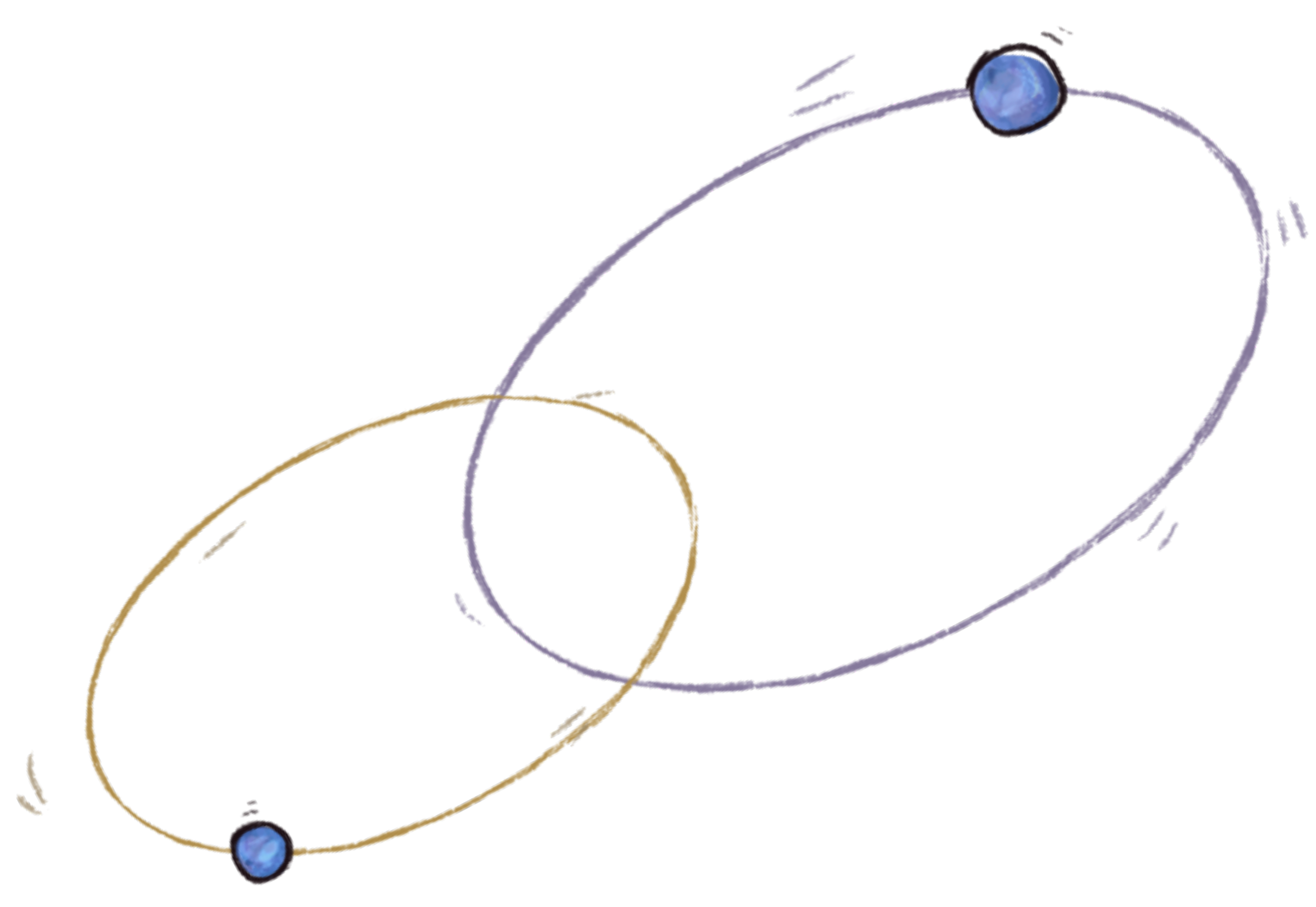
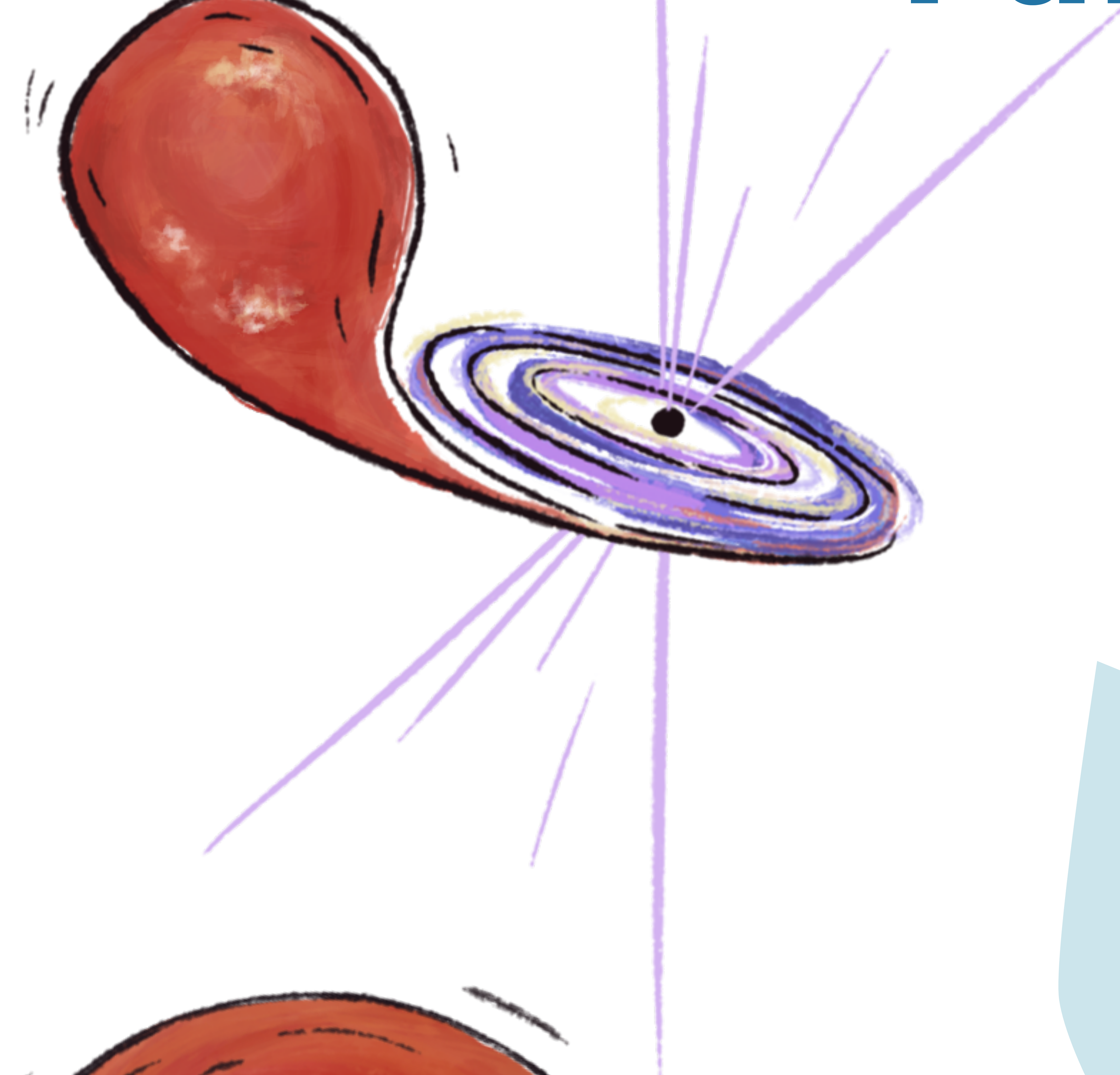
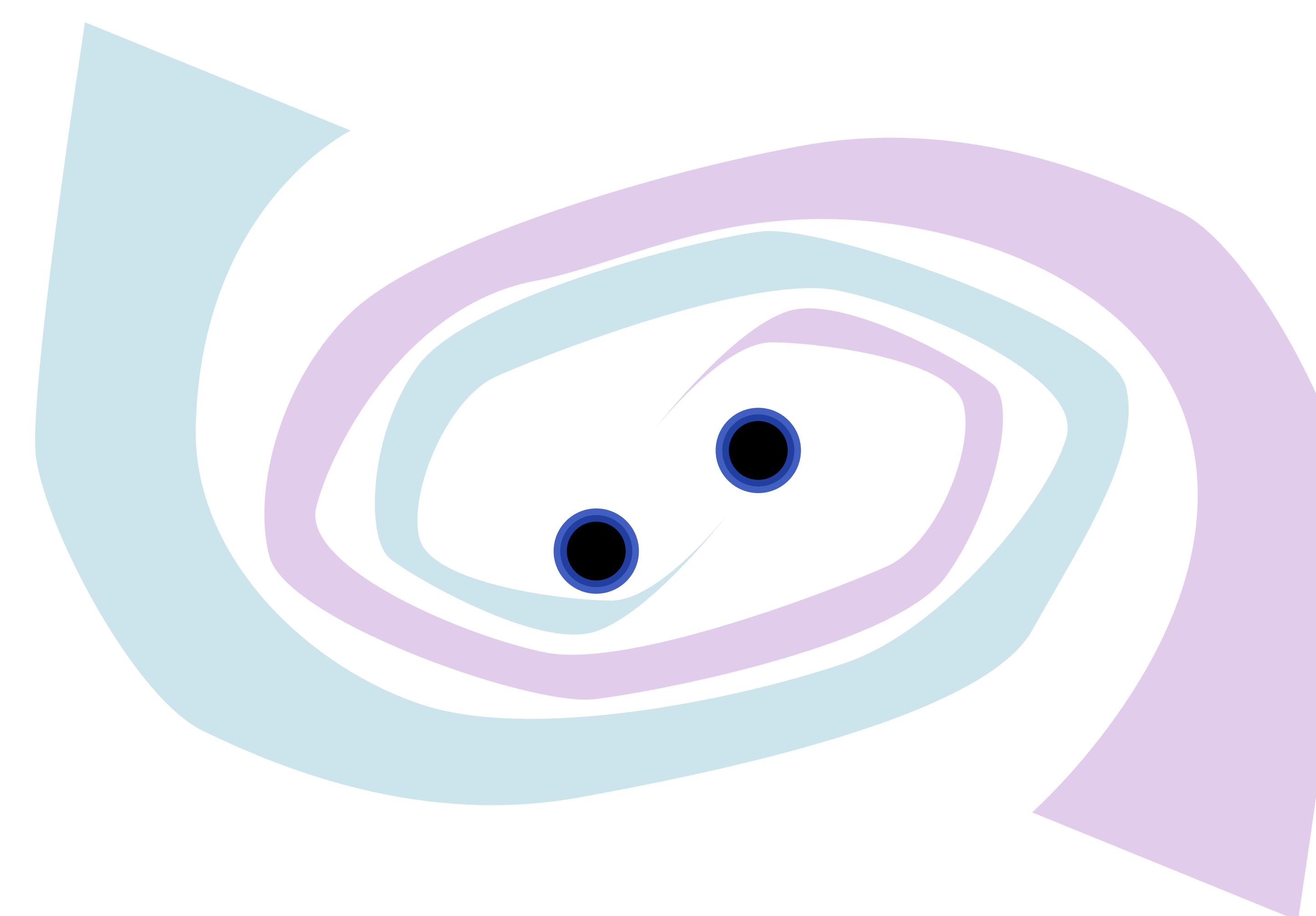
The role of accretion in the formation of gravitational wave sources

Pablo Marchant





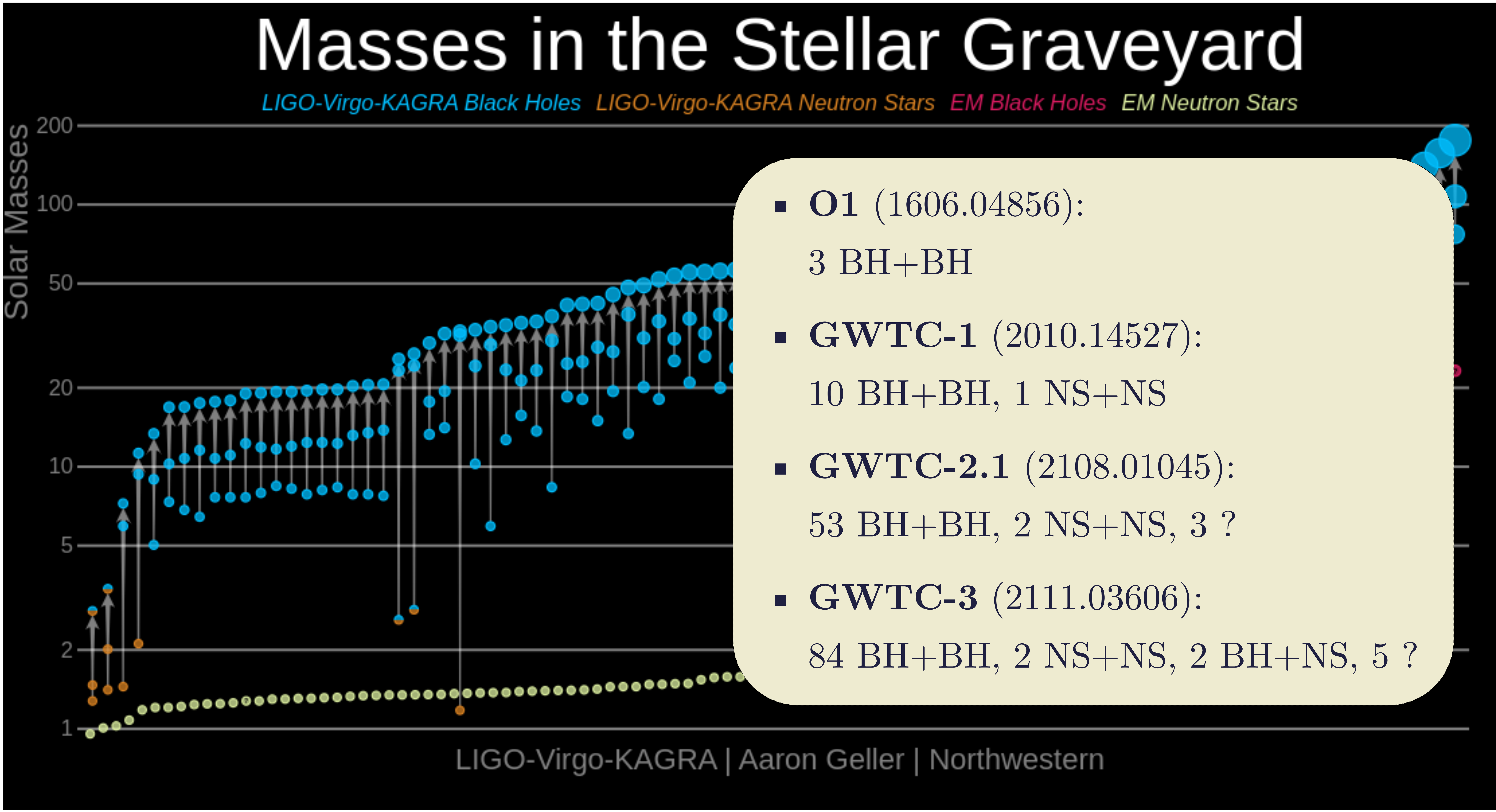


KU LEUVEN

fwo

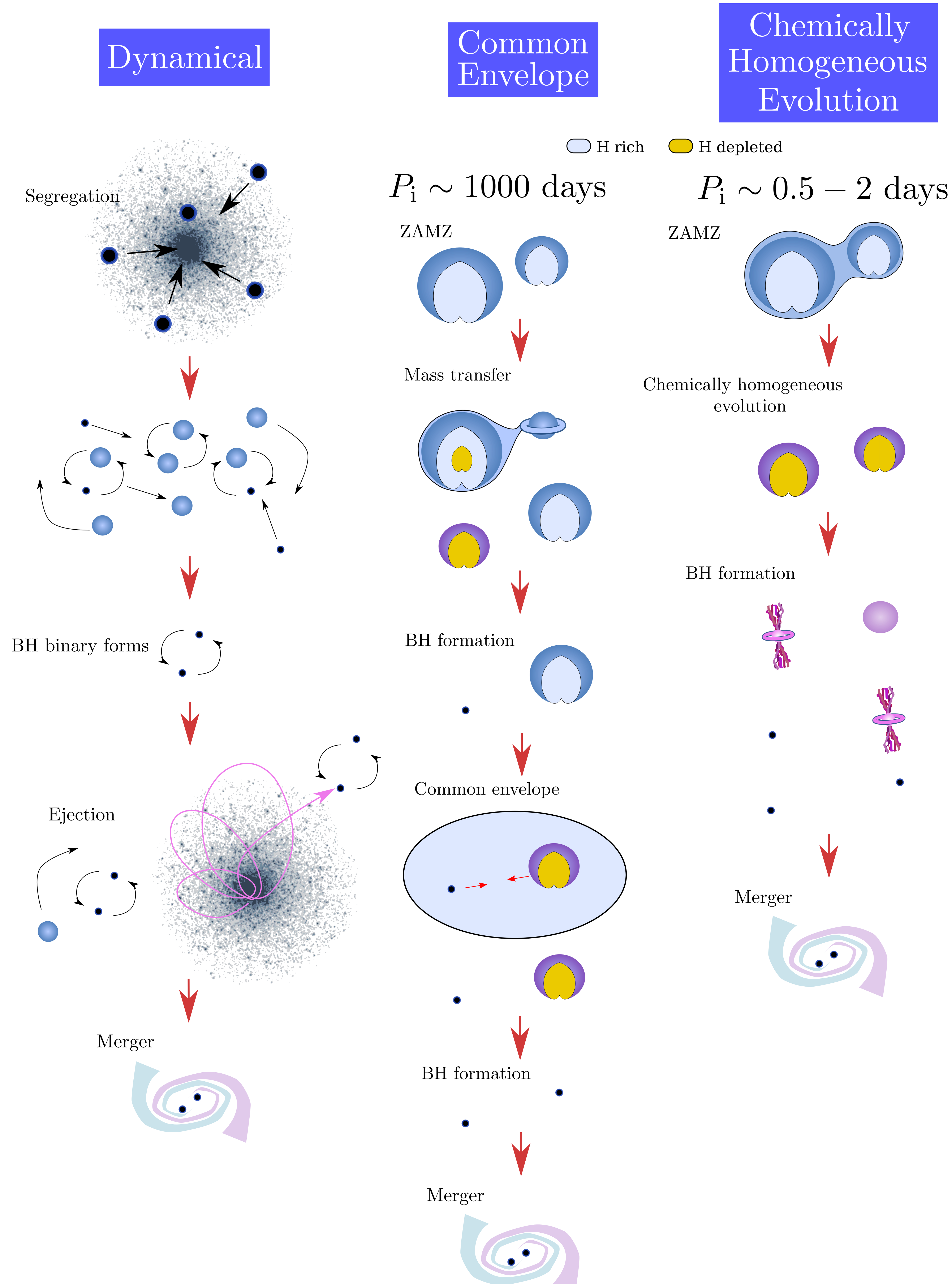
Something you might have seen already...

Something you might have seen already...



- **O1** (1606.04856):
  3 BH+BH
- **GWTC-1** (2010.14527):
  10 BH+BH, 1 NS+NS
- **GWTC-2.1** (2108.01045):
  53 BH+BH, 2 NS+NS, 3 ?
- **GWTC-3** (2111.03606):
  84 BH+BH, 2 NS+NS, 2 BH+NS, 5 ?

Formation scenarios



$$t_d = 7.4\ [\mathrm{Gyr}] \left(\frac{P}{12\ [\mathrm{h}]}\right)^{8/3} \left(\frac{\mathcal{M}}{M_\odot}\right)^{-5/3}$$

$$\mathcal{M} \equiv \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

- Dynamical formation:

  Kulkarni et al. (2003), Sigurdsson & Hernquist (1993), Portegies Zwart & McMillan (2000), Antonini & Perets (2012) Rodriguez et al. (2015), Di Carlo et al. (2019)

- Common envelope evolution:

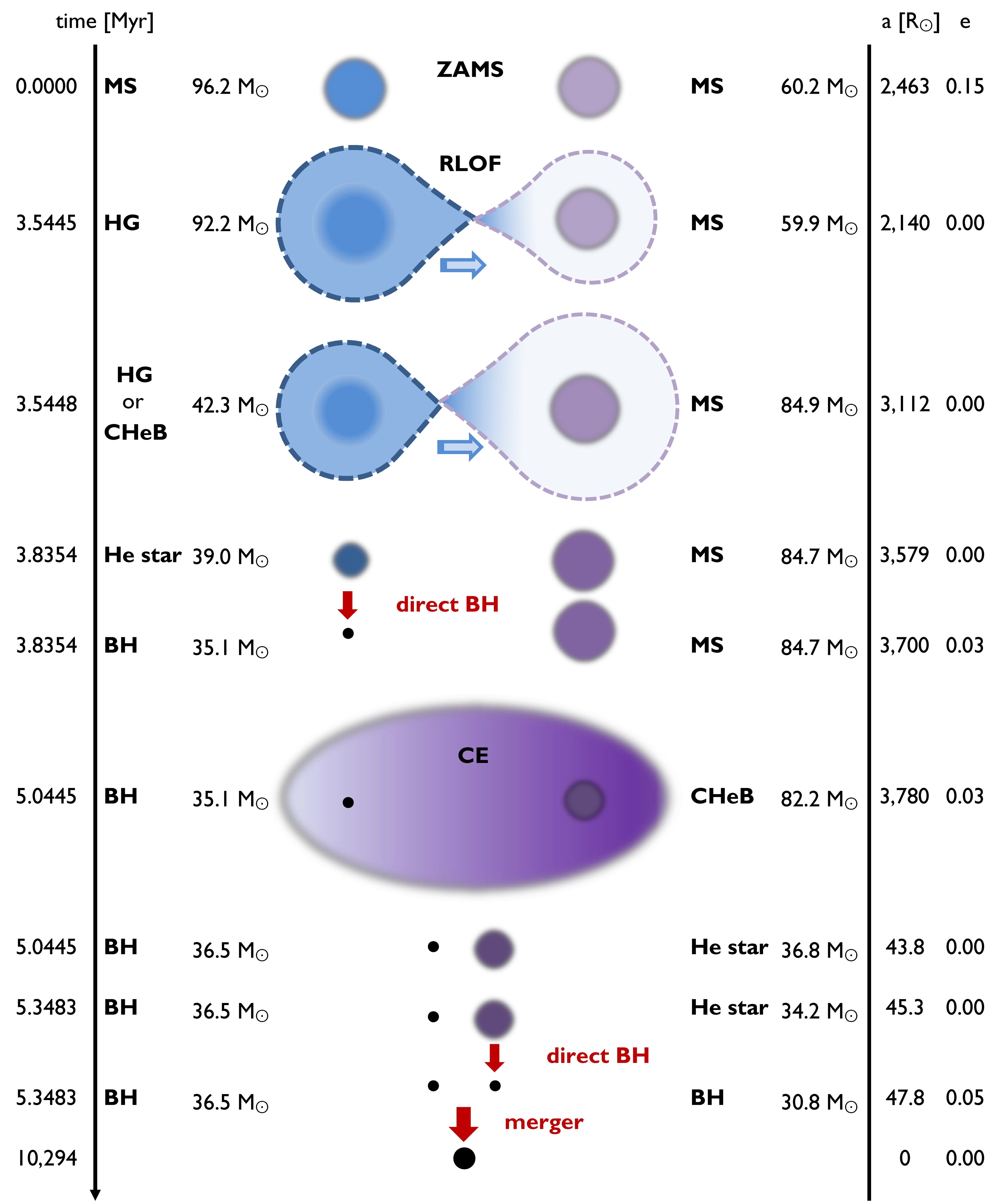
  Paczynski (1976), van den Heuvel (1976), Tutukov & Yungelson (1993), Belczynski et al. (2002), Dominik et al. (2012), Stevenson et al. (2017), Giacobbo & Mapelli (2018)

- Chemically homogeneous evolution:

  Mandel & de Mink (2016); Marchant et al. (2016); de Mink & Mandel (2016); du Buisson et al. (2020); Riley et al. (2020)

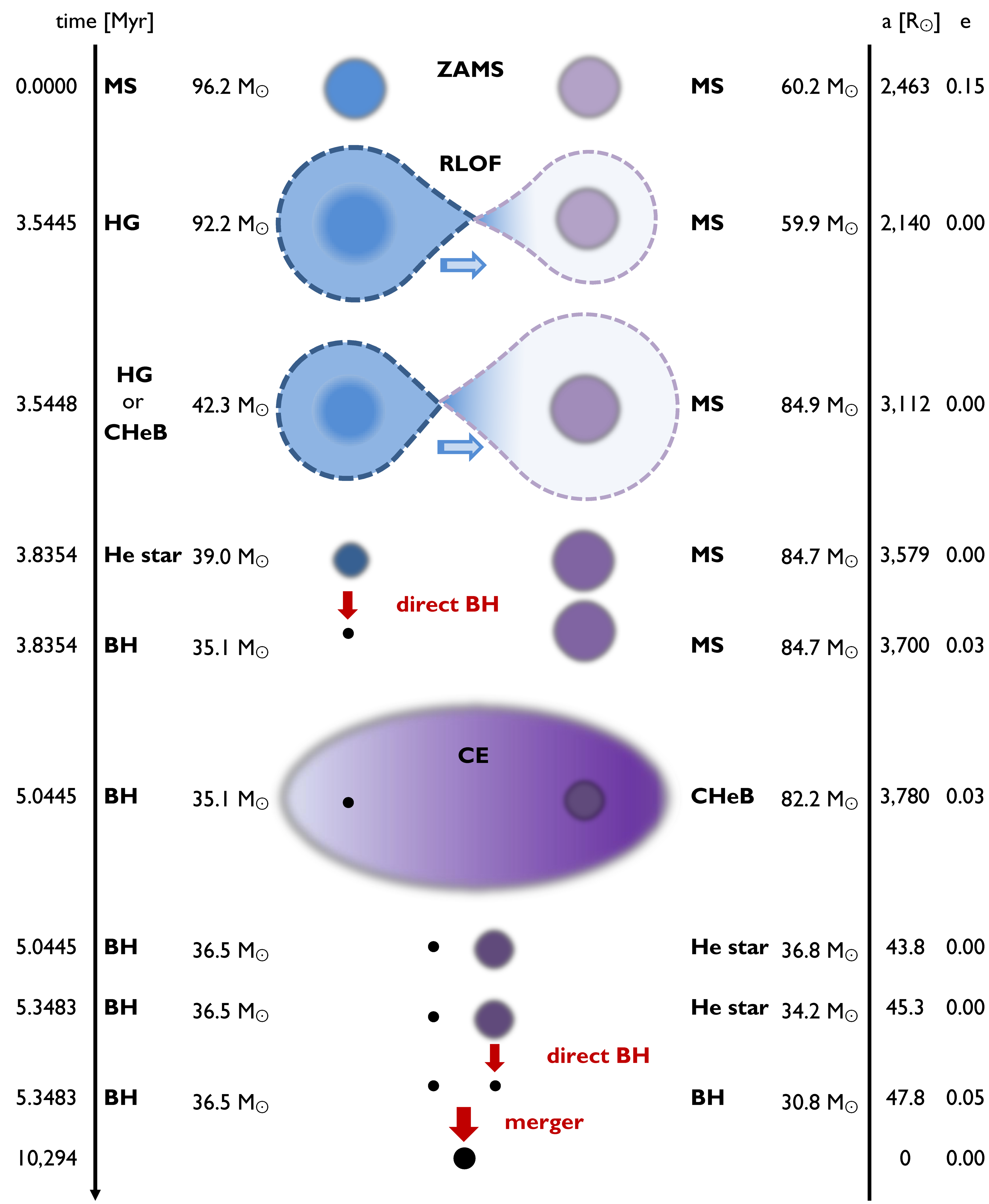
Mass transfer or common envelope?

Belczynski et al. (2016)



Mass transfer or common envelope?

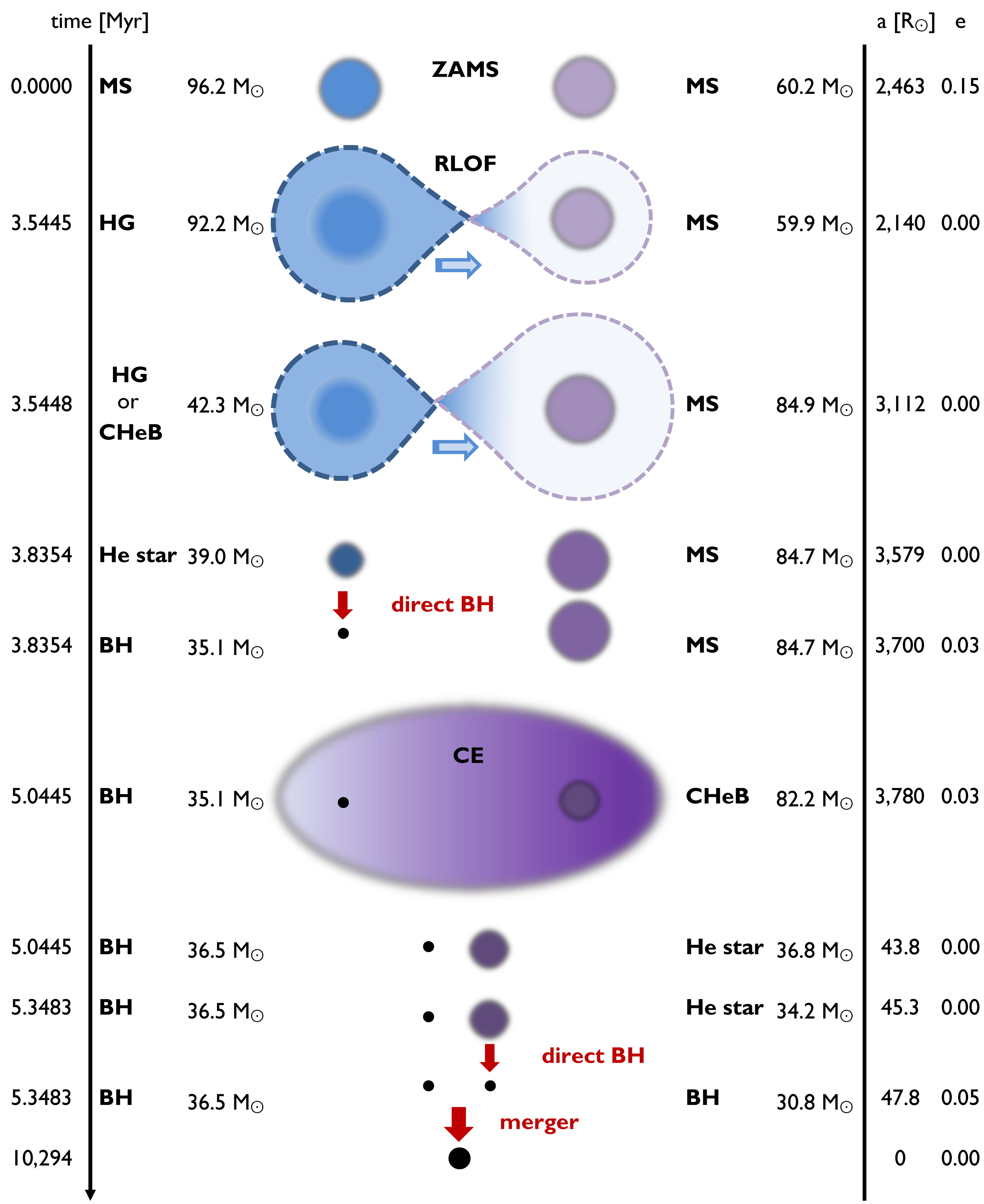
Belczynski et al. (2016)



- Most population results rely on simplified semi-analytical models for single and binary star evolution (tipically the formulation of Hurley et al. 2002).
- Few exceptions include Eldridge & Stanway (2016), du Buisson et al. (2020), Garcia et al. (2021), Fragos et al (2022)

Mass transfer or common envelope?

Belczynski et al. (2016)

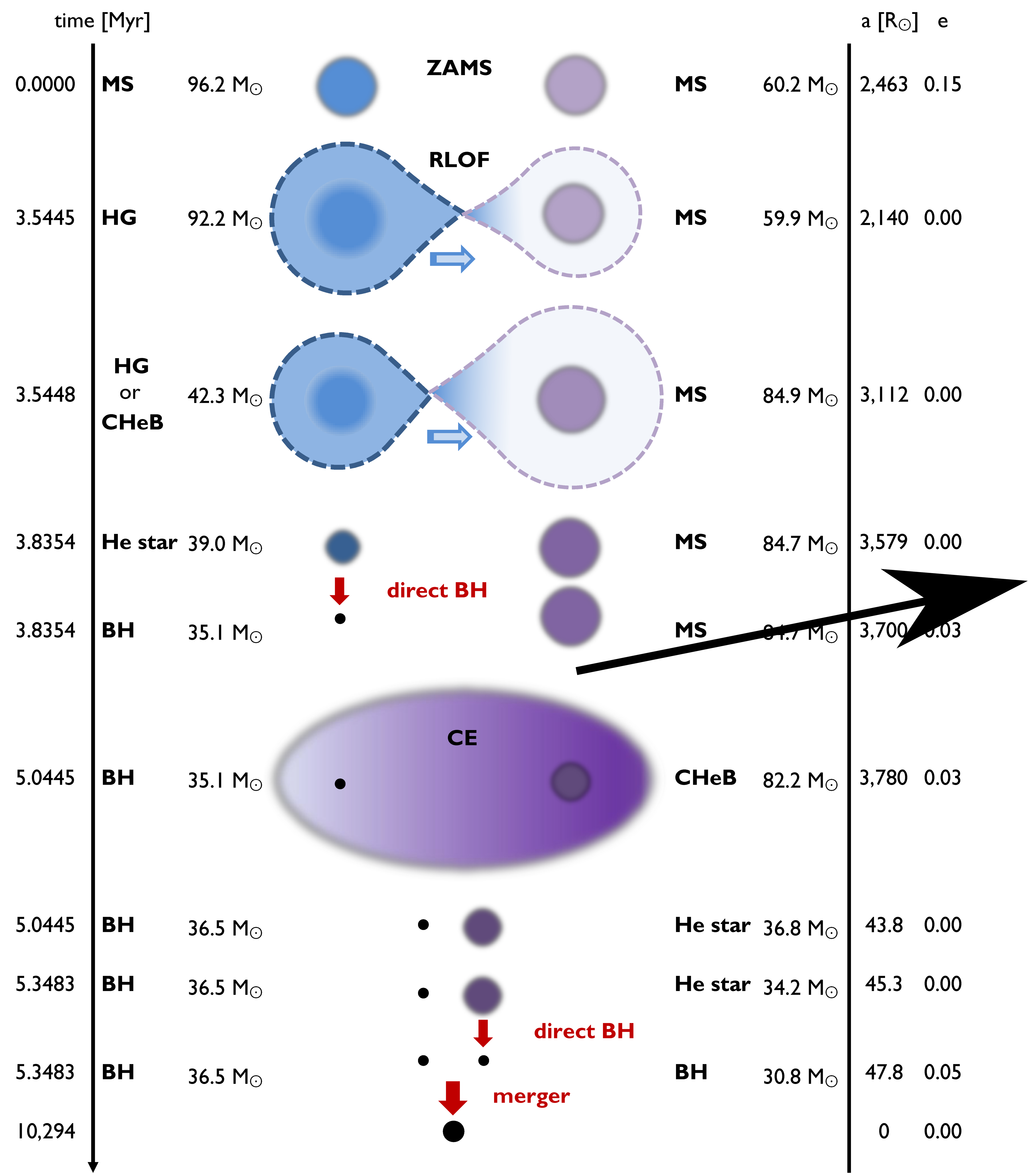


- Most population results rely on simplified semi-analytical models for single and binary star evolution (tipically the formulation of Hurley et al. 2002).
- Few exceptions include Eldridge & Stanway (2016), du Buisson et al. (2020), Garcia et al. (2021), Fragos et al (2022)

$$\Delta E_{\rm orb} = -\alpha E_{\rm bind}$$

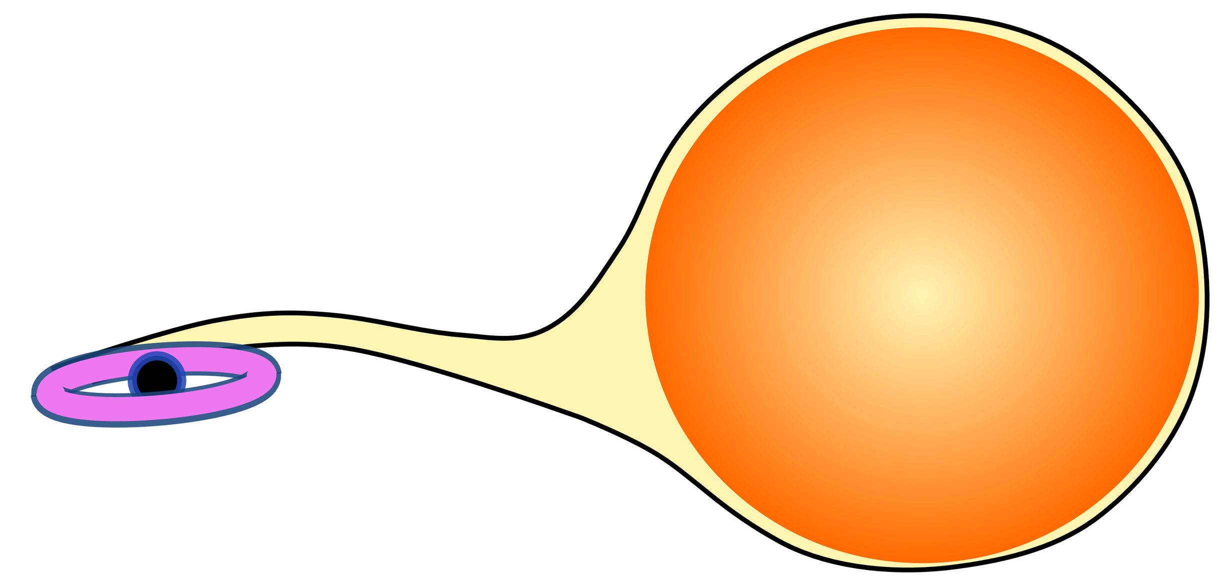
Mass transfer or common envelope?

Belczynski et al. (2016)



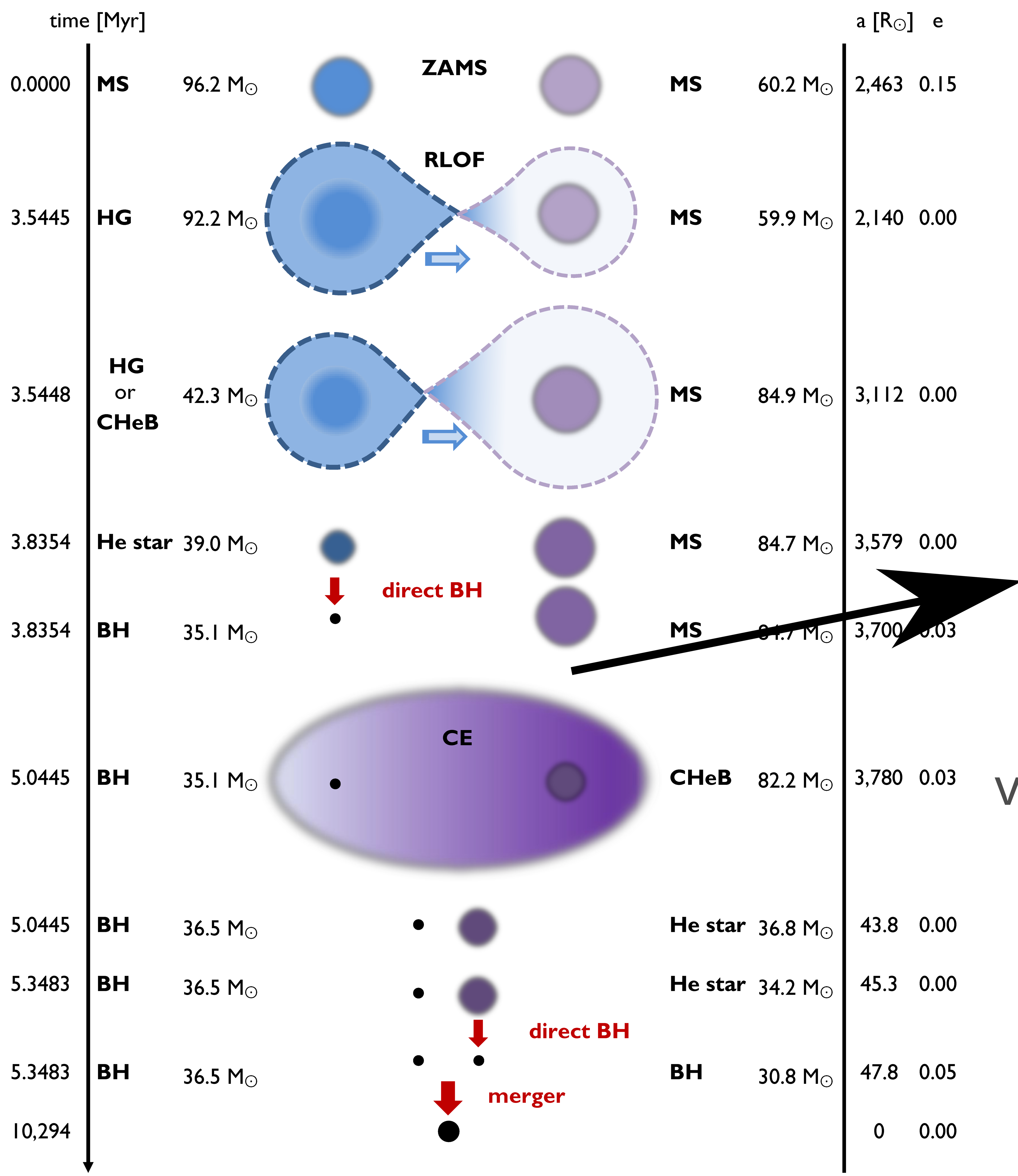
Stars react differently to mass loss if they have convective or radiative envelope (Hjellming & Webbink 1987, Ge et al. 2020). This response determines the stability of mass transfer.

e.g. Pavloovski et al. (2017)



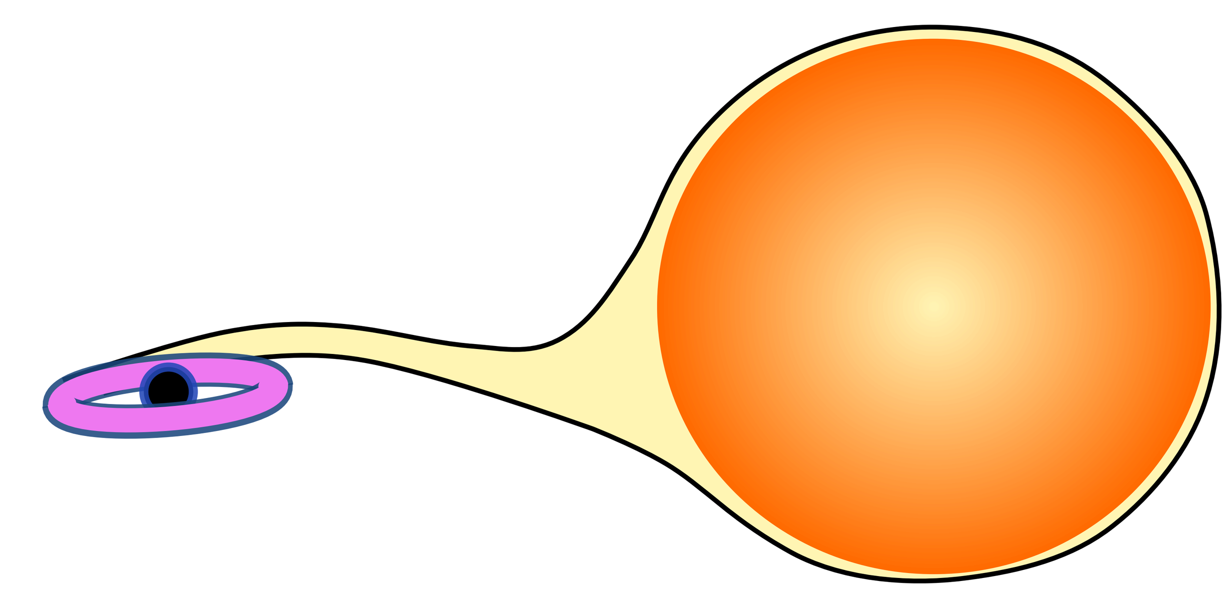
Mass transfer or common envelope?

Belczynski et al. (2016)

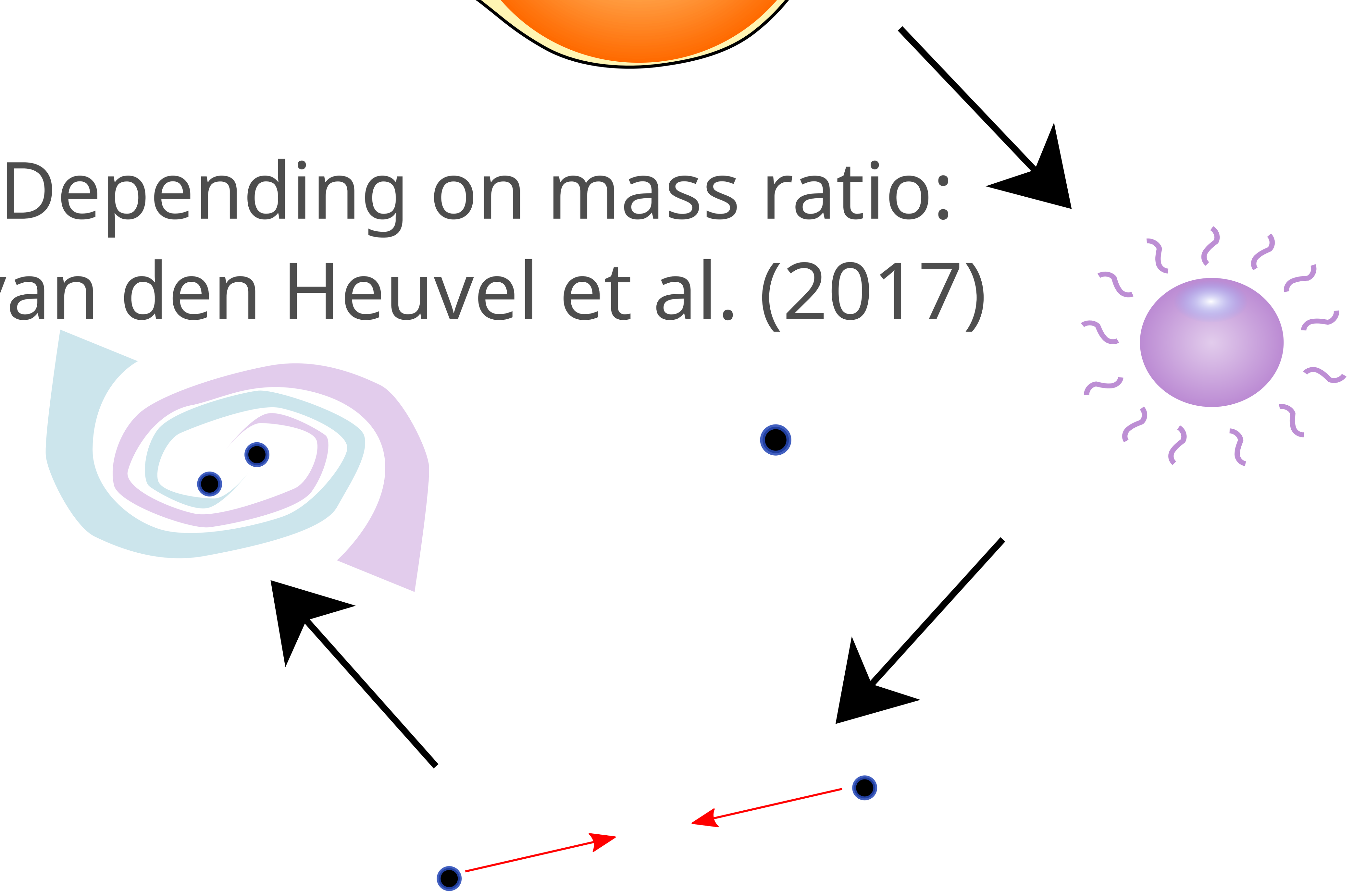


Stars react differently to mass loss if they have convective or radiative envelope (Hjellming & Webbink 1987, Ge et al. 2020). This response determines the stability of mass transfer.

e.g. Pavloovski et al. (2017)

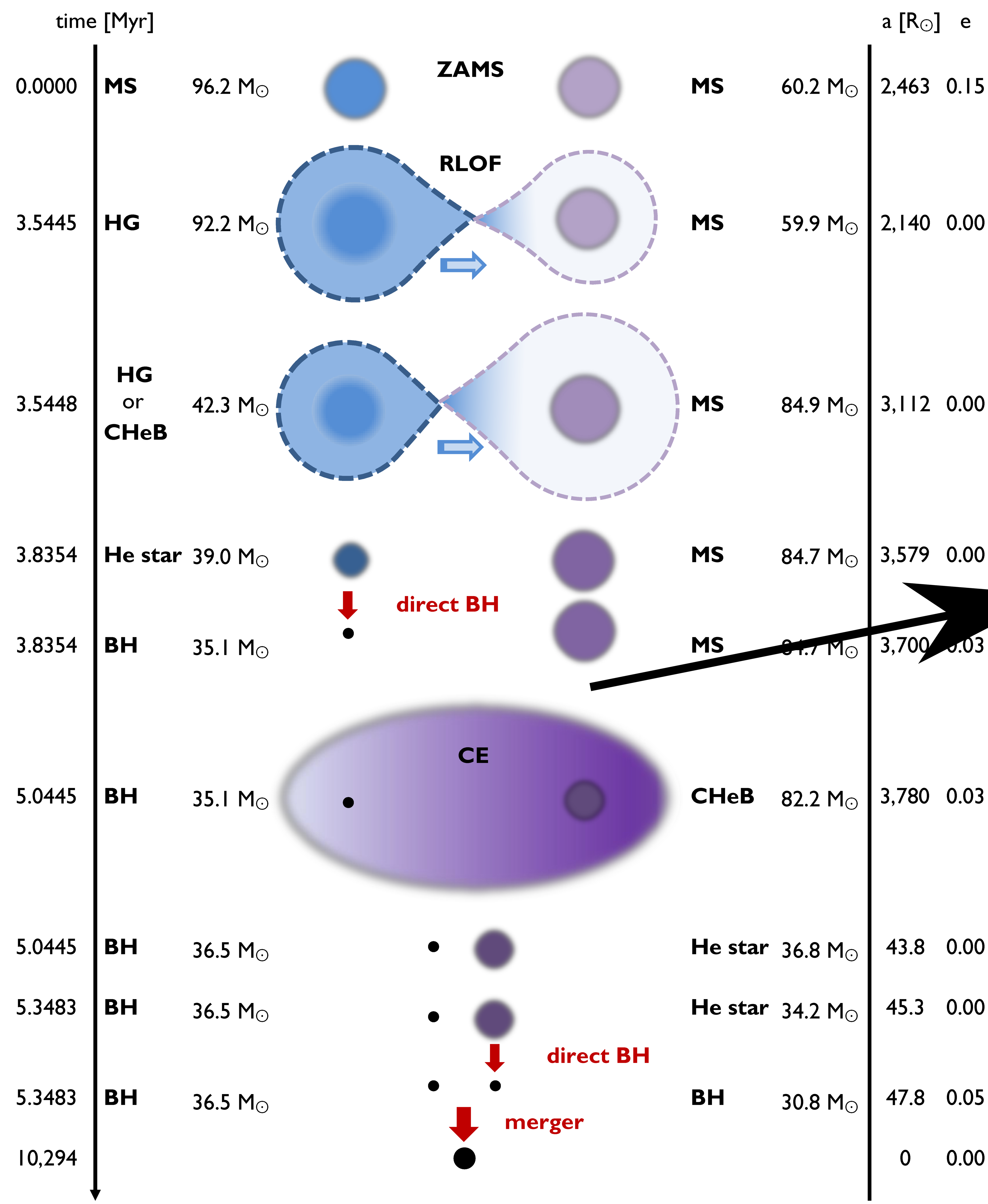


Depending on mass ratio:
van den Heuvel et al. (2017)



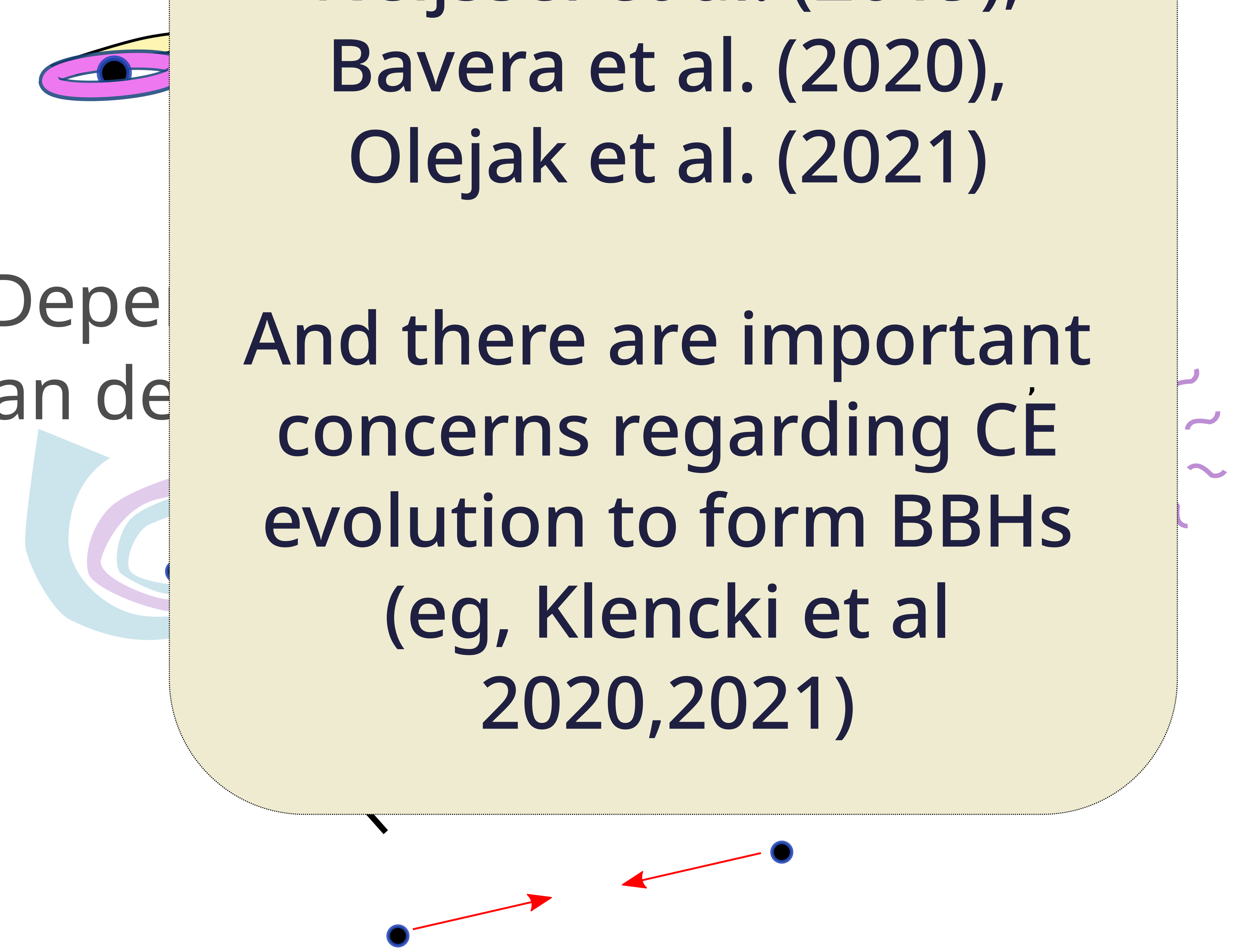
Mass transfer or common envelope?

Belczynski et al. (2016)



Stars react differently to mass loss if they have convective or radiative envelope (Hjellming & Webbink 1987, Ge et al. 2020). This response determines the stability of mass transfer.

e.g



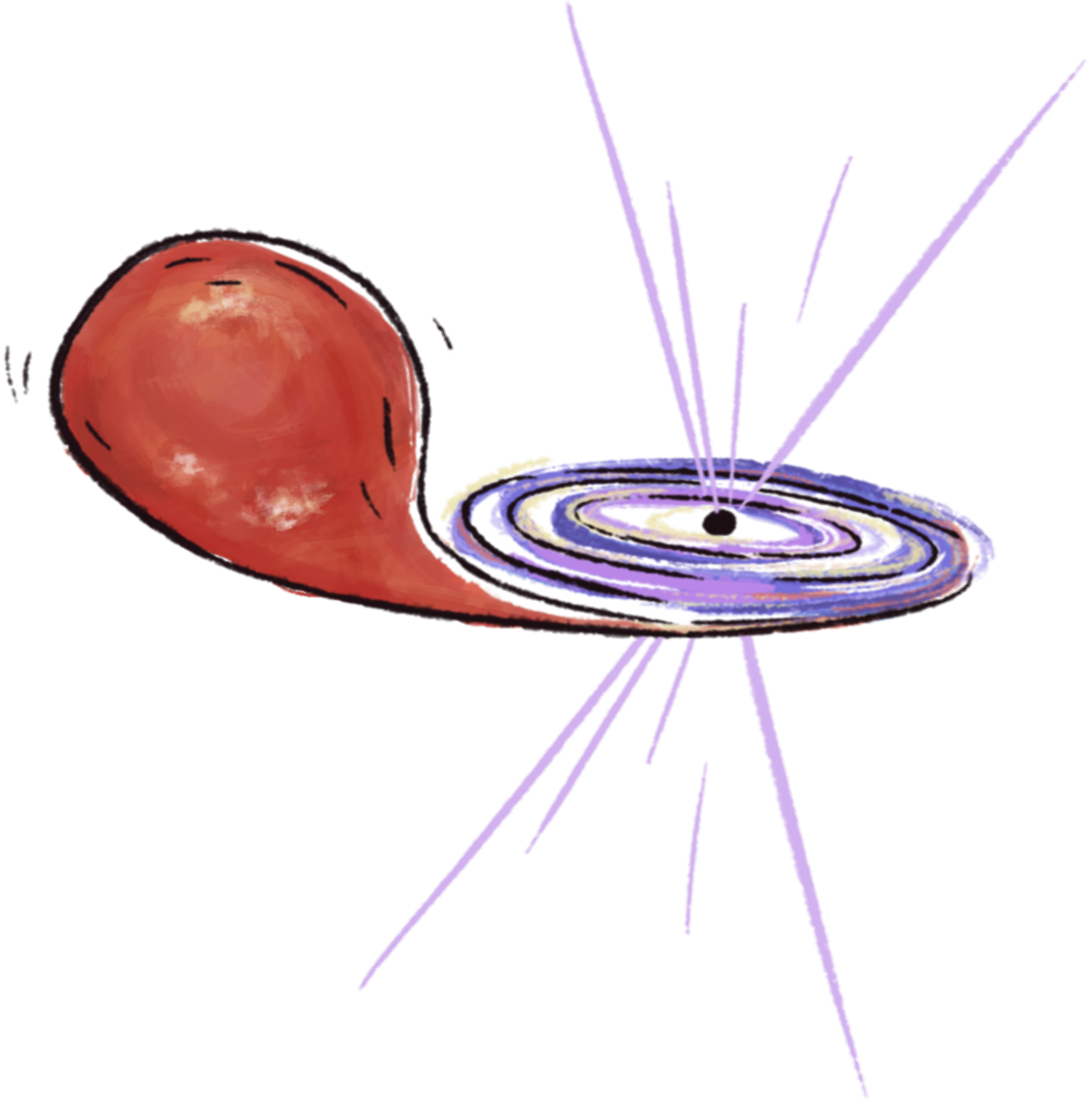
Depe

van de

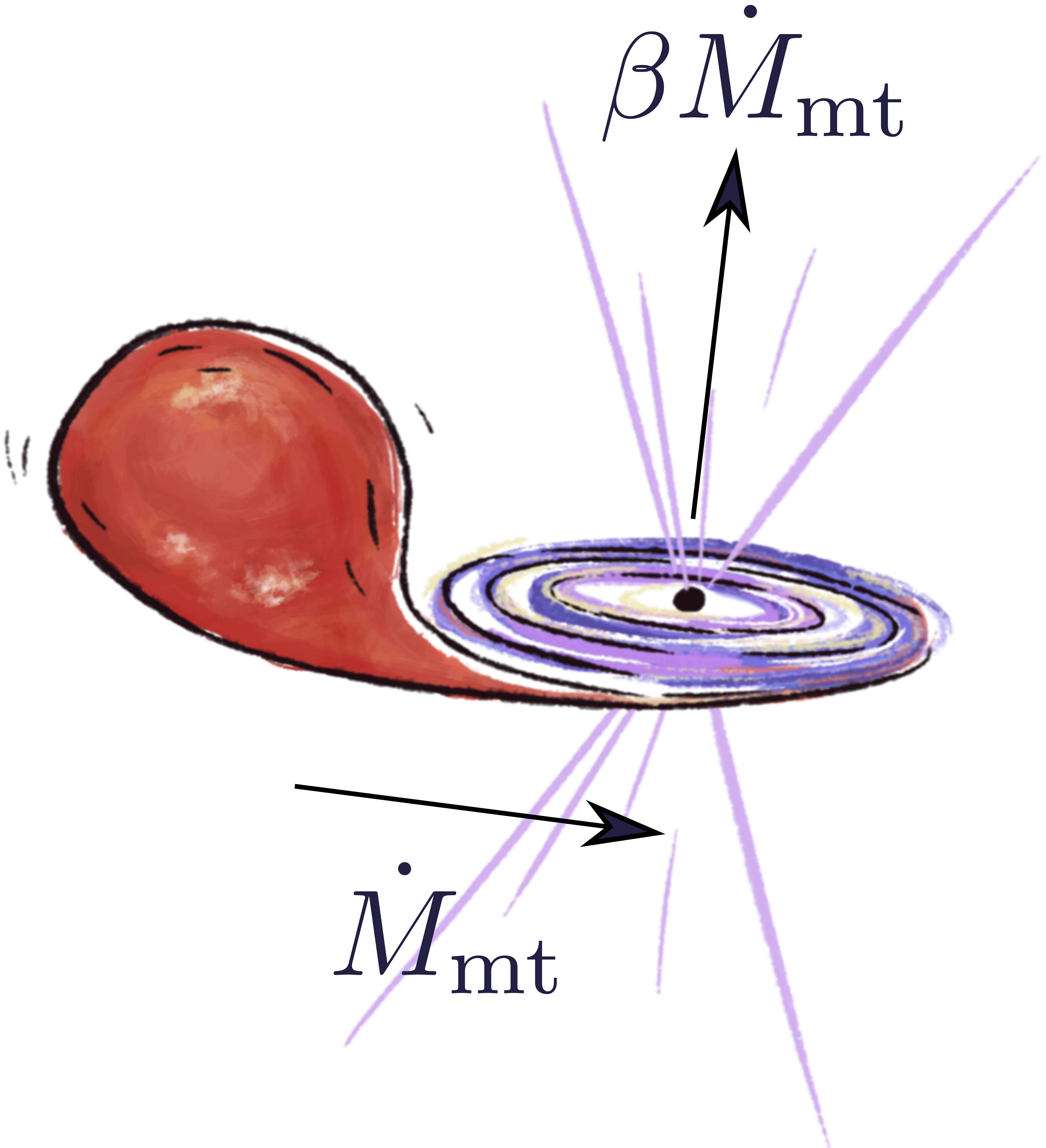
This pathway could potentially dominate! Neijssel et al. (2019), Bavera et al. (2020), Olejak et al. (2021)

And there are important concerns regarding CE evolution to form BBHs (eg, Klencki et al 2020,2021)

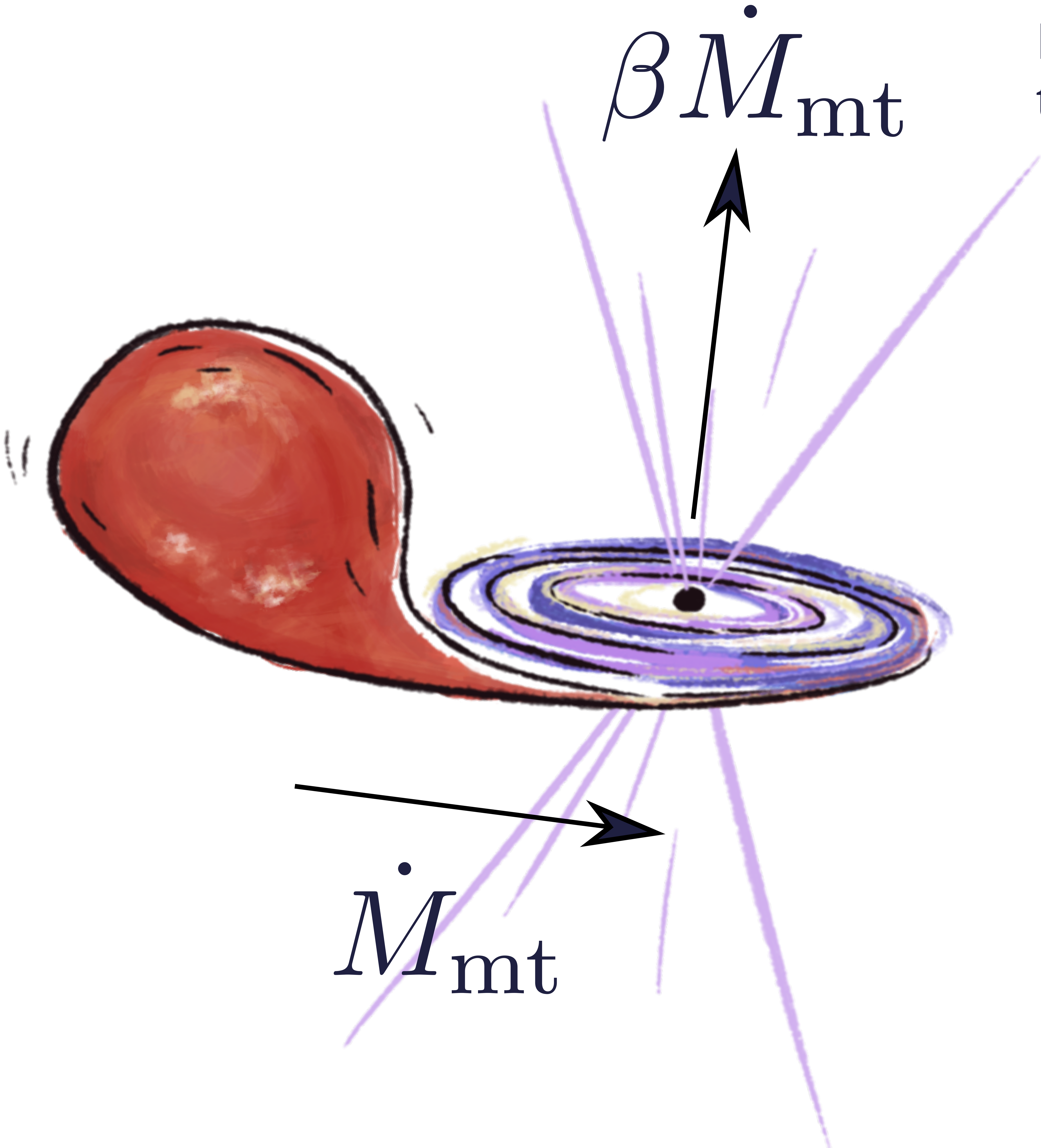
Hardening through mass transfer



Hardening through mass transfer



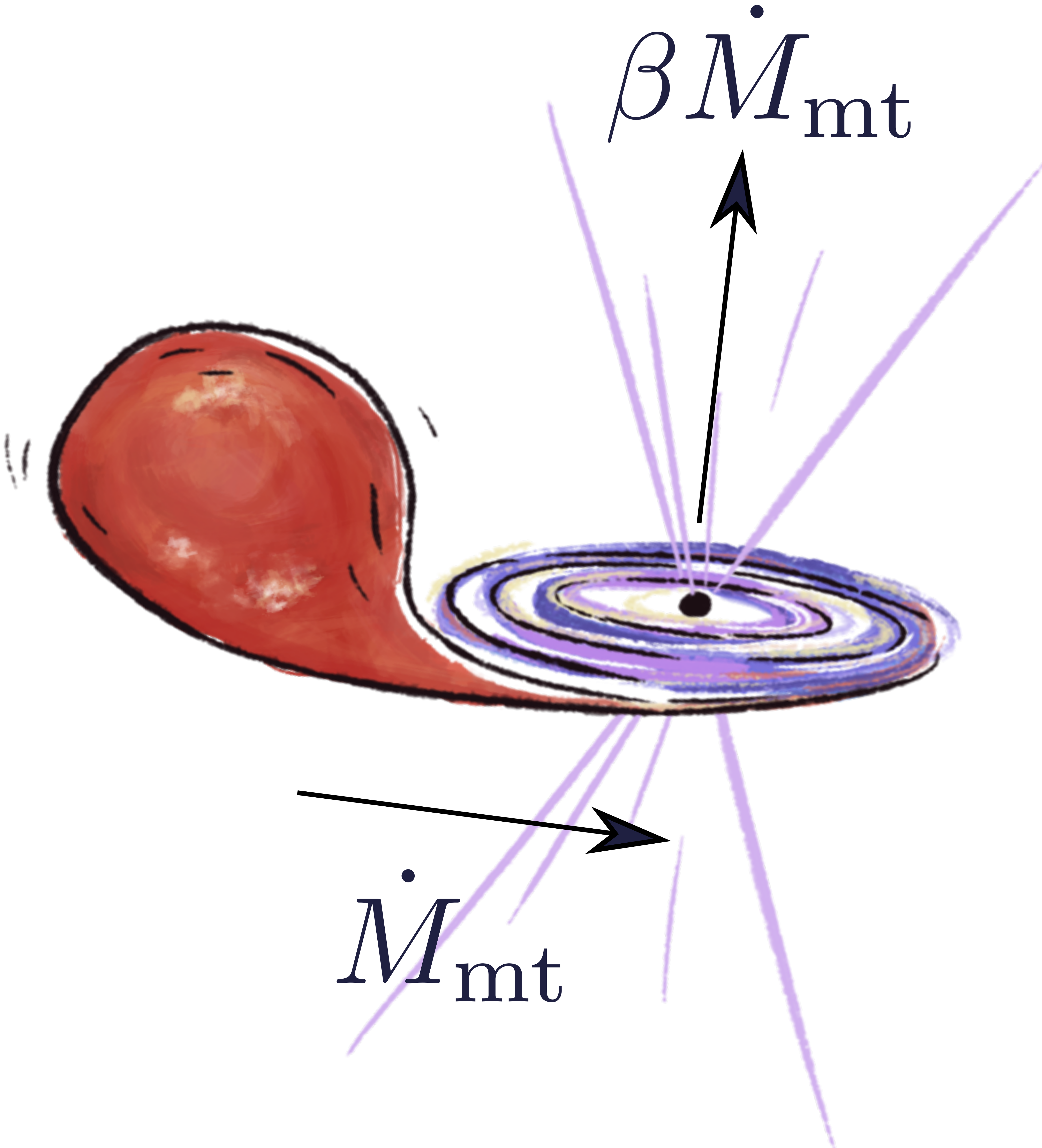
Hardening through mass transfer



Mass transfer is commonly driven on the thermal timescale of the donor

$$\dot{M}_{\rm mt} \simeq \frac{M_{\rm d}}{\tau_{\rm KH}} \simeq 10^{-3}\ M_{\odot}\ {\rm yr}^{-1}$$

Hardening through mass transfer



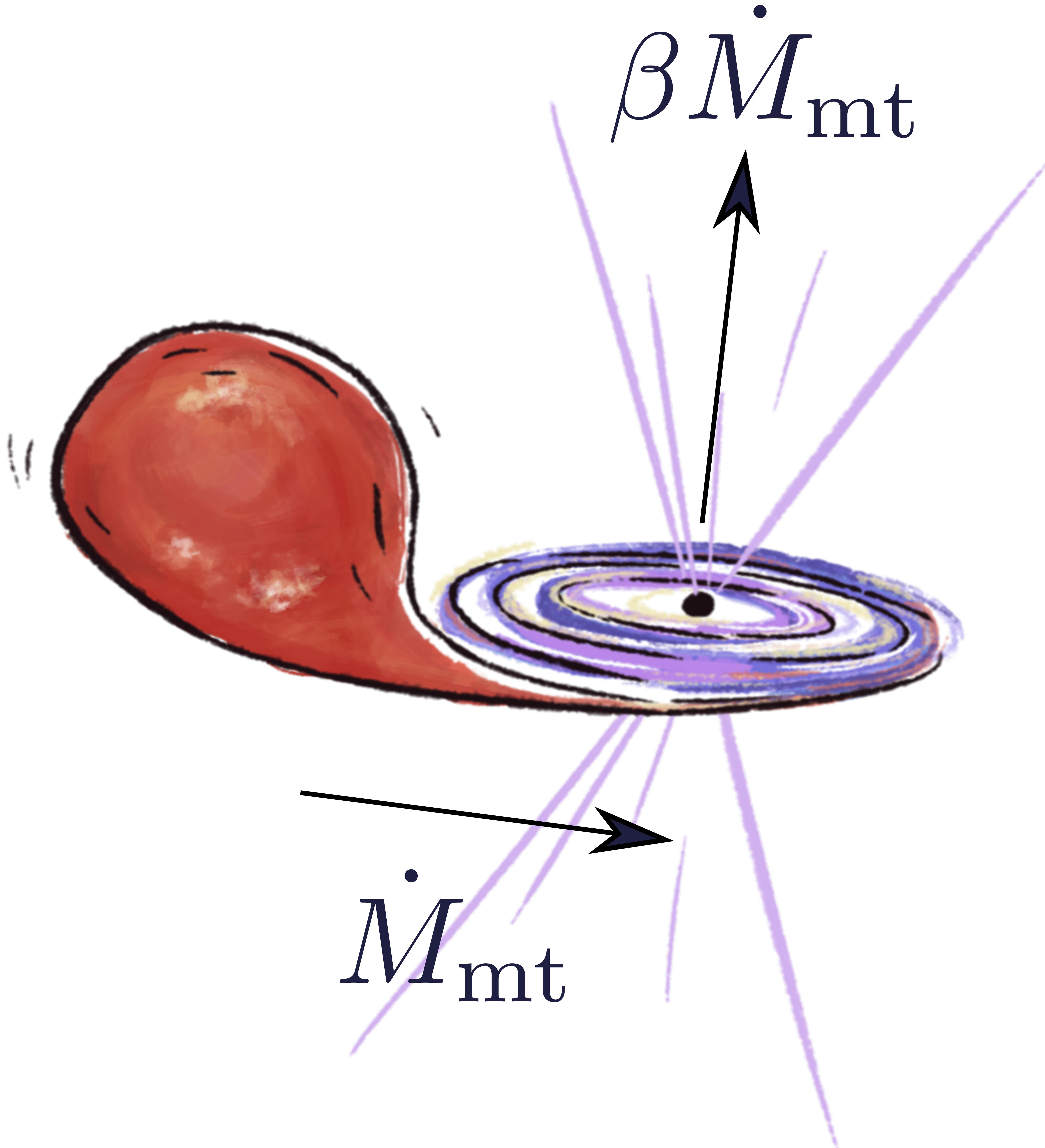
Mass transfer is commonly driven on the thermal timescale of the donor

$$\dot{M}_{\rm mt} \simeq \frac{M_{\rm d}}{\tau_{\rm KH}} \simeq 10^{-3}\ M_\odot\ {\rm yr}^{-1}$$

Eddington limit for the BH is easily reached during mass transfer ($\beta \sim 1$)

$$\dot{M}_{\rm edd} \simeq 3 \times 10^{-7} \left(\frac{M_{\rm BH}}{10 M_\odot}\right)\ M_\odot\ {\rm yr}^{-1}$$

Hardening through mass transfer



Mass transfer is commonly driven on the thermal timescale of the donor

$$\dot{M}_{\rm mt} \simeq \frac{M_{\rm d}}{\tau_{\rm KH}} \simeq 10^{-3}\ M_\odot\ {\rm yr}^{-1}$$

Eddington limit for the BH is easily reached during mass transfer ($\beta \sim 1$)

$$\dot{M}_{\rm edd} \simeq 3 \times 10^{-7} \left(\frac{M_{\rm BH}}{10 M_\odot}\right)\ M_\odot\ {\rm yr}^{-1}$$

Orbital evolution can be computed from orbital angular momentum loss

$$\dot{L} = \beta \dot{M}_{\rm mt} \Omega_{\rm orb} \left(\frac{M_{\rm d}}{M_{\rm d} + M_{\rm BH}} a_{\rm orb}\right)^2$$

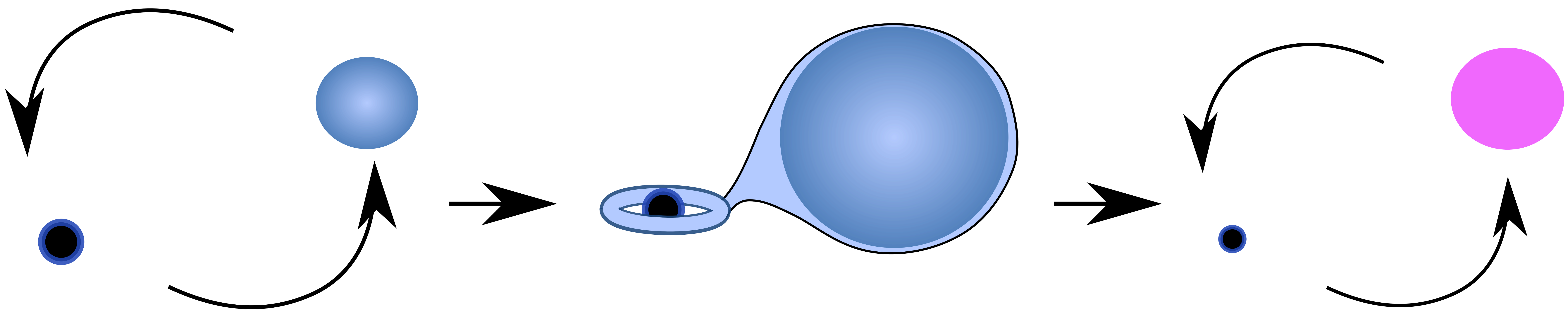
(see, for example, Soberman et al. 1997)

Hardening through mass transfer

$$\frac{P}{P_0} = \left(\frac{q_0+1}{q+1}\right)^2 \left(\frac{q_0}{q}\right)^3 \exp[-3(q_0 - q)],\; q \equiv \frac{M_\mathrm{d}}{M_\mathrm{a}}$$

Hardening through mass transfer

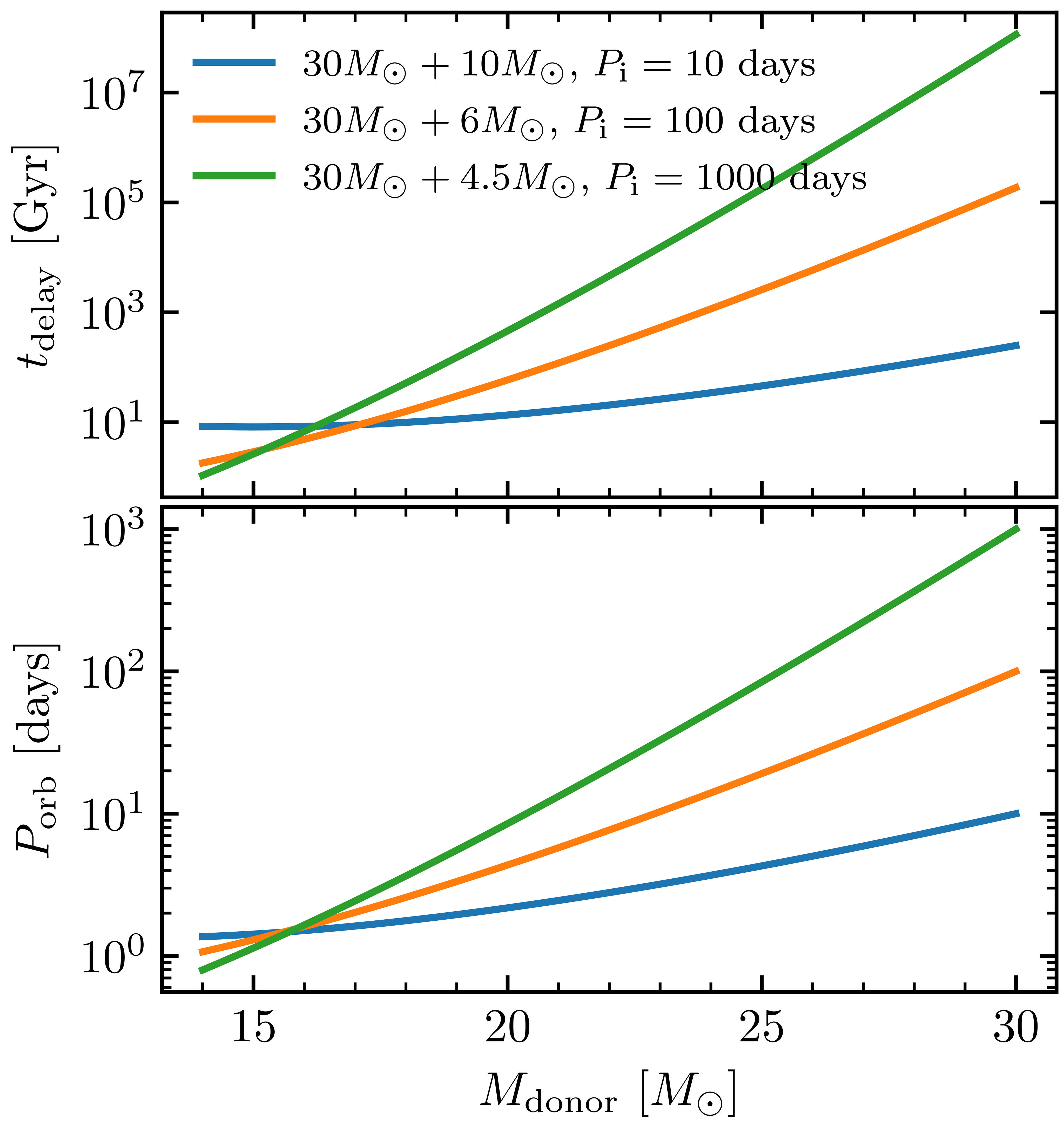
$$\frac{P}{P_0} = \left(\frac{q_0+1}{q+1}\right)^2 \left(\frac{q_0}{q}\right)^3 \exp[-3(q_0 - q)],\ q \equiv \frac{M_\mathrm{d}}{M_\mathrm{a}}$$



$$P_0, q_0 = \frac{M_\mathrm{OB}}{M_\mathrm{BH}} \qquad P_f, q_f = \frac{M_\mathrm{He}}{M_\mathrm{BH}}$$

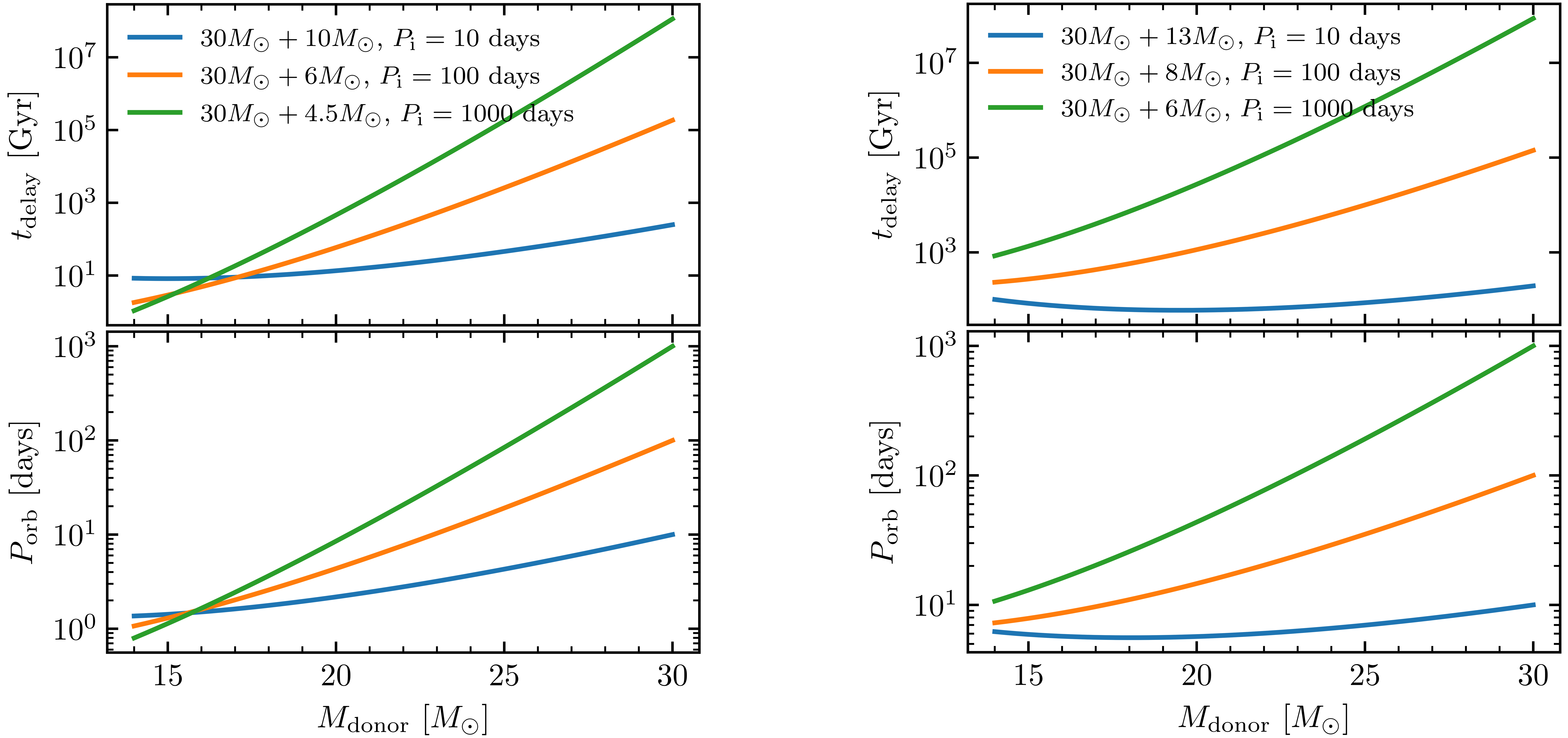
Hardening through mass transfer

$$\frac{P}{P_0} = \left(\frac{q_0+1}{q+1}\right)^2 \left(\frac{q_0}{q}\right)^3 \exp[-3(q_0 - q)],\ q \equiv \frac{M_{\rm d}}{M_{\rm a}}$$



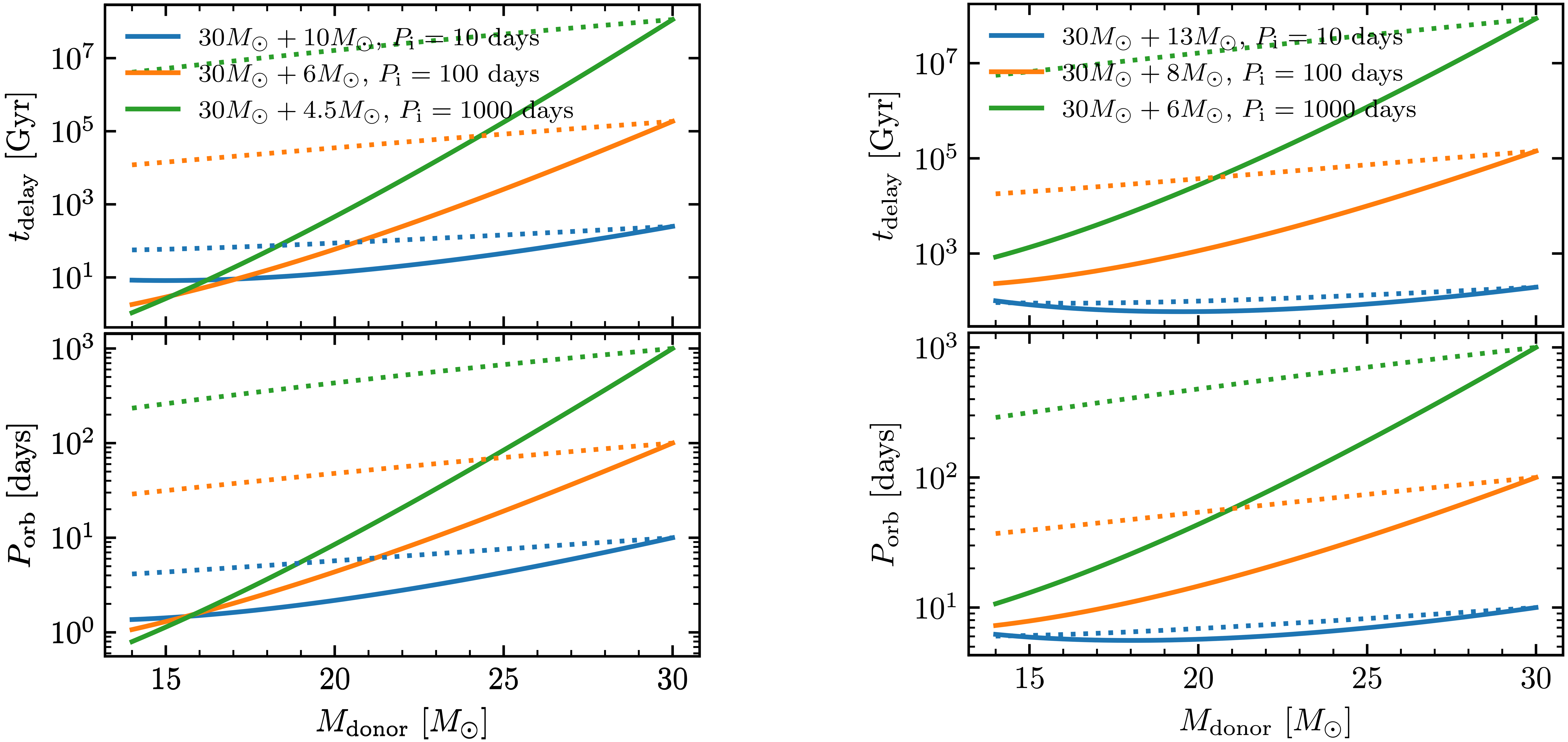
Hardening through mass transfer

$$\frac{P}{P_0} = \left(\frac{q_0+1}{q+1}\right)^2 \left(\frac{q_0}{q}\right)^3 \exp[-3(q_0-q)],\ q \equiv \frac{M_\mathrm{d}}{M_\mathrm{a}}$$



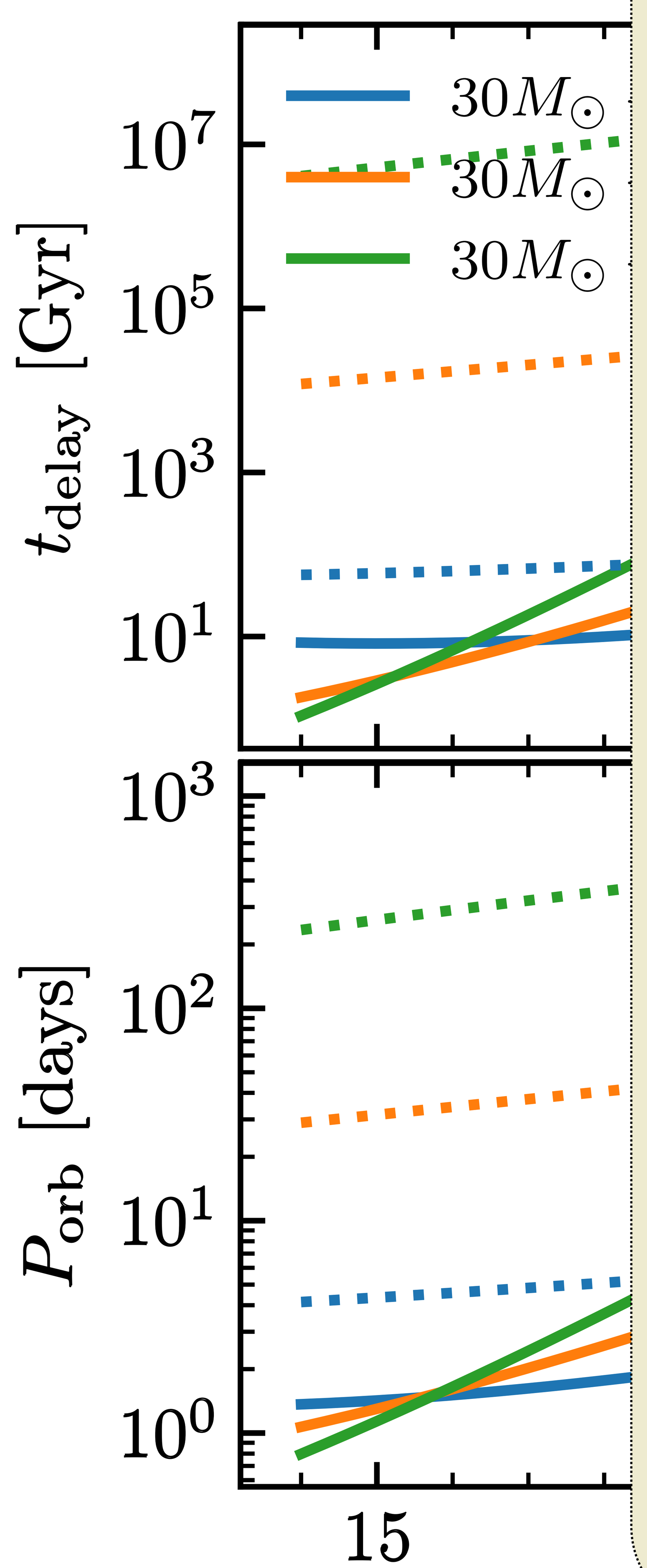
Hardening through mass transfer

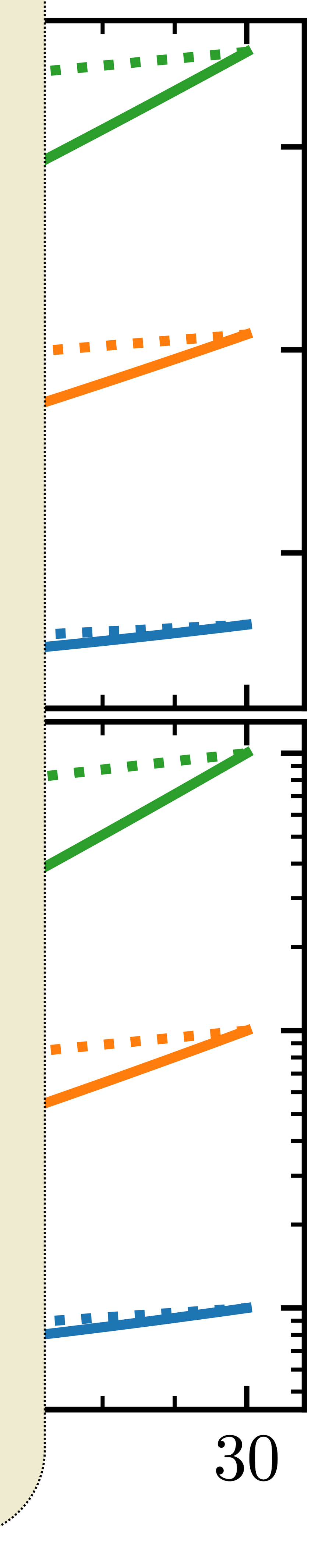
$$\frac{P}{P_0} = \left(\frac{q_0+1}{q+1}\right)^2 \left(\frac{q_0}{q}\right)^3 \exp[-3(q_0 - q)],\ q \equiv \frac{M_\mathrm{d}}{M_\mathrm{a}}$$

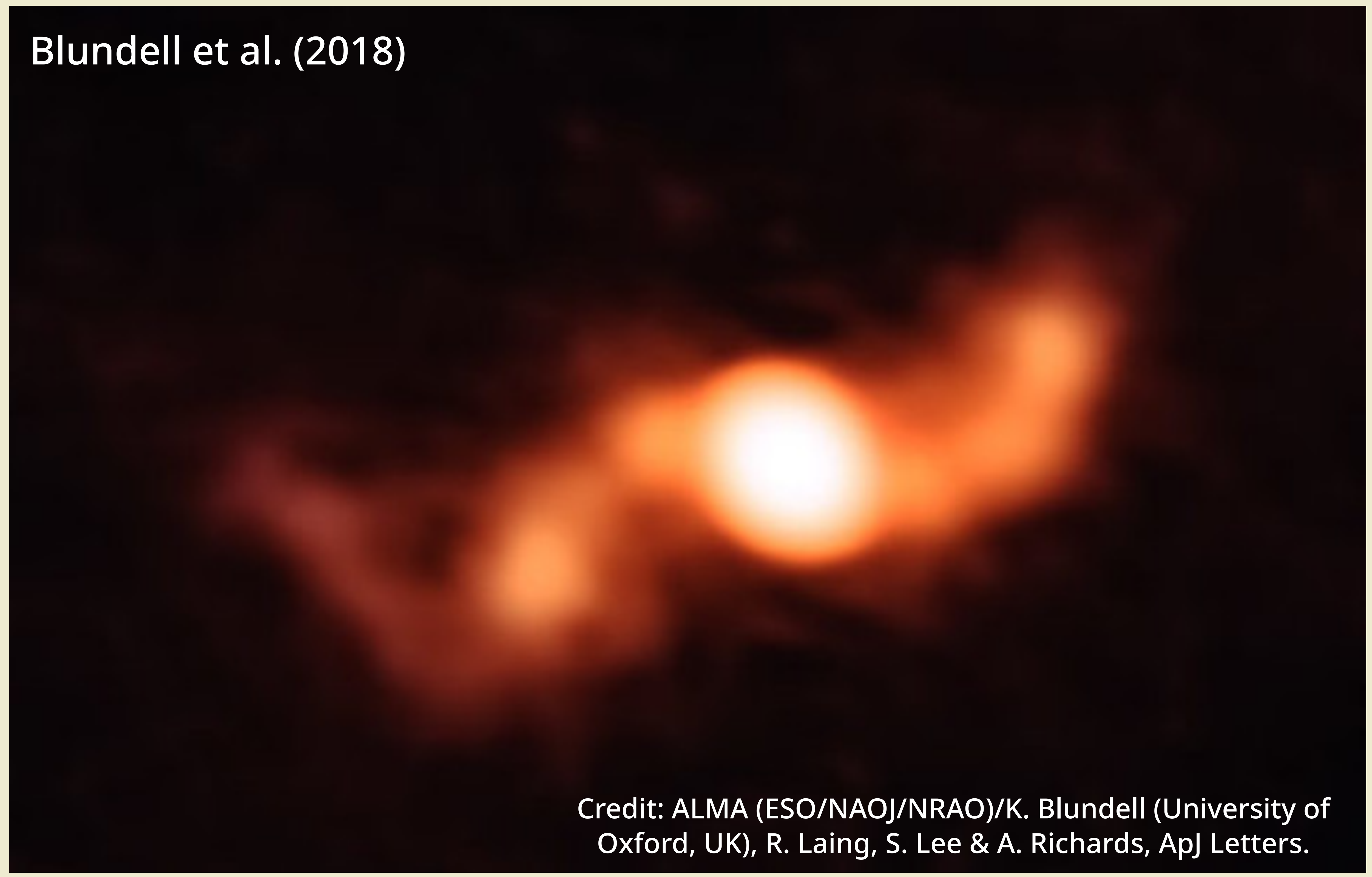


Hardening through mass transfer

$$\frac{P}{P_0} = \left(\quad \right)^2 \left(\quad \right)^3 \ldots \frac{M_\mathrm{d}}{M_\mathrm{a}}$$







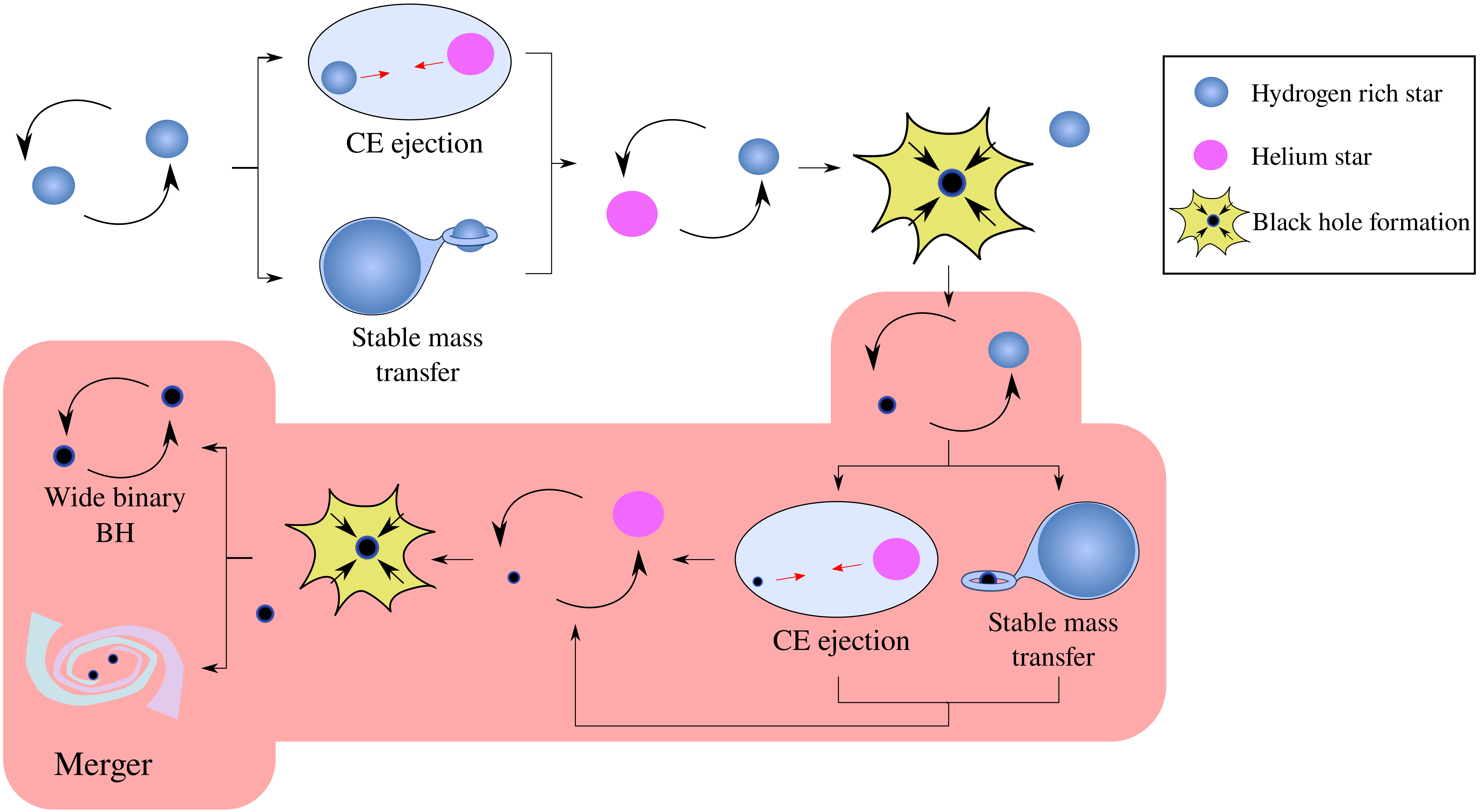
SS433, parameters from Hillwig & Gies (2008)

$M_\mathrm{donor} = 12.3 \pm 3.3\ M_\odot$

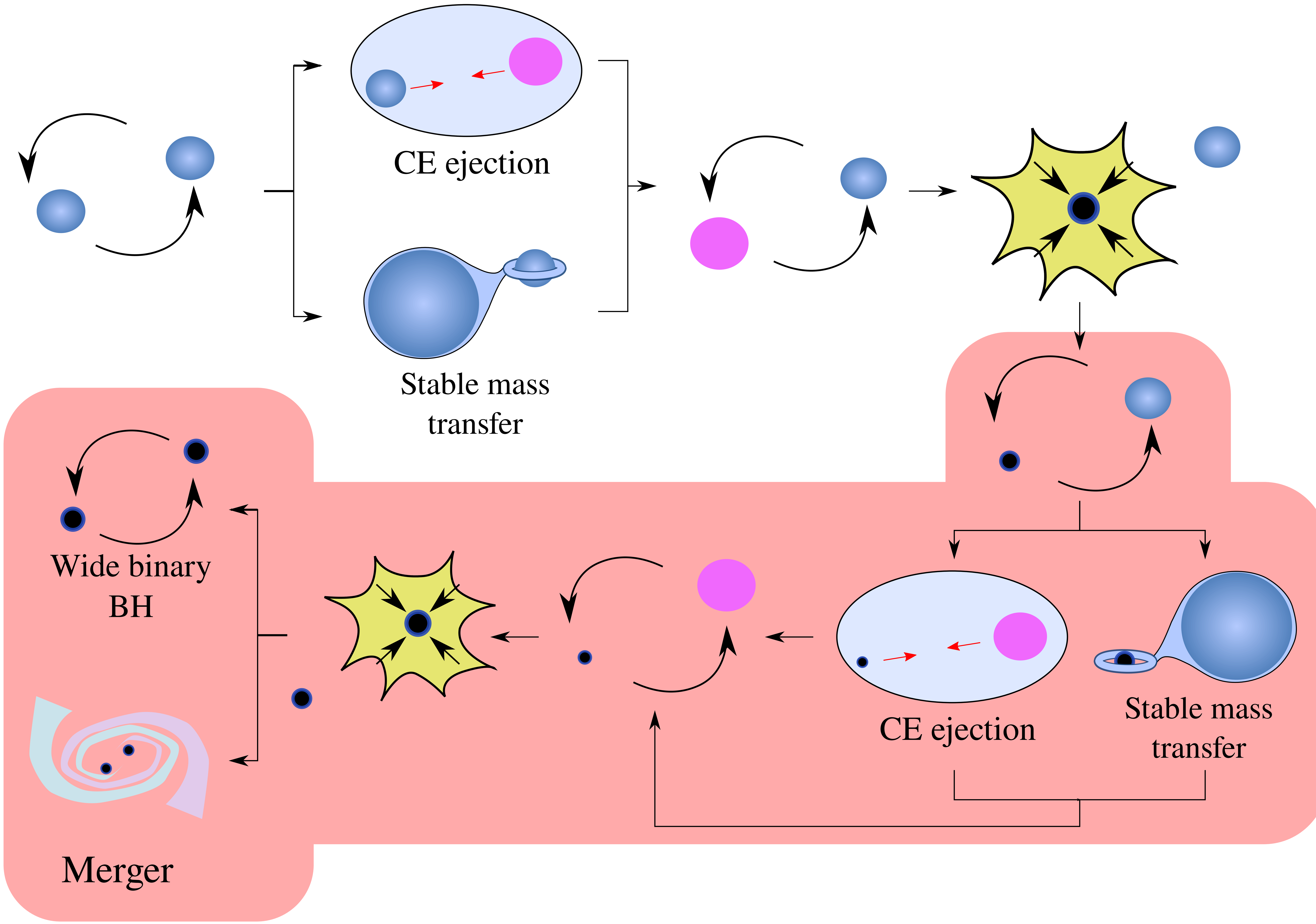
$M_\mathrm{BH} = 4.3 \pm 0.8\ M_\odot$

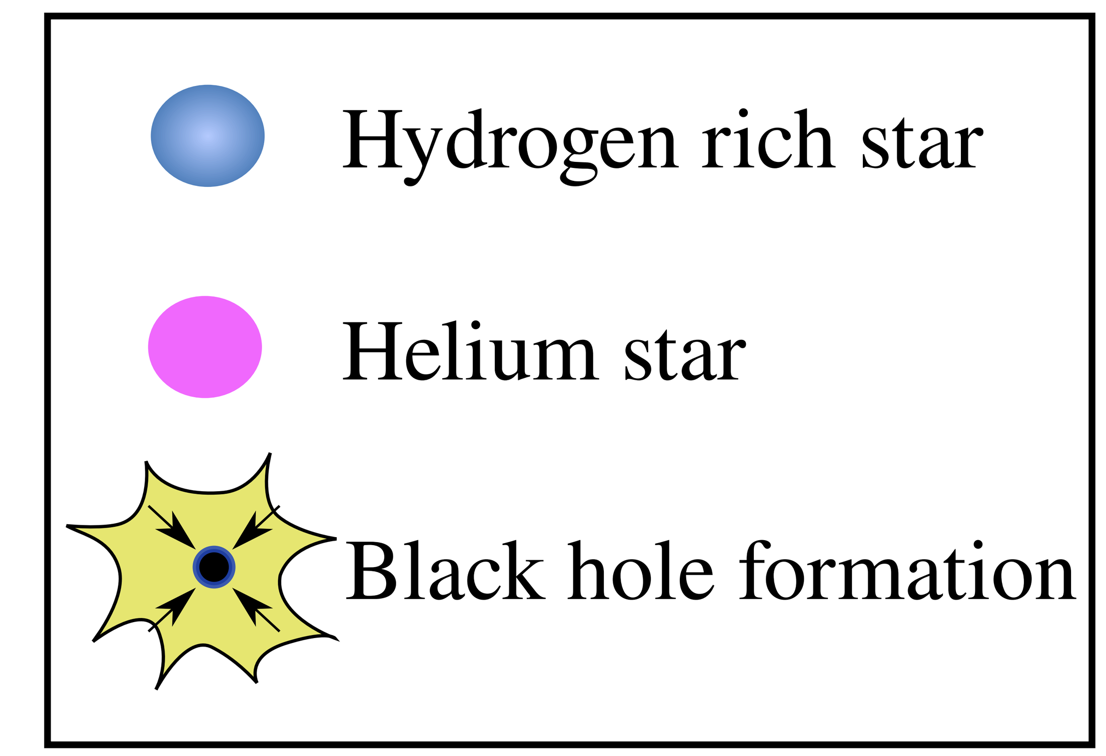
$P_\mathrm{orb} = 13.1$ days

Detailed simulations of the OB+BH phase



Detailed simulations of the OB+BH phase



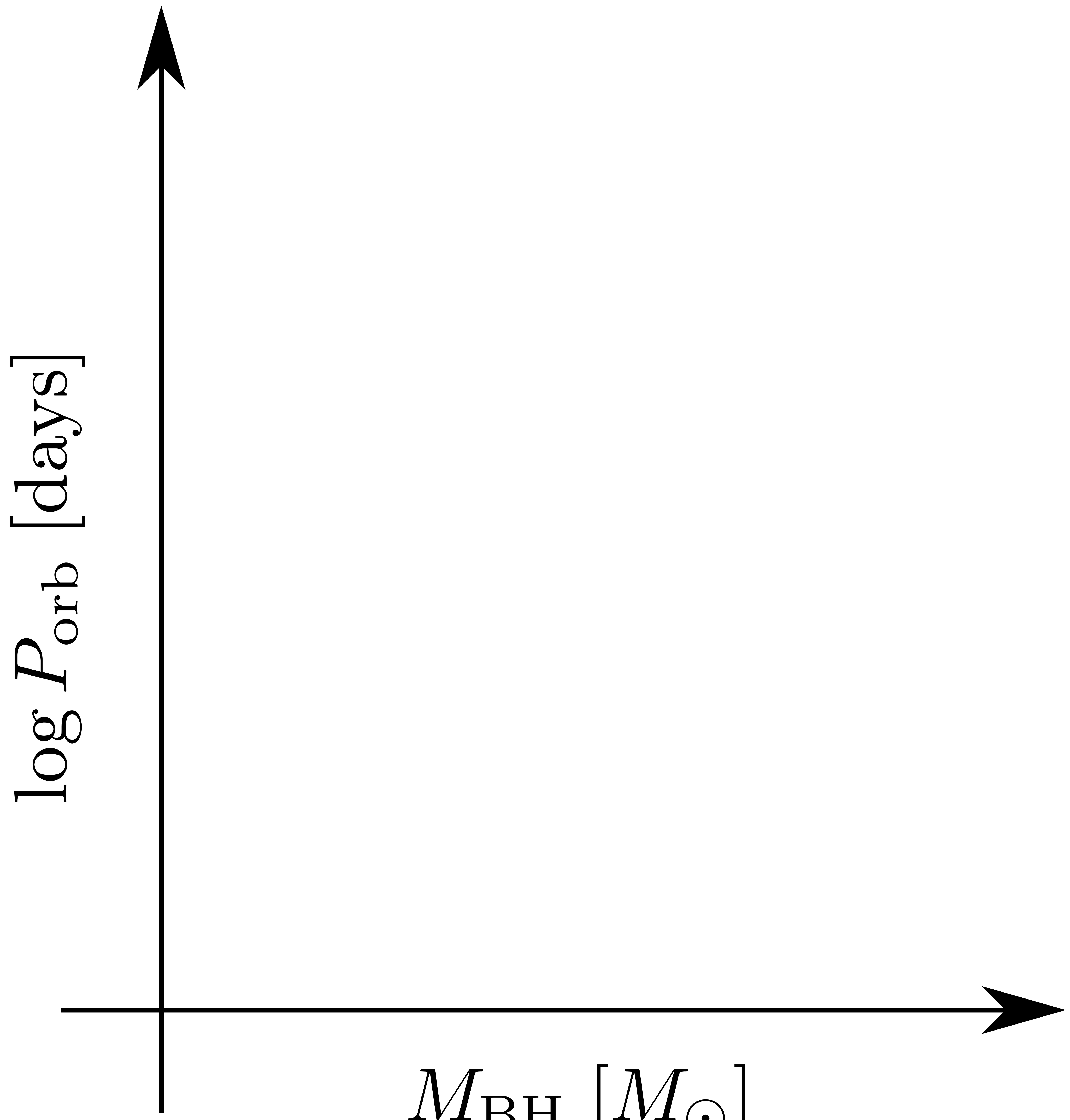


MESA

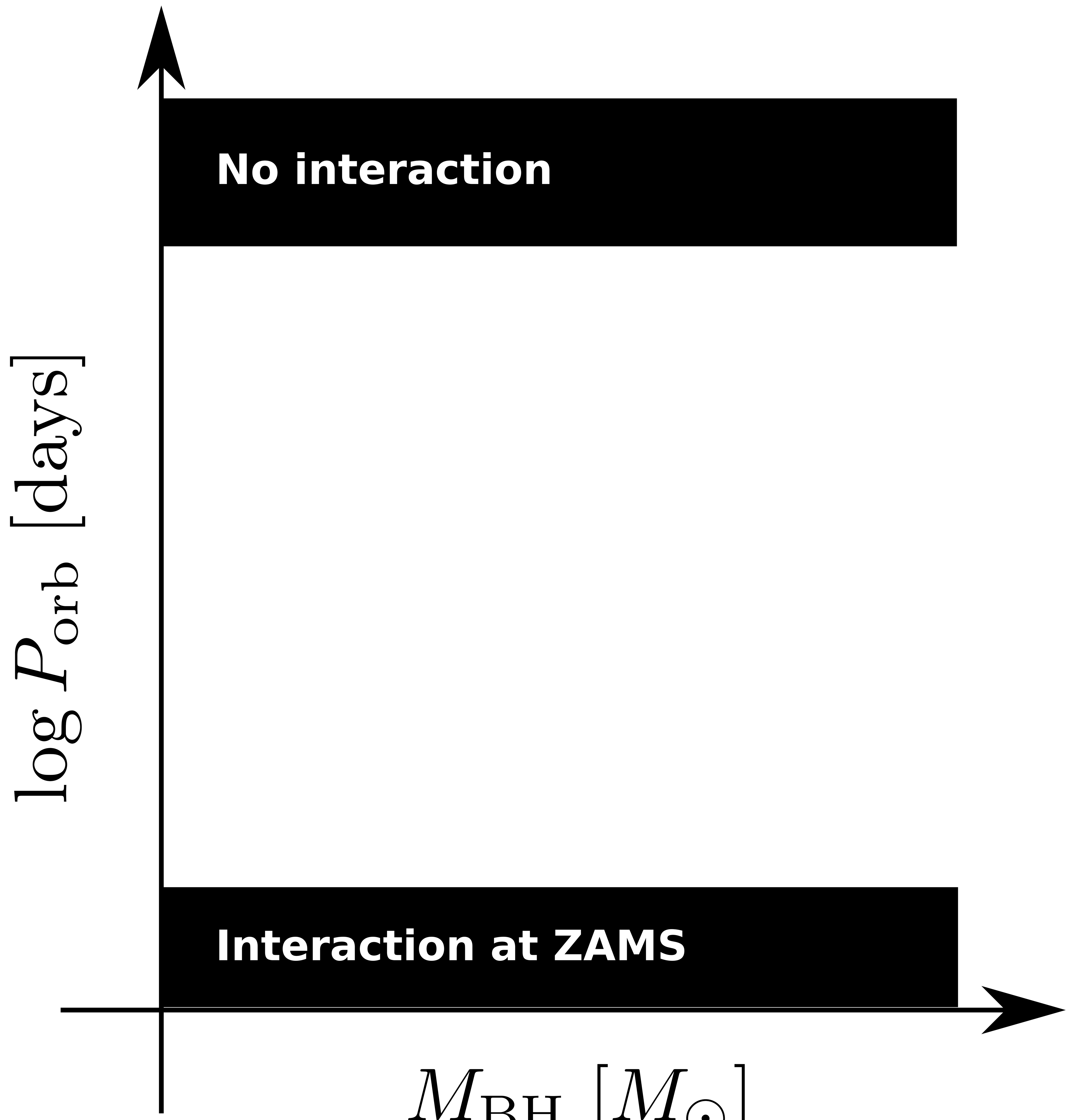
Paxton et al. (2015)

Marchant, Pappas et al. (2021)

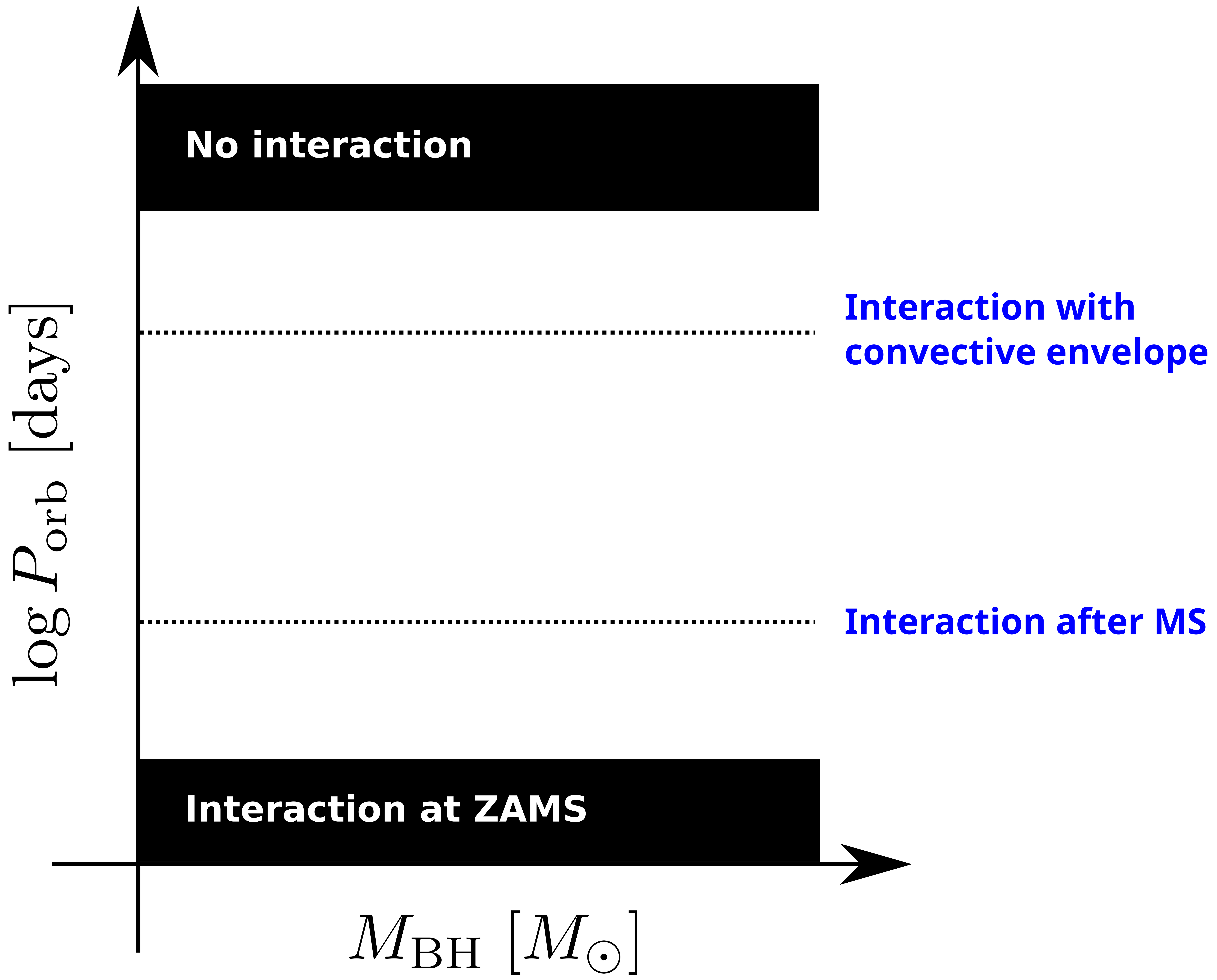
Binary model outcomes



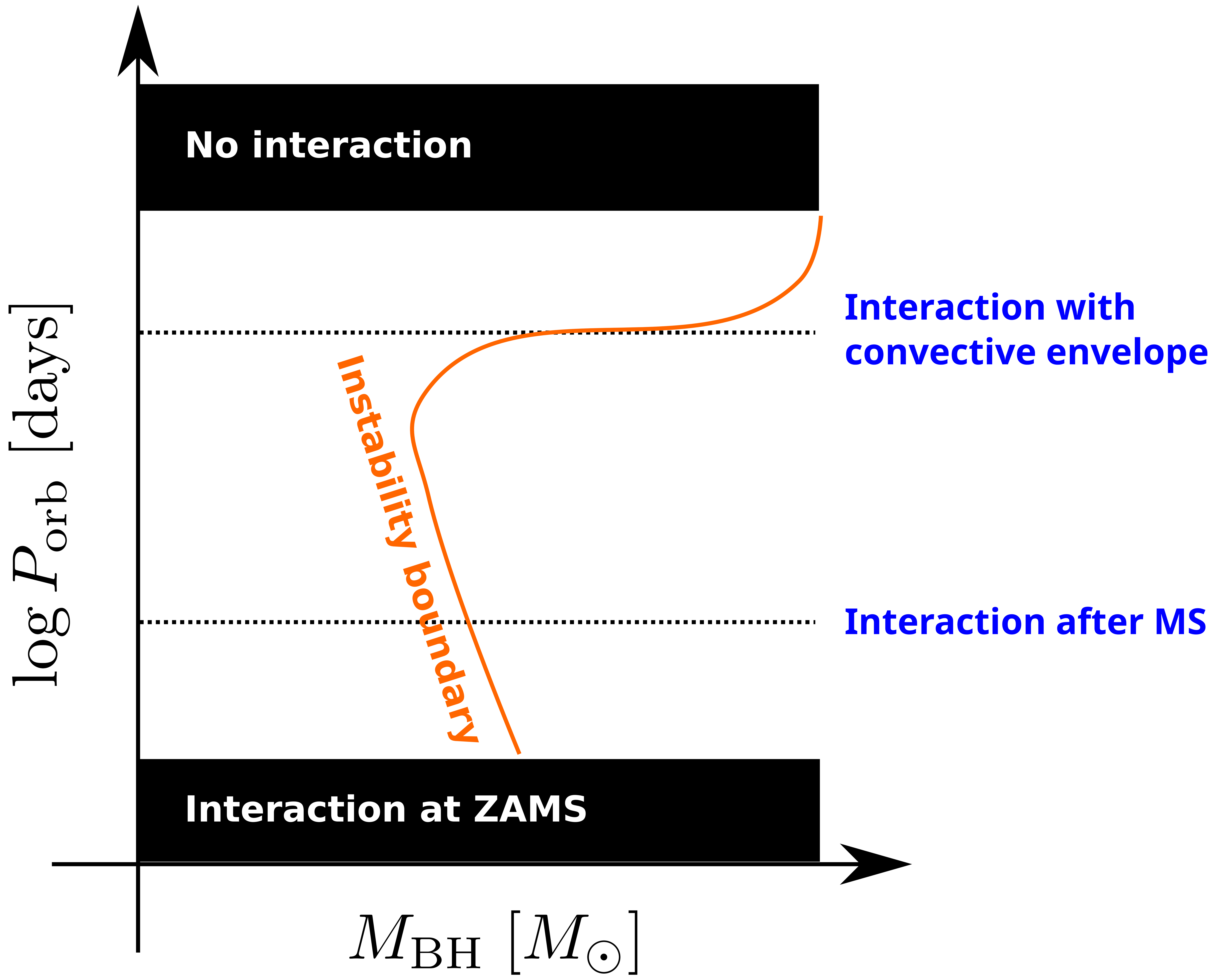
Binary model outcomes



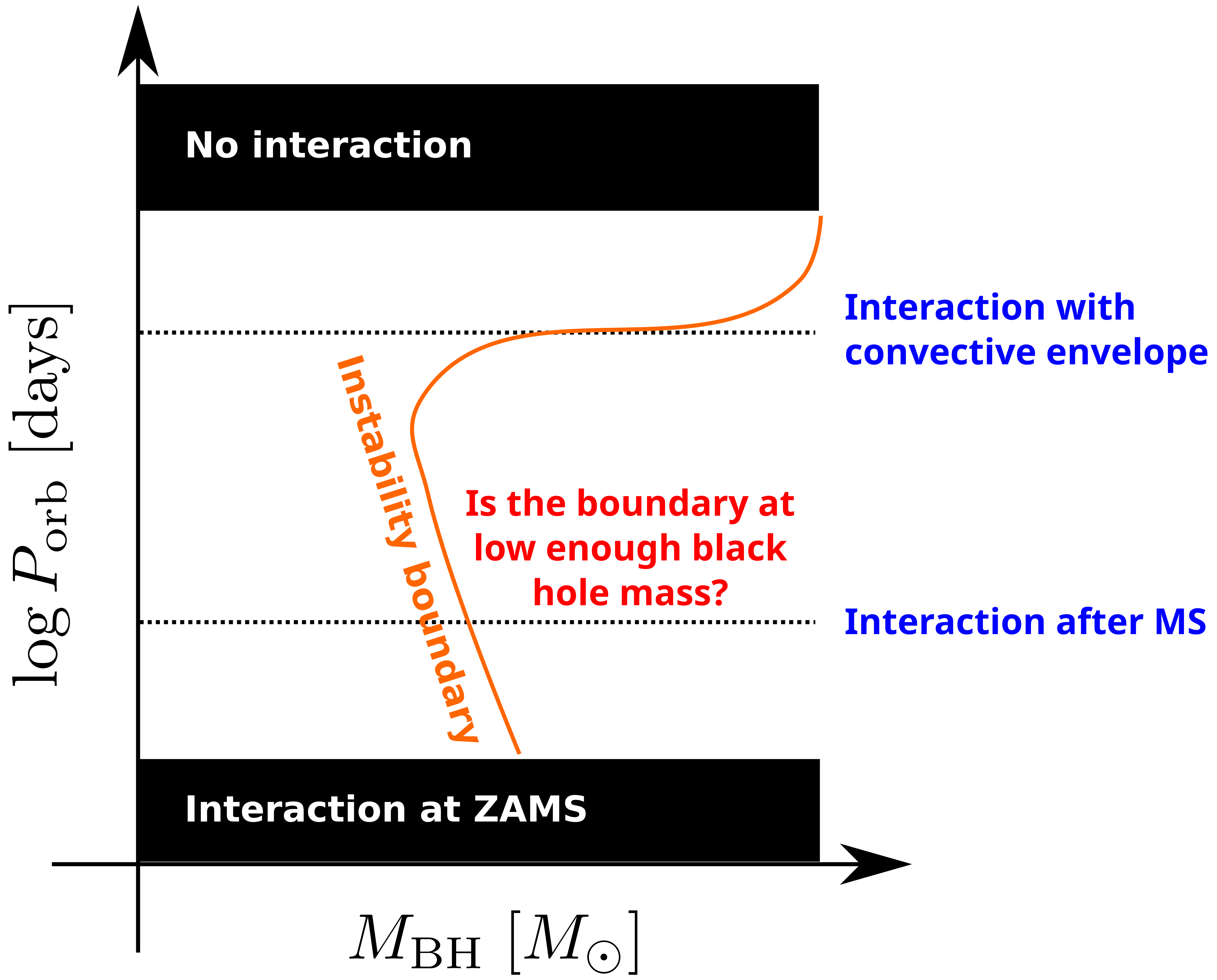
Binary model outcomes



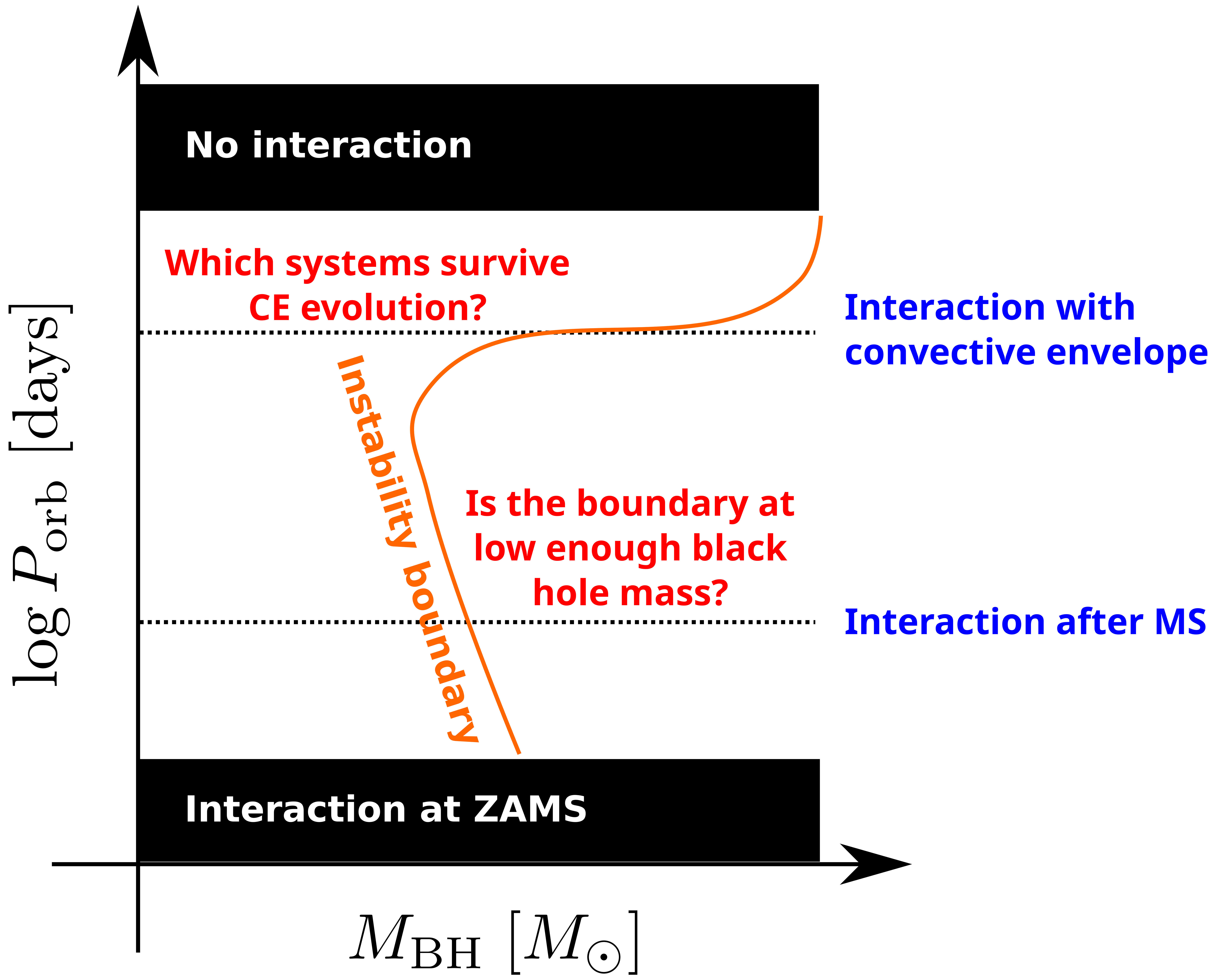
Binary model outcomes



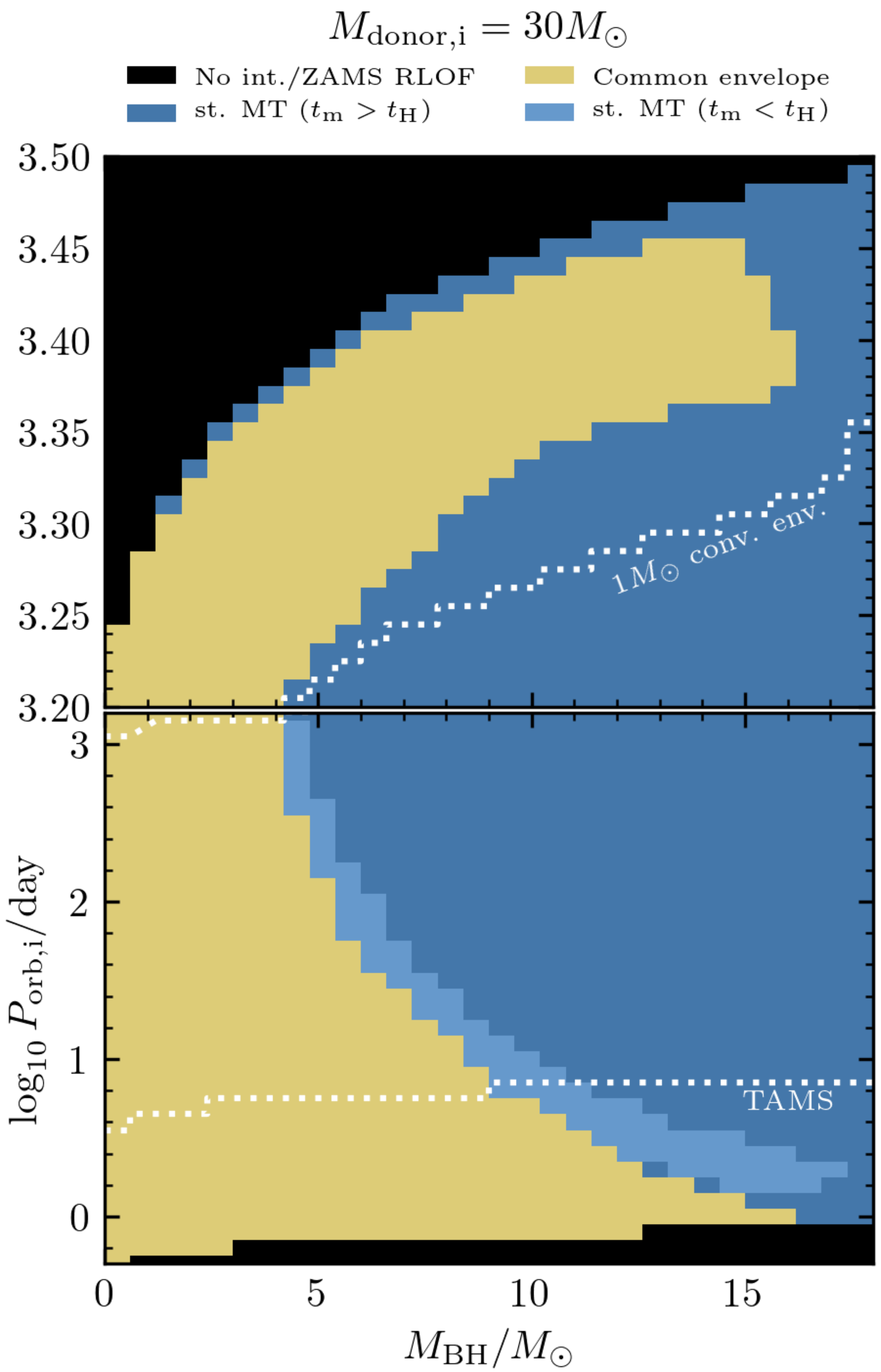
Binary model outcomes



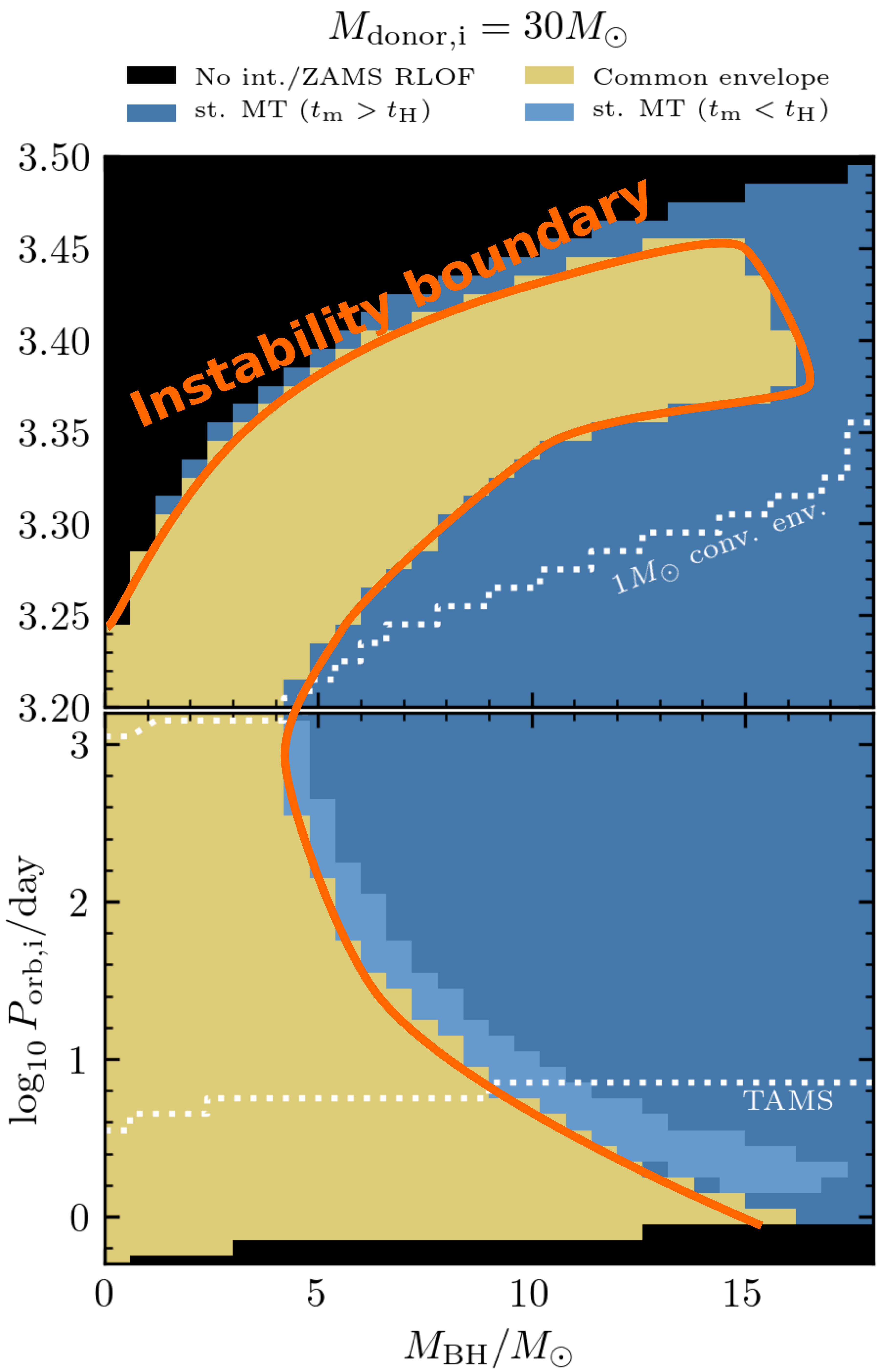
Binary model outcomes



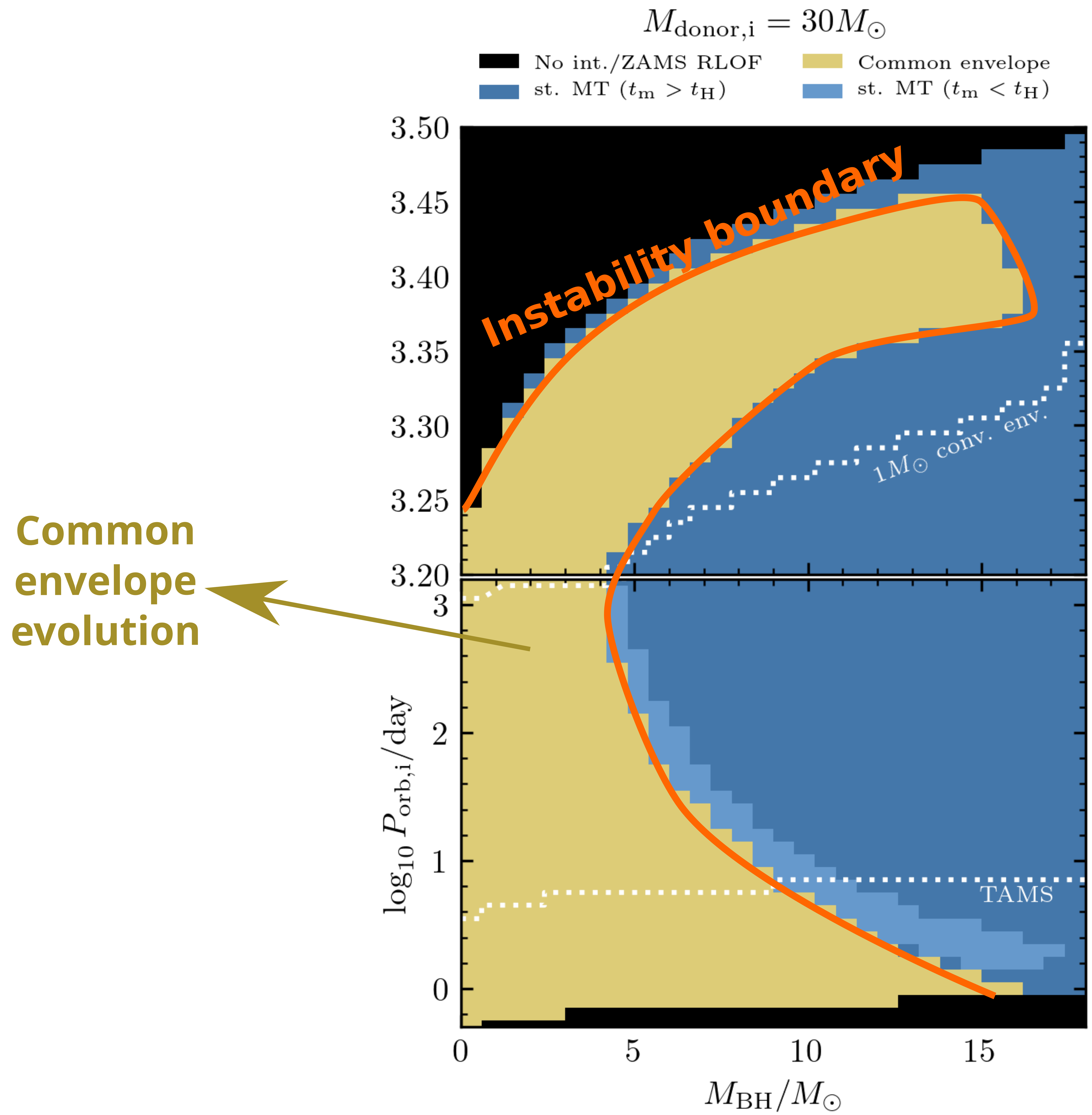
Binary model outcomes



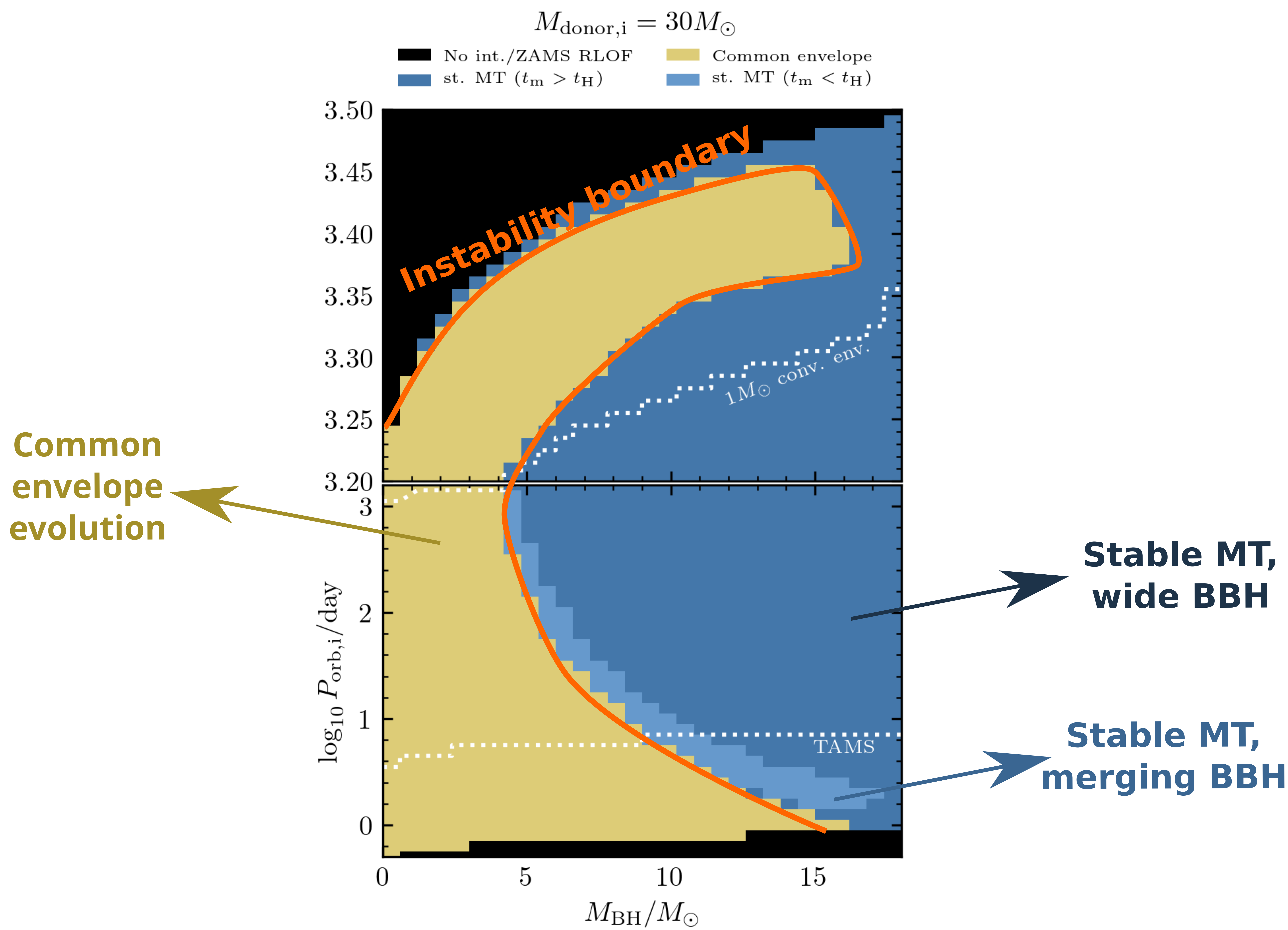
Binary model outcomes



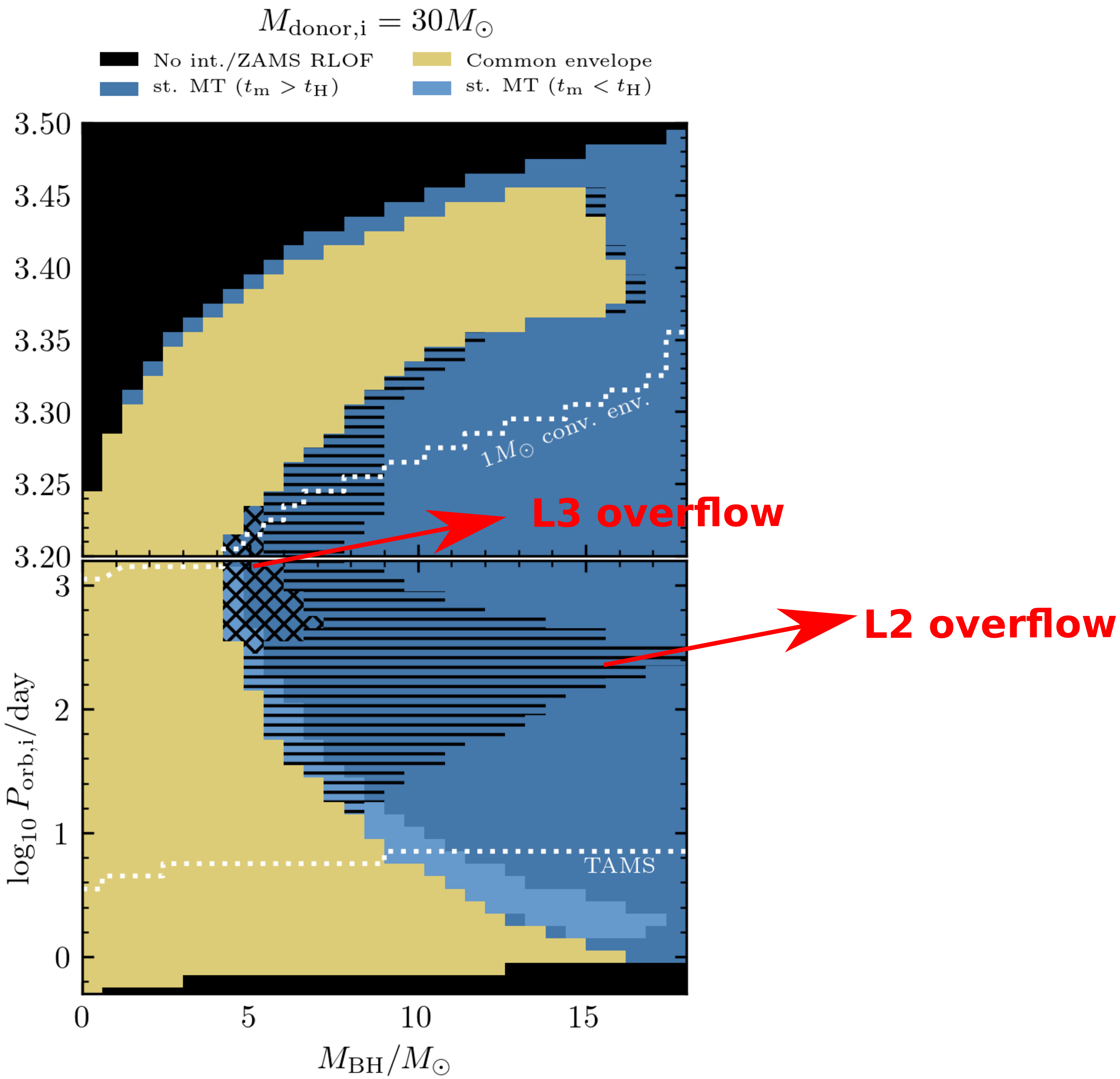
Binary model outcomes



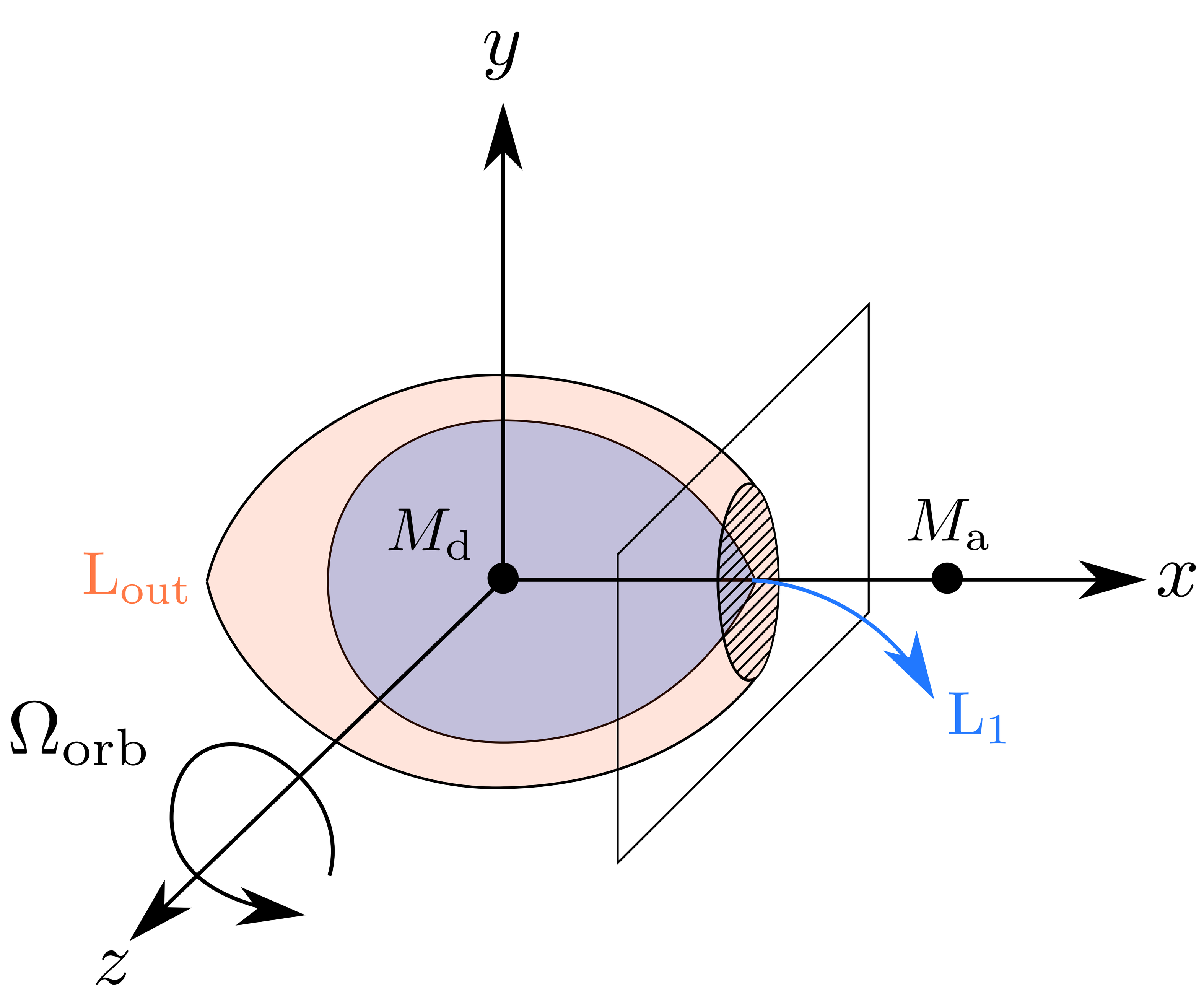
Binary model outcomes



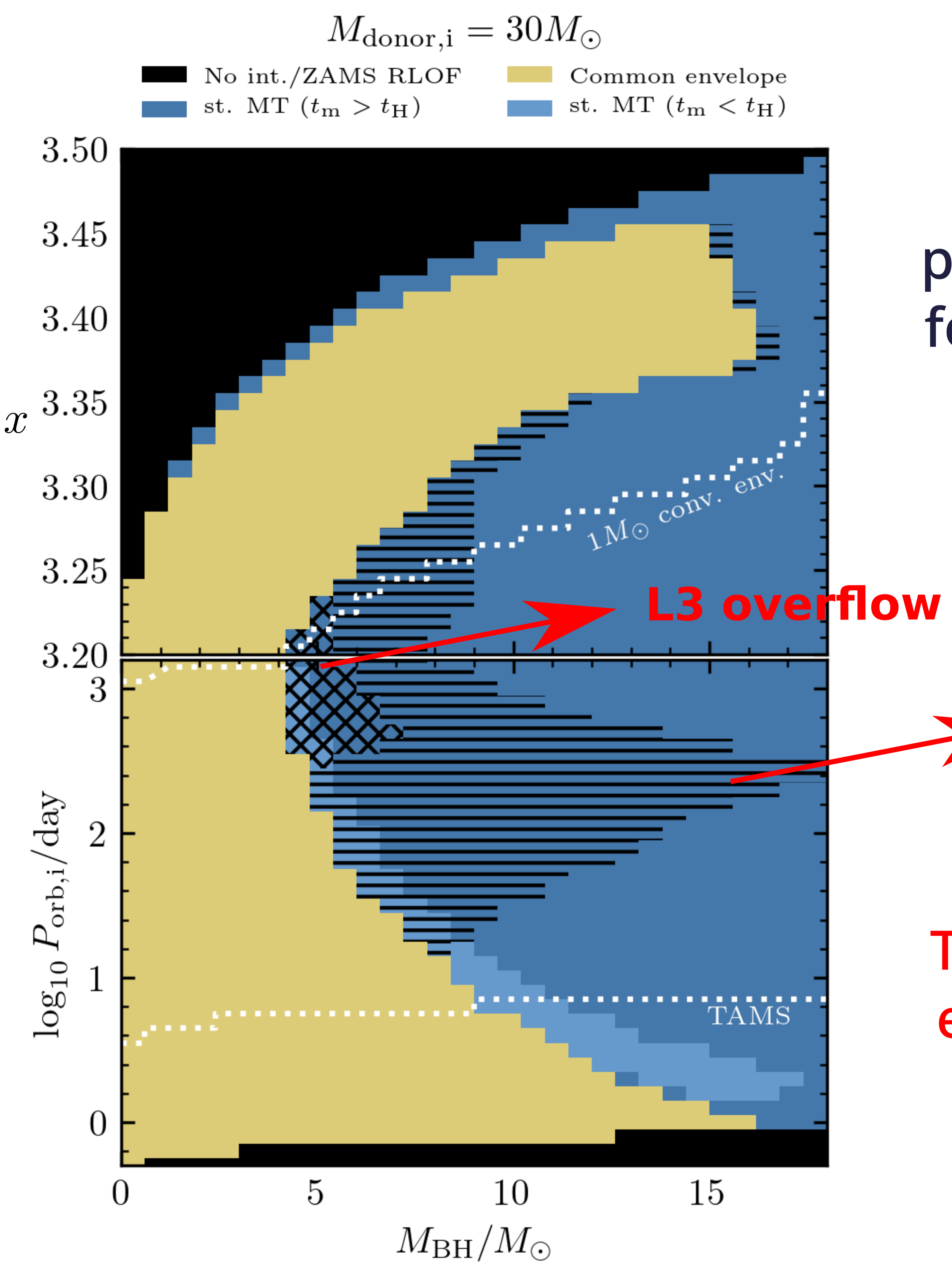
Outer Lagrangian point overflow



Outer Lagrangian point overflow



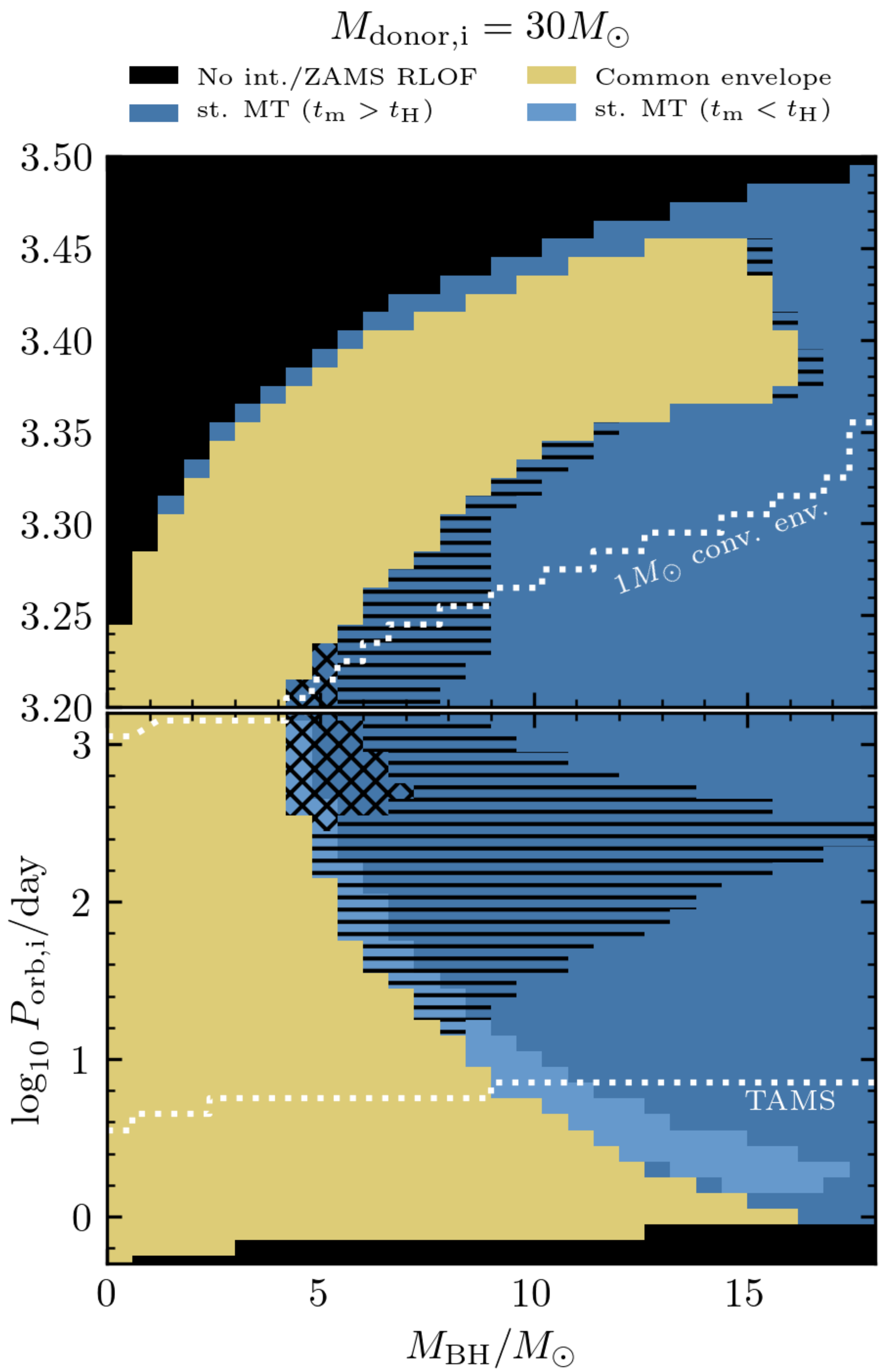
$$j_{L2/3} = \Omega_{orb} X^2_{L2/3}$$



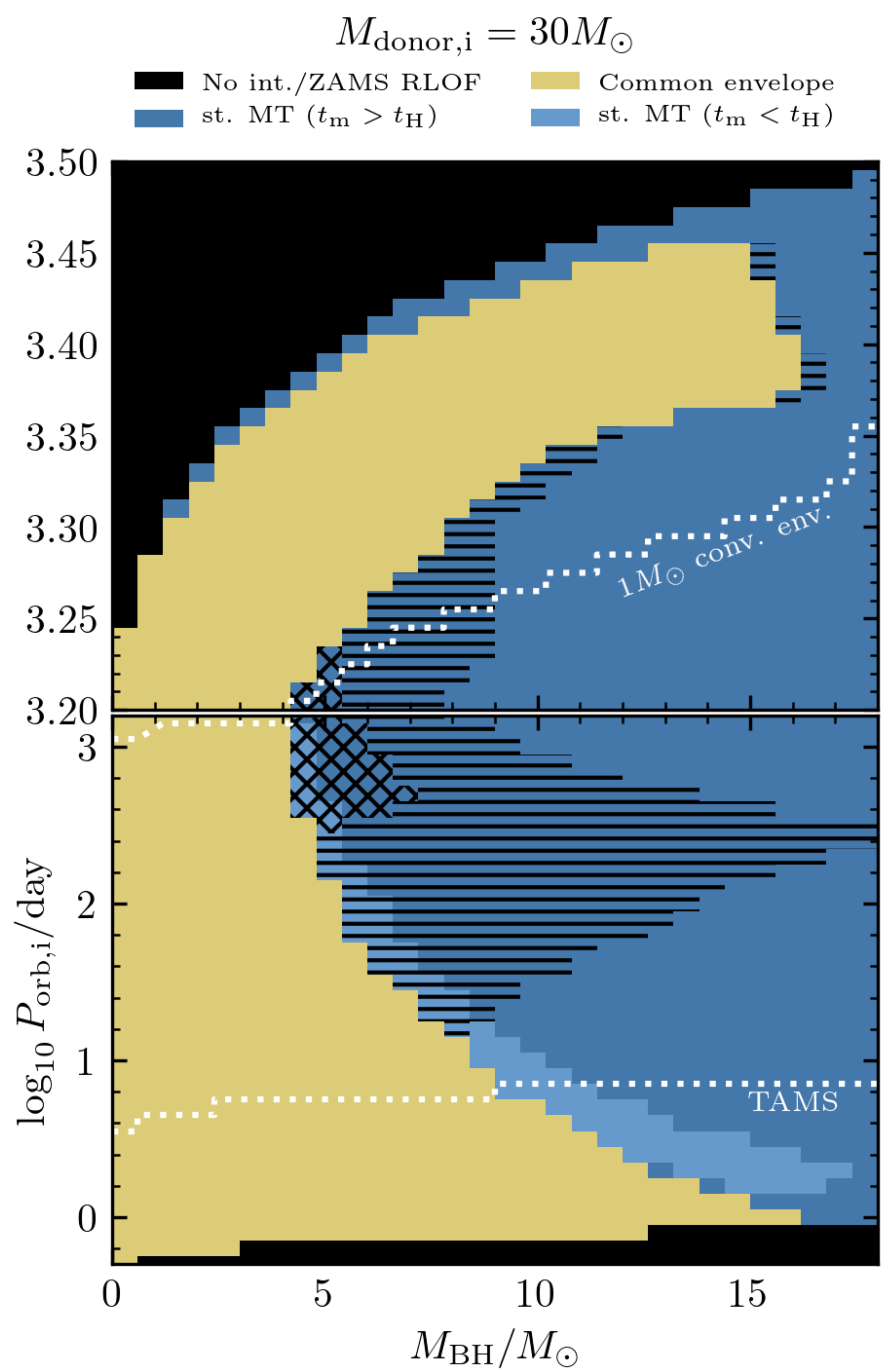
Extension of Kolb & Ritter mass transfer prescription to account for overflow of outer L. points

Typical fraction of 10% ejected through outer L. points, systems remain stable!

Binary model outcomes



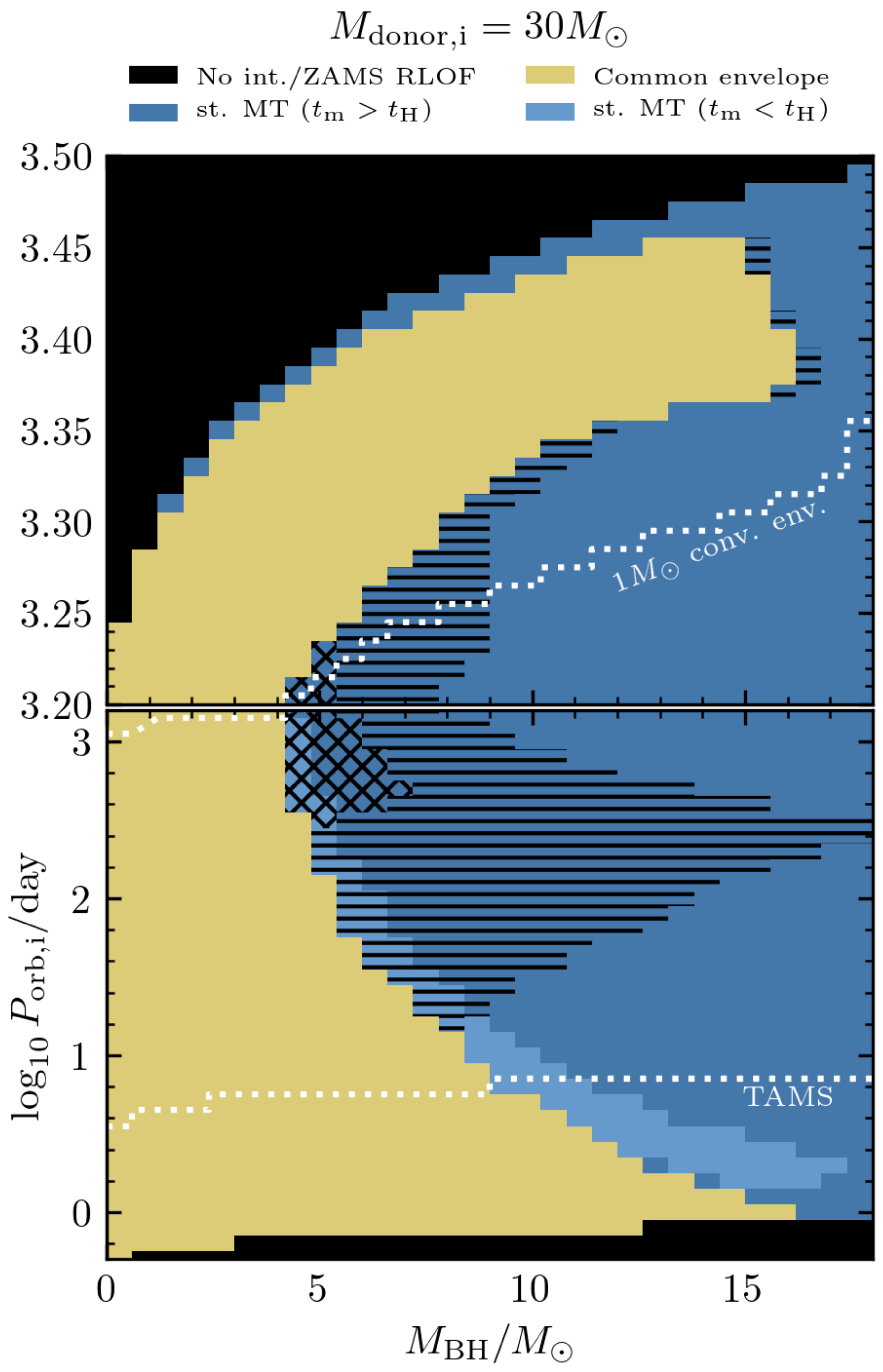
Binary model outcomes



Gallegos-Garcia et al. (2021)

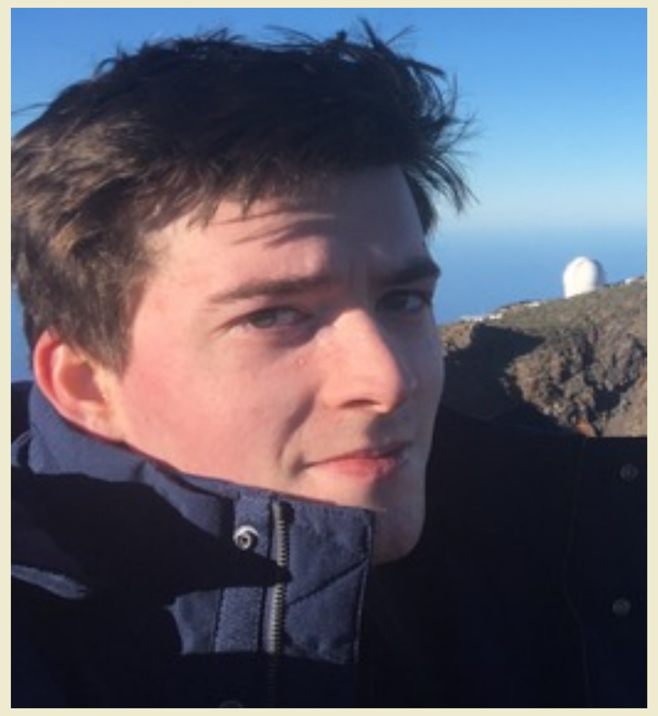
Pop-synth significantly overestimates CE contribution.

Binary model outcomes



Gallegos-Garcia et al. (2021)

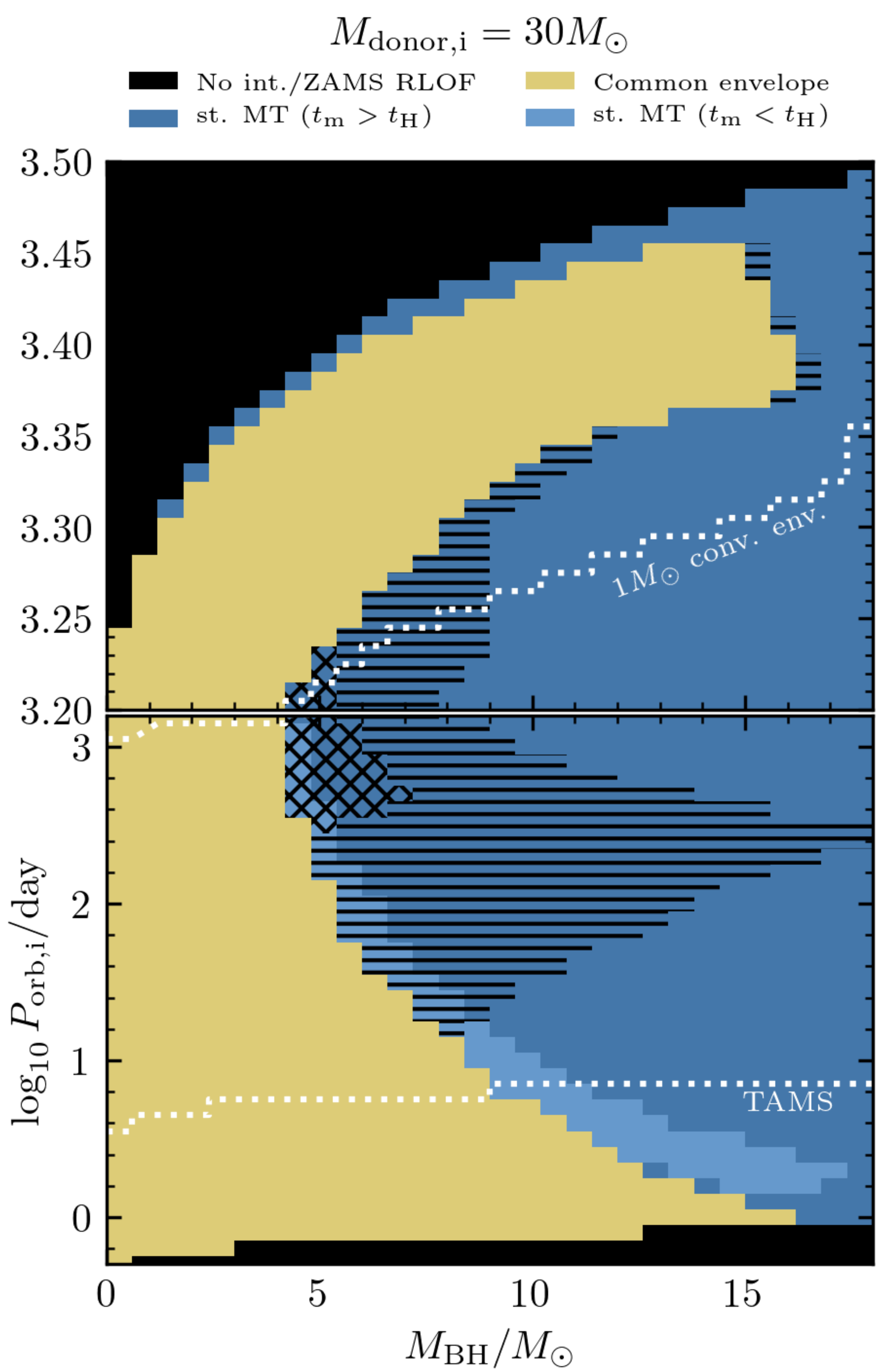
Pop-synth significantly overestimates CE contribution.



Fabry et al. (2021)

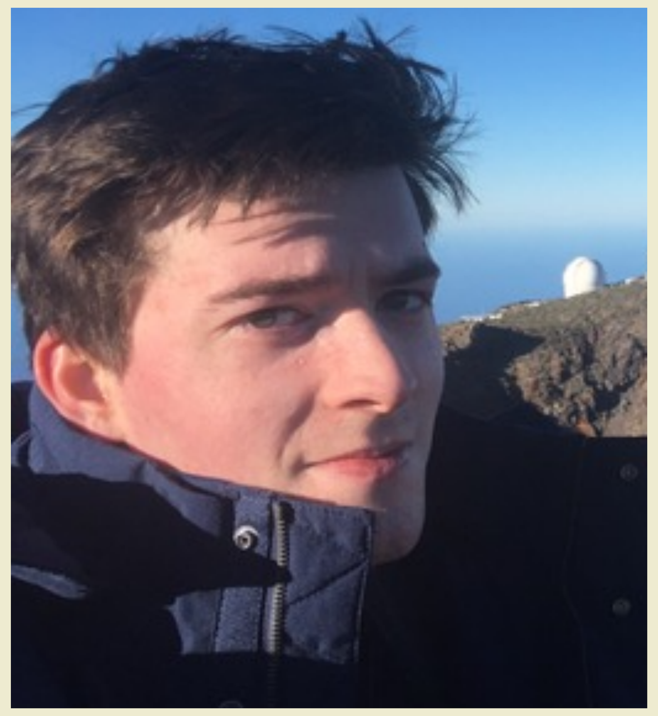
Impact of tidal deformation on stellar structure and evolution. Possible impact in MT stability.

Binary model outcomes



Gallegos-Garcia et al. (2021)

Pop-synth significantly overestimates CE contribution.



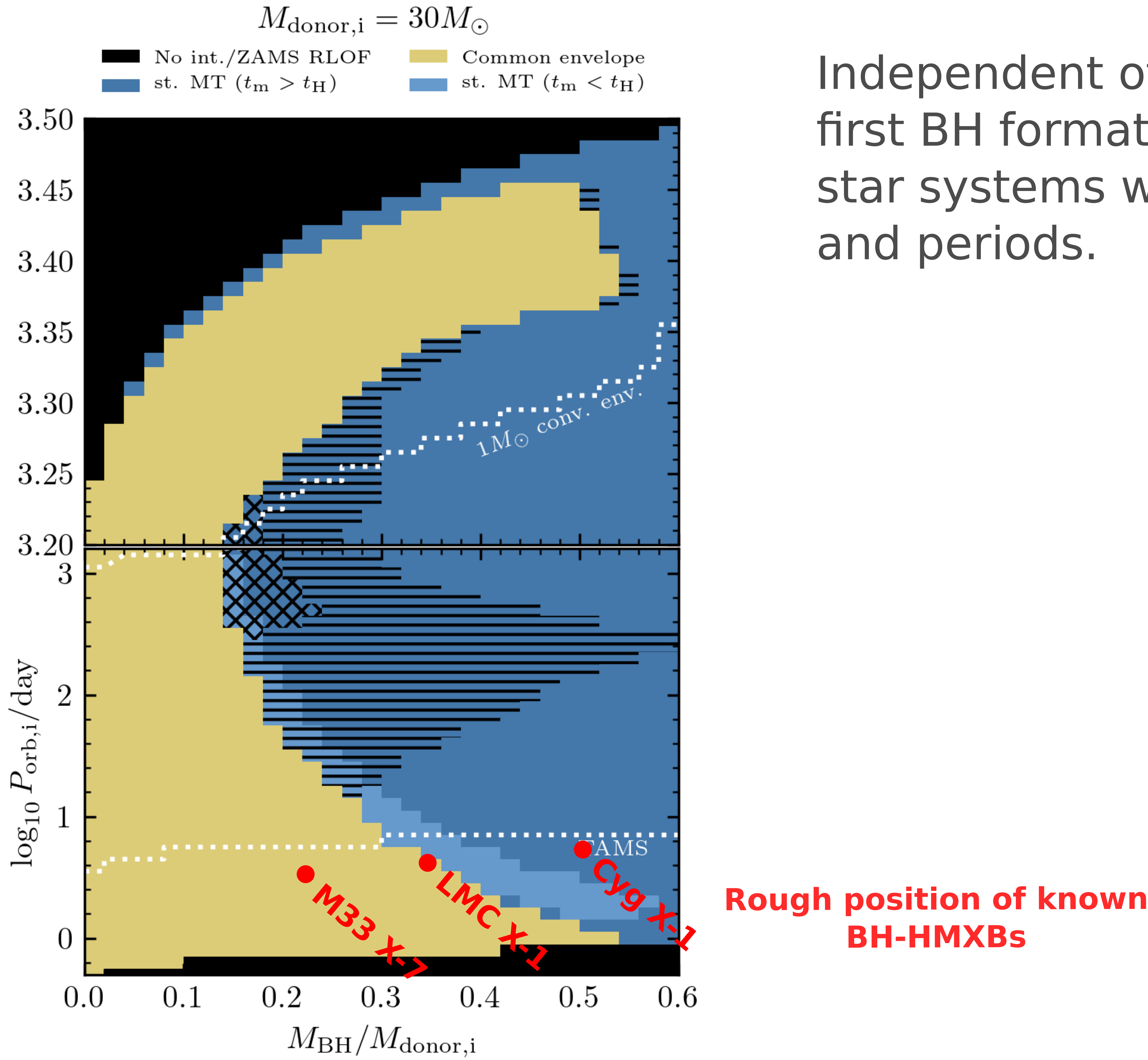
Fabry et al. (2021)

Impact of tidal deformation on stellar structure and evolution. Possible impact in MT stability.

Picco et al. (in preparation)

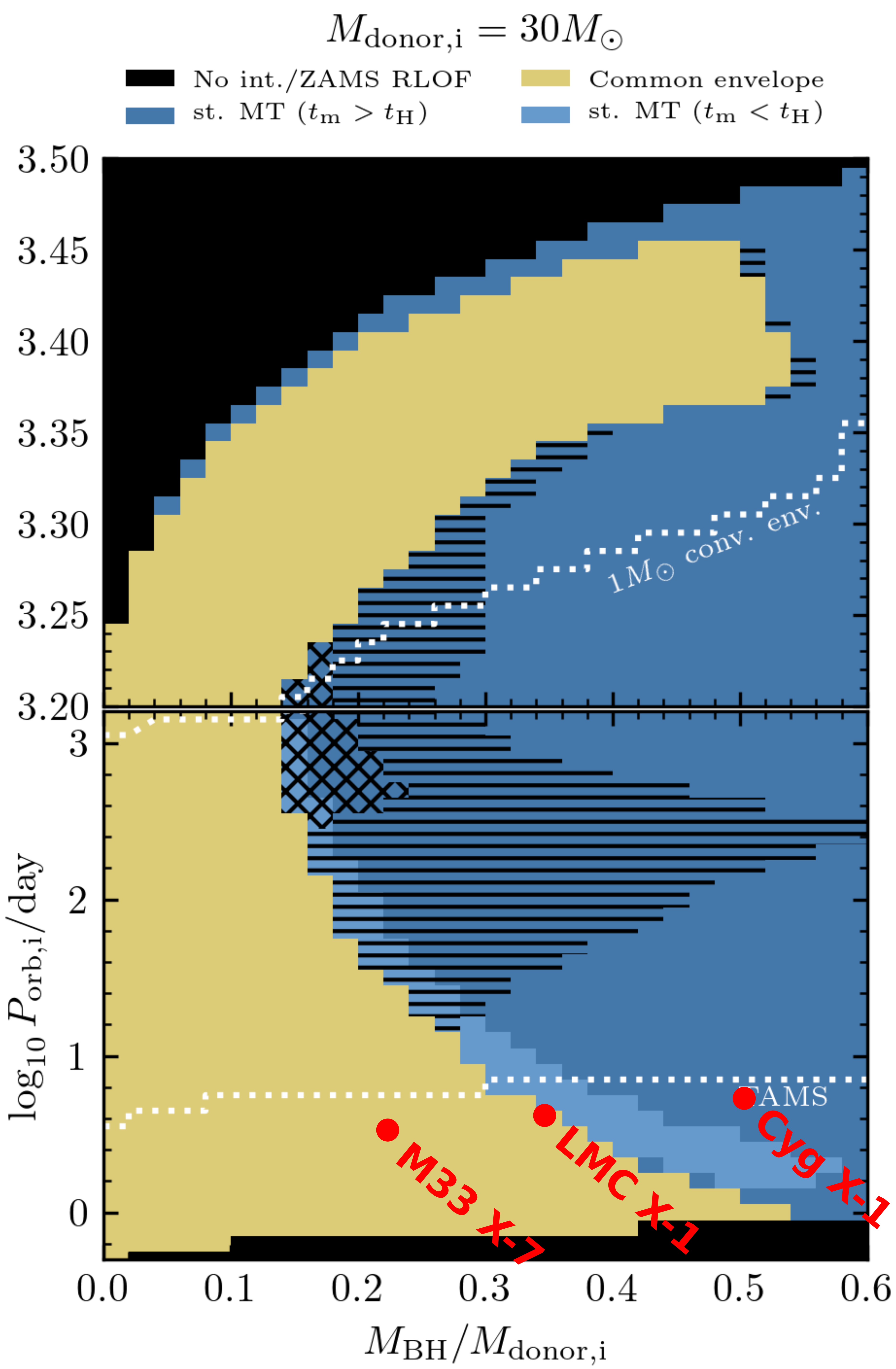
Stable MT potentially important to form NS+NS and WD+WD GW sources

How can EM observations contribute?



Independent of evolution prior to first BH formation, we need BH+O star systems with the right masses and periods.

How can EM observations contribute?



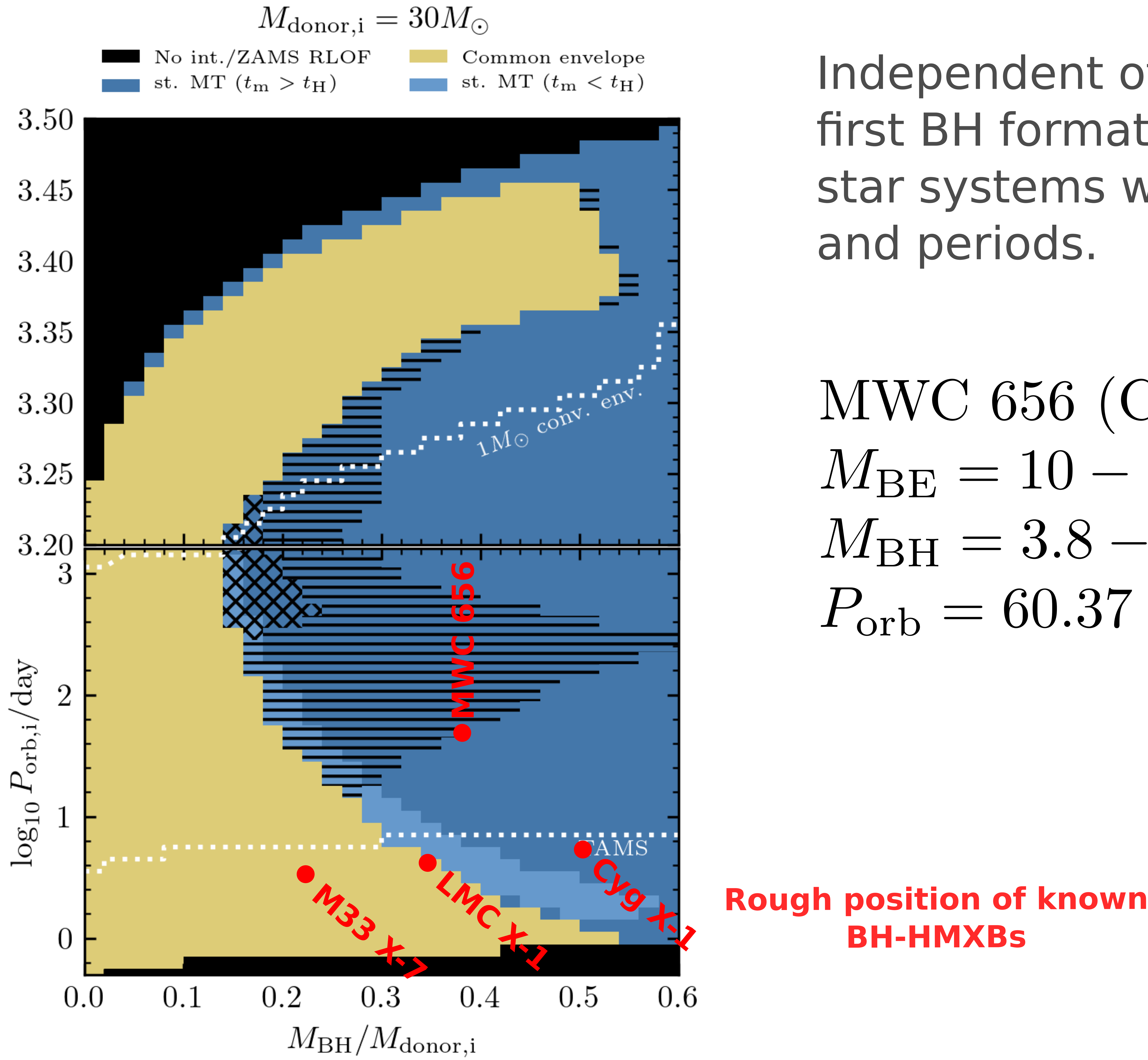
Independent of evolution prior to first BH formation, we need BH+O star systems with the right masses and periods.

Population at higher P is terra incognita.

Maybe not for long?

Rough position of known BH-HMXBs

How can EM observations contribute?



Independent of evolution prior to first BH formation, we need BH+O star systems with the right masses and periods.

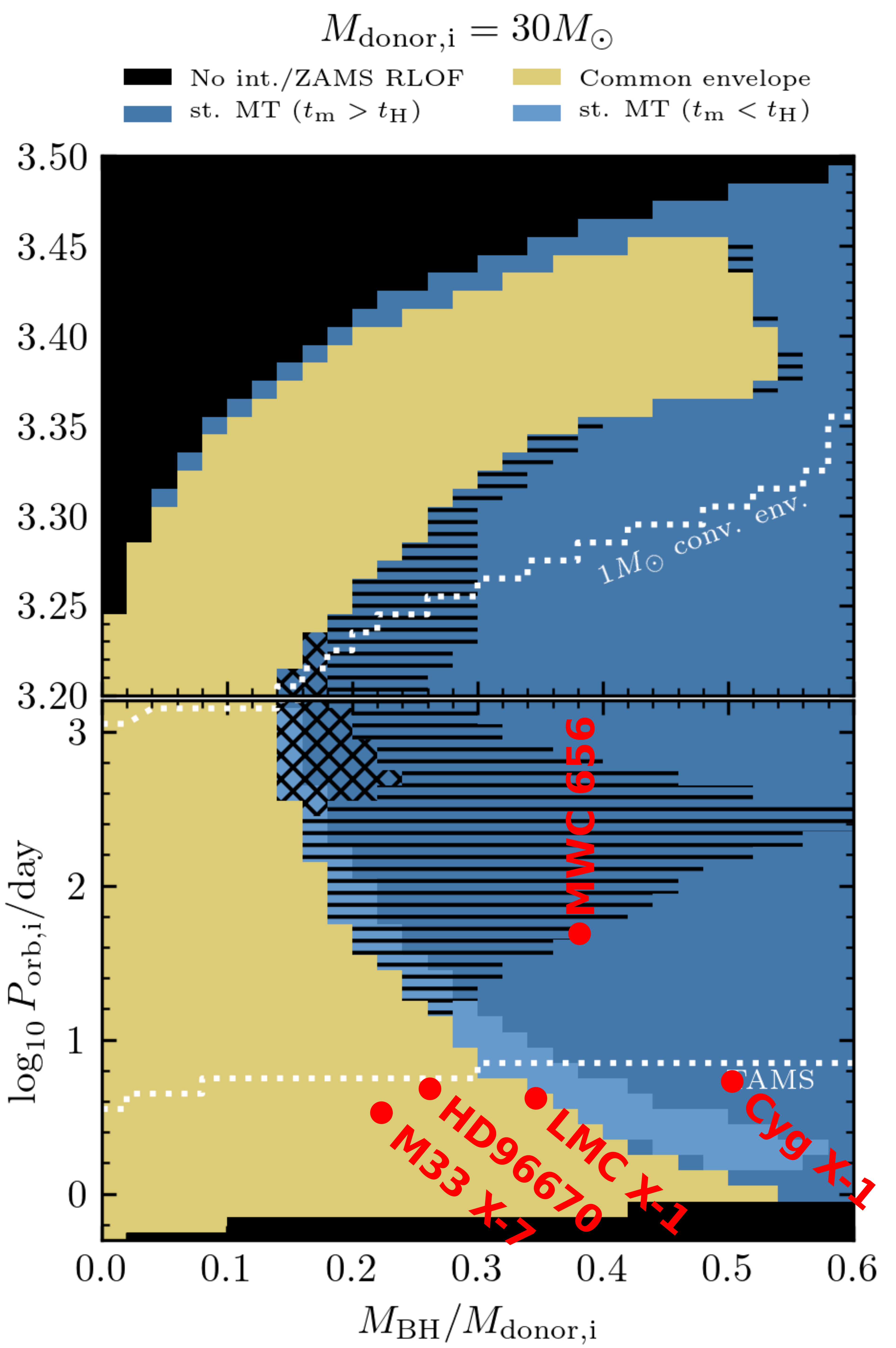
MWC 656 (Casares et al. 2014)

$M_{\rm BE} = 10 - 16\ M_\odot$

$M_{\rm BH} = 3.8 - 6.9\ M_\odot$

$P_{\rm orb} = 60.37$ days

How can EM observations contribute?



Rough position of known BH-HMXBs

Independent of evolution prior to first BH formation, we need BH+O star systems with the right masses and periods.

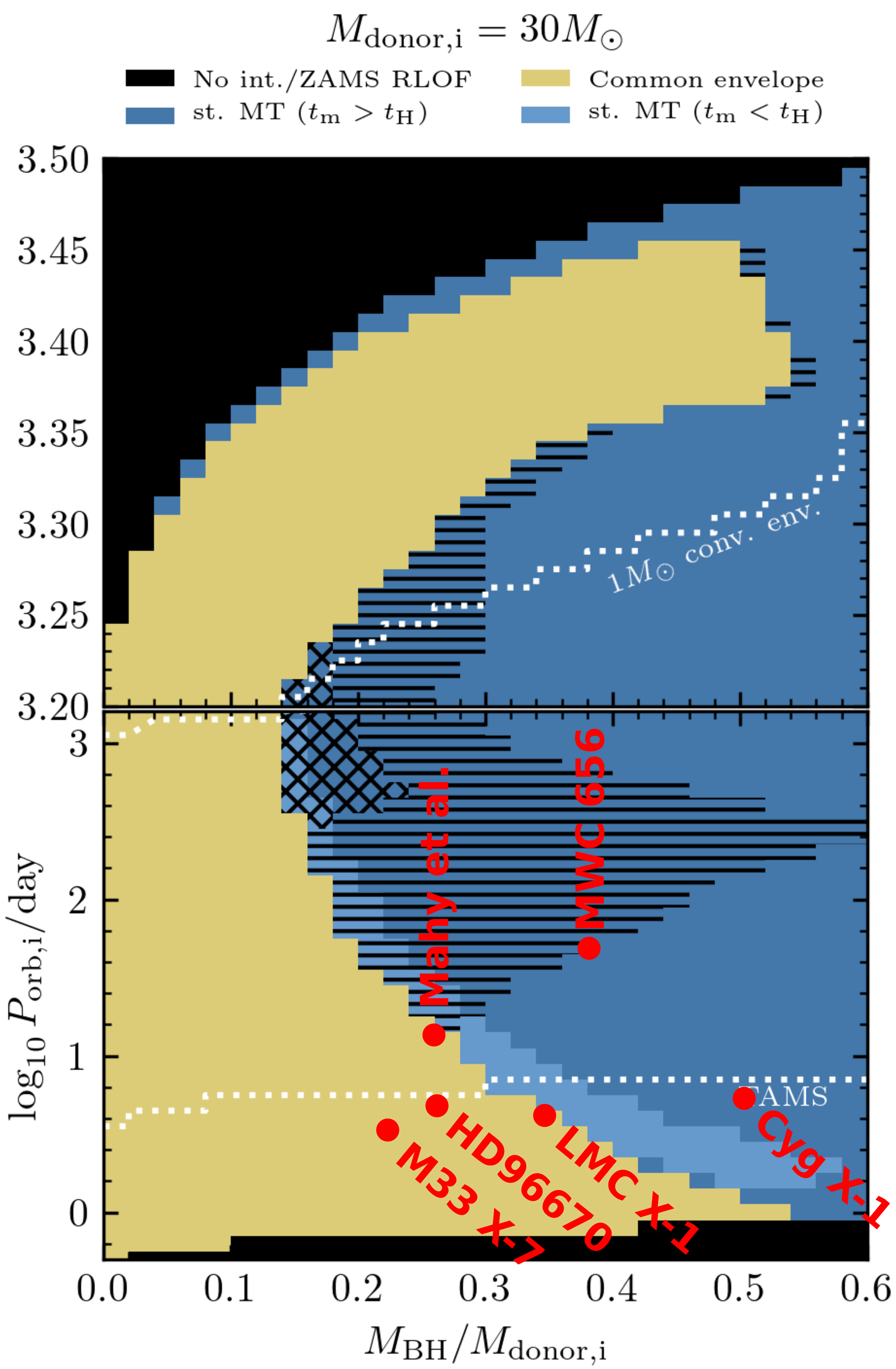
HD96670
(Gomez & Grindlay et al. 2021)

$M_{\rm O} = 22.7^{+5.2}_{-3.6}\ M_\odot$

$M_{\rm BH} = 6.2^{+0.9}_{-0.7}\ M_\odot$

$P_{\rm orb} = 5.28\ \text{days}$

How can EM observations contribute?



Rough position of known BH-HMXBs

Independent of evolution prior to first BH formation, we need BH+O star systems with the right masses and periods.

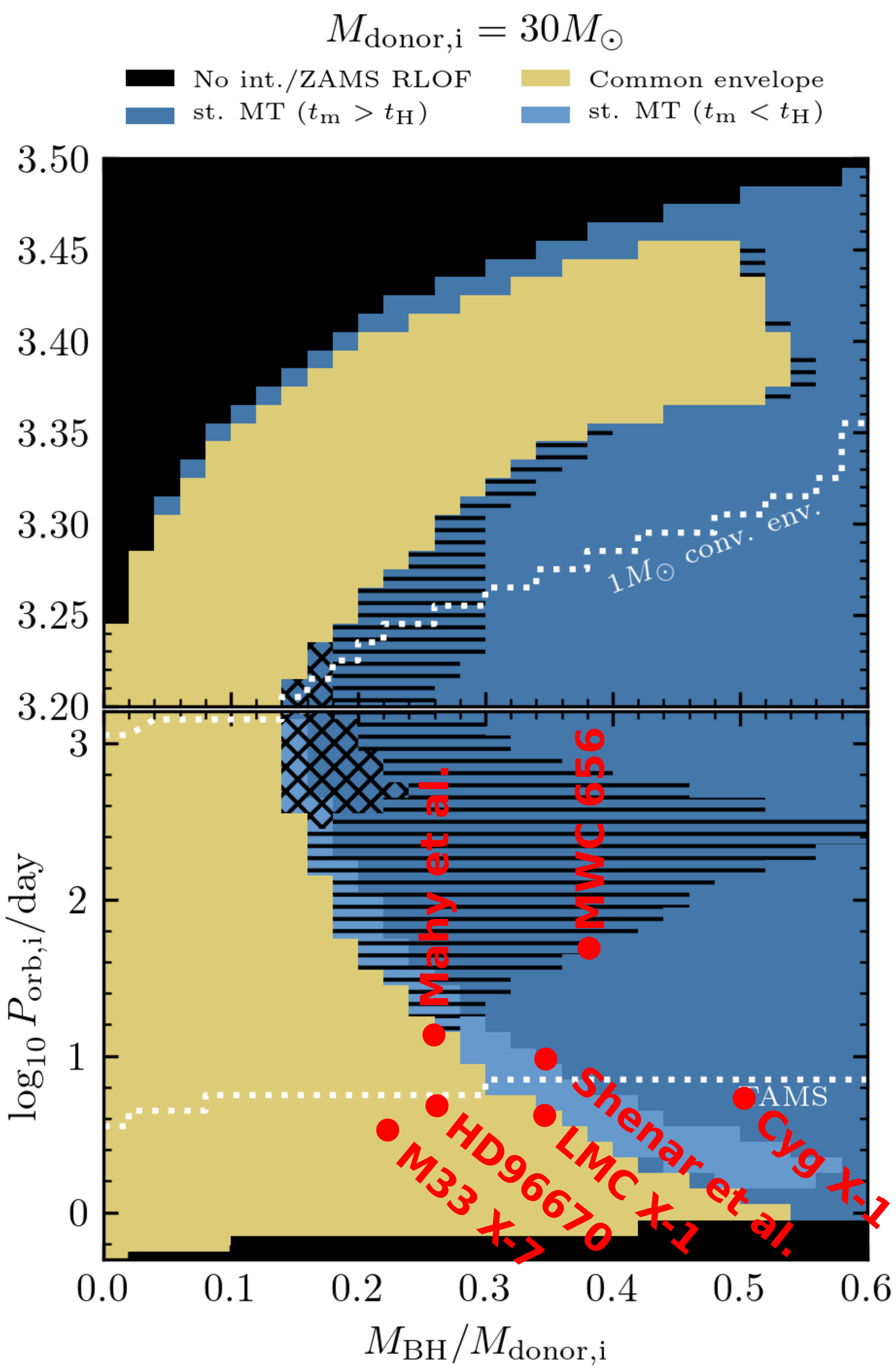
Mahy et al. (submitted)

$M_{\rm O} \sim 26\ M_\odot$

$M_{\rm BH} > 7\ M_\odot$

$P_{\rm orb} = 14.6$ days

How can EM observations contribute?



Rough position of known BH-HMXBs

Independent of evolution prior to first BH formation, we need BH+O star systems with the right masses and periods.

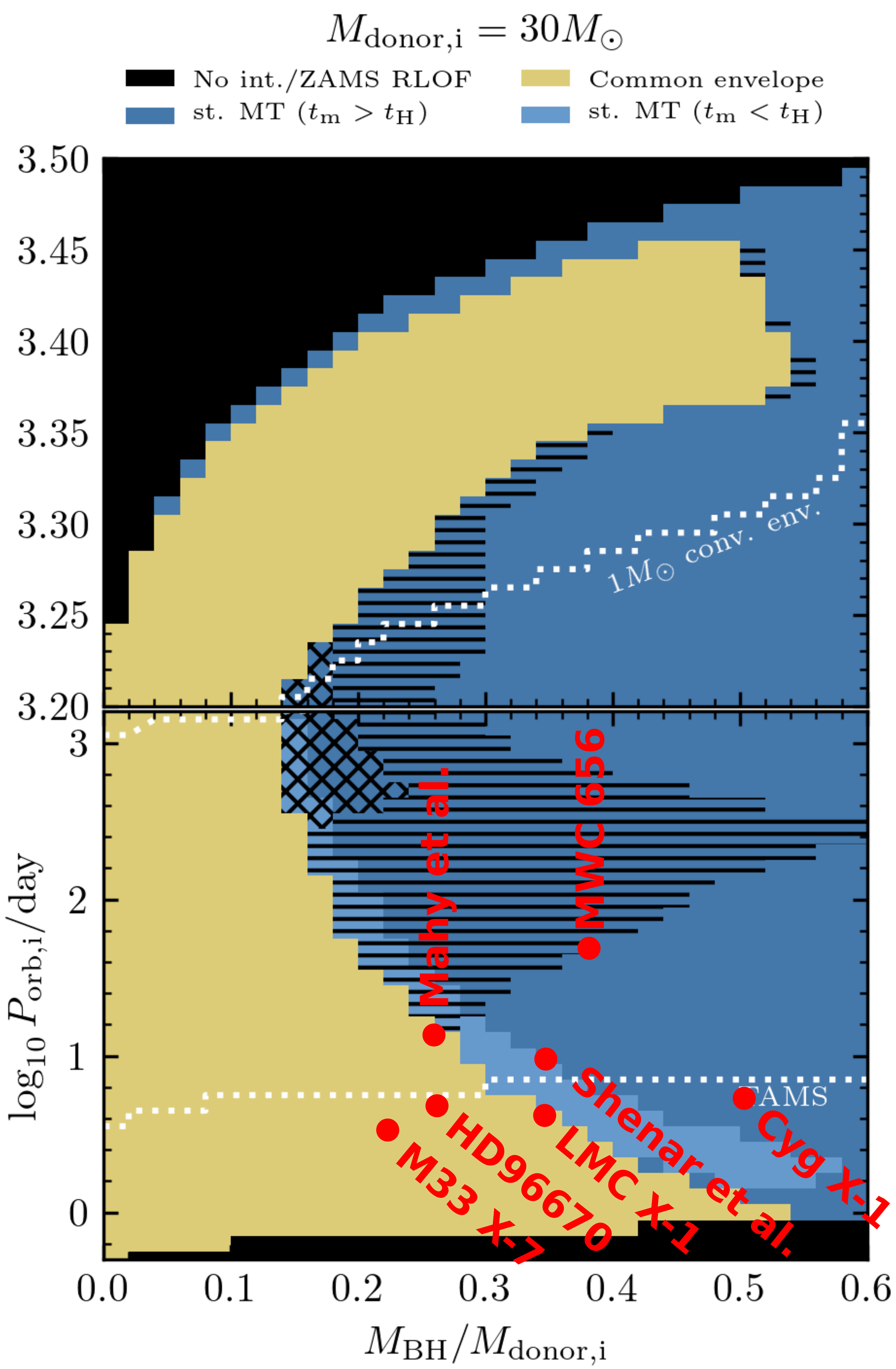
Shenar et al. (in preparation)

$M_{\rm O} = 25 \pm 2.3\ M_\odot$

$M_{\rm BH} > 9.2^{+3.1}_{-1.0}\ M_\odot$

$P_{\rm orb} = 10.4$ days

How can EM observations contribute?



Rough position of known BH-HMXBs

Independent of evolution prior to first BH formation, we need BH+O star ... sses and ...

Sh... n)

M

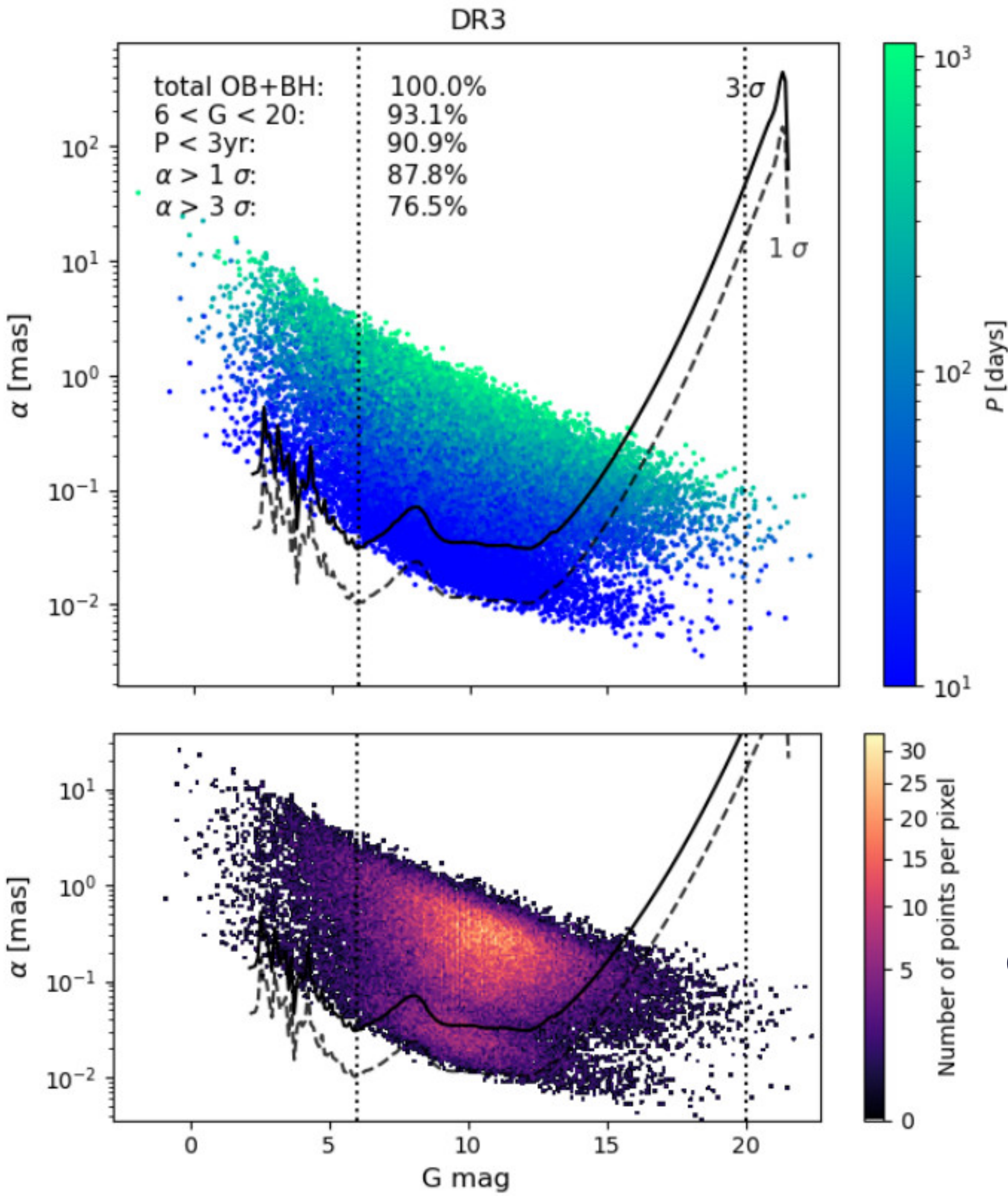
M

$P_{\rm o}$

What are the conditions for a BH+OB star to be X-ray active?

Drop in luminosity expected for wide binaries that don't form disks.
(eg. Sen et al 2021)

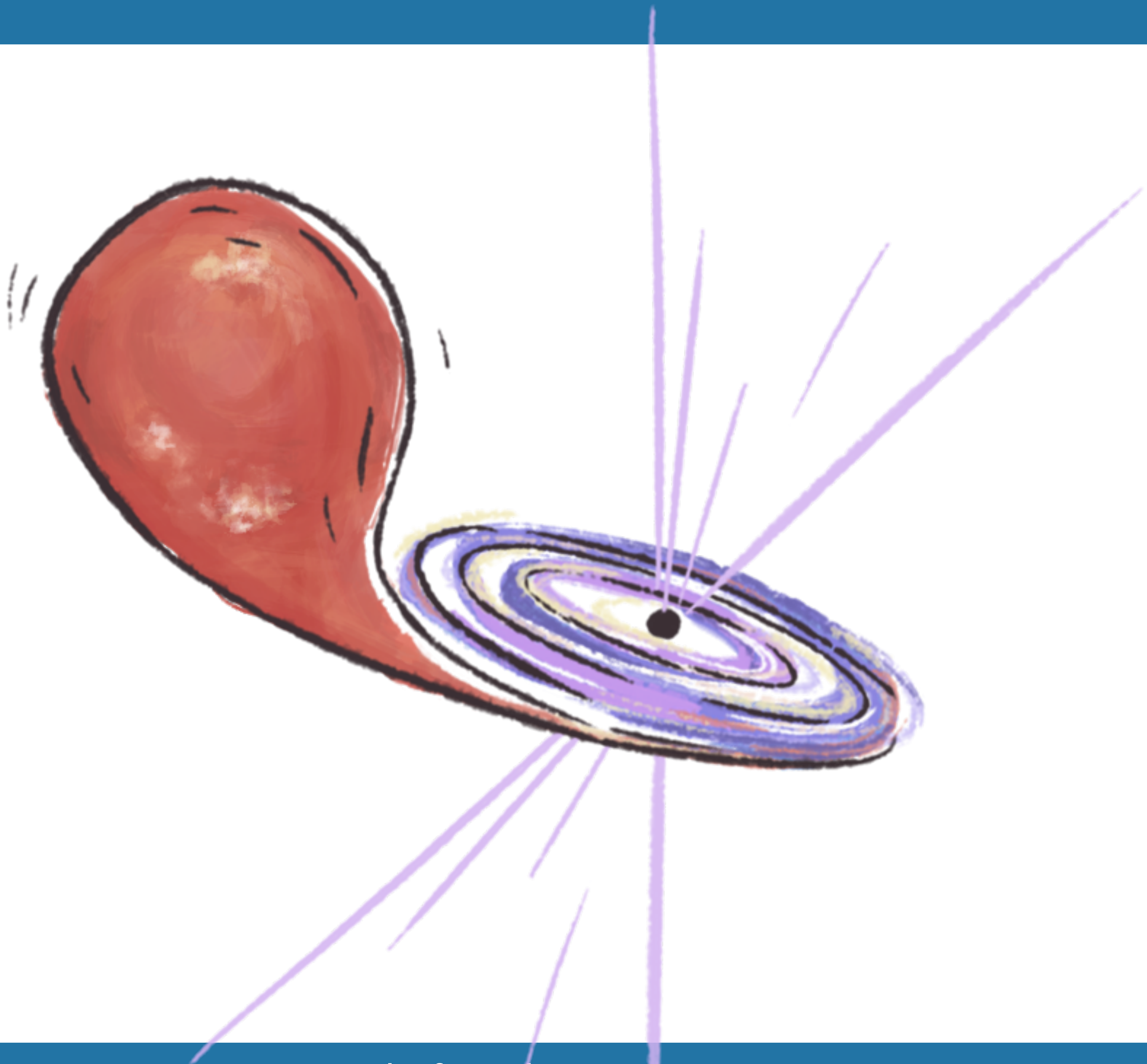
EM taking back the stellar BH crown?

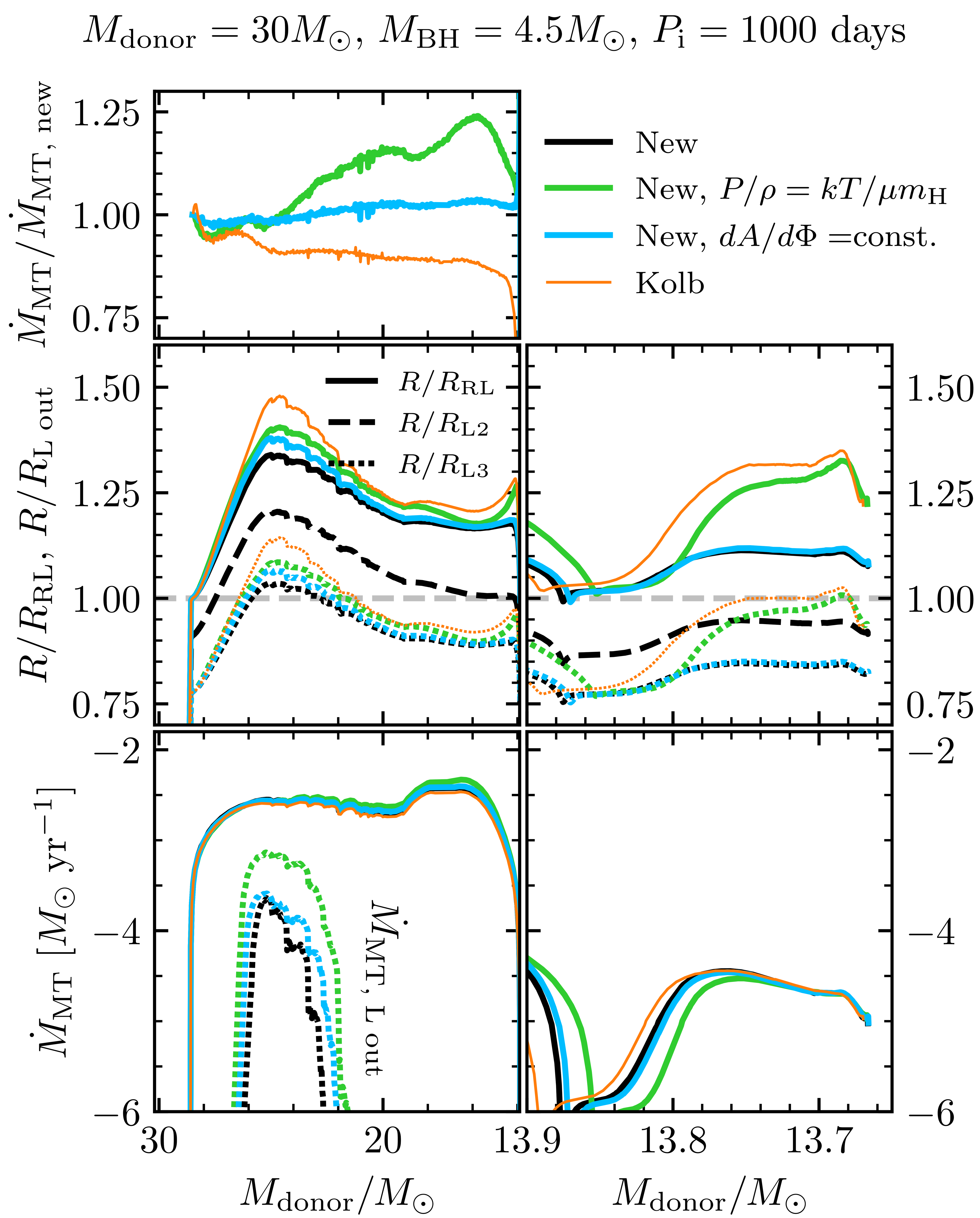


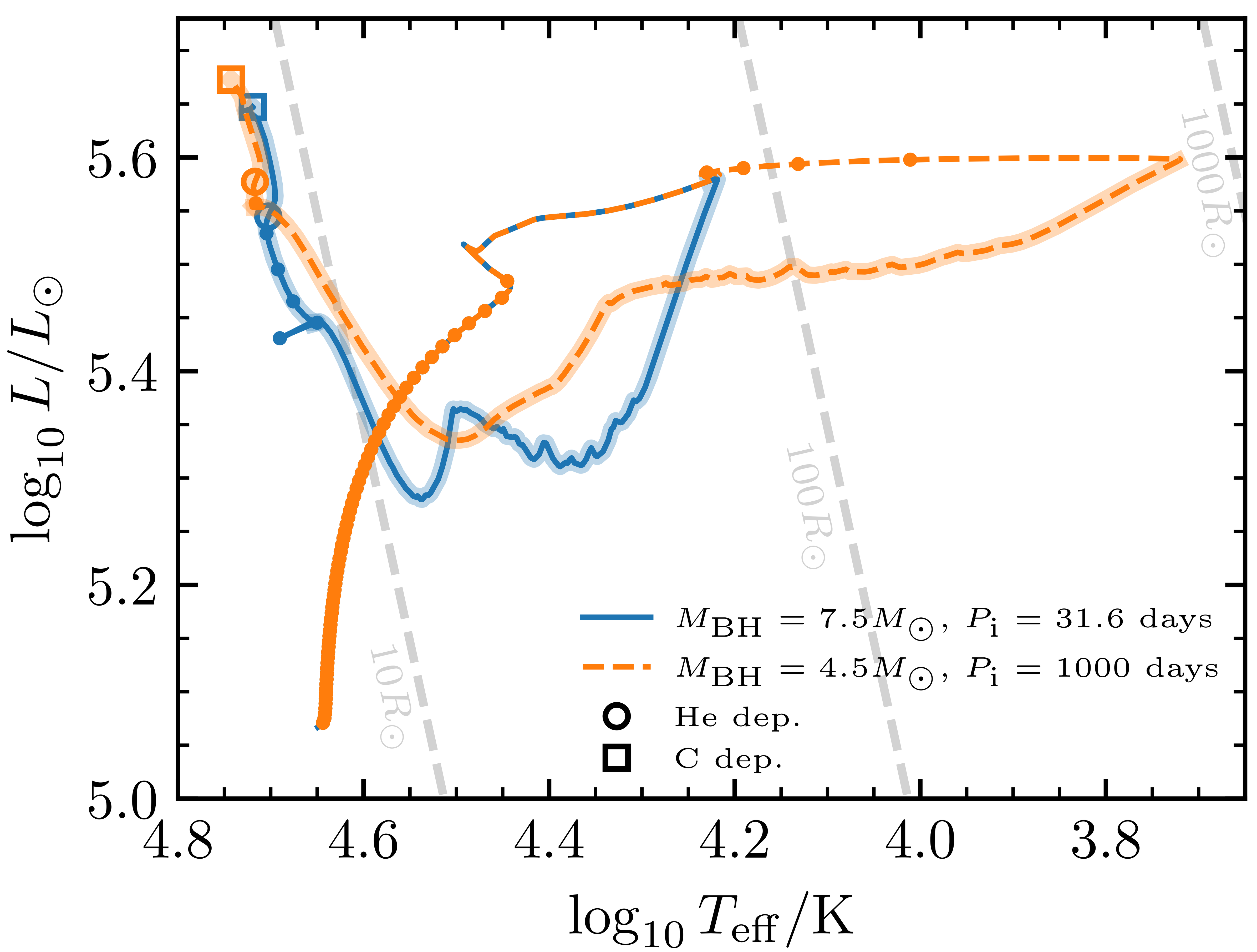
Janssens et al. 2022

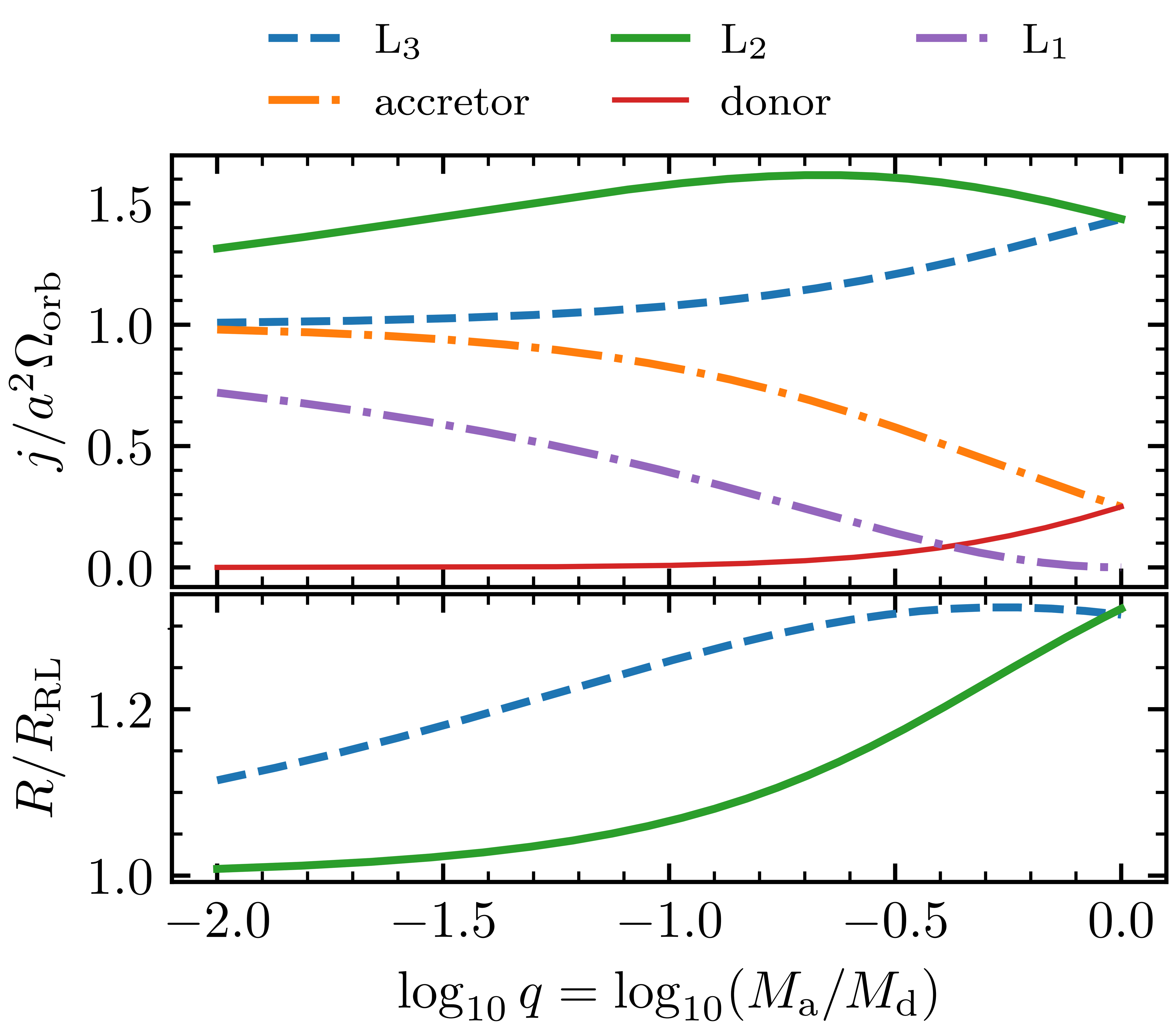
Possible identification of more than a hundred OB+BH systems by Gaia in DR3

Thanks for your attention!

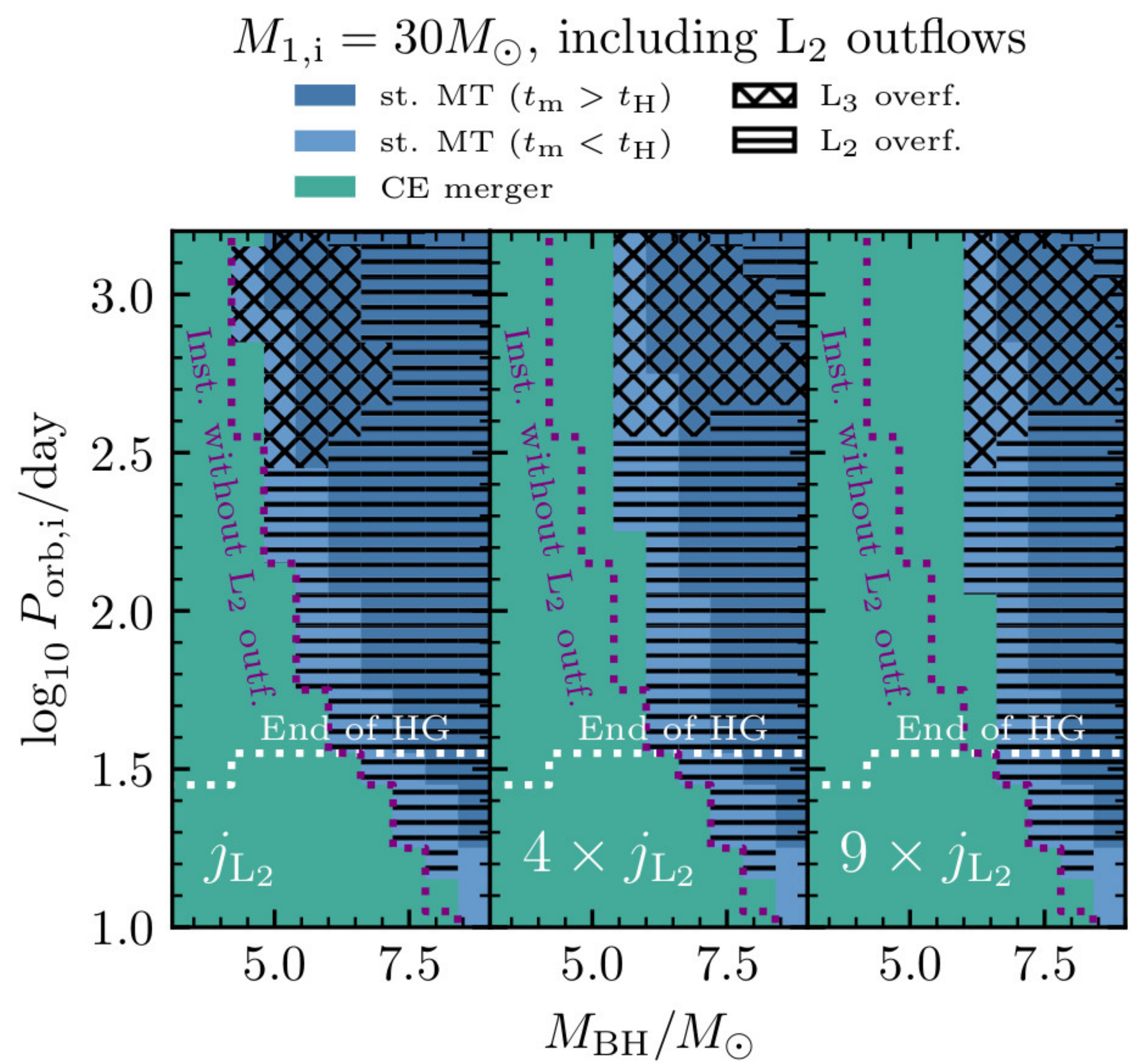



$M_{\rm donor} = 30M_\odot$, $M_{\rm BH} = 4.5M_\odot$, $P_{\rm i} = 1000$ days
New
New, $P/\rho = kT/\mu m_{\rm H}$
New, $dA/d\Phi$ =const.
Kolb
$R/R_{\rm RL}$
$R/R_{\rm L2}$
$R/R_{\rm L3}$
$\dot M_{\rm MT}/\dot M_{\rm MT,\ new}$
$R/R_{\rm RL},\ R/R_{\rm L\ out}$
$\dot M_{\rm MT}\ [M_\odot\ {\rm yr}^{-1}]$
$\dot M_{\rm MT,\ L\ out}$
$M_{\rm donor}/M_\odot$
$M_{\rm donor}/M_\odot$


$M_{\rm BH} = 7.5M_\odot$, $P_{\rm i} = 31.6$ days
$M_{\rm BH} = 4.5M_\odot$, $P_{\rm i} = 1000$ days
He dep.
C dep.
$10R_\odot$
$100R_\odot$
$1000R_\odot$
$\log_{10} L/L_\odot$
$\log_{10} T_{\rm eff}/{\rm K}$



L3
L2
L1
accretor
donor
$j/a^2\Omega_{\rm orb}$
$R/R_{\rm RL}$
$\log_{10} q = \log_{10}(M_{\rm a}/M_{\rm d})$



$M_{1,\rm i} = 30 M_\odot$, including L_2 outflows
st. MT ($t_{\rm m} > t_{\rm H}$)
st. MT ($t_{\rm m} < t_{\rm H}$)
CE merger
L3 overf.
L2 overf.
Inst. without L2 outf.
End of HG
j_{L_2}
$4 \times j_{L_2}$
$9 \times j_{L_2}$
$\log_{10} P_{\rm orb,i}/{\rm day}$
$M_{\rm BH}/M_\odot$