Theoretical studies on formation mechanism of compact binary stars discovered from Gaia DR3

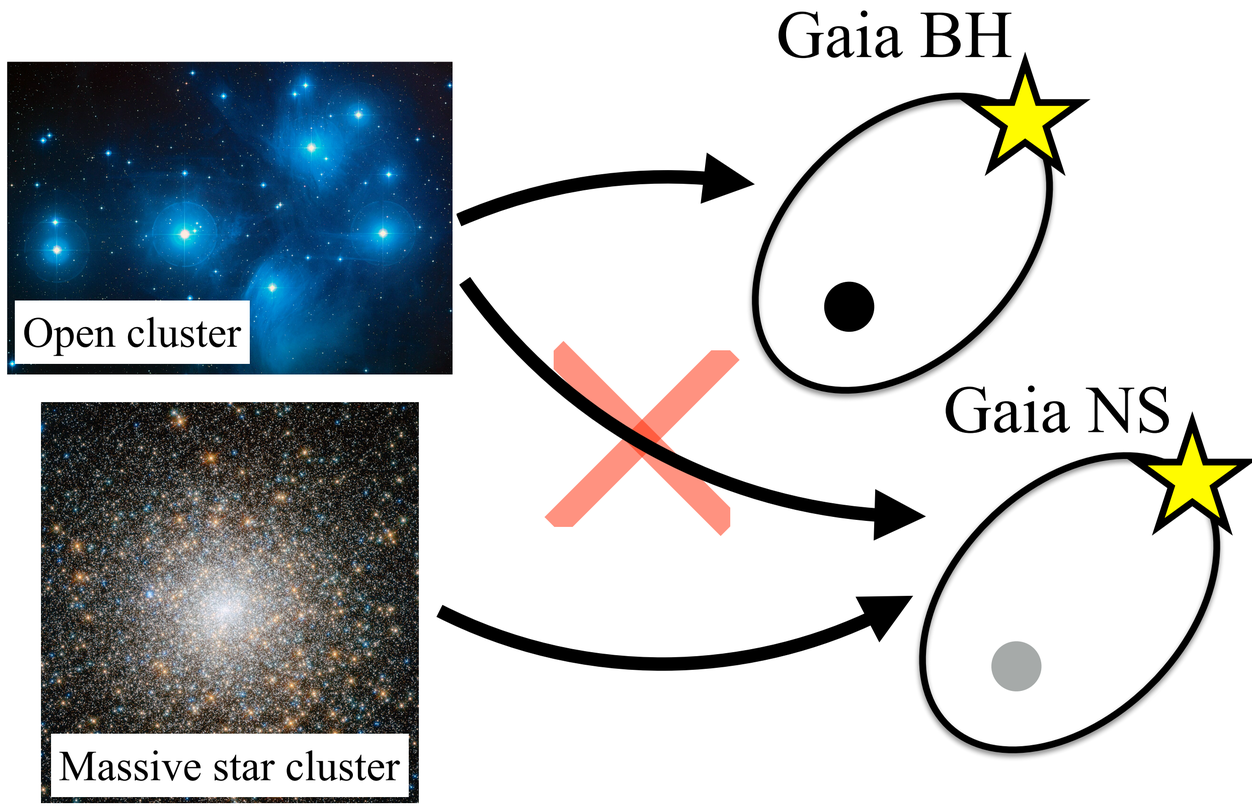
Ataru Tanikawa (Fukui Prefectural University)

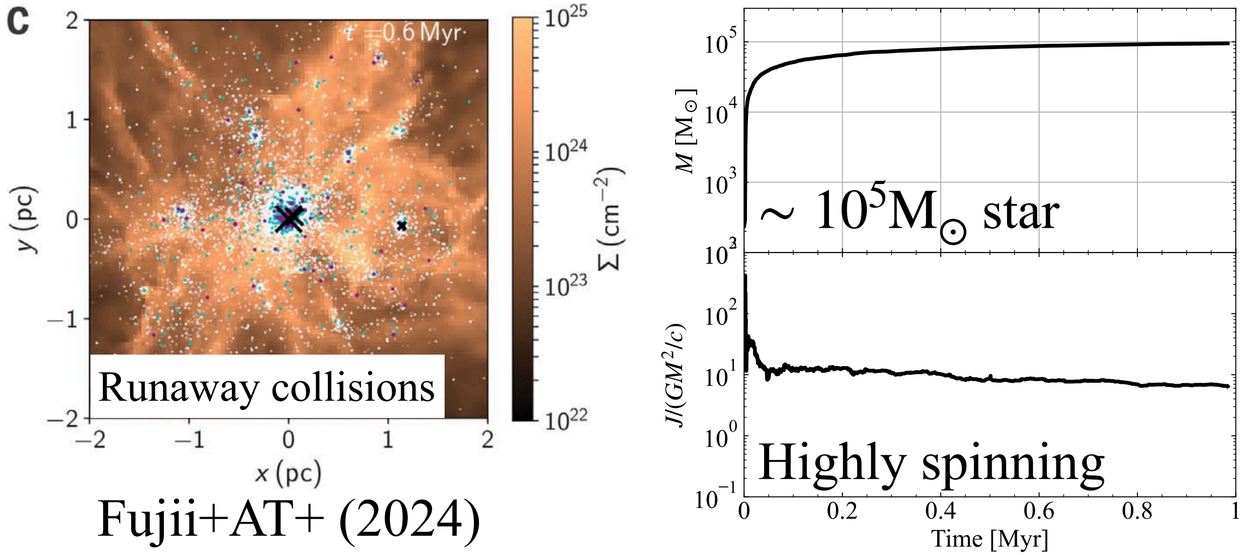
The 3rd conference: “Multimessenger Astrophysics”
at Naruko Kanko Hotel on 19th Nov. 2025

- Tanikawa et al. (2023, ApJ, 946, 79, arXiv:2209.05632)
- Tanikawa et al. (2024a, MNRAS, 527, 4031, arXiv:2303.05743)
- Tanikawa et al. (2024b, OJAp, 7, 39, arXiv:2404.01731)
- Tanikawa et al. (2025, OJAp, 8, 79, arXiv:2407.03662)

Outline

- Gaia BHs and NSs have been discovered by Gaia astrometry.
- They cannot be formed in the conventional binary evolution model.
- We have shown that Gaia BHs can be formed in open clusters, but Gaia NSs cannot.
- We will assess if massive star clusters can form Gaia NSs by N-body simulations.
- Such N-body simulations can be also helpful to solve the formation Little Red Dots and pair instability mass gap events.

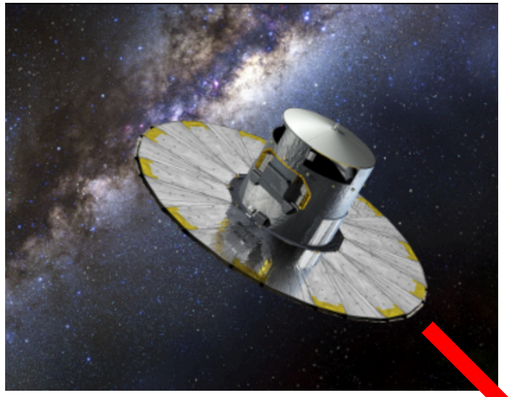




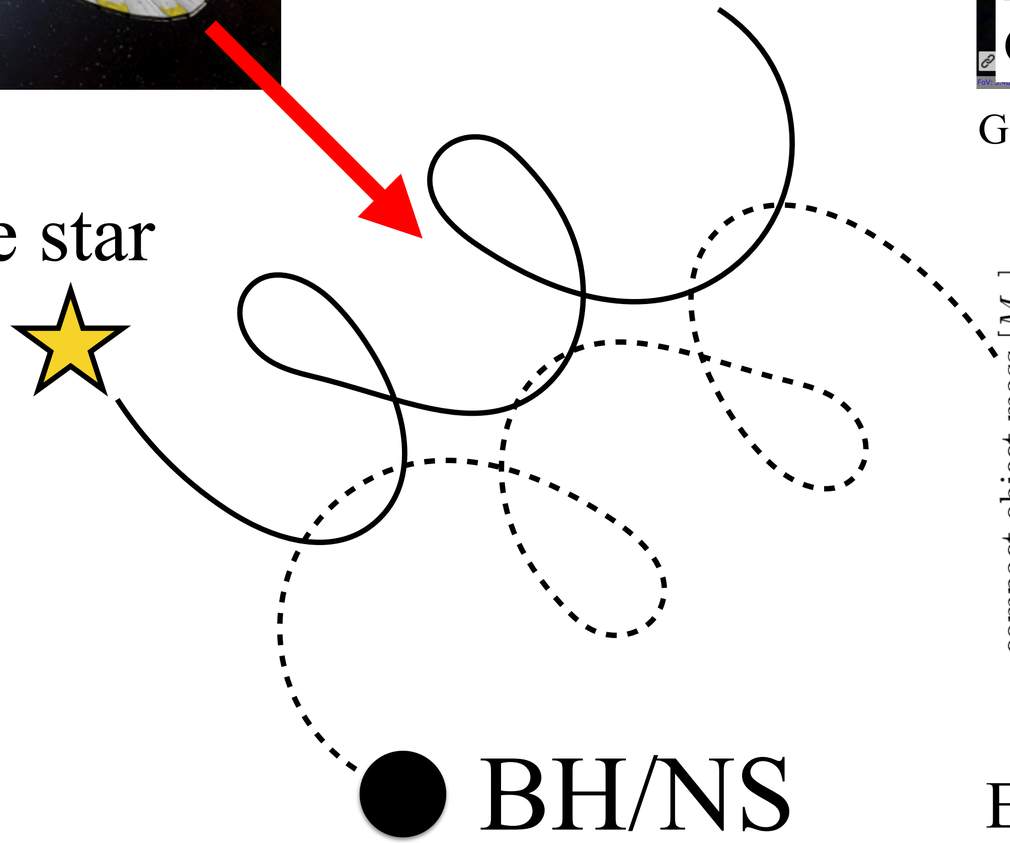
Fujii+AT+ (2024)

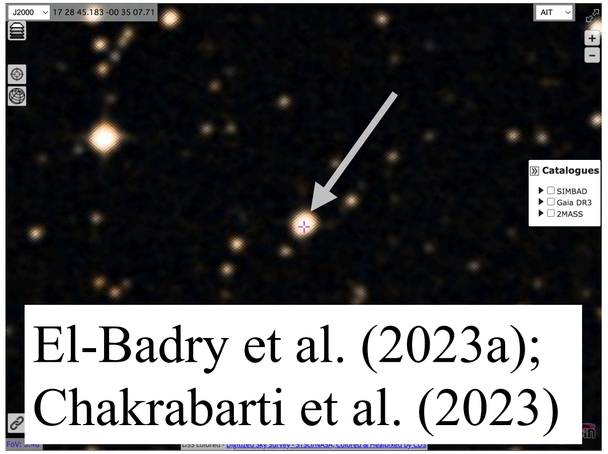
Gaia has discovered compact binaries

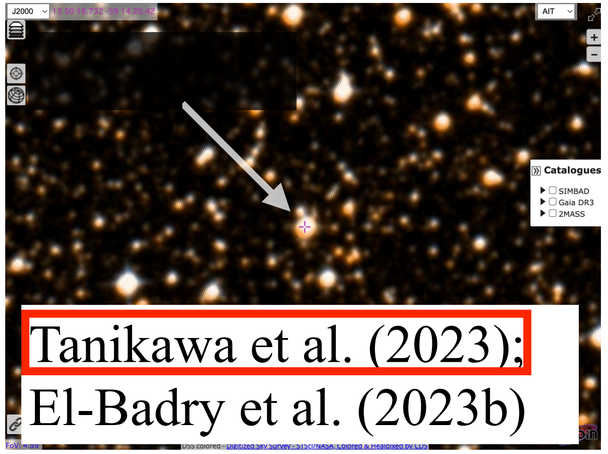
Gaia



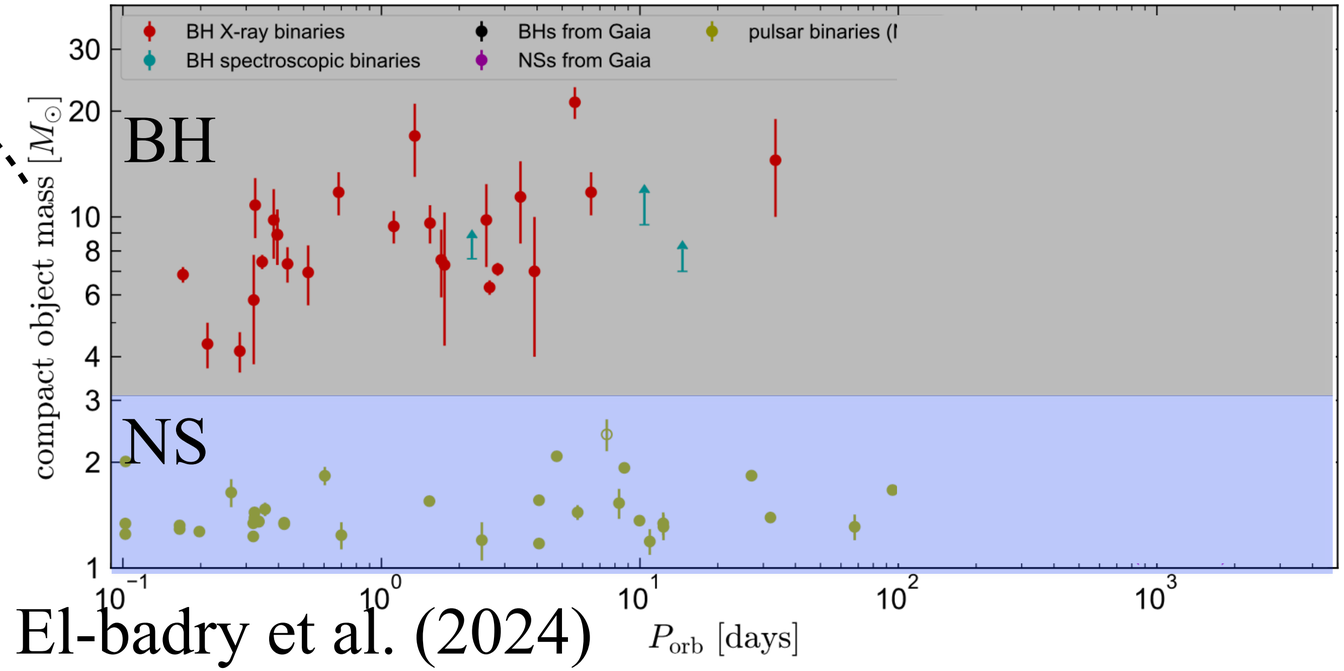
Visible star





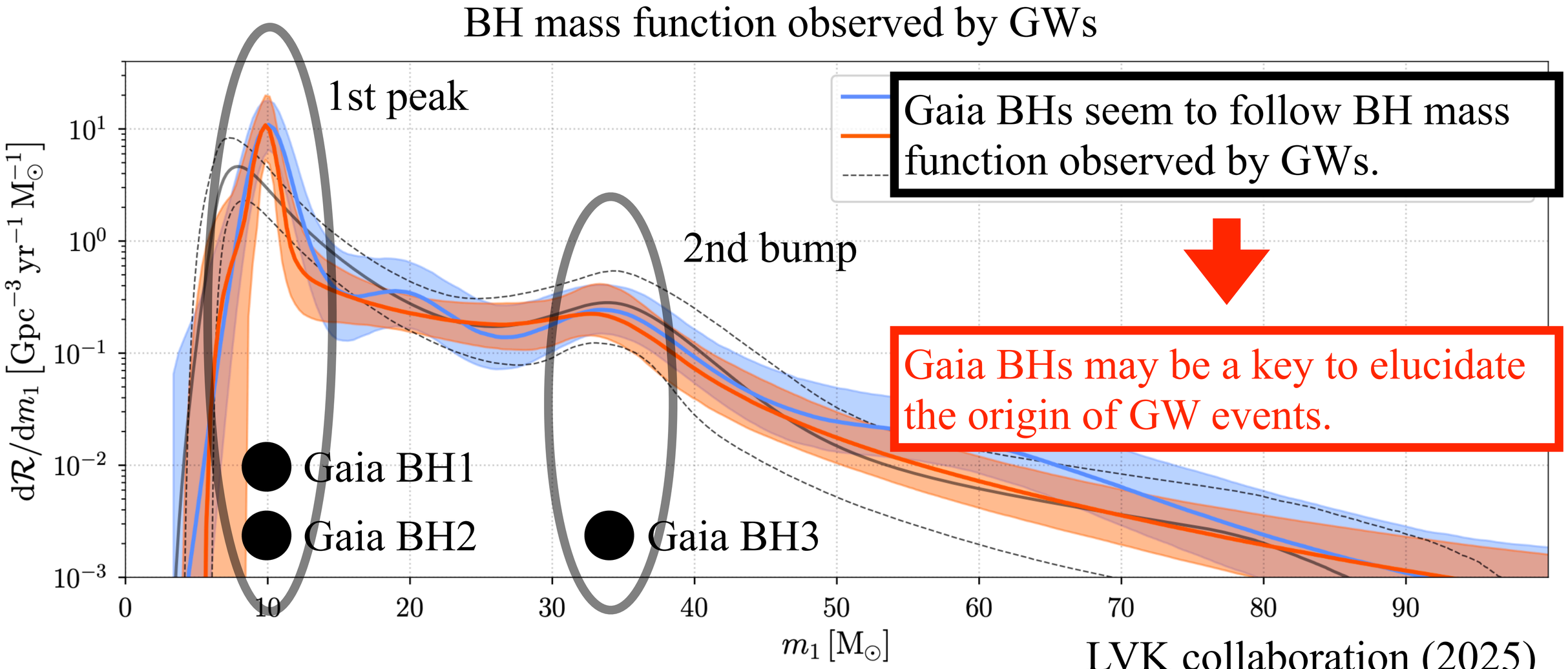


Gaia BH3 (Gaia collaboration 2024); Gaia NS1 (El-Badry et al. (2024a) …



El-badry et al. (2024)

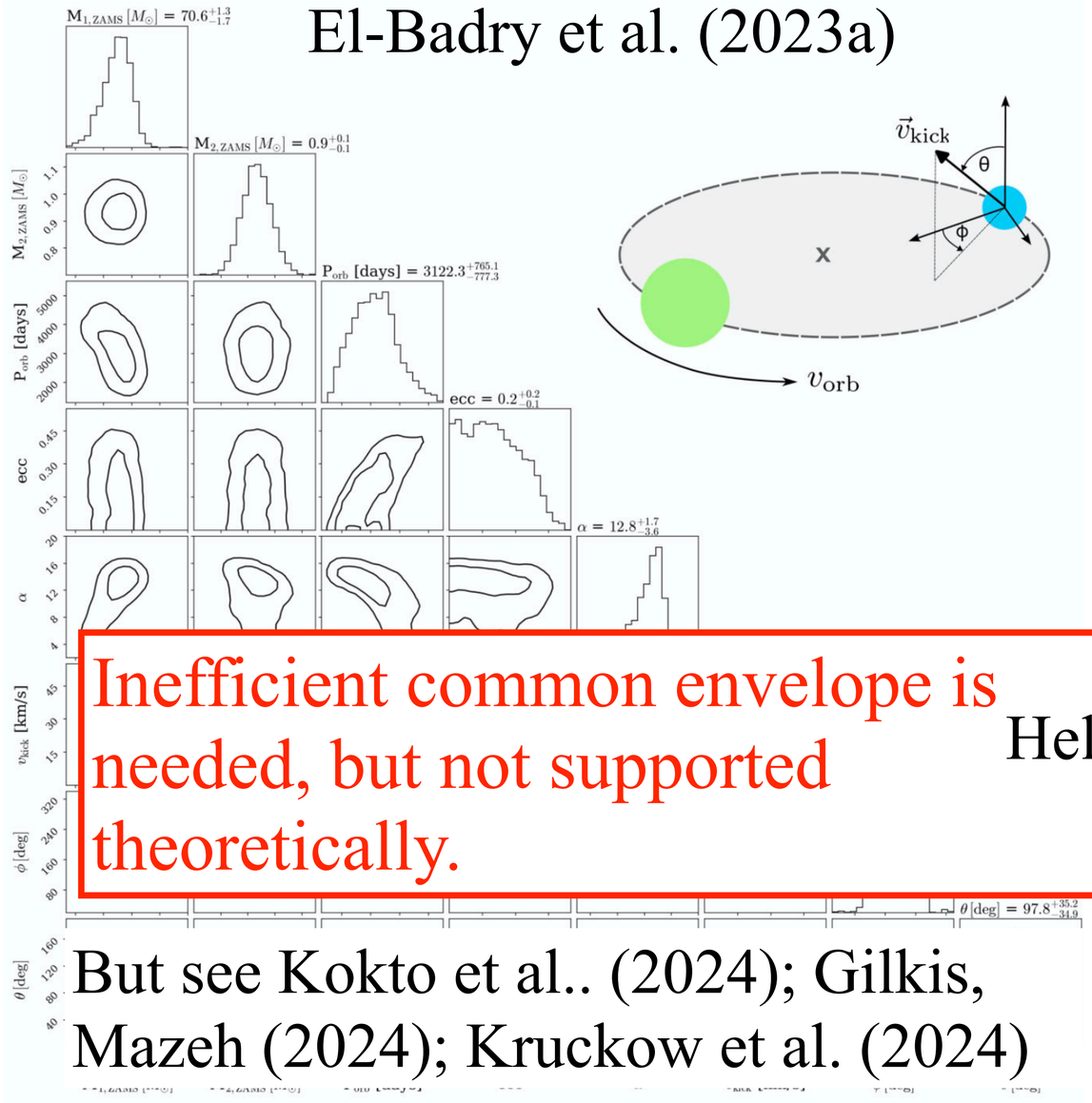
Possible link between GW events and Gaia BHs



LVK collaboration (2025)

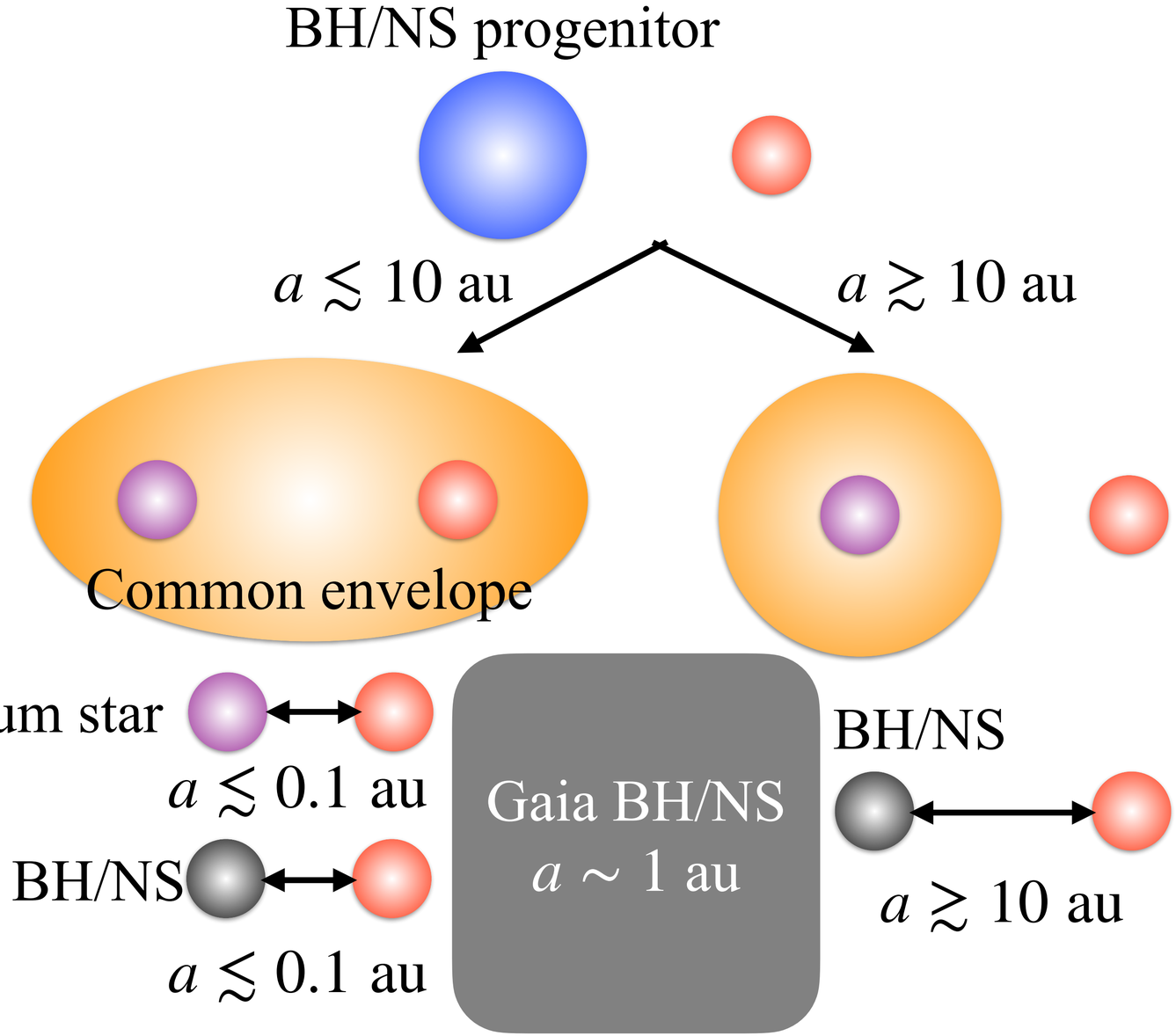
Mystery of the Gaia BH/NS formation

El-Badry et al. (2023a)



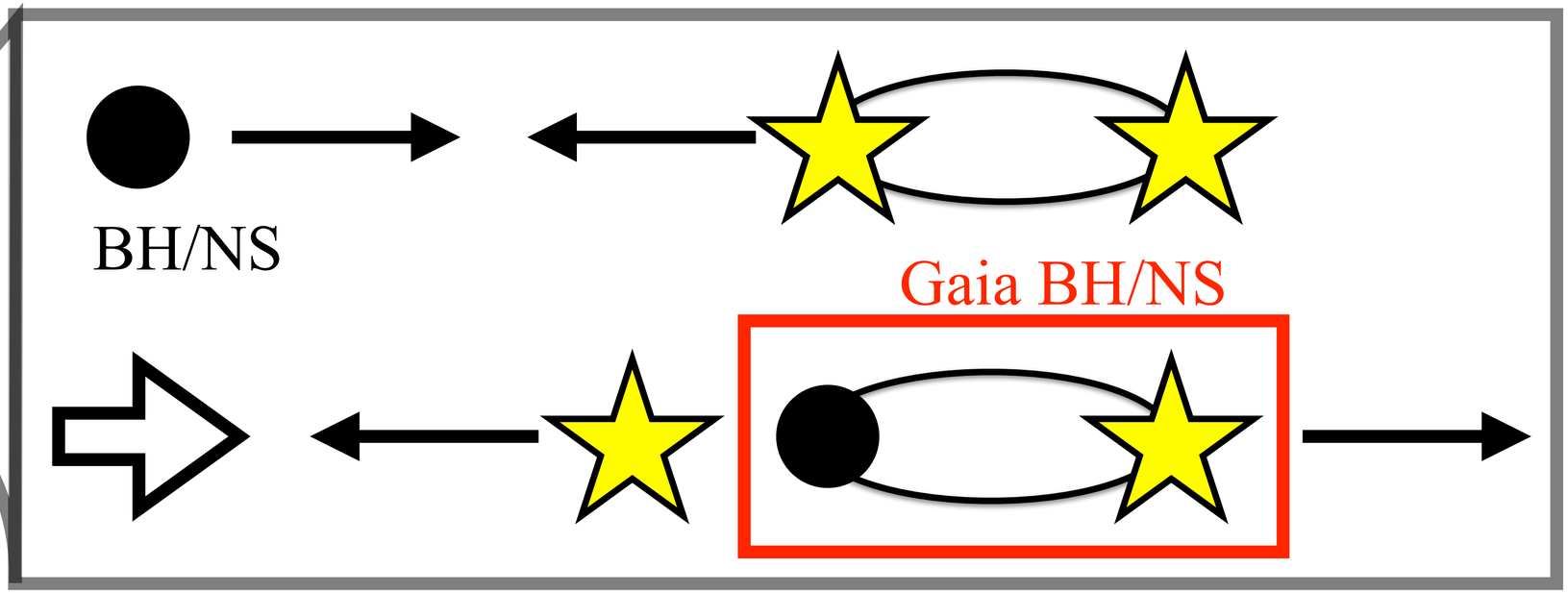
Inefficient common envelope is needed, but not supported theoretically.

But see Kokto et al.. (2024); Gilkis, Mazeh (2024); Kruckow et al. (2024)

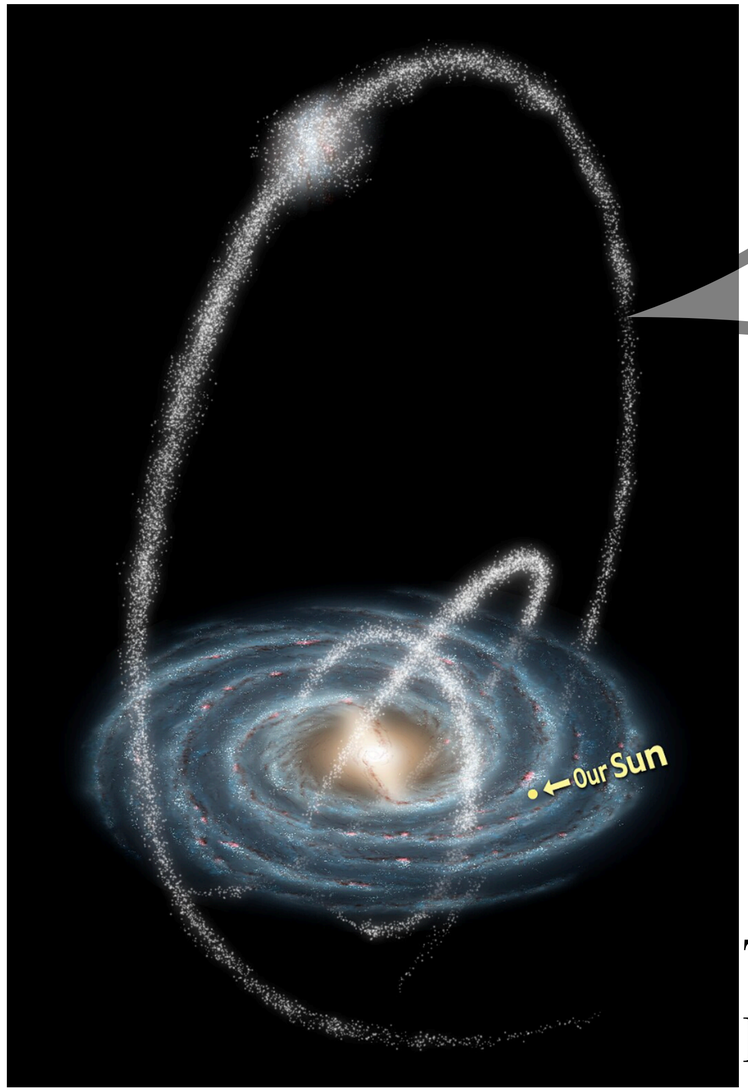


Gaia BH/NS formation in star clusters

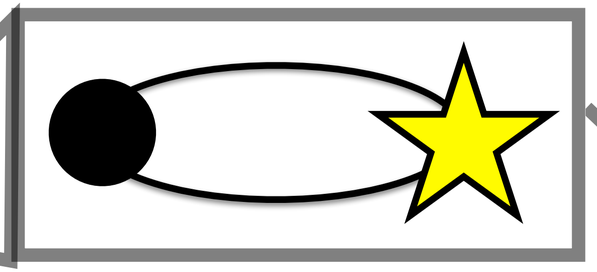
Star cluster

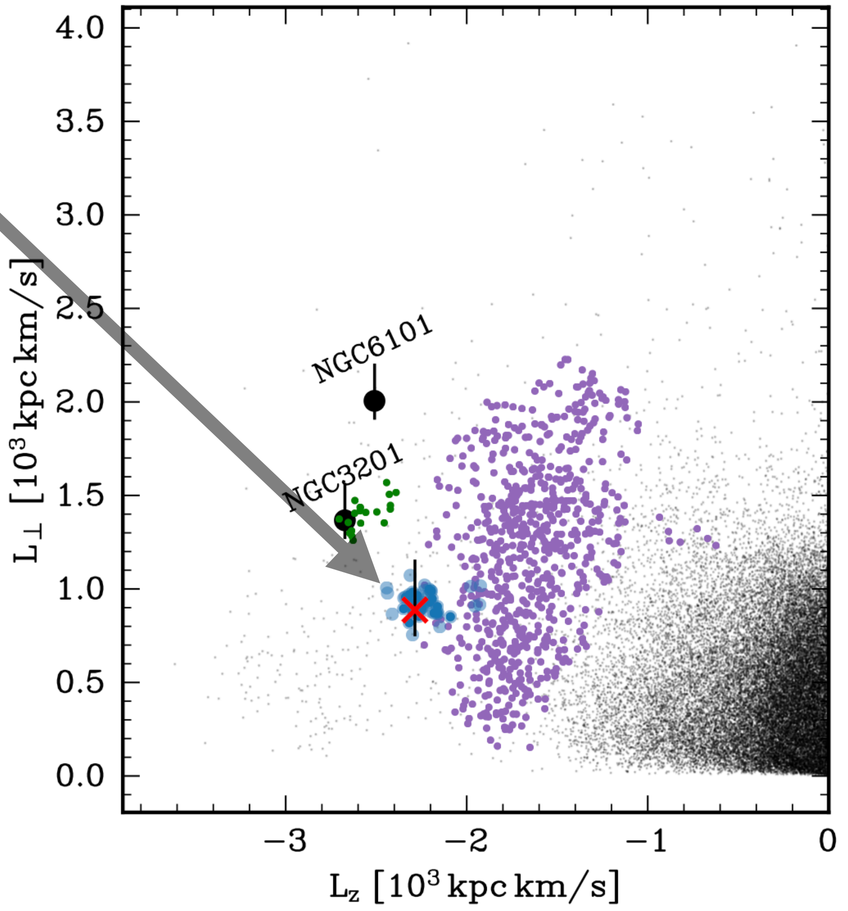


Gaia BH3 found in a disrupted star cluster



Gaia BH3

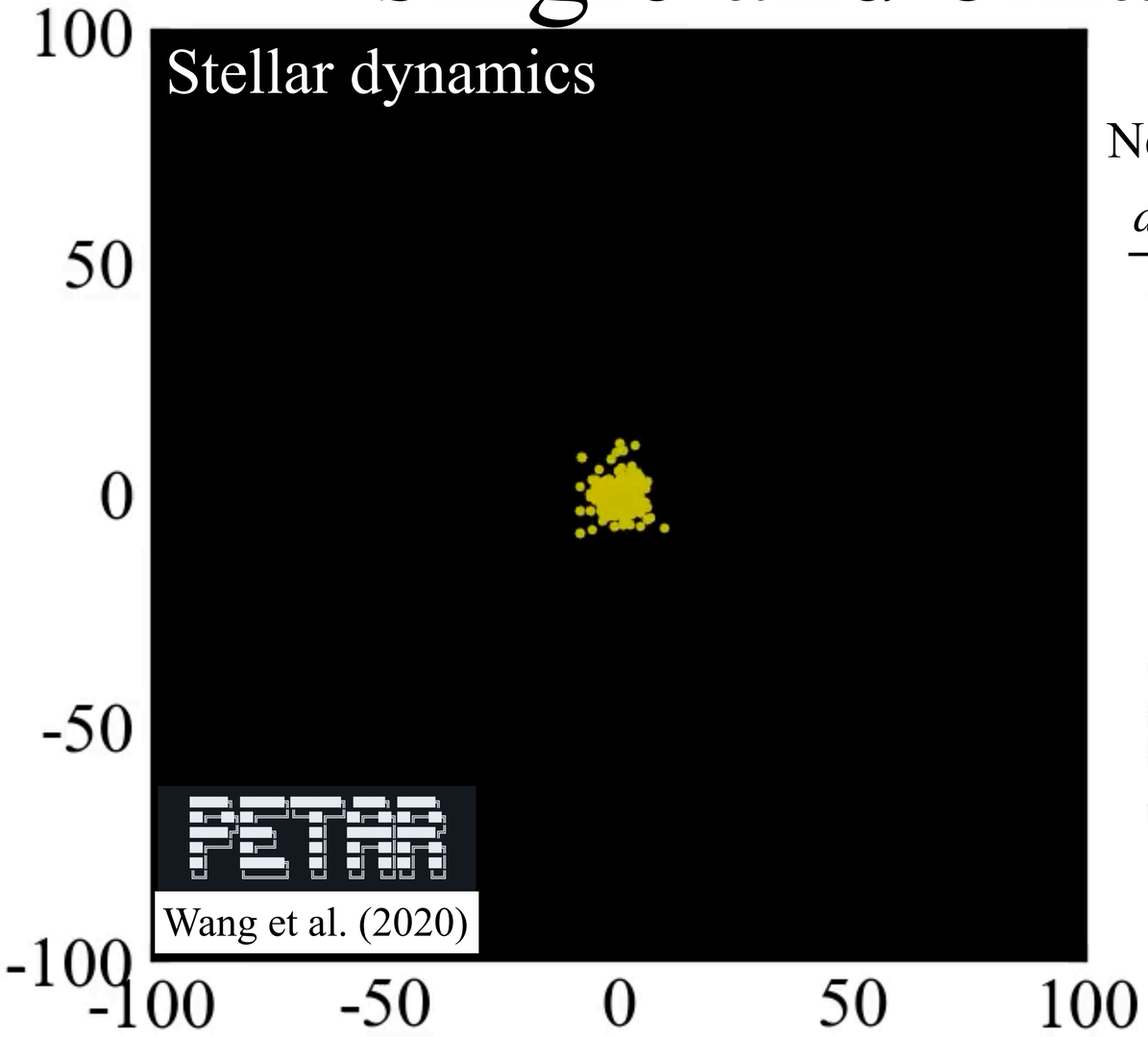




This is just an image!
ED-2 stream is much more faint!

Balbinot et al. (2024)

Gravitational N-body simulation coupled with single and binary star evolution

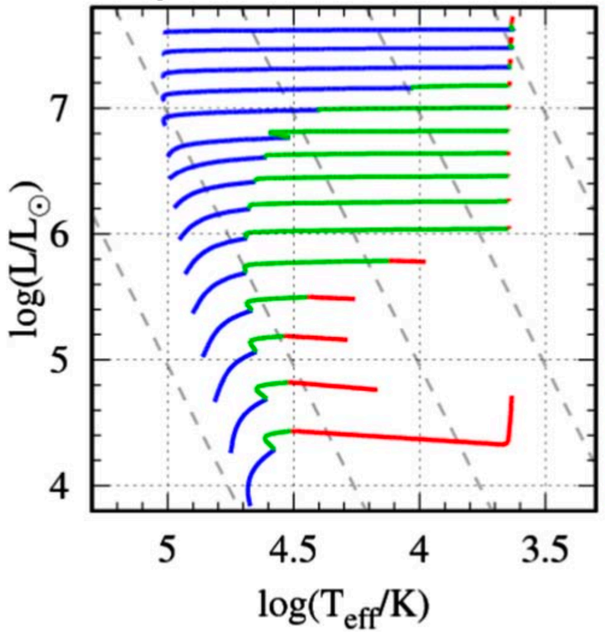


Newton's law of gravitation

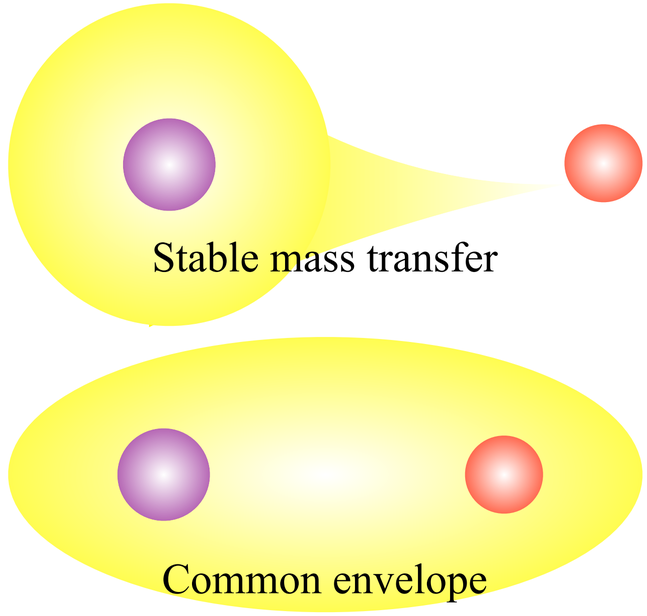
$$\frac{d^2\vec{r}_i}{dt^2} = \sum \frac{m_j}{|\vec{r}_j - \vec{r}_i|^2} \frac{\vec{r}_j - \vec{r}_i}{|\vec{r}_j - \vec{r}_i|}$$

No assumption regarding dynamical binary formation

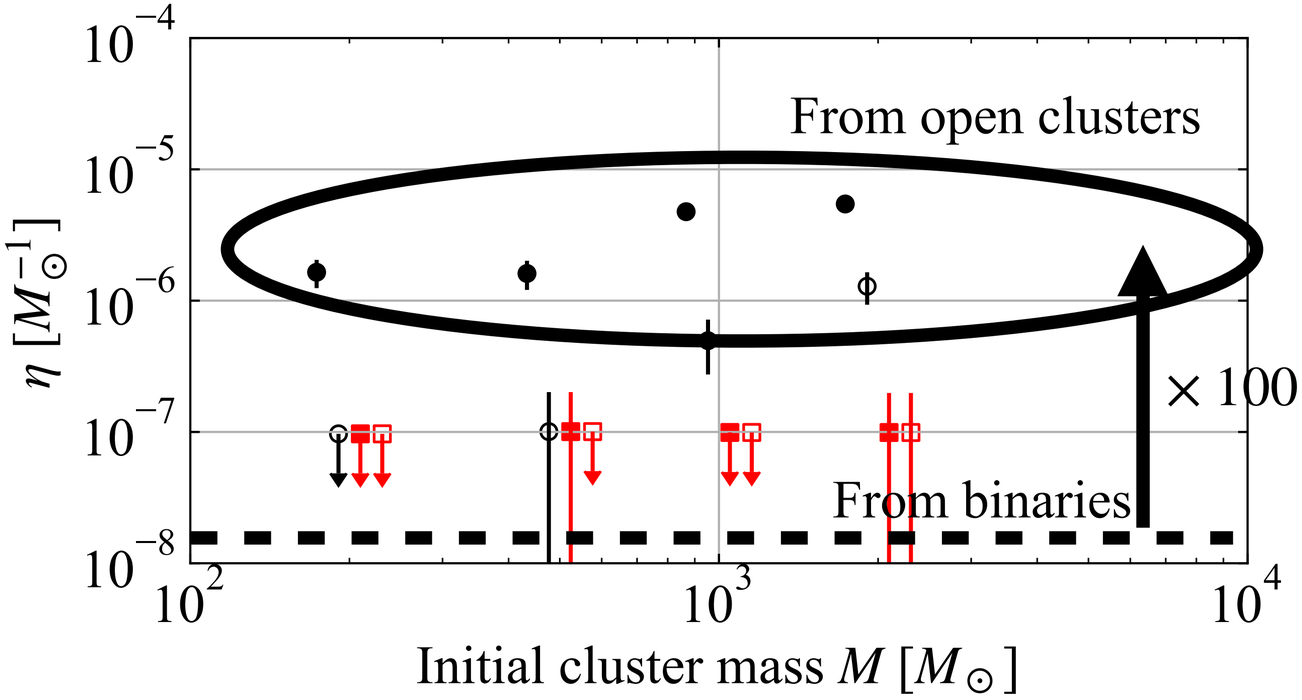
Single star evolution

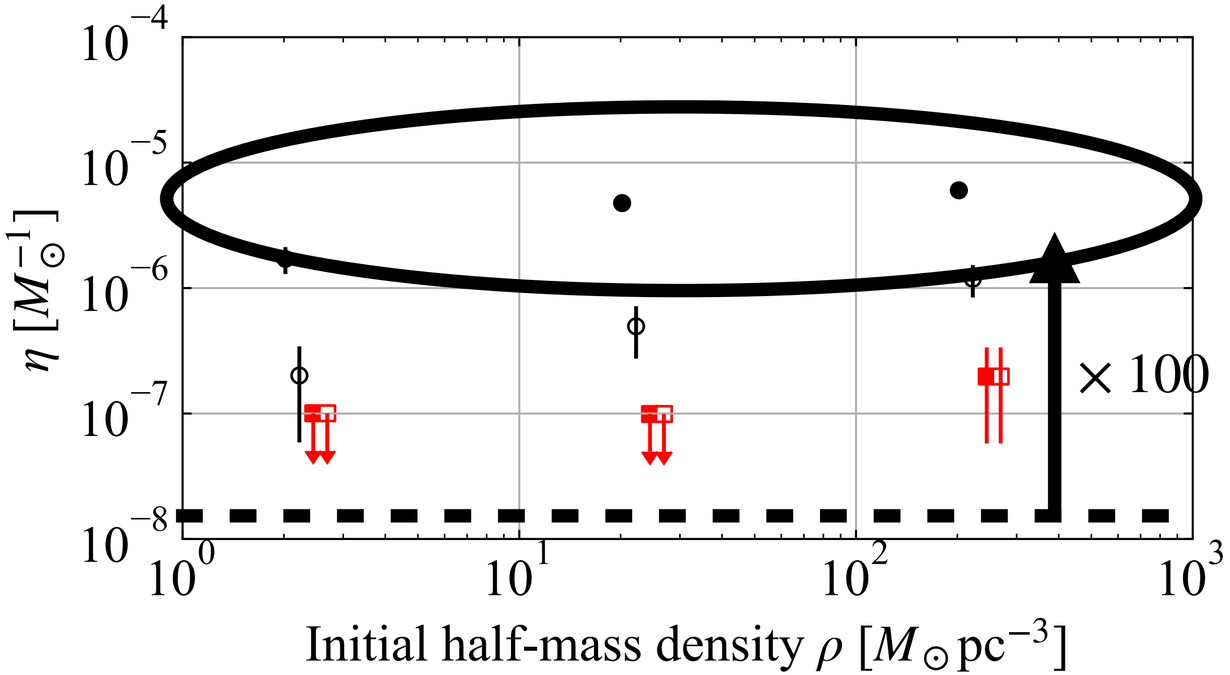


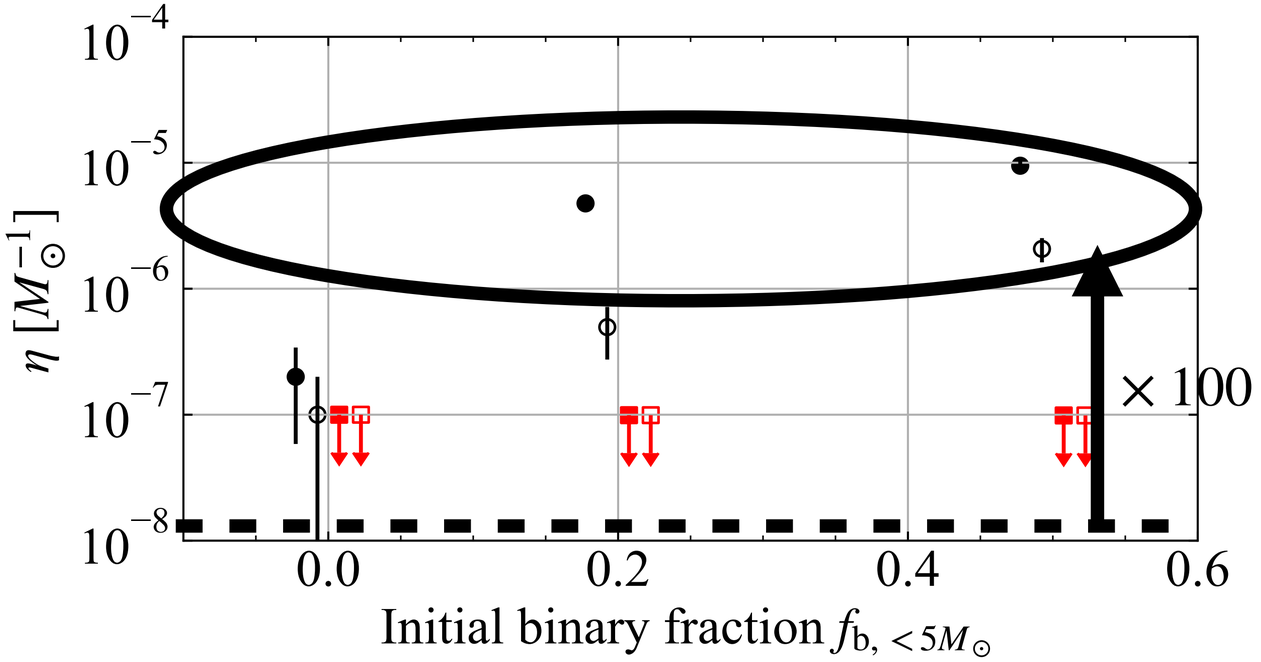
Binary star evolution

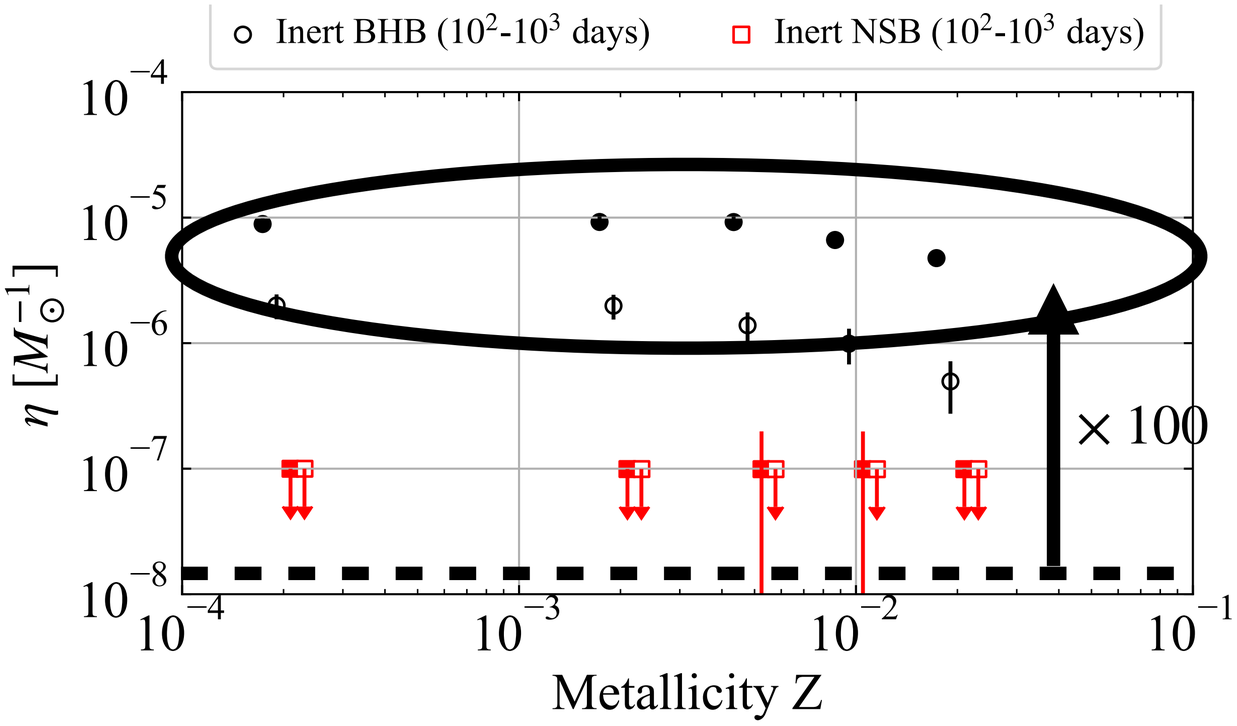


Gaia BH

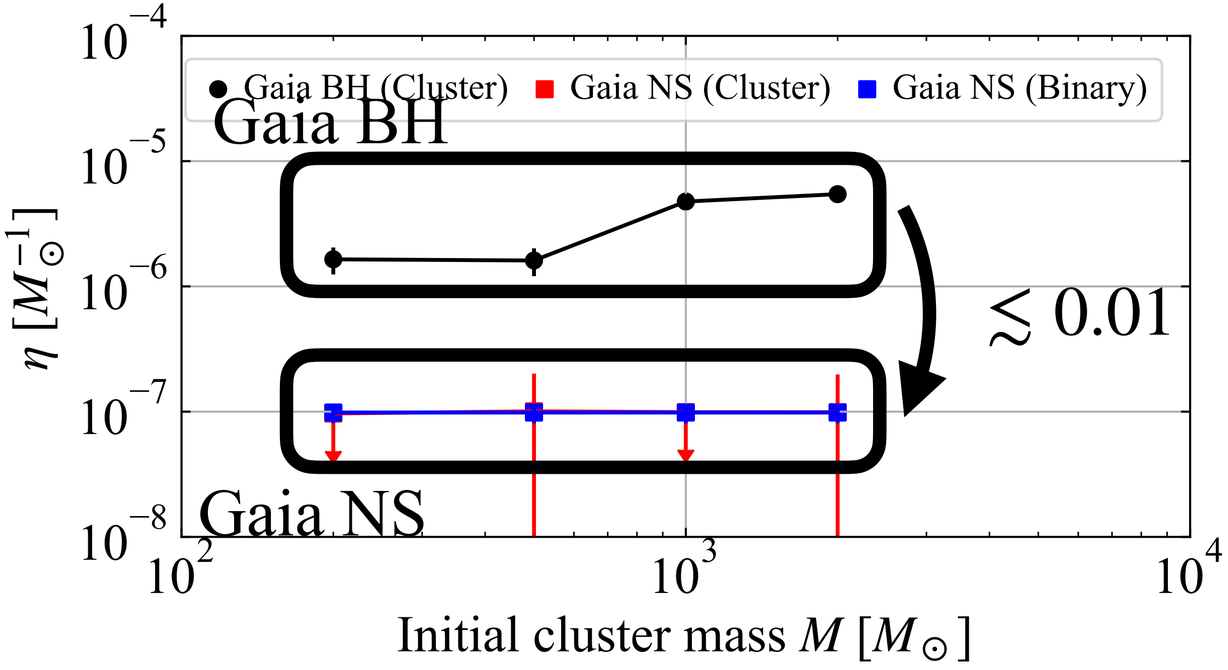

From open clusters
From binaries
× 100
$\eta\ [M_\odot^{-1}]$
Initial cluster mass $M\ [M_\odot]$

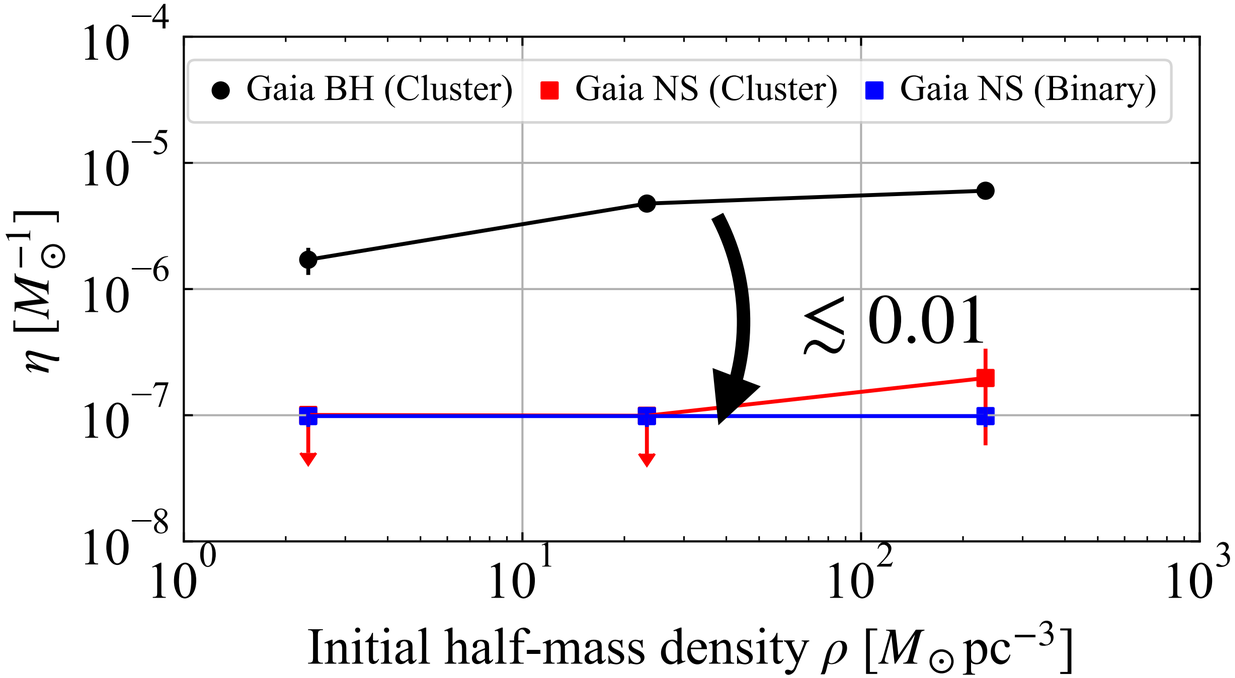

× 100
$\eta\ [M_\odot^{-1}]$
Initial half-mass density $\rho\ [M_\odot\,\mathrm{pc}^{-3}]$

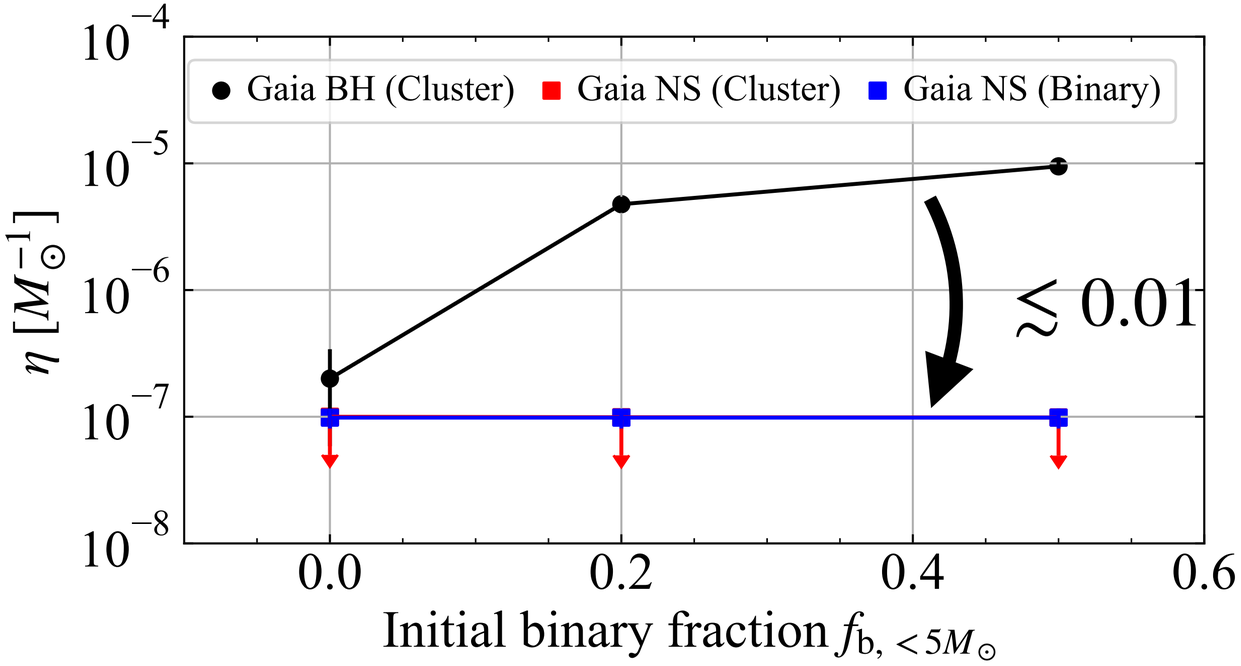

× 100
$\eta\ [M_\odot^{-1}]$
Initial binary fraction $f_{\mathrm{b},<5M_\odot}$

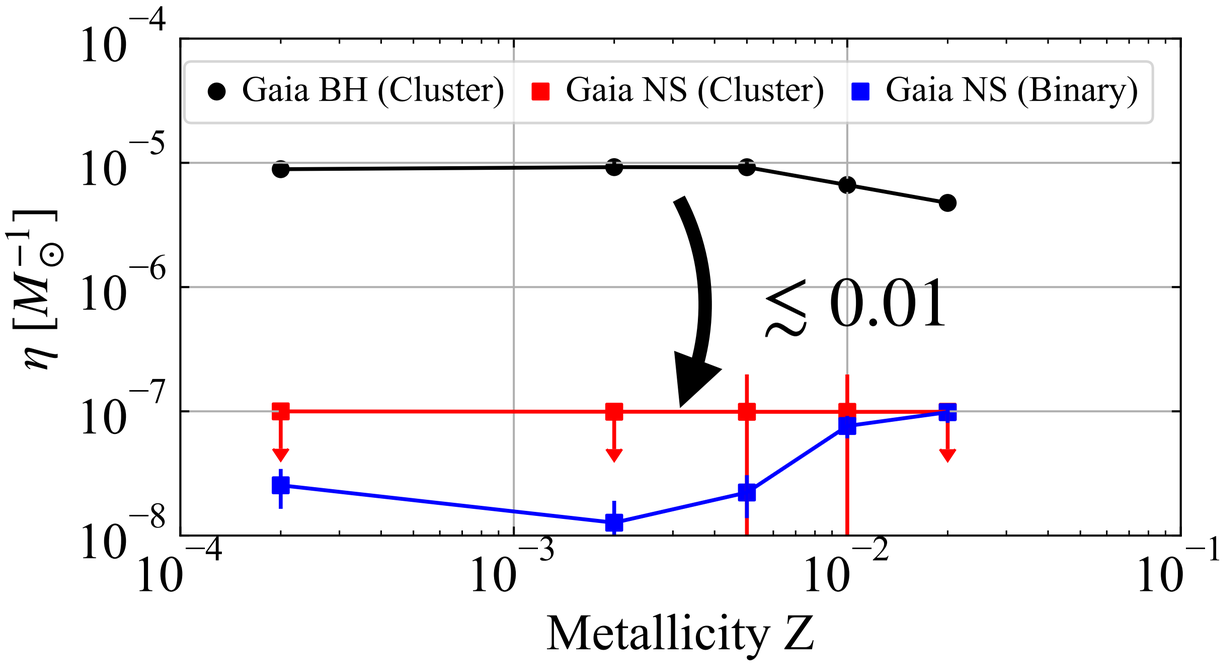

Inert BHB (10^2-10^3 days)
Inert NSB (10^2-10^3 days)
× 100
$\eta\ [M_\odot^{-1}]$
Metallicity Z

Gaia NS


Gaia BH (Cluster)
Gaia NS (Cluster)
Gaia NS (Binary)
Gaia BH
Gaia NS
≲ 0.01
$\eta\ [M_\odot^{-1}]$
Initial cluster mass $M\ [M_\odot]$


Gaia BH (Cluster)
Gaia NS (Cluster)
Gaia NS (Binary)
≲ 0.01
$\eta\ [M_\odot^{-1}]$
Initial half-mass density $\rho\ [M_\odot\,\mathrm{pc}^{-3}]$


Gaia BH (Cluster)
Gaia NS (Cluster)
Gaia NS (Binary)
≲ 0.01
$\eta\ [M_\odot^{-1}]$
Initial binary fraction $f_{\mathrm{b},<5M_\odot}$

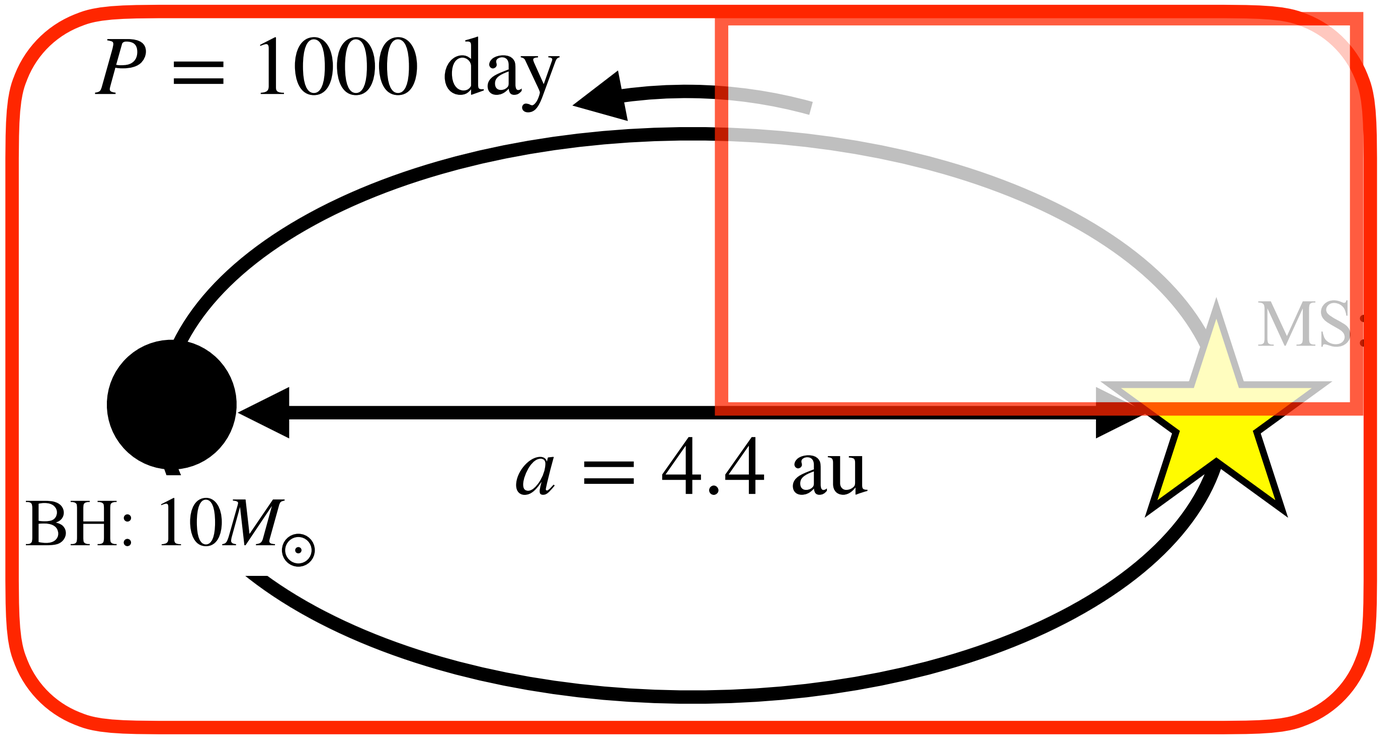

Gaia BH (Cluster)
Gaia NS (Cluster)
Gaia NS (Binary)
≲ 0.01
$\eta\ [M_\odot^{-1}]$
Metallicity Z

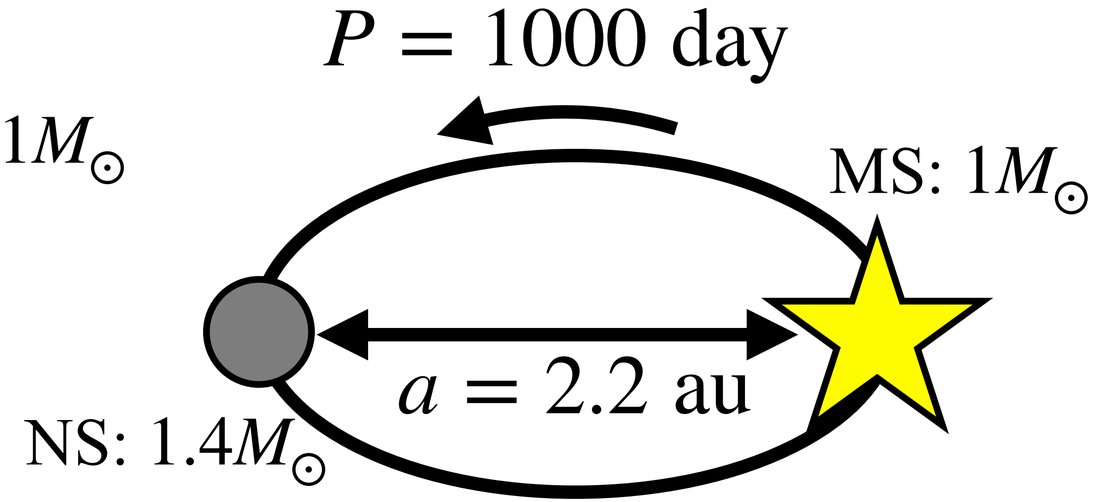
Open clusters cannot form both Gaia BHs and Gaia NSs.

- Observation
  - # of Gaia BHs (3) < # of Gaia NSs (21)
- Intrinsic population
  - # of Gaia BHs < # of Gaia NSs

- Formation efficiencies in open clusters
  - η of Gaia BHs $\gg$ η of Gaia NSs

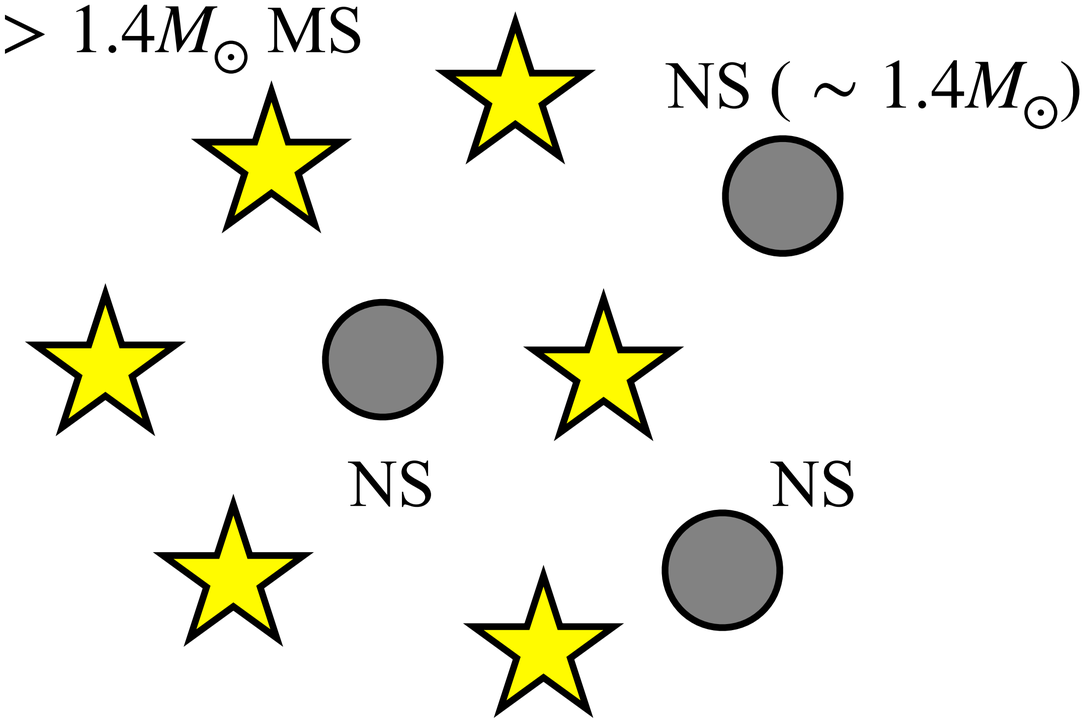
Noticeable contradiction
$\Longrightarrow$ Open clusters cannot form both.



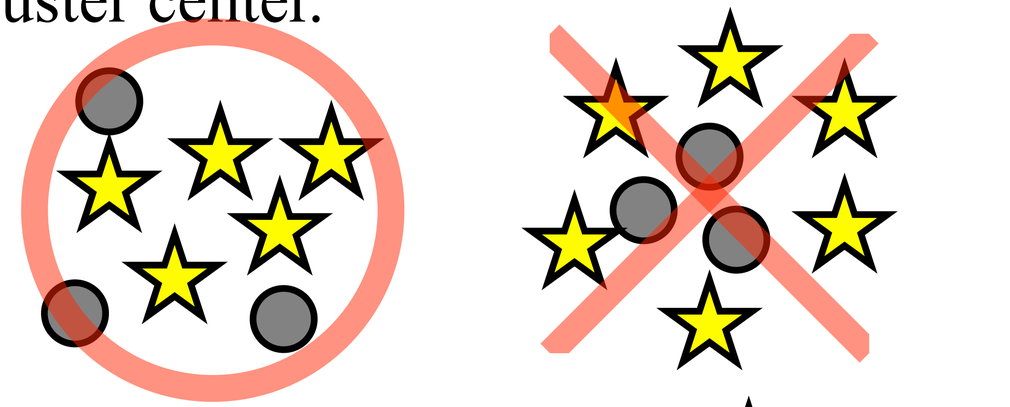


Reason for inefficiency of Gaia NS formation

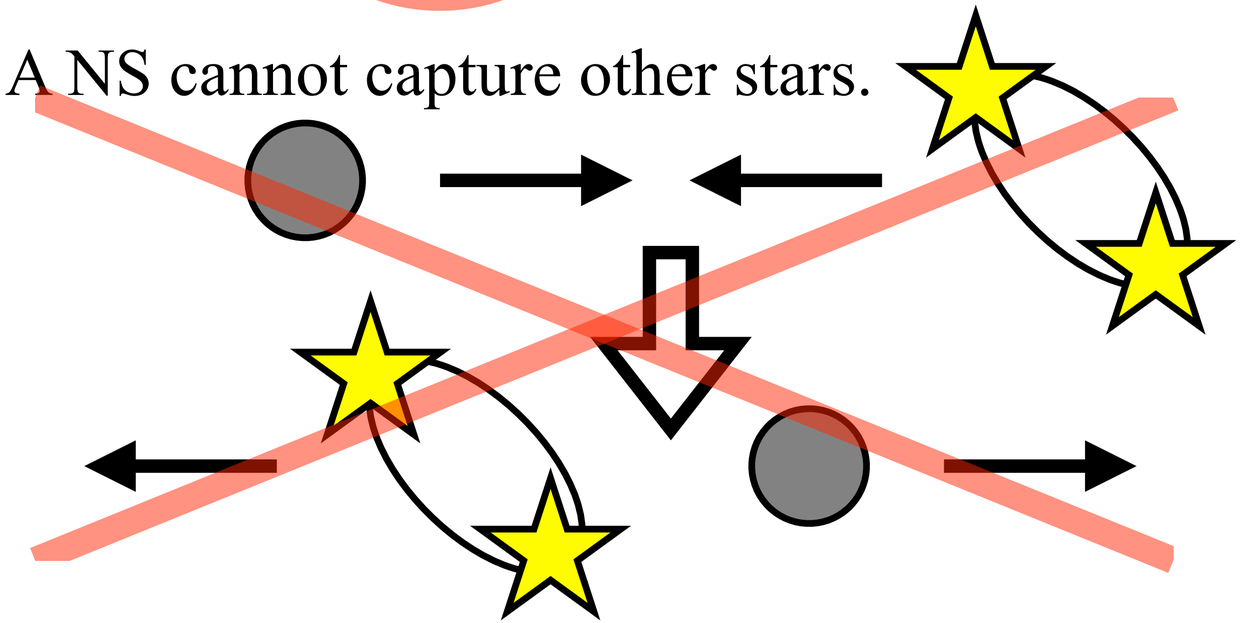
Lifetime of an open cluster ($\lesssim$ 1 Gyr)



Low interaction rate, because NSs are not at the cluster center.

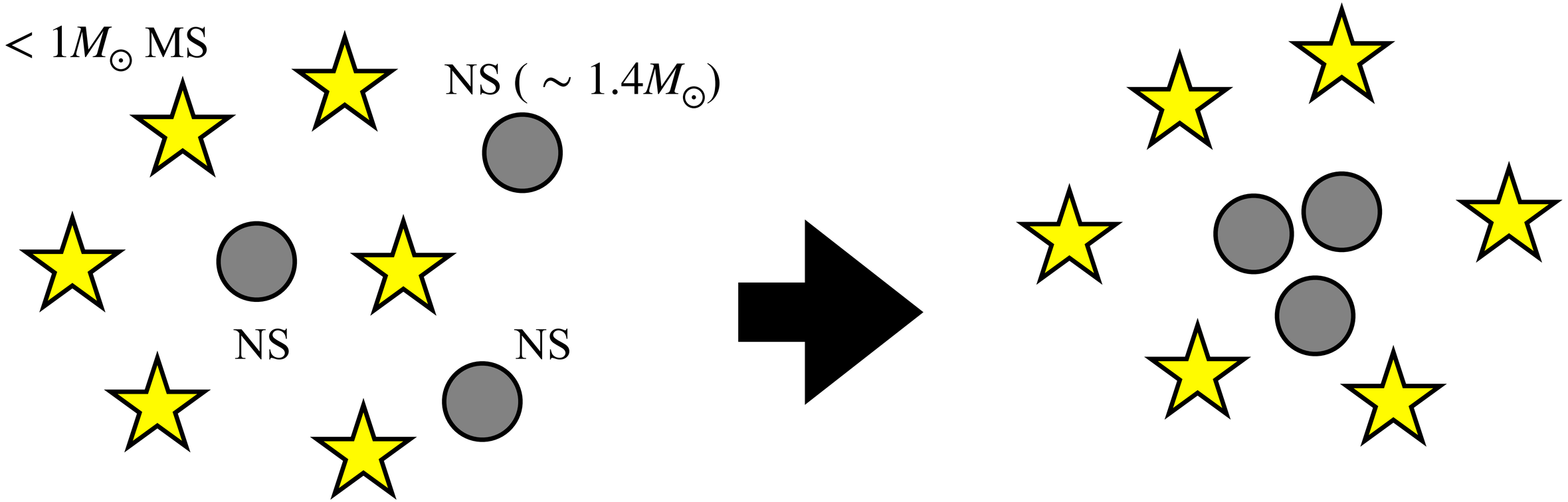


A NS cannot capture other stars.



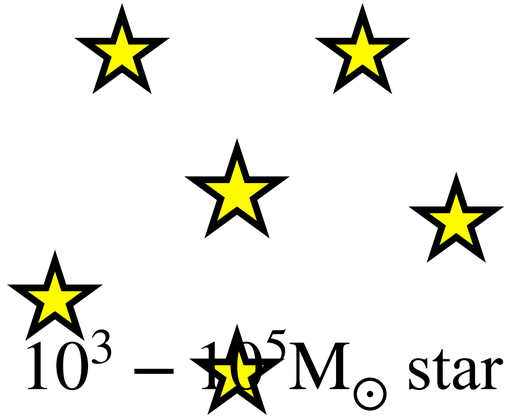
Massive star clusters (e.g. globular clusters)

Lifetime of a massive star clusters ($\gg$ 1 Gyr)

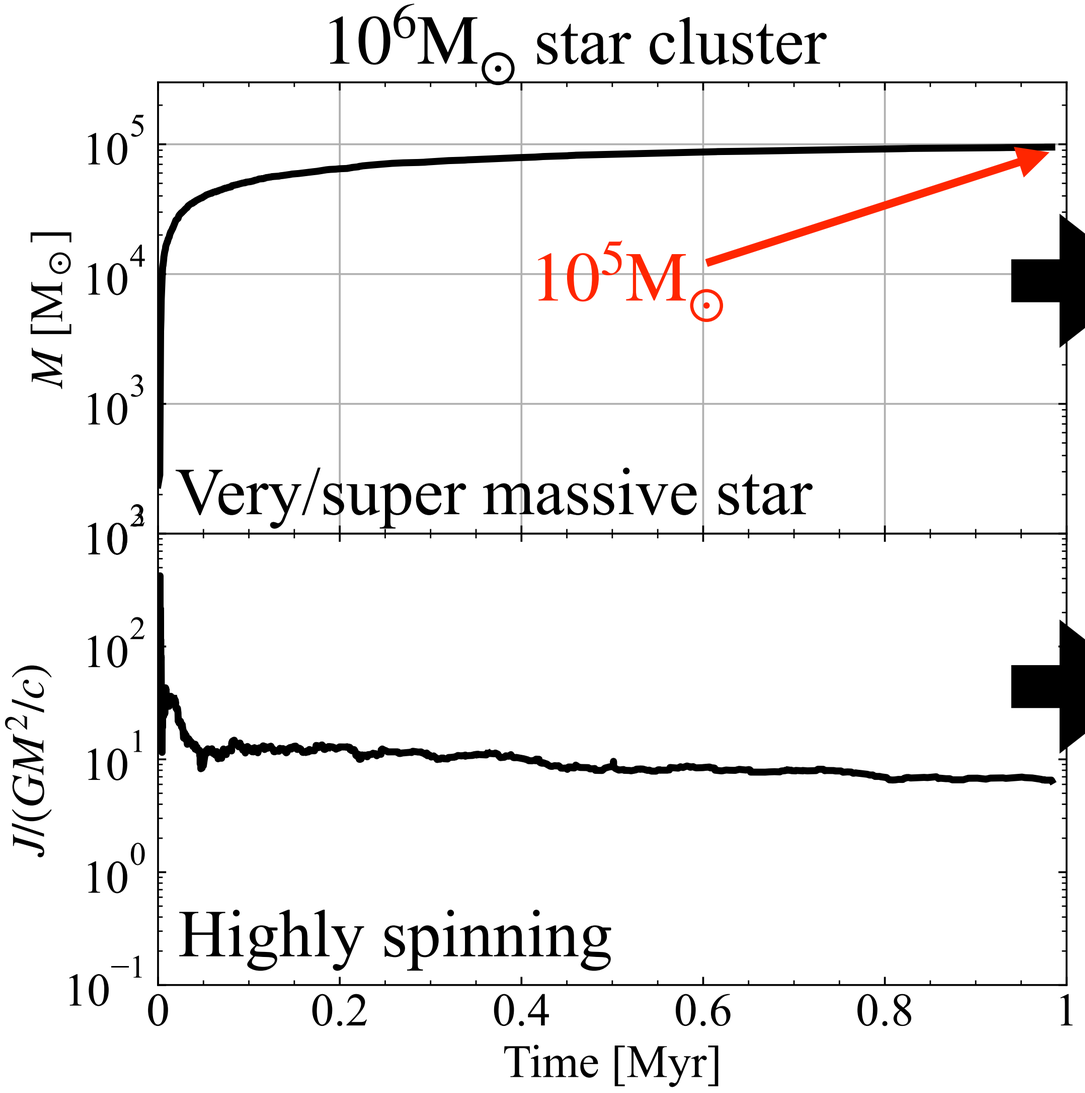


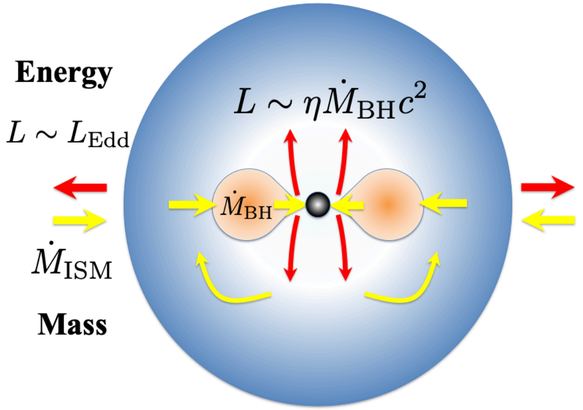
We will perform N-body simulation of massive star clusters in order to assess if Gaia NSs can be formed in such clusters.

By-product (or primary product?)

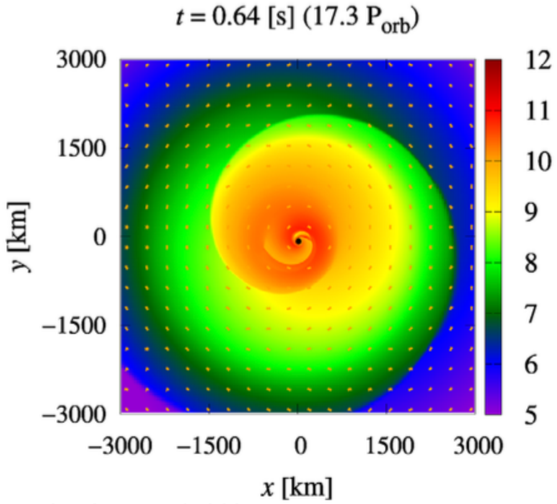


$10^3 - 10^5 M_\odot$ star





Little red dot (Kido et al. 2025)



Pair instability mass gap event (Shibata et al. 2021; Shibata, Fujibayashi 2025; see Sho's talk)

Summary

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- They cannot be formed in the conventional binary evolution model.
- We have shown that Gaia BHs can be formed in open clusters, but Gaia NSs cannot.
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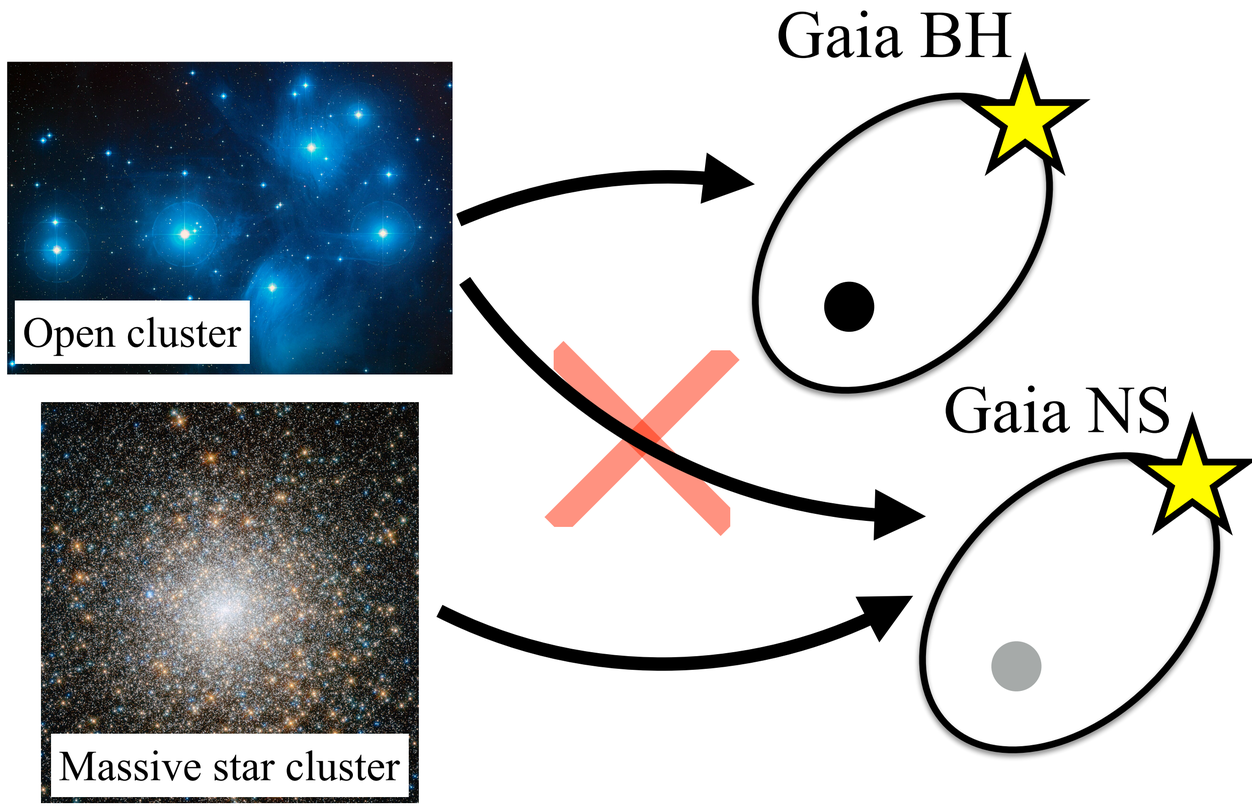
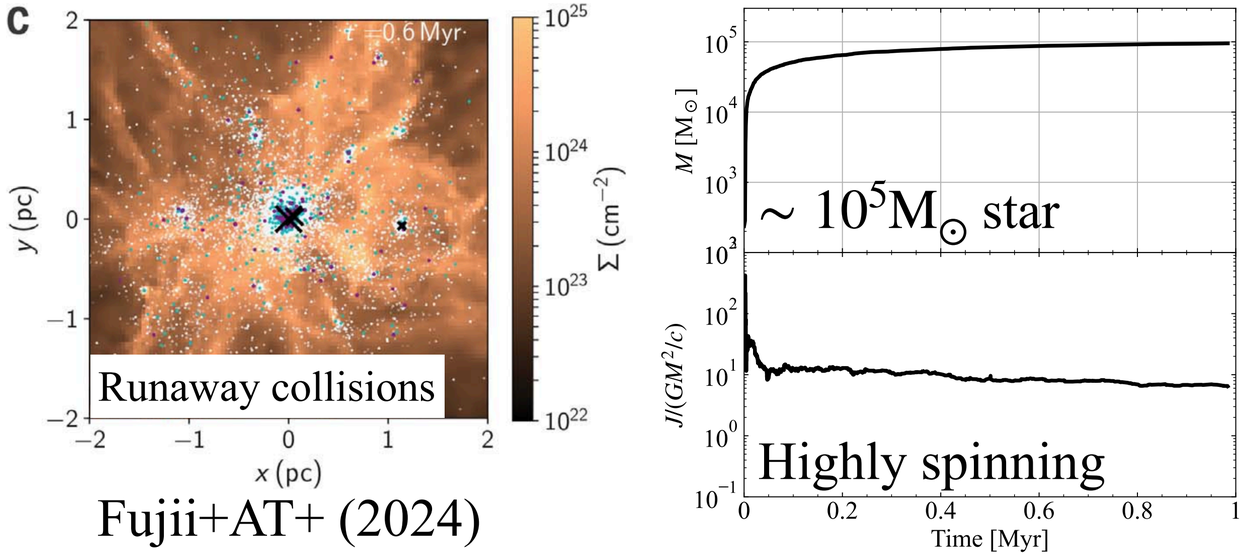
- Such N-body simulations can be also helpful to solve the formation Little Red Dots and pair instability mass gap events.





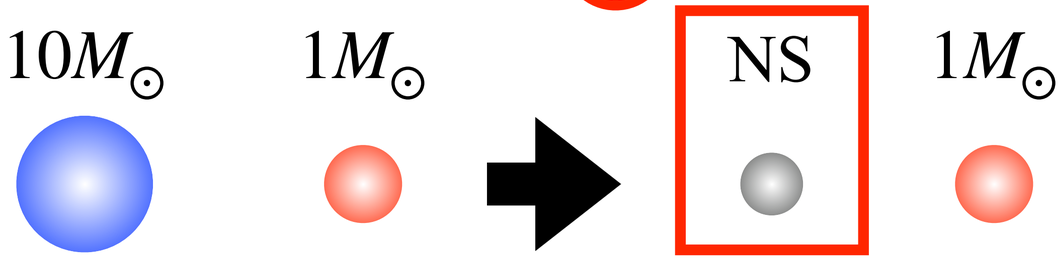
Fujii+AT+ (2024)

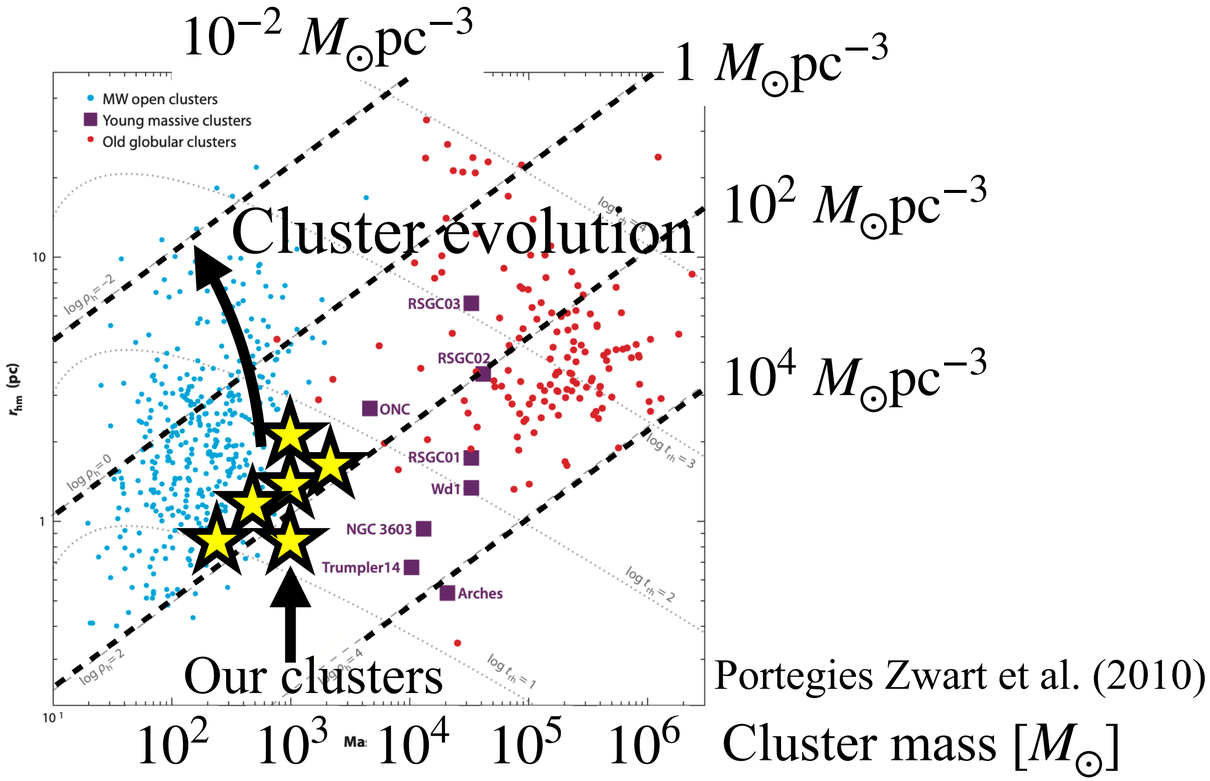
Back-up slides

Our open cluster models

- Initial cluster parameters
  - Cluster mass: $200 - 2000\ M_\odot$
  - Metallicity: $Z = 0.0002 - 0.02$
  - Mass density: $2 - 200\ M_\odot/\mathrm{pc}^3$
  - Binary fraction: 0, 20, 50 %

  $1.4 \times 10^8 M_\odot$ in total
- Initial binary parameters
  - Primary star: Kroupa's IMF ($0.08 \leq m_1/M_\odot \leq 150$)
  - $f(m_2/m_1) \propto (m_2/m_1)^{-0.1}$ $(0.1 \leq m_2/m_1 \leq 1)$





Portegies Zwart et al. (2010)

Gaia BHs could not be formed without dynamical interactions.

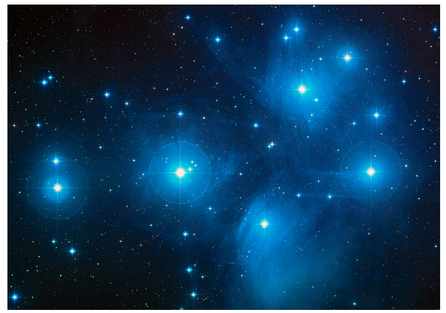
Criteria of Gaia BH/NSs

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

$10^2 \leq P/\mathrm{day} \leq 10^4$

$m_1 \leq 1.1 M_\odot$

$0 \leq e \leq 1$

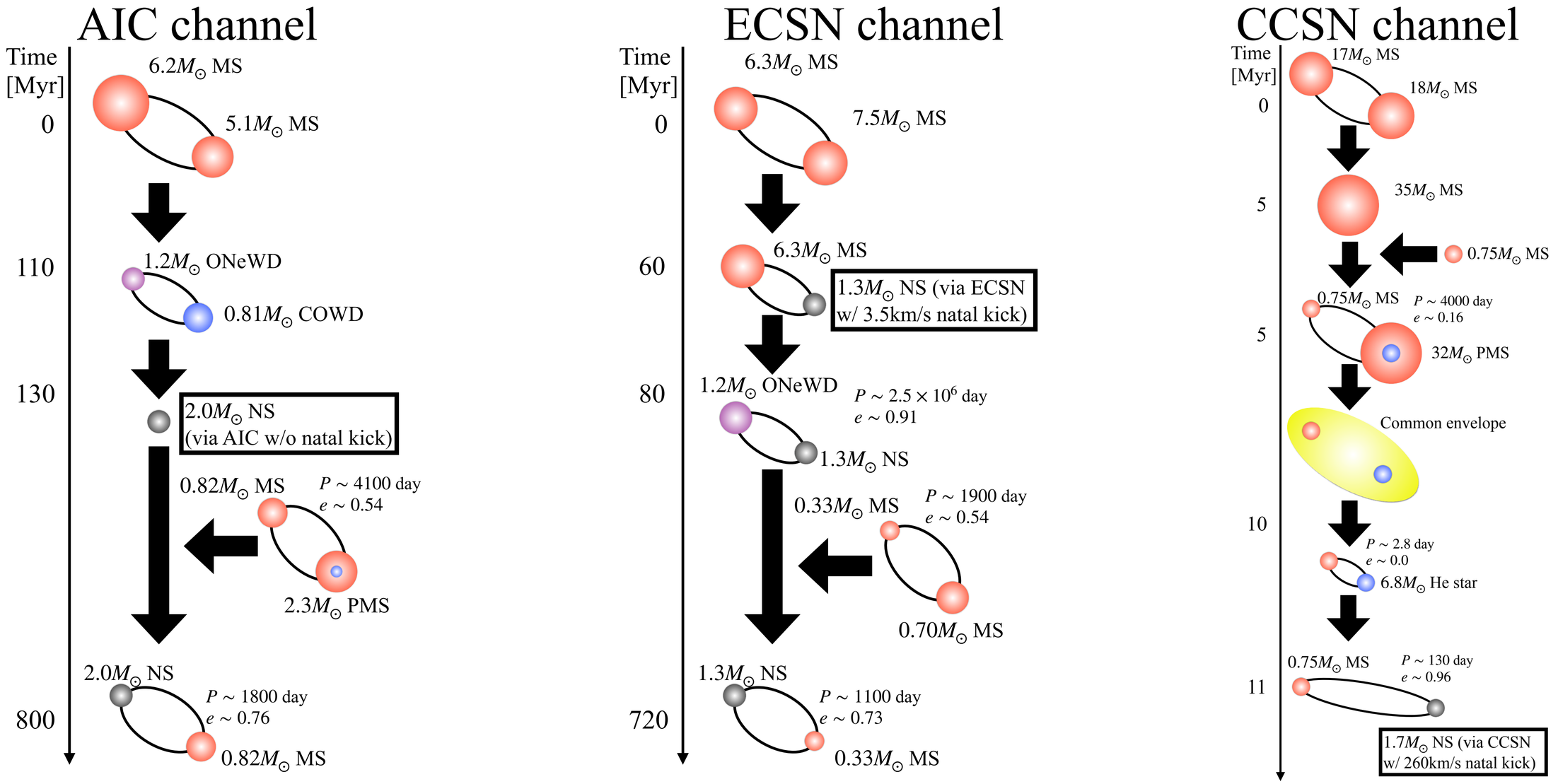


Ejected from its parent cluster

The number of Gaia BHs in the Galactic disk

$\sim 10^{-5} M_{\odot}^{-1}$ for clusters with reasonable mass, density, binary fraction, and metallicity

Formation channels of Gaia NS



No CCSN natal kick model

- We reduce NS natal kicks to zero.
- The formation efficiency of Gaia NSs is still comparable to that of Gaia BHs.
- Moreover, Gaia NSs are formed from primordial binaries, not through dynamical capture.
- No need to consider Gaia NS formation in open clusters in this case.