Gaia BH formation in open star clusters

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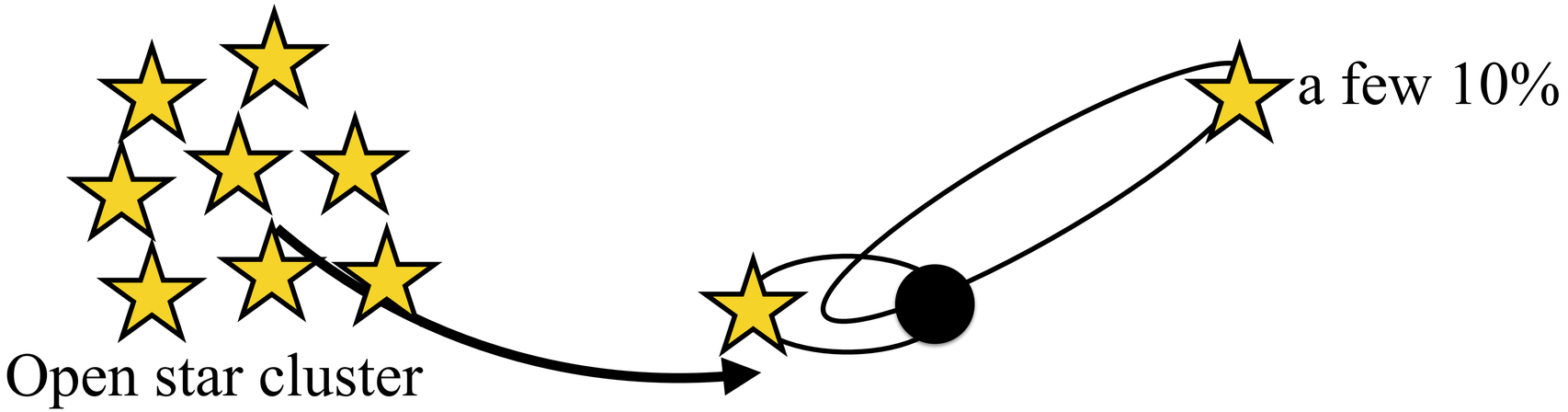
3,2,1: Massive Triples, Binaries and Mergers 2023, Leuven, Belgium

Tanikawa et al. (2023, arXiv:2303.05743)

Tanikawa et al. (2023, ApJ, 946, 79)

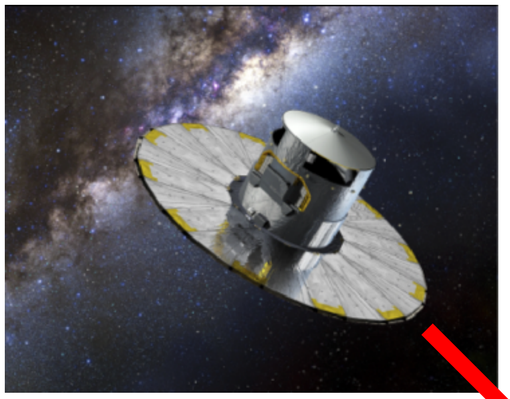
Conclusions

- Gaia BHs are hard to be formed through isolated binary evolution.
- We found that
  - Gaia BHs can be formed in open star clusters more efficiently than in isolated binary stars by at least 2 orders of magnitude.
  - Such Gaia BHs have tertiary stars at high probability.

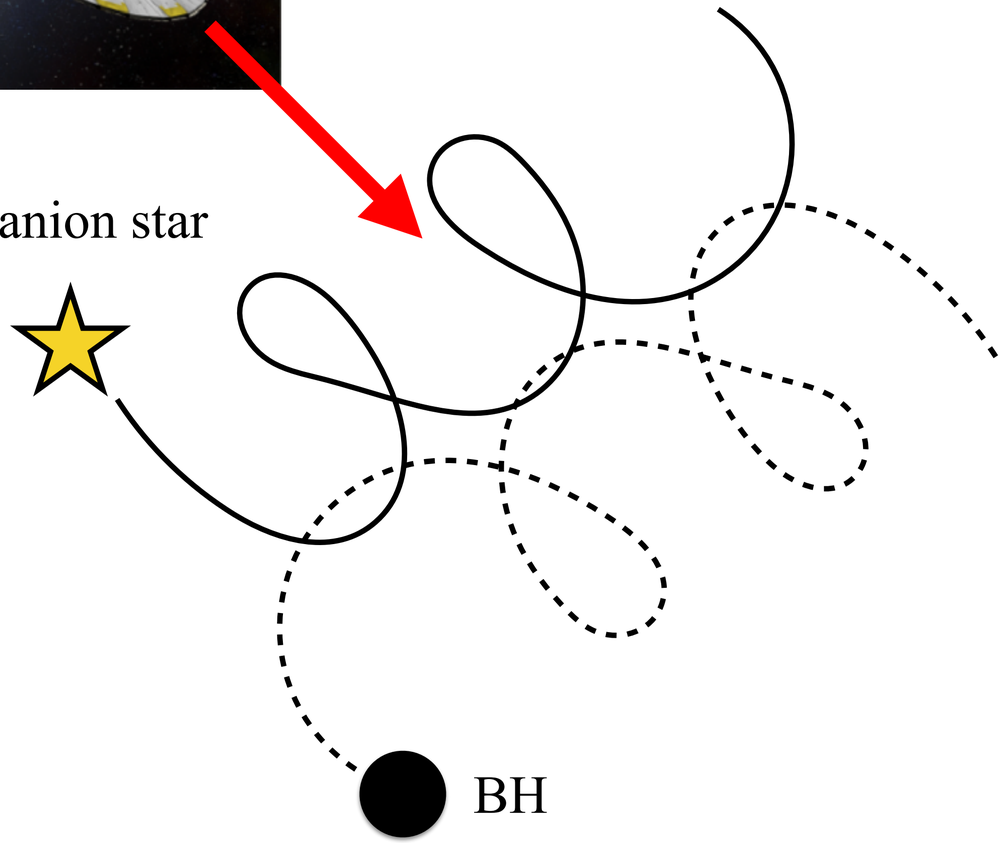


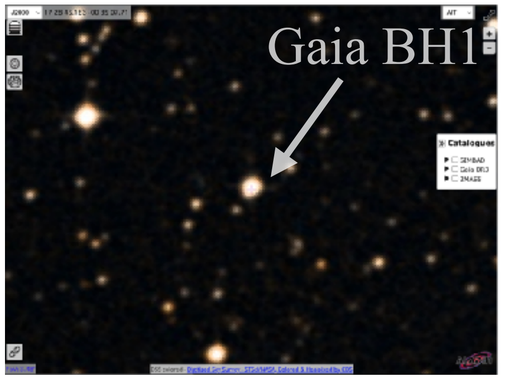
Gaia BH1 and BH2

Gaia

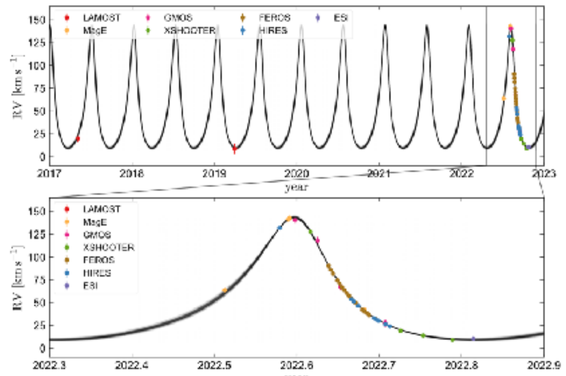


BH companion star

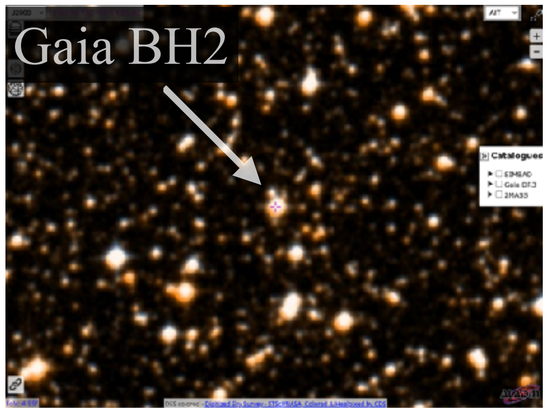




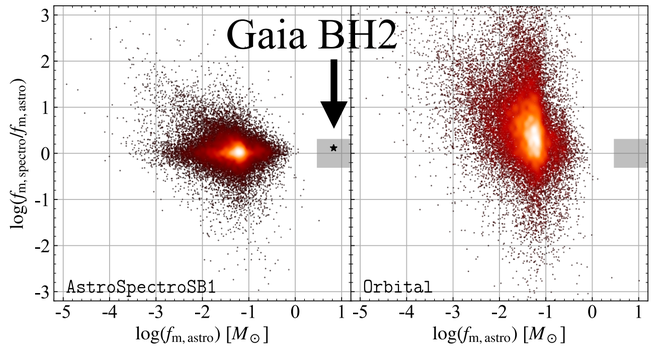
El-Badry et al. (2023a)



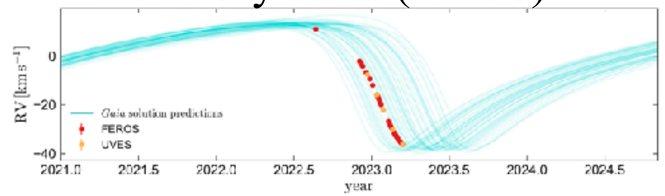
See also Shahaf et al. (2023); Chakrabarti et al. (2023)



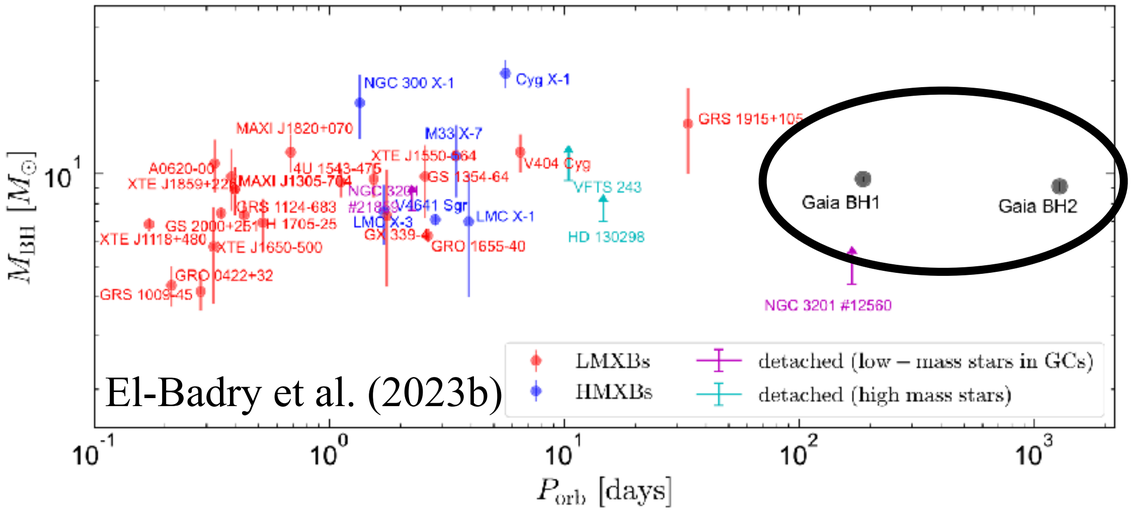
Tanikawa et al. (2023)



El-Badry et al. (2023b)

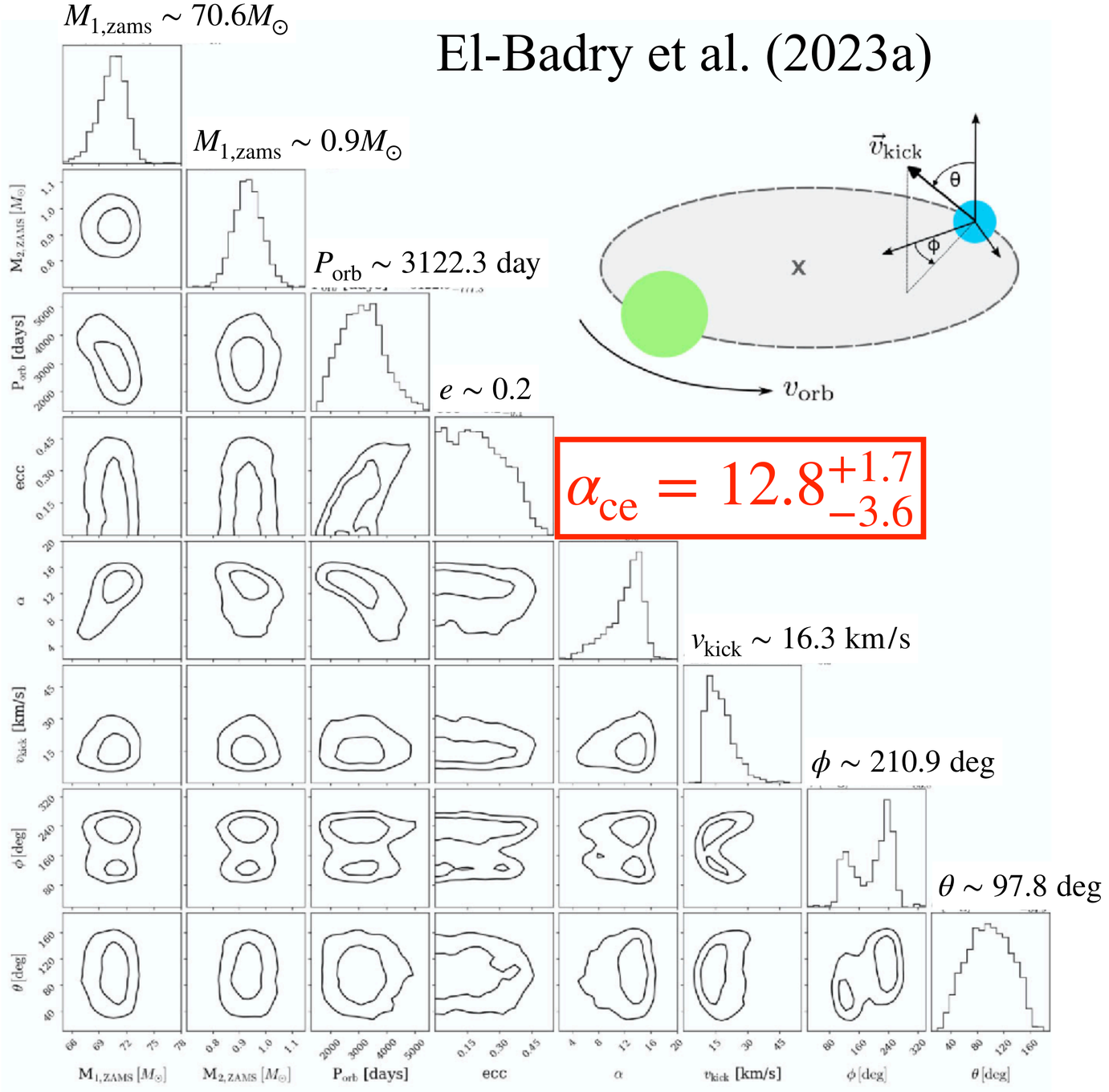


High $\alpha_{\rm ce}$ is needed



El-Badry et al. (2023b)

El-Badry et al. (2023a)

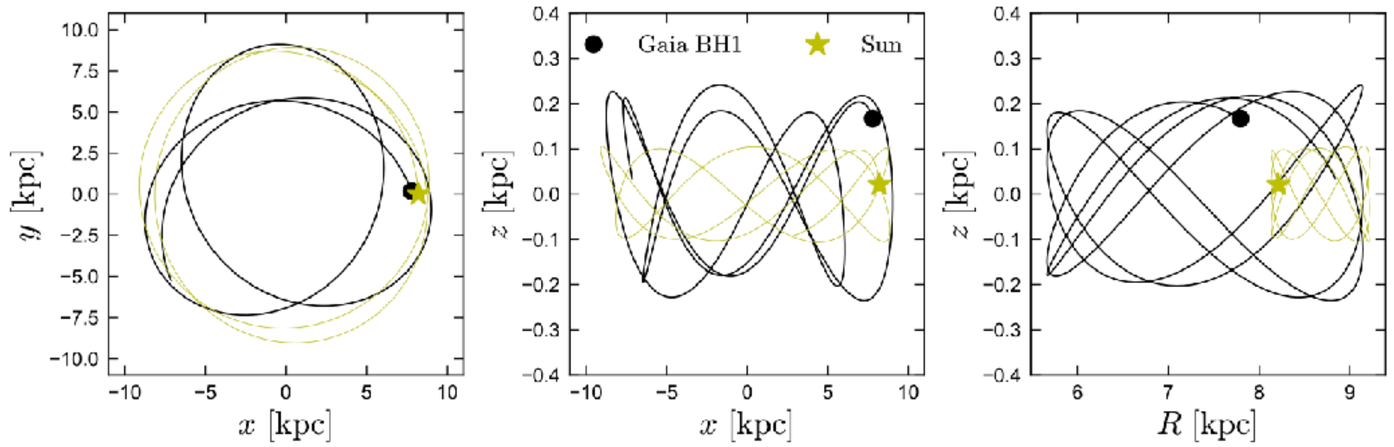


Other channels?

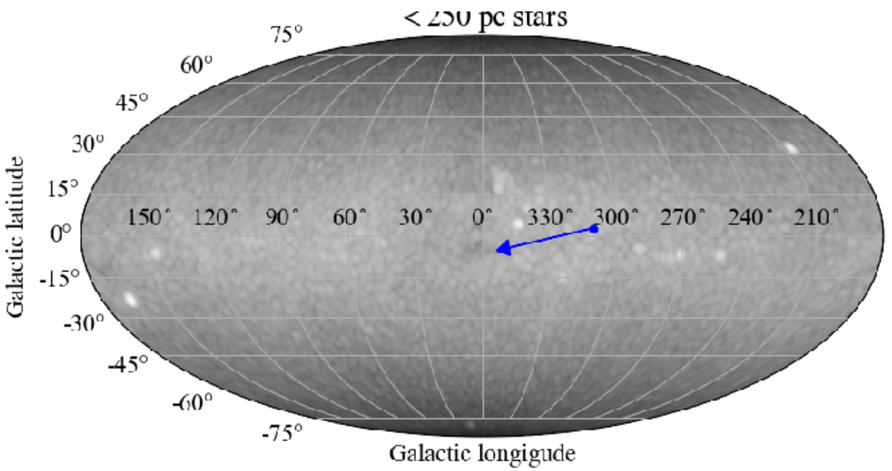
- Hierarchical triple systems (El-Badry et al. 2023ab)
- Open star clusters (Tanikawa et al., arXiv:2303.05743; see also Di Carlo et al, arXiv:2306.1312; Rastello et al. arXiv:2306.14679)

Gaia BH1 and BH2 are *components in the Galactic disk* (El-Badry et al. 2023ab).
$\Longrightarrow$ Impossible in the Galactic globular cluster and the Galactic center

Gaia BH1



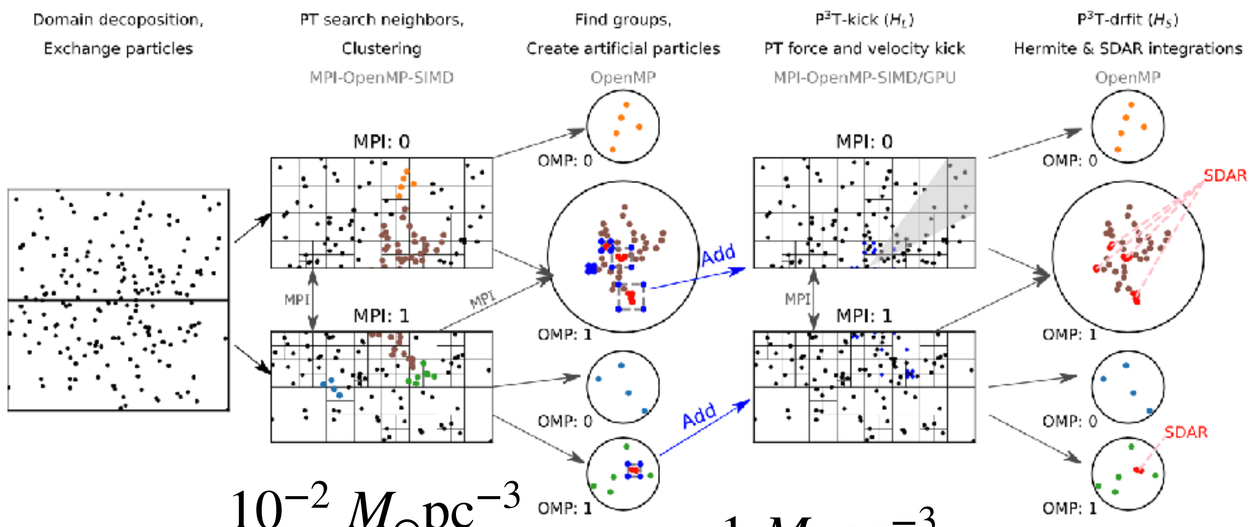
Gaia BH2

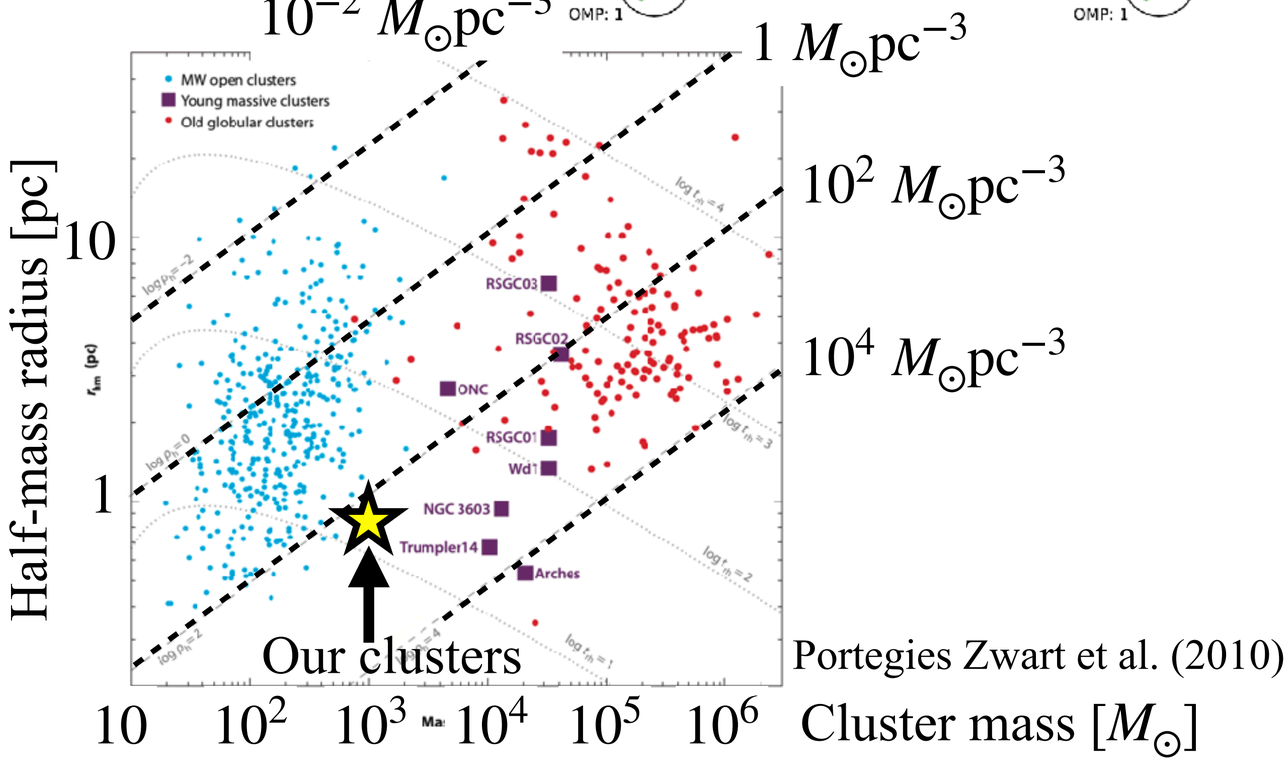


Fiducial model

- N-body code: PeTar (Wang et al. 2020)
- Galactic potential: GALPY (Bovy 2012)
- Binary model: BSE (Hurley et al. 2000; Banerjee et al. 2020)
- Initial condition: McLuster (Kupper et al. 2011)
  - $100 \times 10^3 M_\odot$ clusters for each $Z = 0.02, 0.01, 0.005$
  - Stellar mass density: $\sim 200\ M_\odot \mathrm{pc}^{-3}$
  - Initial binary fraction: 100%
  - Primary IMF: Kroupa (2001)
  - Binary conditions: Sana et al. (2012)
    - $f(m_2/m_1) \propto (m_2/m_1)^{-0.1}$ $(0.1 \leq m_2/m_1 \leq 1)$
    - No progenitor of Gaia BHs at the initial time

Parallel tree algorithm × Algorithmic Regularization





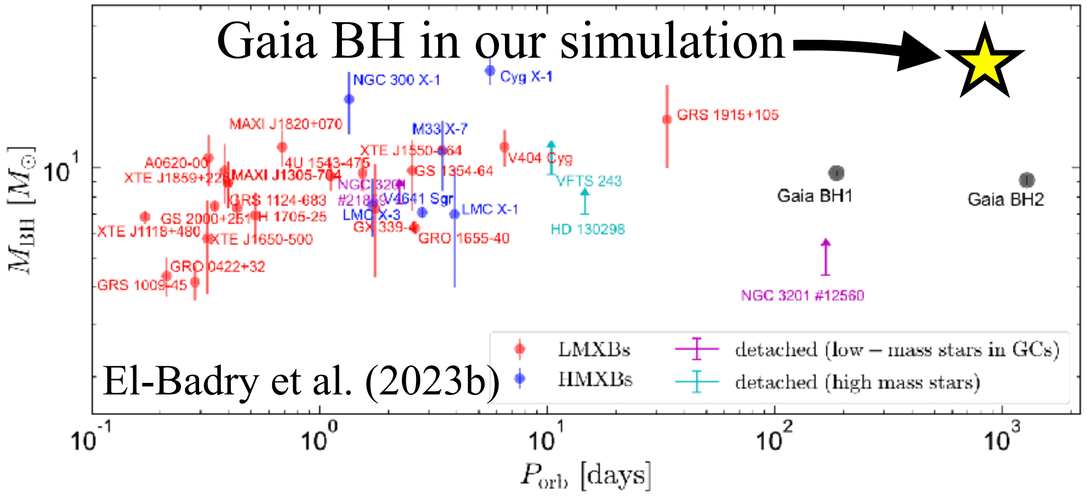
Portegies Zwart et al. (2010)

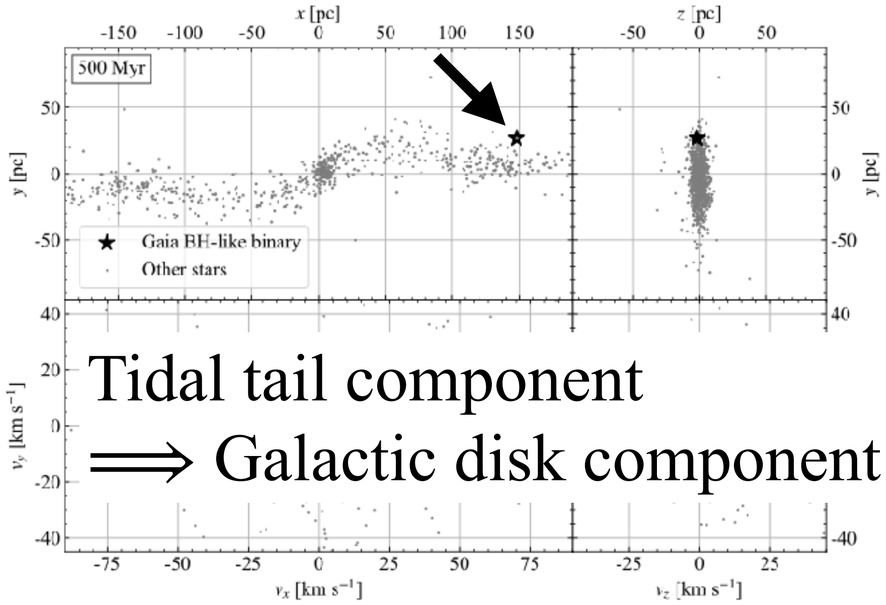
High formation efficiency of Gaia BHs

Parameters	Values	Remarks
Metallicity (Z)	0.005	
BH mass	$21.4M_\odot$	
Secondary mass	$0.82M_\odot$	MS star
Period	8.3×10^2 days	
Eccentricity	0.3-0.8	Oscillating

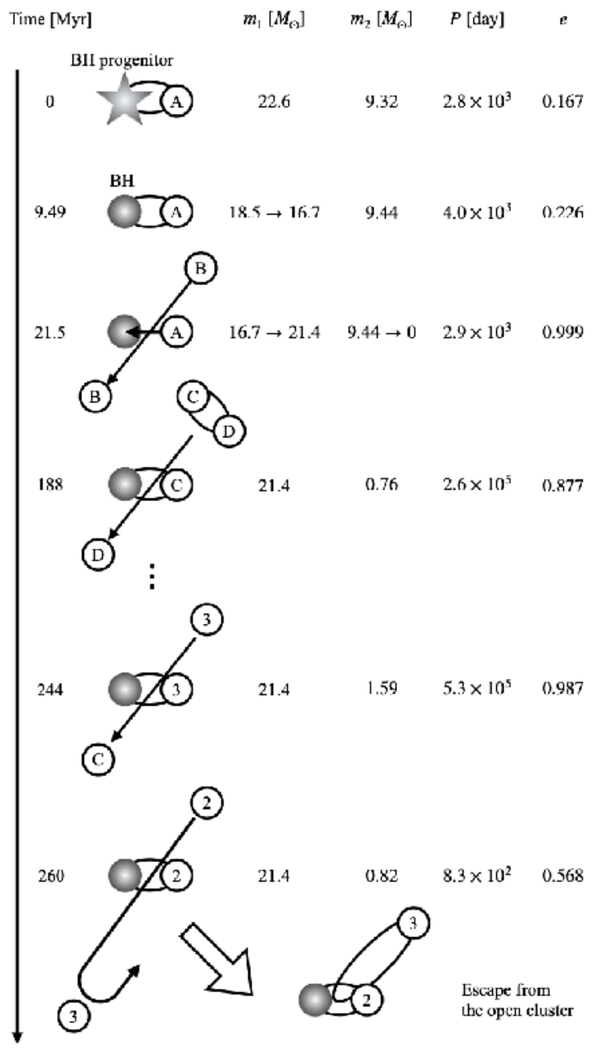
- BH mass ($\sim 10M_\odot$) ✓
- Period ($\sim 10^2 - 10^3$ day) ✓
- Companion mass ($\sim 1M_\odot$) ✓
- Eccentricity (~ 0.5) ✓
- No chemical anomaly ✓
- Galactic disk component ✓

Formation efficiency:
$\sim 3.3 \times 10^{-6}\ M_\odot^{-1}$
$\gg 10^{-8} M_\odot^{-1}$ (isolated binary)



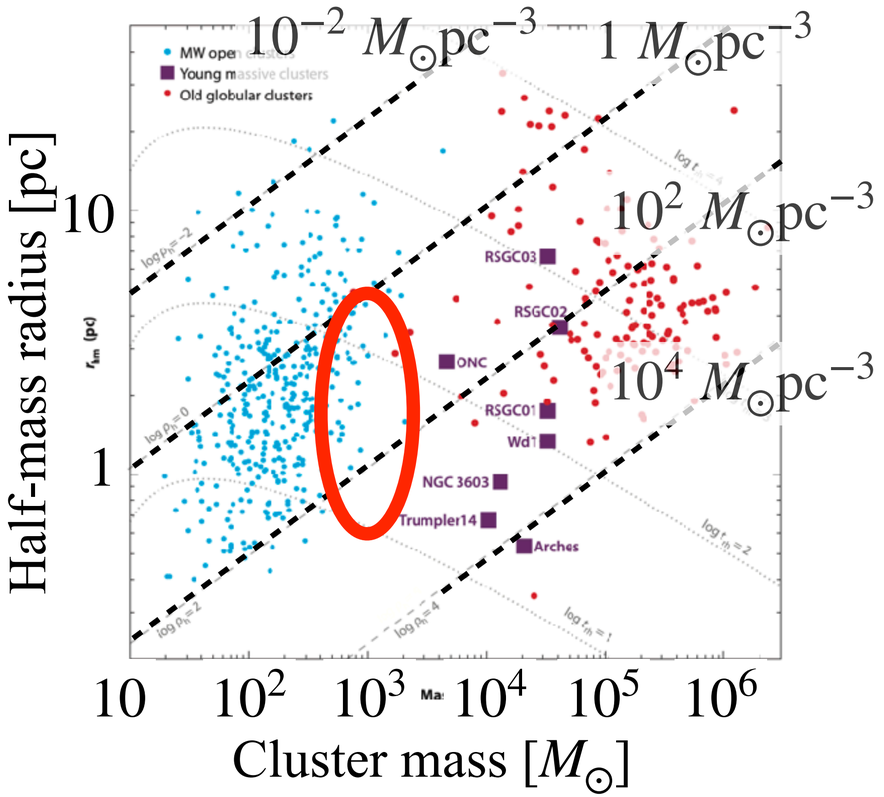


Tidal tail component
$\Longrightarrow$ Galactic disk component



Additional models

- Open star clusters with $\sim 10^7 M_\odot$ in total
- Initial binary fraction: 0, 20, 50, 100 %
- Metallicity: $Z = 0.005, 0.01, 0.02$
- Cluster mass: 500, 1000, 2000 $M_\odot$
- Stellar mass density: 2, 20, 200 $M_\odot$ pc^{-3}

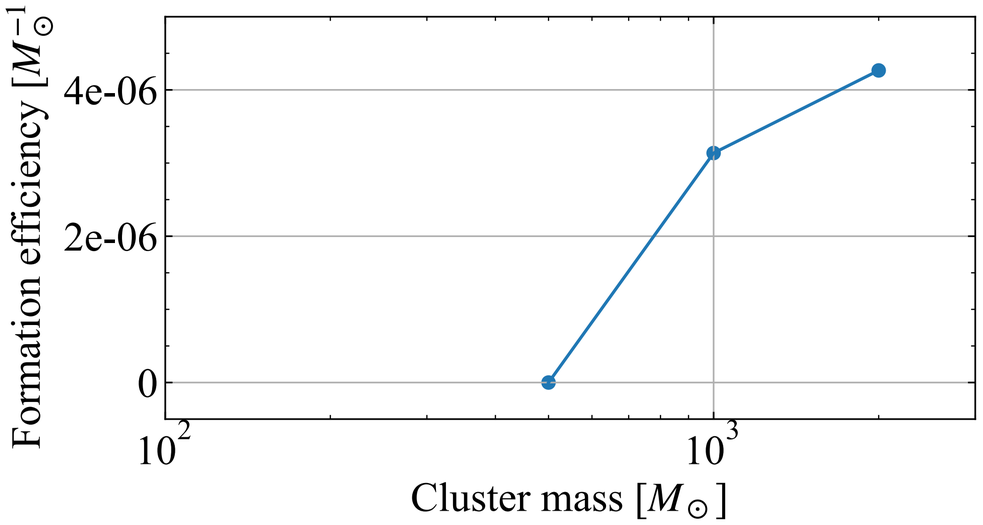


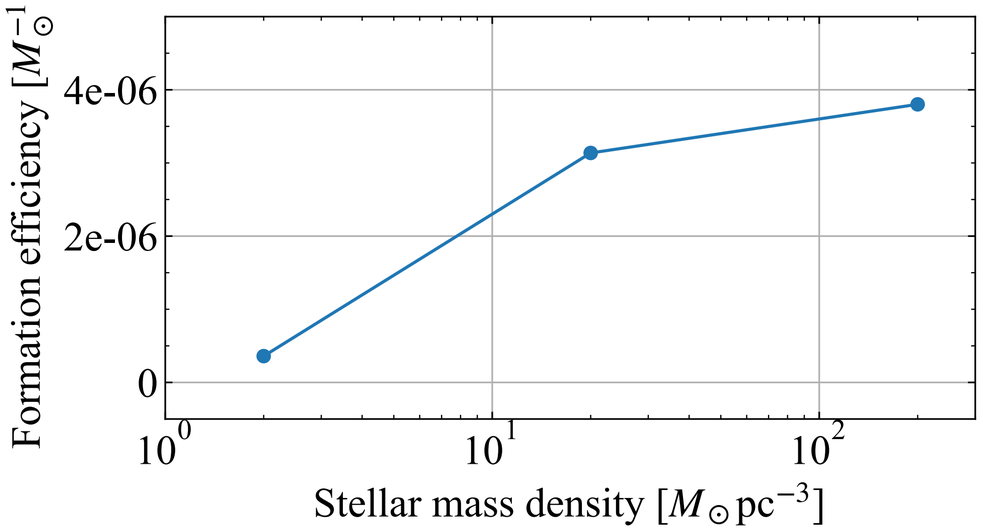
Portegies Zwart et al. (2010)

Dependence on initial conditions

- Initial binary fraction (0-100%):
  - $\Longrightarrow \sim 3 \times 10^{-6} M_{\odot}^{-1}$
- Metallicity (Z=0.005-0.02):
  - $\Longrightarrow 3 \times 10^{-6} M_{\odot}^{-1}$
- Cluster mass ($500 - 2000 M_{\odot}$):
  - $\Longrightarrow 3 \times 10^{-6} M_{\odot}^{-1}$ if $\geq 1000 M_{\odot}$
- Stellar mass density ($2 - 200\ M_{\odot}\ \mathrm{pc}^{-3}$)
  - $\Longrightarrow 3 \times 10^{-6} M_{\odot}^{-1}$ if $\geq 20\ M_{\odot}\ \mathrm{pc}^{-3}$

$$\sim 3 \times 10^{-6} M_{\odot}^{-1}$$





The number of the Galactic Gaia BHs

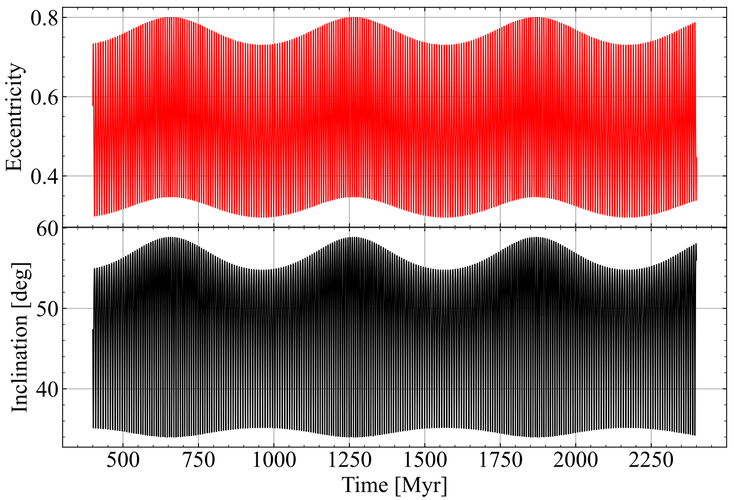
$3 \times 10^{-6} M_\odot^{-1}$ for clusters with reasonable mass and density

$$N_{\rm GaiaBH,MW} \sim 2 \times 10^4 \left(\frac{\eta}{3 \times 10^{-6}} \right) \left(\frac{M_{\rm MW}}{6.1 \times 10^{10} M_\odot} \right) \left(\frac{f_{\rm cluster}}{0.1} \right)$$

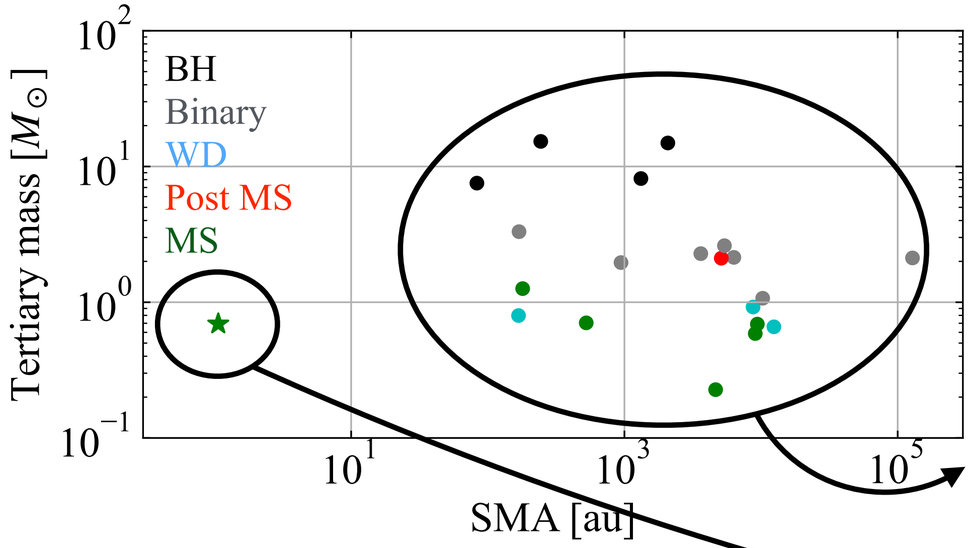
Multiplicity of Gaia BHs in simulation

Parameters	Values	Remarks
Metallicity (Z)	0.005	
BH mass	$21.4 M_\odot$	
Secondary mass	$0.82 M_\odot$	MS star
Period	8.3×10^2 days	
Eccentricity	0.3-0.8	Oscillating
Tertiary mass	$1.59 M_\odot$	MS star
Outer period	1.2×10^6 days	
Outer eccentricity	0.689	
Mutual inclination	34-59 deg	Oscillating

ZLK oscillation during 2Gyr

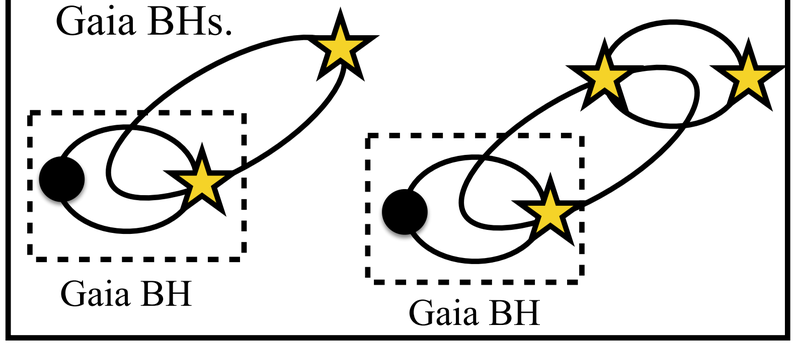


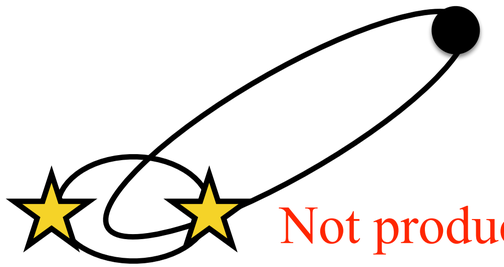
$\Longrightarrow$ a few 10%



Inner binaries = a few 0.1 Gaia BHs

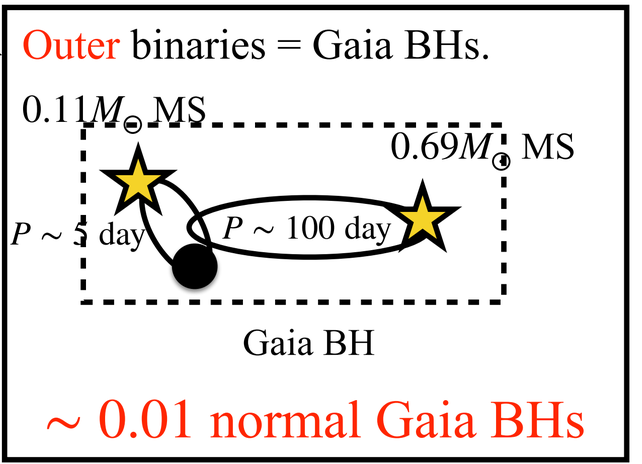
Gaia BHs.





Not produced
(<0.01 normal Gaia BHs)

Outer binaries = Gaia BHs.



$\sim$ 0.01 normal Gaia BHs

Summary

- Gaia BHs are hard to be formed through isolated binary evolution.
- We found that
  - Gaia BHs can be formed in **open star clusters** more efficiently than in isolated binary stars by at least 2 orders of magnitude.
  - Such Gaia BHs can be in **multiple star systems** at a few 10% probability.
- Other objects formed in open star clusters
  - Gaia NS: $\sim 0 M_{\odot}^{-1}$
  - Gaia BH with WD : $\sim 6 \times 10^{-6} M_{\odot}^{-1}$ ($\sim 2 \times$ Gaia BHs)