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Dynamical Origin of *Gaia* BH1 in a Young Star Cluster

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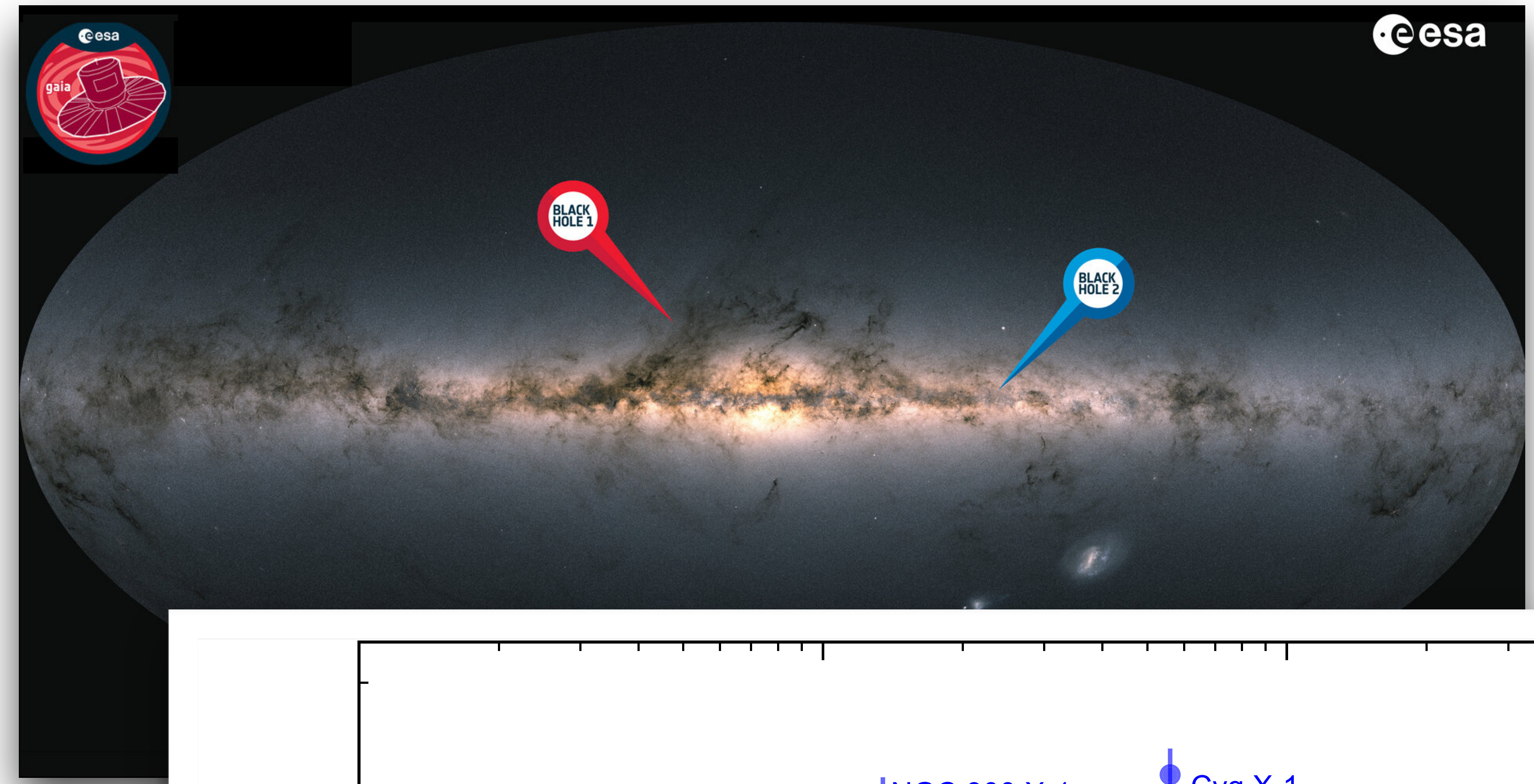
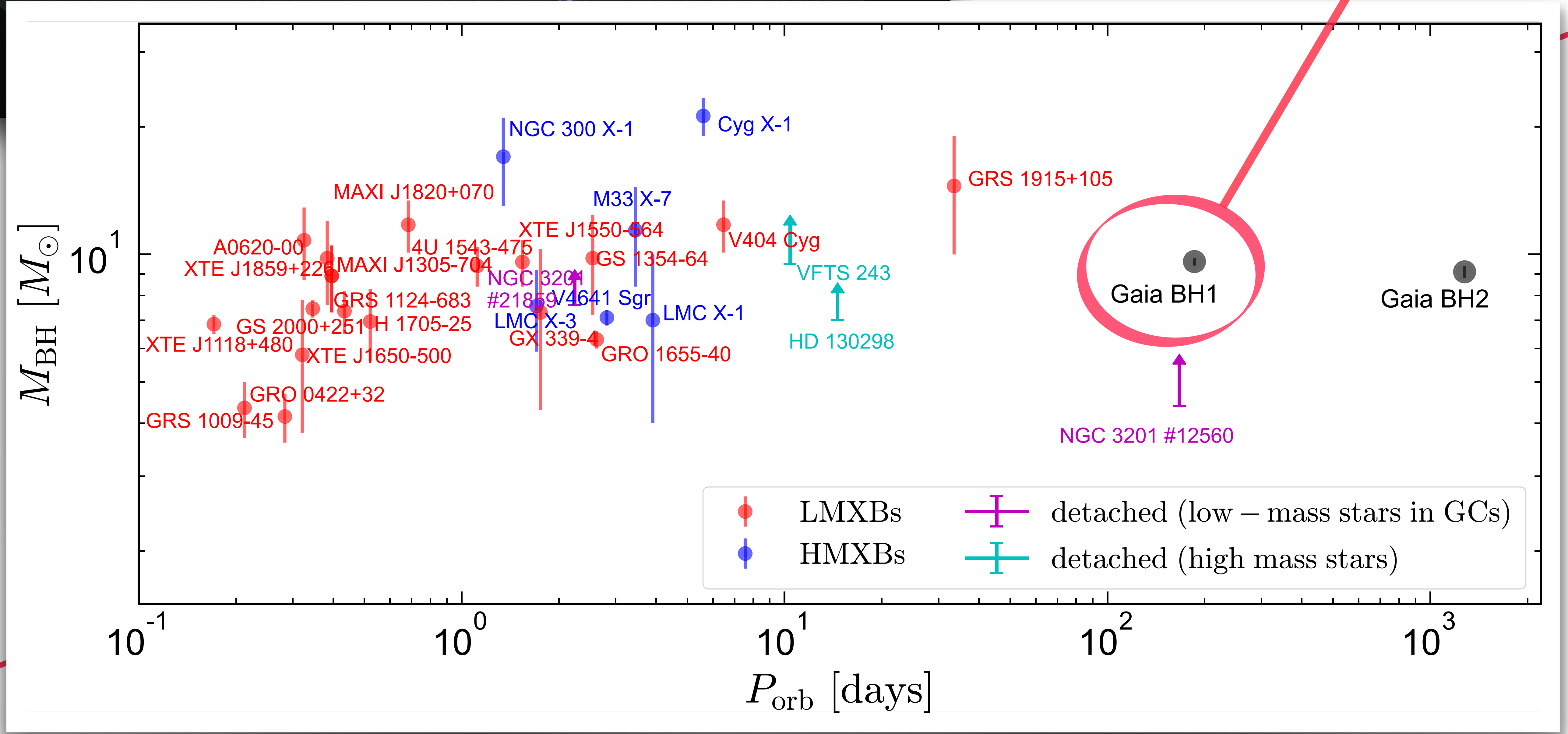
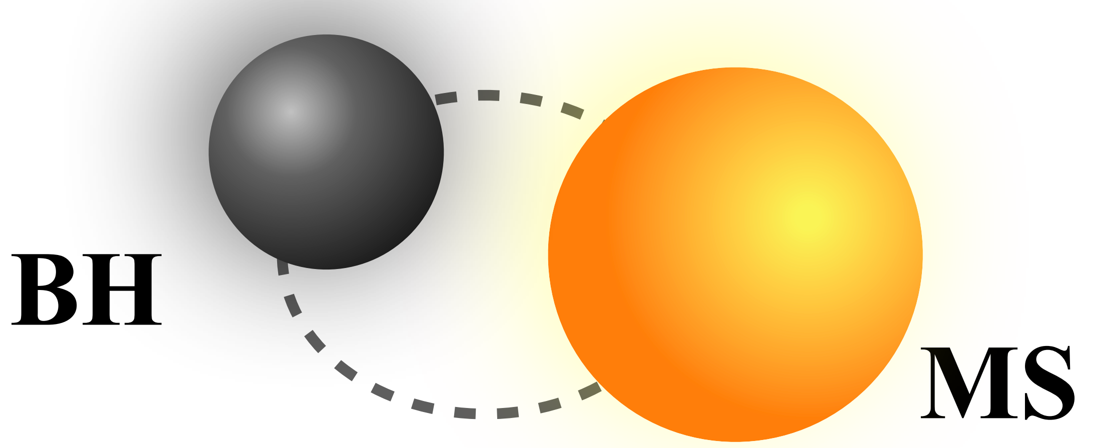
Gaia-BH1

Gaia BH1 : The first Galactic dormant BH detected by *Gaia (DR3)*







El-Badry et al., 2023a,b

Gaia-BH1

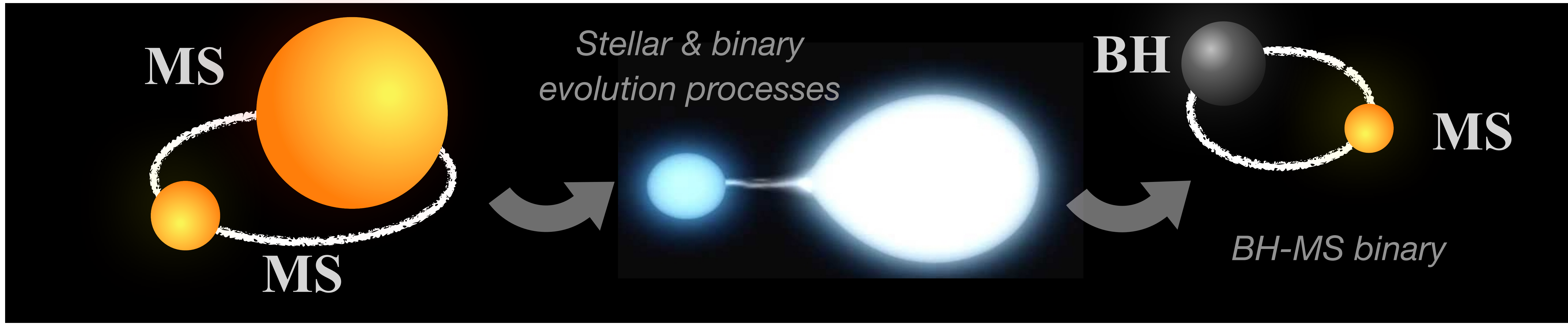
$m_{BH} \sim 9.6\ M_\odot$ $\quad e \sim 0.45$

$m_{MS} \sim 0.93\ M_\odot$ $\quad P \sim 185.6$ days

$q = m_2/m_1 \sim 0.1$ $\quad$ (Fe/H = -0.2)

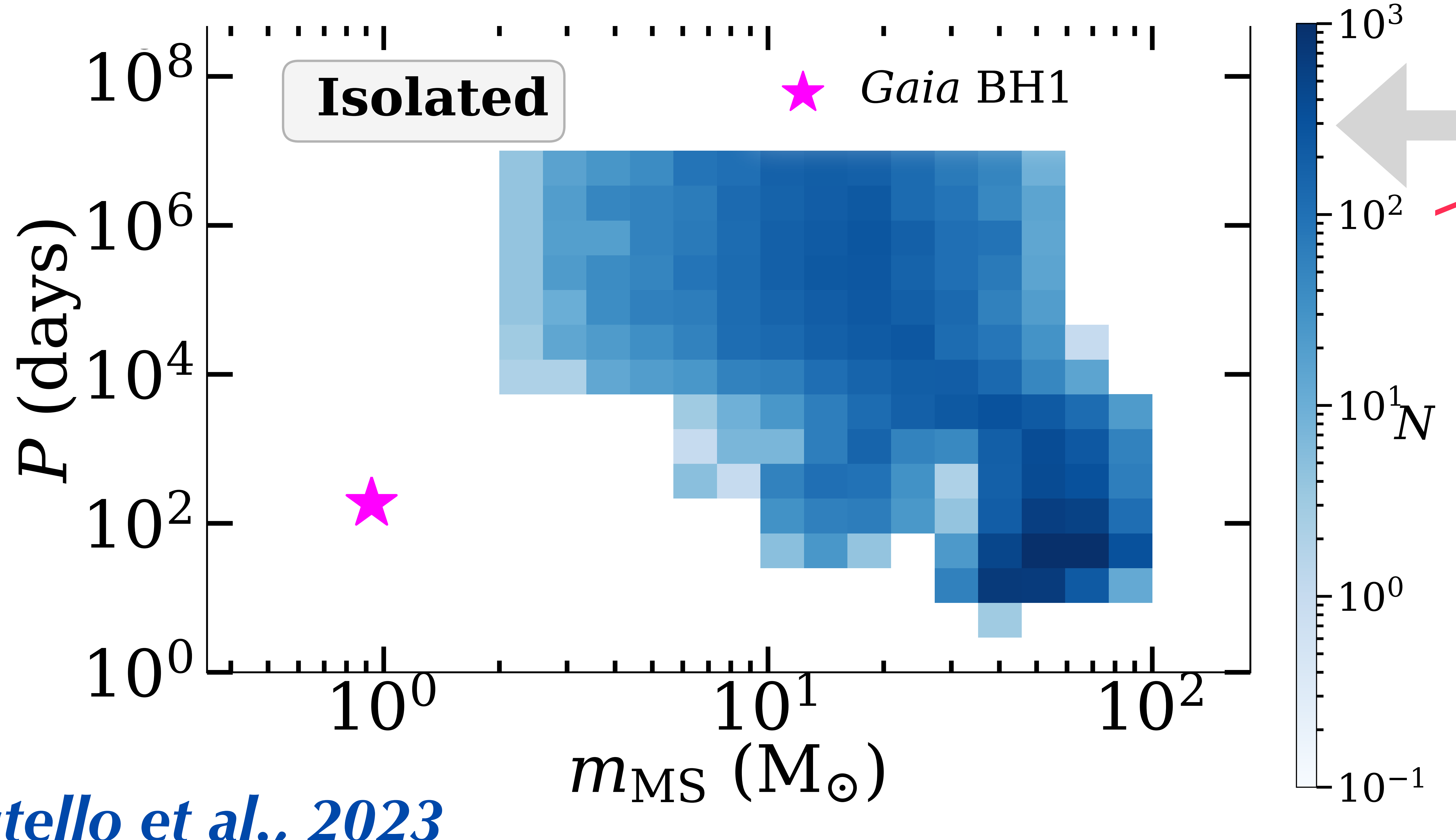
How does it form?

Isolated Binaries



PRIMORDIAL ISOLATED BINARIES in the field

NB: Requires extreme initial mass ratio $q = m_2/m_1 \sim 0.01 - 0.05$ & high CE eff. to form *Gaia* BH1



Rastello et al., 2023

If $q_{\rm min} = \mathbf{m_2/m_1 \sim 0.1}$
$\eta_{\rm ISO} = N_{\rm BH1} / m^{\rm tot*} \sim 0\ M_\odot^{-1}$

If $q_{\rm min}$ assumption is relaxed
$\eta_{\rm ISO} < 10^{-9}\ M_\odot^{-1}$

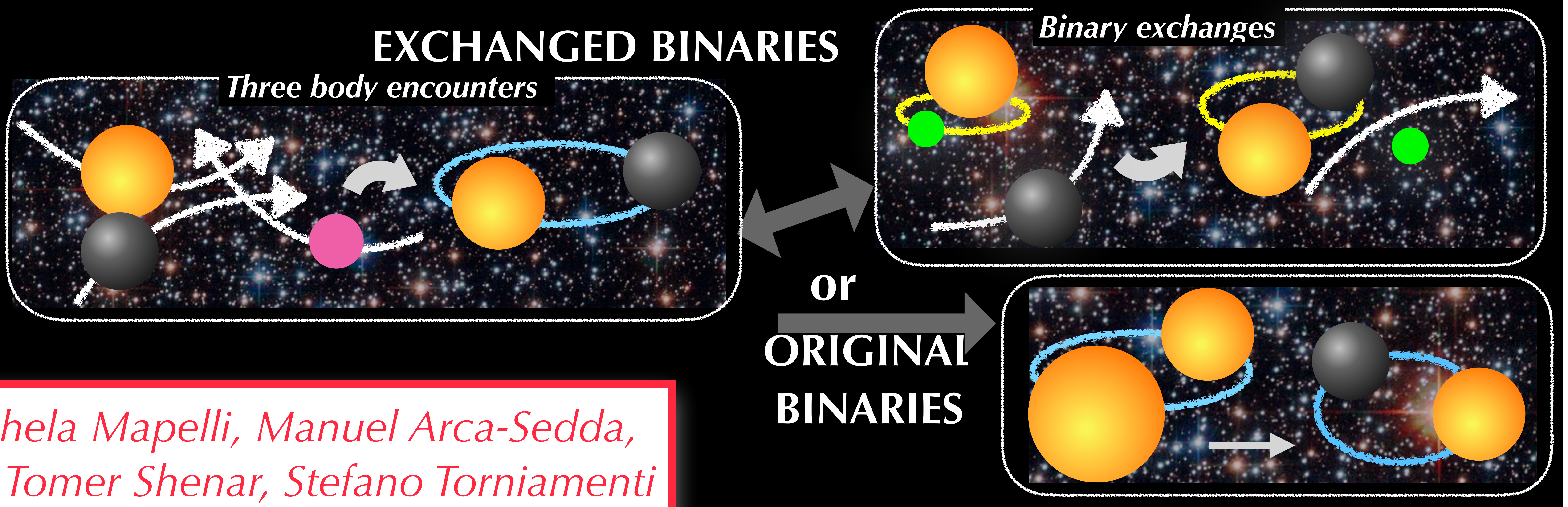
Challenge to form *Gaia* BH1 in ISOLATION

El Badry et al., 2023a,b; Tanikawa et al., 2023; Di Carlo et al., 2023

Dynamical Binaries

DYNAMICAL BINARIES in dense star clusters

(Exchanged & original binaries)



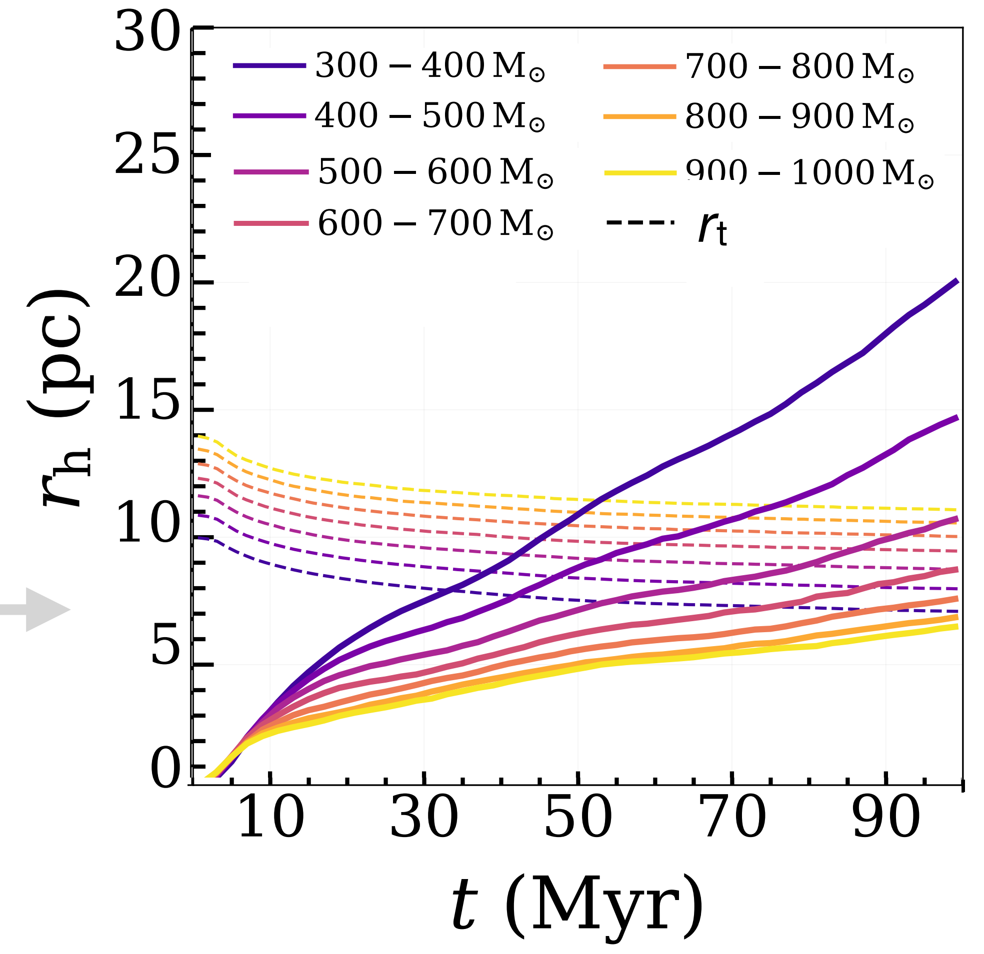
Sara Rastello, *Giuliano Iorio, Michela Mapelli, Manuel Arca-Sedda, Ugo N. Di Carlo, Gastón J. Escobar, Tomer Shenar, Stefano Torniamenti*

2023; arXiv:2306.14679

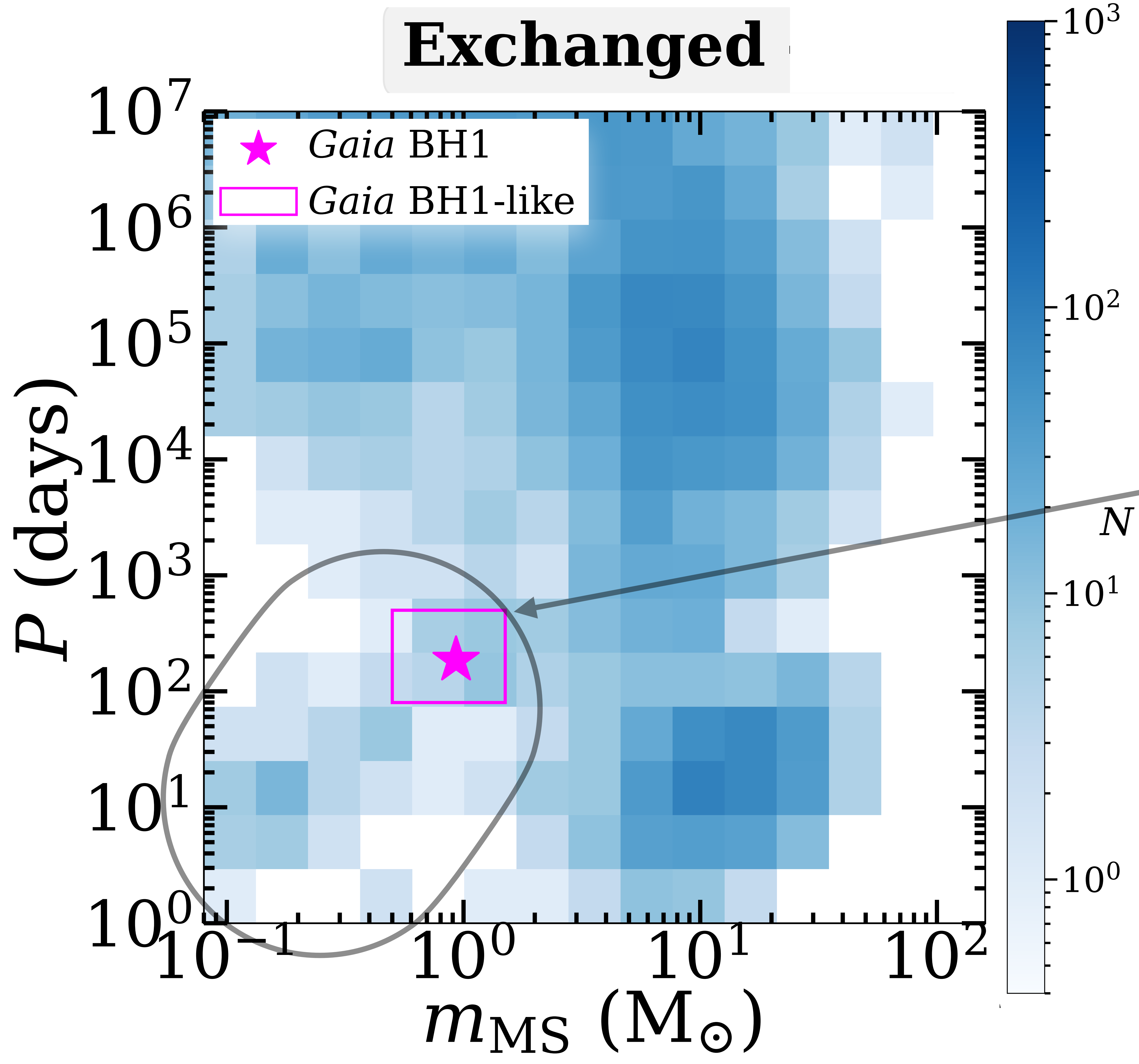
35 k *N*-body simulation of ***Young Star Clusters*** with **NBODY6++GPU** & **MOBSE**

SR+ 2020a, MNRAS, 497, 1563
SR+ 2021 MNRAS, 507, 3612

- Low mass (LM) **YSCs 300 < $M_{\odot}$ < 1000 $M_{\odot}$**
- **100% binaries** among massive stars (>5 $M_{\odot}$) with initial mass ratio ***q*** ∈ **[0.1, 1.0]**
- **Short evolution timescale**
- **Solar** like Metallicity



Exchanged BH-MS binaries



Population of all ejected **exchanged** BH-MS binaries

Gaia BH1

***Gaia* BH1-like**

$0.5 < m_{\rm MS}/M_\odot < 1.5$ $8 < m_{\rm BH}/M_\odot < 12$

$80 < P/\text{days} < 500$ $0.2 < e < 0.7$

short/intermediate-period low MS-mass bin.s

pairing of a MS star and a BH progenitor, CE episode, ejection by natal kick as BH forms;

Dynamical exchanged BH-MS binaries form in LM YSCs with properties similar to *Gaia* BH1 with formation efficiency

$\eta_{\rm DYN} = N_{\rm BH1} / m^{\rm tot,SC} \sim 10^{-7}\ M_\odot^{-1}$

Rastello et al., 2023

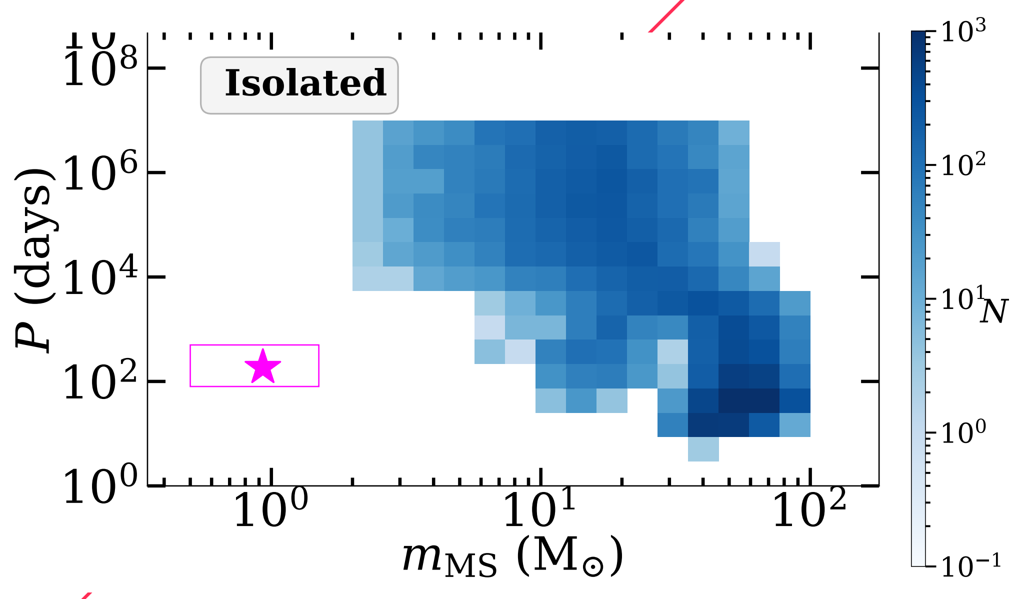
A *Gaia* BH1-like story to tell

A *Gaia* BH1-like story to tell

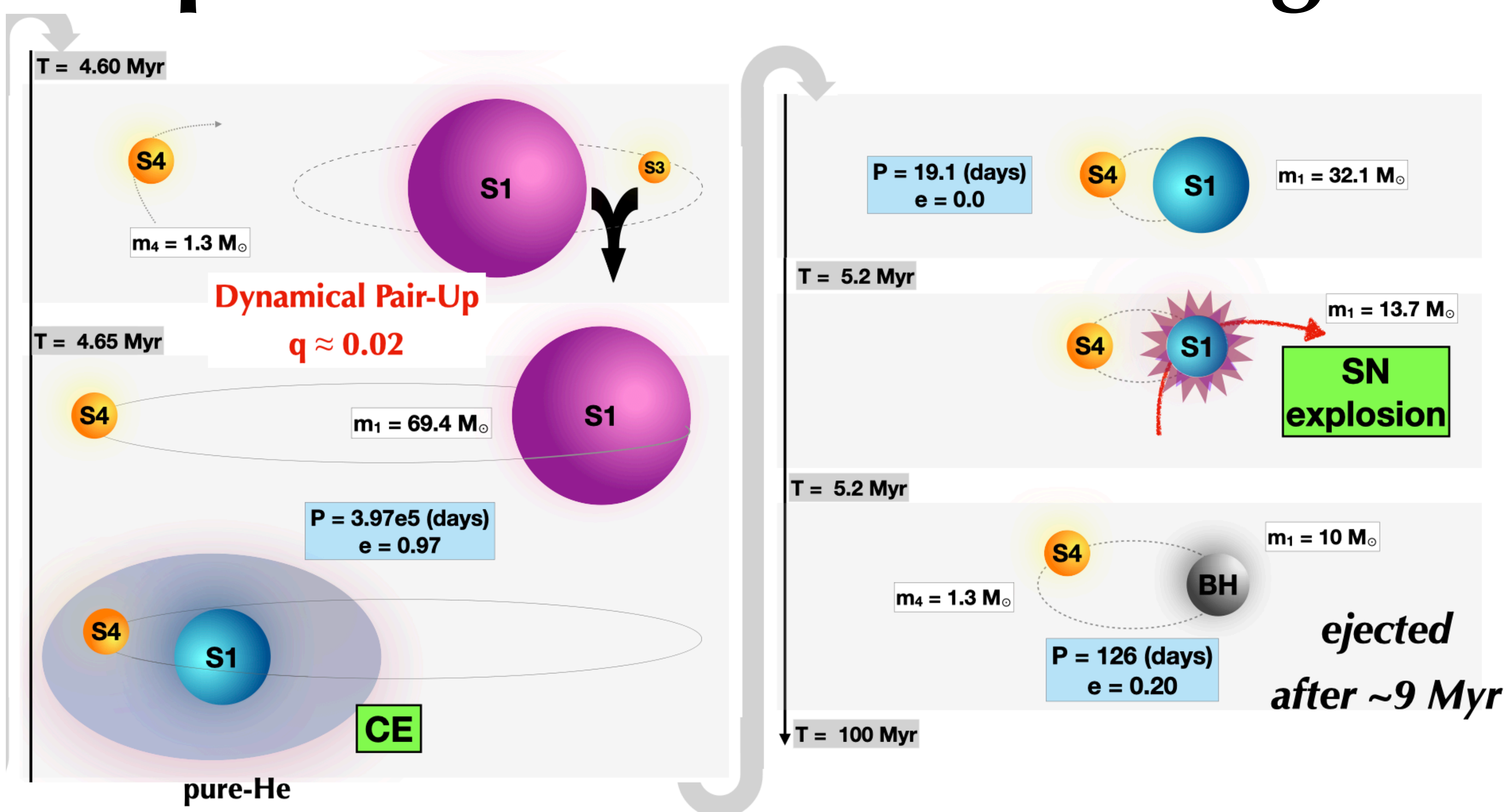
Dynamics wash out the dependence on the initial mass ratio *q*

Dynamics creates a larger variety of configurations at the onset of the CE w.r.t. to Isolated binaries

Take Home



⭐The **Isolated formation scenario** is **rare and strictly dependent on initial configuration** as mass ratio q_{lim}, CE etc;



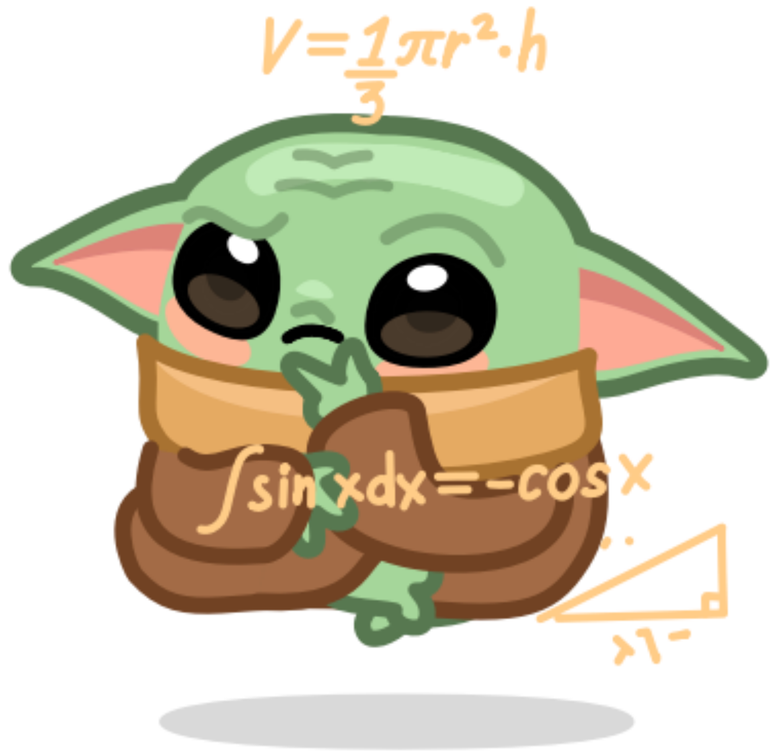
⭐A **dynamical origin** of Gaia-BH1 in YSCs is an **efficient** ($\eta_{DYN} \sim 10^{-7}\ M_\odot^{-1}$) **formation channel**;

Rastello et al., 2023 arXiv:2306.14679

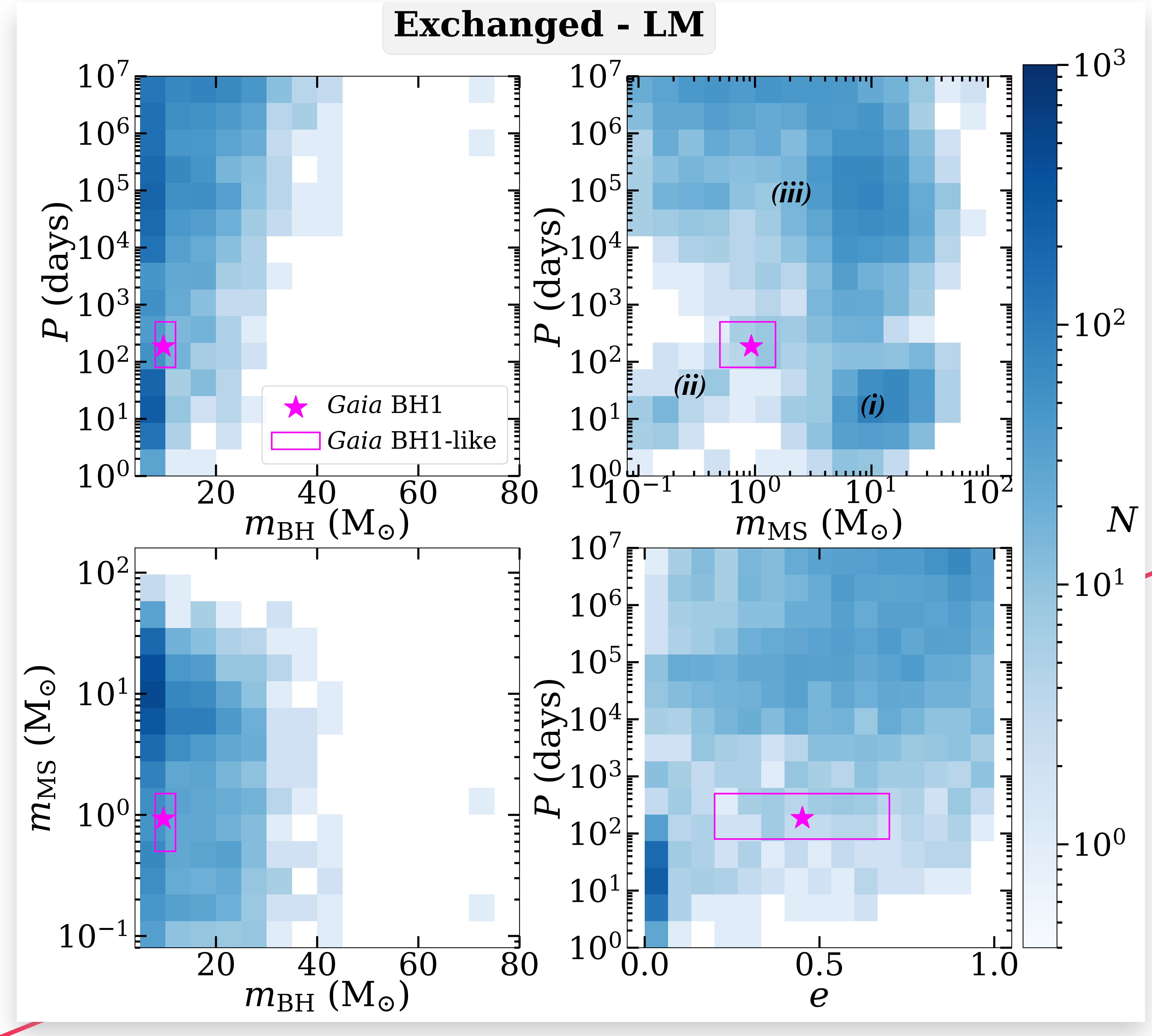
⭐In **low-mass YSCs** Gaia-BH1 like sources form preferentially through the **dynamical pair up of a MS star and the BH progenitor after a CE episode**;

~~Still not convinced?~~

Good!
This is the funny side of science!



Backup: Exchanged BH-MS Binaries I



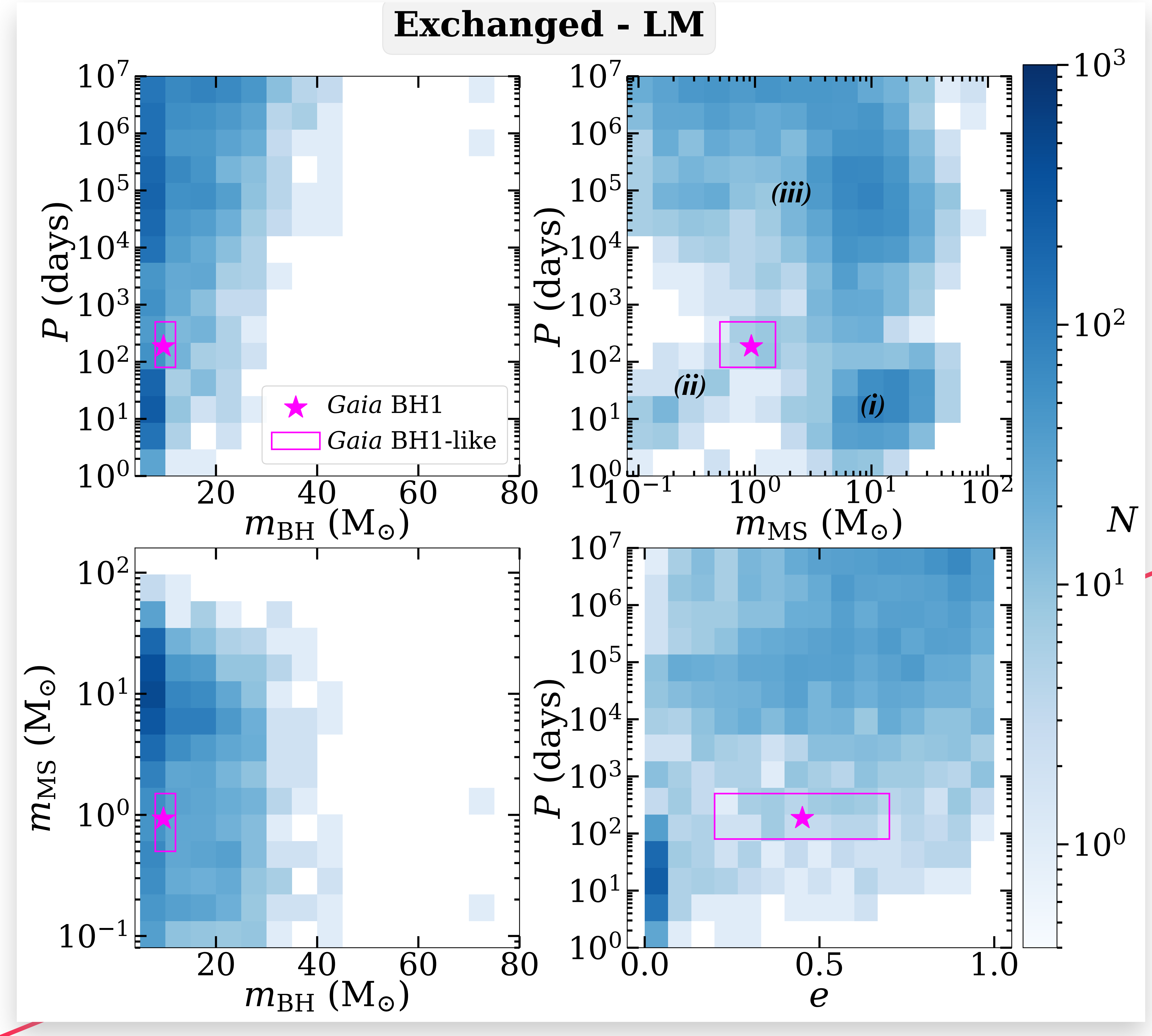
Pop of all **ejected exchanged** BH-MS binaries

i) **short/intermediate-period high MS- mass binaries.** Binaries in this group are mostly circular (**80% with $e \approx 0$)** and most of them (90%) host a **BH with mass < 10 M⊙**;

ii) **short/intermediate-period low MS-mass binaries** ($1 \lessapprox P$/days $\lessapprox 10^3$ and $0.1 \lessapprox m_{MS}/M_\odot \lessapprox 2$). The eccentricity of such binaries lies in the range **$0 < e < 0.6$.** They mainly (**62%) host BHs with mass < 10 M⊙**, even if the BH mass distribution extends up to 30 M⊙;

Groups ***(i)*** and ***(ii)*** form preferentially through the **pairing of a MS star and a BH progenitor that underwent at least one common-envelope episode, they exhibit nearly circular orbits.** The ejection of these binaries is driven by the **natal kick as the primary component turns into a BH**. Roughly 20% of exchanged BH-MS binaries belong to group (i), while only **3–4% binaries fall in group (ii).**

Backup: Exchanged BH-MS Binaries II



Pop of all **ejected exchanged** BH-MS binaries

***iii)* long-period binaries** ($10^4 < P/\text{days} < 10^7$ and $0.1 < m_{MS}/M_\odot <$ 50). These BH-MS binaries have preferentially **eccentric orbits (> 52% have e > 0.7)** and host massive BHs **(~ 50% binaries in which m_{BH} > 10 $M_\odot$**).

Binaries in group ***(iii)*** with a low-mass MS star ($m_{MS} \approx 1 - 2\ M_\odot$) form through the **pair up of a BH and a MS star**, while those with a heavier MS component form through **the pair up of the BH progenitor star and the MS star**. Most ejected exchanged binaries **(75%)** belong to group ***(iii)*****.**

Backup: Original vs Isolated Binaries

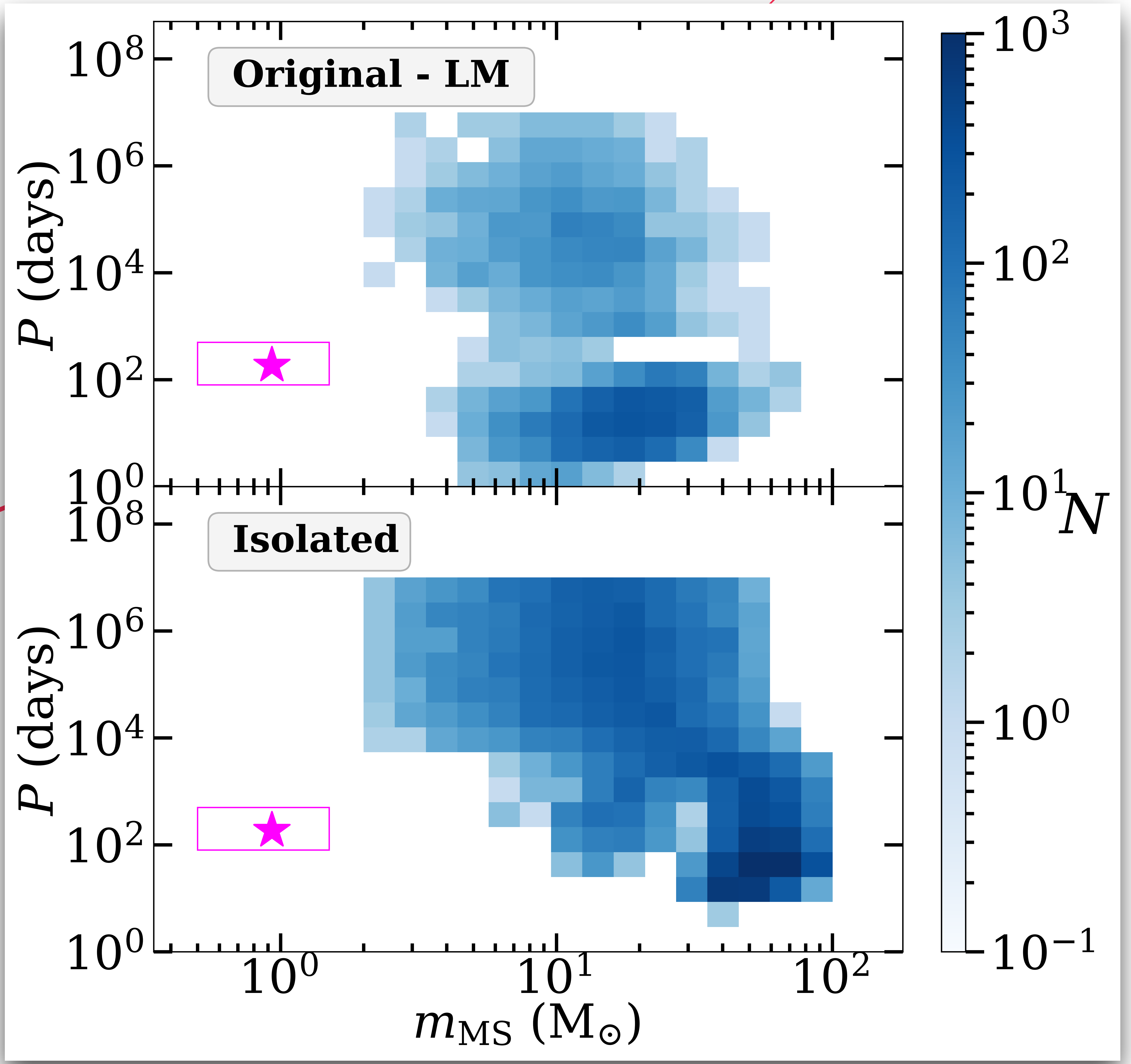
Pop. of all ejected **original** vs **Isolated** (MOBSE) BH-MS binaries

***Gaia* BH1 can form from neither isolated nor original binaries $\eta_{ISO} \sim 0\ M_\odot^{-1}$**

- **Minimum mass ratio $q_{min} = 0.1$** limits the minimum mass of the MS to $\approx 2\ M_\odot$
- **CE efficiency:** isolated evolution requires very high CE eff. (*El Badry et al., 2023a*) to form Gaia BH1-like but found very low rates.

No q_{lim} $\eta_{BH1}^{ISO} \sim 10^{-9}\ M_\odot^{-1}$

consistent with *Tanikawa et al., 2023*



Backup: ICs

Rastello et al., 2020, 2021

SR+ 2021 MNRAS, 507, 3612

SR+ 2020a, MNRAS, 497, 1563

- *YSCs sample according to power law (Lada & Lada 2003)*

  Low-mass YSCs: 300 M⊙ < m_{sc} < 1000 M⊙ &

  High-mass YSCs: 1000 M⊙ < m_{sc} < 10000 M⊙ ***Di Carlo et al., 2021***

- **Fractal** initial conditions *(Di Carlo et al., 2019)*
- Kroupa IMF 0.1 M⊙ < m_* < 150 M⊙ *(Kroupa, 2001)*
- **100% binaries** among massive stars
- **3 metallicities (Z=0.02, 0.002, 0.0002)**
- **Rapid SN model** *(Fryer et al., 2012)*
- t_{ev}**~100 Myr**

NBODY6++GPU +

Wang et al., 2015, 2016

MOBSE

Giacobbo et al., 2018, Giacobbo & Mapelli 2018, 2019

MCLUSTER

Kupper et al., 2011

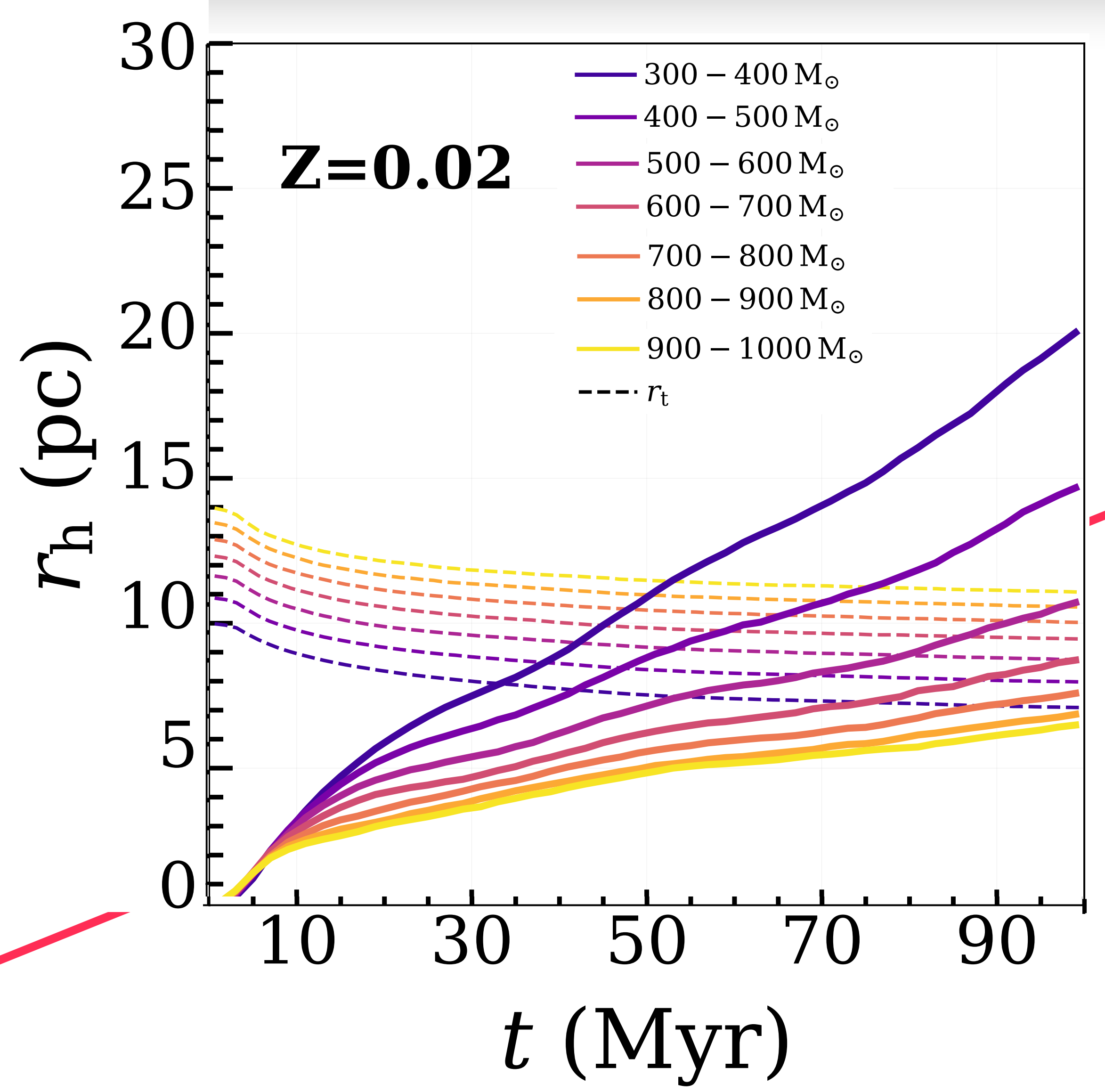
Backup: Young Star Cluster Models

YSCs
- ✶Nursery of massive stars which are progenitors of BHs;
- ✶Dynamically active stellar systems with short evolution time scale t_{rlx} ~10-100 Myr;

R136 cluster; credits: the HST

N-body simulation of realistic YSCs performed with **NBODY6++GPU** & **MOBSE**

SR+ 2020a, MNRAS, 497, 1563
SR+ 2021 MNRAS, 507, 3612

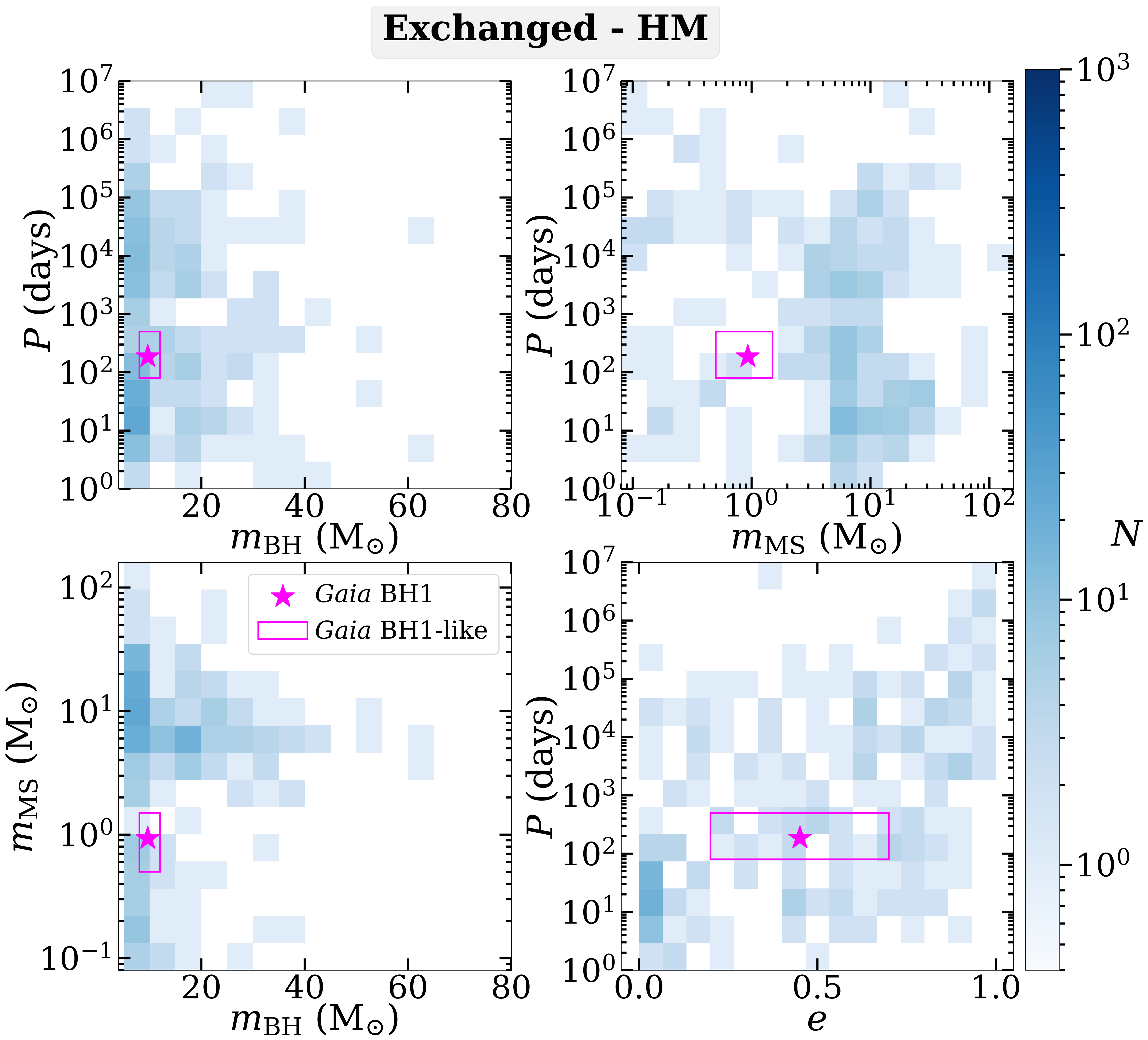


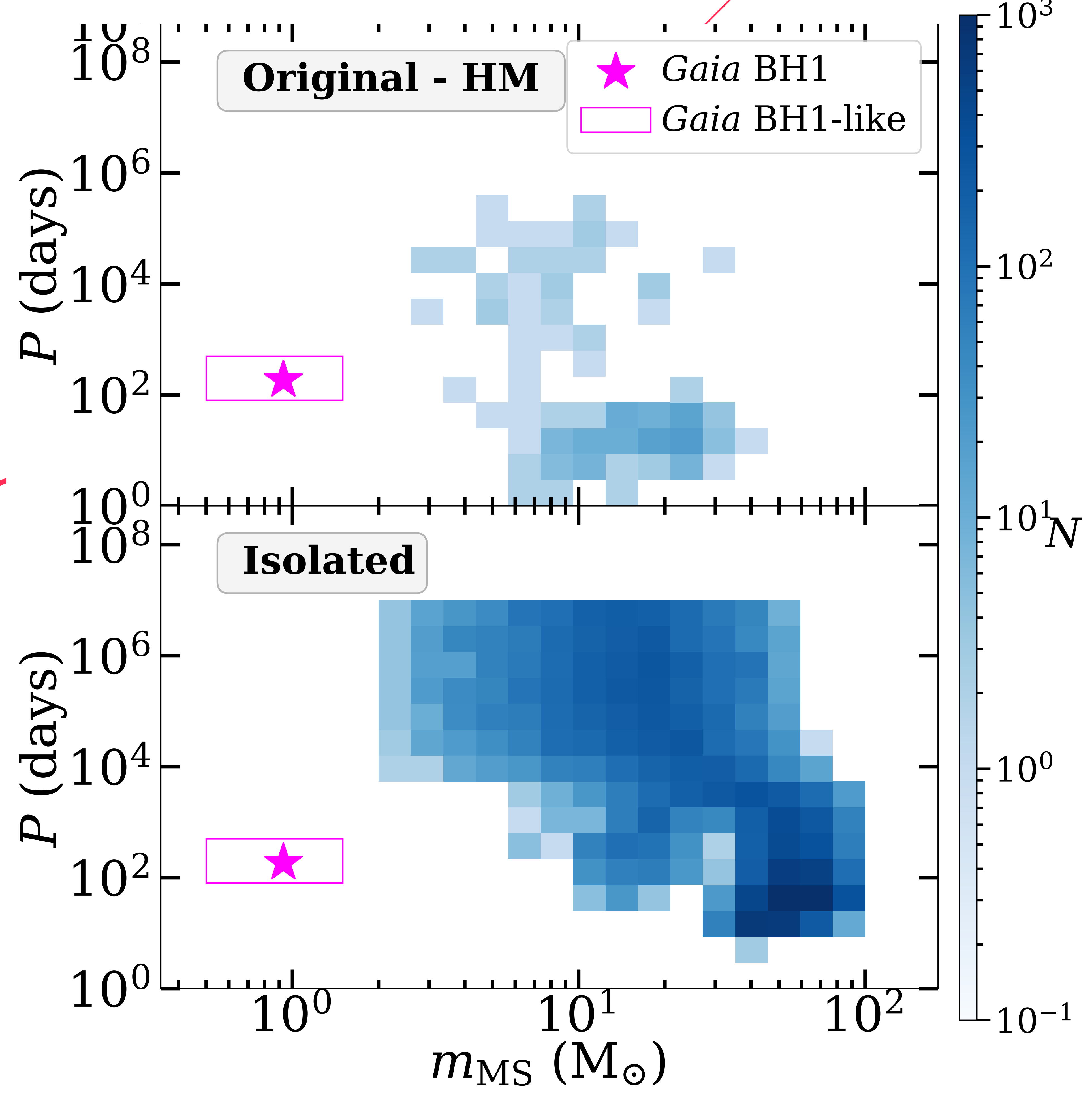
- Low mass (LM) **YSCs 300 < $M_\odot$ < 1000 $M_\odot$**
- **CE eff. α = 5**
- Kroupa IMF 0.1-150 $M_\odot$
- **100% binaries** among massive stars (>5 $M_\odot$)
- Initial mass ratio $\boldsymbol{q} \in$ **[0.1, 1.0]**
- Solar Neighborhood Potential
- **Z=0.02**

(Lada & Lada 2003; Sana et al. 2012)

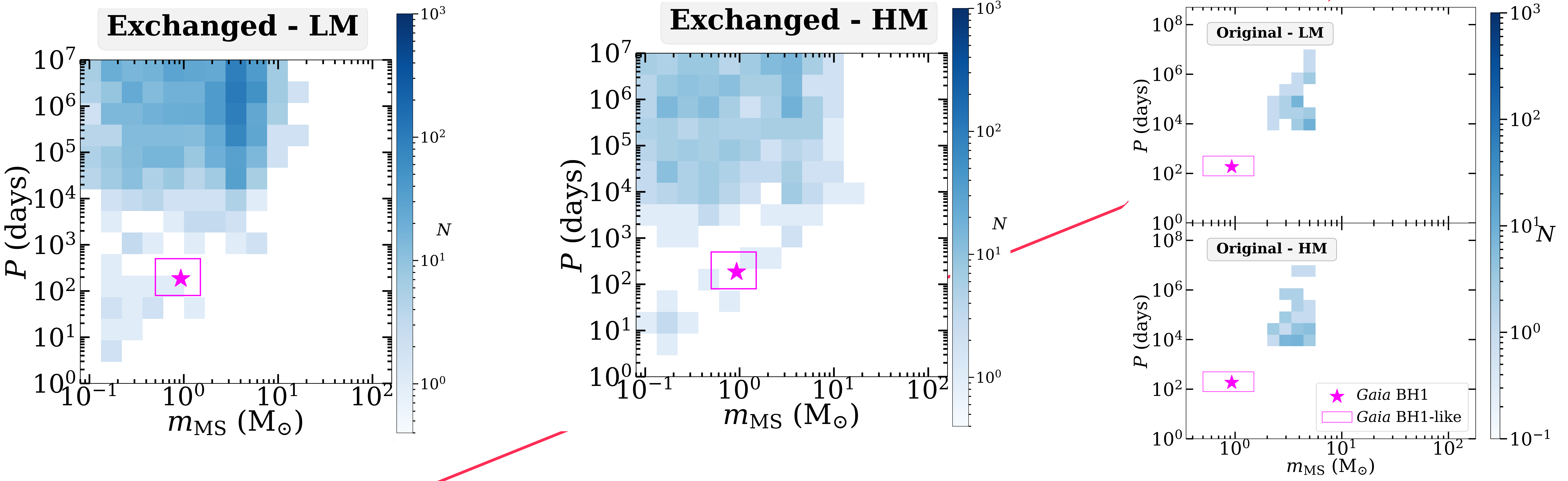
+ Comparison Sample of **Isolated binaries** taken from the *original binaries* of the YSCs evolved with **MOBSE** stand alone

Backup: High-mass YSCs





Backup: Retained BH-MS binaries



- 7% BH-MS retained (most exchanged) in LM and HM YSCs
- Host mostly low-mass MS stars and long-period ($P \geq 1000$ days) binaries that have not been destroyed or ejected yet by dynamical encounters (see also Torniamenti et al. 2023).
- LM clusters retain one *Gaia* BH1-like binary

Backup: Formation Efficiency

$\eta_{DYN} = N_{BH-MS} / m^{tot,SC} \sim$ **10^{-7} $M_\odot^{-1}$**

Formation efficiency (η) of all and ejected BH-MS binaries in YSCs

Rastello et al., 2023	**all BH-MSs** η_{BH1} (10^{-7} $M_\odot^{-1}$)	**ejected BH-MSs** η_{BH1} (10^{-7} $M_\odot^{-1}$)
YSCs	$2.09^{+2.32}_{-1.31}$	$0.95^{+1.74}_{-0.75}$

***Gaia* BH1-like**

$0.5 < m_{MS}/M_\odot < 1.5$ $\quad 8 < m_{BH}/M_\odot < 12$

$80 < P/\text{days} < 500$ $\quad 0.2 < e < 0.7$

Tanikawa et al., 2023 **(no $q_{lim.}$)** $\eta_{BH1}{}^{ISO} \sim$ **10^{-9} $M_\odot^{-1}$** and $\eta_{BH1}{}^{DYN} \sim$ **10^{-6} $M_\odot^{-1}$**

Backup: Binary Evolution Processes

α : **efficiency of energy transfer from orbit to the envelope**

ISOLATED CHANNEL

Gaia BH1-like possible only for α >10 but separation is too short P< 10 days *El-Badry et al., 2023a,b;*

DYNAMICAL CHANNEL

In Dynamics *Gaia*-BH1 like possible for α ~ 5 (*Rastello et al., 2023)*

Why? Dynamics create a large variety of configuration at the onset of the CE "envelope binding energy, ecc, initial separation etc"

Values $\alpha > 10$ unrealistic but **further exploration of the parameter space is needed!!!**

Backup: SN Kick prescriptions

We use the same prescriptions as run **CC15α5** in

Giacobbo & Mapelli (2018).

NSs natal kick randomly drawn from a Maxwellian with a one-dimensional root-mean square

σ =15 km s−1.

BH natal kicks are drawn as

$$\boldsymbol{v_{BH} = (1 - f_{fb})\, v_{NS}}$$

where v_{NS} is the NS kick drawn as described above and f_{fb} is the fallback fraction defined in *Fryer et al. (2012b).*

Backup: Numerical codes

NBODY6++GPU *Wang et al., 2015, 2016*

- Hybrid parallelized code (**MPI+OpenMP+CUDA**)
- 4th-order Hermite int. + block time step
- Regularization
- Neighbor scheme (irregular/regular force)

Coupled with the Pop. Synthesis code

MOBSE

<u>**M**assive **O**bjects **B**inary **S**tellar **E**volution</u>

- Upgrade of BSE (Hurley et al. 2000, 2002)
- New prescriptions for core-collapse SNe (*rapid* & *delayed* SN model)
- Update natal kick for BHs (V_{kick})

Giacobbo et al., 2018,
Giacobbo & Mapelli 2018, 2019