Binary black hole mergers

J-GEM Kick-off workshop 2021/07/02

Speaker: Ataru Tanikawa[1]

Collaborators: Fujii M. S.[1], Hosokawa T.[2], Kinugawa T.[1], Kumamoto J.[1], Hijikawa K.[1], Omukai K.[3], Leigh N. W. C.[4], Susa H.[5], Takahashi K.[6], Trani A. A.[1], Umeda H.[1], Wang L.[1], Yoshida T.[2]

Institutes: [1]The University of Tokyo, [2]Kyoto University, [3]Tohoku University, [4]University of Concepcion, [5]Konan University, [6]Max Planck Institute

Contents

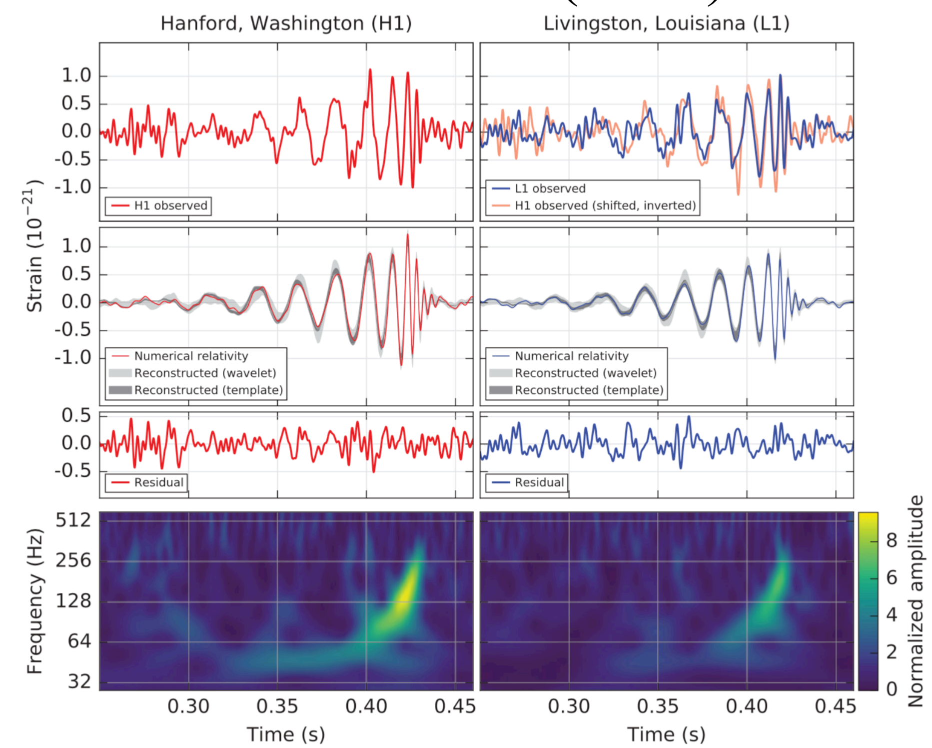
- Binary black hole (BBH) mergers in O1-O3a
- GW190521: the pair instability mass gap event
- Our study: Isolated binary scenario
- Expectation for O4
- Electromagnetic (EM) counterparts

BBH mergers in O1-O3a

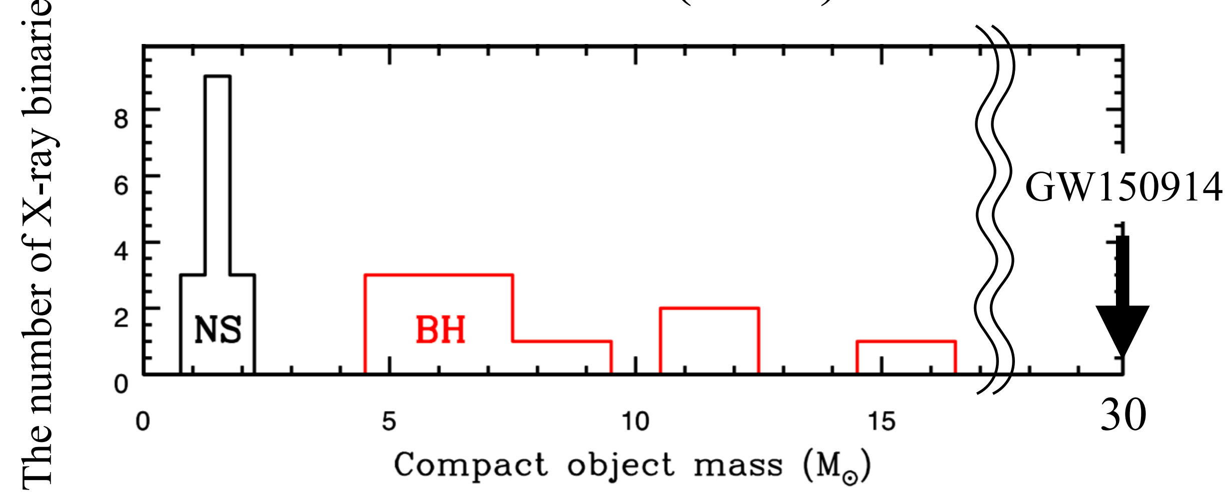
The first detection: GW150914

- 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)



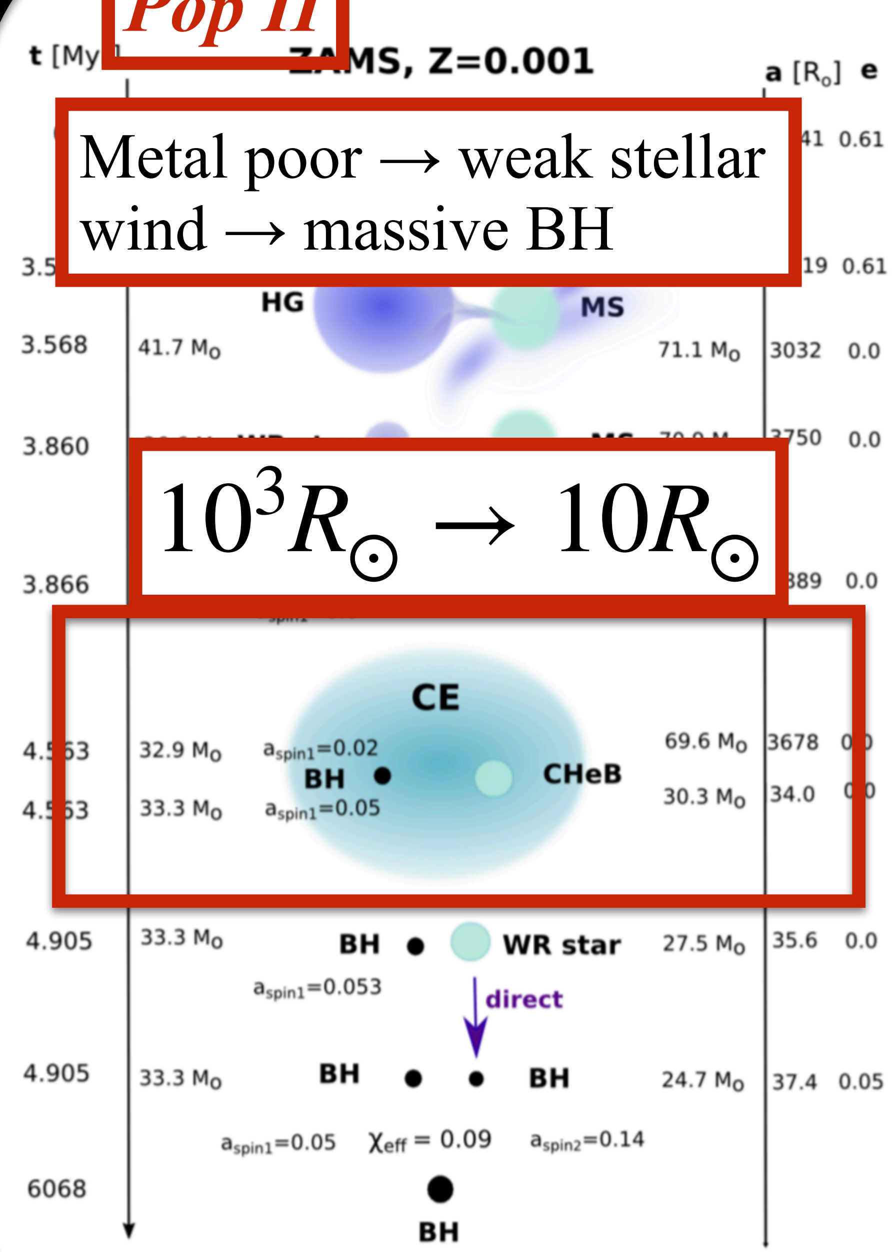
Many formation scenarios

Isolated binary stars

Pop II

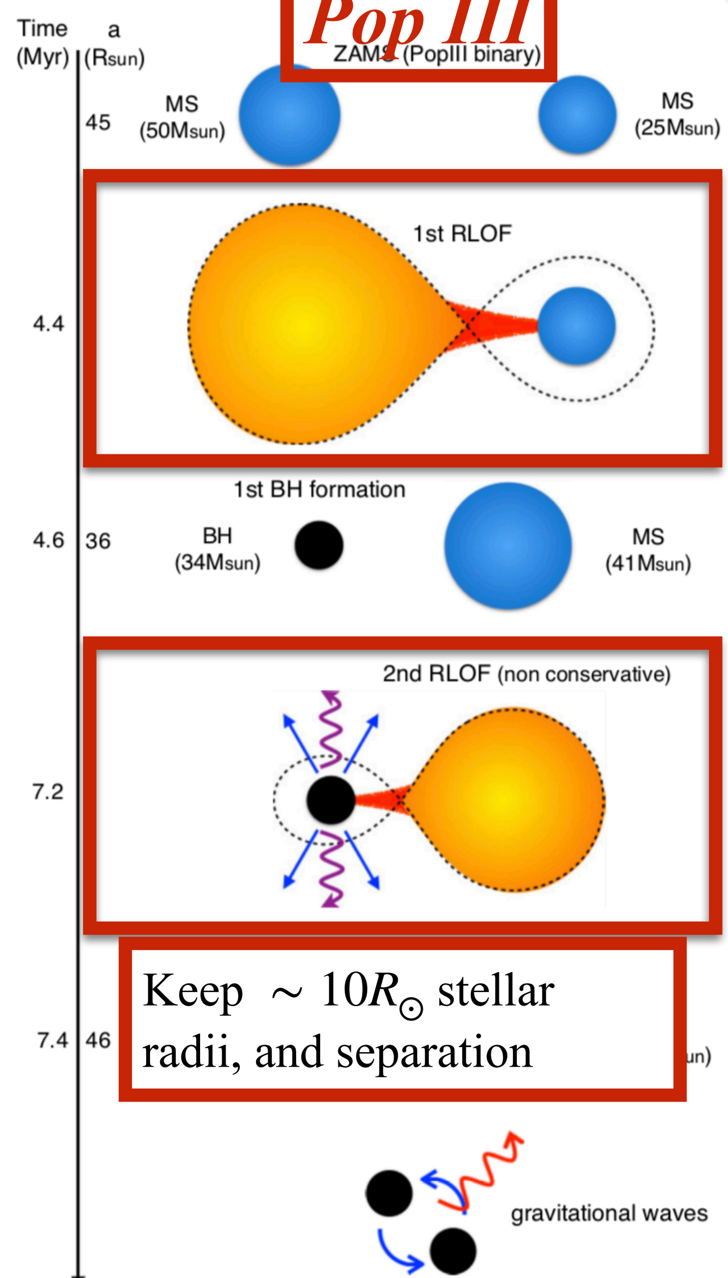
Metal poor → weak stellar wind → massive BH

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



Belczynski et al. (2020)

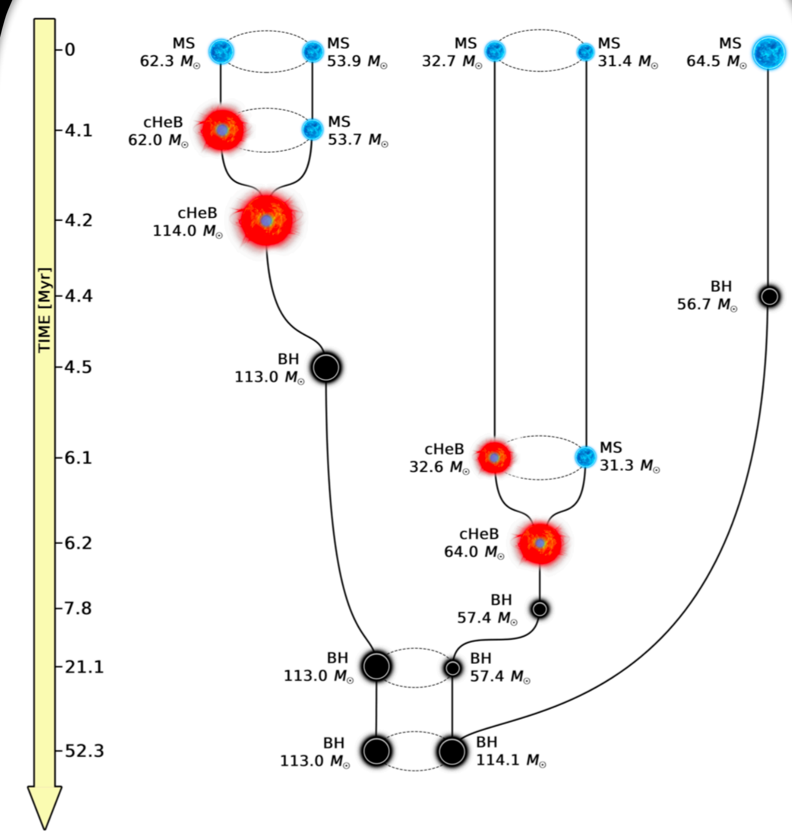
Pop III



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

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

Star cluster



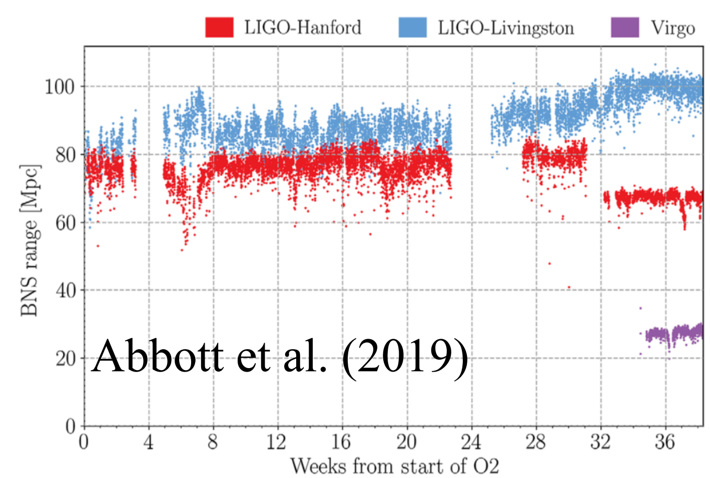
Di Carlo et al. (2021)

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

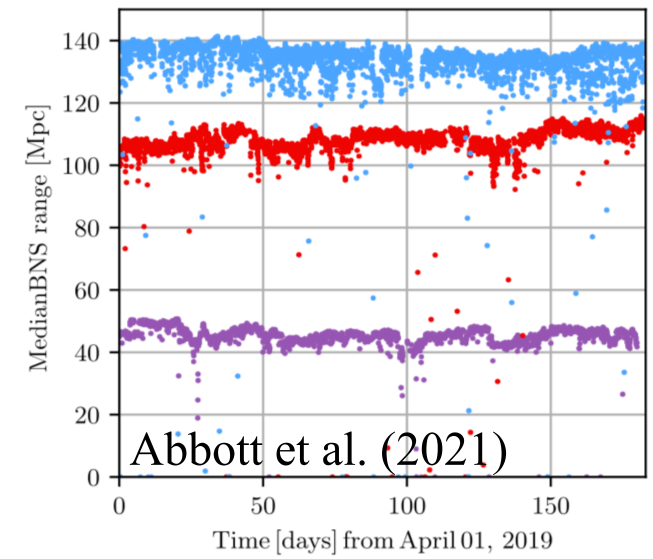
From O1/O2 to O3a

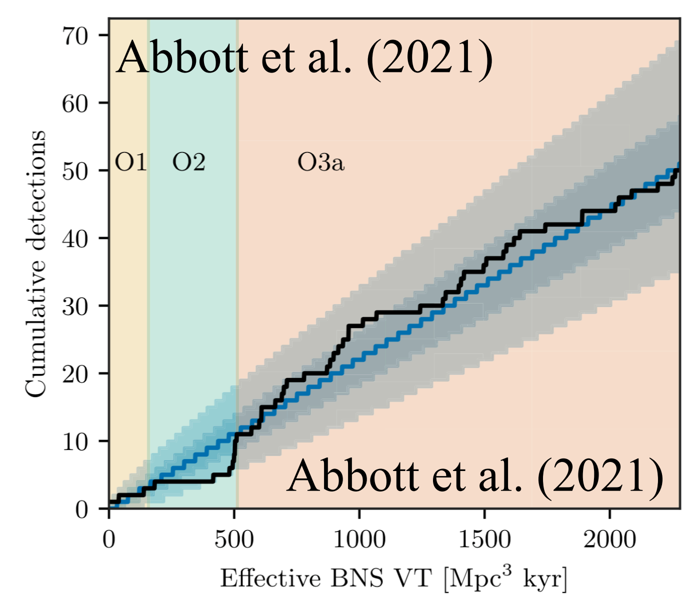
- Sensitivity (BNS range)
  - LIGO-H: 90Mpc → 135Mpc
  - LIGO-L: 80Mpc → 108Mpc
  - Virgo: 25Mpc → 45Mpc
- Virgo joining
  - Partial → Full
- Detection
  - 1 per 100 days → 1 per week
  - 10 → ~ 50 published events

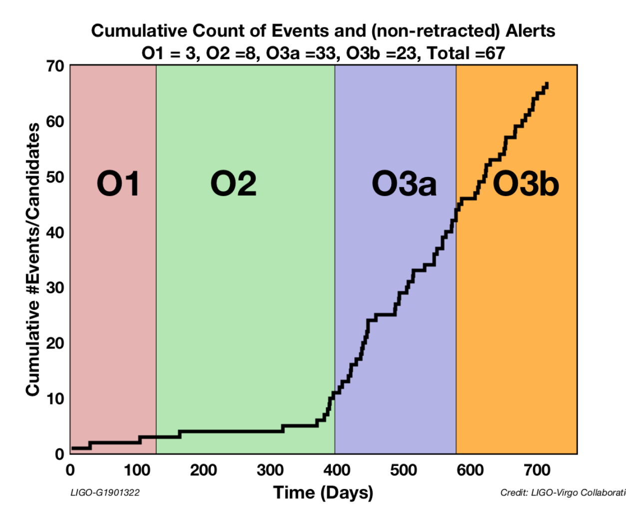
BNS range (O2)



BNS range (O3a)

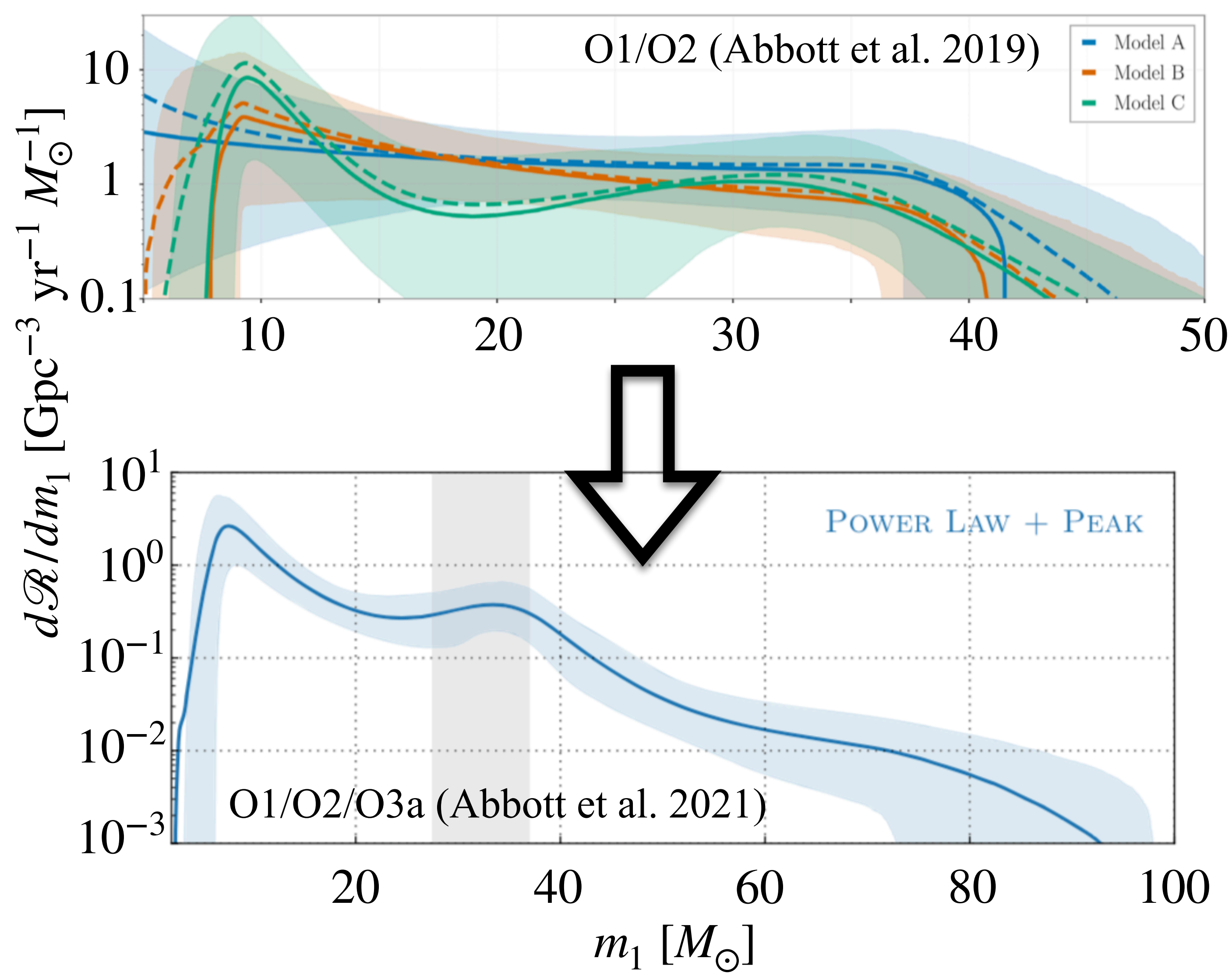






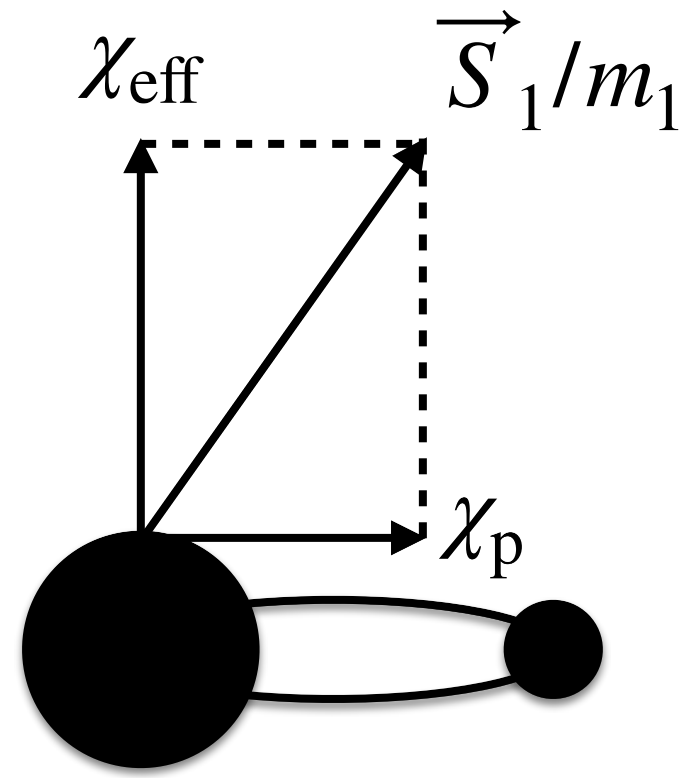
Statistics: Primary BH mass

- The global maximum at $\sim 8M_{\odot}$
  - The lower mass gap: $\lesssim 5M_{\odot}$
  - Consistent with X-ray observations (Farr et al. 2011)
- The second peak at $\sim 40M_{\odot}$
  - Cliff or break? (O1/O2)
  - Break (O1/O2/O3a)

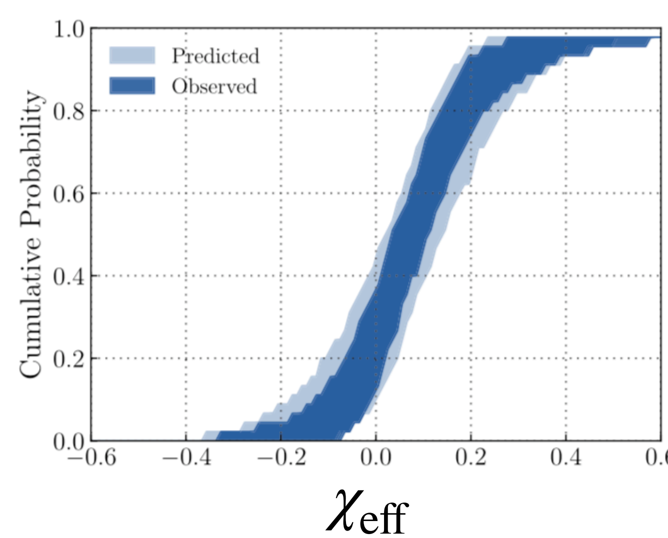


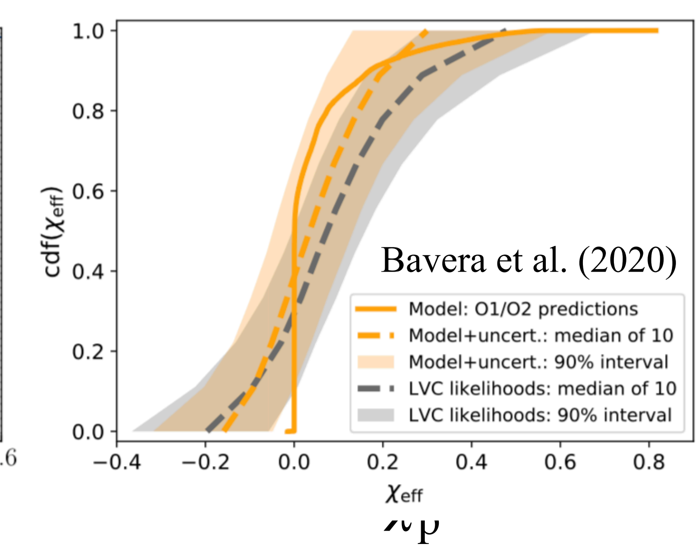
Statistics: BH spin

- Effective spin:
  $$\chi_{\rm eff} = \frac{1}{m_1+m_2}\left(\frac{S_{1,\parallel}}{m_1}+\frac{S_{2,\parallel}}{m_2}\right)$$
- Spin precession: $\chi_{\rm p} = \max\left(\frac{S_{1,\perp}}{m_1^2}, \frac{S_{2,\perp}}{m_2^2}\kappa(q)\right)$
- Multiple origins?
  - Isolated binary: positive spins
  - Star cluster: isotropic spins
- Note
  - $\gtrsim 500$ km/s BH natal kicks required for negative $\chi_{\rm eff}$ from isolated binary
  - Observational errors may smear out the sharp peak at $\chi_{\rm eff} = 0$.



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

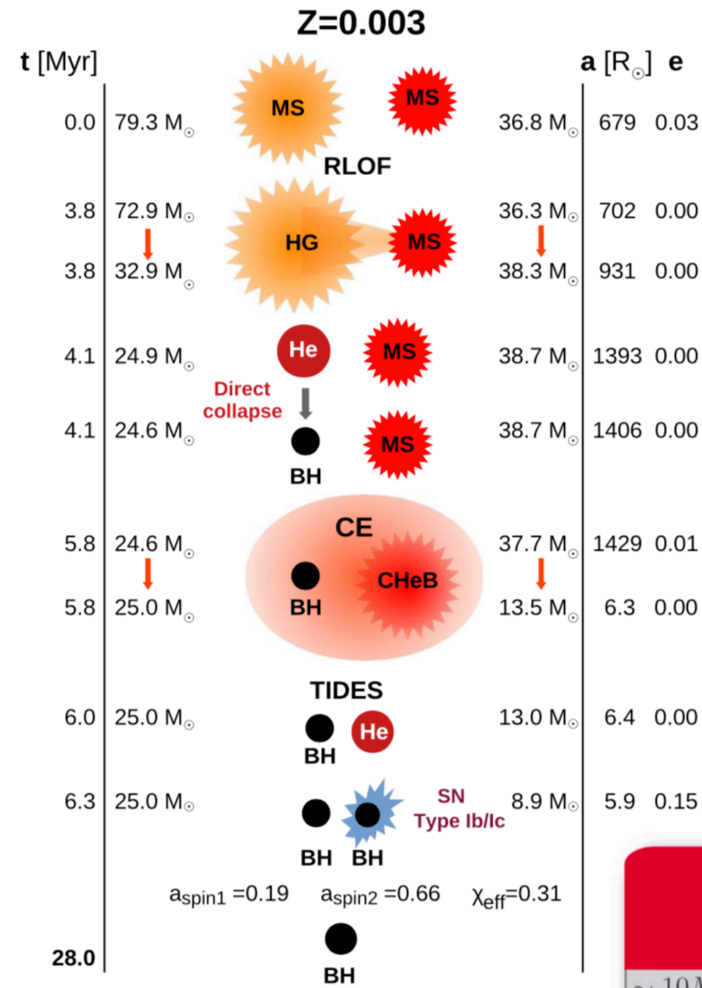




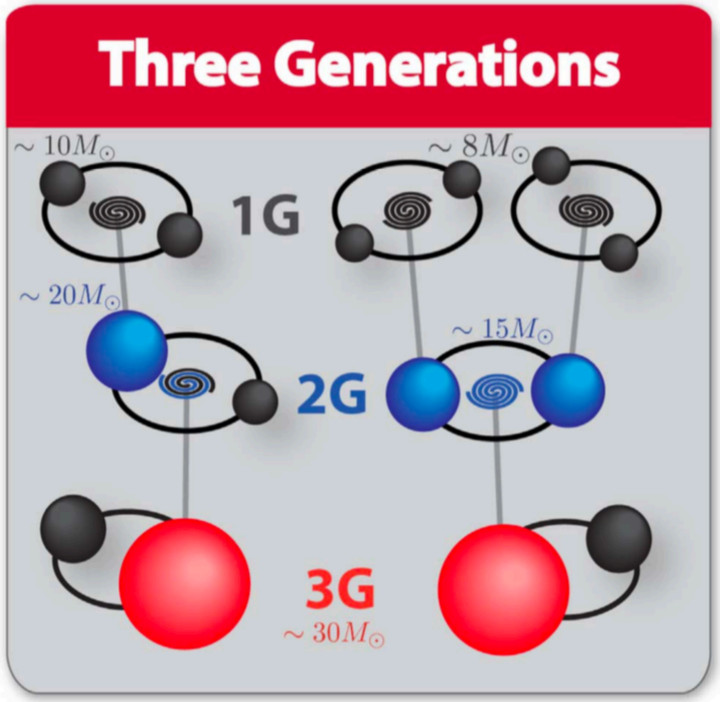
O1/O2/O3a (Abbott et al. 2021)

Distinct event: GW190412

- Mass ratio $q(=m_2/m_1)$
  - GW190412: $q \sim 0.25$
    - $m_1 \sim 30.1 M_\odot, m_2 \sim 8.3 M_\odot$
  - Other BBHs: $q \sim 1$
- Spins: $\chi_{\rm eff} \sim 0.25, \chi_{\rm p} \sim 0.31, \chi_1 \sim 0.44$
- Isolated binary
  - Its $\chi_{\rm p}$ and χ_1 are not explained.
- Star cluster
  - High-metallicity clusters
  - 3rd generation BHs



Isolated binary
(Olejak et al. 2020)

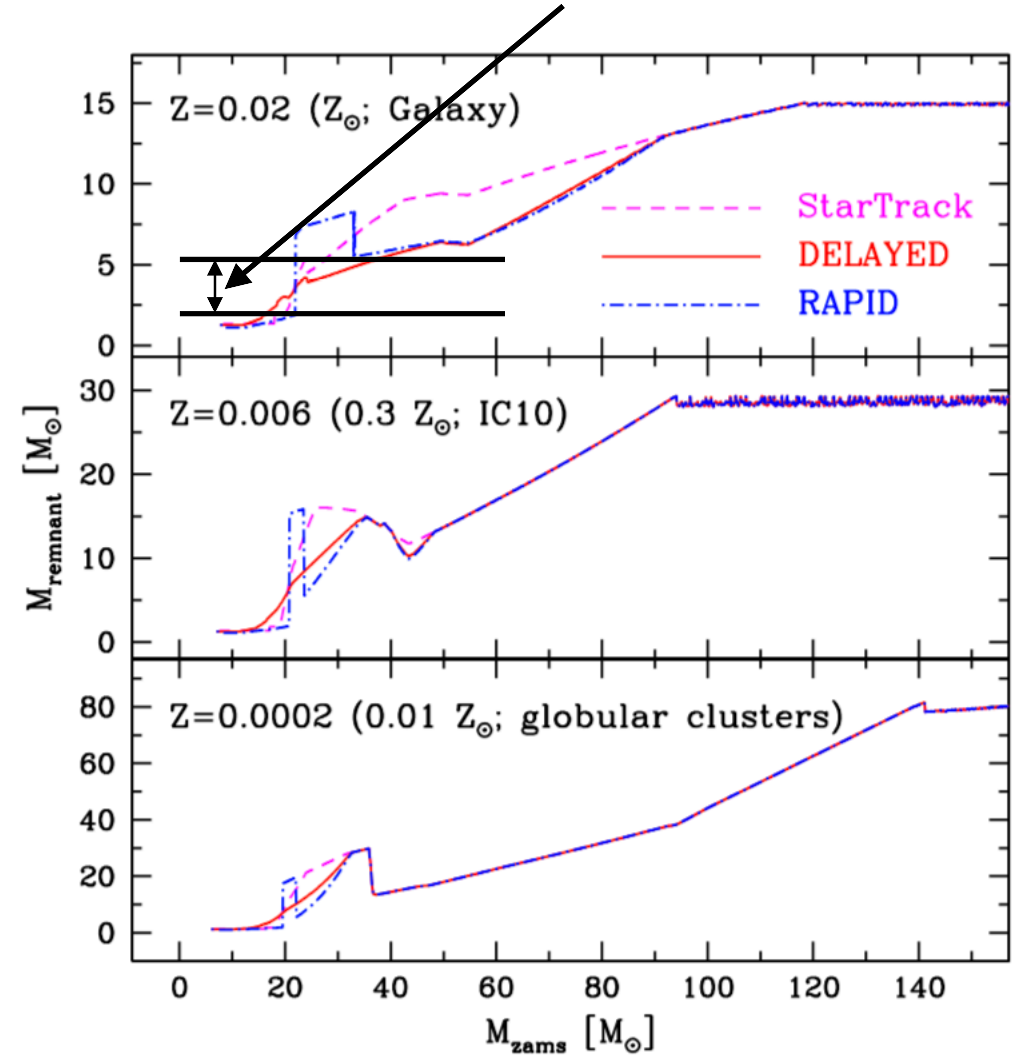


High-metallicity cluster
(Rodriguez et al. 2020)

Distinct event: GW190814

- Masses
  - $m_1 = 23.2^{+1.0}_{-0.9} M_\odot$
  - $m_2 = 2.59^{+0.08}_{-0.08} M_\odot$
  - BH-BH, BH-NS, or other?
- Difficult to be explained by the current population synthesis and star cluster simulations
  - Fryer's rapid supernova model adopted
  - No NS/BH in the range of $2 - 5 M_\odot$

No BH/NS (the lower mass gap)

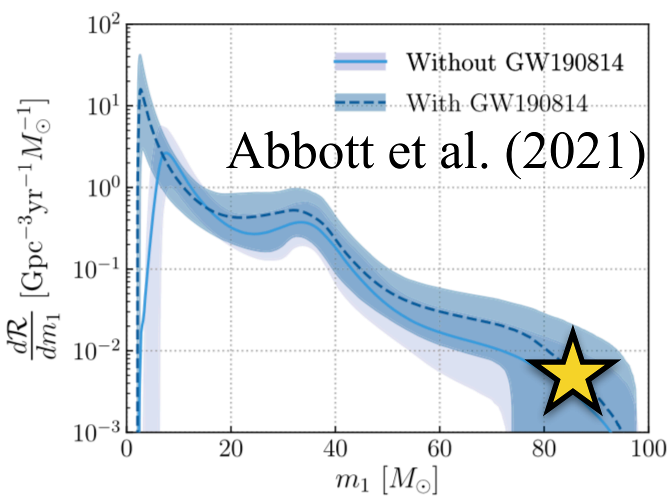


Fryer et al. (2012)

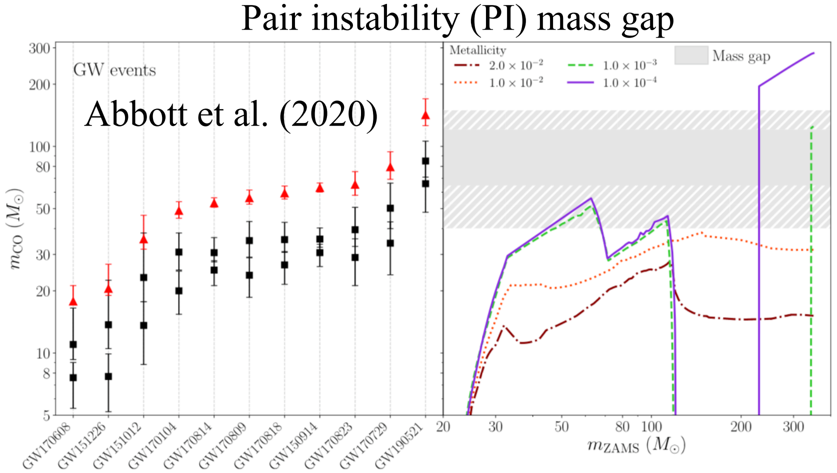
GW190521 : the pair instability mass gap event

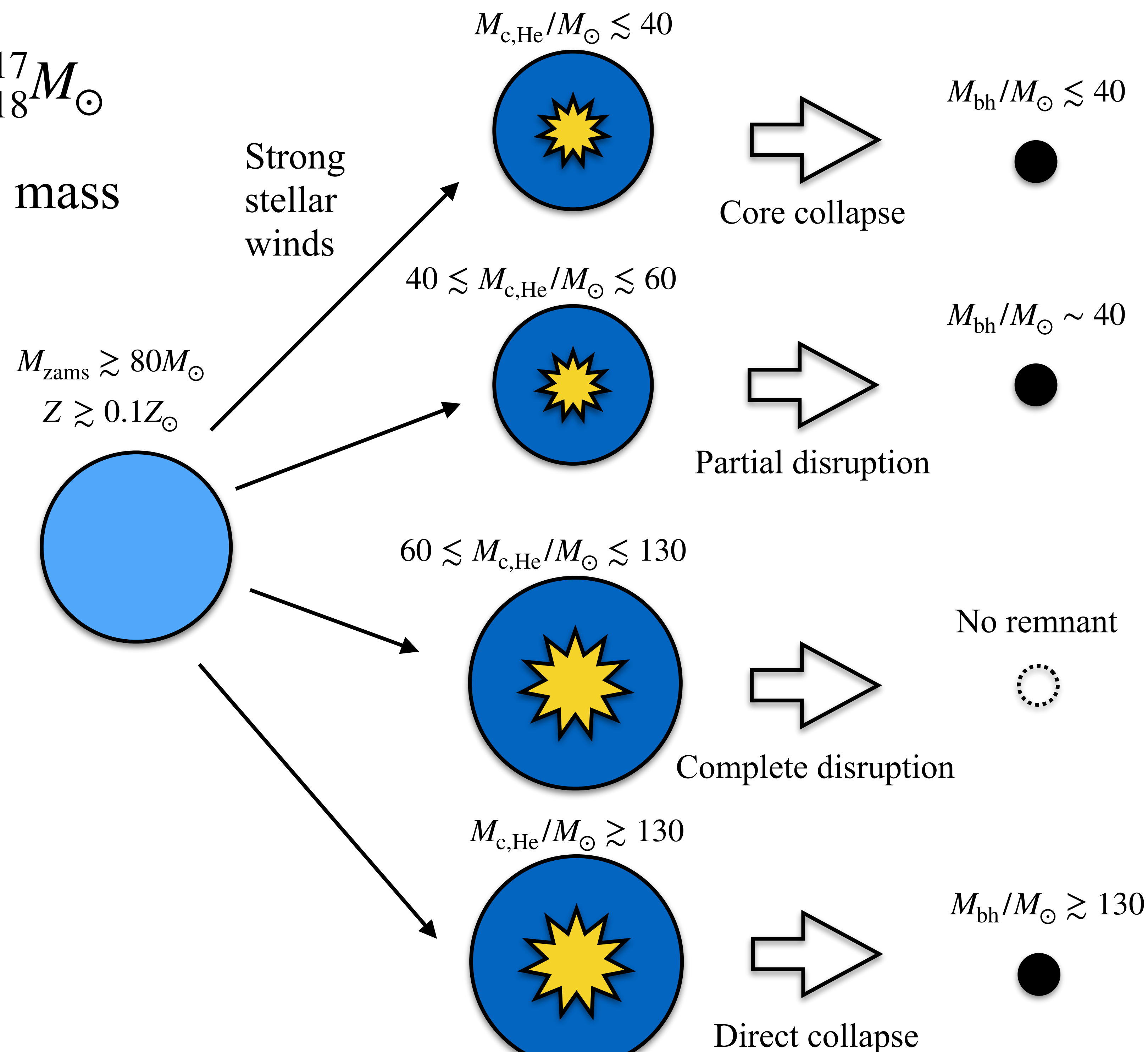
Distinct event: GW190521

- $m_1 = 85^{+21}_{-14} M_\odot$, $m_2 = 66^{+17}_{-18} M_\odot$
- Pair instability (the higher) mass gap: $40 - 130 M_\odot$
- The break confirmed

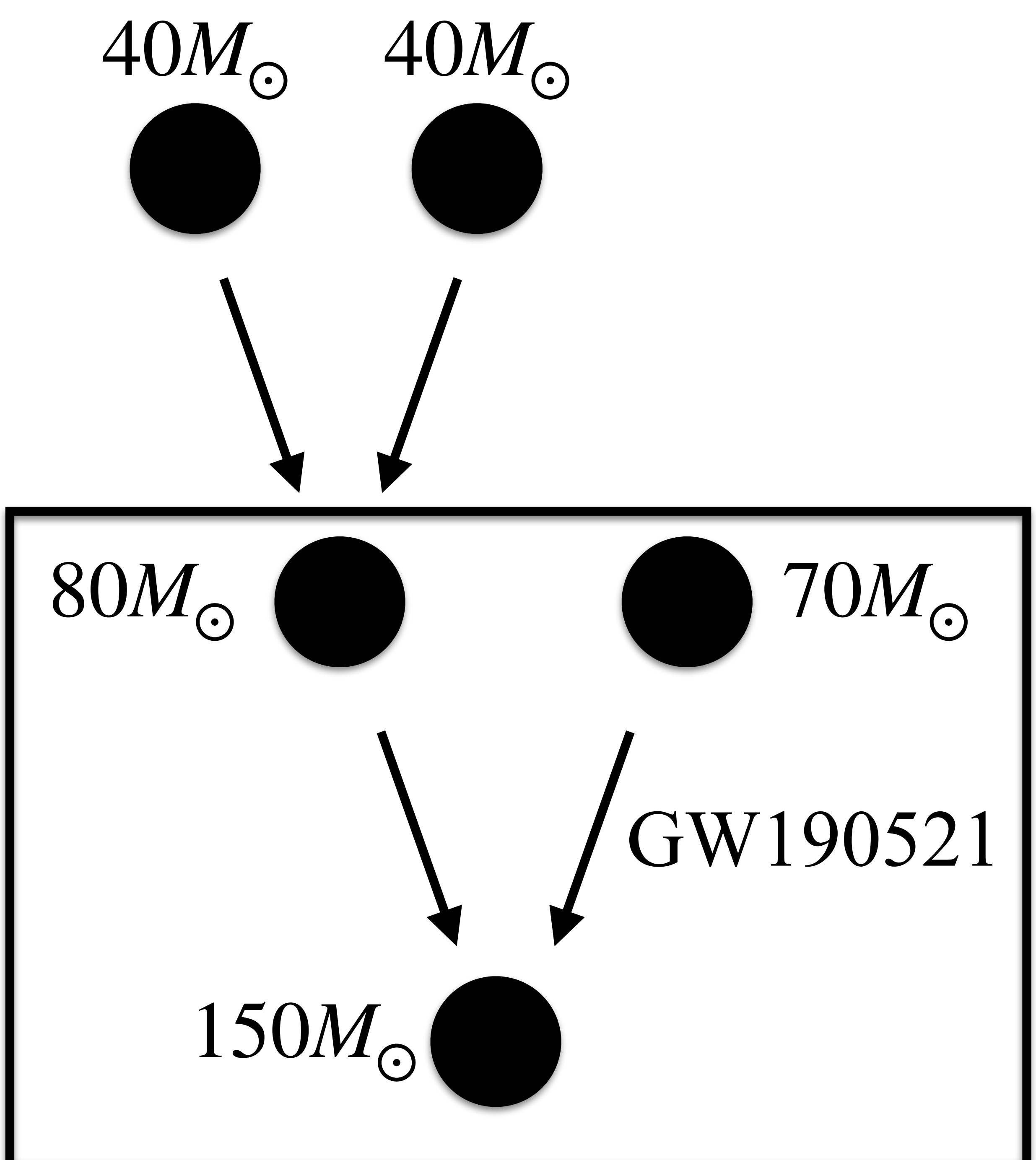


Pair instability (PI) mass gap

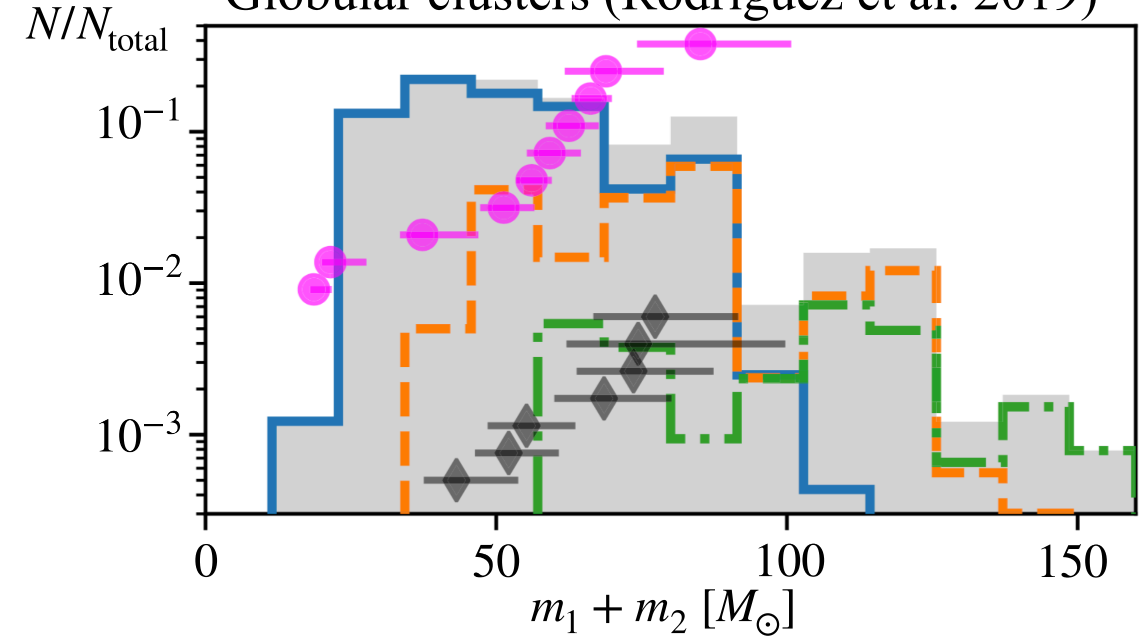




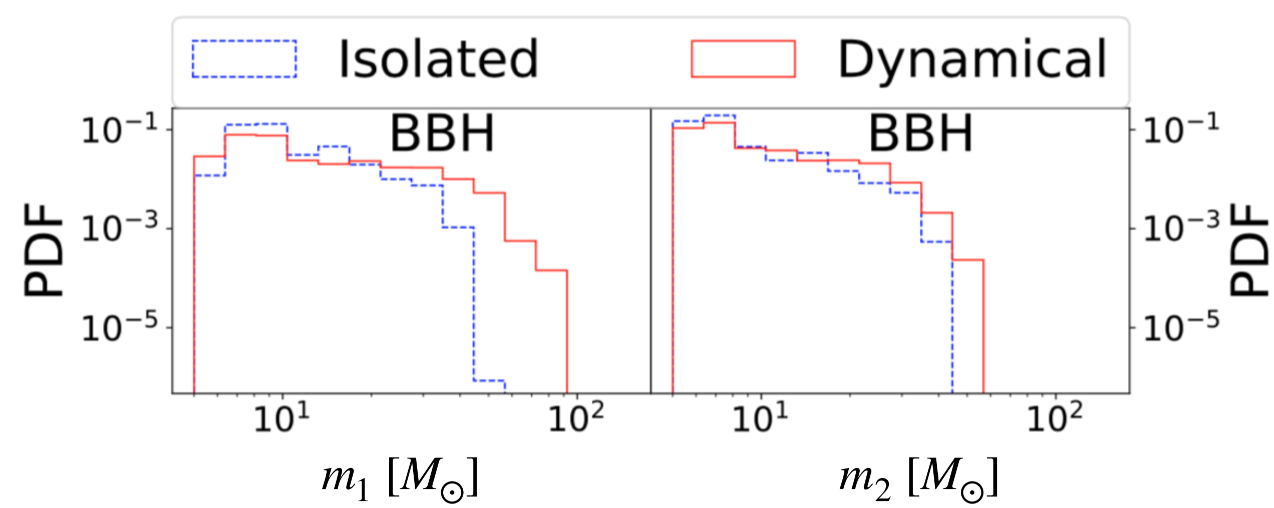
Star cluster scenario



Globular clusters (Rodriguez et al. 2019)



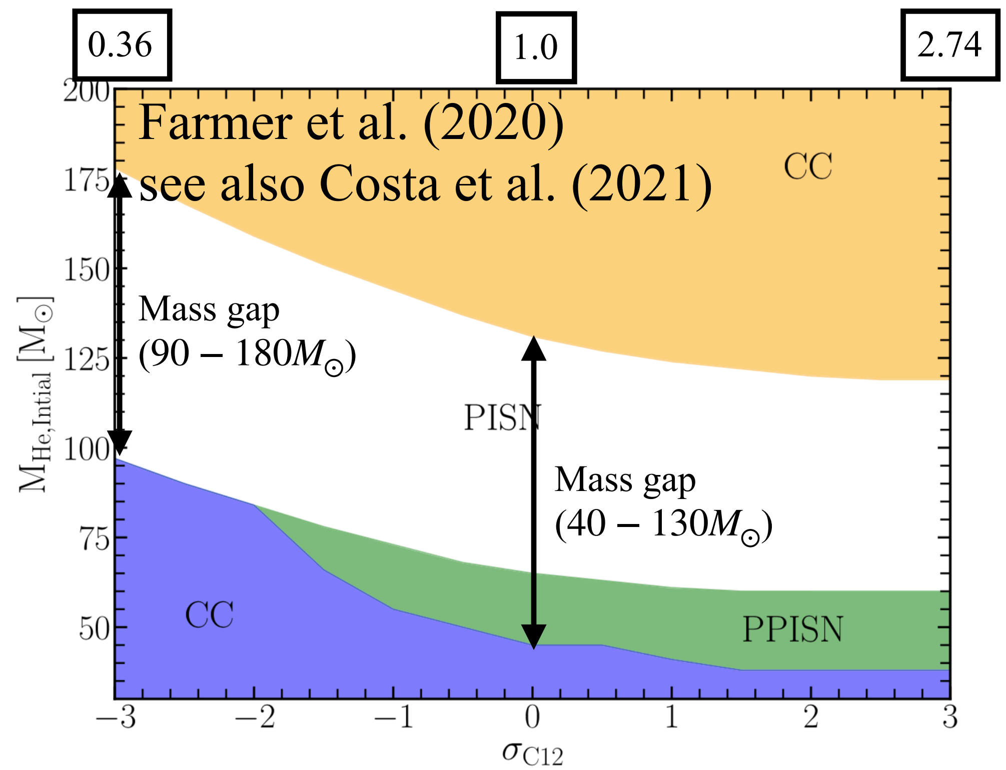
Open clusters (Santoliquido et al. 2020)

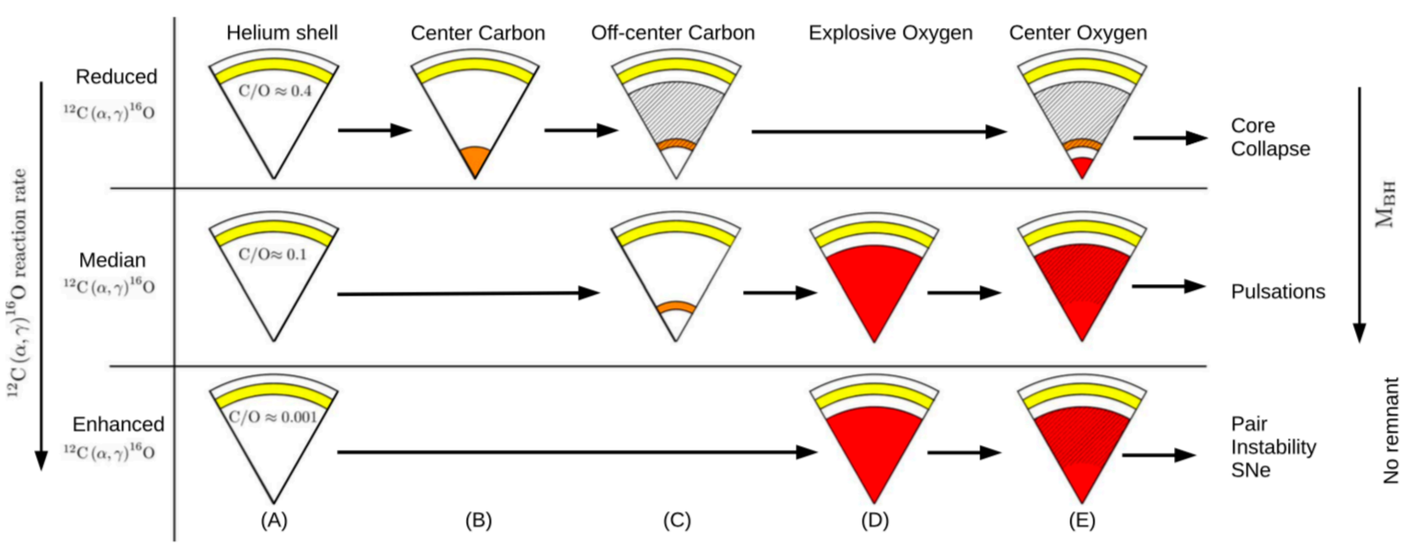


See also AGN disks (Tagawa et al. 2020)

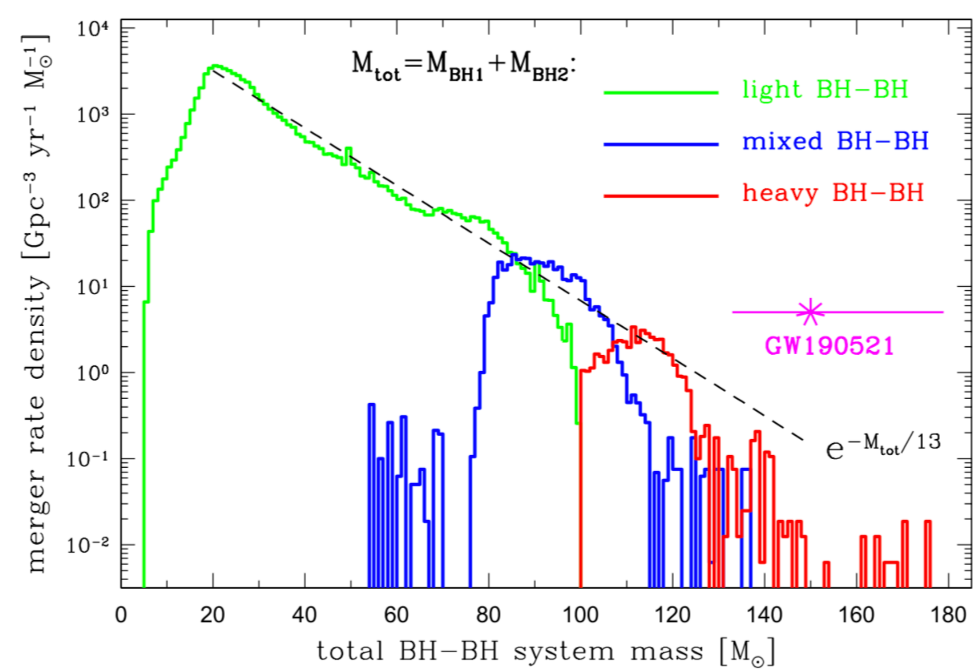
Uncertainty in the PI mass gap

- Large C/O at the end of helium core burning phase
- Sufficient carbon burning at the central and off-center regions
- Onset of convection above the carbon burning shell
- Homogeneous contraction prevented by the convection
- No explosive oxygen burning





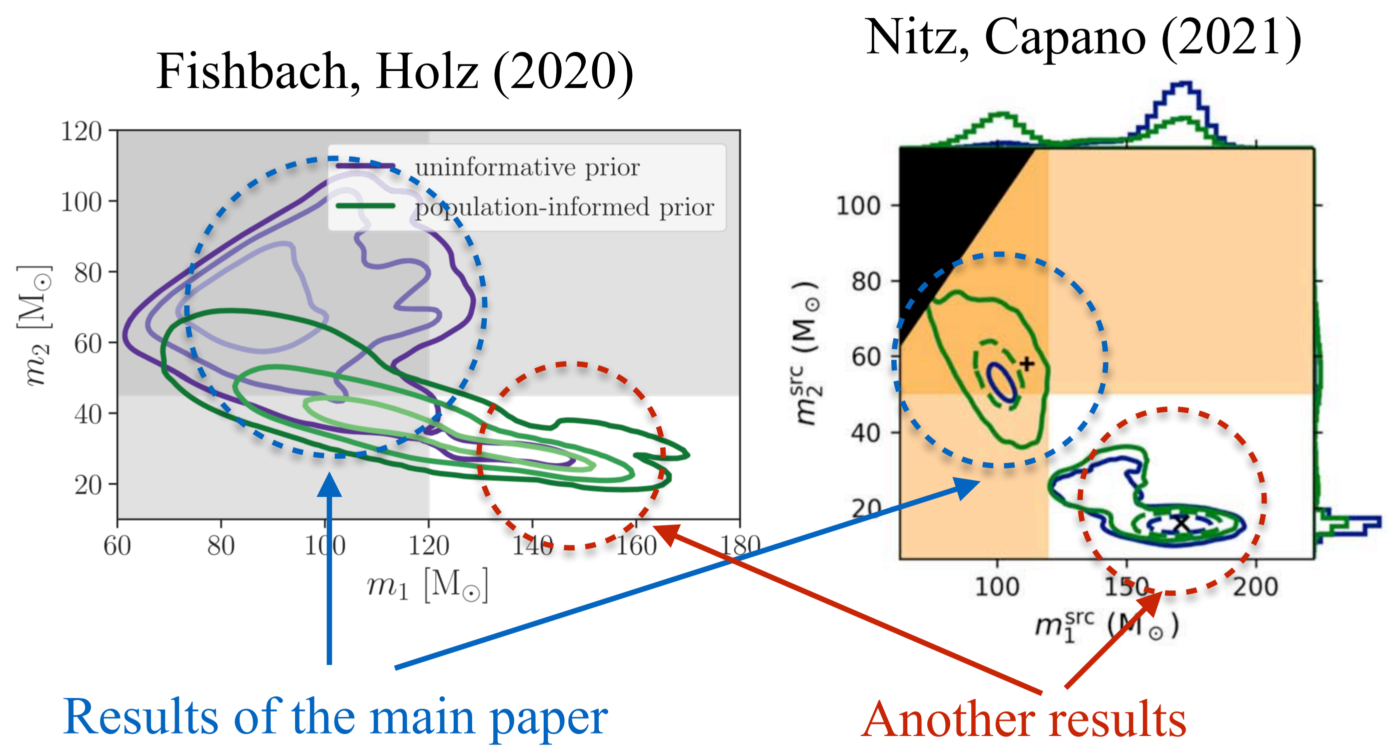
Farmer et al. (2020)
see also Takahashi (2018)

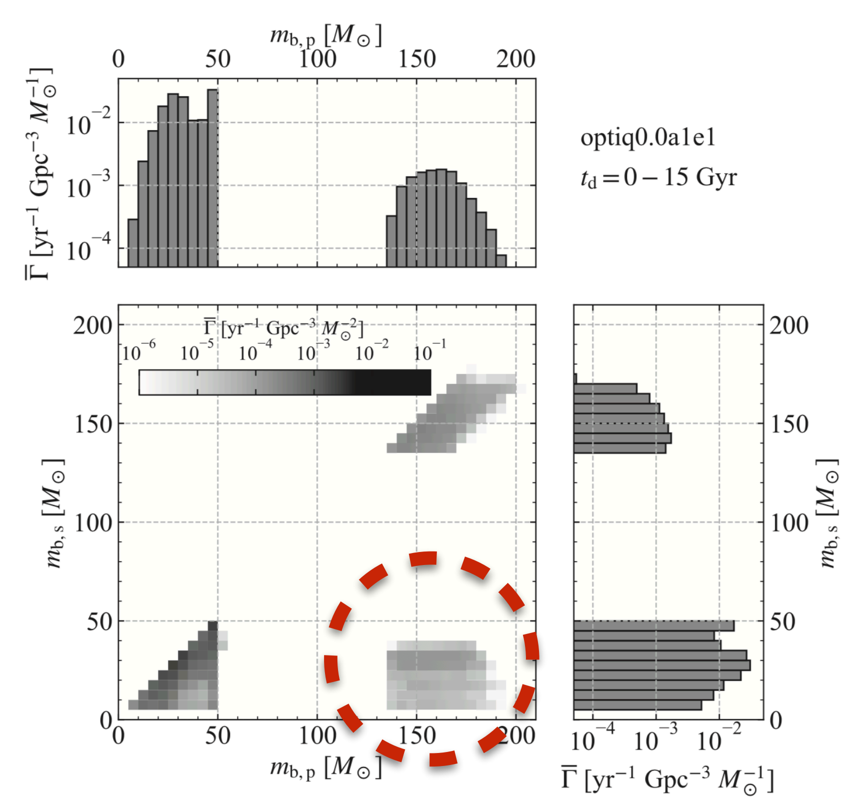


Belczynski (2020)

Uncertainty in the mass estimate

- Different priors for GW190521
  - Avoiding of the pair instability mass gap
  - $m_1 > 130 M_\odot$, $m_2 < 40 M_\odot$
- Pop III BBHs
  - $\sim 0.01\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$ comparable to the GW190521-like event rate
  - GW190521 may be Pop III origin.

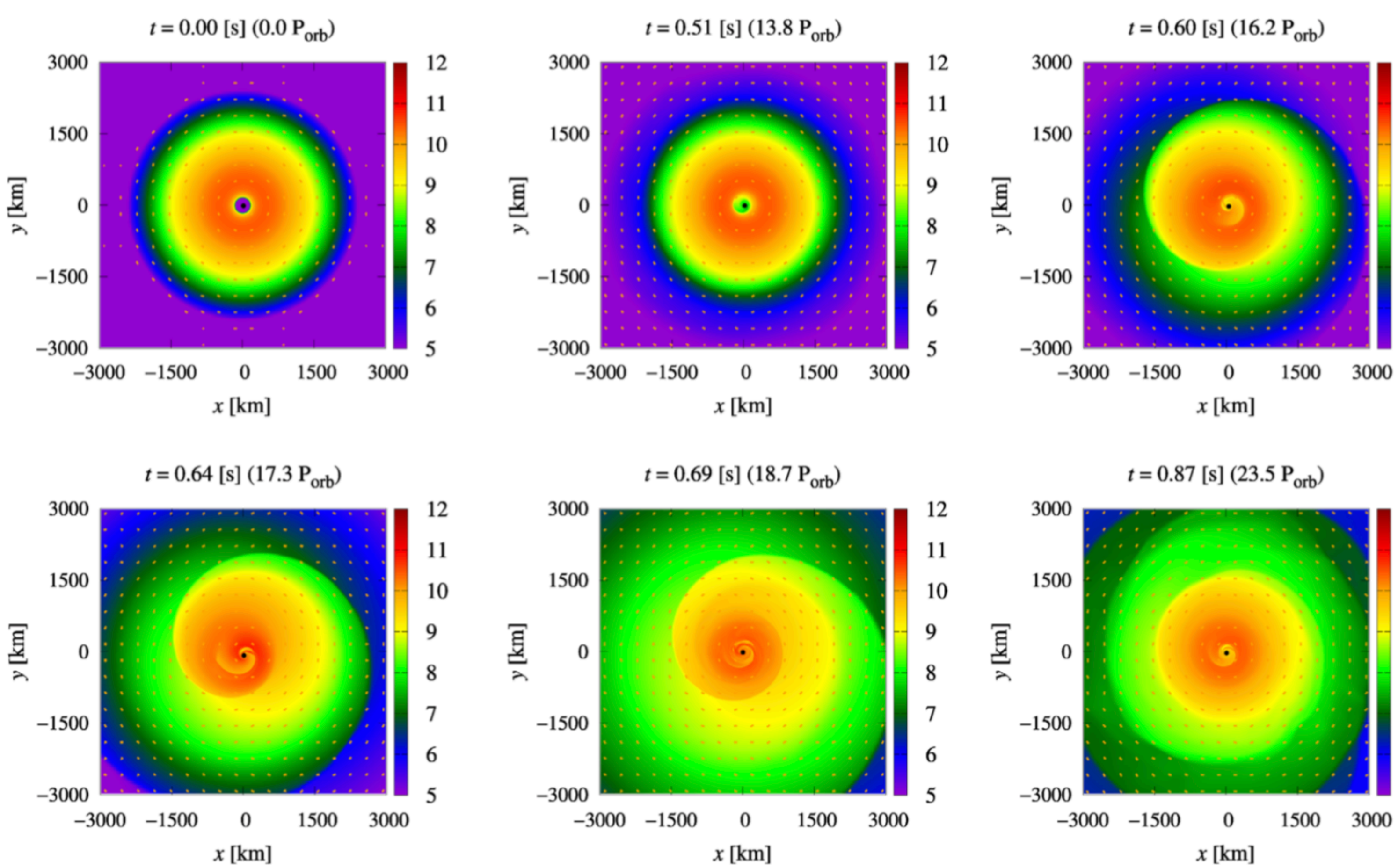


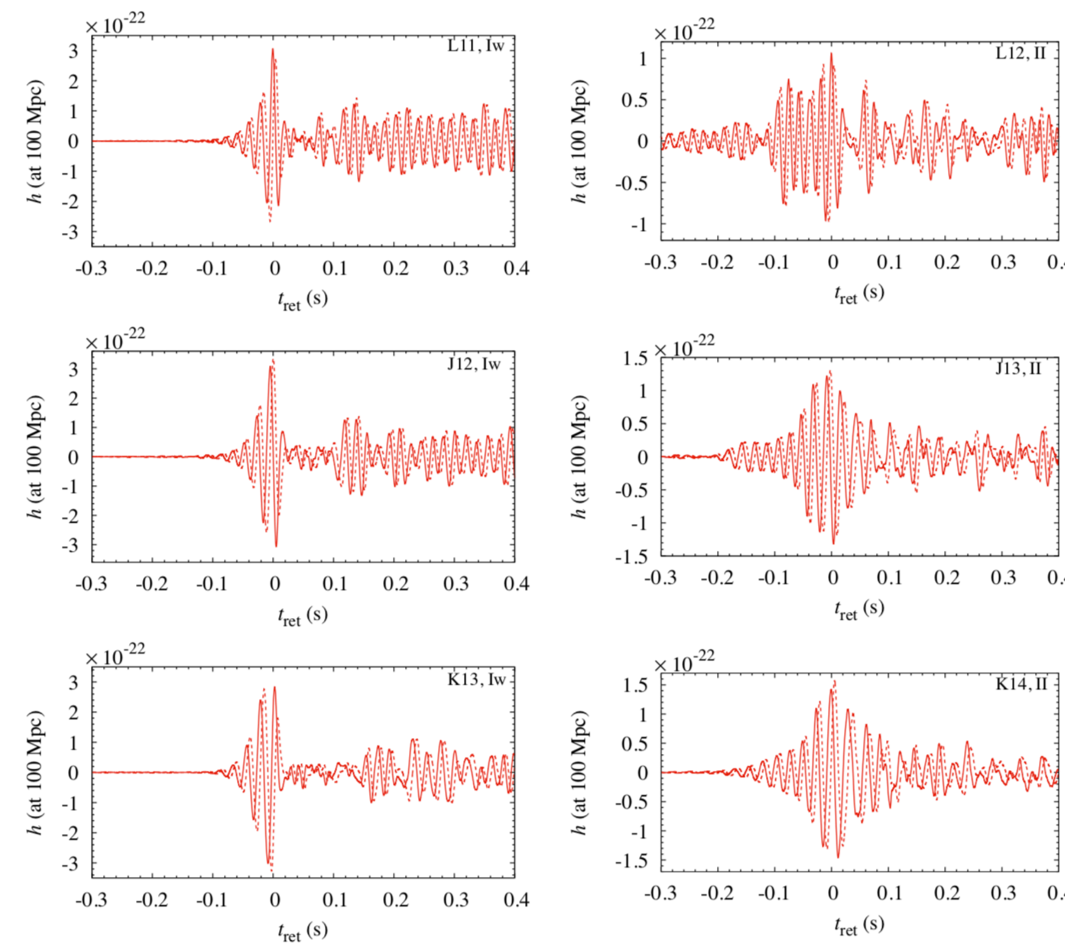


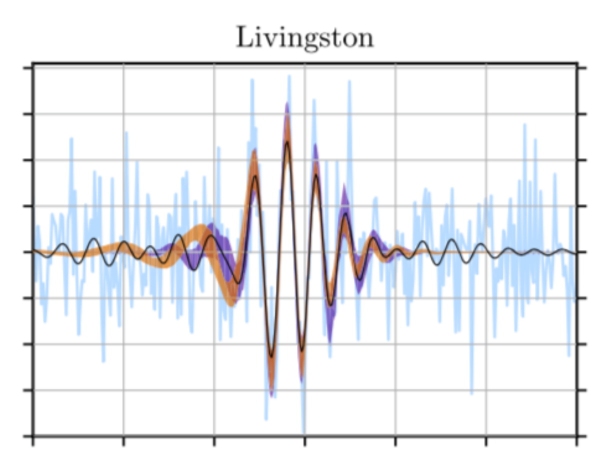
Tanikawa et al. (2021, ApJ, 910, 30)

One-armed spiral-shape instability

Shibata, Kiuchi, Fujibayashi, Sekiguchi (2021)







GW190521 (Abbott et al. 2020)

EM counterparts?

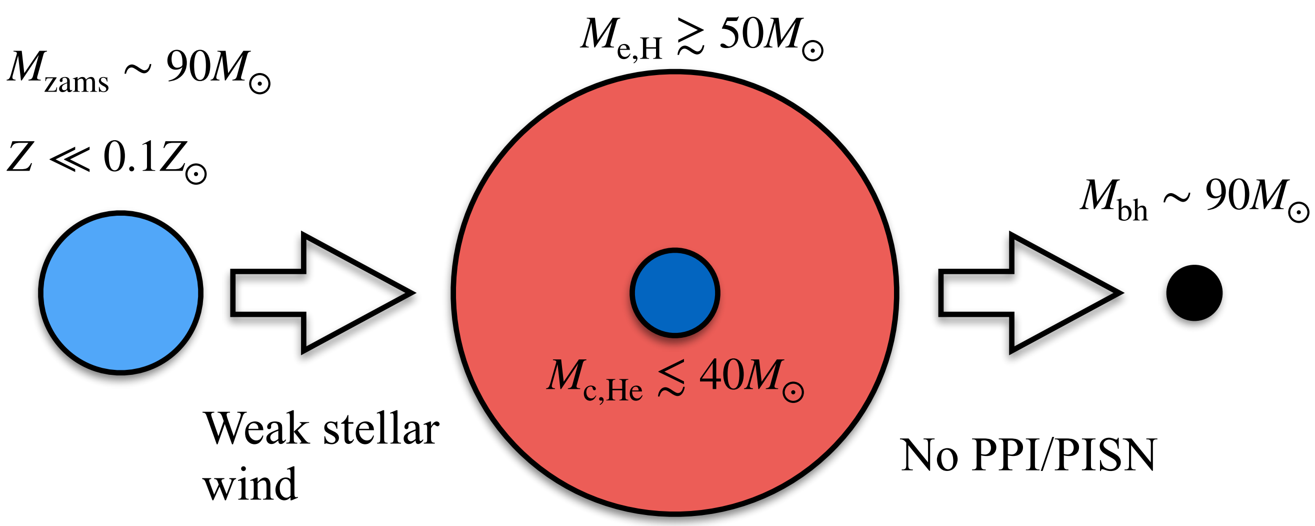
Our study:
Isolated binary scenario

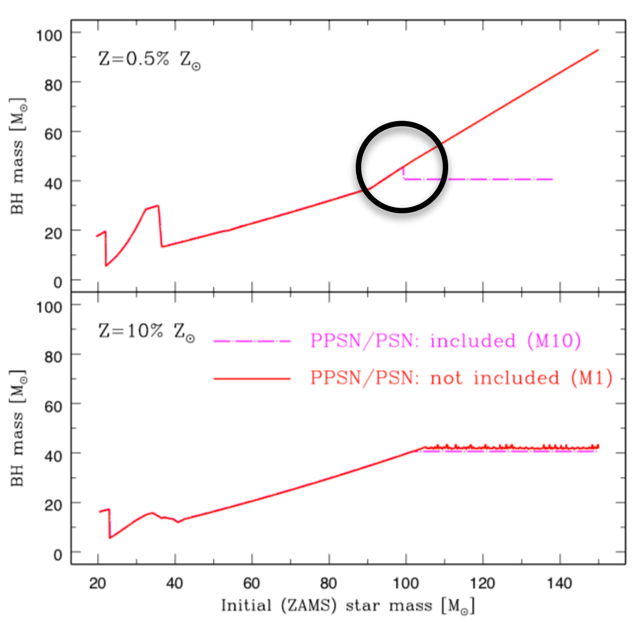
Our stand point

- Primary BH mass distribution including GW190521
- GW190512 as the pair instability mass gap event
- The standard pair instability mass gap $(40 - 130 M_{\odot})$
- Isolated binary evolution

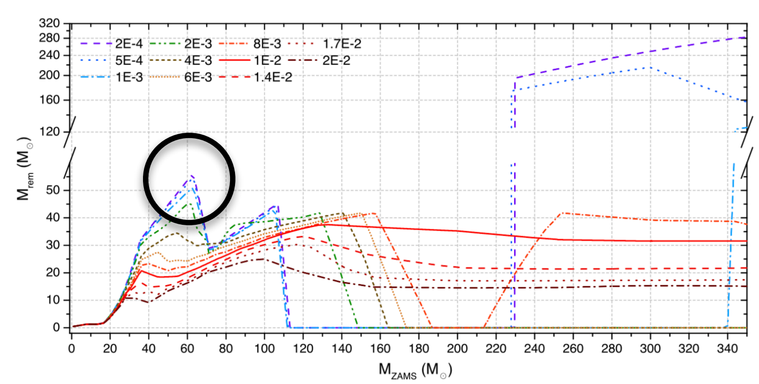
Revisit of the PI mass gap

Single star evolution





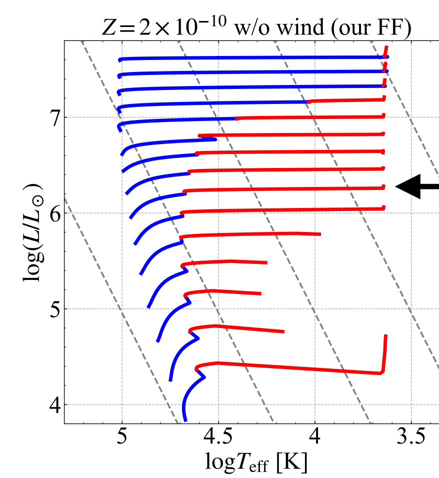
Belczynski et al. (2016)



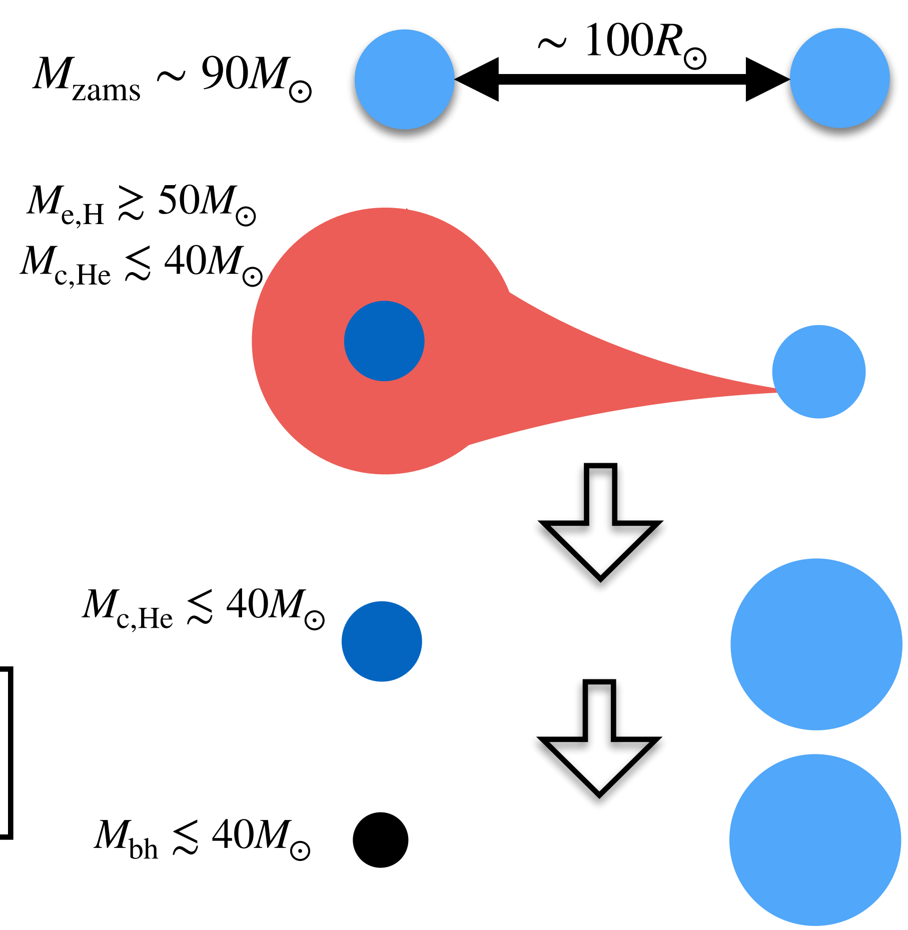
Spera, Mapelli (2017)

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

Binary star evolution

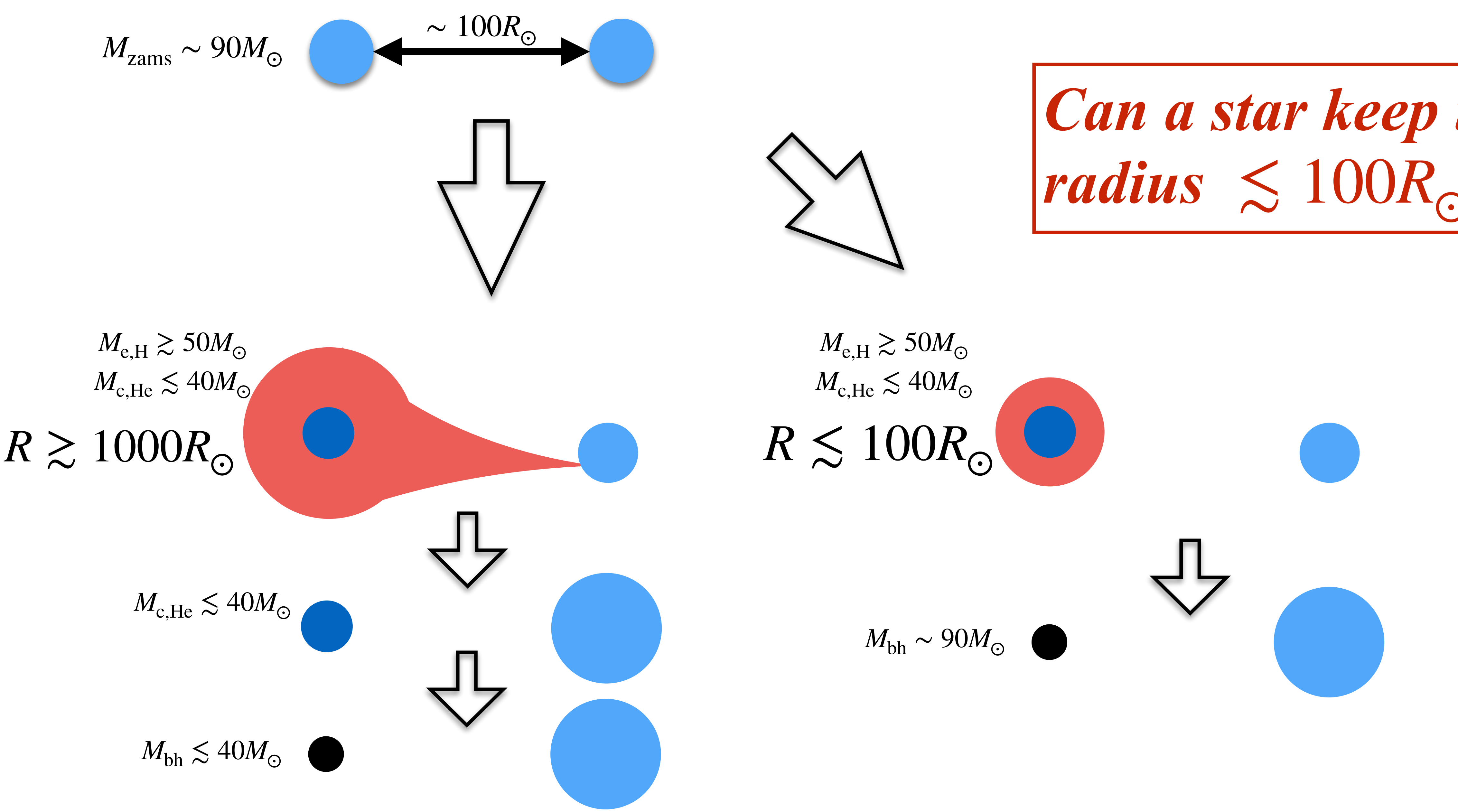


- $M_{tot} \sim 80M_\odot$
- $M_c \sim 40M_\odot$
- $R \gtrsim 10^3 R_\odot$



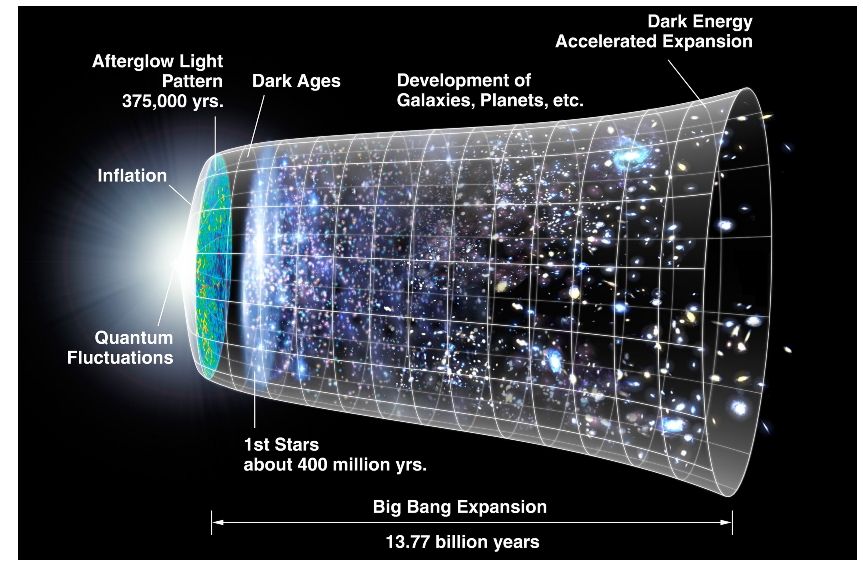
Stellar radius

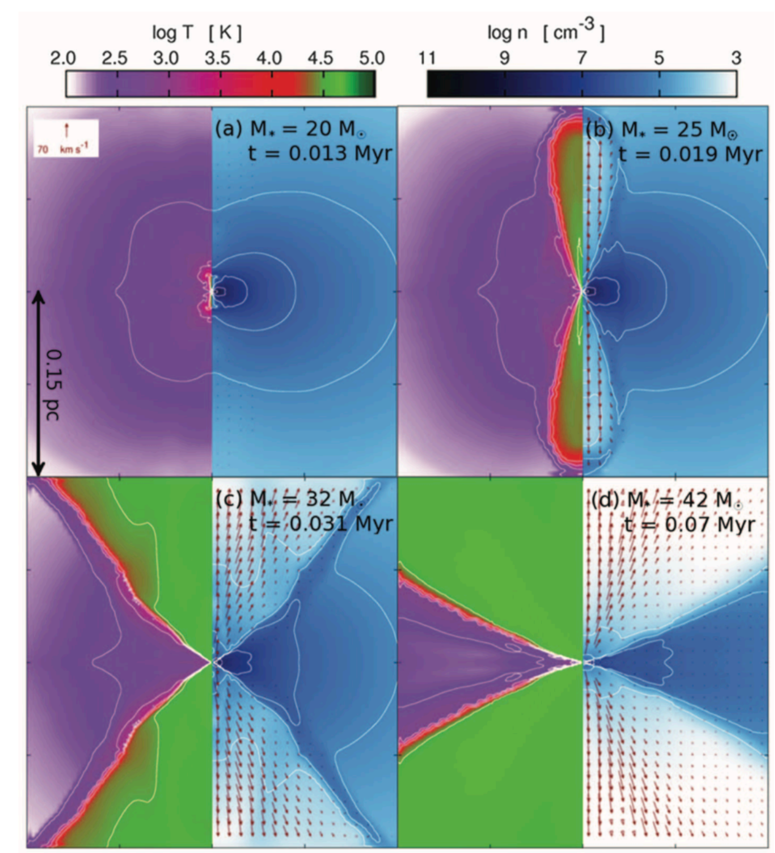
Can a star keep its radius $\lesssim 100R_\odot$?



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)



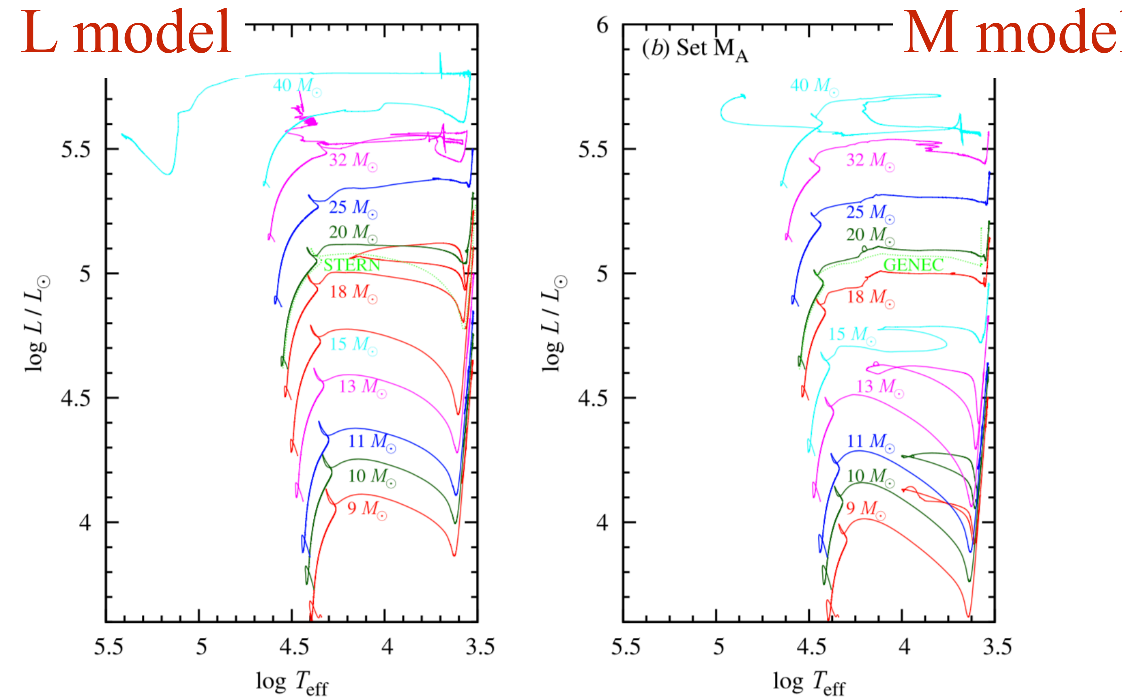


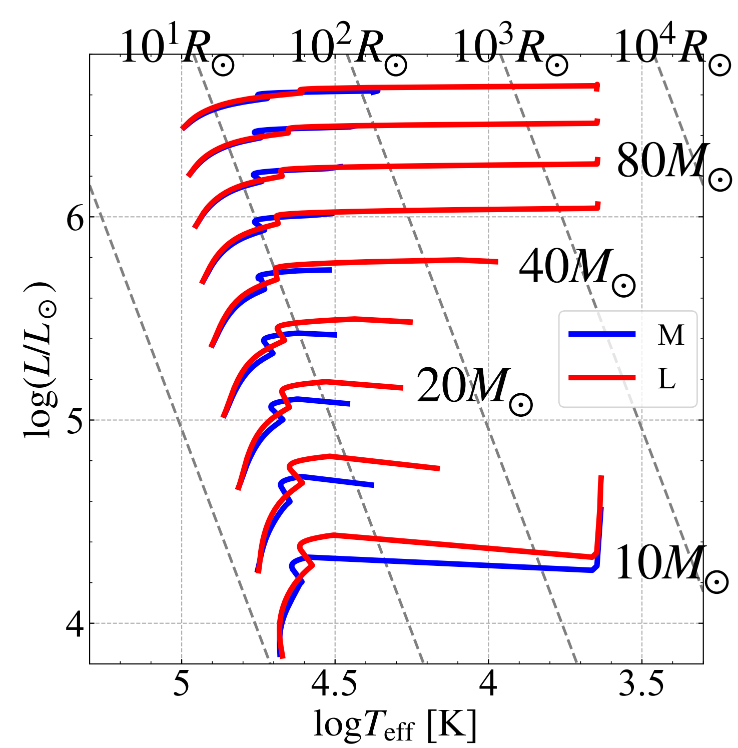
Hosokawa et al. (2011)

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 $80 M_\odot$ star
  - M model: $\sim 40 R_\odot$, similar to Farrell et al. (2020)
  - L model: $\sim 3 \times 10^3 R_\odot$, similar to Yoon et al. (2012)

Yoshida et al. (2019)

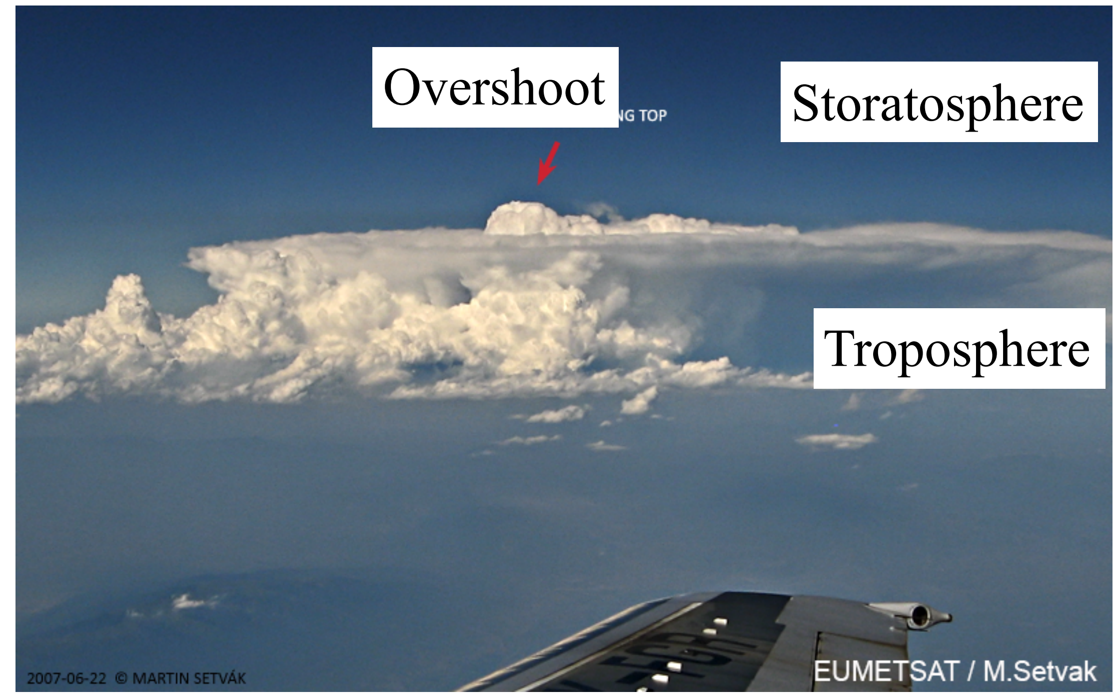




Two Pop. III models

Convective overshoot

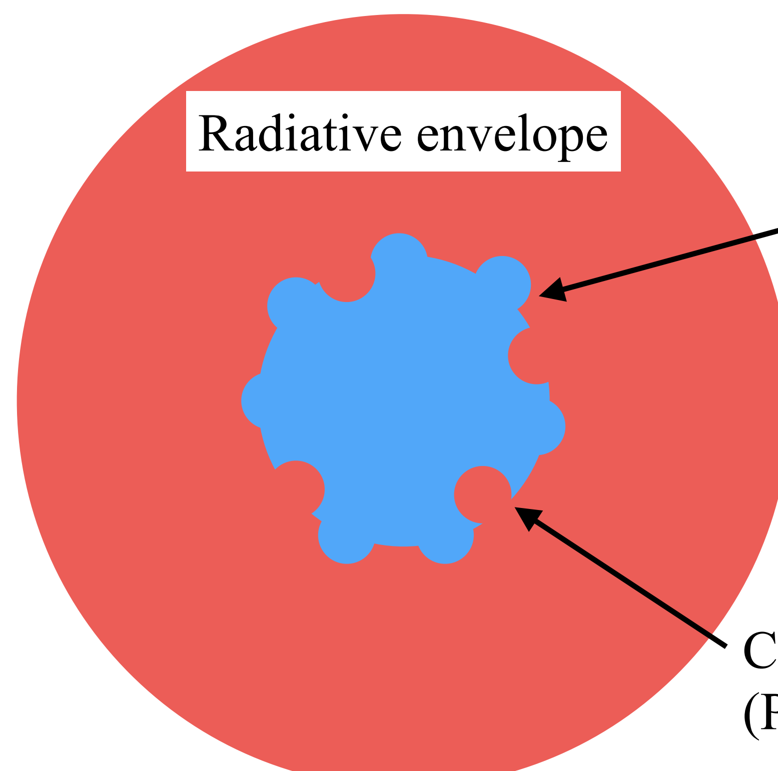
- More effective overshoot
  - Larger He core at the end of MS
  - Larger luminosity in post-MS
  - Larger radius in post-MS



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

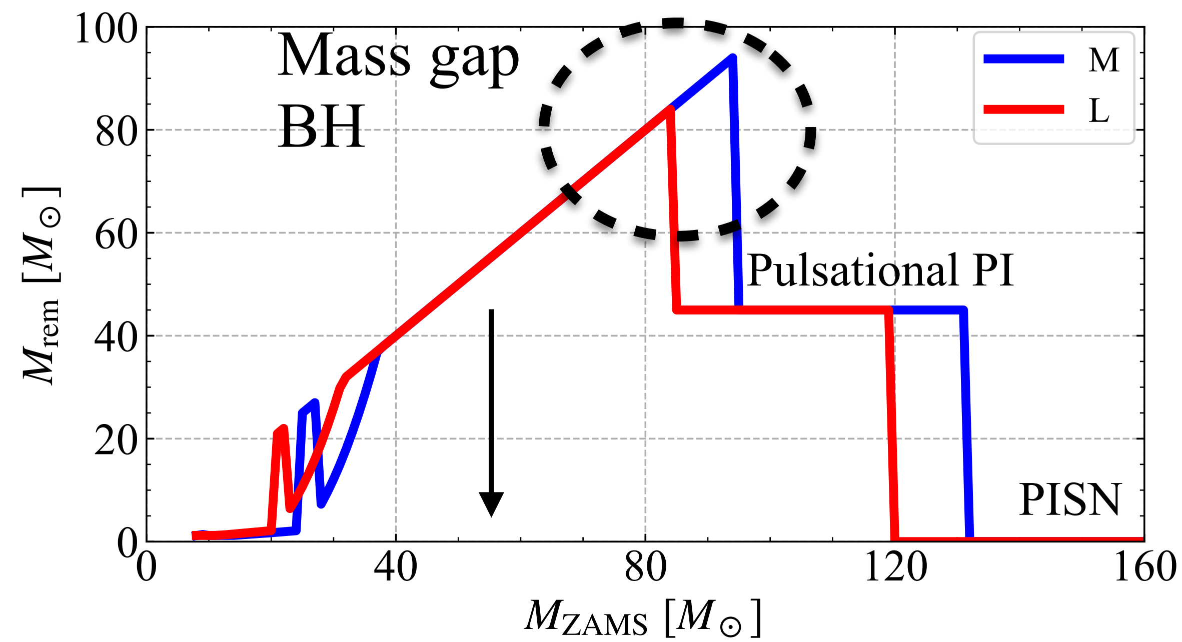
Both consistent with Pop I/II stars

Different radii for Pop III stars

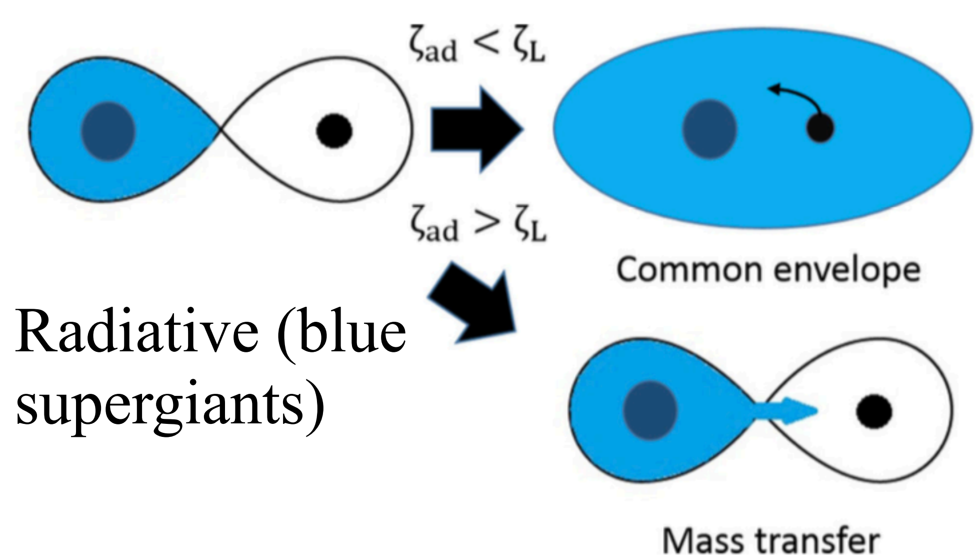


Numerical setup

- 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



Convective (red supergiants)

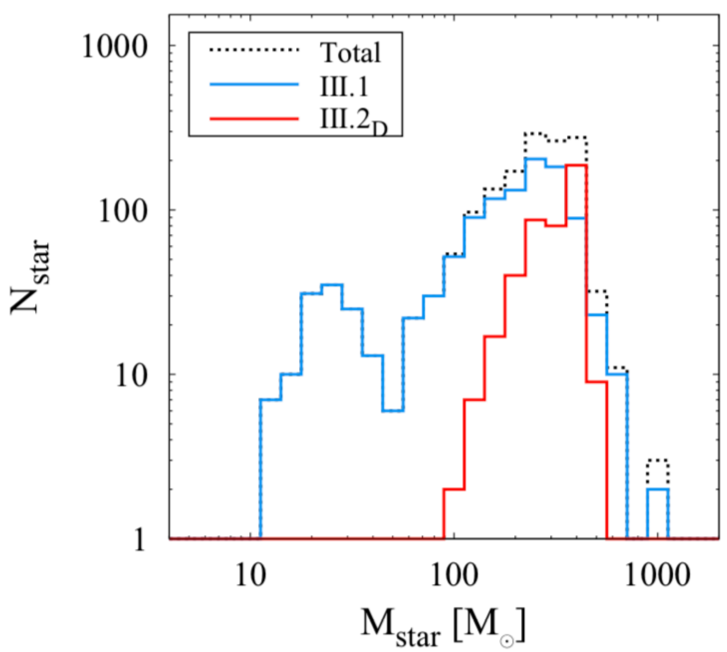


Radiative (blue supergiants)

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: $f(e) \propto e$

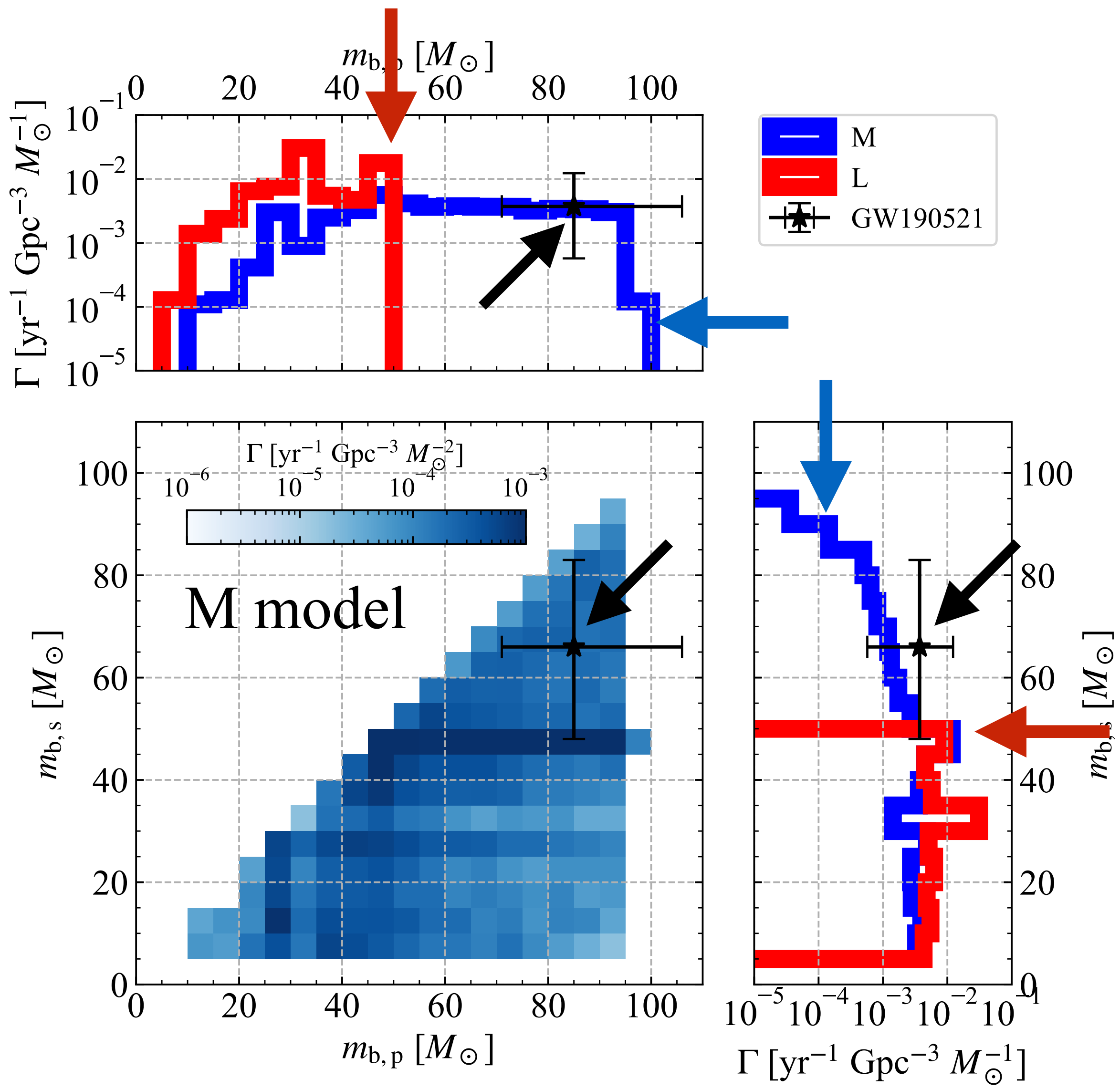
Pop III IMF



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.



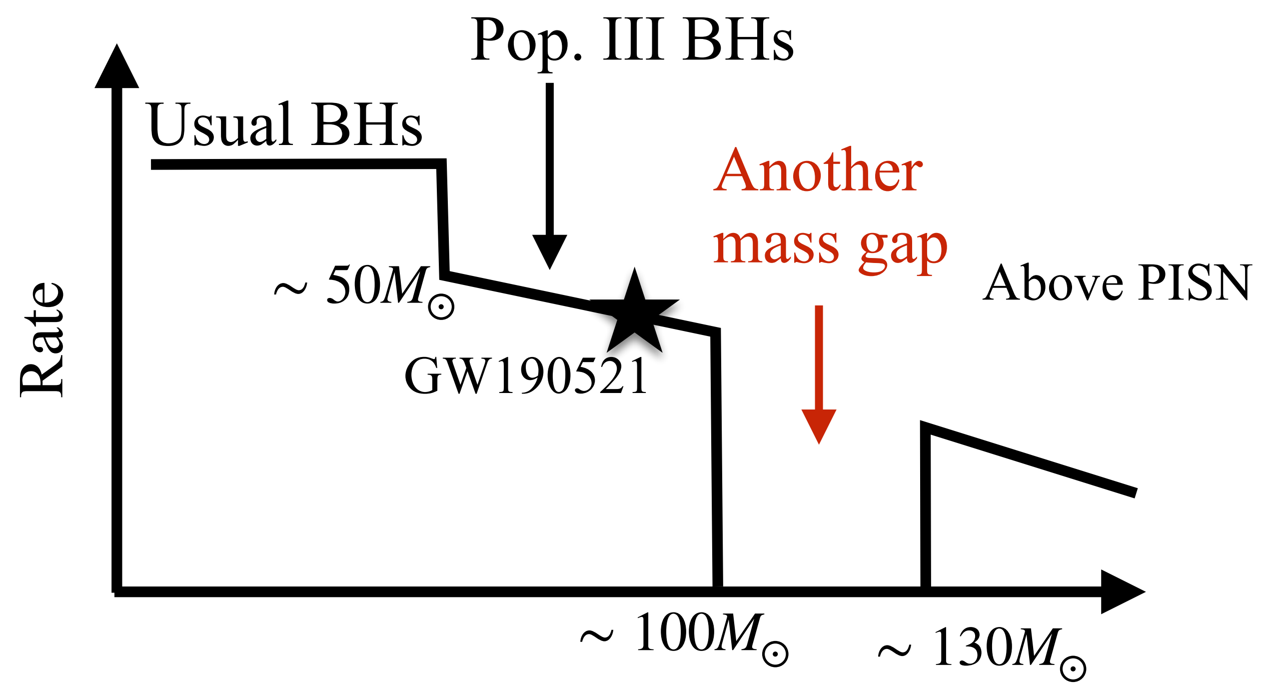
Pop III stars can form the PI mass-gap event if overshoot is ineffective.

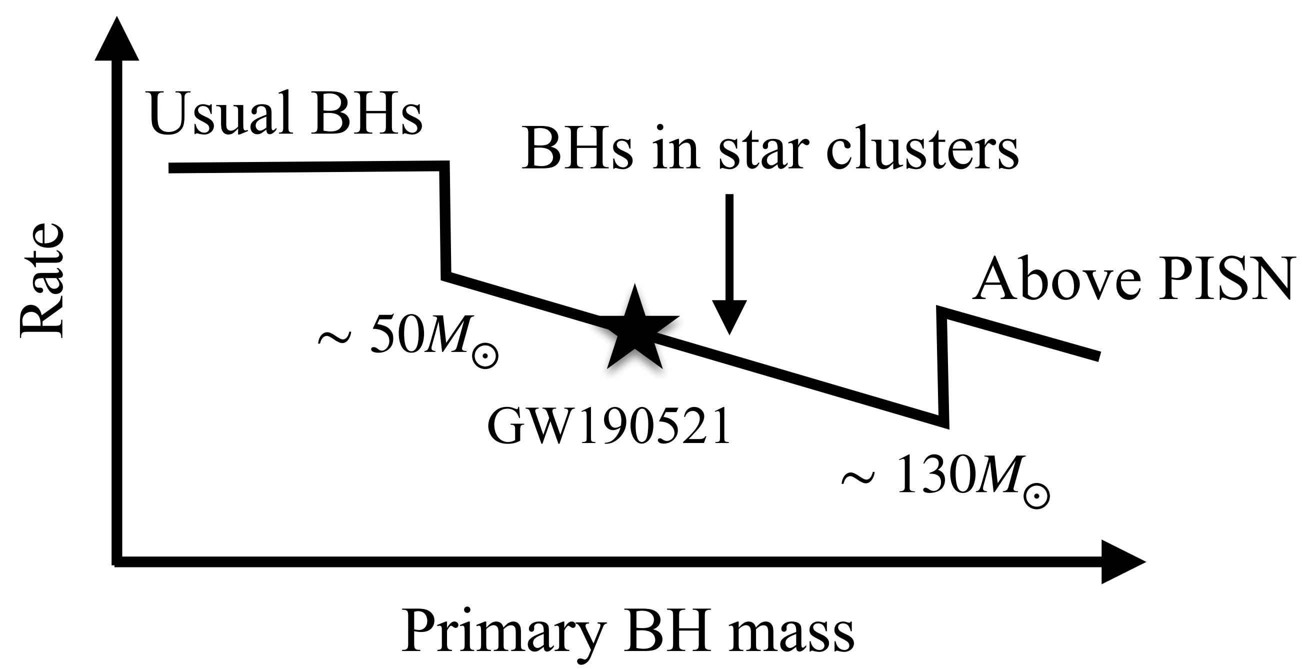
Tanikawa et al. (2021, MNRAS, 505, 2170)

Expectation for O4

Identification of BBH origins

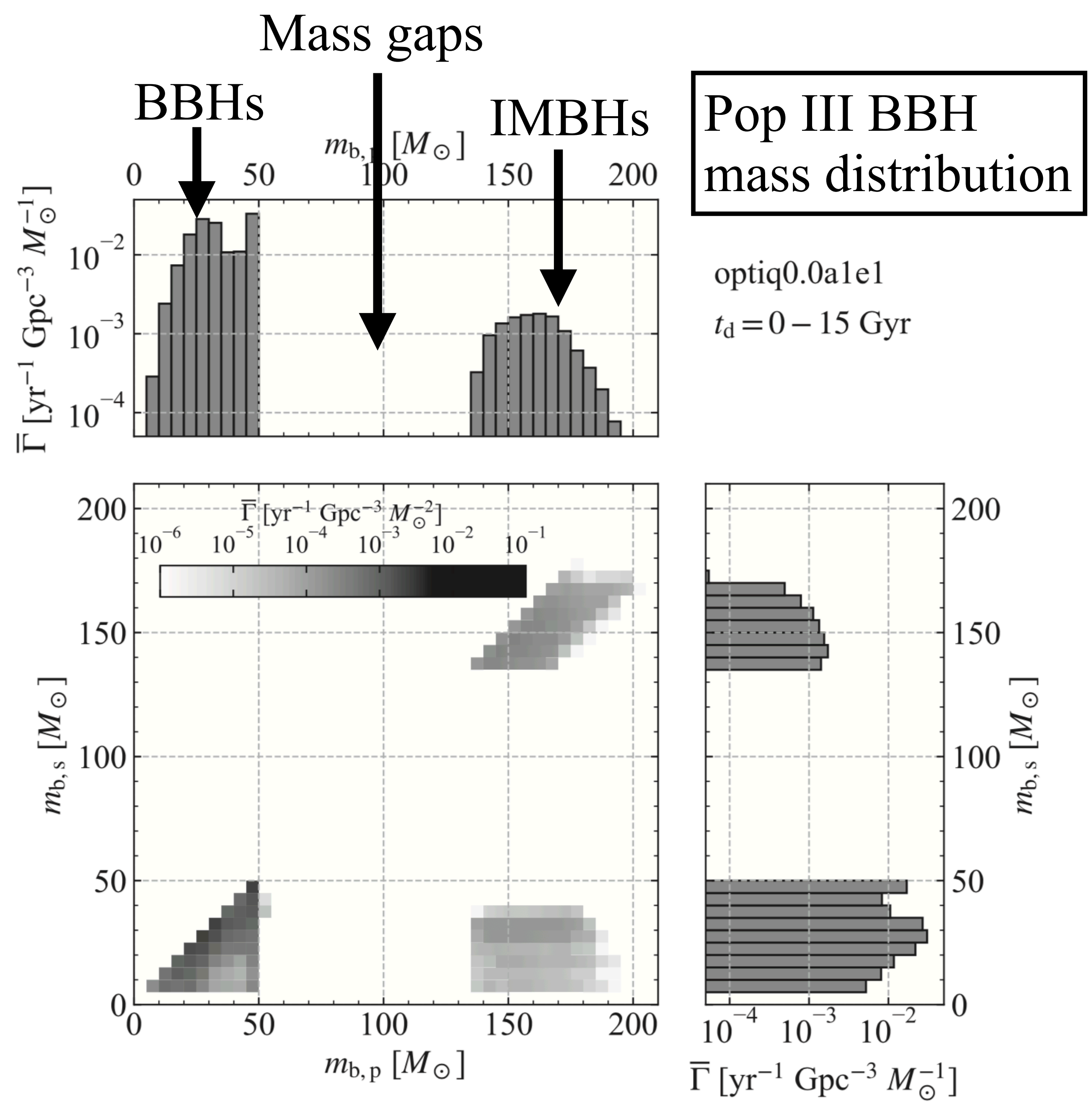
- Even if the M model is correct, no Pop. III binary can form BBHs with $100 - 130 M_{\odot}$.
- If GW190521 is Pop. III, the merger rate of BBHs with $100 - 130 M_{\odot}$ is much smaller than with $50 - 100 M_{\odot}$.





IMBH mergers

- Pop III stars can form many massive stars with $\gtrsim 100 M_\odot$.
- Such stars can overcome pair instability, and form IMBHs with $\gtrsim 100 M_\odot$.
- The IMBH merger rate is $\sim 0.01\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$ insensitive to Pop III initial conditions and stellar wind models.
- The current upper limit of IMBH mergers is $\sim 0.056\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$ (LVK, arXiv:2105.15120), slightly larger than the Pop III IMBH merger rate.
- ***IMBHs may be detected in O4.***

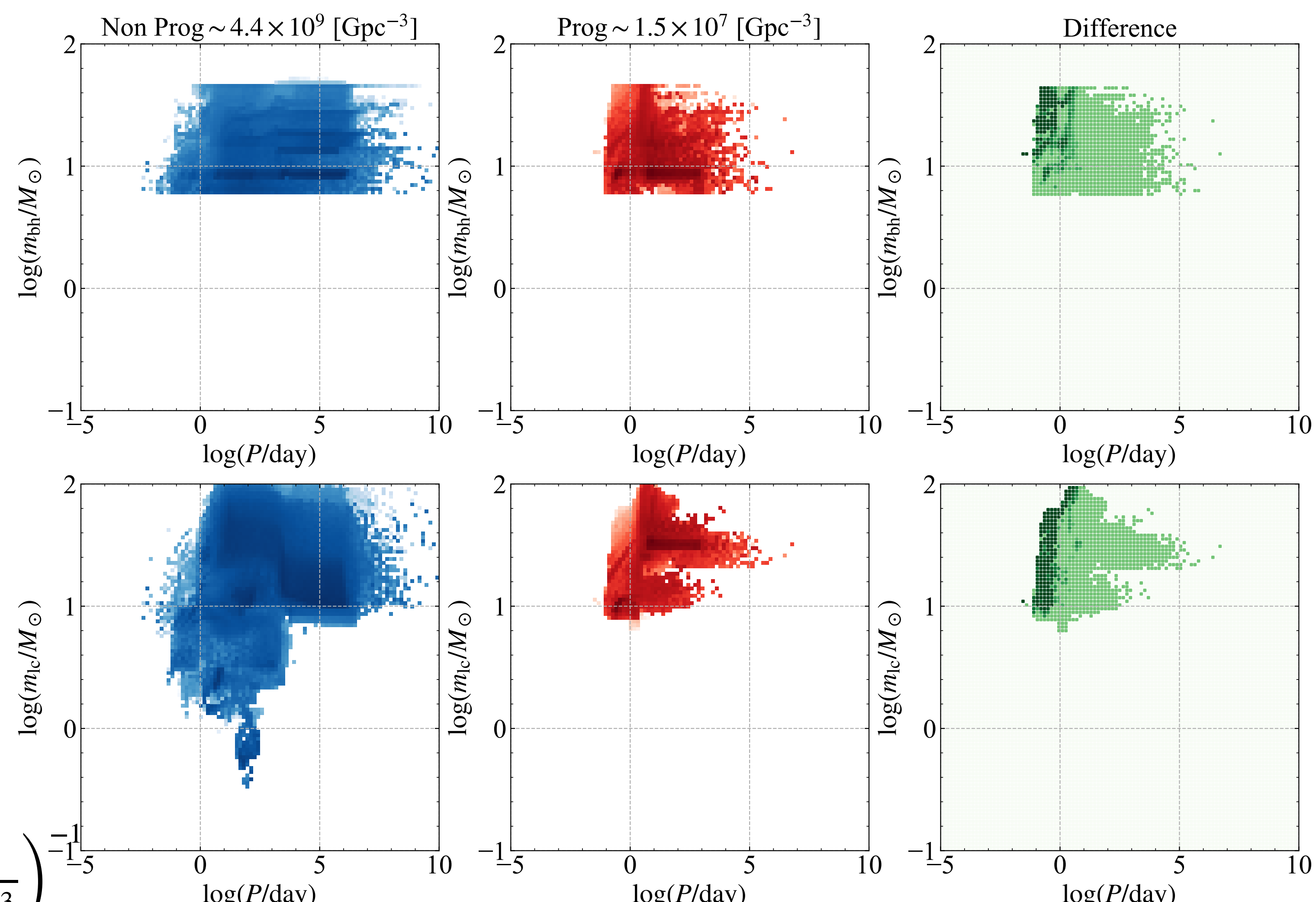


Tanikawa et al. (2021, ApJ, 910, 30)

EM counterparts

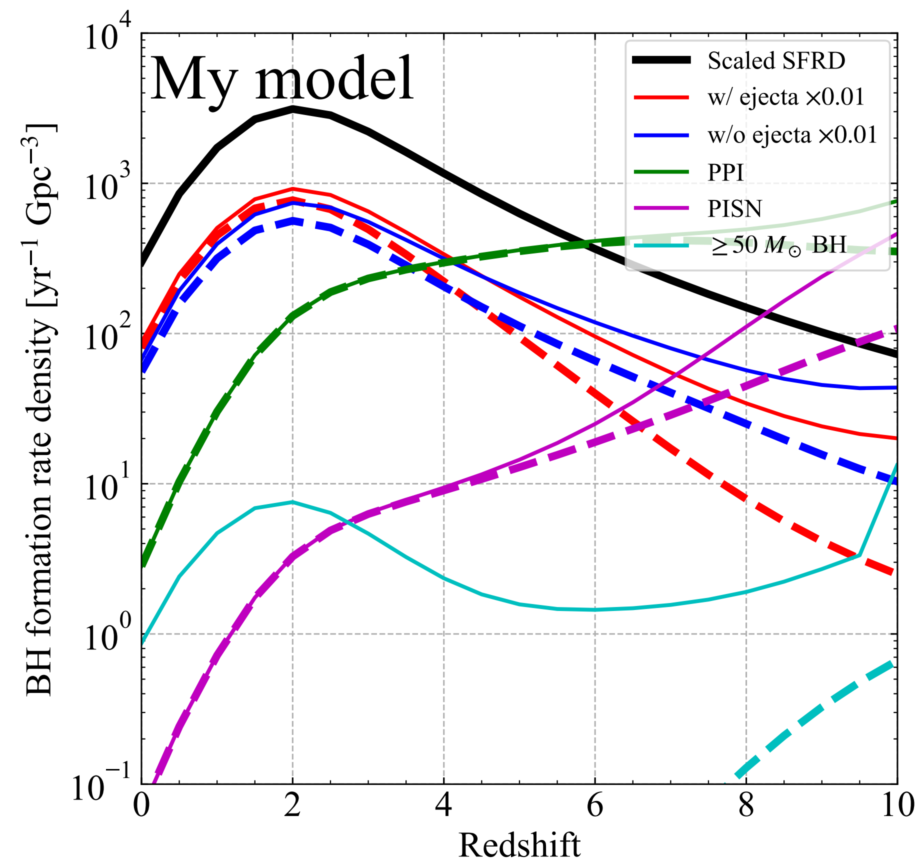
BH-LCs as BBH progenitors

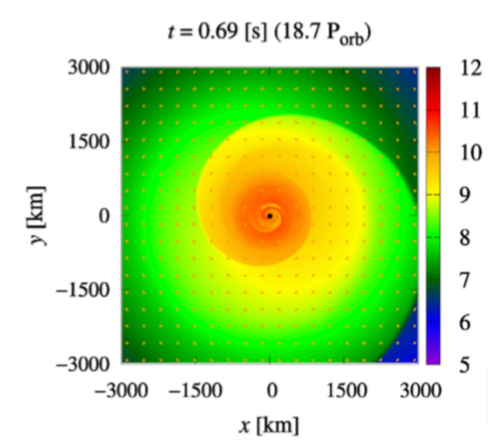
- Non BBH progenitors: $\sim 4.4 \times 10^9$ [Gpc^{-3}]
- BBH progenitors: $\sim 1.5 \times 10^7$ [Gpc^{-3}]
- The total Fraction: ~ 0.34 %
- High-mass X-ray binary
  - $P \lesssim 1$ day
  - $\sim 2.4 \times 10^6$ [Gpc^{-3}]
  - $\sim 0.54 \left(\frac{M_{\mathrm{local}}}{10^{12} M_\odot}\right)\left(\frac{\rho_{\mathrm{universe}}}{3 \cdot 10^{-31} \mathrm{gcm}^{-3}}\right)$

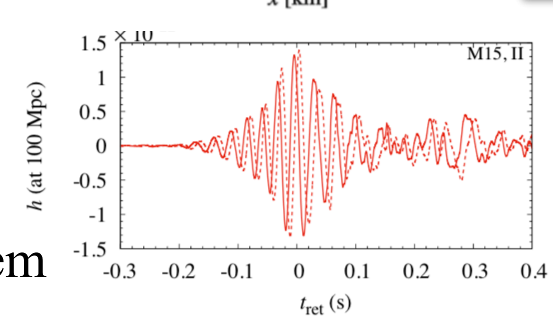


BH formation rate

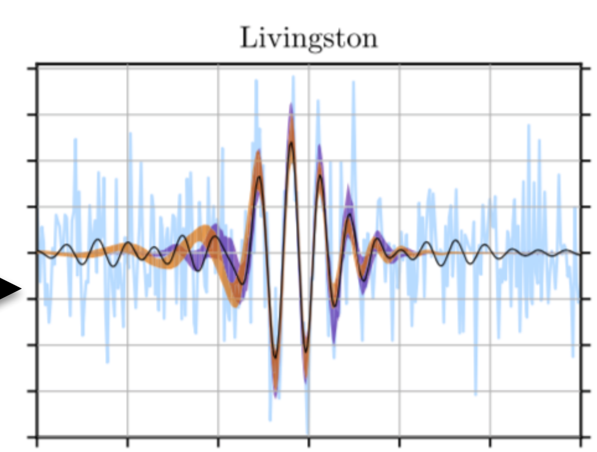
- BH formation rate: $\sim 10^4$ [yr^{-1} Gpc^{-3}]
  - Much larger than the BBH merger rate (~ 20 [yr^{-1} Gpc^{-3}])
  - Difficult to say that it is a progenitor of a BBH even if it is discovered.
- $\geq 50\ M_\odot$ BH formation rate: ~ 1 [yr^{-1} Gpc^{-3}]
  - GWs like GW190521? (Shibata, Kiuchi, Fujibayashi, Sekiguchi 2021)
  - Roughly consistent with the GW190521-like events?







BH+disk system



GW190521 (Abbott et al. 2020)

Summary

- ~ 50 BBH mergers have been discovered until O3a.
- The BH mass distribution becomes clear, but the BH spin distribution seems to contain large errors.
- The pair instability mass gap event GW190521 has great impacts on suggested formation scenarios.
- The M model with ineffective convective overshoot can reproduce the BH mass distribution including the mass gap.
- We expect another mass gap ($100 - 130 M_{\odot}$) and IMBH merger in O4.
- EM counterparts are difficult, but there are several possibilities.