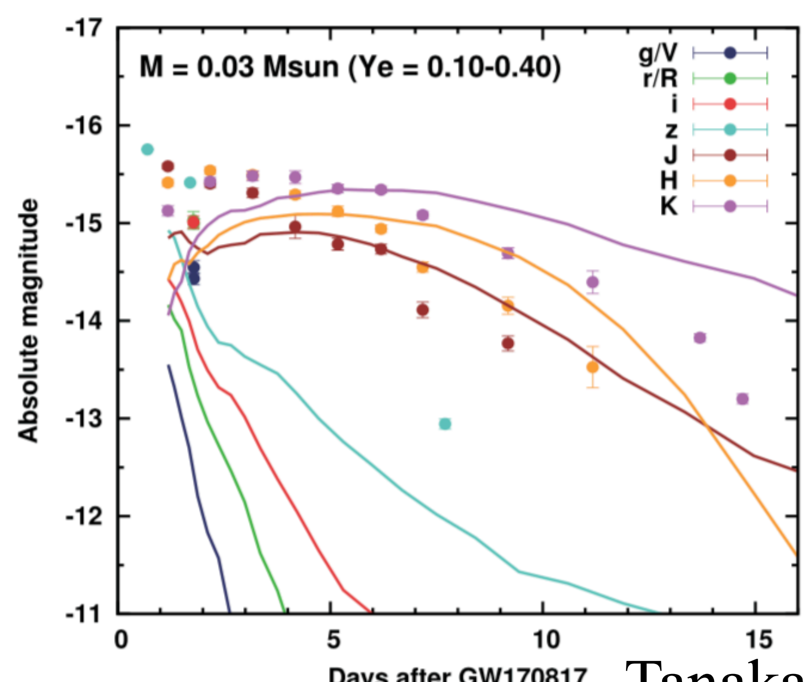
GW170814 (Abbott et al. 2017)

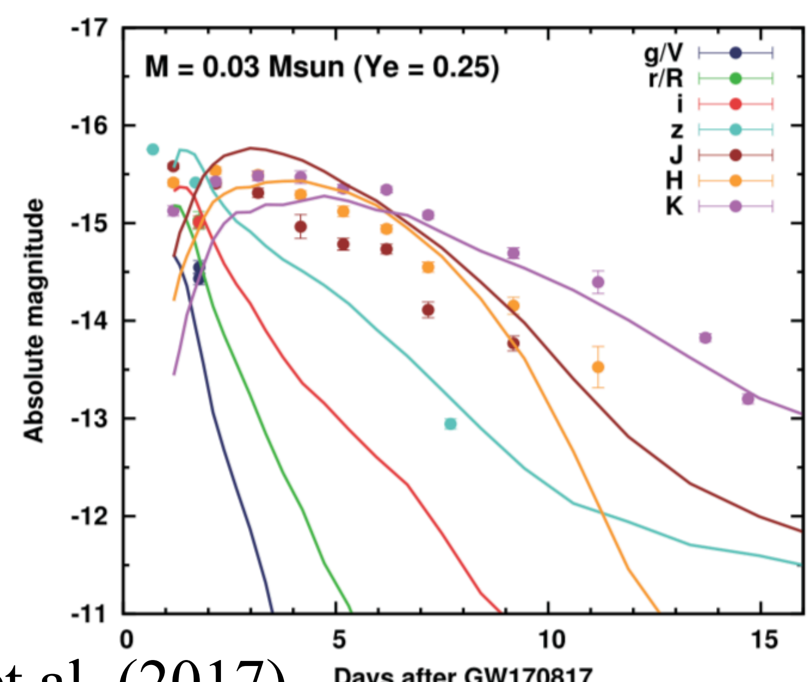


GW170817, NS merger



Tominaga et al. (2018)



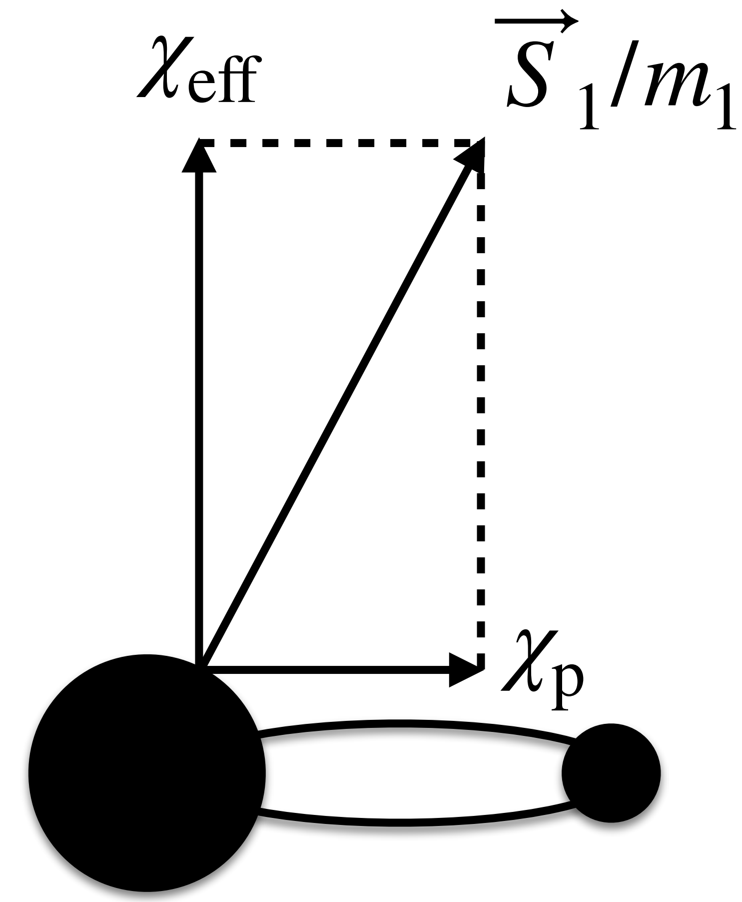


Tanaka et al. (2017)

7)

Clues for identification

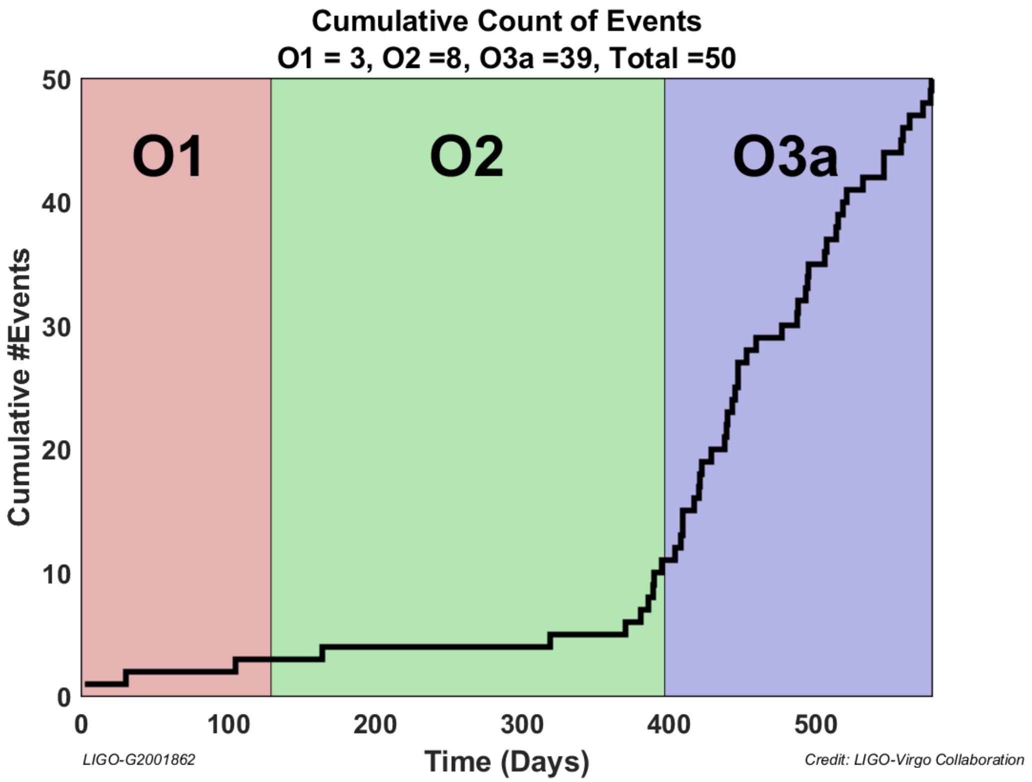
- BH merger rate density: R [yr^{-1} Gpc^{-3}]
- Primary BH mass: m_1 [$M_\odot$]
- Secondary BH mass: m_2 [$M_\odot$]
  - Mass ratio: $q = m_2/m_1$
- Effective spin: χ_{eff}
  - $\chi_{\mathrm{eff}} = \dfrac{1}{m_1 + m_2}\left(\dfrac{S_{1,\parallel}}{m_1} + \dfrac{S_{2,\parallel}}{m_2}\right)$
- Spin precession: χ_{p}
  - $\chi_{\mathrm{p}} = \max\left(\dfrac{S_{1,\perp}}{m_1^2}, \dfrac{S_{2,\perp}}{m_2^2}\kappa(q)\right)$
- Redshift: z
- Eccentricity: e (not discussed much because of circularization)

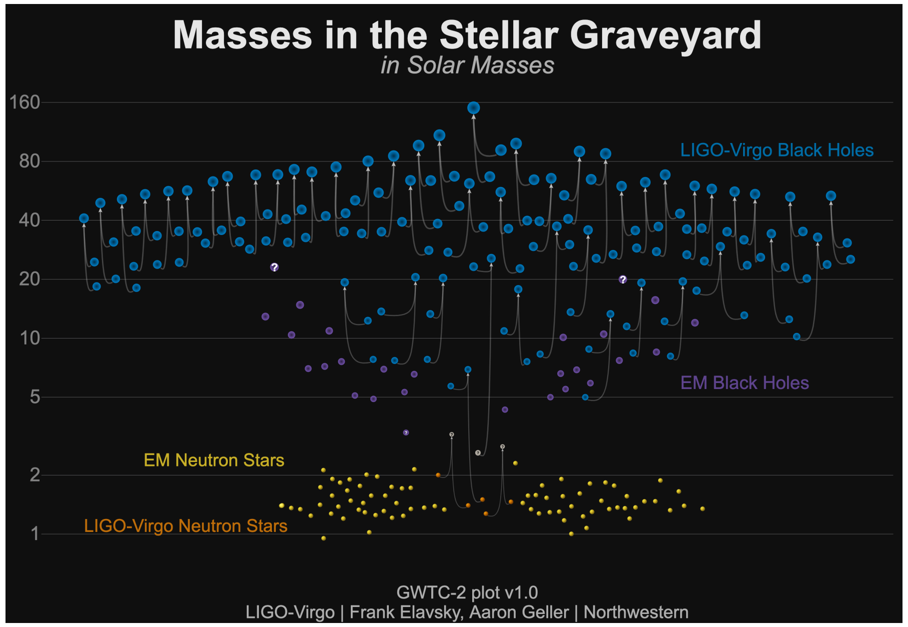


- $m_1 \gg m_2$
- $S_1 \neq 0$
- $S_2 = 0$

GW observing runs

- O1: 12 Sep. 2015 to 19 Jan. 2016
  - LIGO-Livingston (L)
  - LIGO-Hanford (H)
- O2: 30 Nov. 2016 to 25 Aug. 2017
  - Virgo (V) joined.
- O3a: 1 Apr. 2019 to 1 Oct. 2019
  - L: 88Mpc to 135Mpc for NS-NS
  - H: 66Mpc to 108Mpc
  - V: 26Mpc to 45Mpc
- O3b: 1 Nov. 2019 to 27 Mar. 2020
  - Not published



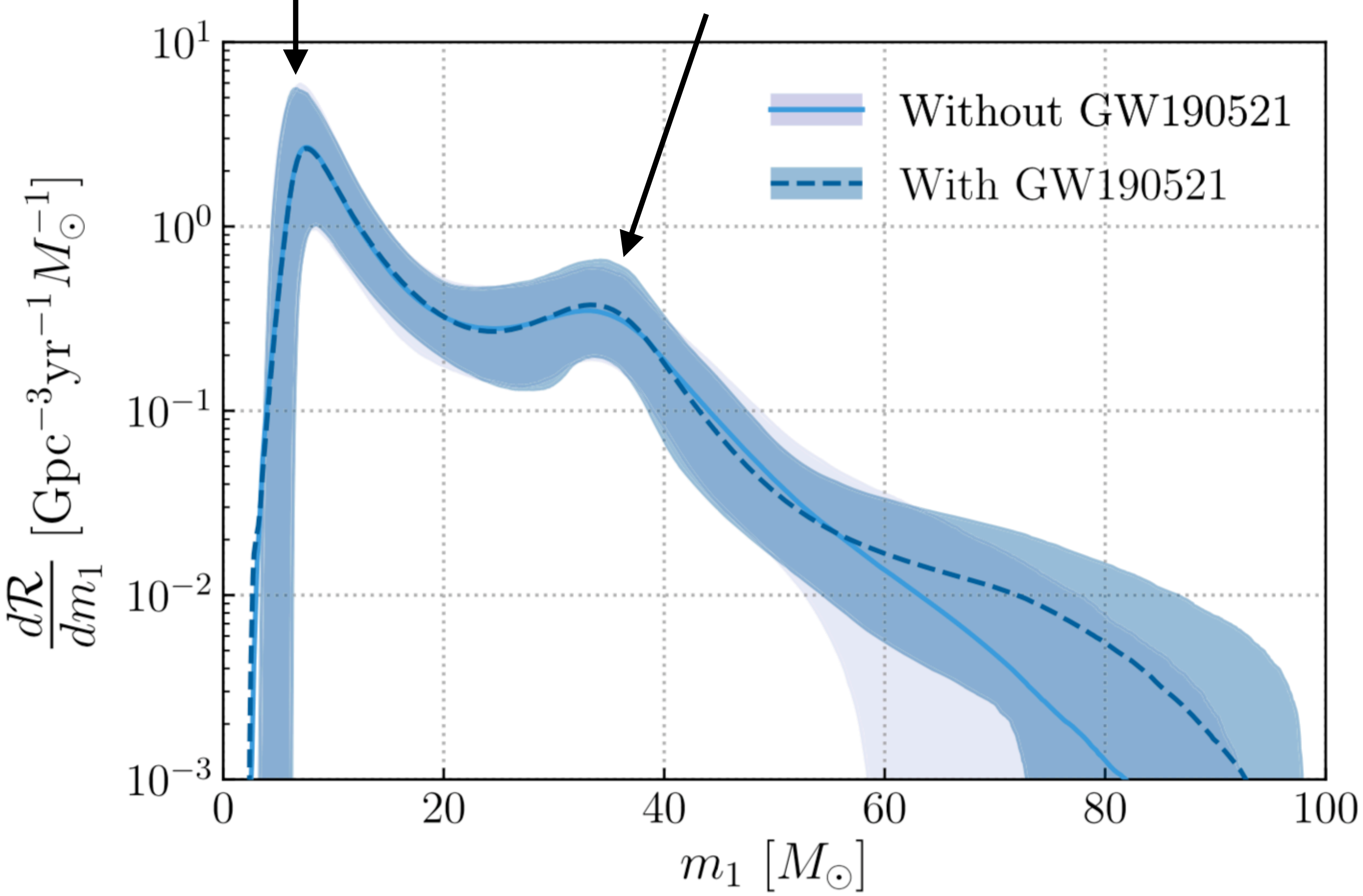


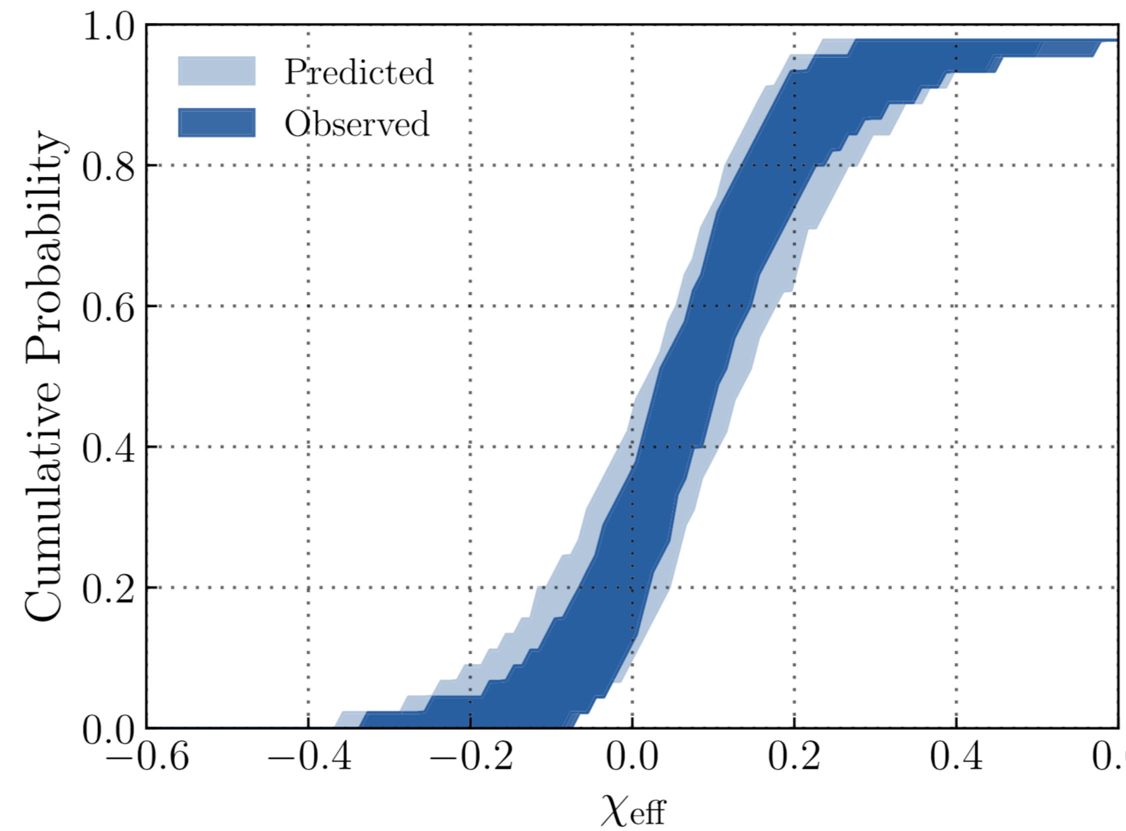
Properties of BH mergers

- The local BH merger rate density: $R \sim 23.9^{+14.3}_{-8.6}$ [yr^{-1} Gpc^{-3}]

Global maximum at $\lesssim 7.8^{+1.8}_{-2.0} M_\odot$

Break or the 2nd peak at $\sim 37 M_\odot$

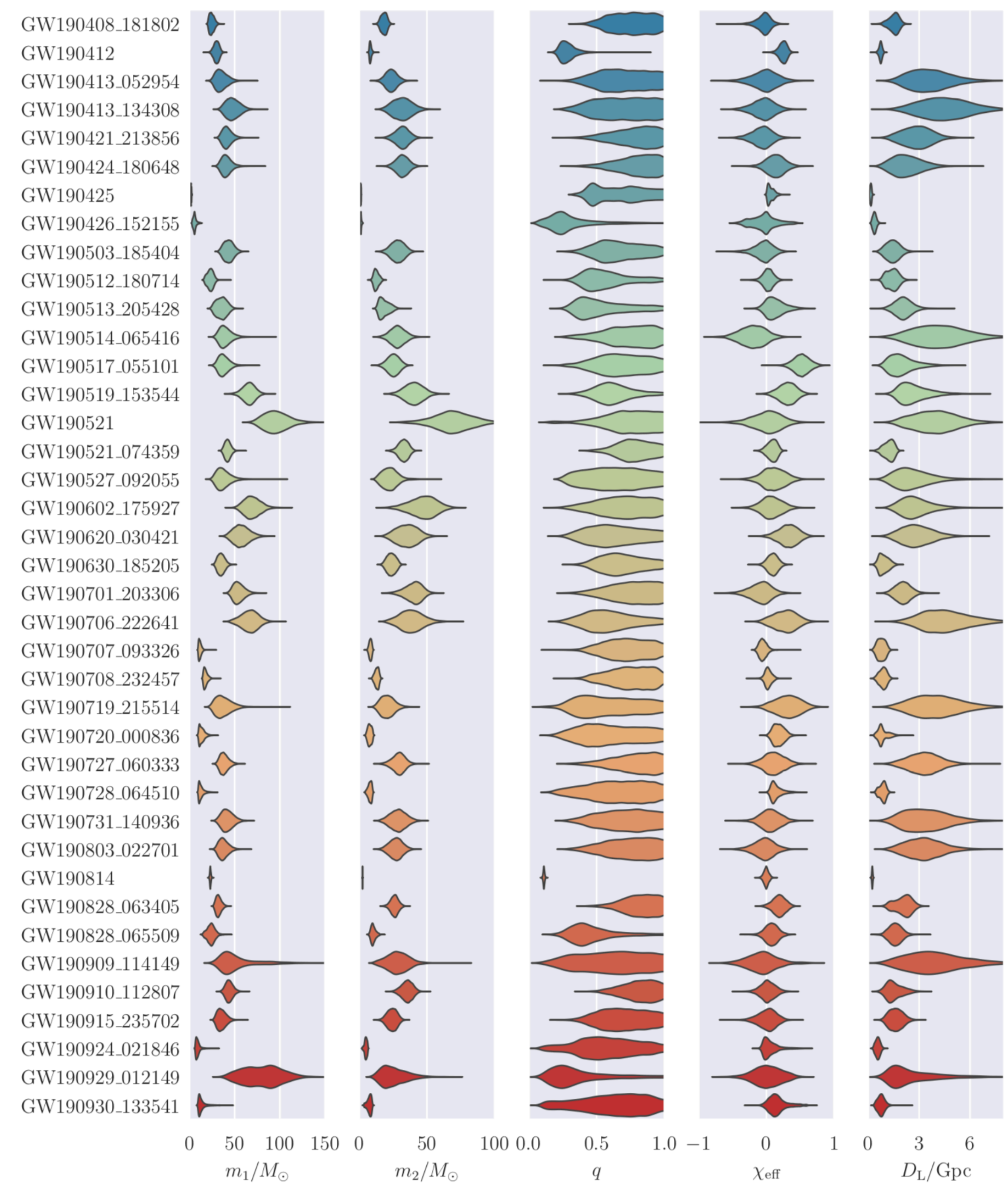




- Isolated binary: aligned spins
- Star cluster: isotropic spins
  → Mixed with the two channels?
  (But see Bavera et al. 2020)

How about the errors

- Not small
- Mass seems to contain errors of a few 10 %.
    - But, it may not affect the mass distribution.
- Spin seems to be consistent with $\chi_{\rm eff} = 0$ for all events.
    - We cannot assess if isolated binary evolution or star cluster are correct.
    - At least, BH-BHs have not to have large $\chi_{\rm eff}$.

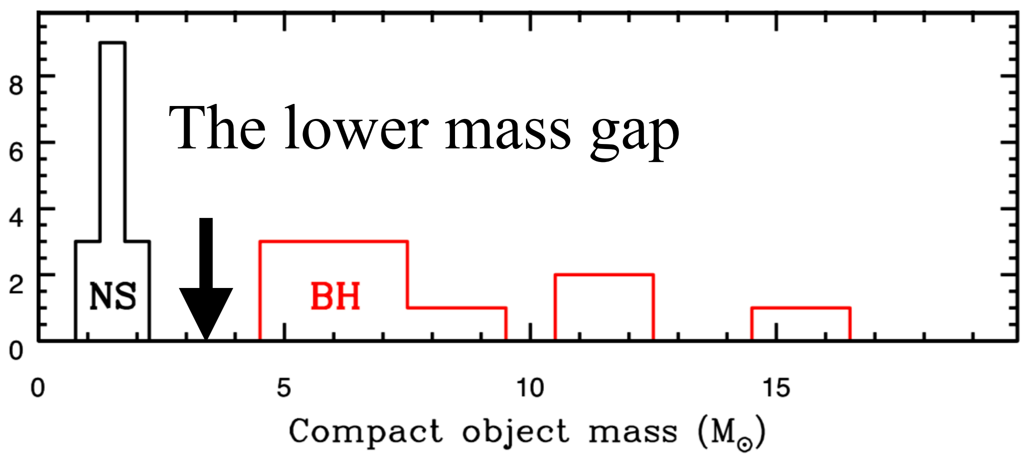


Abbott et al. (2020, arXiv:2010.14527)

Peculiar events

- GW190412
  - $q \sim 0.25$ ($m_1 = 31.7^{+3.6}_{-3.5} M_\odot$, $m_2 = 8.0^{+0.9}_{-0.7} M_\odot$)
  - Typical BH mergers: $q \sim 1$
- GW190814
  - $m_1 = 23.2^{+1.0}_{-0.9} M_\odot$
  - $m_2 = 2.59^{+0.08}_{-0.08} M_\odot$
  - BH-BH, BH-NS, or other?
- GW190521 (later)

Casares et al. (2017)



Our study

- There is no confirmed formation scenario.
- More than one formation scenario may be correct.
- We make predictions of BH merger properties.
  - Open clusters
  - Pop III binary stars

Merging binary BHs formed in open clusters

Kumamoto J.

Trani A. A.

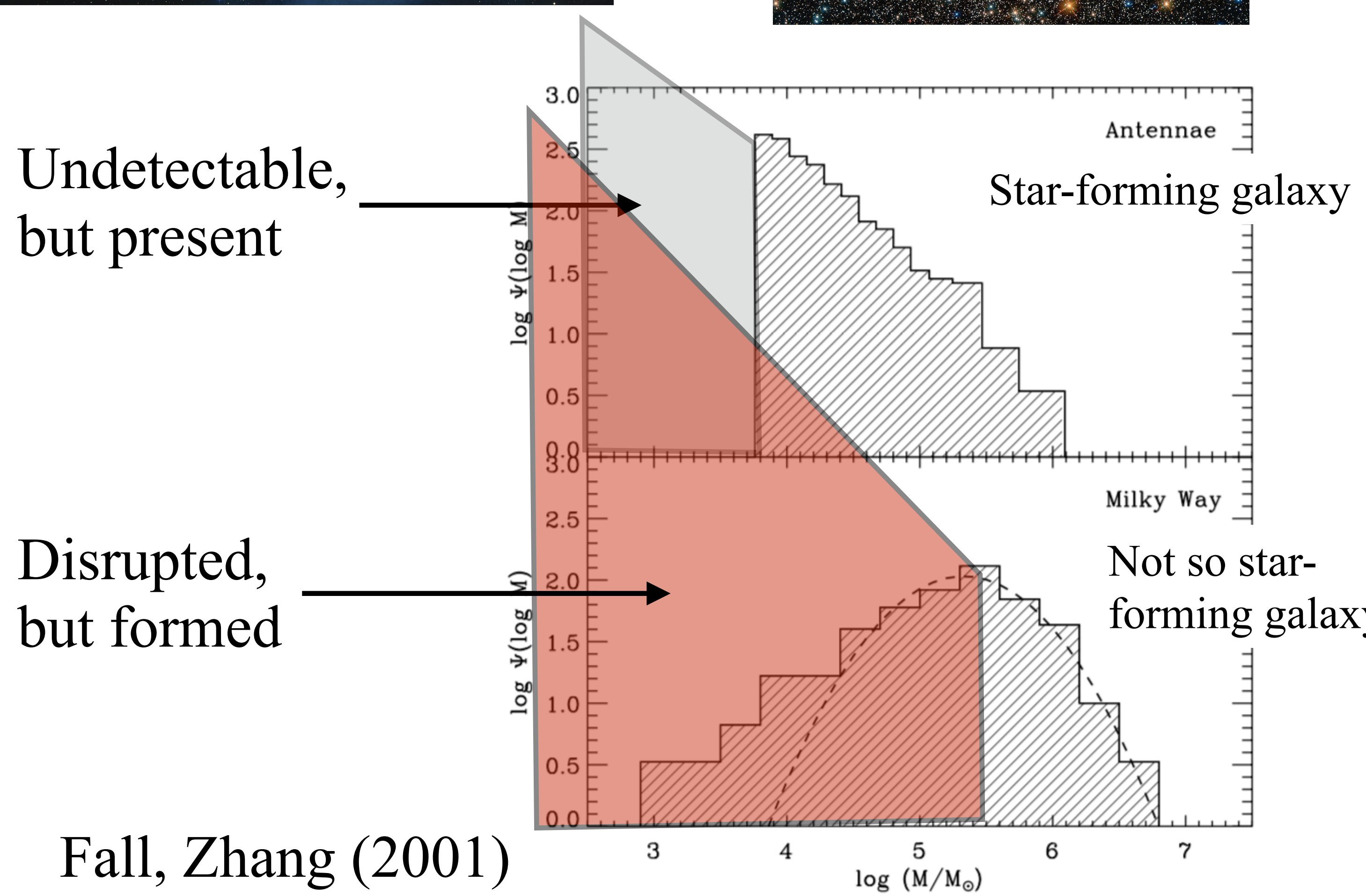
Open clusters

- Open clusters
  - $M_{\rm tot} \sim 10^3 - 10^4 M_\odot$
  - $T_{\rm life} \sim 100$ Myr
- Globular cluster
  - $M_{\rm tot} \sim 10^5 - 10^6 M_\odot$
  - $T_{\rm life} \gtrsim 10$ Gyr
- Why open clusters?
  - Forming currently
  - Many formed previously

Promising formation sites of merging binary BHs

Open cluster (Pleiades)

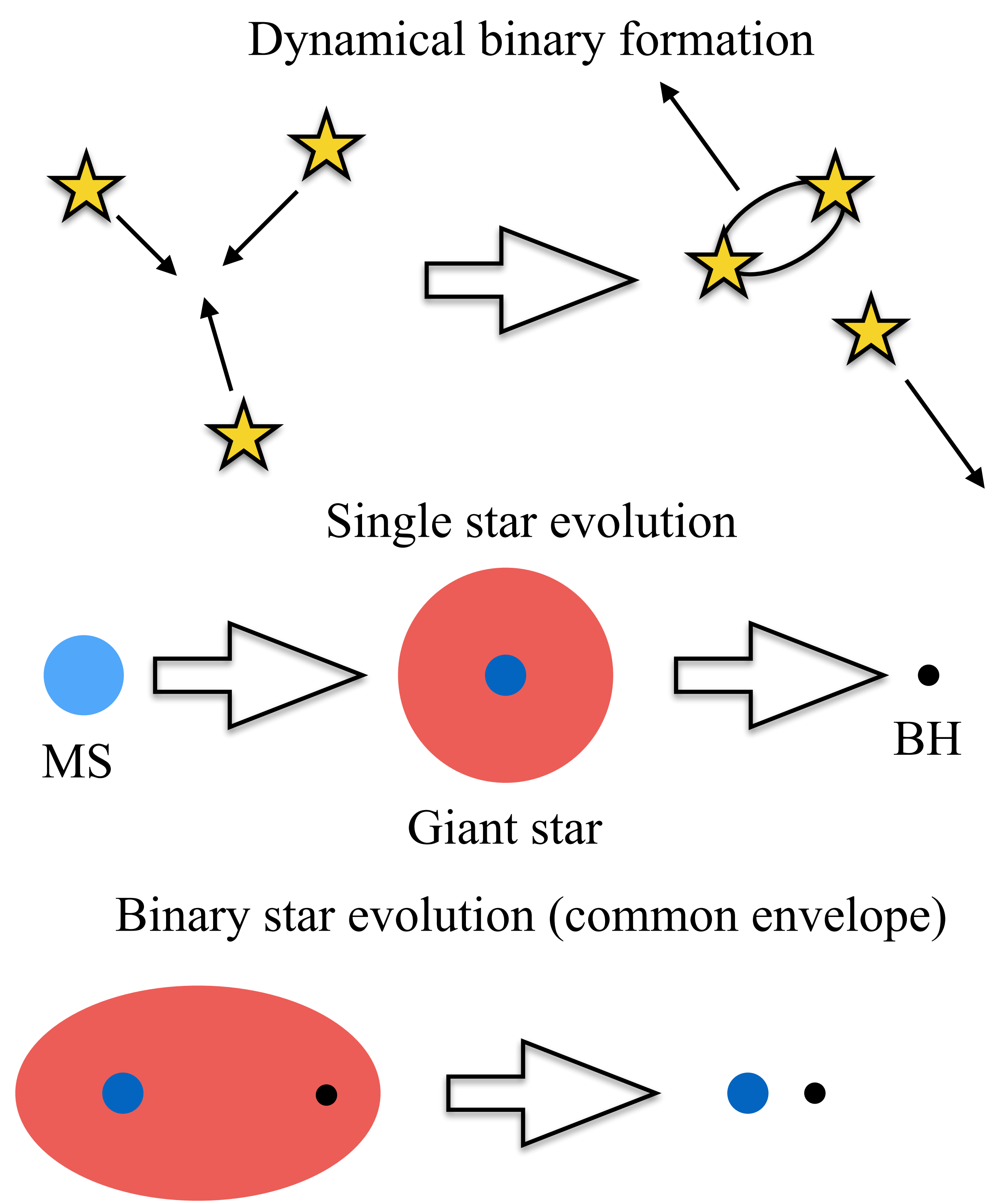
Globular cluster (M15)



Fall, Zhang (2001)

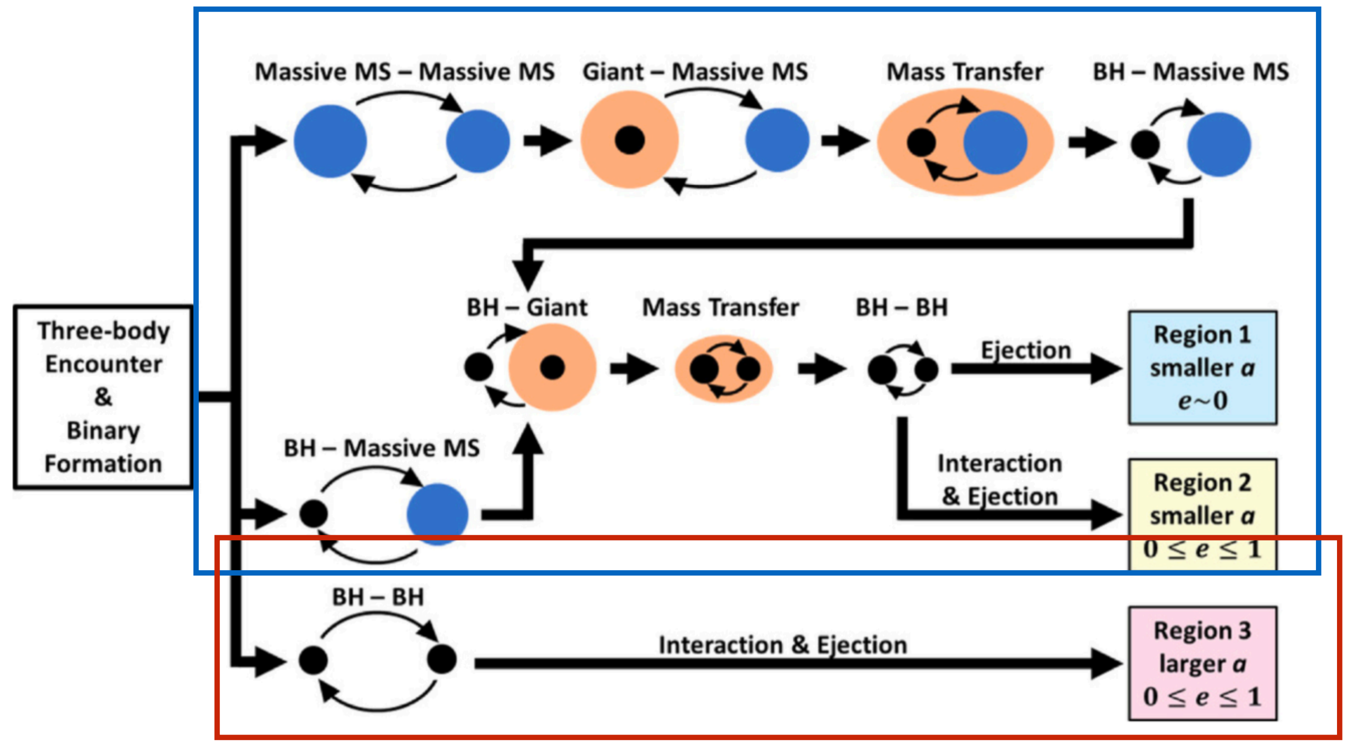
Methods

- NBODY6++GPU code
- N-body simulation
  - $$\frac{d^2\vec{r}_i}{dt^2} = \sum_j^N \frac{Gm_j}{|\vec{r}_j - \vec{r}_i|^3}\left(\vec{r}_j - \vec{r}_i\right)$$
- Single star evolution
  - ***Main sequence → Giant (→ Helium star) → BH*** (Hurley et al. 2000)
  - Stellar wind mass loss (Belczynski et al. 2010)
  - Supernova model (Belczynski et al. 2002)
- Binary star evolution (Hurley et al. 2002)
  - Tidal interaction, ***common envelope***, stable mass transfer, magnetic braking, etc.
- Initial conditions
  - $M_{\rm cl,tot} \sim 2500 M_\odot$, $\rho_{\rm hm} \sim 10^4\ M_\odot\ {\rm pc}^{-3}$
  - Kroupa's IMF ($0.08 M_\odot < m_* < 150 M_\odot$)
  - $Z = 0.1, 0.25, 0.5, 1 Z_\odot$
  - Several 100 clusters for each metallicity



Formation channels

- High metallicity ($Z = Z_\odot$)
  - Dynamical formation of merging binary BHs
  - Similar to globular clusters
- Low metallicity ($Z < Z_\odot$)
  - Dynamical formation of main-sequence binary, and orbital shrink through common envelope
  - Similar to isolated binary evolution
- Clue to identify BH-BH origin?

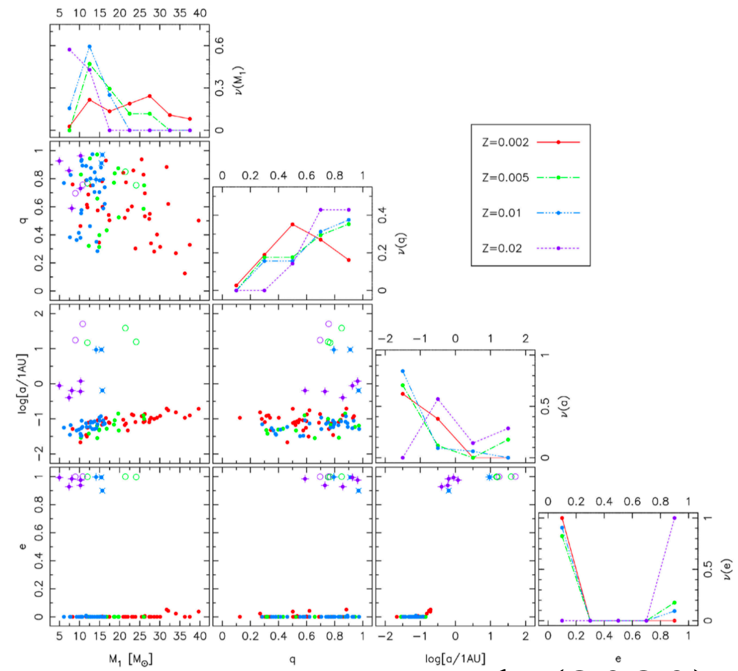


Kumamoto et al. (2019)

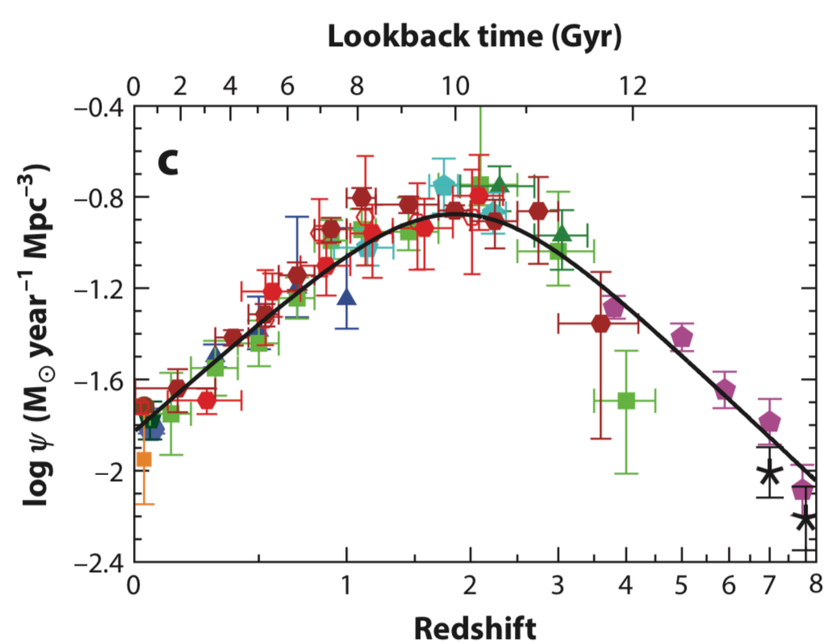
- Dynamical formation of BHs
  - $Z = Z_\odot$: binary BHs compact, because of low mass ($\lesssim 10M_\odot$)
  - ~~$Z < Z_\odot$: binary BHs not compact, because of high mass ($\gtrsim 10M_\odot$)~~
- Common envelope
  - ~~$Z = Z_\odot$: no envelope because of strong stellar wind~~
  - $Z < Z_\odot$: sufficient envelope because of weak stellar wind

Estimate of BH merger rate

- N-body results
  - The number of merging binary BHs
  - m_1, m_2, a, e
- Star formation history
  - Total star formation rate (Madau, Fragos 2017)
  - Cosmic evolution of metallicity distribution (Chruslinska, Nelemans 2019)
  - Cluster mass fraction: 20%



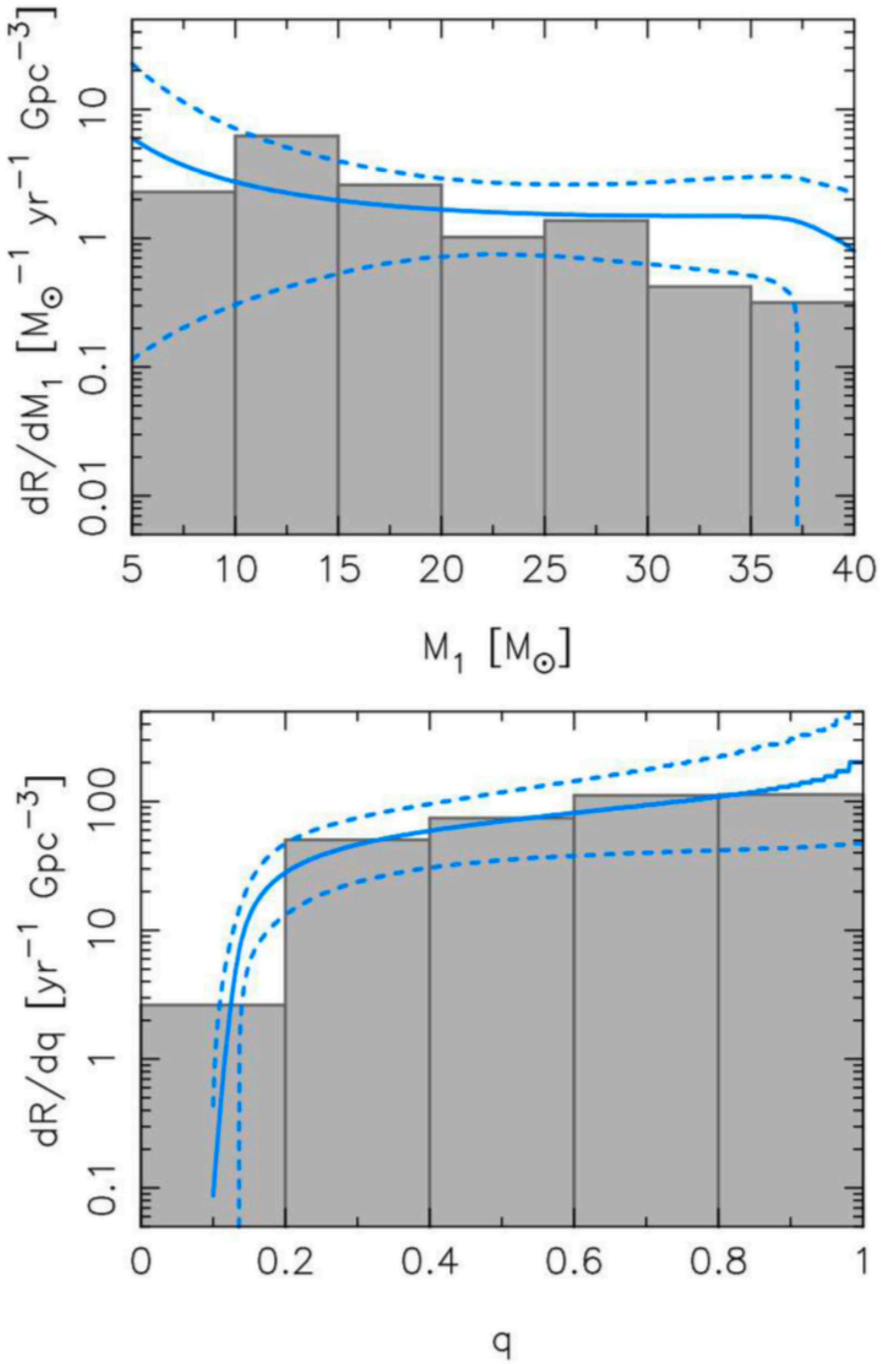
Kumamoto et al. (2020)



Madau, Dickinson (2014)

Mass distribution

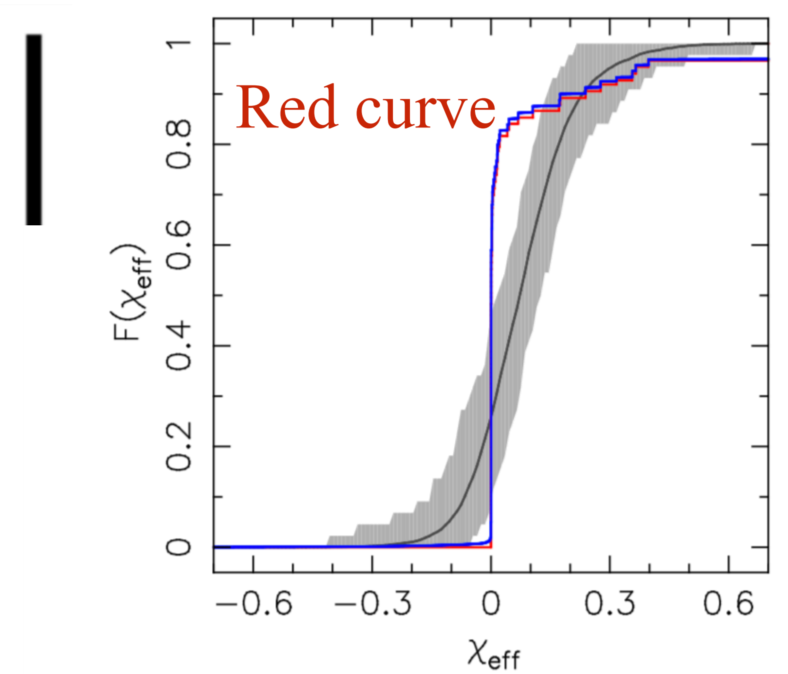
- $R \sim 70$ yr^{-1} Gpc^{-3}
- Consistent with GW observations, at least for $\lesssim 40 M_\odot$
- Require $Z < 0.1 Z_\odot$ open clusters, and more sophisticated initial conditions for $\gtrsim 40 M_\odot$

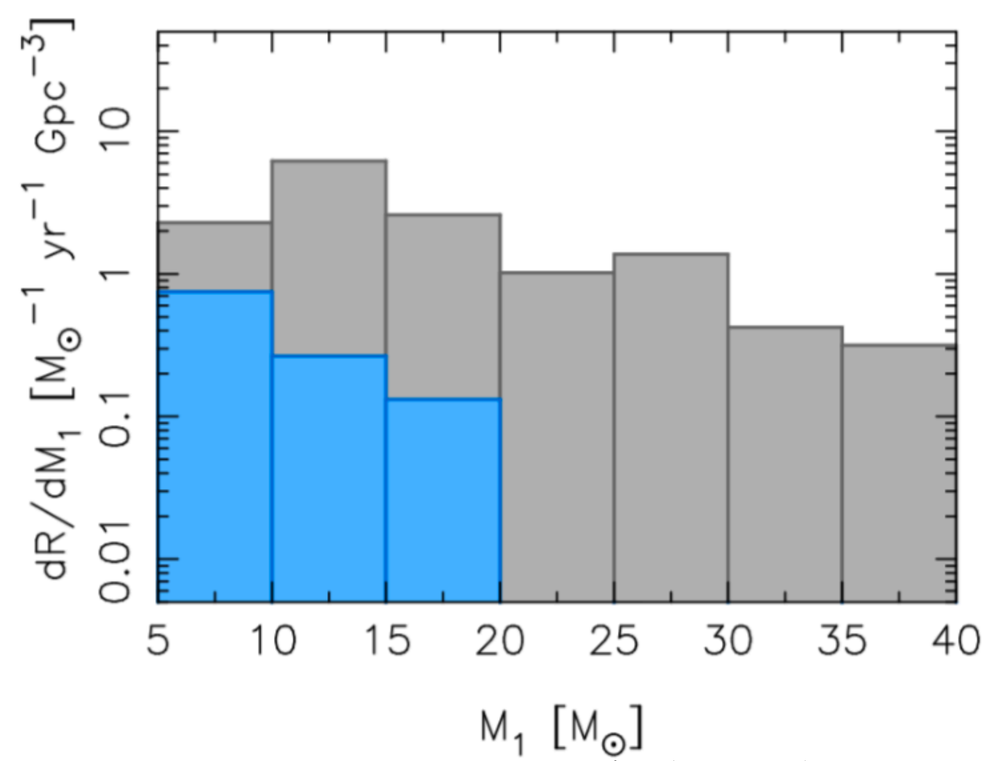


Kumamoto et al. (2020)

Spin distribution

- Spin generated through tidal interactions during BH progenitors (Kushnir et al. 2016; Hotokezaka, Piran 2017)
- 90% zero spin, 10% non-negligible spin, 0% negative spin
- Negative correlation between mass and spin



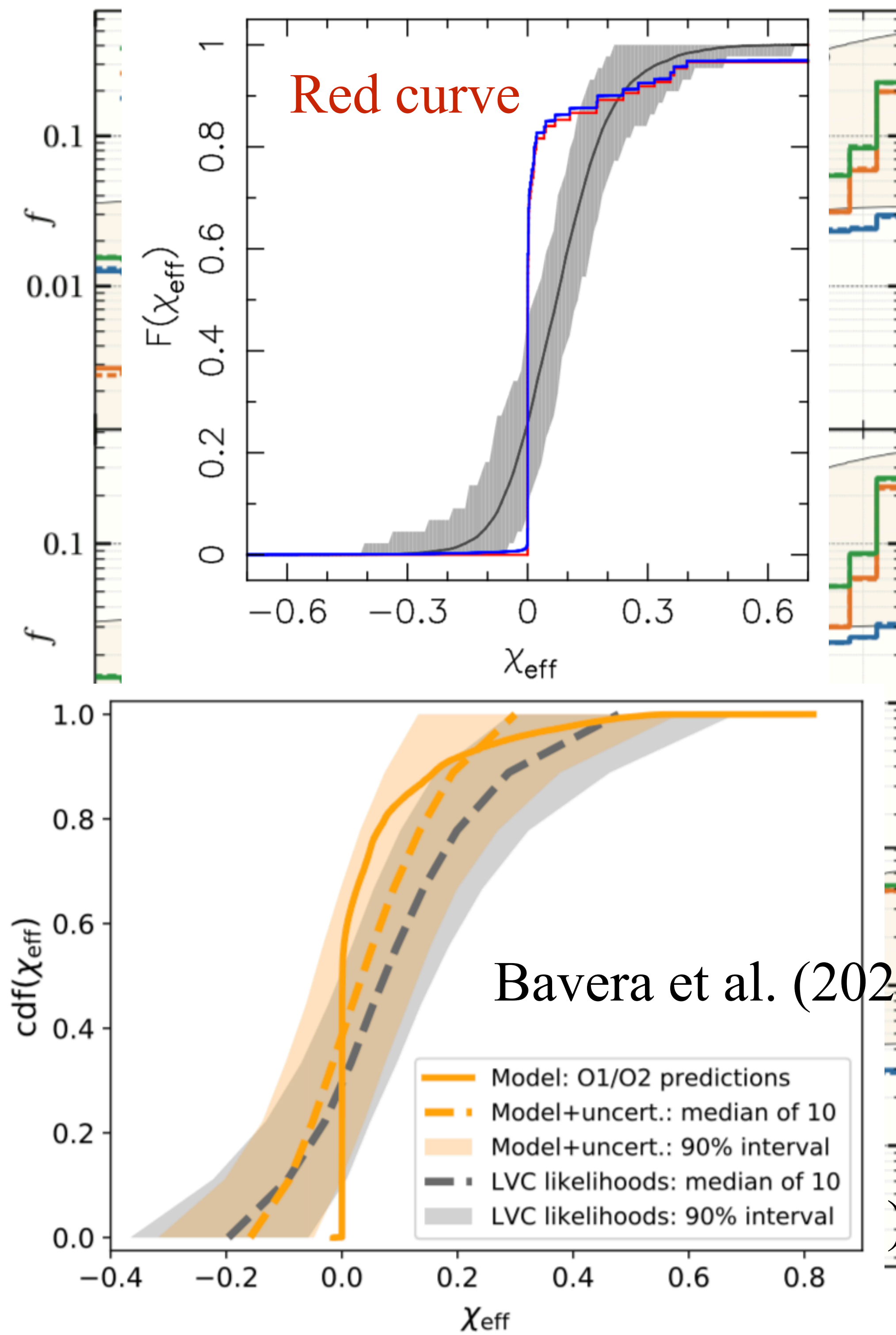


Kumamoto et al. (2021)

Spin misalignment

- 10 % of merging BHs can interaction with another BH before they merge.
- Their spins can be misaligned through single close encounter in open clusters.
- Negative spin, but small fraction

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



Bavera et al. (2020)

Pair instability mass gap event: GW190521

GW190521

- Merger of $85^{+21}_{-14}M_{\odot}$ and $66^{+17}_{-18}M_{\odot}$ BHs
- The primary BH has only a 0.32% probability of being below $65M_{\odot}$.
- Pair instability mass gap: $40 - 130M_{\odot}$
- Possible scenarios
  - Cluster origins (Rodriguez et al. 2019; Di Carlo et al. 2020; Tagawa et al. 2020; Fragione et al. 2020; Rizzuto et al. 2021)
  - Uncertainty of PI mass gap boundary (Farmer et al. 2020; Belczynski et al. 2020; Costa et al. 2021)
  - ***Uncertainty of convective overshoot***

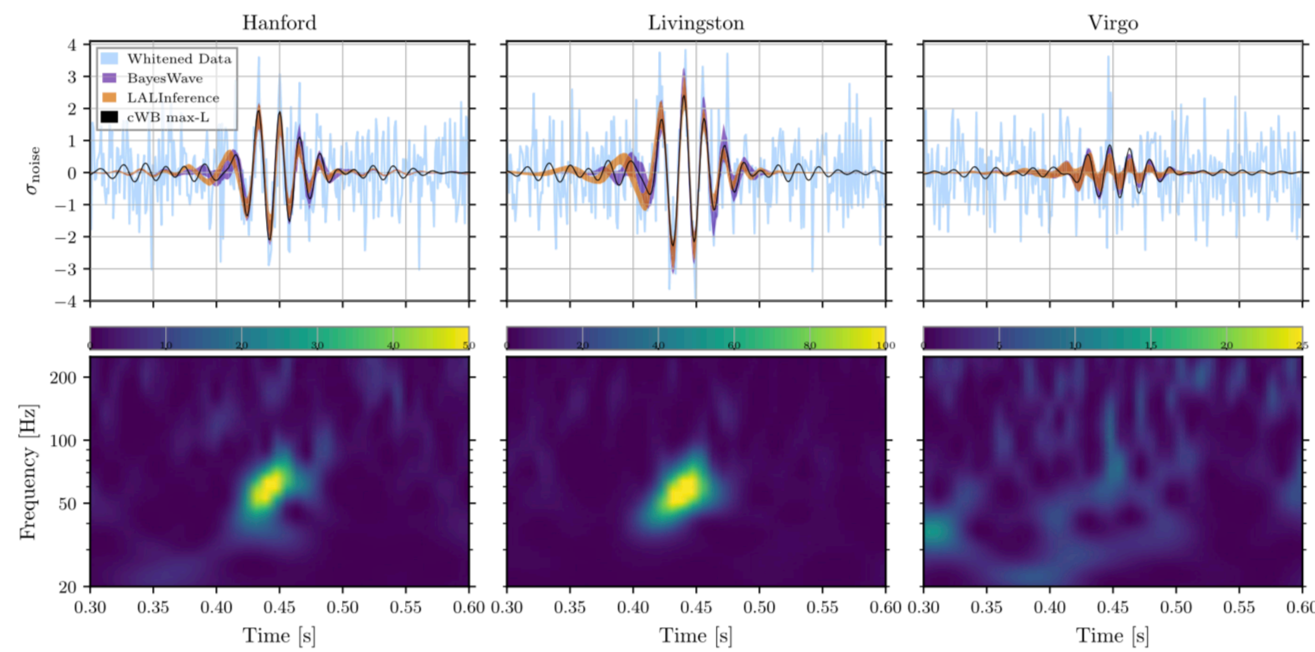
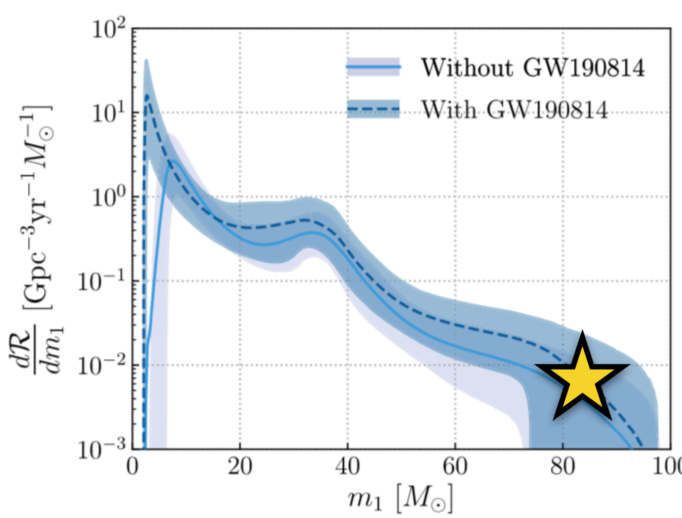


TABLE I. Parameters of GW190521 according to the NRSur7dq4 waveform model. We quote median values with 90% credible intervals that include statistical errors.

Parameter	
Primary mass	$85^{+21}_{-14}\ M_{\odot}$
Secondary mass	$66^{+17}_{-18}\ M_{\odot}$
Primary spin magnitude	$0.69^{+0.27}_{-0.62}$
Secondary spin magnitude	$0.73^{+0.24}_{-0.64}$
Total mass	$150^{+29}_{-17}\ M_{\odot}$
Mass ratio ($m_2/m_1 \leq 1$)	$0.79^{+0.19}_{-0.29}$
Effective inspiral spin parameter ($\chi_{\rm eff}$)	$0.08^{+0.27}_{-0.36}$
Effective precession spin parameter ($\chi_{\rm p}$)	$0.68^{+0.25}_{-0.37}$
Luminosity Distance	$5.3^{+2.4}_{-2.6}$ Gpc
Redshift	$0.82^{+0.28}_{-0.34}$
Final mass	$142^{+28}_{-16}\ M_{\odot}$
Final spin	$0.72^{+0.09}_{-0.12}$
$P\ (m_1 < 65\ M_{\odot})$	0.32%
$\log_{10}$ Bayes factor for orbital precession	$1.06^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for nonzero spins	$0.92^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for higher harmonics	$-0.38^{+0.06}_{-0.06}$

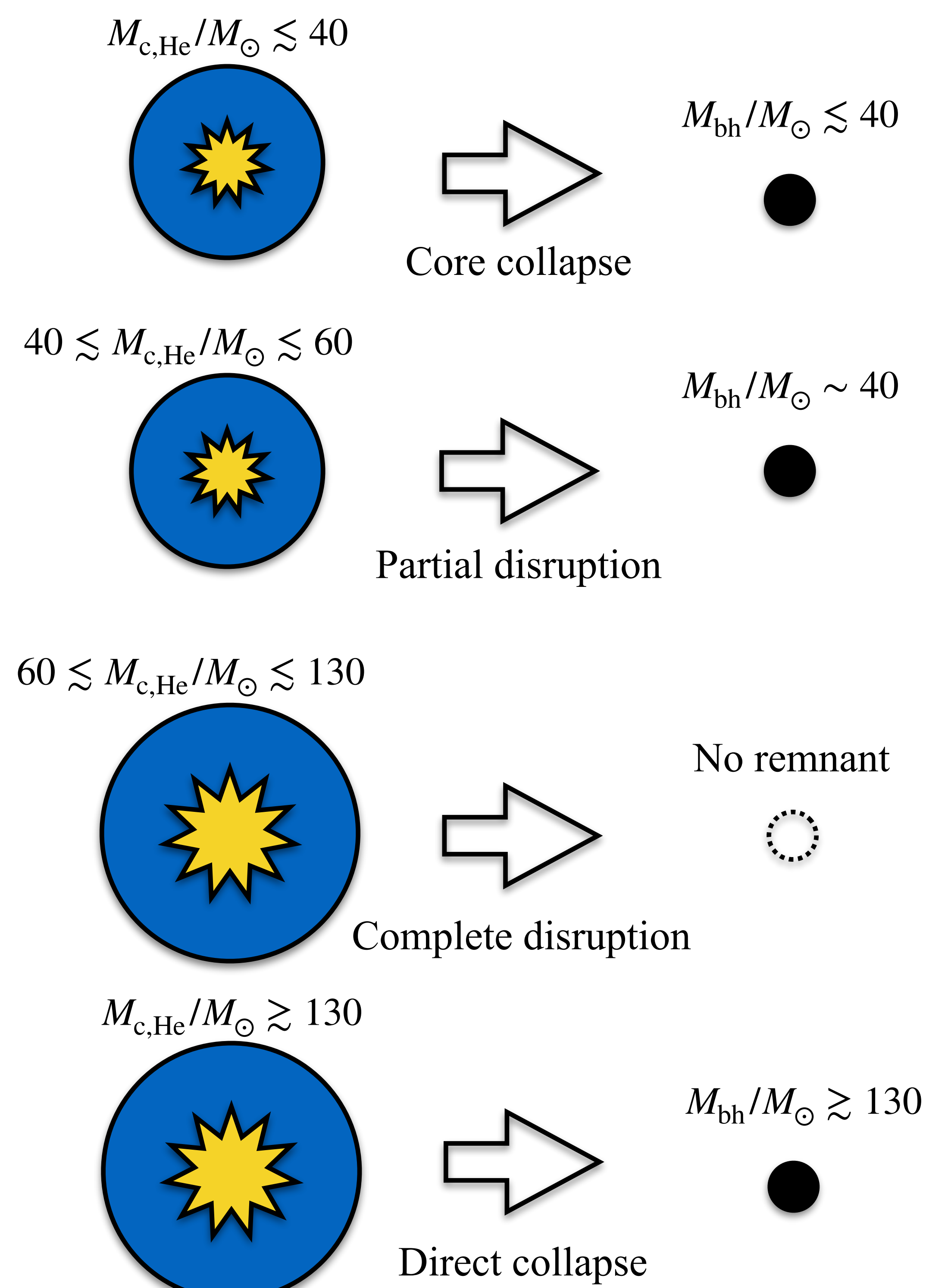
Abbott et al. (2020)



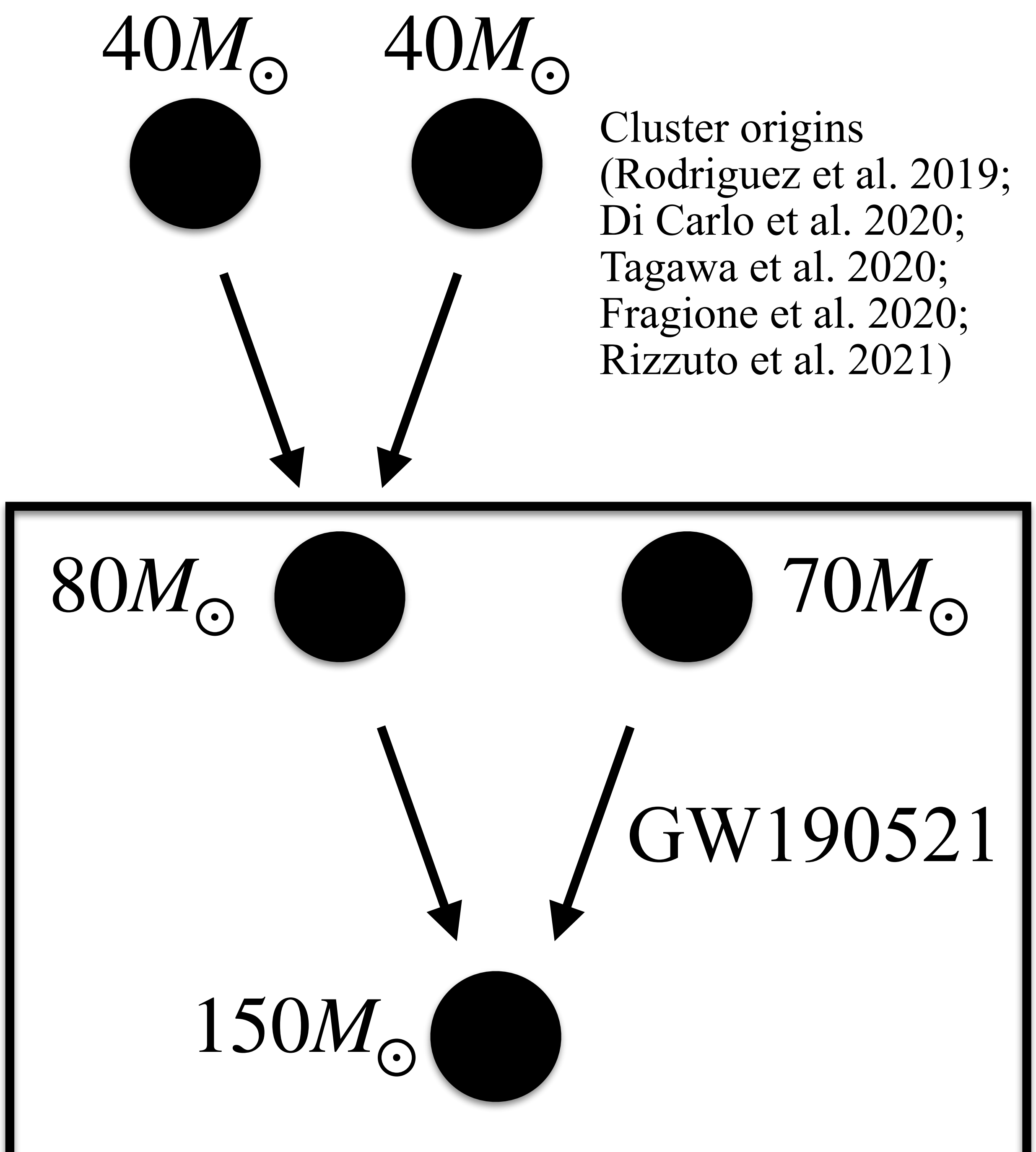
Abbott et al. (2021)

Pair instability (PI) mass gap

- Pair instability
  - Gamma-ray absorption in creating electron-position pairs
  - Stellar contraction
  - Runaway nuclear reaction
  - Stellar explosion
- Mass gap
  - Mass range without BHs
  - $40 - 130 M_\odot$ by PI

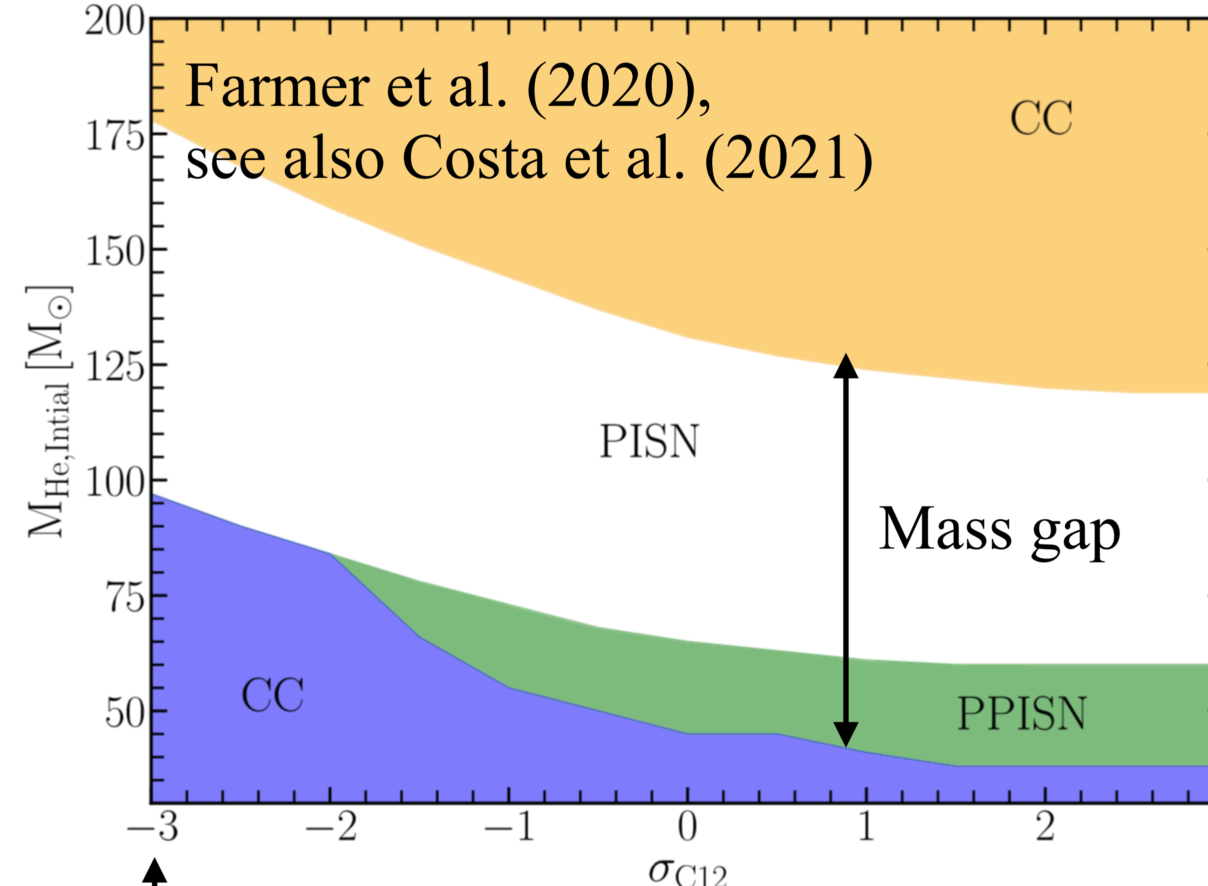


Many scenarios



Cluster origins
(Rodriguez et al. 2019;
Di Carlo et al. 2020;
Tagawa et al. 2020;
Fragione et al. 2020;
Rizzuto et al. 2021)

Uncertainty of boundary of PI mass gap



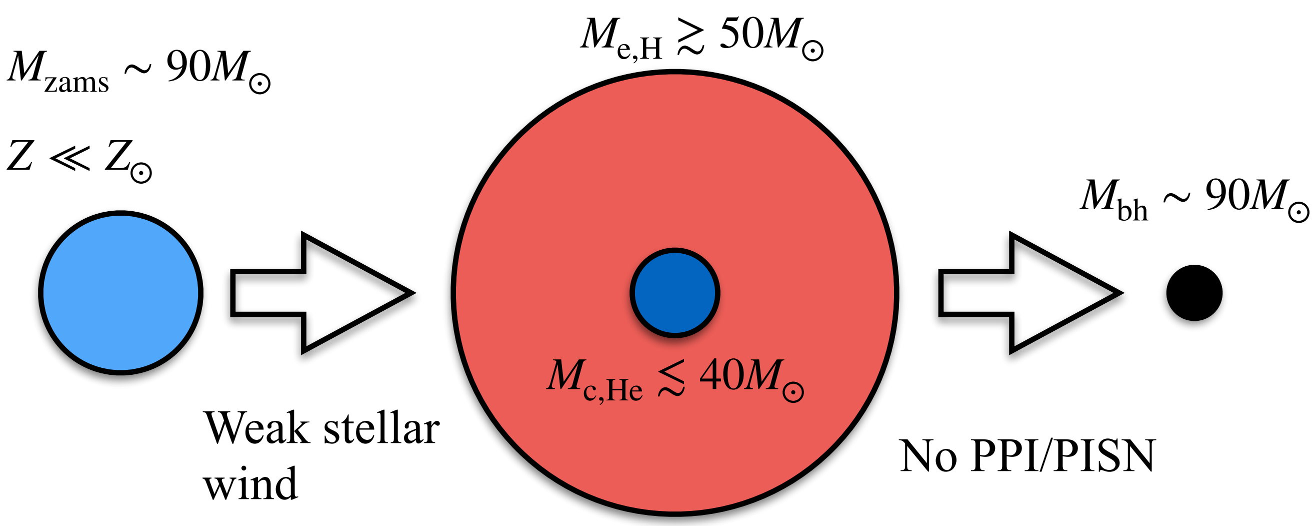
Standard $^{12}C(\alpha,\gamma)^{16}O$ rate

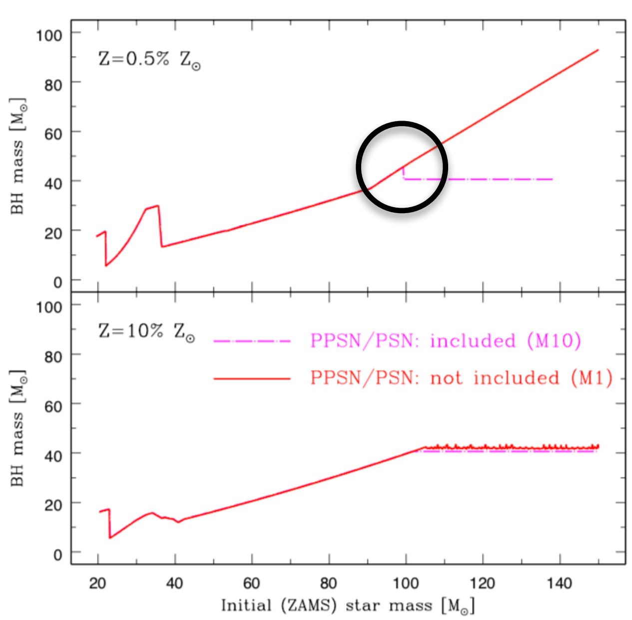
$\sim$ 1/3 of the standard $^{12}C(\alpha,\gamma)^{16}O$ rate

→ $90M_\odot$ ***BH can be formed, avoiding PI.***

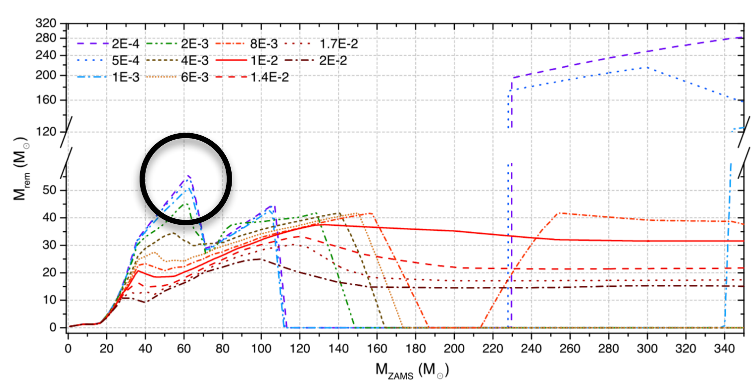
Revisit of the PI mass gap

Single star evolution





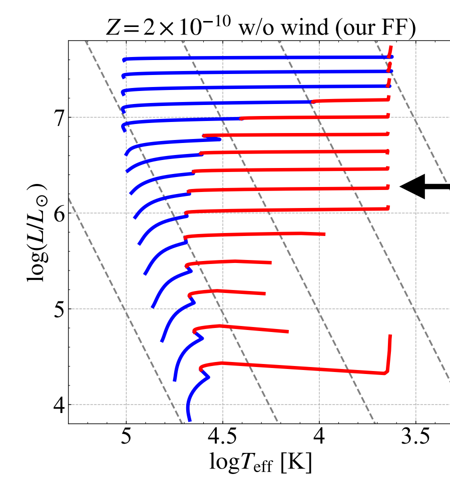
Belczynski et al. (2016)



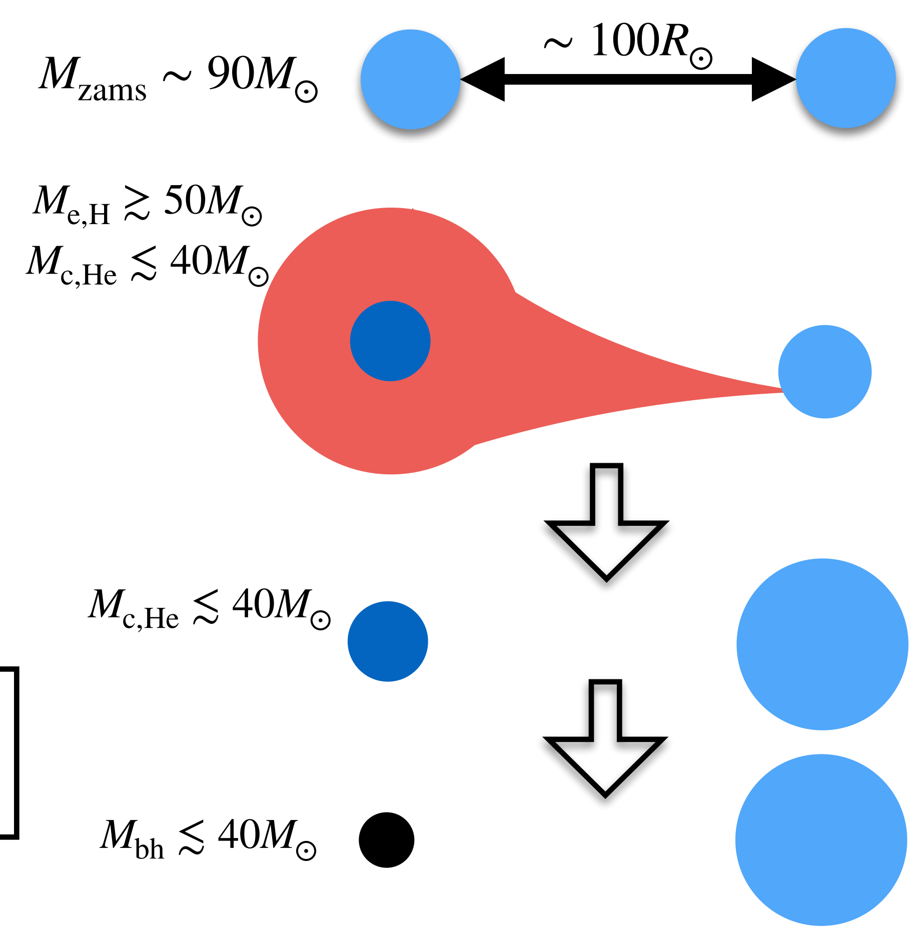
Spera, Mapelli (2017)

Single star can form PI mass gap BH ***if it has massive envelope***.

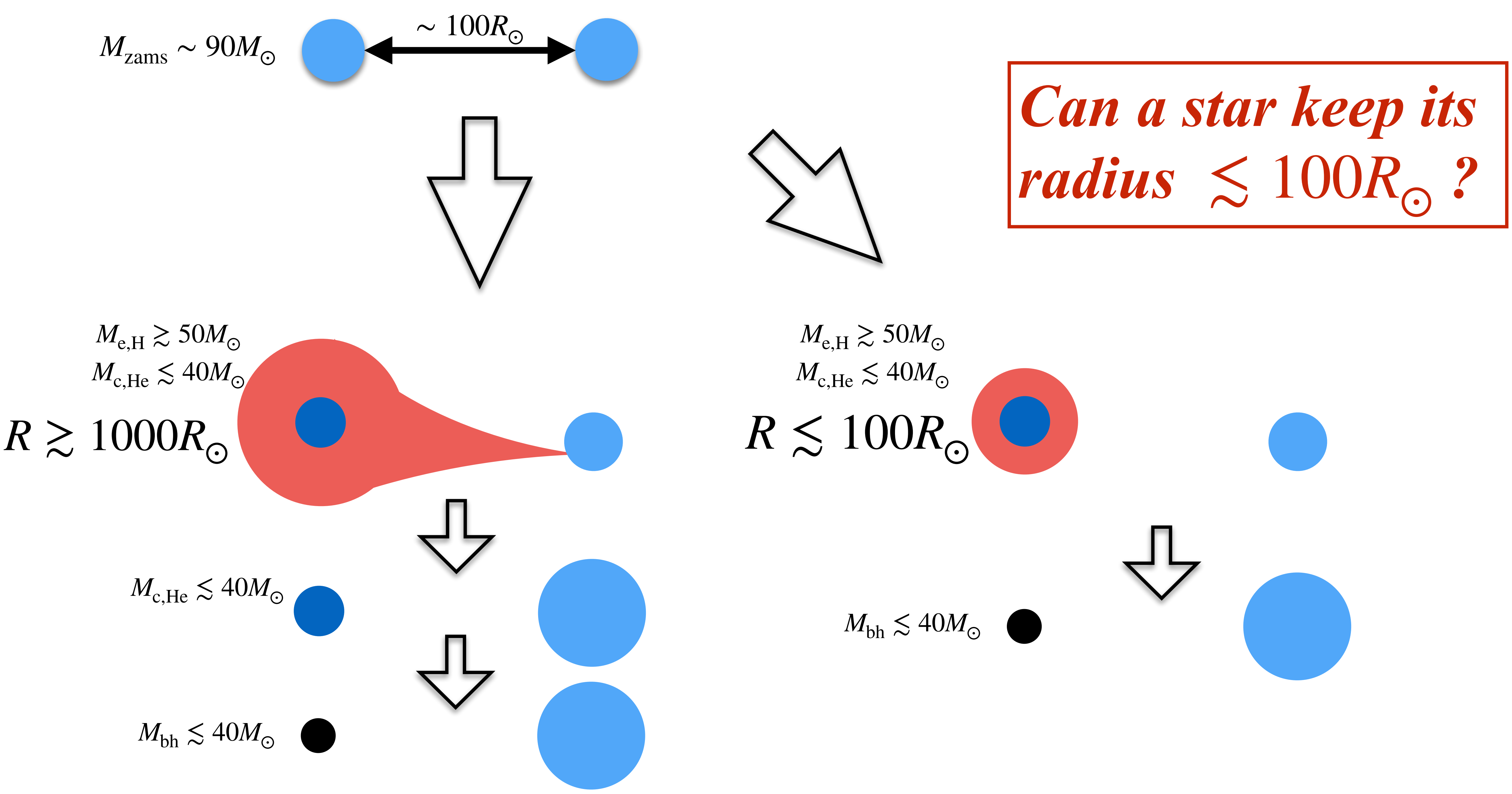
Binary star evolution



- $M_{tot} \sim 80M_{\odot}$
- $M_{c} \sim 40M_{\odot}$
- $R \gtrsim 10^{3}R_{\odot}$

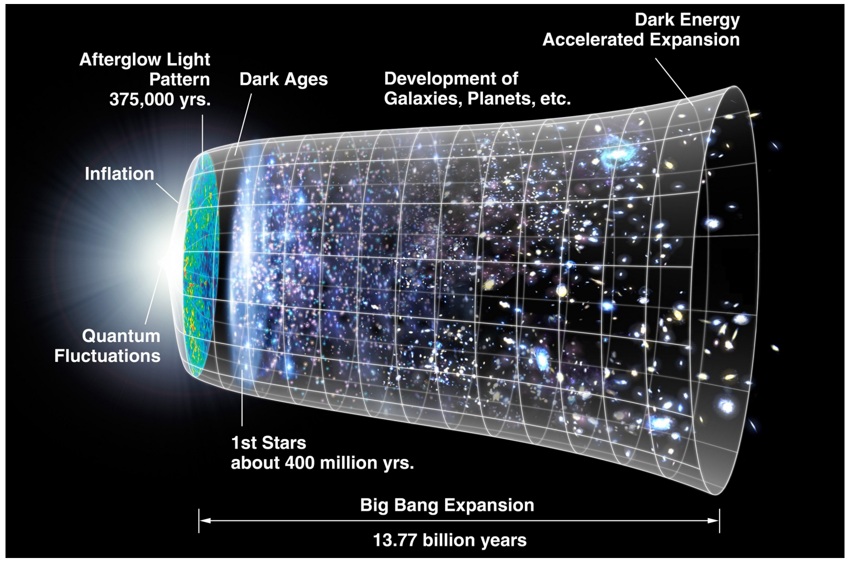


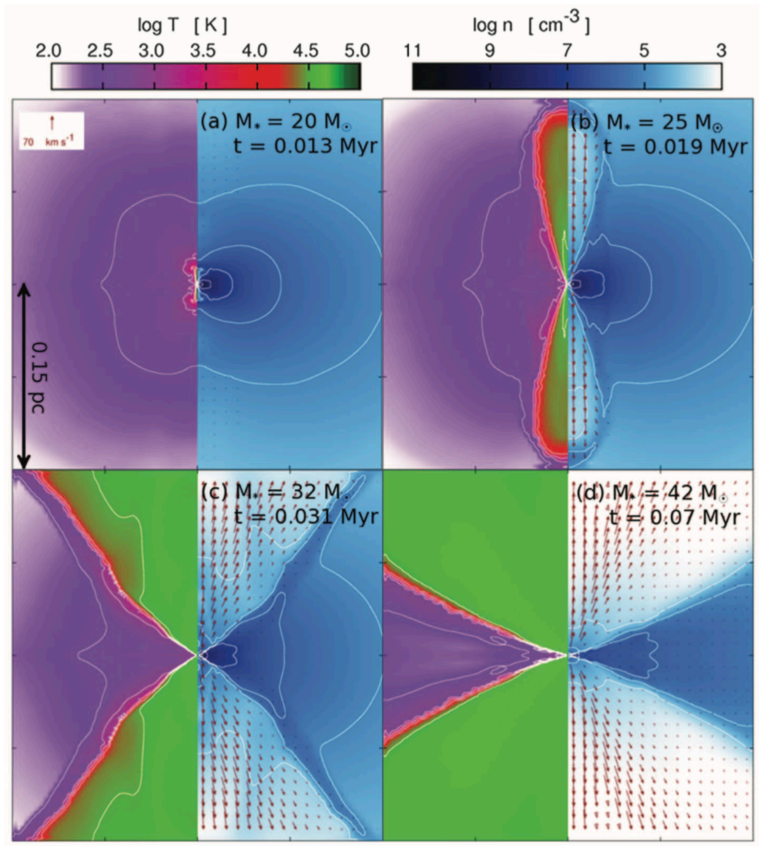
Stellar radius



Population III stars

- Consisting of primordial gas (mostly H and He)
- Born in the high-redshift universe
- Astrophysical importance: stellar nucleosynthesis, reionization, …
- Top-heavy initial mass function (IMF) predicted theoretically (Omukai, Nishi 1998; Abel et al. 2002; Bromm, & Larson 2004)
- Not yet discovered (Frebel, Norris 2015 for review)





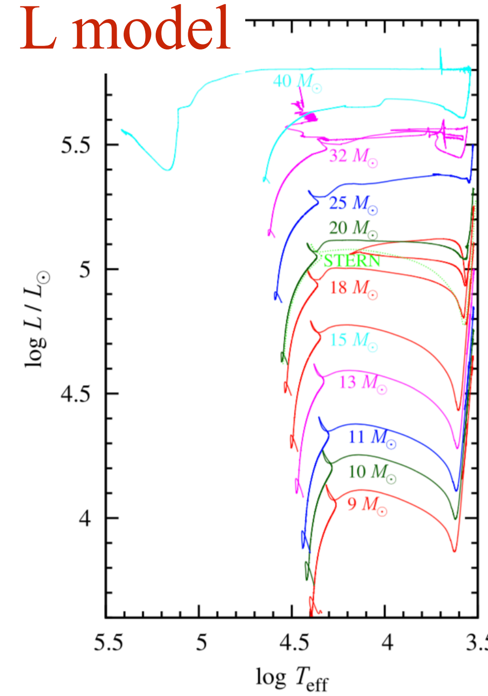
Hosokawa et al. (2011)

Pop III star evolution model

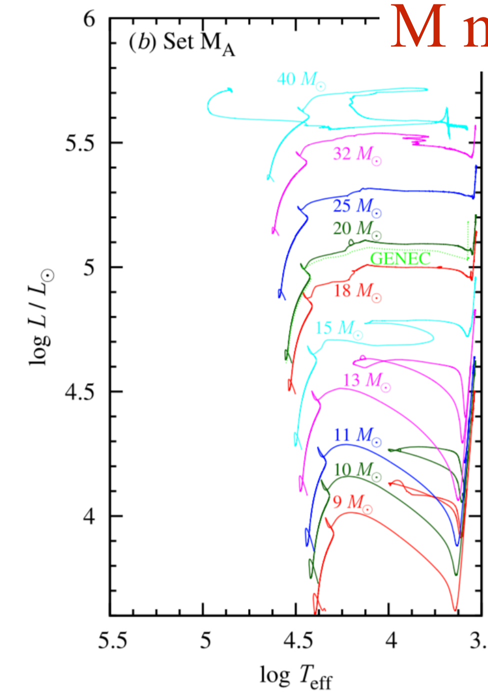
- No massive Pop. III stars discovered so far
- Extrapolation from nearby stars to Pop. III stars
  - L model: similar to Stern (Brott et al. 2011)
  - M model: similar to GENEC (Ekstrom et al. 2012; Farrell et al. 2020)
- The maximums radius of a $80M_{\odot}$ star
  - M model: $\sim 40R_{\odot}$, similar to Farrell et al. (2020)
  - L model: $\sim 3\times10^{3}R_{\odot}$, similar to Yoon et al. (2012)

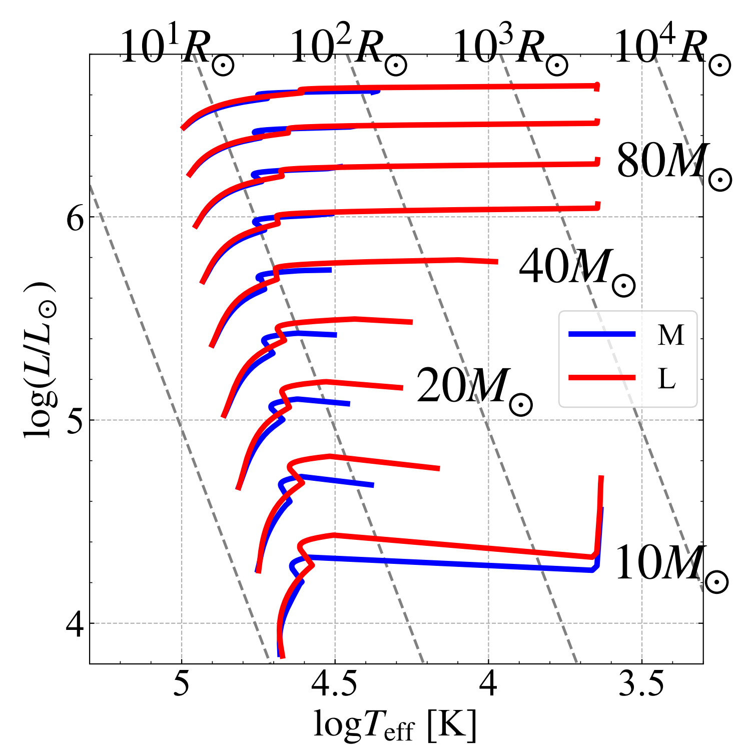
Yoshida et al. (2019)

L model



M model





Two Pop. III models

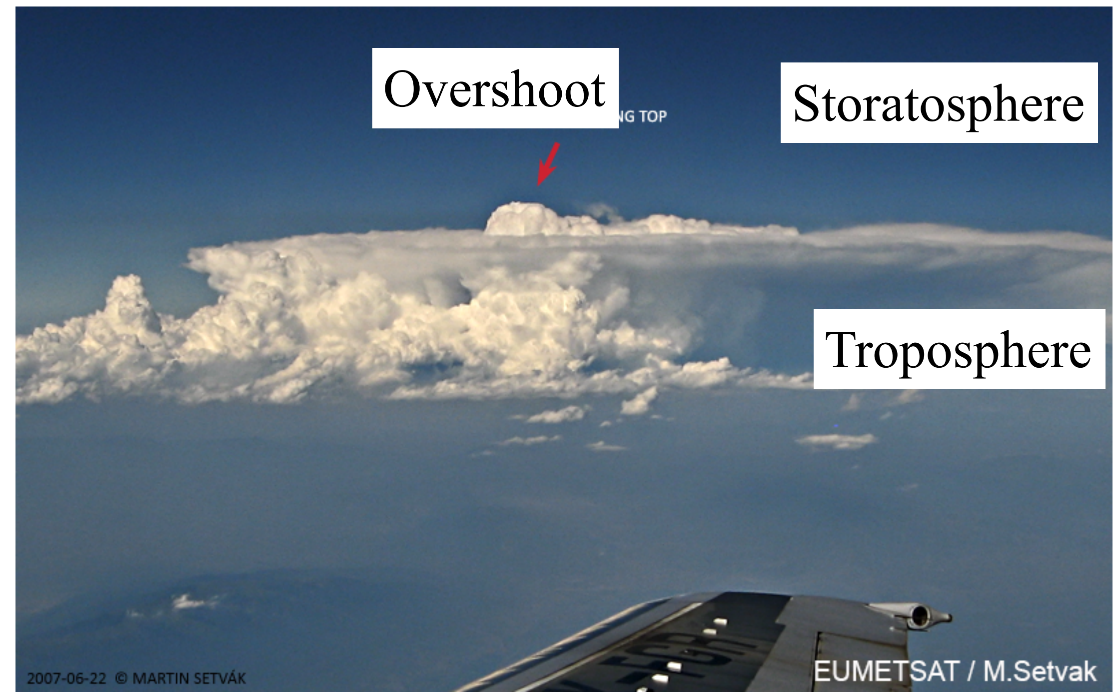
Convective overshoot

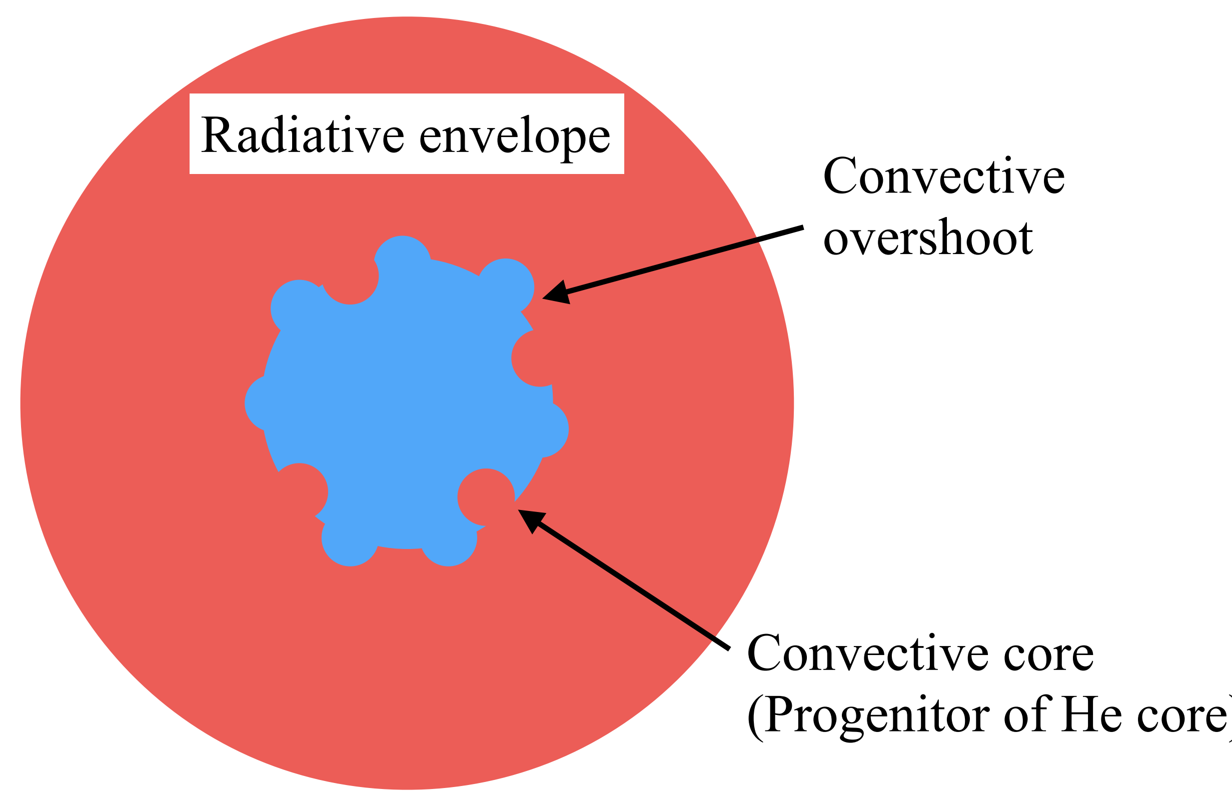
- More effective overshoot
  - Larger He core at the end of MS
  - Larger luminosity in post-MS
  - Larger radius in post-MS

- Effectiveness of overshoot
  - M model: less effective overshoot
  - L model: more effective overshoot

Both consistent with Pop I/II stars

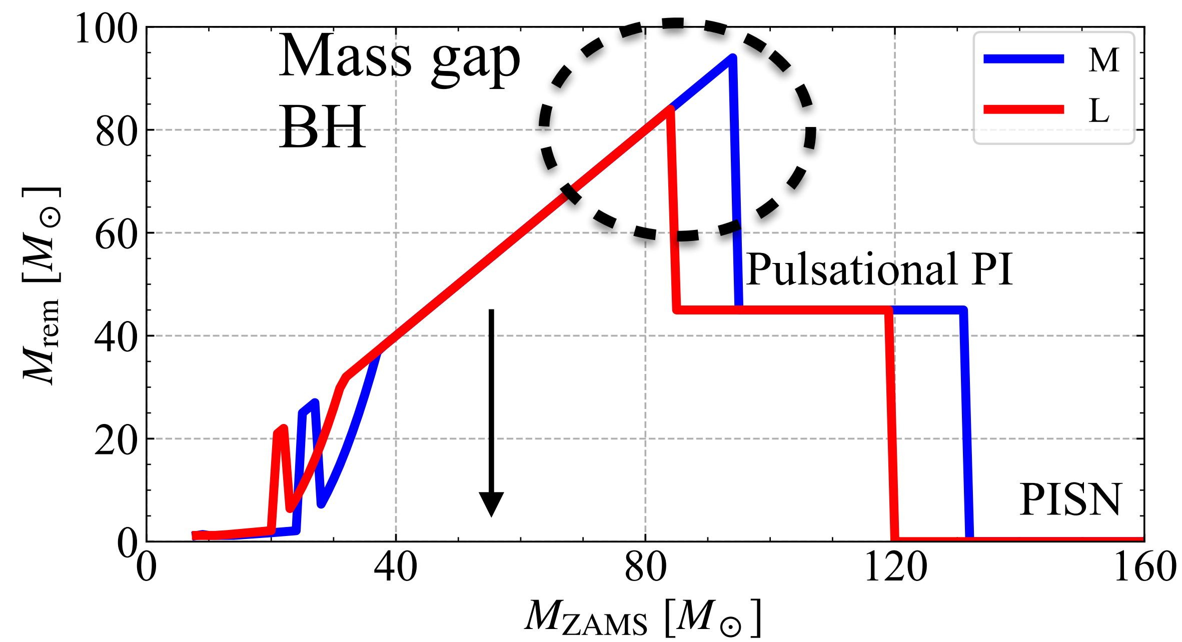
Different radii for Pop III stars

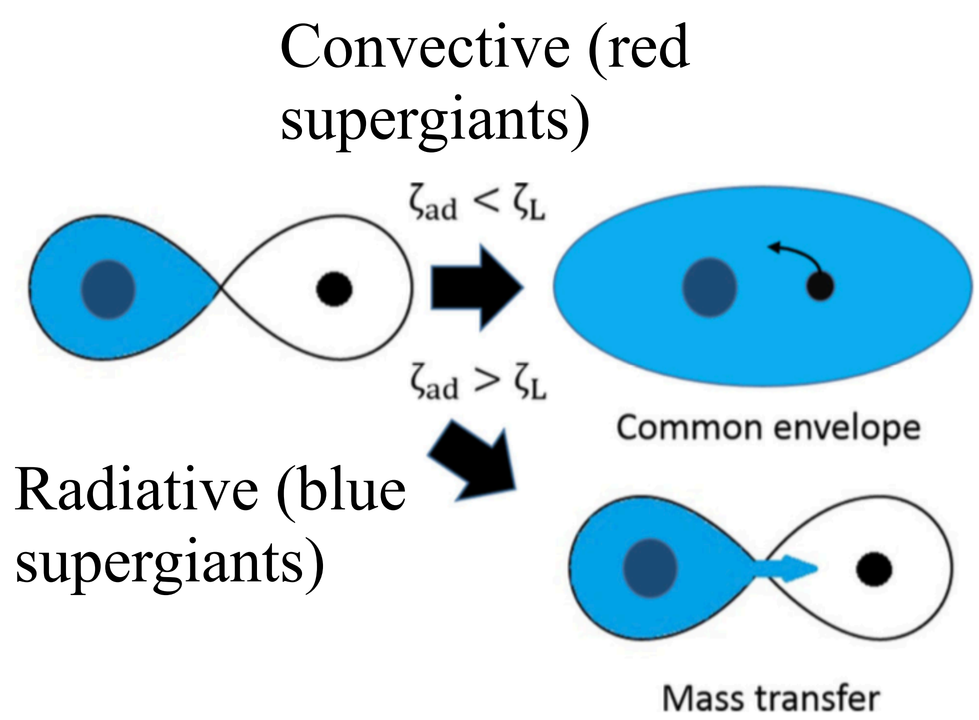




Numerical setup

- The L and M models
- No stellar wind
- Fryer's rapid model for supernova with pair instability (PI) model like the strong PI of Belczynski et al. (2020).
- No natal kick
- Stellar envelope property in Post-MS phases
  - Radiative: $\log(T_{\mathrm{eff}}) > 3.65$
    - CHeB phase in the original BSE
  - Convective: $\log(T_{\mathrm{eff}}) < 3.65$
    - AGB phase in the original BSE

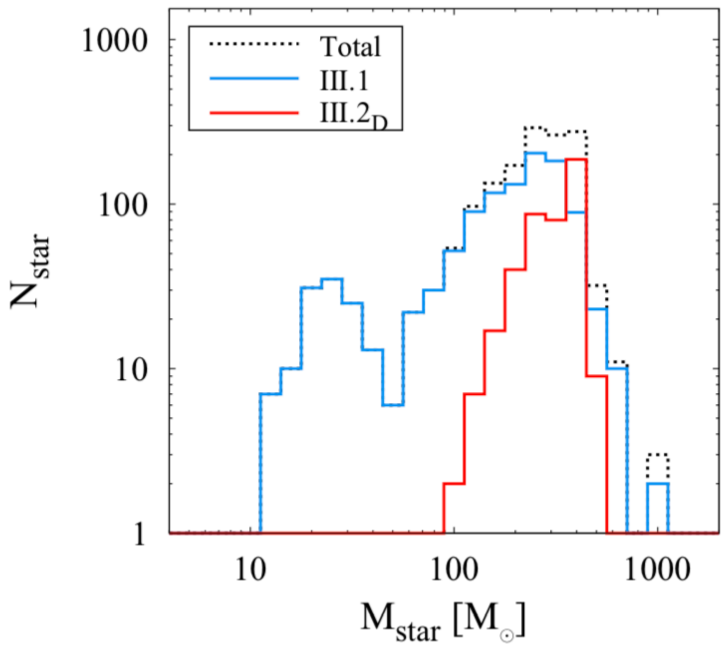




Initial conditions

- Instantaneous formation of Pop III stars: $\sim 10^{13} M_{\odot} \mathrm{Gpc}^{-3}$ at $z \sim 10$
  - Consistent with numerically predicted results (Magg et al. 2016; Skinner, Wise 2020; but see Inayoshi et al. 2021)
- Binary fraction: 1 (e.g. Sugimura et al. 2020)
- Primary IMF: $f(m_1) \propto m_1^{-1}$ $(10M_{\odot} \leq m_1 \leq 150M_{\odot}$
- Mass ratio: $f(q) \propto \mathrm{const}$ $(10M_{\odot}/m_1 \leq q \leq 1)$
- Semi-major axis: $f(a) \propto a^{-1}$ $(10R_{\odot} \leq a \leq 2000R_{\odot}$
- Eccentricity: $f(e) \propto e$

Pop III IMF

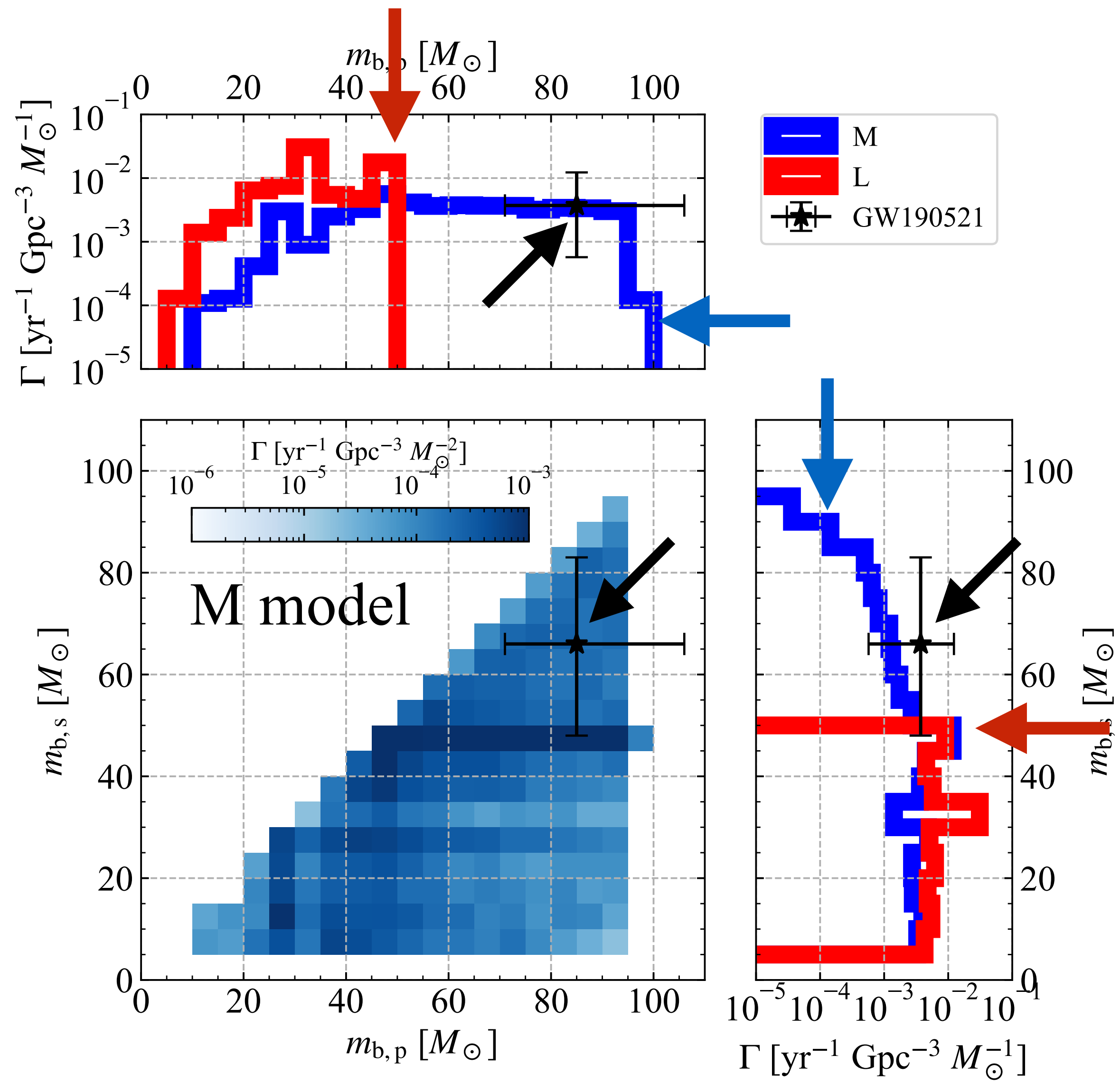


Hirano et al. (2015)

BH mass distribution

- M model
  - The maximum mass: $\sim 100 M_\odot$
  - Stars lose little mass through binary interactions.
  - Pop. III stars can form GW190521-like BH-BHs.
- L model
  - The maximum mass: $\sim 50 M_\odot$
  - Stars lose their H envelopes through binary interactions.
  - No Pop. III stars can form GW190521-like BH-BHs.

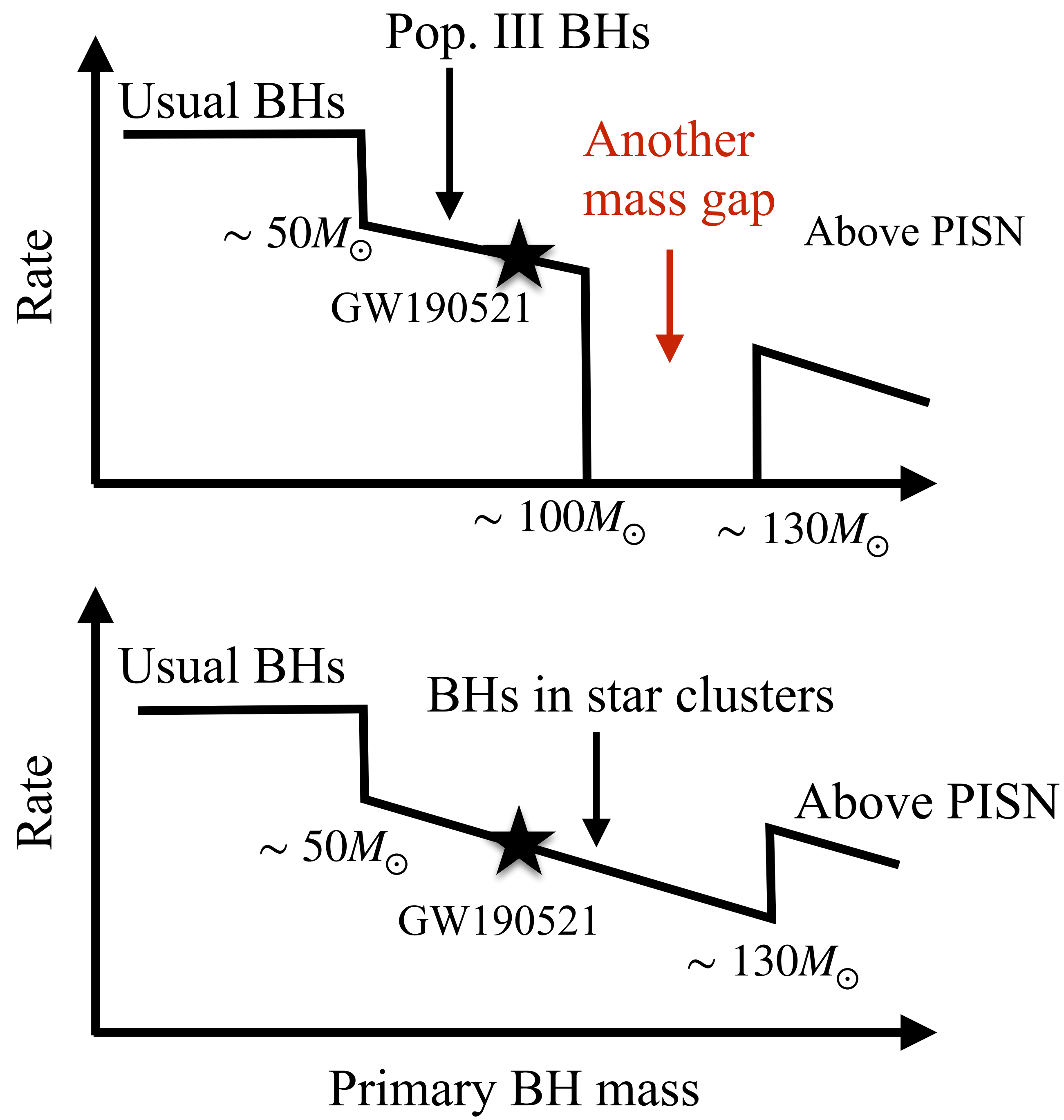
Pop III stars can form the PI mass-gap event if overshoot is ineffective.



Tanikawa et al. (2021, MNRAS, 505, 2170)

Difference from cluster origin

- Even if the M model is correct, no Pop. III binary can form BH-BHs with $100 - 130 M_\odot$.
- If GW190521 is Pop. III, the merger rate of BH-BHs with $100 - 130 M_\odot$ is much smaller than with $50 - 100 M_\odot$.



Expectations for O4

- After June 2022
- Improved sky localization because of KAGRA joining
  - Electromagnetic counterparts?
- More many BH mergers discovered
  - The presence of $100 - 130 M_\odot$ mass gap
  - Intermediate mass BH ($\gtrsim 100 M_\odot$) mergers

Summary

- The origins of BH mergers have been under debate.
- Open clusters can be a promising formation site of merging BH mergers.
- Pop III stars can form the PI mass-gap event GW190521 if convective overshoot is not effective.