Binary-star evolution & binary population synthesis

Katie Breivik — CMU — McWilliams Center

EMIT MMA Summer School

Binary stars are a

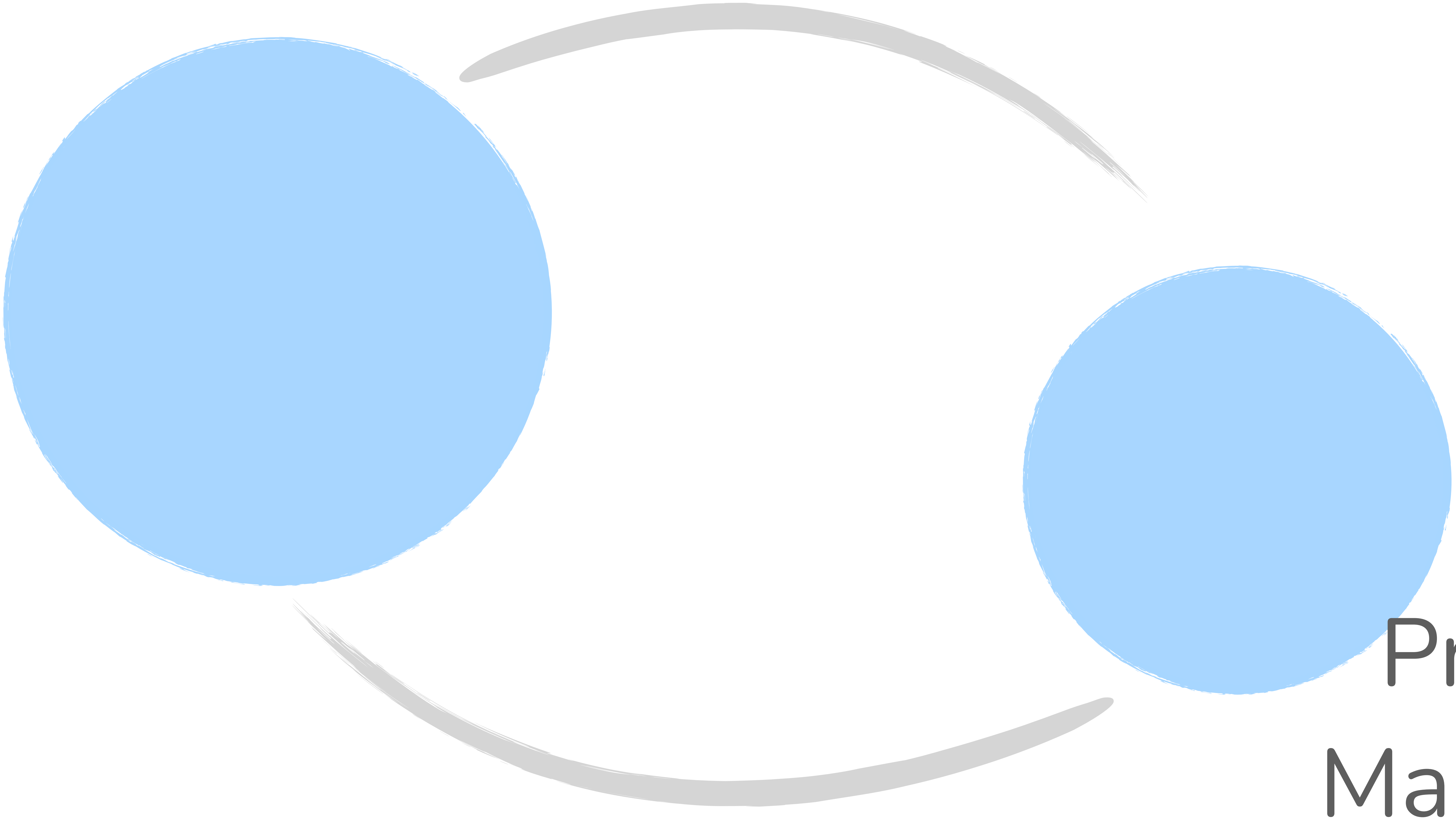
critical component or limiting noise source

for basically ***all*** areas of astronomy

Most massive stars and many lower-mass stars are born with a companion

e.g.
Raghavan+10
Sana+12
Duchêne+13
Moe+17
Price-Whelan+20
Mazzola-Daher+20

Most massive stars and many lower-mass stars are born with a companion



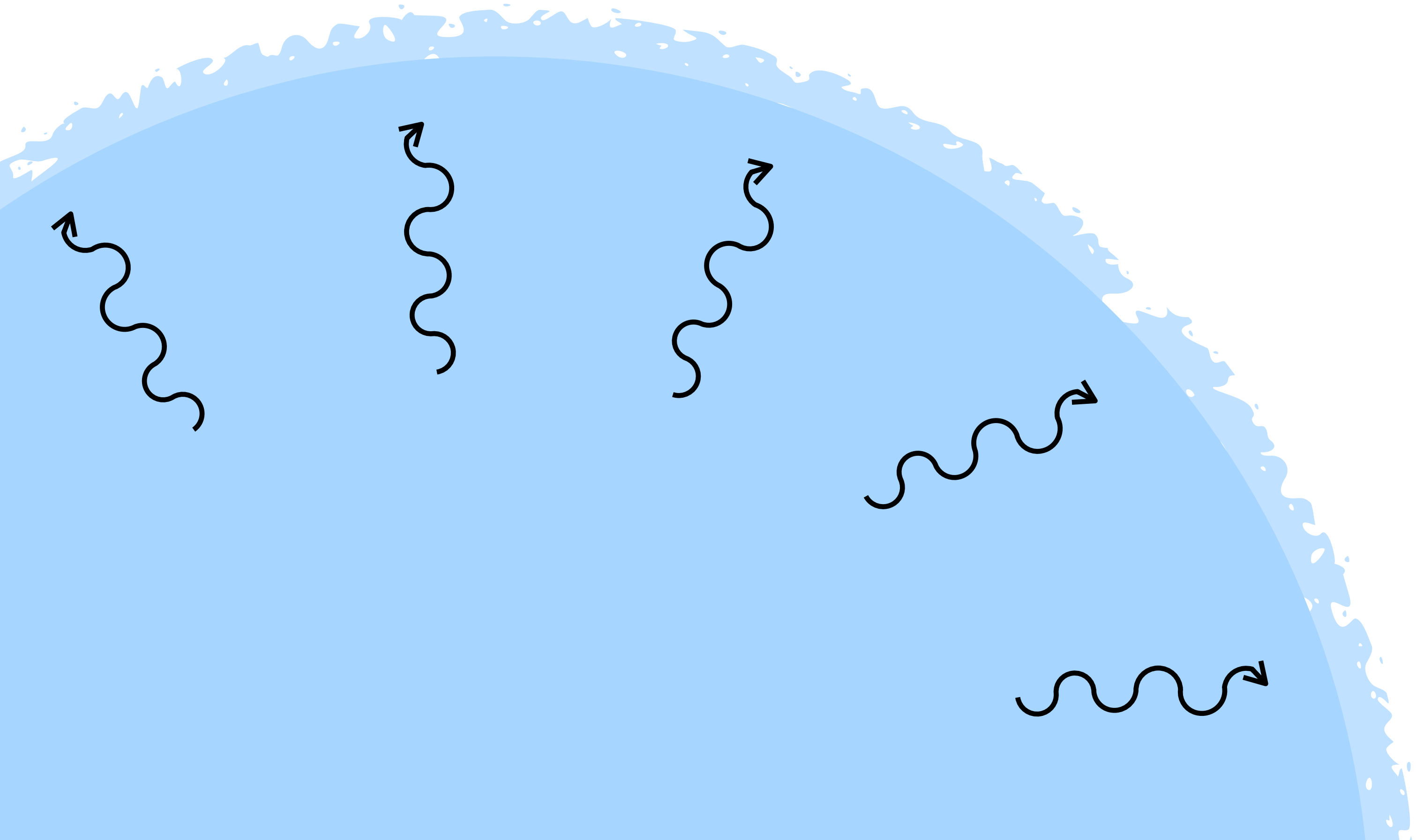
e.g.
Raghavan+10
Sana+12
Duchêne+13
Moe+17
Price-Whelan+20
Mazzola-Daher+20

Most massive stars and many lower-mass stars are born with a companion

A binary companion introduces potential for *interactions*

winds are the primary driver for orbital evolution of

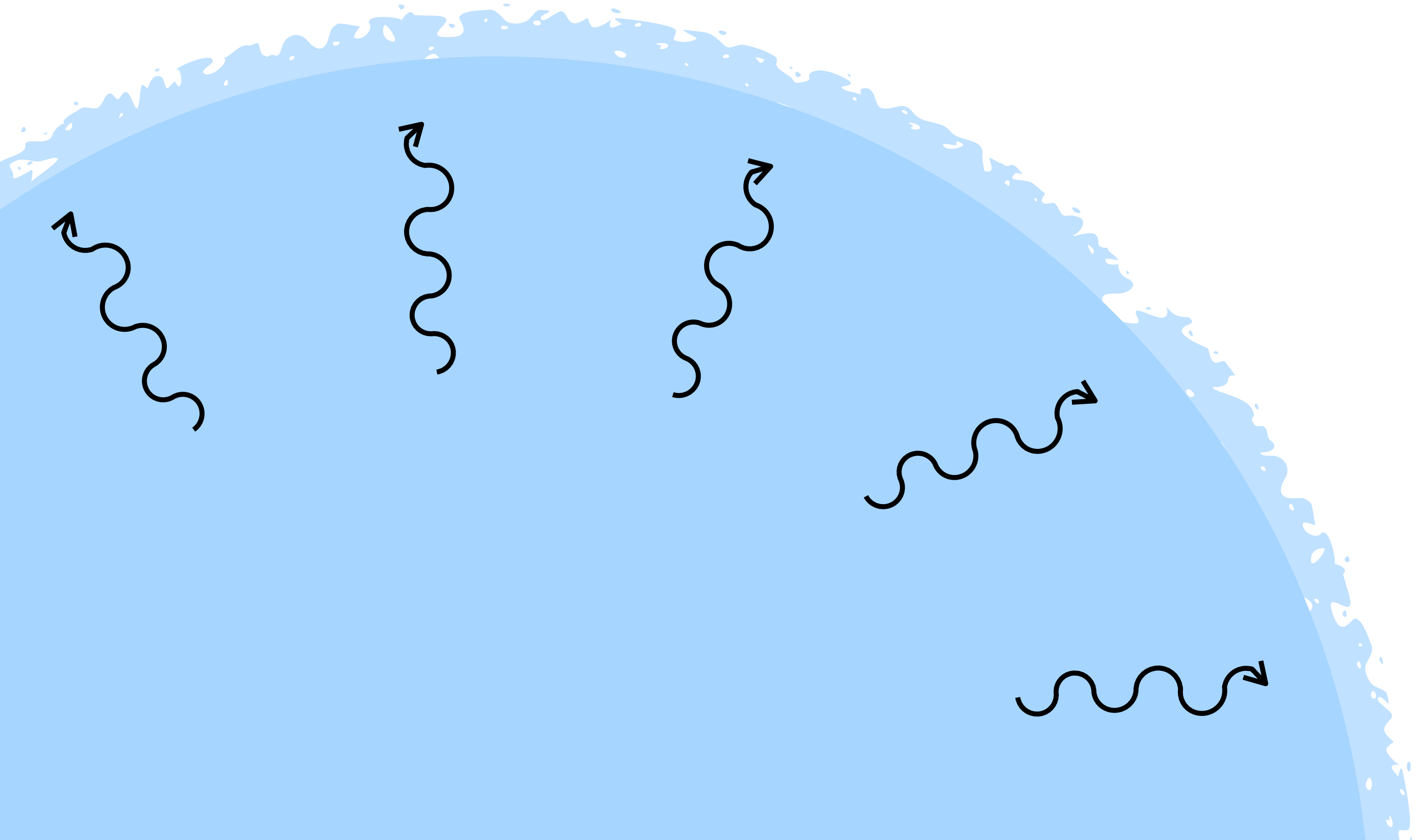
detached binaries



winds are the primary driver for orbital evolution of

detached binaries

$$J_{\text{orb}} = \sum_i M_i r_i^2 \omega_i^2 = M_1 M_2 \left(\frac{Ga}{M_{\text{T}}}\right)^2$$

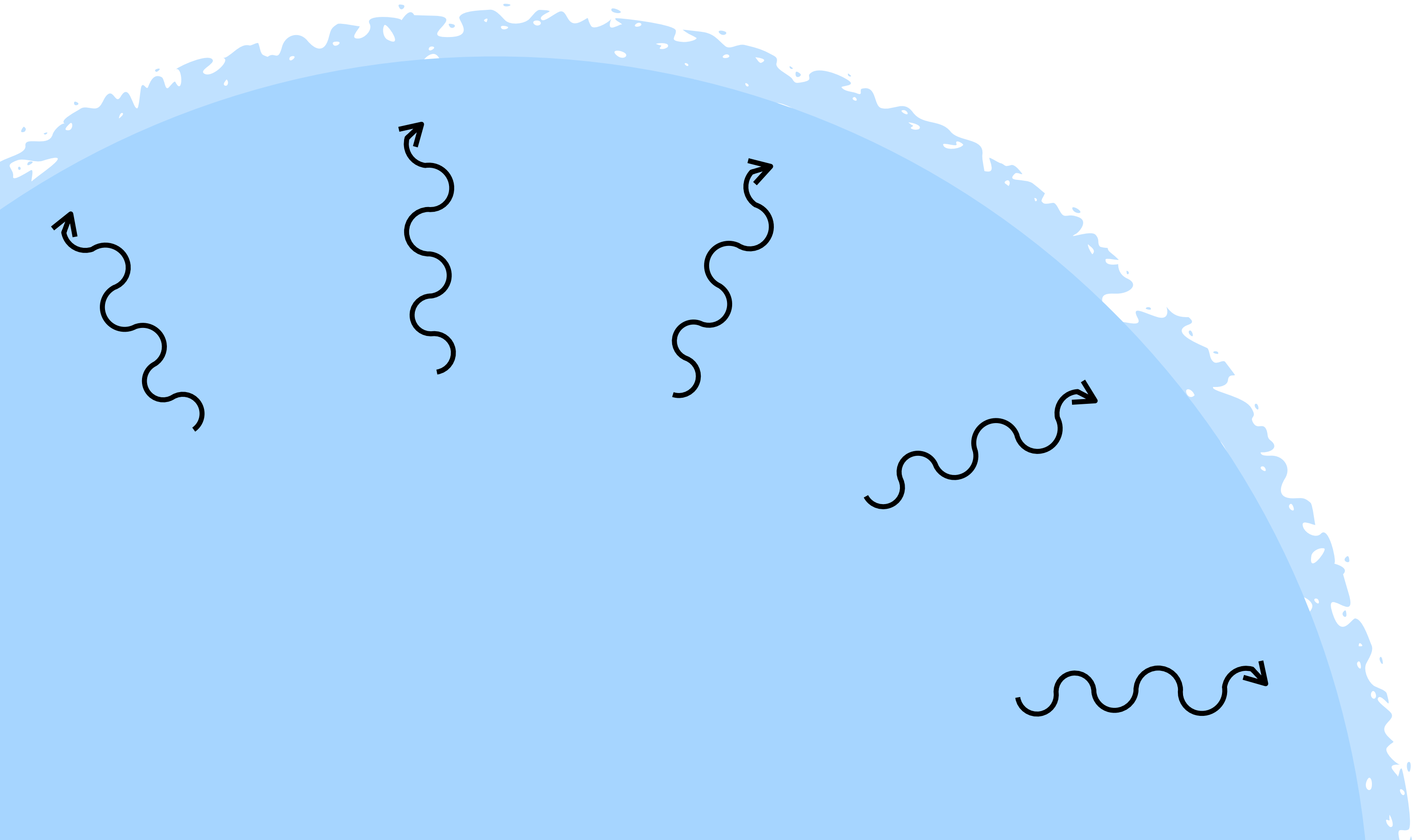


winds are the primary driver for orbital evolution of

detached binaries

$$J_{\rm orb} = \sum_i M_i r_i^2 \omega_i^2 = M_1 M_2 \left(\frac{Ga}{M_{\rm T}} \right)^2$$

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$



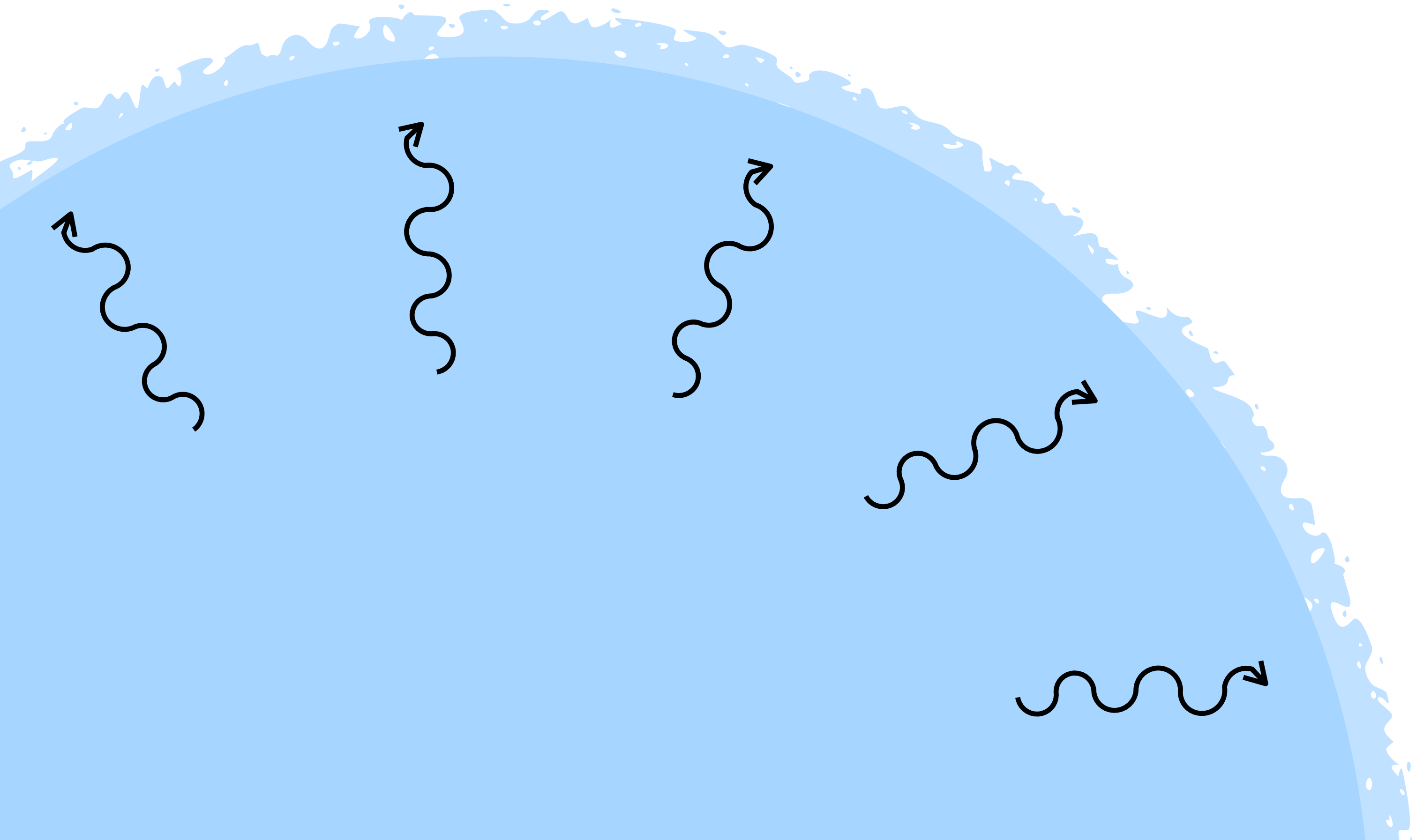
winds are the primary driver for orbital evolution of

detached binaries

$$J_{\rm orb} = \sum_i M_i r_i^2 \omega_i^2 = M_1 M_2 \left(\frac{Ga}{M_{\rm T}}\right)^2$$

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$

$$\dot{M}_1 = \dot{M}_{1,\rm wind} \qquad \dot{M}_2 = \dot{M}_{2,\rm wind} \qquad \dot{M}_T = \dot{M}_{1,\rm wind} + \dot{M}_{2,\rm wind}$$

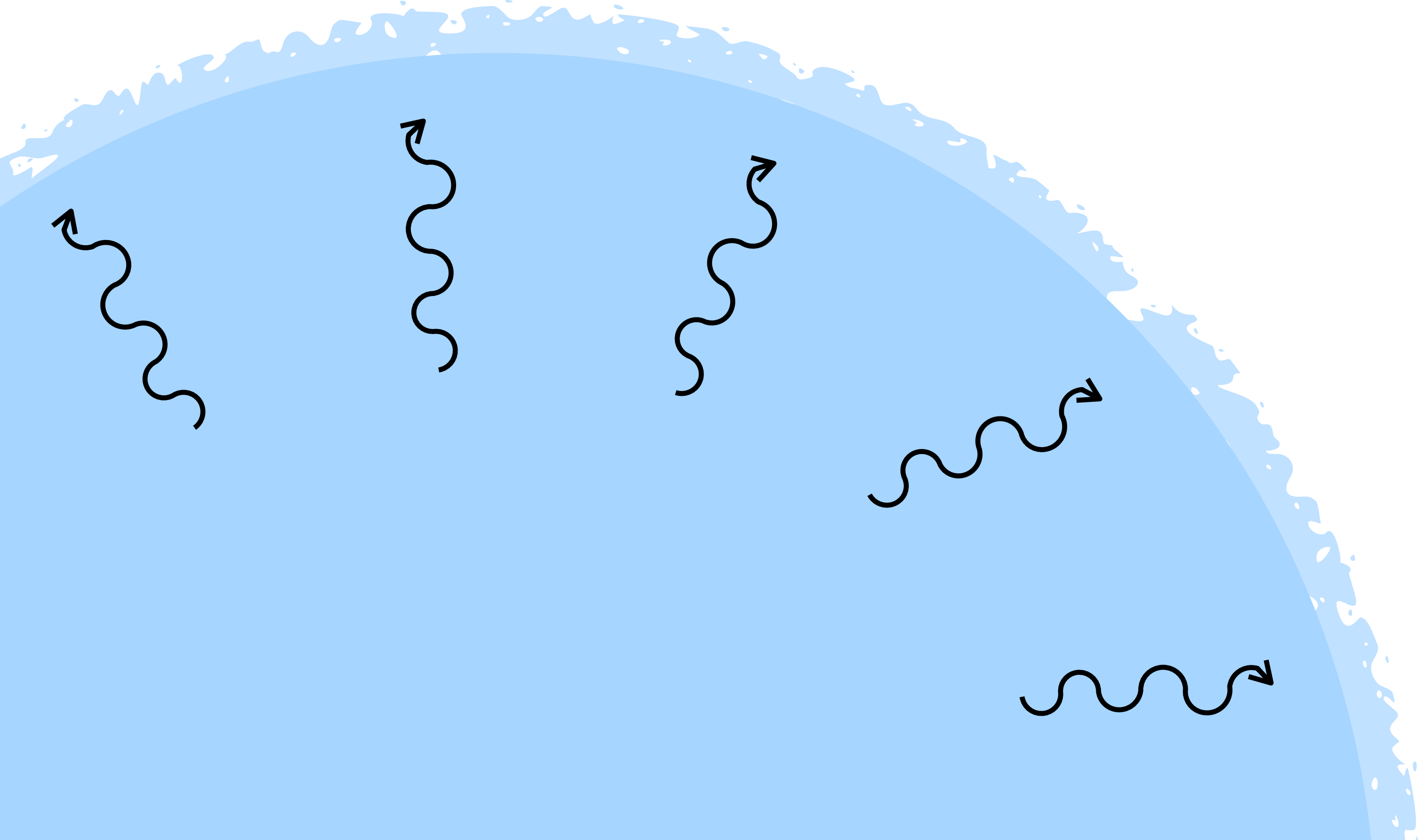


winds are the primary driver for orbital evolution of

detached binaries

$$J_{\rm orb} = \sum_i M_i r_i^2 \omega_i^2 = M_1 M_2 \left(\frac{Ga}{M_{\rm T}}\right)^2 \qquad \frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$

$$\dot{M}_1 = \dot{M}_{1,\rm wind} \qquad \dot{M}_2 = \dot{M}_{2,\rm wind} \qquad \dot{M}_T = \dot{M}_{1,\rm wind} + \dot{M}_{2,\rm wind}$$



Radiatively driven (line-driven) winds depend *strongly on* mass and composition

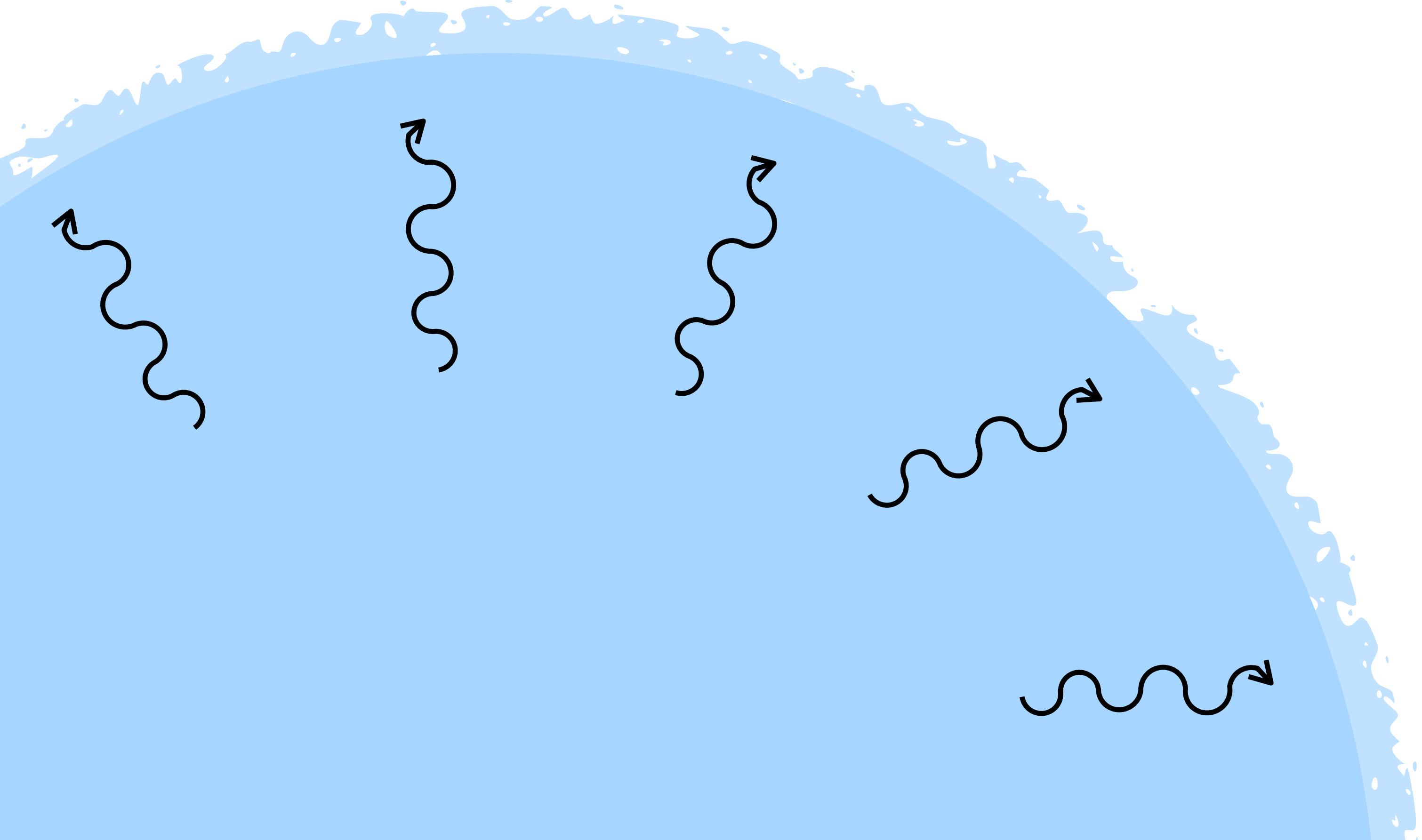
Vink+2001,2005

winds are the primary driver for orbital evolution of

detached binaries

$$J_{\rm orb} = \sum_i M_i r_i^2 \omega_i^2 = M_1 M_2 \left(\frac{Ga}{M_{\rm T}}\right)^2 \qquad \frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$

$$\dot{M}_1 = \dot{M}_{1,\rm wind} \qquad \dot{M}_2 = \dot{M}_{2,\rm wind} \qquad \dot{M}_T = \dot{M}_{1,\rm wind} + \dot{M}_{2,\rm wind}$$



Radiatively driven (line-driven) winds depend *strongly on* mass and composition

Vink+2001,2005

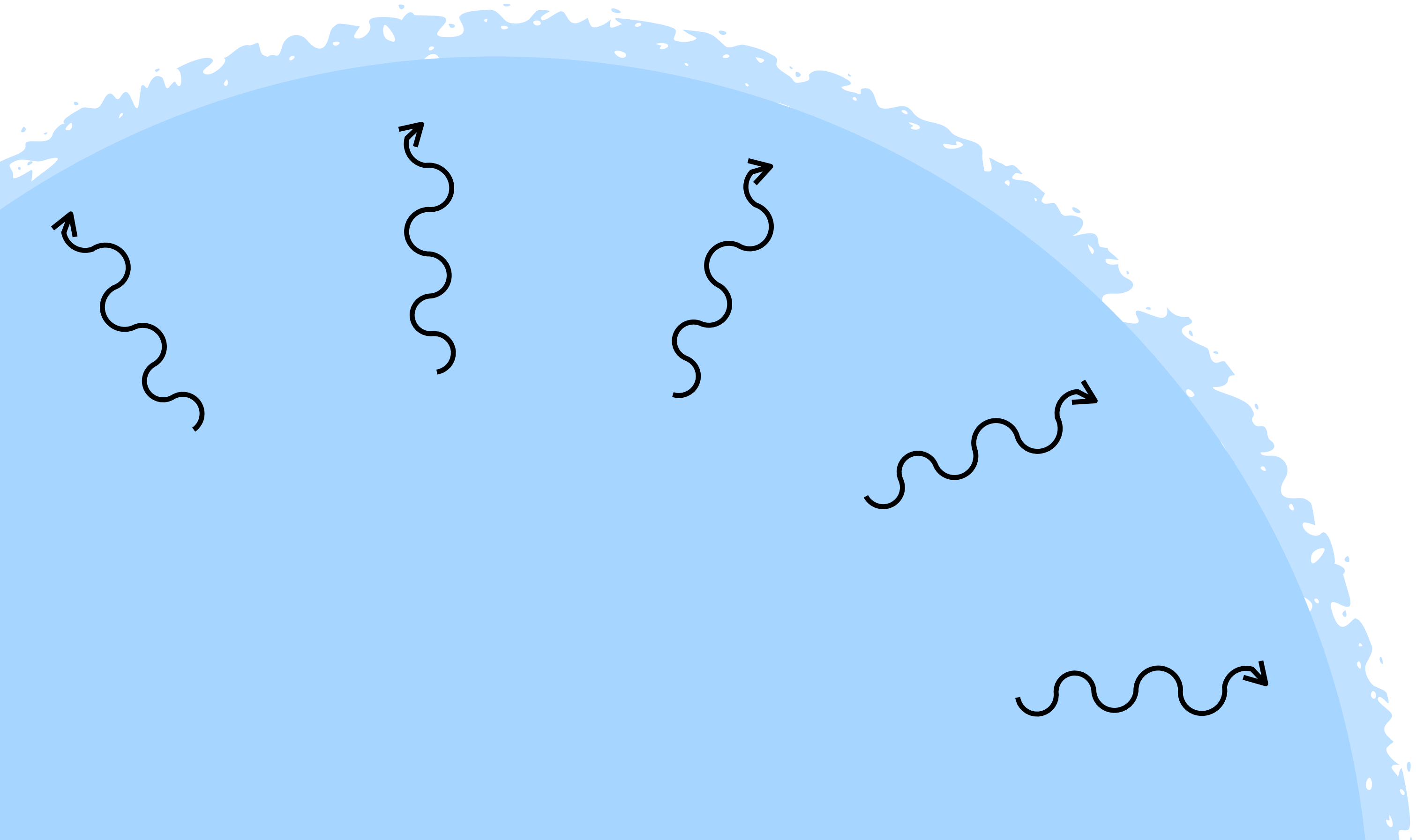
$$\dot{M}_{1,\rm wind} >> \dot{M}_{2,\rm wind}$$

winds are the primary driver for orbital evolution of

detached binaries

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$

$$\dot{M}_1 = \dot{M}_{1,\rm wind} \qquad \dot{M}_T = \dot{M}_{1,\rm wind}$$



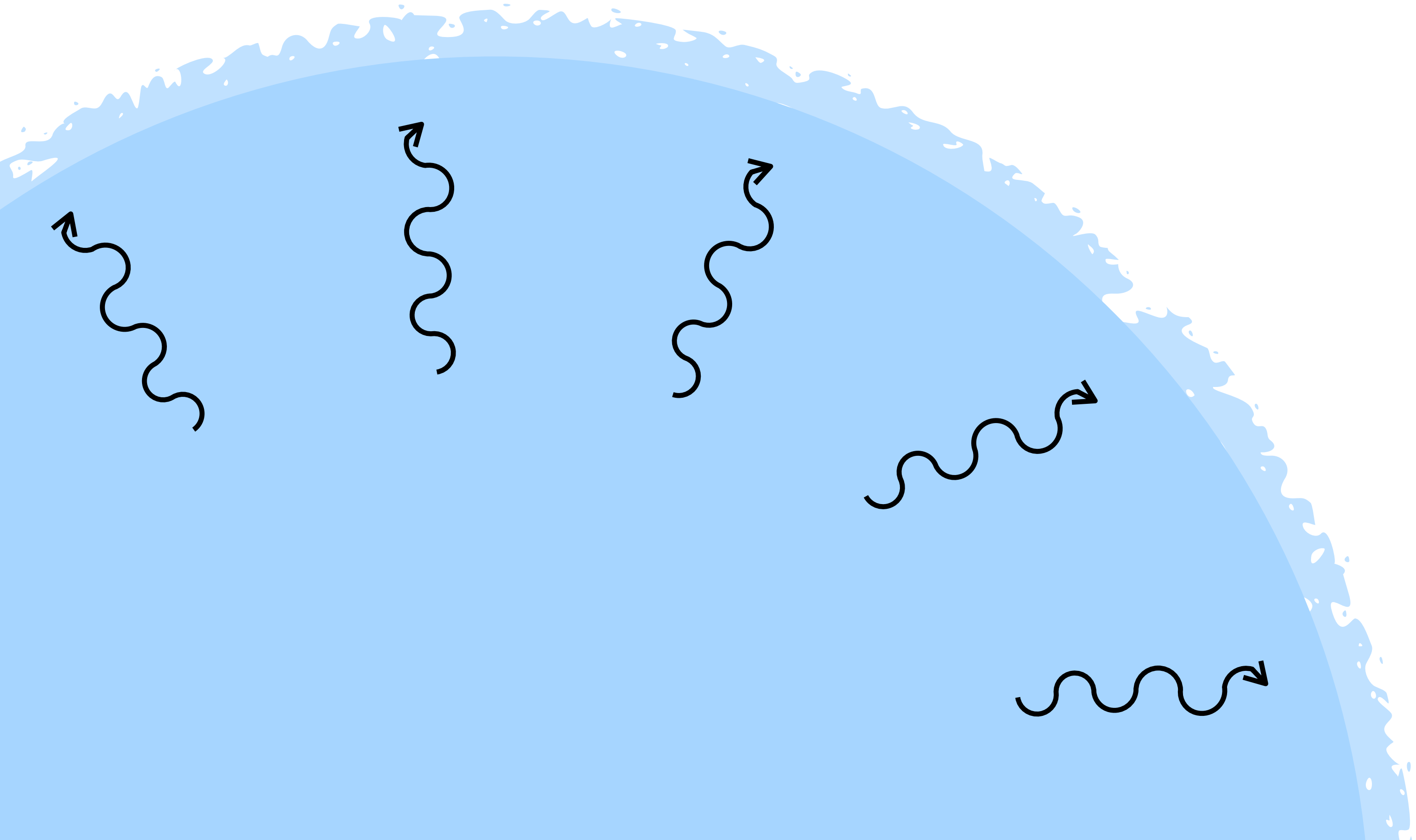
winds are the primary driver for orbital evolution of

detached binaries

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$

$$\dot{M}_1 = \dot{M}_{1,\rm wind} \qquad \dot{M}_T = \dot{M}_{1,\rm wind}$$

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}}{J} - 2\frac{\dot{M}_{1,\rm wind}}{M_1} + \frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$



winds are the primary driver for orbital evolution of

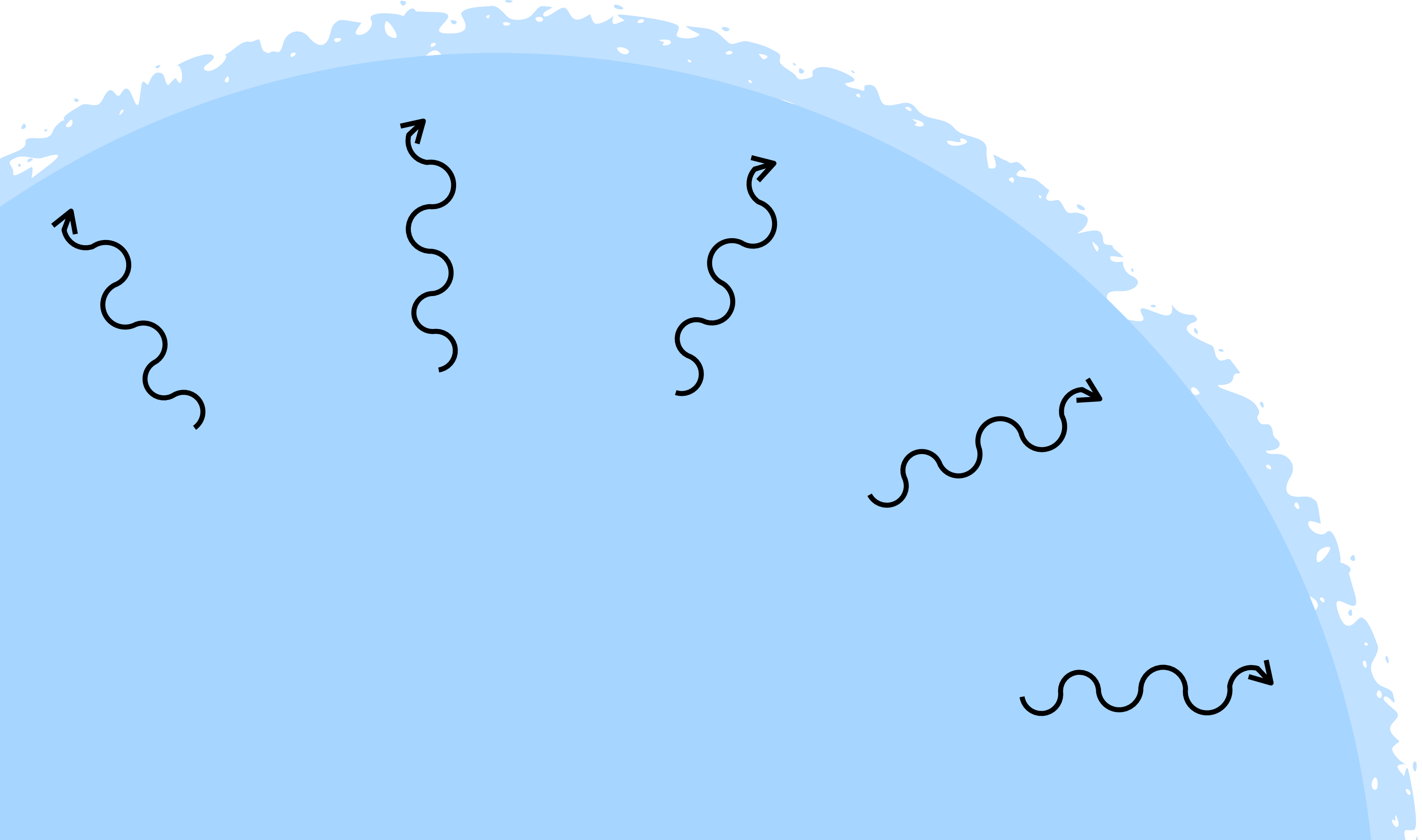
detached binaries

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$

$$\dot{M}_1 = \dot{M}_{1,\rm wind} \qquad \dot{M}_T = \dot{M}_{1,\rm wind}$$

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}}{J} - 2\frac{\dot{M}_{1,\rm wind}}{M_1} + \frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$

$$\left(\frac{\dot{J}}{J_{\rm orb}}\right)_{\rm wind} = \frac{M_2}{M_1}\frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$



winds are the primary driver for orbital evolution of

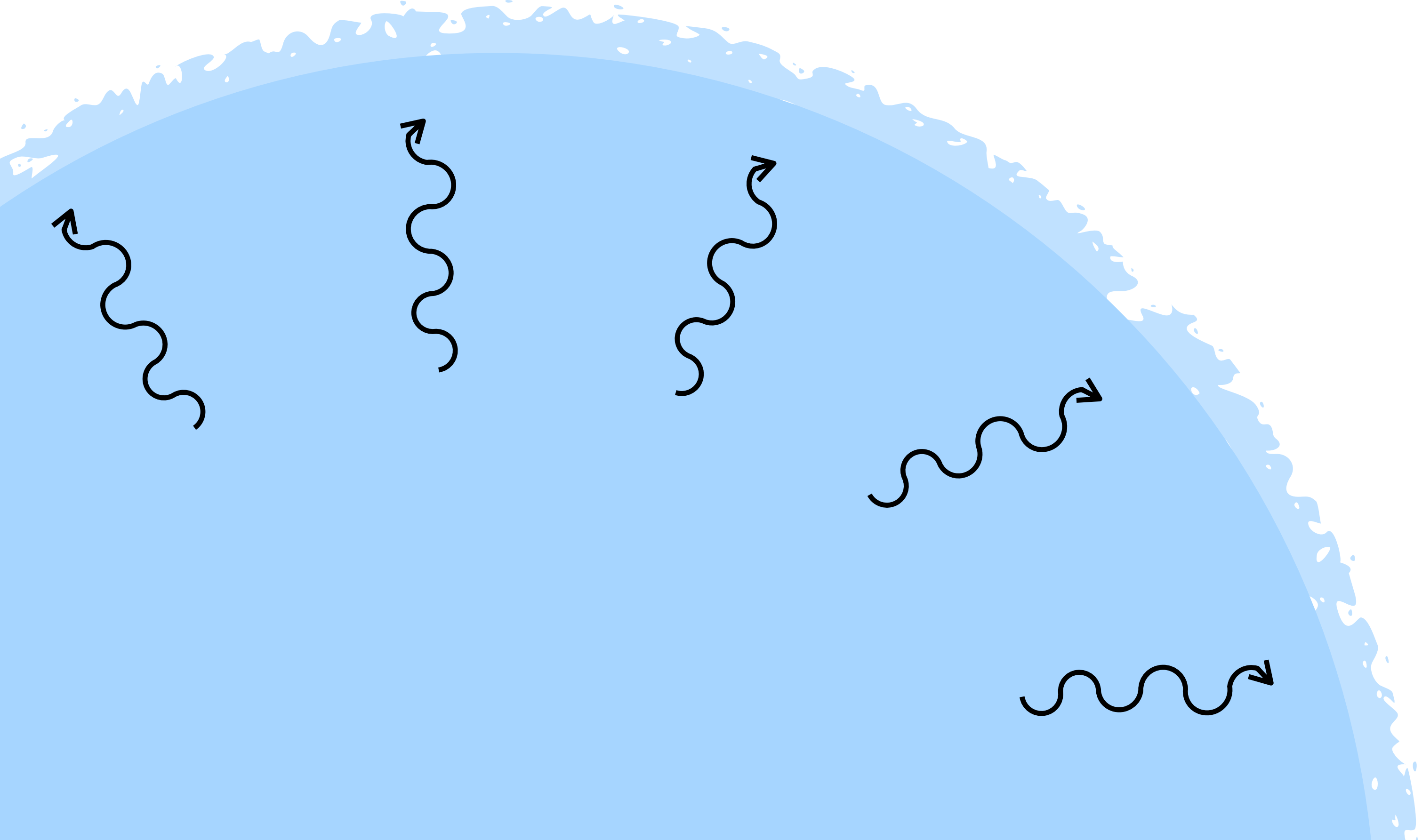
detached binaries

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$

$$\dot{M}_1 = \dot{M}_{1,\rm wind} \qquad \dot{M}_T = \dot{M}_{1,\rm wind}$$

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}}{J} - 2\frac{\dot{M}_{1,\rm wind}}{M_1} + \frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$

$$\left(\frac{\dot{J}}{J_{\rm orb}}\right)_{\rm wind} = \frac{M_2}{M_1}\frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$



$$\frac{\dot{a}}{a} = -\frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$

winds are the primary driver for orbital evolution of

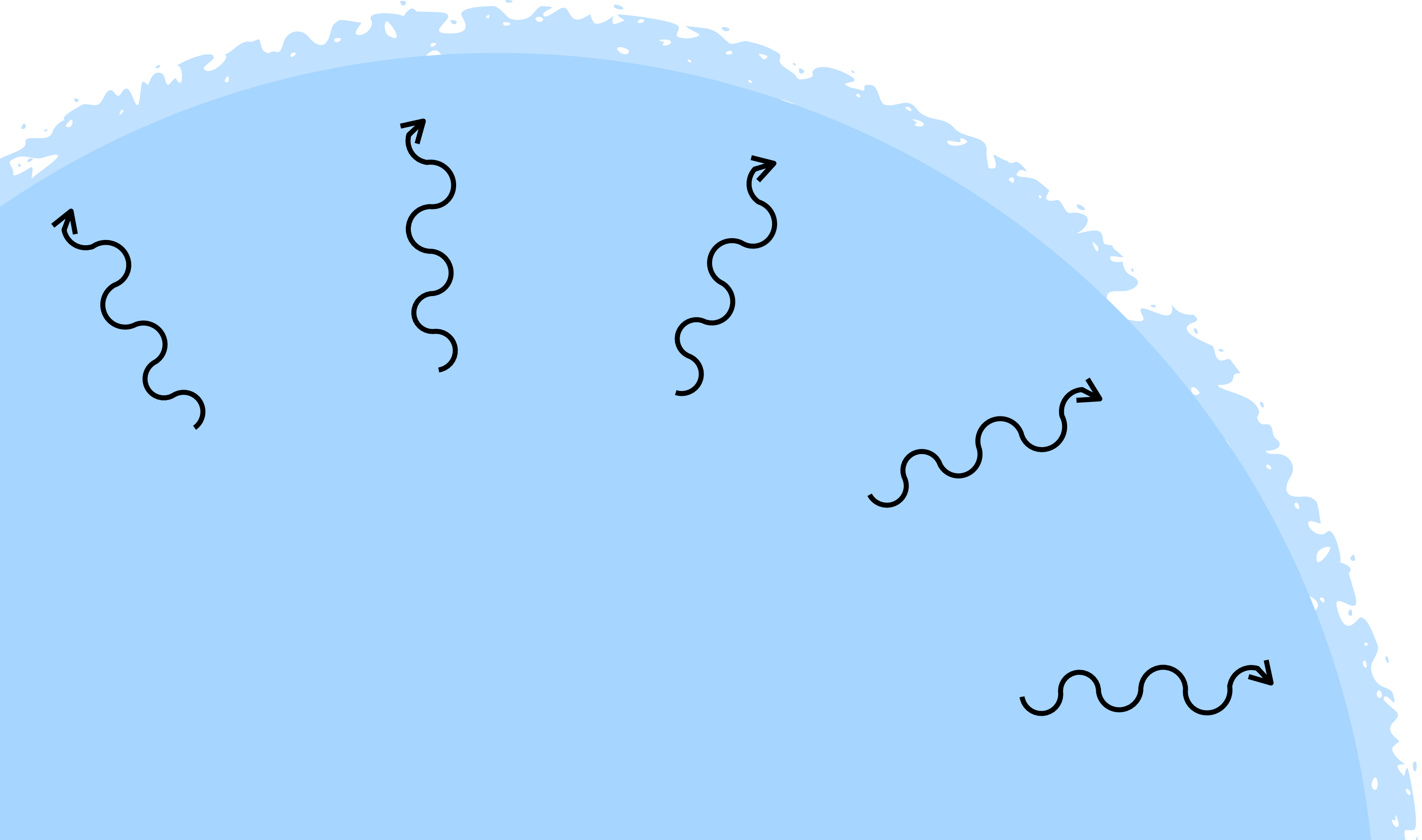
detached binaries

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{1}{2}\frac{\dot{a}}{a}$$

$$\dot{M}_1 = \dot{M}_{1,\rm wind} \qquad \dot{M}_T = \dot{M}_{1,\rm wind}$$

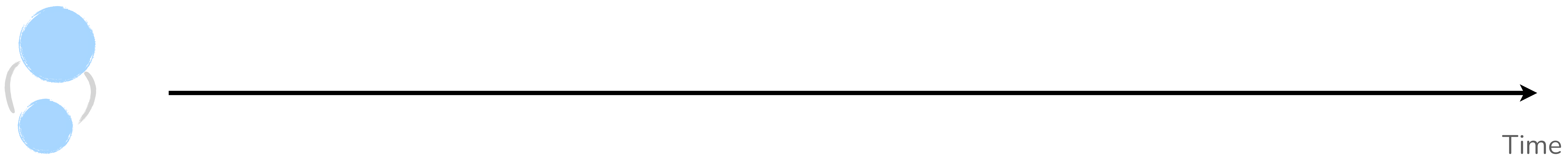
$$\frac{\dot{a}}{a} = 2\frac{\dot{J}}{J} - 2\frac{\dot{M}_{1,\rm wind}}{M_1} + \frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$

$$\left(\frac{\dot{J}}{J_{\rm orb}}\right)_{\rm wind} = \frac{M_2}{M_1}\frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$



$$\frac{\dot{a}}{a} = -\frac{\dot{M}_{1,\rm wind}}{M_1 + M_2}$$

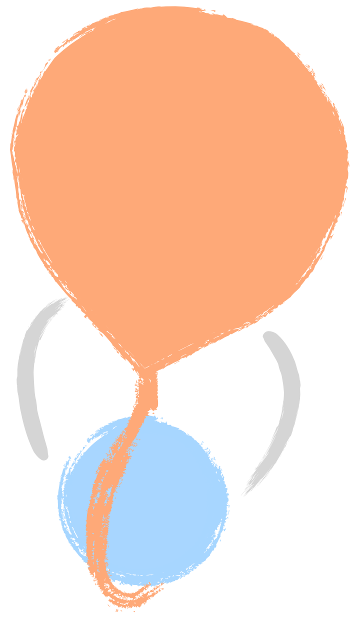
Wind mass loss widens orbits


Time


Time

Adiabatic exponents describe stability of mass transfer

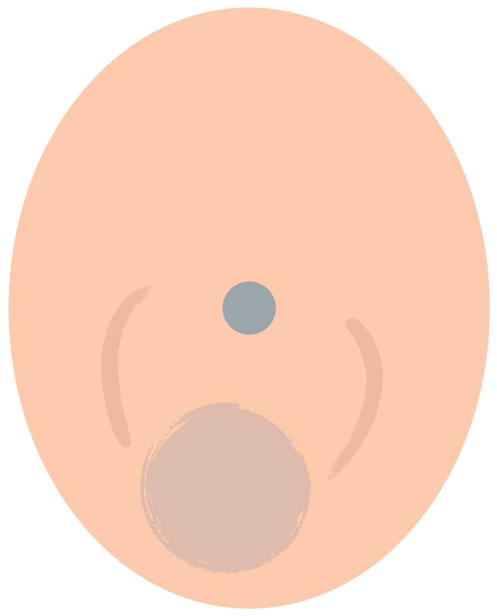
Adiabatic exponents describe stability of mass transfer



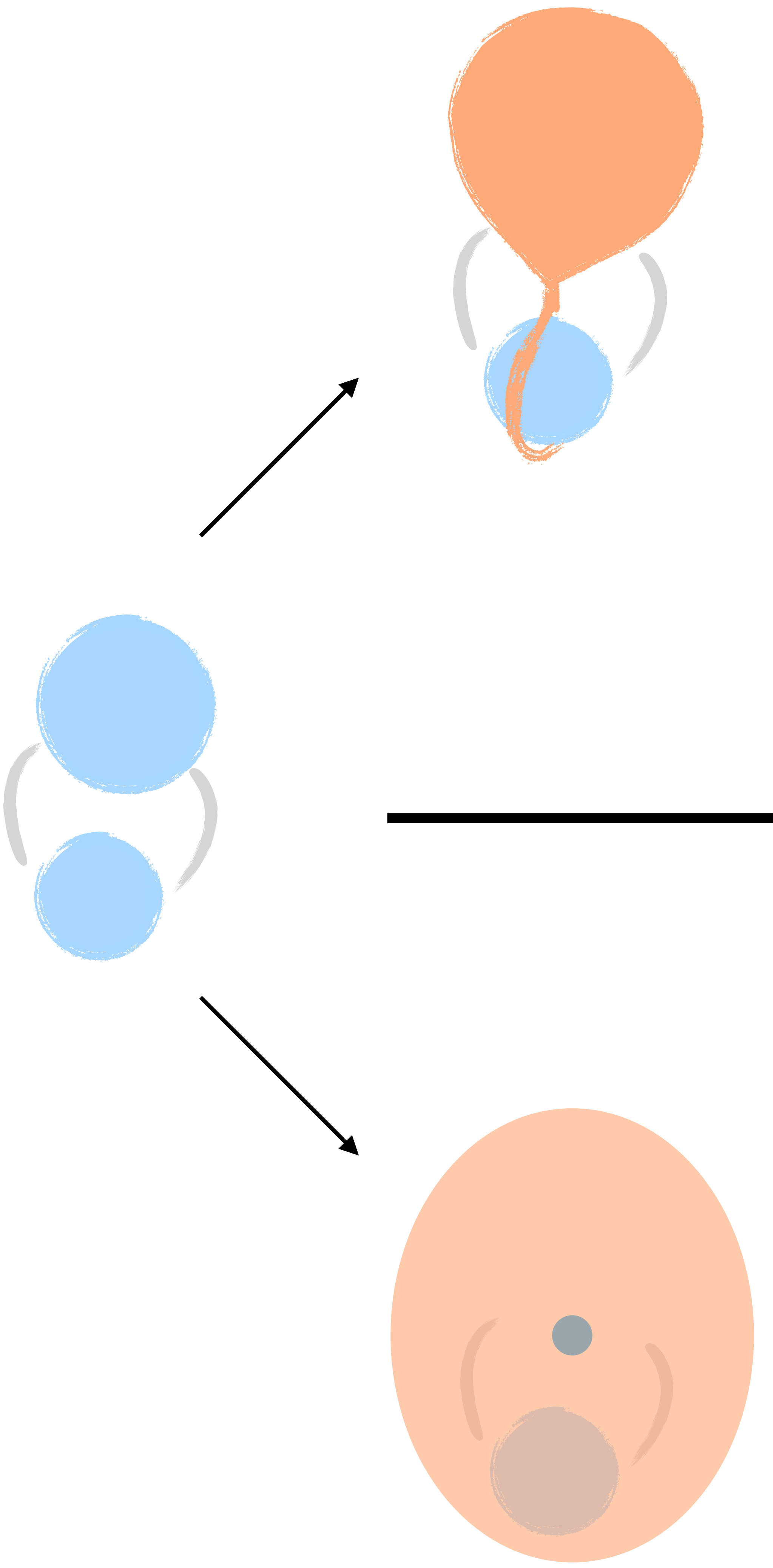
$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

Time



Adiabatic exponents describe stability of mass transfer



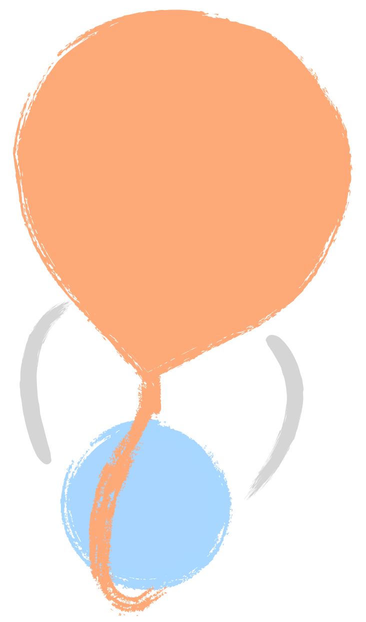
$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

$$\zeta_{R_{\mathrm{RL}}} = \frac{\partial \ln(R_{\mathrm{RL}})}{\partial \ln(M_{\mathrm{donor}})}$$

Time

Adiabatic exponents describe stability of mass transfer

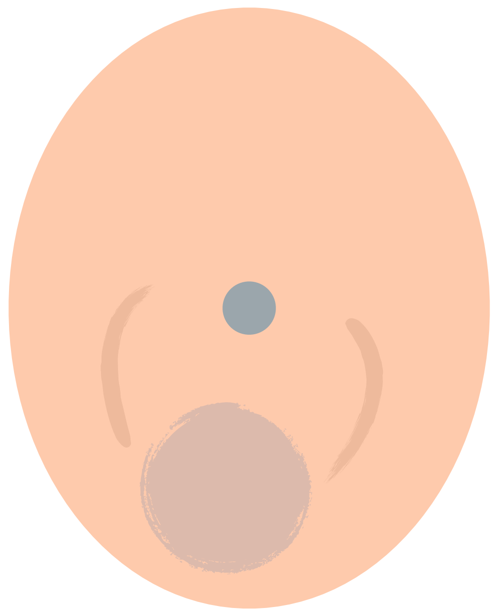


$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

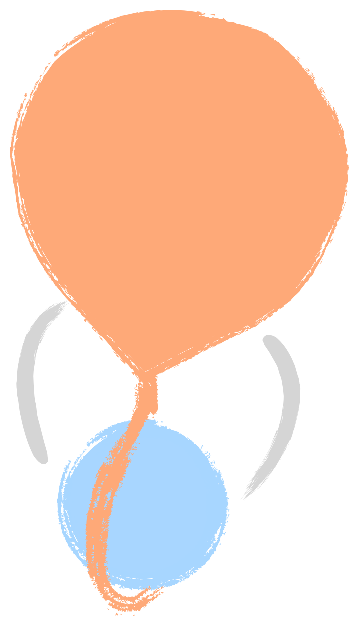
$$\zeta_{R_{\rm RL}} = \frac{\partial \ln(R_{\rm RL})}{\partial \ln(M_{\rm donor})}$$

Time



$$R_{\rm RL}/a = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

Adiabatic exponents describe stability of mass transfer

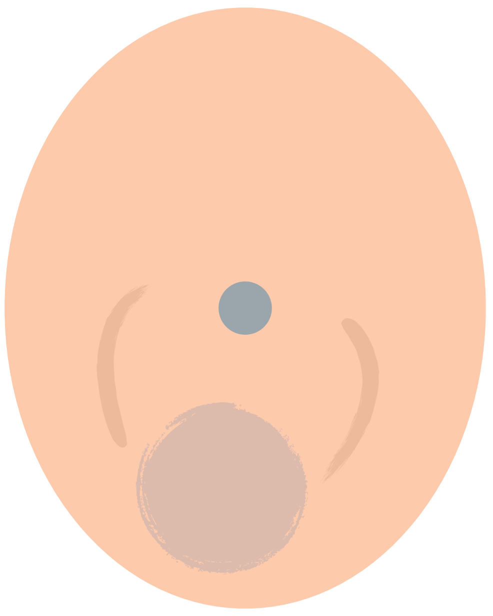


$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

$$\zeta_{R_{\rm RL}} = \frac{\partial \ln(R_{\rm RL})}{\partial \ln(M_{\rm donor})}$$

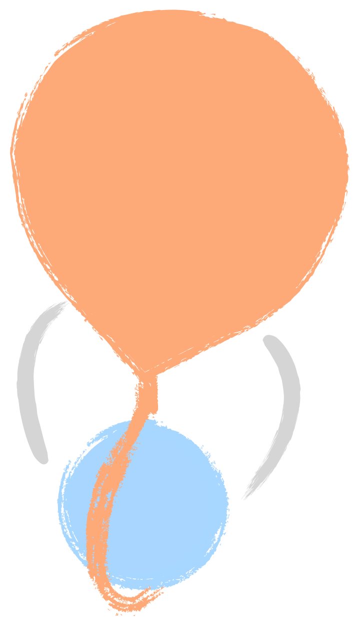
Time



$$R_{\rm RL}/a = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}$$

$$M_{\rm T} = M_{\rm don} + M_{\rm acc}$$

Adiabatic exponents describe stability of mass transfer

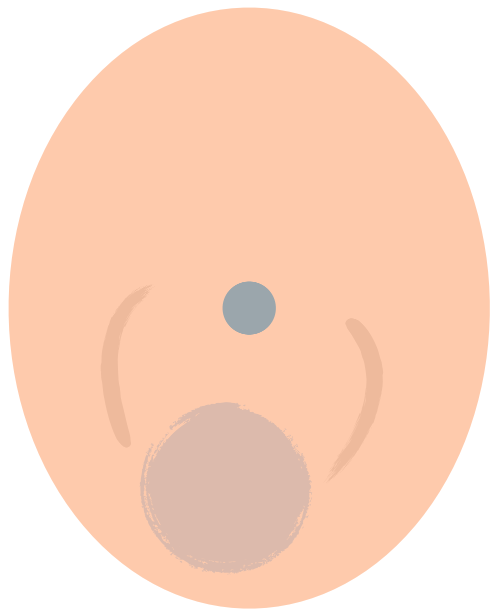


$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

$$\zeta_{R_{\mathrm{RL}}} = \frac{\partial \ln(R_{\mathrm{RL}})}{\partial \ln(M_{\mathrm{donor}})}$$

Time

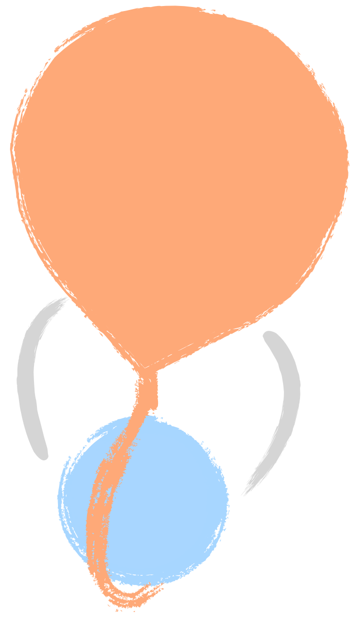


$$R_{\mathrm{RL}}/a = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

$$M_{\mathrm{T}} = M_{\mathrm{don}} + M_{\mathrm{acc}}$$

$$a = \left(\frac{J_{\mathrm{orb}}}{M_{\mathrm{don}} M_{\mathrm{acc}}}\right)^2 \frac{M_{\mathrm{T}}}{G}$$

Adiabatic exponents describe stability of mass transfer

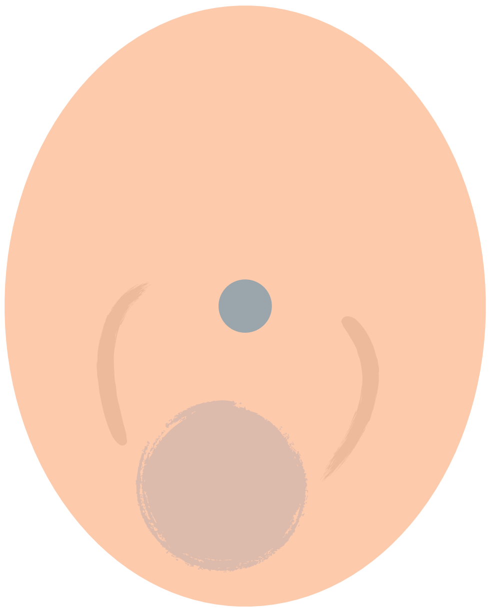


$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

$$\zeta_{R_{\rm RL}} = \frac{\partial \ln(R_{\rm RL})}{\partial \ln(M_{\rm donor})}$$

Time



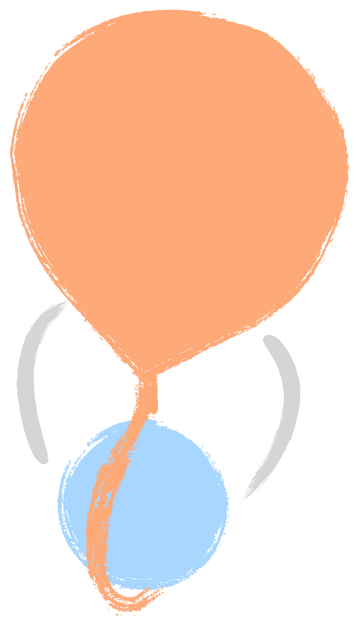
$$R_{\rm RL}/a = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

$$M_{\rm T} = M_{\rm don} + M_{\rm acc}$$

$$a = \left(\frac{J_{\rm orb}}{M_{\rm don}M_{\rm acc}}\right)^2 \frac{M_{\rm T}}{G}$$

$$\dot{M}_{\rm don} = -\dot{M}_{\rm acc}$$

Adiabatic exponents describe stability of mass transfer

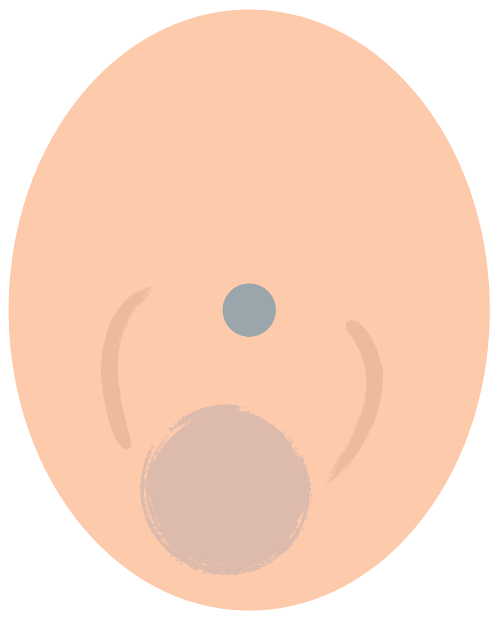


$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

$$\zeta_{R_{\rm RL}} = \frac{\partial \ln(R_{\rm RL})}{\partial \ln(M_{\rm donor})} = \frac{\partial \ln a}{\partial \ln M_{\rm donor}} + \frac{\partial \ln R_{\rm RL}/a}{\partial \ln q}\frac{\partial \ln q}{\partial \ln M_{\rm donor}}$$

Time



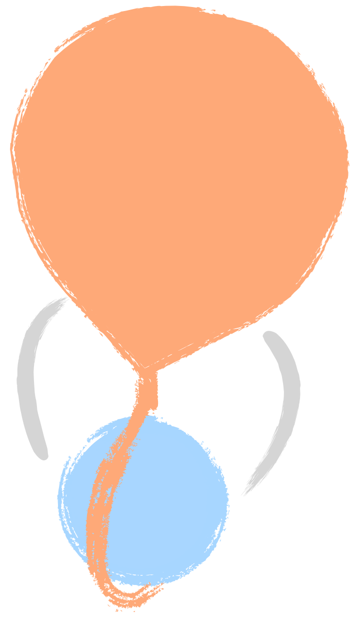
$$R_{\rm RL}/a = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}$$

$$M_{\rm T} = M_{\rm don} + M_{\rm acc}$$

$$a = \left(\frac{J_{\rm orb}}{M_{\rm don}M_{\rm acc}}\right)^2 \frac{M_{\rm T}}{G}$$

$$\dot{M}_{\rm don} = -\dot{M}_{\rm acc}$$

Adiabatic exponents describe stability of mass transfer

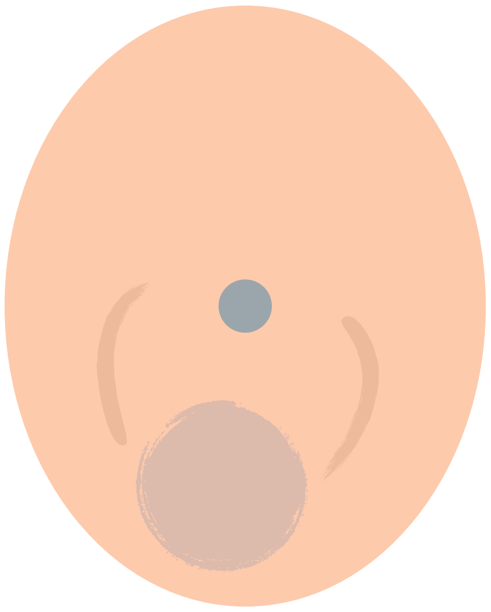


$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

$$\zeta_{R_{\mathrm{RL}}} = \frac{\partial \ln(R_{\mathrm{RL}})}{\partial \ln(M_{\mathrm{donor}})} = \frac{\partial \ln a}{\partial \ln M_{\mathrm{donor}}} + \frac{\partial \ln R_{\mathrm{RL}}/a}{\partial \ln q}\frac{\partial \ln q}{\partial \ln M_{\mathrm{donor}}}$$

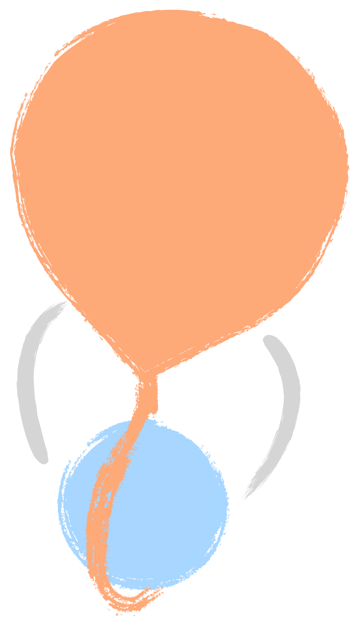
Time



$$\zeta_{R_{\mathrm{RL}}} = \frac{2M_{\mathrm{don}}^2 - 2M_{\mathrm{acc}}^2 - M_{\mathrm{don}}M_{\mathrm{acc}}(1-\beta)}{M_{\mathrm{acc}}(M_{\mathrm{don}} + M_{\mathrm{acc}})} + \left[\frac{2}{3} - \frac{q^{1/3}}{3}\frac{1.2q^{1/3} + 1/(1+q^{1/3})}{0.6q^{2/3} + \ln(1+q^{1/3})}\right]\left[1 + \beta\frac{M_{\mathrm{don}}}{M_{\mathrm{acc}}}\right]$$

e.g. Soberman 1997

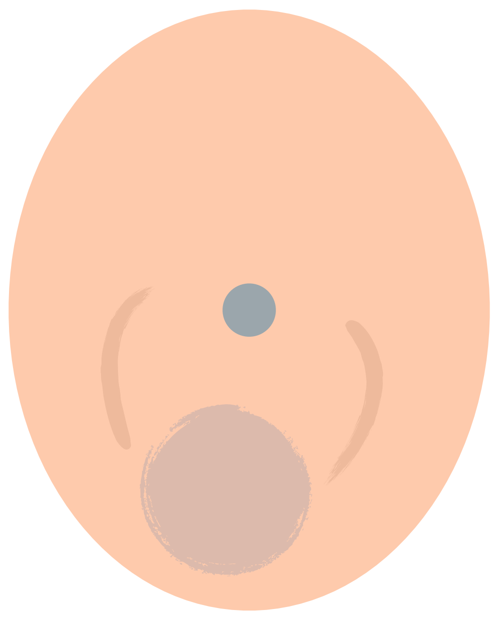
Adiabatic exponents describe stability of mass transfer



$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

How do different radial quantities depend on mass loss?

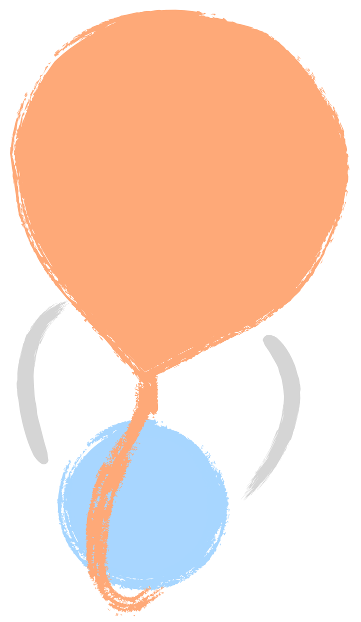
$$\zeta_{R_{\rm RL}} = \frac{\partial \ln(R_{\rm RL})}{\partial \ln(M_{\rm donor})} = \frac{\partial \ln a}{\partial \ln M_{\rm donor}} + \frac{\partial \ln R_{\rm RL}/a}{\partial \ln q}\frac{\partial \ln q}{\partial \ln M_{\rm donor}}$$



$$\zeta_{\star} = \frac{\partial \ln R_{\rm donor}}{\partial \ln M_{\rm donor}}$$

$\zeta_{\star}$ depends on the structure of the star

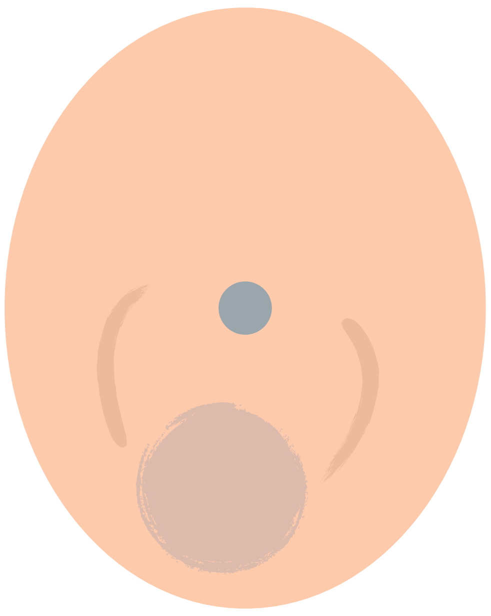
Adiabatic exponents describe stability of mass transfer



$$\zeta = \frac{\partial \ln R}{\partial \ln M}$$

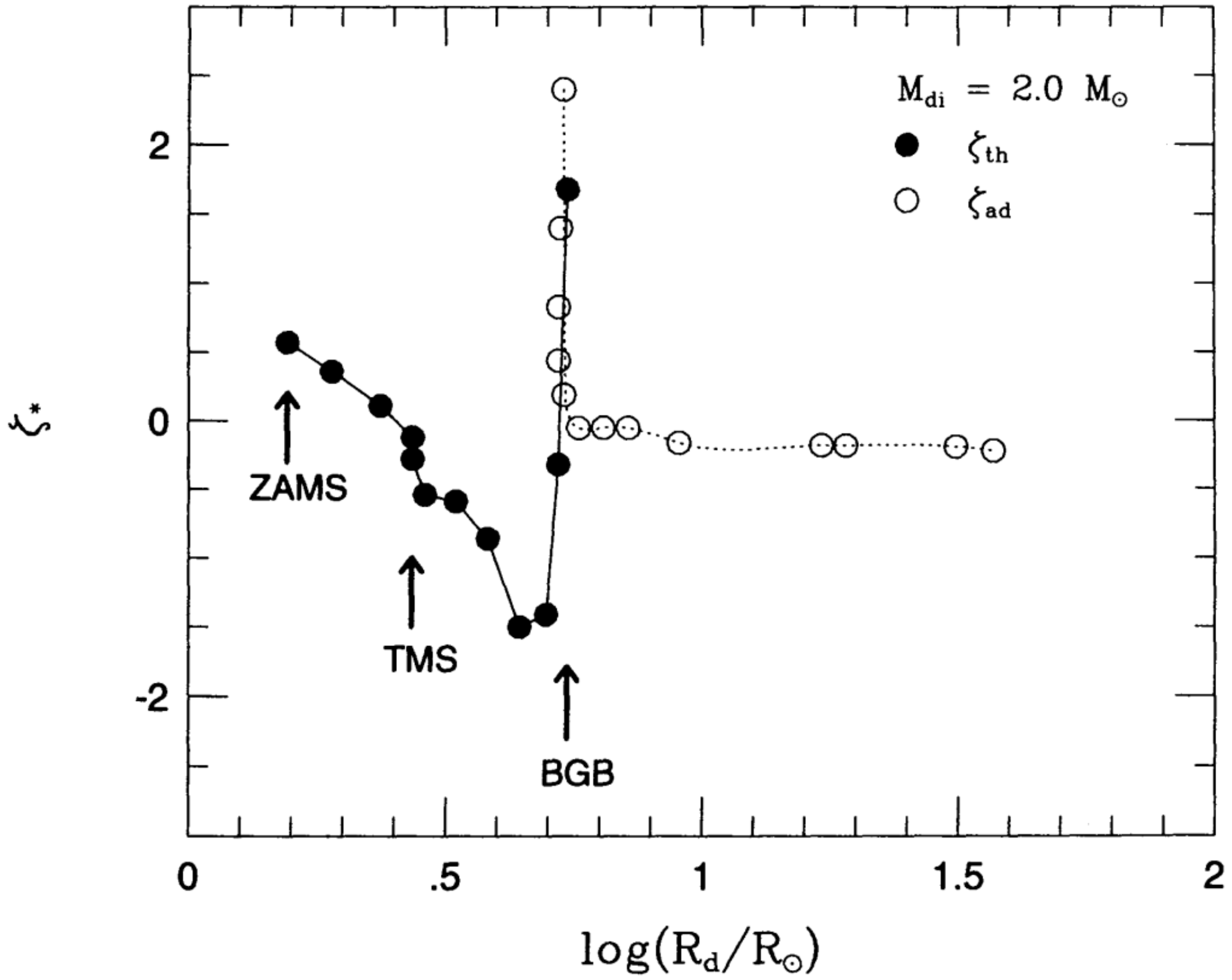
How do different radial quantities depend on mass loss?

$$\zeta_{R_{\mathrm{RL}}} = \frac{\partial \ln(R_{\mathrm{RL}})}{\partial \ln(M_{\mathrm{donor}})} = \frac{\partial \ln a}{\partial \ln M_{\mathrm{donor}}} + \frac{\partial \ln R_{\mathrm{RL}}/a}{\partial \ln q}\frac{\partial \ln q}{\partial \ln M_{\mathrm{donor}}}$$

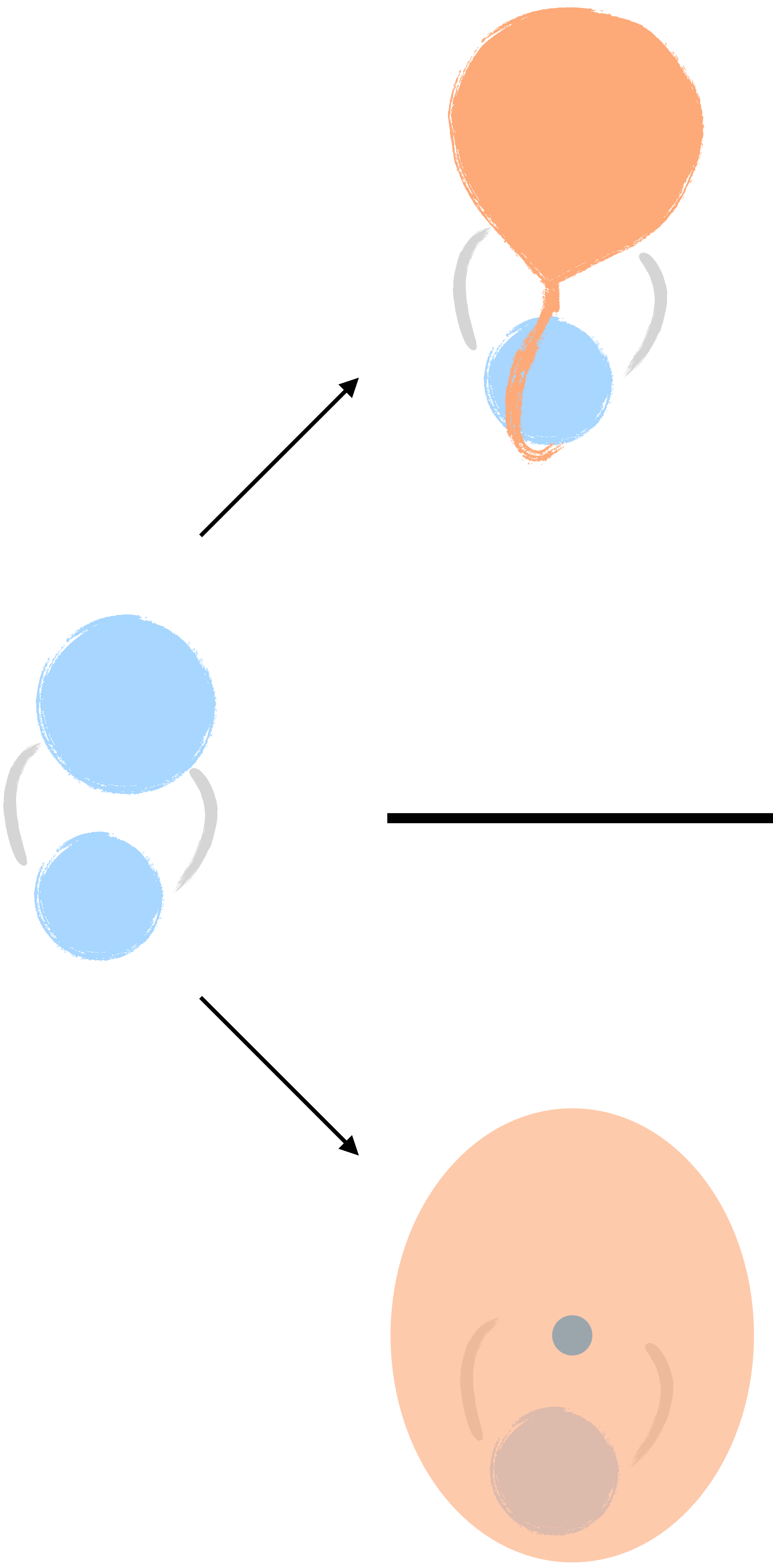


$$\zeta_\star = \frac{\partial \ln R_{\mathrm{donor}}}{\partial \ln M_{\mathrm{donor}}}$$

$\zeta_\star$ depends on the structure of the star

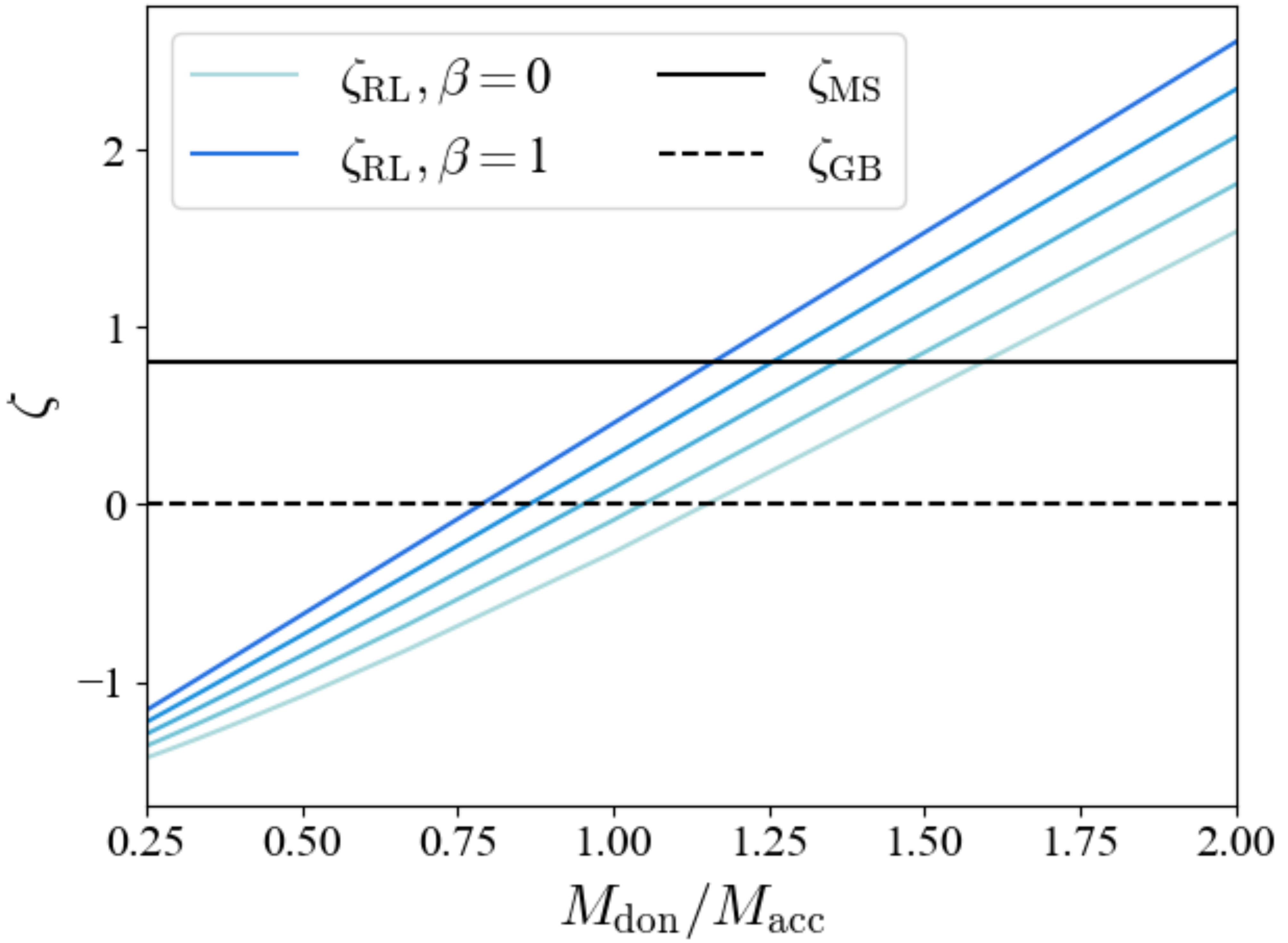


e.g. Hjellming & Webbink 1987

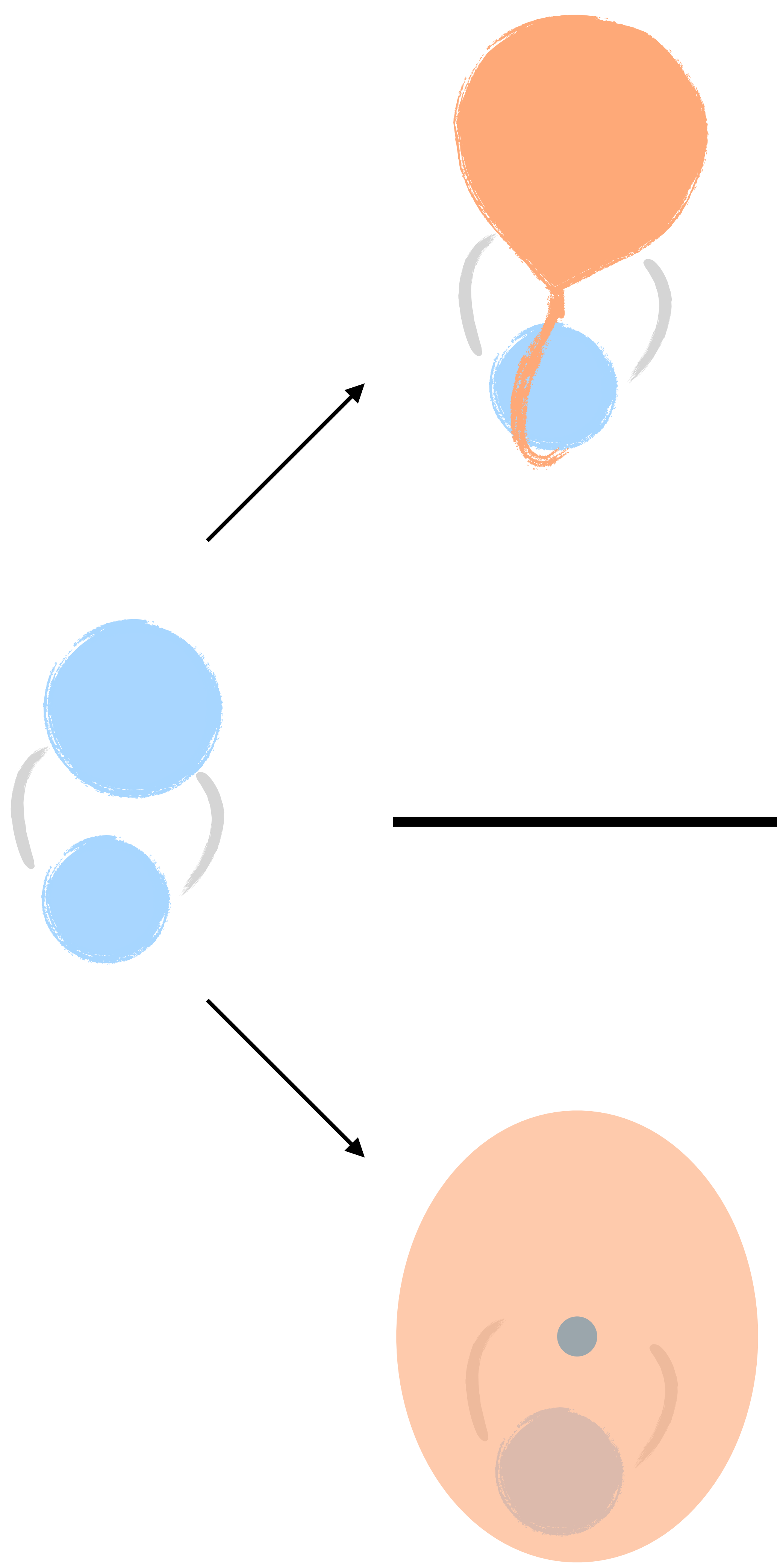


$$\zeta_{R_{\mathrm{RL}}} = \frac{\partial \ln(R_{\mathrm{RL}})}{\partial \ln(M_{\mathrm{donor}})}$$

$$\zeta_{\star} = \frac{\partial \ln R_{\mathrm{donor}}}{\partial \ln M_{\mathrm{donor}}}$$

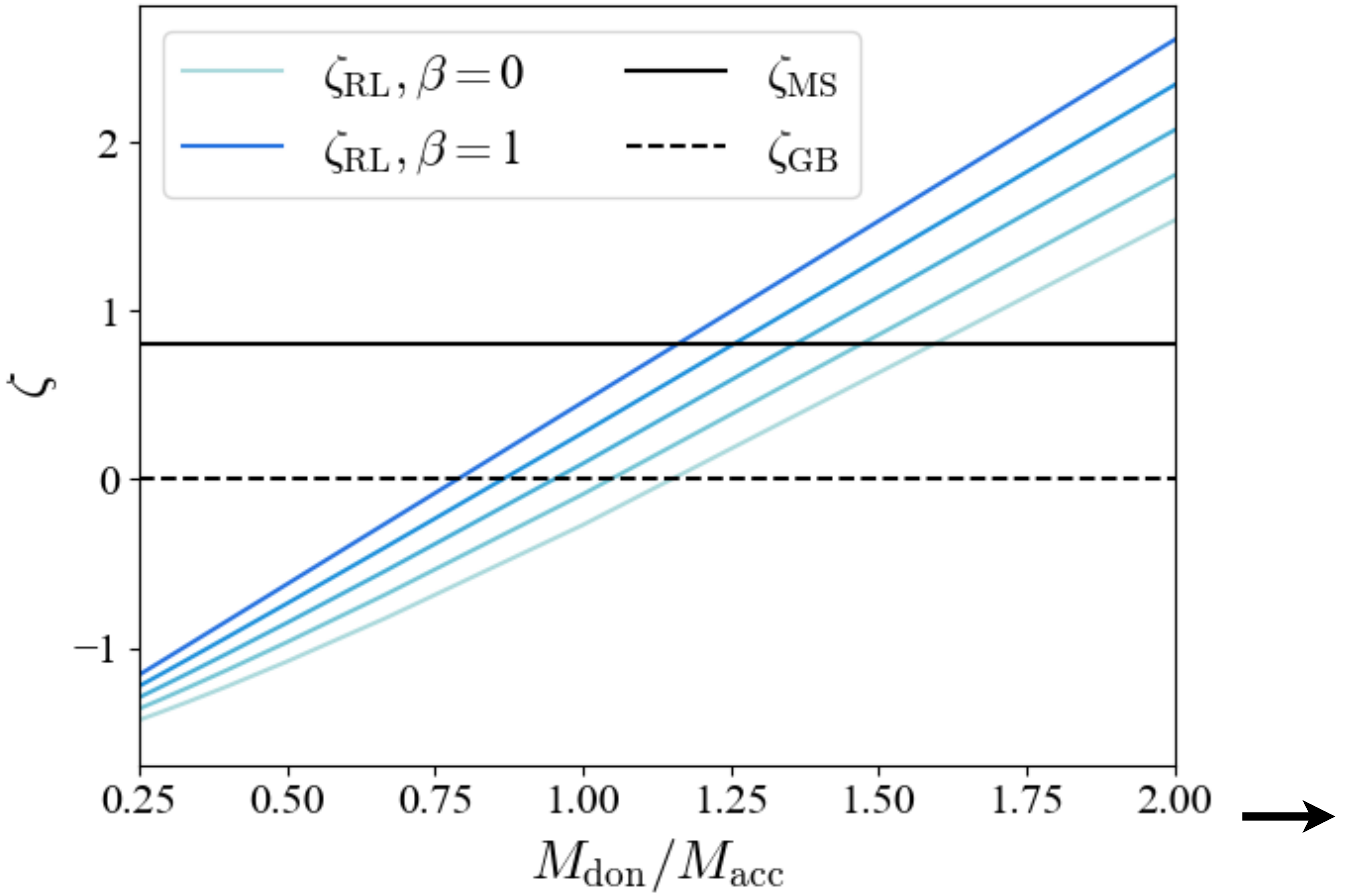


Time



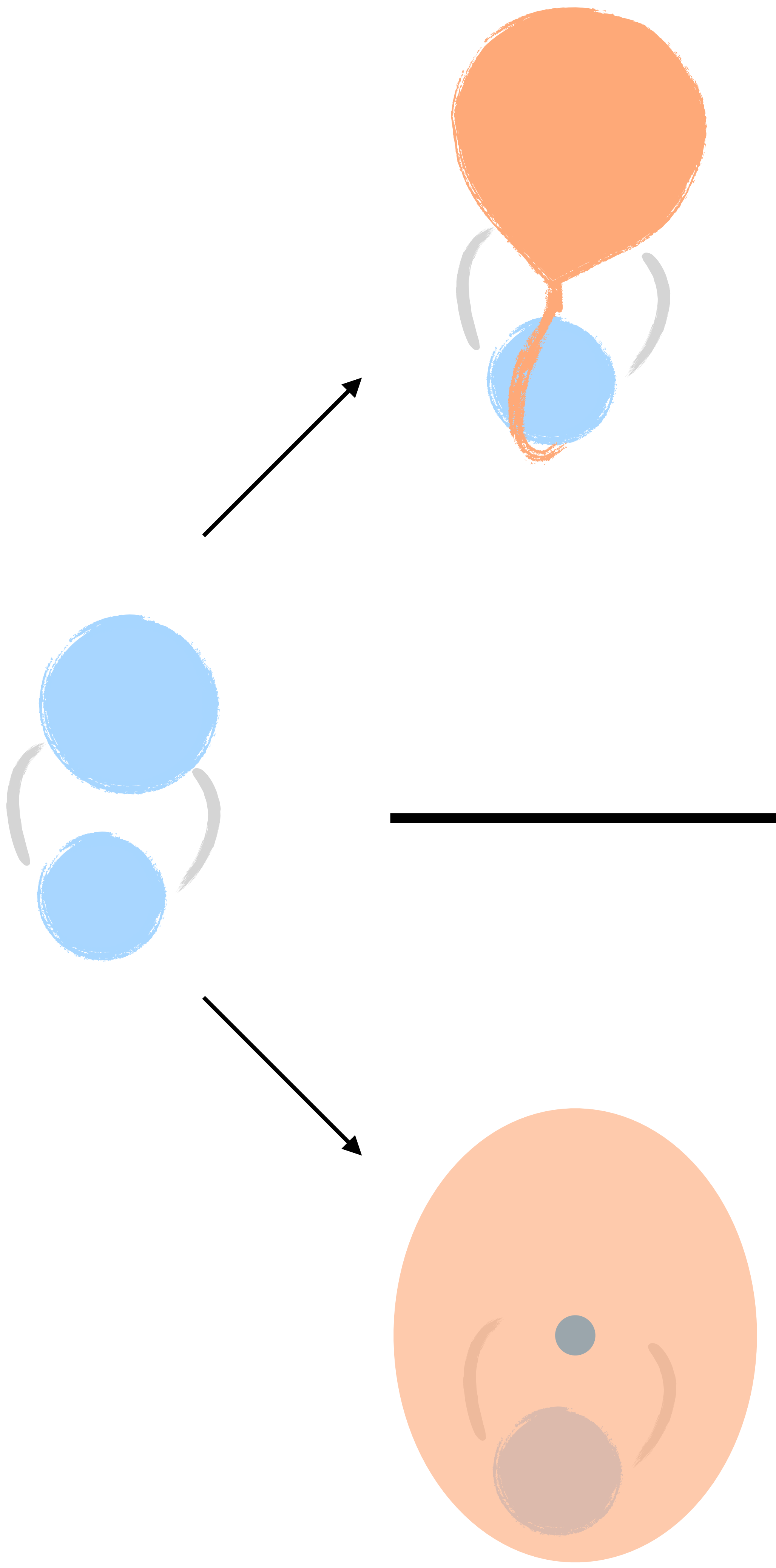
$$\zeta_{R_{RL}} = \frac{\partial \ln(R_{RL})}{\partial \ln(M_{donor})}$$

$$\zeta_{\star} = \frac{\partial \ln R_{donor}}{\partial \ln M_{donor}}$$



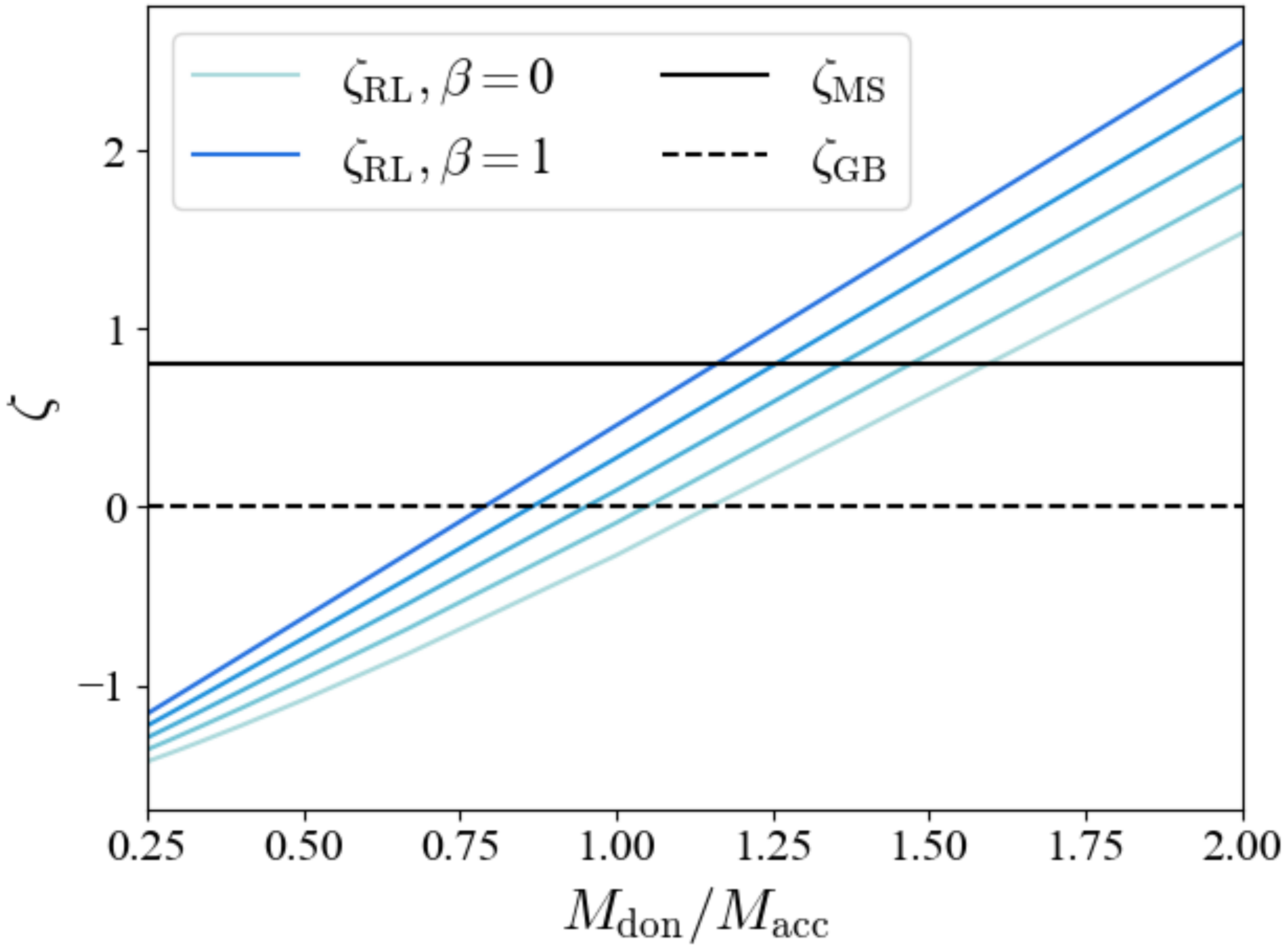
Time

If $\zeta_{R_{RL}} < \zeta_{\star}$, the star's radius responds more quickly than the Roche-radius —> stable mass transfer



$$\zeta_{R_{\mathrm{RL}}} = \frac{\partial \ln(R_{\mathrm{RL}})}{\partial \ln(M_{\mathrm{donor}})}$$

$$\zeta_{\star} = \frac{\partial \ln R_{\mathrm{donor}}}{\partial \ln M_{\mathrm{donor}}}$$

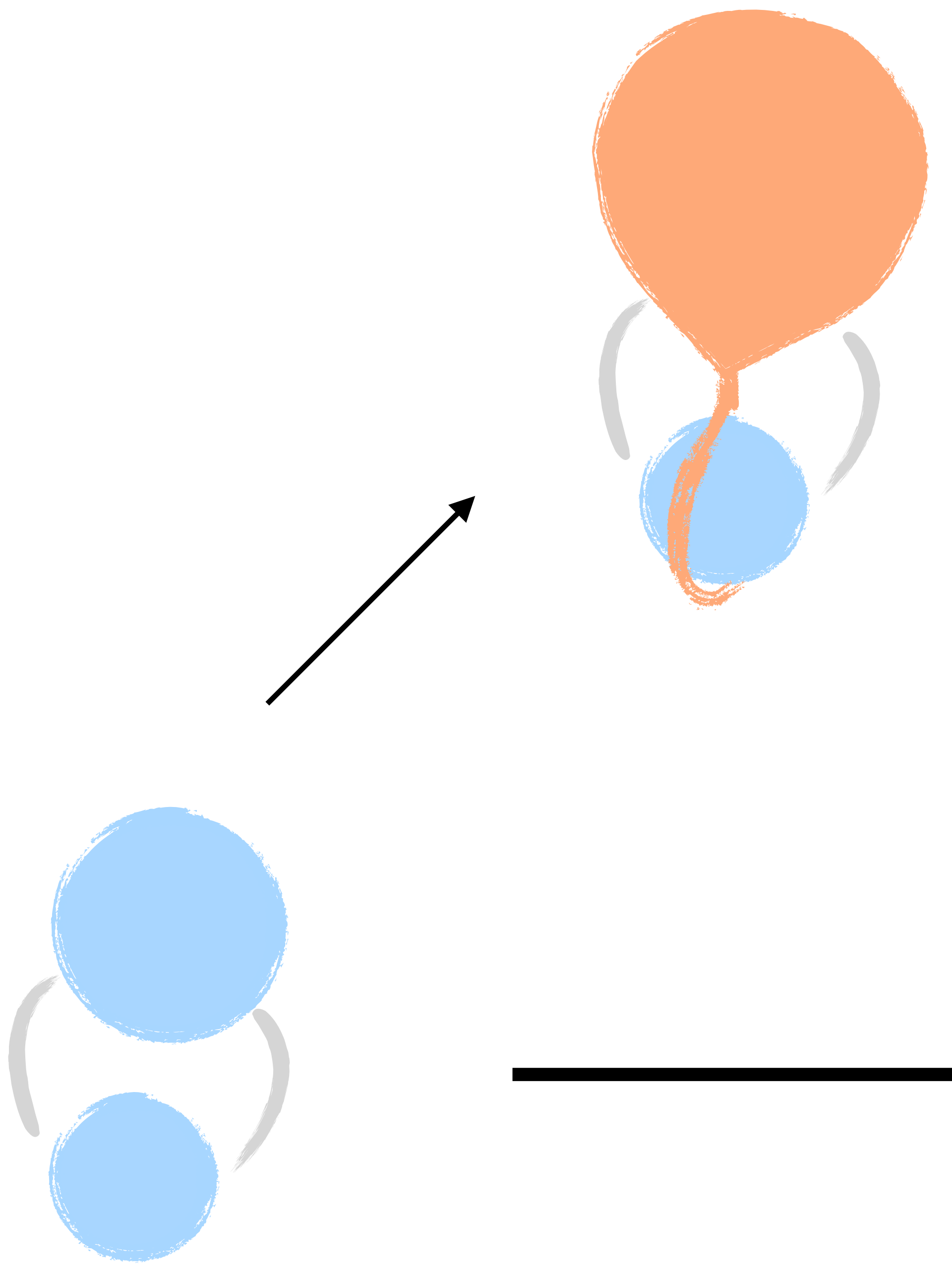


Time

If $\zeta_{\mathrm{R_{RL}}} < \zeta_{\star}$, the star's radius responds more quickly than the Roche-radius —> stable mass transfer

Otherwise — common envelope is initiated

During stable mass transfer, the orbit responds to mass exchange

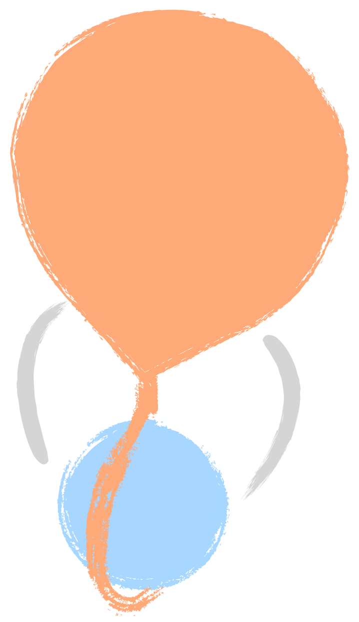


$$\frac{\dot{a}}{a} = 2\frac{\dot{M}_{\rm d}}{M_{\rm d}}(q-1)$$

fully conservative

Time

During stable mass transfer, the orbit responds to mass exchange



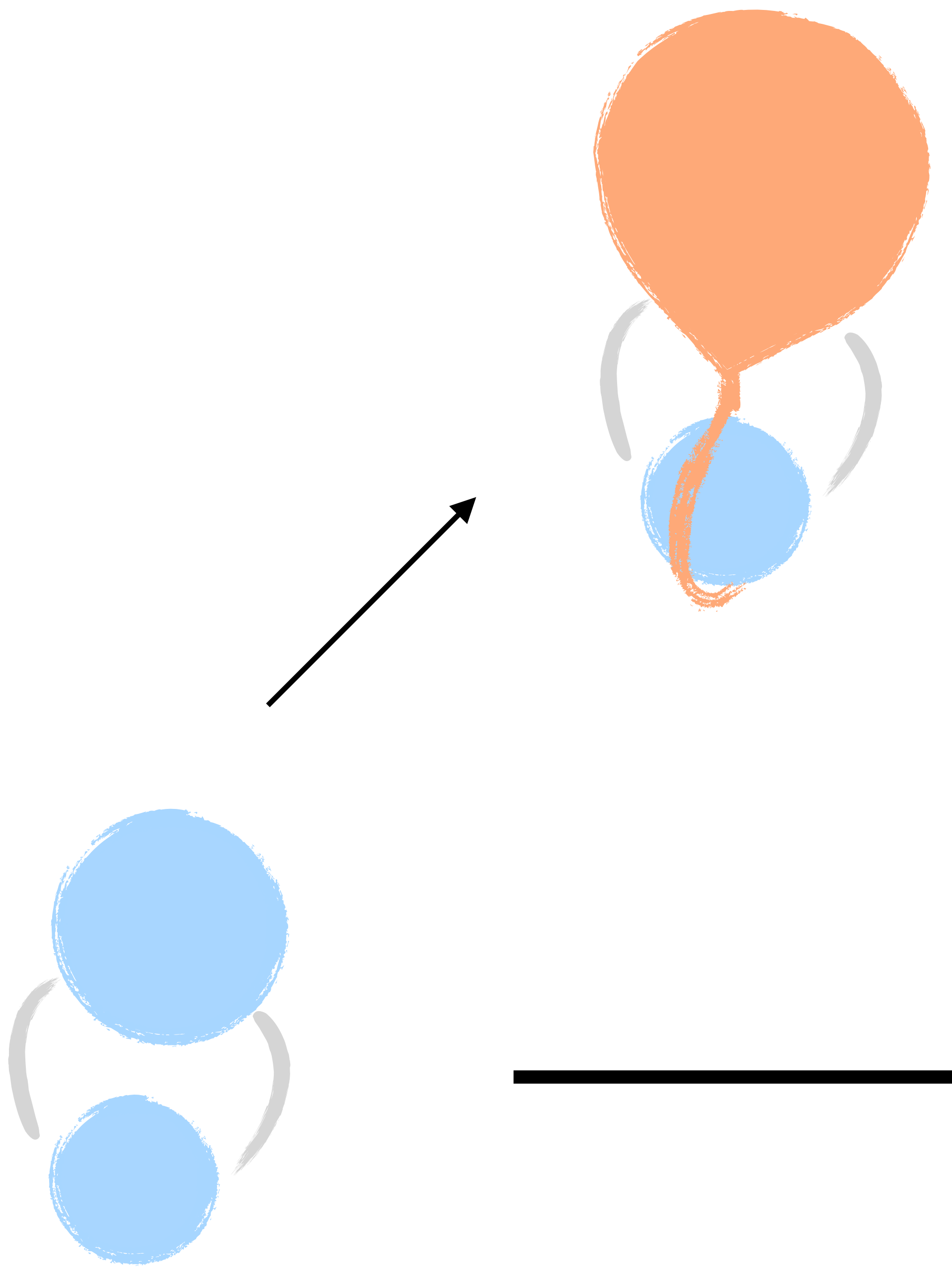
$$\frac{\dot{a}}{a} = 2\frac{\dot{M}_\mathrm{d}}{M_\mathrm{d}}(q-1)$$

$\dot{M}_\mathrm{d} < 0$ due to *mass loss*

fully conservative

Time

During stable mass transfer, the orbit responds to mass exchange



$$\frac{\dot{a}}{a} = 2\frac{\dot{M}_\mathrm{d}}{M_\mathrm{d}}(q-1)$$

fully conservative

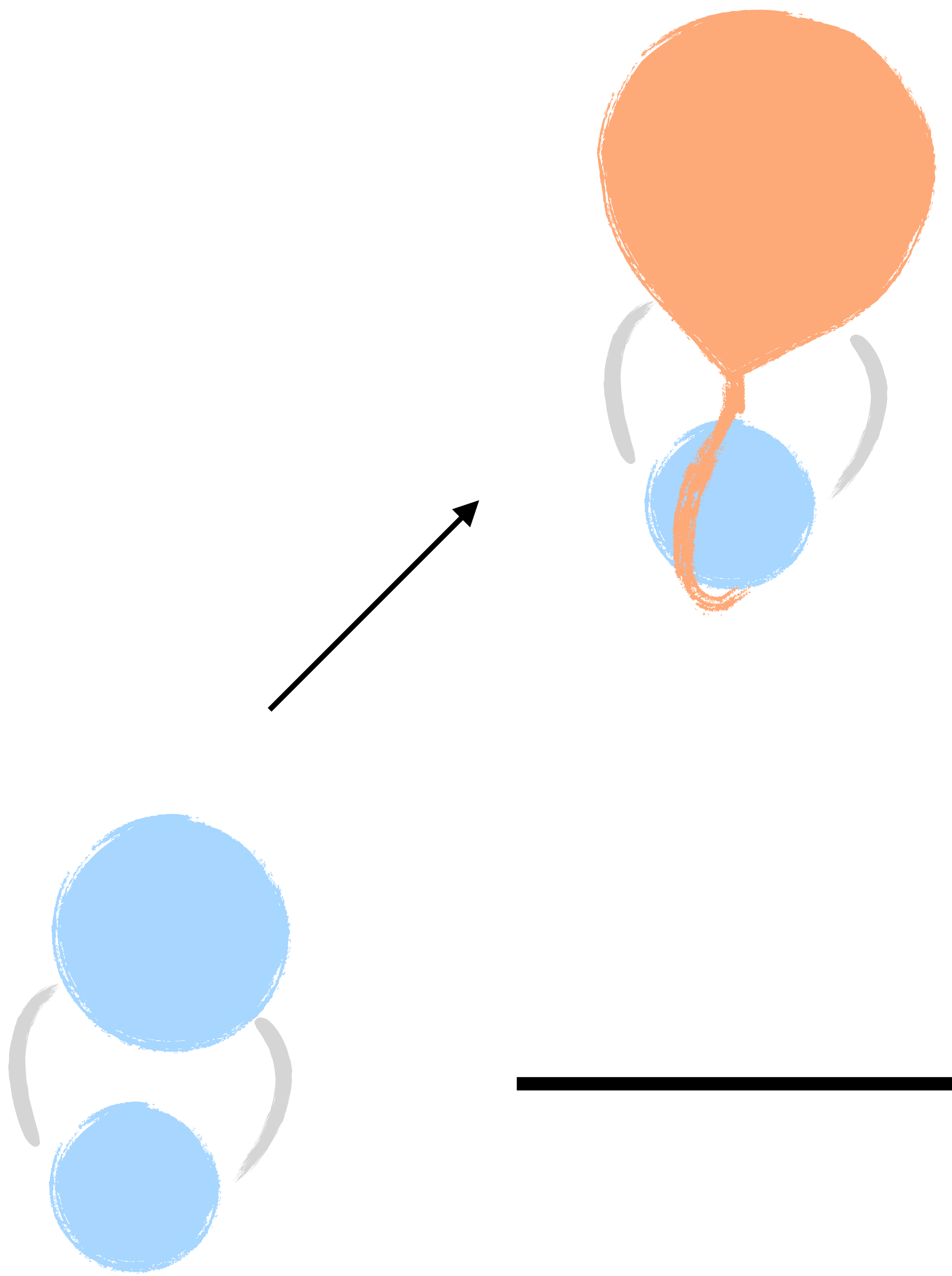
$\dot{M}_\mathrm{d} < 0$ due to *mass loss*

If $q > 1$ the orbit shrinks

If $q < 1$ the orbit widens

Time

During stable mass transfer, the orbit responds to mass exchange



$$\frac{\dot{a}}{a} = 2\frac{\dot{M}_{\rm d}}{M_{\rm d}}(q-1)$$

fully conservative

$\dot{M}_{\rm d} < 0$ due to *mass loss*

If $q > 1$ the orbit shrinks

If $q < 1$ the orbit widens

Time

$$\frac{\dot{a}}{a} = \frac{\dot{q}}{q}\frac{2q^2-(1-\beta)q-2}{(1+\beta q)(1+q)}$$

not conservative

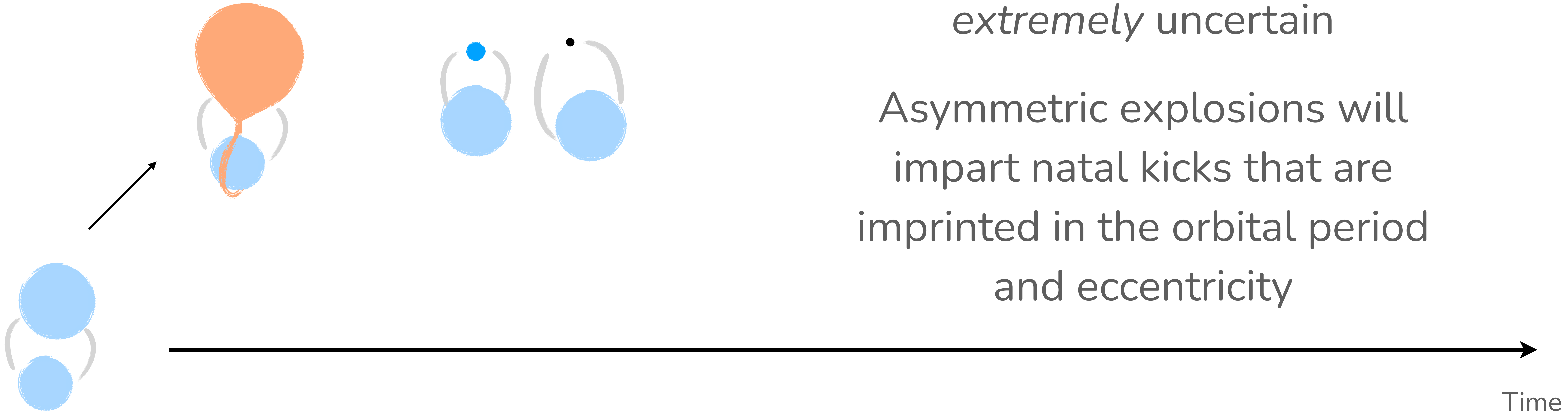
If only a fraction of mass (β) is accreted,
the orbital evolution is suppressed


Time


Time

Time

Compact object formation is *extremely* uncertain

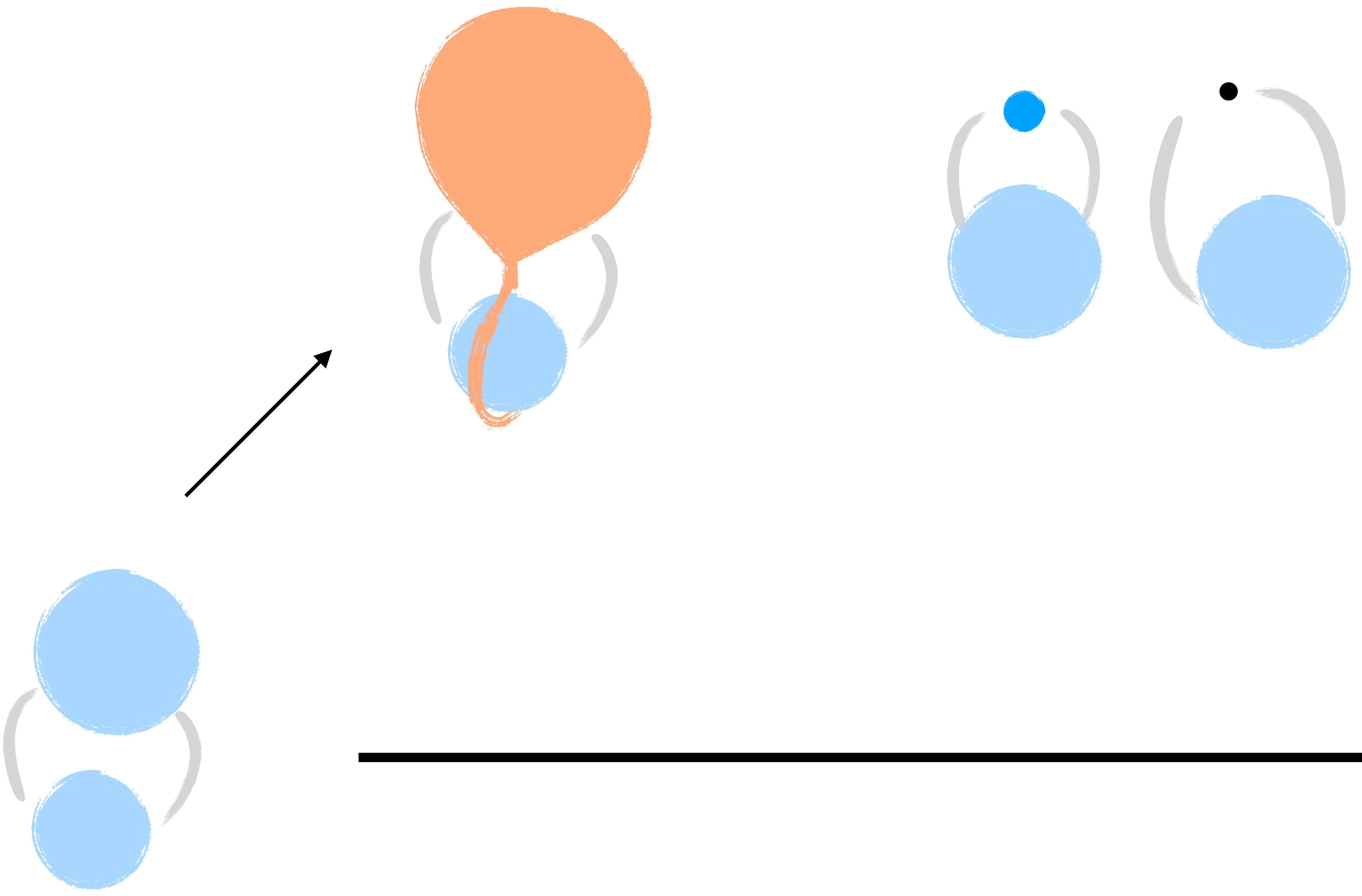


Compact object formation is *extremely* uncertain

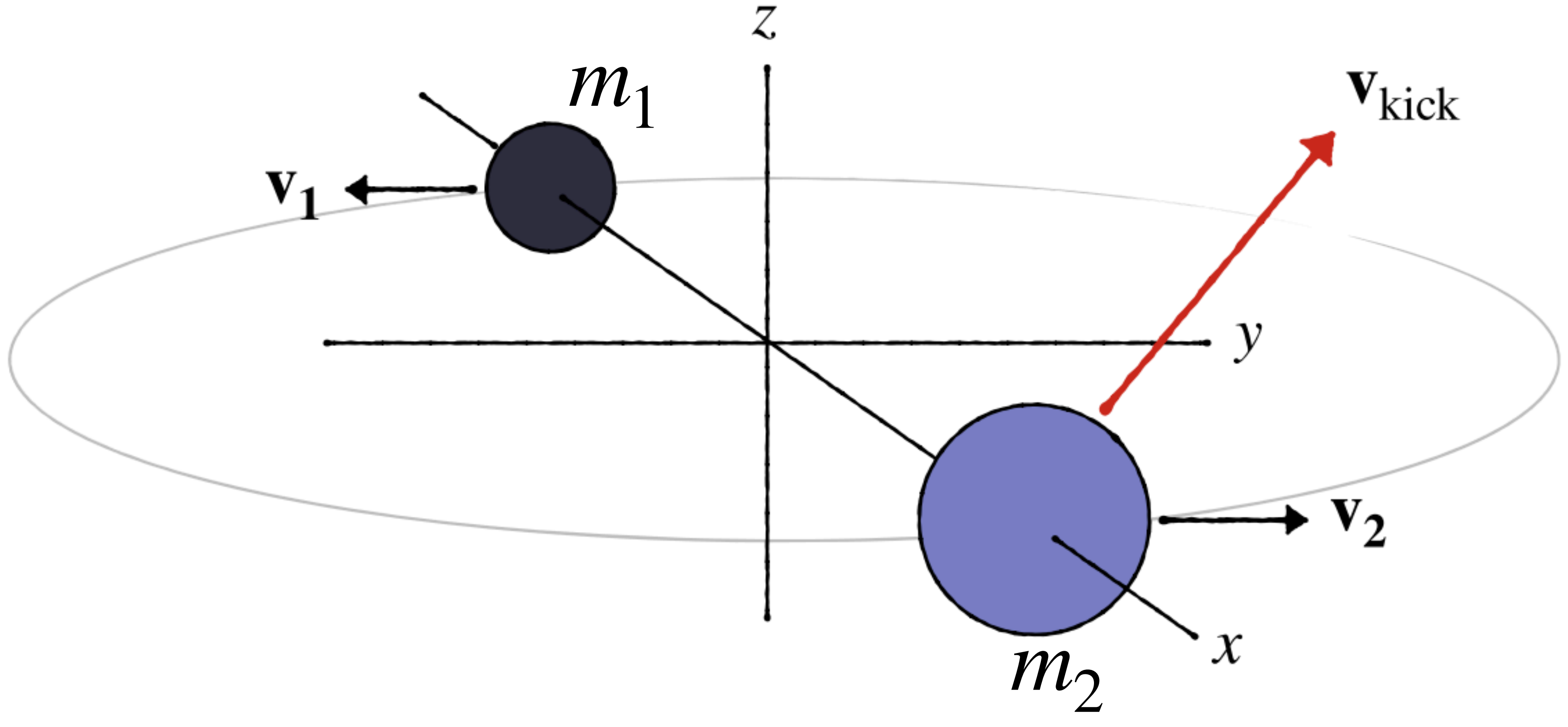
Asymmetric explosions will impart natal kicks that are imprinted in the orbital period and eccentricity

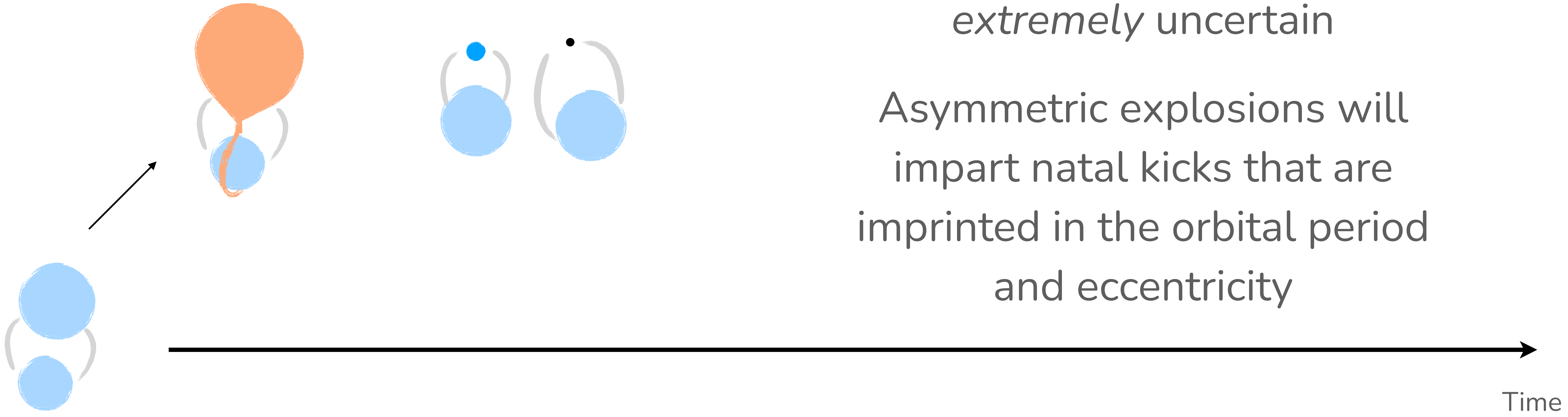
Compact object formation is *extremely* uncertain

Asymmetric explosions will impart natal kicks that are imprinted in the orbital period and eccentricity



Time

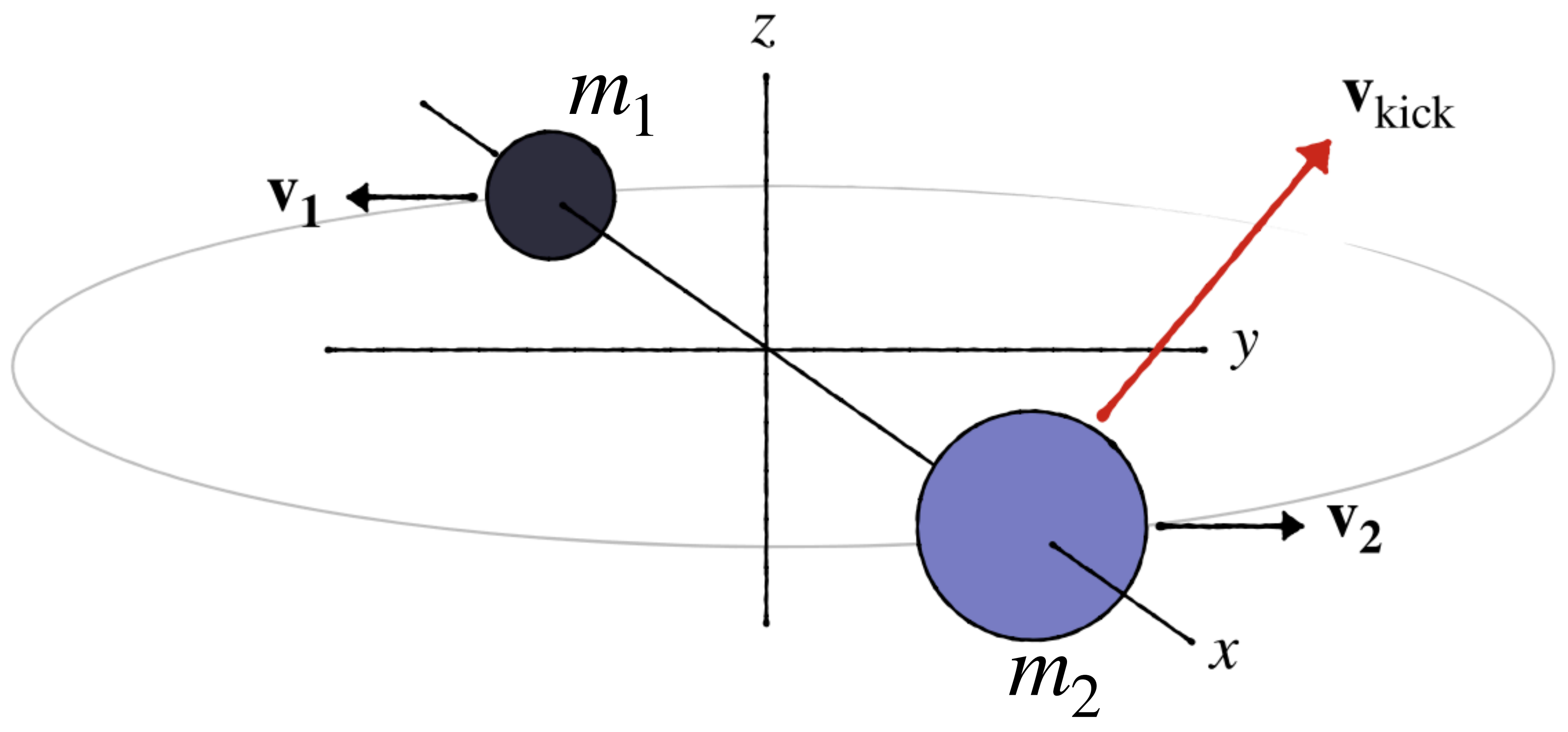




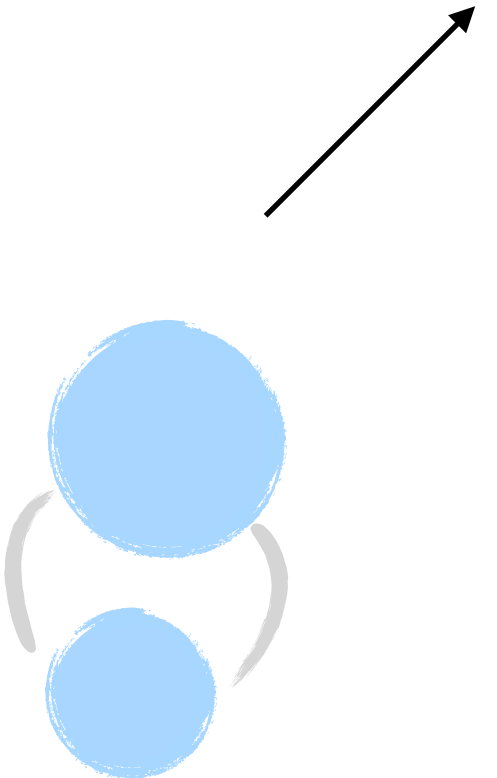
Compact object formation is *extremely* uncertain

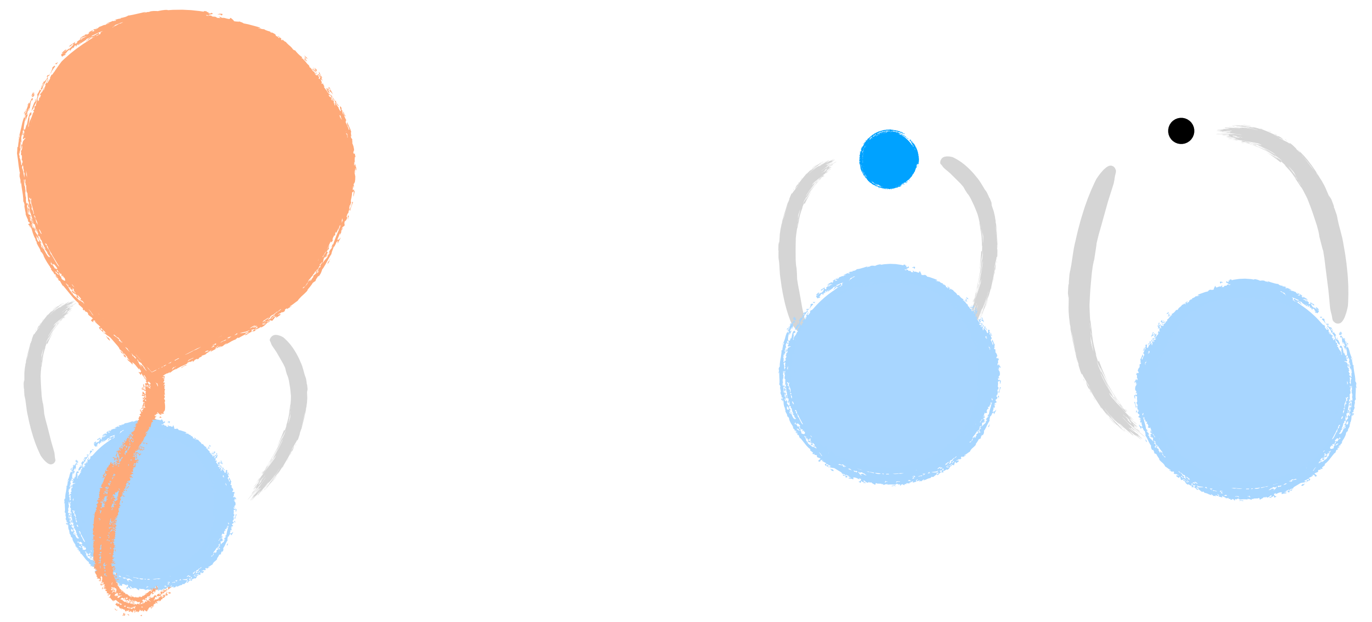
Asymmetric explosions will impart natal kicks that are imprinted in the orbital period and eccentricity

We assign masses based on prescriptions drawn from core collapse modeling
(e.g. Fryer+12,22, Mandel+20)



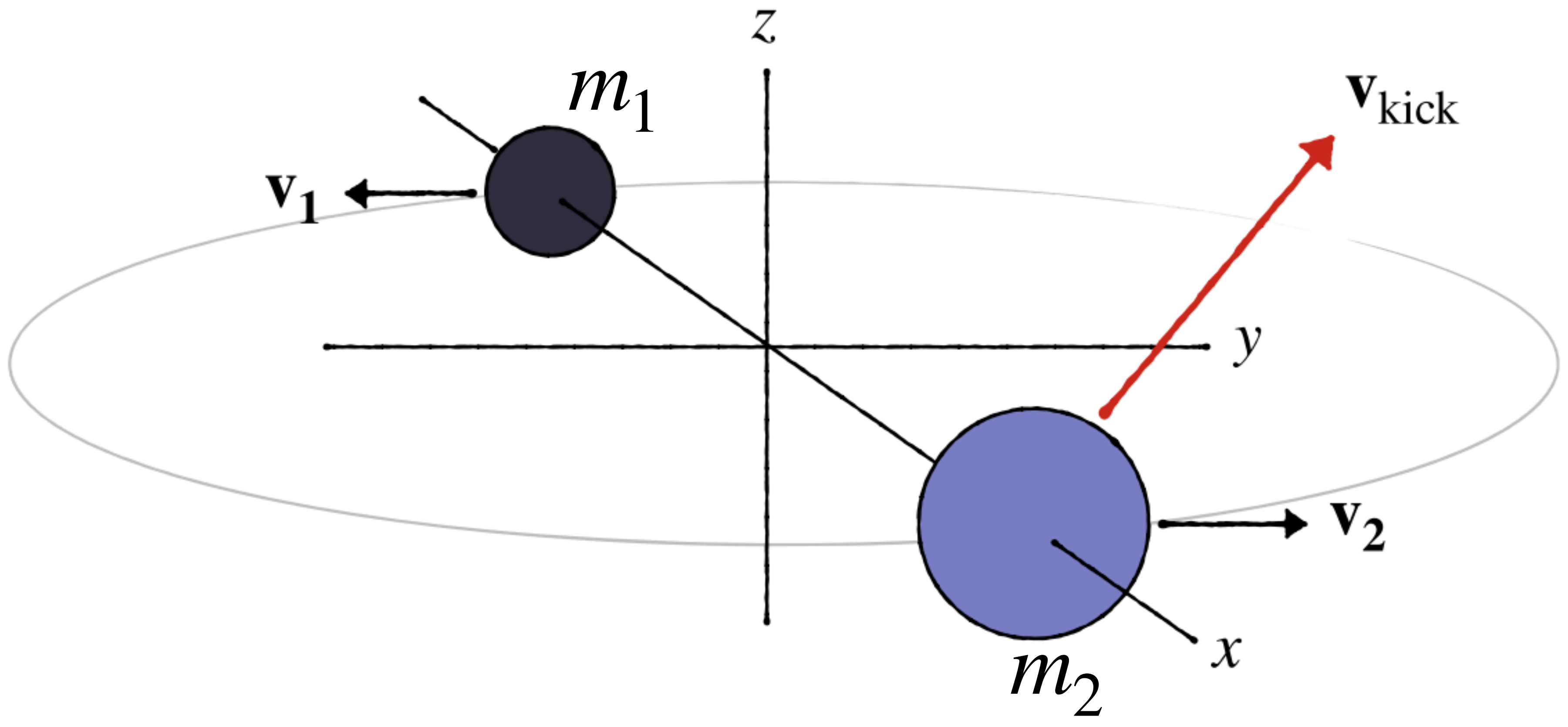
Asymmetric explosions will impart natal kicks that are imprinted in the orbital period and eccentricity





$$a_f = G(M_1 + M_2)\left[\frac{2G(M_1 + M_2)}{a_i} - v_{\rm k}^2 - v_{\rm orb}^2 - 2\vec{v}_{\rm k} \cdot \vec{v}_{\rm orb}\right]^{-1}$$

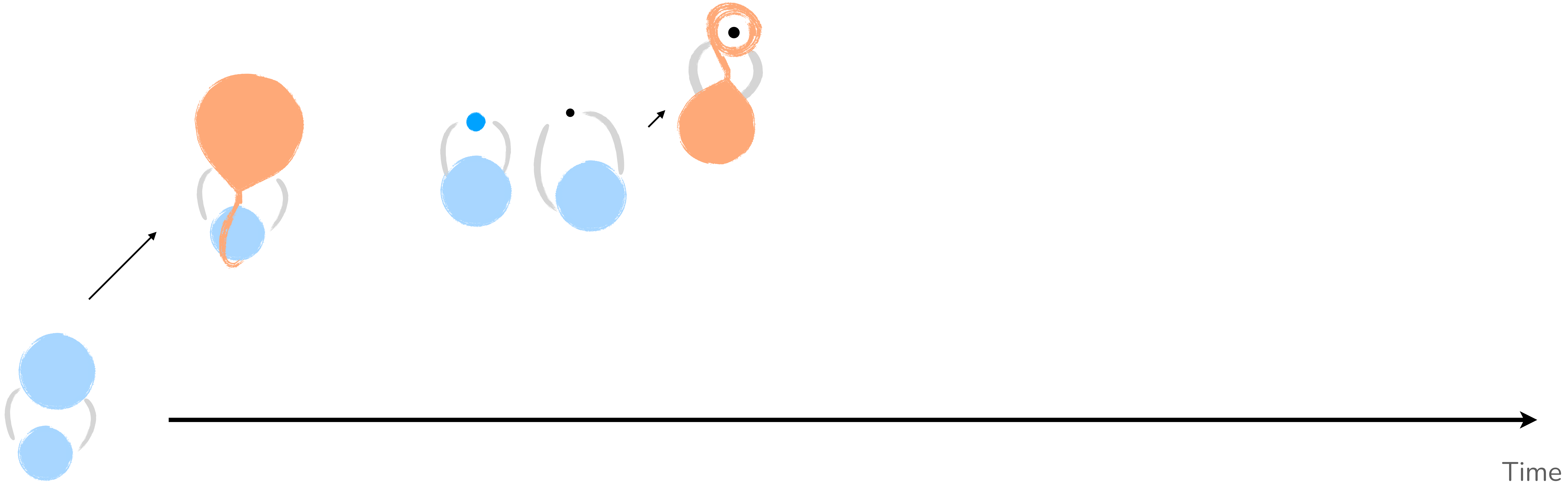
Time

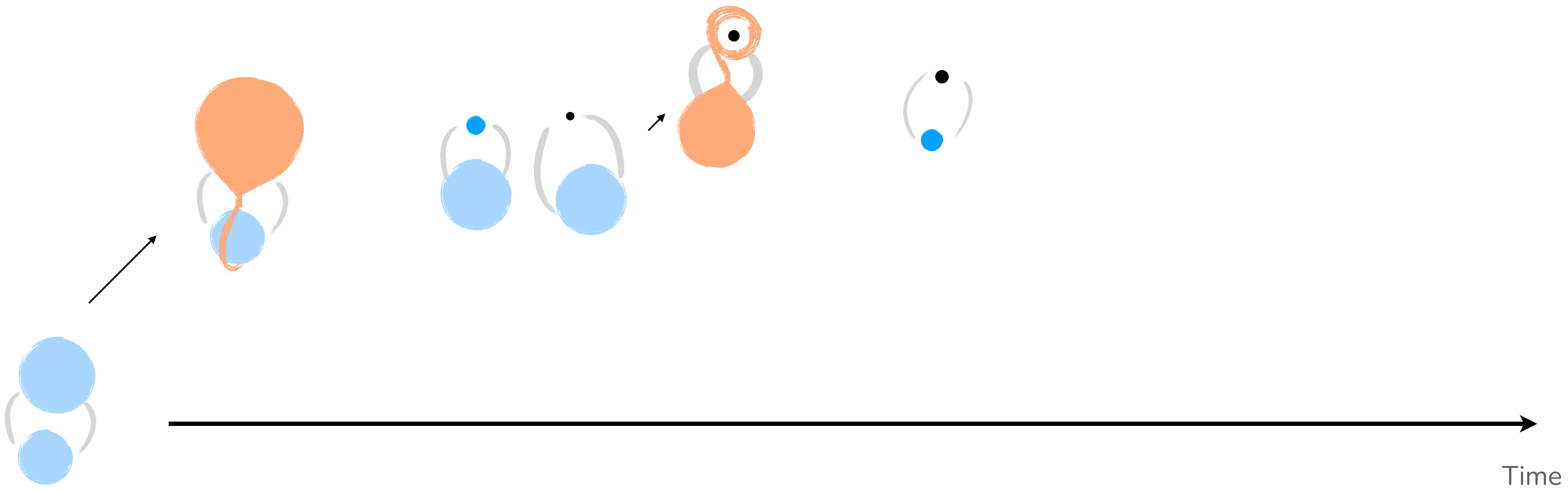


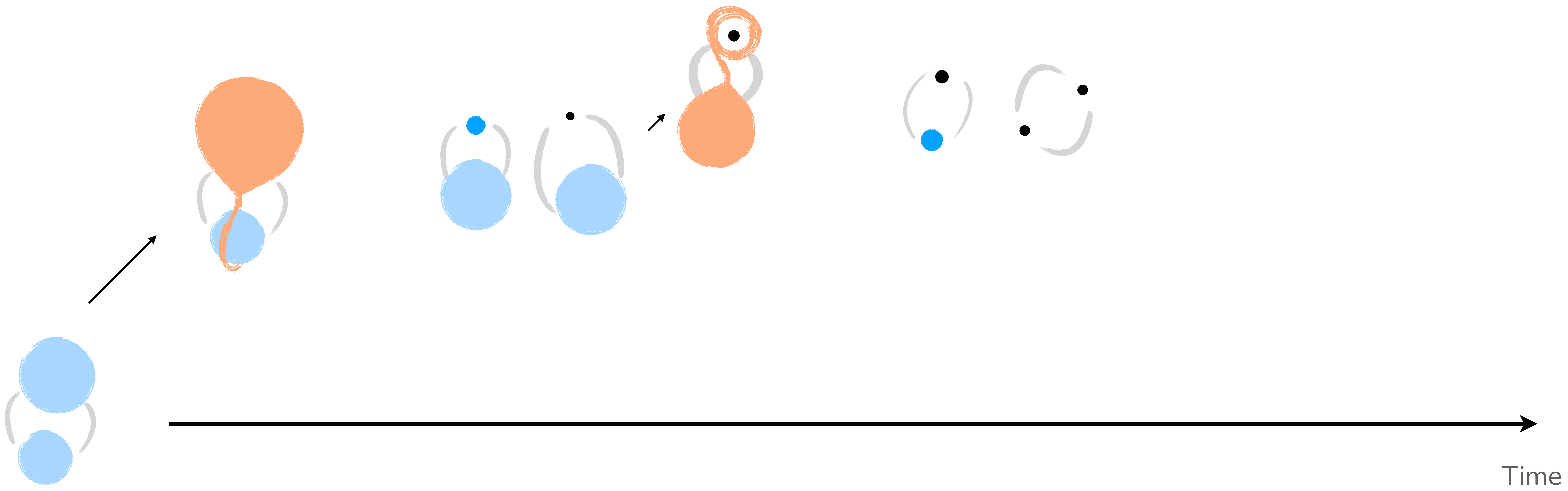
$$1 - e_f^2 = \frac{a_i^2}{a_f}\frac{(v_{\rm k,y}^2 + v_{\rm k,z}^2 v_{\rm orb}^2 + 2\vec{v}_{\rm k} \cdot \vec{v}_{\rm orb})}{G(M_1 + M_2)}$$

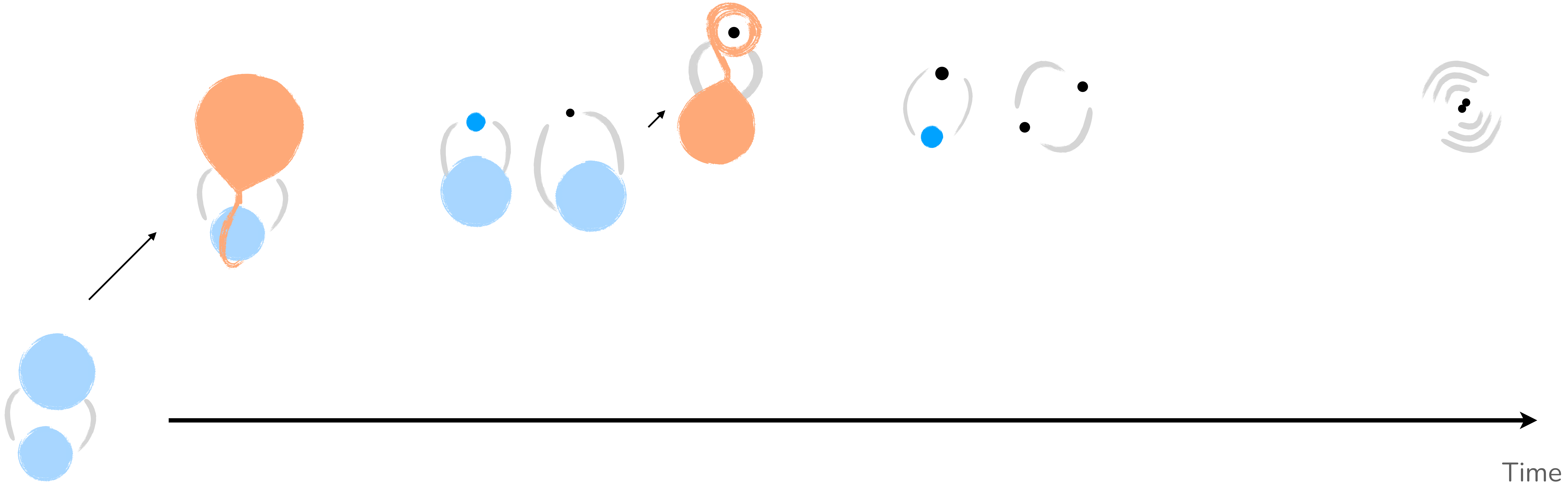
e.g. Kalogera 1996, Callister+2022

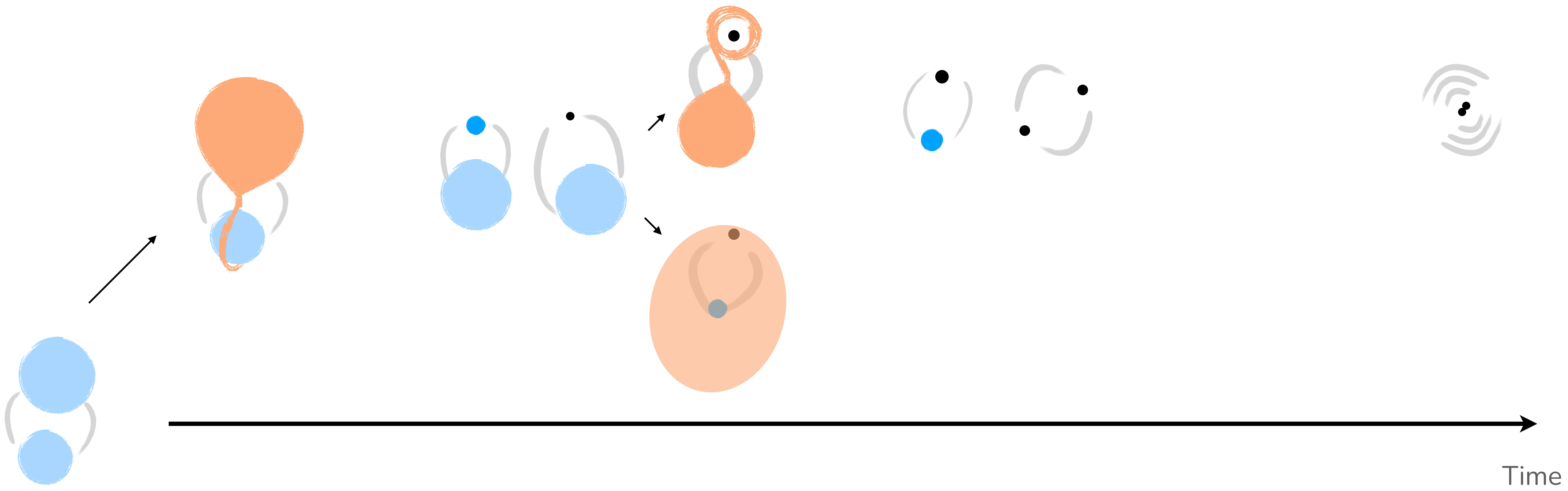

Time


Time


Time

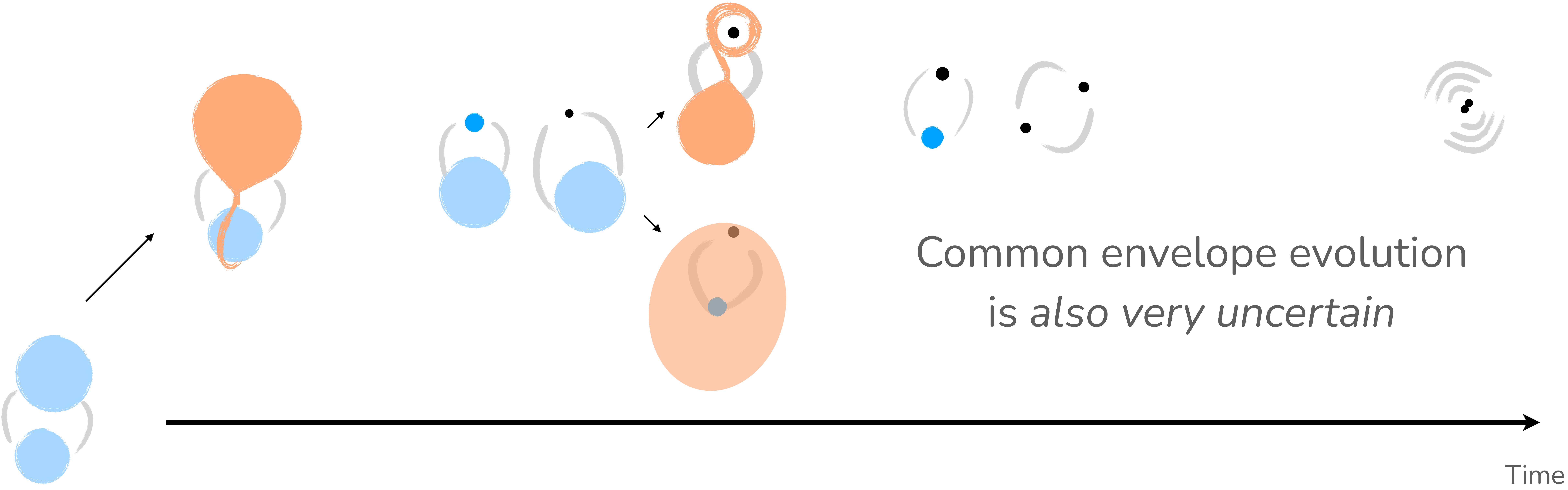

Time

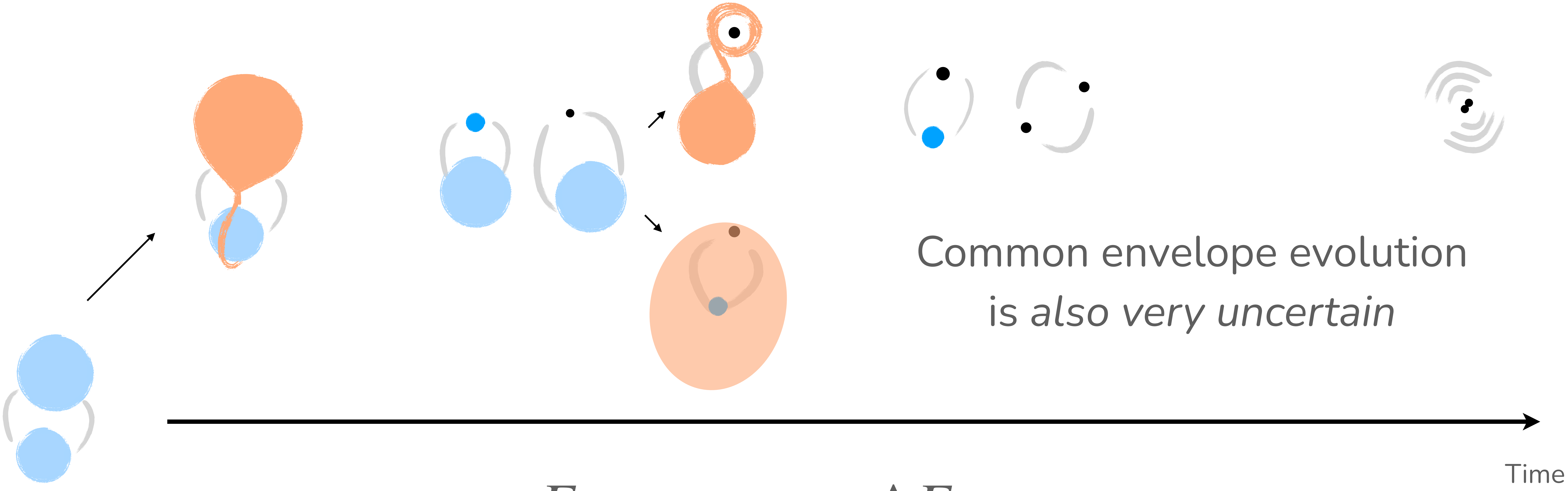

Time


Time

Common envelope evolution

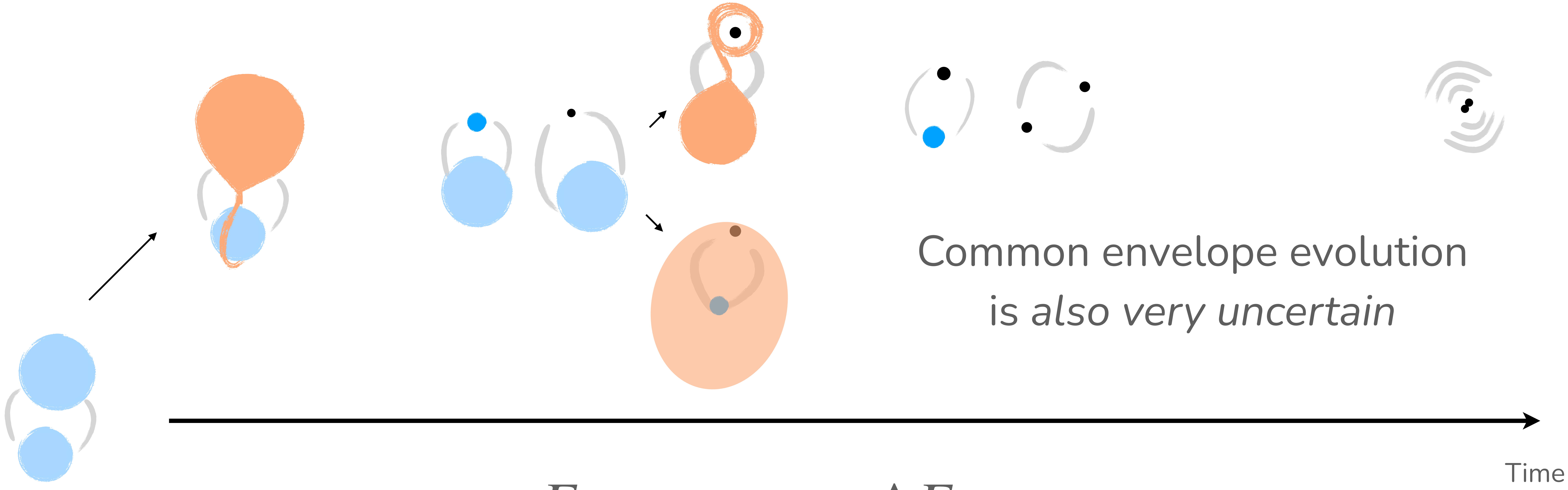
is *also very uncertain*





Common envelope evolution
is *also very uncertain*

$$E_{\mathrm{bind,env}} = \alpha_{\mathrm{CE}} \Delta E_{\mathrm{orb}}$$

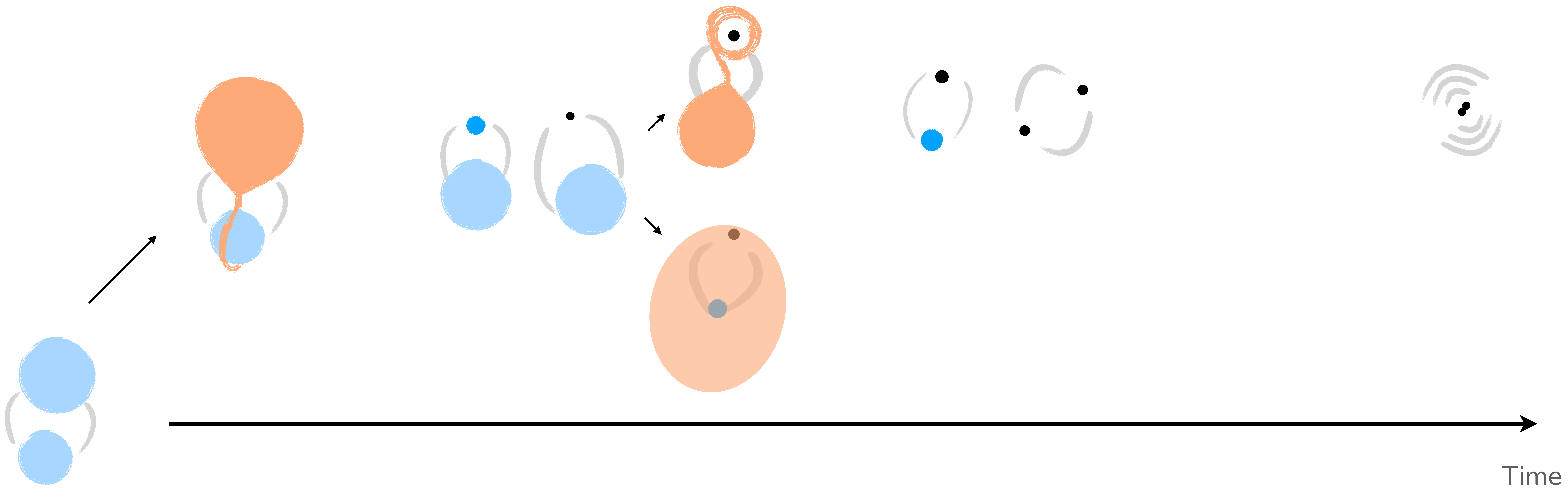


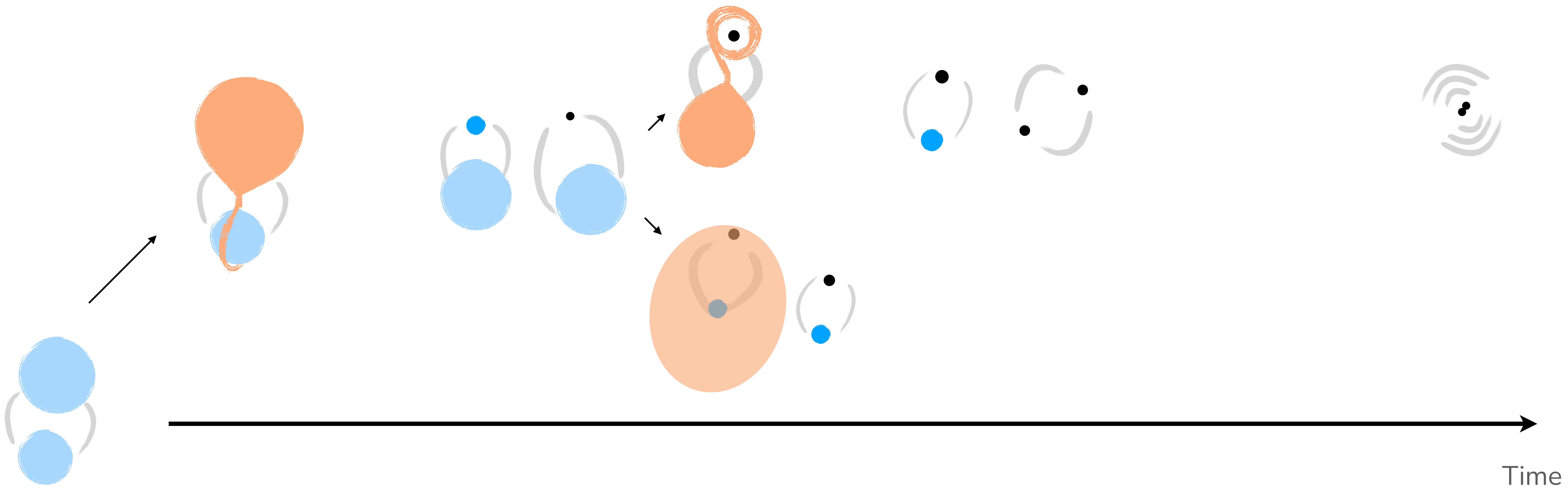
Common envelope evolution is *also very uncertain*

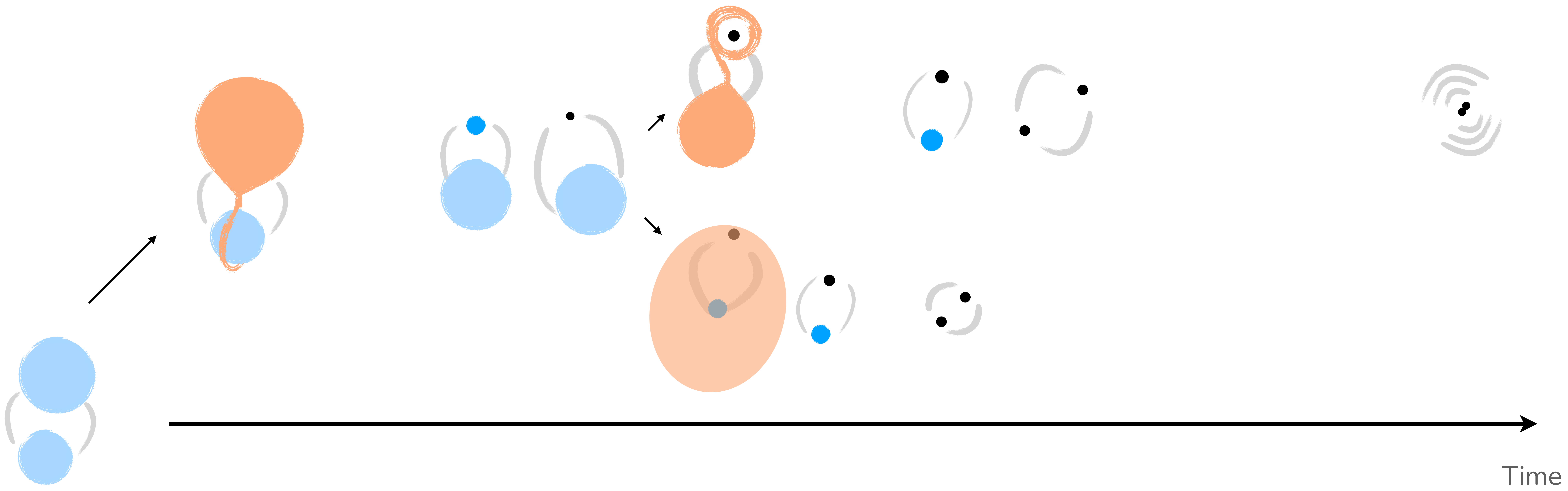
$$E_{\mathrm{bind,env}} = \alpha_{\mathrm{CE}} \Delta E_{\mathrm{orb}}$$

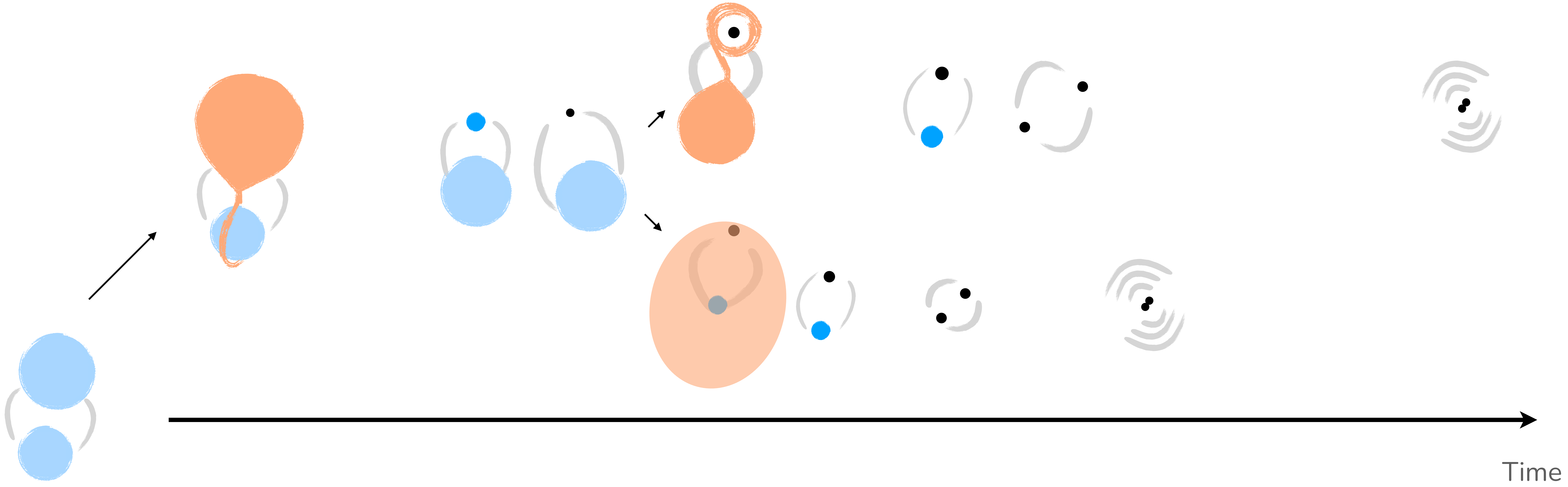
$$\frac{G M_{\mathrm{env}} M_1}{\lambda_{\mathrm{env}} R_1} = \alpha_{\mathrm{CE}} \left[\frac{G M_{1,\mathrm{f}} M_2}{2 a_{\mathrm{f}}} - \frac{G M_{1,\mathrm{i}} M_2}{2 a_{\mathrm{i}}} \right]$$

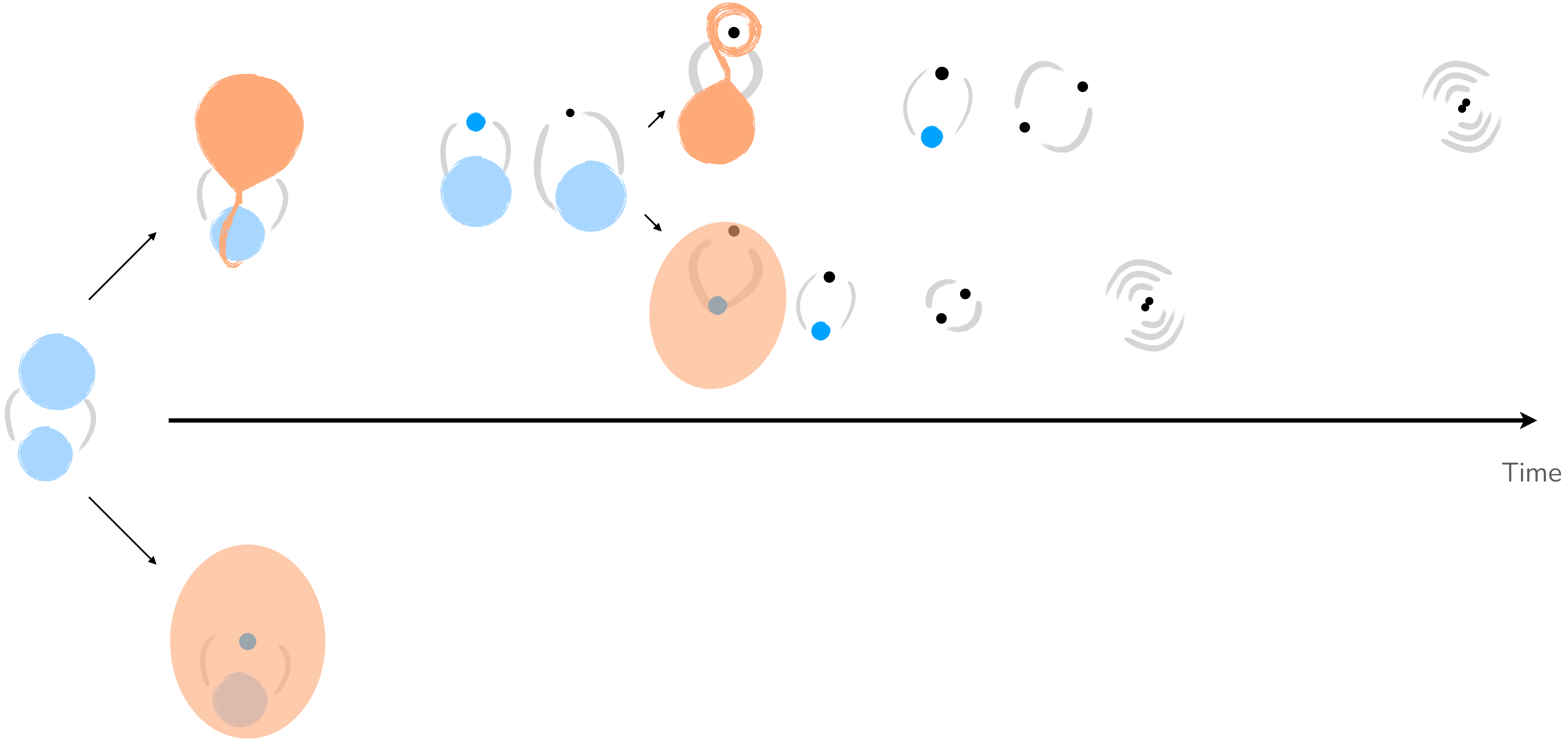
e.g. Webbink+1990

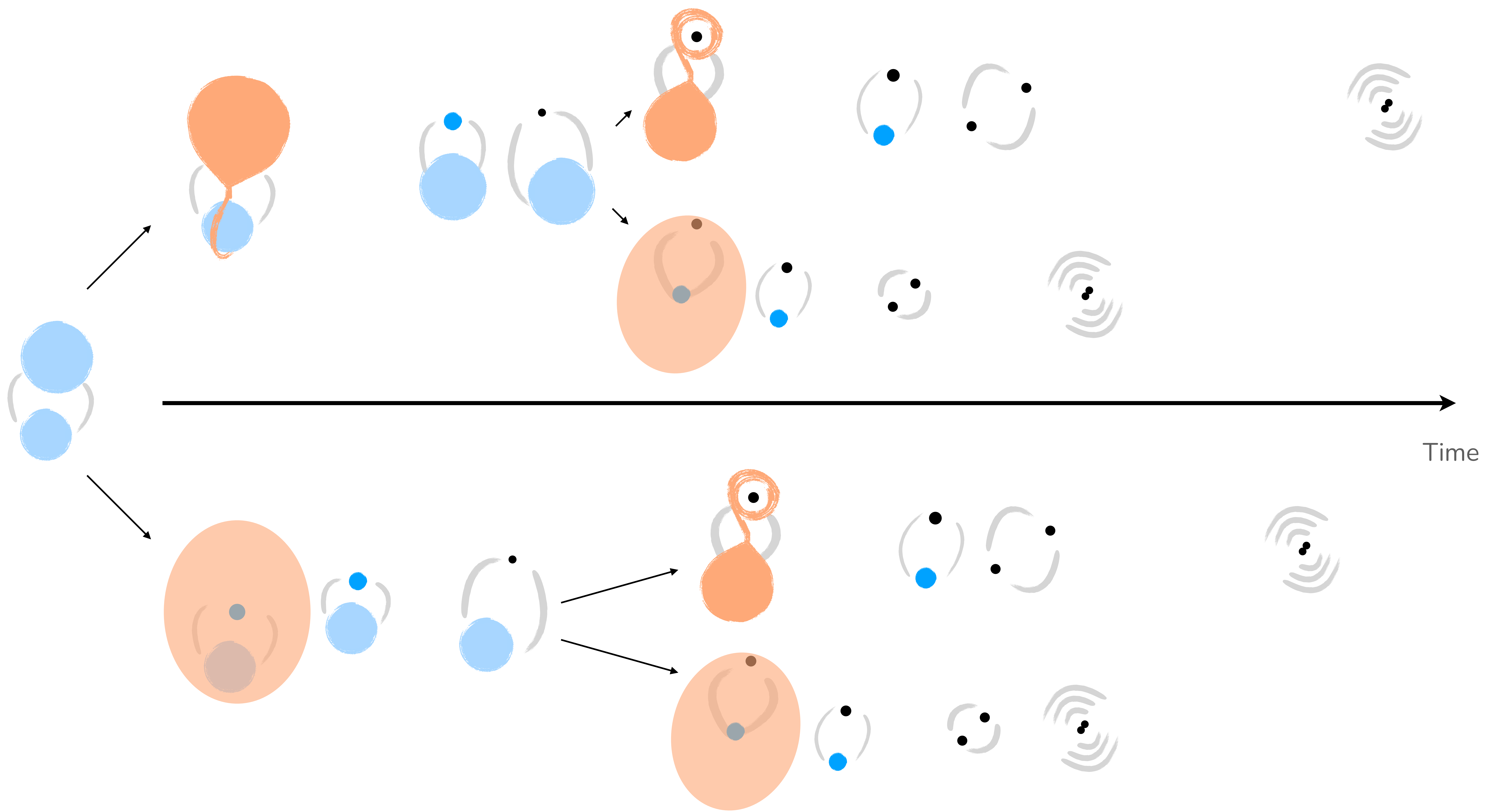

Time

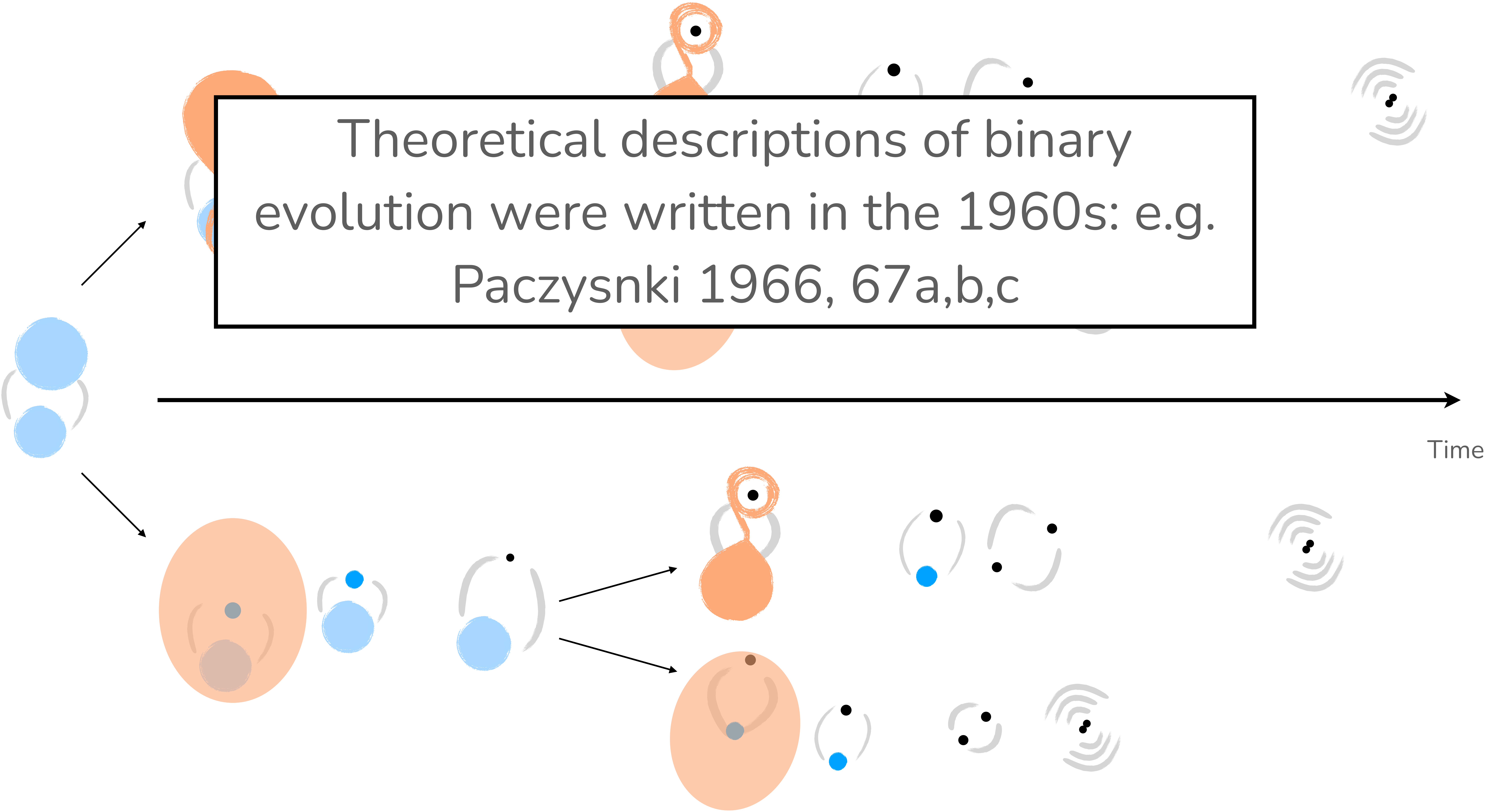

Time


Time


Time


Time

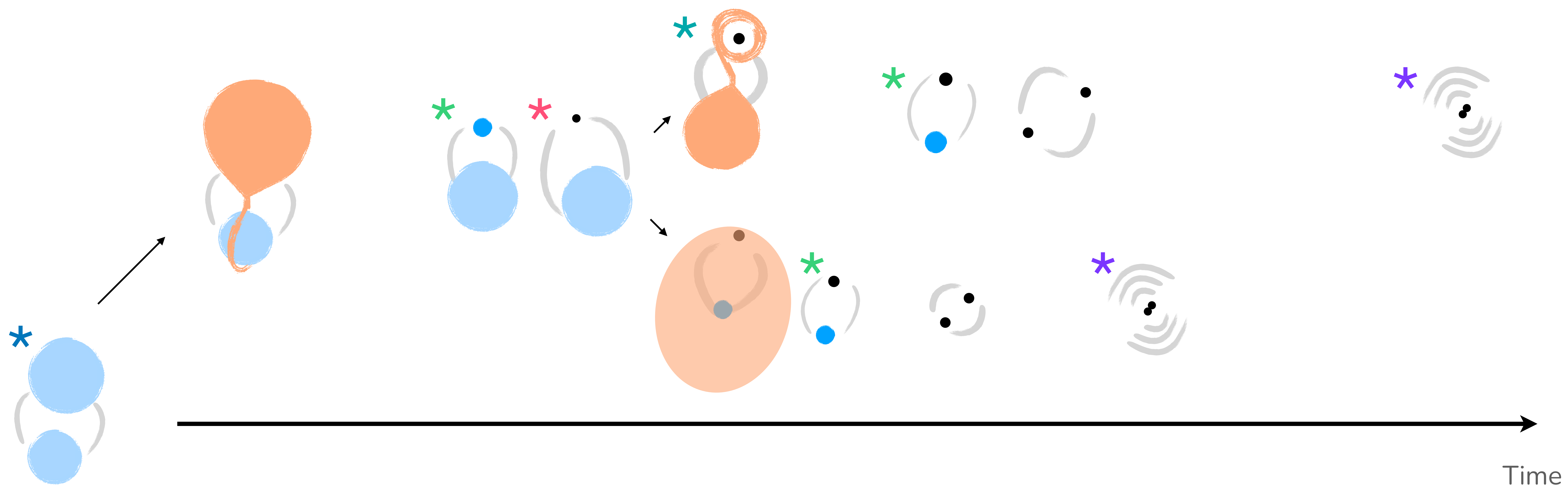

Time



Theoretical descriptions of binary evolution were written in the 1960s: e.g. Paczysnki 1966, 67a,b,c

Theoretical descriptions of binary evolution were written in the 1960s: e.g. Paczysnki 1966, 67a,b,c

Time



Large catalogs for these populations are a recent development!

e.g. Sana+12, Moe+17

e.g. Giesers+18,19, Anguiano+22, El-Badry+23a,b,24, Shahaf+23, Yamaguchi+24

e.g. GWTC-3 (2022)

e.g. Drout+23, Götberg+23

e.g. Miller-Jones+21

Roche-overflow mass transfer is the dominant driver of uncertainty in the formation and evolution of close stellar remnant populations

Roche-overflow mass transfer is the dominant driver of uncertainty in the formation and evolution of close stellar remnant populations

The compact-object formation mechanism plays a critical role in the characteristics and formation rates neutron stars and black holes

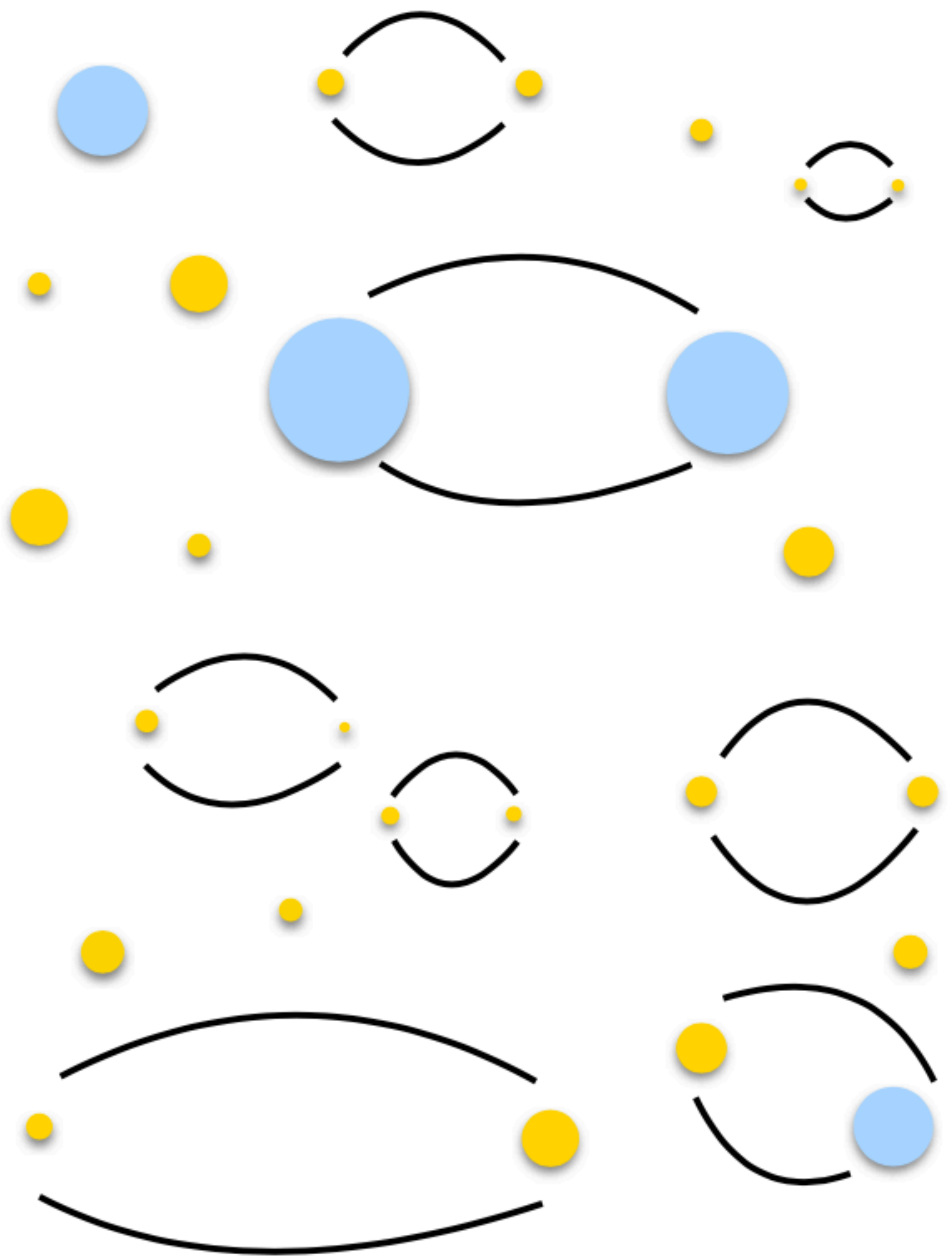
Roche-overflow mass transfer is the dominant driver of uncertainty in the formation and evolution of close stellar remnant populations

The compact-object formation mechanism plays a critical role in the characteristics and formation rates neutron stars and black holes

Binary population synthesis provides a means to understand how these uncertain physical processes & many others! shape stellar populations across all evolutionary phases.

Simulating a population of BH binaries

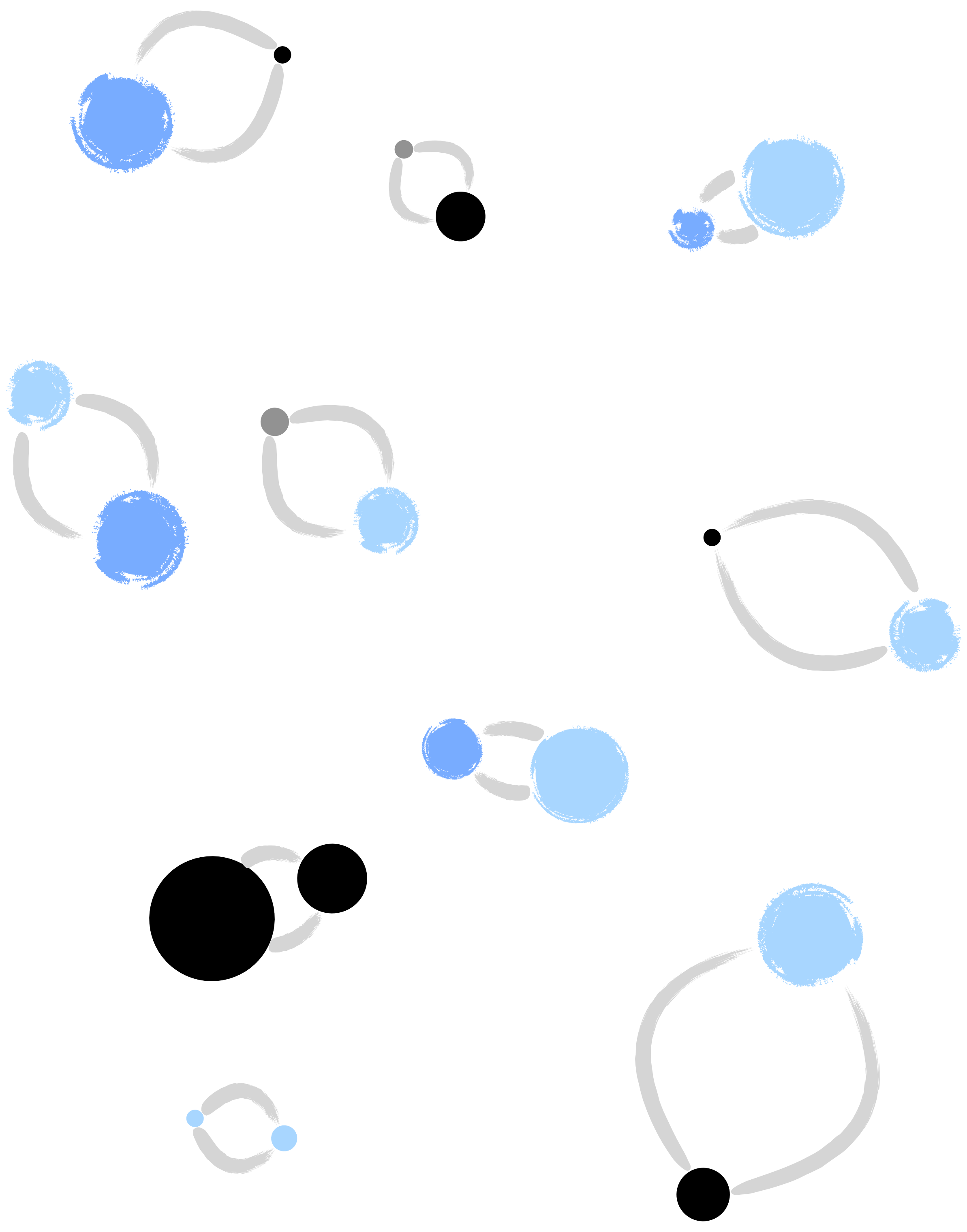
initialize ZAMS population



evolve w/ your favorite code

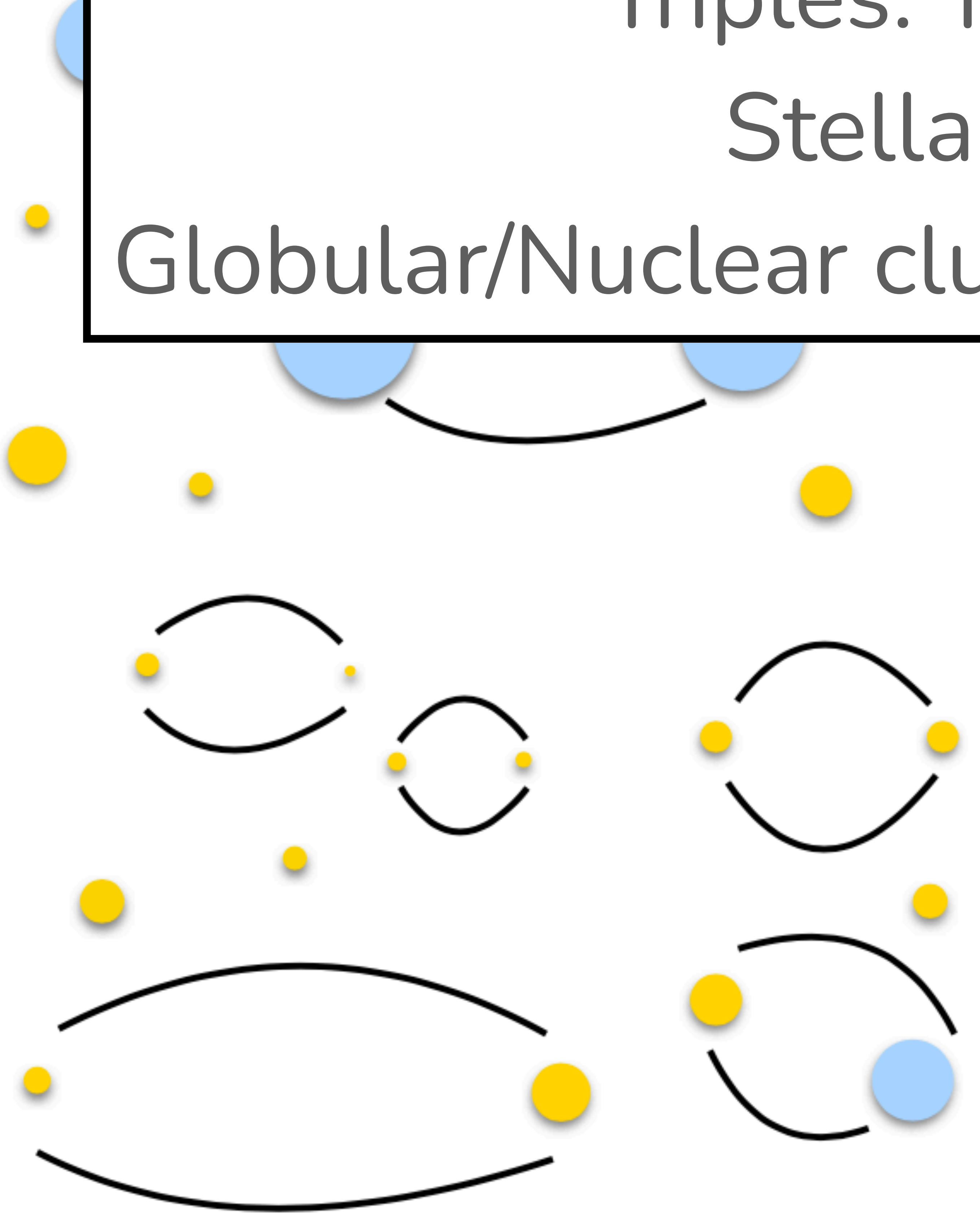
Scenario Machine (Lipunov+1996)
IBiS (Tutukov+1996)
SeBa (Portegies-Zwart+1996)
BSE (Hurley+2000,2002)
StarTrack (Belcyznski+2002)
binary_c (Izzard+2004)
BPASS (Eldridge+2017)
ComBinE (Kruckow+2018)
MOBSE (Giacobbo+2018)
COSMIC (Breivik+2020)
COMPAS (TeamCOMPAS+2022)
POSYDON (Fragos+2023)
SEVN (Iorio+2023)
METISSE (Agrawal,Breivik+2025)

collect the BH binaries & repeat if necessary



Simulating a population of BH binaries

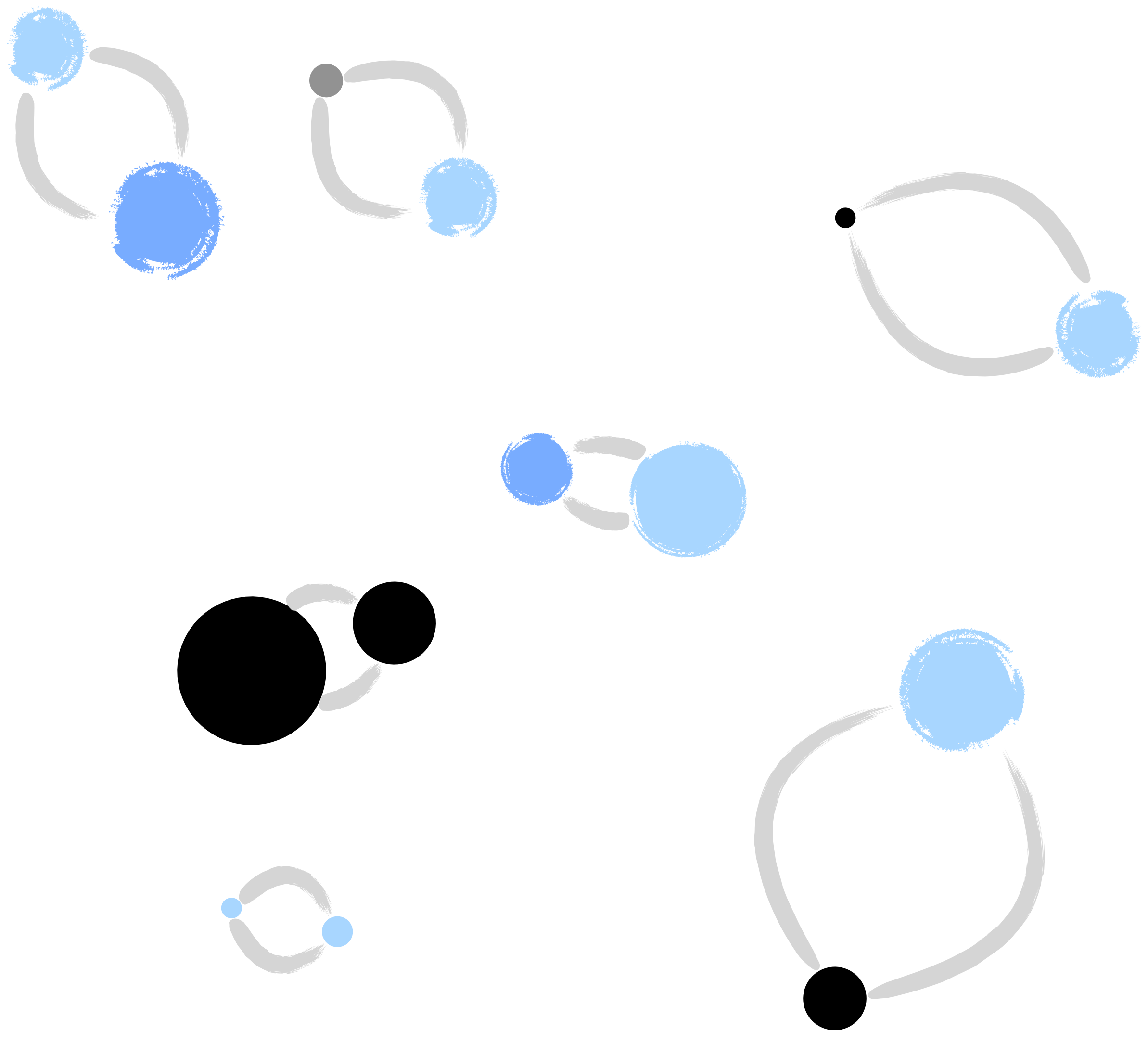
initialize ZAMS population



evolve w/ your favorite code

Scenario Machine (Lipunov+1996)

collect the BH binaries & repeat if necessary



This is for isolated binaries, there are also:

Triples: TRES (Toonen+2020), MSE (Hamers+2021)

Stellar clusters: NBODY6 (e.g. Di Carlo+2019)

Globular/Nuclear clusters: MOCCA (Giersz+1998), CMC (Rodriguez+2022)

BPASS (Eldridge+2017)

ComBinE (Kruckow+2018)

MOBSE (Giacobbo+2018)

COSMIC (Breivik+2020)

COMPAS (TeamCOMPAS+2022)

POSYDON (Fragos+2023)

SEVN (Iorio+2023)

METISSE (Agrawal,Breivik+2025)

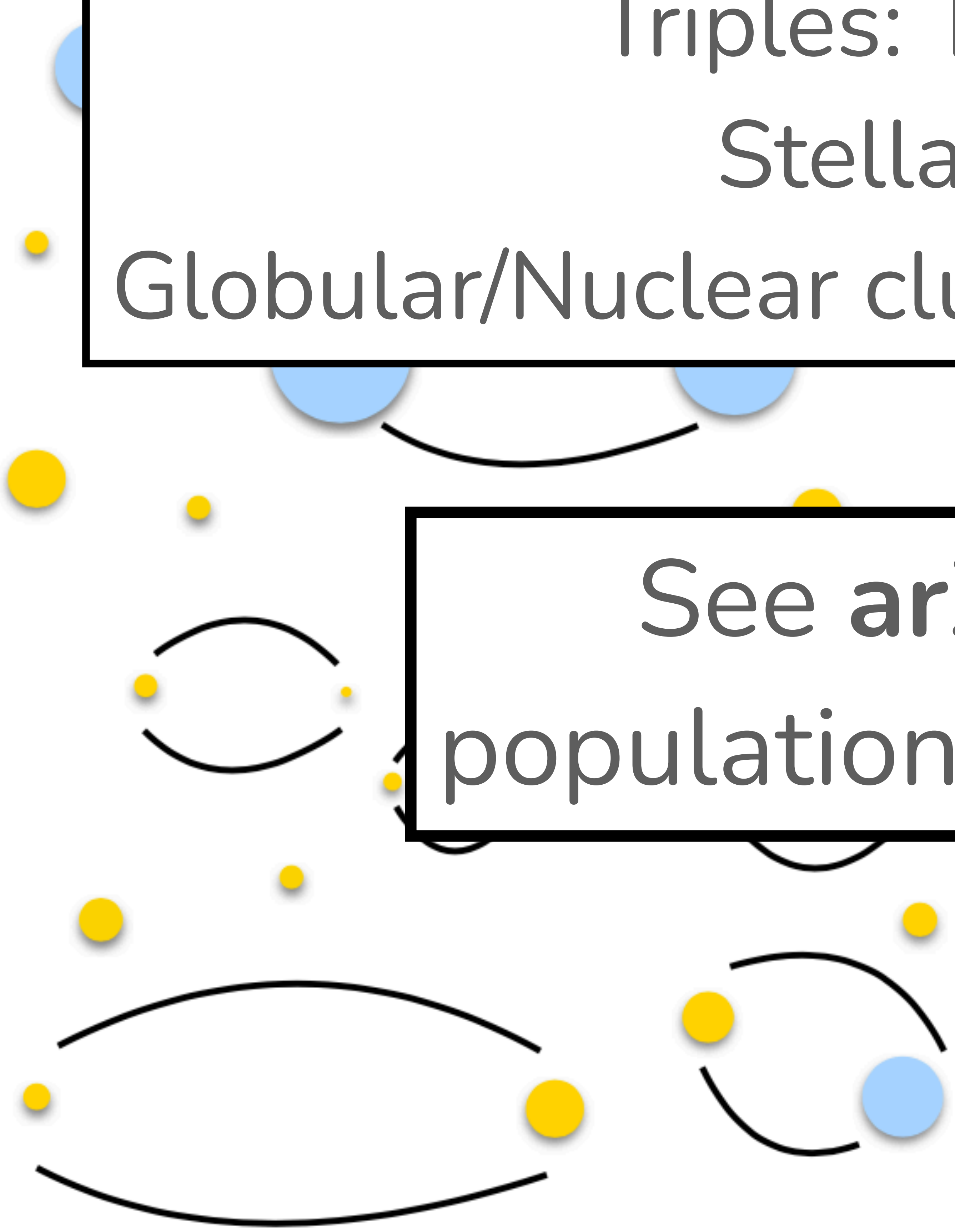
Simulating a population of BH binaries

initialize ZAMS population

evolve w/ your favorite code

Scenario Machine (Lipunov+1996)

collect the BH binaries & repeat if necessary



This is for isolated binaries, there are also:

Triples: TRES (Toonen+2020), MSE (Hamers+2021)

Stellar clusters: NBODY6 (e.g. Di Carlo+2019)

Globular/Nuclear clusters: MOCCA (Giersz+1998), CMC (Rodriguez+2022)

BPASS (Eldridge+2017)

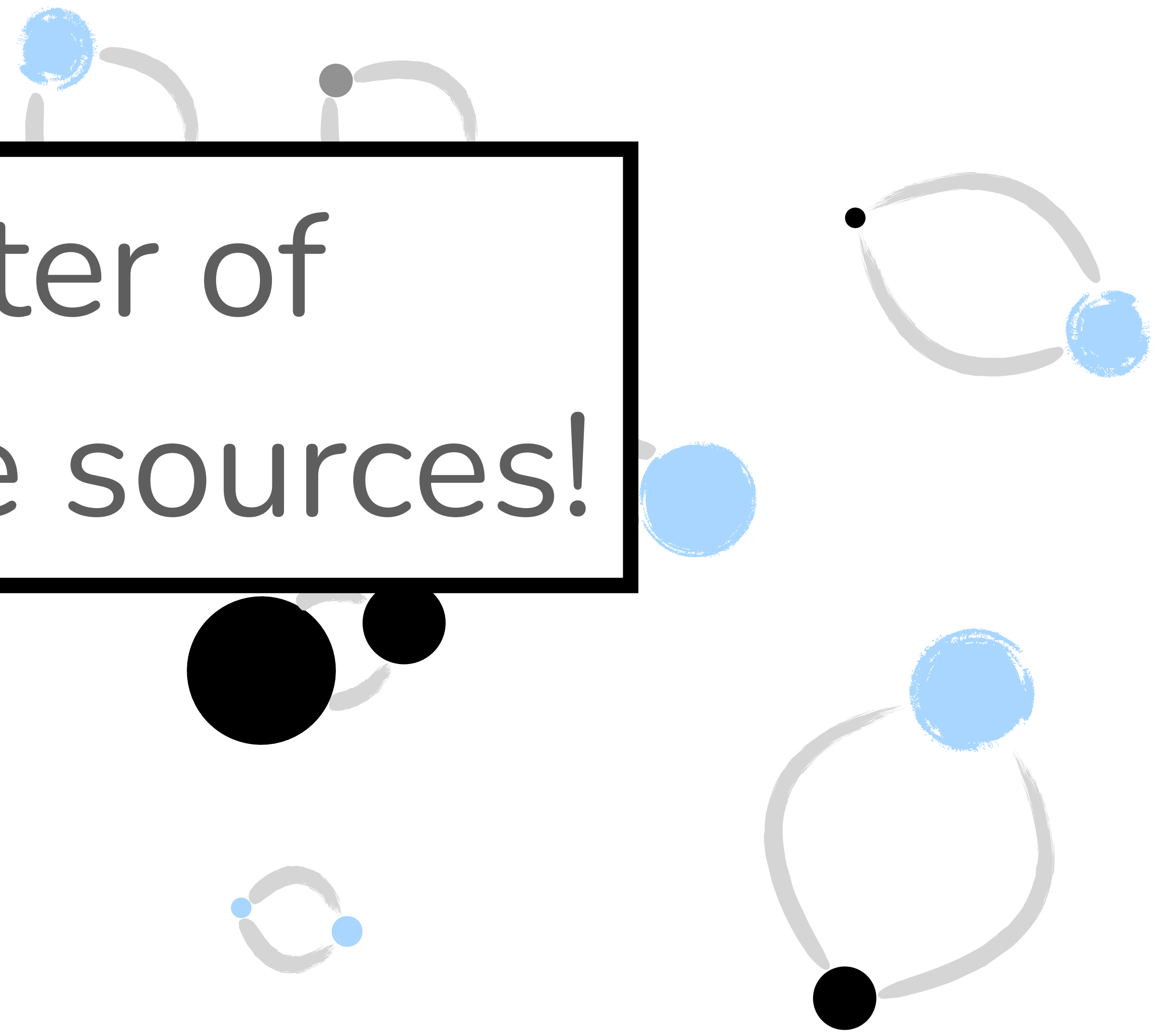
See **arXiv: 2502.03523**: a review chapter of population synthesis for gravitational wave sources!

COMPAS (TeamCOMPAS+2022)

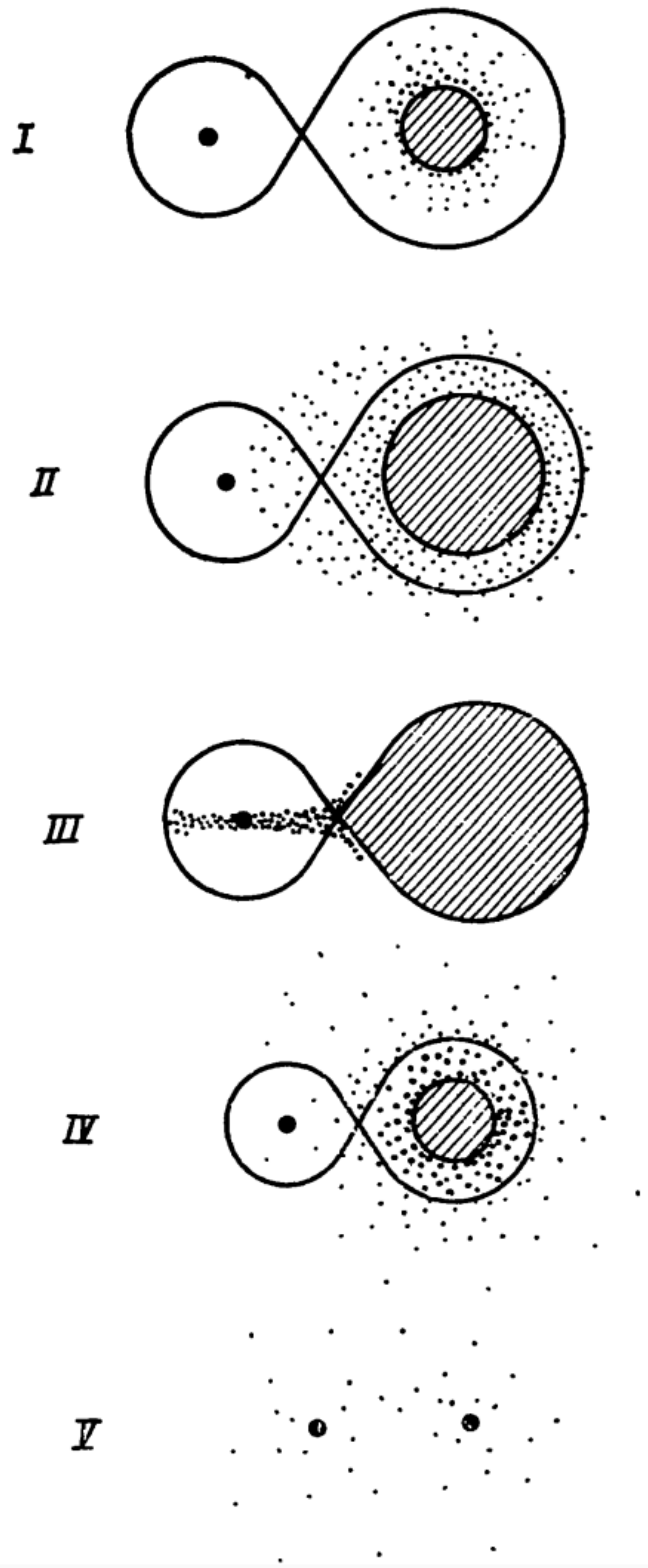
POSYDON (Fragos+2023)

SEVN (Iorio+2023)

METISSE (Agrawal,Breivik+2025)

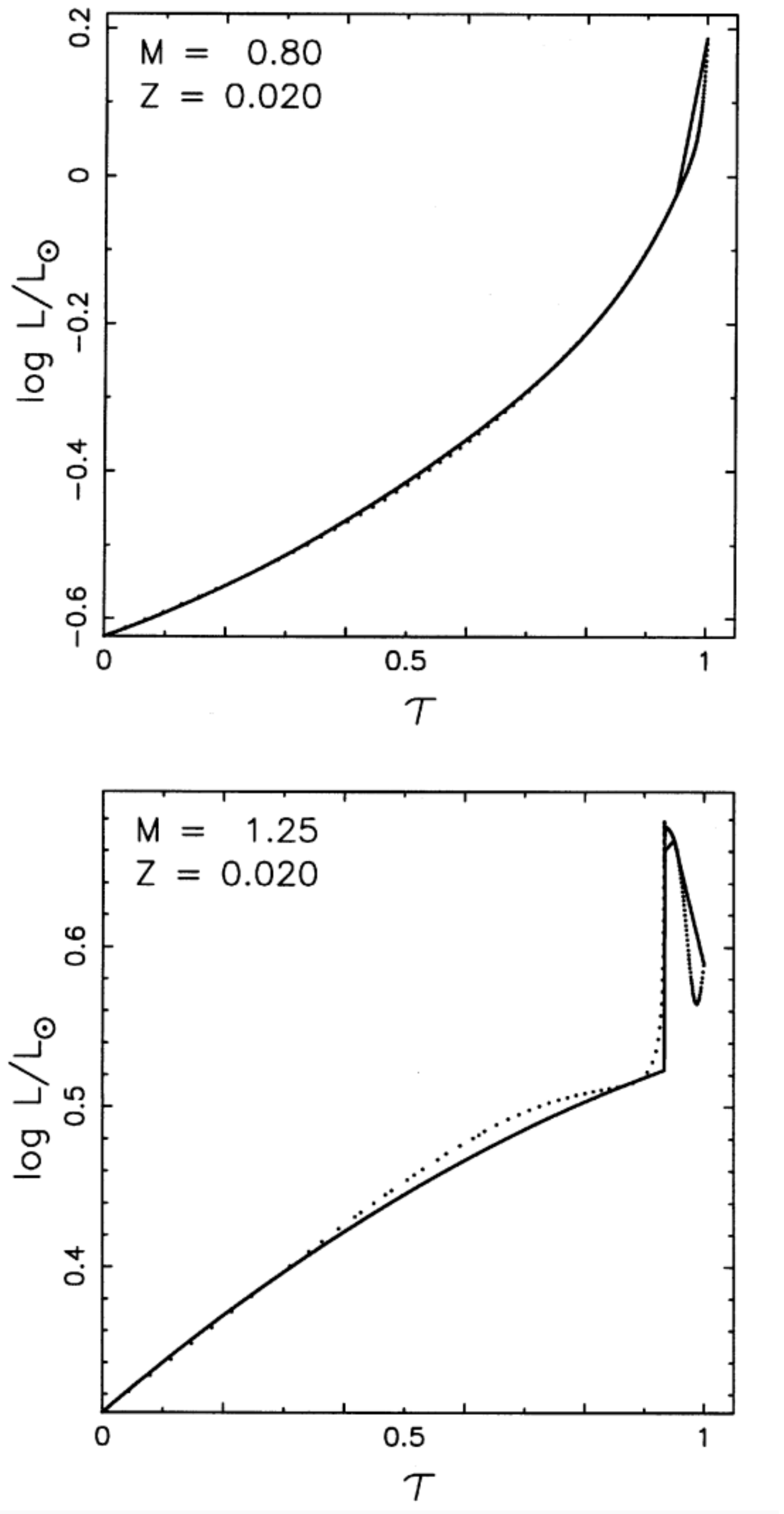


early pop-synth



Kornilov & Lipunov 1983

“the Hurley fits”



Hurley+2000,2002

community development

SeBa
AMUSE

Portegeis Zwart+1996

COSMIC

Breivik+2020

COMPAS

Team COMPAS, Riley+2022

contemporary pop-synth

detailed models

POSYDON

Fragos+2022

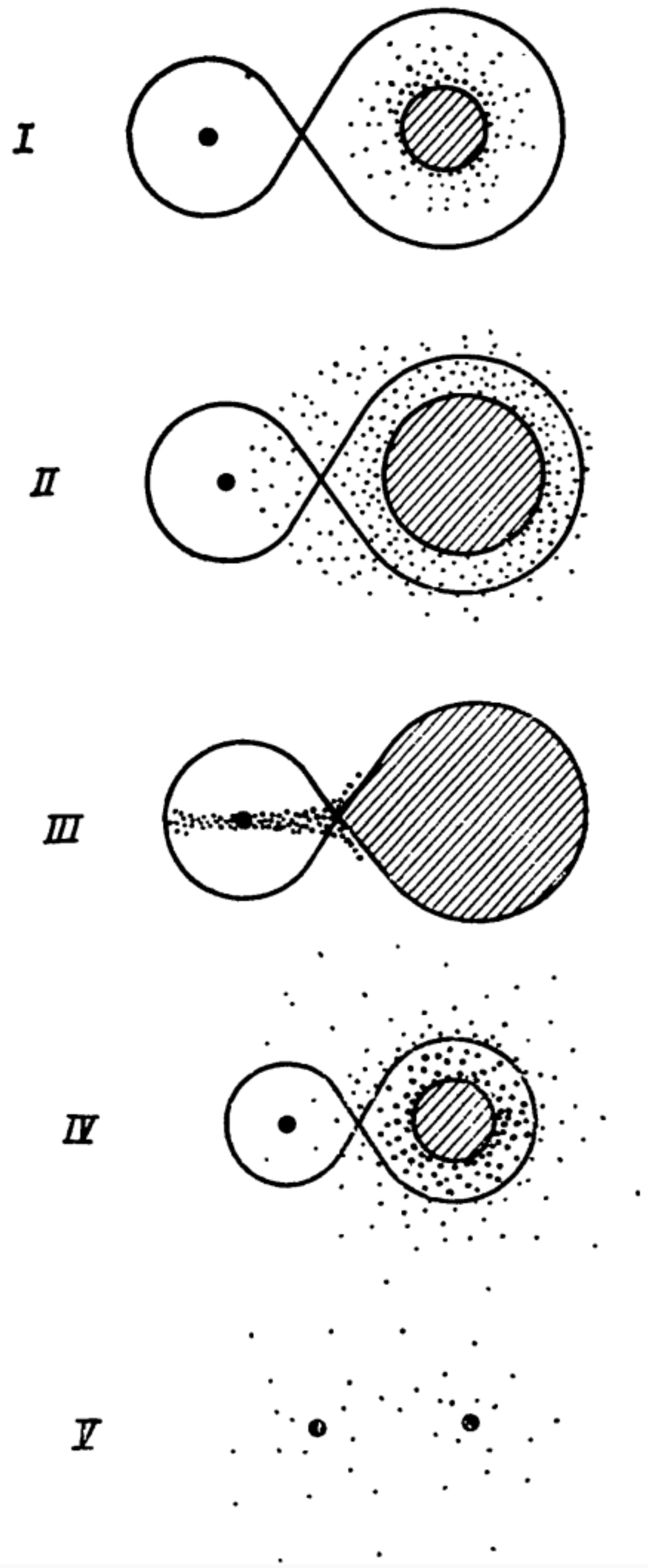
METISSE / SEVN

Agrawal+2022
Iorio+2023

Extensions to pop synth

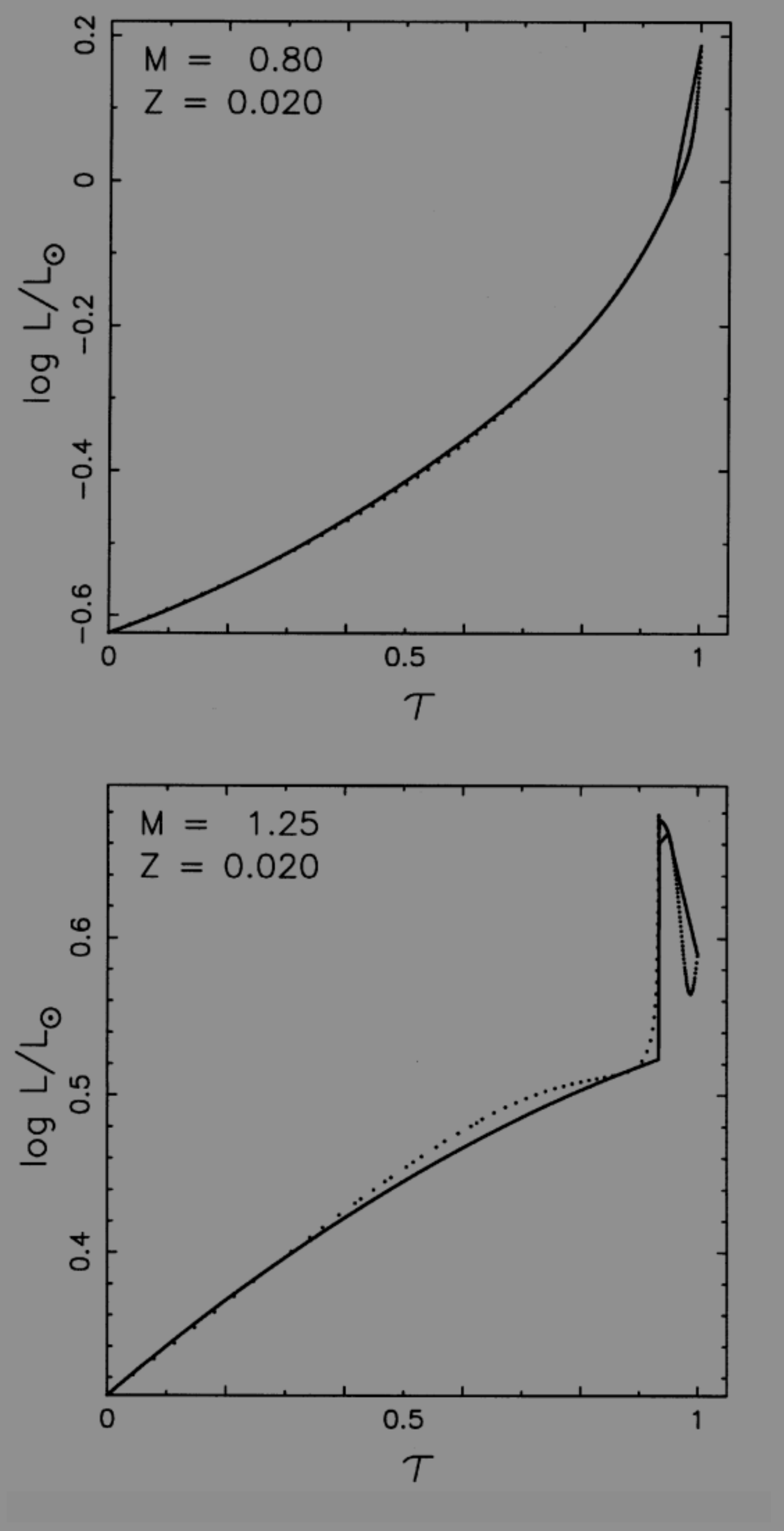
Andrews+18,
Wong+23, Wagg+25

early pop-synth



Kornilov & Lipunov 1983

“the Hurley fits”



Hurley+2000,2002

community development

AMUSE SeBa

Portegeis Zwart+1996

COSMIC

Breivik+2020

COMPAS

Team COMPAS, Riley+2022

contemporary pop-synth

detailed models

POSYDON

Fragos+2022

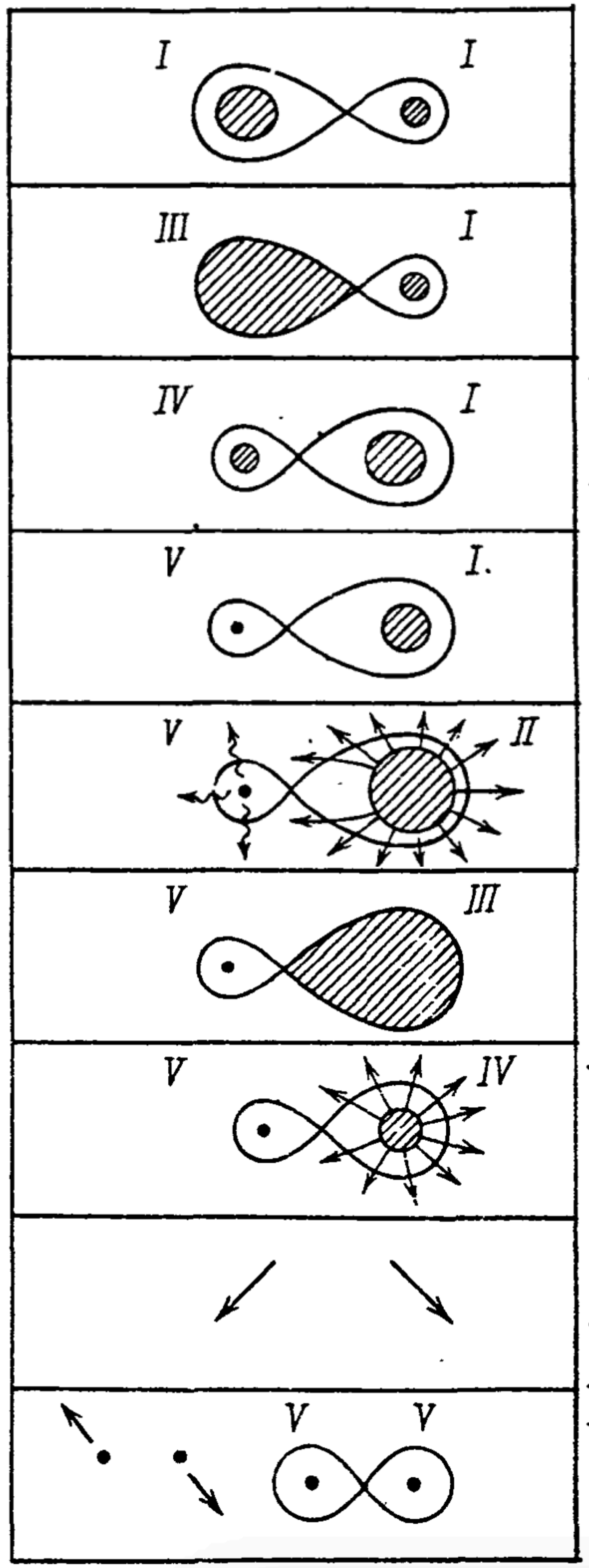
METISSE / SEVN

Agrawal+2022
Iorio+2023

dartboard

BackPop

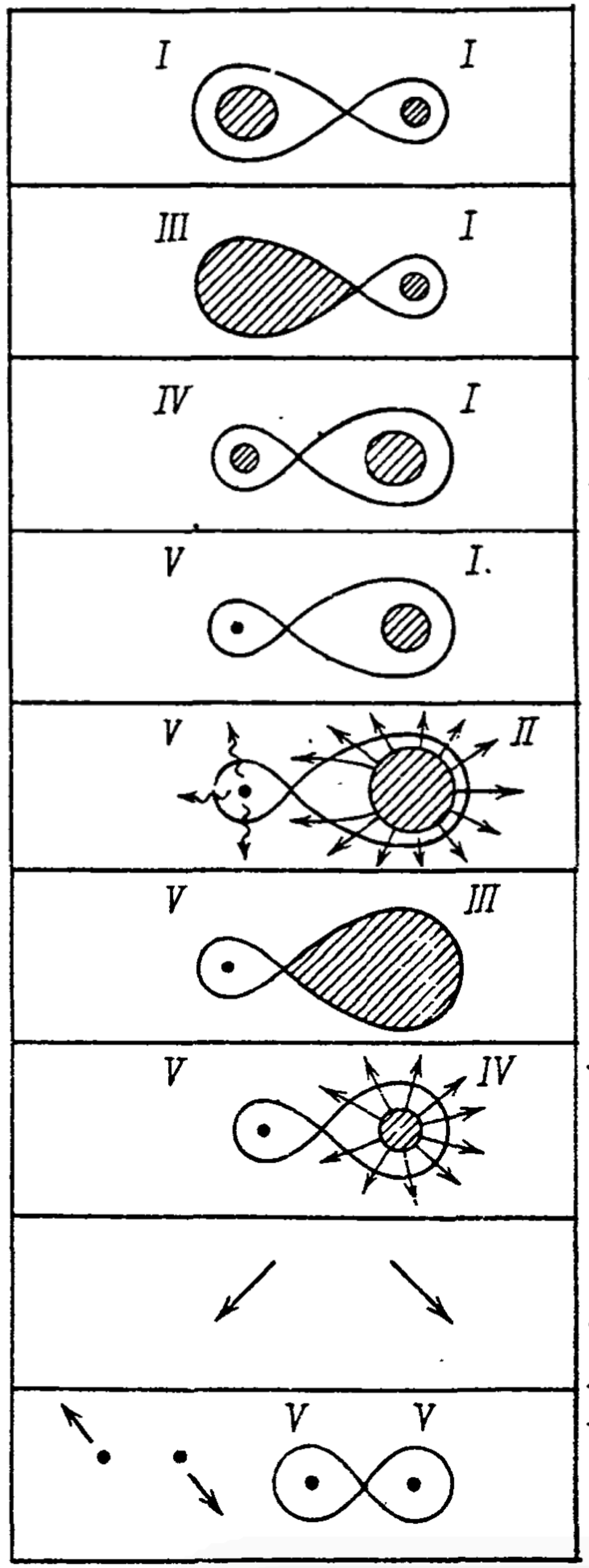
Andrews+18, Wong+23



Lipunov 1991

Caveats &/or assumptions

- Only case A, case B, case C mass transfer
- 100% conservative mass transfer
- No common envelope
- No “natal" kicks

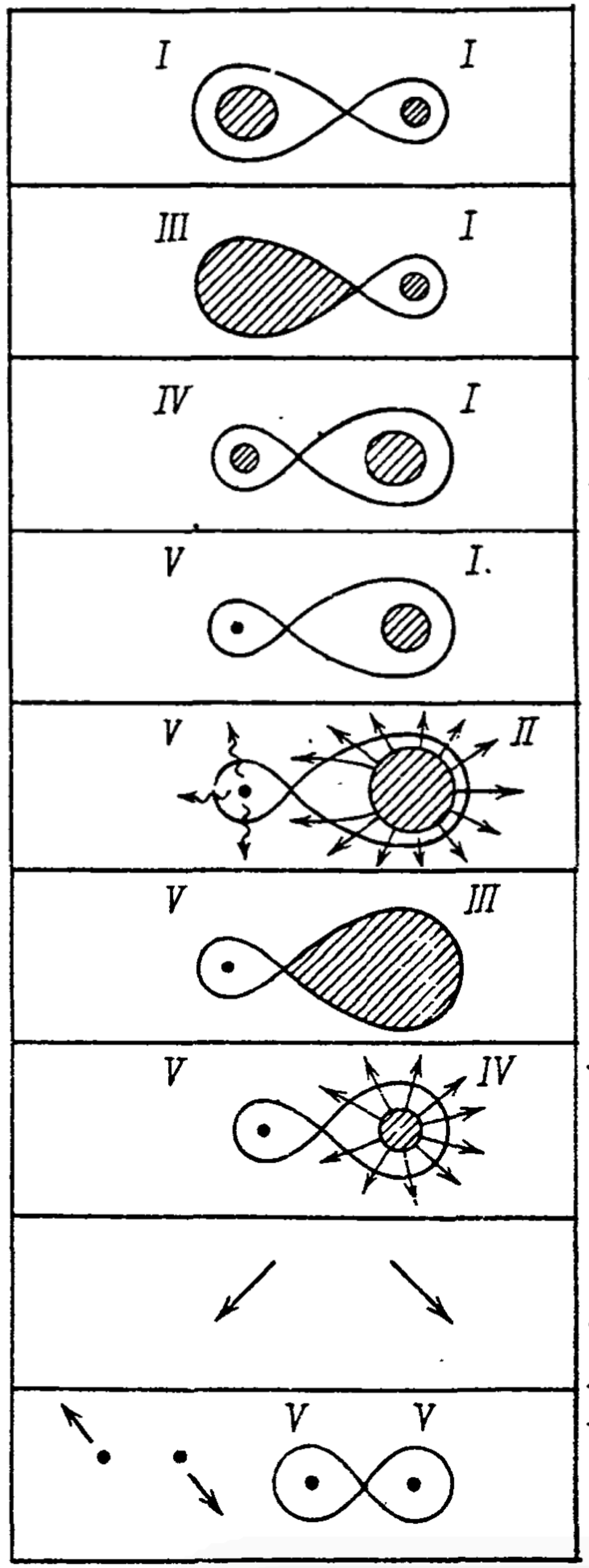


Lipunov 1991

$$\lg t_H \approx 9.9 - 3.8 \lg m_o + \lg^2 m_o \qquad \dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

Caveats &/or assumptions

- Only case A, case B, case C mass transfer
- 100% conservative mass transfer
- No common envelope
- No “natal" kicks



Lipunov 1991

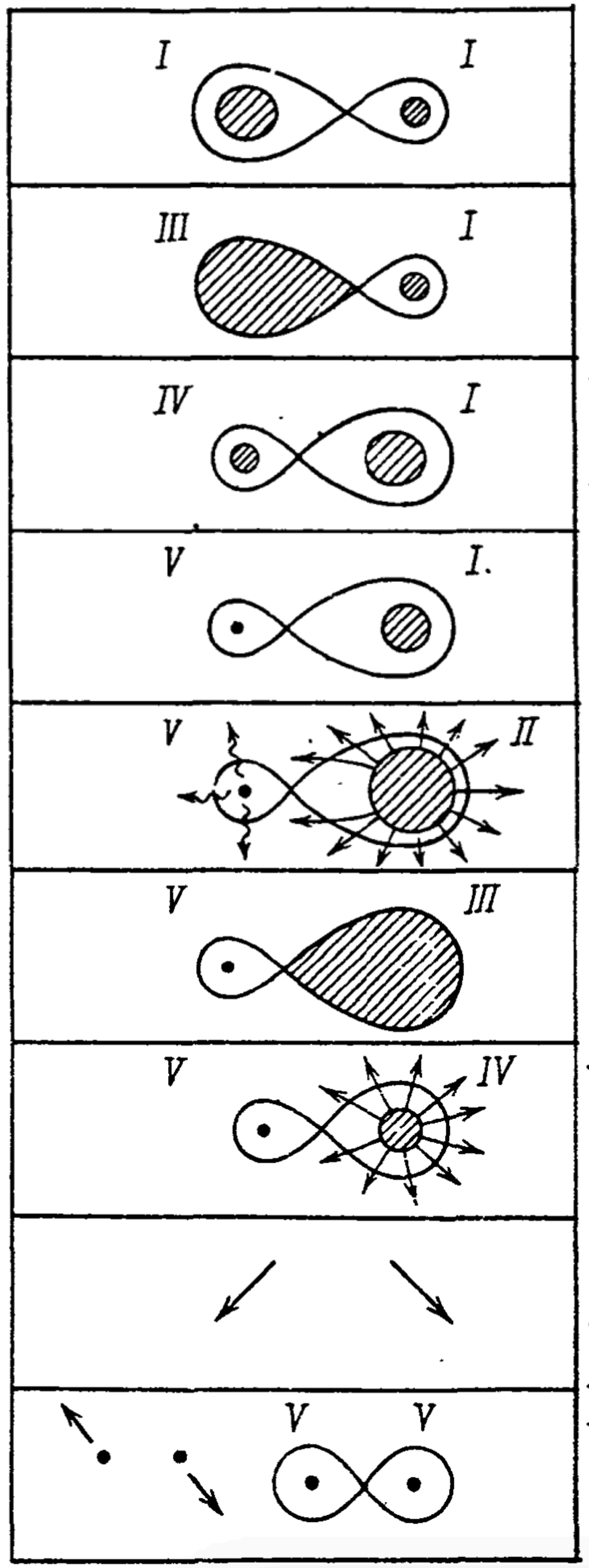
$$\lg t_H \approx 9.9 - 3.8 \lg m_o + \lg^2 m_o$$

$$\dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

$$t_{th} \approx \frac{GM^2}{RL} \approx 3 \cdot 10^7 m^{-2} \text{ yrs}$$

Caveats &/or assumptions

- Only case A, case B, case C mass transfer
- 100% conservative mass transfer
- No common envelope
- No “natal" kicks



Lipunov 1991

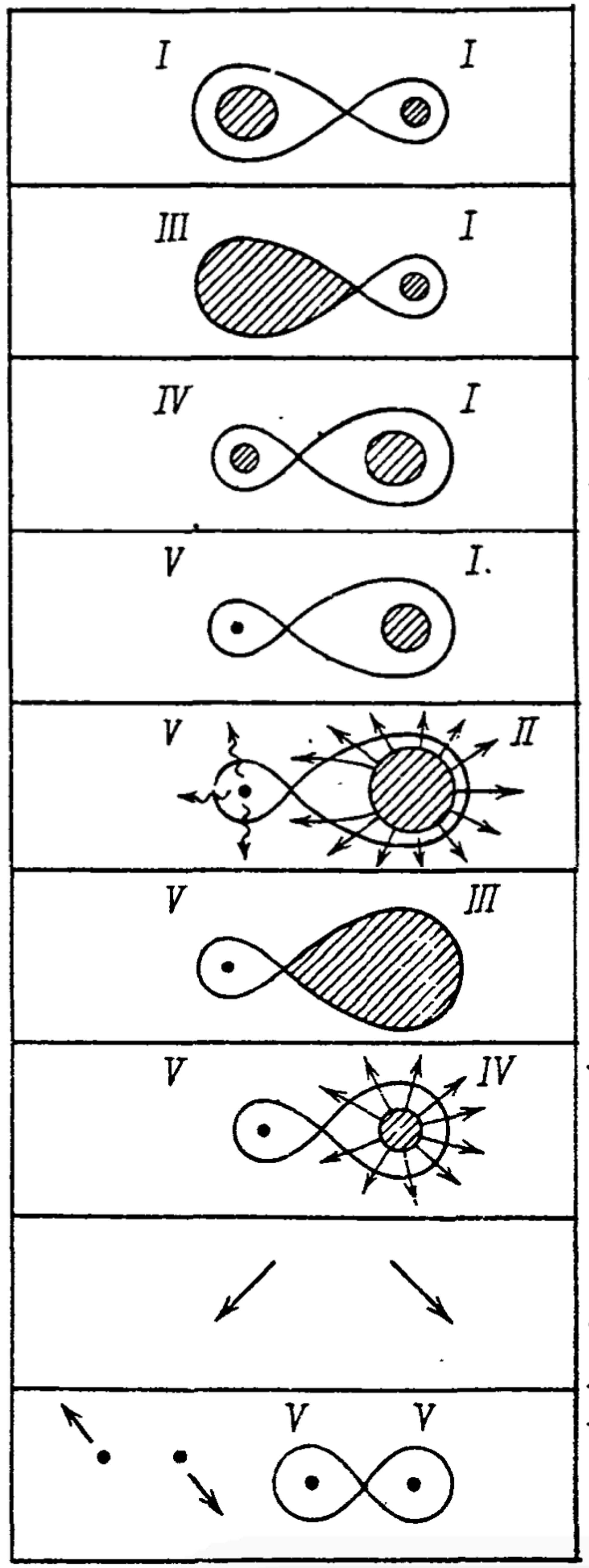
$$\lg t_H \approx 9.9 - 3.8 \lg m_o + \lg^2 m_o \qquad \dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

$$t_{th} \approx \frac{GM^2}{RL} \approx 3 \cdot 10^7 m^{-2} \text{ yrs}$$

$$M_2 = M_{2,0} + M_{1,0} - M_1 \qquad a_1 = a_0 \left(\frac{M_{1,0} \cdot M_{2,0}}{M_1 \cdot M_2}\right)$$

Caveats &/or assumptions

- Only case A, case B, case C mass transfer
- 100% conservative mass transfer
- No common envelope
- No “natal" kicks



Lipunov 1991

$$\lg t_H \approx 9.9 - 3.8 \lg m_o + \lg^2 m_o \qquad \dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

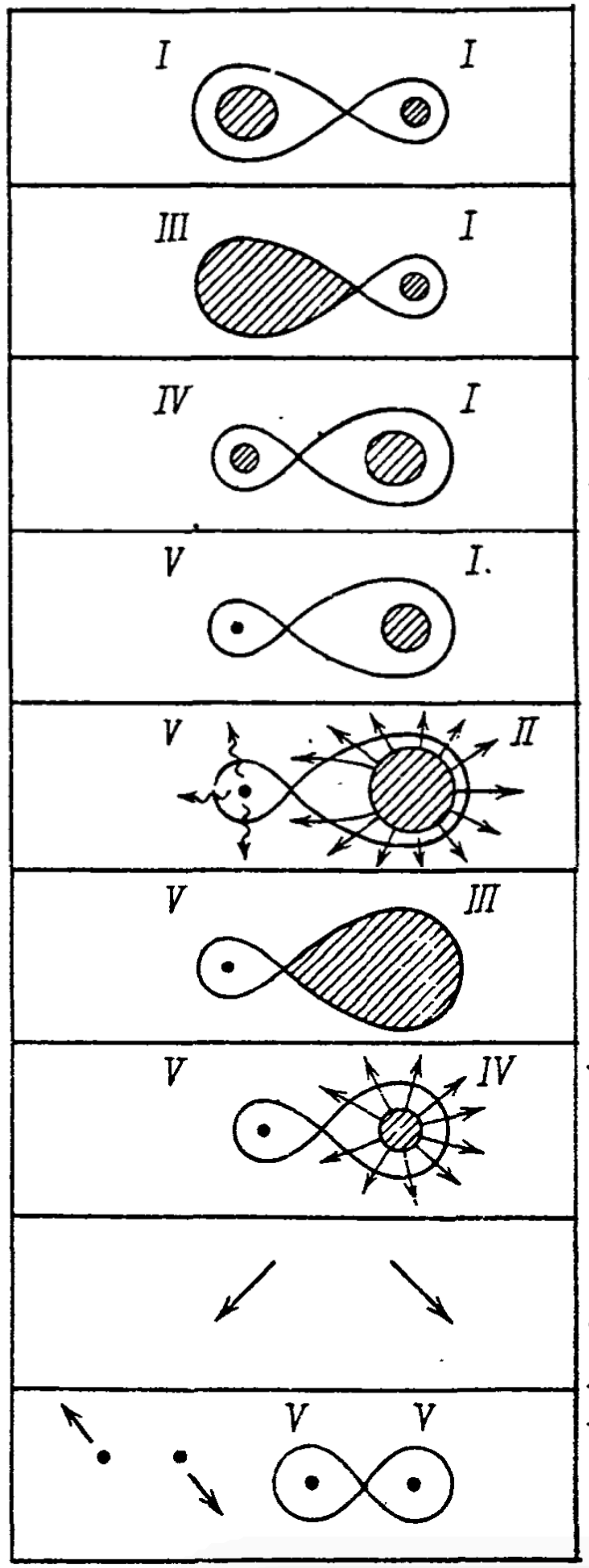
$$t_{th} \approx \frac{GM^2}{RL} \approx 3 \cdot 10^7 m^{-2} \text{ yrs}$$

$$M_2 = M_{2,0} + M_{1,0} - M_1 \qquad a_1 = a_0 \left(\frac{M_{1,0} \cdot M_{2,0}}{M_1 \cdot M_2}\right)$$

$$a = a_1 \frac{1+q_*}{1+2q_* - q} \qquad q_* = M_1/M_2, \quad q = M_x/M_2$$

Caveats &/or assumptions

- Only case A, case B, case C mass transfer
- 100% conservative mass transfer
- No common envelope
- No “natal" kicks



Lipunov 1991

$$\lg t_H \approx 9.9 - 3.8 \lg m_o + \lg^2 m_o \qquad \dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

$$t_{th} \approx \frac{GM^2}{RL} \approx 3 \cdot 10^7 m^{-2} \text{ yrs}$$

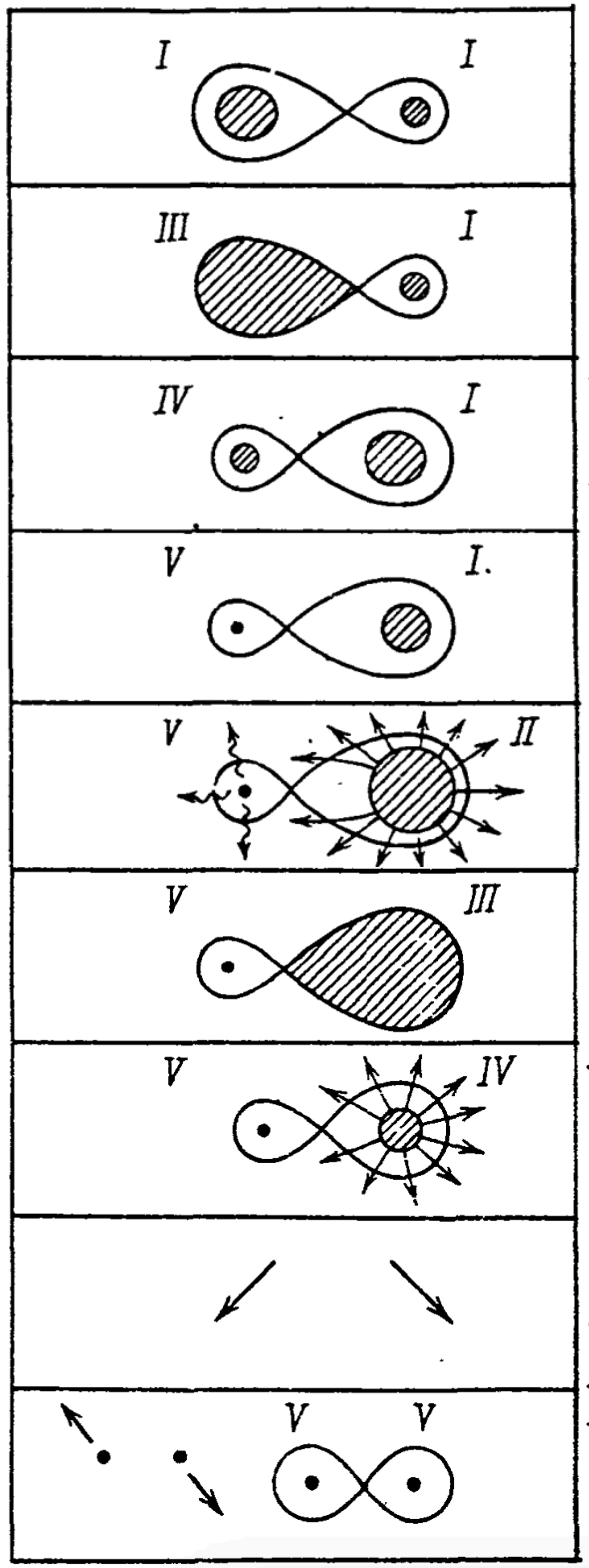
$$M_2 = M_{2,0} + M_{1,0} - M_1 \qquad a_1 = a_0 \left(\frac{M_{1,0} \cdot M_{2,0}}{M_1 \cdot M_2}\right)$$

$$a = a_1 \frac{1+q_*}{1+2a_* - q} \qquad q_* = M_1/M_2, \quad q = M_x/M_2$$

$$\dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

Caveats &/or assumptions

- Only case A, case B, case C mass transfer
- 100% conservative mass transfer
- No common envelope
- No “natal" kicks



Lipunov 1991

$$\lg t_H \approx 9.9 - 3.8 \lg m_o + \lg^2 m_o \qquad \dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

$$t_{th} \approx \frac{GM^2}{RL} \approx 3 \cdot 10^7 m^{-2} \text{ yrs}$$

$$M_2 = M_{2,0} + M_{1,0} - M_1 \qquad a_1 = a_0 \left(\frac{M_{1,0} \cdot M_{2,0}}{M_1 \cdot M_2}\right)$$

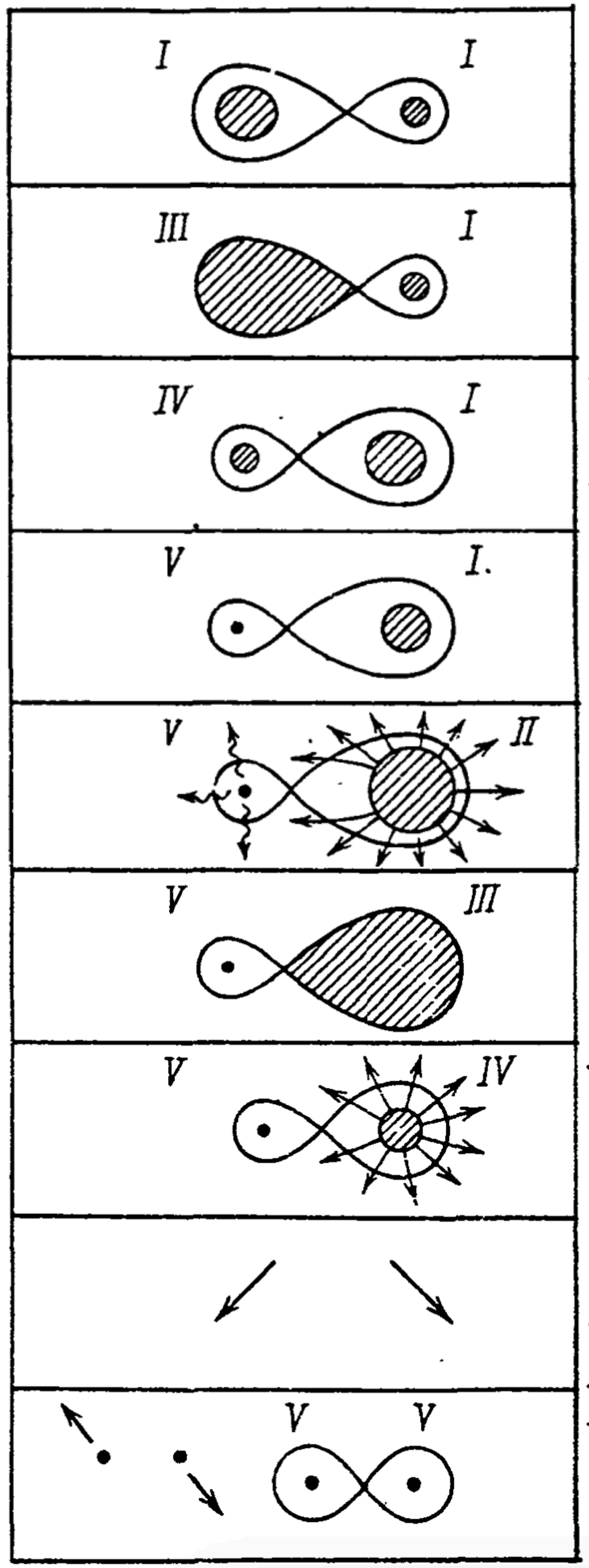
$$a = a_1 \frac{1+q_*}{1+2q_* - q} \qquad q_* = M_1/M_2, \quad q = M_x/M_2$$

$$\dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

$$M_2 = M_{2,0} + \cancel{M_{1,0} - M_1} \qquad a_1 = a_0 \left(\frac{M_{1,0} \cdot M_{2,0}}{M_1 \cdot M_2}\right)$$

Caveats &/or assumptions

- Only case A, case B, case C mass transfer
- 100% conservative mass transfer
- No common envelope
- No “natal" kicks



Lipunov 1991

$$\lg t_H \approx 9.9 - 3.8 \lg m_o + \lg^2 m_o \qquad \dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

$$t_{th} \approx \frac{GM^2}{RL} \approx 3 \cdot 10^7 m^{-2} \text{ yrs}$$

$$M_2 = M_{2,0} + M_{1,0} - M_1 \qquad a_1 = a_0 \left(\frac{M_{1,0} \cdot M_{2,0}}{M_1 \cdot M_2}\right)$$

$$a = a_1 \frac{1+q_*}{1+2q_* - q} \qquad q_* = M_1/M_2, \quad q = M_x/M_2$$

$$\dot{M}_o = \alpha_w \frac{L_o}{v_\infty c}$$

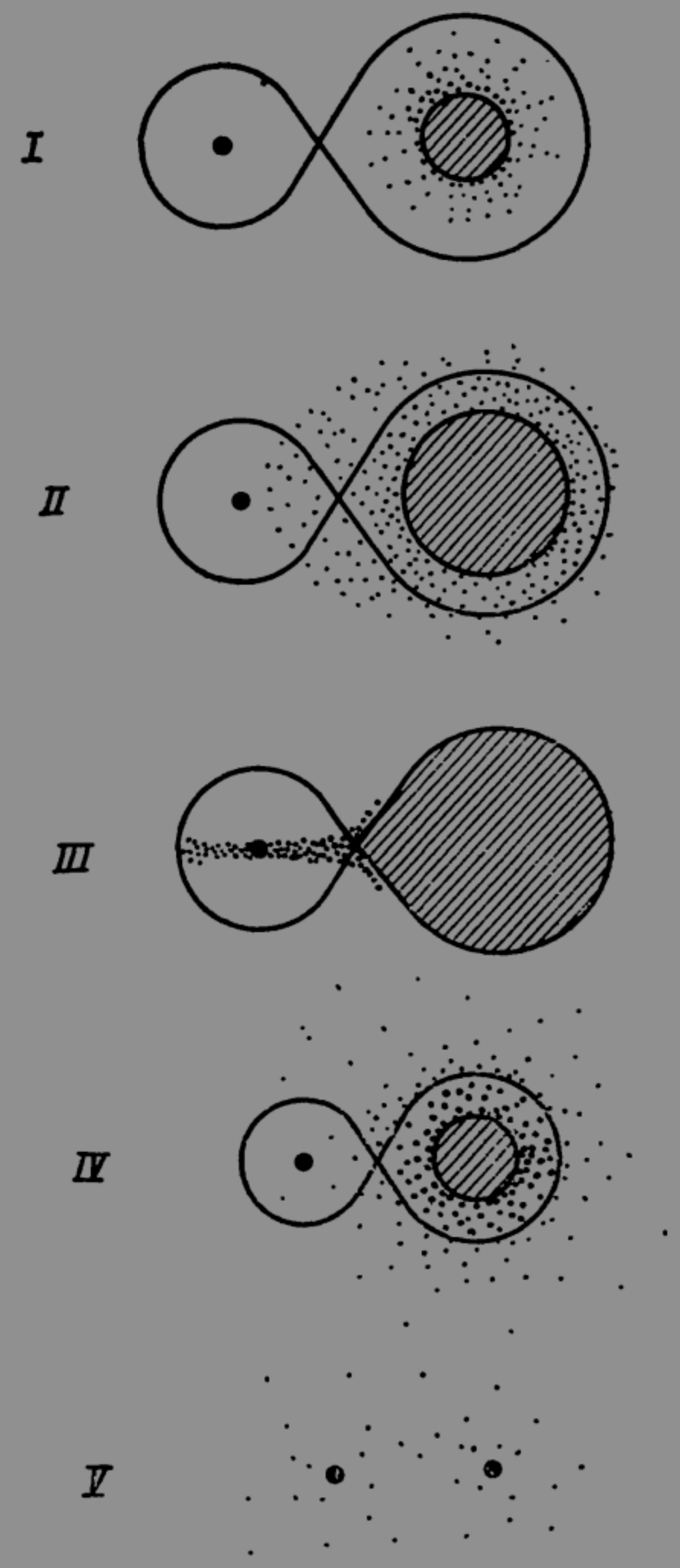
$$M_2 = M_{2,0} + M_1\cancel{{}_{,0} - M_1} \qquad a_1 = a_0 \left(\frac{M_{1,0} \cdot M_{2,0}}{M_1 \cdot M_2}\right)$$

$$a = a_1 \frac{1+q_*}{1+2q_* - q} \qquad q_* = M_1/M_2, \quad q = M_x/M_2$$

Caveats &/or assumptions

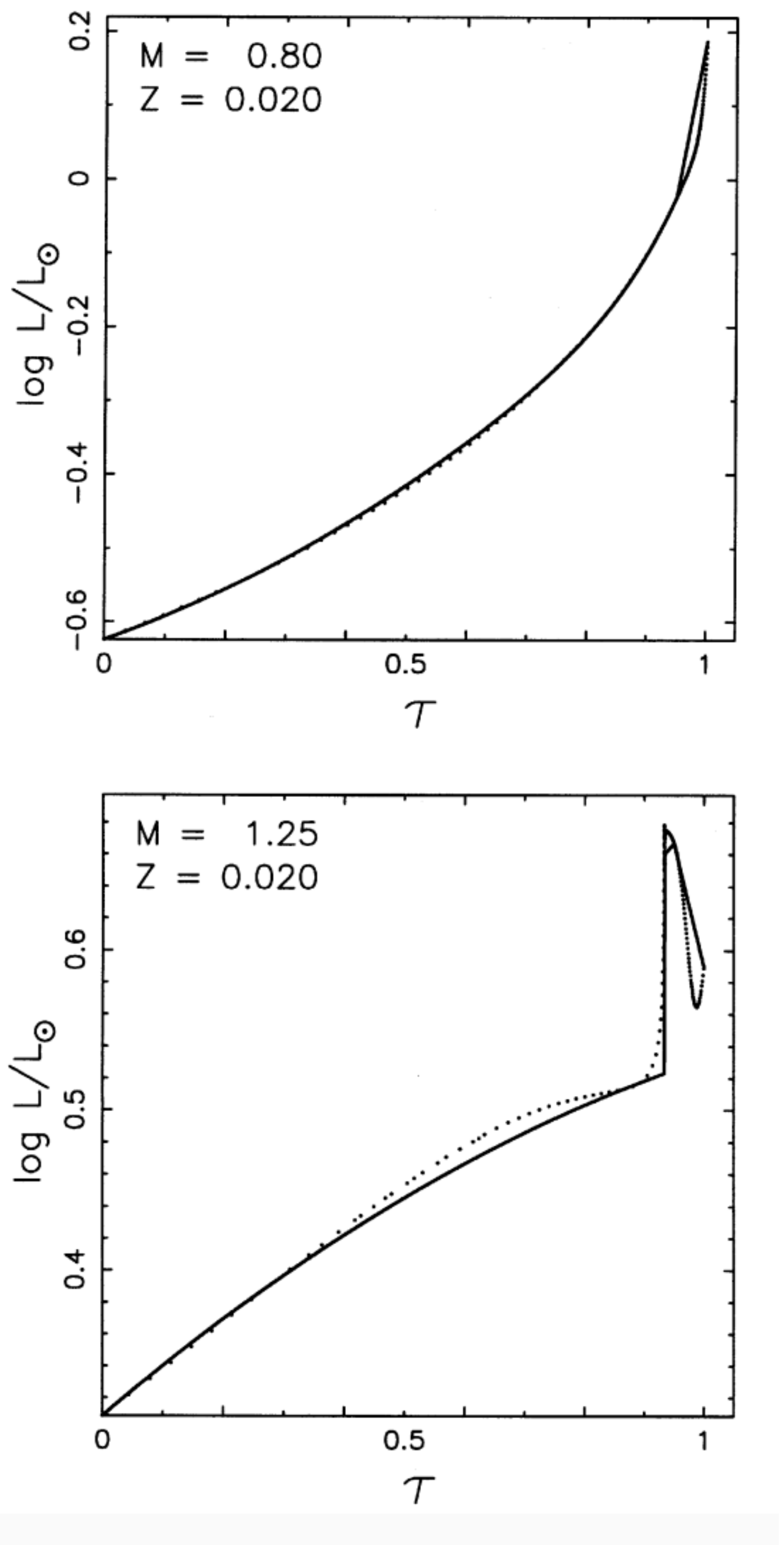
- Only case A, case B, case C mass transfer
- 100% conservative mass transfer
- No common envelope
- No “natal" kicks

early pop-synth



Kornilov & Lipunov 1983

"the Hurley fits"



Hurley+2000,2002

community development

AMUSE SeBa

Portegeis Zwart+1996

COSMIC

Breivik+2020

COMPAS

Team COMPAS, Riley+2022

contemporary pop-synth

detailed models

POSYDON

Fragos+2022

METISSE / SEVN

Agrawal+2022

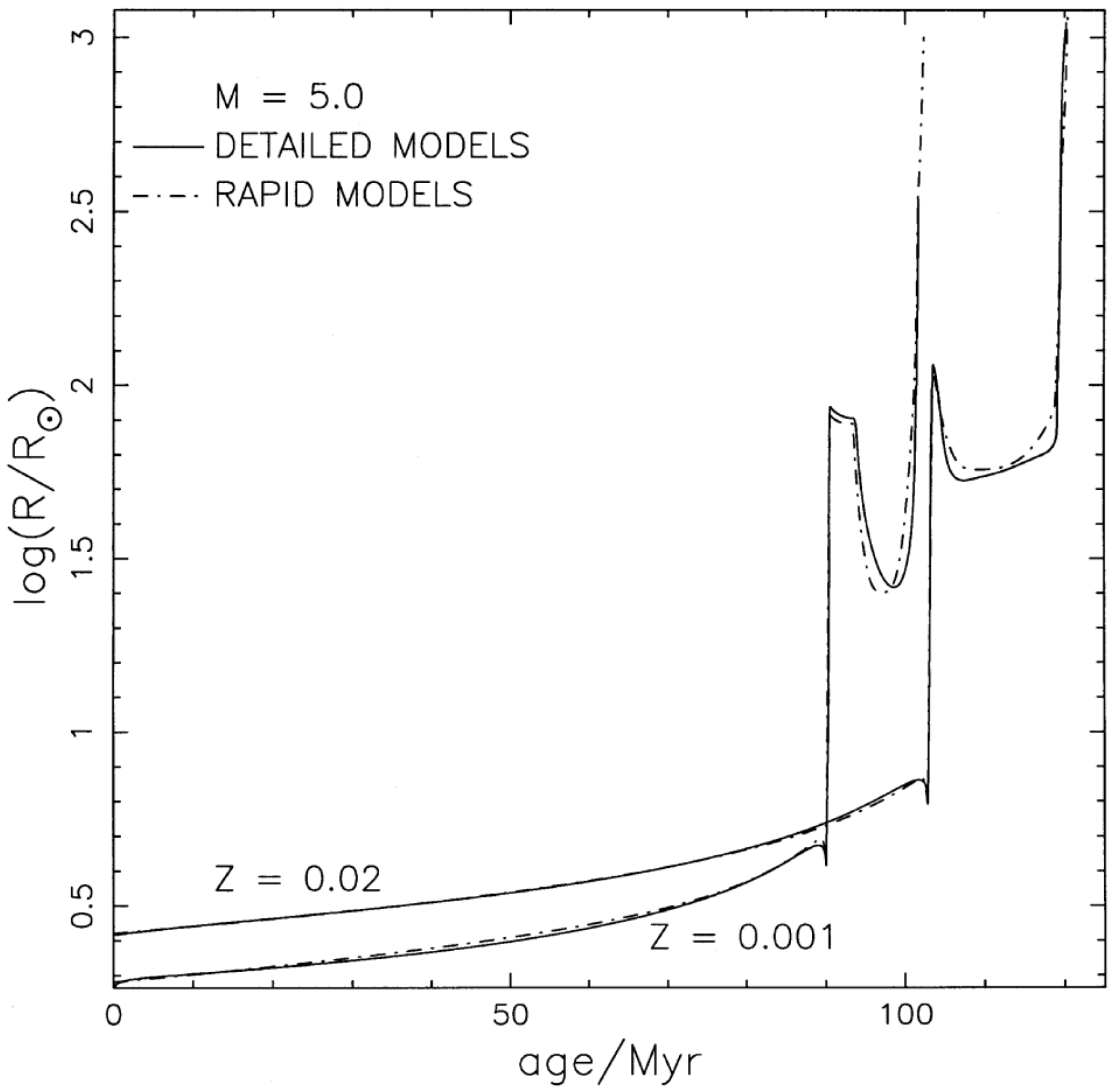
Iorio+2023

dartboard

BackPop

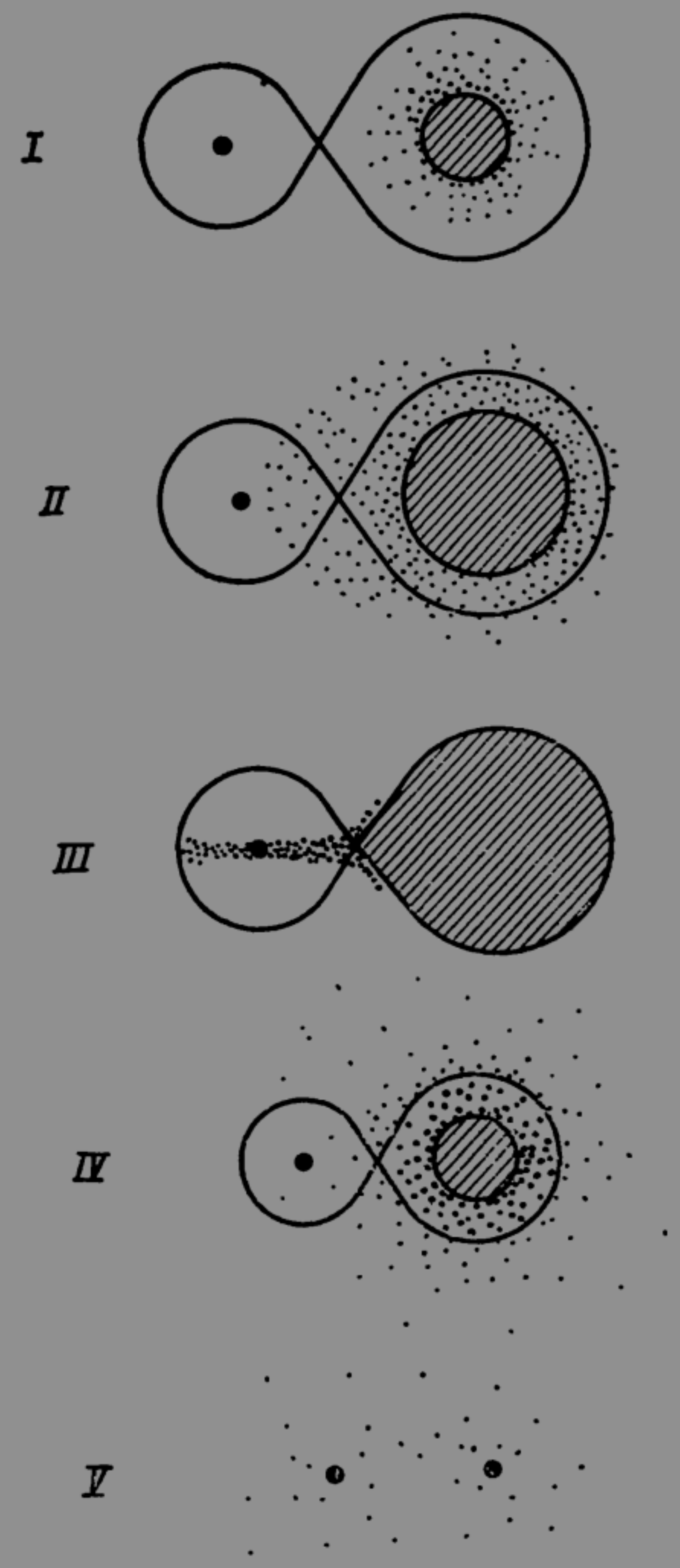
Andrews+18, Wong+23

Hurley, Pols, Tout 2000



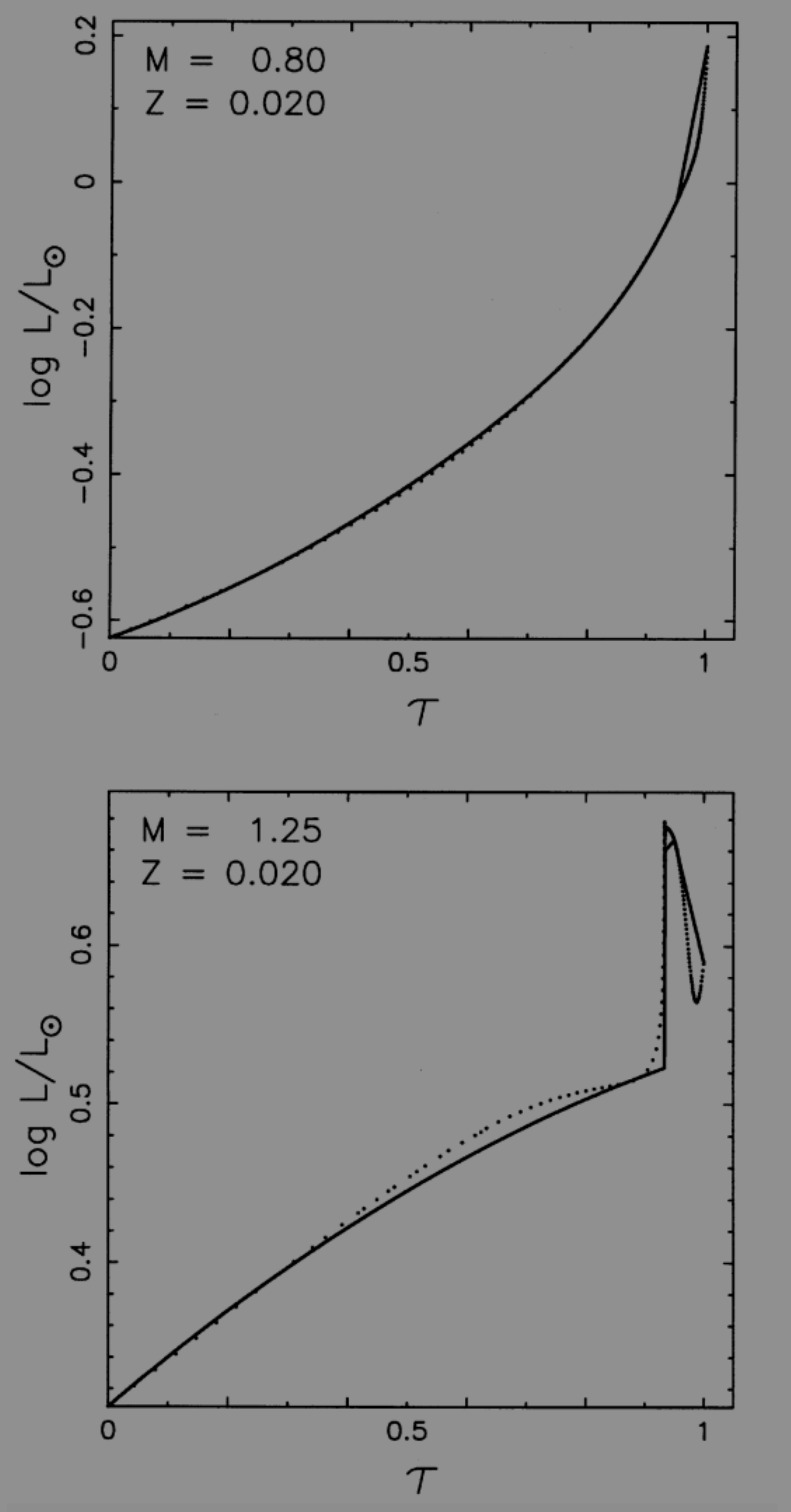
The CPU time required by the BSE algorithm to evolve 500 000 binaries up to the age of the Galaxy is approximately 20 h, or 0.144 s per binary, on a Sun SparcUltra10 workstation (containing a 300-MHz processor).

early pop-synth



Kornilov & Lipunov 1983

"the Hurley fits"



Hurley+2000,2002

community development

SeBa

AMUSE

Portegeis Zwart+1996

COSMIC

Breivik+2020

COMPAS

Team COMPAS, Riley+2022

contemporary pop-synth

detailed models

POSYDON

Fragos+2022

METISSE / SEVN

Agrawal+2022

Iorio+2023

dartboard

BackPop

Andrews+18, Wong+23

This is *not* the way to share code in the 21st century!

> On Sat, Oct 6, 2018 at 6:20 PM Smadar Naoz [redacted] wrote:
>
> > Thank you, looking forward to hearing back from you.
> >
> > On Sat, Oct 6, 2018 at 5:37 PM Kyle Kremer [redacted] wrote:
> >
> > > Hi Vicky,
> > >
> > > Yes, Katie has the most up-to-date version. She will be in town this week, so while she's here, I will make sure we have the latest version and then we (or Katie) can pass it along to Smadar.
> > >
> > > Kyle
> > >
> > > On Sat, Oct 6, 2018 at 7:31 PM Chase Kimball [redacted] wrote:
> > >
> > > > I'd imagine Katie's is the most up to date. Mine isn't far off, but it has done hacky hooks in it for catching systems just before SN.
> > > >
> > > > On Sat, Oct 6, 2018, 7:26 PM Vicky Kalogera [redacted] wrote:
> > > >
> > > > > Kyle, Chase,
> > > > >
> > > > > Who has/maintains the latest/best BSE version of ours ? Smadar Naoz (ex CIERA Fellow, now UCLA faculty) would like to use it for one of her projects and I said she could have it.
> > > > >
> > > > > Vicky

COSMIC:

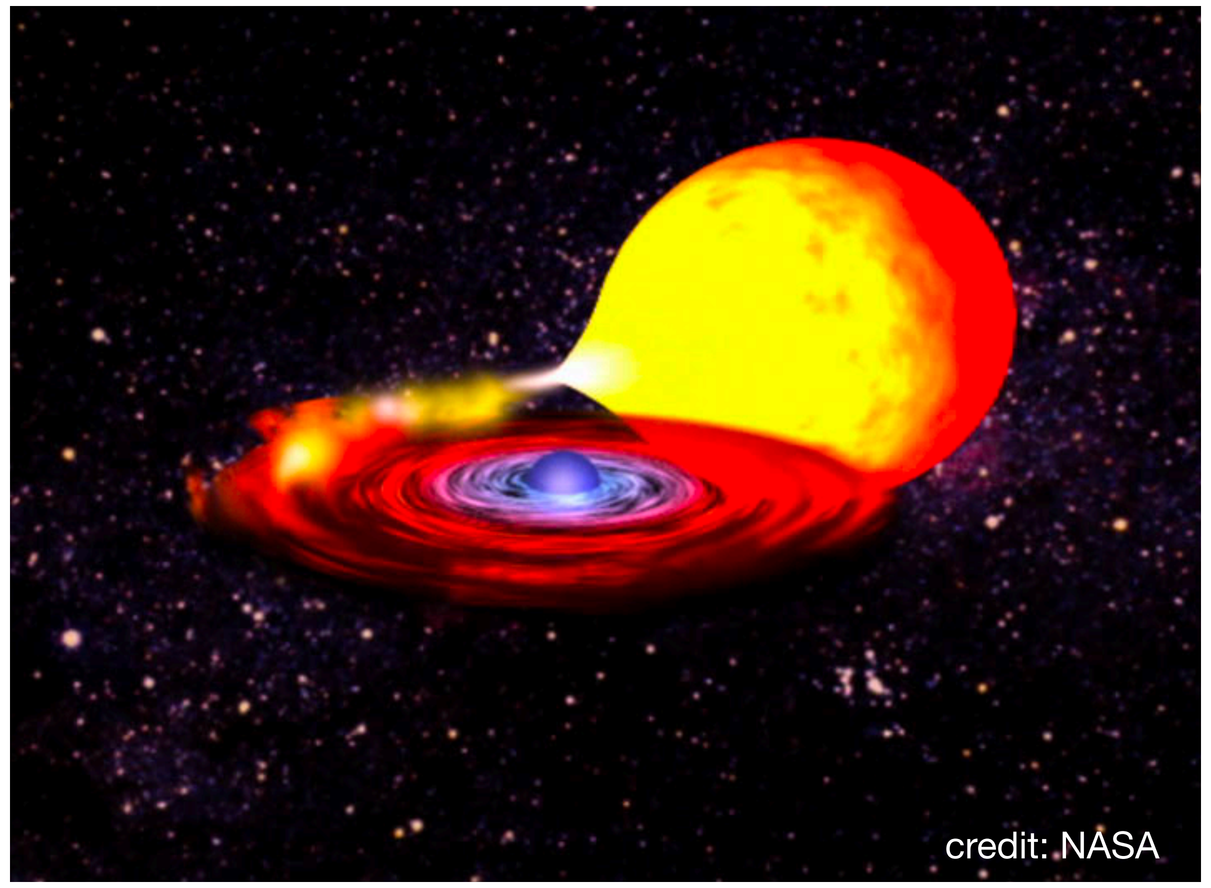
- integrated w/ globular cluster dynamics: CMC — see arXiv:2106.02643 for deets!
- integrated w/ Galactic dynamics: cogsworth — see arXiv:2409.04543 for deets!
- Updated single star evolution w/ METISSE — paper coming soon!

Compact
Object
Synthesis and
Monte-Carlo
Investigation
Code

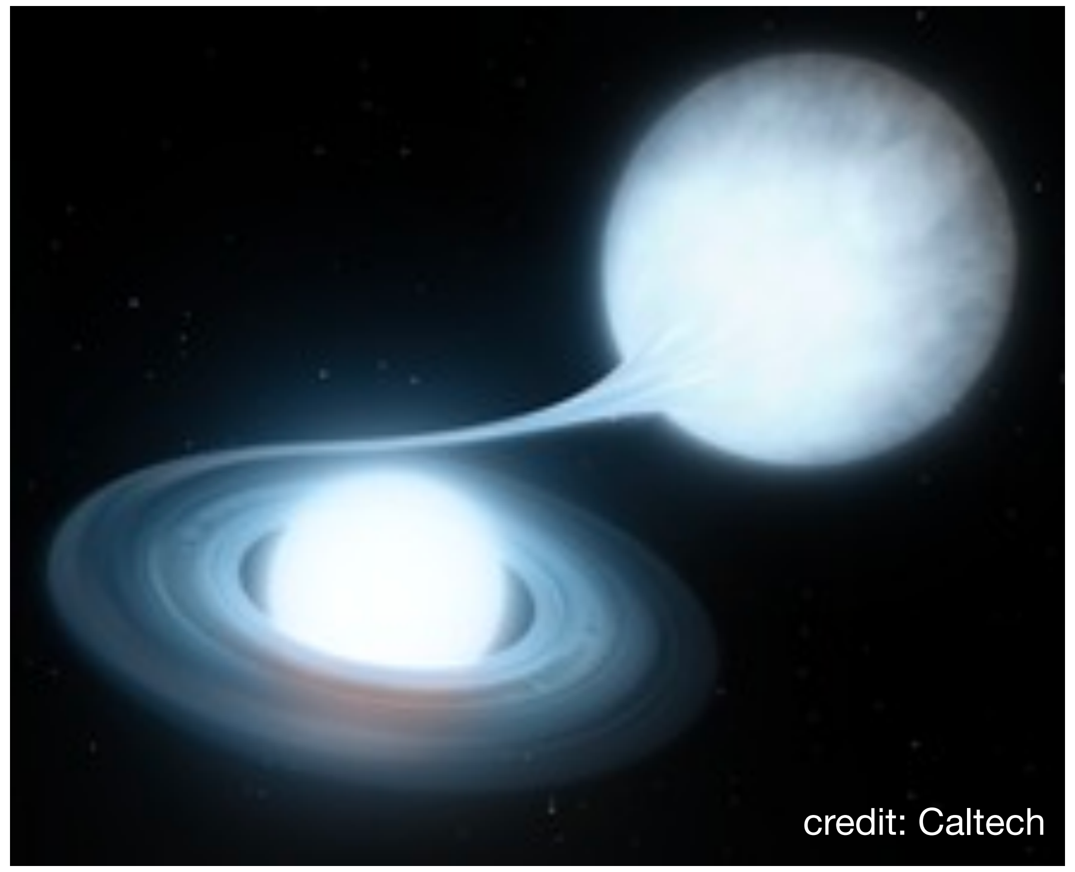
See cosmic-popsynth.github.io or Breivik, Coughlin, Zevin+2020 for details!

COSMIC fueled science — 115 studies so far!

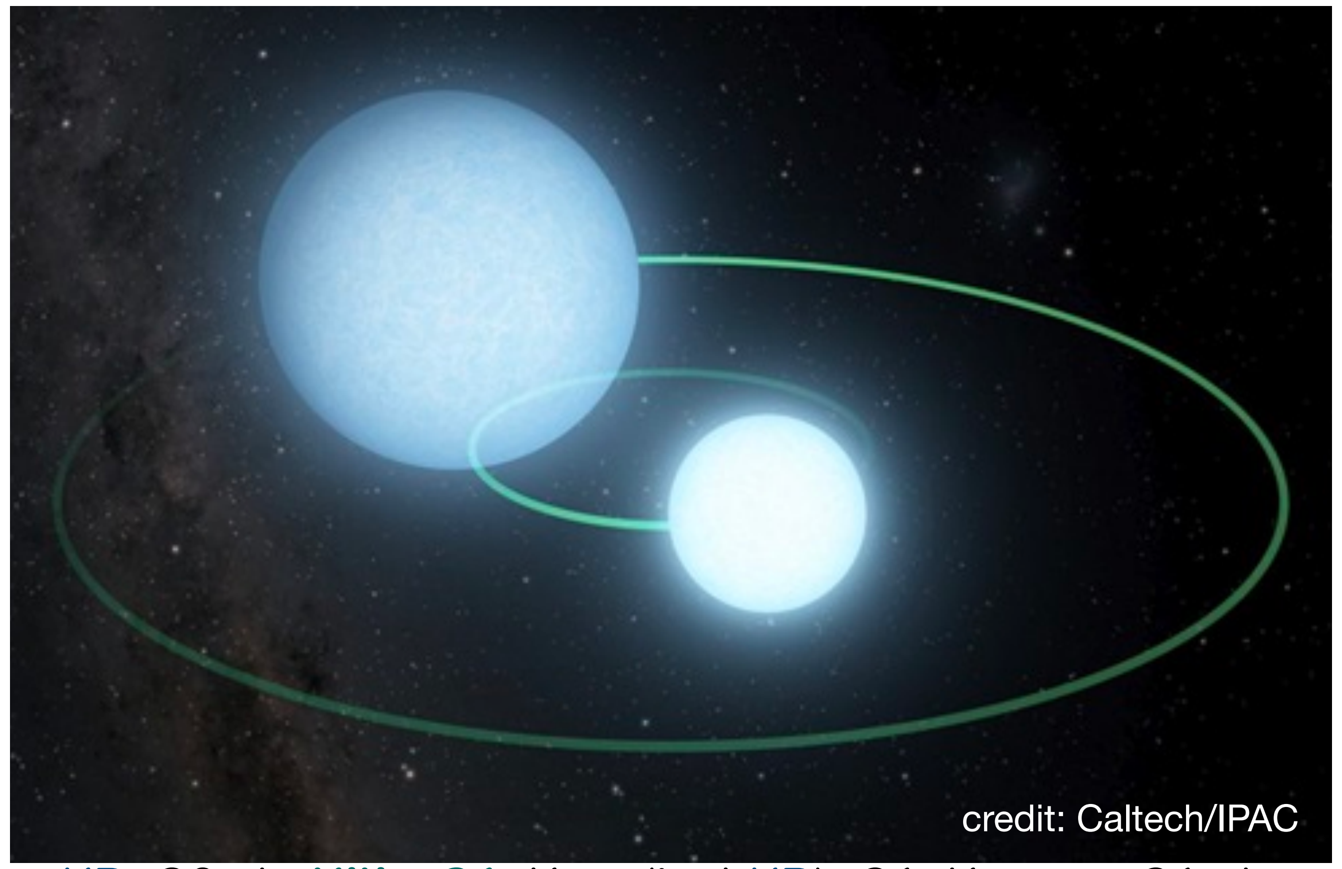
Leiner+21; Geller+21; Jayasinghe+21; Renzo+21; Grunblatt+(incl KB)23; Sayeed(incl KB)+23; Blomberg(incl KB)+24; **Lam+2024; Miller+2024**



Zevin+20; Marchant, KB+20; Siegel+(incl KB)23; **Lloyd-Ronning+24**; **Nyadzani+25**

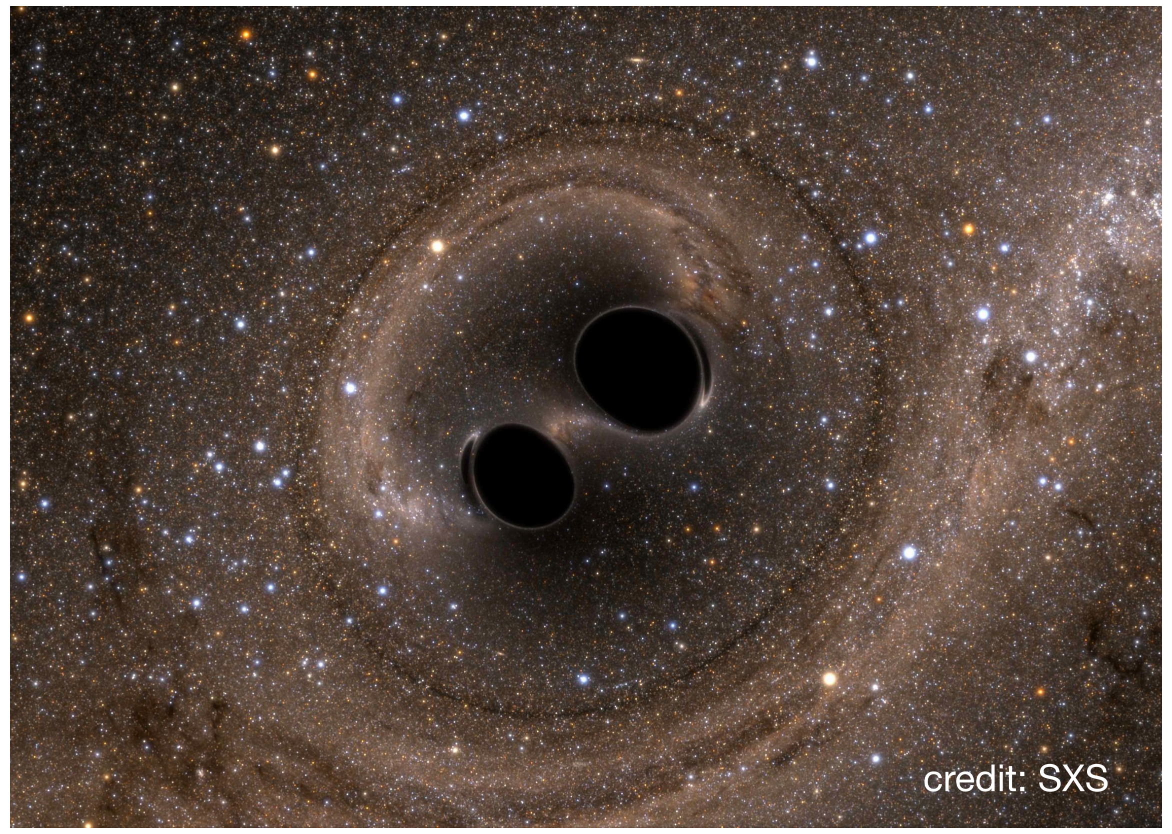


Kremer, KB+17; KB+18, Biscoveanu+22; Scaringi, KB+23, Shen+(incl KB)23



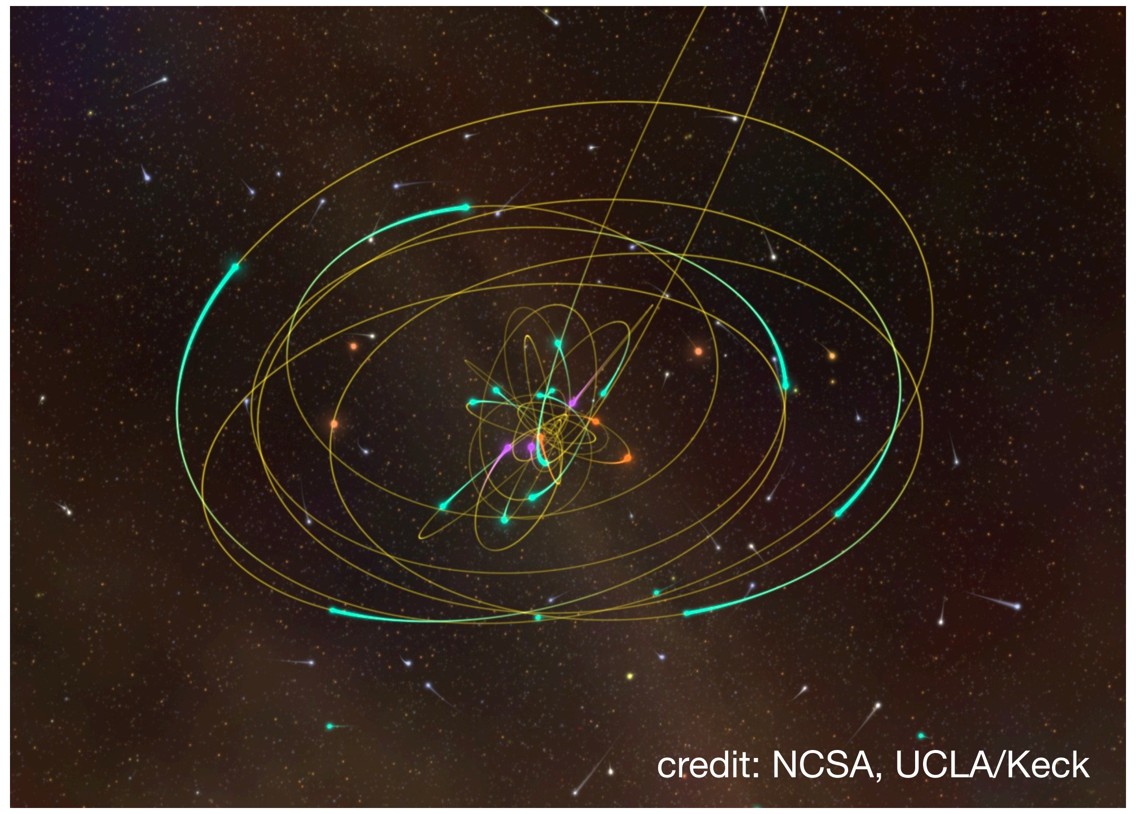
KB+20a,b; **Kilic+21**; Katz (incl KB)+21; Kremer+21a,b; Digman+22,23; Thiele, KB+23; **Khurana+23;** Delfavero,KB+24, **Kołaczek-Szymański+24; Shahaf+25; Pellouin+25;** Rubio,KB+25; **Boileau+25; Yamaguchi+25**

KB+17,19; Andrews, KB+23; Kıroğlu+22, 24; Chawla+22,23; Andrews+22; El-Badry (incl KB)+22,23; **Weller+23;** Di Carlo (incl KB)+24, **Brown+24;** Wagg,KB+24; Nagarajan+25; Wagg+25b,c



KB+16; Bavera+21,22a,b,c; Andrews+21; Zevin+20,21,22; Wong,KB+21,23; Roman-Garza+21; **Gallegos-Garcia+21; Franciolini+22; Mandhai+22; Sicilia+22; Mastrogiovanni+22**; Fragos+23; **Knoly+23**, Srinivasan+23, **Lehouc+23, Li+25; Khurana+25**

Ye+19,20,22a,b,23,24a,b,c,d; Kremer+20,23,24; Zevin+19; Martinez+20,22; Gonzales+21; Rui+21; Vitral+23; Cabrera+23; Rodriguez+22,23; Weatherford+23; Payne+24; Gonzales+24a,b; Bruel+24; **Badger+24**



Stephan+(incl. KB)19

Wang+(incl. KB)21

Rose+23; Shariat+24a,b

Open software interlude

Open software interlude

KB's principles of software

Open software interlude

KB's principles of software

1. The most important user is current &/or future you

Open software interlude

KB's principles of software

1. The most important user is current &/or future you
2. If you want to build a user base, you *must* consider the interface — no matter how good your models are, people bounce off a difficult interface

Open software interlude

KB’s principles of software

1. The most important user is current &/or future you
2. If you want to build a user base, you *must* consider the interface — no matter how good your models are, people bounce off a difficult interface
3. The number of minutes you spend writing documentation is roughly equal to the number of emails you will save yourself from in the future

Open software interlude

KB's principles of software

1. The most important user is current &/or future you
2. If you want to build a user base, you *must* consider the interface — no matter how good your models are, people bounce off a difficult interface
3. The number of minutes you spend writing documentation is roughly equal to the number of emails you will save yourself from in the future
4. You are not responsible for maintaining your code until the end of time

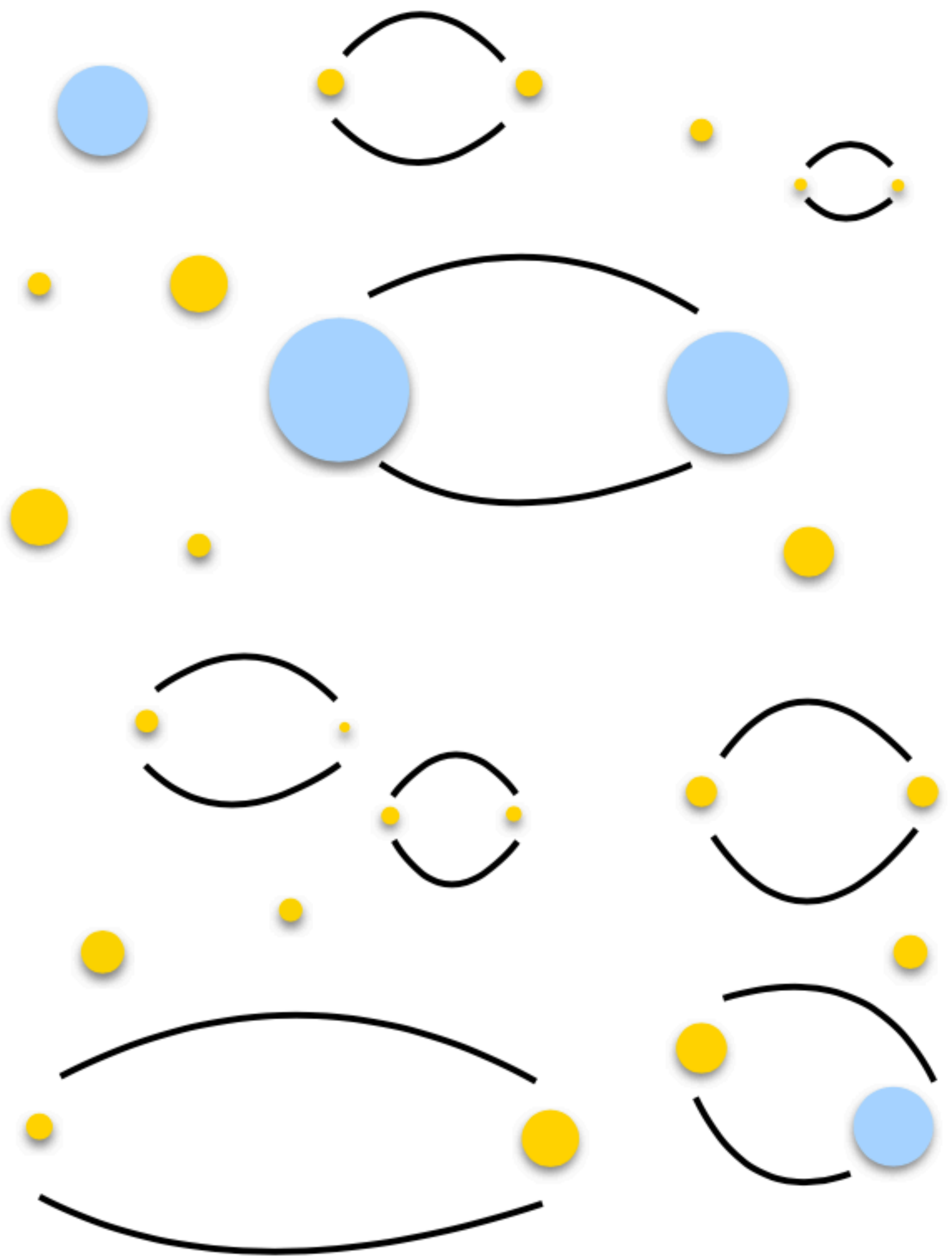
Open software interlude

KB's principles of software

1. The most important user is current &/or future you
2. If you want to build a user base, you *must* consider the interface — no matter how good your models are, people bounce off a difficult interface
3. The number of minutes you spend writing documentation is roughly equal to the number of emails you will save yourself from in the future
4. You are not responsible for maintaining your code until the end of time
5. There is no good or bad code — only public and private code

Simulating a population of BH binaries

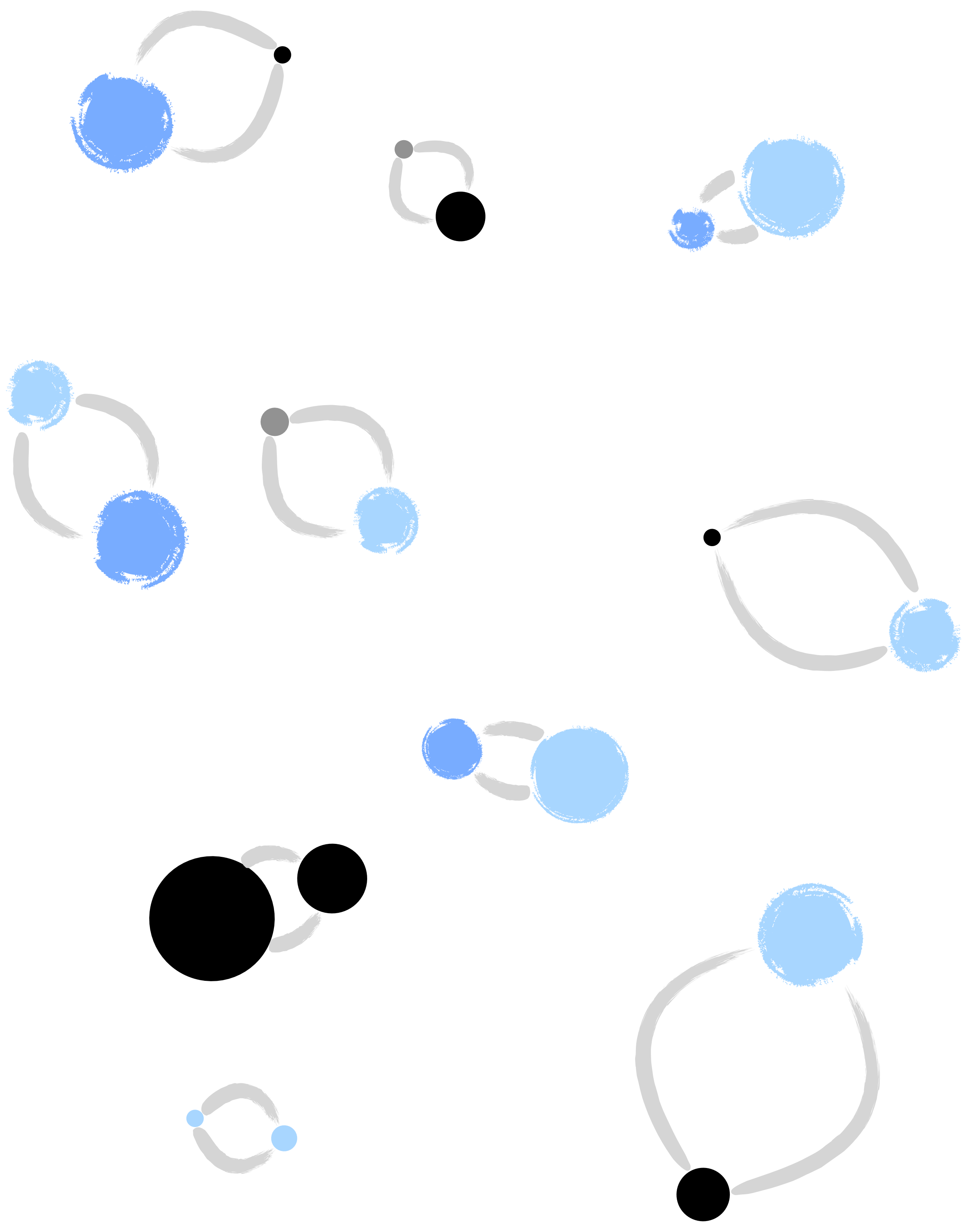
initialize ZAMS population



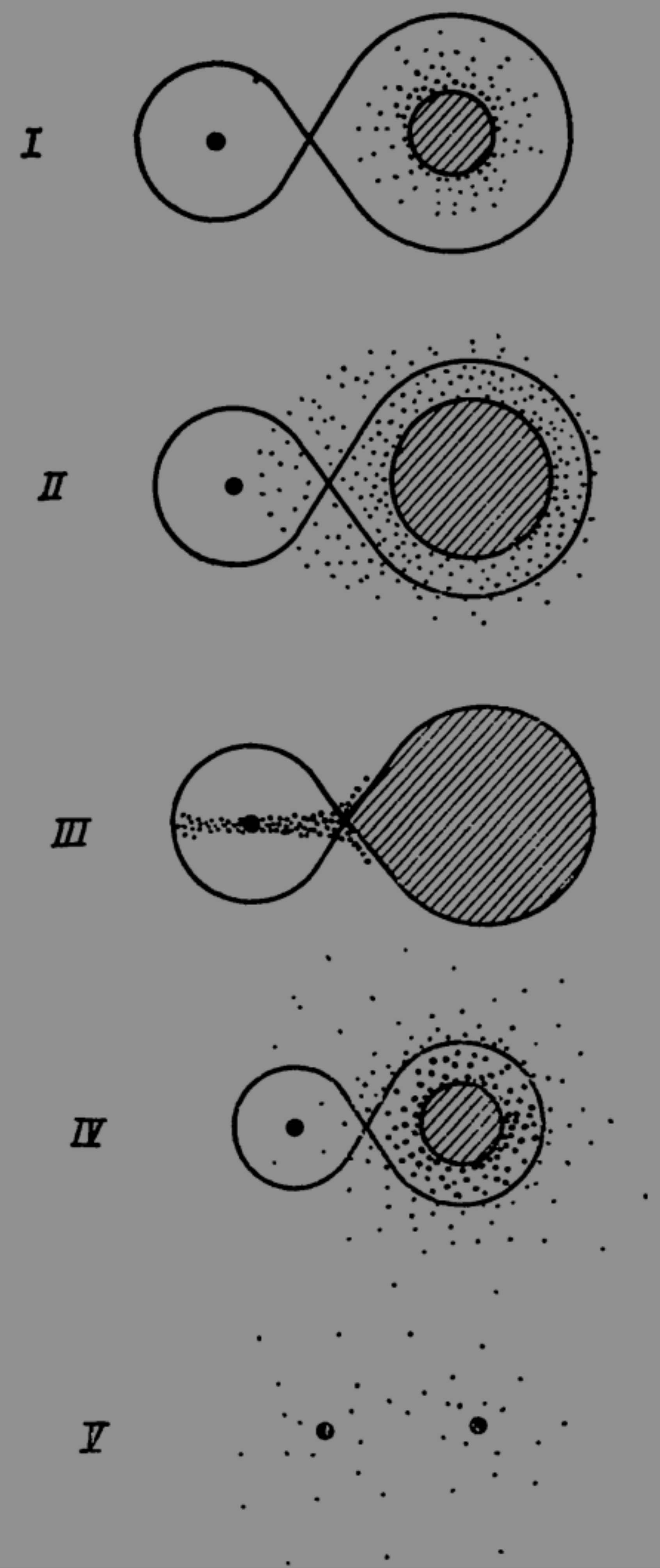
evolve w/ your favorite code

Scenario Machine (Lipunov+1996)
IBiS (Tutukov+1996)
SeBa (Portegies-Zwart+1996)
BSE (Hurley+2000,2002)
StarTrack (Belcyznski+2002)
binary_c (Izzard+2004)
BPASS (Eldridge+2017)
ComBinE (Kruckow+2018)
MOBSE (Giacobbo+2018)
COSMIC (Breivik+2020)
COMPAS (TeamCOMPAS+2022)
POSYDON (Fragos+2023)
SEVN (Iorio+2023)
METISSE (Agrawal,Breivik+2025)

collect the BH binaries & repeat if necessary

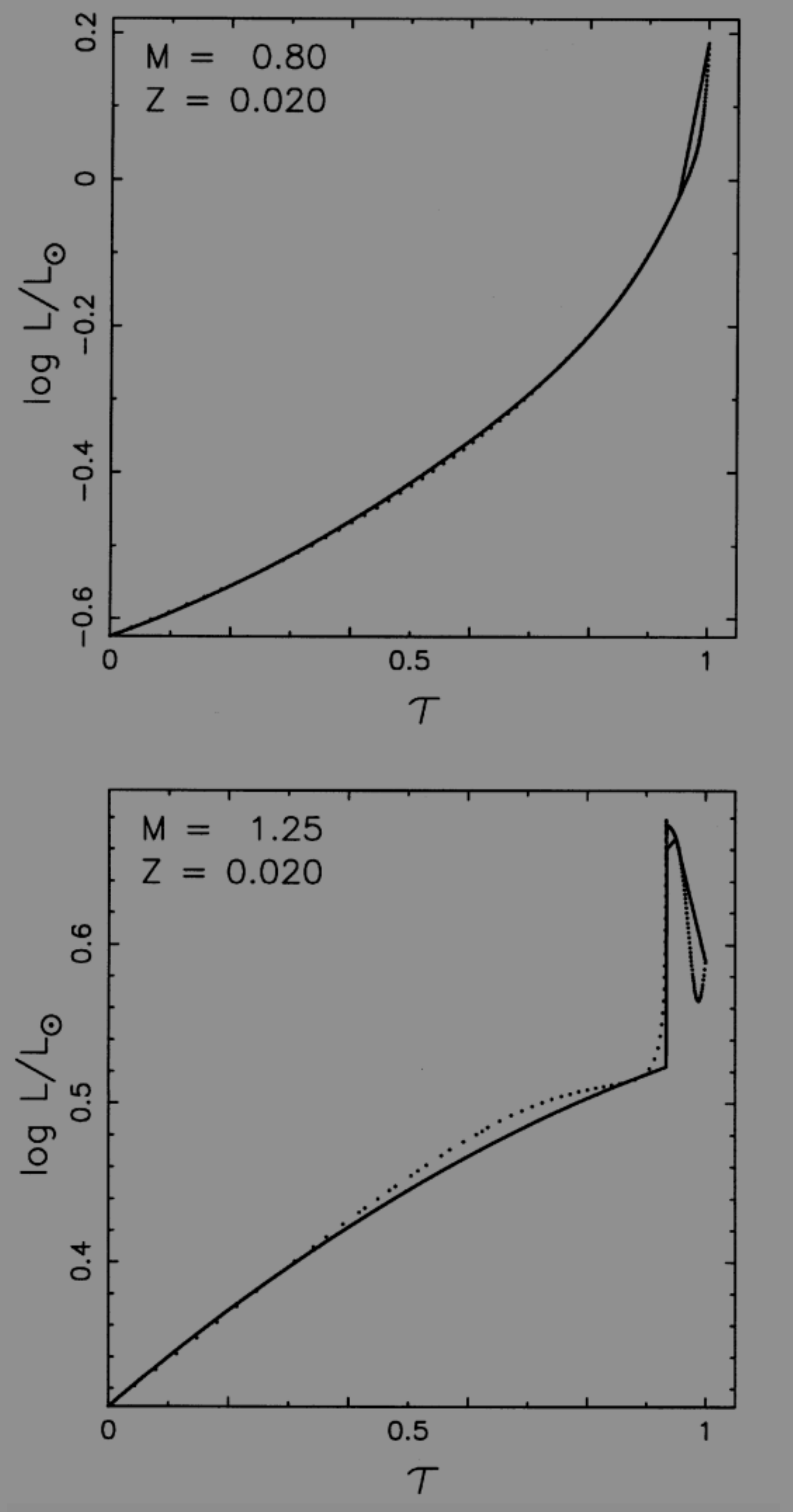


early pop-synth



Kornilov & Lipunov 1983

“the Hurley fits”



Hurley+2000,2002

community development

AMUSE SeBa

Portegeis Zwart+1996

COSMIC

Breivik+2020

COMPAS

Team COMPAS, Riley+2022

contemporary pop-synth

detailed models

POSYDON

Fragos+2022

METISSE / SEVN

Agrawal+2022
Iorio+2023

dartboard

BackPop

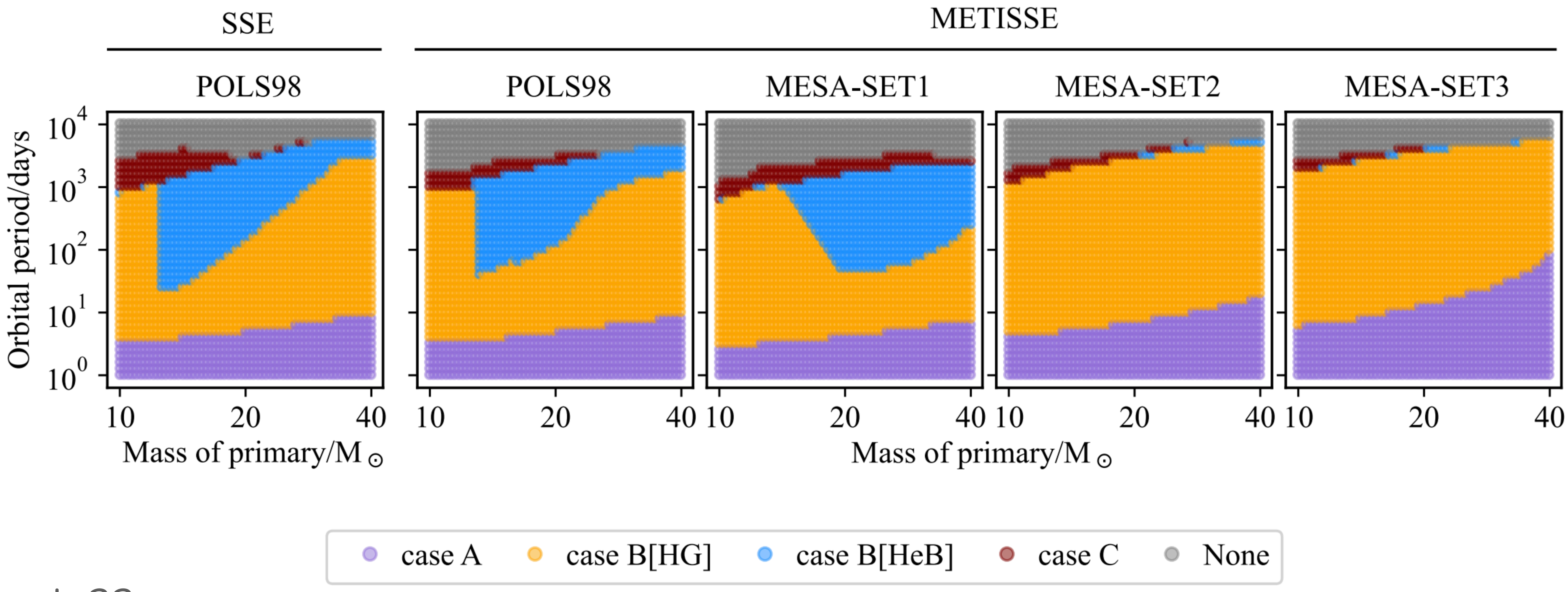
Andrews+18, Wong+23

	detailed	hybrid	rapid
	Fragos+2022	METISSE / SEVN Agrawal+2022 Iorio+2023	SeBa
stellar evolution	MESA	MESA/PARSEC/BEC/etc.	Hurley fits
binary interactions	MESA	Hurley algorithm (BSE)	Hurley(-ish) algorithm
Computation per binary evolution assumption set	MESA	2k cpu hours for 15 metallicity bins*	2k cpu hours for 15 metallicity bins

	detailed	hybrid	rapid
	Fragos+2022	METISSE / SEVN Agrawal+2022 Iorio+2023	SeBa
stellar evolution	MESA	MESA/PARSEC/BEC/etc.	Hurley fits
binary interactions	MESA	Hurley algorithm (BSE)	Hurley(-ish) algorithm
Computation per binary evolution assumption set	MESA	2k cpu hours for 15 metallicity bins*	2k cpu hours for 15 metallicity bins

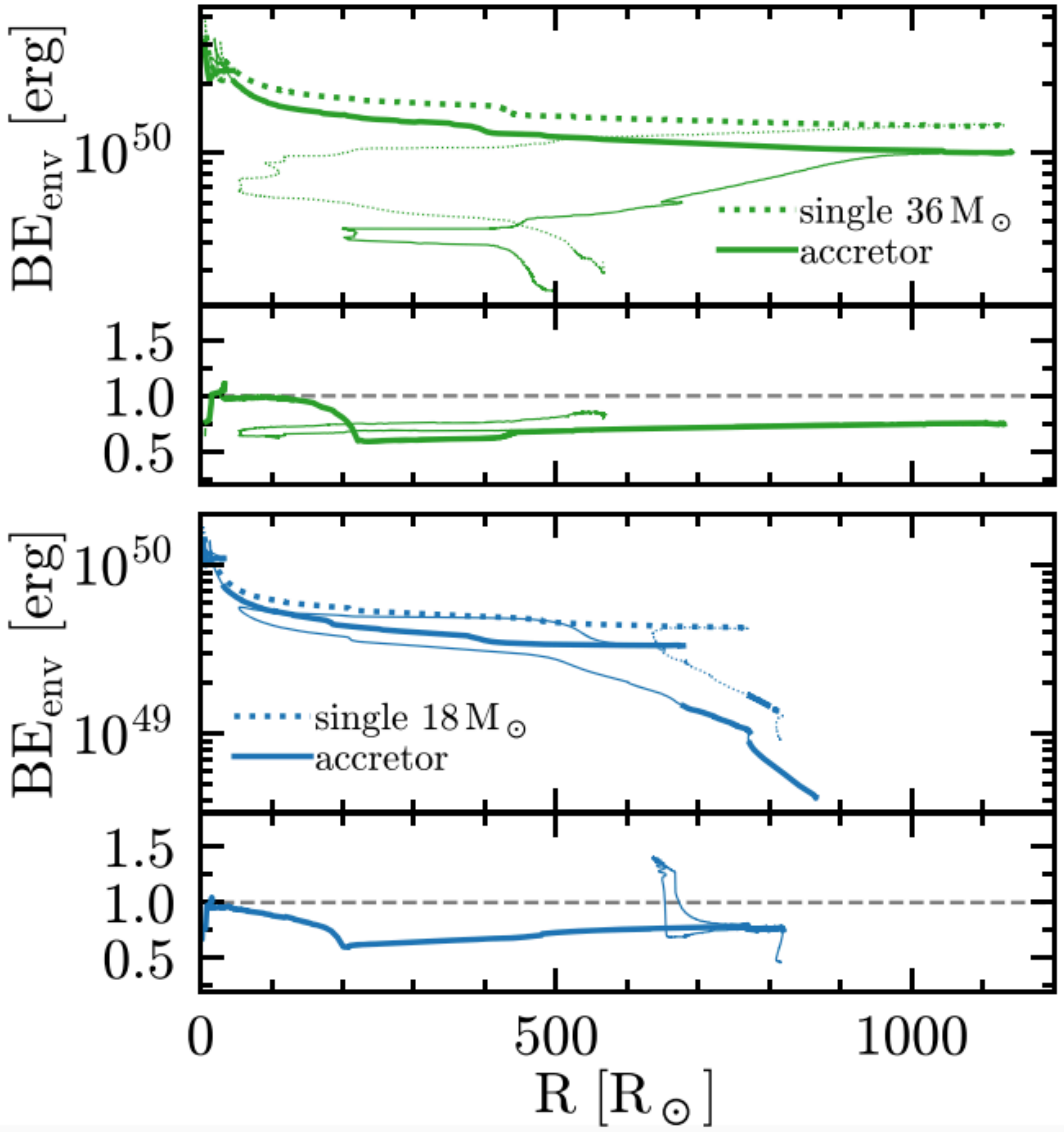
Bleeding edge: merging the hybrid and rapid codes

The case for hybrid models: we don't understand convective overshooting yet

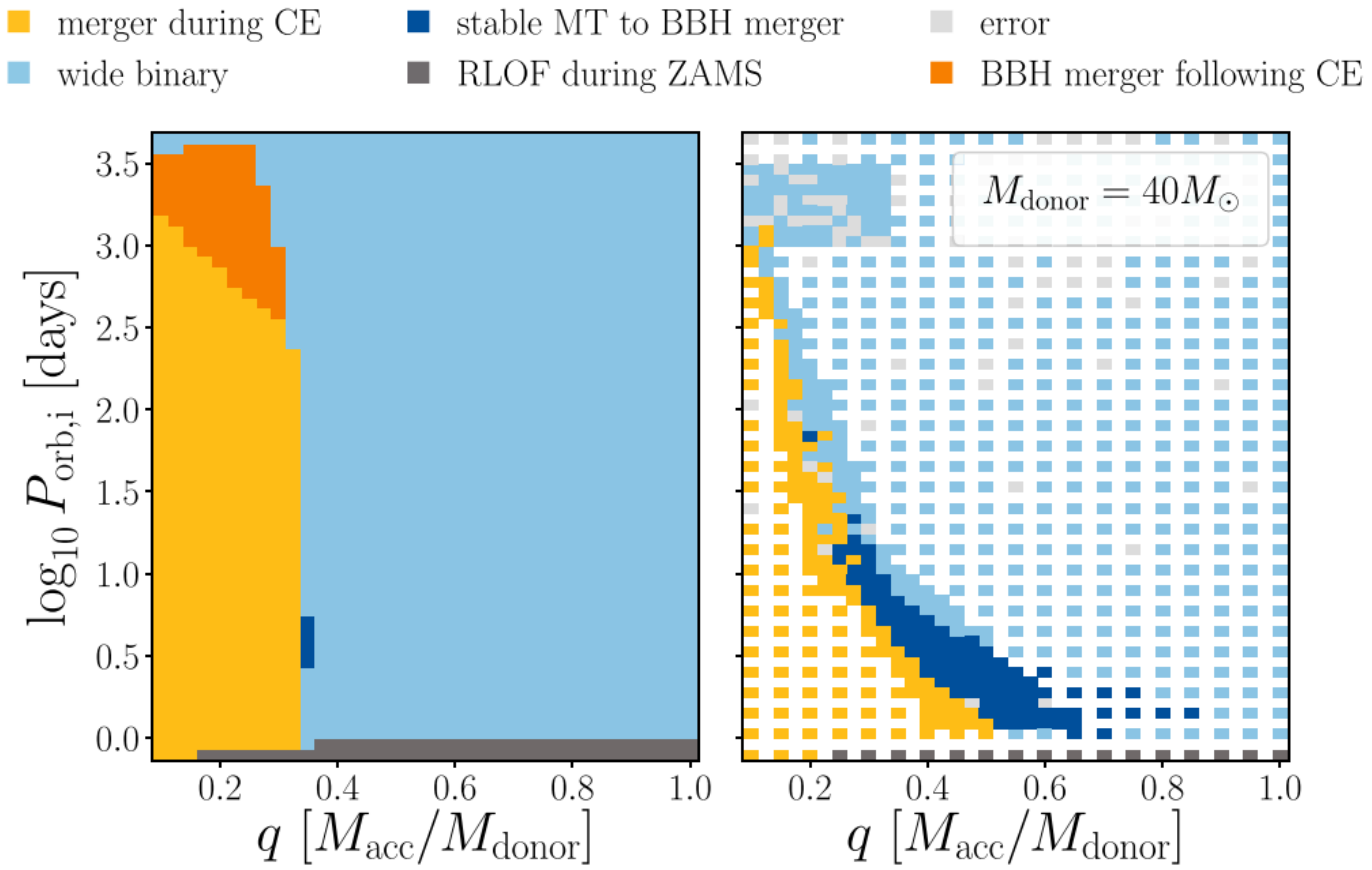


Aggrawal+23

The case for detailed models: capturing the response of the donor and accretor is necessary for accurate predictions



Renzo+23



Gallegos-Garcia+22

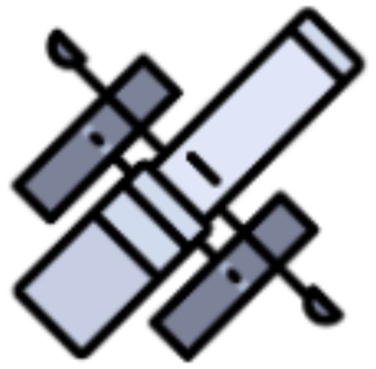
cogsworth

self-consistent population synthesis and galactic dynamics

Perform binary stellar evolution

Integrate galactic orbits

Sample star formation histories

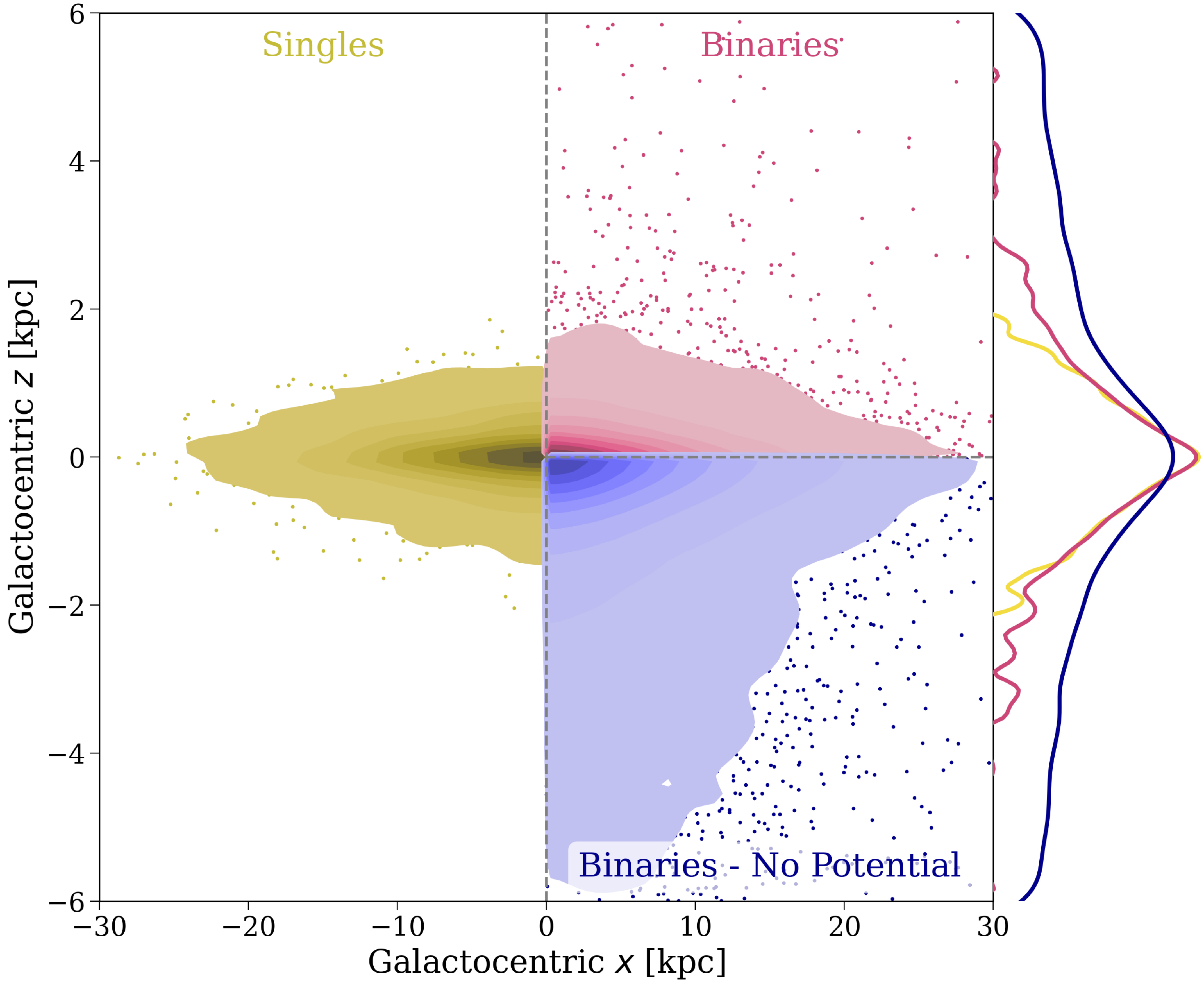


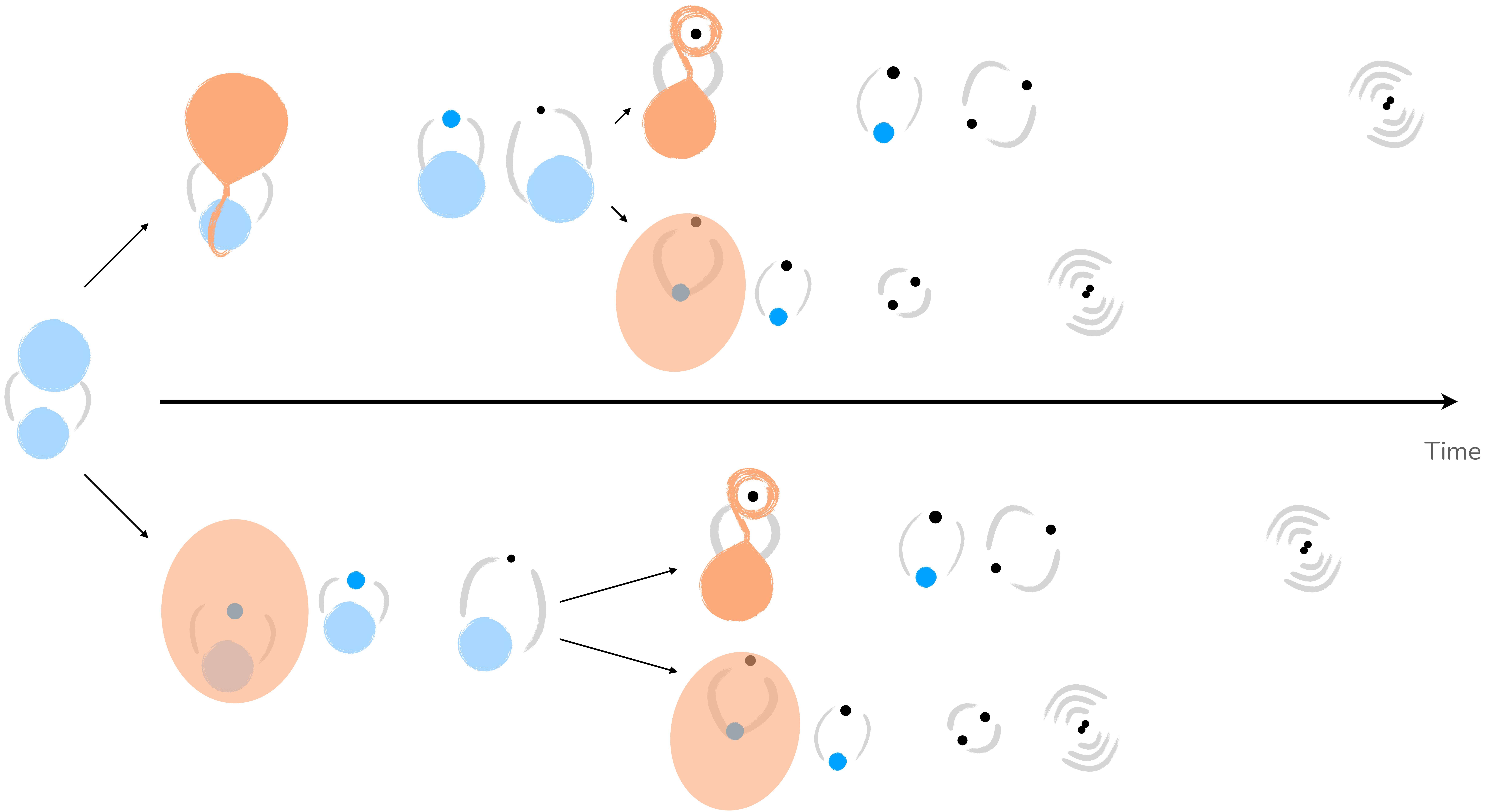
Predict observables

Paper: Wagg, *KB* et al. 2024 [2409.04543]

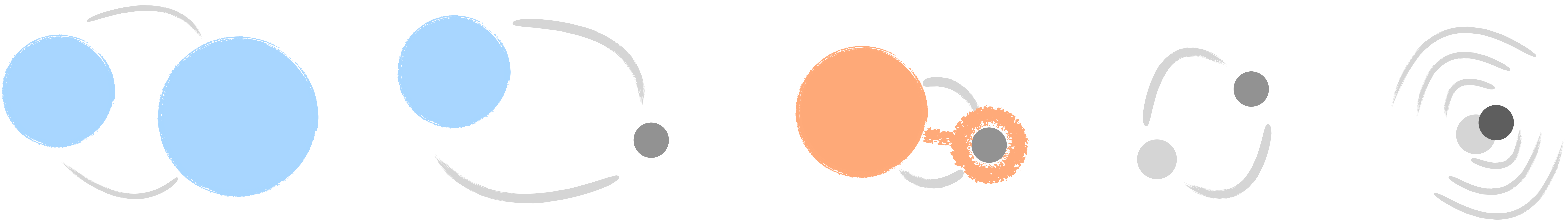
Docs: cogsworth.readthedocs.io

Led by Tom Wagg





Time



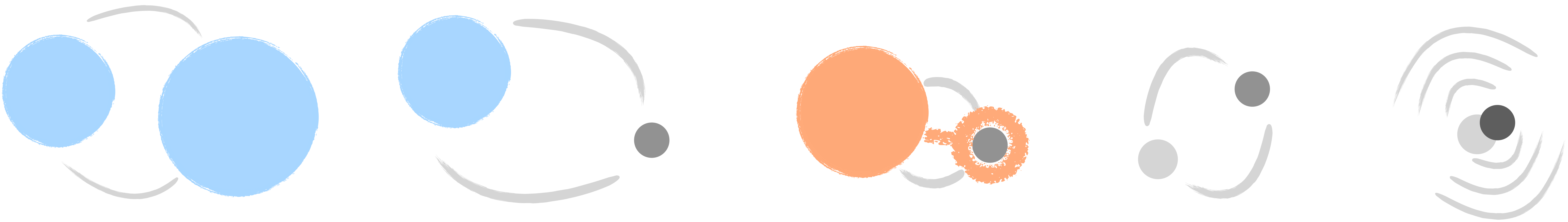
detached
binary star

detached
remnant + star

accreting
remnant + star

close
remnant + remnant

All close double stellar remnants pass through each evolutionary stage

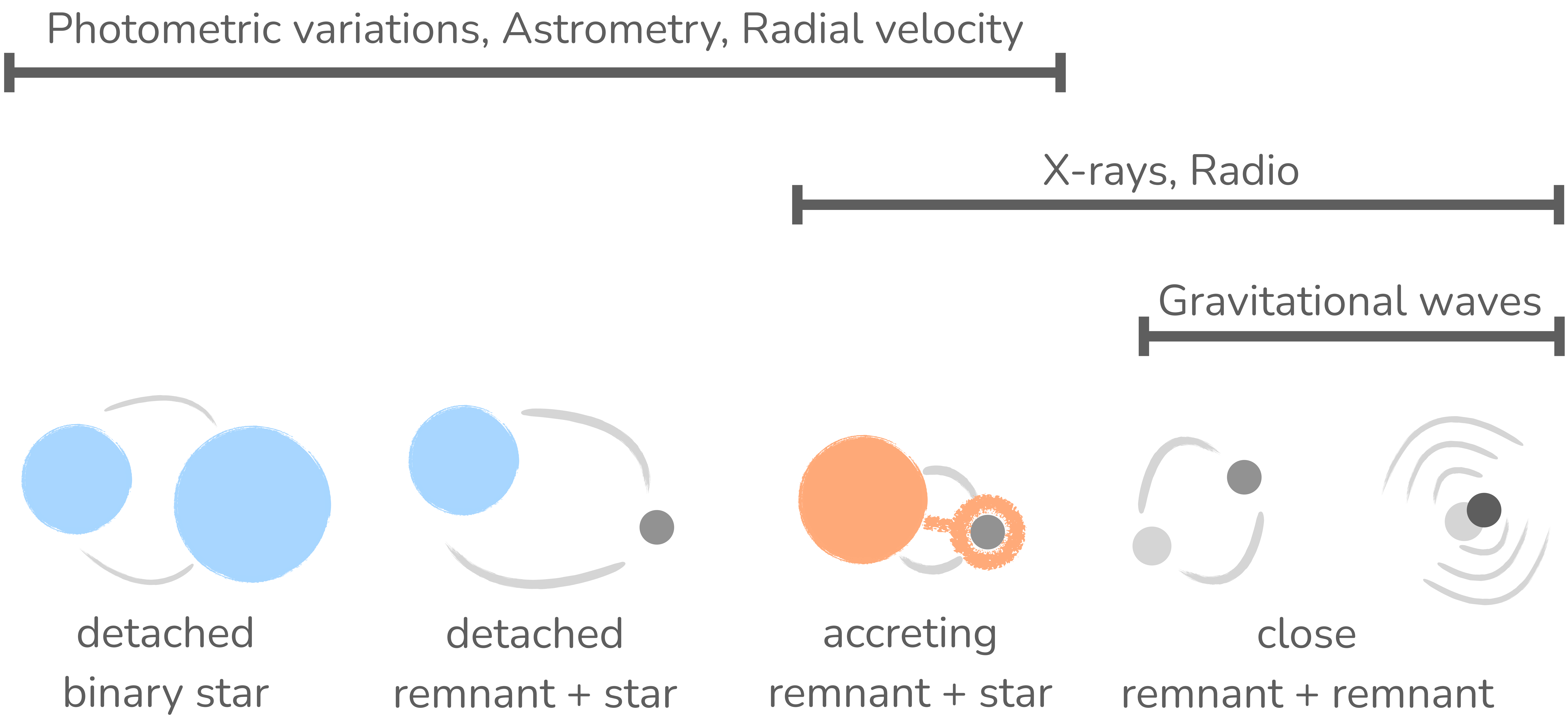


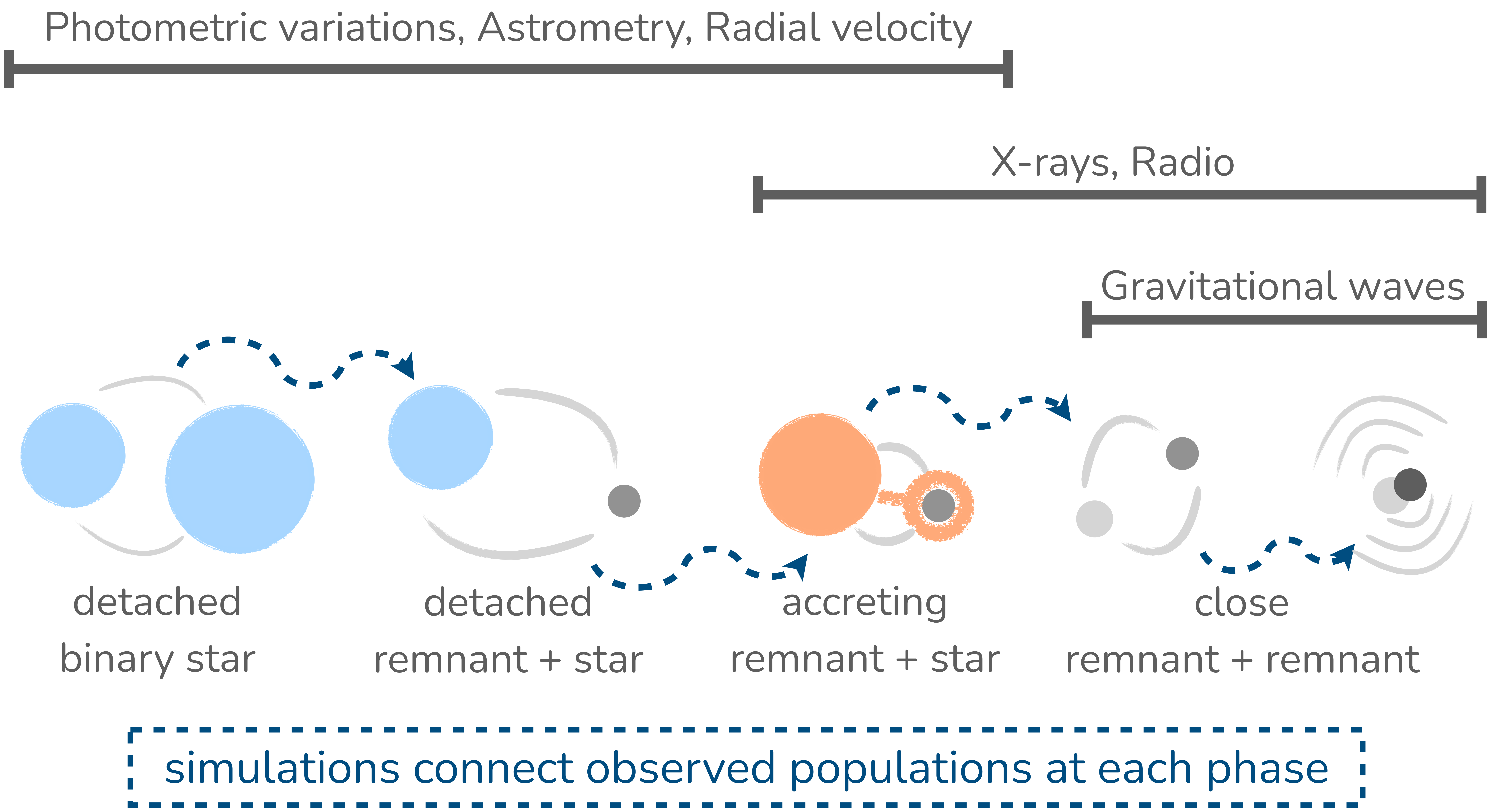
detached binary star

detached remnant + star

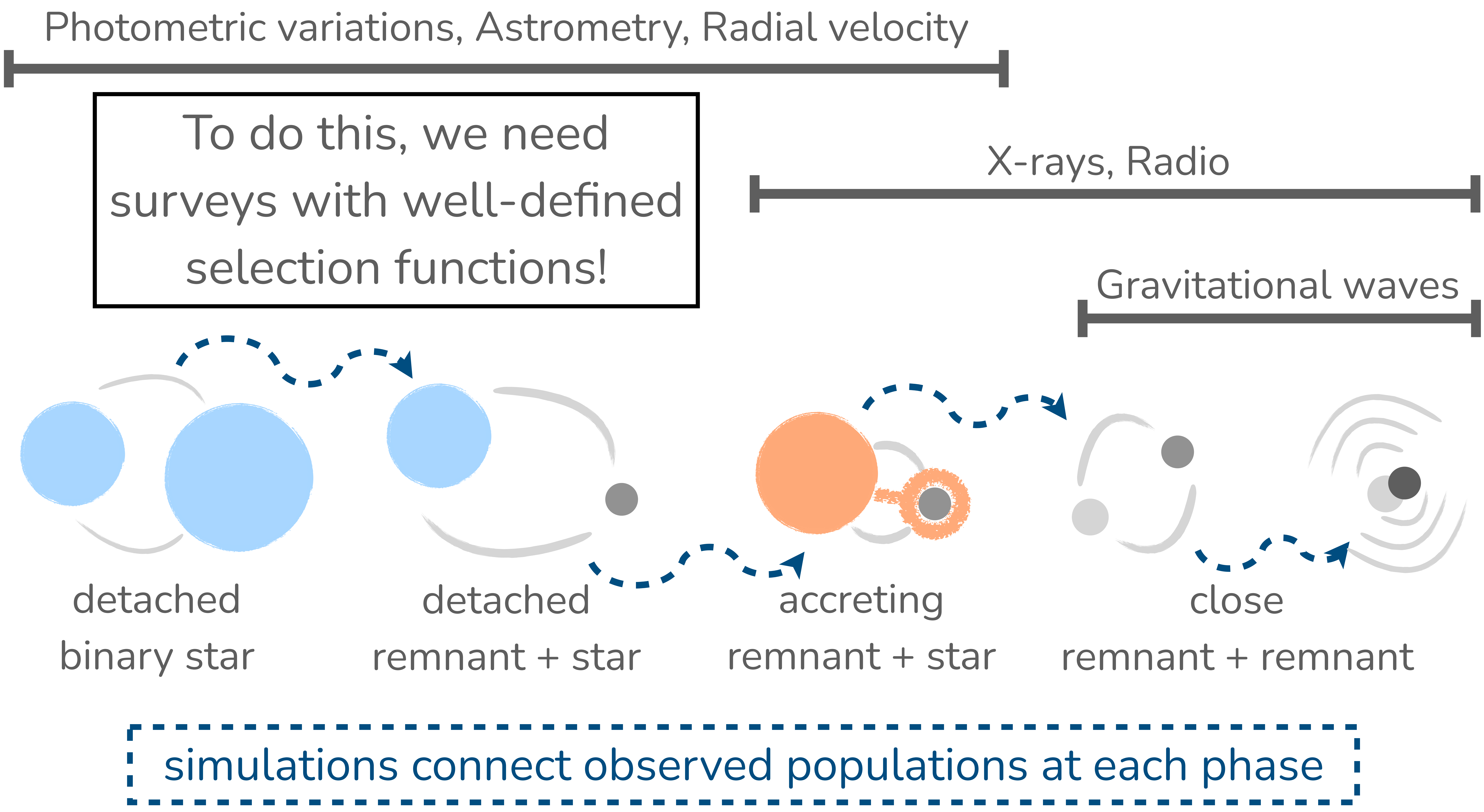
accreting remnant + star

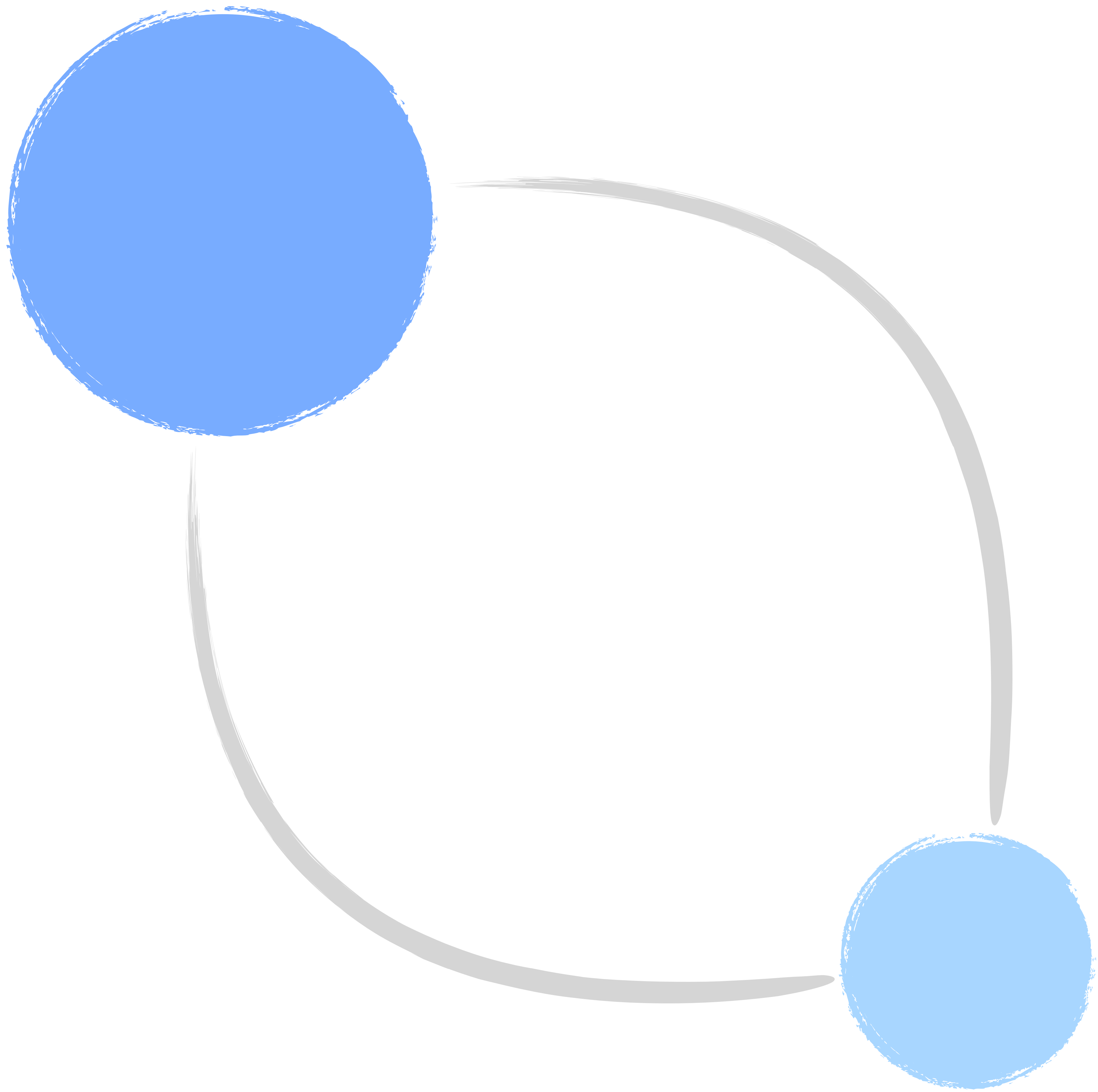
close remnant + remnant


Photometric variations, Astrometry, Radial velocity
X-rays, Radio
Gravitational waves
detached
binary star
detached
remnant + star
accreting
remnant + star
close
remnant + remnant



Photometric variations, Astrometry, Radial velocity
X-rays, Radio
Gravitational waves
detached
binary star
detached
remnant + star
accreting
remnant + star
close
remnant + remnant
simulations connect observed populations at each phase


Photometric variations, Astrometry, Radial velocity
To do this, we need surveys with well-defined selection functions!
X-rays, Radio
Gravitational waves
detached binary star
detached remnant + star
accreting remnant + star
close remnant + remnant
simulations connect observed populations at each phase



Close double stellar remnants are **excellent** mHz gravitational wave sources

$$h \simeq 5 \times 10^{-18} \left(\frac{\mathcal{M}}{\mathrm{M}_\odot} \right)^{5/3} \left(\frac{P_{\mathrm{orb}}}{1\,\mathrm{hr}} \right)^{-2/3} \left(\frac{d}{1\,\mathrm{kpc}} \right)^{-1}$$

~160 DWDs from ~10^5 WD candidates

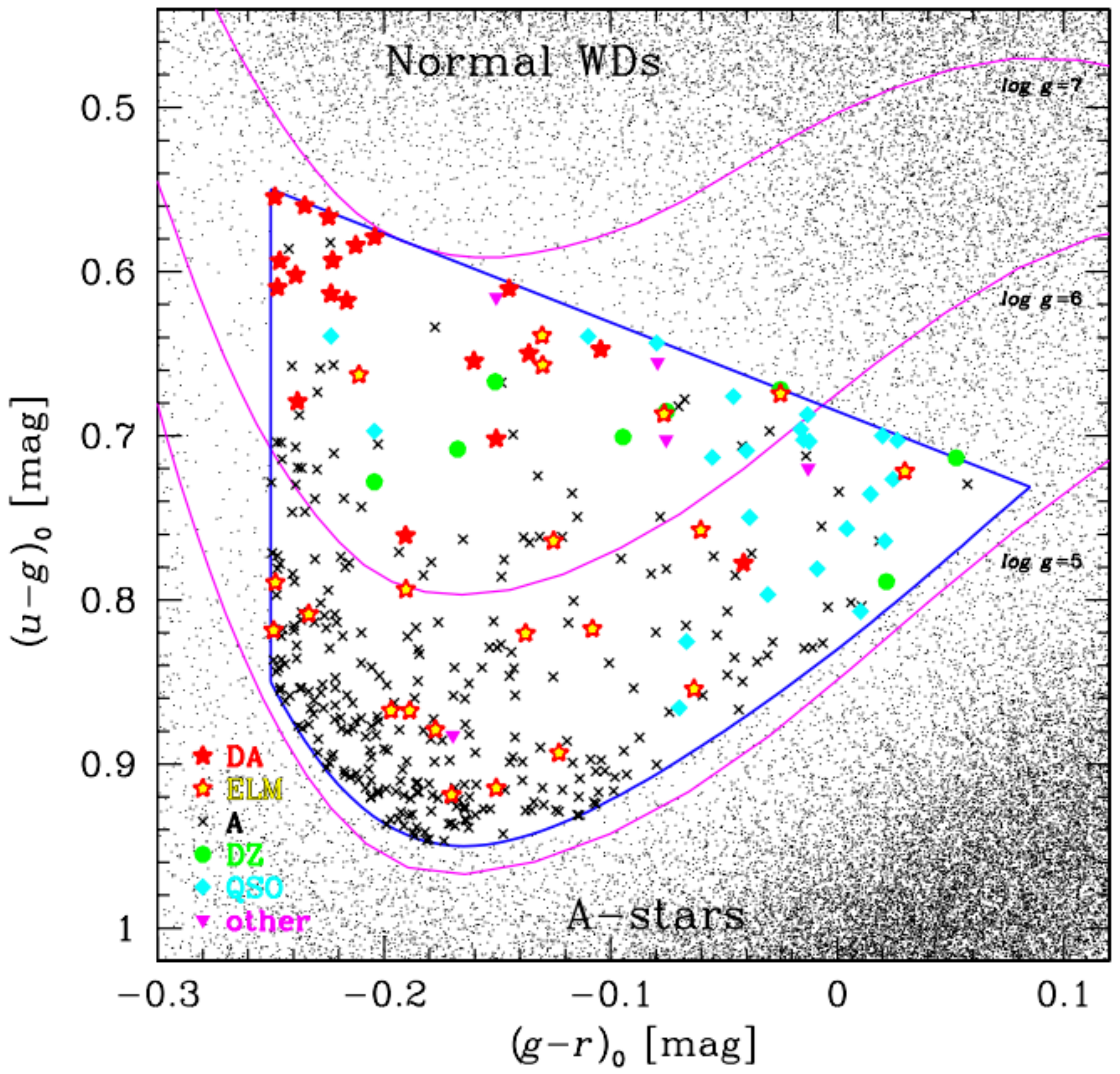
~160 DWDs from ~10^5 WD candidates

ELM survey

e.g. Brown+2020

98 DWDs w/ M<0.3 M$_\odot$
from color selection
and RV followup

Brown+2012



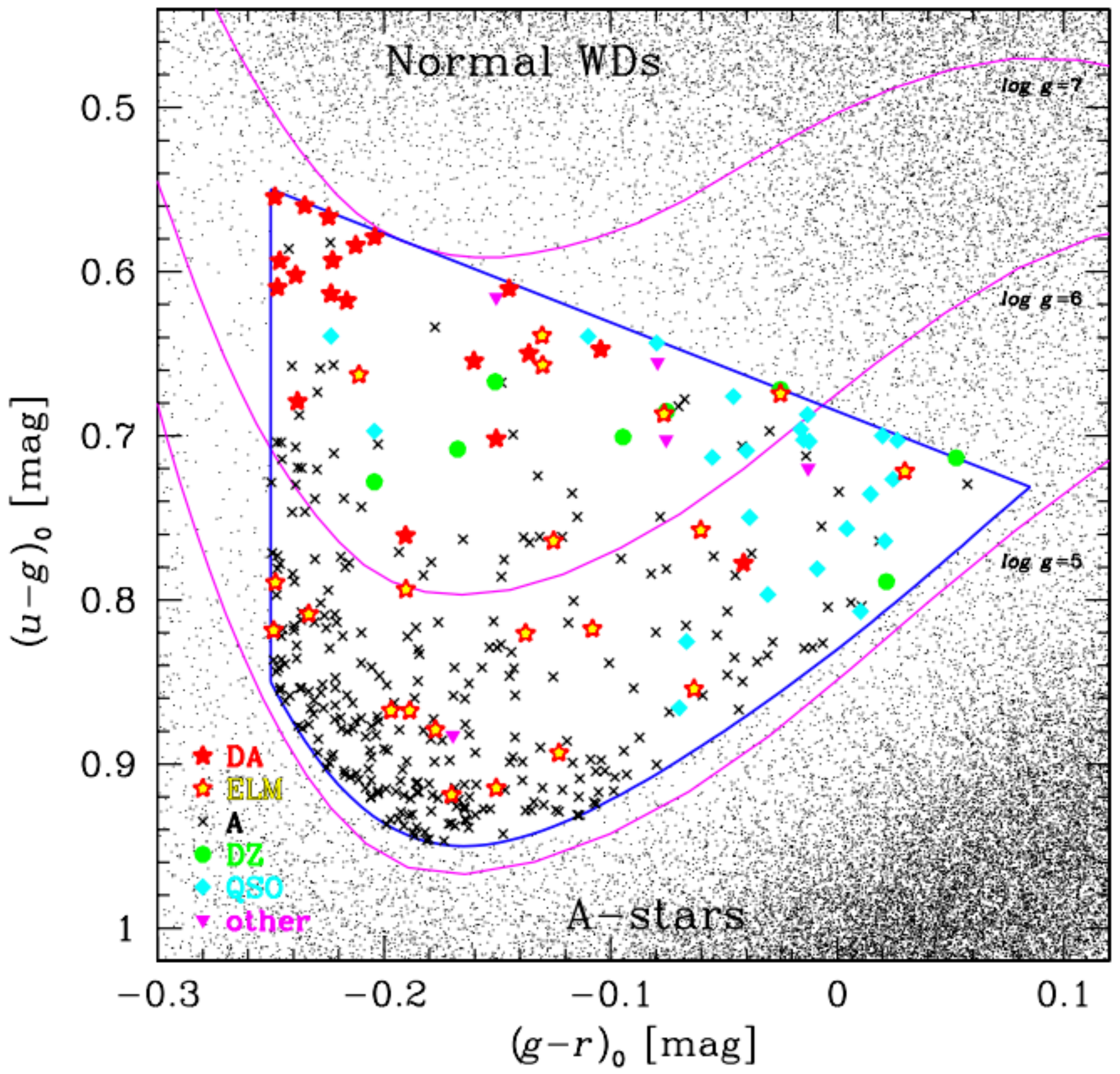
~160 DWDs from ~10^5 WD candidates

ELM survey

e.g. Brown+2020

98 DWDs w/ M<0.3 M$_\odot$
from color selection
and RV followup

Brown+2012

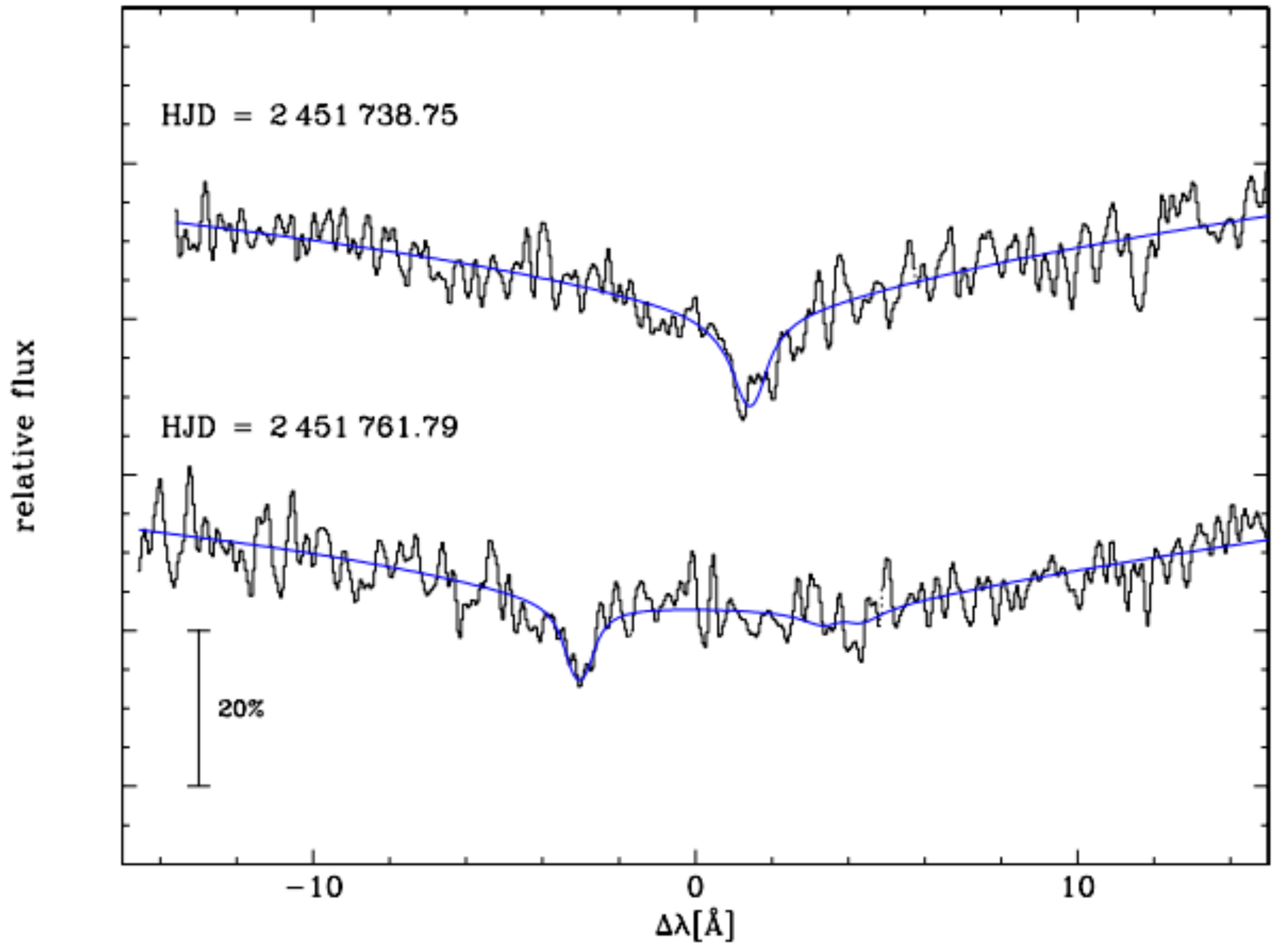


SWARMS & SPY

e.g. Badenes+2008,2012,
Napiwotzky+2020

SWARMS: 15 DWD candidates
SPY: 39 DWDs
from RV variations

Napiwotzky+2020



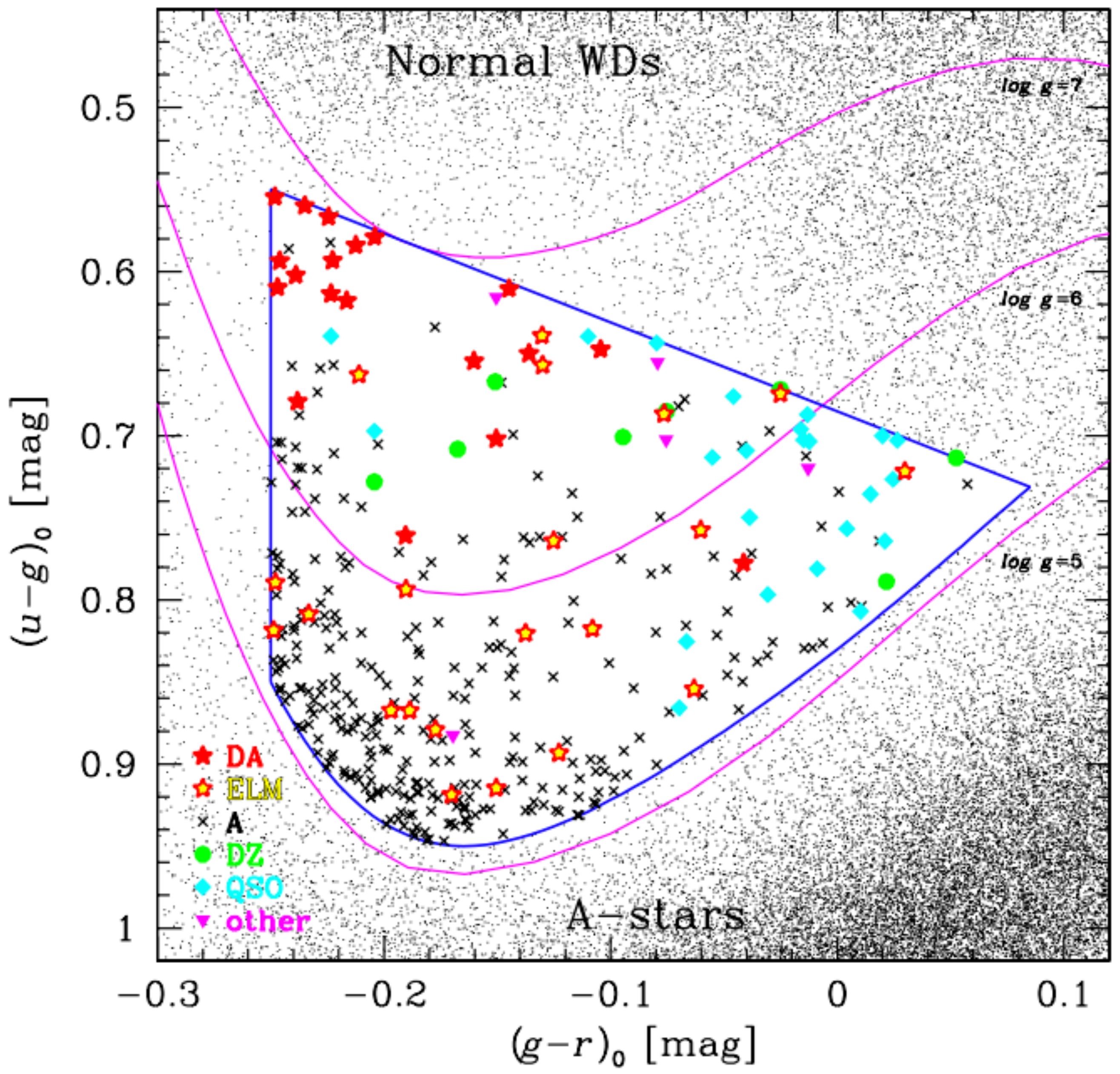
~160 DWDs from ~10^5 WD candidates

ELM survey

e.g. Brown+2020

98 DWDs w/ M<0.3 $M_\odot$
from color selection
and RV followup

Brown+2012

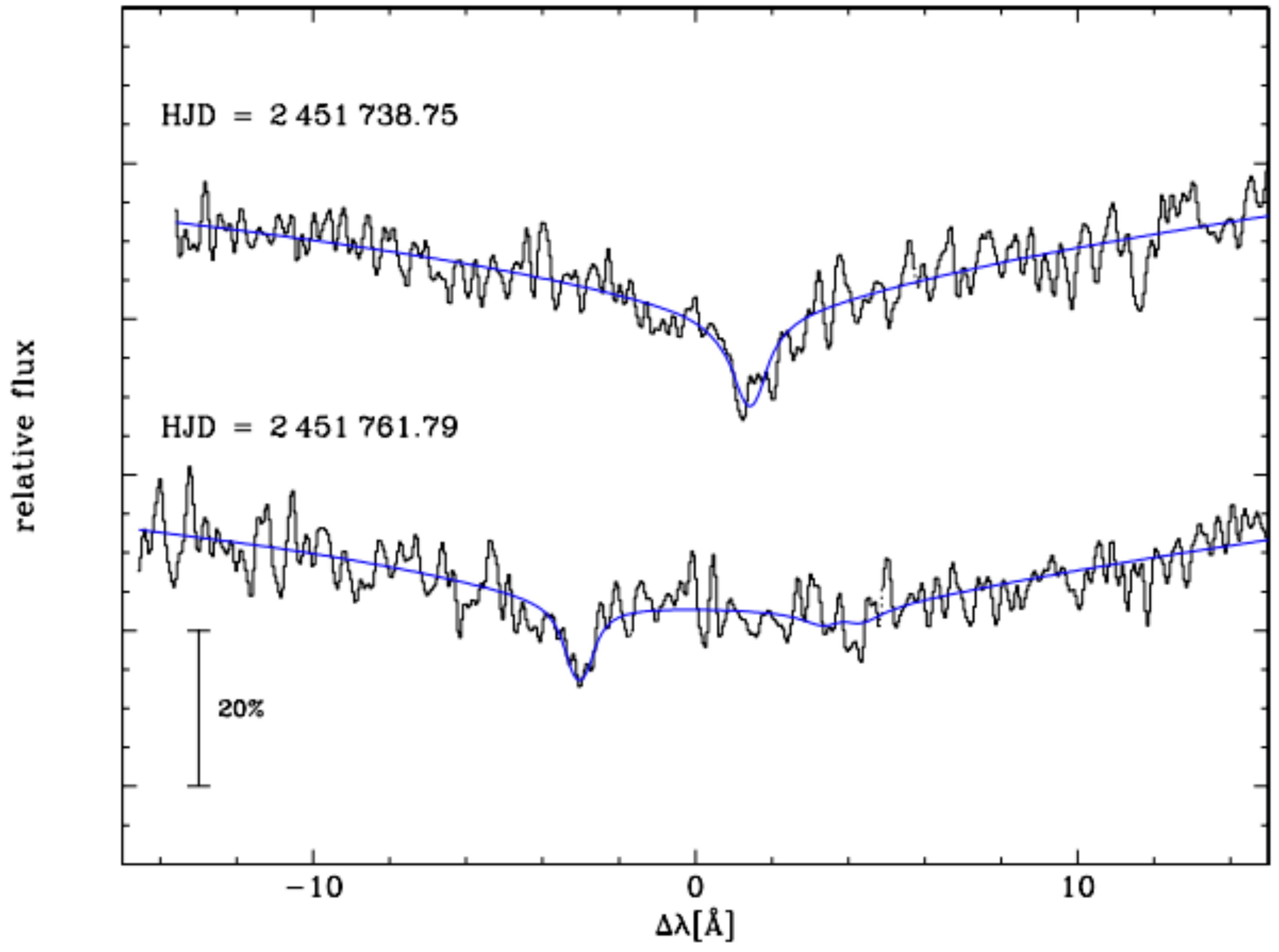


SWARMS & SPY

e.g. Badenes+2008,2012,
Napiwotzky+2020

SWARMS: 15 DWD candidates
SPY: 39 DWDs
from RV variations

Napiwotzky+2020

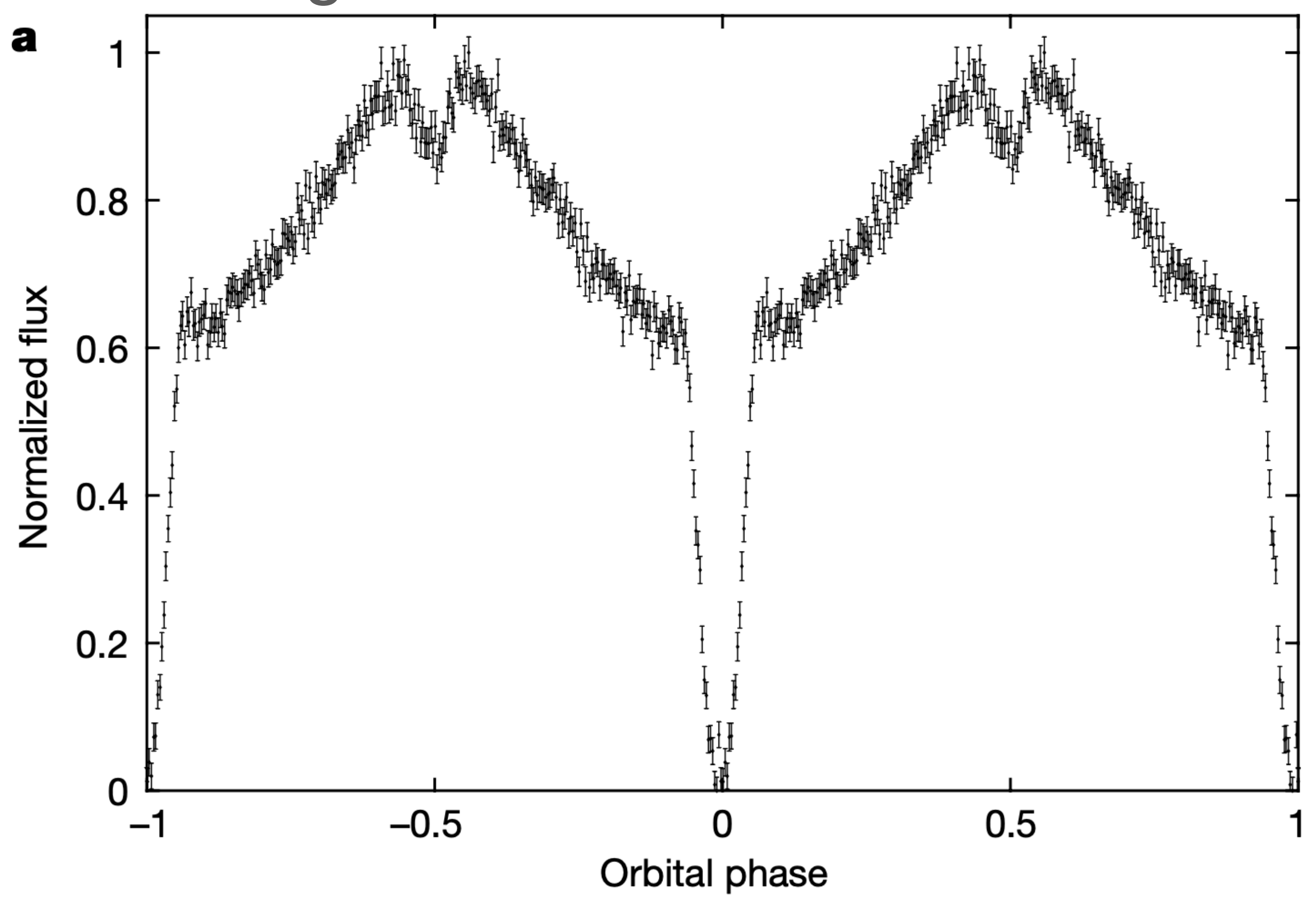


ZTF

e.g. Burdge+2020

15 short period DWDs
from photometric eclipses

Burdge+2019



~160 DWDs from ~10^5 WD candidates

ELM survey

e.g. Brown+2020

98 DW

from

anc

Brown-

SWARMS & SPY

e.g. Badenes+2008,2012,

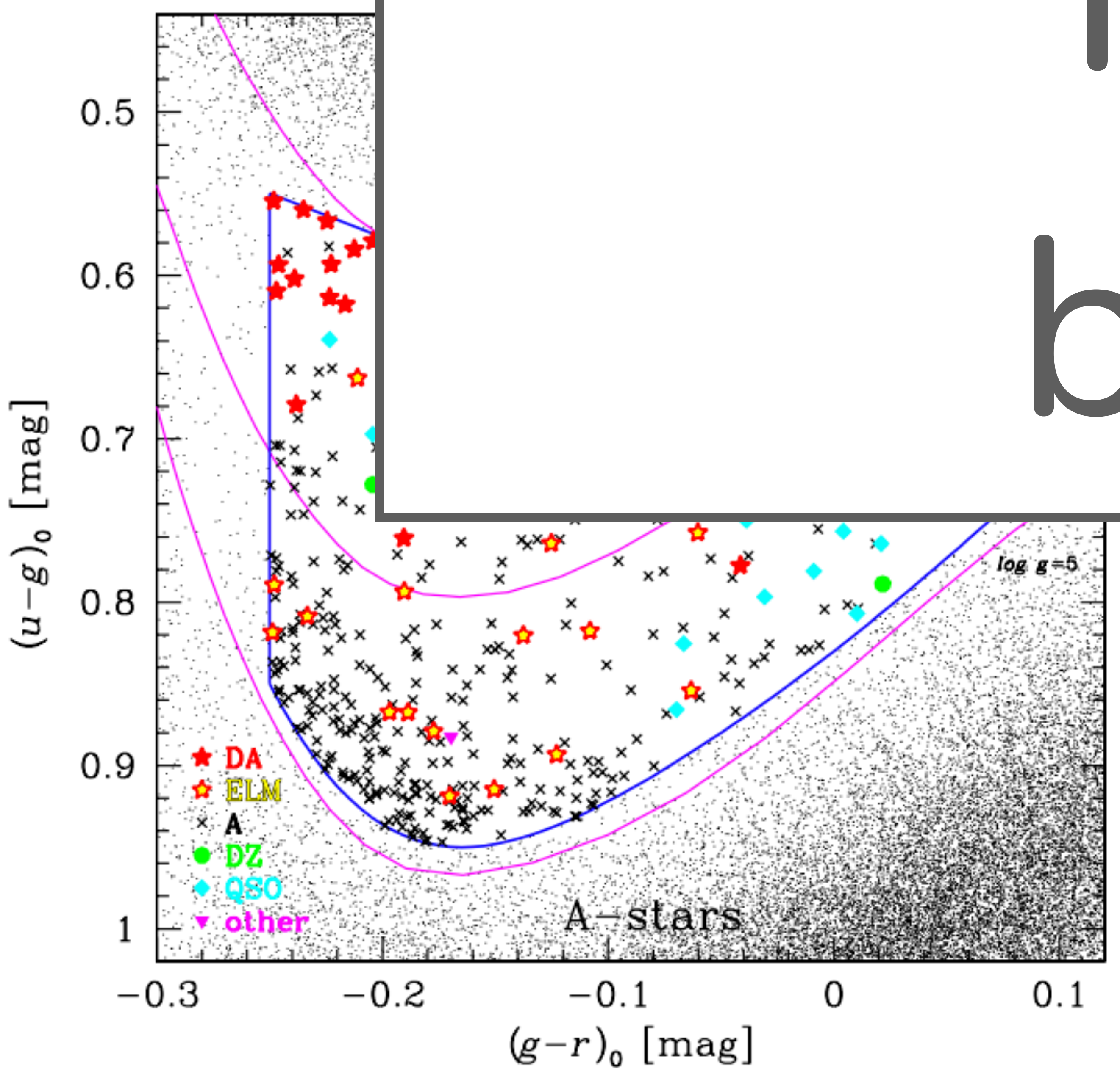
ZTF

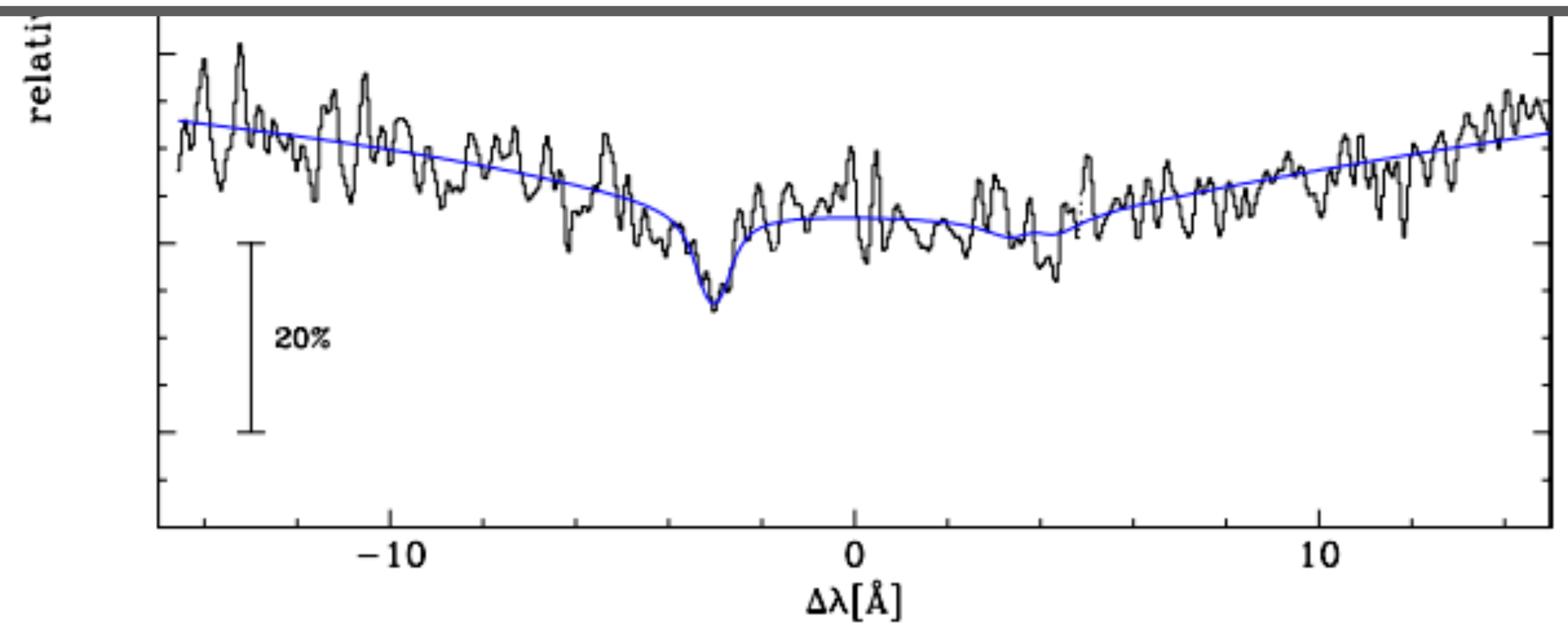
e.g. Burdge+2020

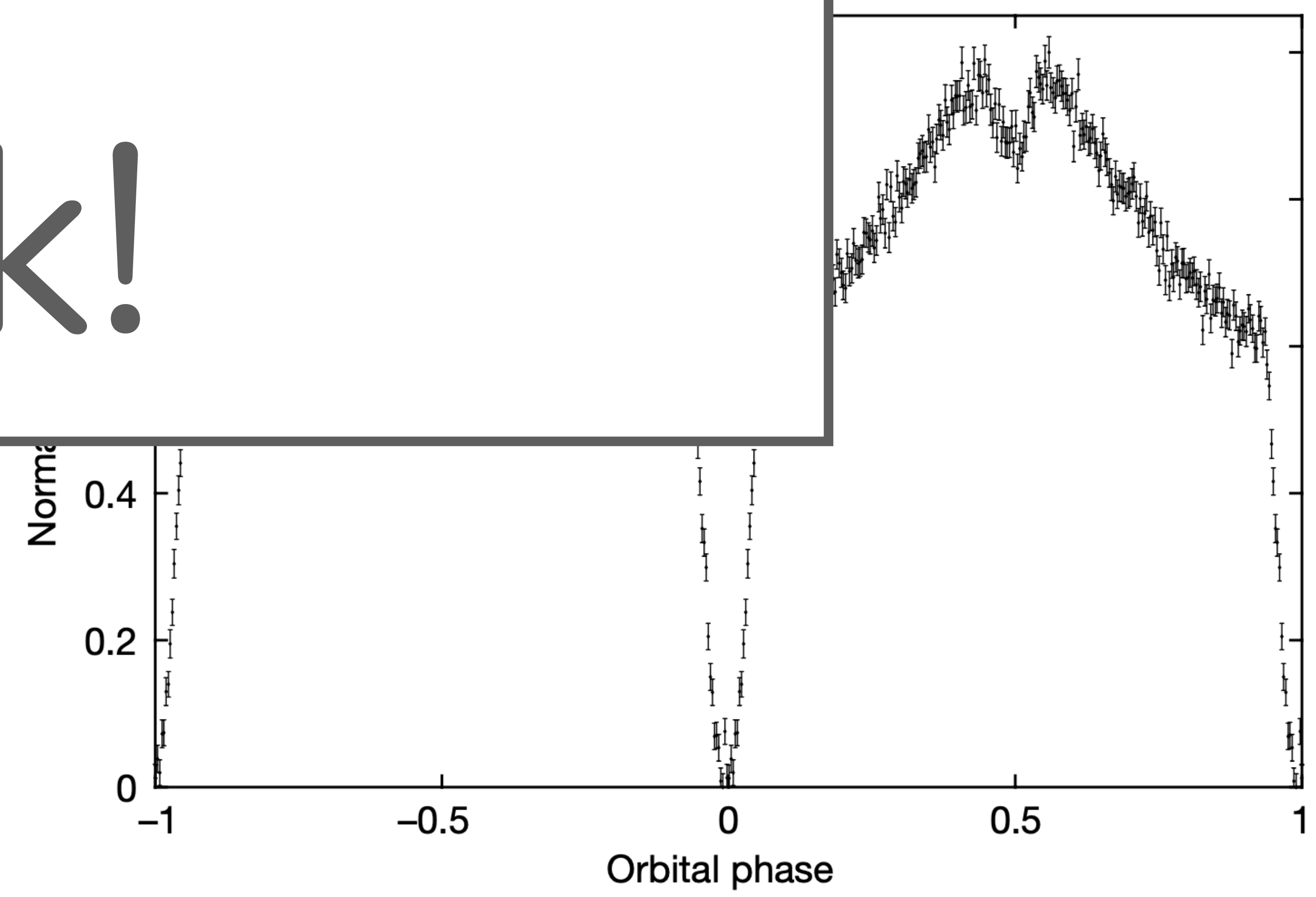
DWDs

eclipses

Photometric surveys are finding DWDs — but it's hard work!





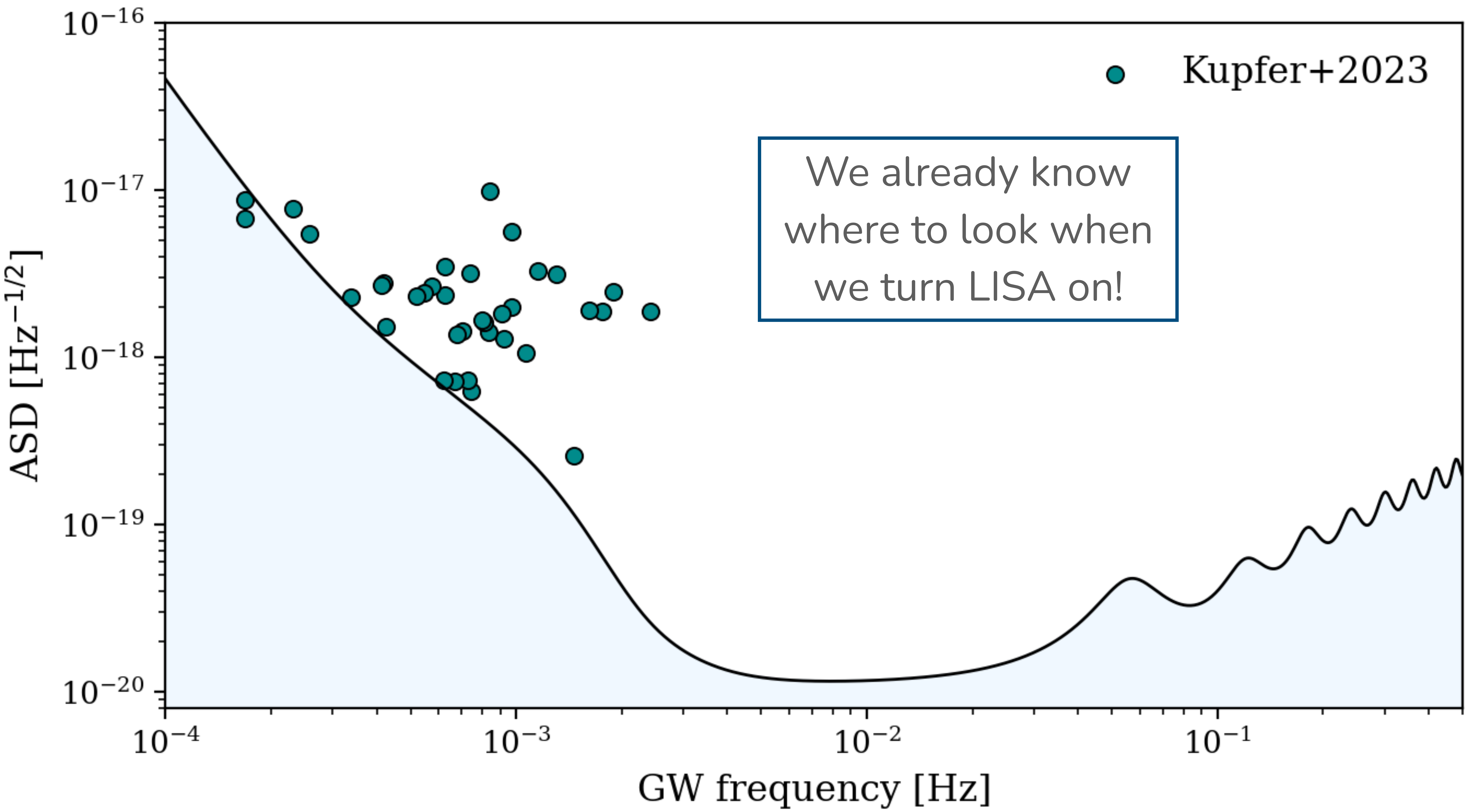


LEGWORK

Tom Wagg
Flatiron

pip install legwork

For all your stellar-origin binary LISA SNR calculation needs!



Kupfer+2023
We already know where to look when we turn LISA on!
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
ASD [$\mathrm{Hz}^{-1/2}$]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
GW frequency [Hz]

White dwarfs are the end state for 99% of all stars

e.g. Kroupa 2001

10s of millions of double white dwarfs are predicted to exist in the Milky Way

e.g. Nelemans+01, Ruiter+10, Nissanke+12, Korol+17,19,20, Lamberts+19, KB+20a,b, Thiele,KB+23

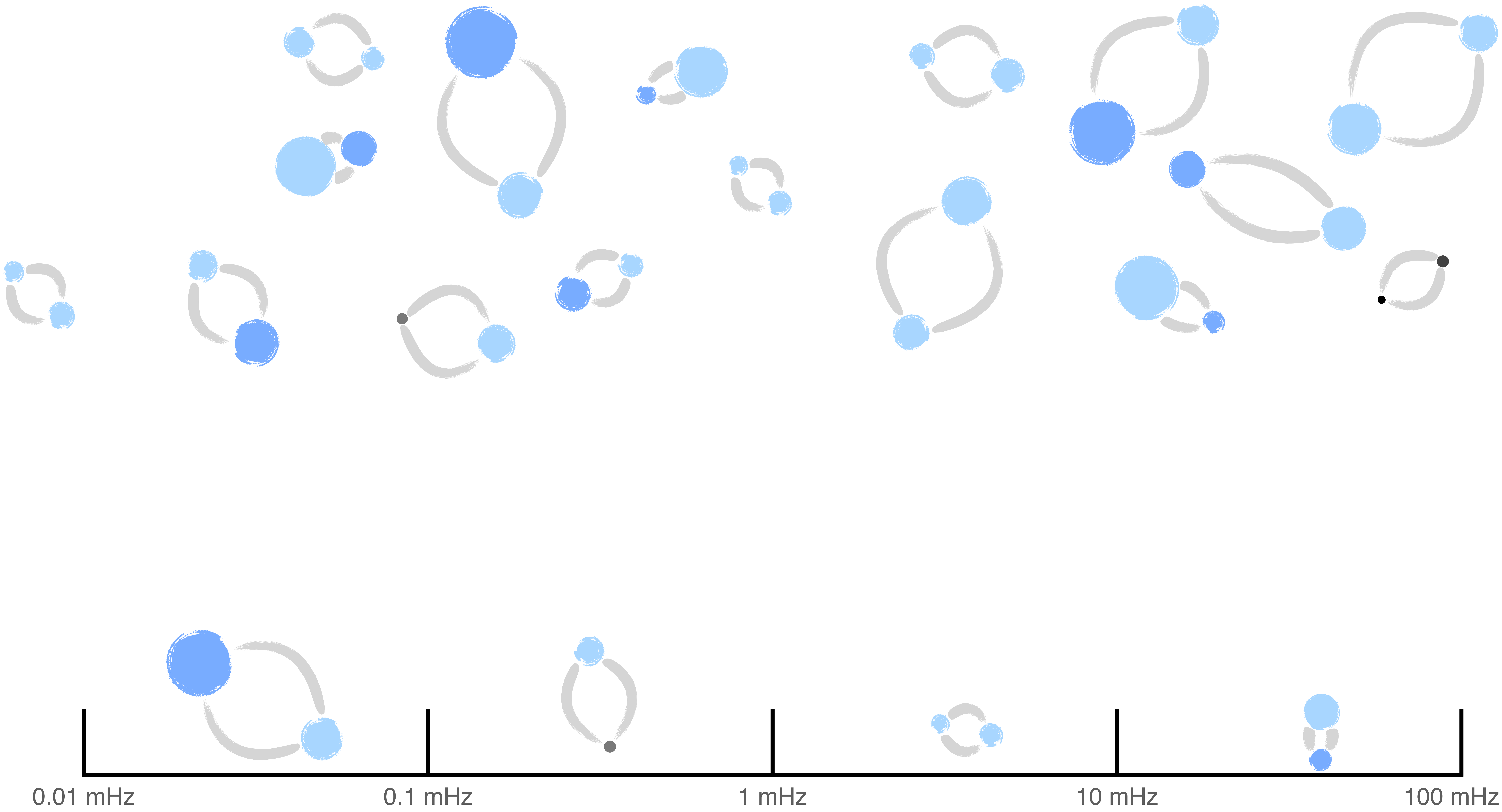
The rest of the stellar remnants are NSs/BHs

e.g. Kroupa 2001

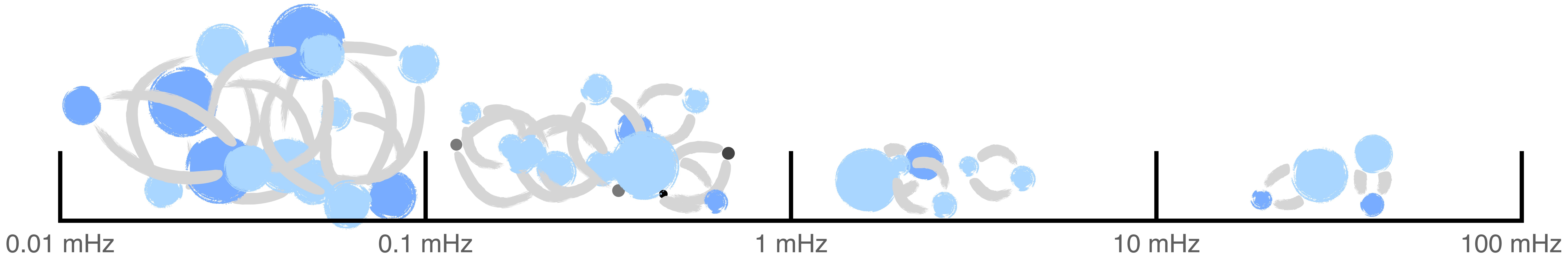
10s-100s of double compact objects are predicted to exist in the Milky Way

e.g. Nelemans+01, Belczynski+10, Liu+14,
Lamberts+18, Sesana+20, KB+20a, Shao+21, Lau+20, Andrews+20, Wagg+22

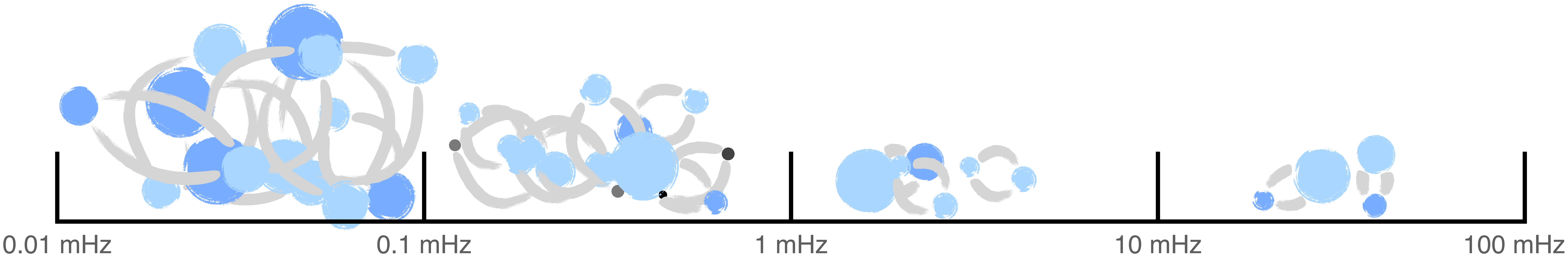

0.01 mHz
0.1 mHz
1 mHz
10 mHz
100 mHz



0.01 mHz
0.1 mHz
1 mHz
10 mHz
100 mHz

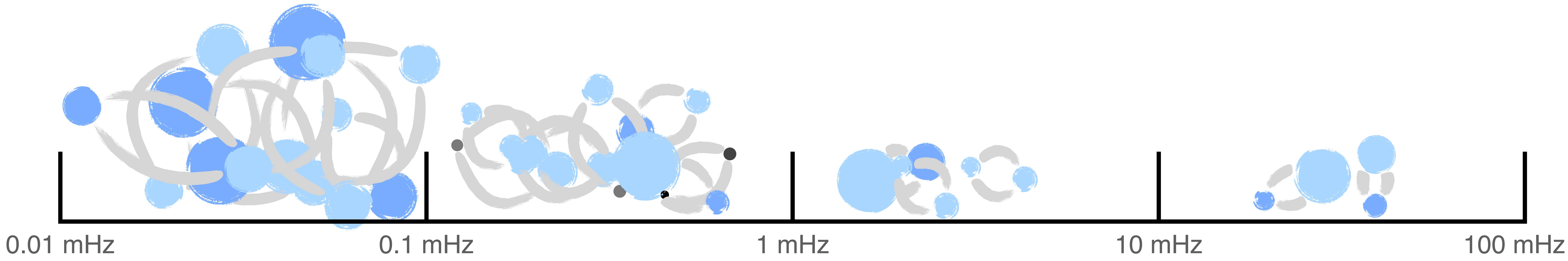

0.01 mHz
0.1 mHz
1 mHz
10 mHz
100 mHz

$$\dot{f}_{\mathrm{GW}} \propto f_{\mathrm{GW}}^{11/3} \mathscr{M}_c^{5/3}$$

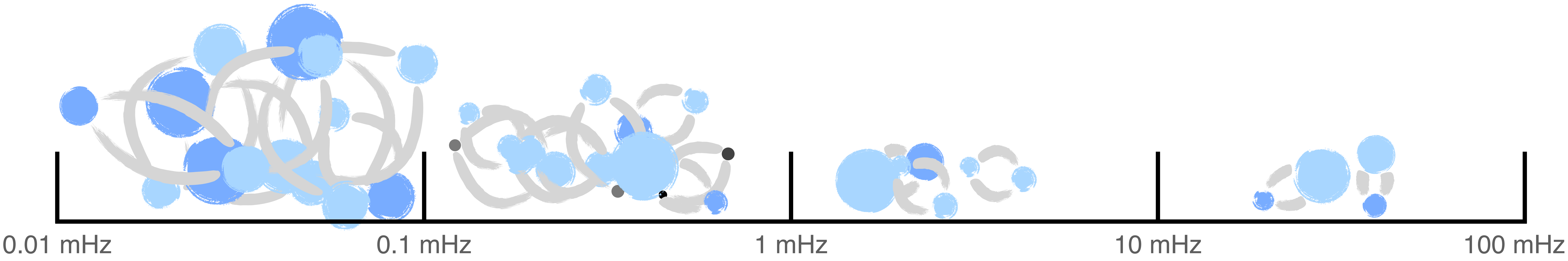


$$\dot{f}_{\mathrm{GW}} \propto f_{\mathrm{GW}}^{11/3} \mathcal{M}_c^{5/3}$$

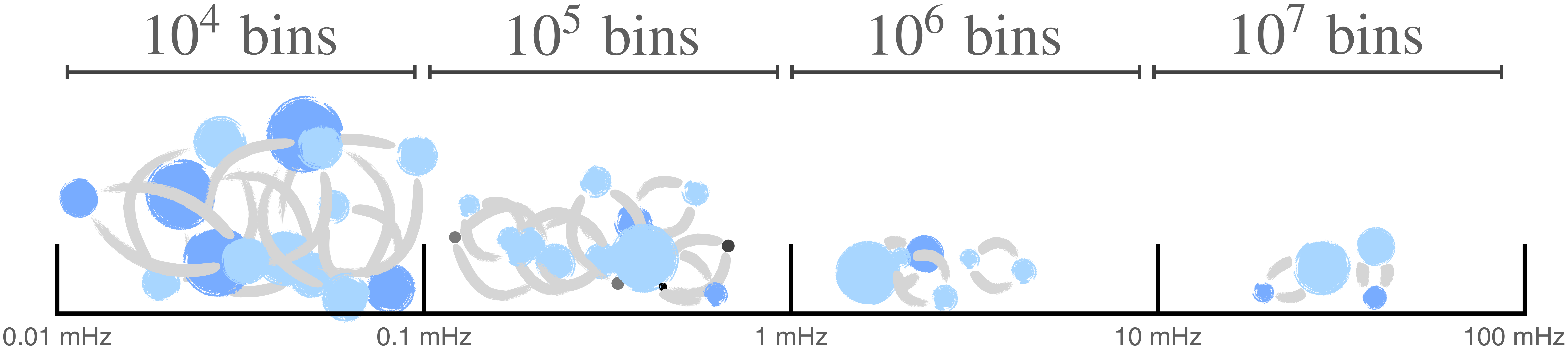
Binaries at 0.05 mHz evolve **~2 million** times slower than binaries at 5 mHz!

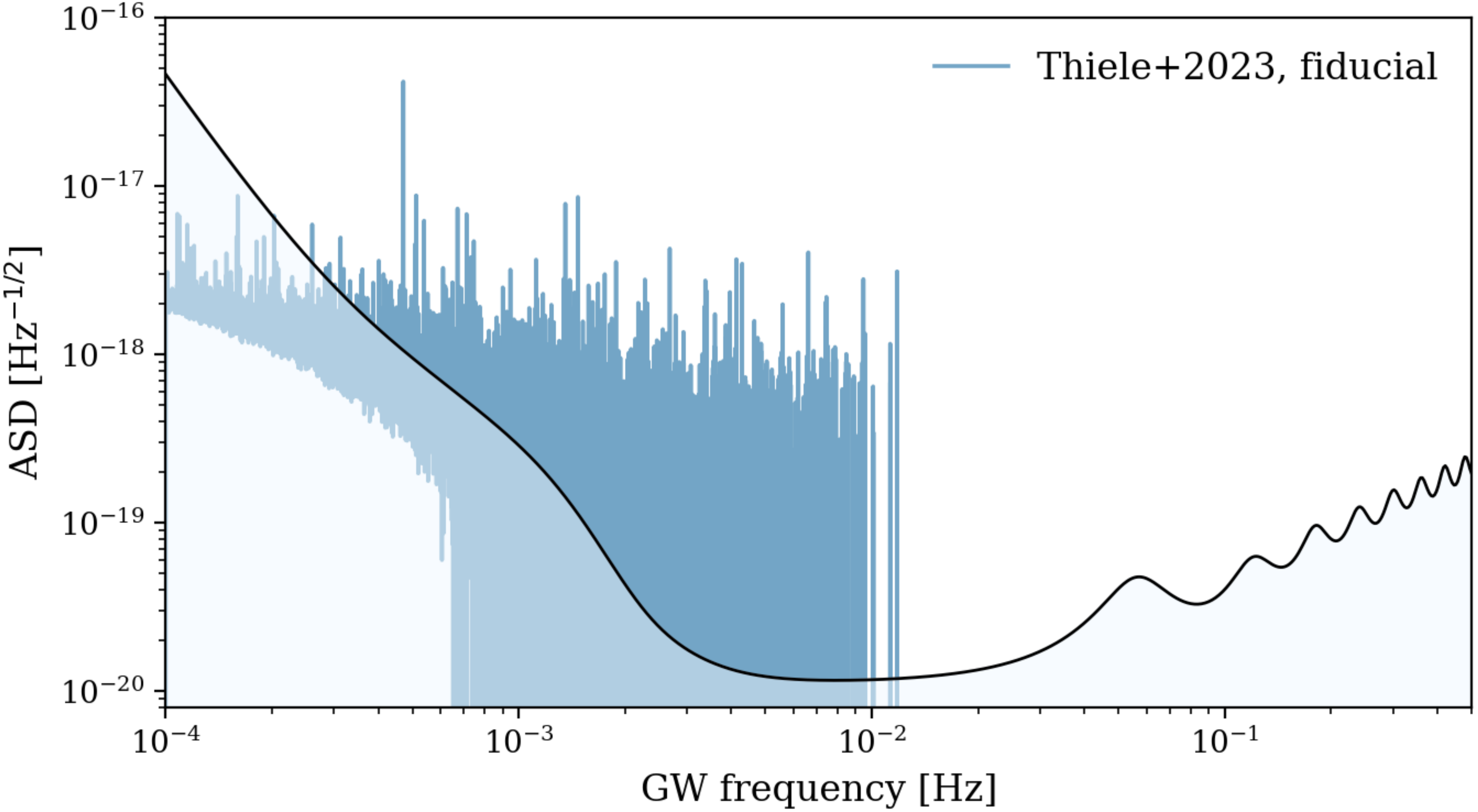


$$\Delta f_{\mathrm{LISA}} = 1/T_{\mathrm{obs}} \simeq 10^{-8}\,\mathrm{Hz}$$

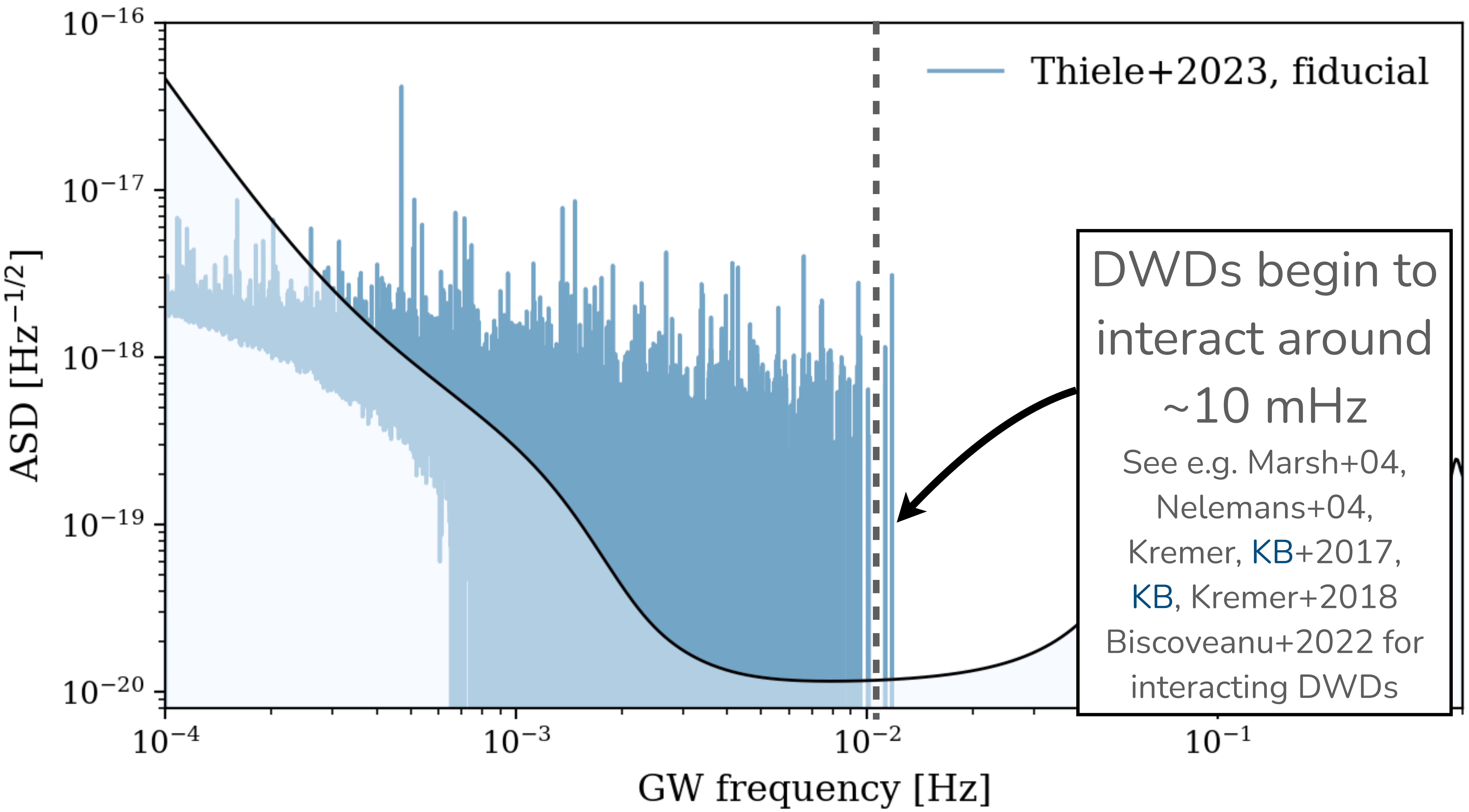


$$\Delta f_{\mathrm{LISA}} = 1/T_{\mathrm{obs}} \simeq 10^{-8}\,\mathrm{Hz}$$

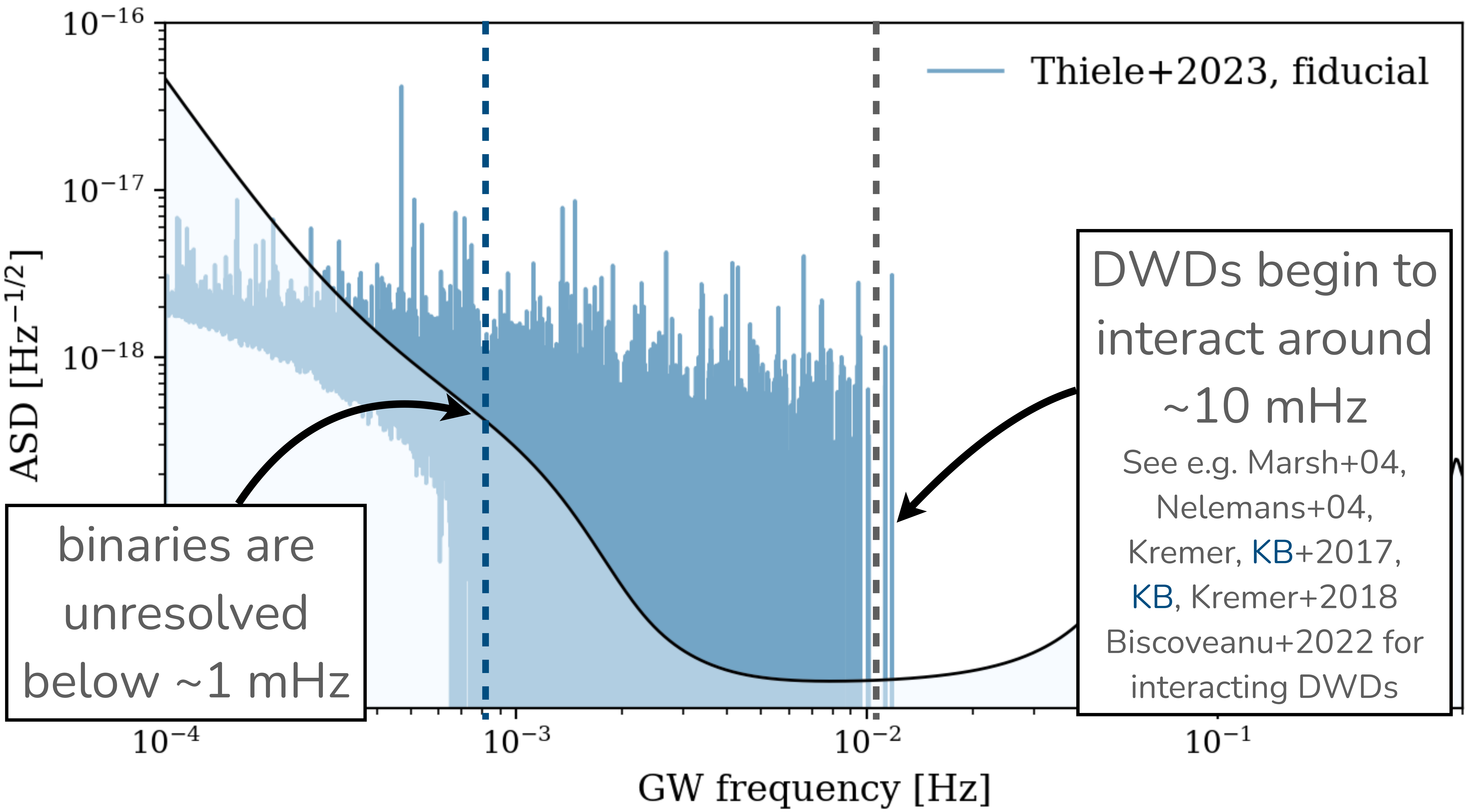




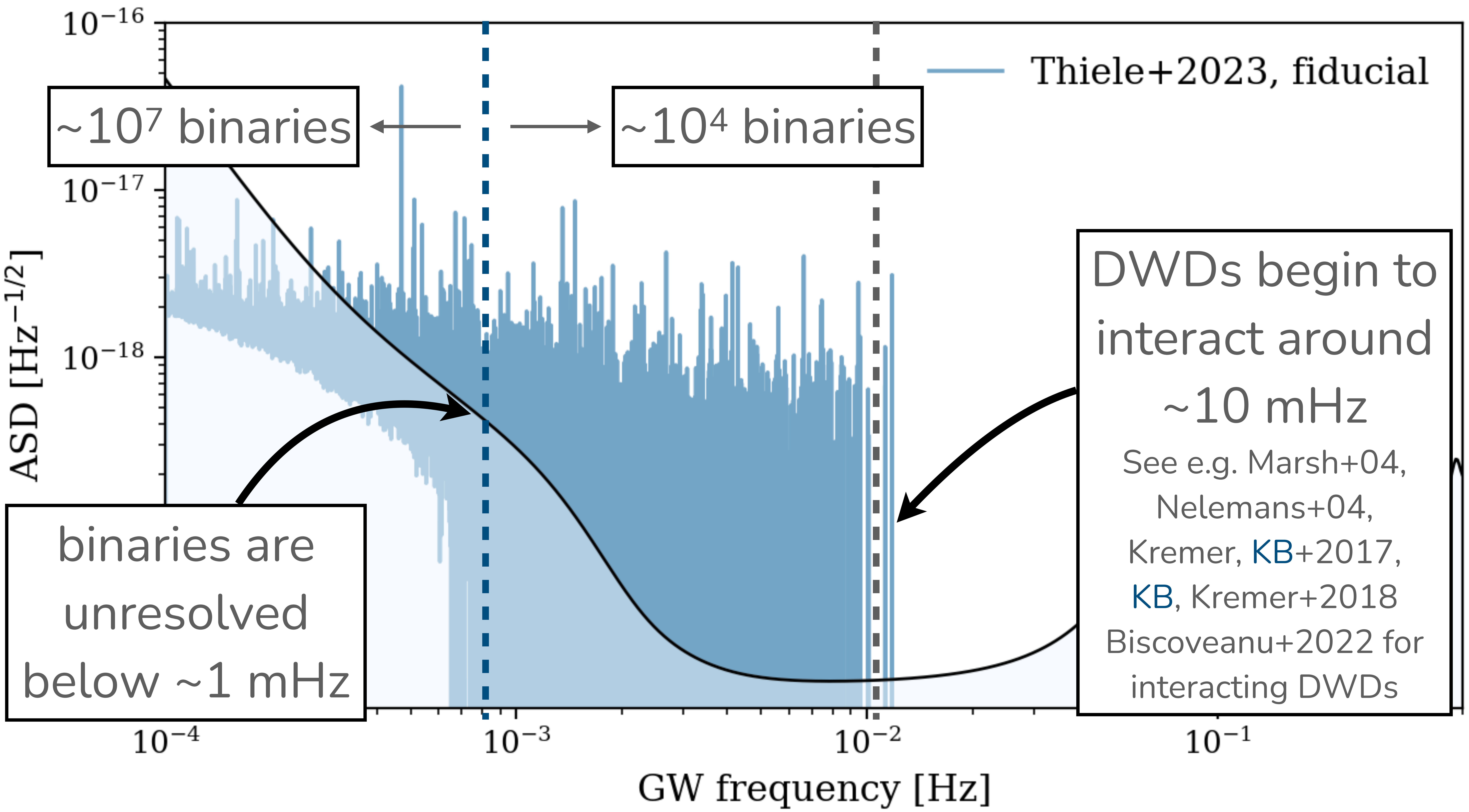
Thiele+2023, fiducial
ASD [Hz$^{-1/2}$]
GW frequency [Hz]
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-4}
10^{-3}
10^{-2}
10^{-1}



Thiele+2023, fiducial
DWDs begin to interact around ~10 mHz
See e.g. Marsh+04, Nelemans+04, Kremer, KB+2017, KB, Kremer+2018 Biscoveanu+2022 for interacting DWDs
ASD [Hz$^{-1/2}$]
GW frequency [Hz]
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-4}
10^{-3}
10^{-2}
10^{-1}



Thiele+2023, fiducial
ASD [Hz$^{-1/2}$]
GW frequency [Hz]
10^{-16}
10^{-17}
10^{-18}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
binaries are unresolved below ~1 mHz
DWDs begin to interact around ~10 mHz
See e.g. Marsh+04, Nelemans+04, Kremer, KB+2017, KB, Kremer+2018 Biscoveanu+2022 for interacting DWDs



Thiele+2023, fiducial
~10⁷ binaries
~10⁴ binaries
DWDs begin to interact around ~10 mHz
See e.g. Marsh+04, Nelemans+04, Kremer, KB+2017, KB, Kremer+2018 Biscoveanu+2022 for interacting DWDs
binaries are unresolved below ~1 mHz
ASD [Hz^{-1/2}]
GW frequency [Hz]