Gaiaによる不活性コンパクト連星探査とその形成の理論研究

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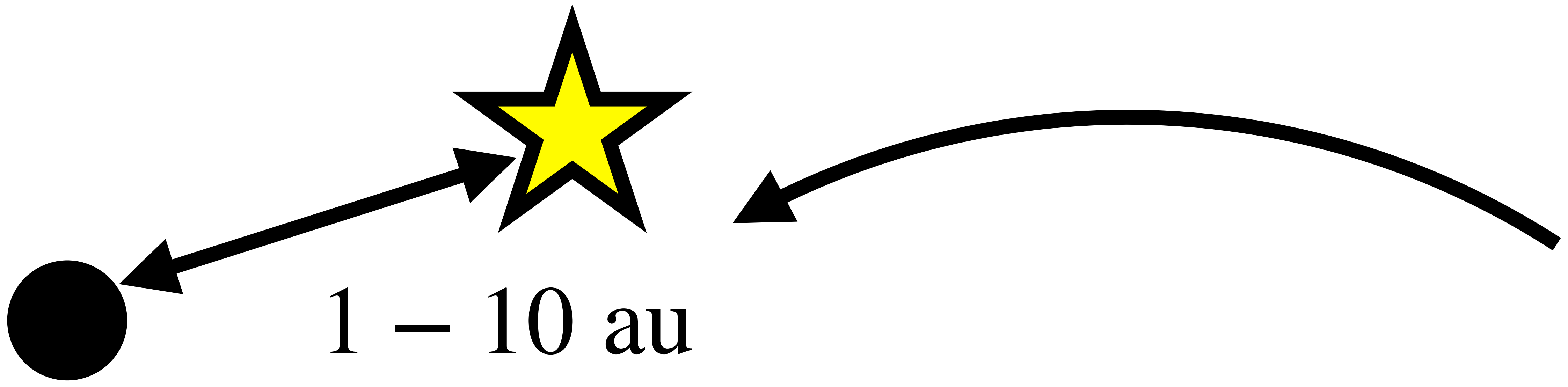
初代星研究会＠北海道大学

- Tanikawa et al. (2023, ApJ, 946, 79, arXiv:2209.05632)
- Tanikawa et al. (2023, MNRAS in press, arXiv:2303.05743)

Summary in advance

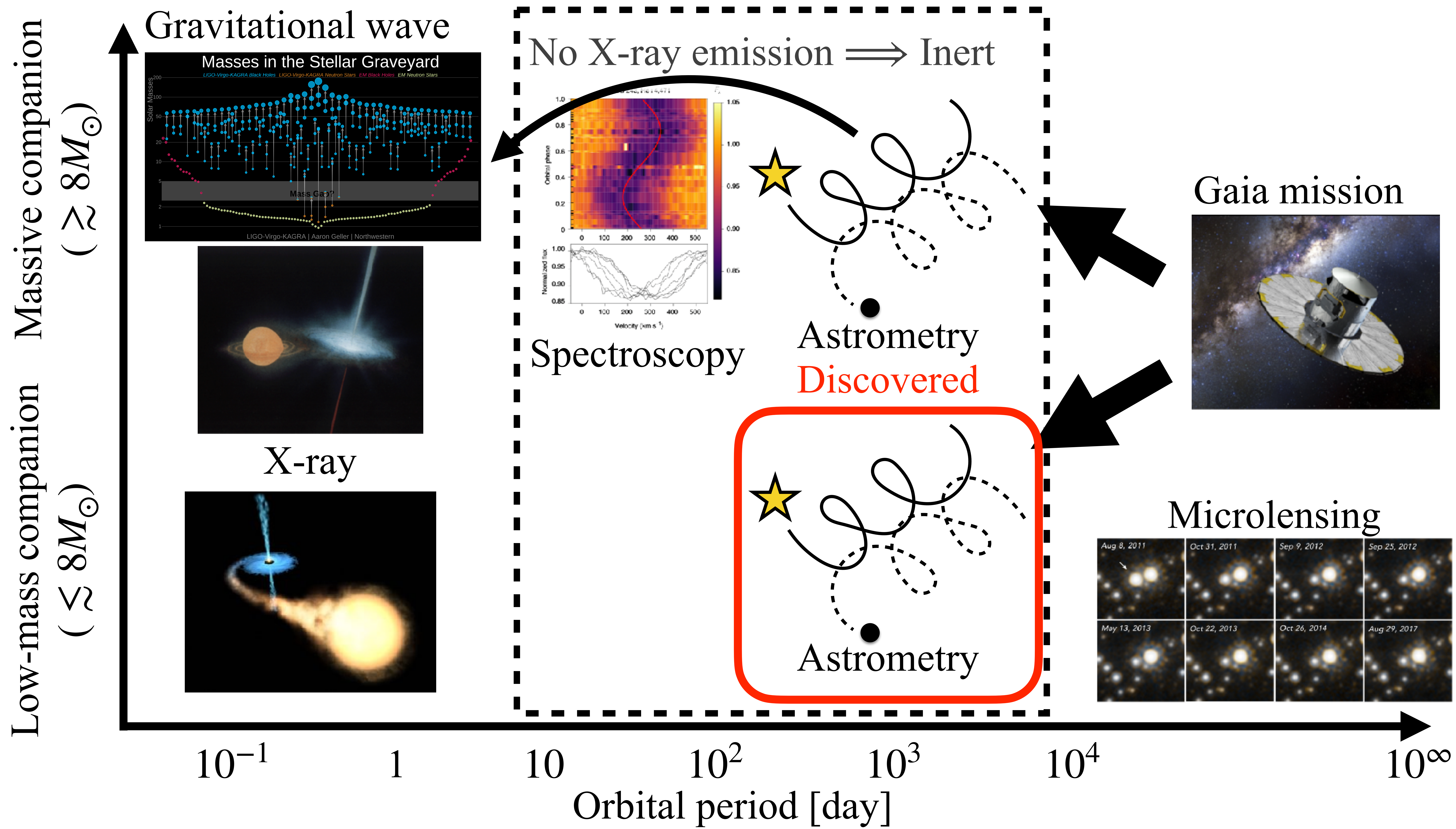
- 重力波による連星BHの発見によりBH探査が活況
- X線で暗い「不活性」なBH連星 （Gaia BH）がGaia DR3から発見 (e.g. Tanikawa et al. 2023, ApJ, 946, 79)
- Gaia BHは連星よりも散開星団で１００倍効率良く形成可能 (Shikauchi+Tanikawa+ 2020; Tanikawa et al. 2023, MNRAS in press).
- せいめいGAOES-RV・なゆたMALLSによりGaia BH/NSを探査中



Masses in the Stellar Graveyard

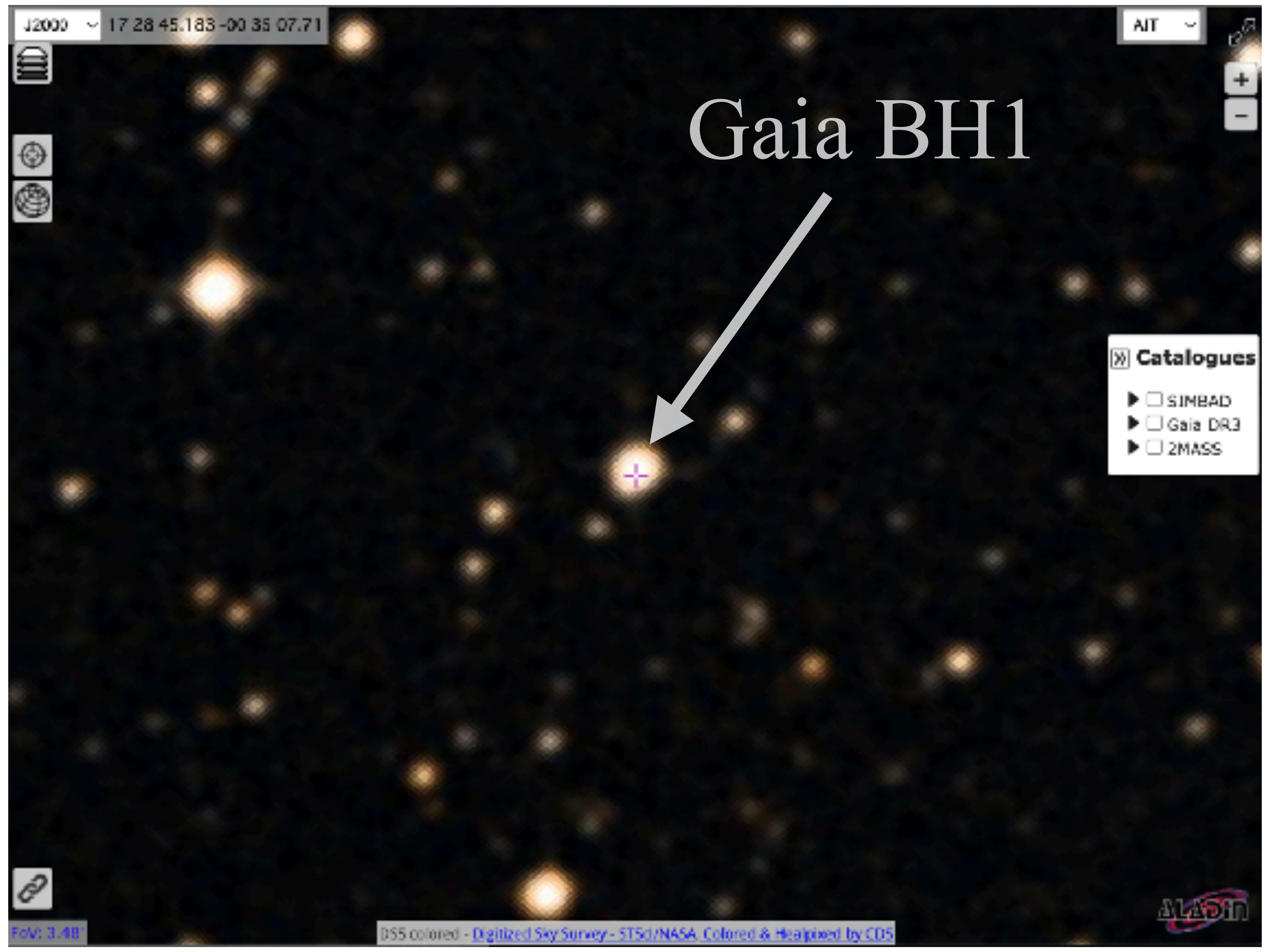
⟹Theory on masive single and binary star evolution

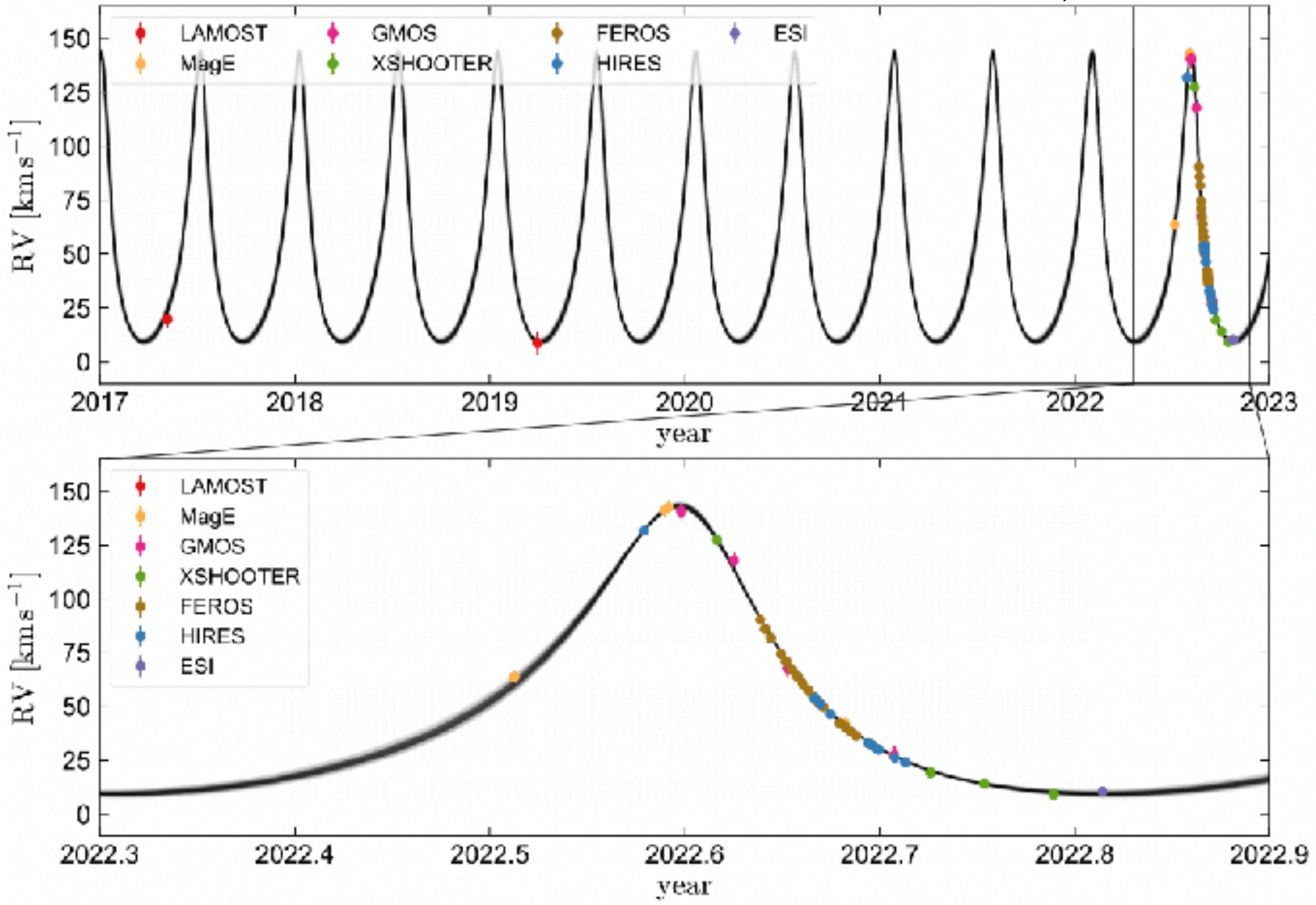
⟹Search for stellar-mass BHs in different ways



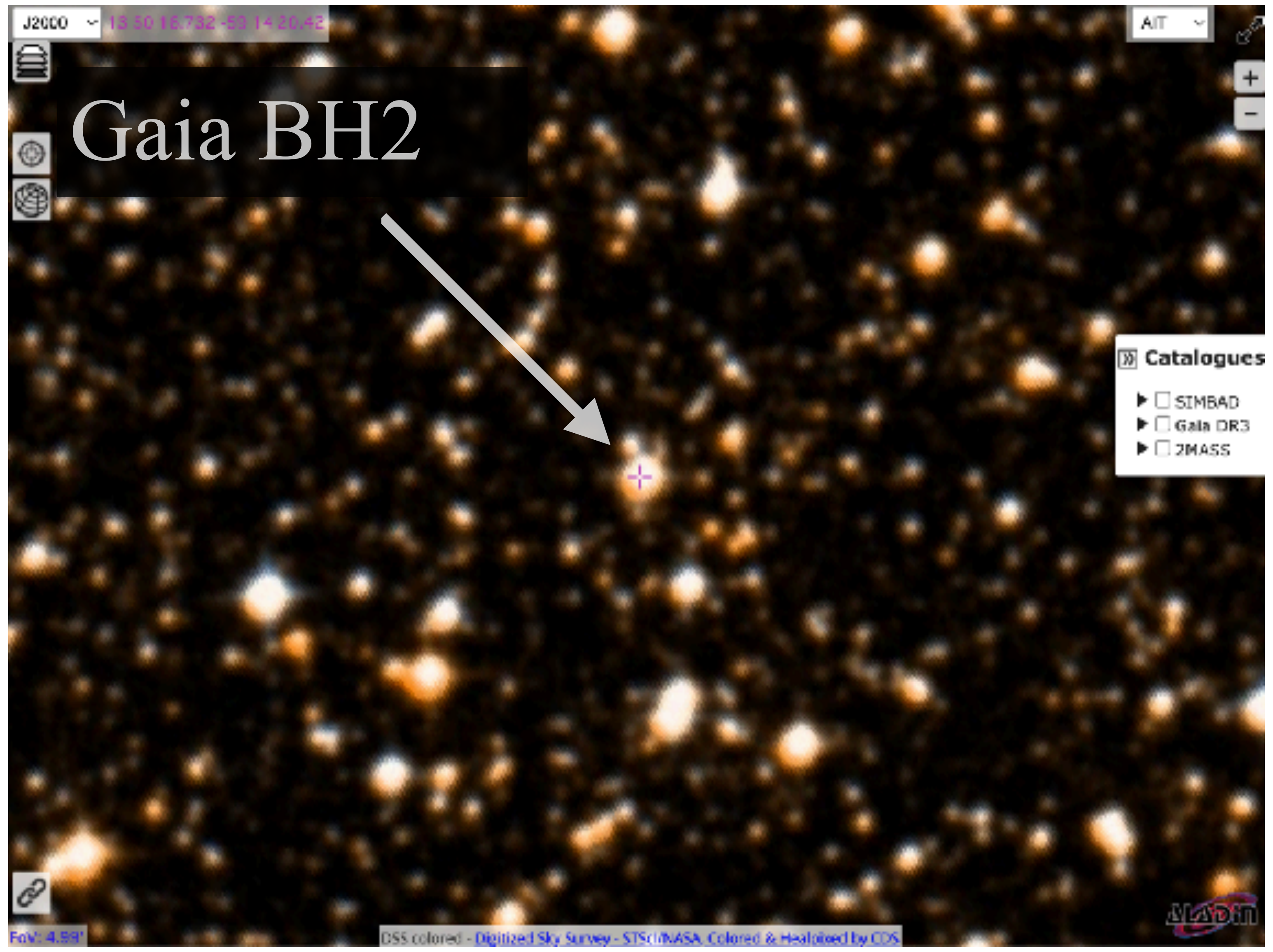
Gravitational wave
Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern
No X-ray emission ⟹ Inert
Spectroscopy
Astrometry
Discovered
Astrometry
Gaia mission
X-ray
Microlensing
Aug 8, 2011
Oct 31, 2011
Sep 9, 2012
Sep 25, 2012
May 13, 2013
Oct 22, 2013
Oct 26, 2014
Aug 29, 2017
Massive companion ($\gtrsim 8M_\odot$)
Low-mass companion ($\lesssim 8M_\odot$)
10^{-1}
1
10
10^2
10^3
10^4
10^∞
Orbital period [day]

El-Badry et al. (2023; see also Chakrabarti et al. 2023)





- Andrews+ (2207.00680)
  - 偽陽性: N/A (0/0)
  - 偽陰性: 100% (0/1)
- Shahaf+(2209.00828)
  - 偽陽性: 75% (3/4)
  - 偽陰性: 0% (0/1)
- Tanikawa+(2209.05632)
  - 偽陽性: 0% (0/1)
  - 偽陰性: 0% (0/1)



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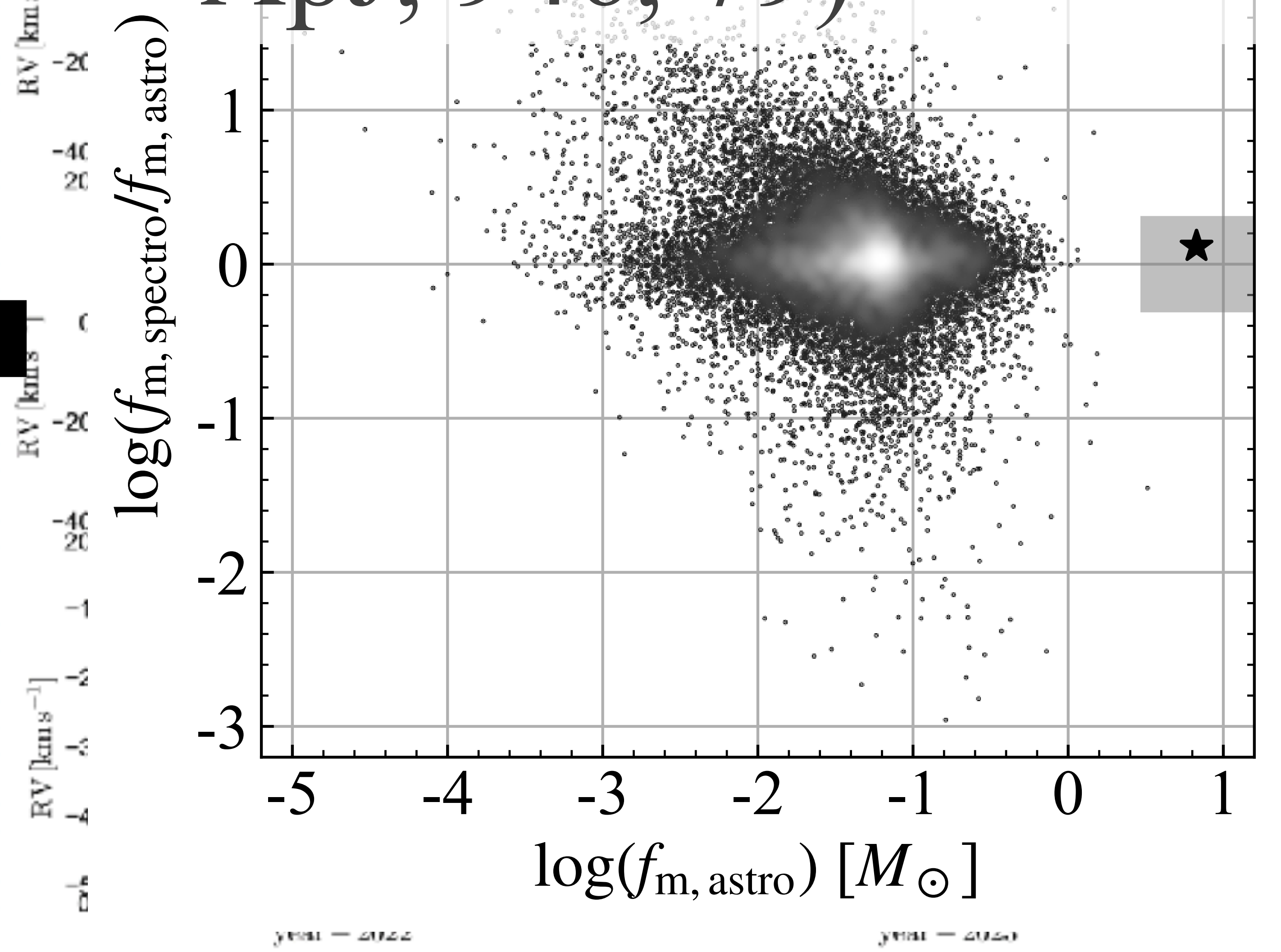
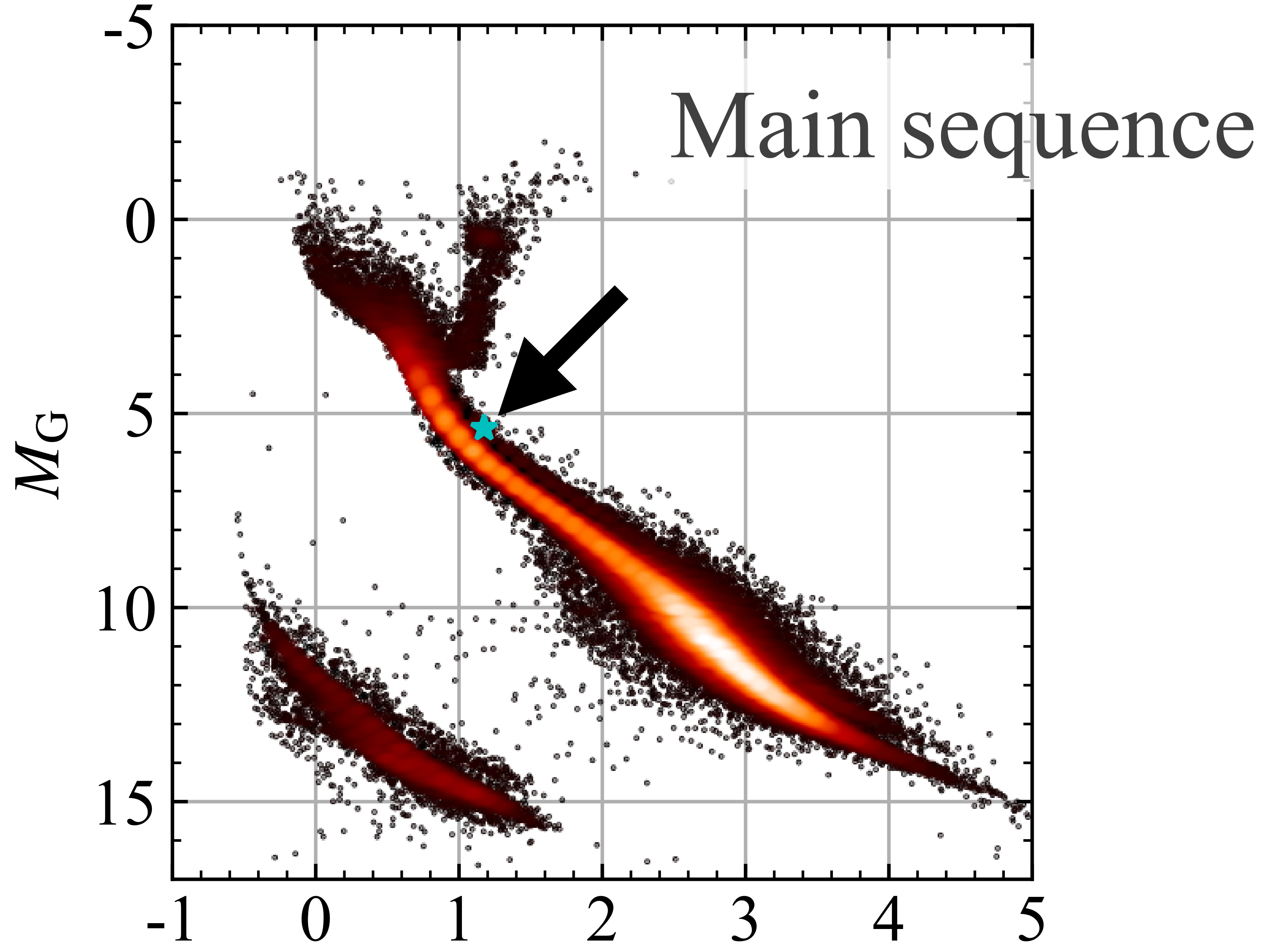
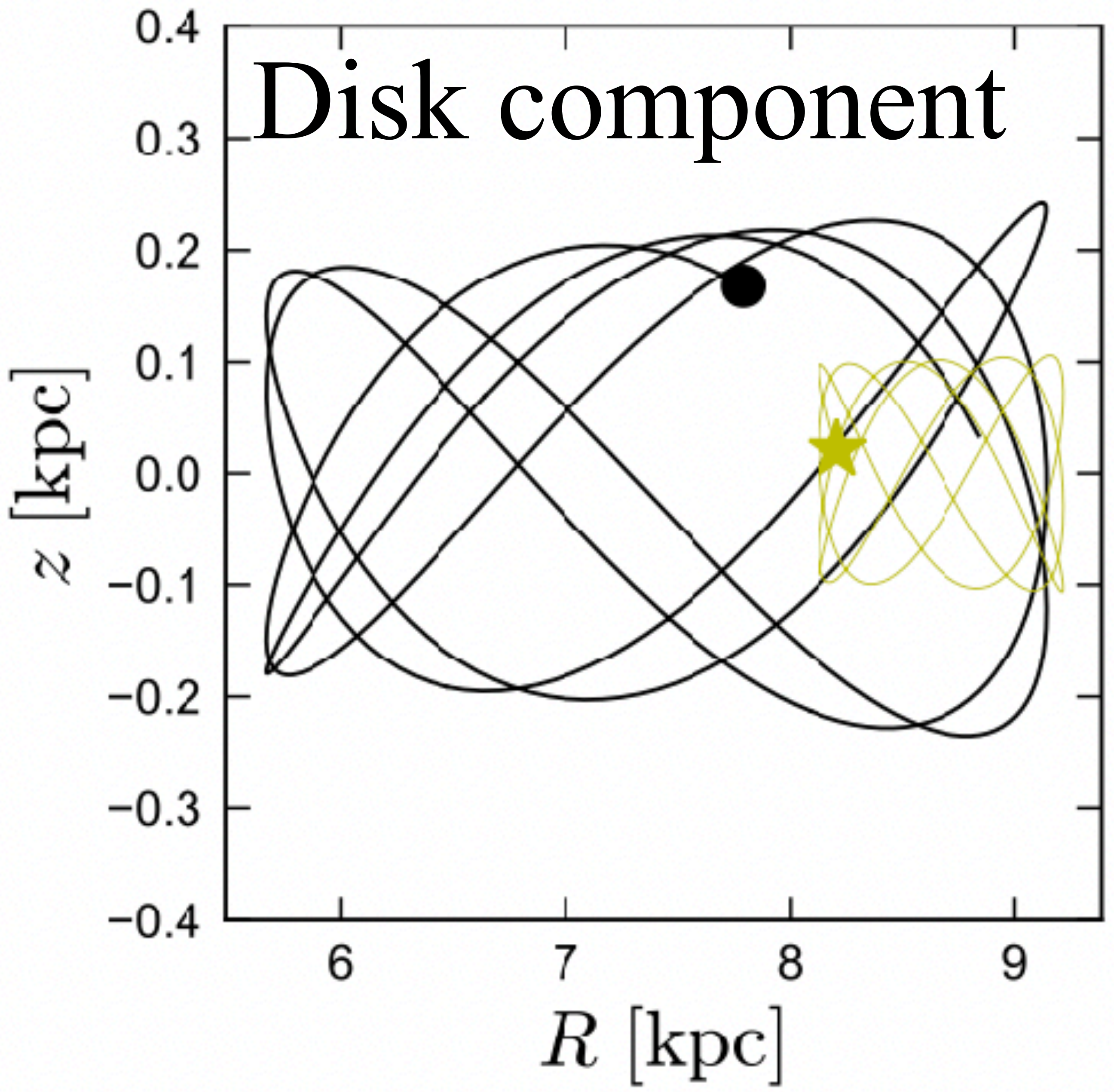


We discovered Gaia BH2 not at random.

Gaia BH1

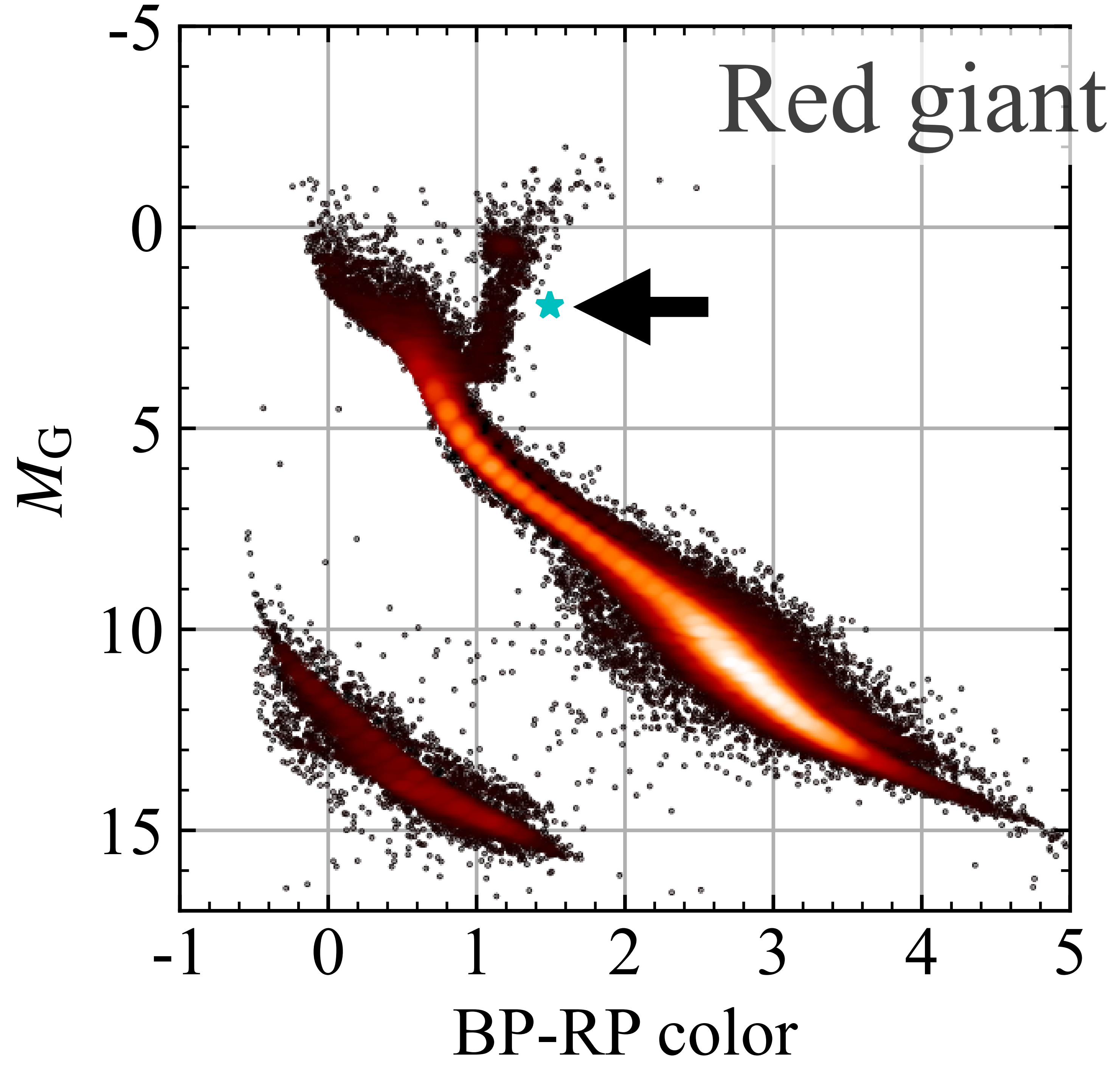
- $M_{\mathrm{BH}} = 9.62 M_{\odot}$
- $M_{\mathrm{comp}} = 0.93 M_{\odot}$
- $P = 185.59$ d
- $a = 1.40$ au
- $e = 0.451$
- $[\mathrm{Fe/H}] = -0.2$

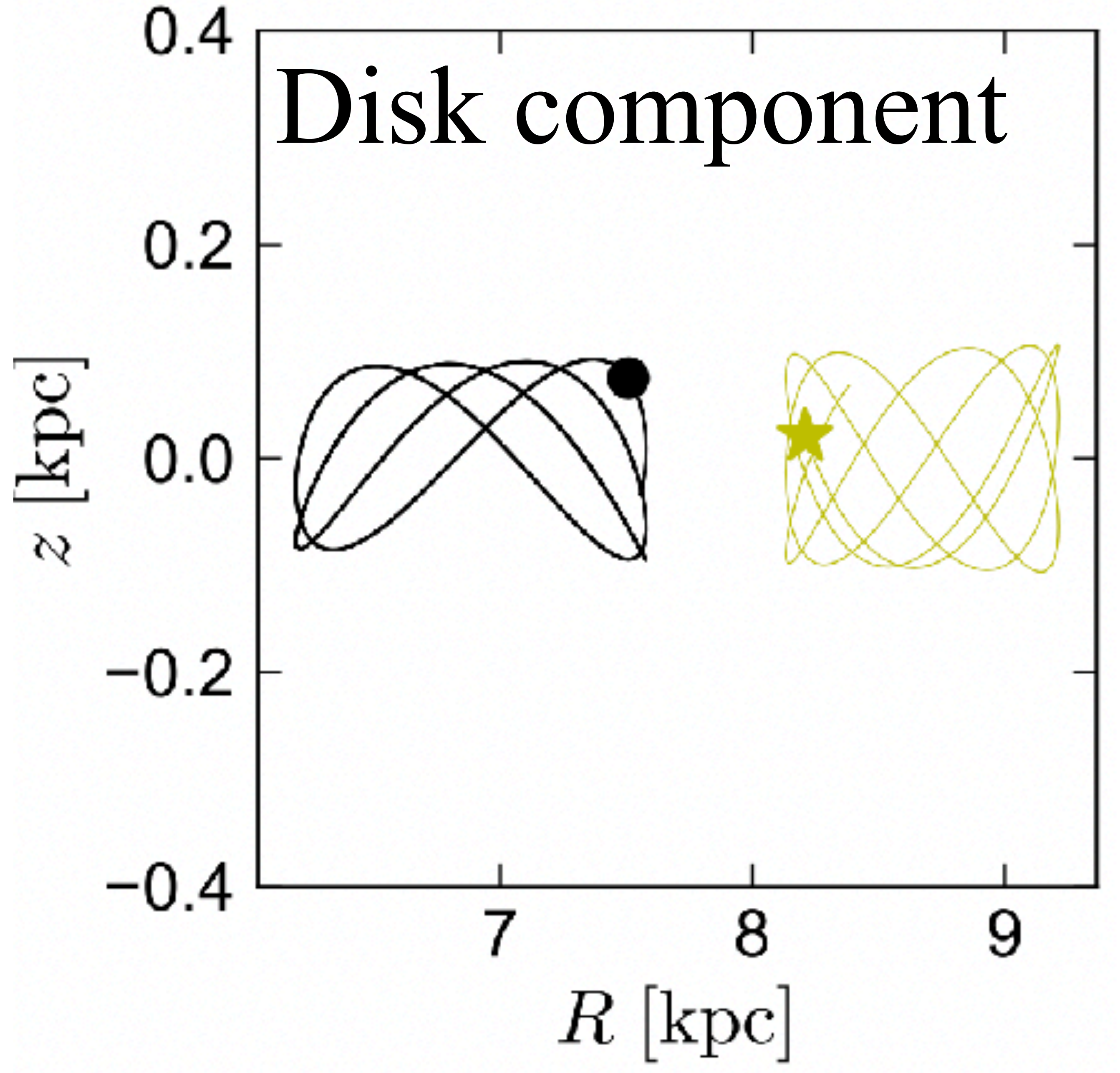


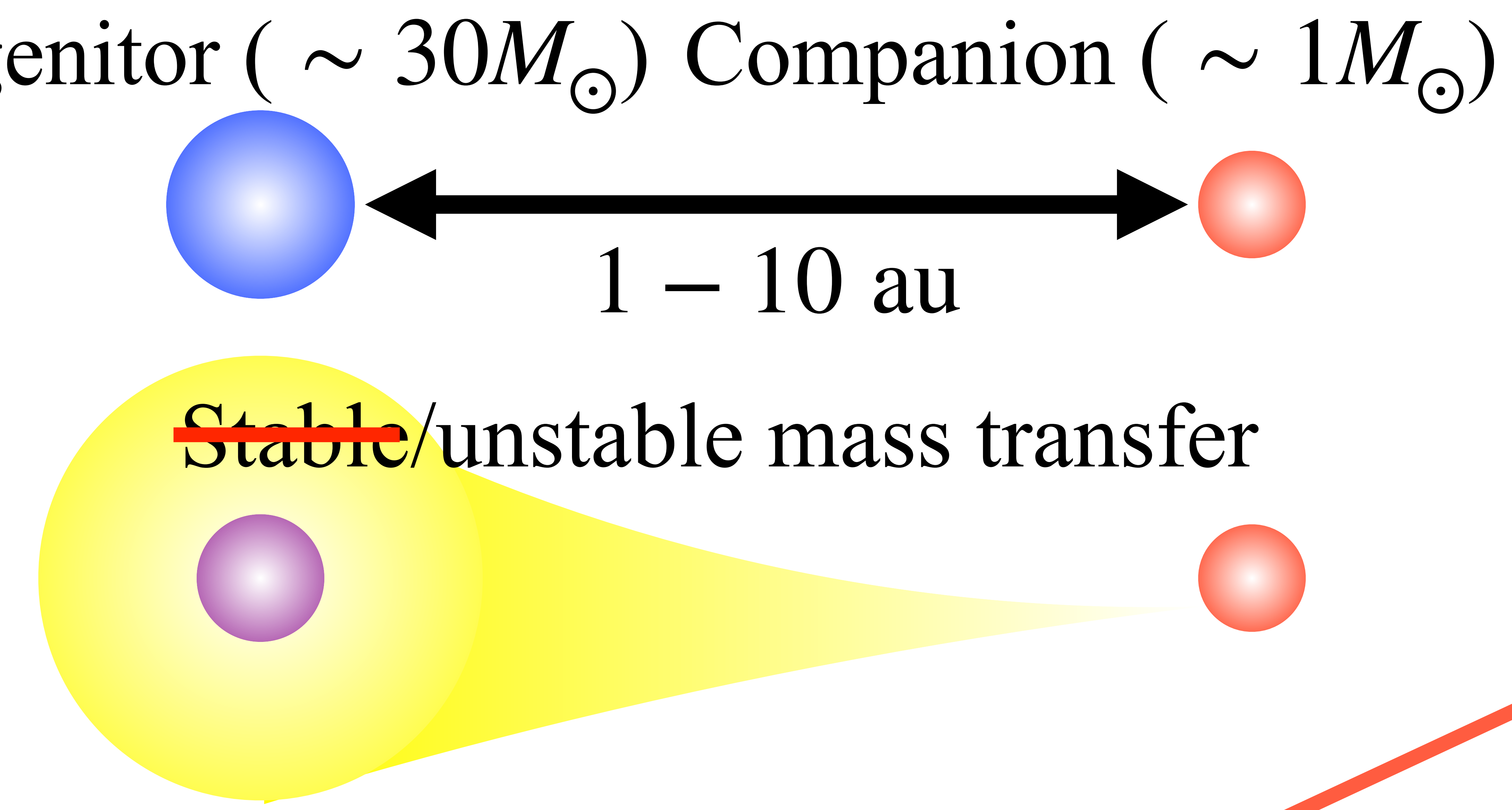


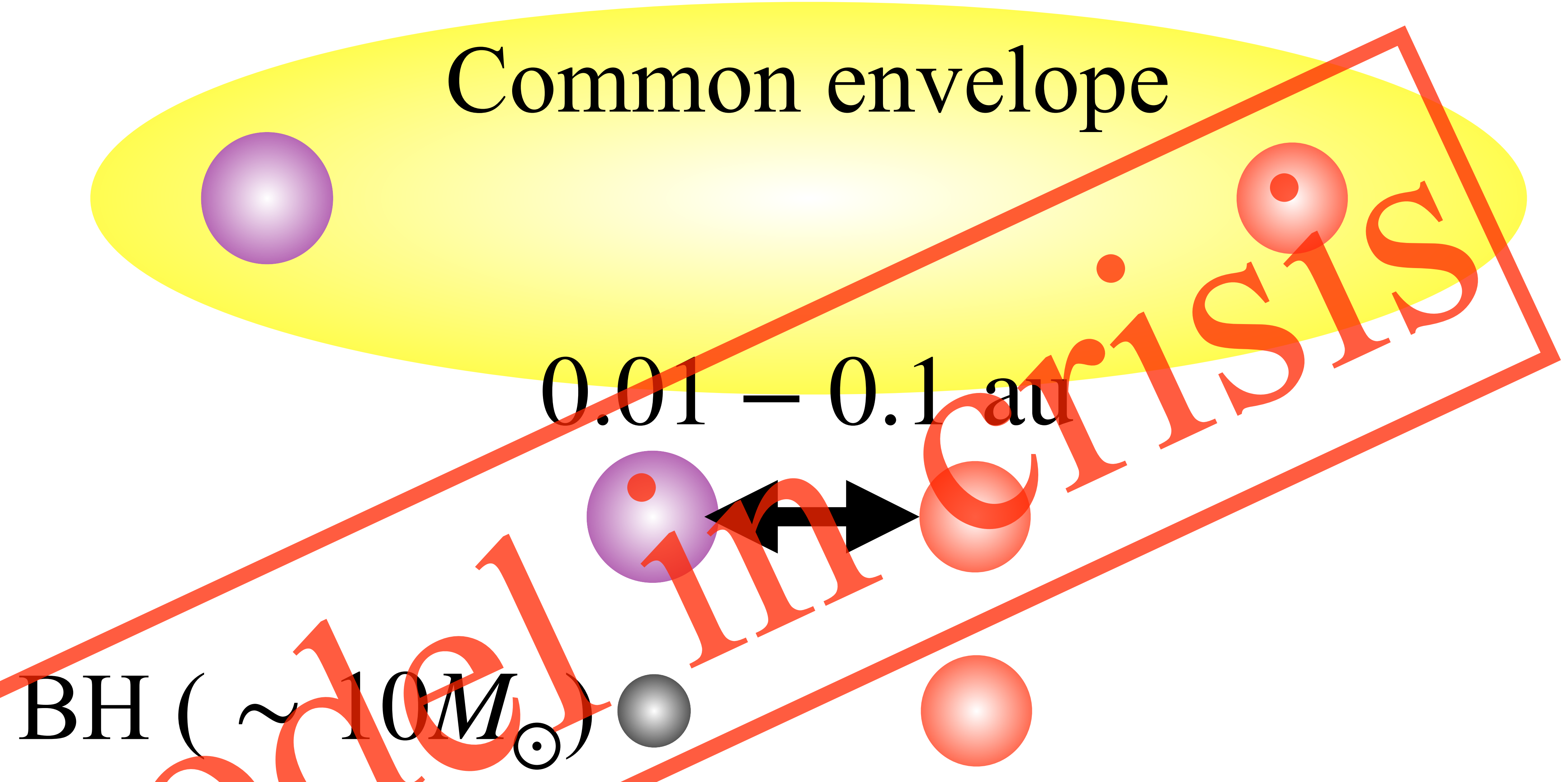
Gaia BH2

- $M_{\mathrm{BH}} = 8.94 M_{\odot}$
- $M_{\mathrm{comp}} = 1.07 M_{\odot}$
- $P = 1276.7$ d
- $a = 4.96$ au
- $e = 0.5176$
- $[\mathrm{Fe/H}] = -0.22$



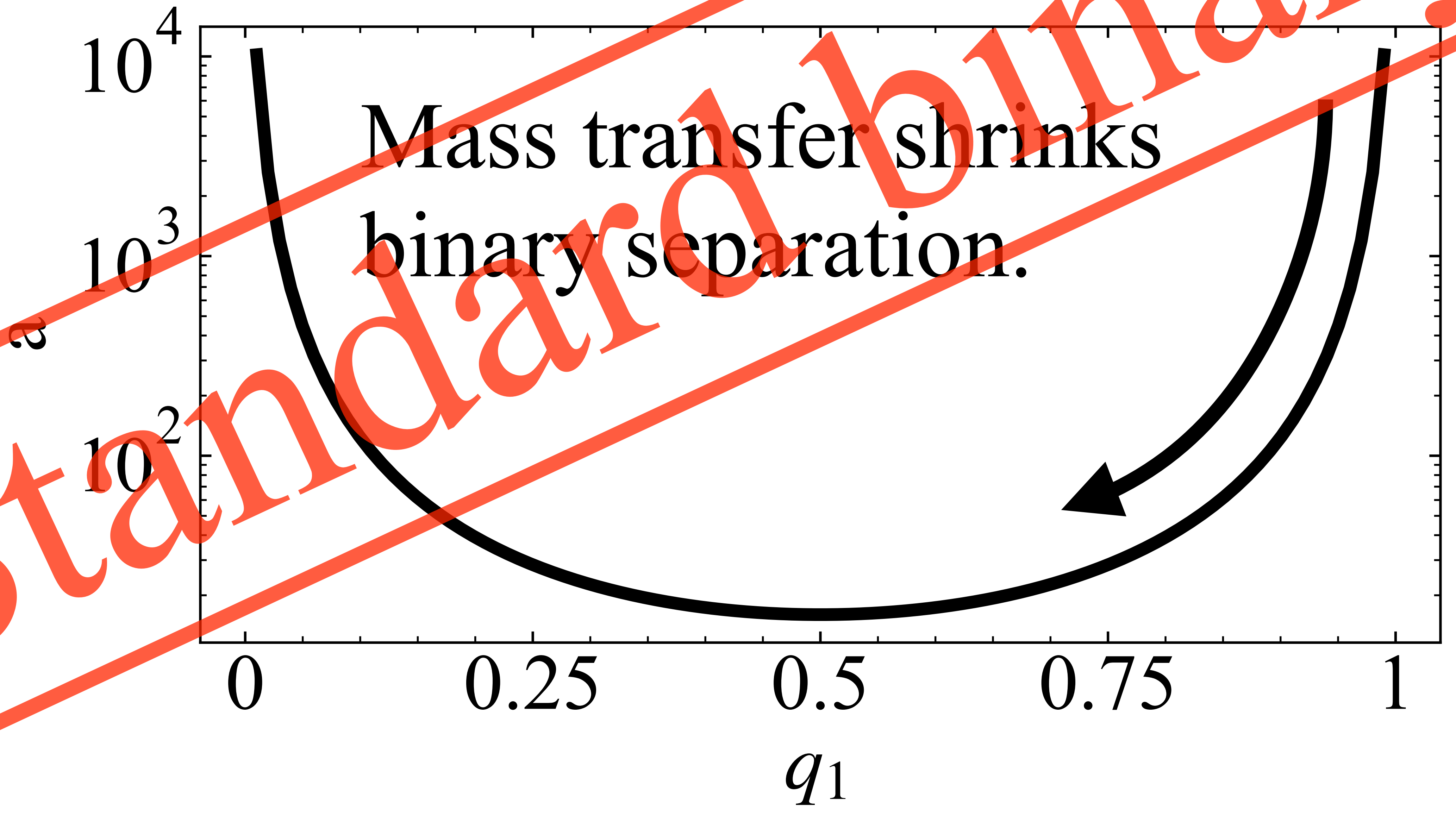






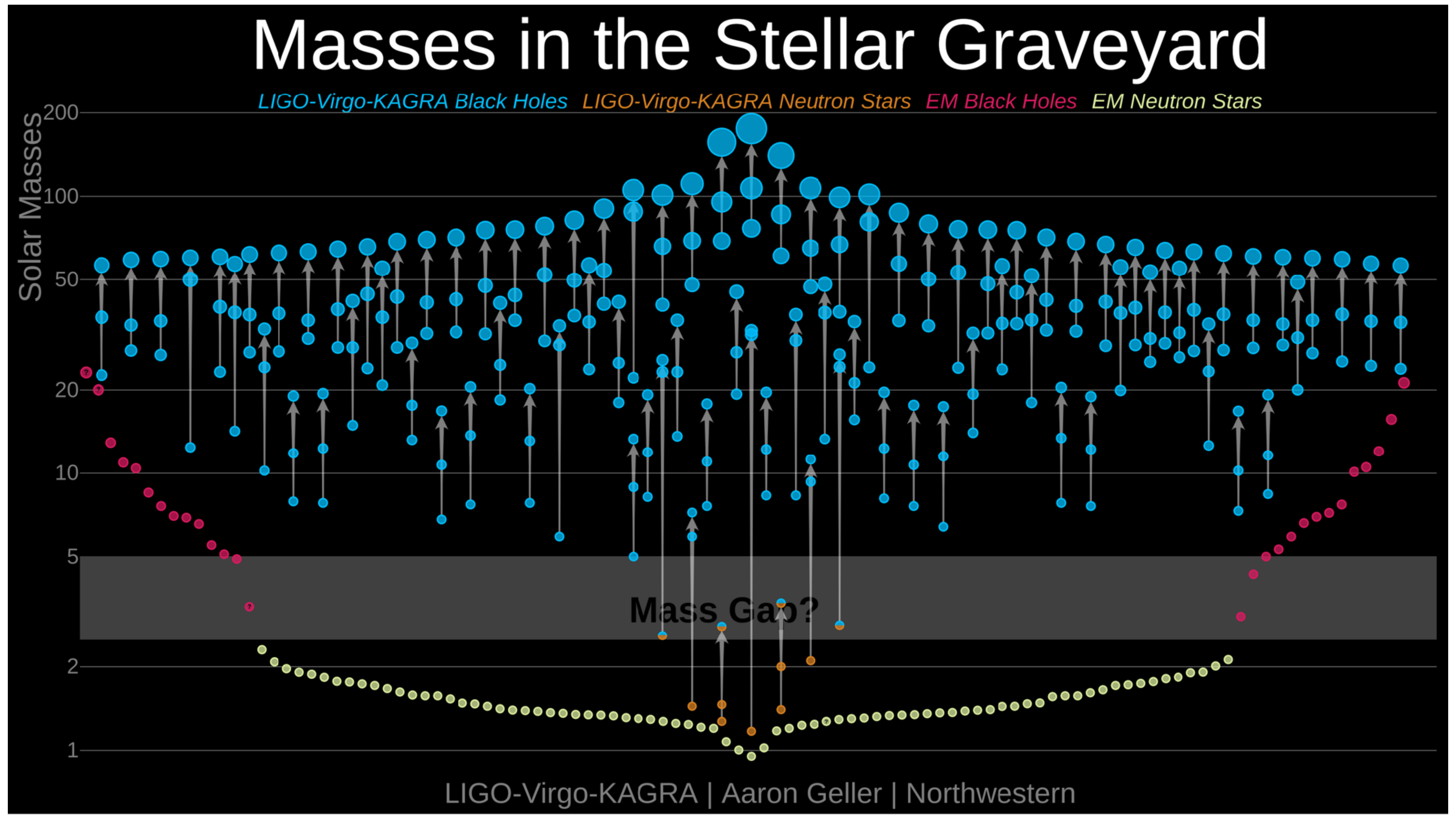
Standard binary model in crisis

$$a = \frac{J^2 M}{G M_1^2 M_2^2} = \frac{J^2}{G M^3 q_1^2 (1-q_1)^2} \quad (q_1 = M_1/M)$$

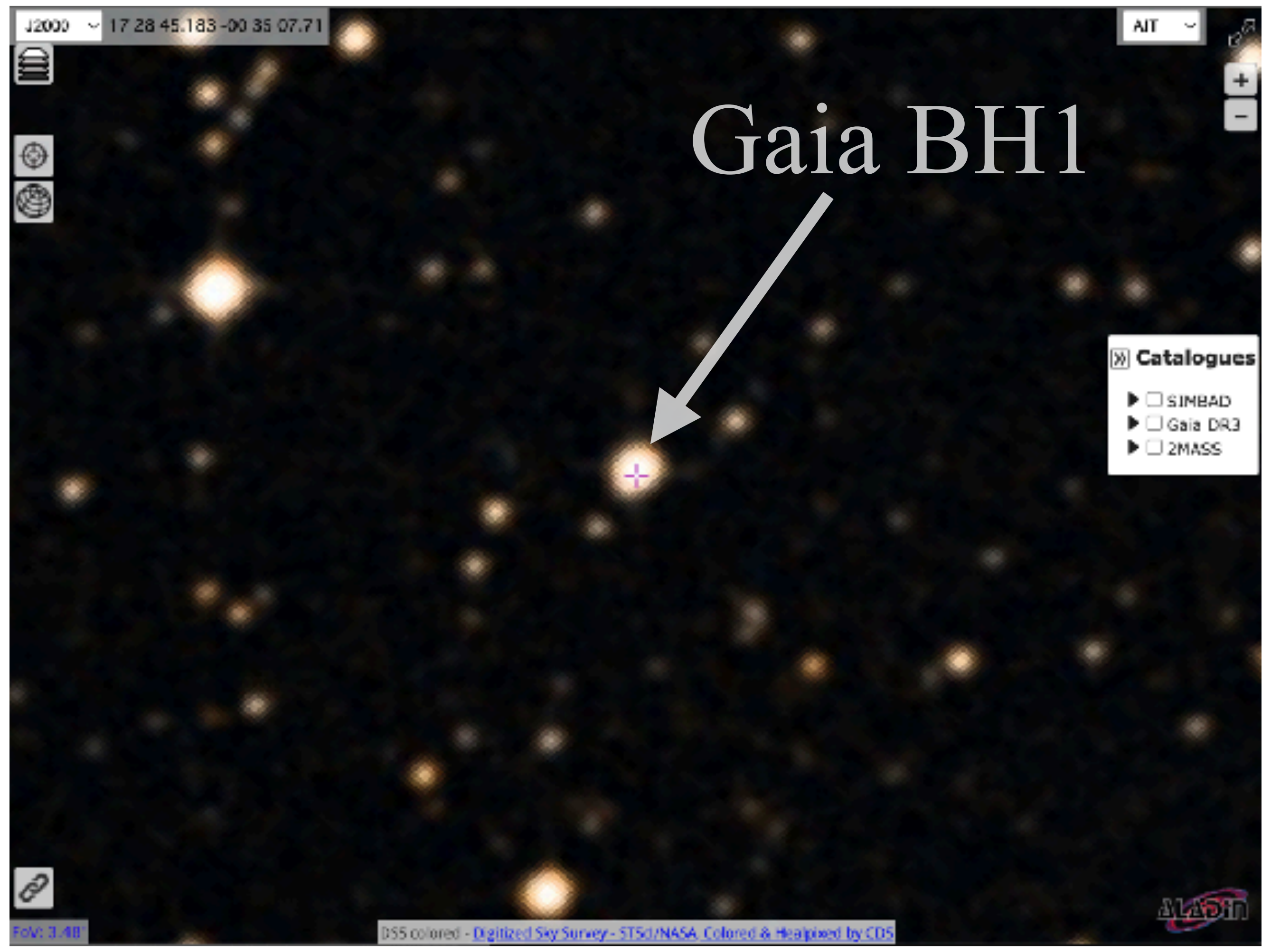


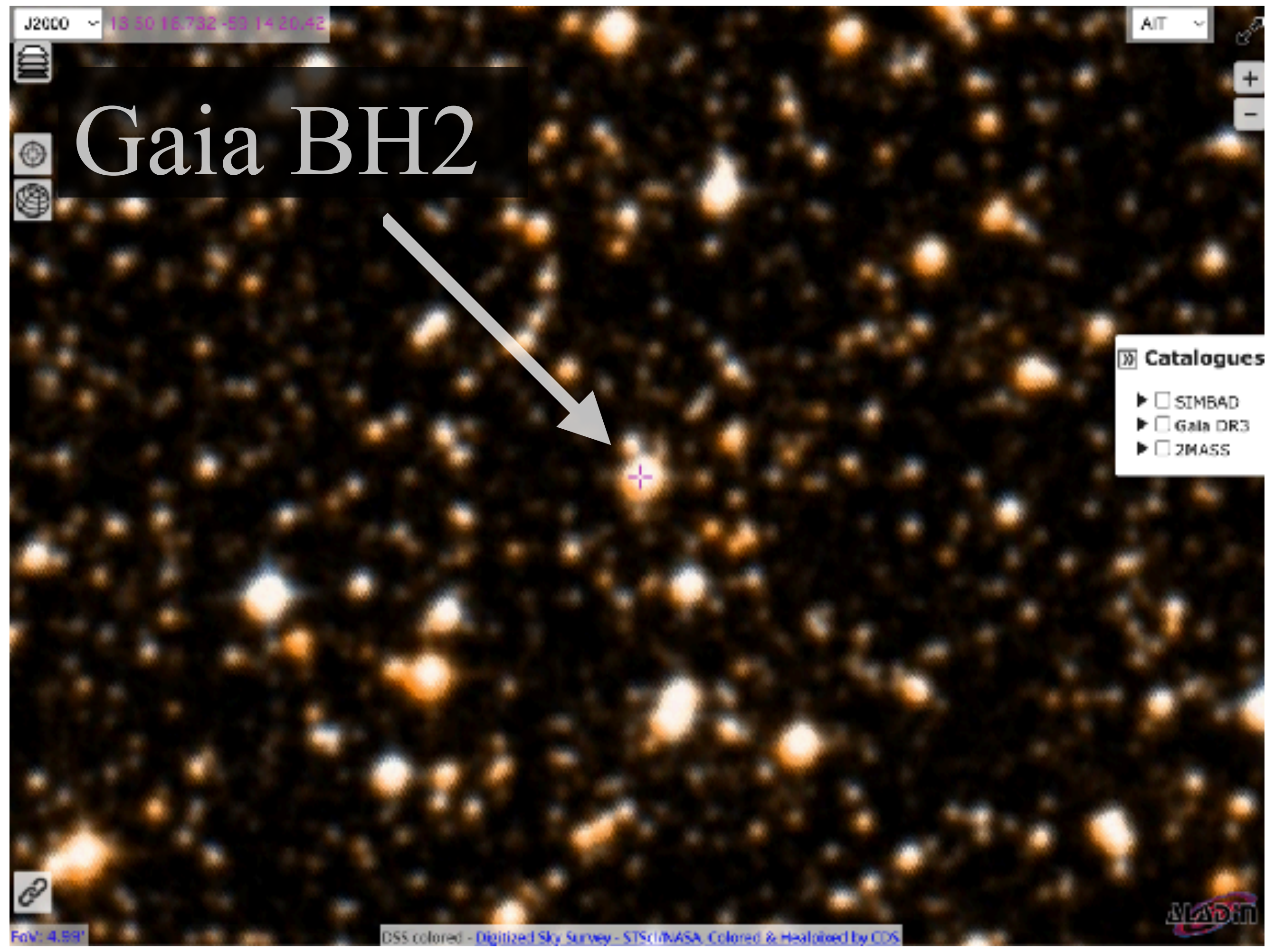
- $E_{\rm env} = \alpha_{\rm CE} \left(E_{\rm orbit,fin} - E_{\rm orbit,init}\right) \sim \alpha_{\rm CE} E_{\rm orbit,fin}$
- $E_{\rm env} = \dfrac{G M_{\rm core} M_{\rm env}}{\lambda_{\rm CE} R_{\rm env}}$, $E_{\rm orbit} = \dfrac{G M_{\rm core} M_{\rm comp}}{2 a_{\rm orbit}}$
- $a_{\rm orbit,fin} \sim 0.025\ {\rm au} \left(\dfrac{\alpha_{\rm CE}}{1.0}\right) \left(\dfrac{\lambda_{\rm CE}}{0.1}\right) \left(\dfrac{M_{\rm comp}}{1 M_\odot}\right) \left(\dfrac{M_{\rm core}}{10 M_\odot}\right)^{-1}$
- $\Longrightarrow a_{\rm orbit,fin} \ll a_{\rm GaiaBH} \sim 1$ au
- $\Longrightarrow \alpha_{\rm CE} > 10$ is required, but it is difficult for massive stars (private communication with Ryosuke Hirai)

The origin of Gaia BHs



- Binary (Pop I/II, Pop III)
- Triple/Quadruple (Pop I/II, Pop III)
- Open cluster
- Globular cluster
- Galactic center/AGN disk
- Primordial BH

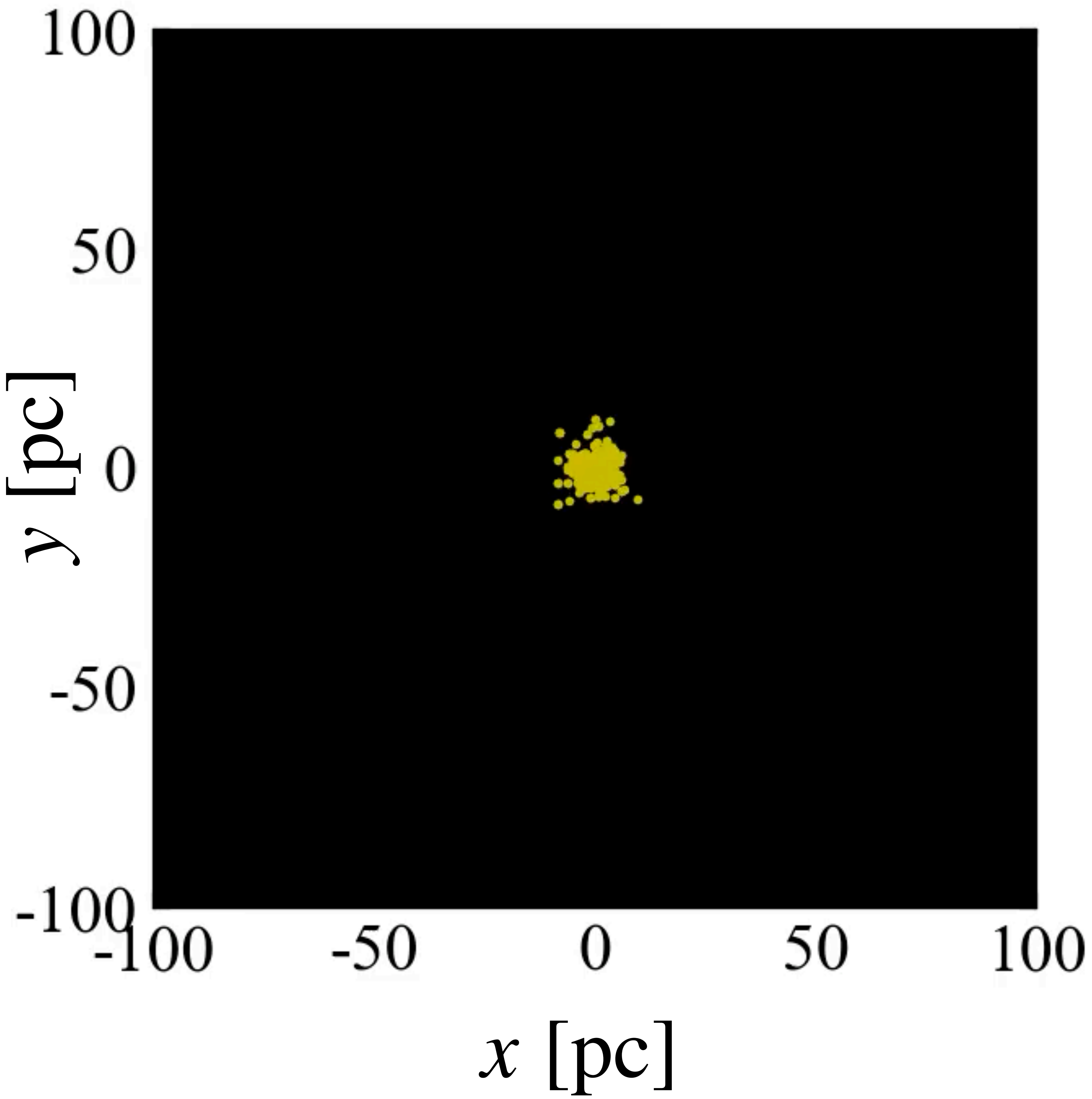


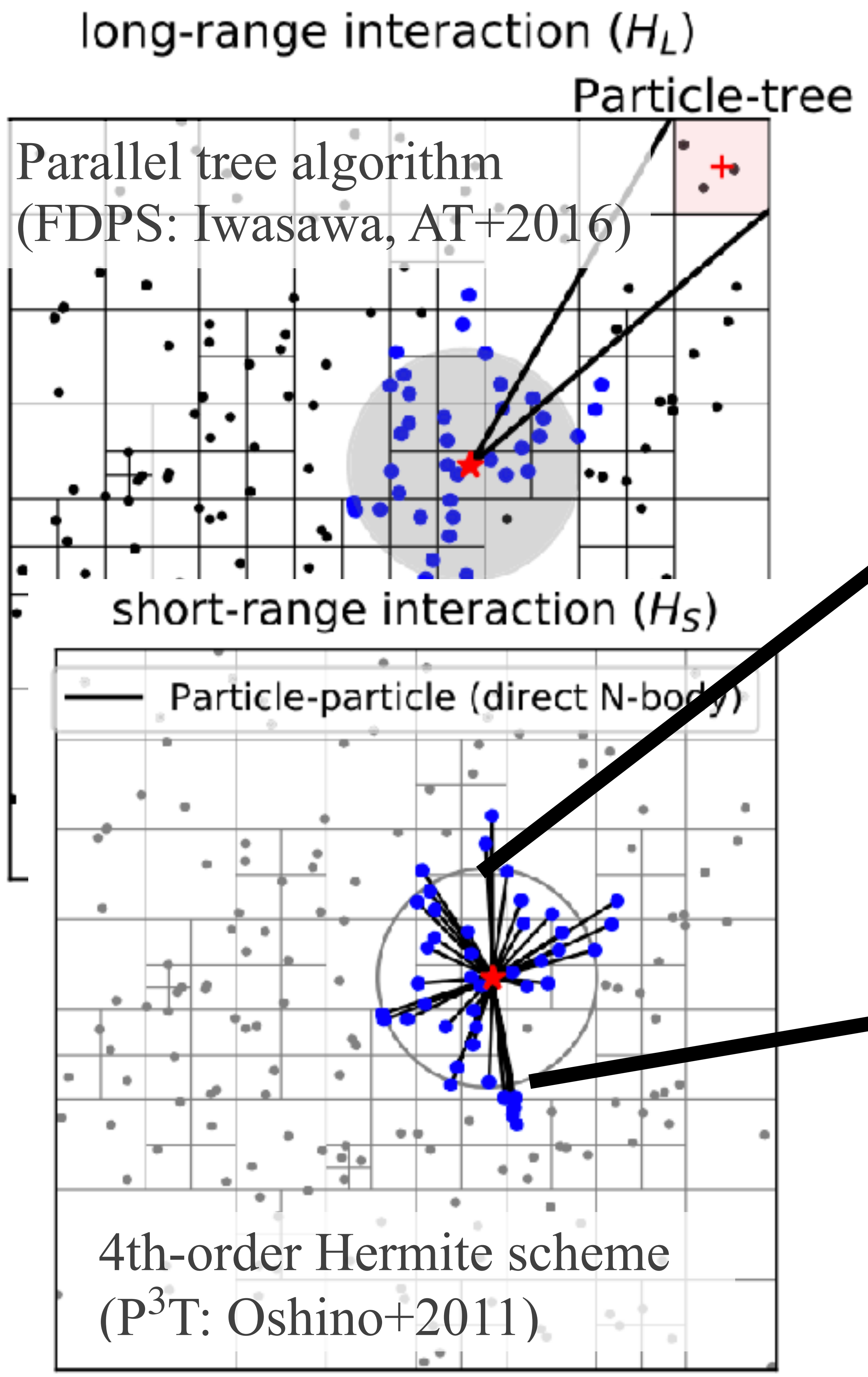


∵ Previous slide ∵ Companion's metallicity

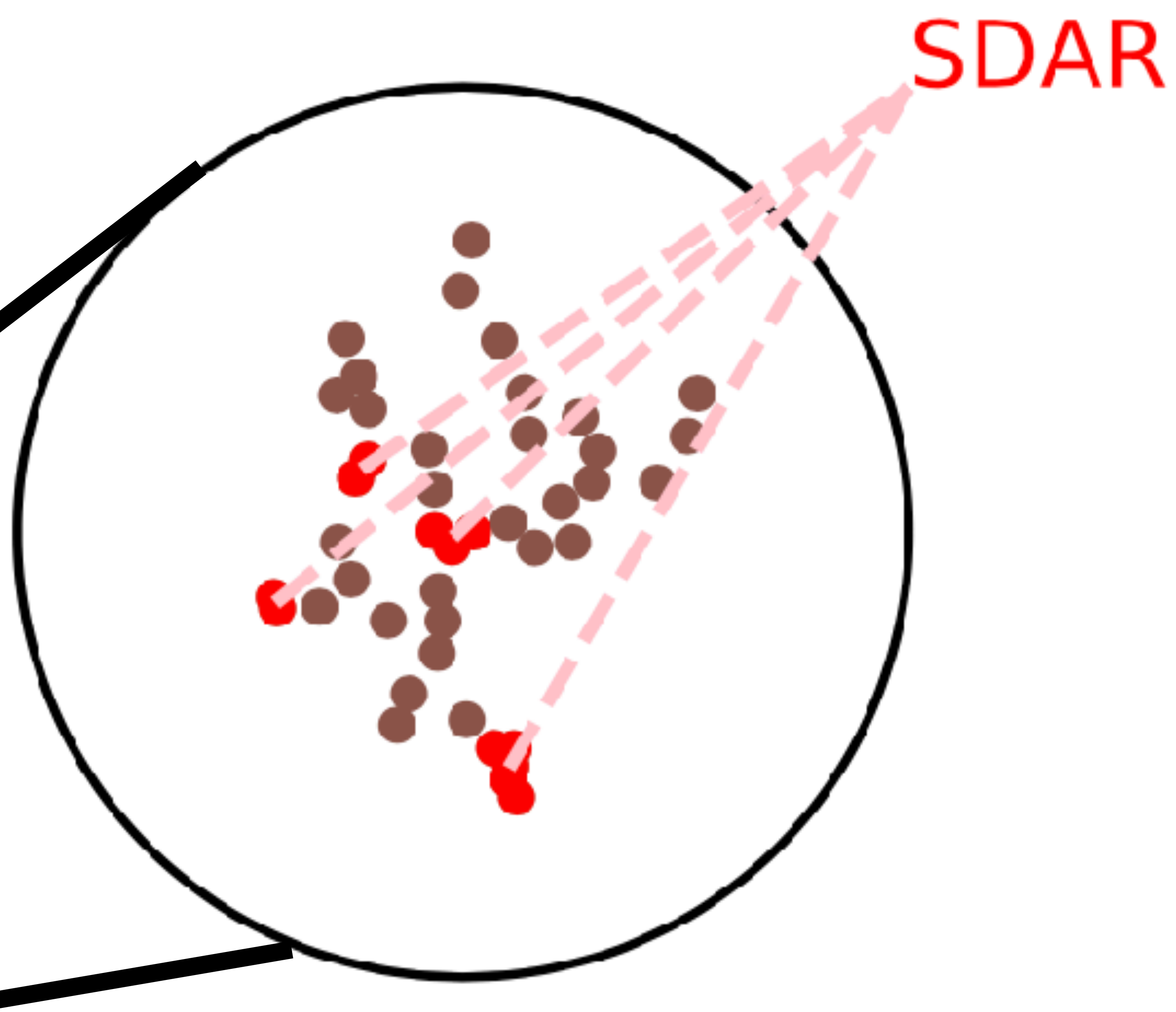
- ~~Binary (Pop I/II, Pop III)~~
- Triple/Quadruple (Pop I/II, ~~Pop III~~)
- Open cluster
- ~~Globular cluster~~ ∵ Disk components
- ~~Galactic center/AGN disk~~
- ~~Primordial BH~~ ∵ Small capture rate

N-body simulation for open clusters
PeTar (Wang et al. 2020)





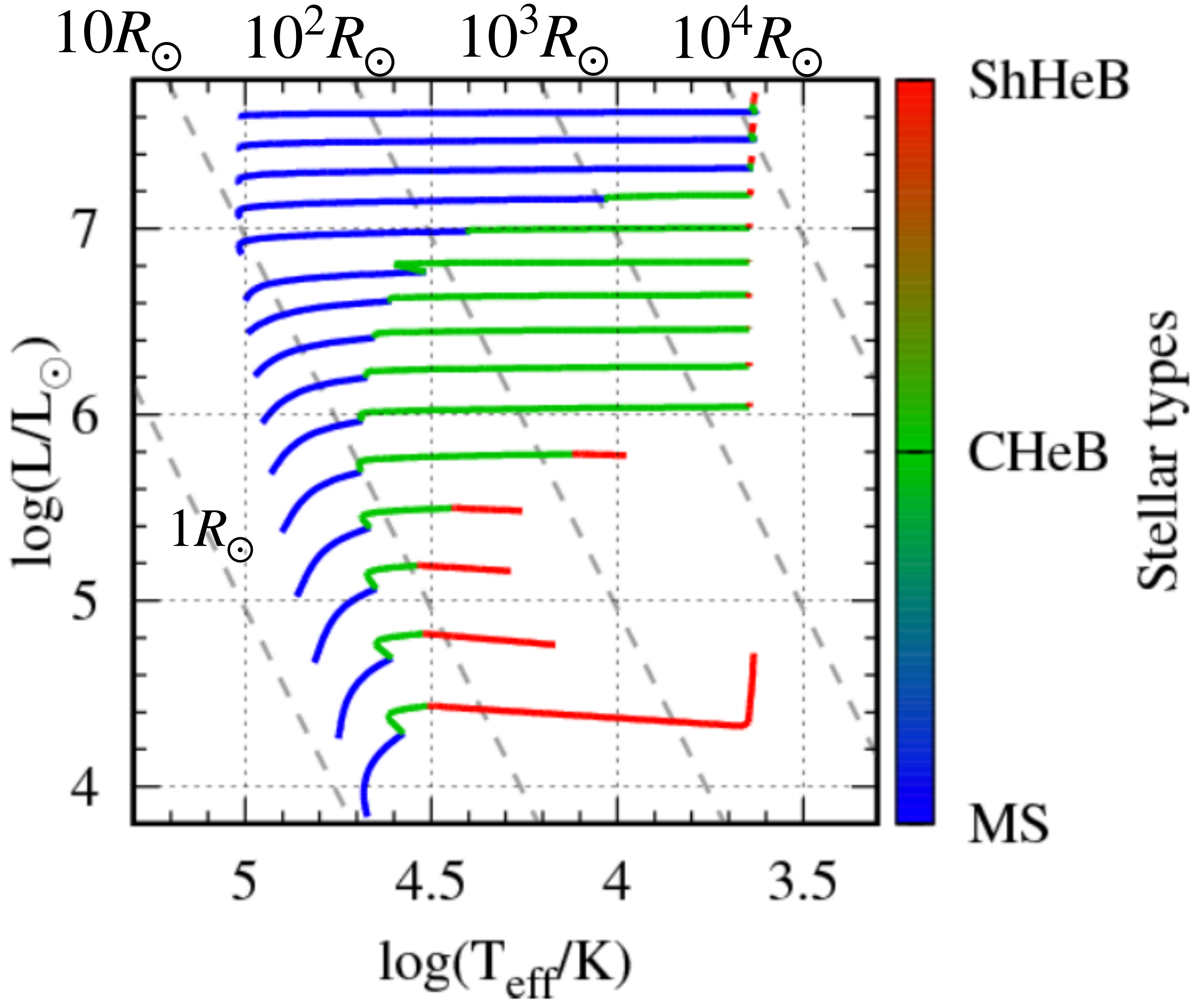
Binary and close encounter



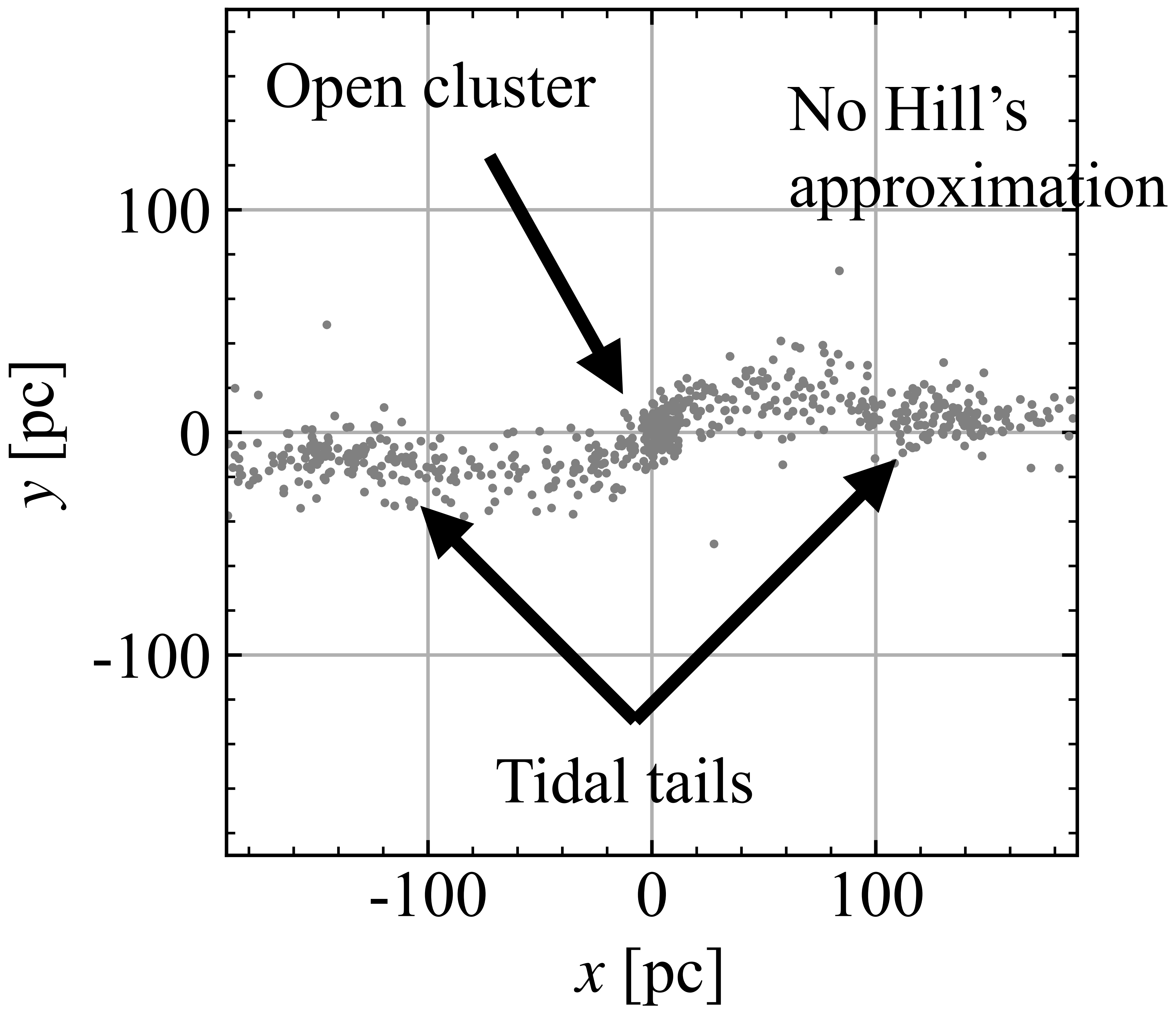
SDAR: Slow-Down Algorithmic Regularization (Wang+2020)

Physical effects

Single/Binary star evolution
(BSEEMP: AT+20)



Galactic potential
(GALPY: Bovy12)

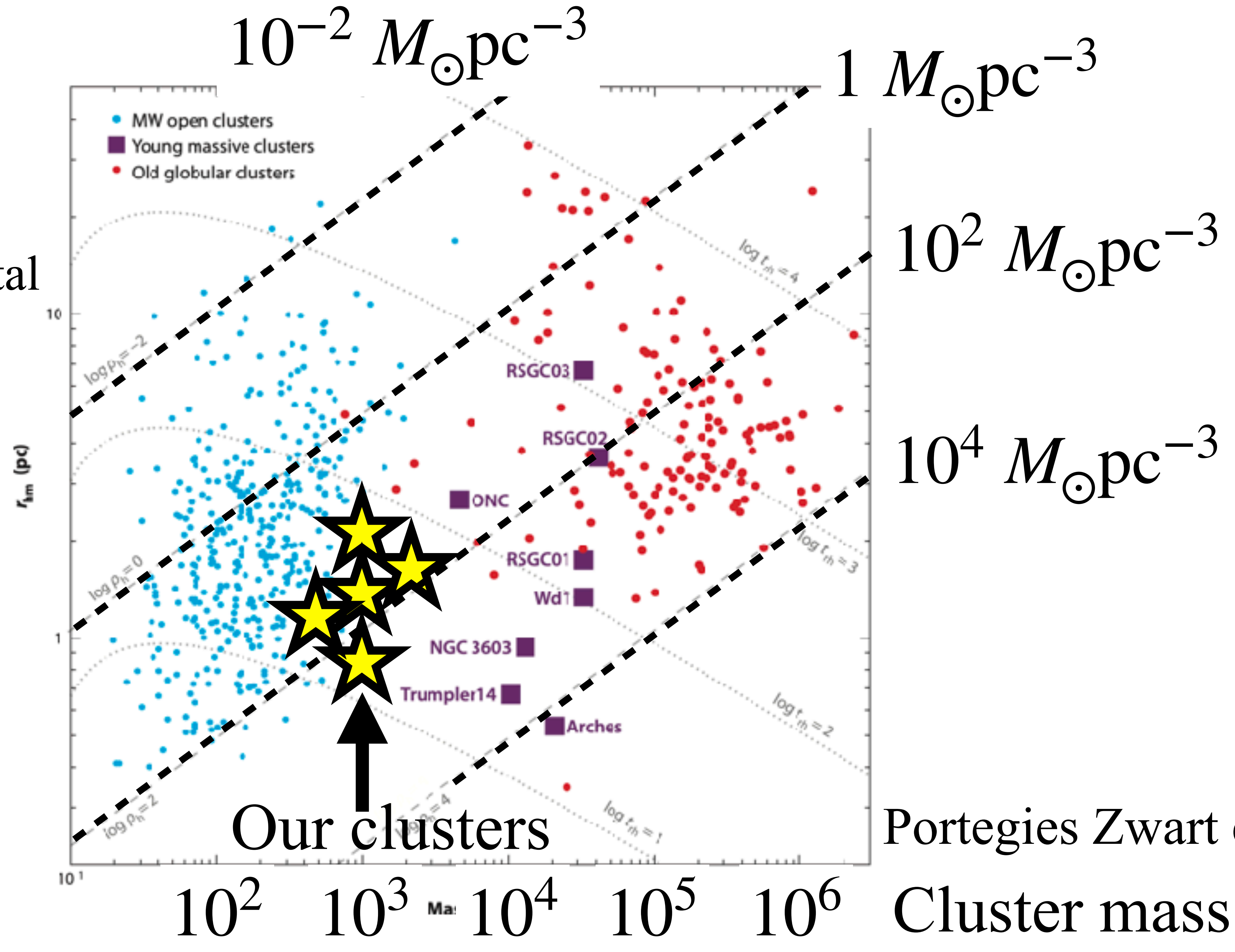


Initial conditions of open clusters

- Cluster mass: $500 - 2000 M_\odot$
- Global density: $2 - 200\ M_\odot\ \mathrm{pc}^{-3}$
- Binary fraction: 0, 20, 50%
- SN model: w/o and w/ $3 - 5 M_\odot$

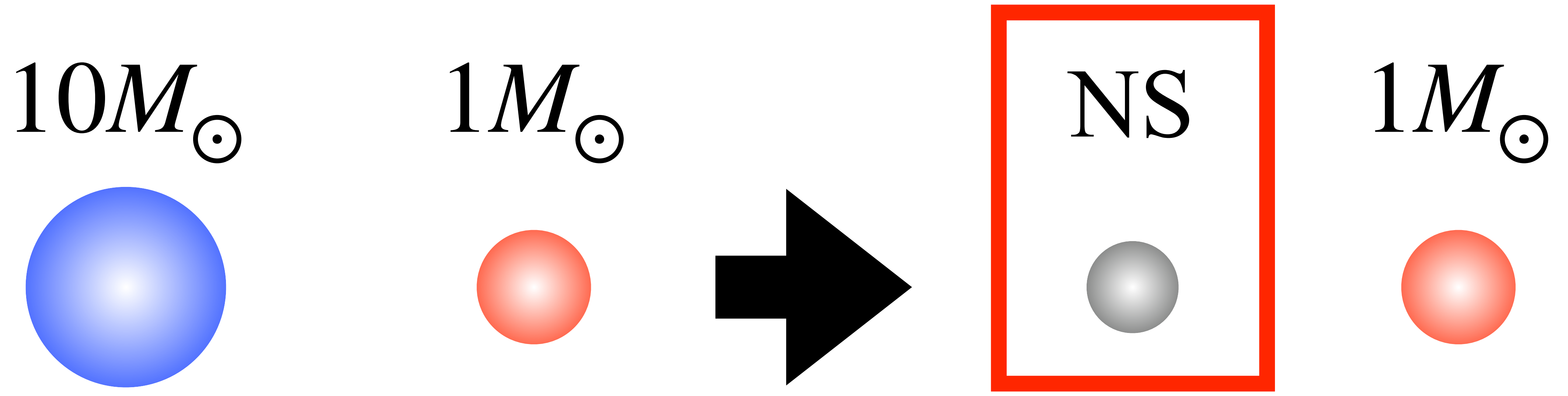
$10^6 - 10^7 M_\odot$ in total for each set

- Initial binary stars
  - Primary star: Kroupa's IMF
  - $f(m_2/m_1) \propto (m_2/m_1)^{-0.1}\ (0.1 \leq m_2/m_1 \leq 1)$



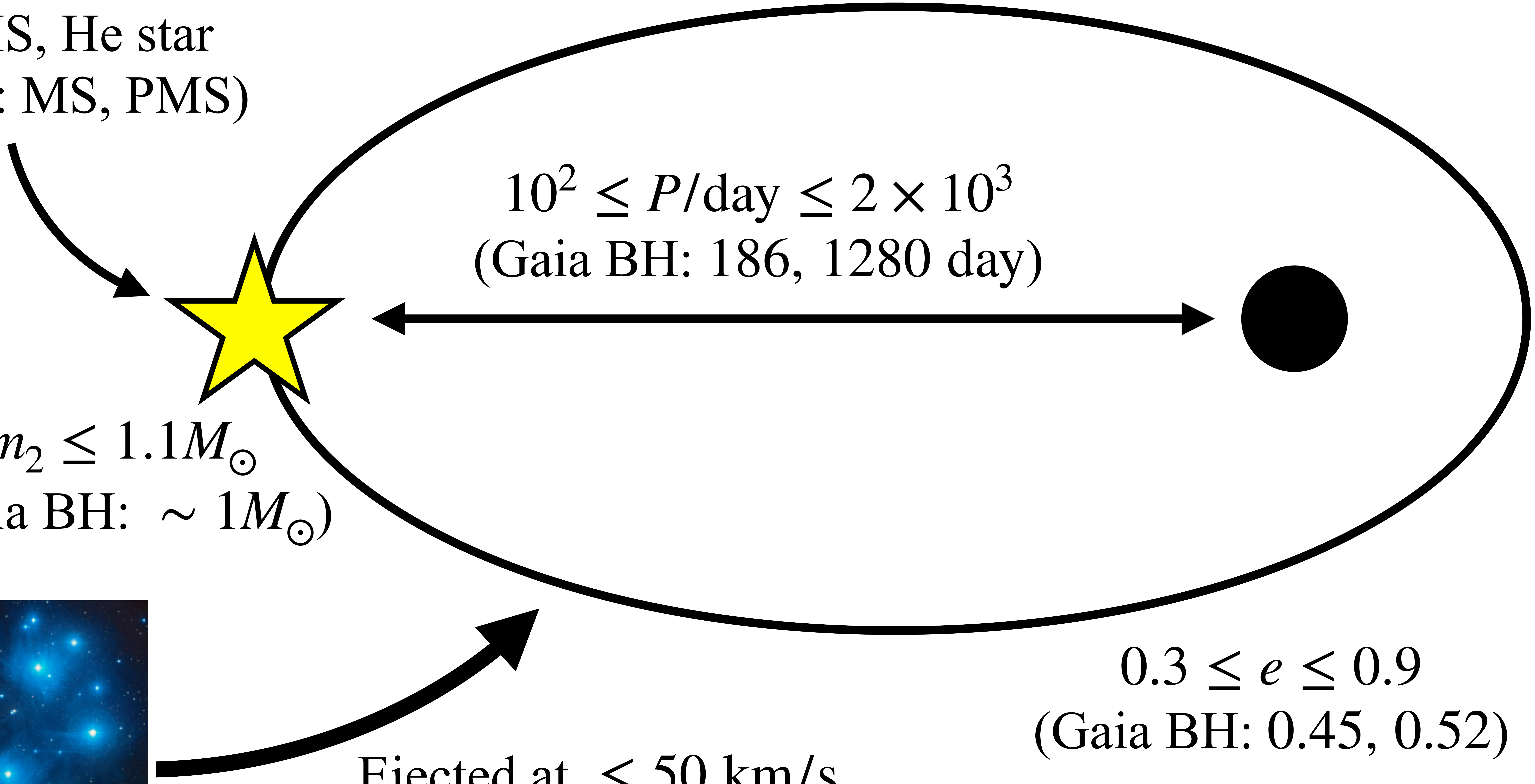
Portegies Zwart et al. (2010)

Gaia BHs could not be formed without dynamical interactions.



Criteria of Gaia BHs

MS, PMS, He star
(Gaia BH: MS, PMS)

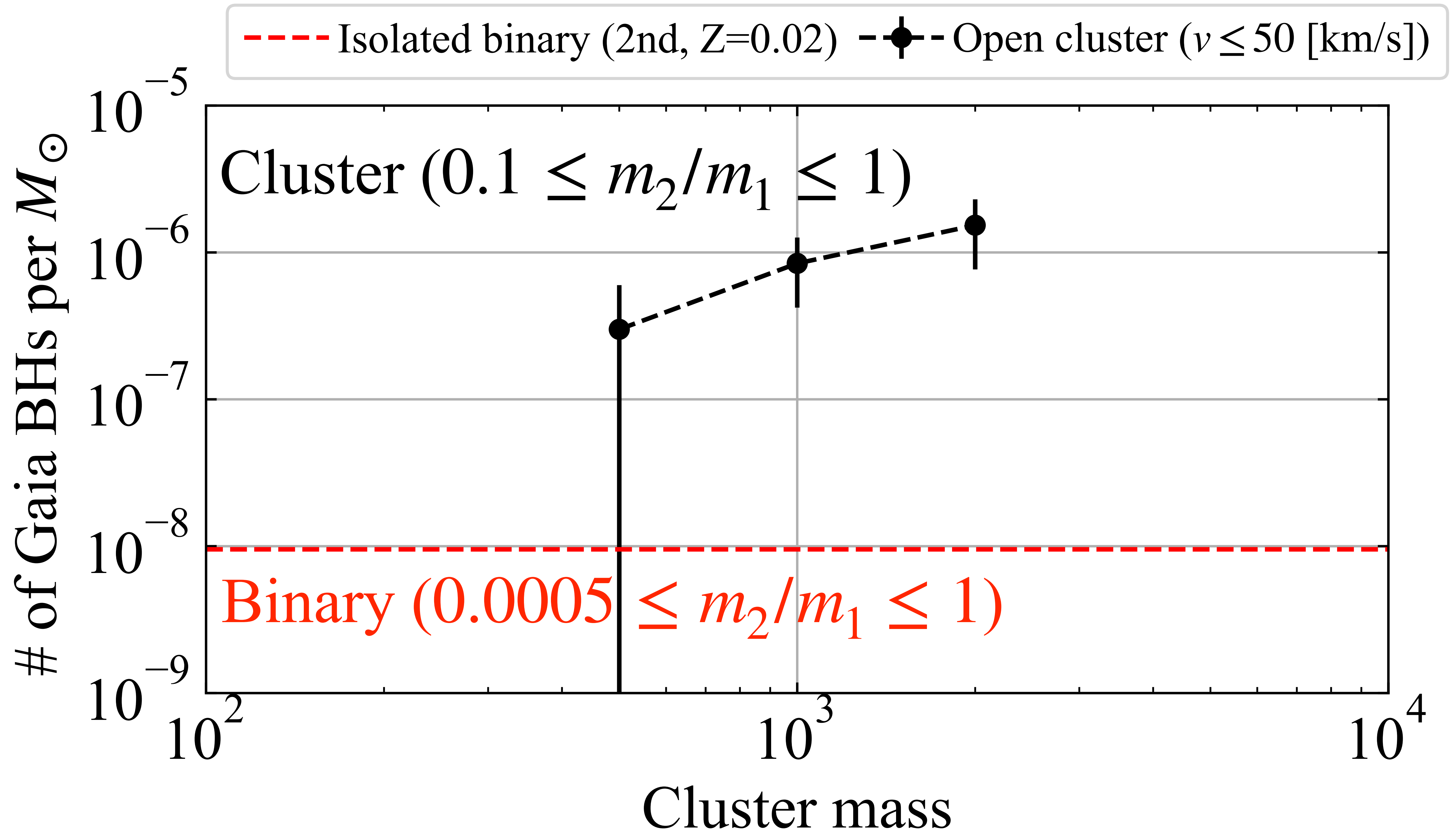


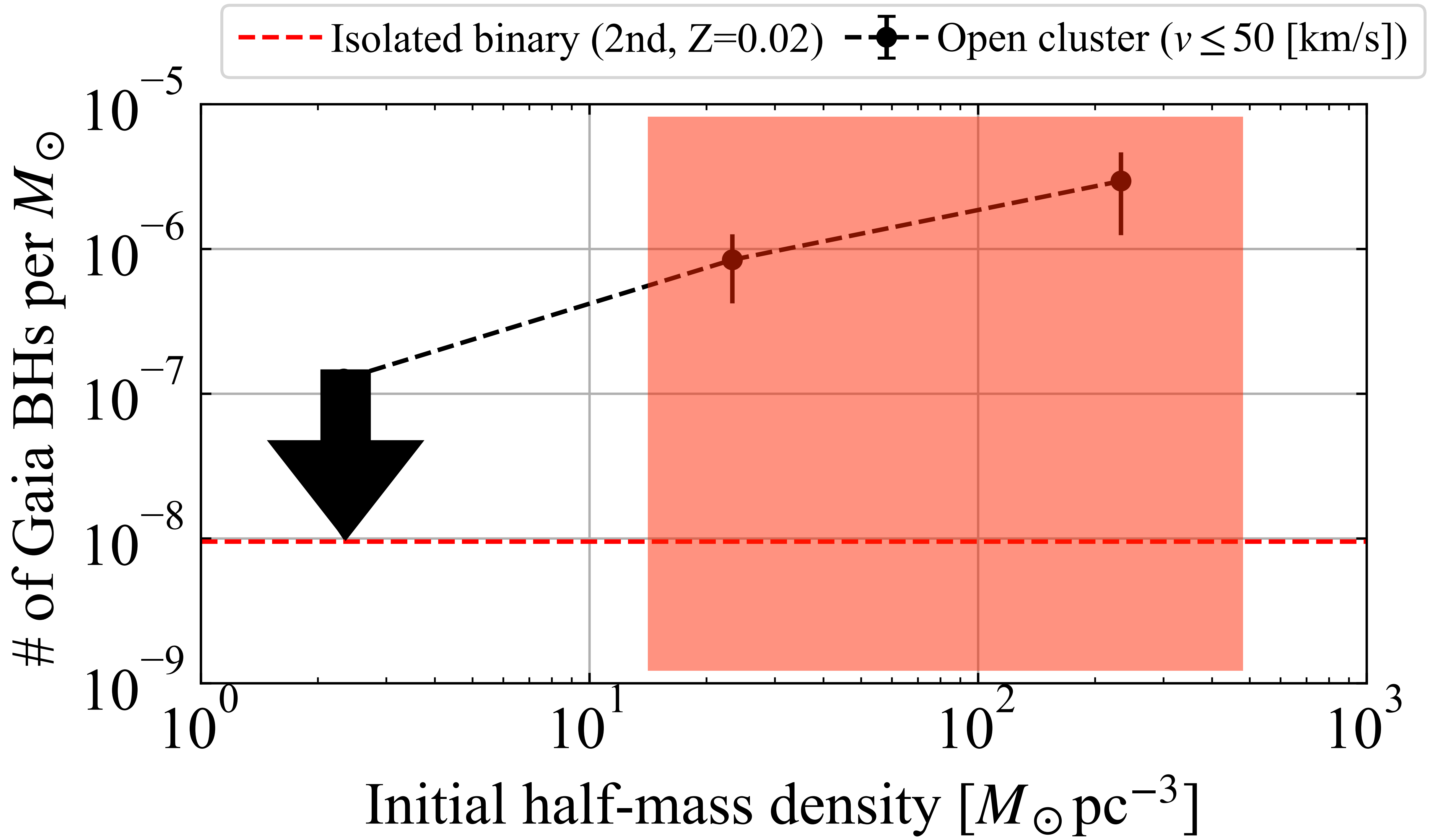
$10^2 \leq P/\mathrm{day} \leq 2 \times 10^3$
(Gaia BH: 186, 1280 day)

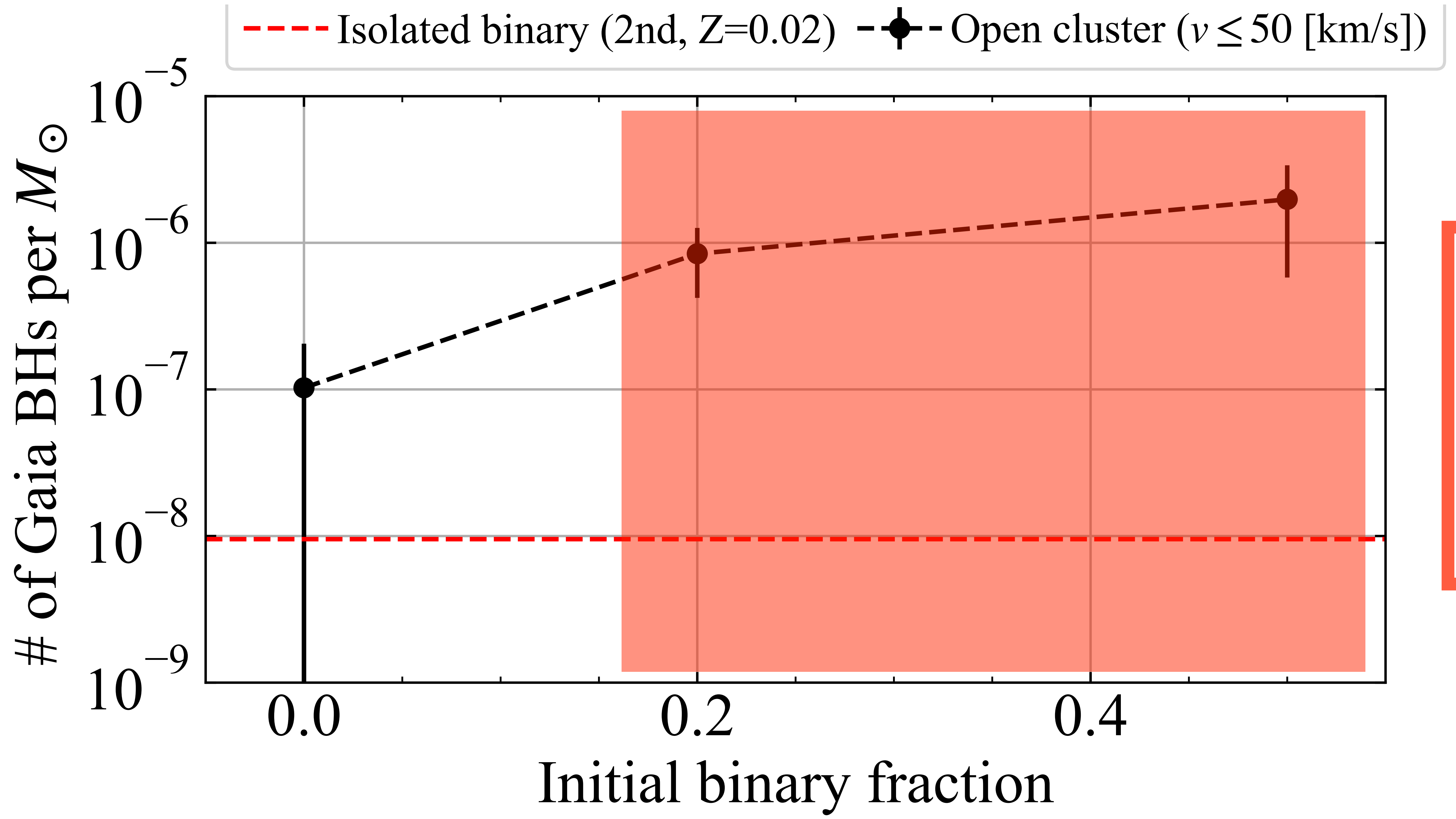
$m_2 \leq 1.1 M_\odot$
(Gaia BH: $\sim 1 M_\odot$)

Ejected at ≤ 50 km/s

$0.3 \leq e \leq 0.9$
(Gaia BH: 0.45, 0.52)







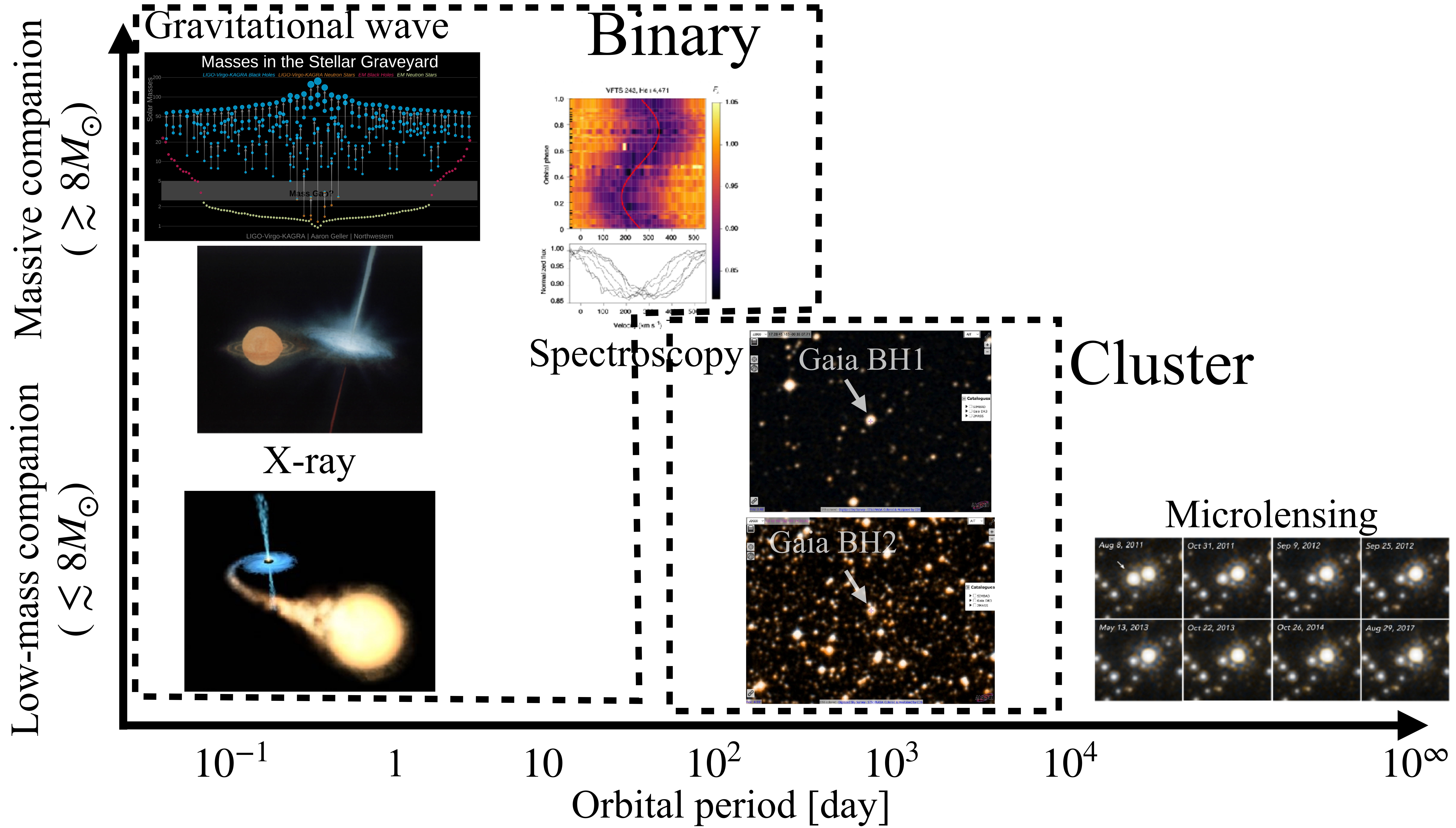
At least 100 times efficient if open clusters have reasonably high density and high binary fraction.

The number of Gaia BHs in Milky Way

$\sim 10^{-6} M_\odot^{-1}$ for clusters with reasonable mass, density and binary fraction

$$N_{\rm GaiaBH,MW} \sim 6 \times 10^3 \left(\frac{\eta}{10^{-6} M_\odot^{-1}} \right) \left(\frac{M_{\rm MW}}{6.1 \times 10^{10} M_\odot} \right) \left(\frac{f_{\rm cluster}}{0.1} \right)$$

Sufficiently large to explain the presence of Gaia BHs



Massive companion ($\gtrsim 8M_\odot$)
Low-mass companion ($\lesssim 8M_\odot$)
Gravitational wave
Masses in the Stellar Graveyard
Mass Gap?
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern
Binary
X-ray
Spectroscopy
Cluster
Gaia BH1
Gaia BH2
Microlensing
Aug 8, 2011
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10^{-1}
1
10
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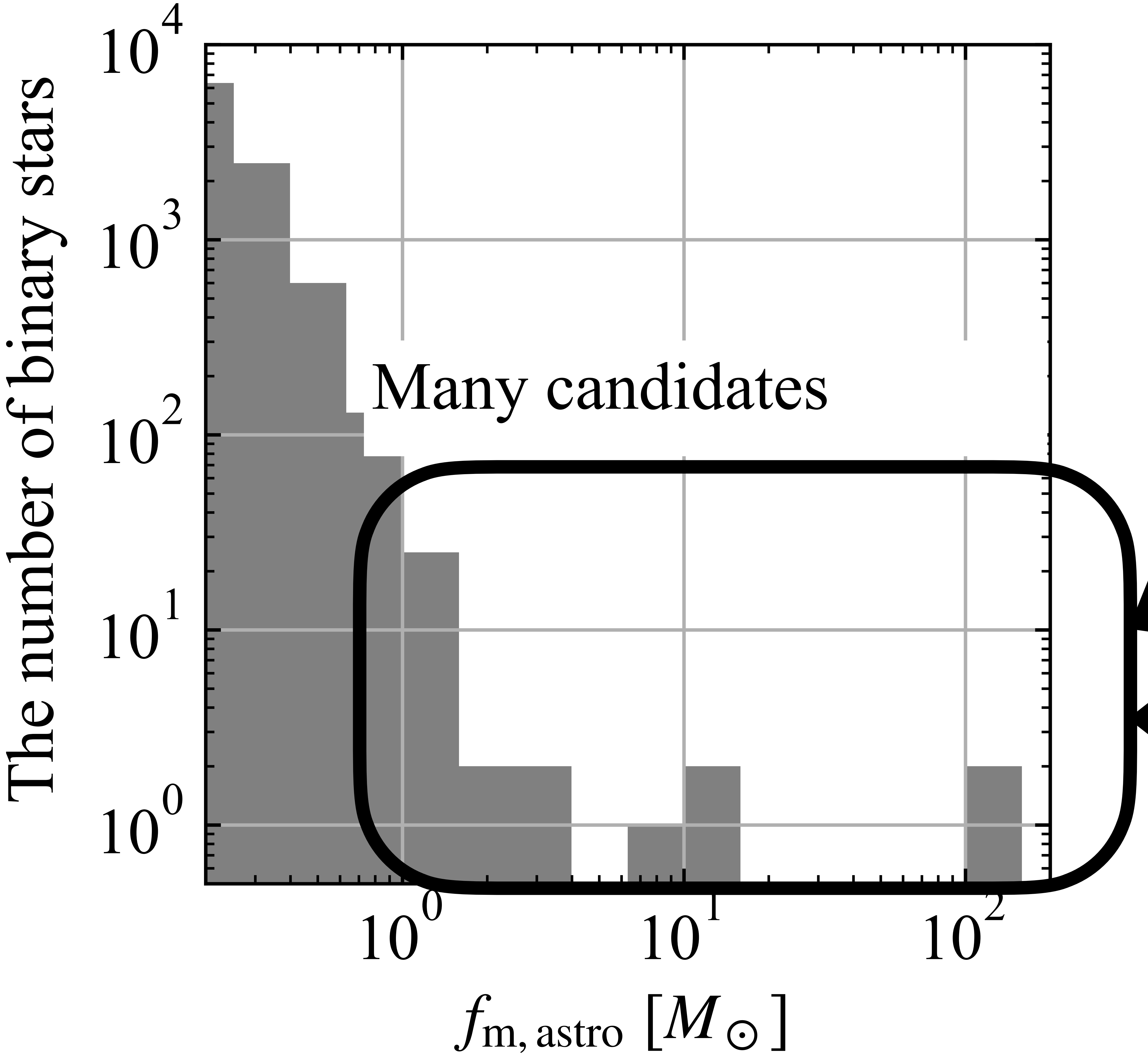
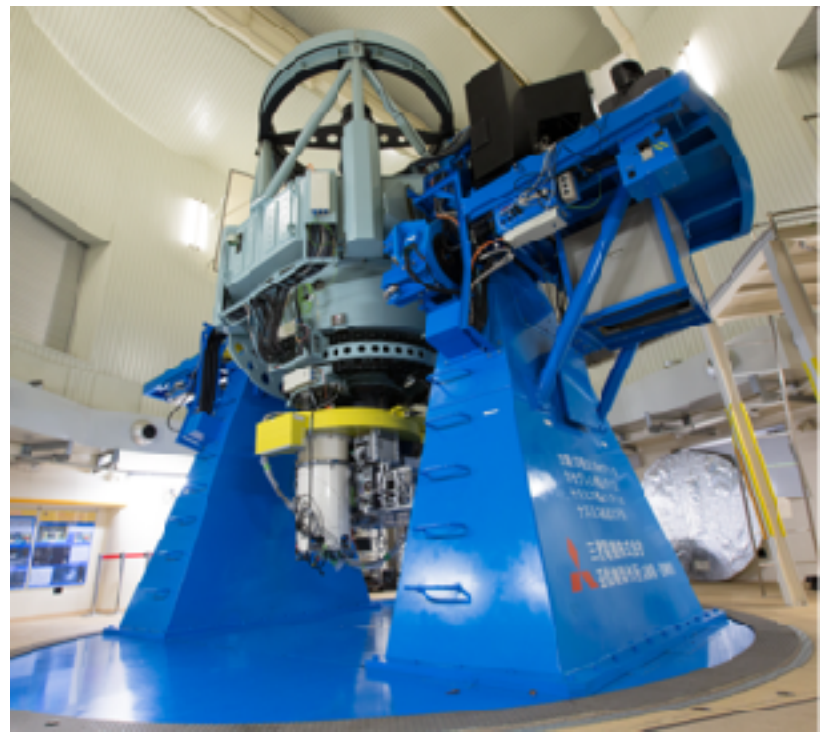
10^4
10^∞
Orbital period [day]

“Gaia NSs” or another Gaia BHs



Seimei GAOES-RV

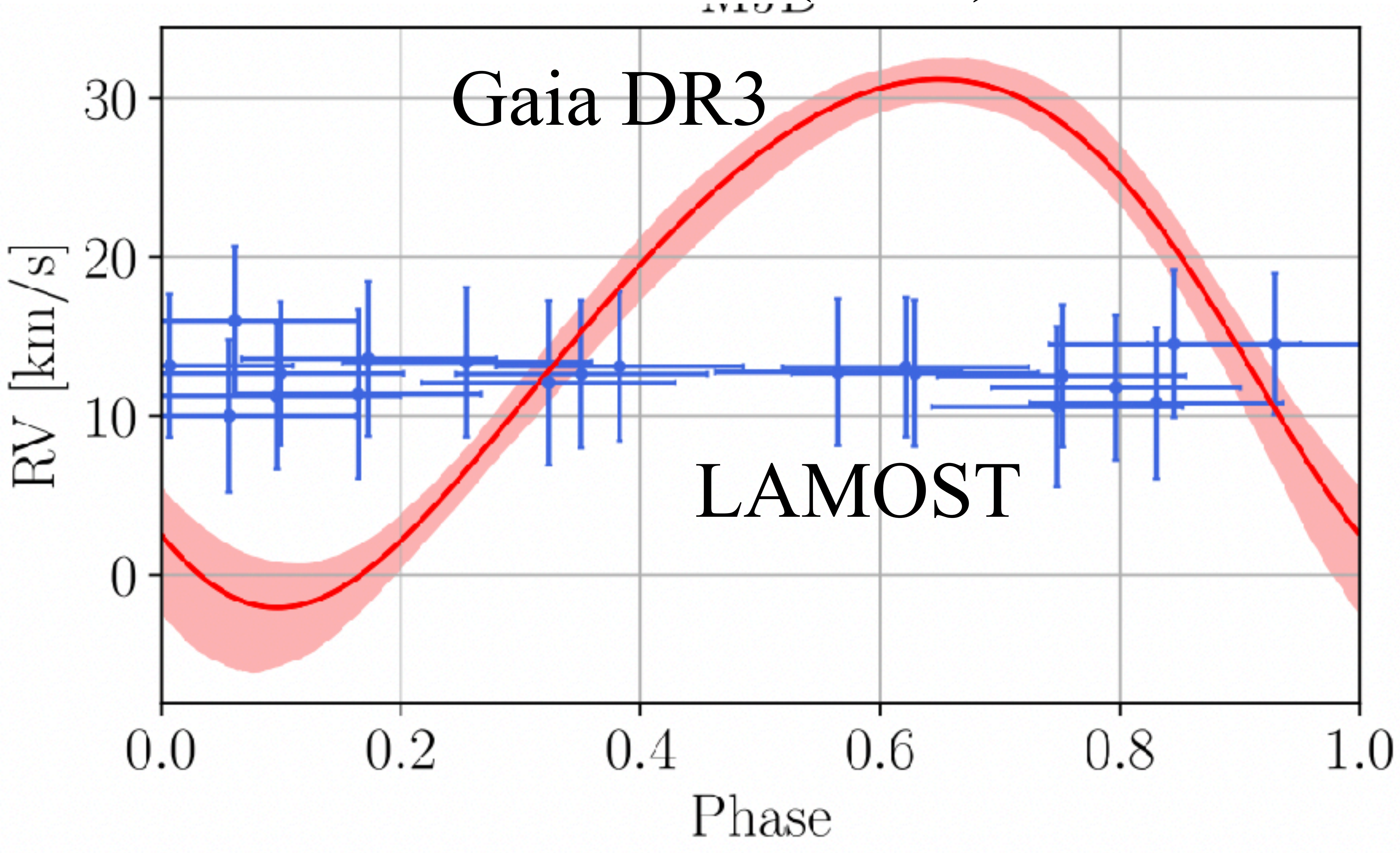
NAYUTA MALLS



Follow-up RV observations

Needs for follow-up observations

Bashi et al. (2022)



Gaiaの偽陽性

Possible candidates

Summary

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