Inert compact binary formation in open clusters

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Collaborators: Long Wang (Sun Yat-sen University),
Michiko S. Fujii (The University of Tokyo)

MODEST-24: Exploring Dense Stellar Systems Across Cosmic Time
22 August Warsaw

- Tanikawa et al. (2024, MNRAS, 527, 4031, arXiv:2303.05743)
- Tanikawa et al. (2024, OJAp, 7, 39, arXiv:2404.01731)

Conclusions of this talk

- Gaia mission and its follow-up observations have discovered many inert compact binaries, so-called Gaia BHs and Gaia NSs.
- These Gaia BHs and Gaia NSs cannot be formed in the conventional binary evolution model (but see Kotko et al. 2024; Iorio et al. 2024; El-Badry et al. 2024; Poojan’s talk).
- Gaia BHs can be formed efficiently in open clusters (Tanikawa et al. 2024, MNRAS, 527, 4031; see also Rastello et al. 2023; Di Carlo et al. 2024; Marin Pina et al. 2024).
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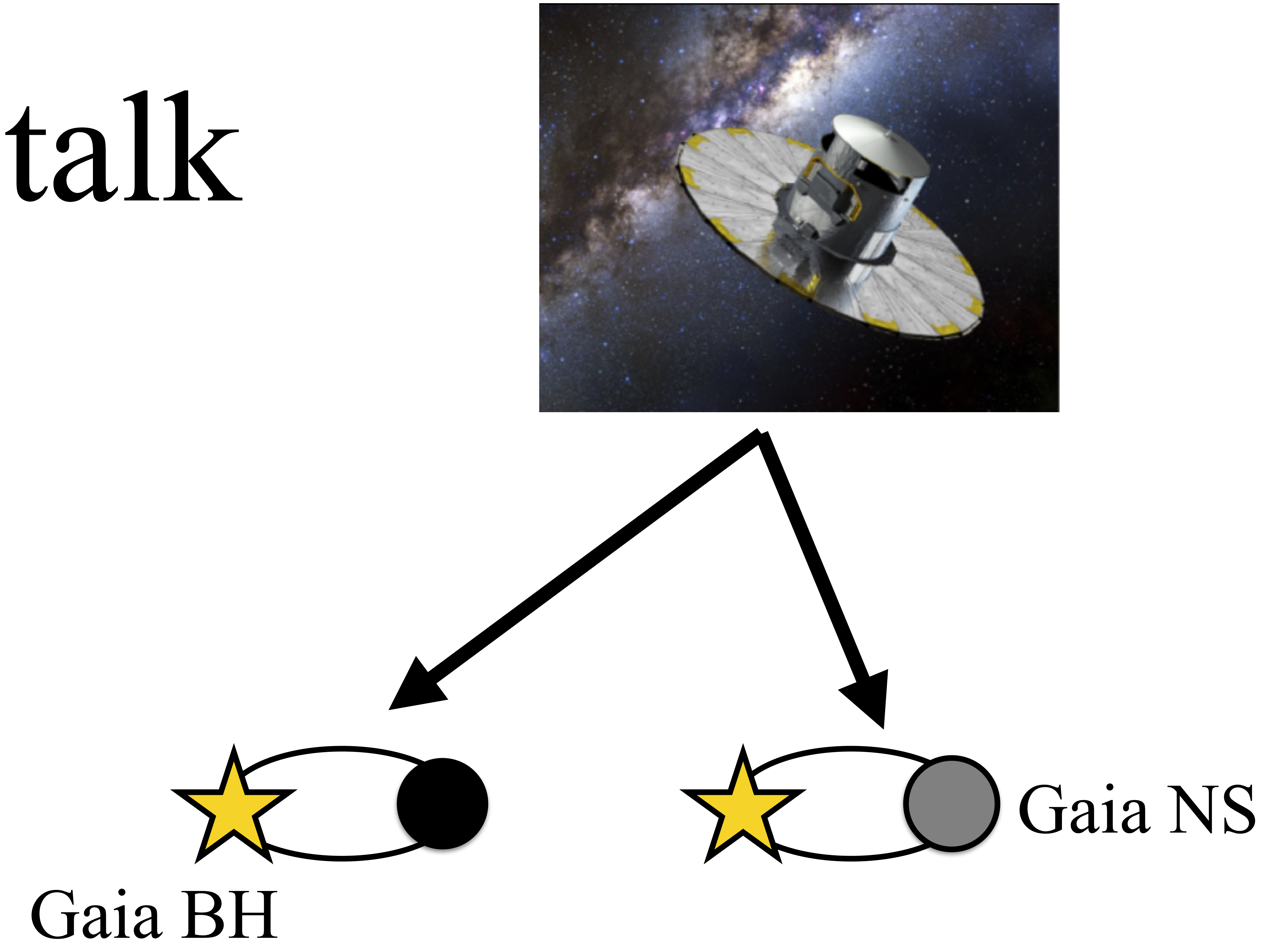

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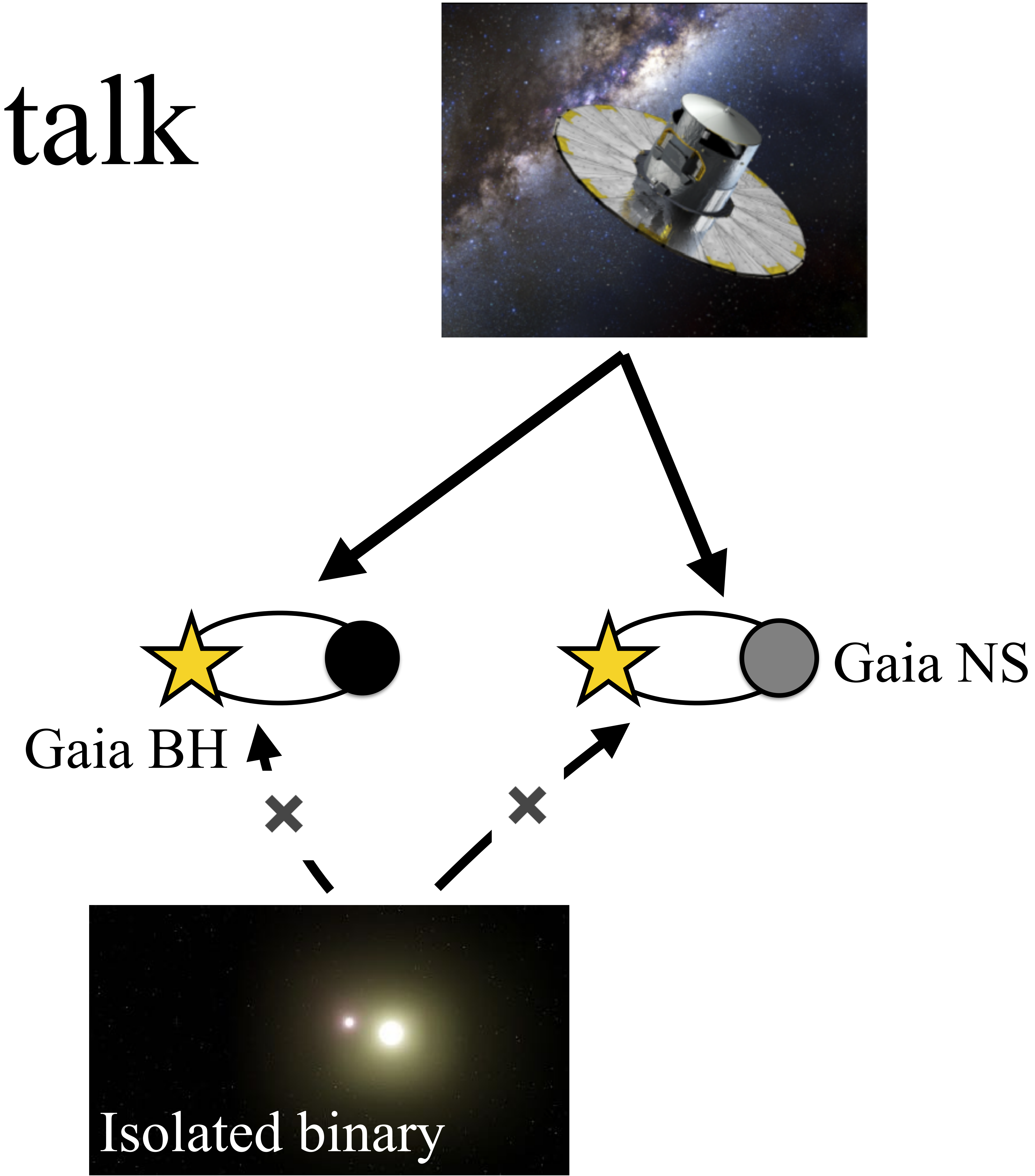

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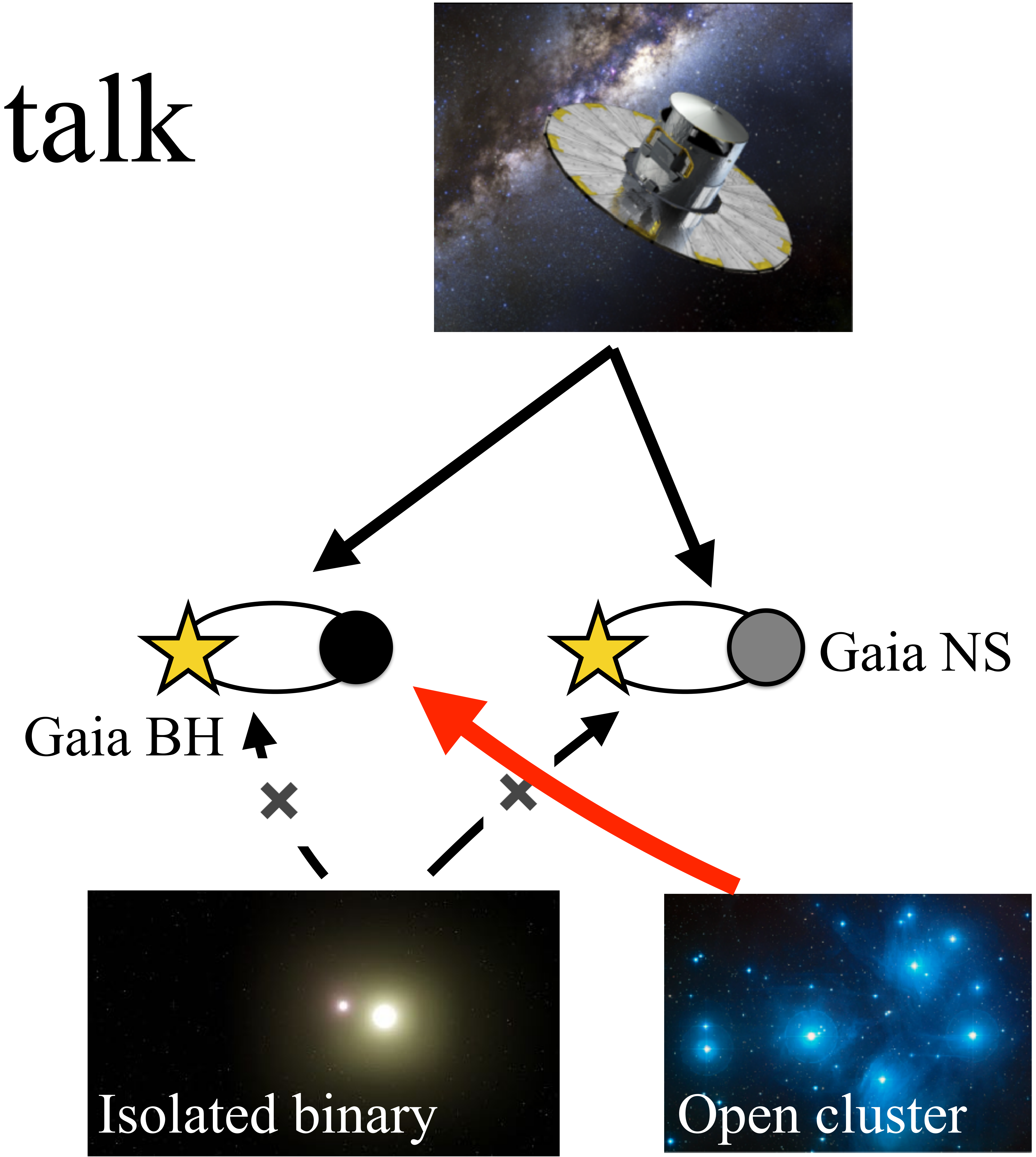

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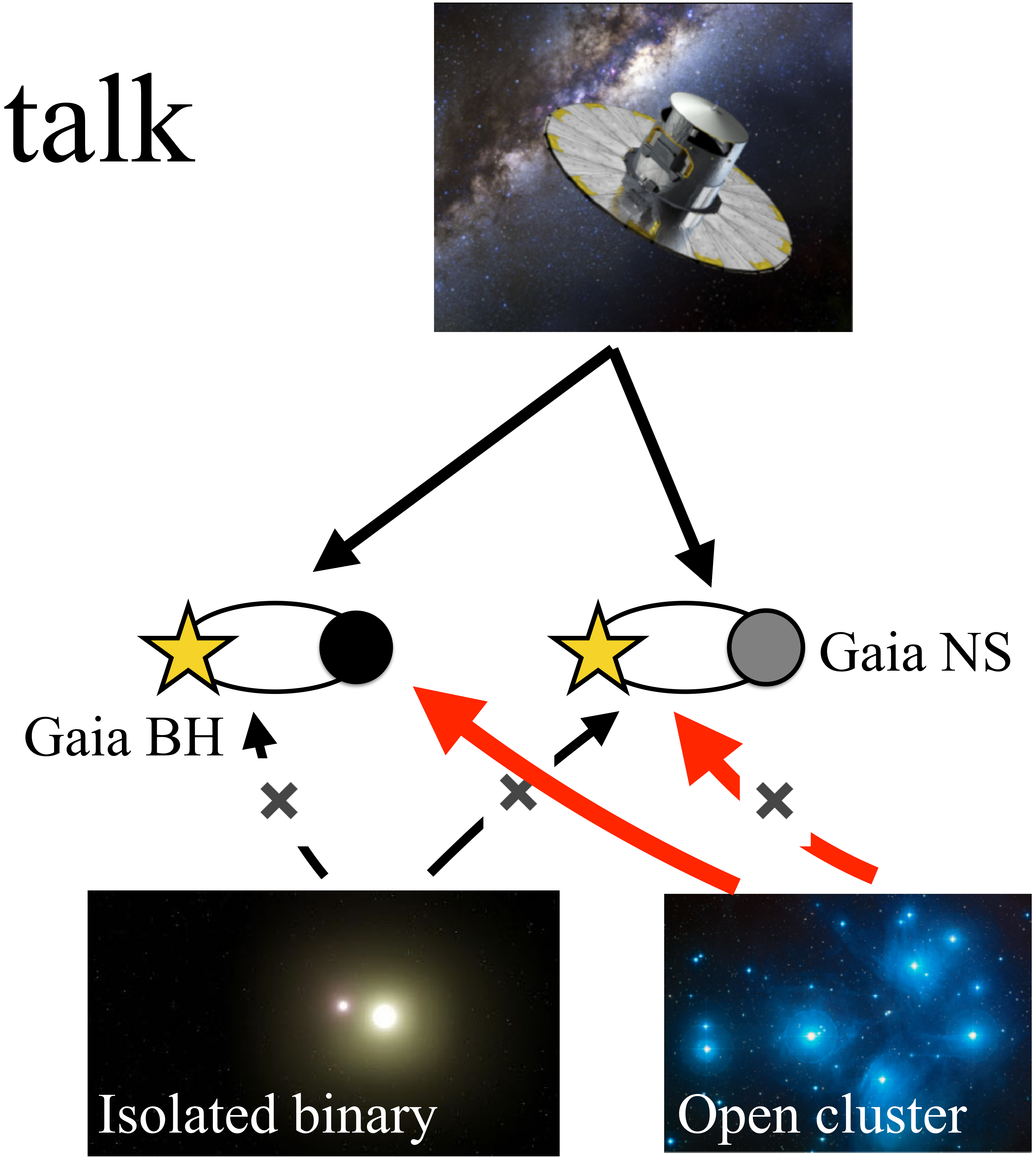

Gaia has discovered compact binaries

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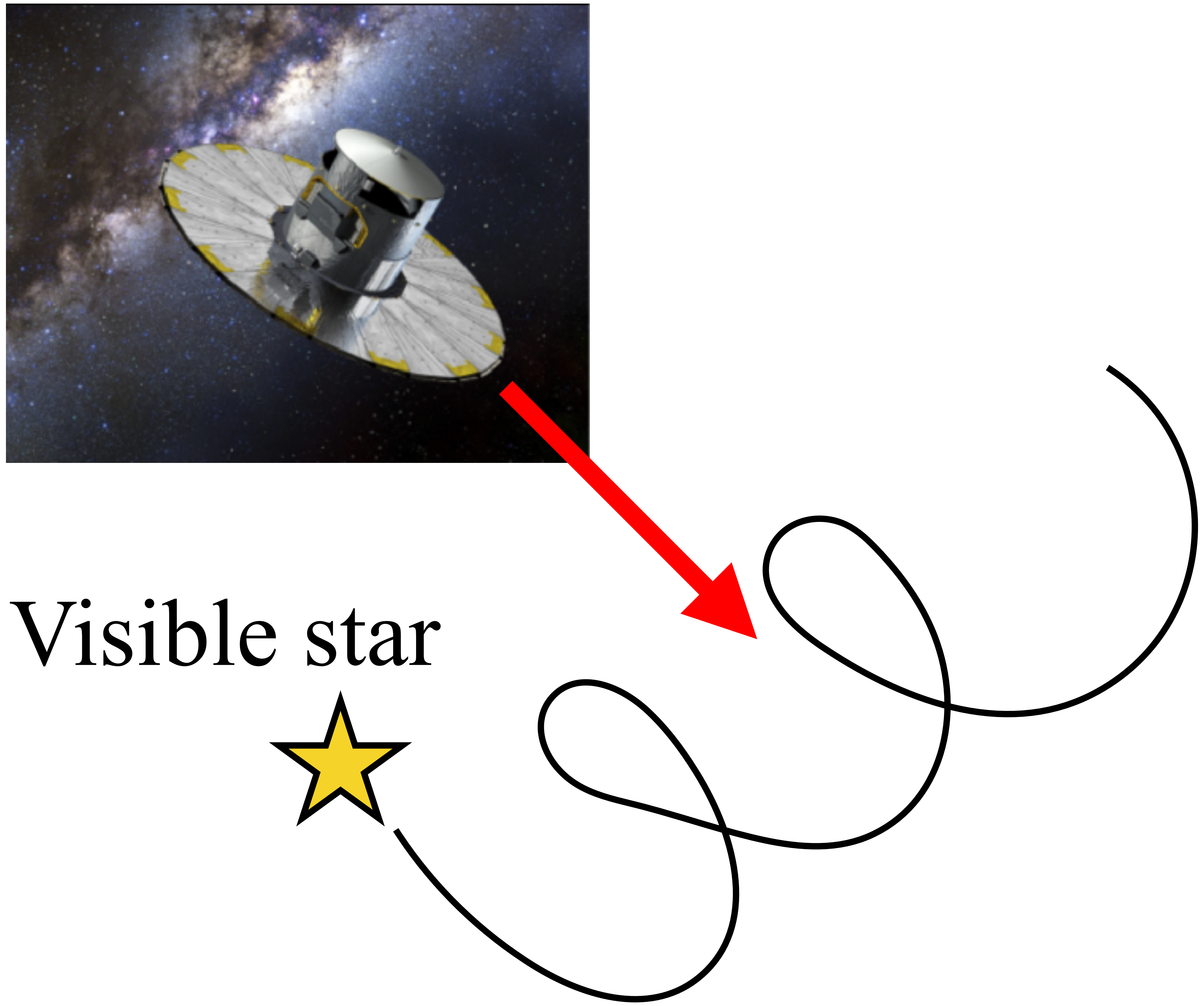
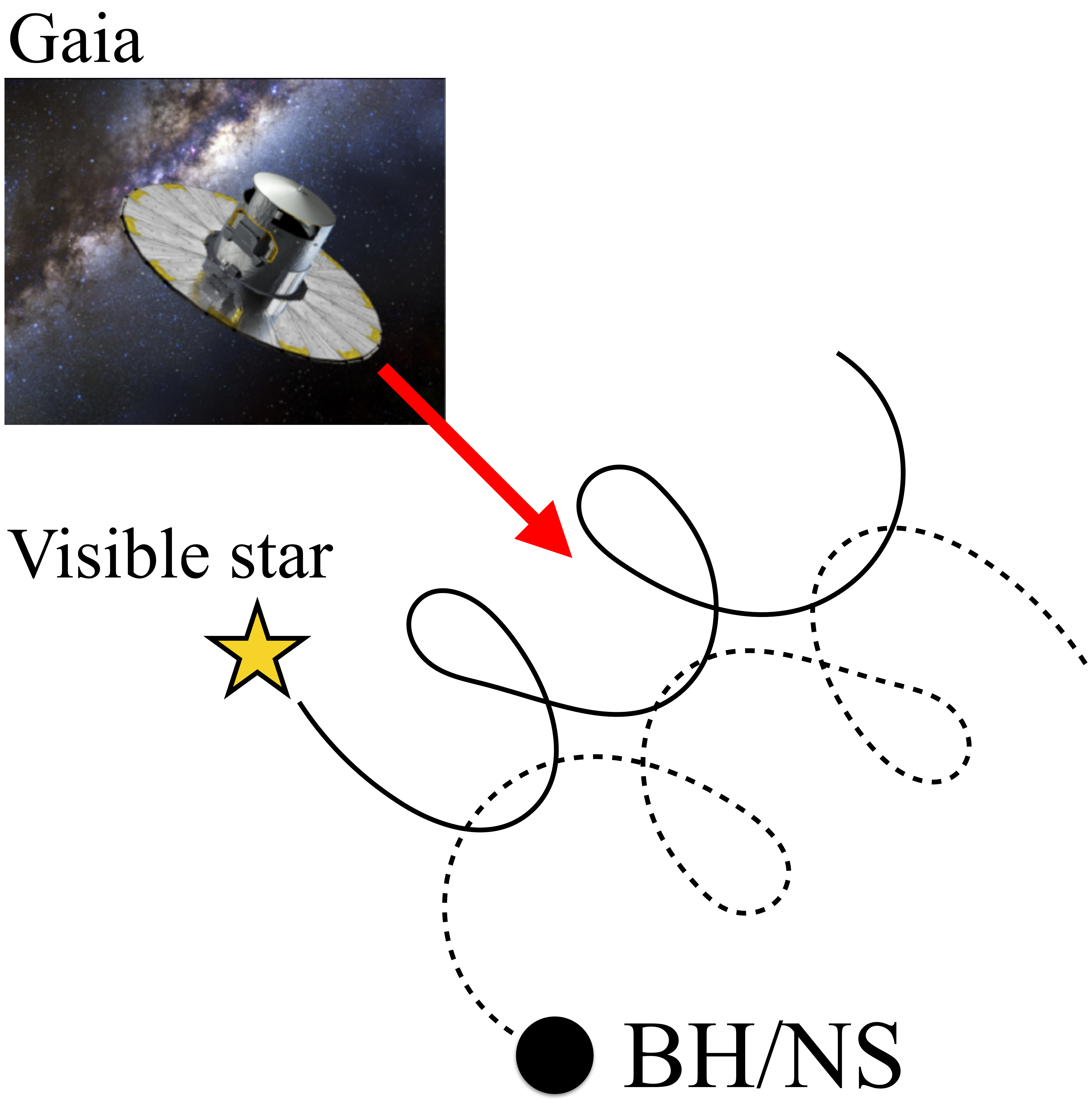
Gaia



Visible star

Gaia has discovered compact binaries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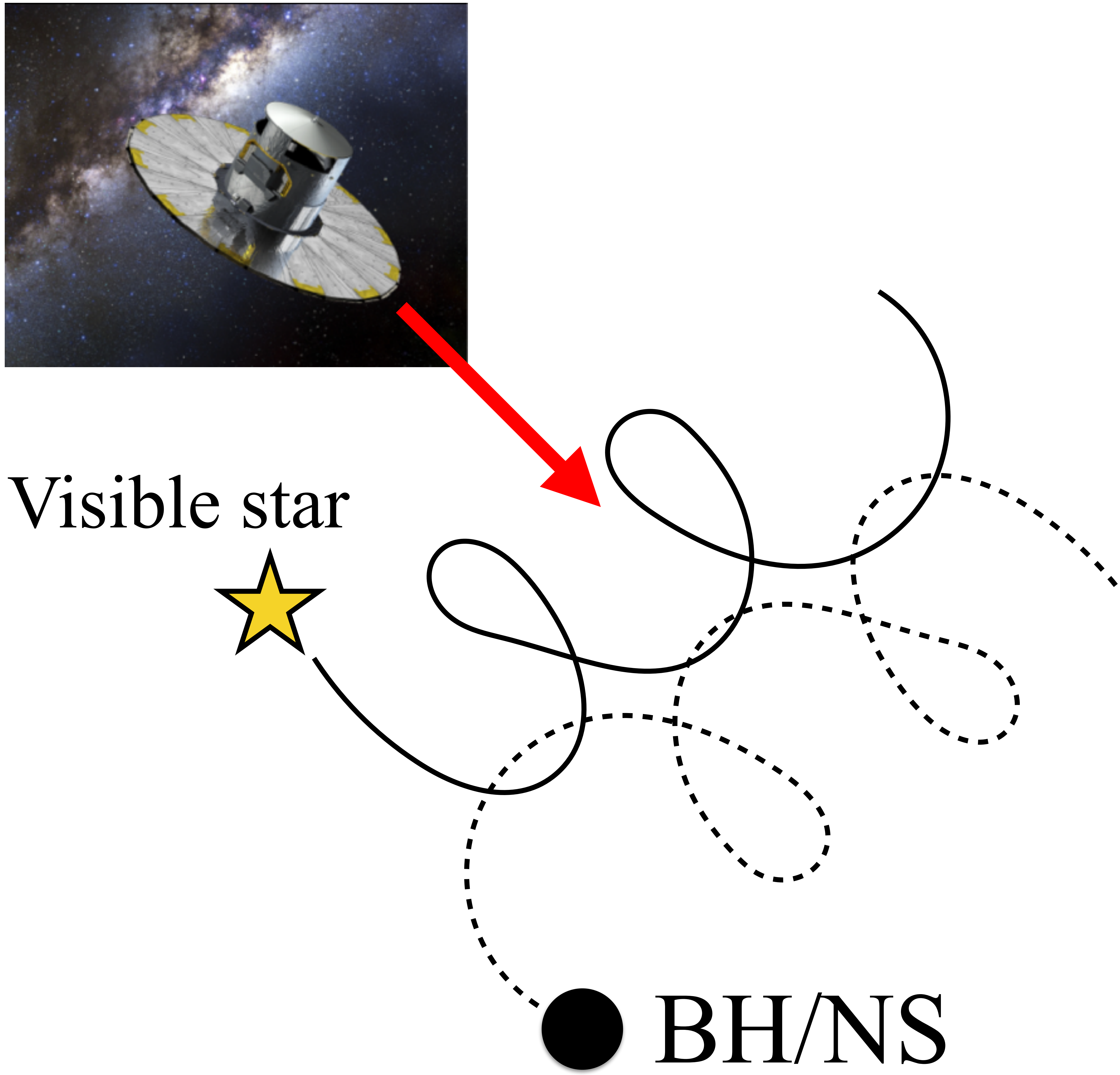
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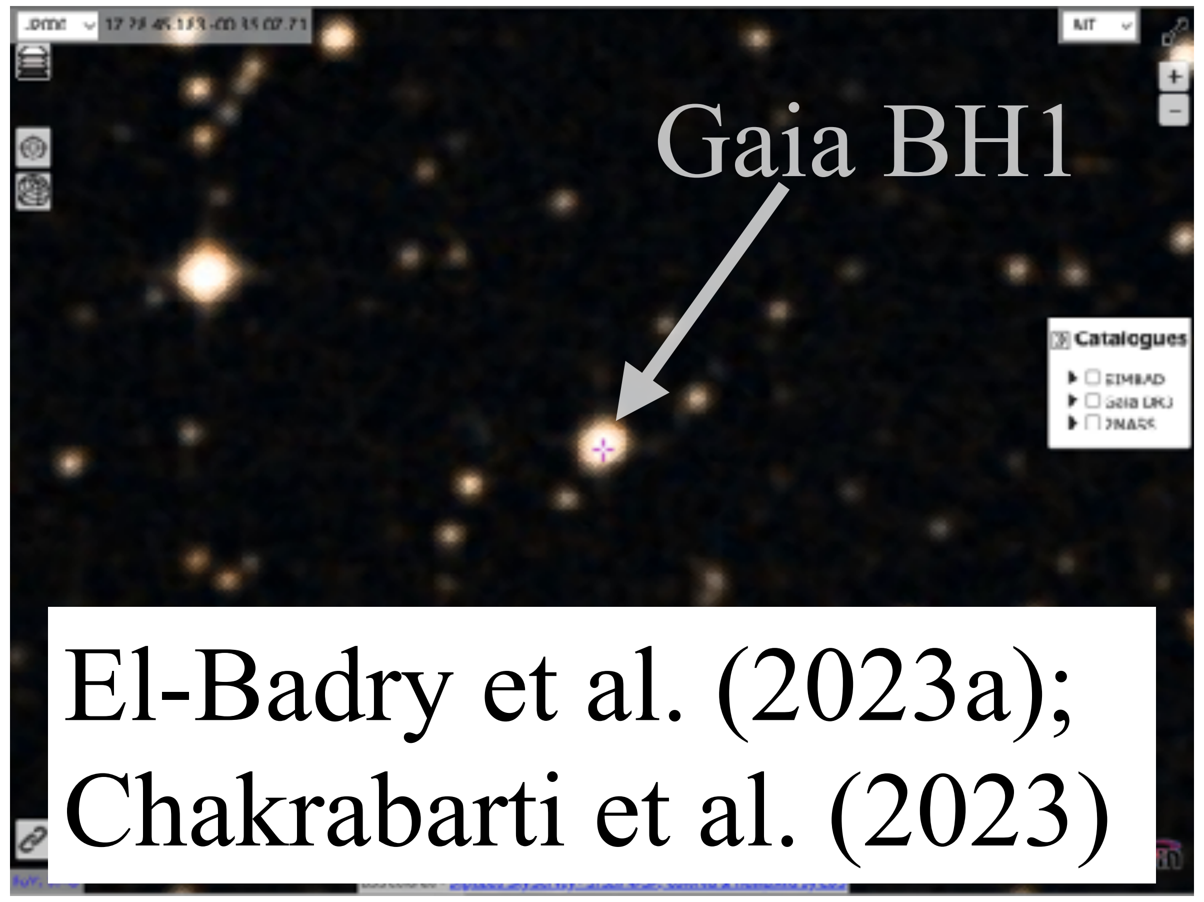

El-Badry et al. (2023a);
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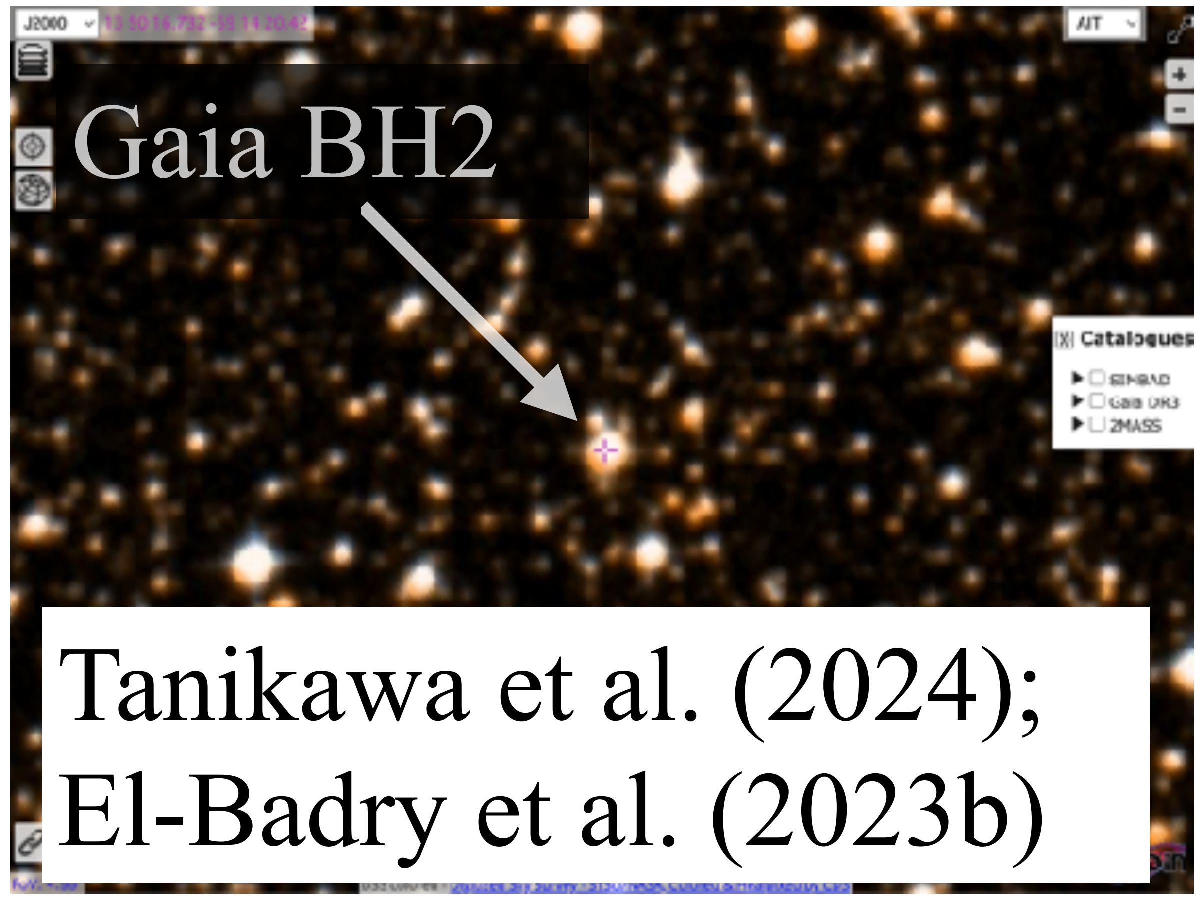

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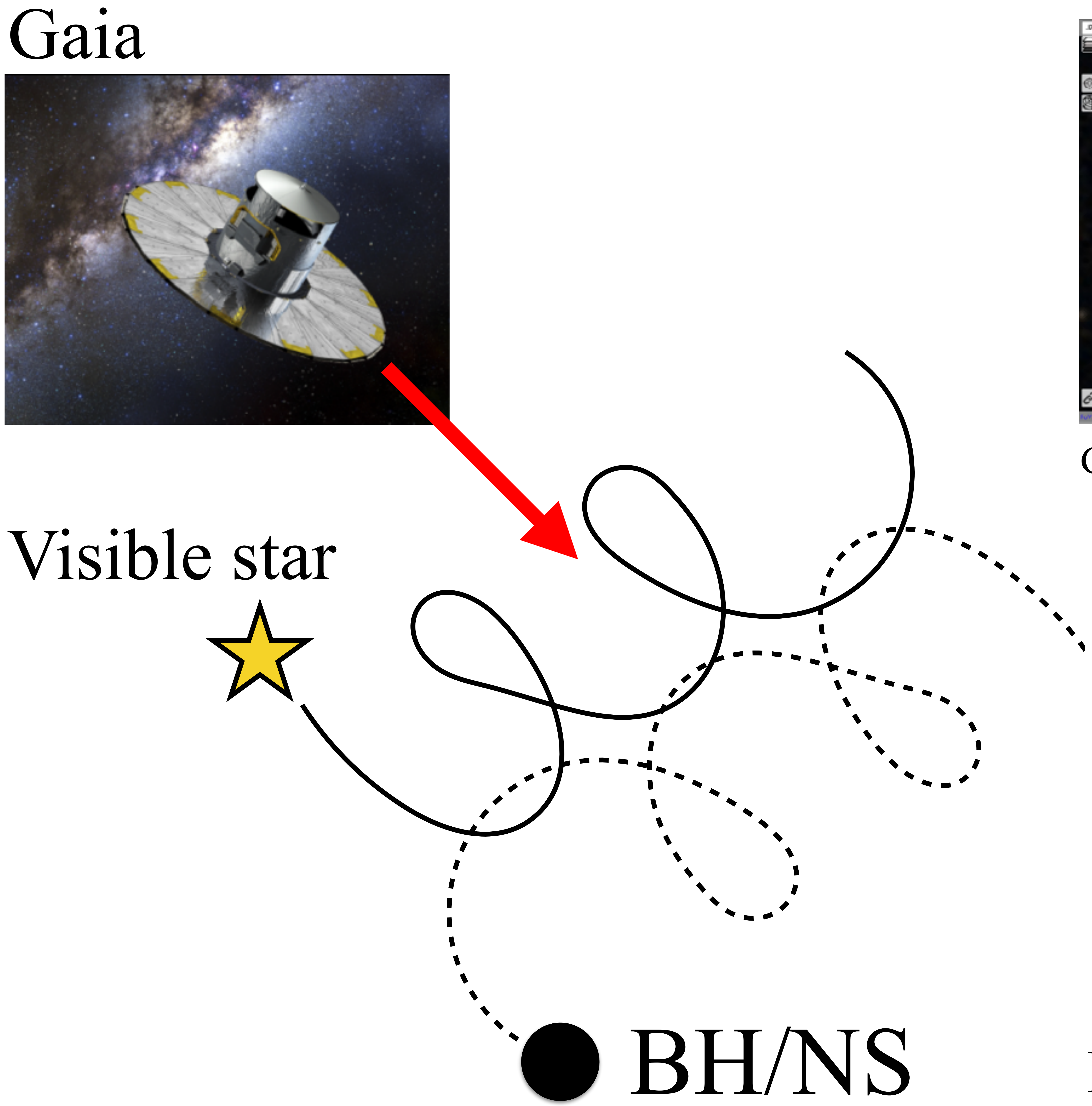

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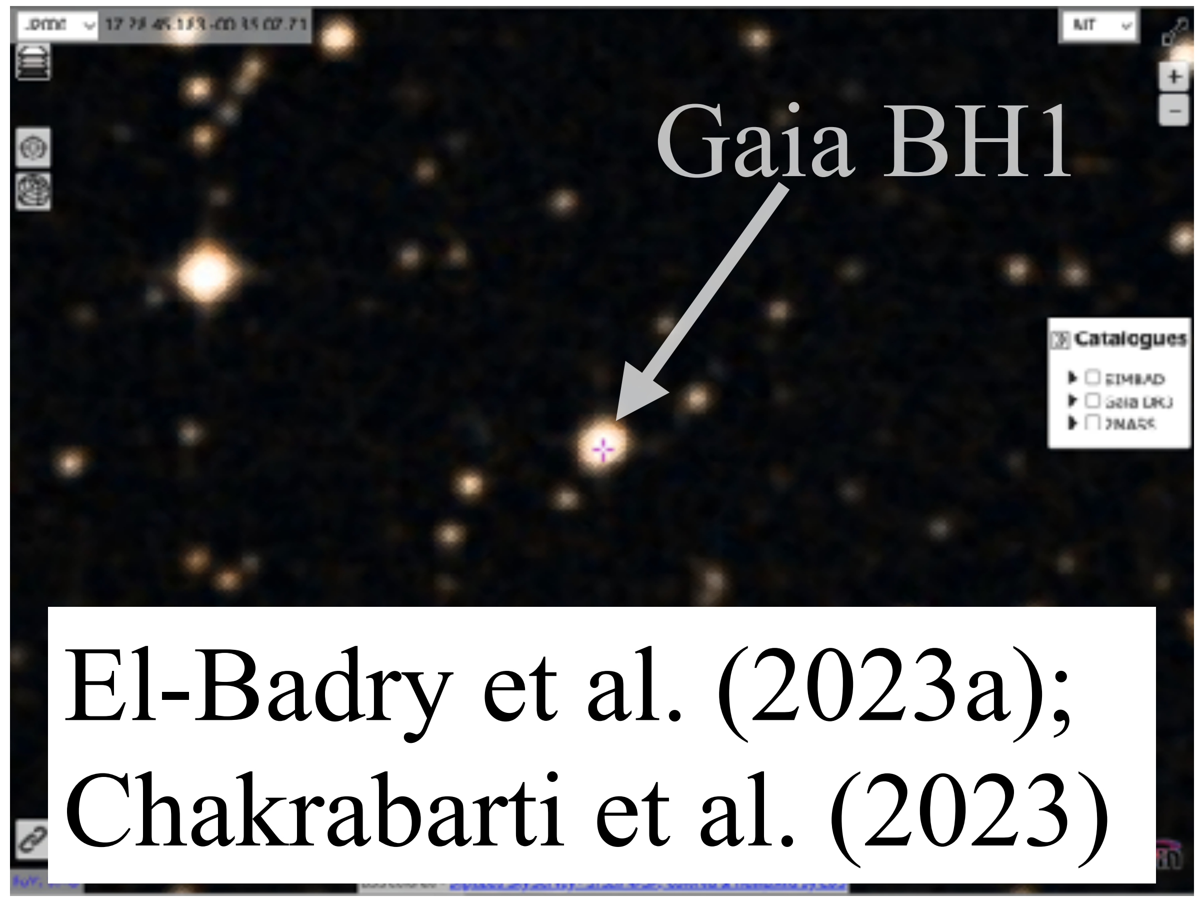

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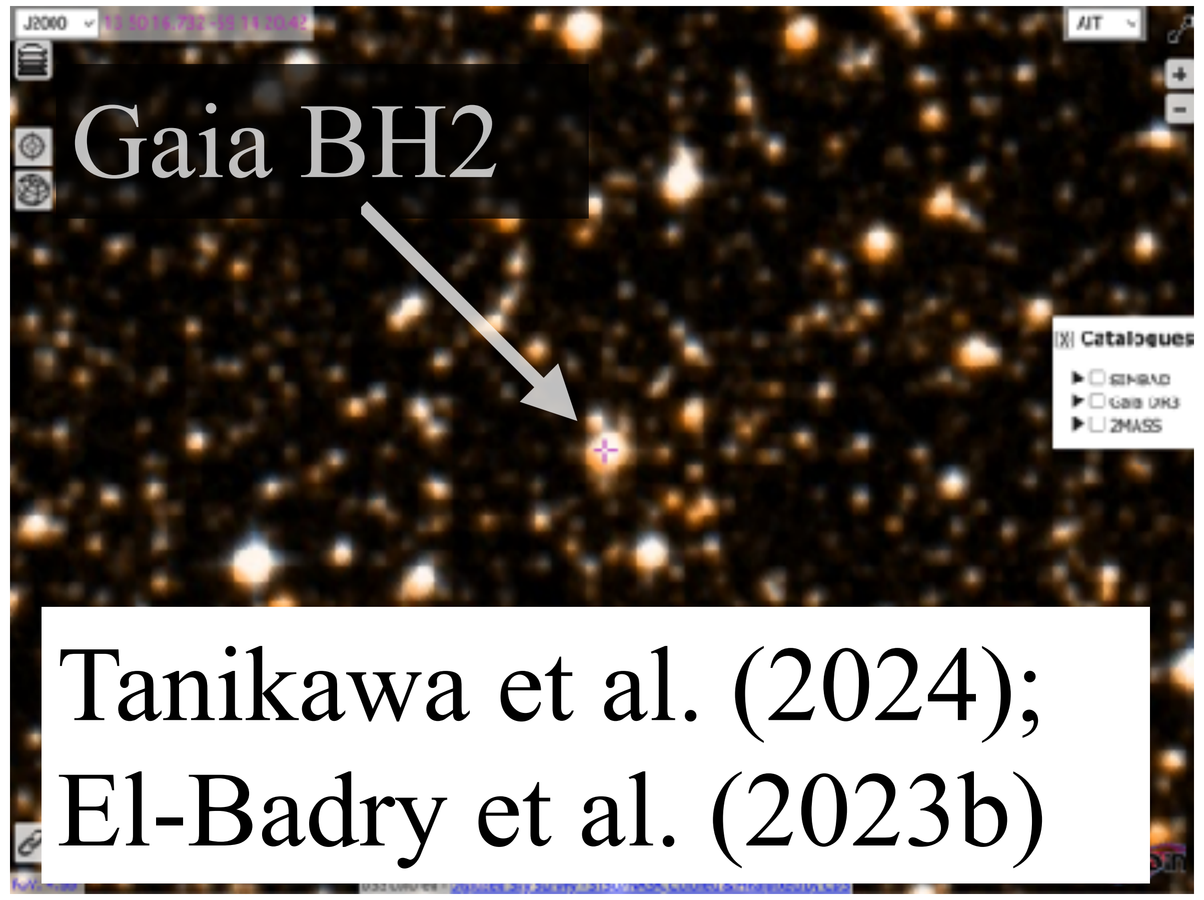

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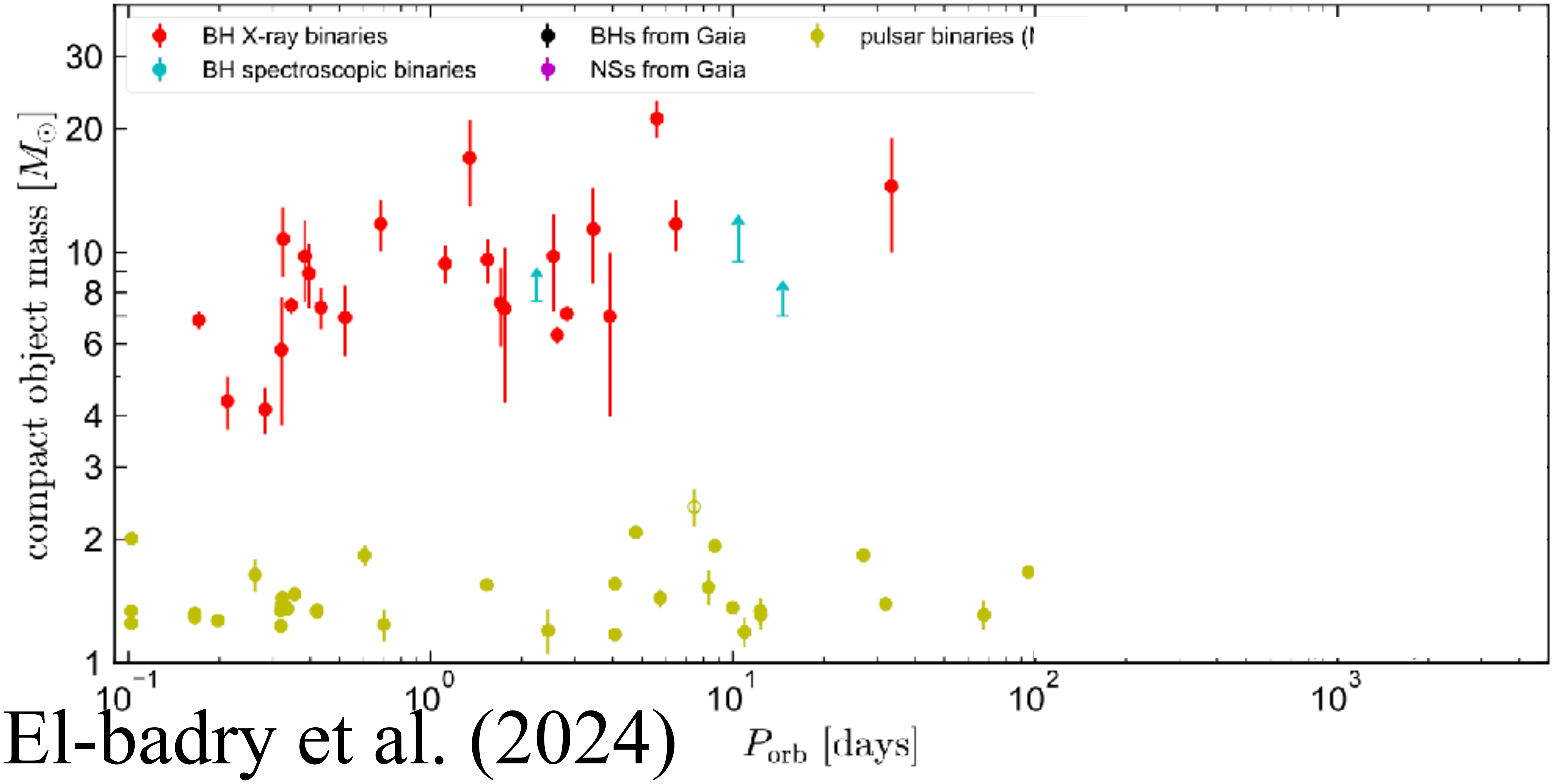

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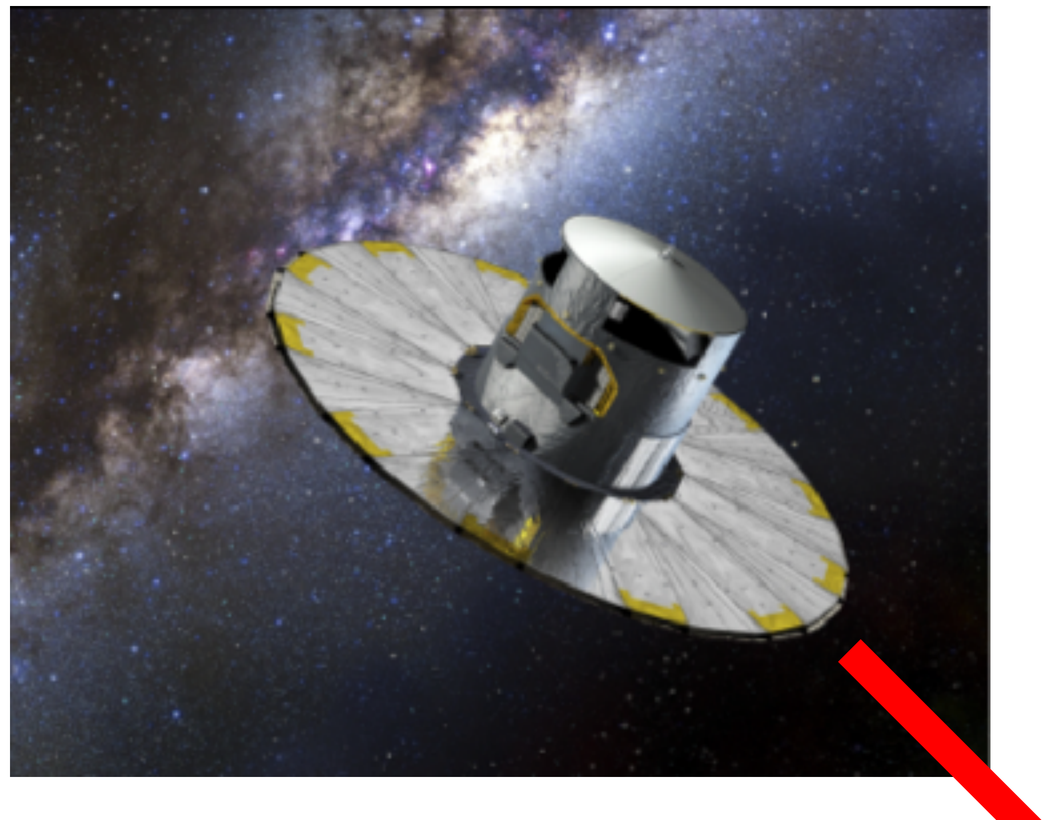

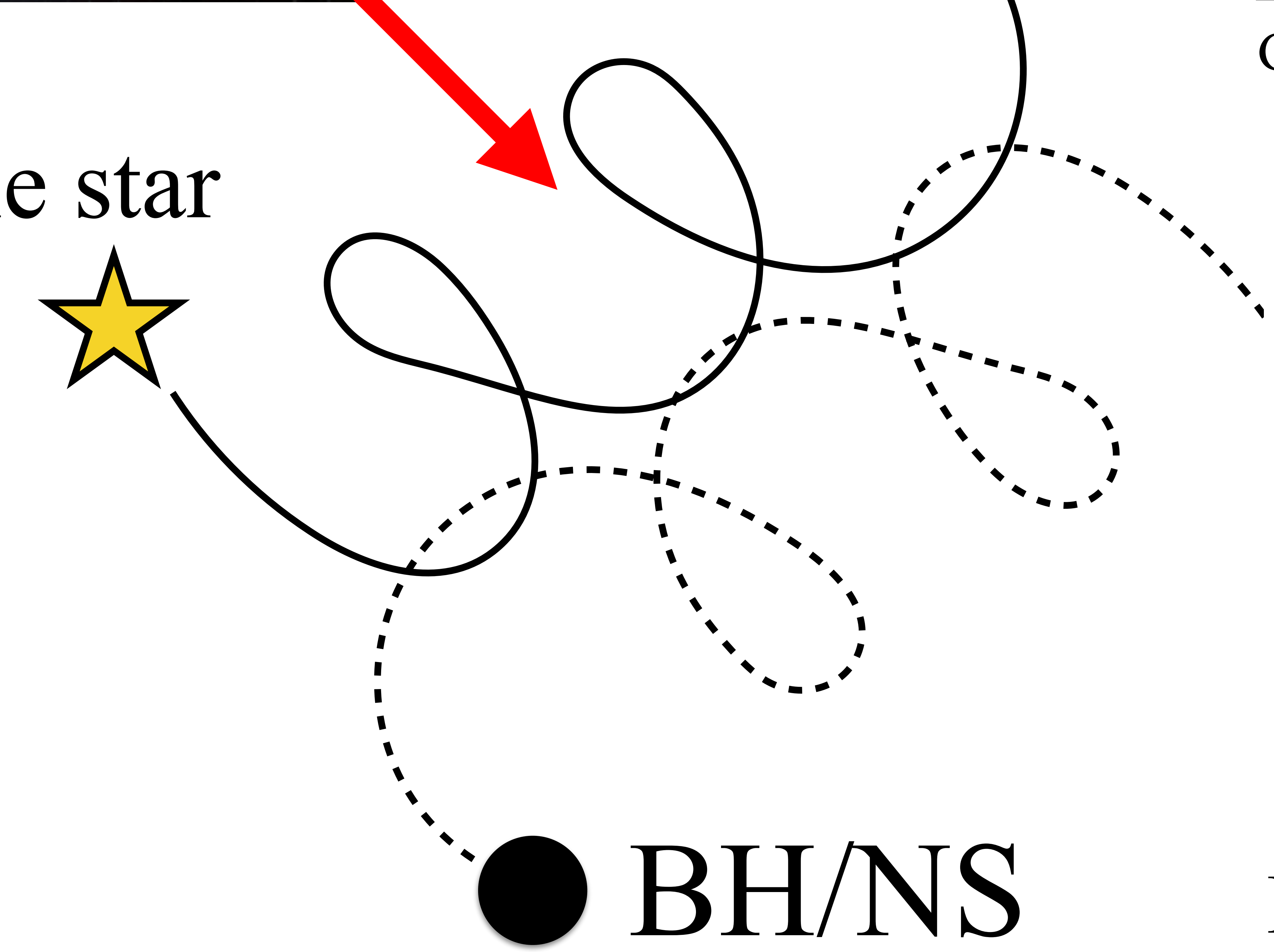
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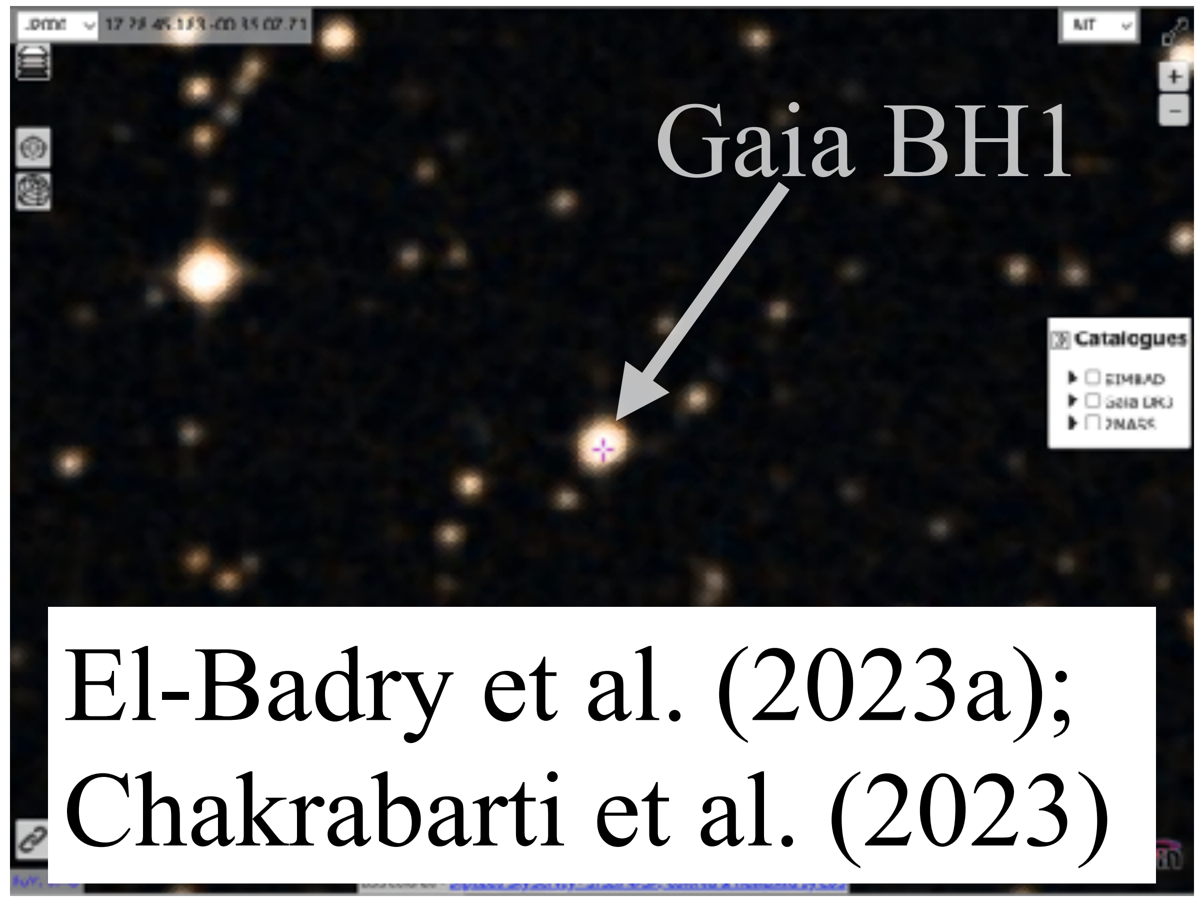

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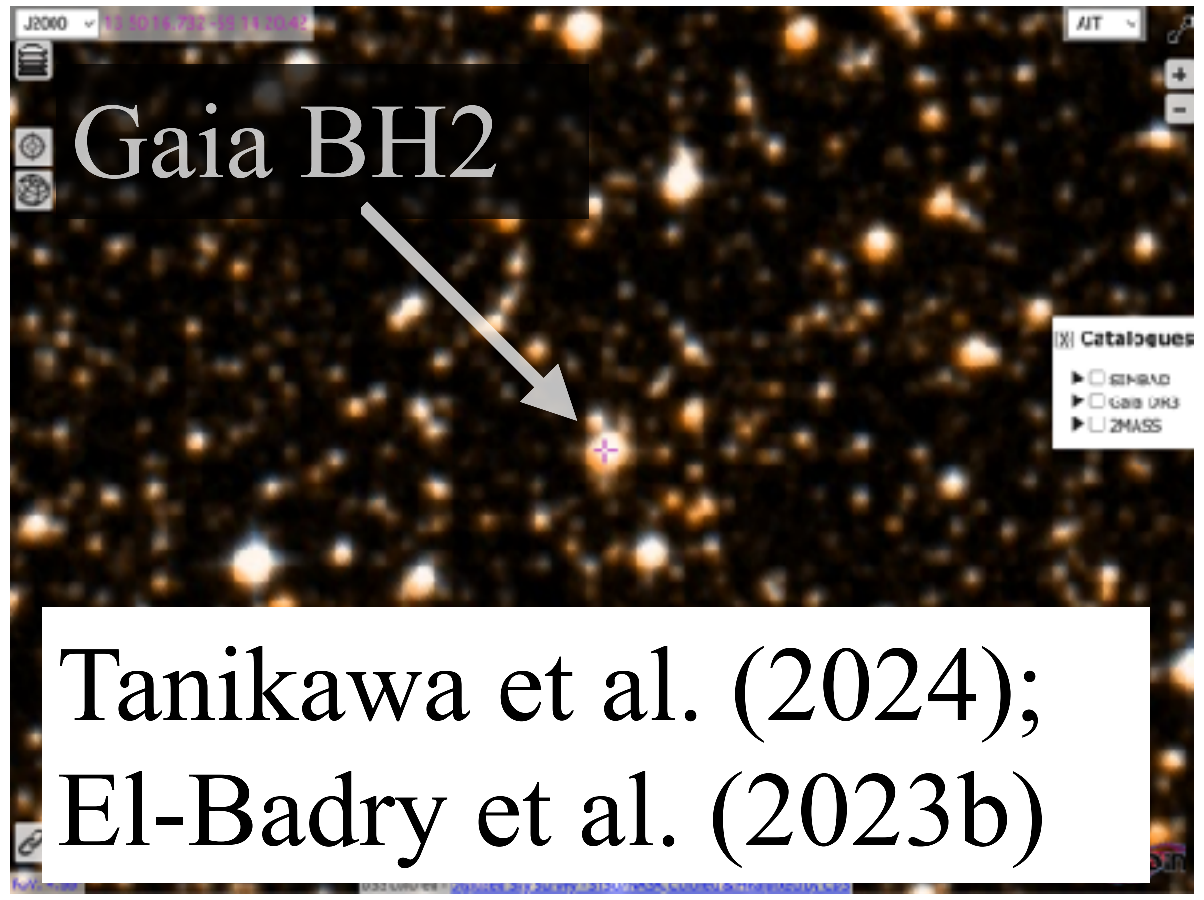

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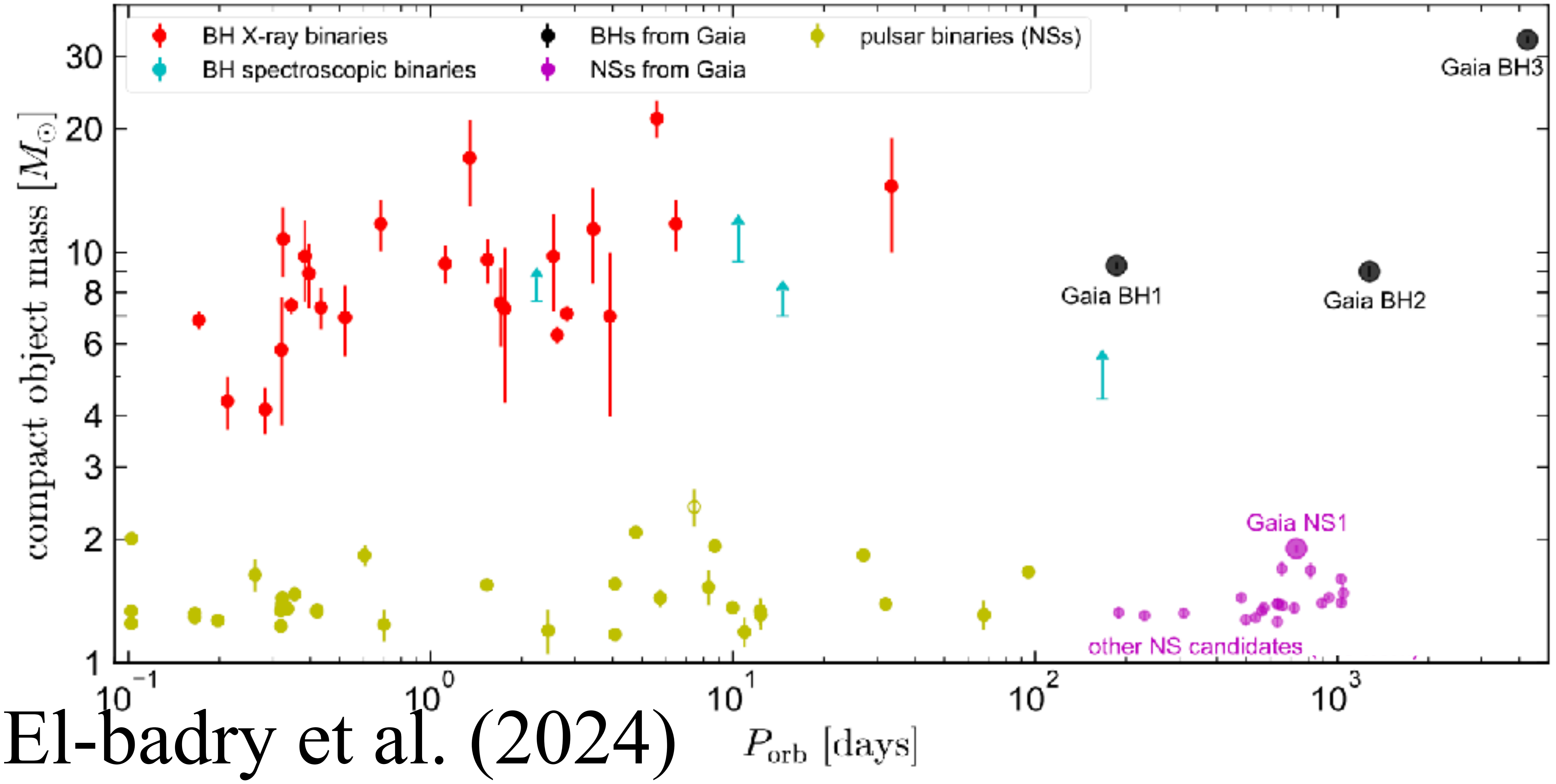

El-badry et al. (2024)

Inert/dormant/non-interaction compact binary

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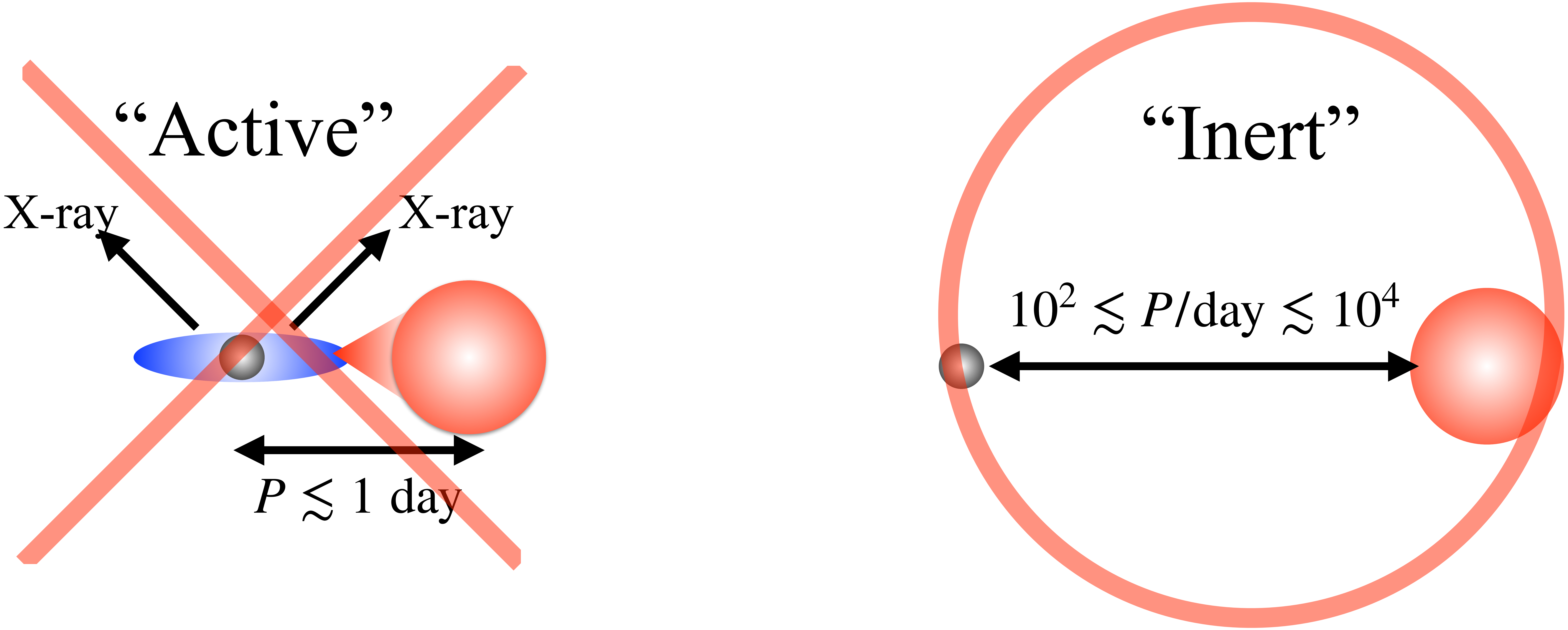
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X-ray
X-ray
$P \lesssim 1$ day
"Inert"
$10^2 \lesssim P/\mathrm{day} \lesssim 10^4$

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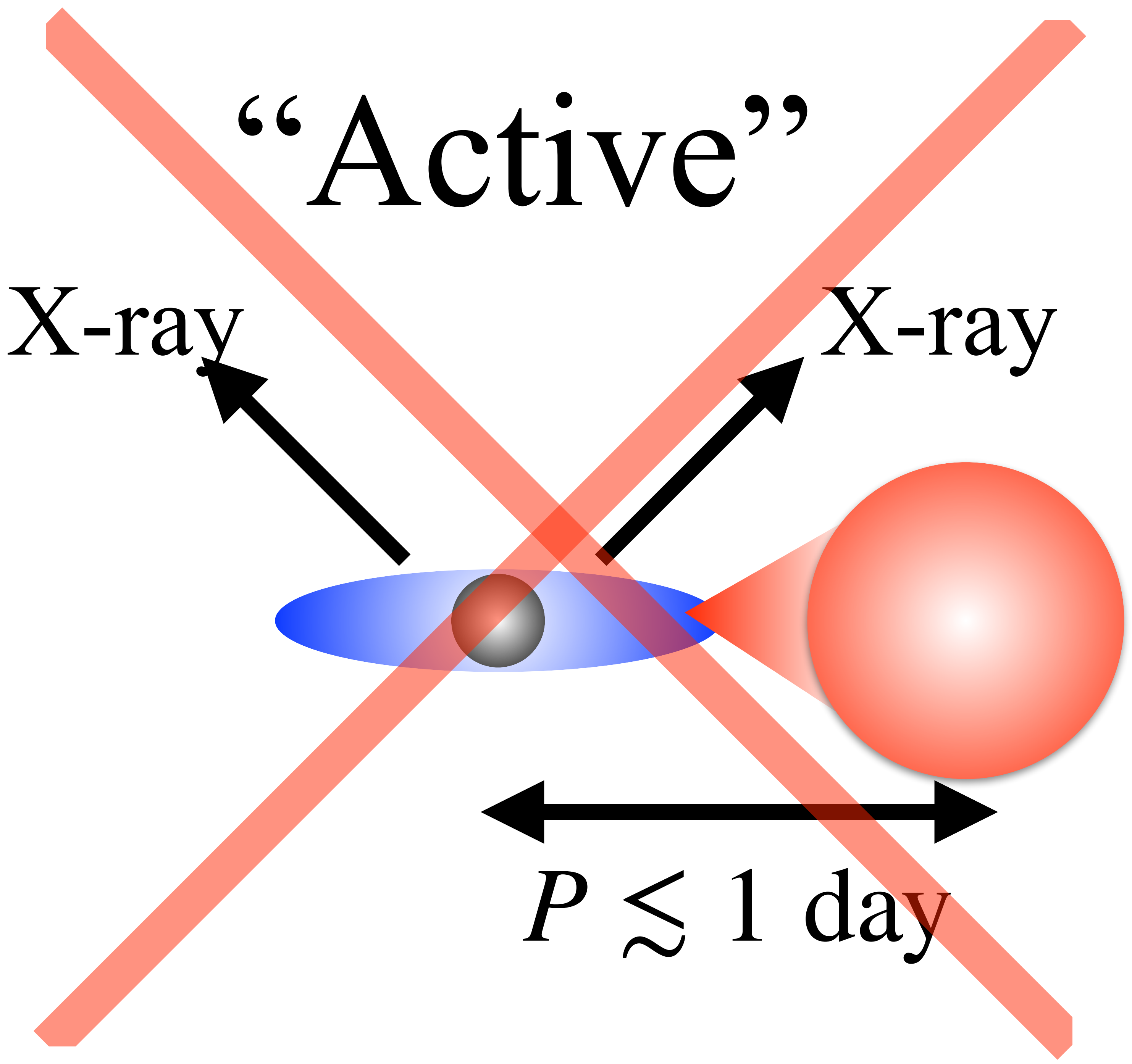
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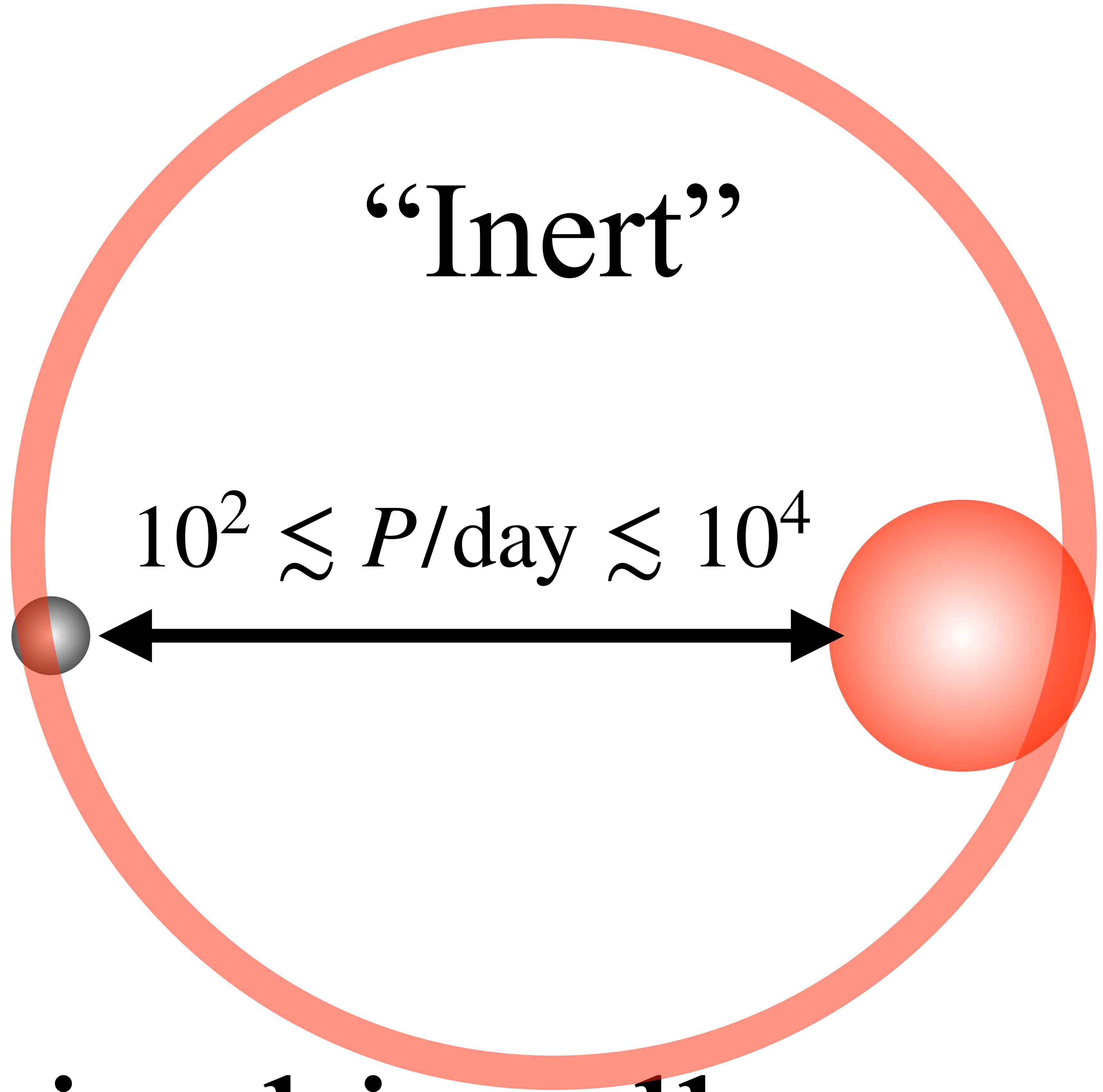
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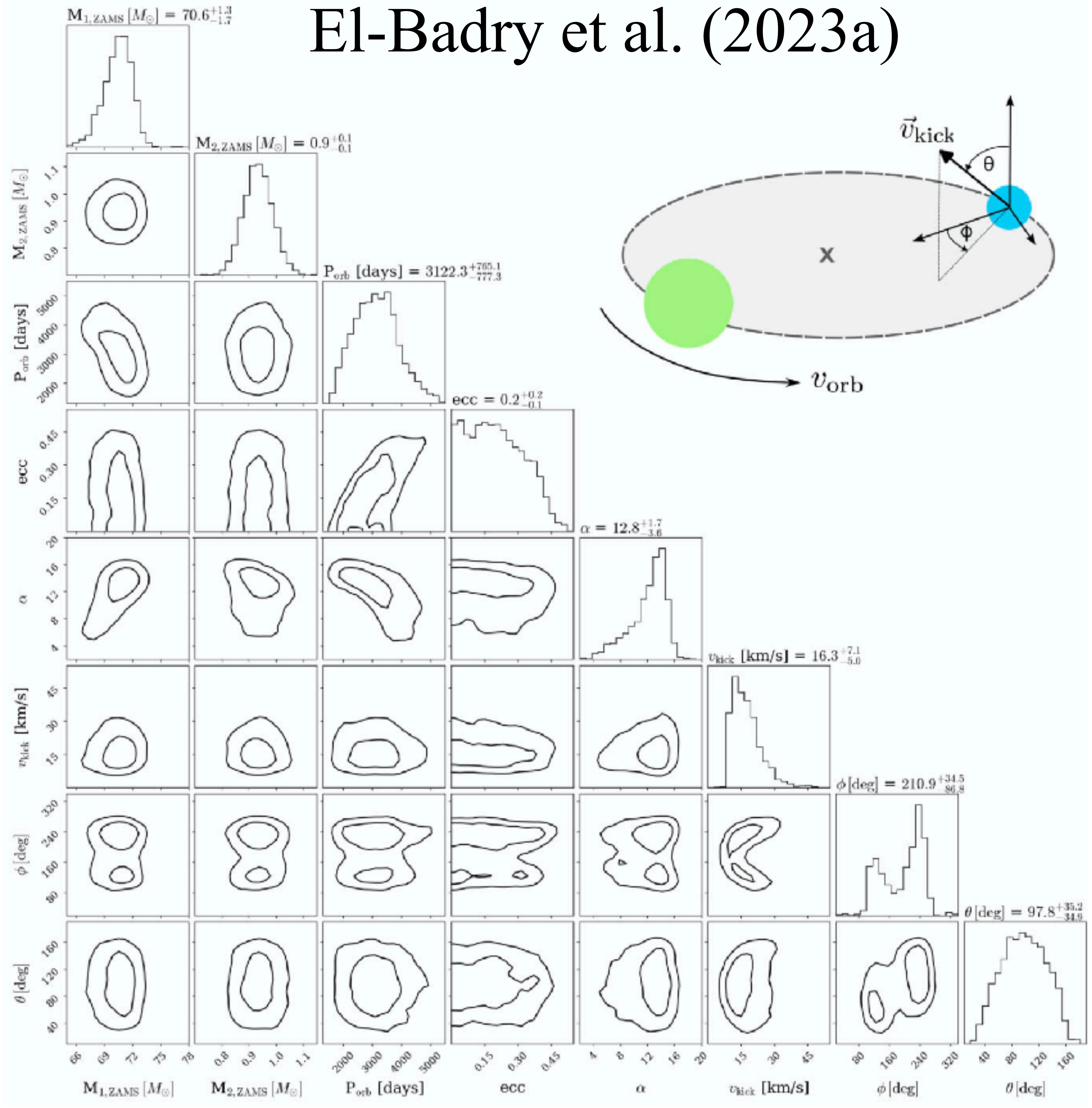
I use the term “inert” in this talk.

High α_{ce} is needed for isolated binary channel



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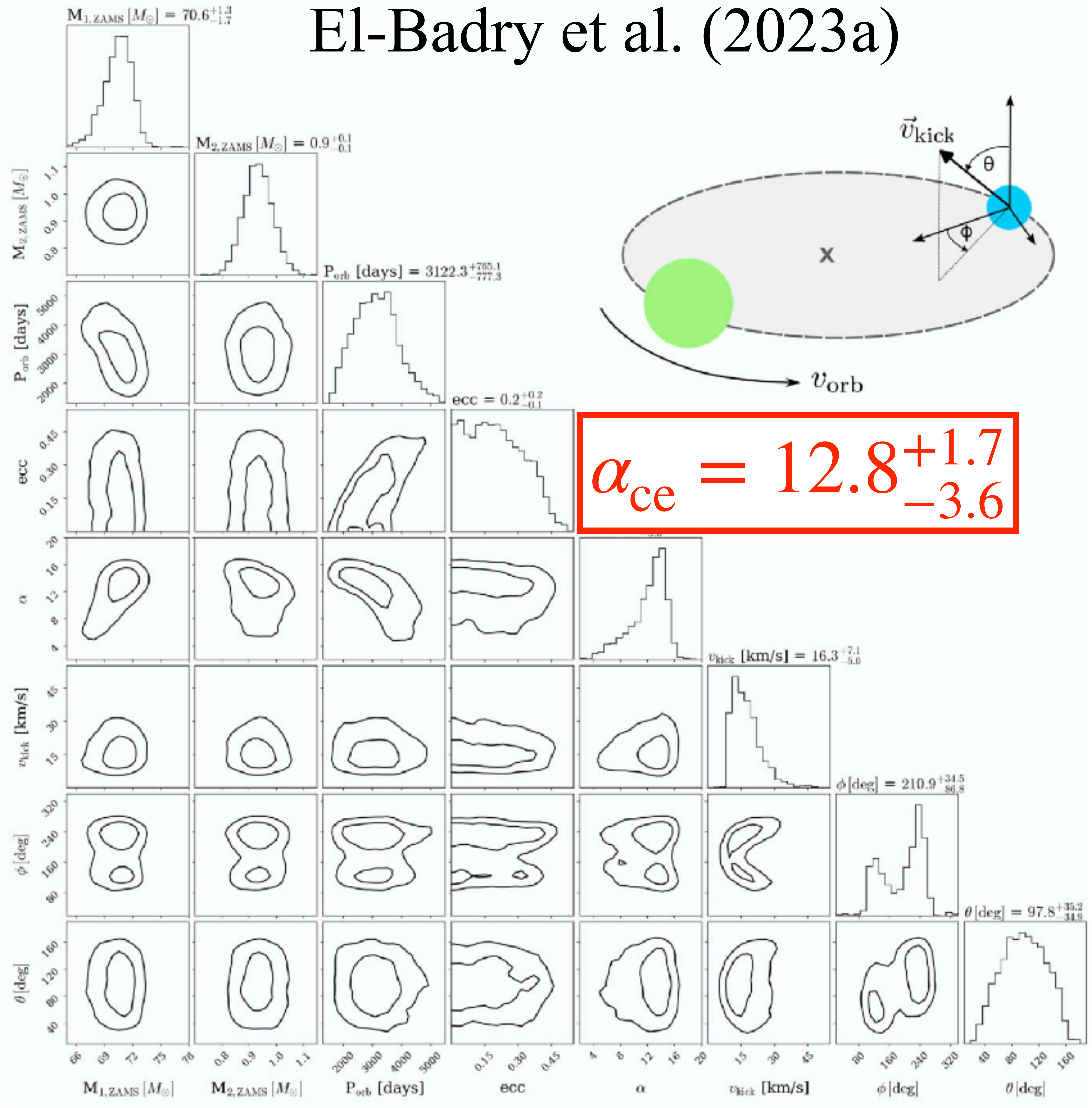

El-Badry et al. (2023a)

$$\boxed{\alpha_{ce} = 12.8^{+1.7}_{-3.6}}$$

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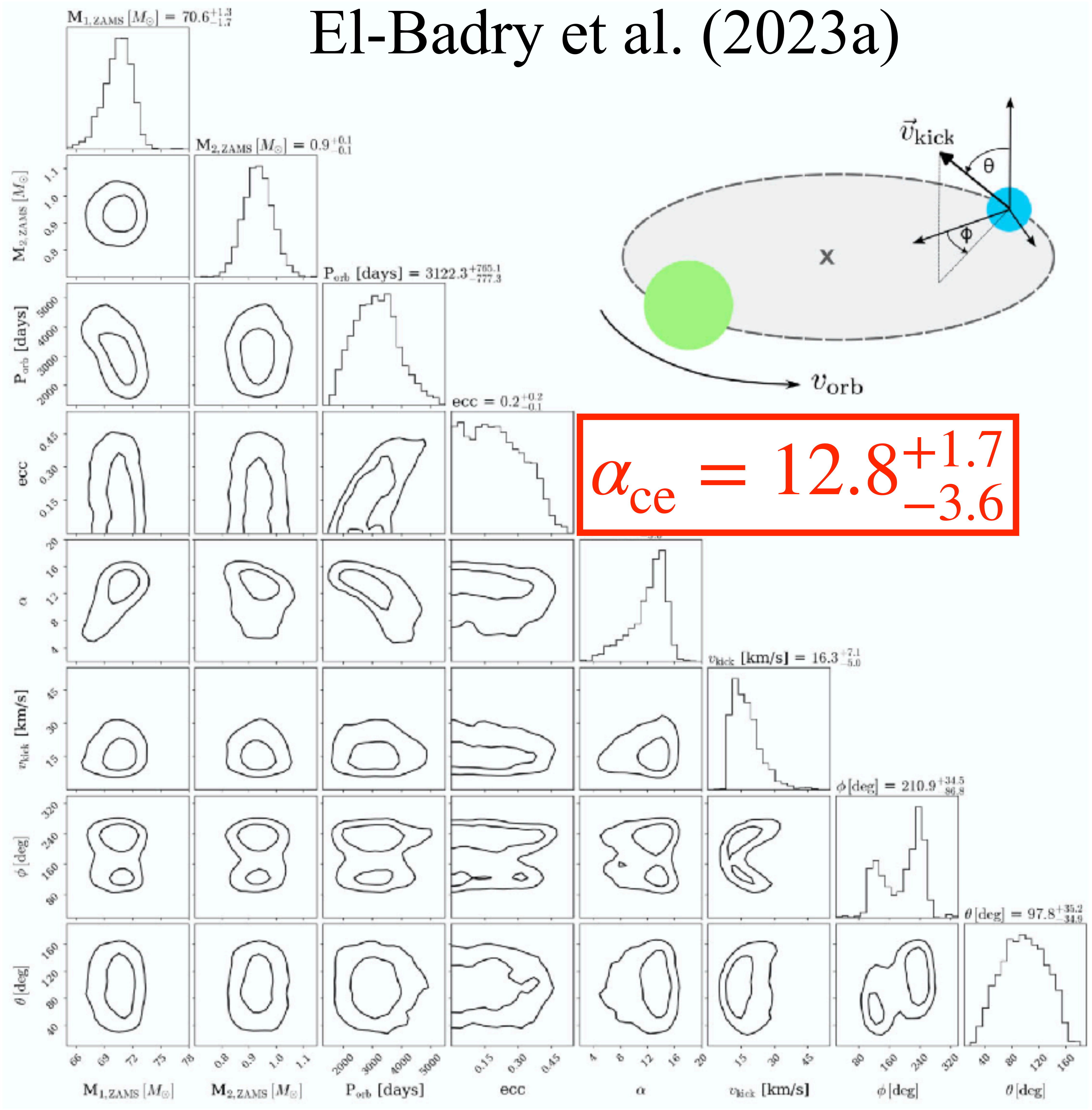

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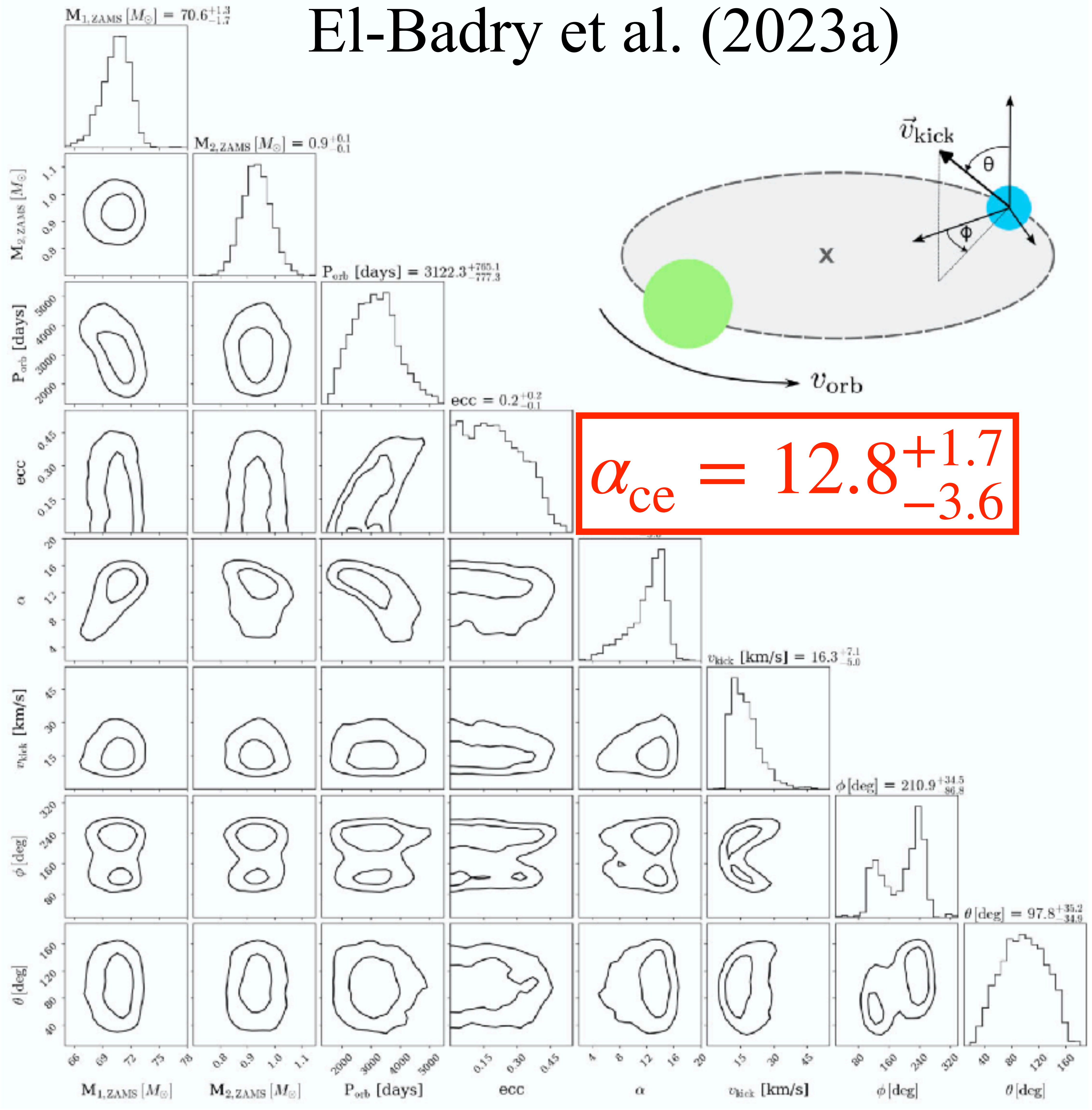

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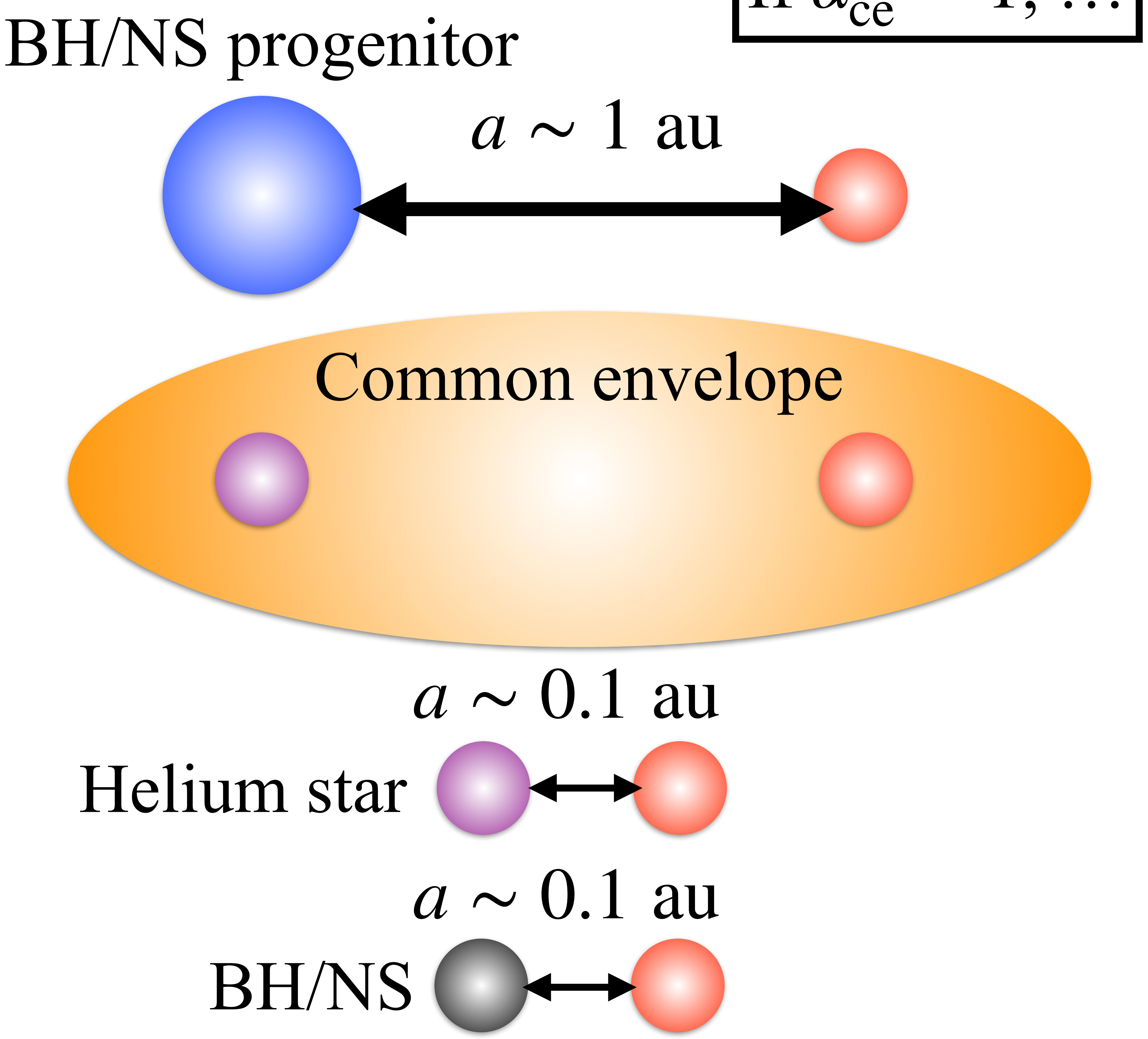

BH/NS progenitor

$a \sim 1$ au

Common envelope

$a \sim 0.1$ au

Helium star

$a \sim 0.1$ au

BH/NS

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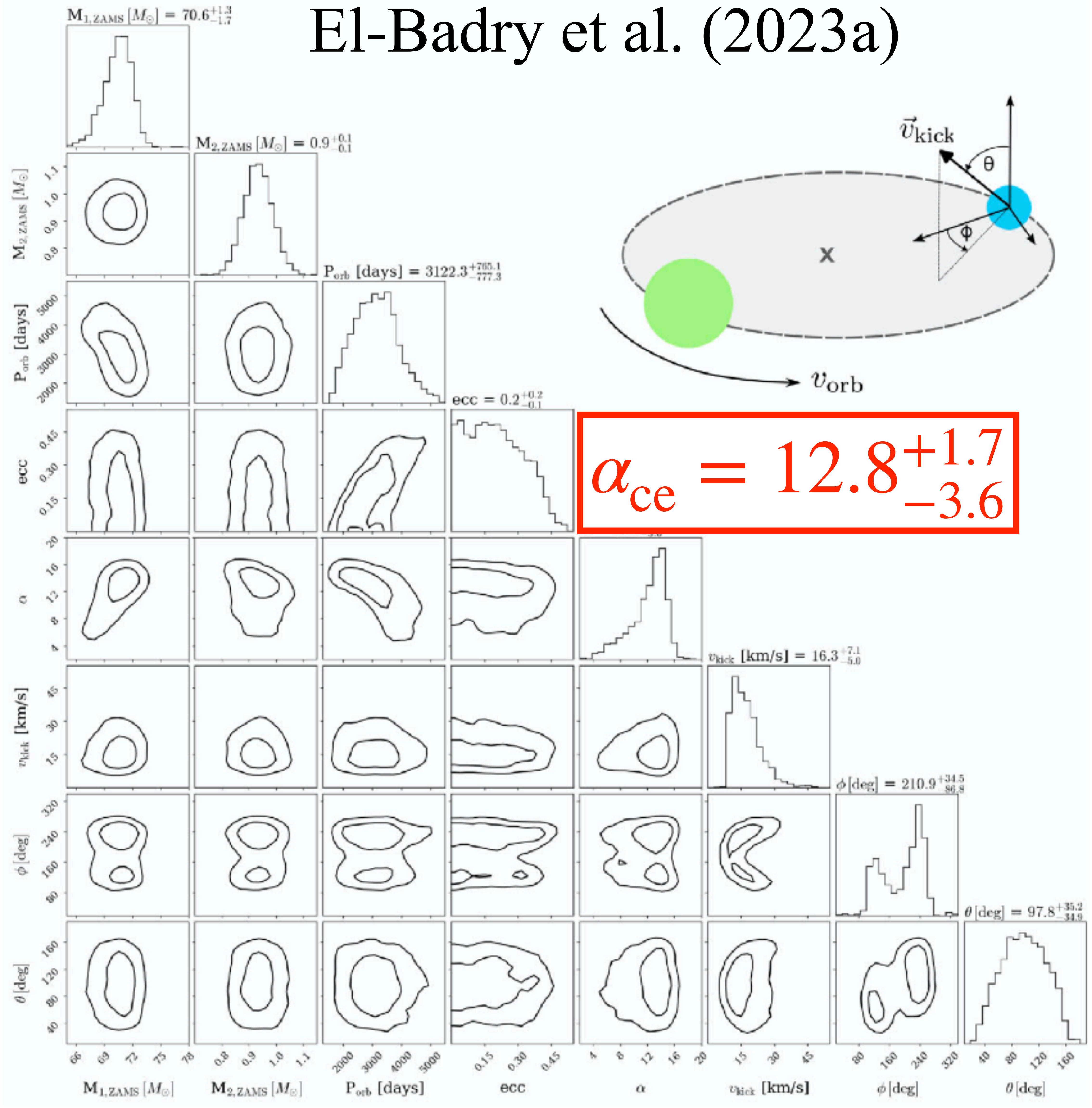

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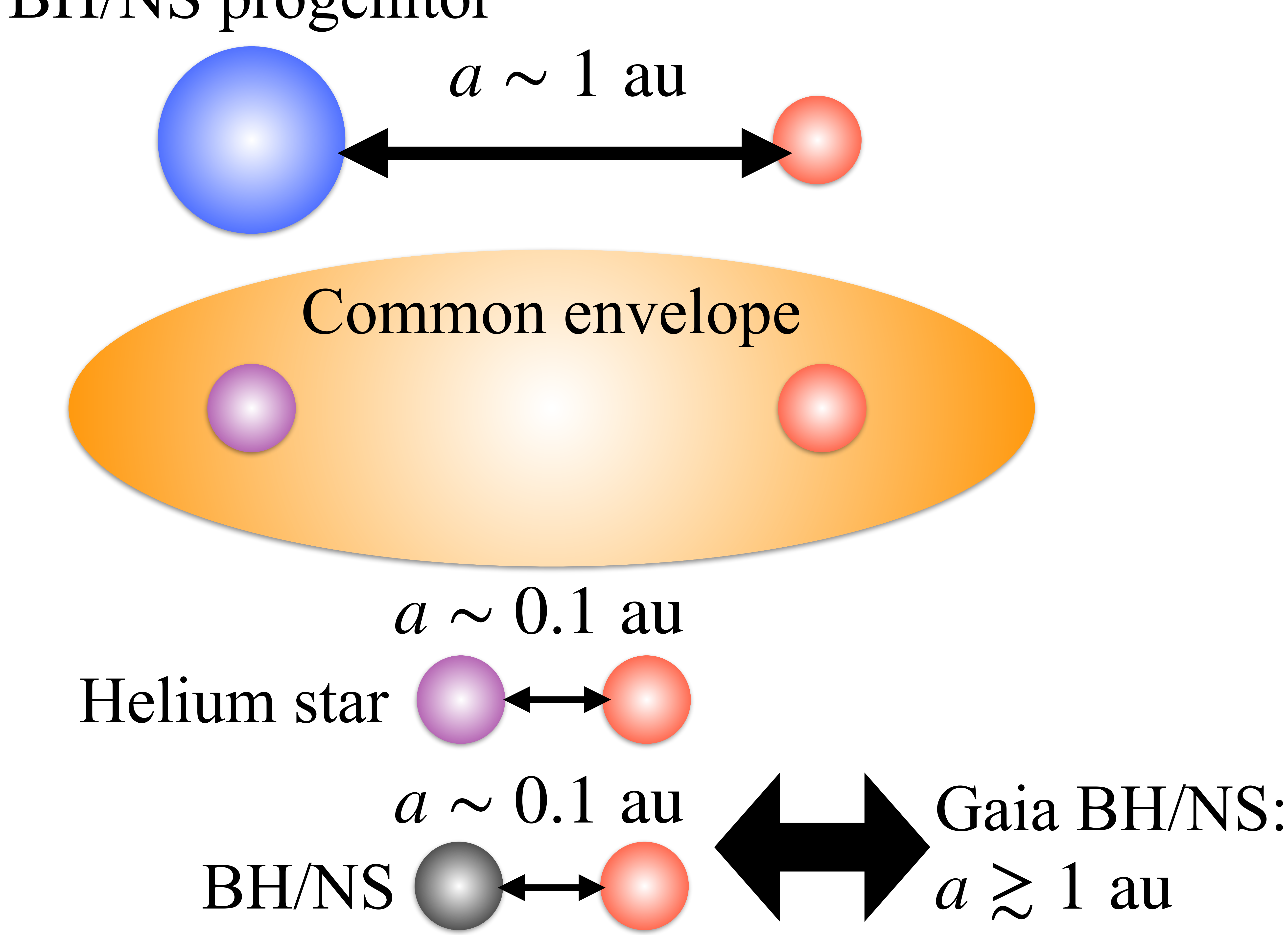
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BH/NS

Gaia BH/NS:
$a \gtrsim 1$ au

Other possible channels

- Dynamical capture in open clusters

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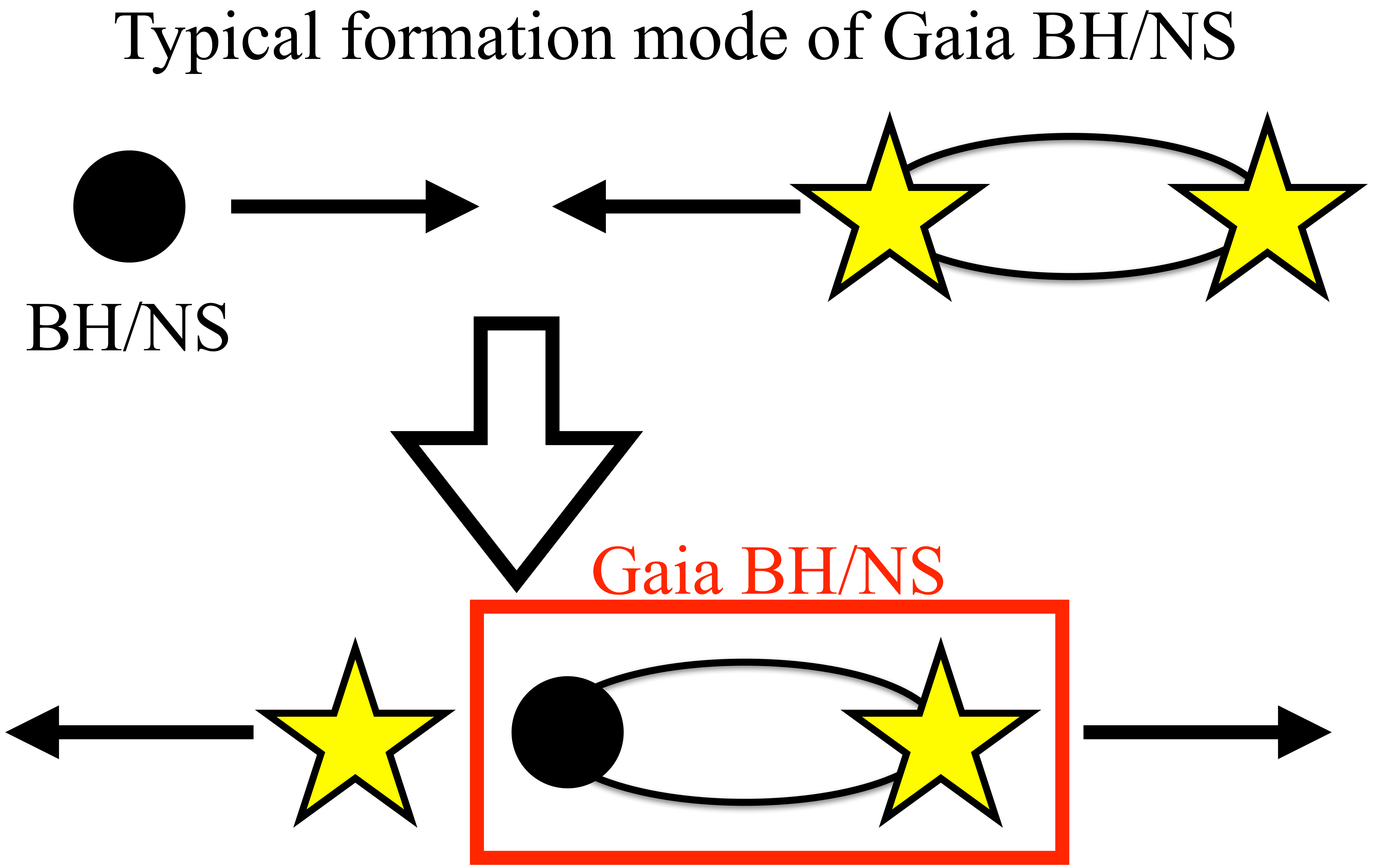
Typical formation mode of Gaia BH/NS
BH/NS
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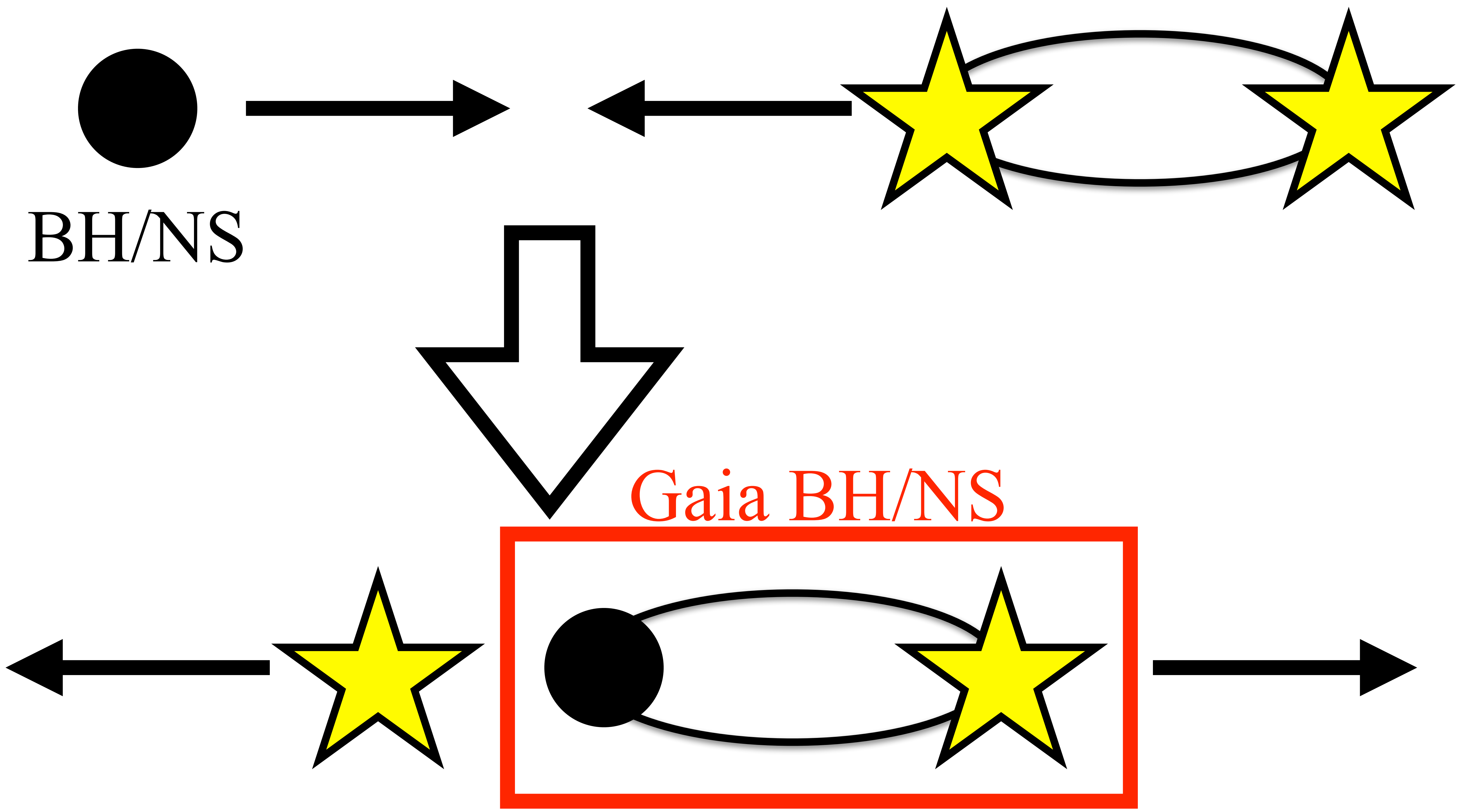
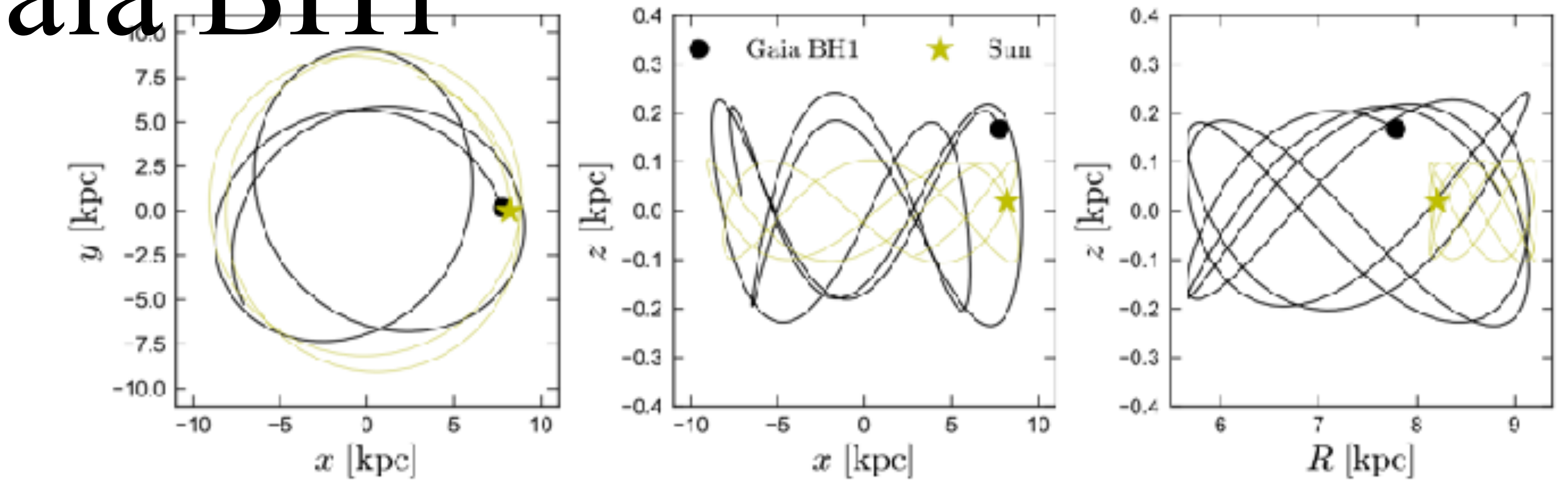


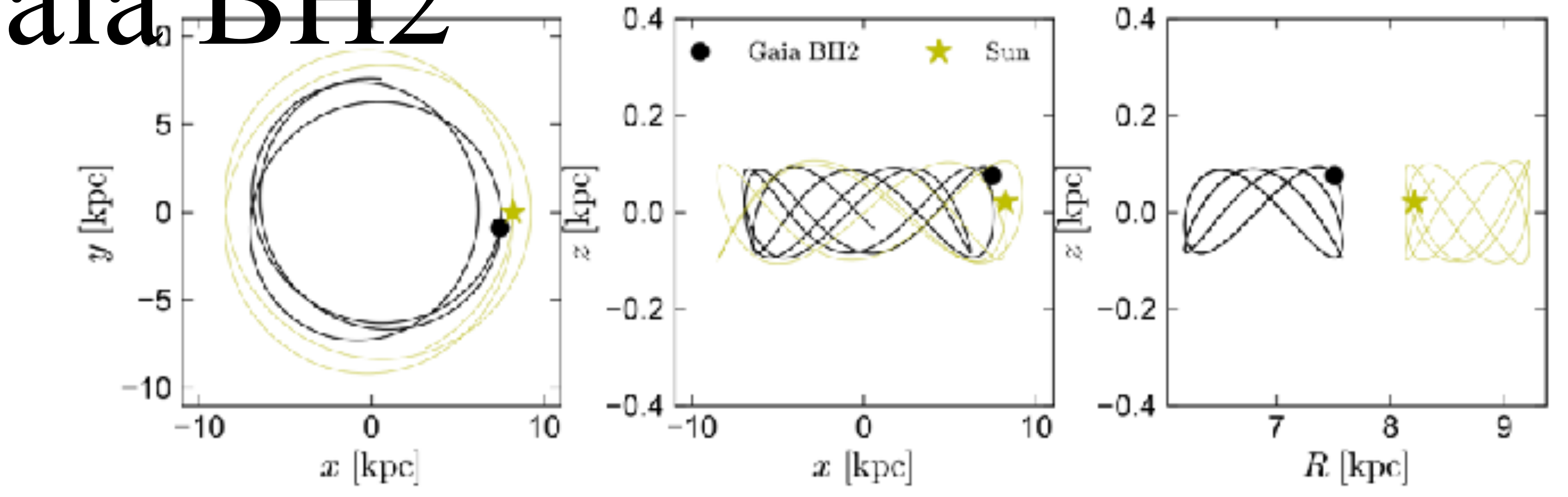
BH/NS

Gaia BH/NS

Gaia BH1



Gaia BH2



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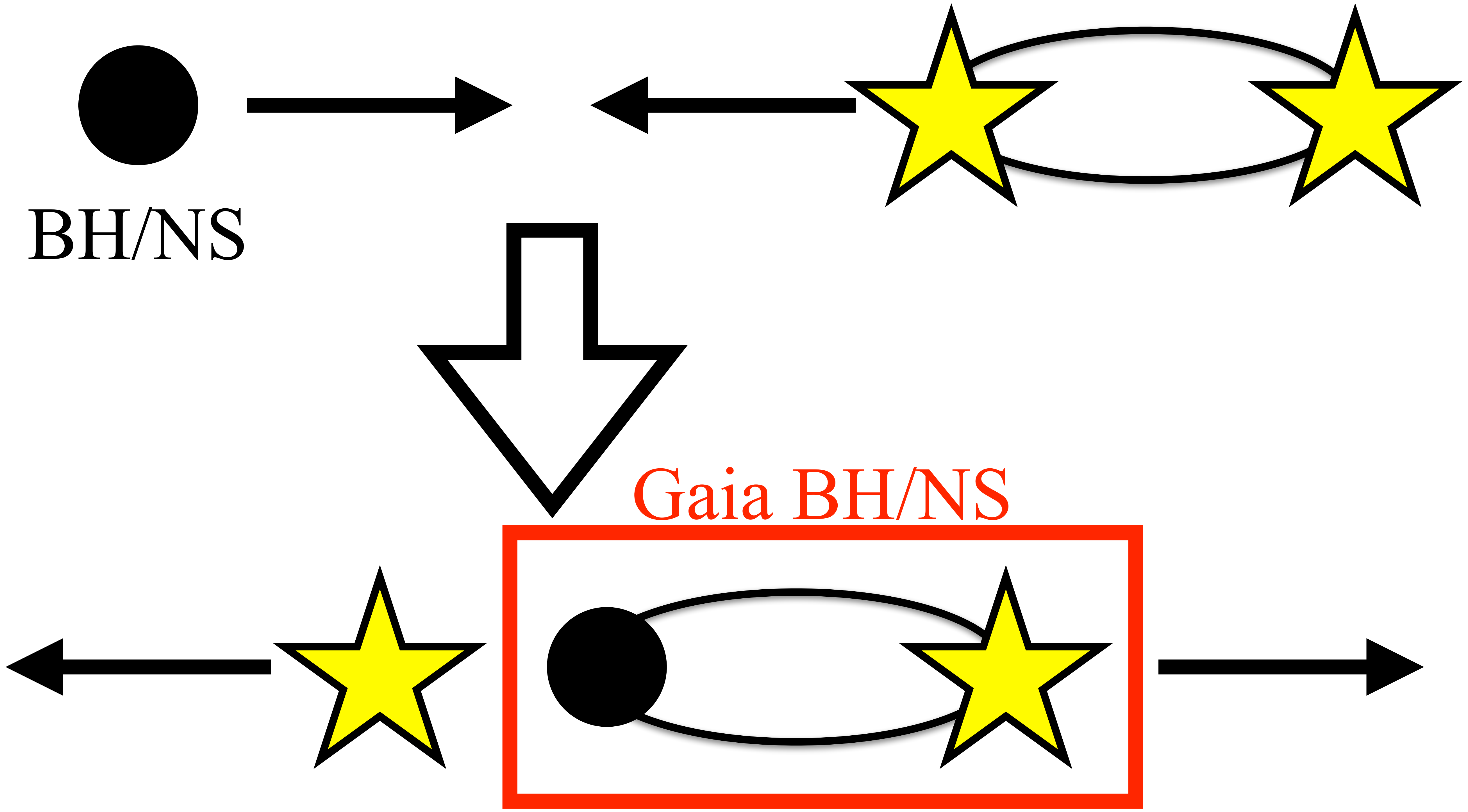

BH/NS
Gaia BH/NS

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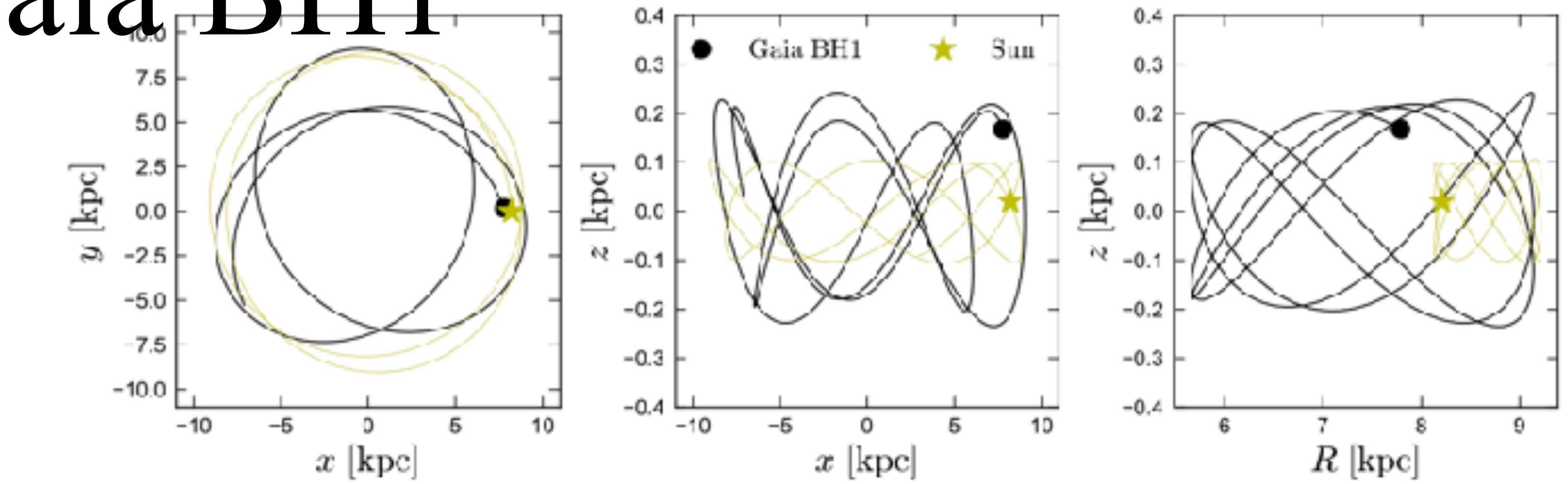

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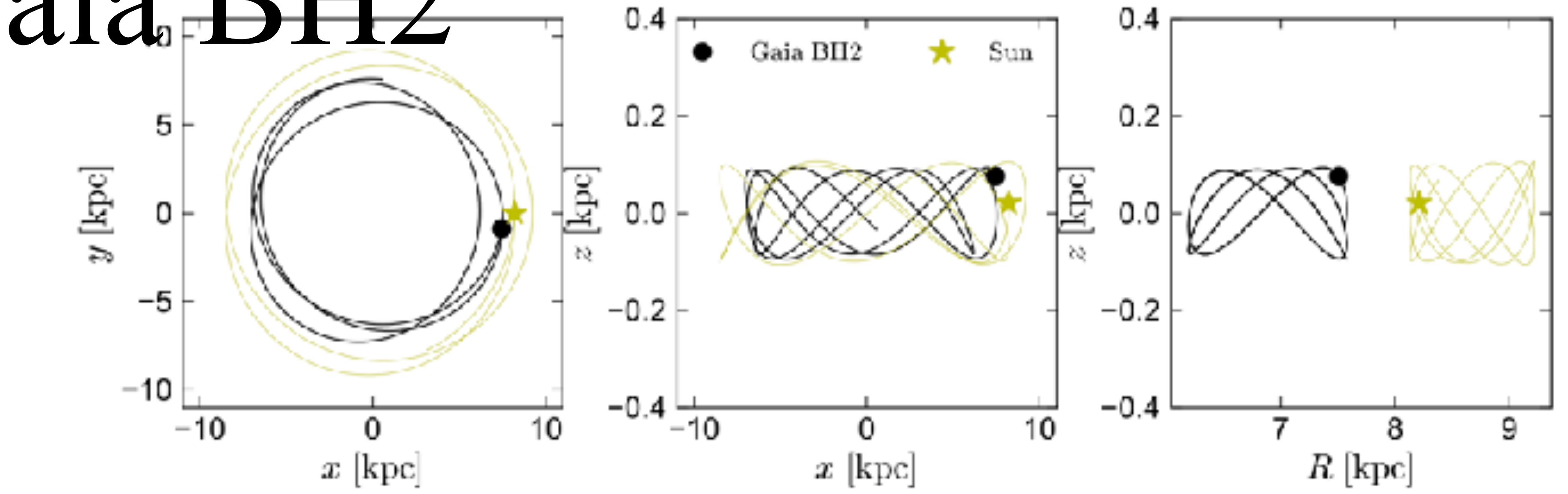
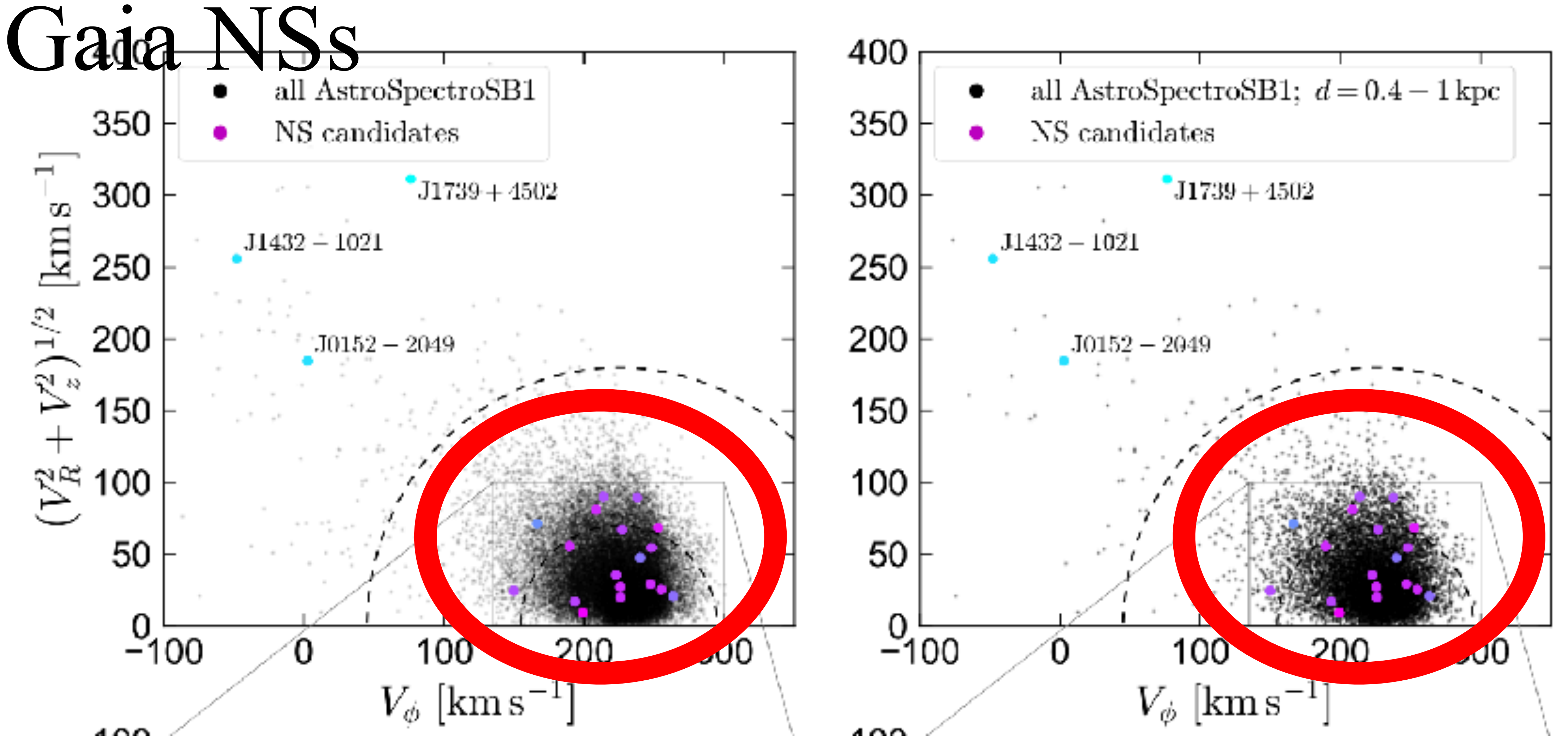


Gaia NSs



Our open cluster models

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- Cluster parameters
  - Cluster mass: $200 - 2000\ M_{\odot}$
  - Metallicity: $Z = 0.0002 - 0.02$
  - Mass density: $2 - 200\ M_{\odot}/\mathrm{pc}^3$
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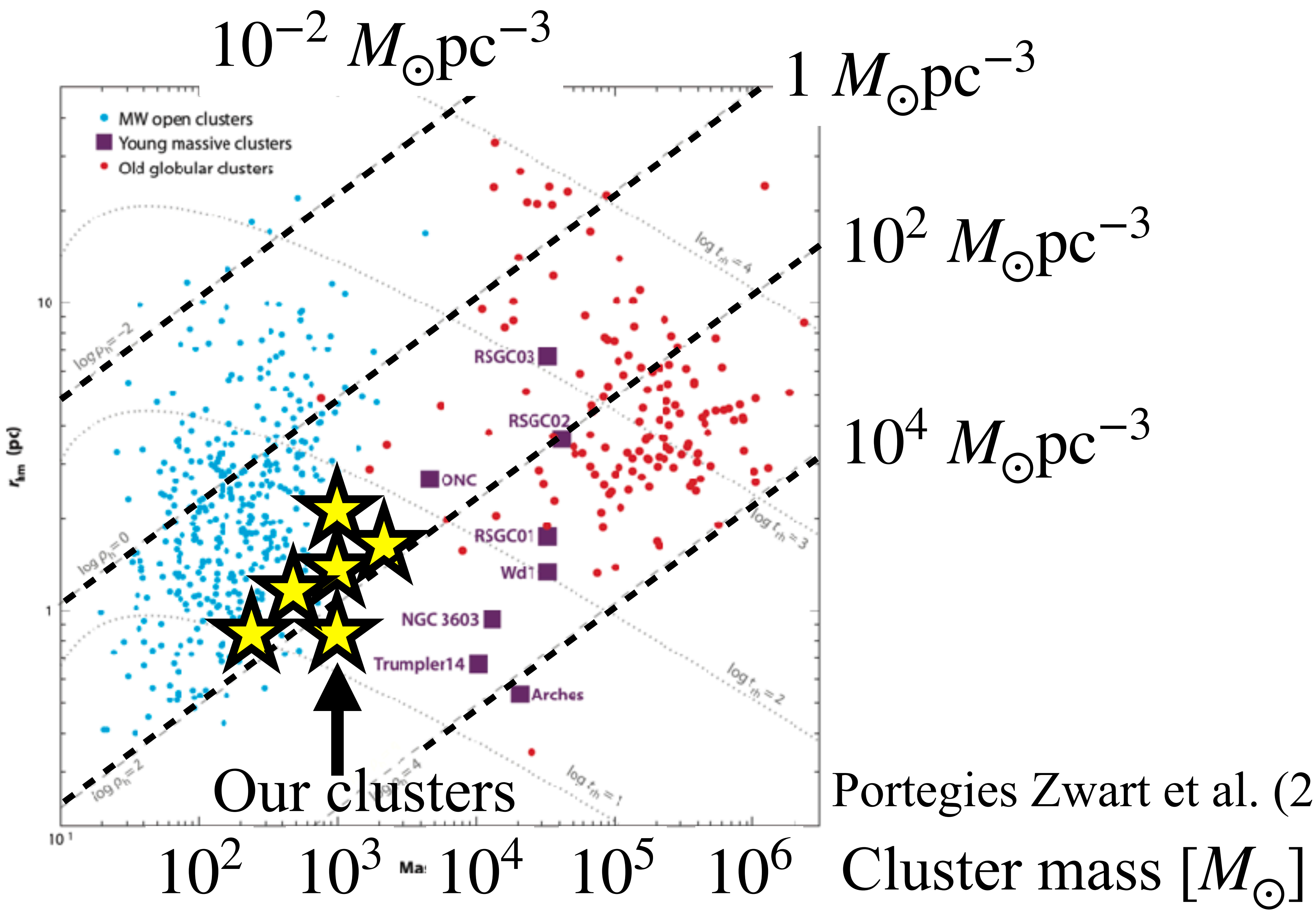

Portegies Zwart et al. (2010)

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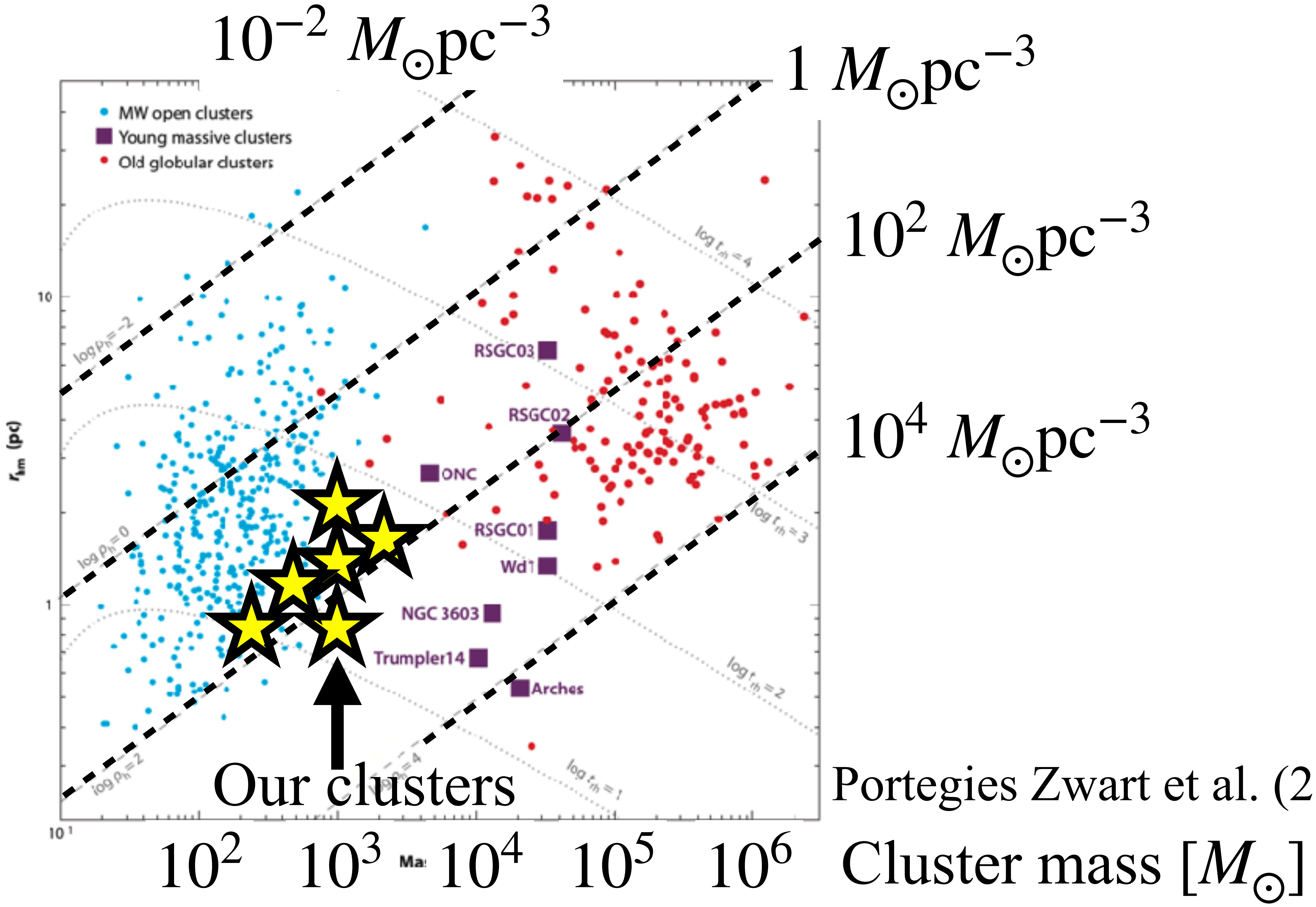

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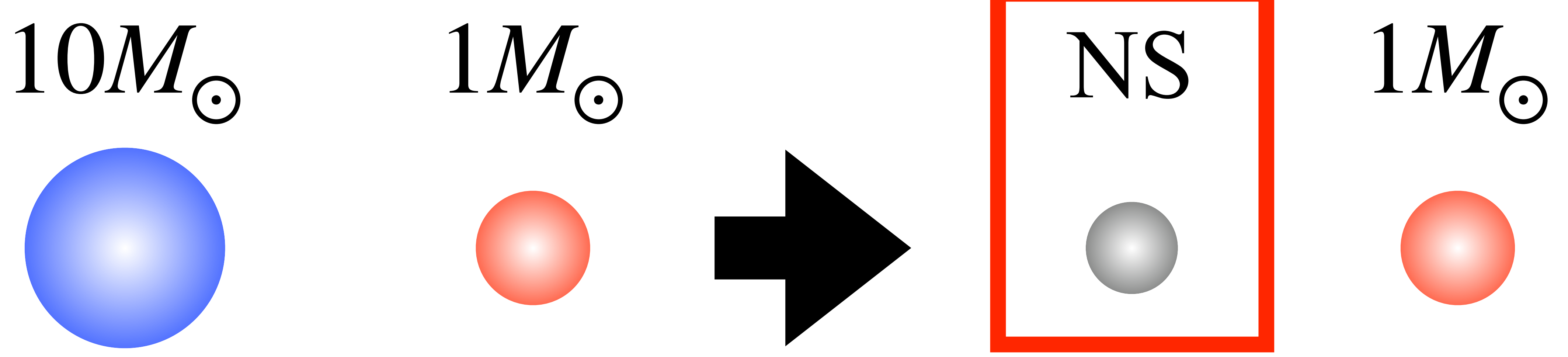

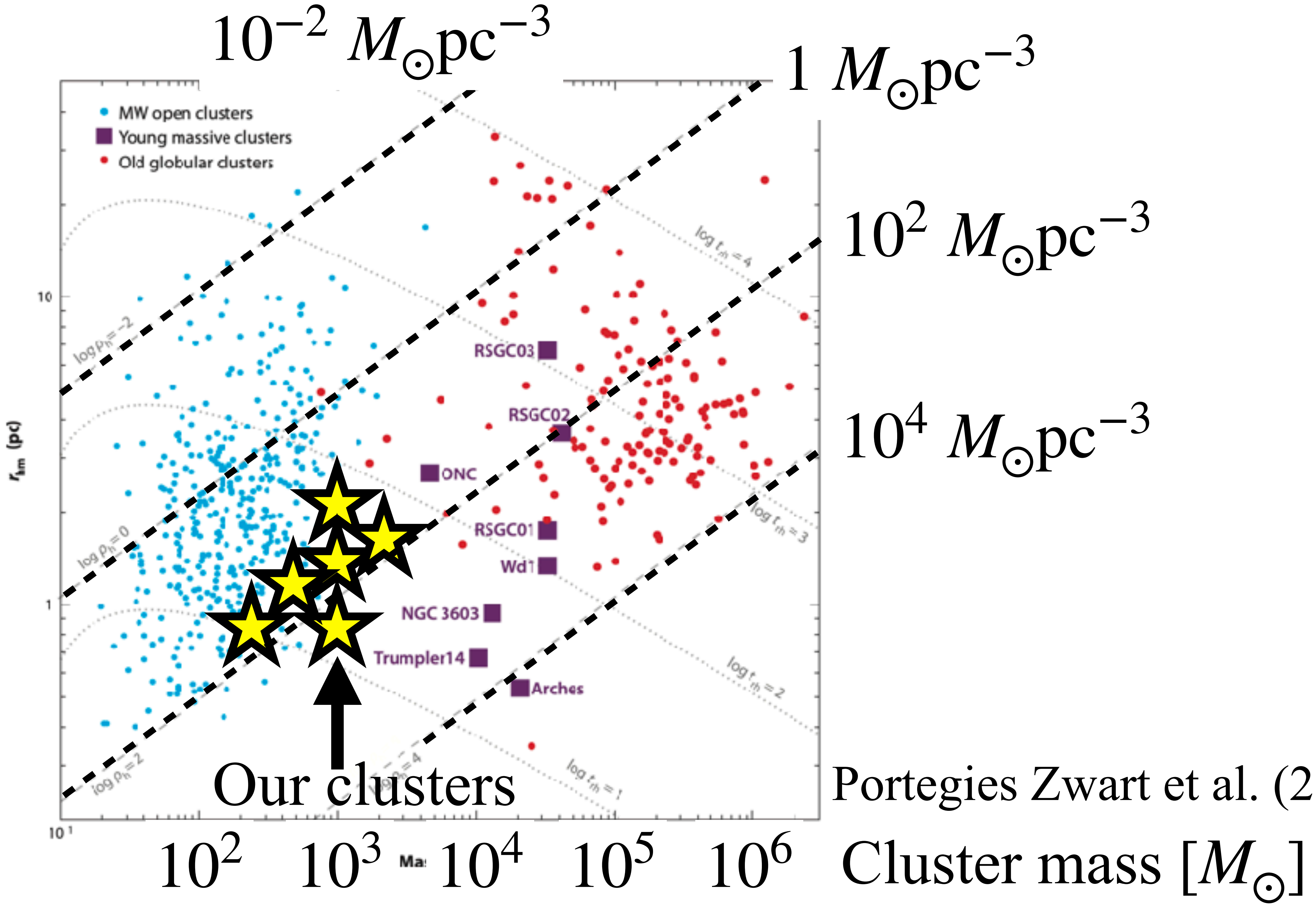

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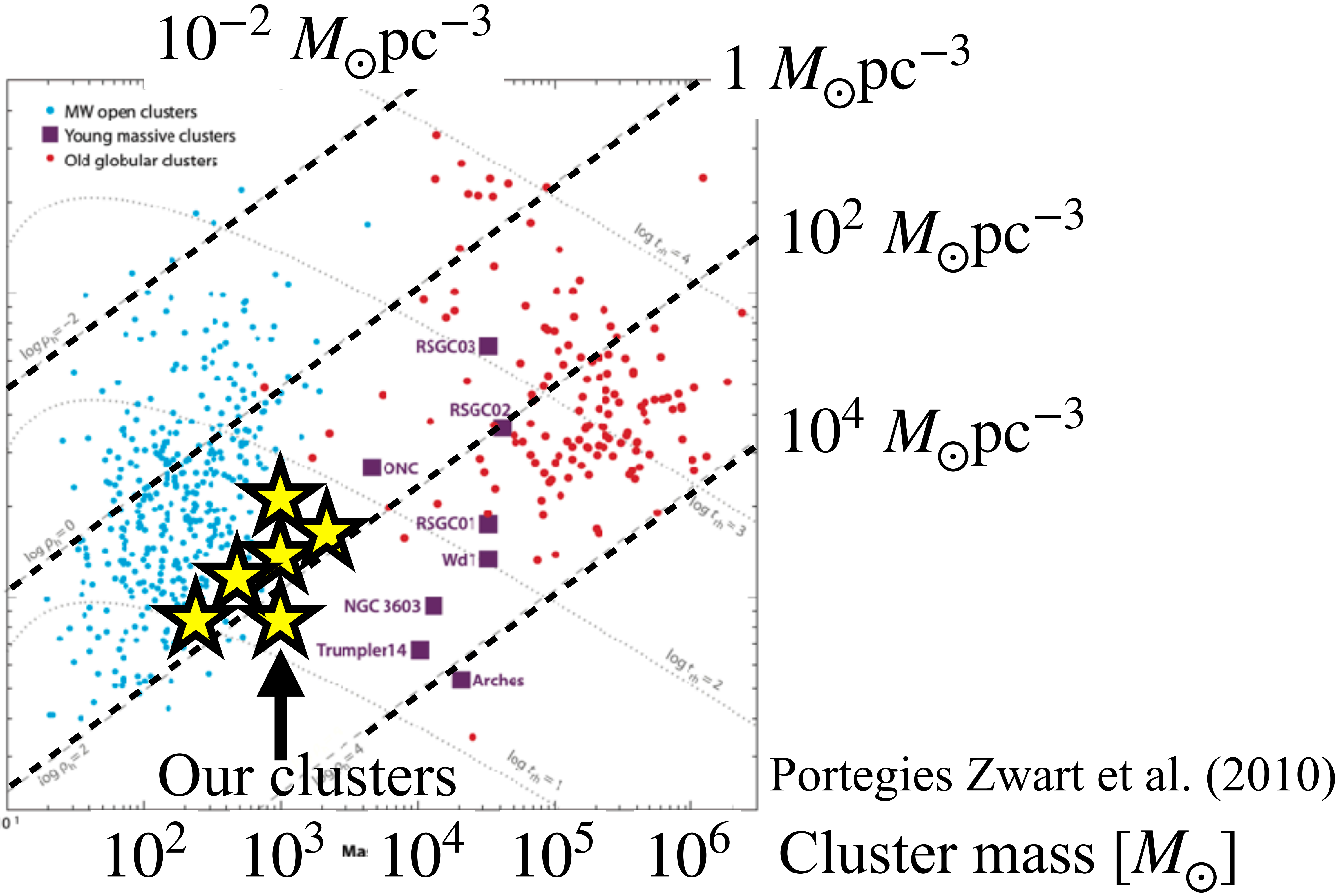

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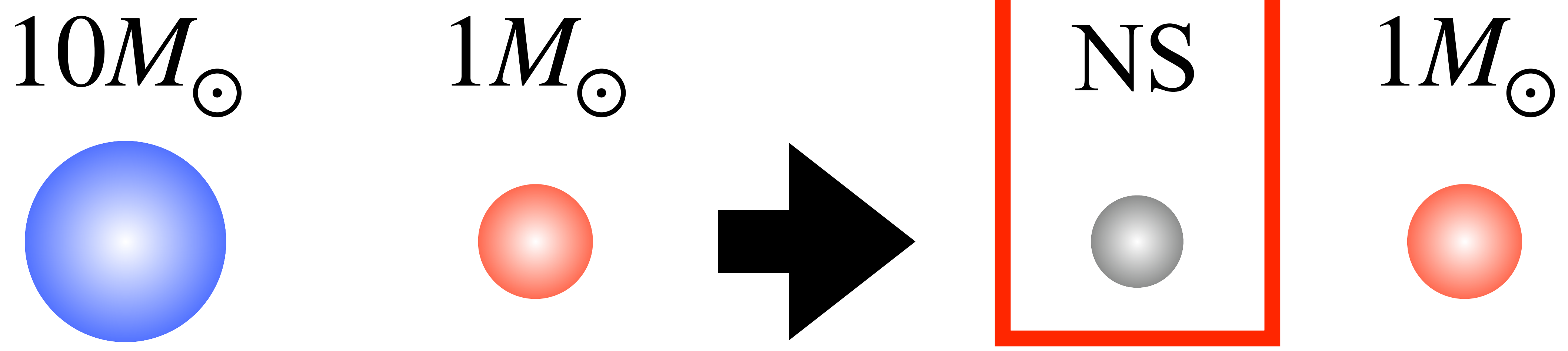
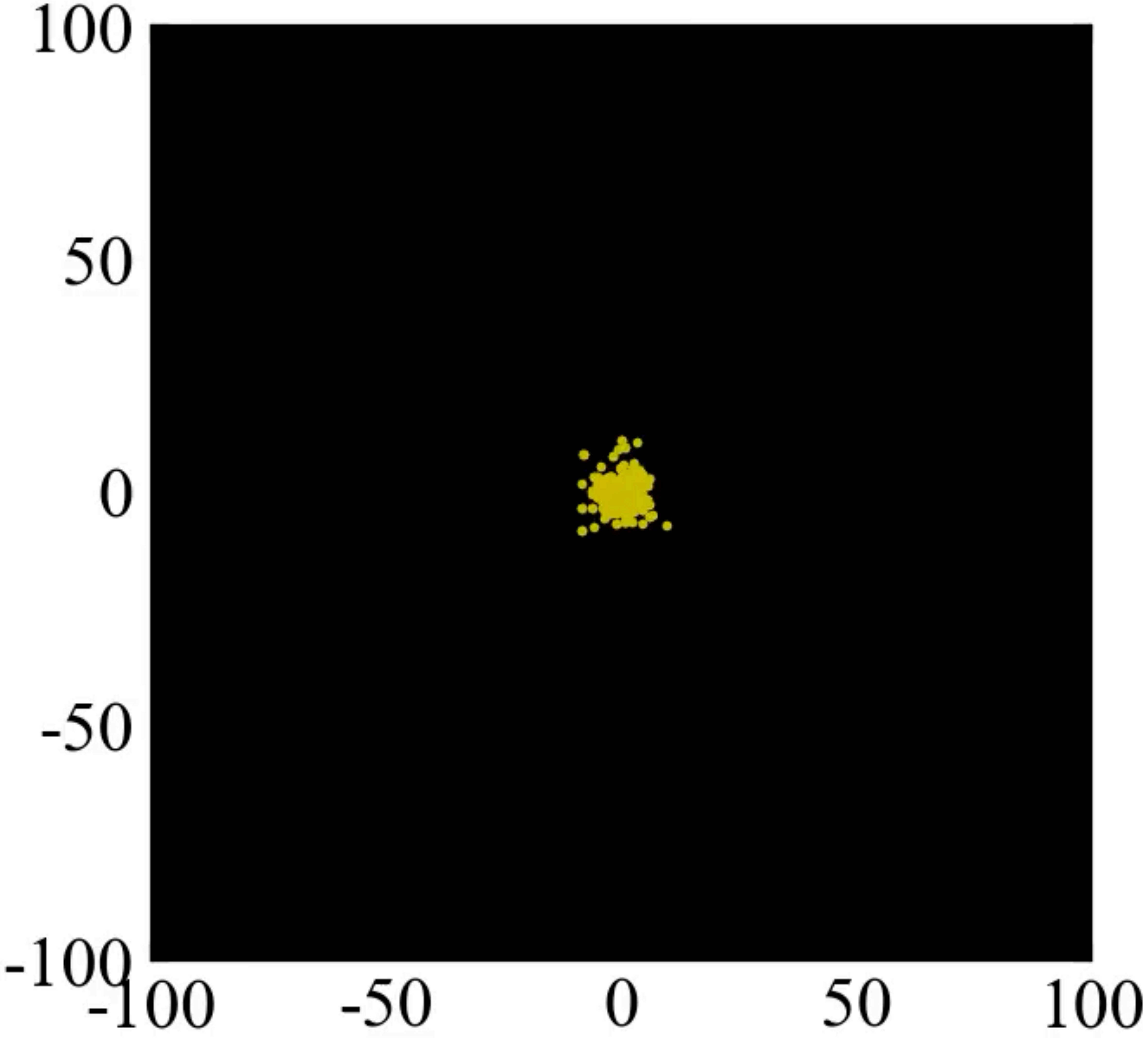


Gaia BHs could not be formed without dynamical interactions.

N-body simulation



PETAR

Wang et al. (2020)

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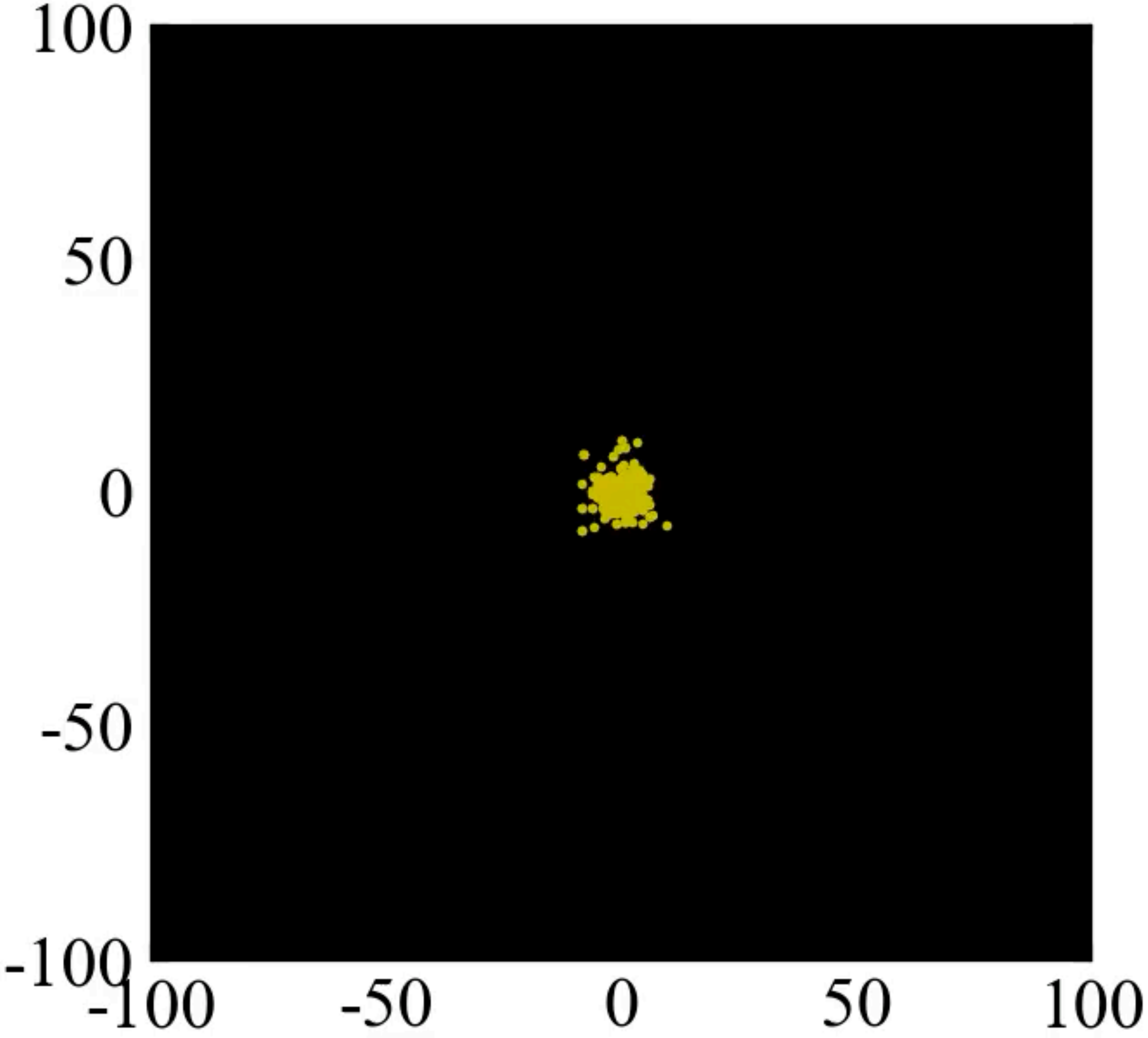

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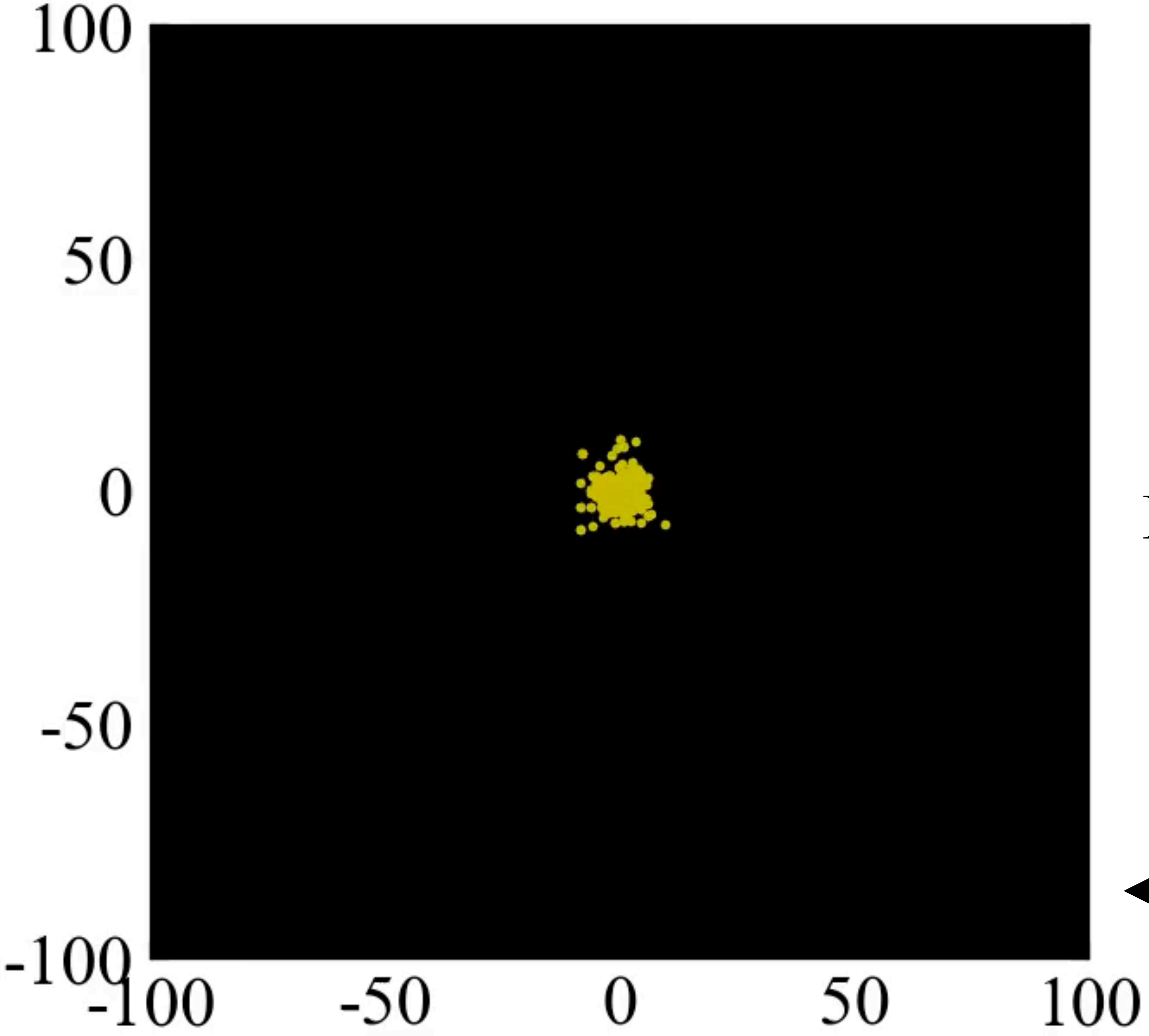

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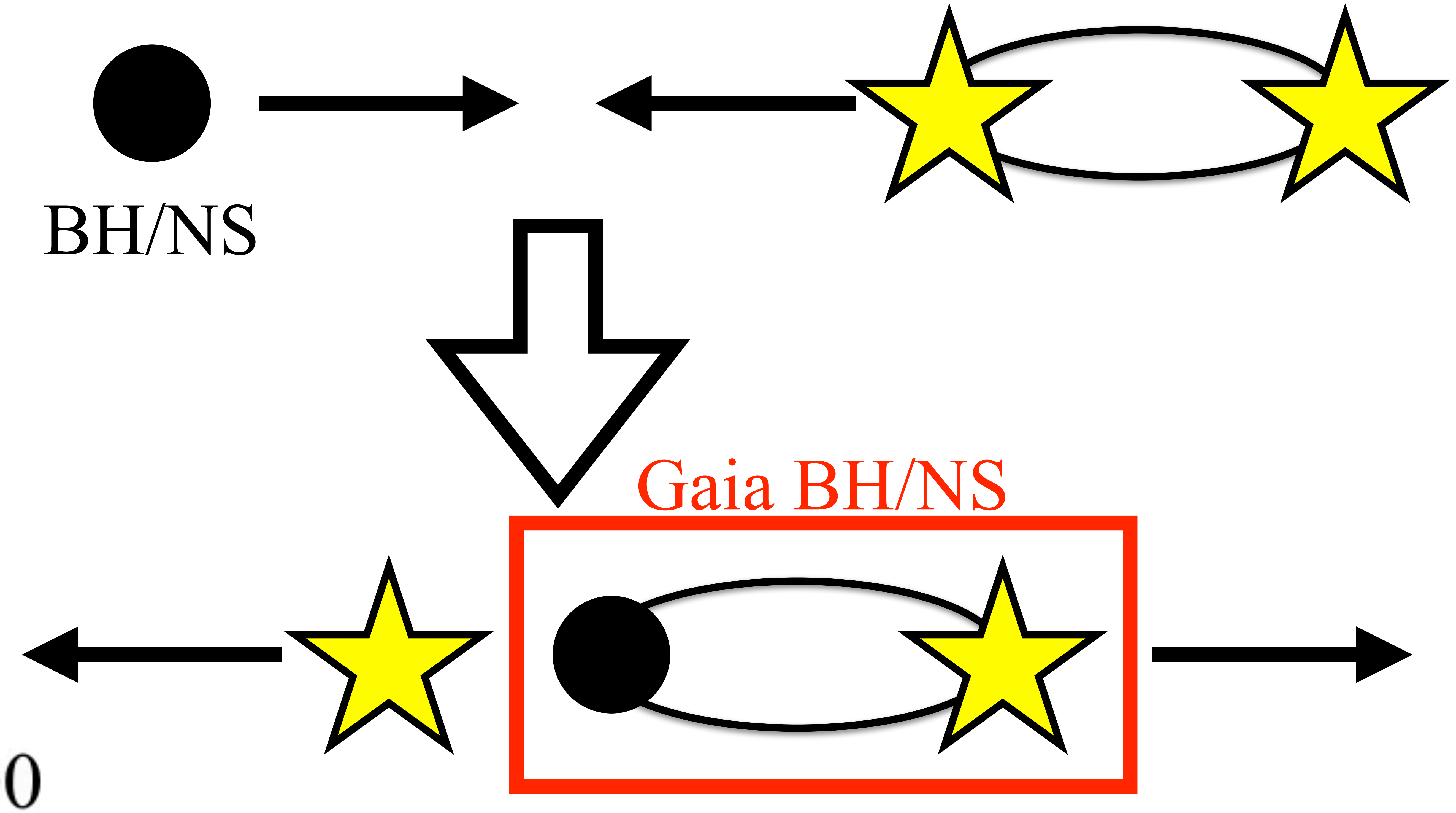
BH/NS
Gaia BH/NS

Criteria of Gaia BH/NS

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$m_1 \leq 1.1 M_\odot$

BH/NS

Criteria of Gaia BH/NS

MS, PMS, He star

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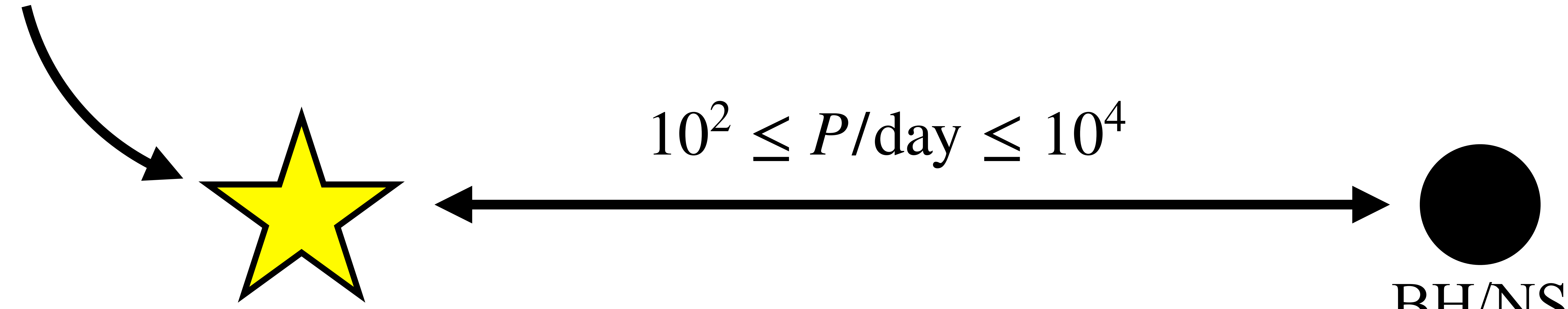

MS, PMS, He star

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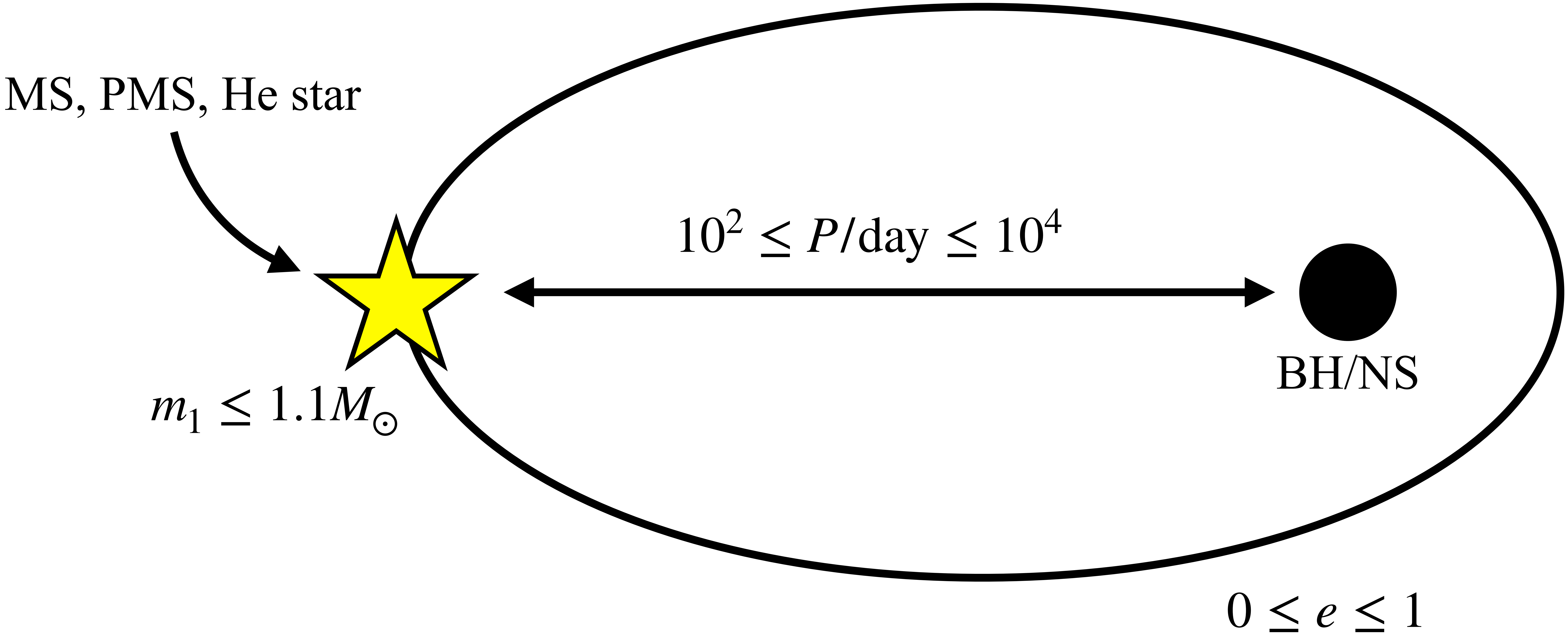
$m_1 \leq 1.1 M_\odot$

BH/NS

Criteria of Gaia BH/NS



MS, PMS, He star

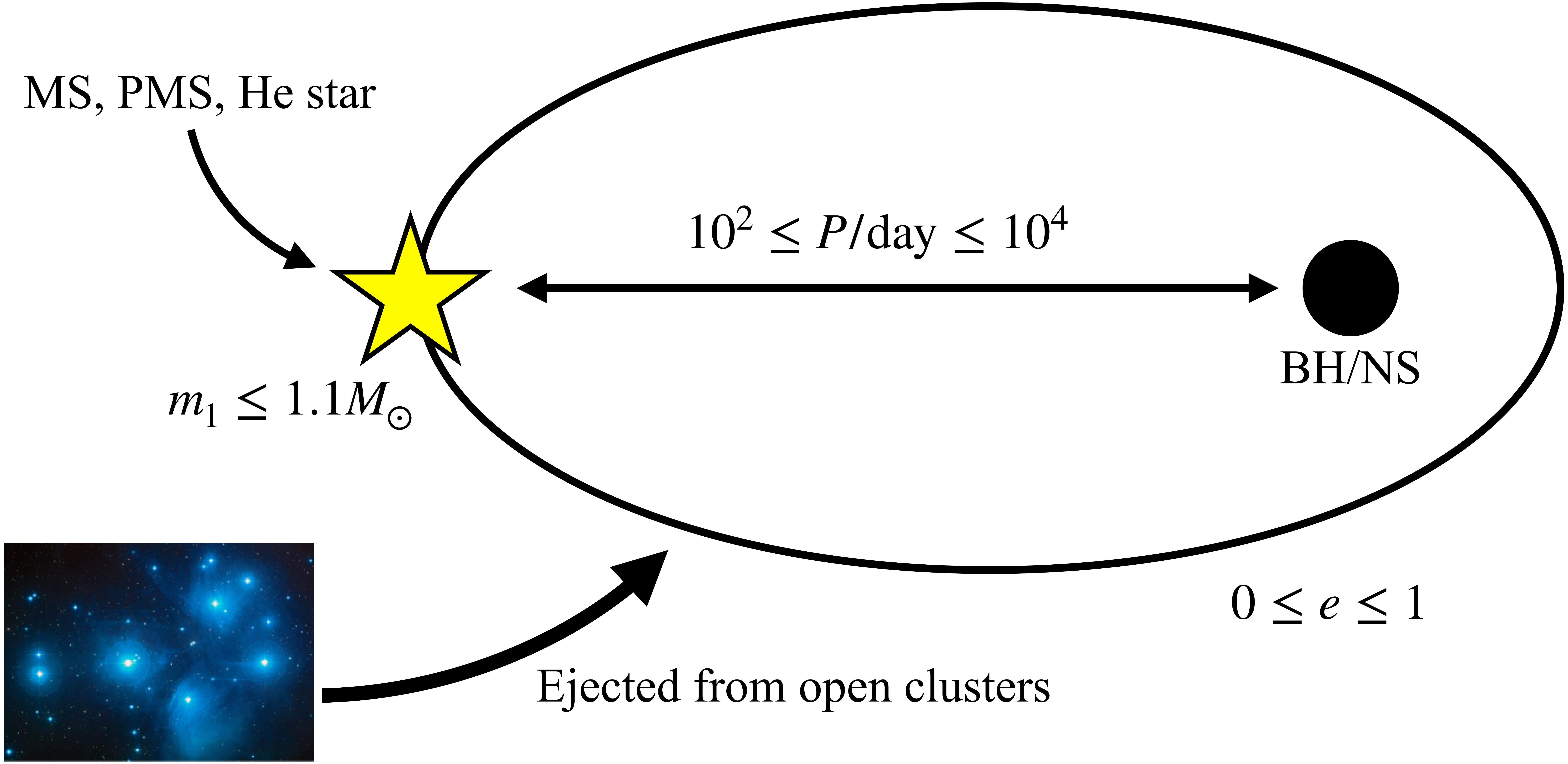
$m_1 \leq 1.1 M_\odot$

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

BH/NS

$0 \leq e \leq 1$

Criteria of Gaia BH/NS



MS, PMS, He star

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

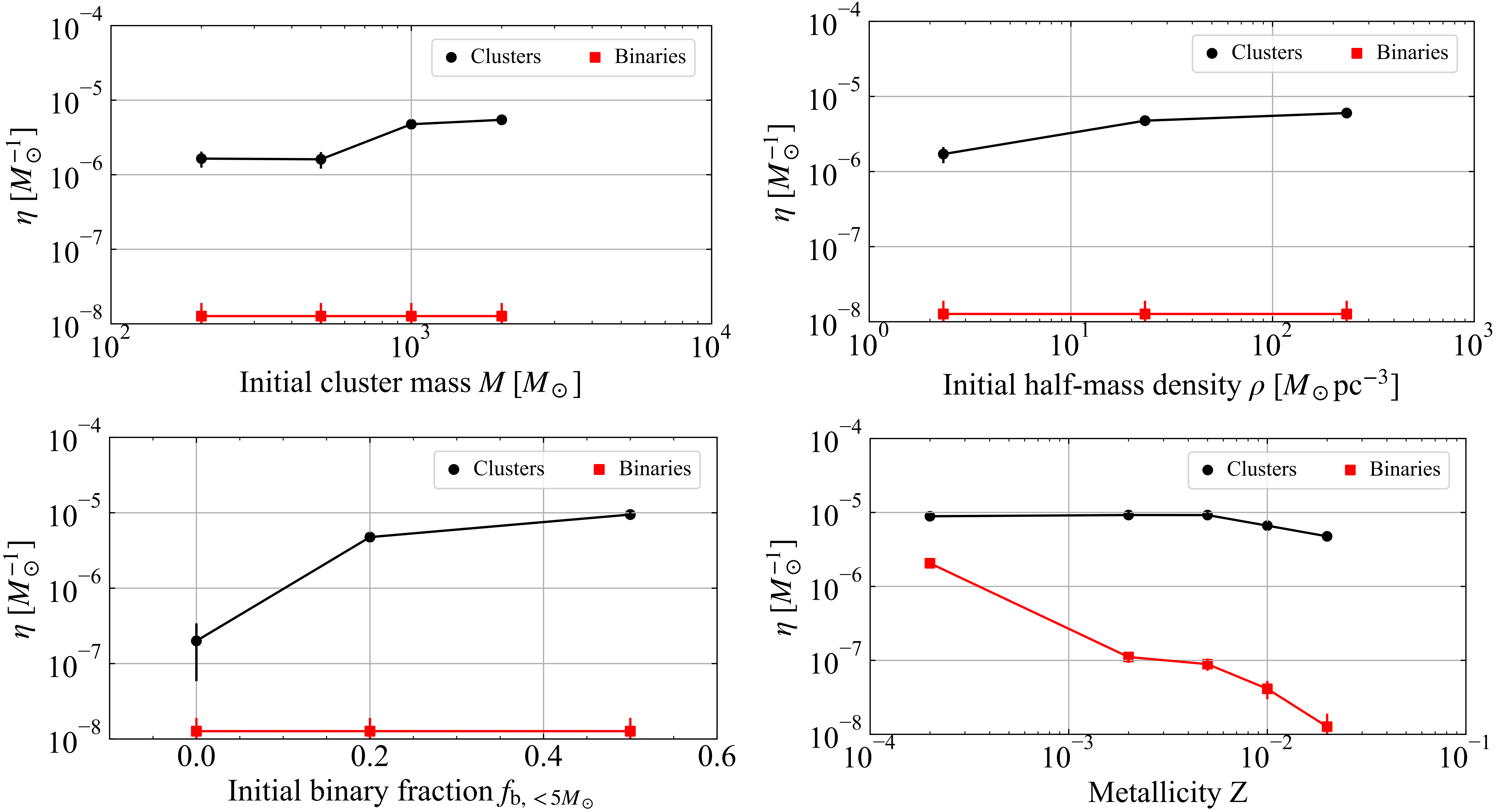
BH/NS

$m_1 \leq 1.1 M_\odot$

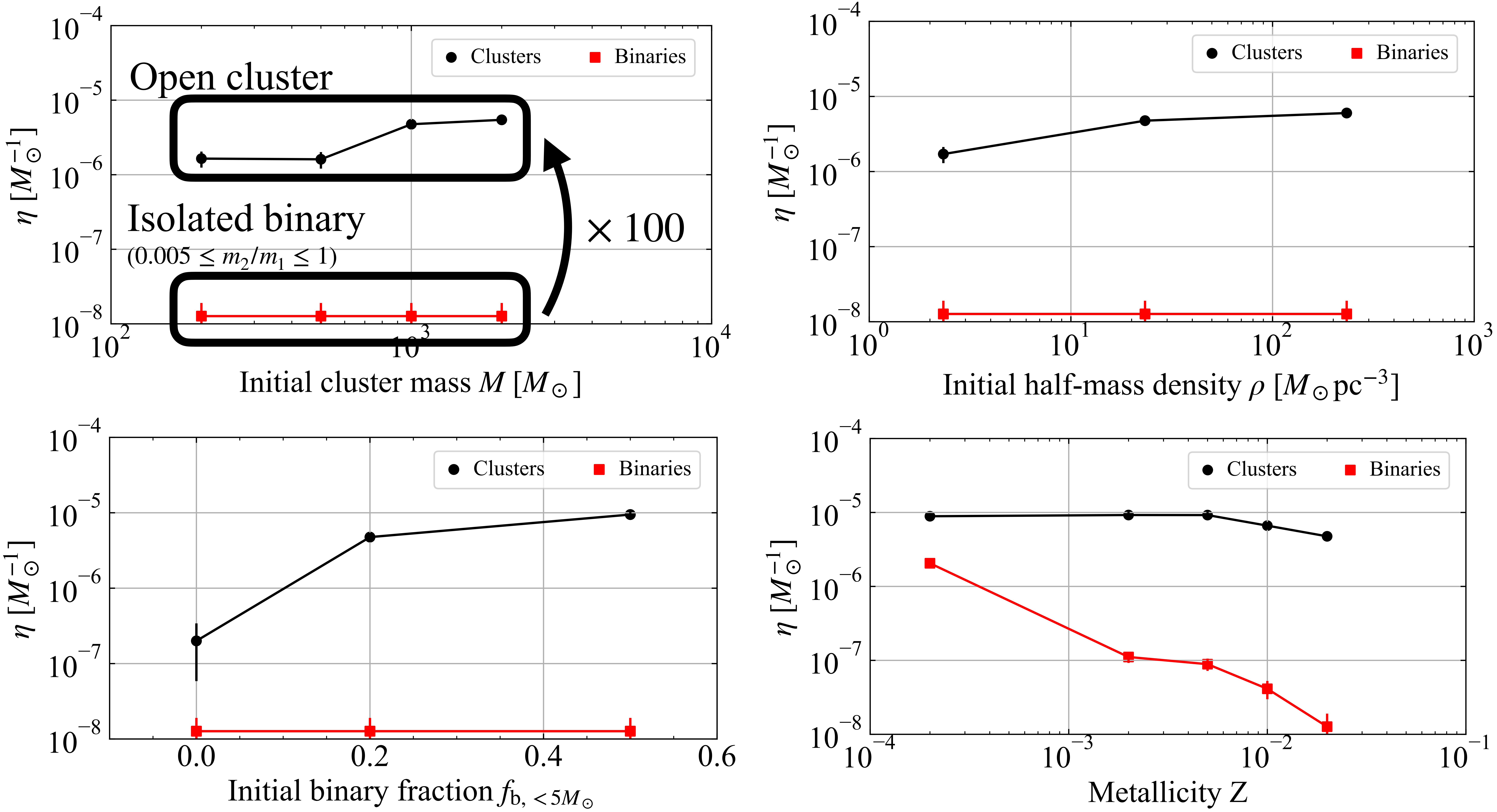
$0 \leq e \leq 1$

Ejected from open clusters

Formation efficiency of Gaia BH



Clusters
Binaries
$\eta\ [M_\odot^{-1}]$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{2}
10^{3}
10^{4}
Initial cluster mass $M\ [M_\odot]$
10^{0}
10^{1}
10^{2}
10^{3}
Initial half-mass density $\rho\ [M_\odot\,\mathrm{pc}^{-3}]$
0.0
0.2
0.4
0.6
Initial binary fraction $f_{\mathrm{b},<5M_\odot}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Metallicity Z



Open cluster
Isolated binary
(0.005 ≤ m_2/m_1 ≤ 1)
× 100
Clusters
Binaries
$\eta\ [M_\odot^{-1}]$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{2}
10^{3}
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Clusters
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10^{-4}
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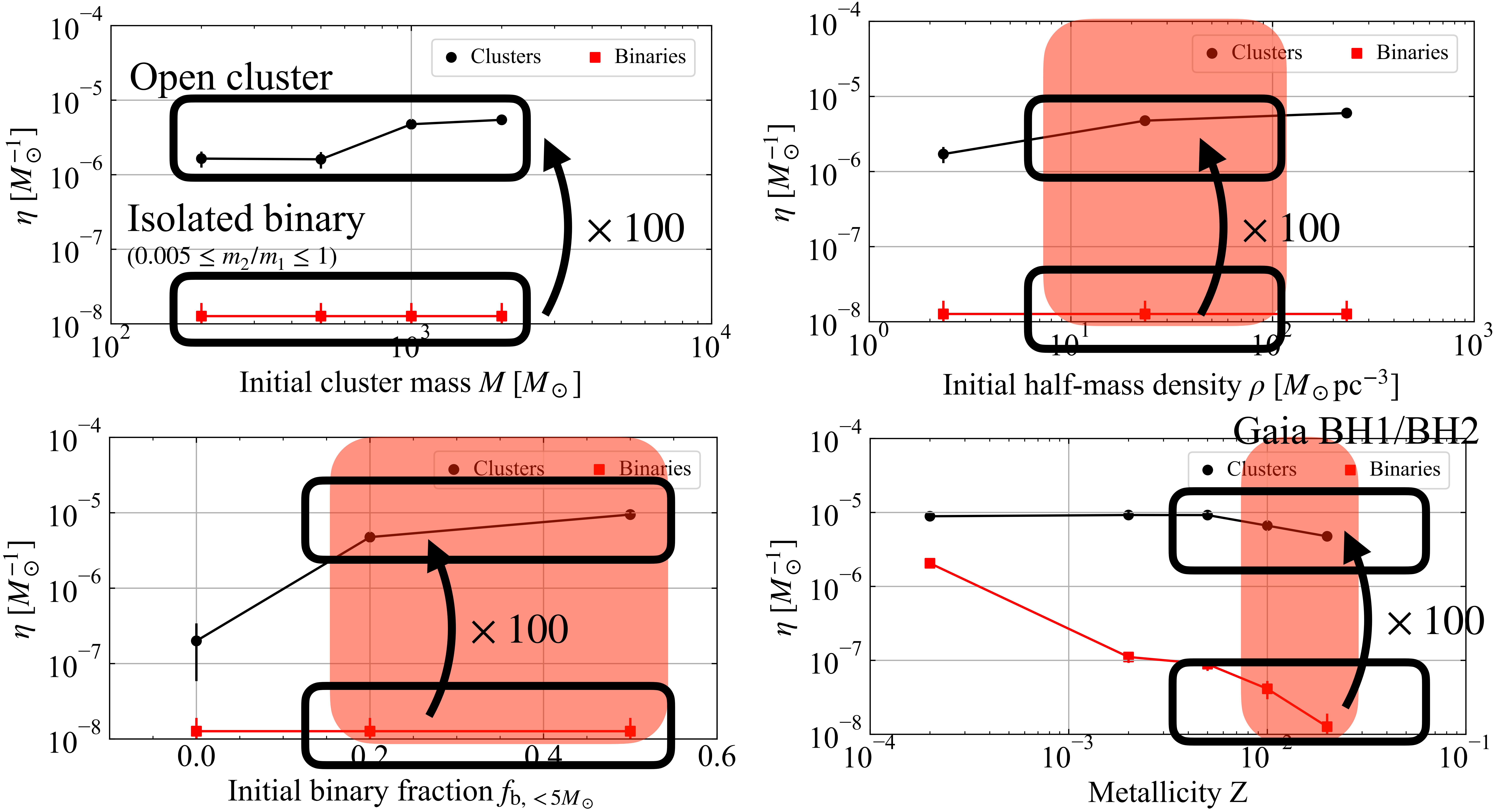
Open cluster
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Binaries
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10^{-4}
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10^{4}
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10^{0}
10^{1}
10^{2}
10^{3}
Initial half-mass density $\rho\ [M_\odot\,\mathrm{pc}^{-3}]$
0.0
0.2
0.4
0.6
Initial binary fraction $f_{\mathrm{b},<5M_\odot}$
Gaia BH1/BH2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Metallicity Z

The number of Gaia BHs in the Galactic disk

The number of Gaia BHs in the Galactic disk

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

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

The number of Gaia BHs in the Galactic disk

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Sufficiently large to explain the presence of Gaia BHs

Formation efficiency of Gaia NS

Gaia BH (Cluster)
Gaia NS (Cluster)
Gaia NS (Binary)
$\eta\ [M_\odot^{-1}]$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{2}
10^{3}
10^{4}
Initial cluster mass $M\ [M_\odot]$
10^{0}
10^{1}
10^{2}
10^{3}
Initial half-mass density $\rho\ [M_\odot\,\mathrm{pc}^{-3}]$
0.0
0.2
0.4
0.6
Initial binary fraction $f_{\mathrm{b},<5M_\odot}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Metallicity Z

Gaia BH (Cluster)
Gaia NS (Cluster)
Gaia NS (Binary)
Gaia BH
Gaia NS
$\lesssim 0.01$
$\eta\ [M_\odot^{-1}]$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{2}
10^{3}
10^{4}
Initial cluster mass $M\ [M_\odot]$
10^{0}
10^{1}
10^{2}
10^{3}
Initial half-mass density $\rho\ [M_\odot\,\mathrm{pc}^{-3}]$
0.0
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Gaia BH (Cluster)
Gaia NS (Cluster)
Gaia NS (Binary)
Gaia BH
Gaia NS
$\lesssim 0.01$
$\eta\ [M_\odot^{-1}]$
10^{-4}
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10^{-4}
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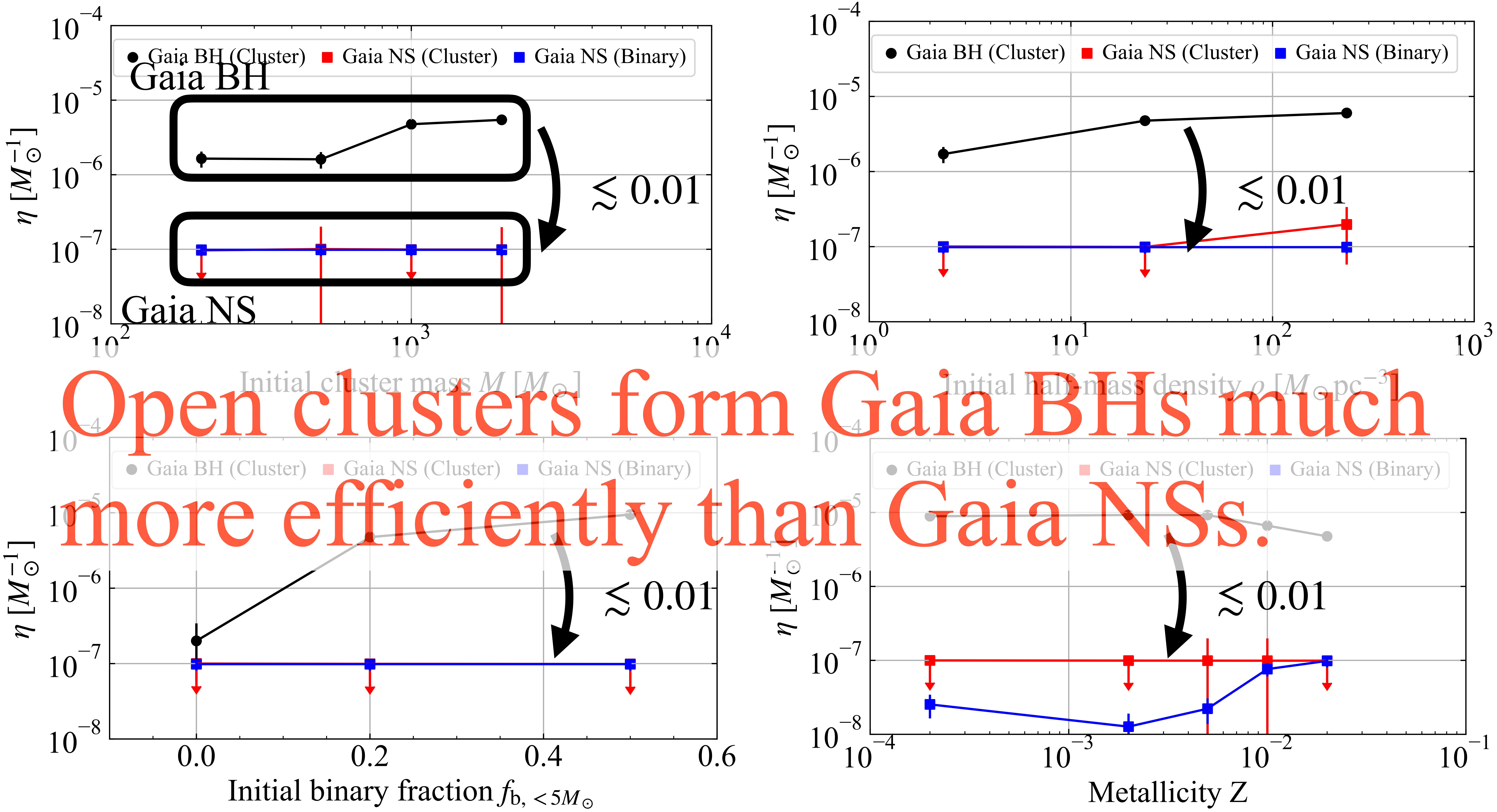
Metallicity Z



Open clusters form Gaia BHs much more efficiently than Gaia NSs.

Open clusters cannot form both Gaia BHs and Gaia NSs.

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

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

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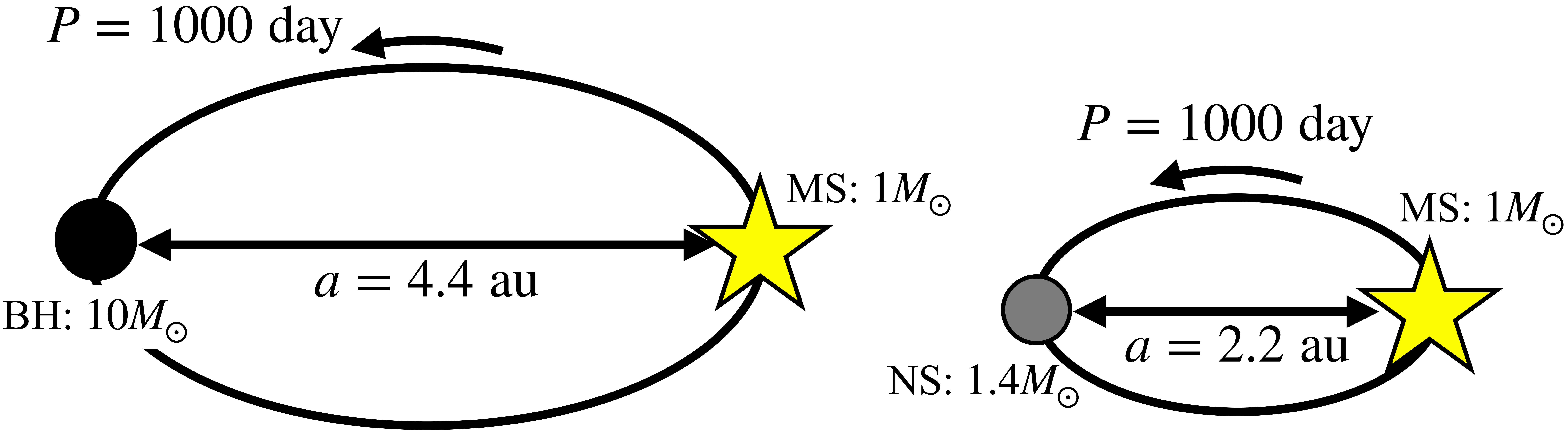
$P = 1000$ day
MS: $1M_\odot$
$a = 4.4$ au
BH: $10M_\odot$
$P = 1000$ day
MS: $1M_\odot$
$a = 2.2$ au
NS: $1.4M_\odot$

Open clusters cannot form both Gaia BHs and Gaia NSs.

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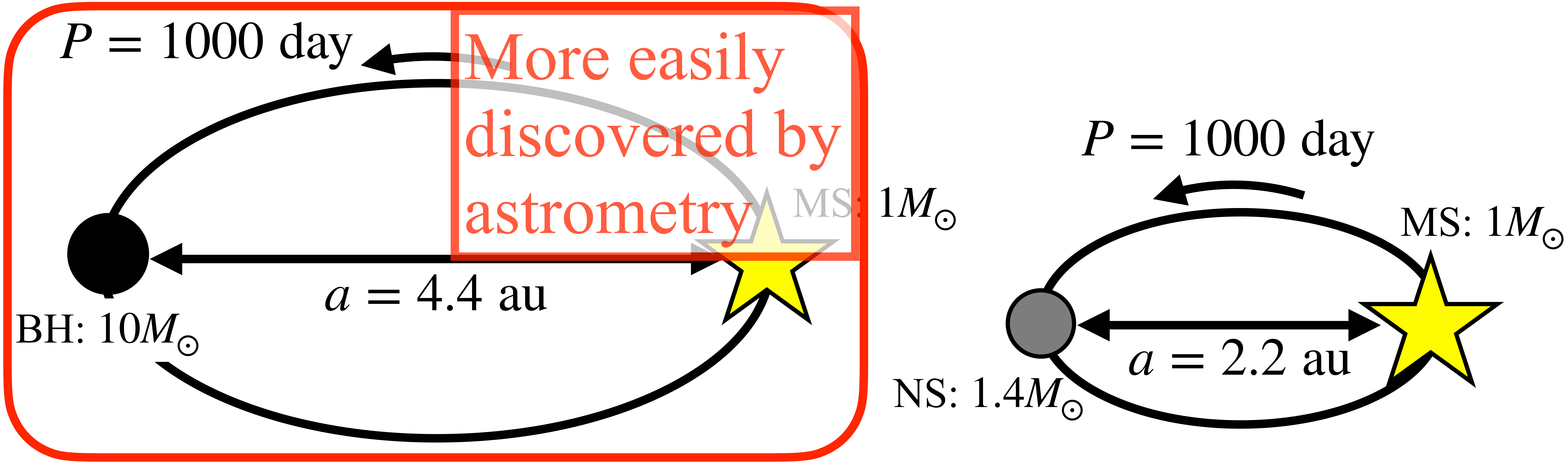

More easily discovered by astrometry

$P = 1000$ day
MS: $1M_\odot$
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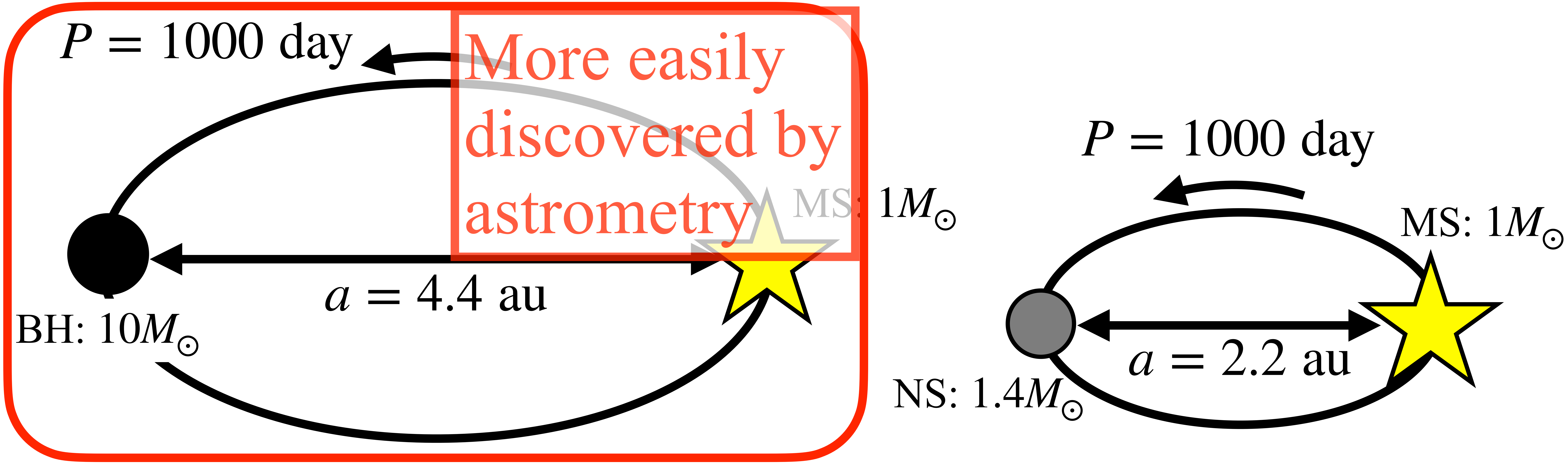
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More easily discovered by astrometry

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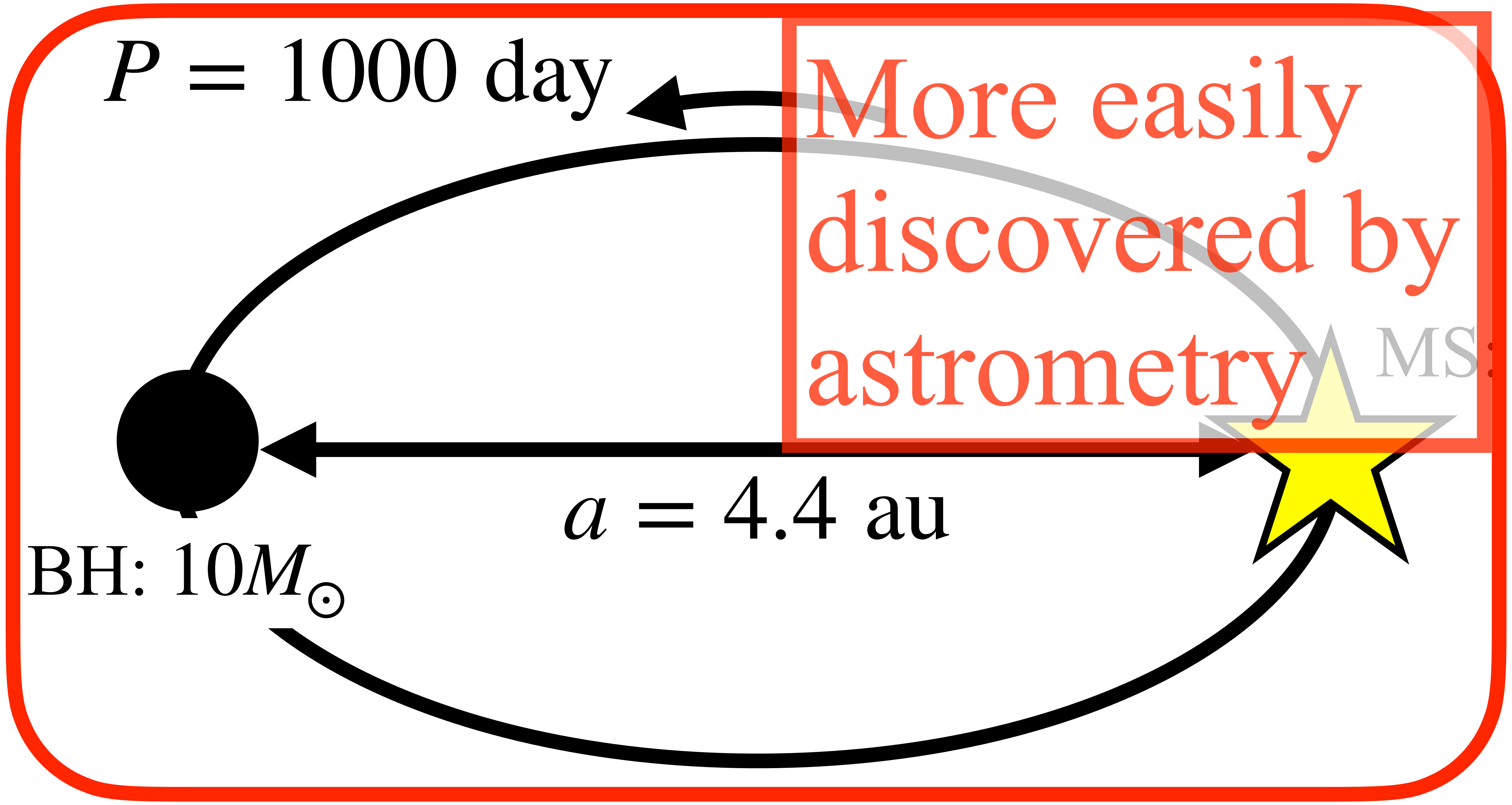
  - # of Gaia BHs (3) < # of Gaia NSs (21)
- Intrinsic population
  - # of Gaia BHs < # of Gaia NSs

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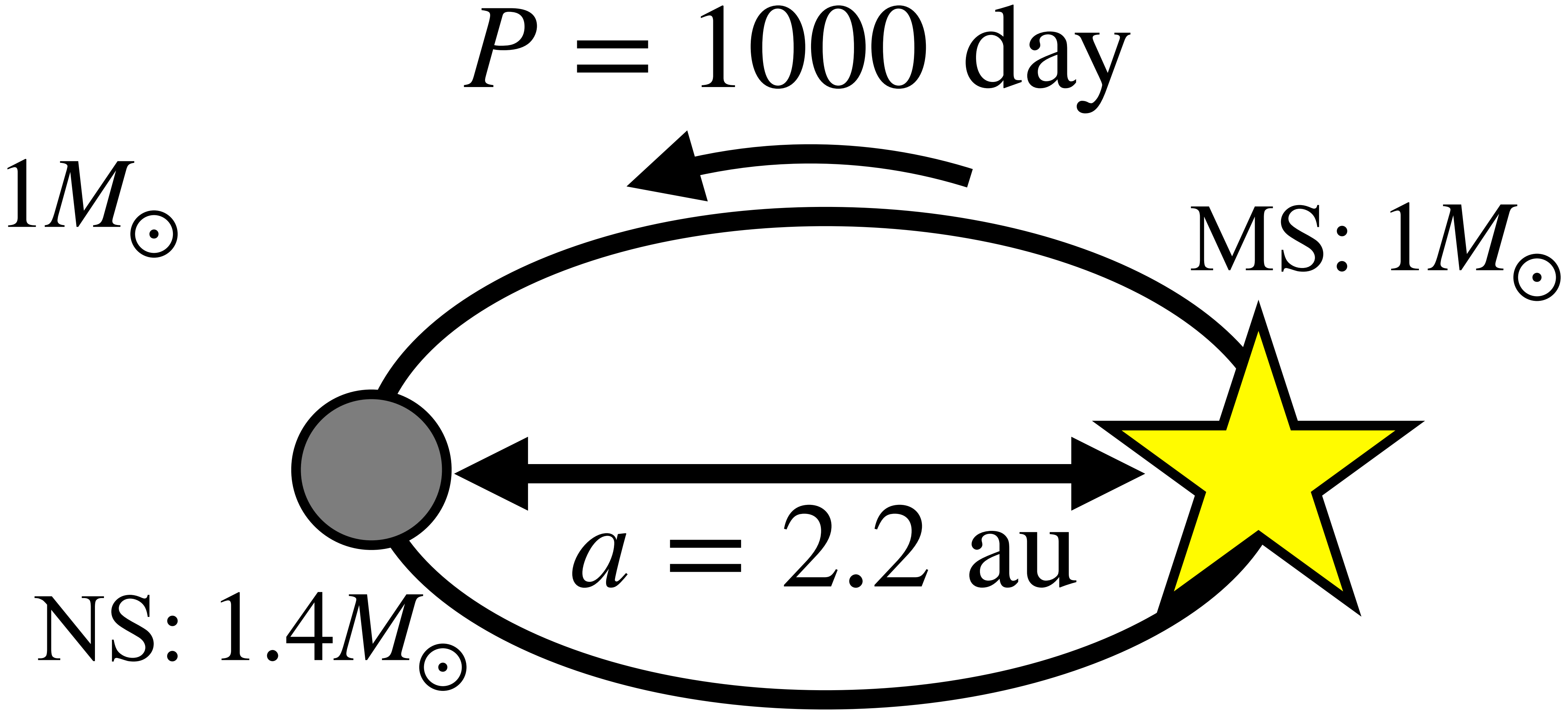
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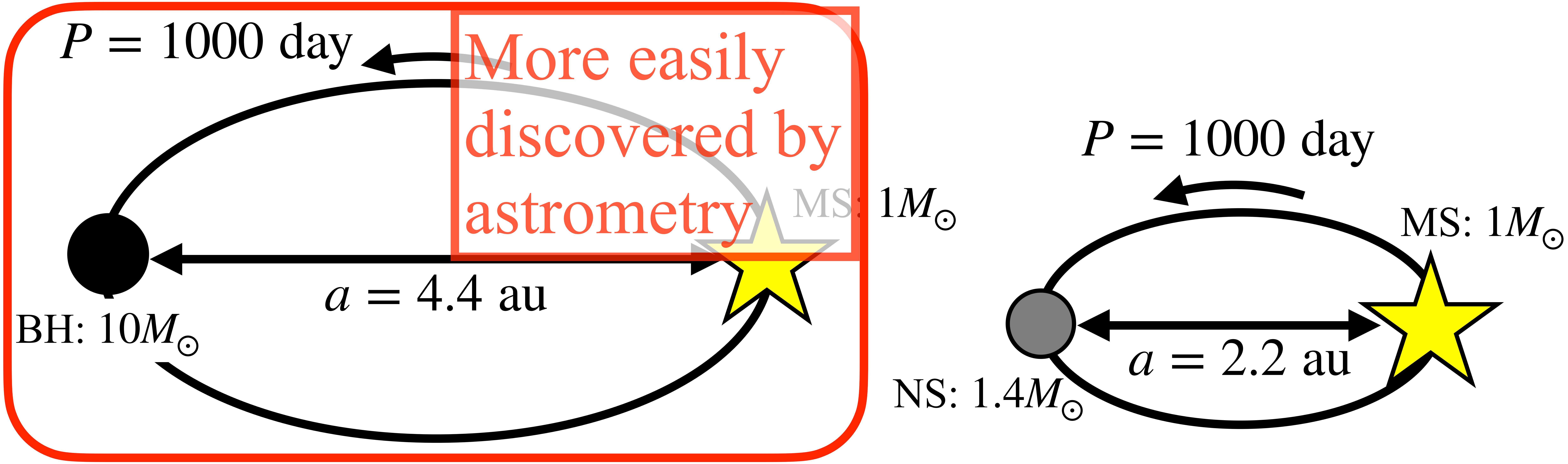
Noticeable contradiction

$\Longrightarrow$ Open clusters cannot form both.



$P = 1000$ day
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  - Underproduction of Gaia NSs compared to Gaia BHs (This talk)

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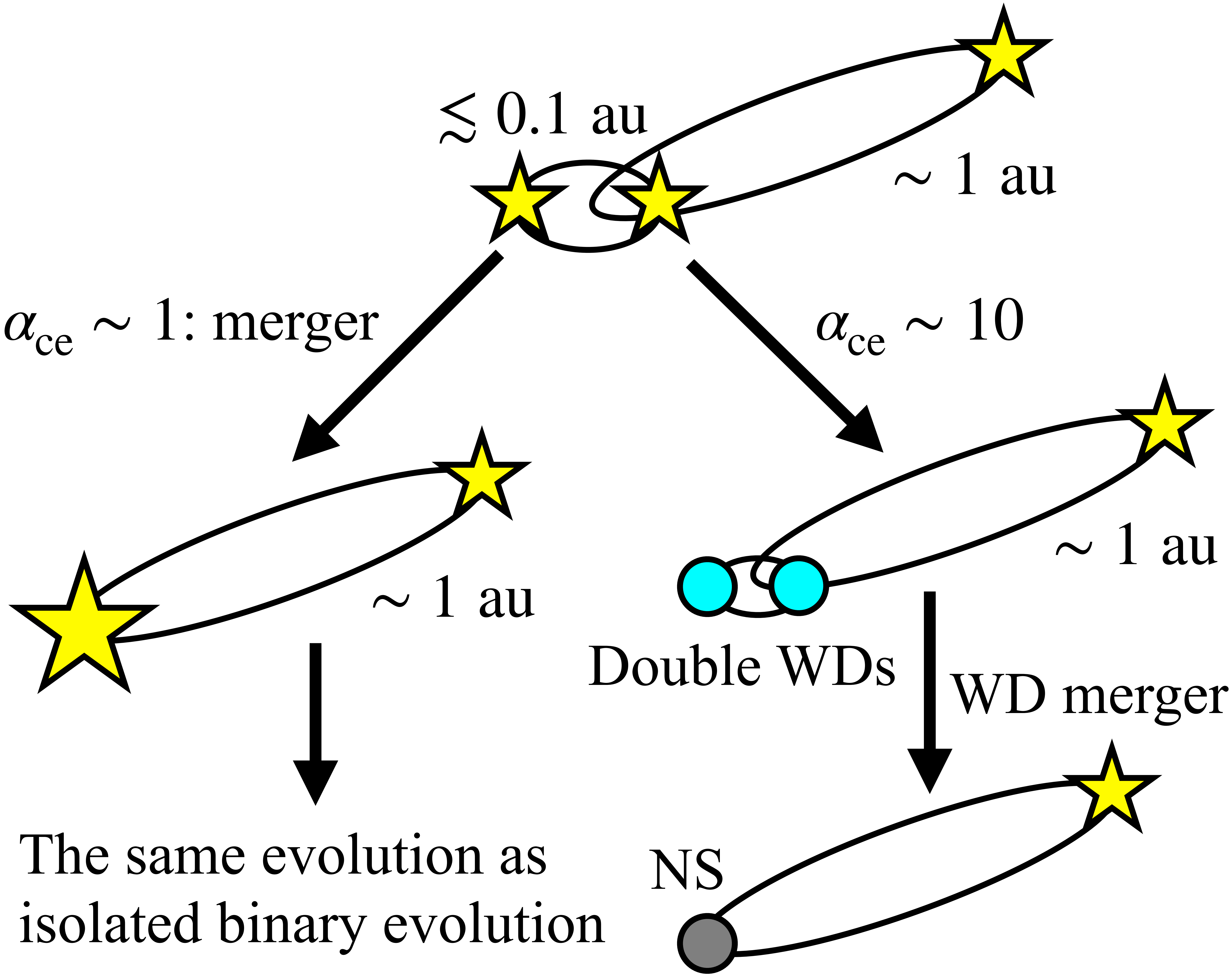
$\lesssim 0.1$ au
~ 1 au
$\alpha_{\rm ce} \sim 1$: merger
$\alpha_{\rm ce} \sim 10$
~ 1 au
~ 1 au
Double WDs
WD merger
The same evolution as isolated binary evolution
NS

Gaia NS formation remains an open question

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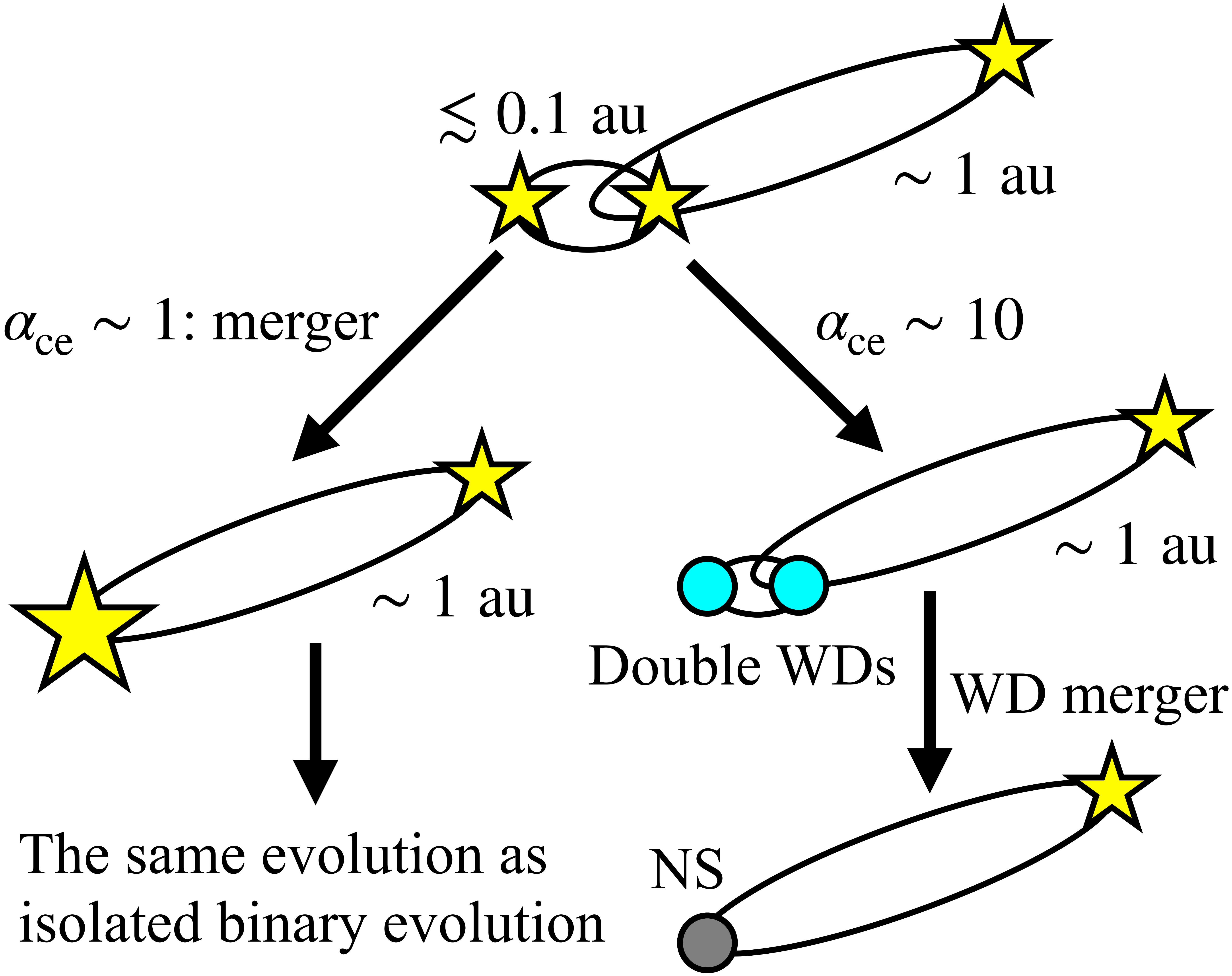
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NS

Conclusions of this talk

- Gaia mission and its follow-up observations have discovered many inert compact binaries, so-called Gaia BHs and Gaia NSs.
- These Gaia BHs and Gaia NSs cannot be formed in the conventional binary evolution model (but see Kotko et al. 2024; Iorio et al. 2024; El-Badry et al. 2024; Poojan's talk).
- Gaia BHs can be formed efficiently in open clusters (Tanikawa et al. 2024, MNRAS, 527, 4031; see also Rastello et al. 2023; Di Carlo et al. 2024; Marin Pina et al. 2024).
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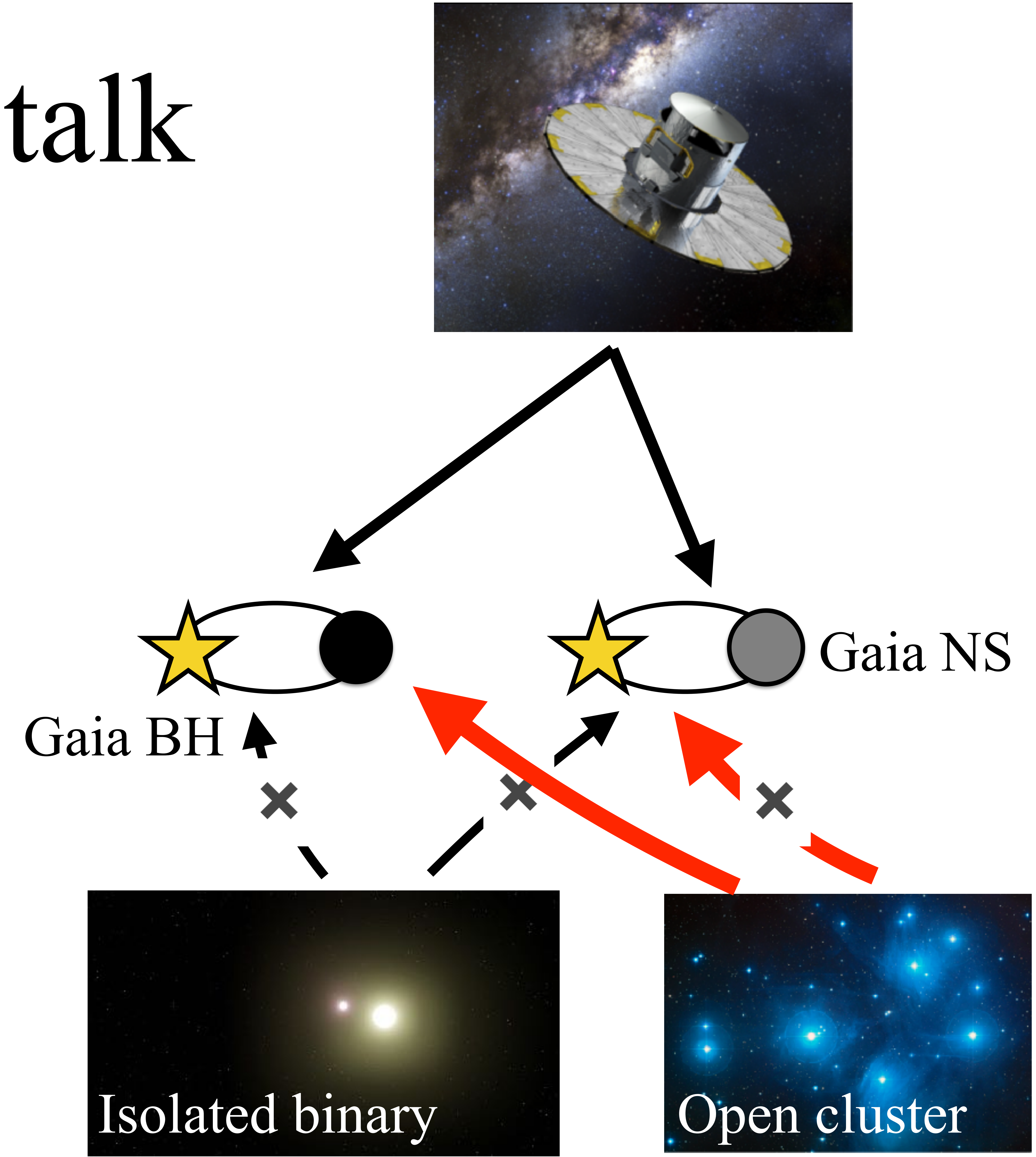

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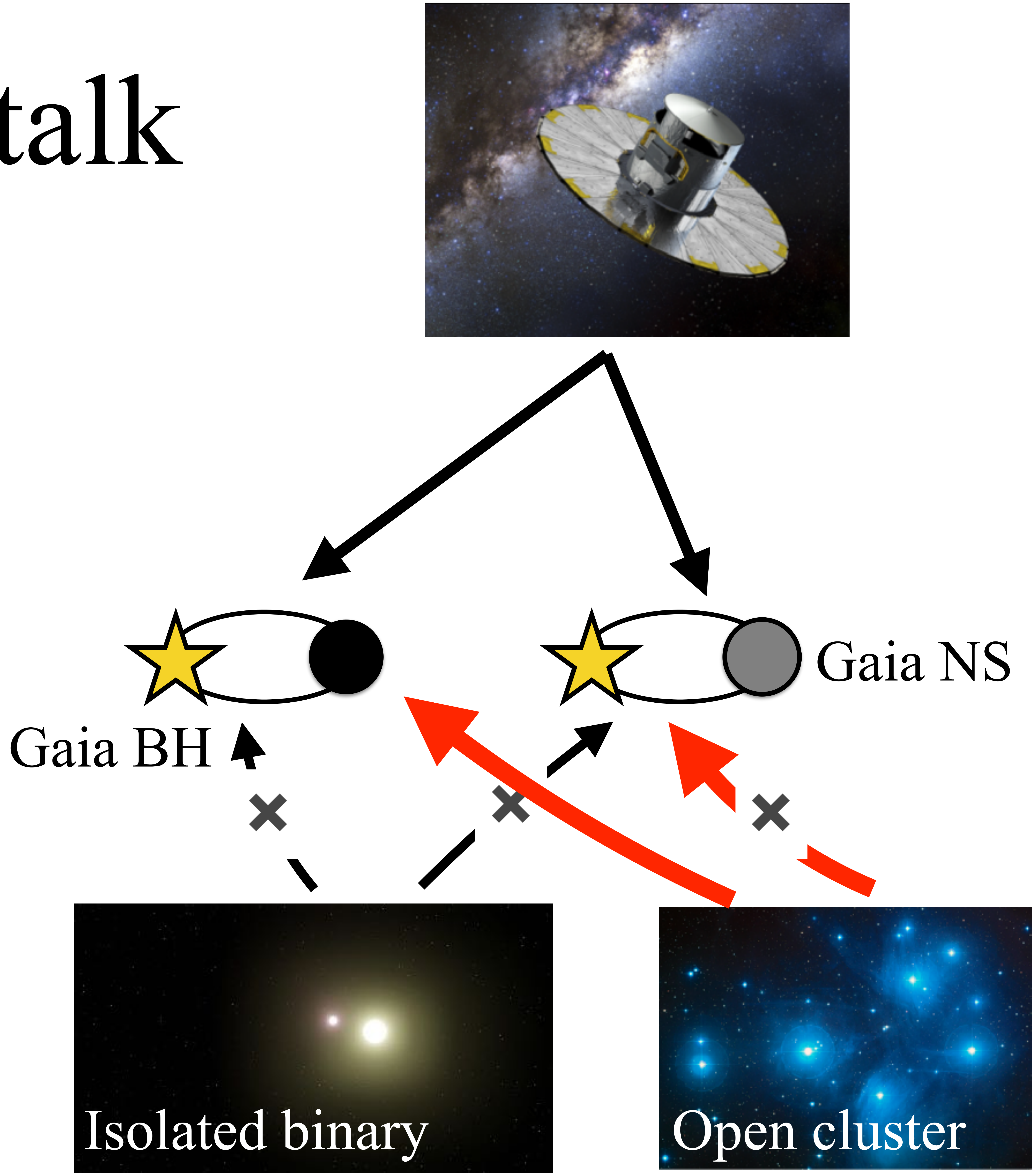

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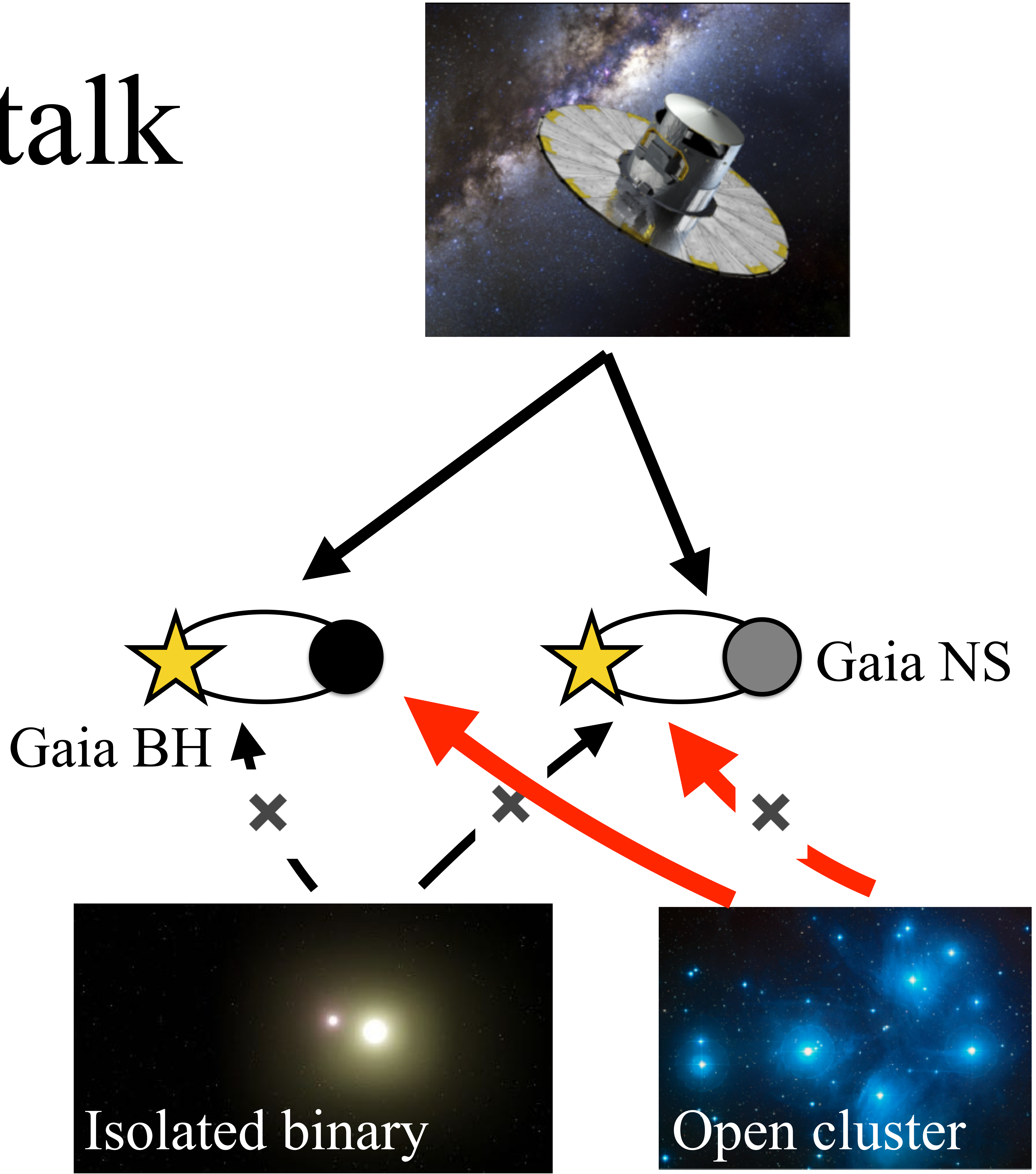

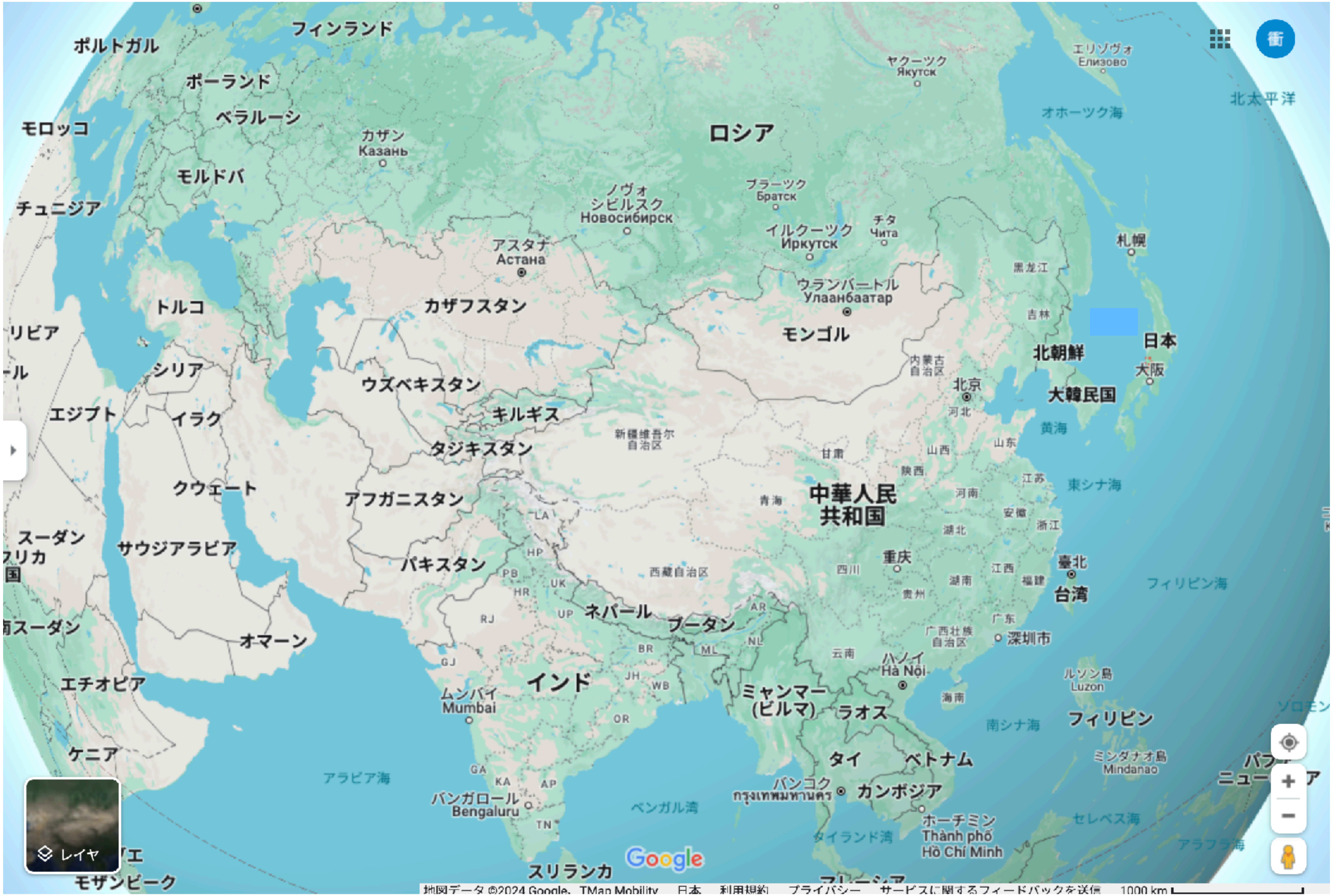
フィンランド
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カザン
Казань
ロシア
ヤクーツク
Якутск
エリゾヴォ
Елизово
北太平洋
オホーツク海
モルドバ
ノヴォシビルスク
Новосибирск
ブラーツク
Братск
チュニジア
アスタナ
Астана
イルクーツク
Иркутск
チタ
Чита
札幌
黑龙江
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ムンバイ
Mumbai
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(ビルマ)
ラオス
海南
ルソン島
Luzon
OR
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Mindanao
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Bengaluru
バンコク
กรุงเทพมหานคร
カンボジア
ベンガル湾
TN
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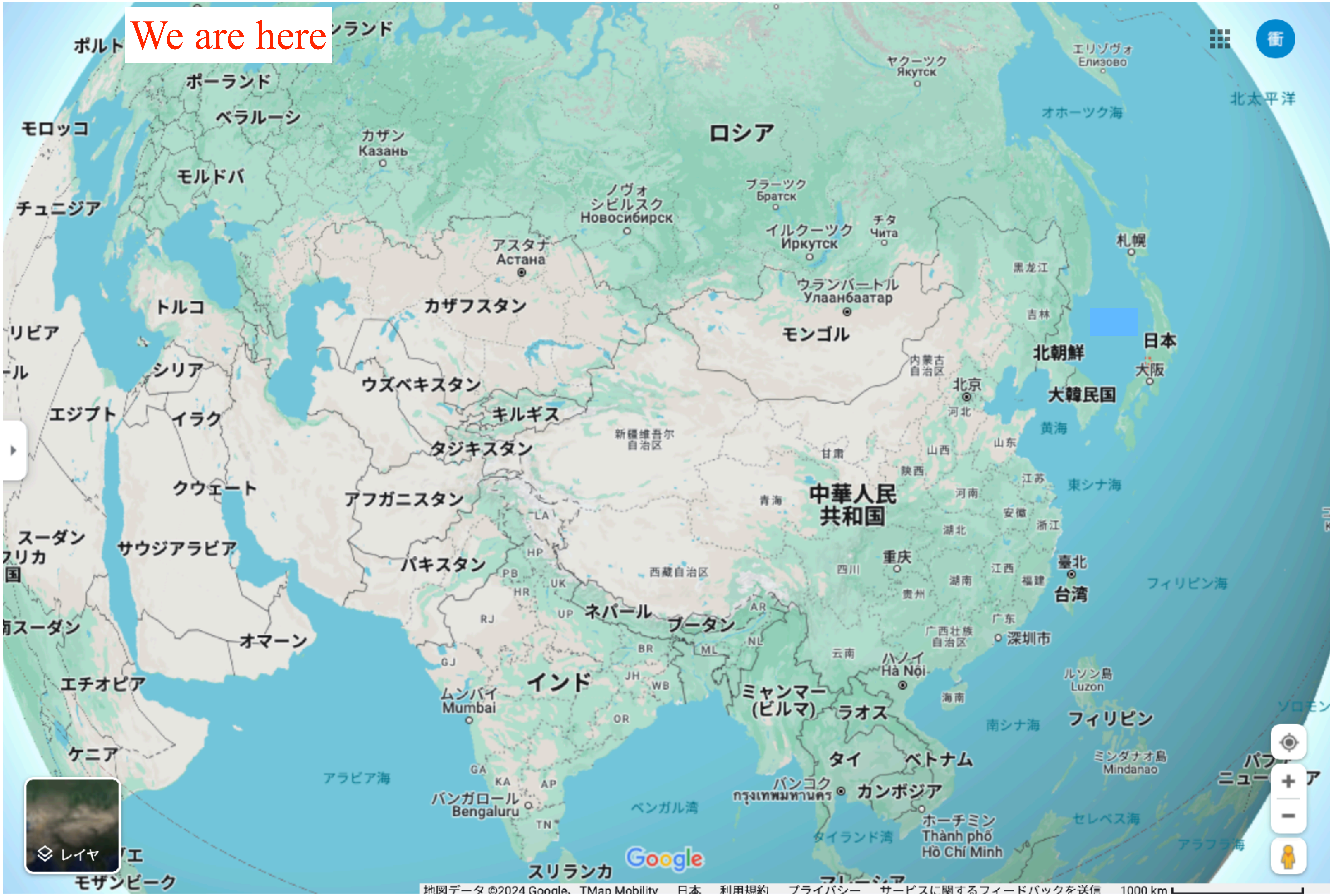
プライバシー
サービスに関するフィードバックを送信
1000 km



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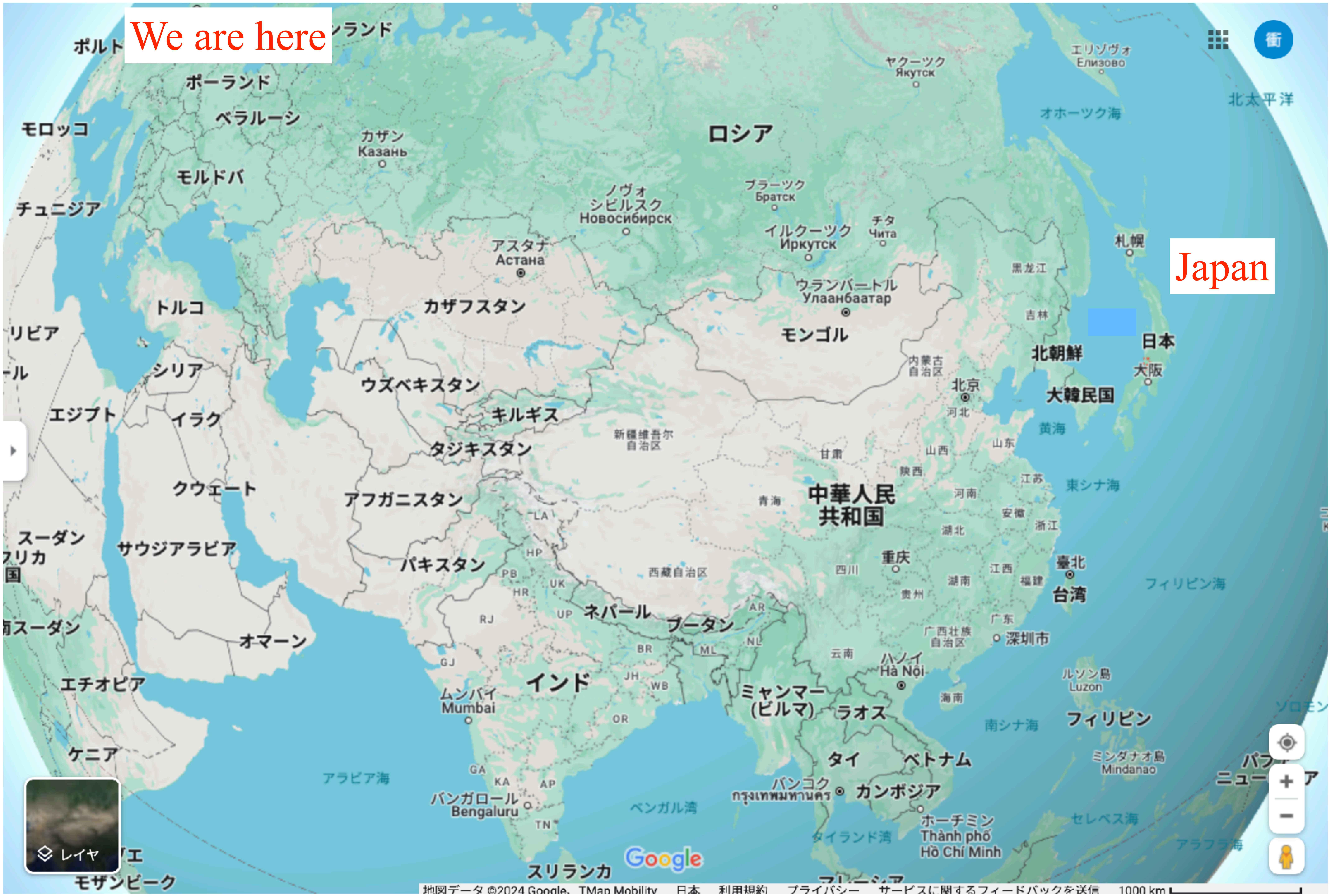

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Japan

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エリゾヴォ
Елизово
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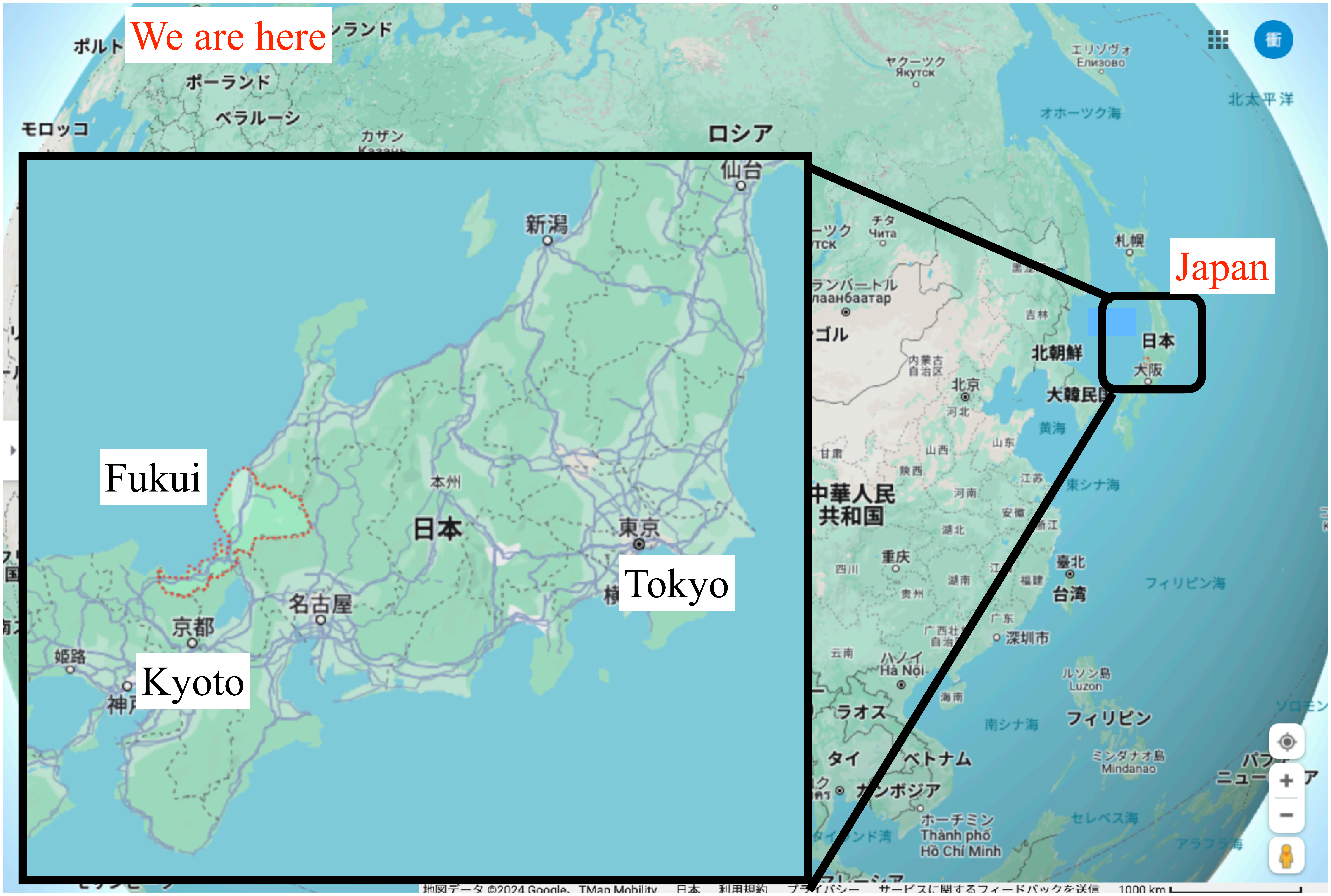

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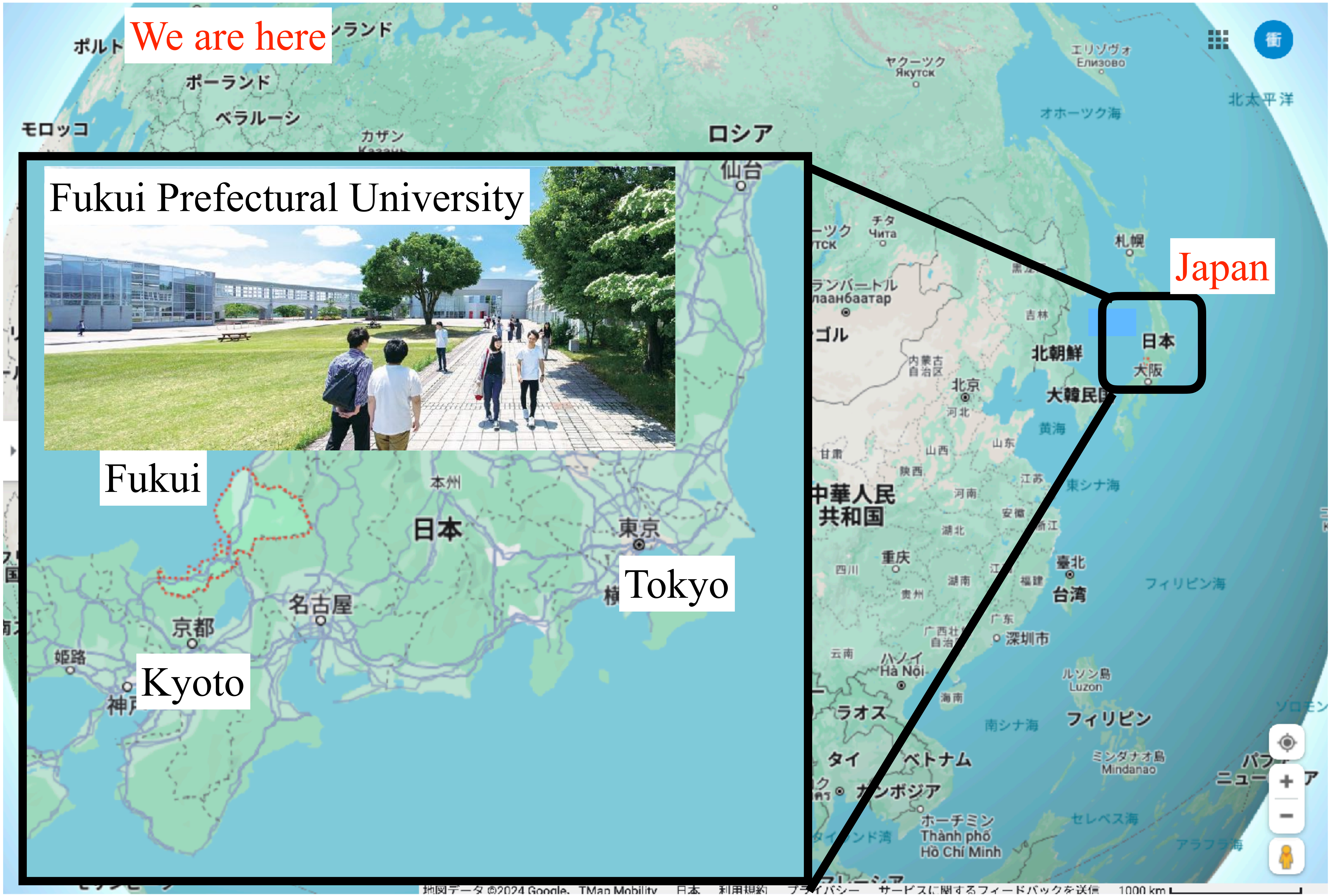
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We ar

Tojinbo

Fukui Pref

Fukui

Kyot

Eiheiji: The biggest Zen Buddhism temple in Japan

Japan

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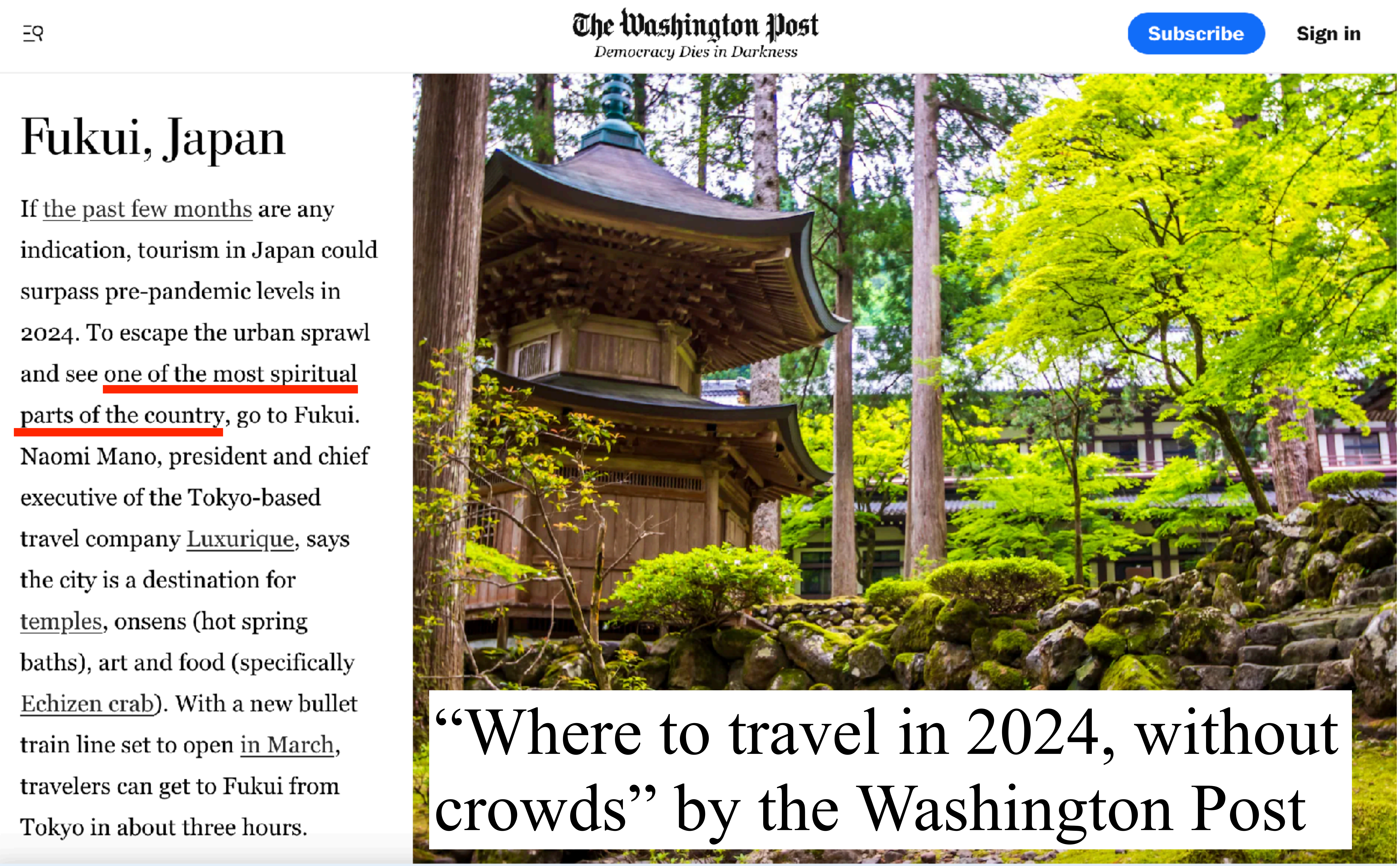
1000 km



The Washington Post
Democracy Dies in Darkness

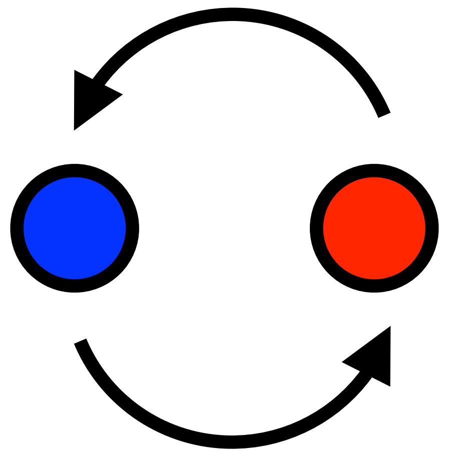
Fukui, Japan

If the past few months are any indication, tourism in Japan could surpass pre-pandemic levels in 2024. To escape the urban sprawl and see one of the most spiritual parts of the country, go to Fukui. Naomi Mano, president and chief executive of the Tokyo-based travel company Luxurique, says the city is a destination for temples, onsens (hot spring baths), art and food (specifically Echizen crab). With a new bullet train line set to open in March, travelers can get to Fukui from Tokyo in about three hours.

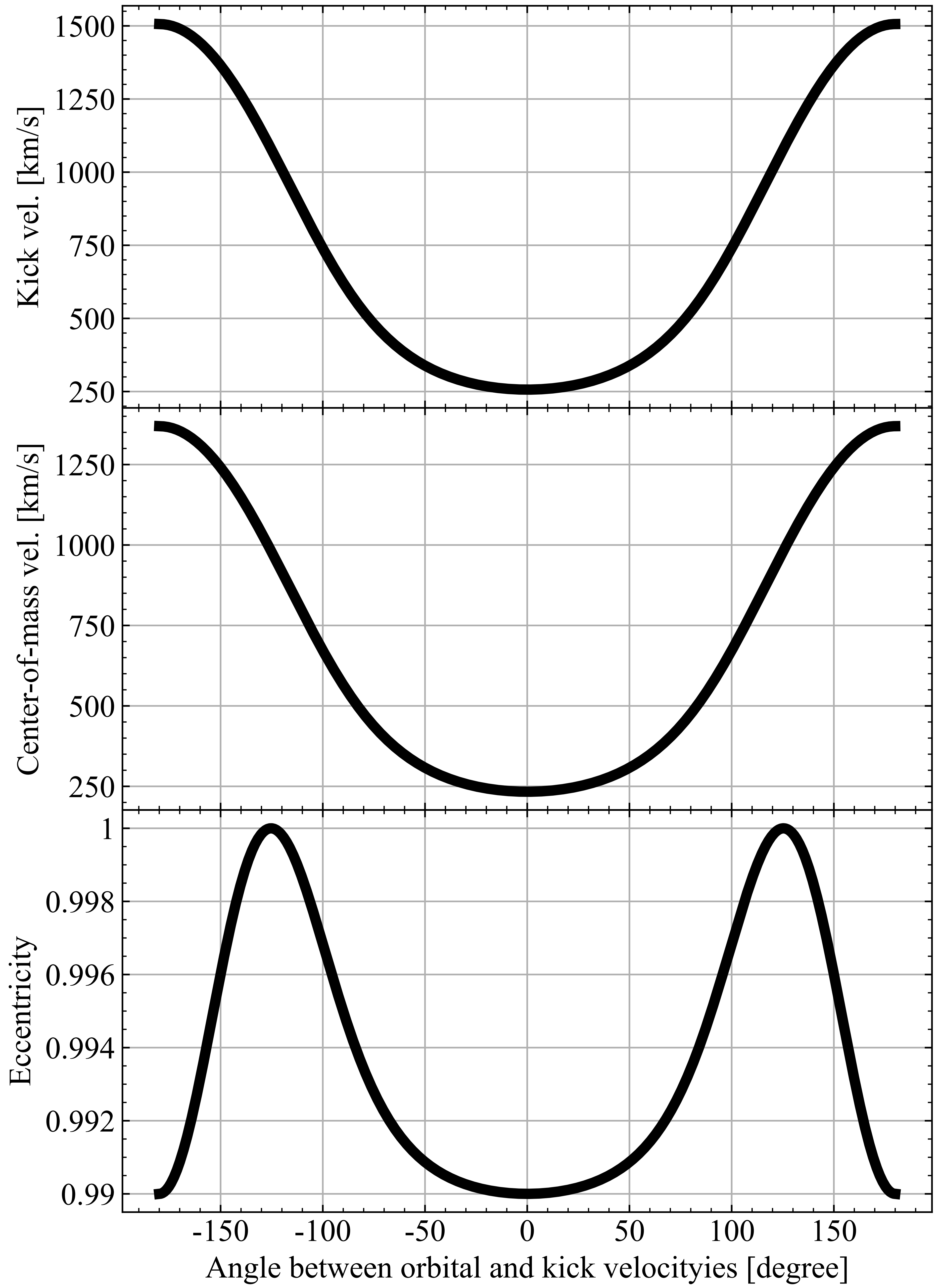
“Where to travel in 2024, without crowds” by the Washington Post

Eihei

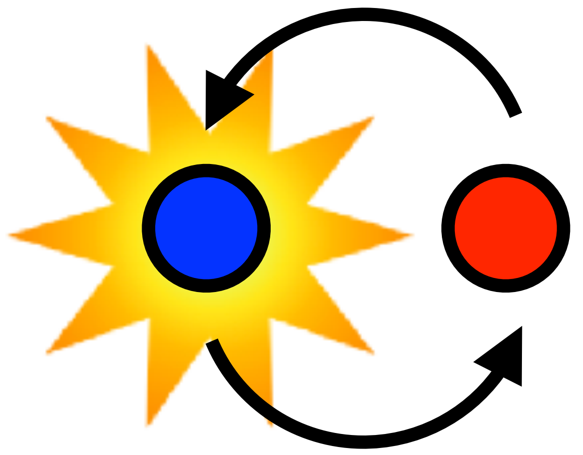
Natal kick?



- $m_1 = 10M_\odot$, $m_2 = 1M_\odot$
- $a_i = 0.025$ au, $e_i = 0 \Longrightarrow a_i = 2.5$ au
- Large kick velocity is needed ($v_\mathrm{k} \gtrsim 250$ km/s).
- Center-of-mass velocity exceeds ~ 250 km/s.
  - Inconsistent with the fact that Gaia BHs are the Galactic disk components.
- Eccentricity is quite high ($\gtrsim 0.99$).
  - Inconsistent with moderate eccentricities of Gaia BHs (~ 0.5).



Natal kick?



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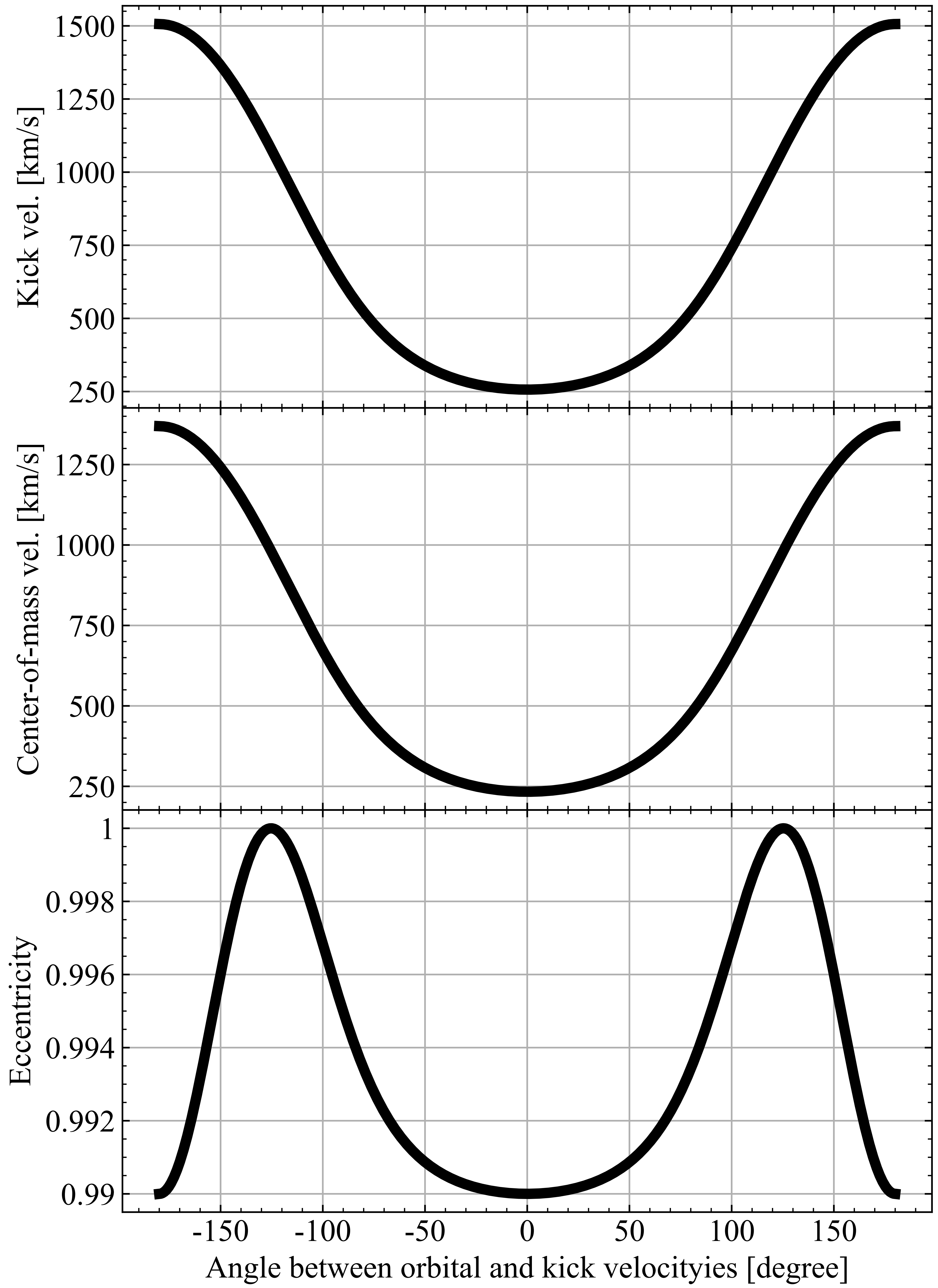
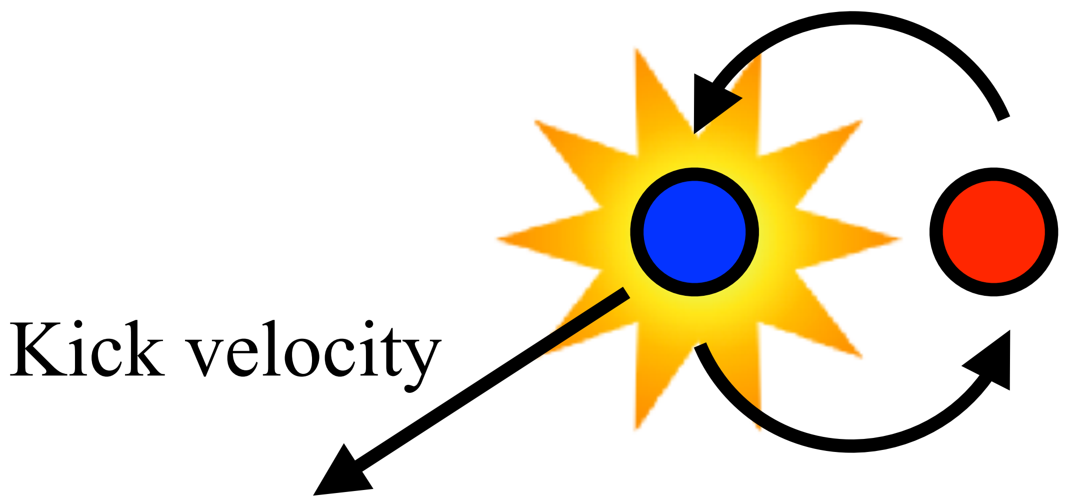


Natal kick?



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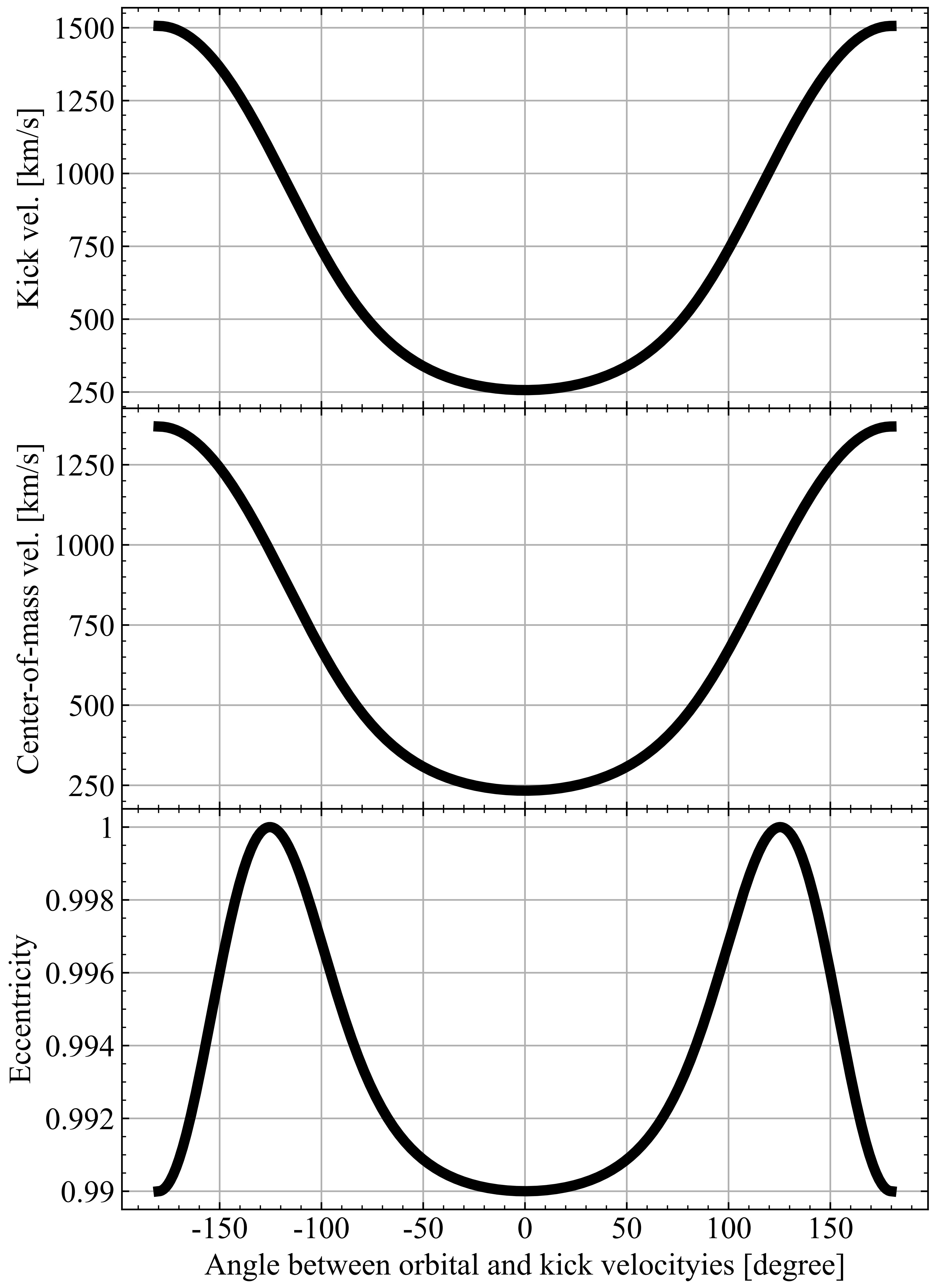
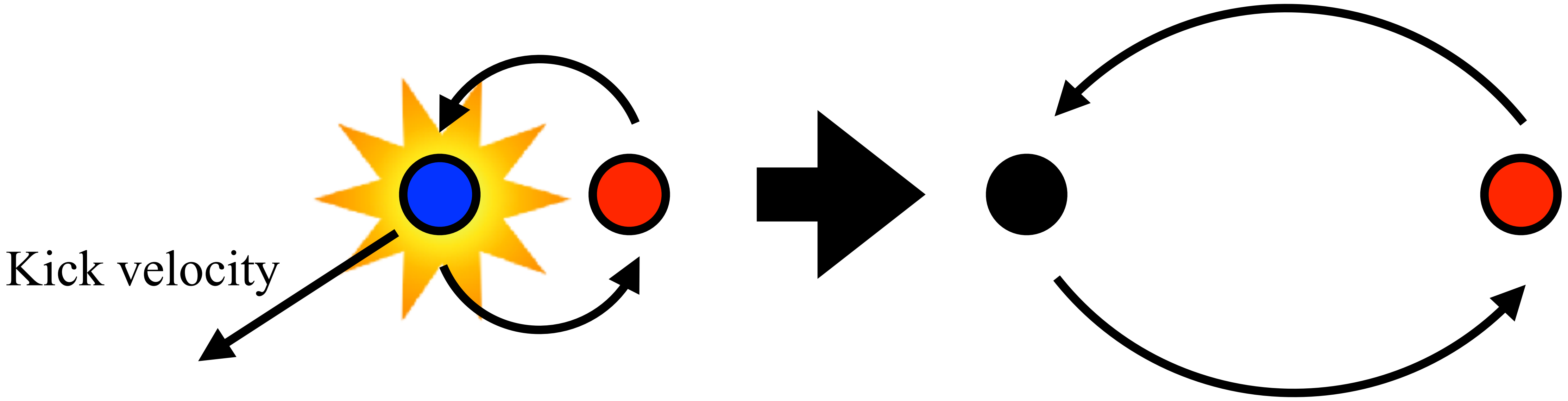


Natal kick?



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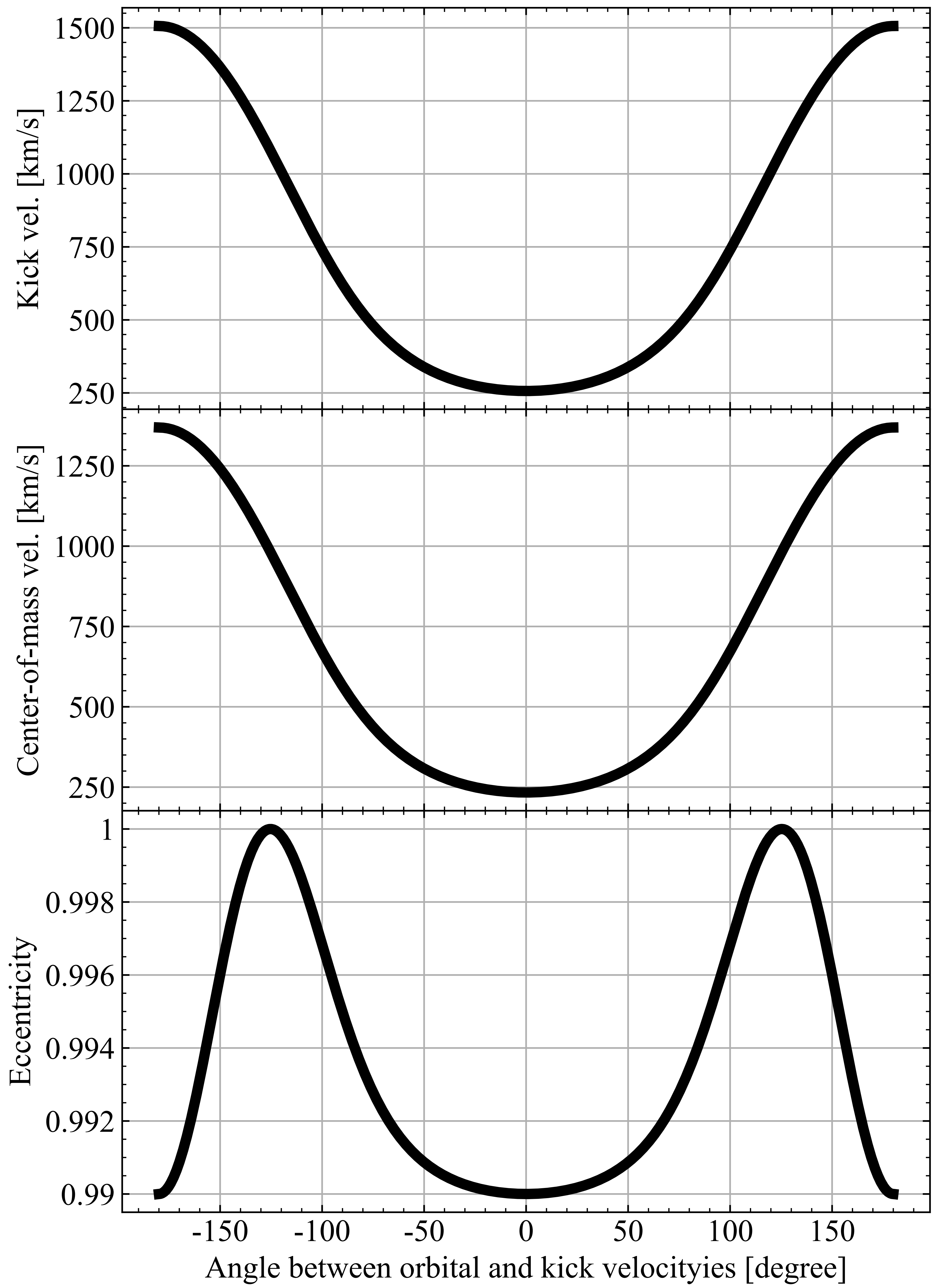
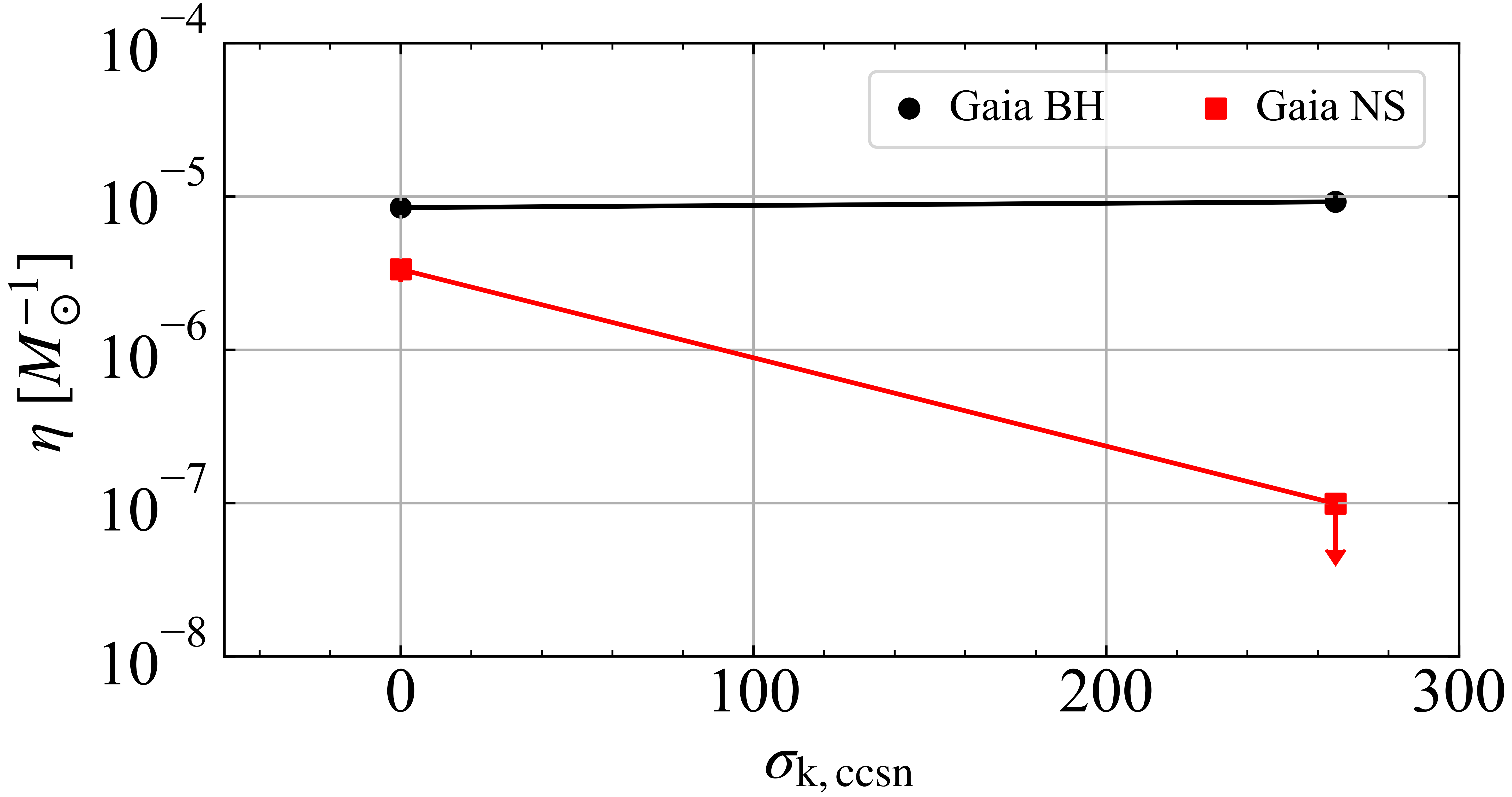


The number of Gaia BHs captured by PBHs

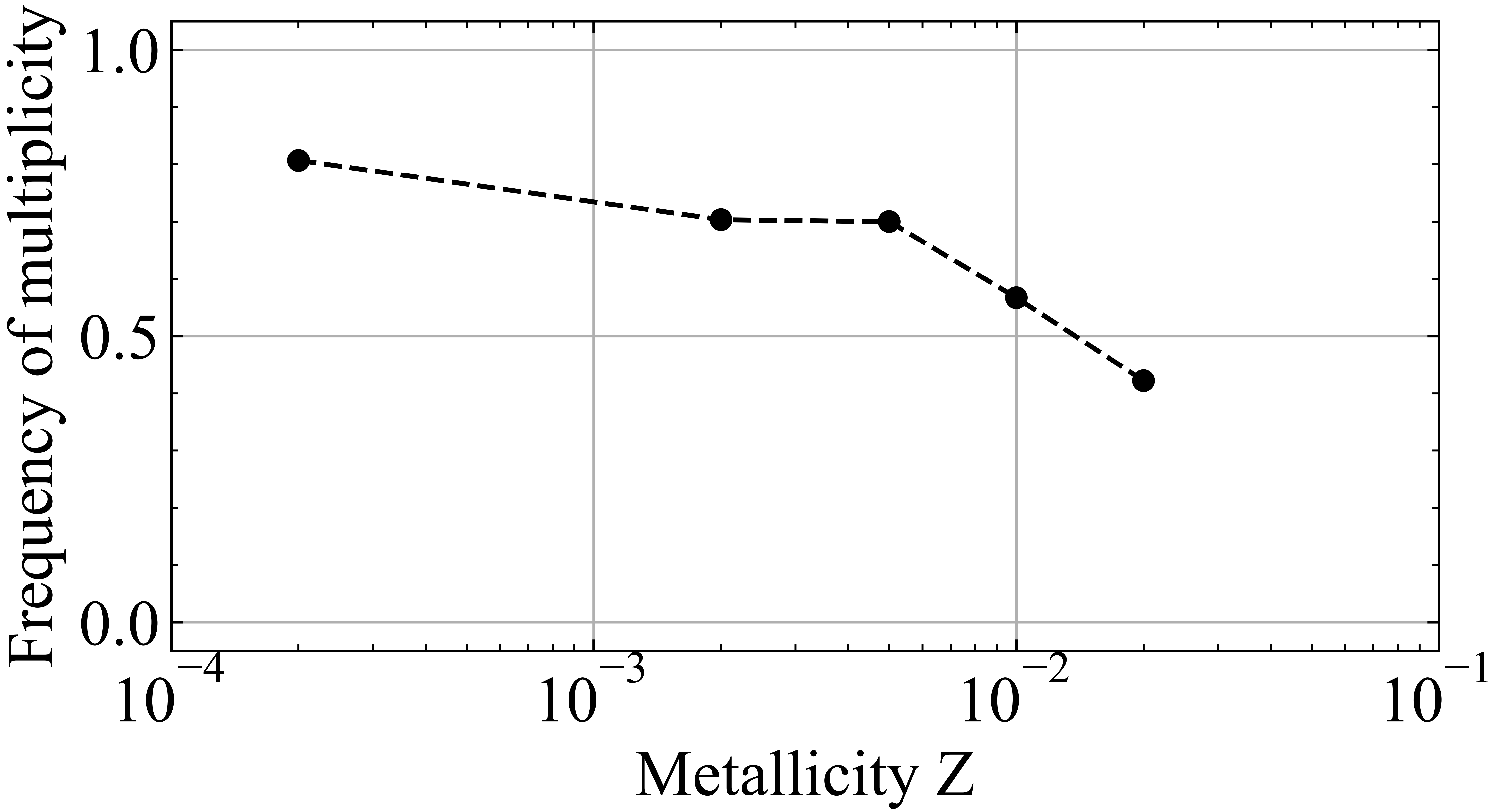
- $N_{\mathrm{GBH}} = N_{\mathrm{PBH}} n_{\mathrm{star}} \sigma v \mathrm{T}$
- $N_{\mathrm{PBH}} \sim 2 \times 10^{3} \left(\frac{M_{\mathrm{DM}}}{2 \times 10^{11} M_{\odot}}\right) \left(\frac{M_{\mathrm{PBH}}}{10 M_{\odot}}\right)^{-1} \left(\frac{f_{\mathrm{PBH}}}{10^{-3}}\right) \left(\frac{f_{\mathrm{disk}}}{10^{-3}}\right) \left(\frac{f_{\mathrm{corotate}}}{0.1}\right)$
- $n_{\mathrm{star}} \sim 2\ \mathrm{pc}^{-3} \left(\frac{M_{\mathrm{disk}}}{6 \times 10^{10} M_{\odot}}\right) \left(\frac{M_{\mathrm{star}}}{1 M_{\odot}}\right)^{-1} \left(\frac{R_{\mathrm{disk}}}{10\mathrm{kpc}}\right)^{-2} \left(\frac{h_{\mathrm{disk}}}{100\mathrm{pc}}\right)^{-1}$
- $\sigma = \pi a^{2} \left(\cancel{1} + \frac{G(M_{\mathrm{PBH}} + M_{\mathrm{star}})}{a v^{2}}\right) \sim 5.8 \times 10^{-10}\ \mathrm{pc}^{2} \left(\frac{M_{\mathrm{PBH}} + M_{\mathrm{star}}}{11 M_{\odot}}\right) \left(\frac{a}{1\mathrm{au}}\right)^{-1} \left(\frac{v}{50\mathrm{km/s}}\right)^{-2}$
- $N_{\mathrm{GBH}} \sim 1 \left(\frac{N_{\mathrm{PBH}}}{2 \times 10^{3}}\right) \left(\frac{n_{\mathrm{star}}}{2\mathrm{pc}^{-3}}\right) \left(\frac{\sigma}{5.8 \times 10^{-10}\mathrm{pc}^{2}}\right) \left(\frac{v}{50\mathrm{km/s}}\right) \left(\frac{T}{10\mathrm{Gyr}}\right)$

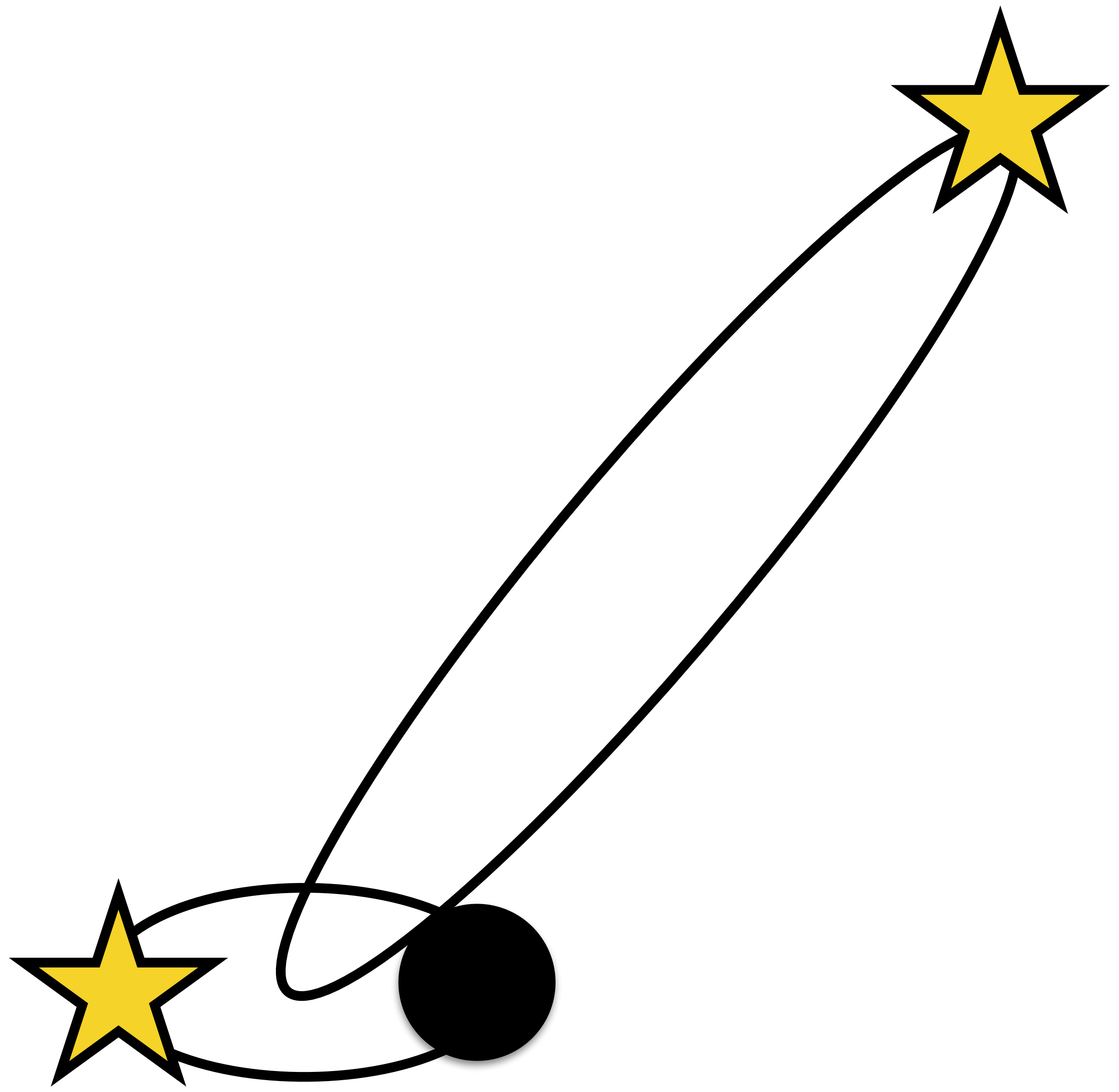
No natal kick model

- 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.

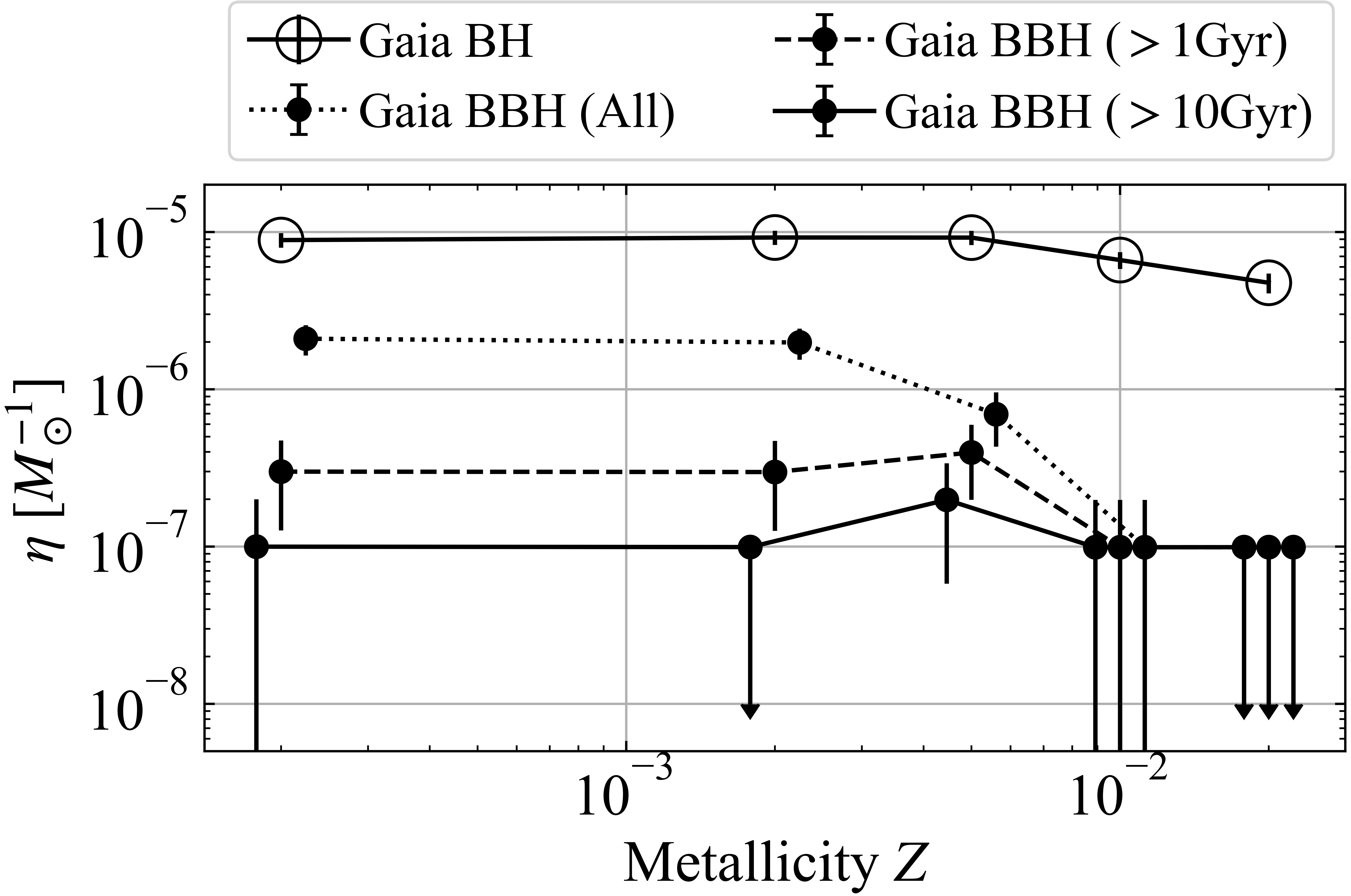


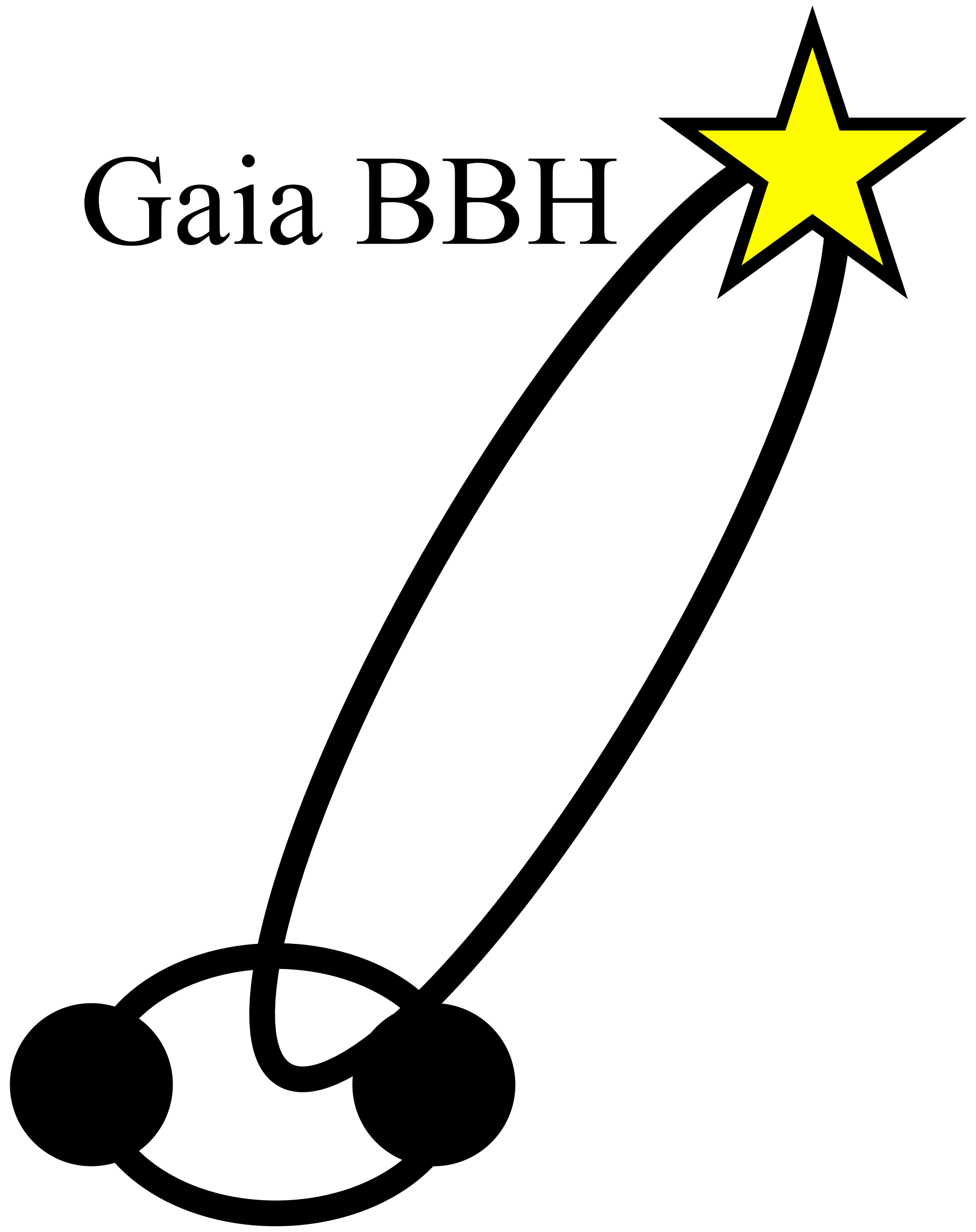
Frequency of 3rd stars



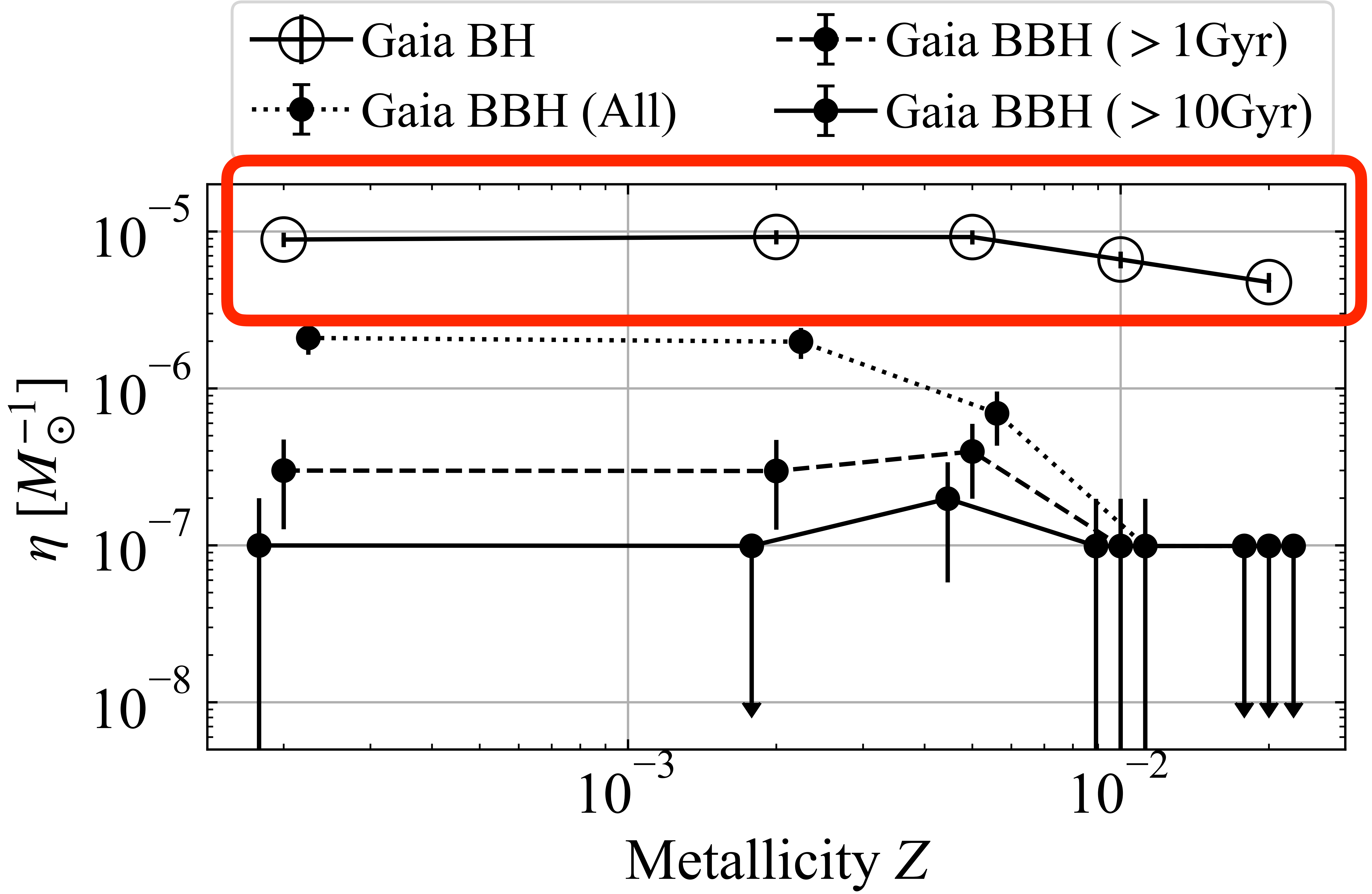


Fraction of Gaia BBHs

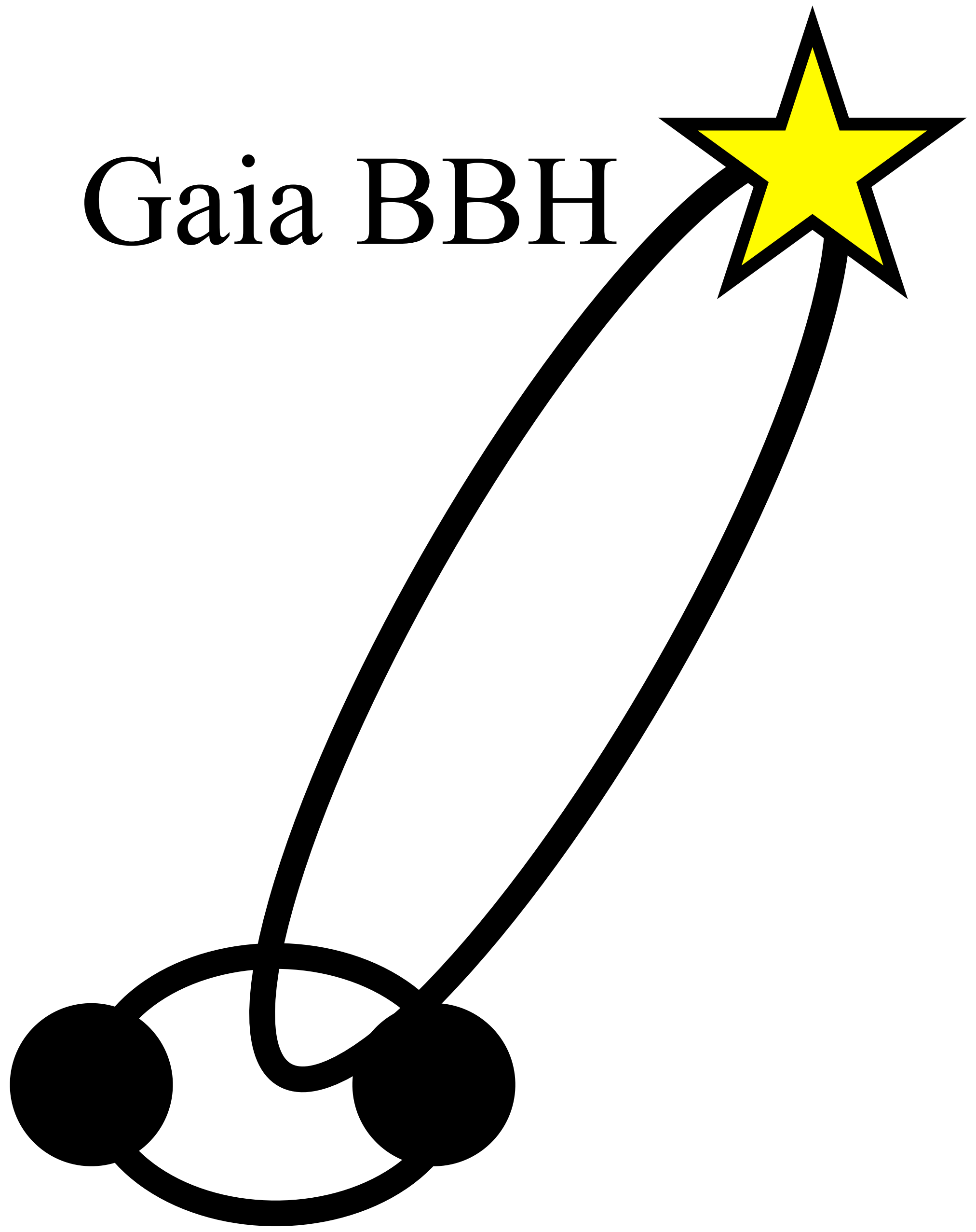




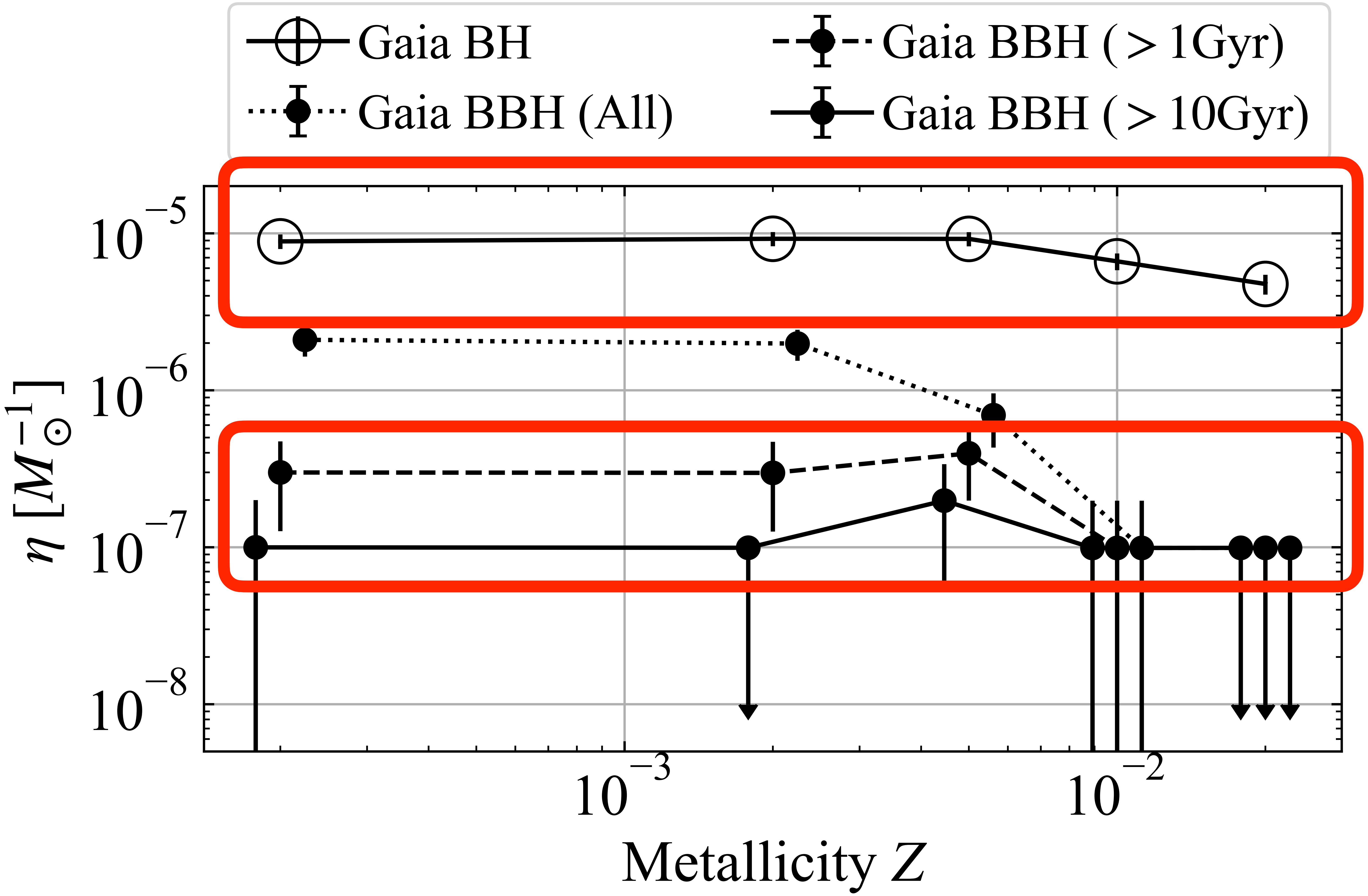
Fraction of Gaia BBHs



Gaia BHs

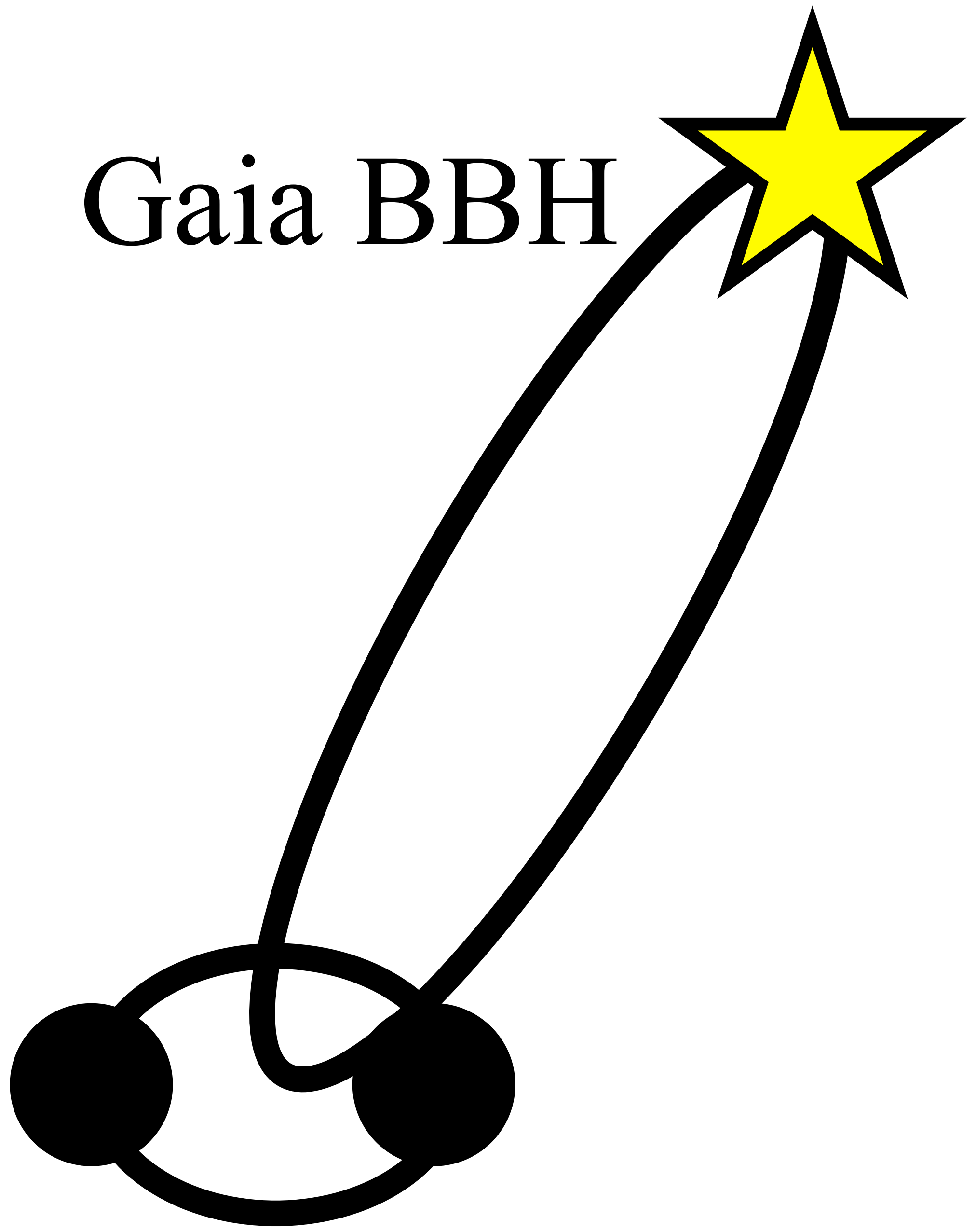


Fraction of Gaia BBHs

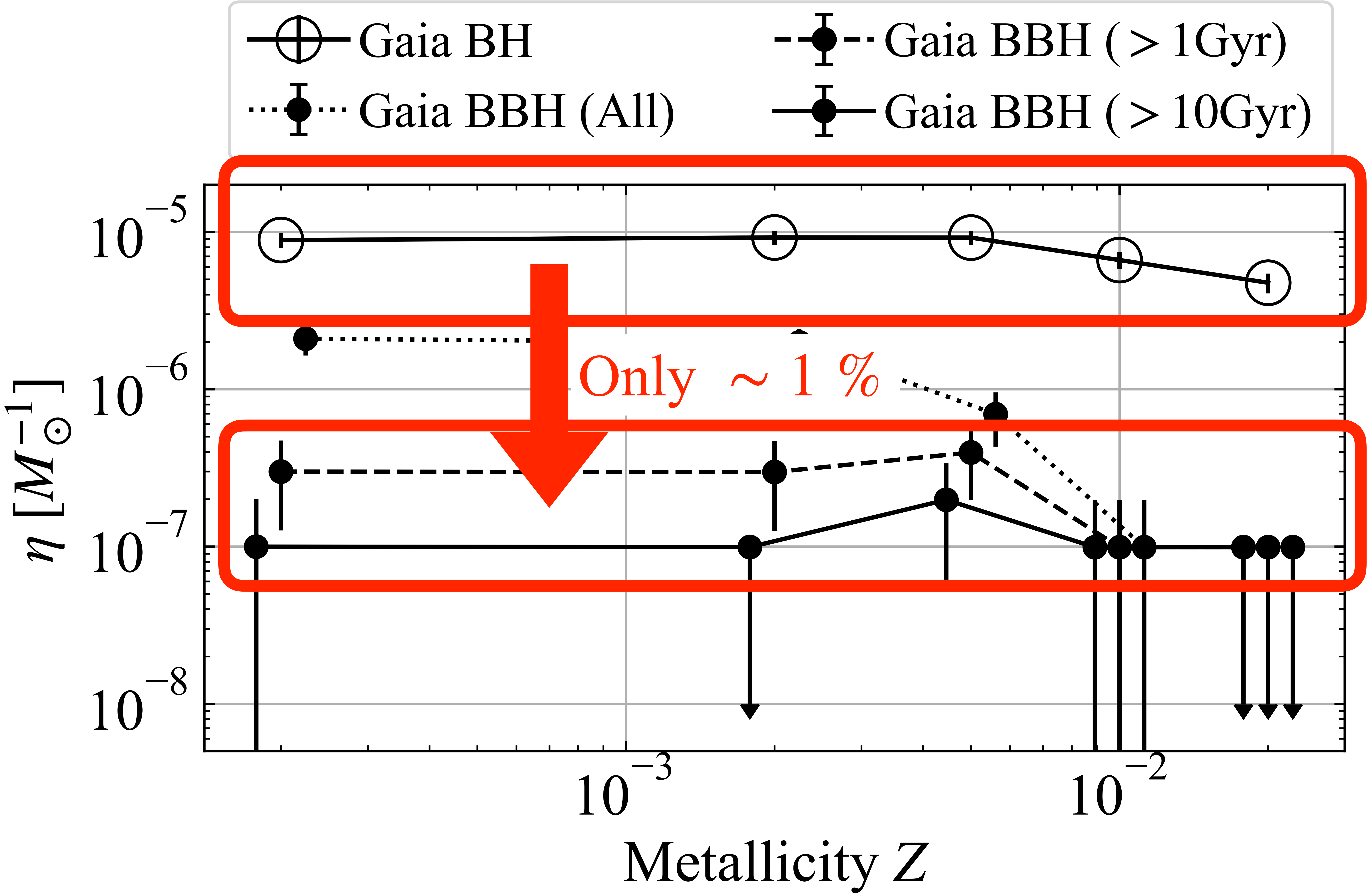


Gaia BHs

Observable
(long-lived)
Gaia BBHs



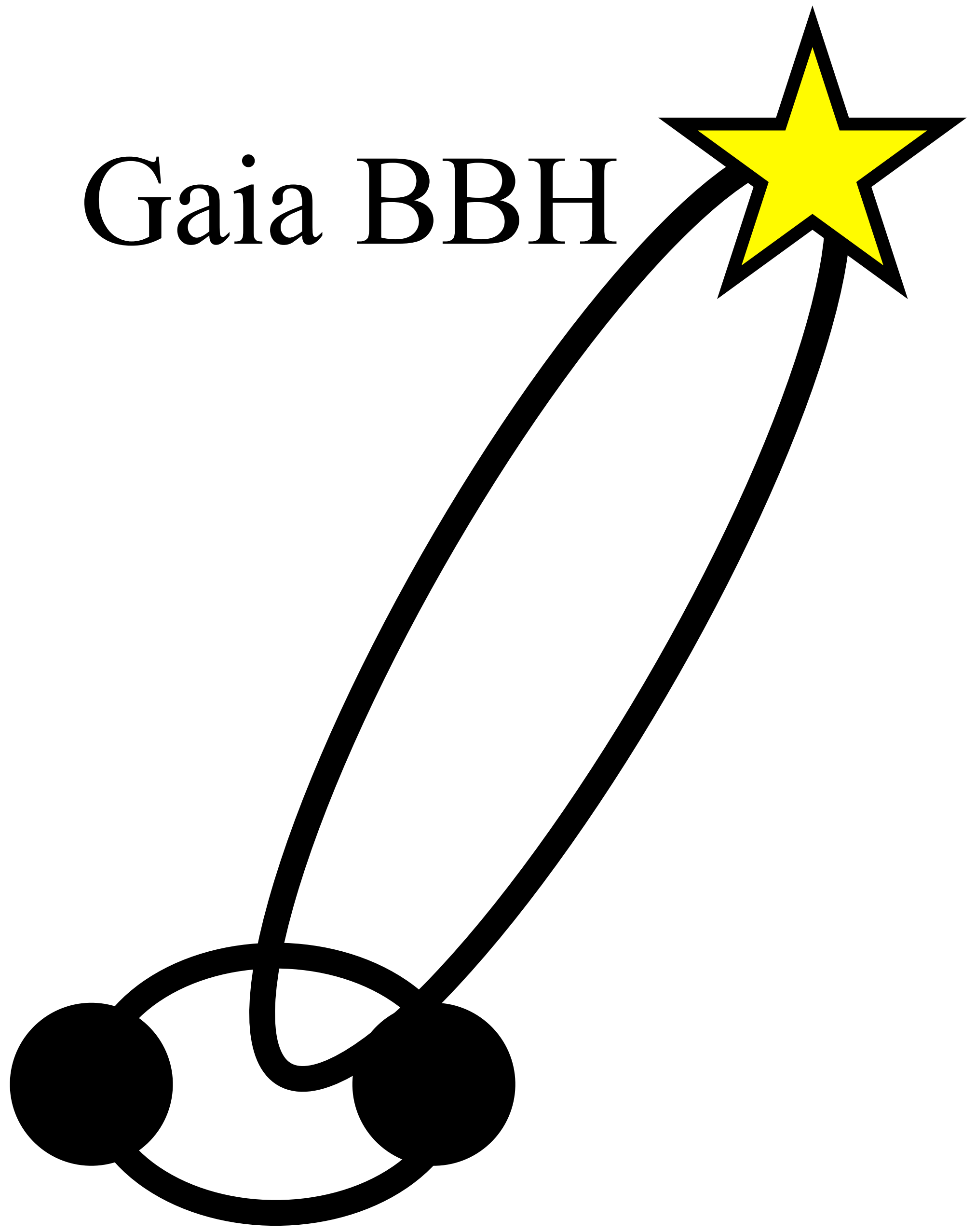
Fraction of Gaia BBHs

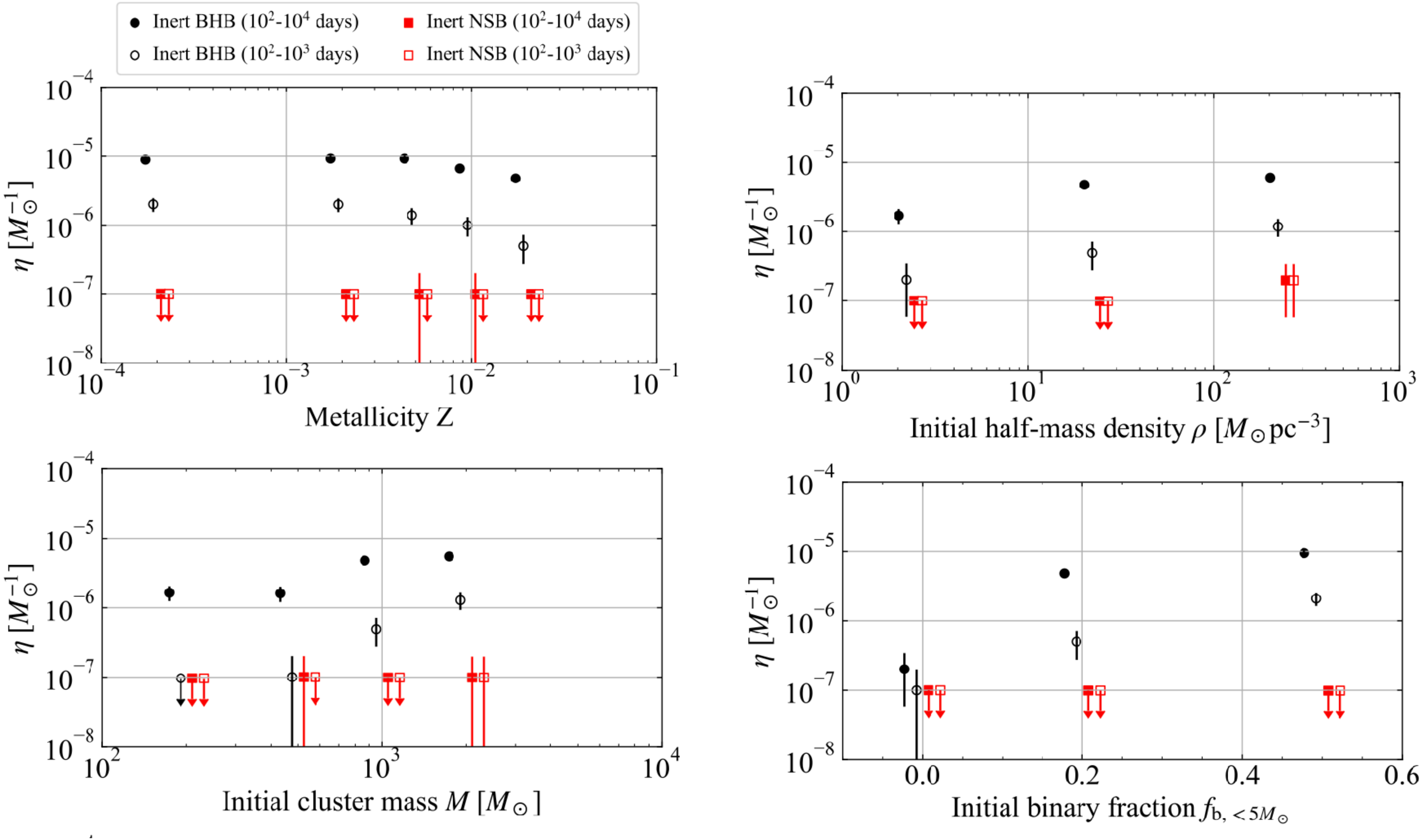


Only ~ 1 %

Gaia BHs

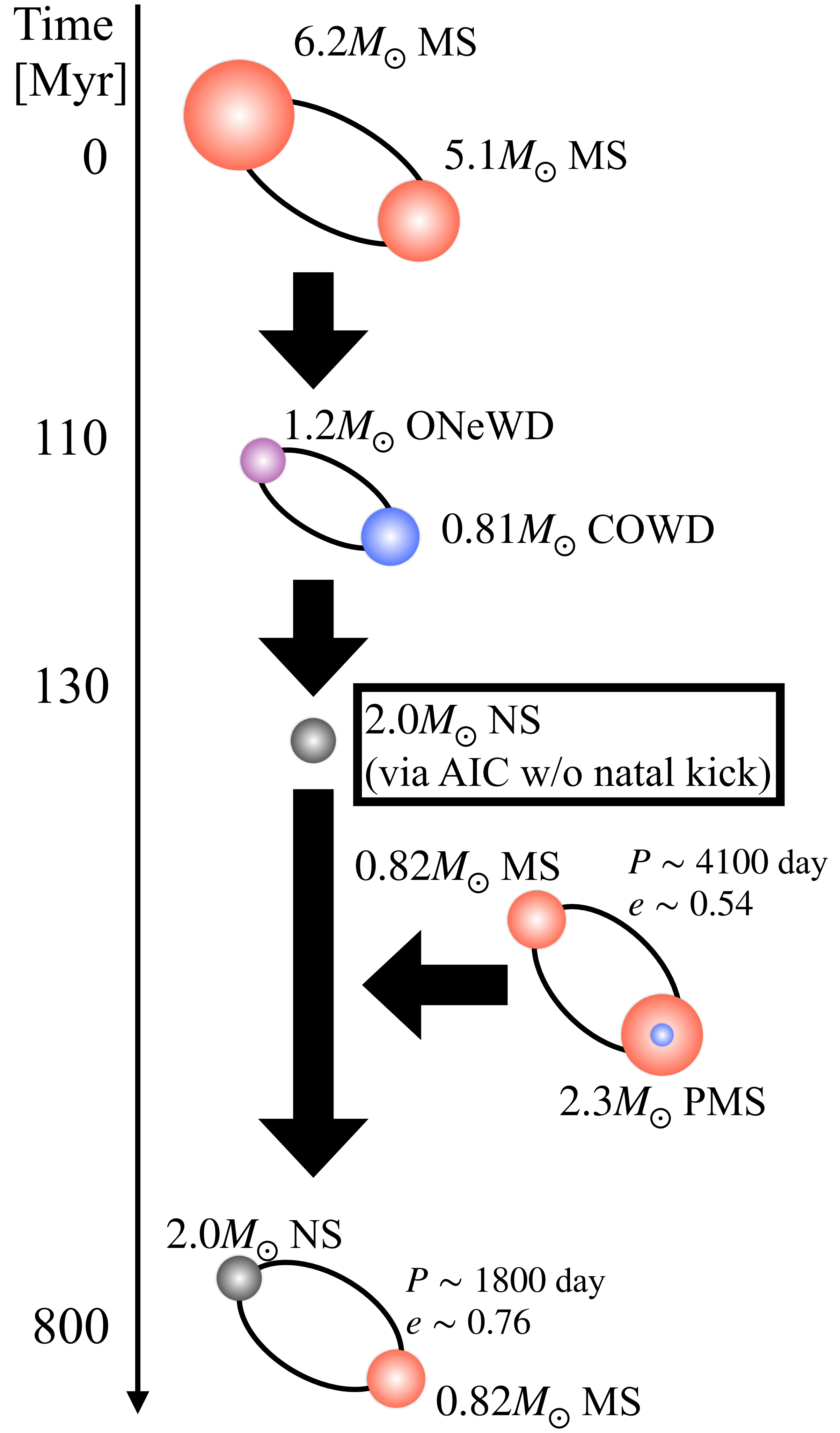
Observable (long-lived) Gaia BBHs




● Inert BHB (10^2-10^4 days)
○ Inert BHB (10^2-10^3 days)
■ Inert NSB (10^2-10^4 days)
□ Inert NSB (10^2-10^3 days)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$\eta\ [M_\odot^{-1}]$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Metallicity Z
10^{0}
10^{1}
10^{2}
10^{3}
Initial half-mass density $\rho\ [M_\odot \mathrm{pc}^{-3}]$
10^{2}
10^{3}
10^{4}
Initial cluster mass $M\ [M_\odot]$
0.0
0.2
0.4
0.6
Initial binary fraction $f_{\mathrm{b},<5M_\odot}$

Formation channel of Gaia NS

AIC channel



Time [Myr]

0

$6.2M_\odot$ MS

$5.1M_\odot$ MS

110

$1.2M_\odot$ ONeWD

$0.81M_\odot$ COWD

130

$2.0M_\odot$ NS
(via AIC w/o natal kick)

$0.82M_\odot$ MS

$P \sim 4100$ day
$e \sim 0.54$

$2.3M_\odot$ PMS

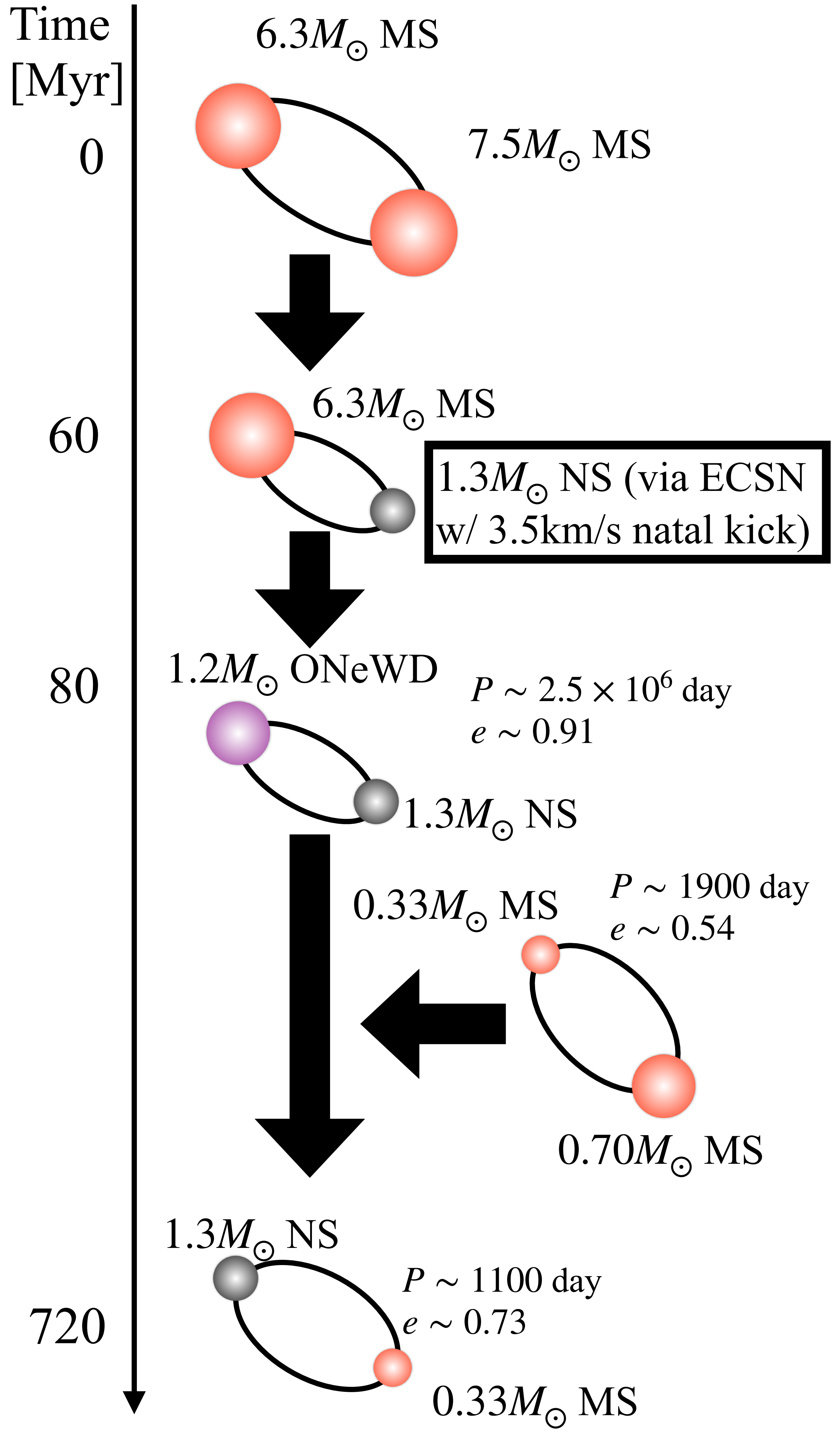
800

$2.0M_\odot$ NS

$P \sim 1800$ day
$e \sim 0.76$

$0.82M_\odot$ MS

ECSN channel



Time [Myr]

0

$6.3M_\odot$ MS

$7.5M_\odot$ MS

60

$6.3M_\odot$ MS

$1.3M_\odot$ NS (via ECSN
w/ 3.5km/s natal kick)

80

$1.2M_\odot$ ONeWD

$P \sim 2.5 \times 10^6$ day
$e \sim 0.91$

$1.3M_\odot$ NS

$0.33M_\odot$ MS

$P \sim 1900$ day
$e \sim 0.54$

$0.70M_\odot$ MS

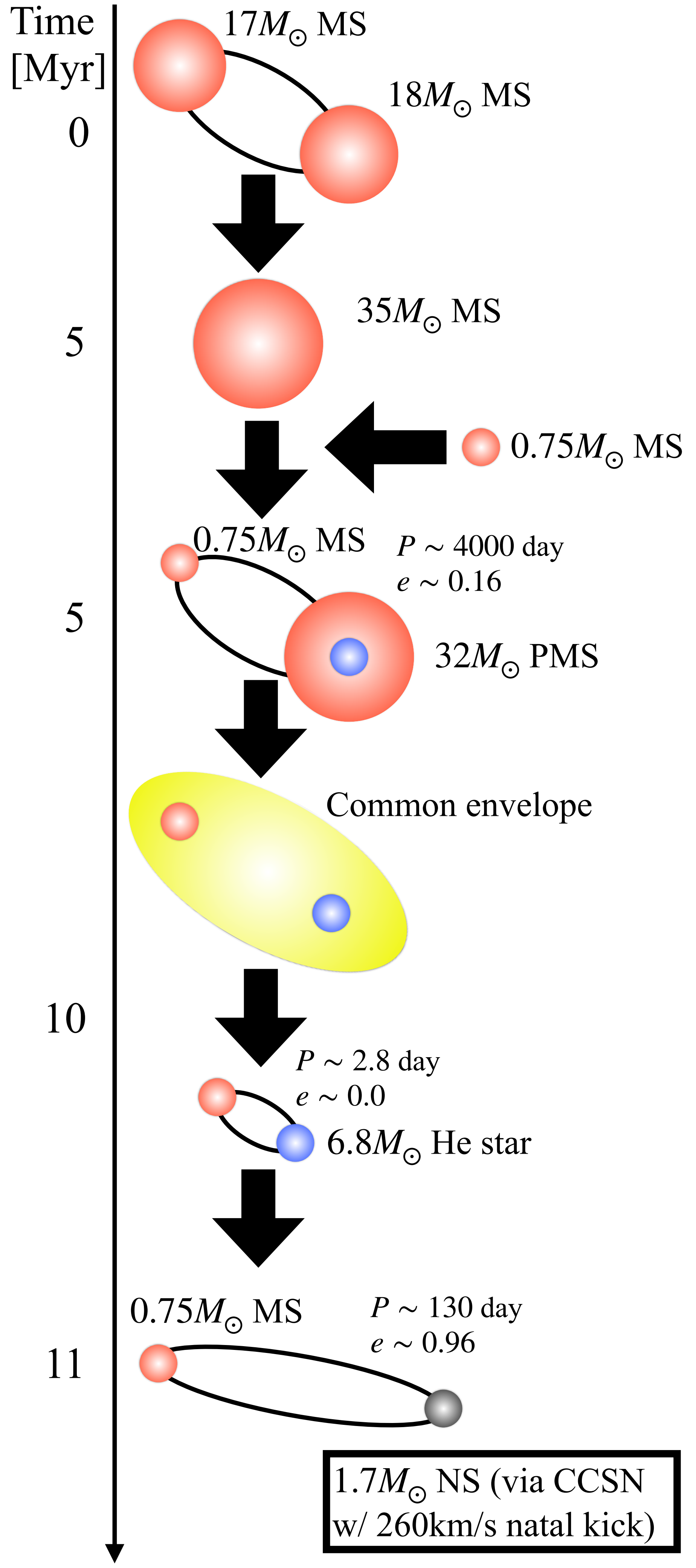
720

$1.3M_\odot$ NS

$P \sim 1100$ day
$e \sim 0.73$

$0.33M_\odot$ MS

CCSN channel



Time [Myr]

0

$17M_\odot$ MS

$18M_\odot$ MS

5

$35M_\odot$ MS

$0.75M_\odot$ MS

5

$0.75M_\odot$ MS

$P \sim 4000$ day
$e \sim 0.16$

$32M_\odot$ PMS

Common envelope

10

$P \sim 2.8$ day
$e \sim 0.0$

$6.8M_\odot$ He star

11

$0.75M_\odot$ MS

$P \sim 130$ day
$e \sim 0.96$

$1.7M_\odot$ NS (via CCSN
w/ 260km/s natal kick)