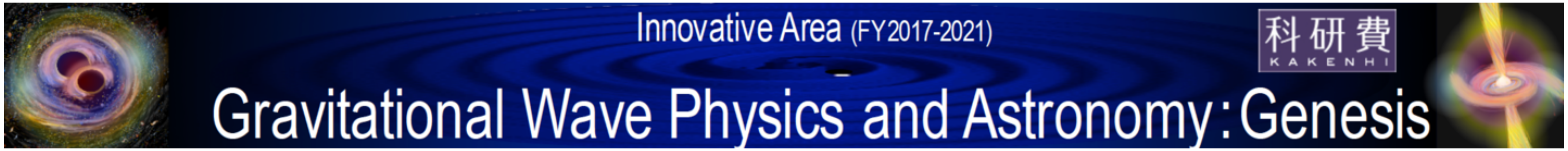
# 連星ブラックホール形成過程の理論研究

初代星・初代銀河研究会２０２２

２０２２年１１月徳島大学

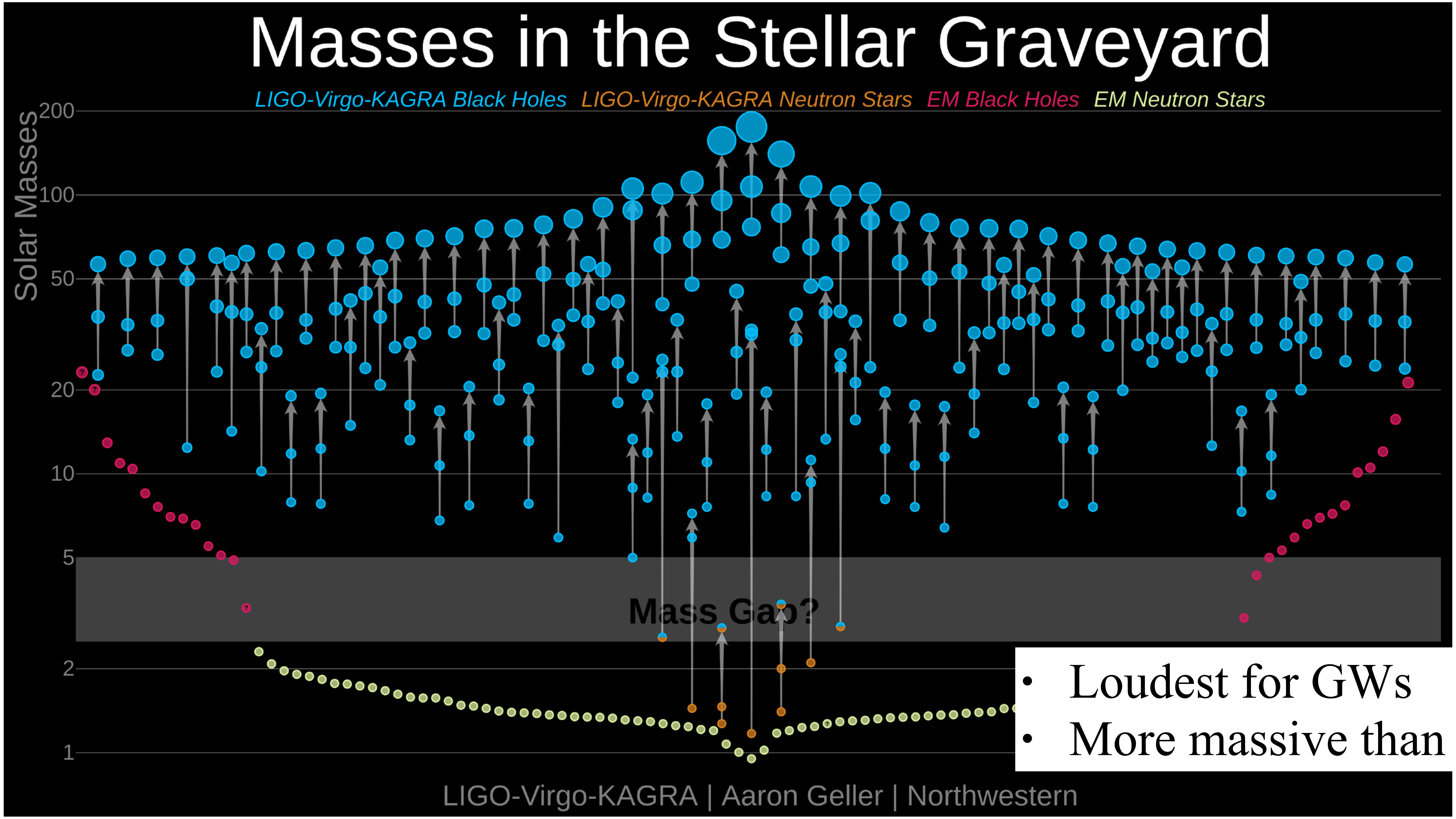
谷川衝（東大駒場）



# Contents

- Isolated binary scenario(s) for merging binary BH formation
- How to assess the isolated binary scenario(s)
- BH binary (not binary BH) exploration

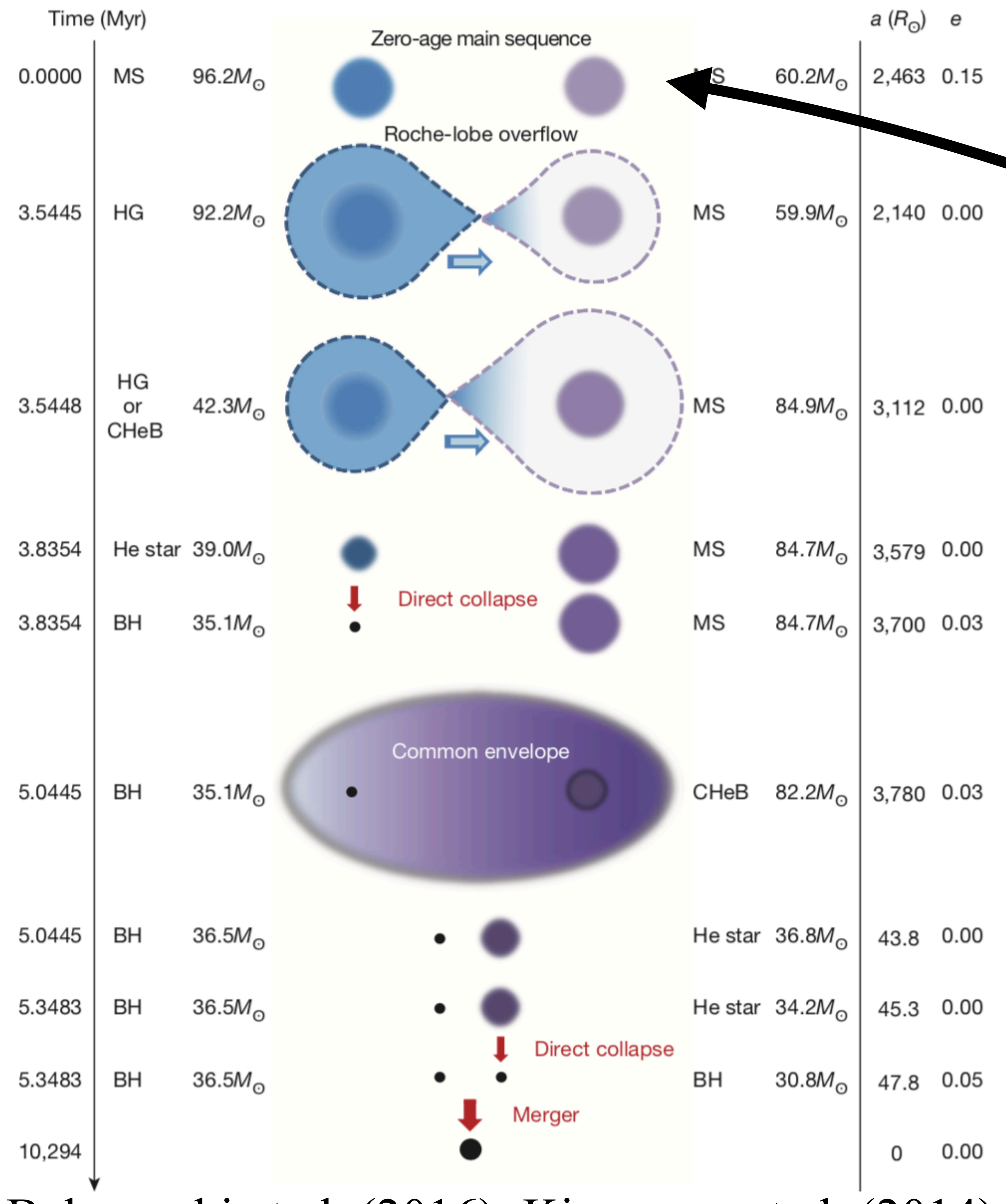
# Merging binary black holes (BHs)




- Loudest for GWs
- More massive than EM BHs

# The origin of merging binary BHs

## Isolated binary

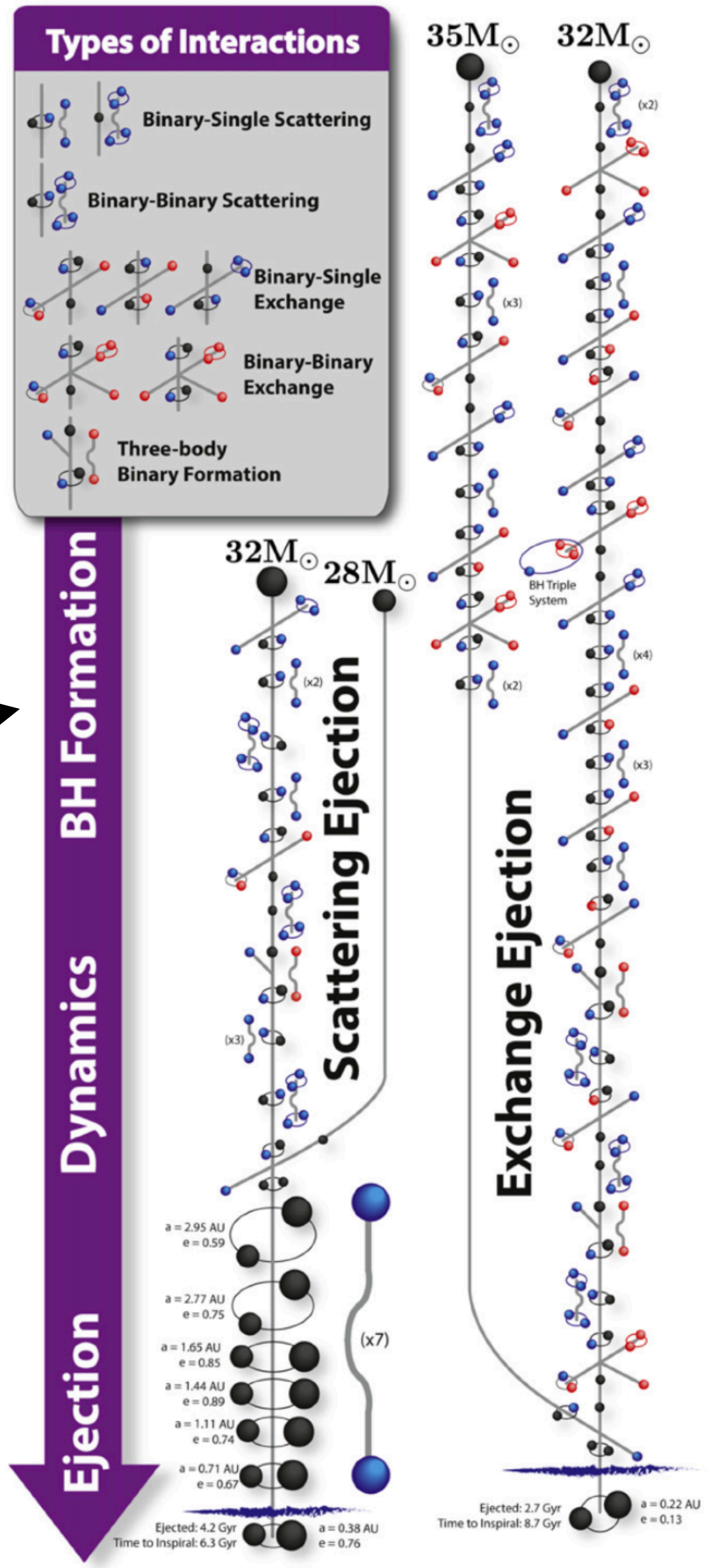



Belczynski et al. (2016); Kinugawa et al. (2014)
Tanikawa et al. (2022)

## Dense star cluster

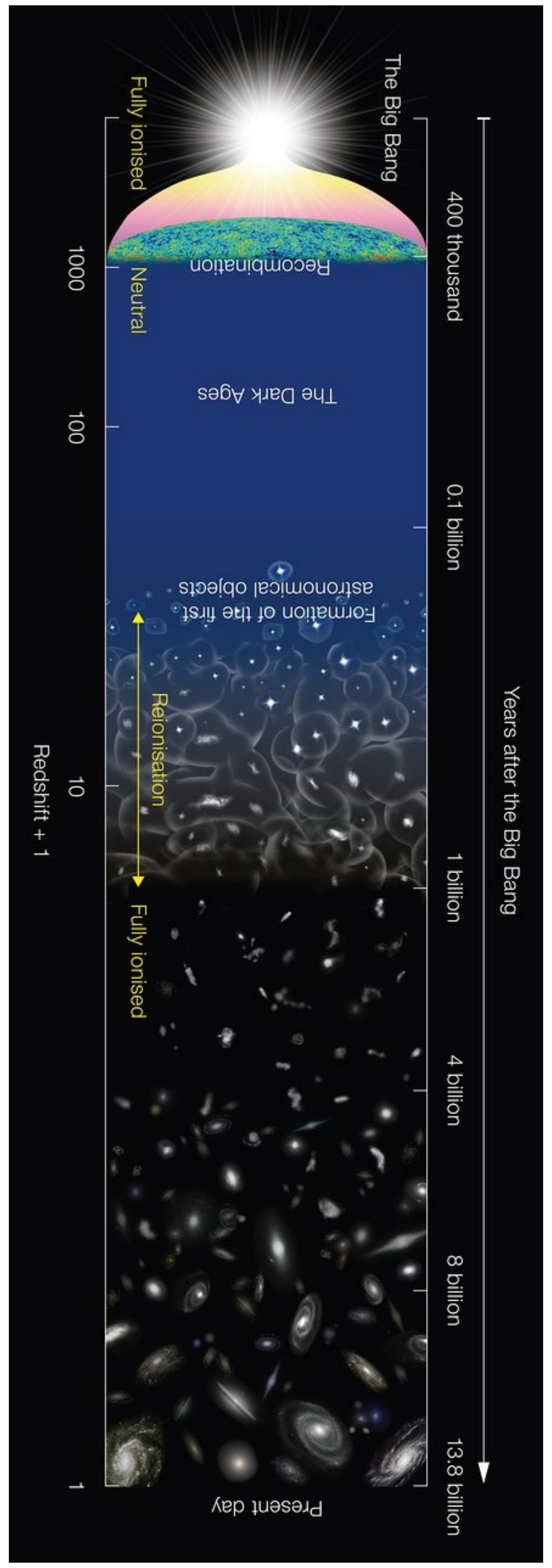

Eta Carinae © ESA/HUBBLE/NASA

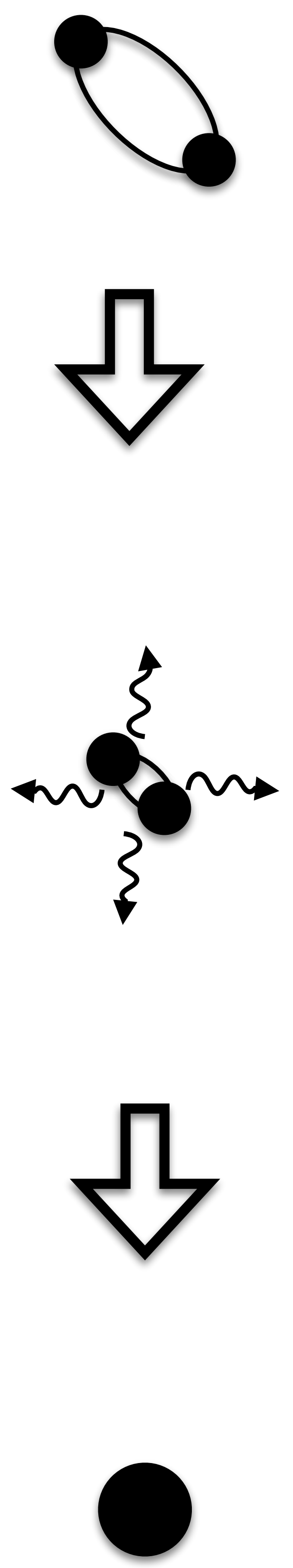

M15 © NASA




Rodriguez et al. (2016); Tanikawa (2013);
Kumamoto et al. (2019); Tagawa et al. (2020)

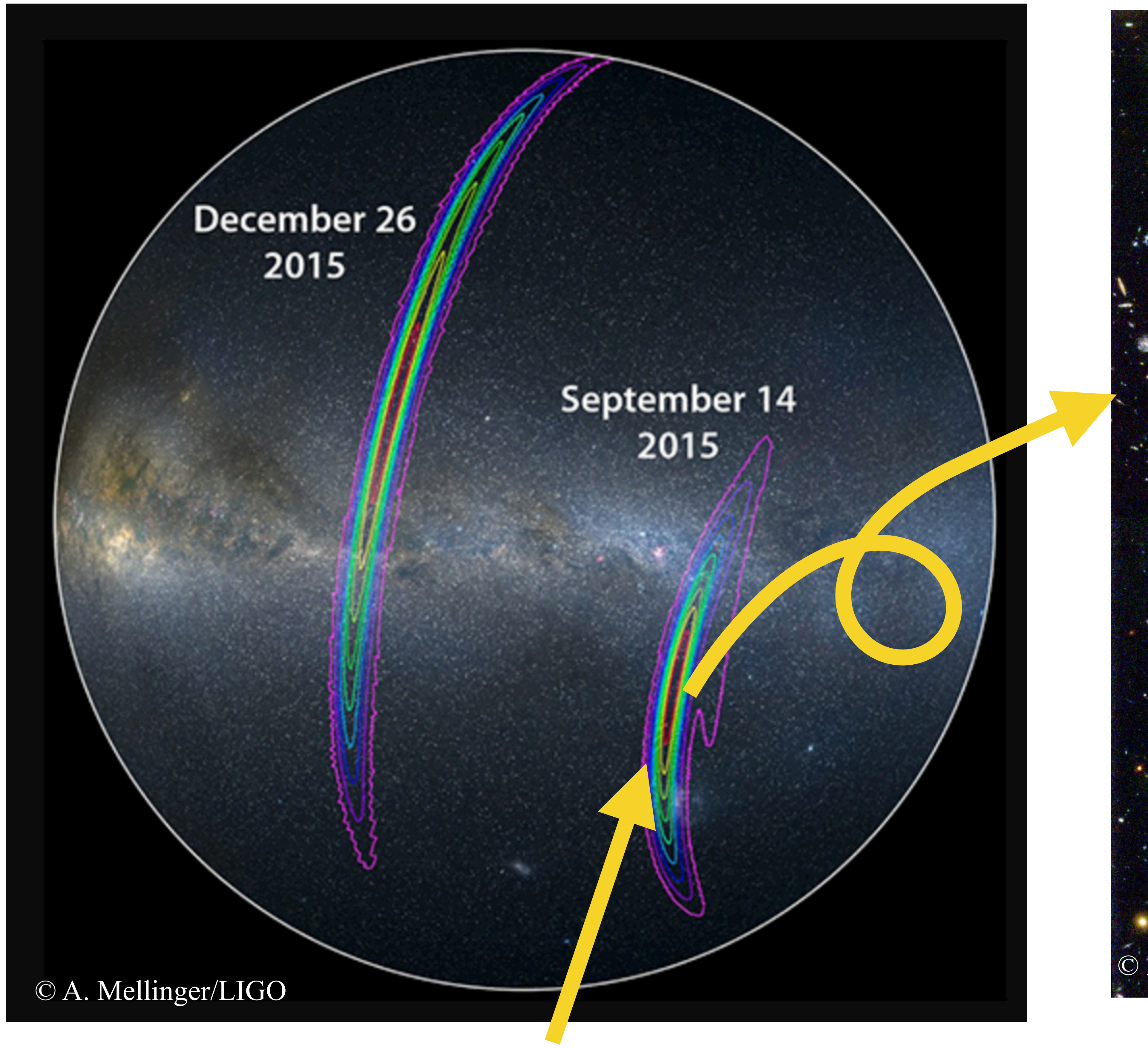
## Primordial BH



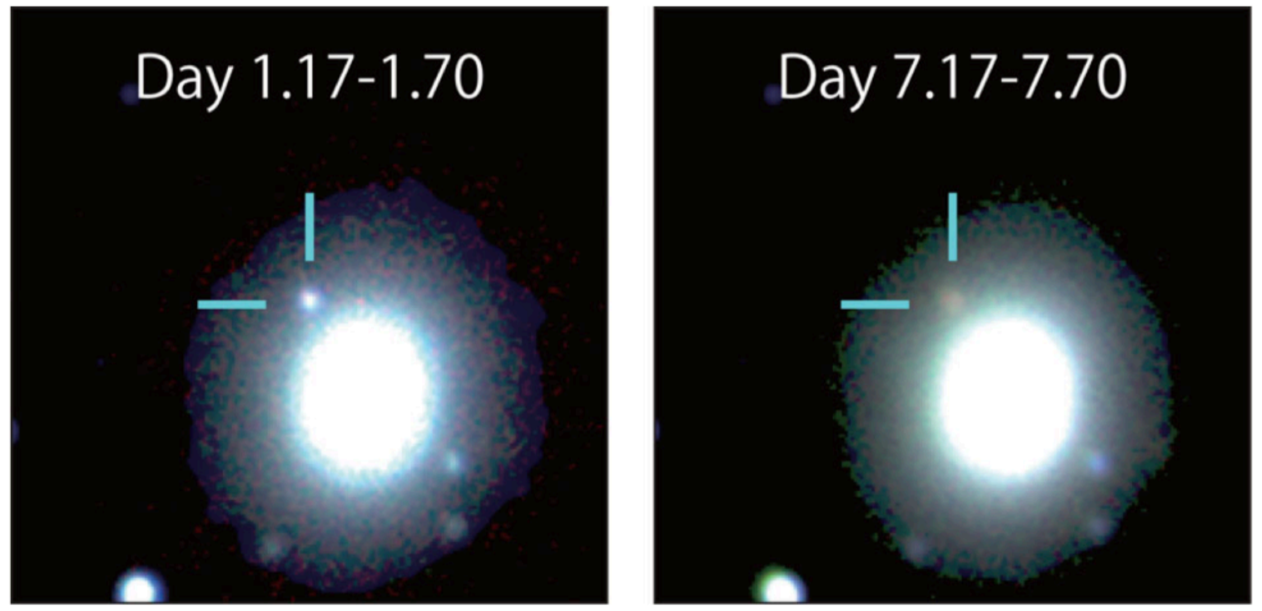
Ioka et al. (1998); Sasaki et al. (2016)

# Low spatial resolution



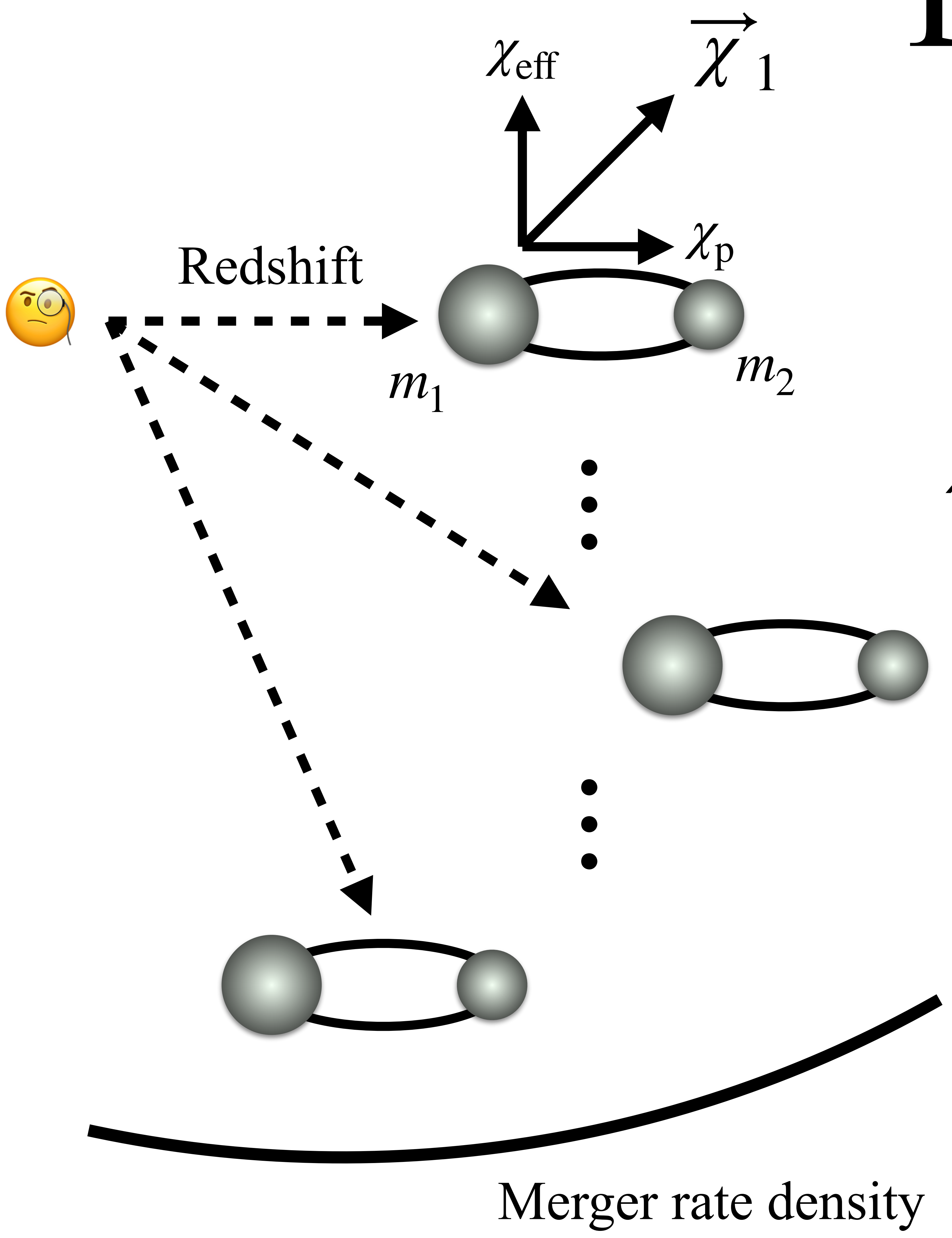

Possible region of a binary black hole merger


Binary neutron star


Utsumi et al. (2017)

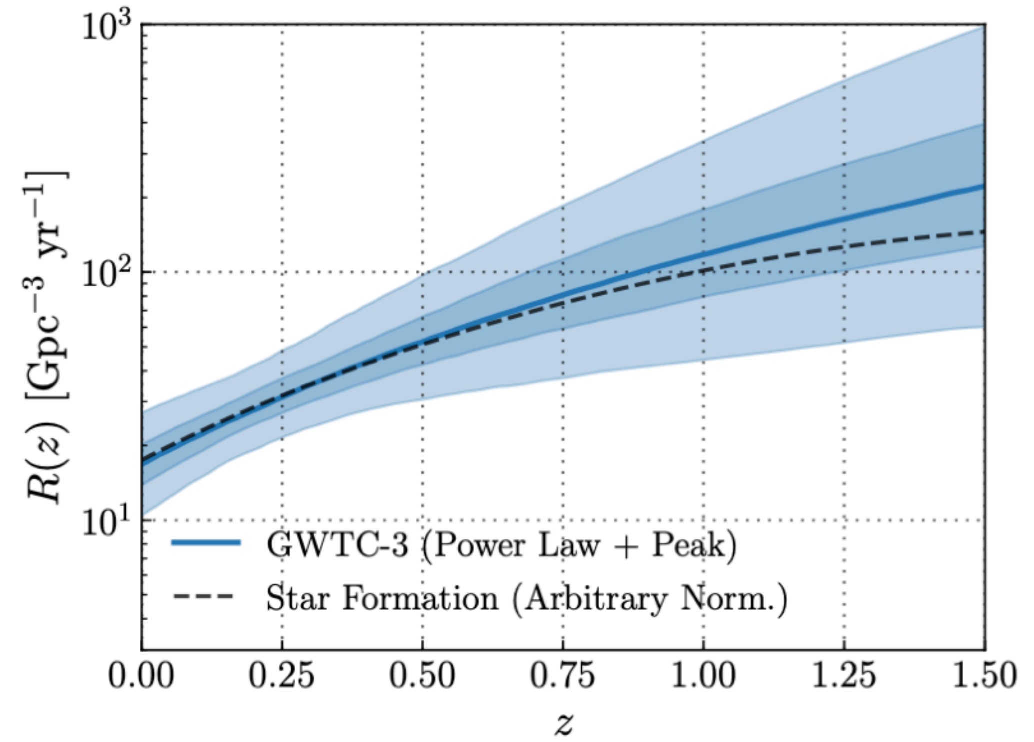
# BH properties

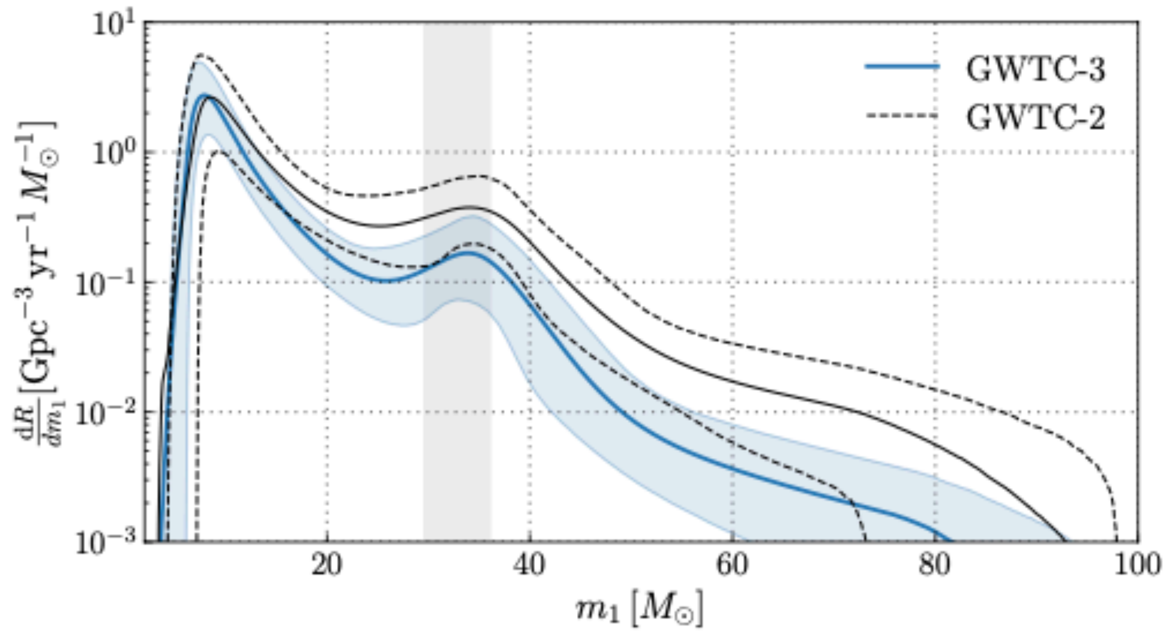


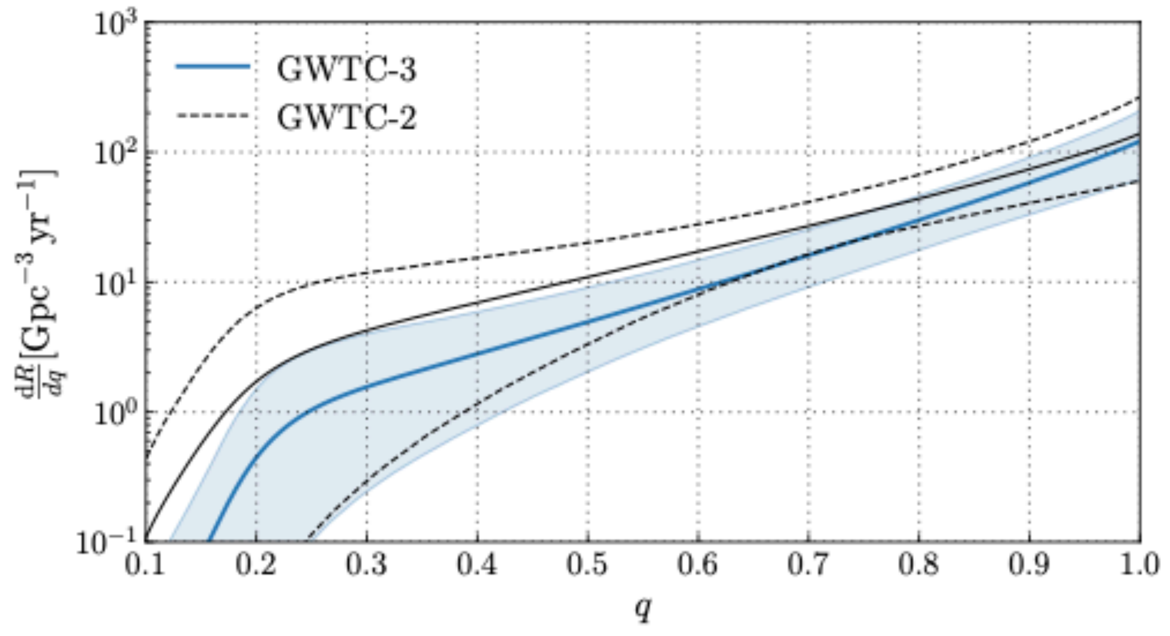

$$q = m_2/m_1$$

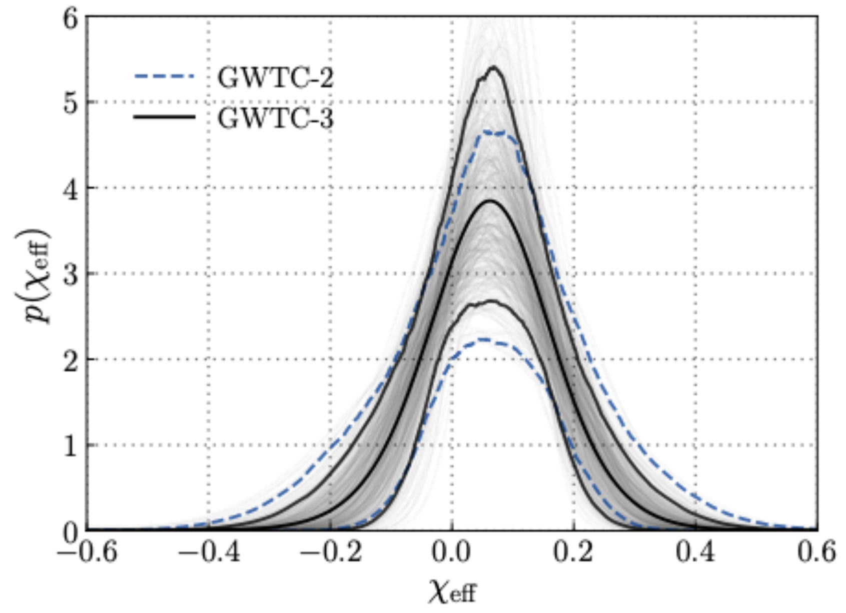
$$\chi_{\rm eff} = \frac{1}{M}\left(\frac{\chi_{1,\parallel}}{m_1} + \frac{\chi_{2,\parallel}}{m_2}\right)$$

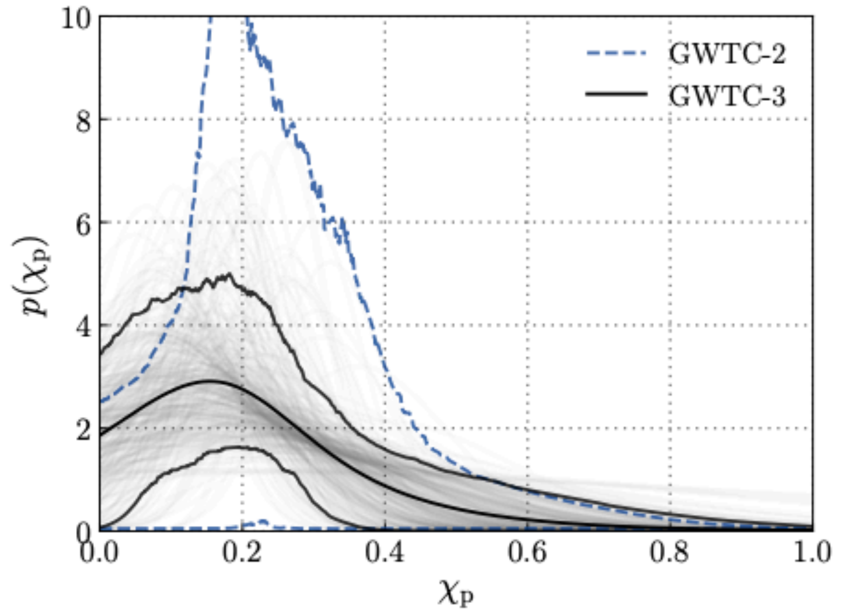
$$\chi_{\rm p} = \max\left(\frac{\chi_{1,\perp}}{m_1}, \kappa(q)\frac{\chi_{2,\perp}}{m_2}\right)$$




The origin of merging binary BHs?

GWTC-3 (Abbott et al. 2021)

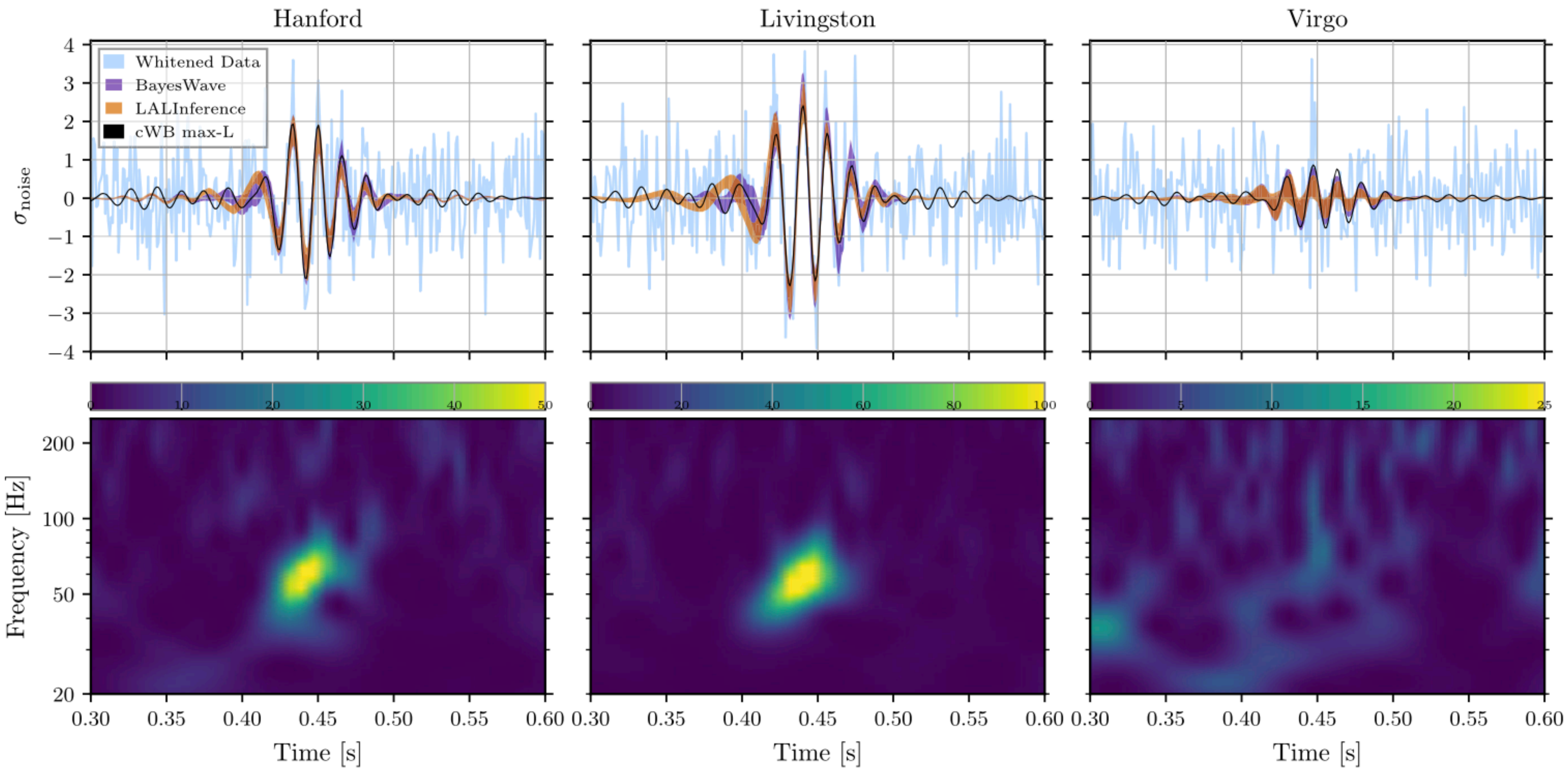
# Attack on the isolated binary scenario

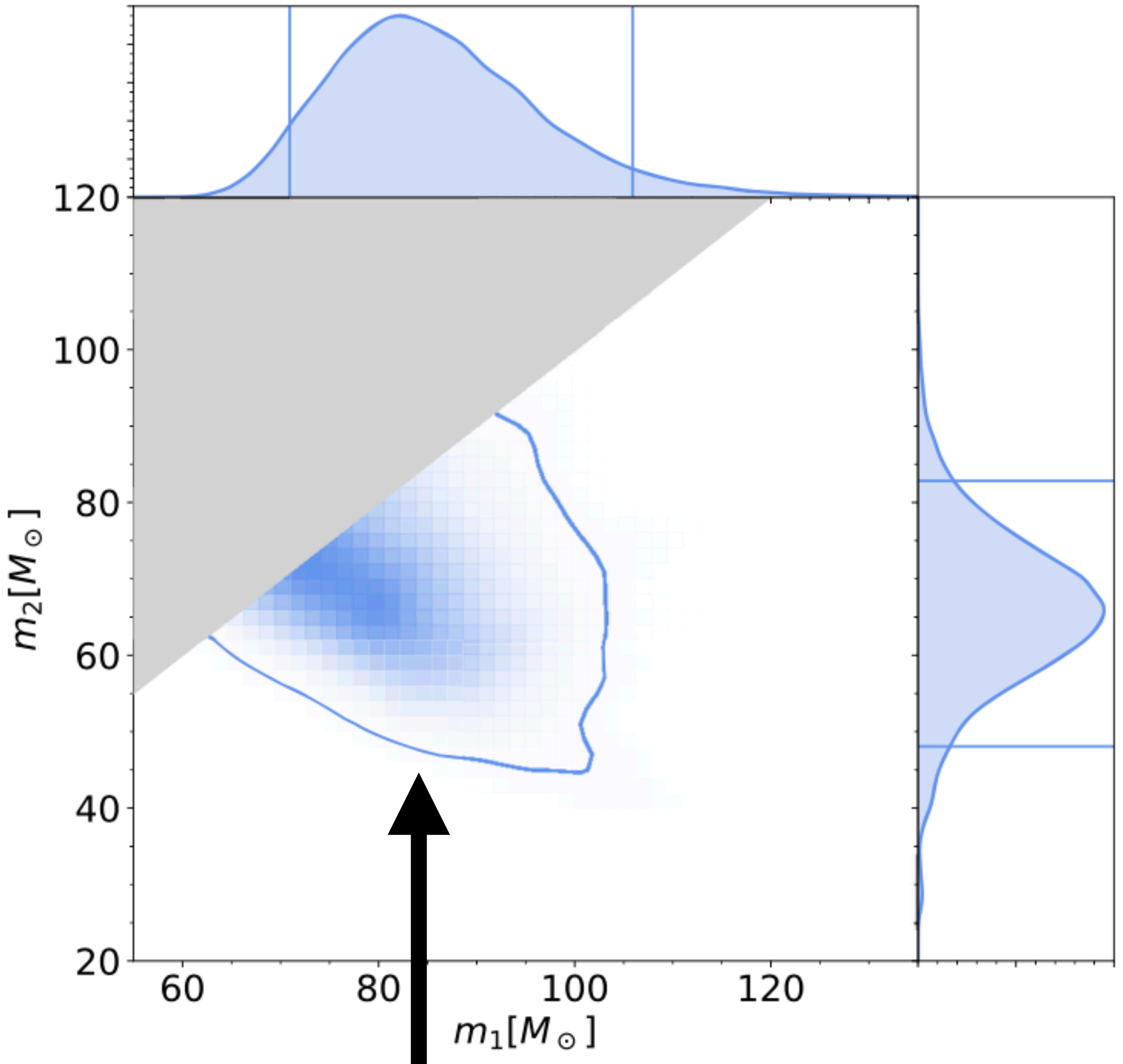
- The isolated binary scenario
  - A sufficiently large number of BHs ✓
  - Mass and spin parameter space limited ✖ ← Possibly rejected by only one event
- The dense star cluster scenario
  - A small number of BHs ✖
  - Wide parameter space of mass and spin ✓

Possibly rejected by only one event

- GW190521: the pair instability mass gap merger
- GW190412: the asymmetric merger
- (GW190814: the lower mass gap merger)

# GW190521: the pair instability mass gap event

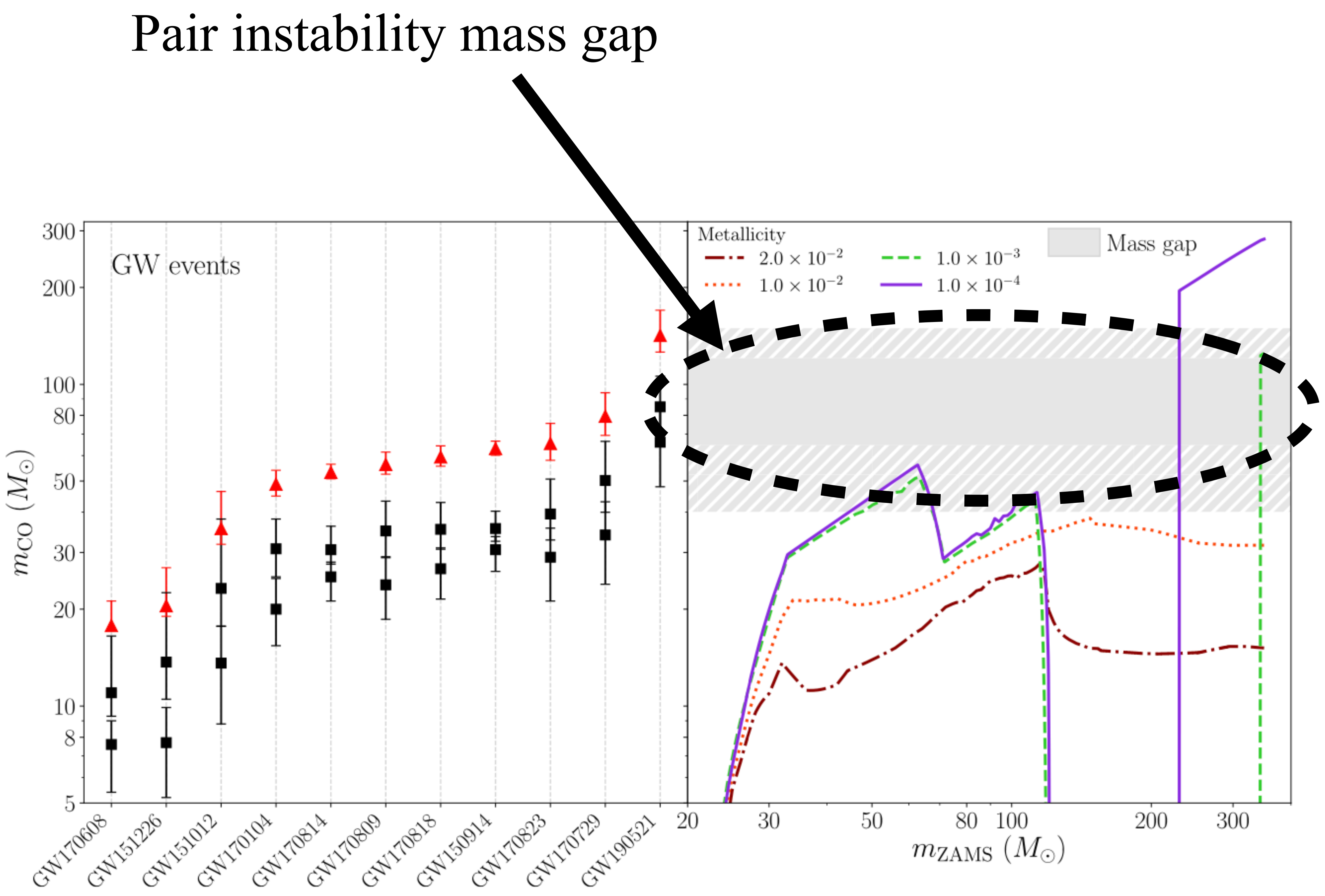


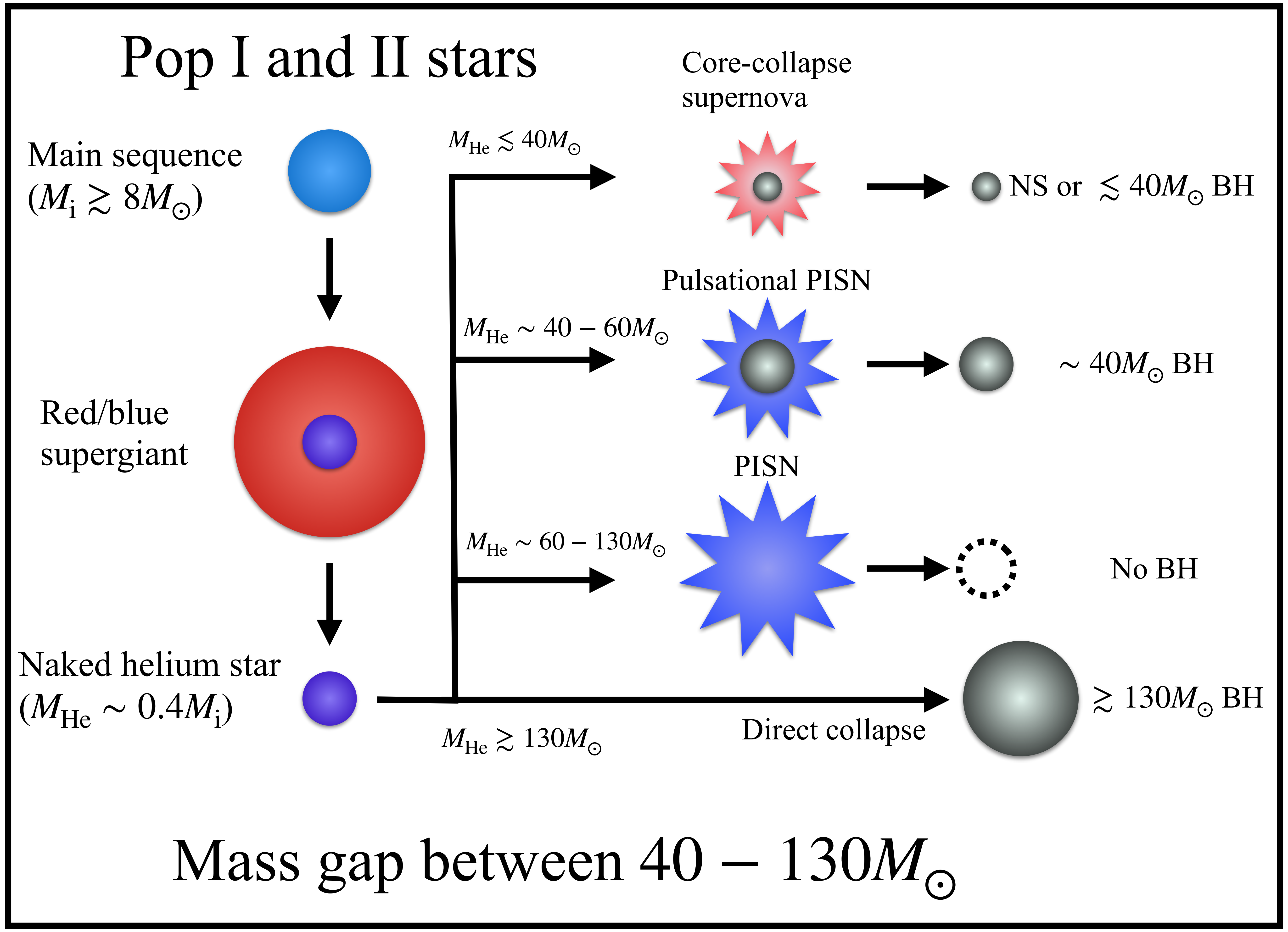

Abbott et al. (2020, PRL, 125, 101102)

$m_1 = 85^{+21}_{-14} M_\odot$, $m_2 = 66^{+17}_{-18} M_\odot$

# Pair instability mass gap



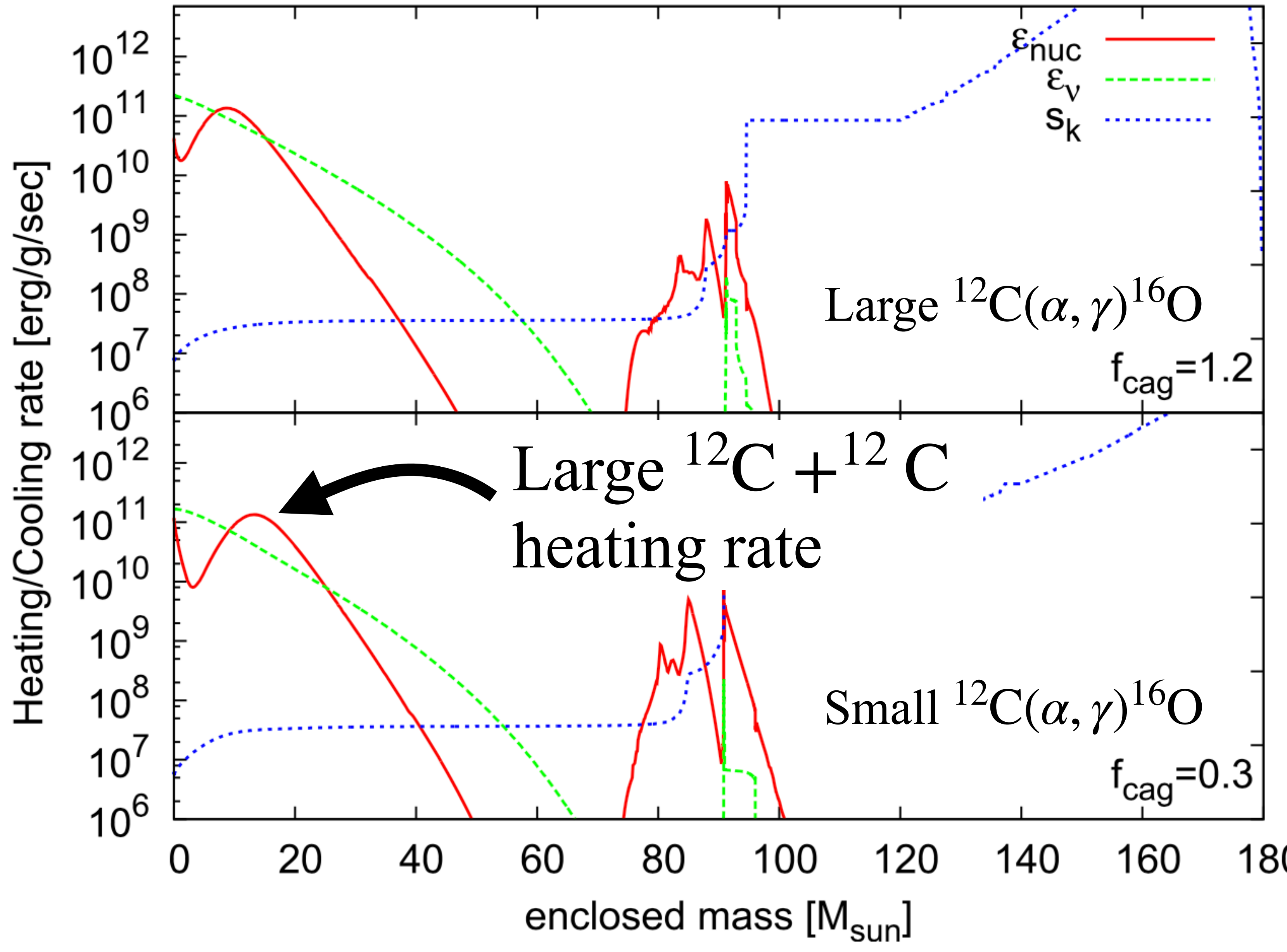

Abbott et al. (2020, ApJL, 900, 13)

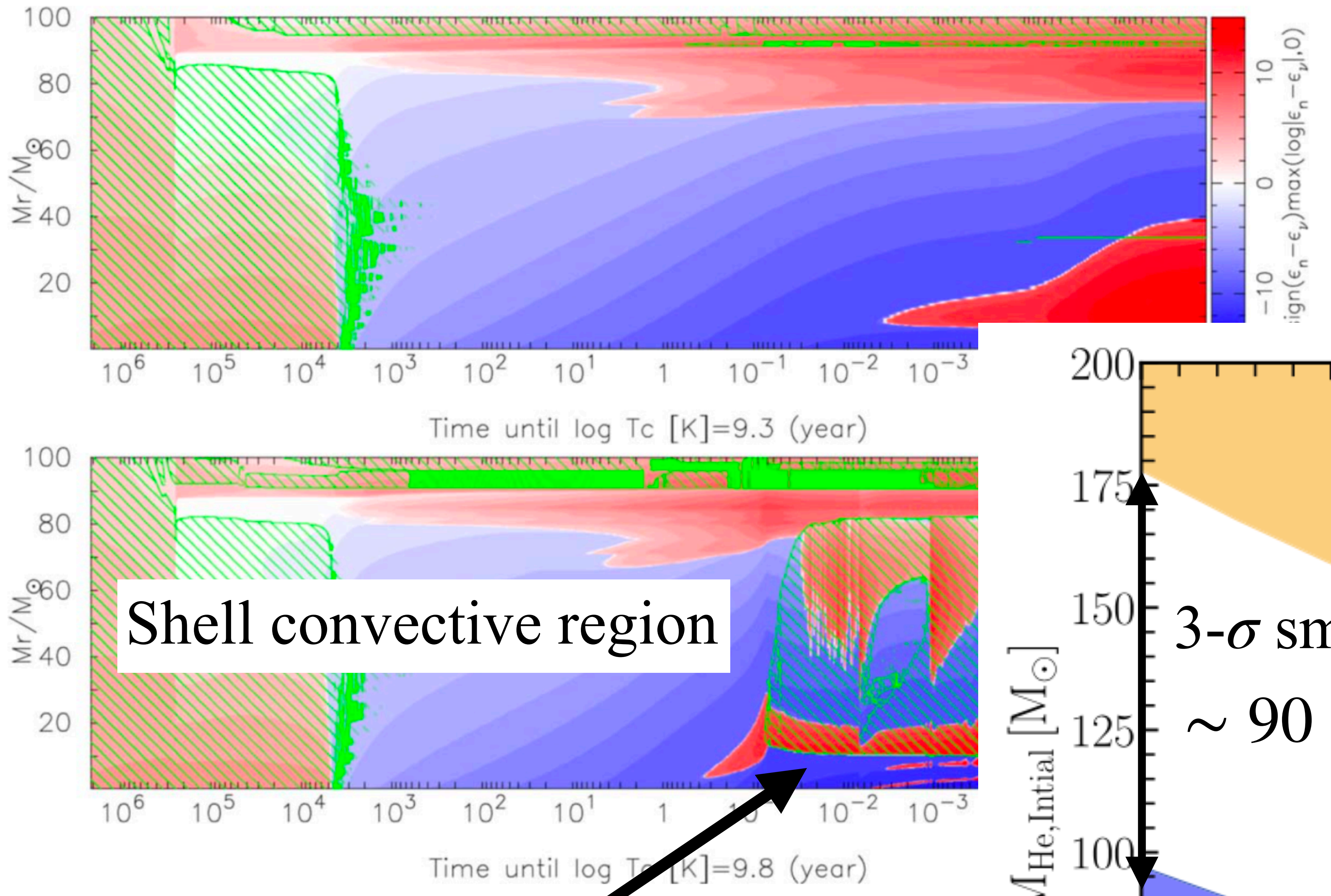


# Main stream: mass gap shifted upward

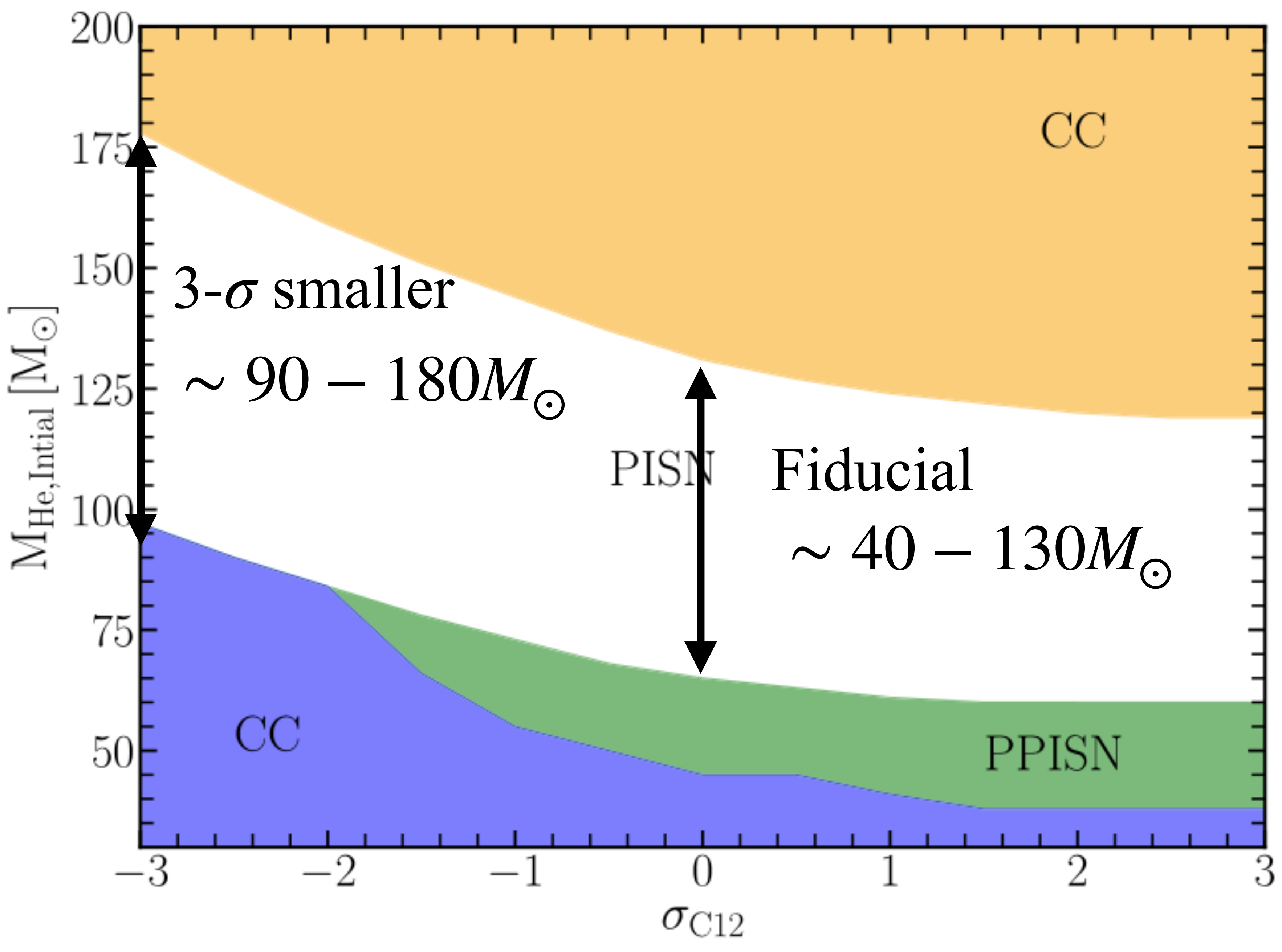
Koh Takahashi (2018, ApJ, 863, 153)

川下さんのトーク
（２日目）



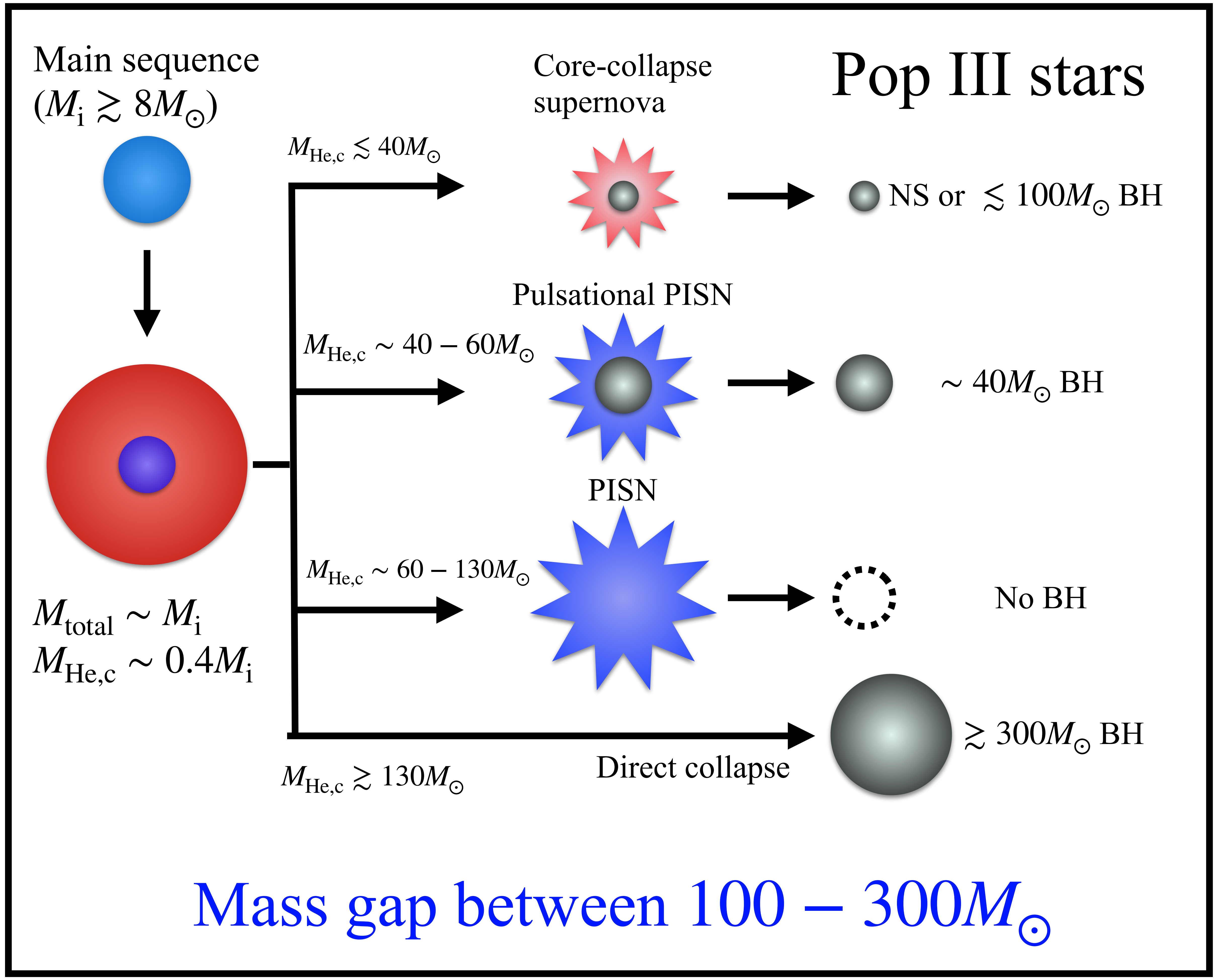




Farmer et al. (2020)

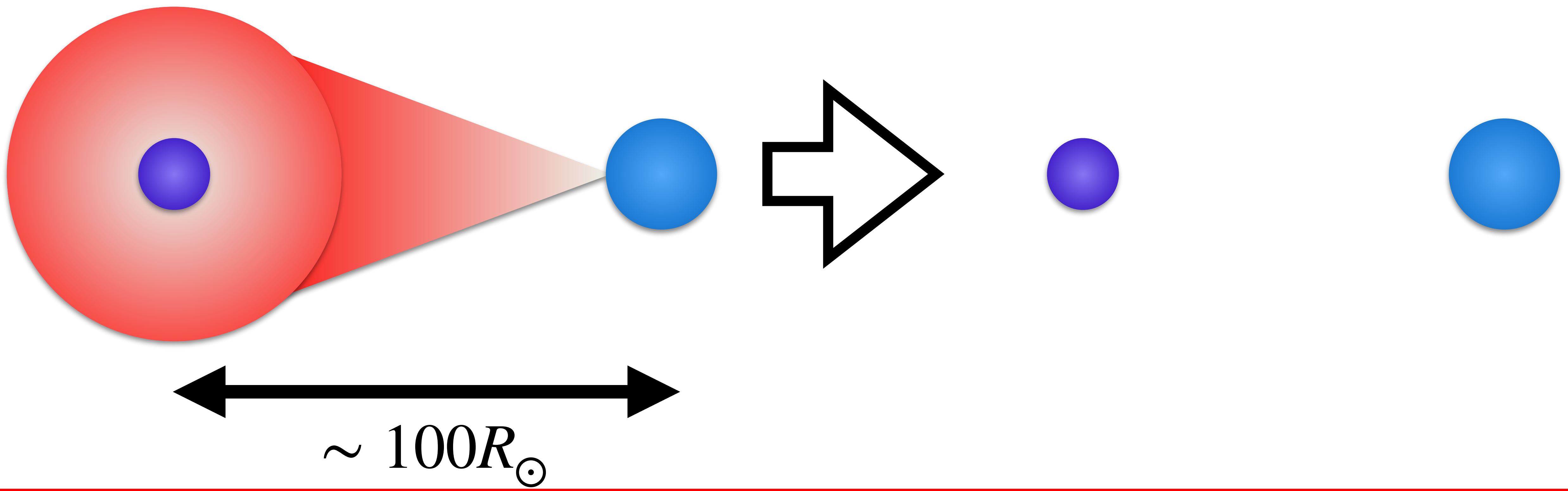



Effectively less-massive core
→ Pair creation inactive

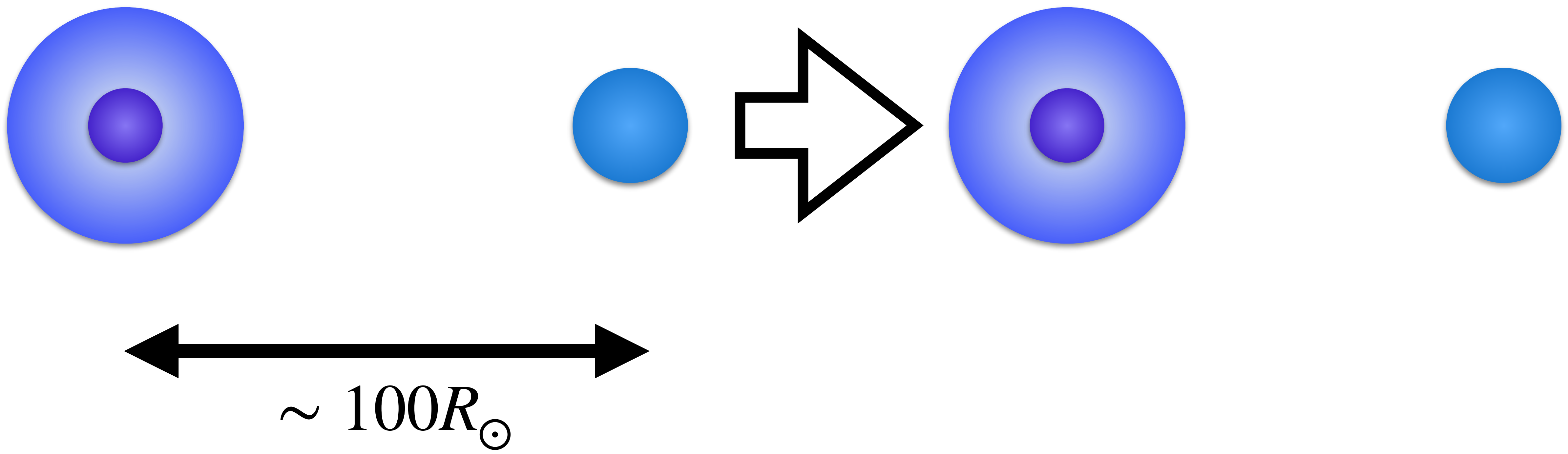
# Tanikawa's model: Pop III stars




Large overshoot → Large He core → Large radius




Small overshoot → Small He core → Small radius

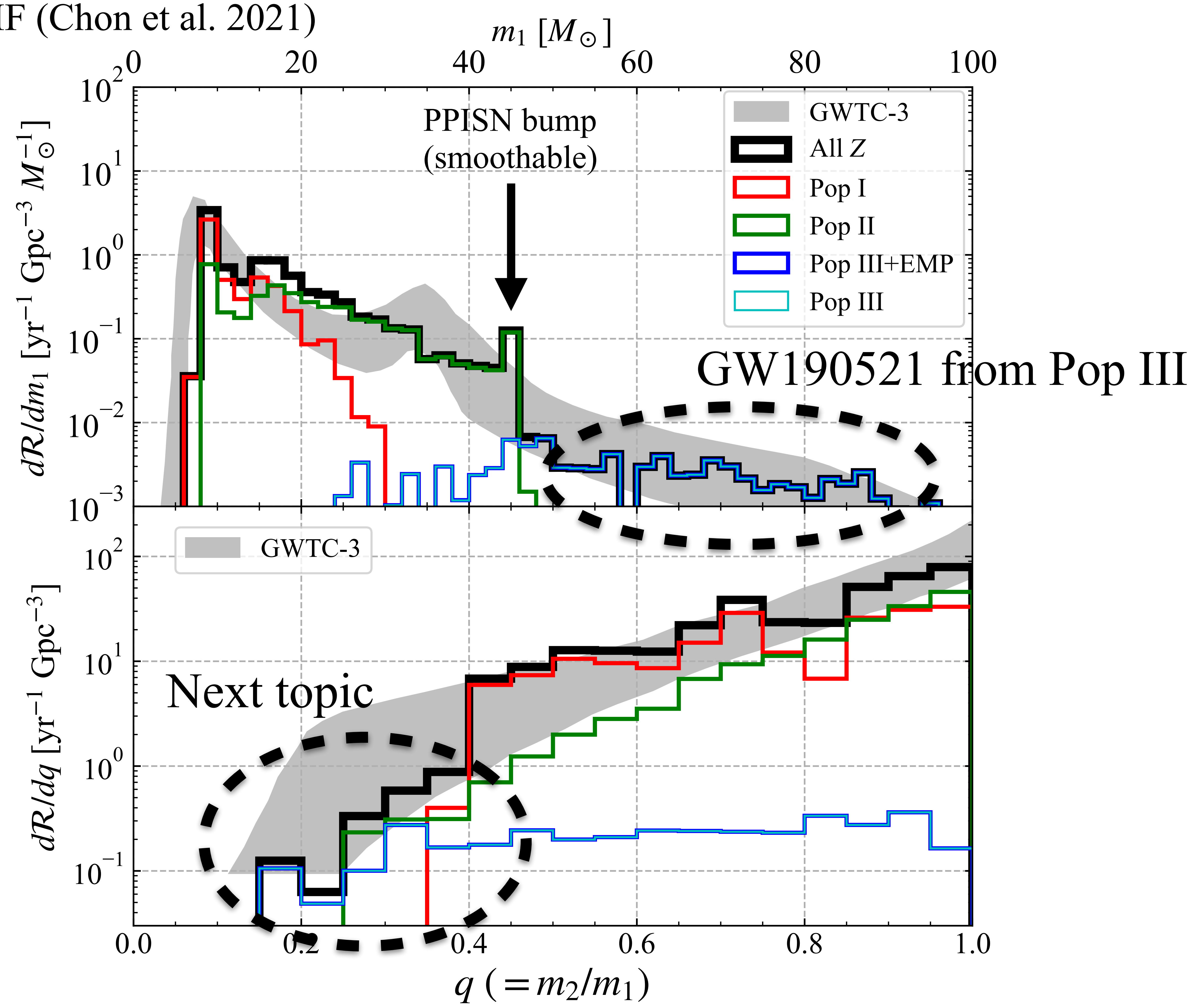


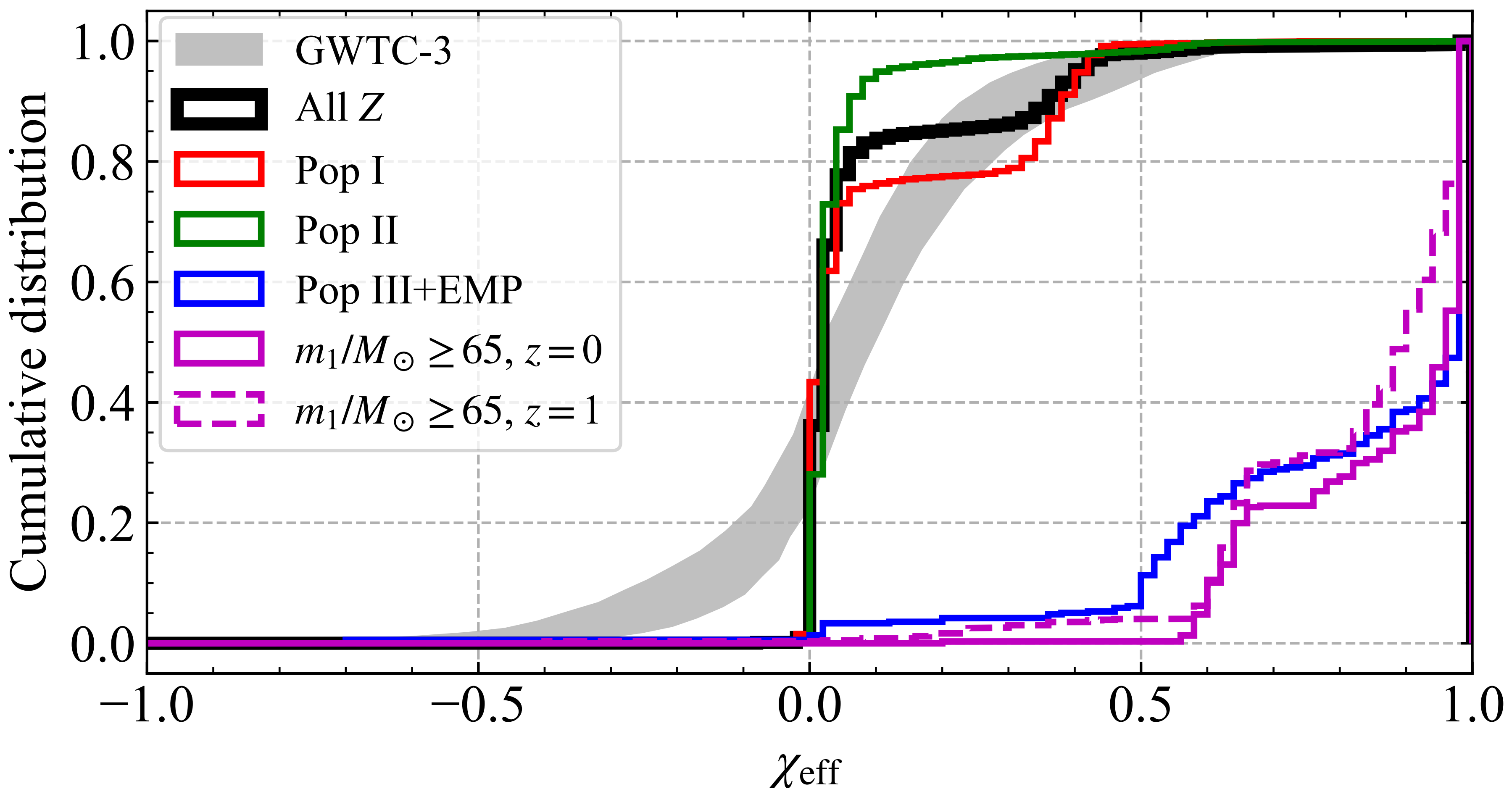

Tanikawa et al. (2021, MNRAS, 505, 2170)

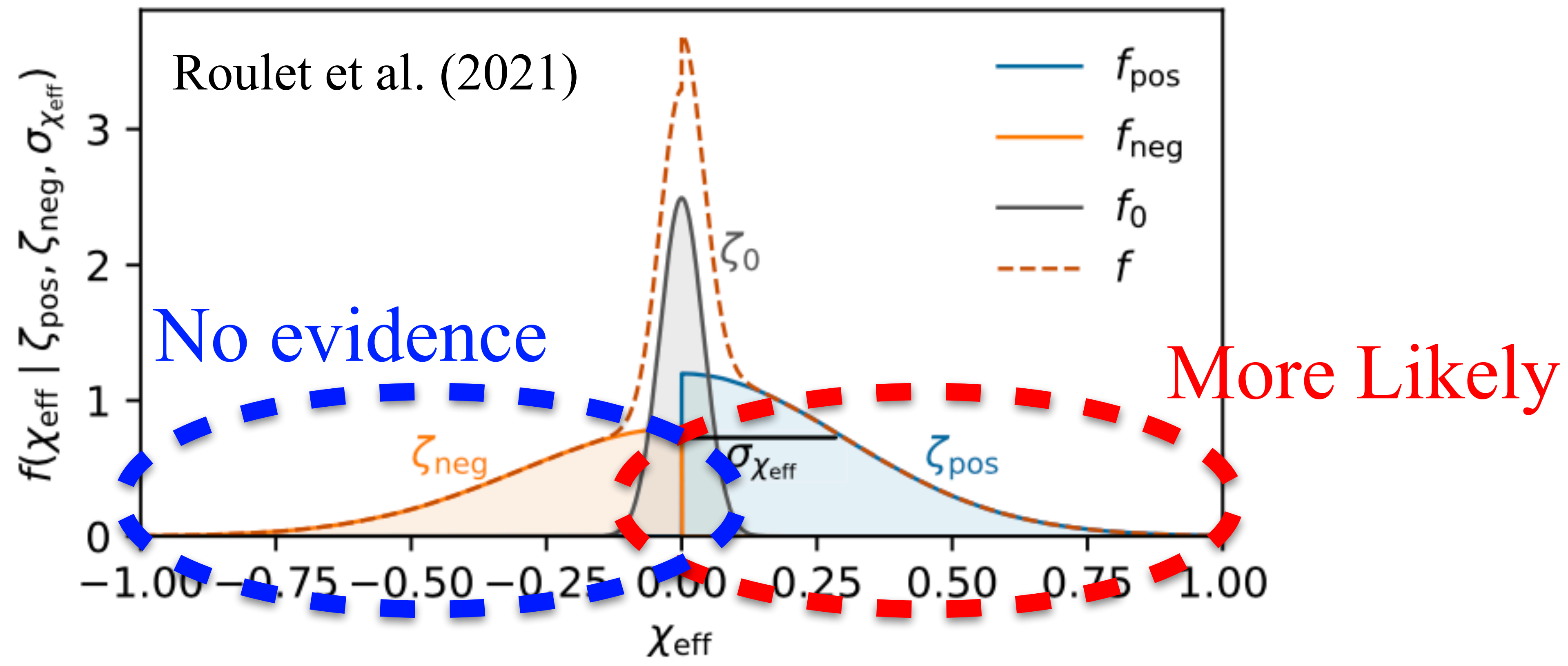
# Comparison with GW observations

Tanikawa et al. (2022, ApJ, 926, 83)

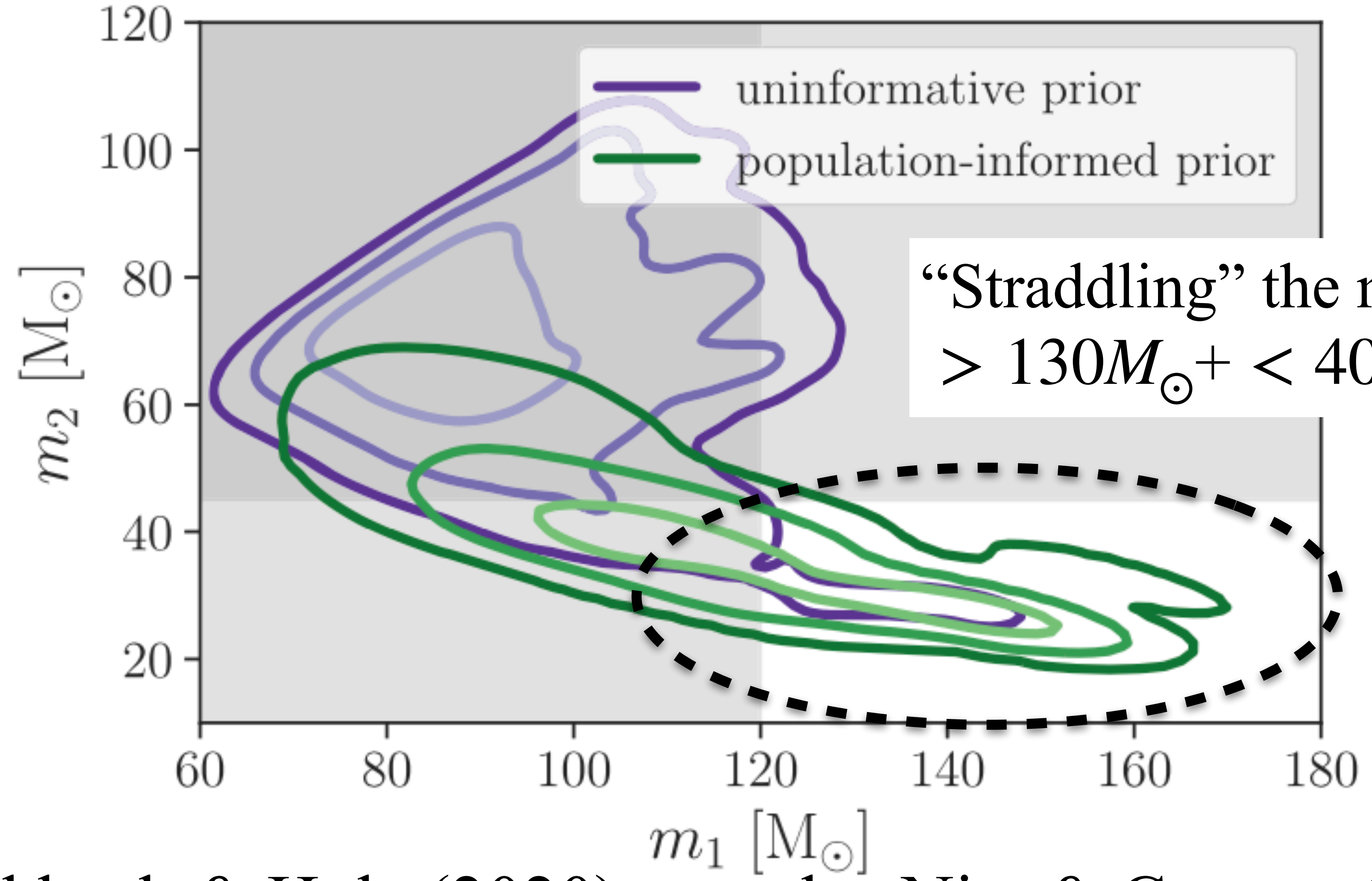
Chon's IMF (Chon et al. 2021)



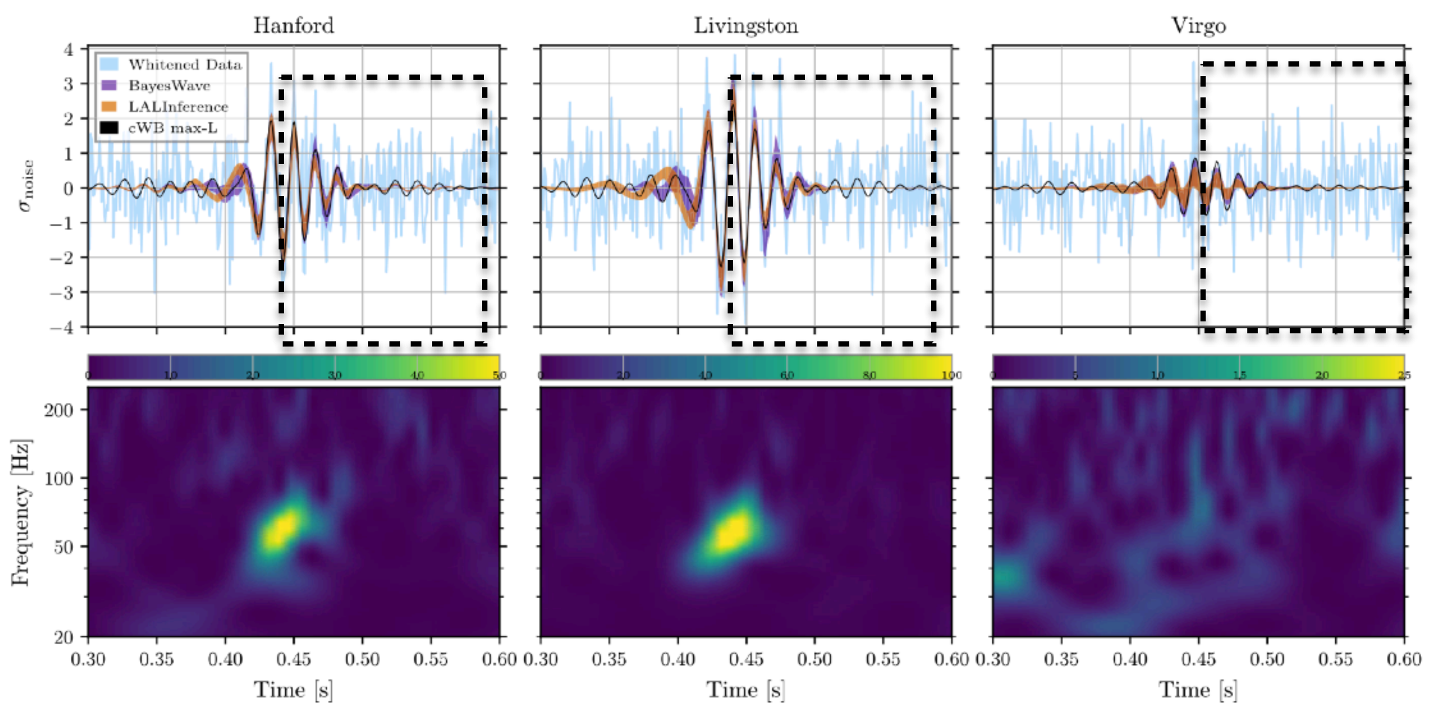
# Prior-dependent BH mass




“Straddling” the mass gap: $> 130M_\odot + < 40M_\odot$

Fishbach & Holz (2020); see also Nitz & Capano (2021)

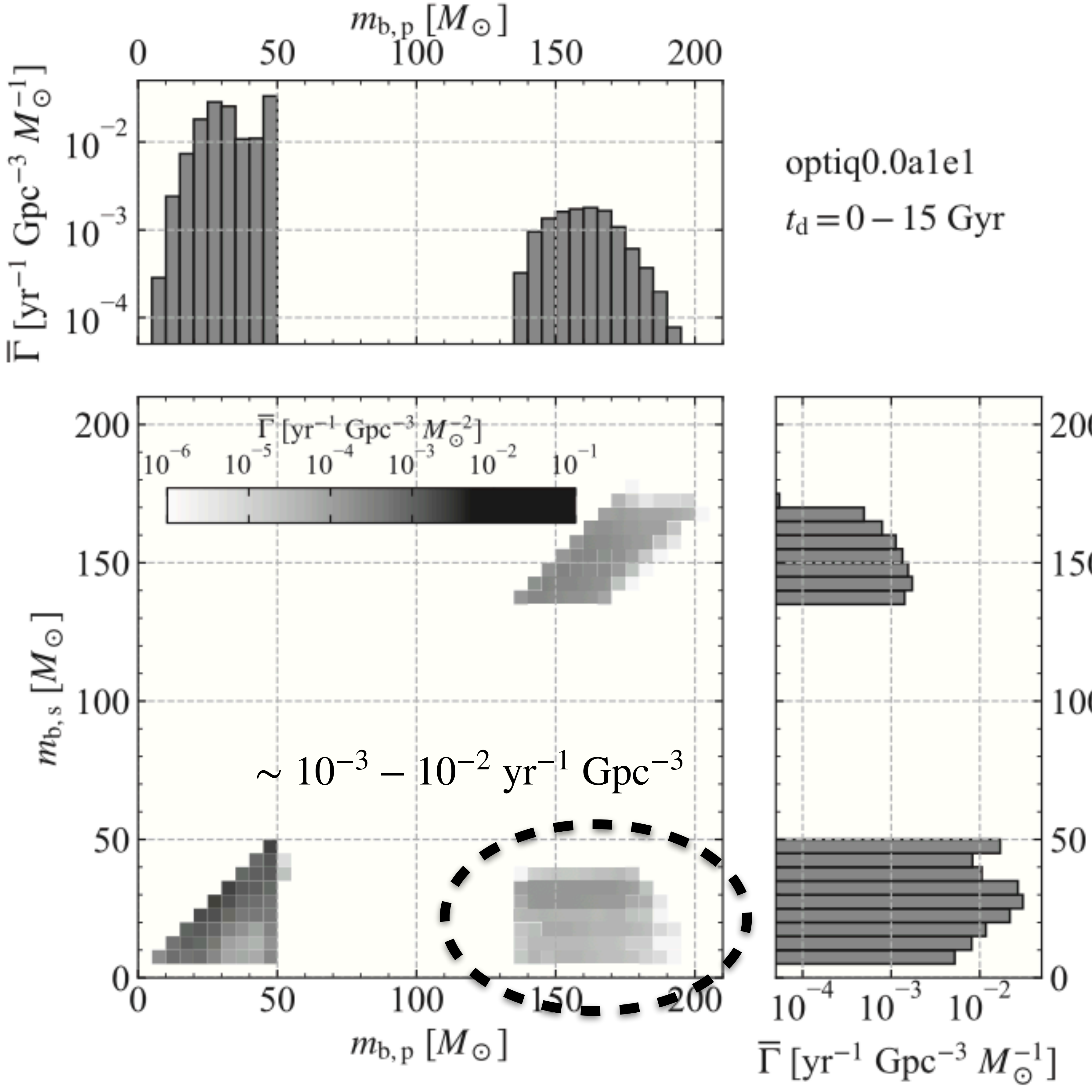
GW190521 (Abbott et al. 2020)




The ringdown signal was seen, but the chirp signal was not seen well…

- frequency: ~ 66Hz
- Damping time: ~ 19ms

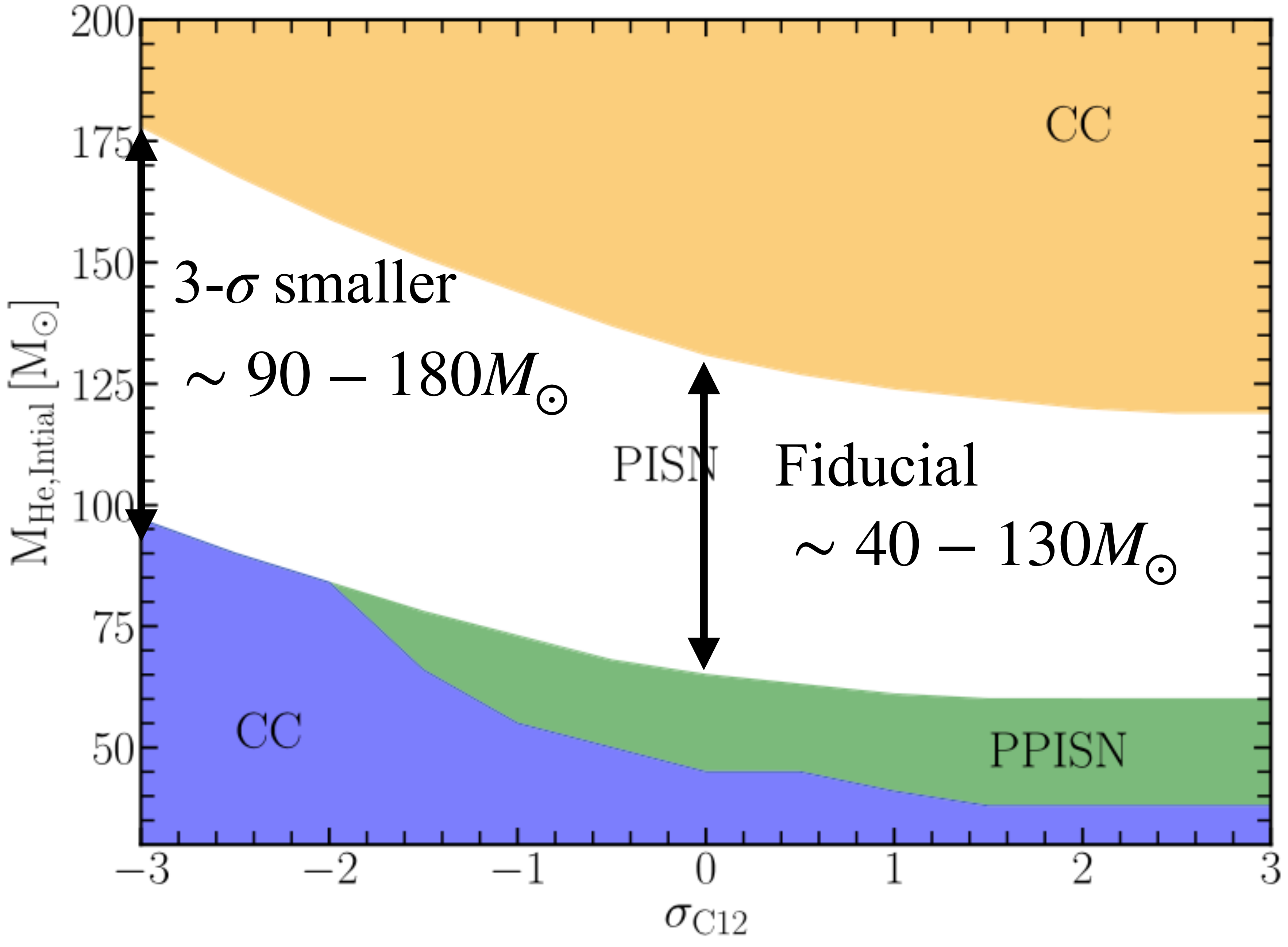
- Redshifted mass: $\sim 252M_\odot$
- Source mass: $\sim 142M_\odot$

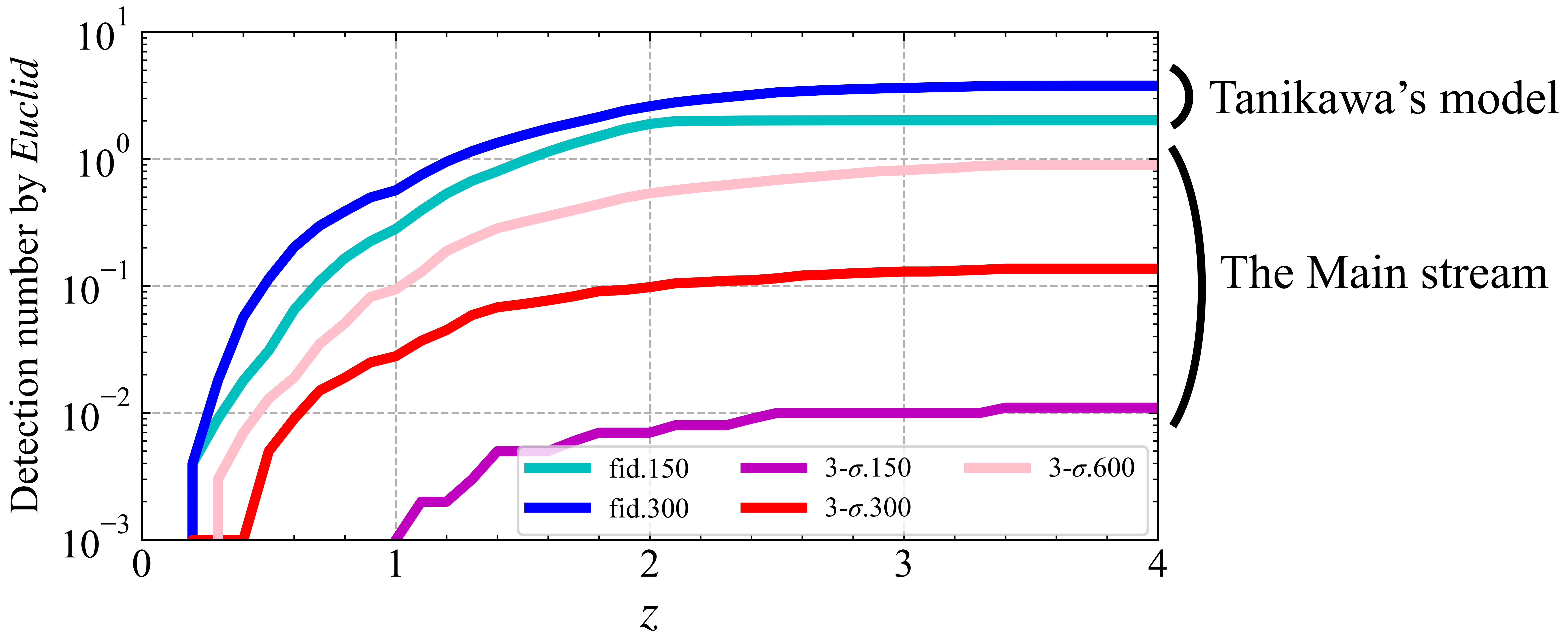



Tanikawa et al. (2021, ApJ, 910, 30); see also Hijikawa et al. (2021)

# PISN survey by Euclid telescope

Farmer et al. (2020)

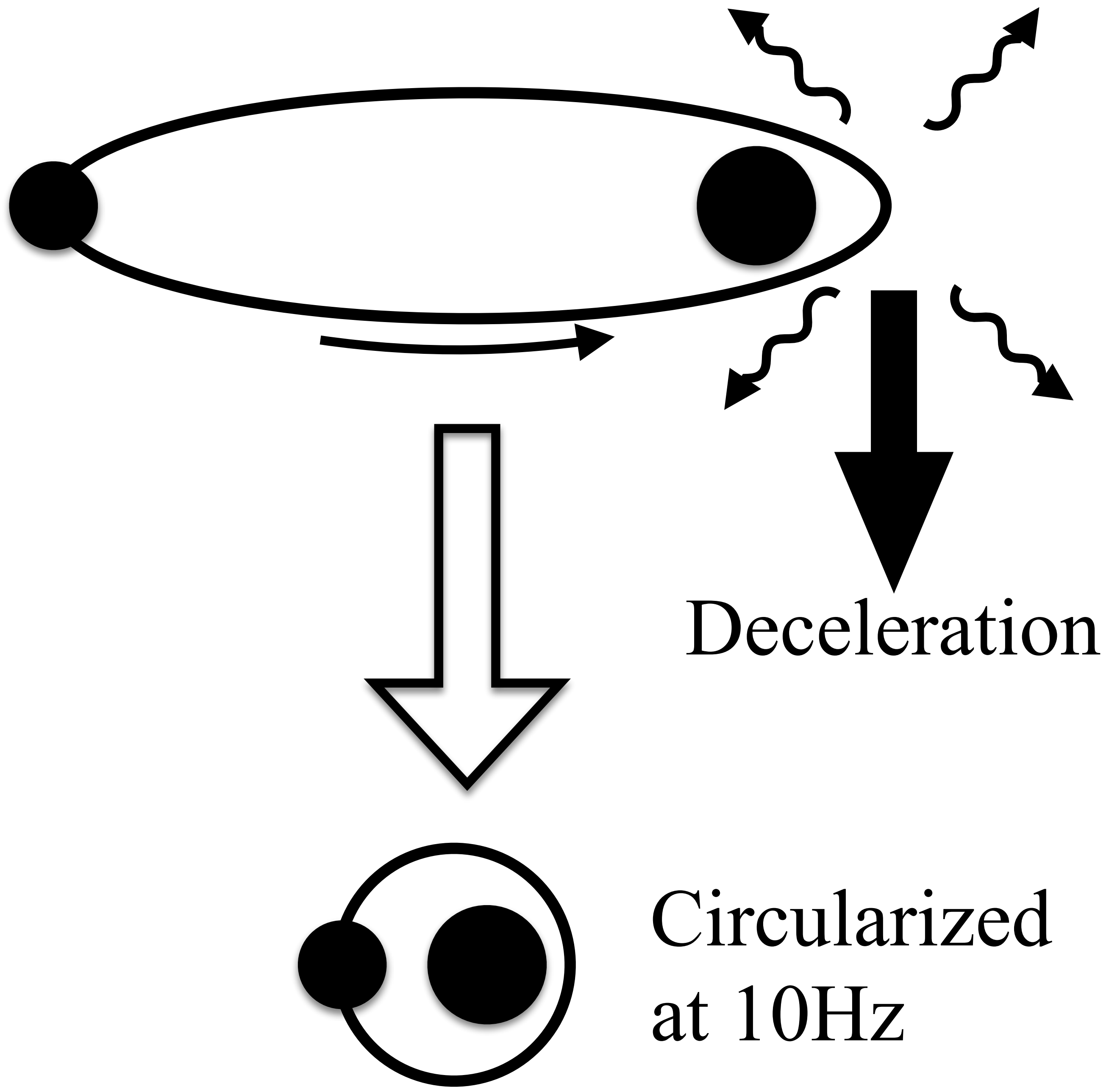


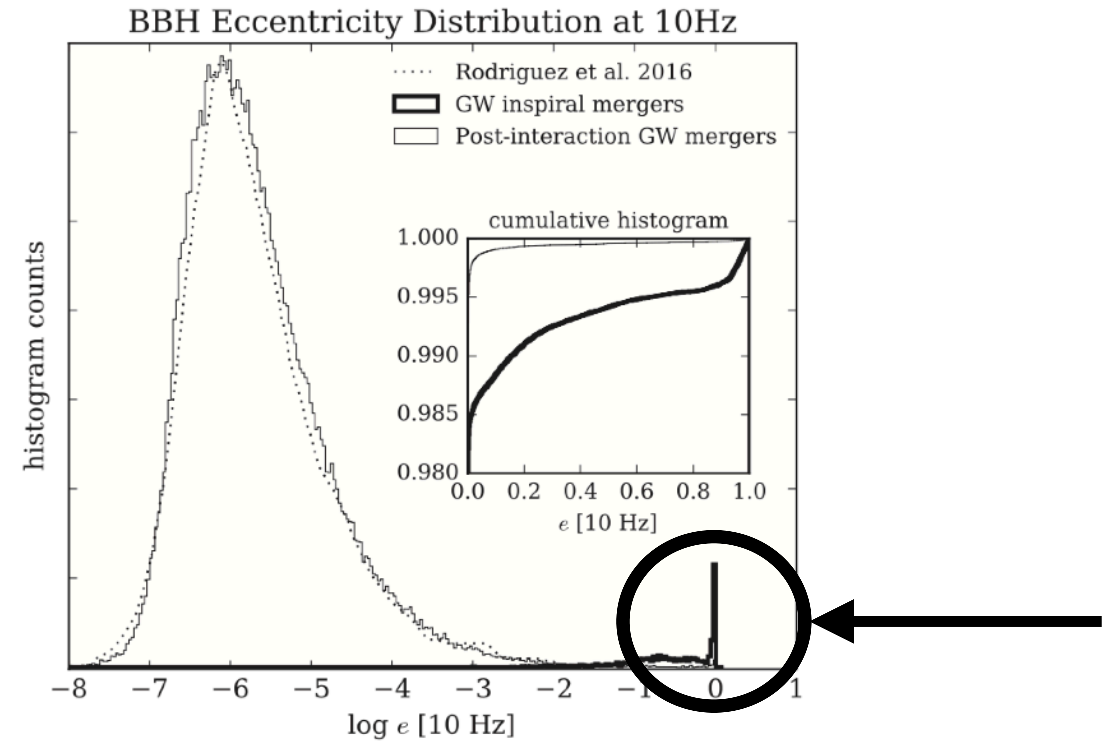

Tanikawa et al. (2022, arXiv:2204.09402)

# Multi-band GW observations

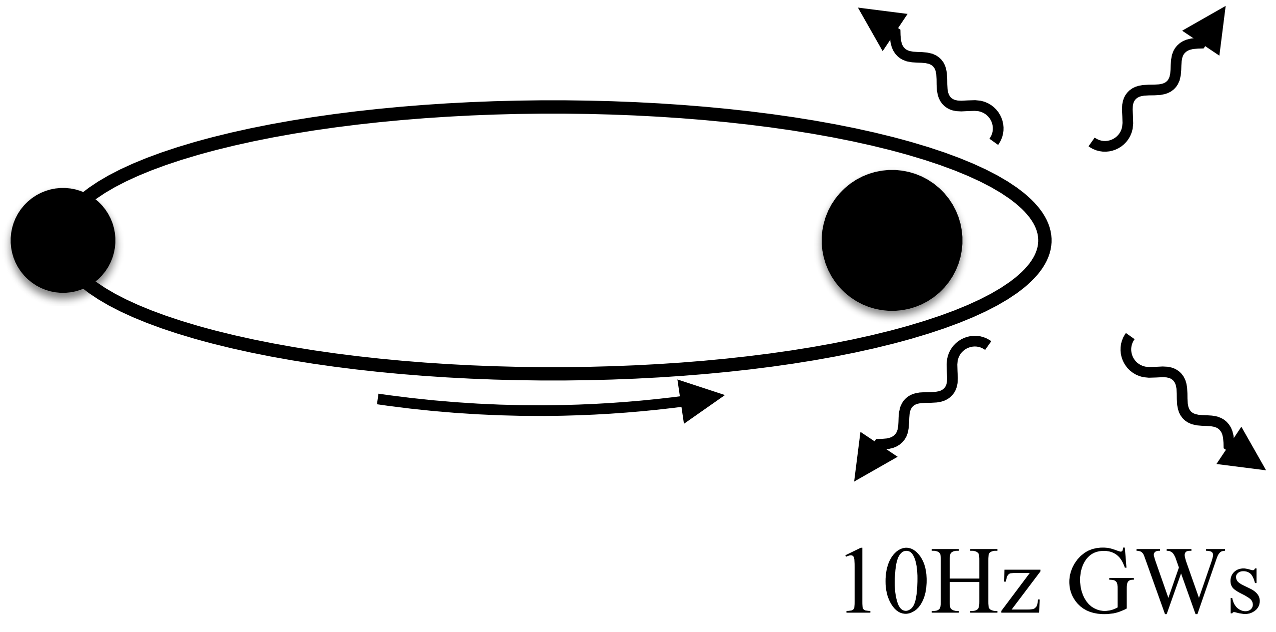
**Isolated binary**

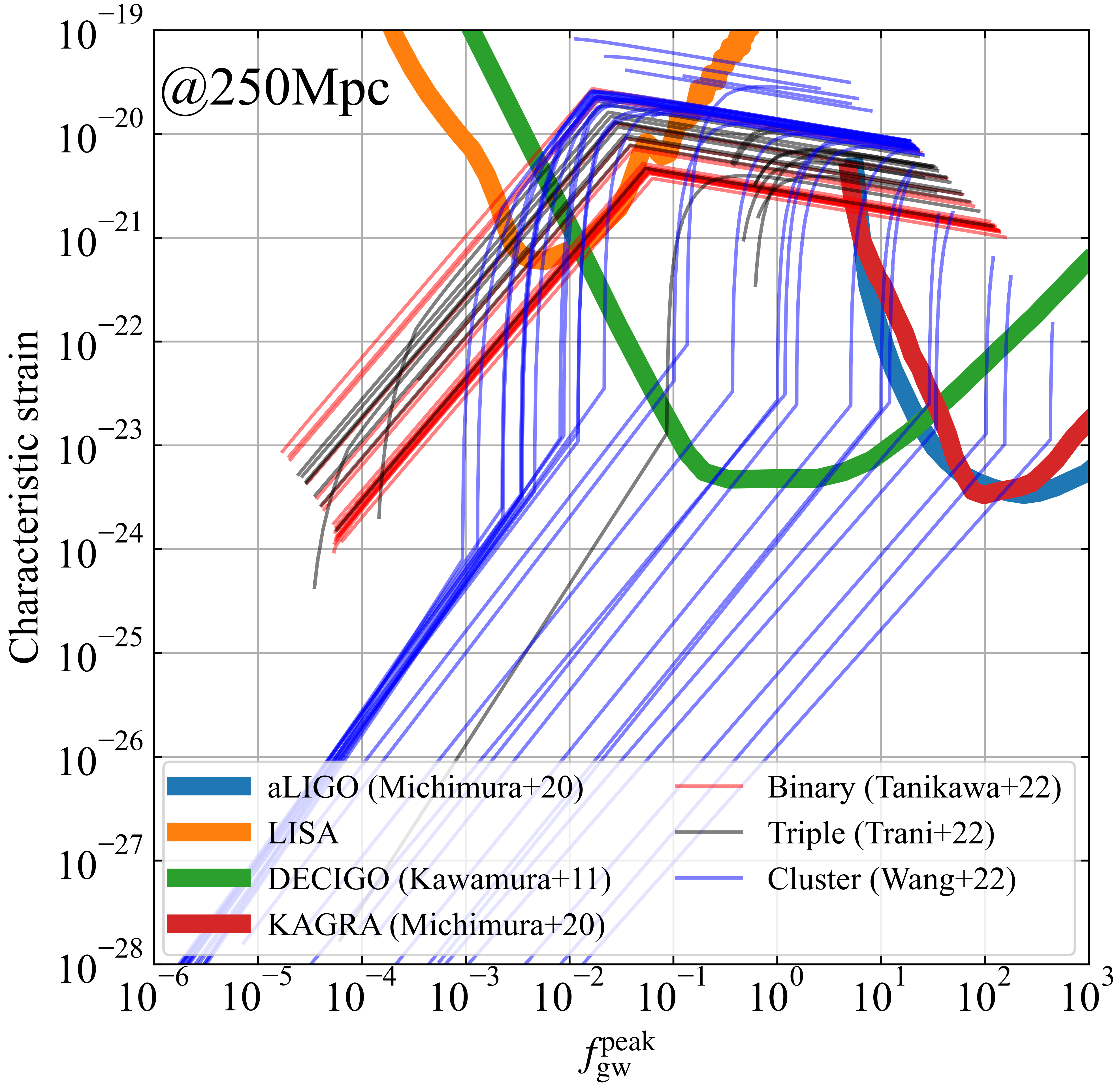



**Cluster**



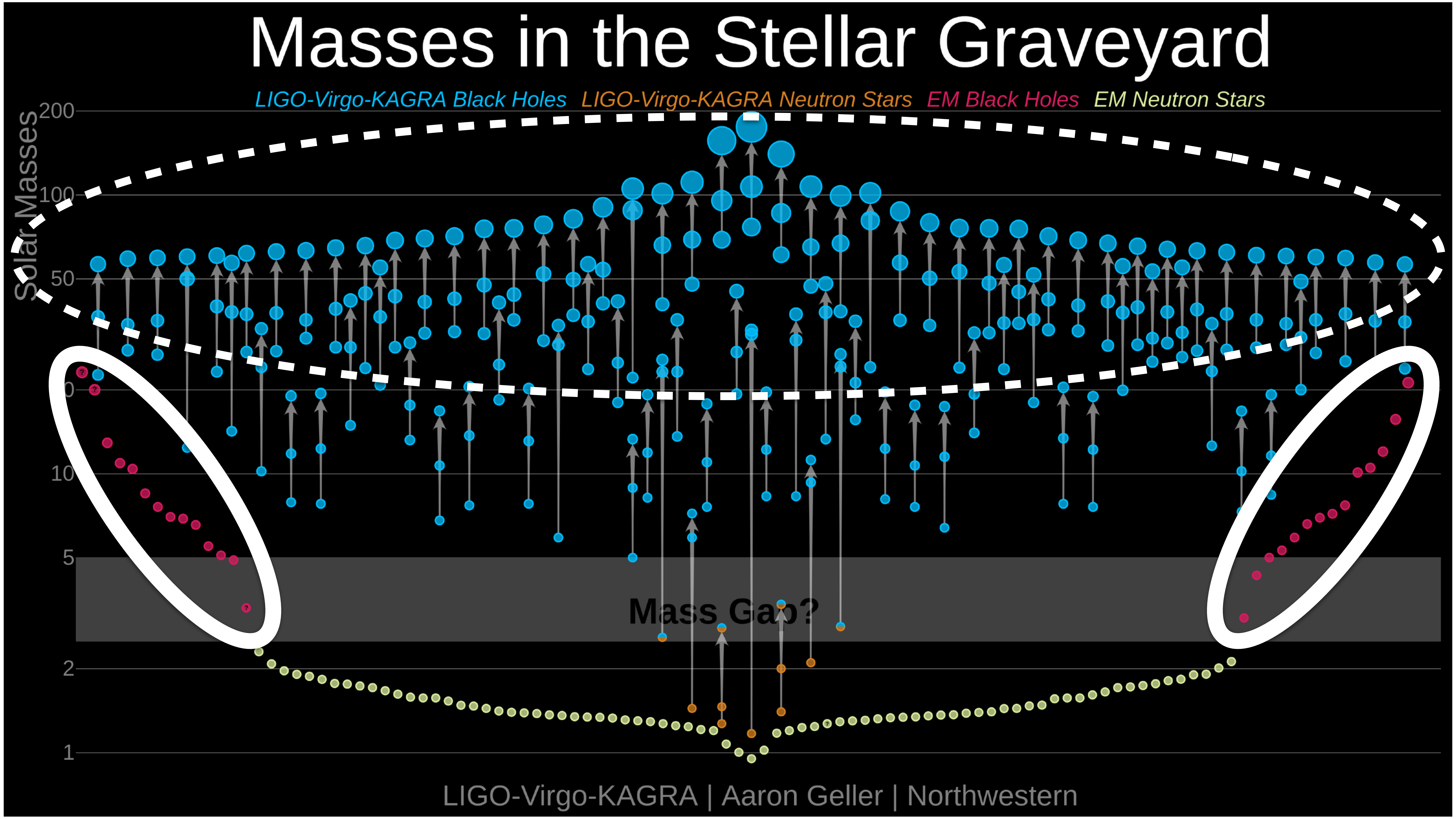

Samsing, Ramirez-Ruiz (2017)



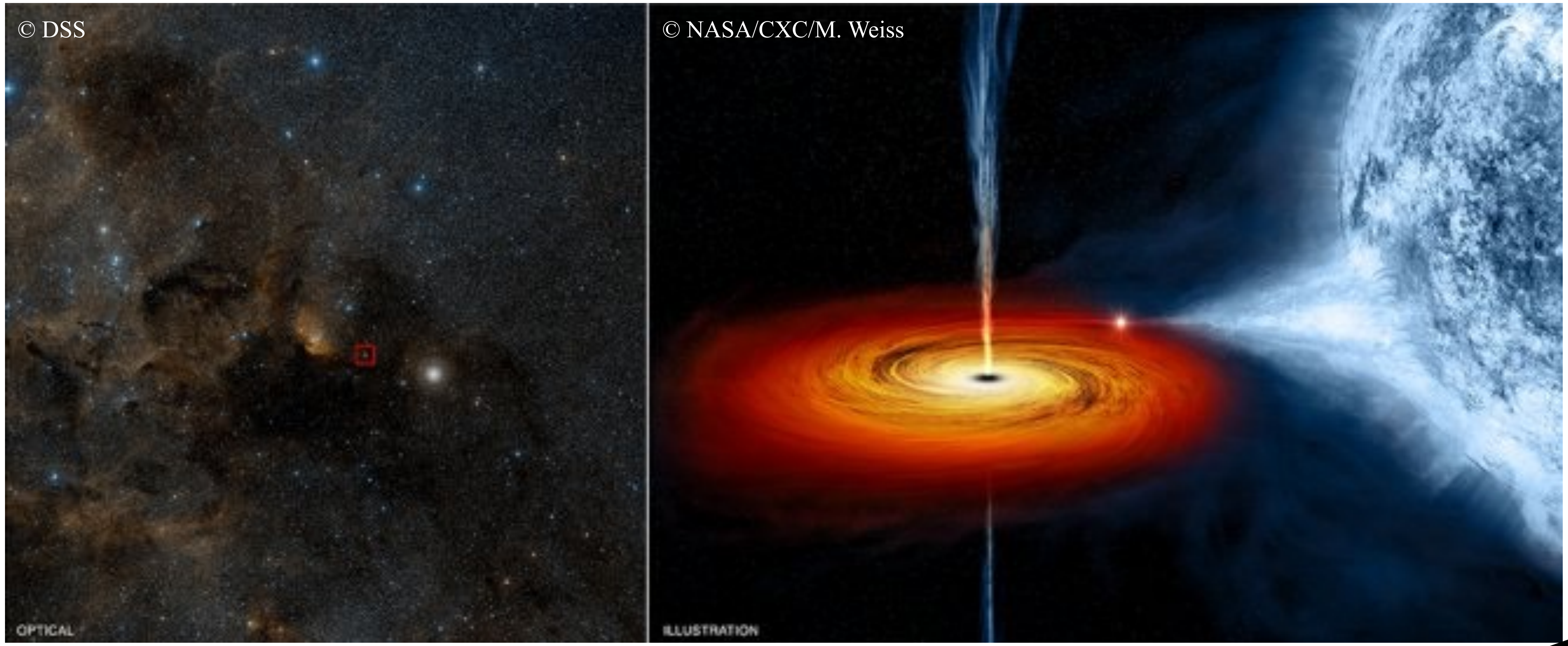




Special thanks to A. Trani and L. Wang

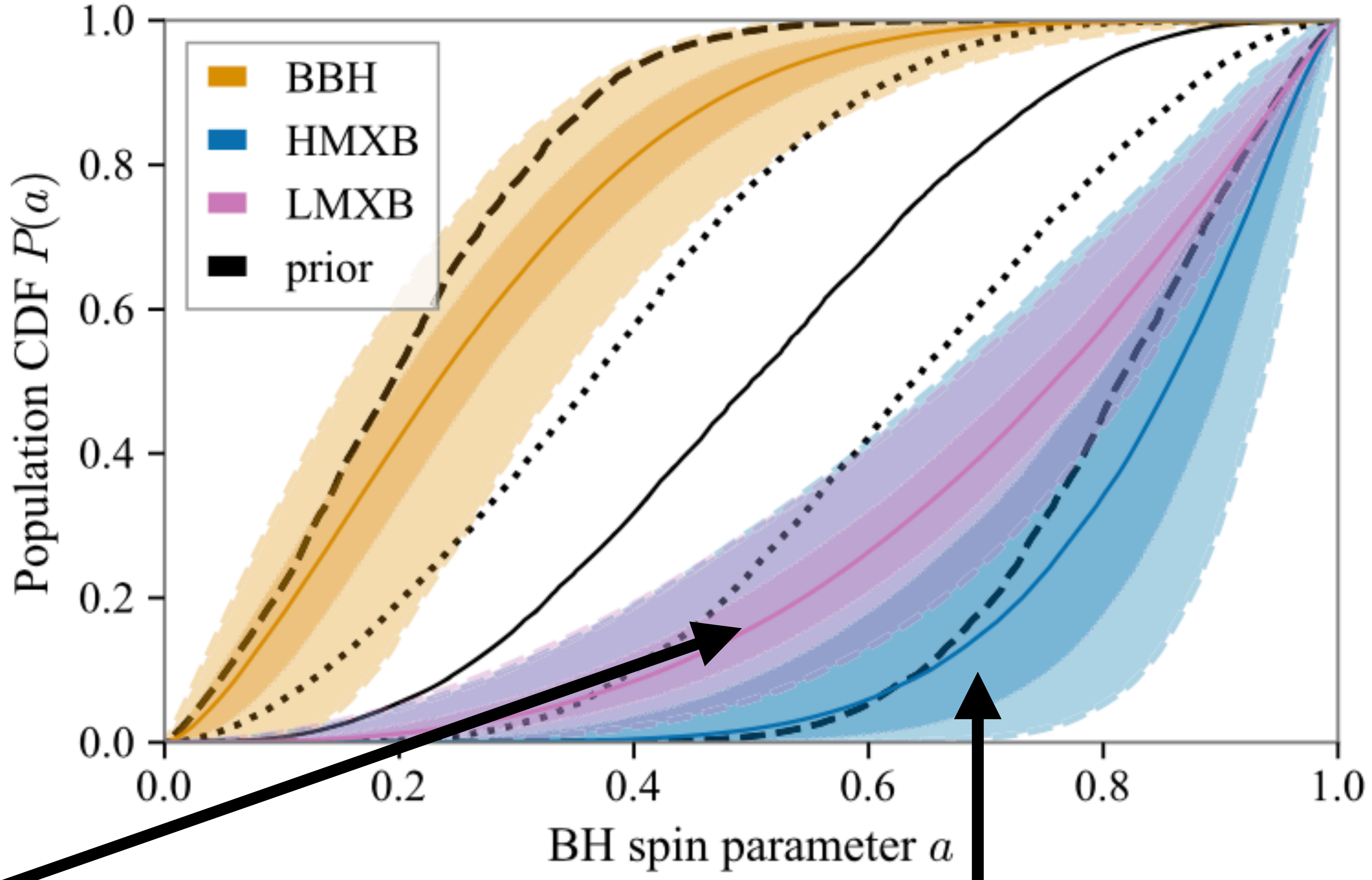
# BH binary exploration



# BH X-ray binary



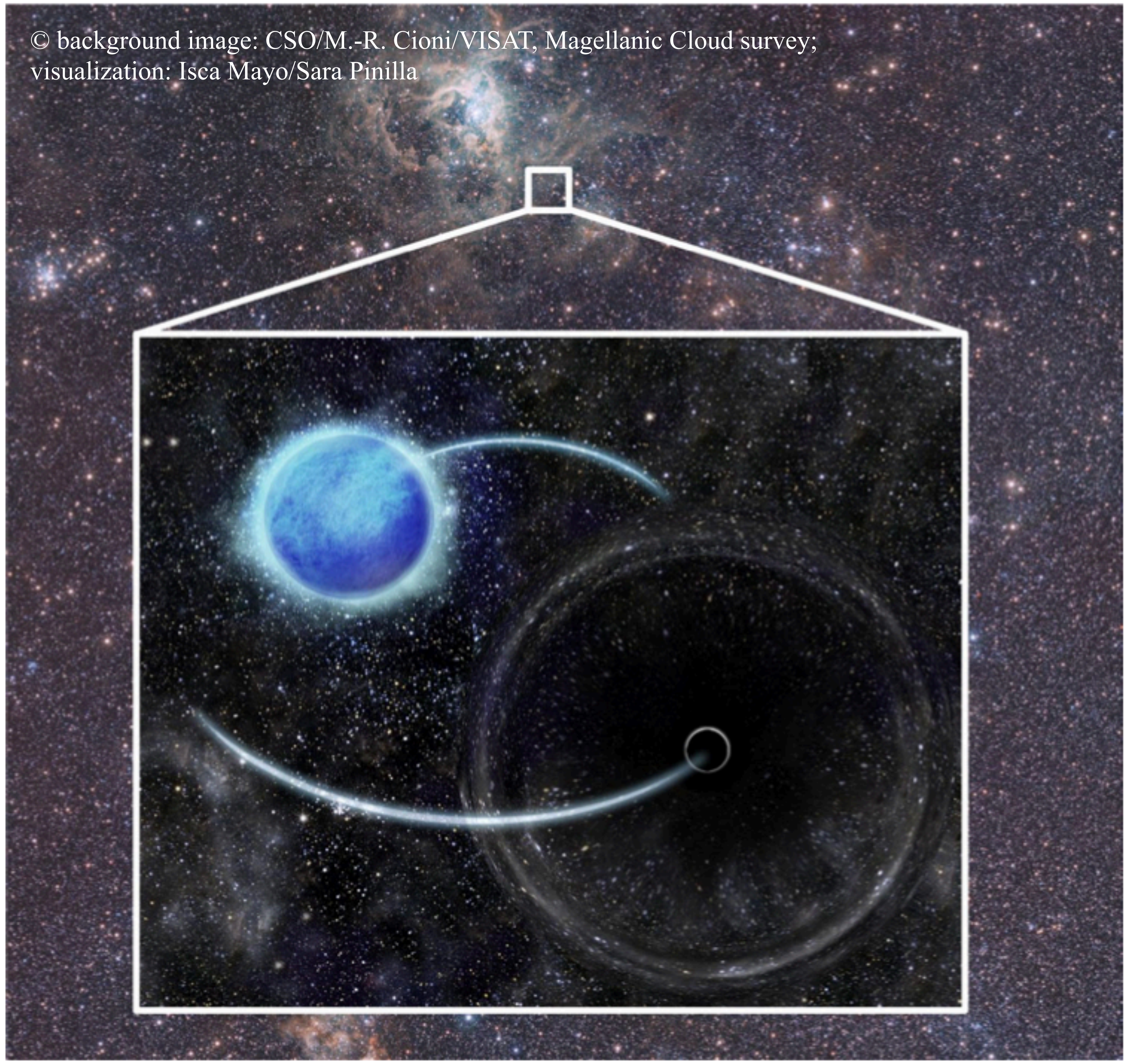

Fishbach & Kalogera (2022)



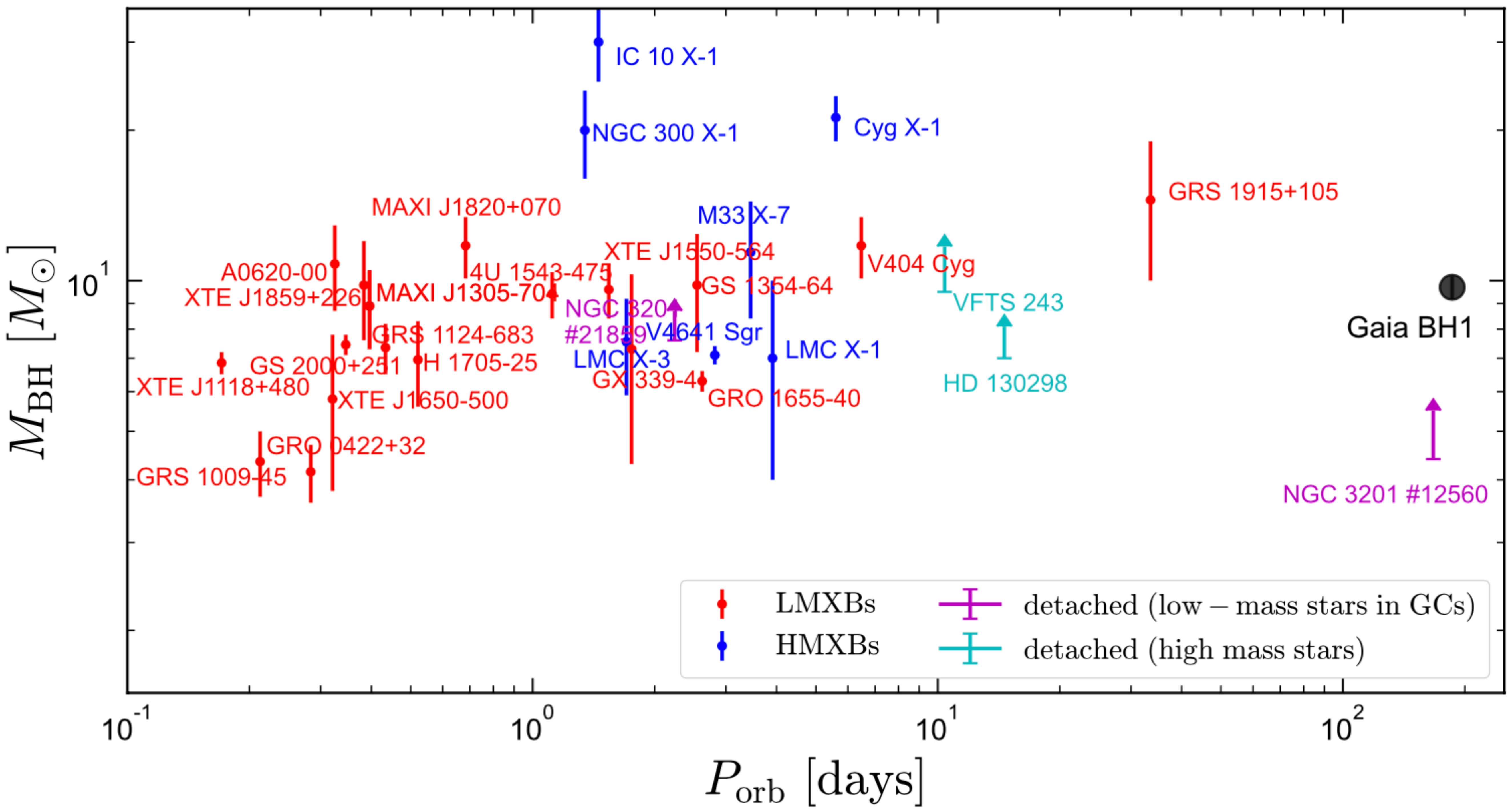

HMXB: Subpopulation of merging binary BHs?

LMXB: spun-up by mass accretion?

# Non-interacting BH binary




El-Badry et al. (2022)




BH binaries with longer periods ( $\gtrsim$ 10 days)

# Spectroscopic binary

- NGC 3210 BH (Giesers et al. 2018) ✓
- LB-1 (Liu et al. 2019) ✗
- 2MASS J05215658+4359220 (Thompson et al. 2019) ✗
- HR 6819 (Rivinius et al. 2020) ✗
- NGC 2004#115 (Lennon et al. 2021) ✗
- Unicorn (Jayasinghe et al. 2021) ✗
- Giraffe (Jayasinghe et al. 2022) ✗
- NGC 1850 BH1 (Saracino et al. 2022) ✗
- VFTS 243 (Shenar et al. 2022) ✓

Rejected by K. El-Badry (BH destroyer)

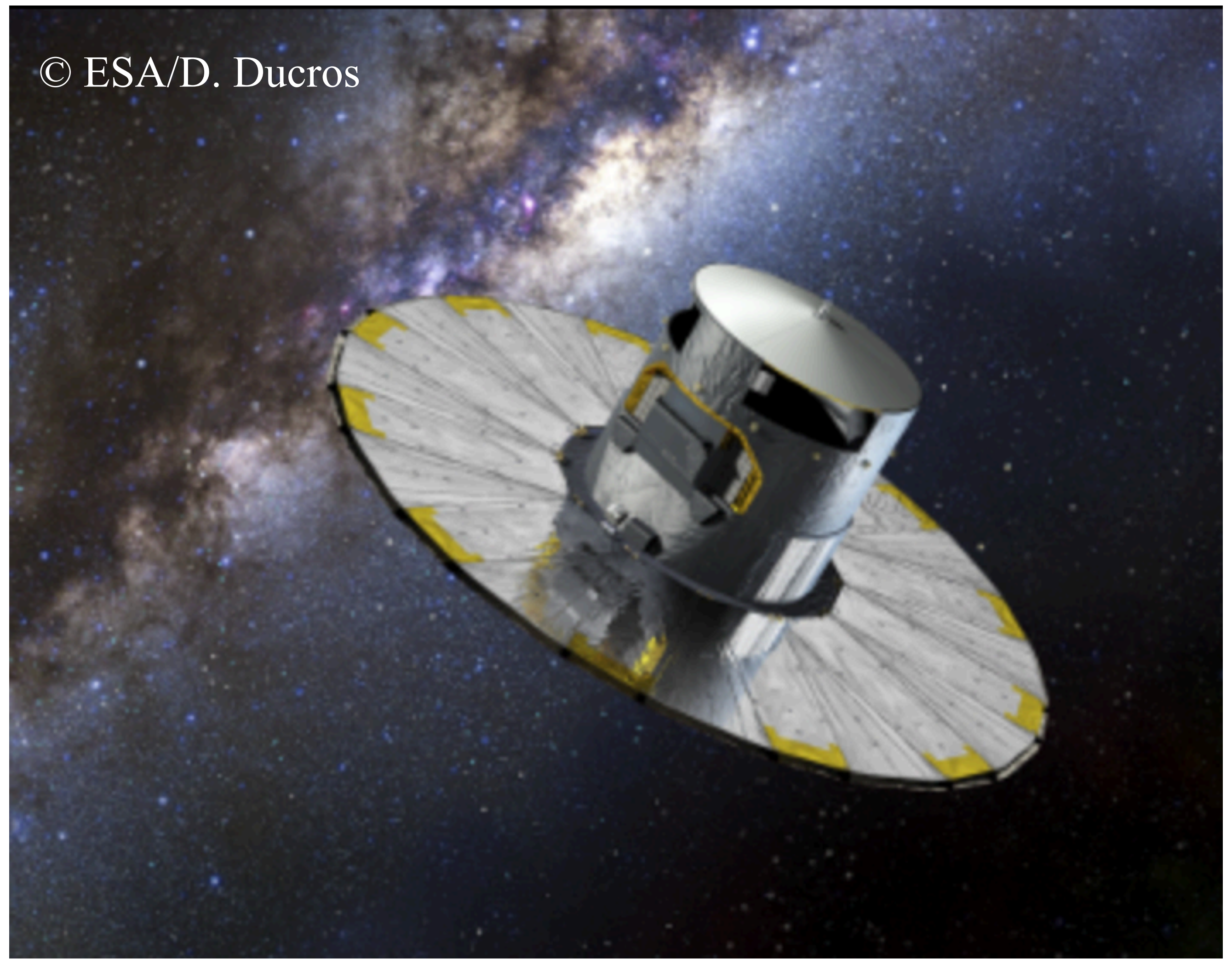
Observables if synchronized (e.g. Thompson et al. 2019), but highly uncertain

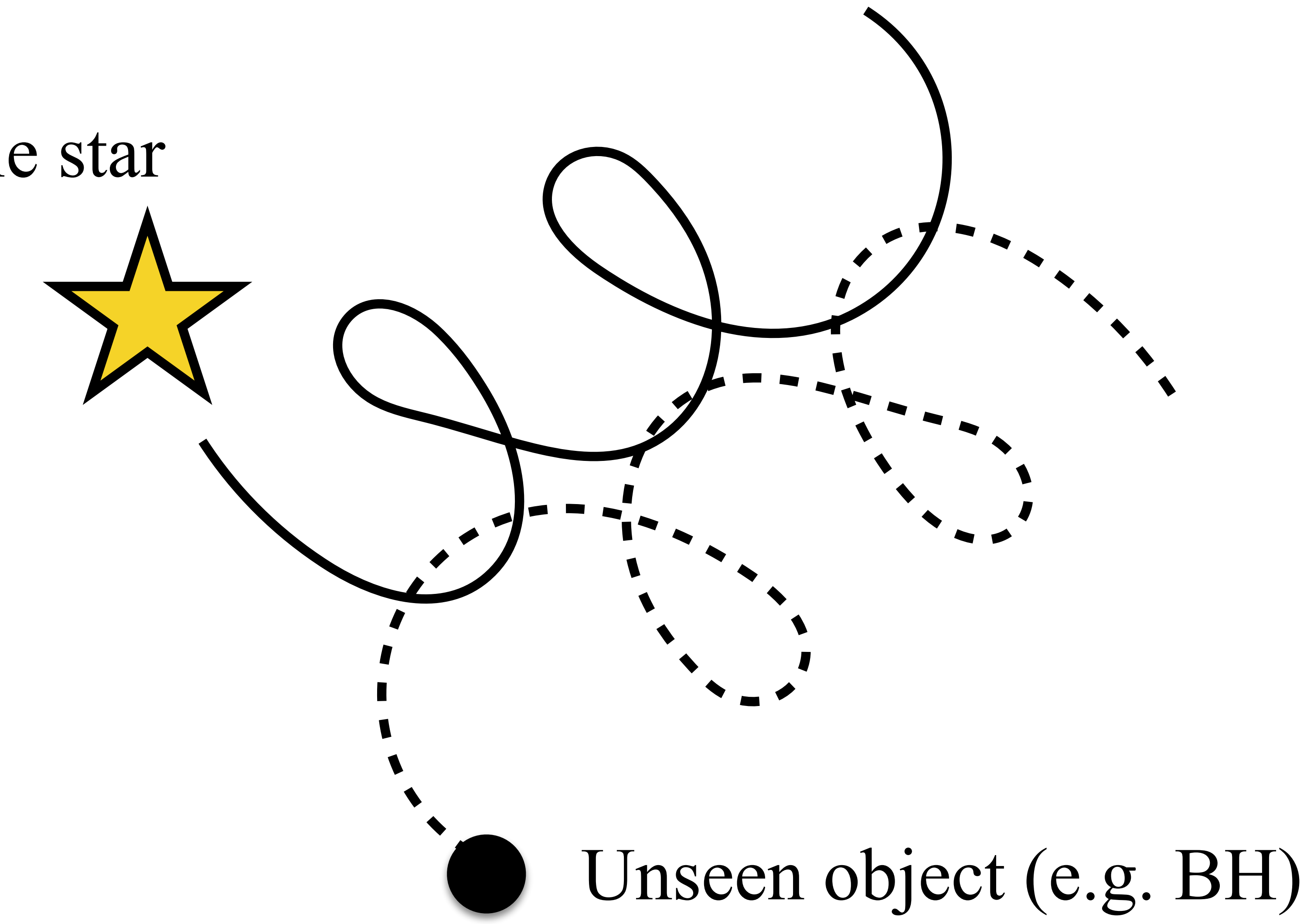
$$f(M) \equiv \frac{M_{\rm unseen}^3 \sin^3 i}{(M_{\rm unseen} + M_{\rm visible})^2} = \frac{K_{\rm visible}^3 P}{2\pi G}(1 - e^2)^{3/2}$$

Observables by spectroscopy

Highly uncertain
(e.g. Algol-type problem by El-badry et al. 2022)

# Gaia: astrometry with spectroscopy




Observables by astrometry

$$f(M) \equiv \frac{M_{\rm unseen}^3 \sin^3 i}{(M_{\rm unseen} + M_{\rm visible})^2} = \frac{K_{\rm visible}^3 P}{2\pi G}(1 - e^2)^{3/2}$$

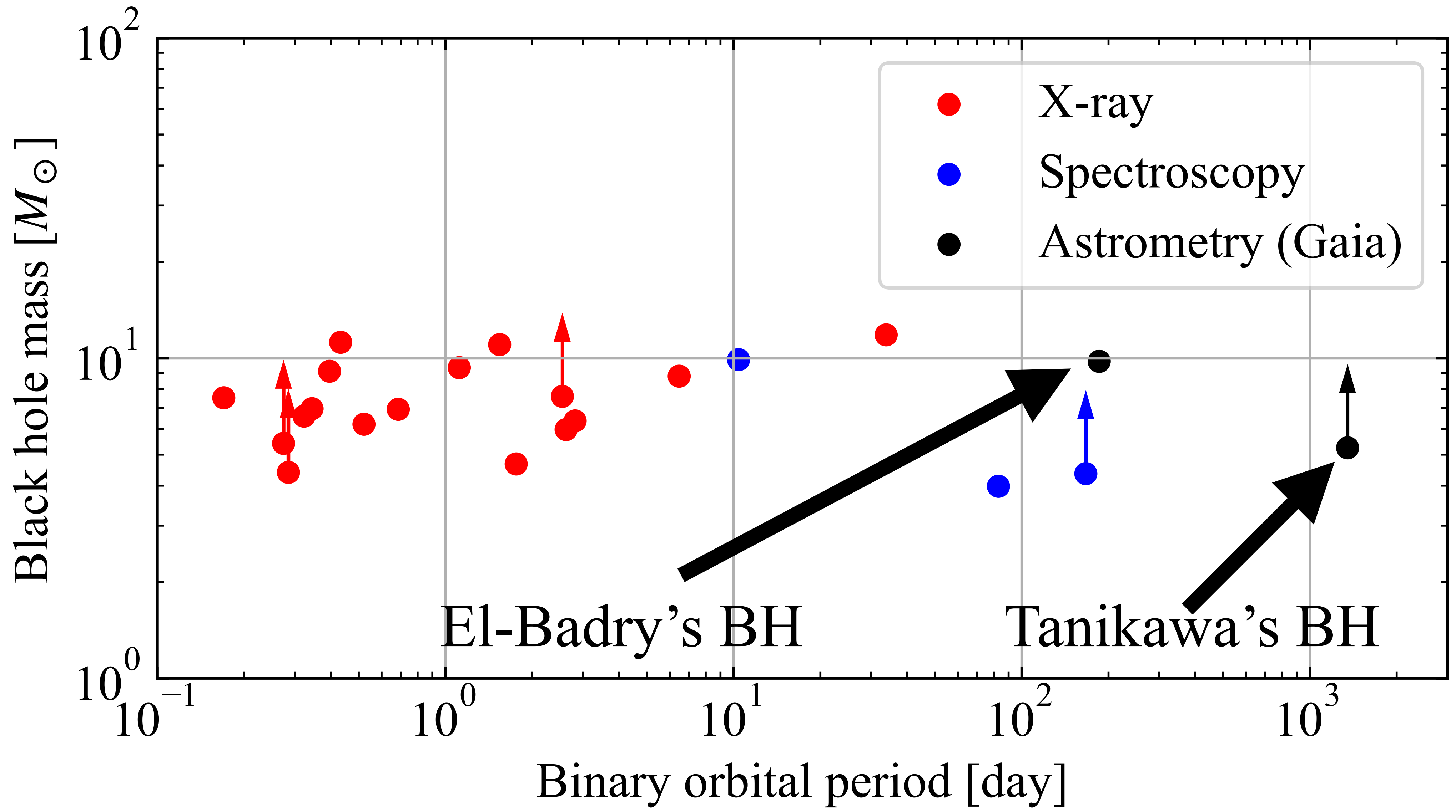
Highly uncertain
(e.g. Algol-type problem by El-badry et al. 2022)

Observables by spectroscopy
and astrometry

# Promising BH candidate

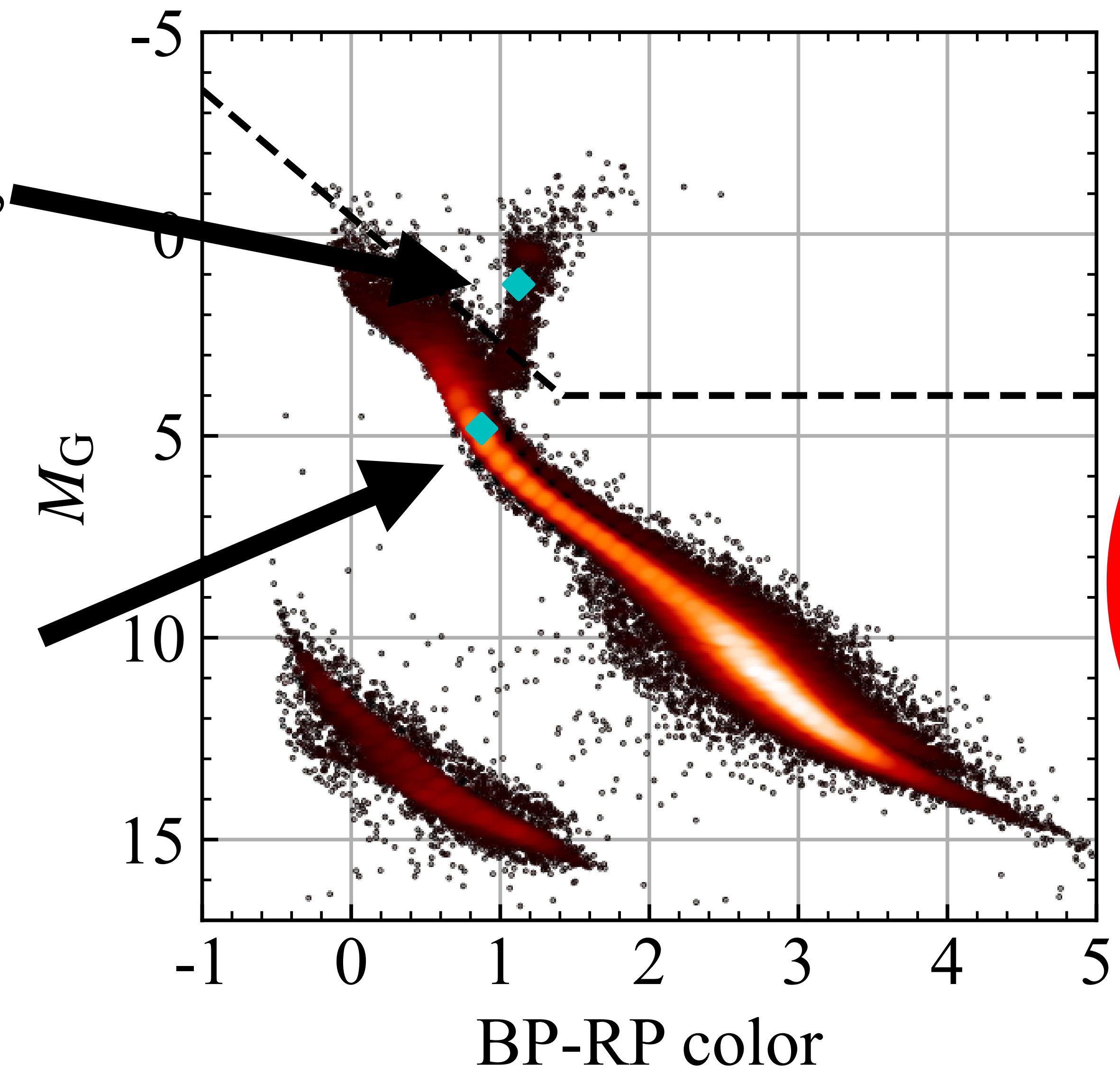
$$f(M) \equiv \frac{M_{\rm unseen}^3}{(M_{\rm unseen}+M_{\rm visible})^2} = \frac{K_{\rm visible}^3 P}{2\pi G}(1-e^2)^{3/2}\sin^{-3} i \geq 5.25 M_\odot$$

$$M_{\rm unseen} \geq 5.25 M_\odot$$




Tanikawa et al (2022, arXiv:2209.05632)

El-Badry et al (2022, arXiv:2209.06833)

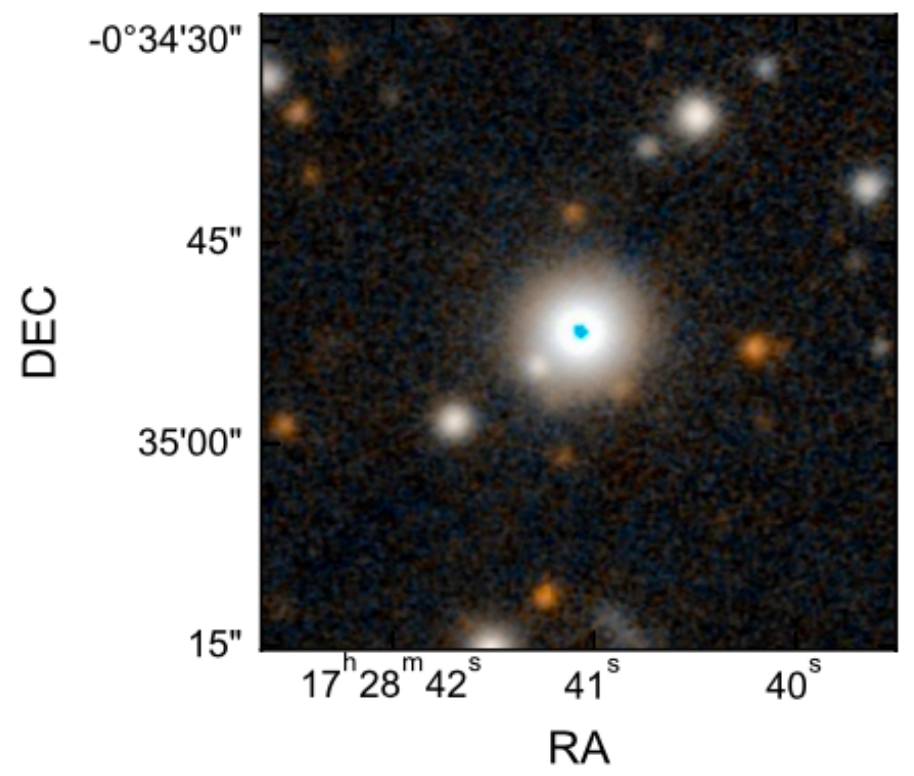


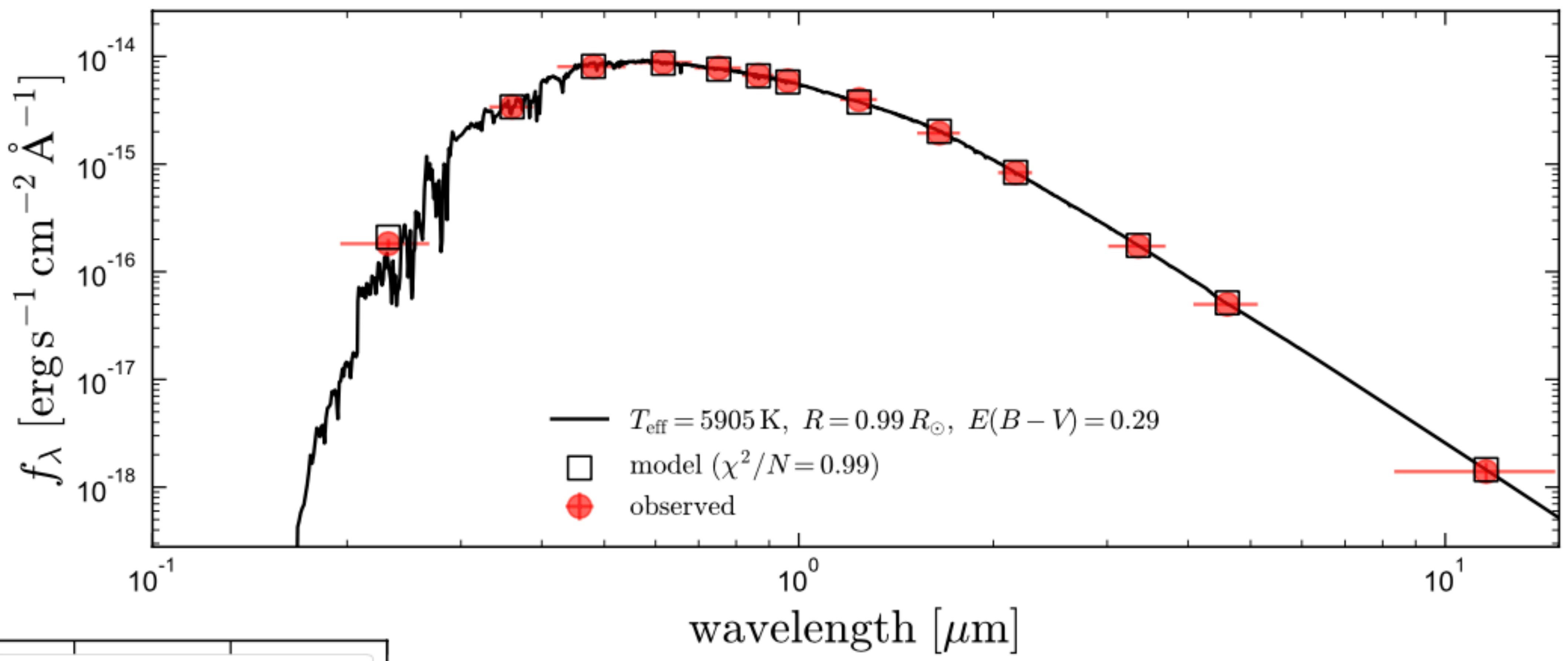

Tanikawa's BH

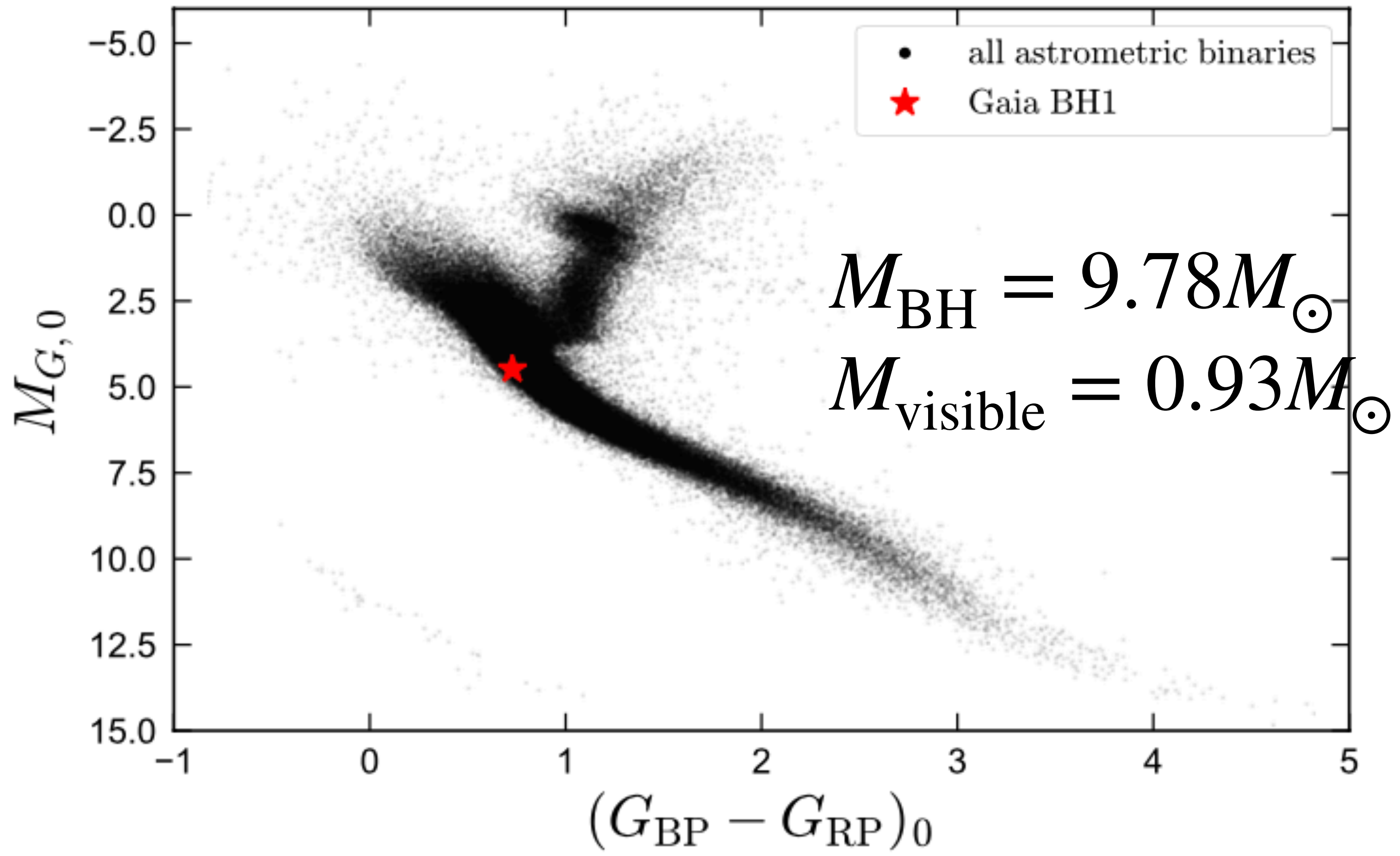
| Gaia DR3 source ID | $\tilde{M}$ [$M_\odot$] | $P_{\rm orb}$ [days] | $(a_0 \times d)$ [au] | GoF | rv_amplitude_robust [km s$^{-1}$] | expected RV amplitude | Verdict |
|---|---|---|---|---|---|---|---|
| 3640889032890567040 | 122 ± 47 | 1076 ± 12 | 10.2 ± 1.3 | 10.3 | 12.9 | 674 ± 154 | ✗ |
| 4467000291193143808 | 119 ± 71 | 1647 ± 520 | 13.4 ± 2.2 | 4.9 | | 358 ± 182 | ✗ |
| 4373465352415301632 | 11.5 ± 2.5 | 185.8 ± 0.3 | 1.44 ± 0.10 | 0.3 | | 165 ± 20 | ✓ |
| 6281177228434199296 | 10.8 ± 1.6 | 153.9 ± 0.4 | 1.24 ± 0.06 | 8.0 | 20.1 | 171 ± 10 | ✗ |
| 5870569352746779008 | 6.7 ± 0.5 | 1352 ± 45 | 4.52 ± 0.13 | 3.1 | 37.0 | 50 ± 2 | ¯_(ツ)_/¯ |
| 3664684869697065984 | 3.5 ± 2.6 | 1220 ± 233 | 3.35 ± 1.13 | 3.6 | 18.3 | 54 ± 14 | ✗ |

El-Badry et al (2022, arXiv:2209.06833)

# El-Badry's BH

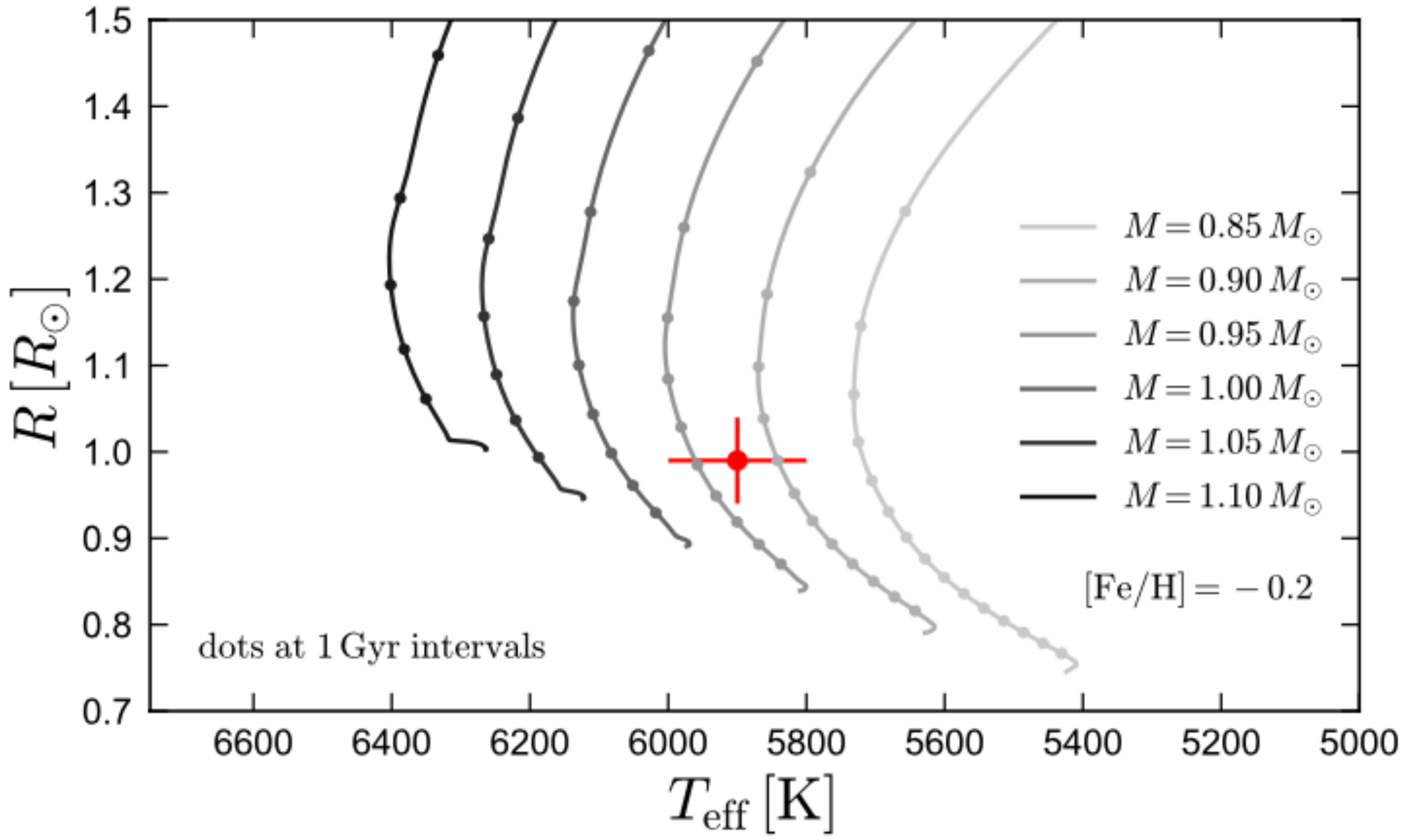


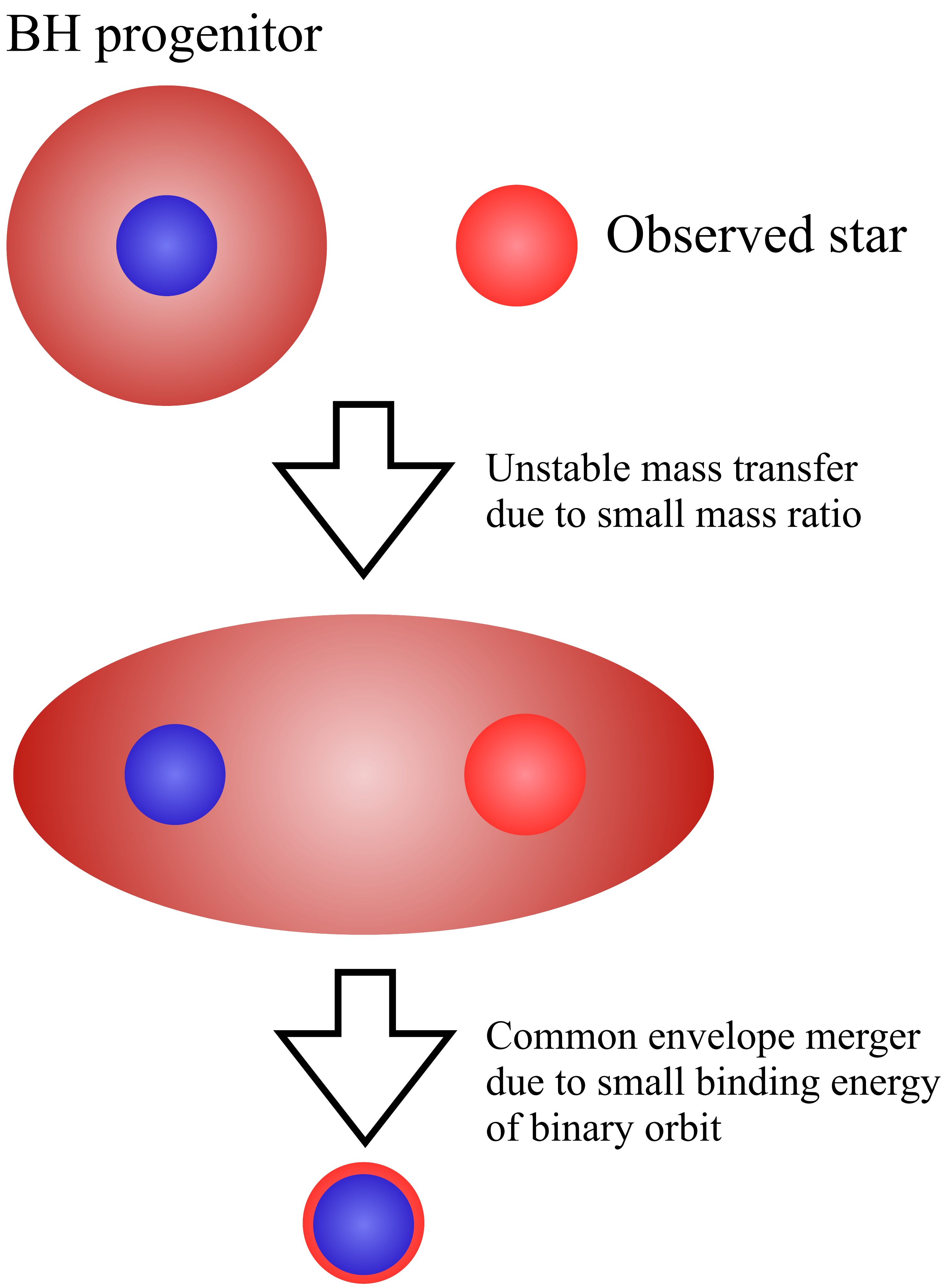




$M_{\rm BH} = 9.78 M_\odot$

$M_{\rm visible} = 0.93 M_\odot$

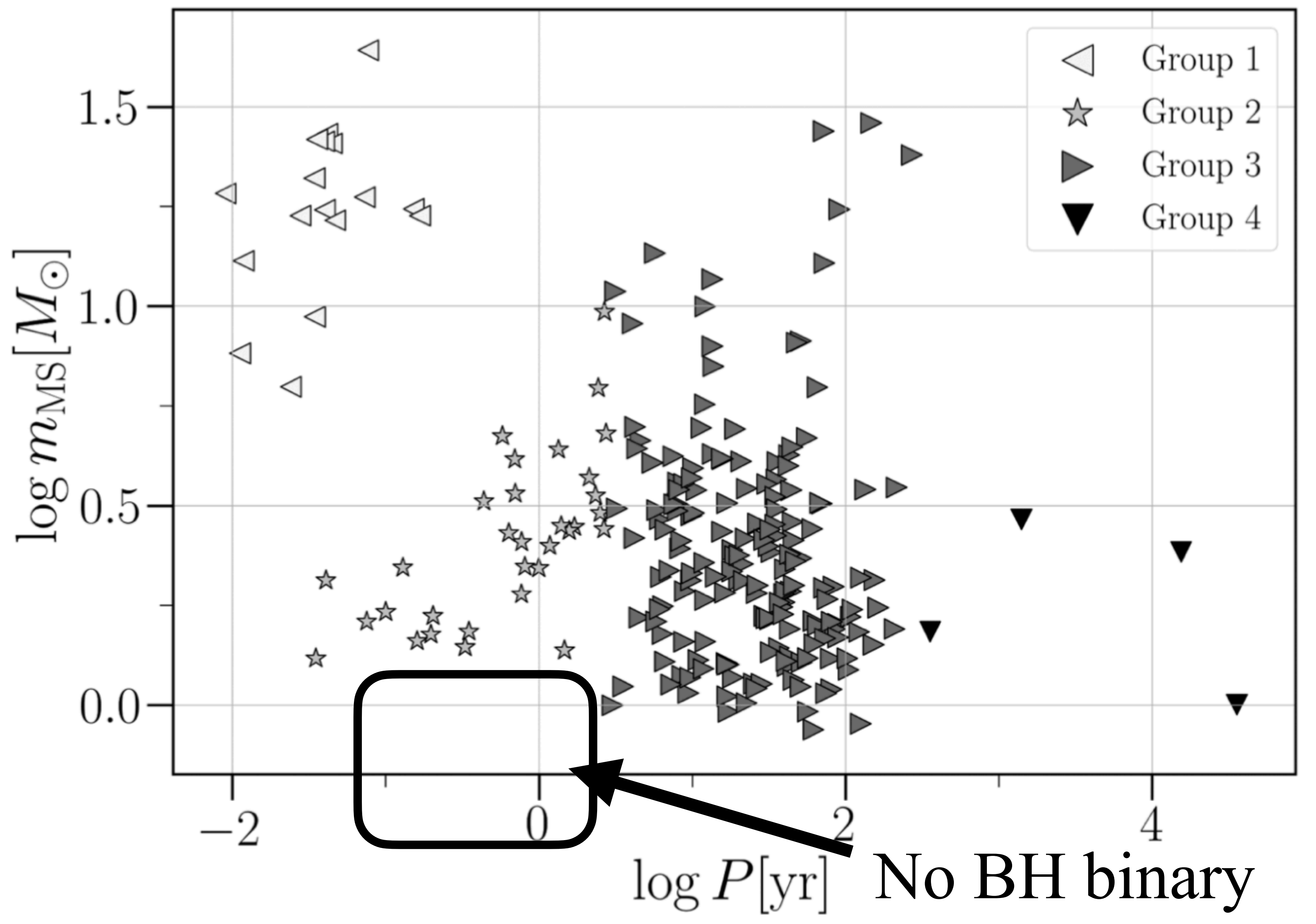


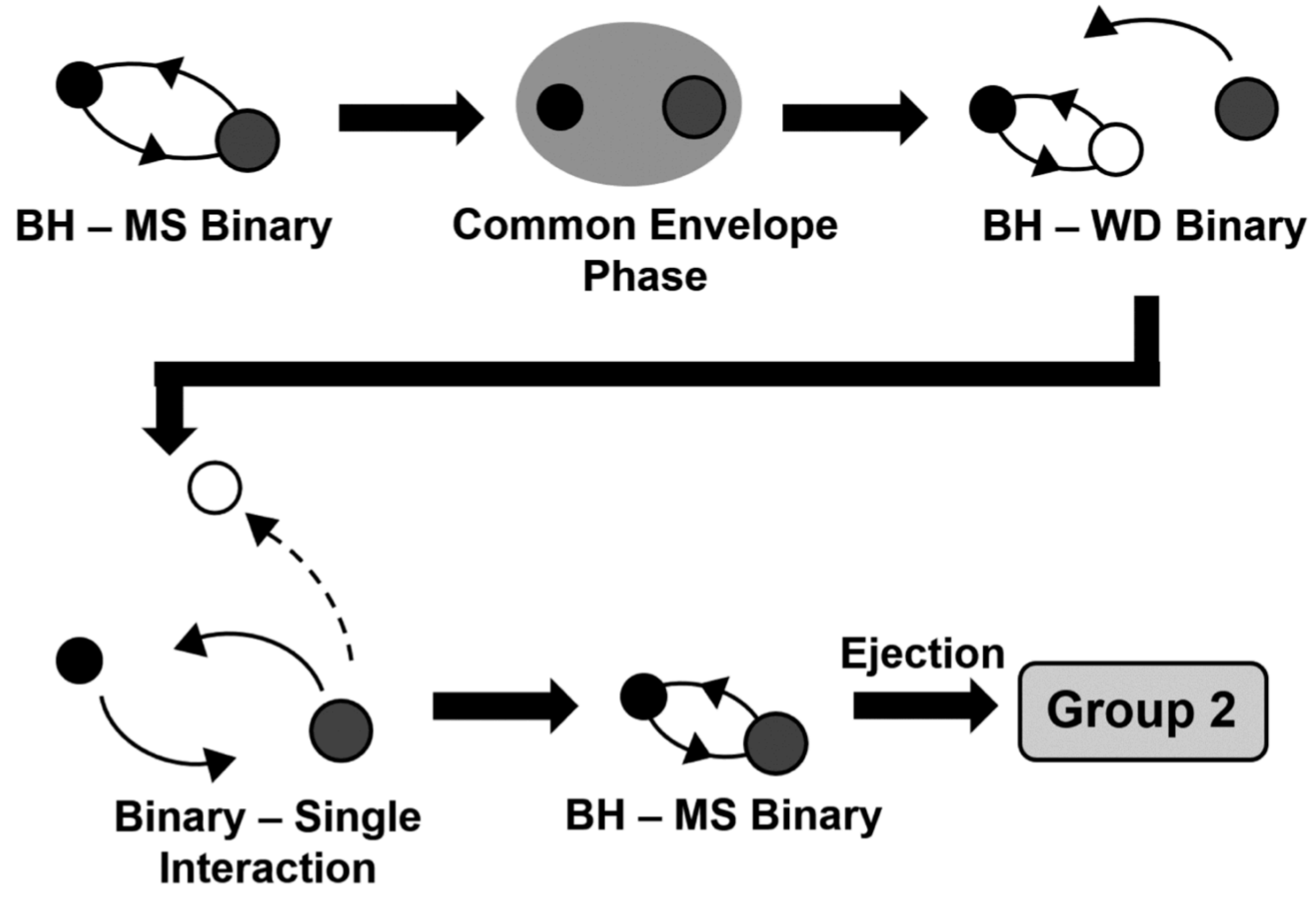




Crisis of the conventional binary evolution model?

# El-Badry's BH in an open cluster?

Shikauchi et al. (2020, PASJ, 72, 45)




Difficult to be formed in an open cluster

# Summary

- The isolated binary scenario(s) can explain not only the BH properties, but also peculiar events like GW190521 and GW190412.

- These scenarios may be constrained by future projects, such as Euclid PISN survey.

- BH binary exploration is providing further information for understanding binary evolution.

- LIGO-Virgo-KAGRA O4 will add much more binary BH population next year.