Binary evolution and X-ray binaries:
Theory and simulations

Image: NASA/CXC/M.Weiss

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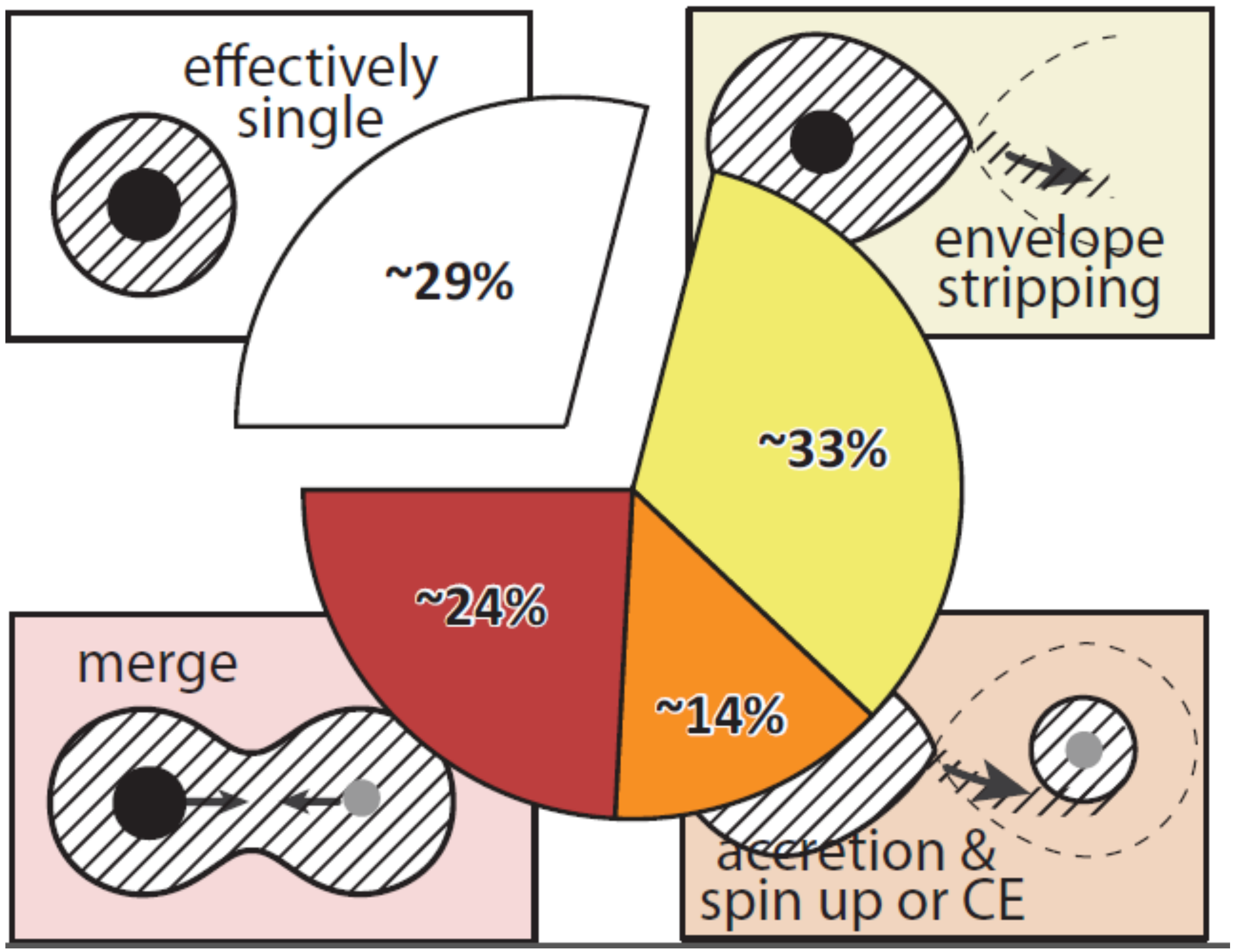
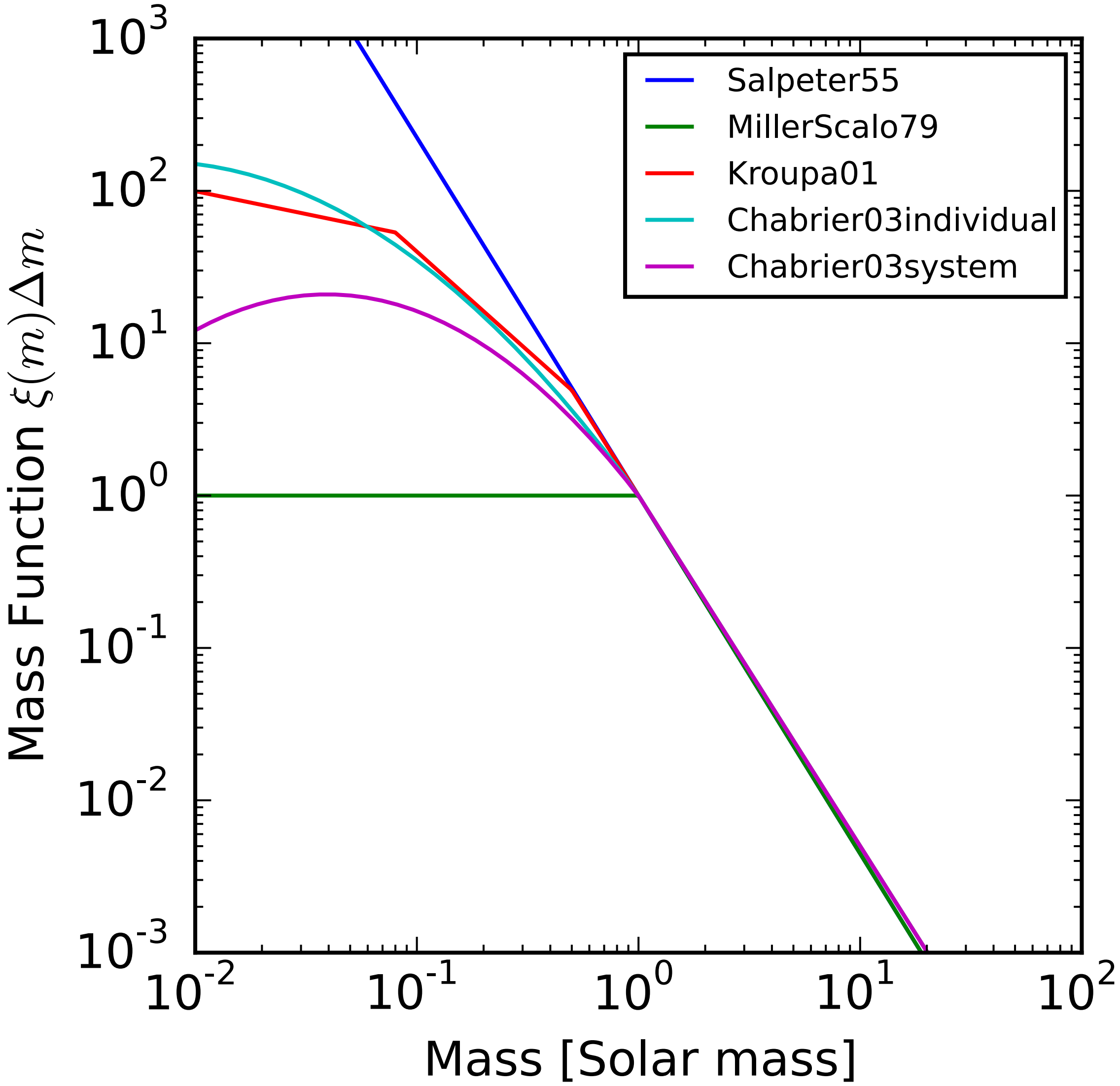
Why care about binary stars?

~70% massive stars expected to be in binaries



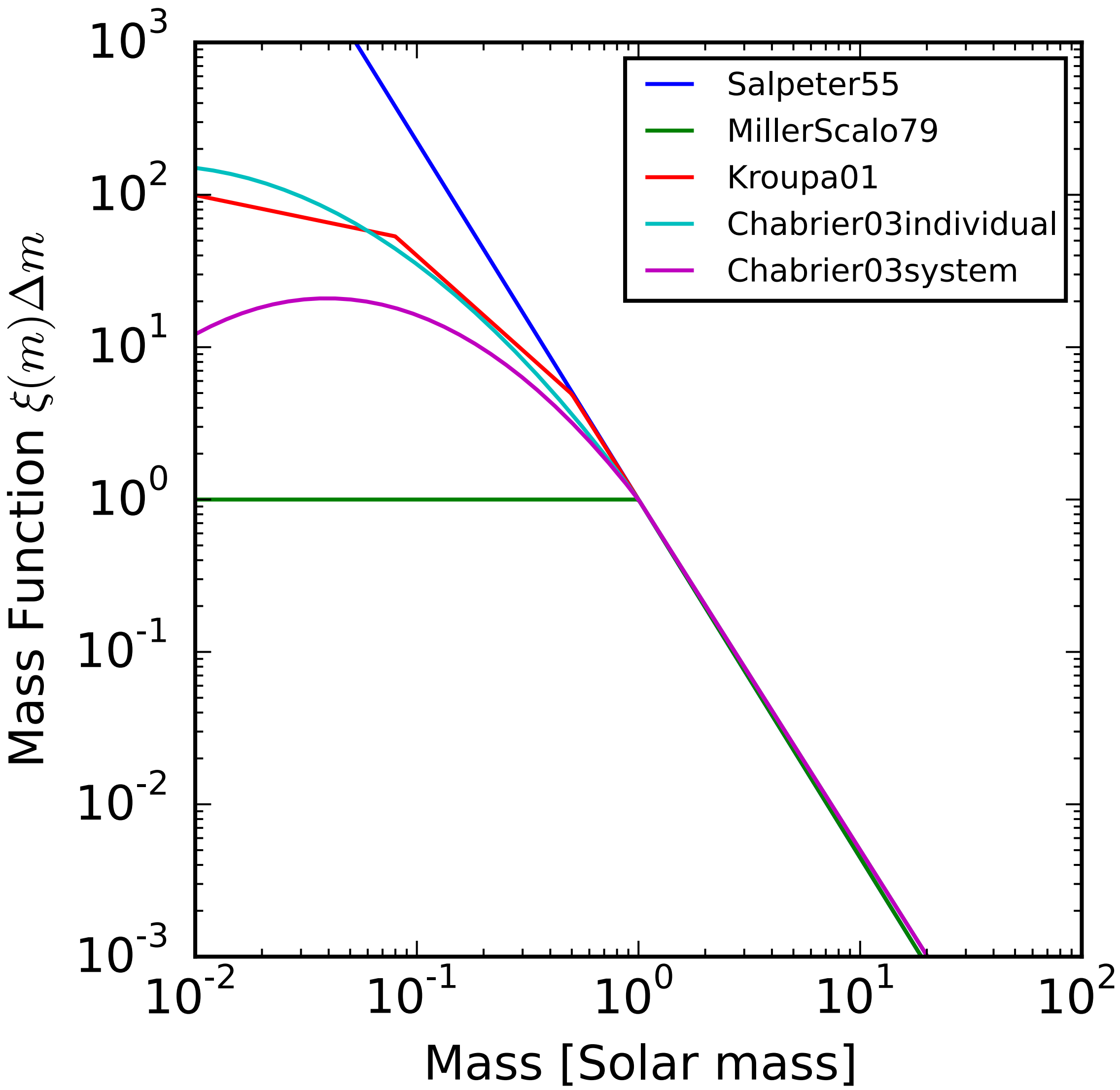
Adapted from Sana et al. (2012),
Courtesy S.E de Mink

Why care about binary stars?

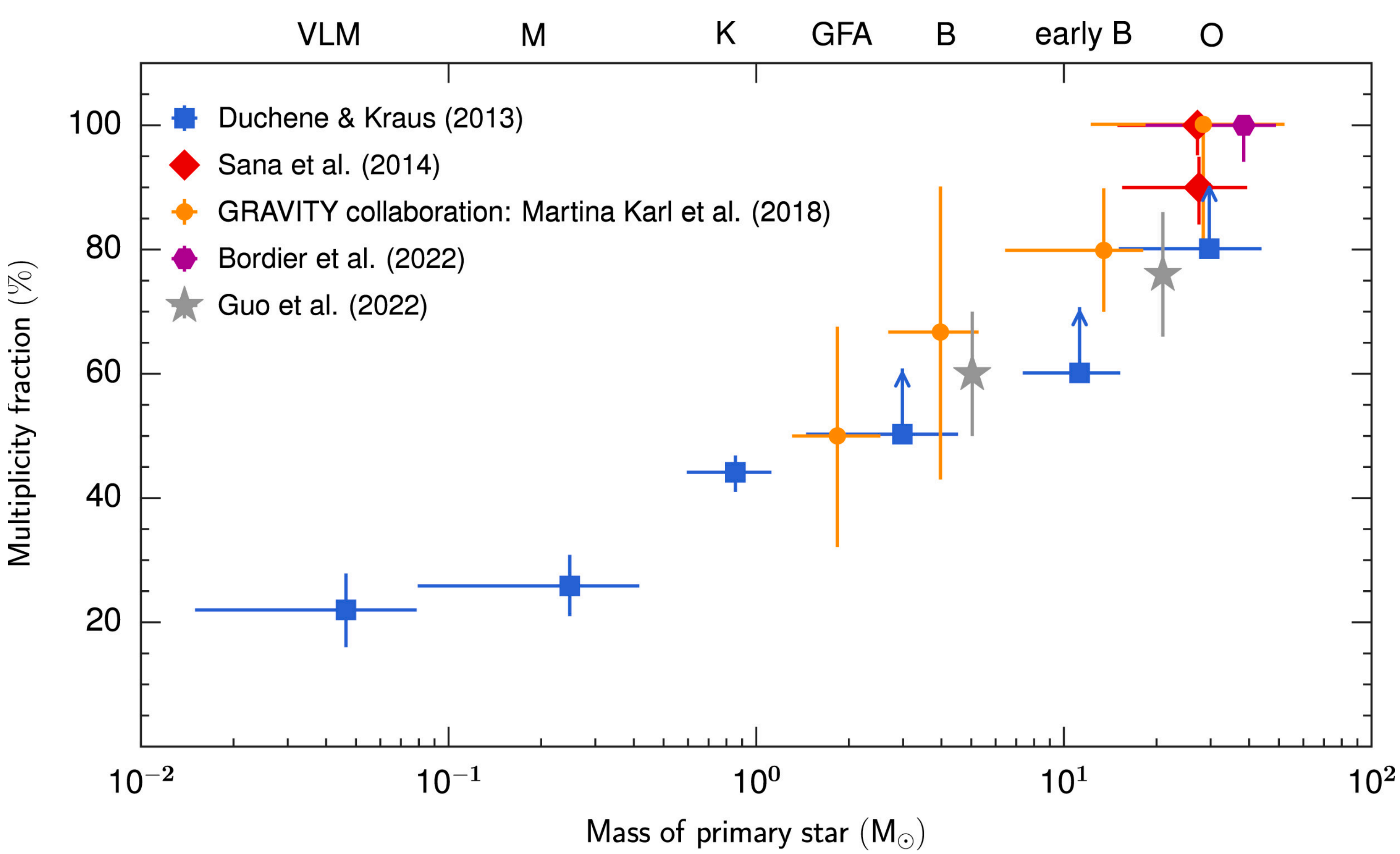


- Describes the probability of a star that has a certain mass during its formation
- More low mass stars than high mass stars

Why care about binary stars?



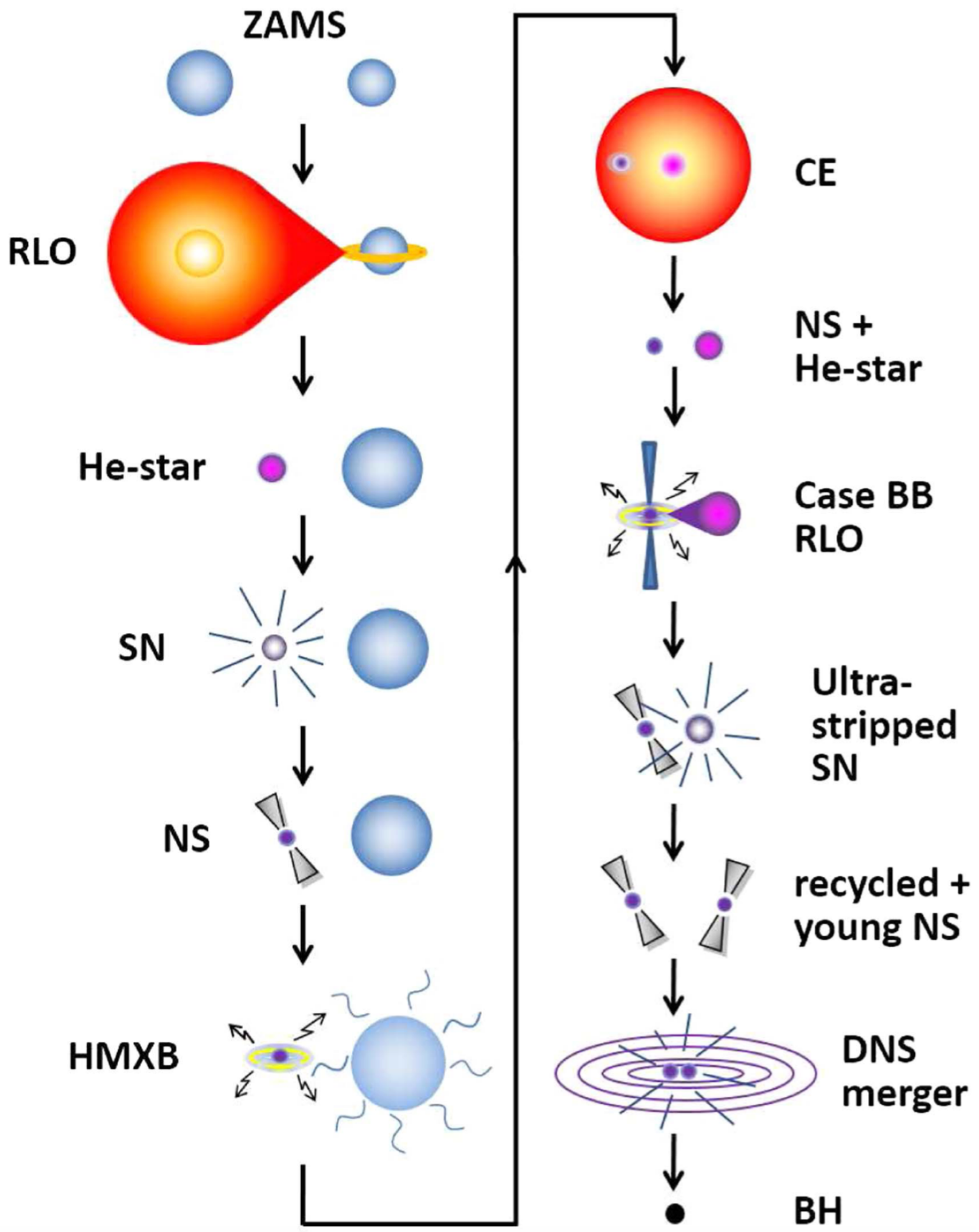
Binary fraction decreases with stellar mass



- Describes the probability of a star that has a certain mass during its formation
- More low mass stars than high mass stars

50 to 70% stars expected to be in binaries

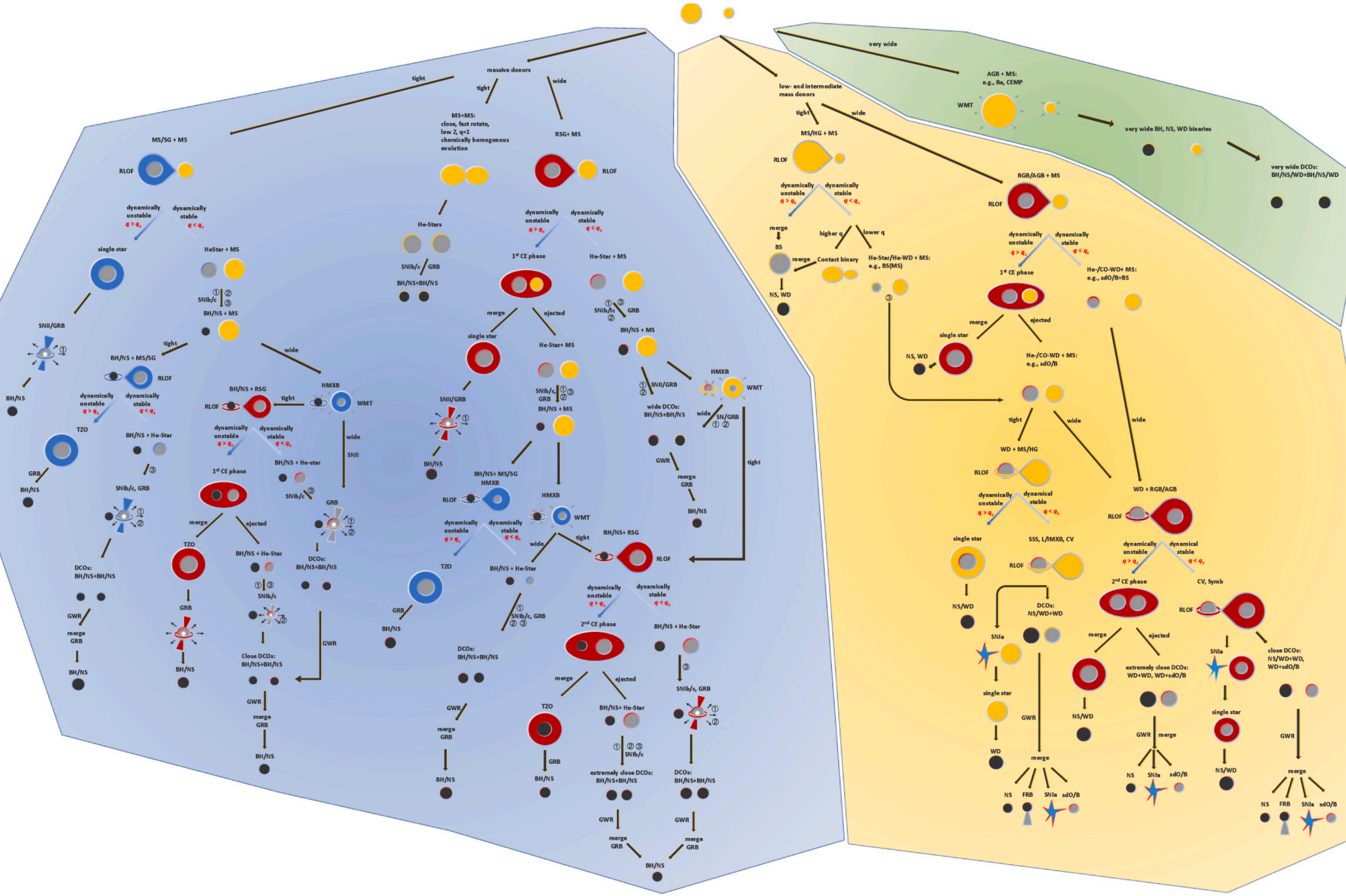
Why care about binary stars?



Tauris et al. (2017)

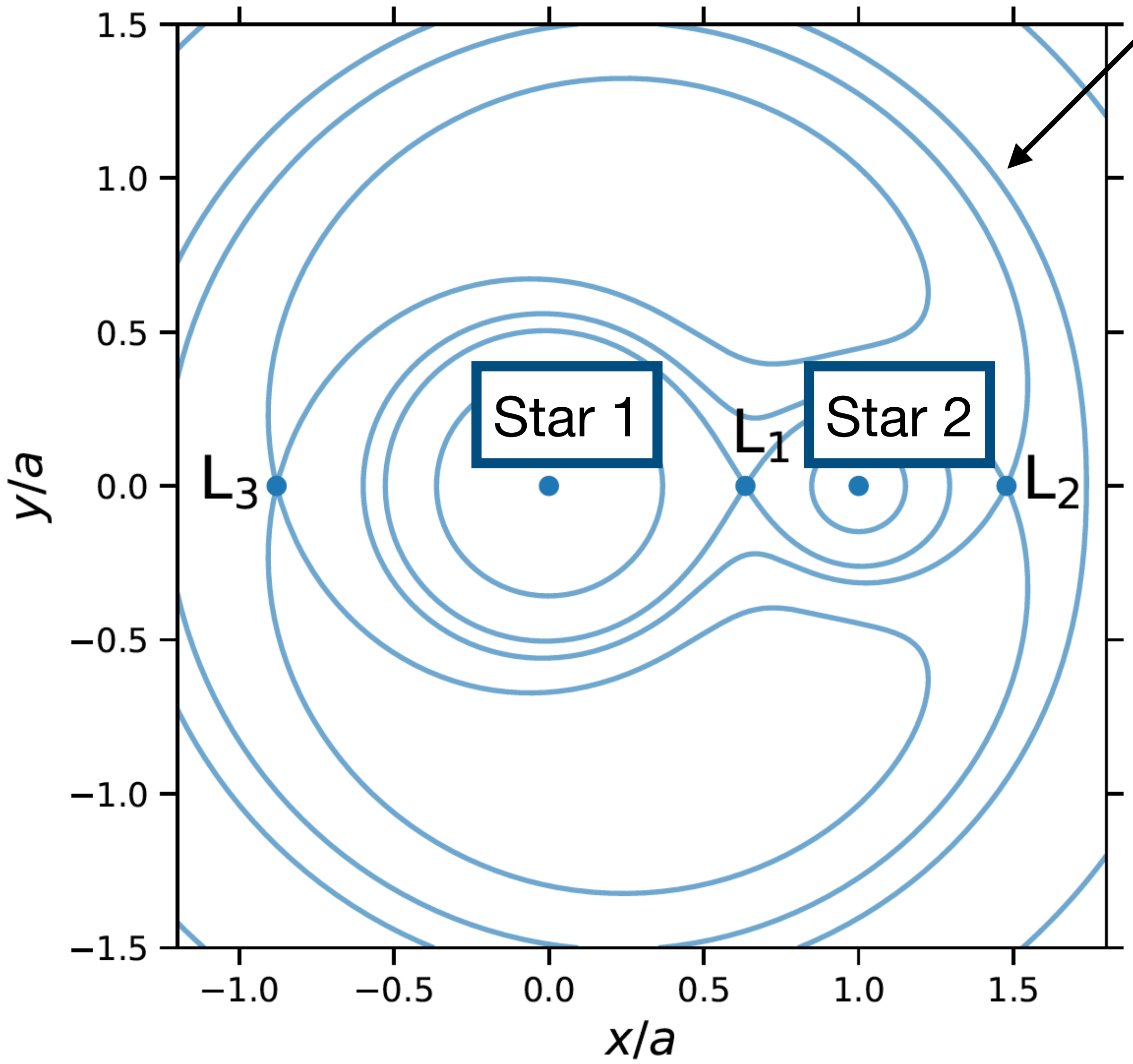
Why care about binary stars?

Chen et al. (2023)



Why care about binary stars?

Gravitational equipotential lines



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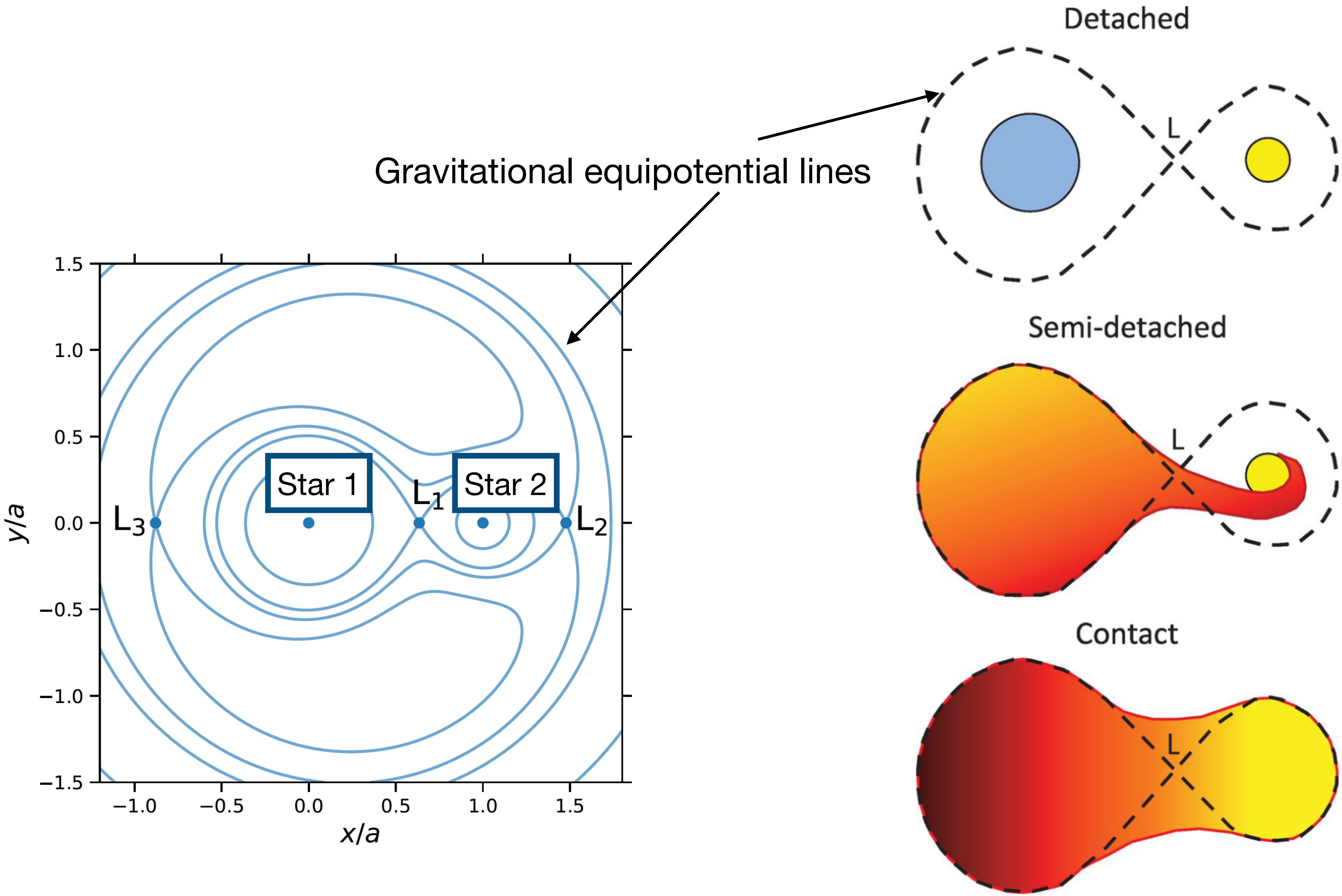
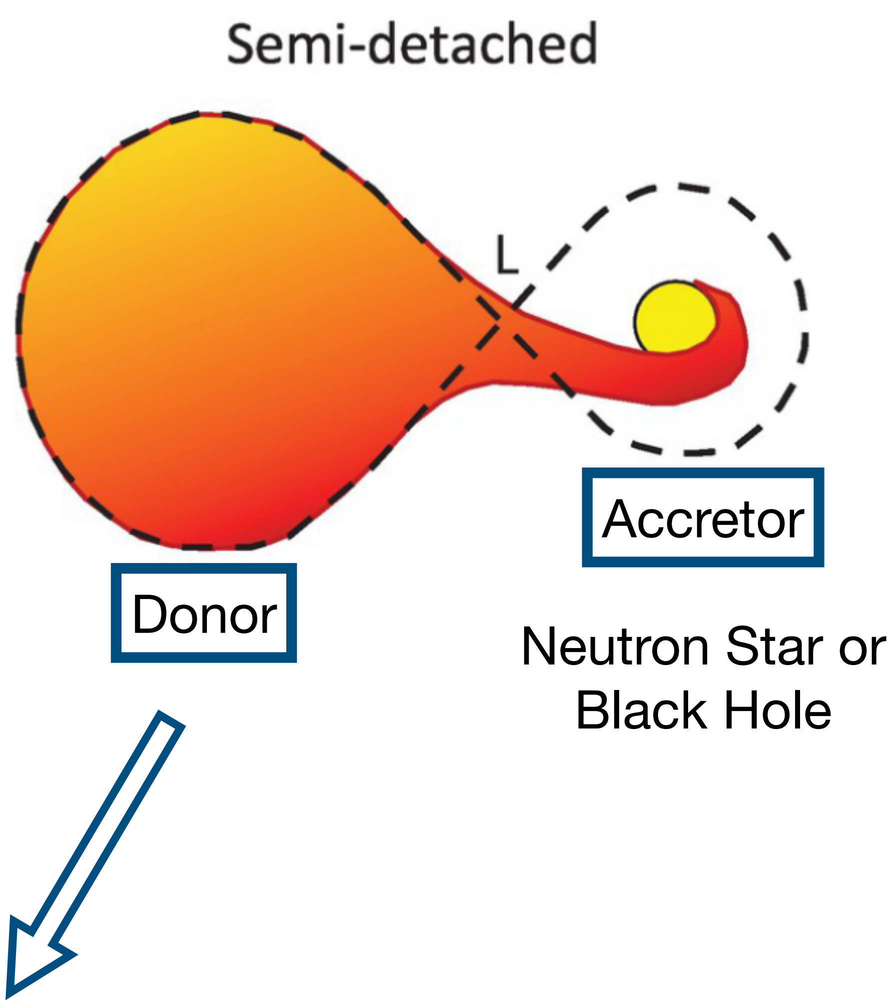


Walker (2017)

X-ray binaries (XRBs)

X-ray binary (or XRB)

A binary star system where one of the stars is a compact object and accreting matter from the other star



X-ray binary

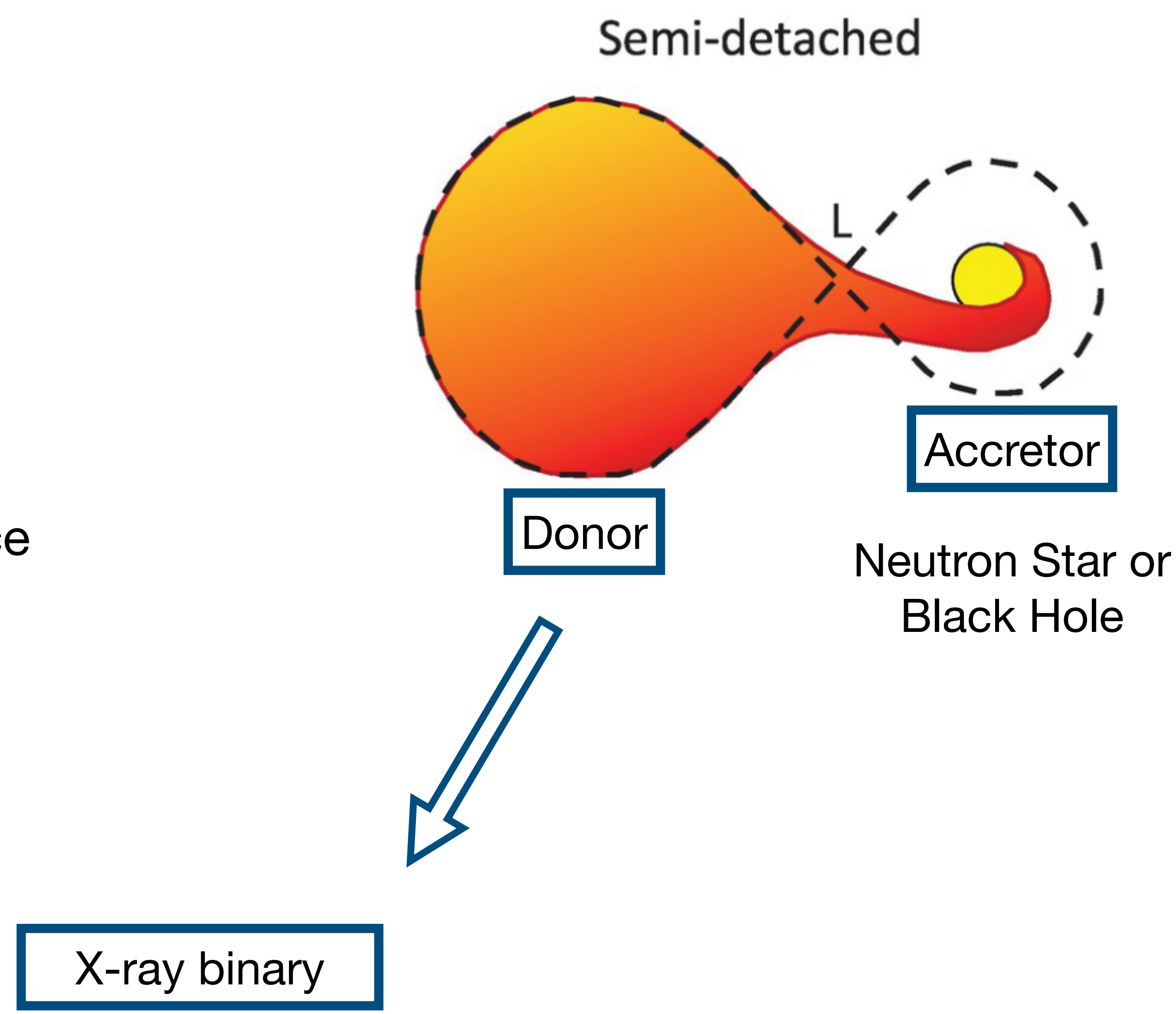
Accretion power

$$\Delta E_{\rm acc} = GMm/R_*$$

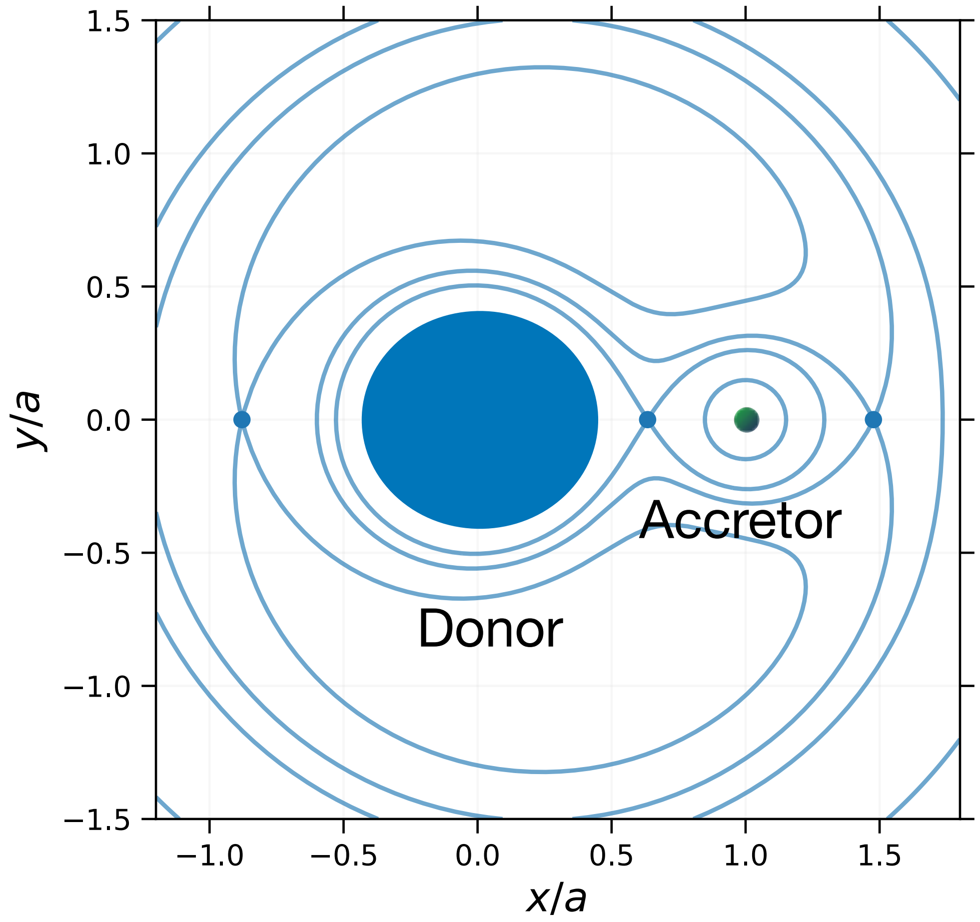
$$L_{\rm acc} = GM\dot{M}/R_* = \eta \dot{M} c^2$$

Outward radiation = Inward gravitational force

$$L_{\rm Edd} = 4\pi G M m_{\rm p} c/\sigma_{\rm T}$$
$$\cong 1.3 \times 10^{38} (M/M_\odot)\, {\rm erg\ s^{-1}}$$



Mass transfer in XRBs



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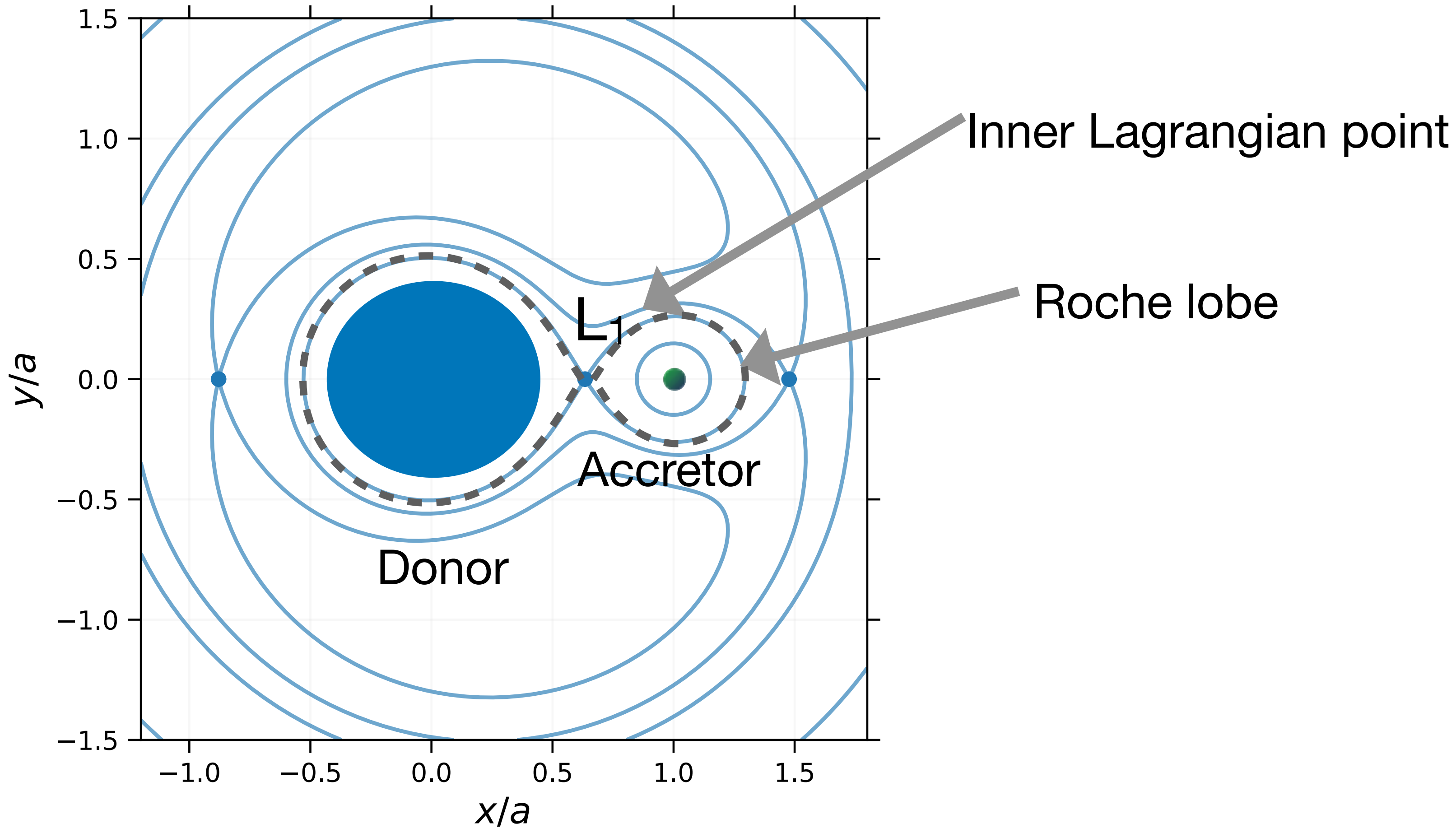

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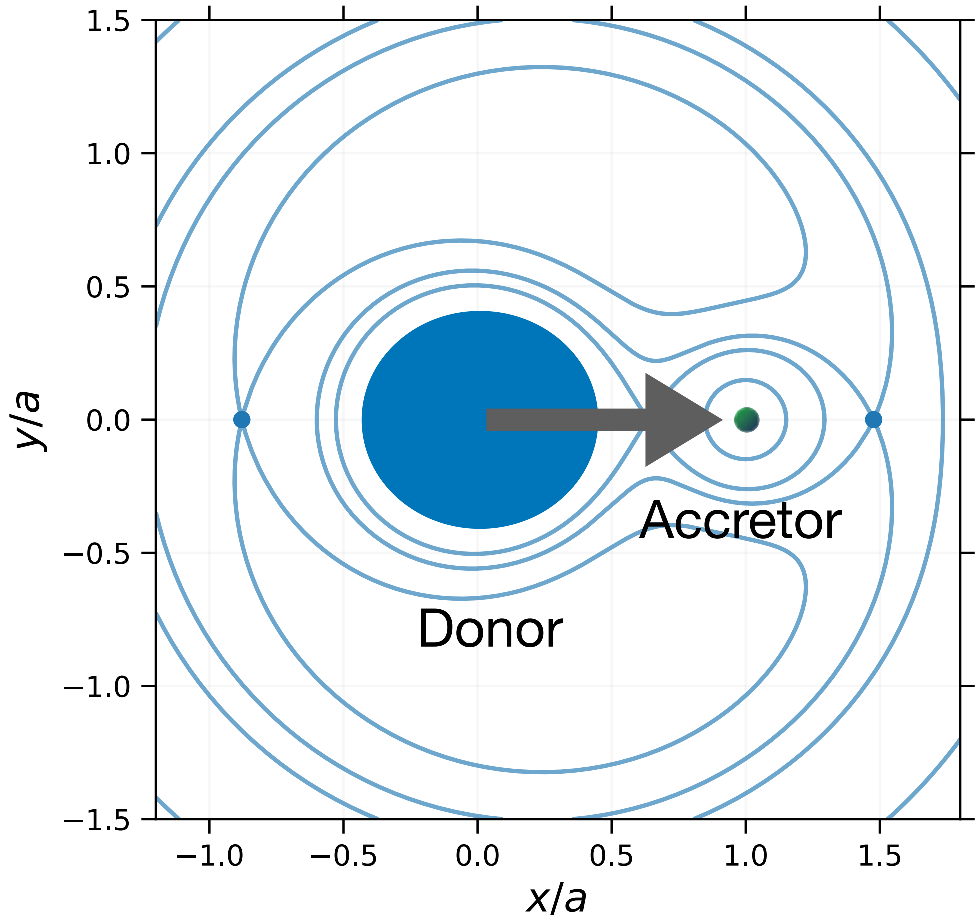
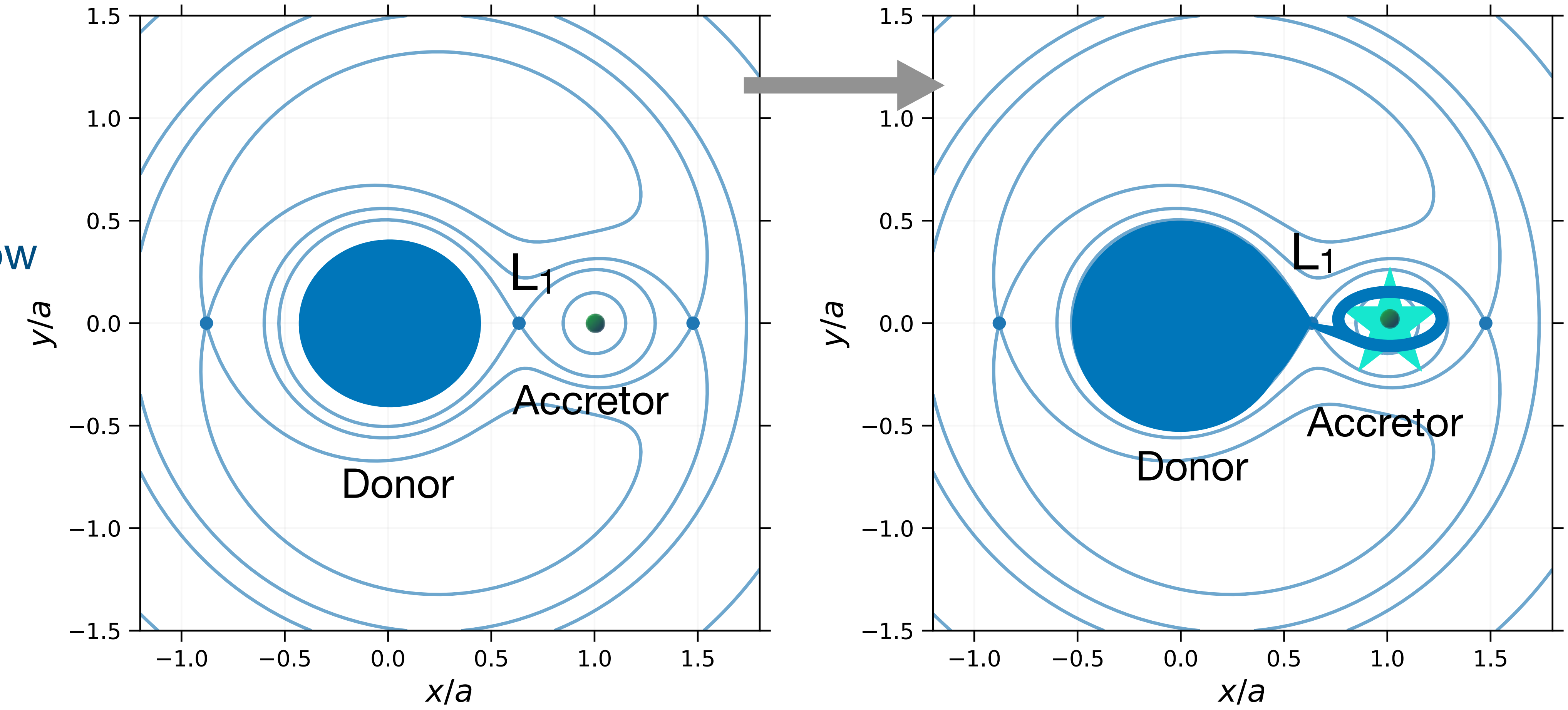


Mass transfer in XRBs

- Roche-lobe overflow



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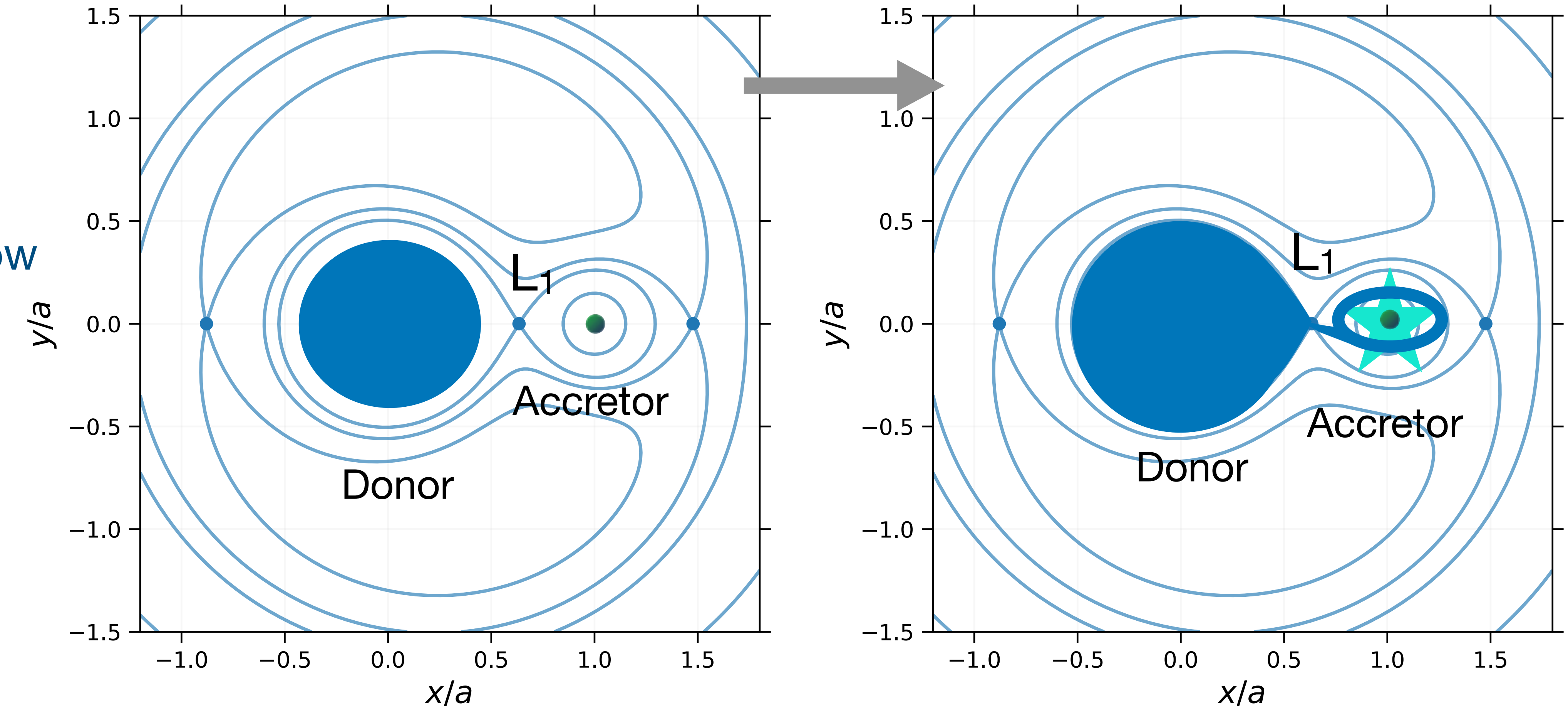
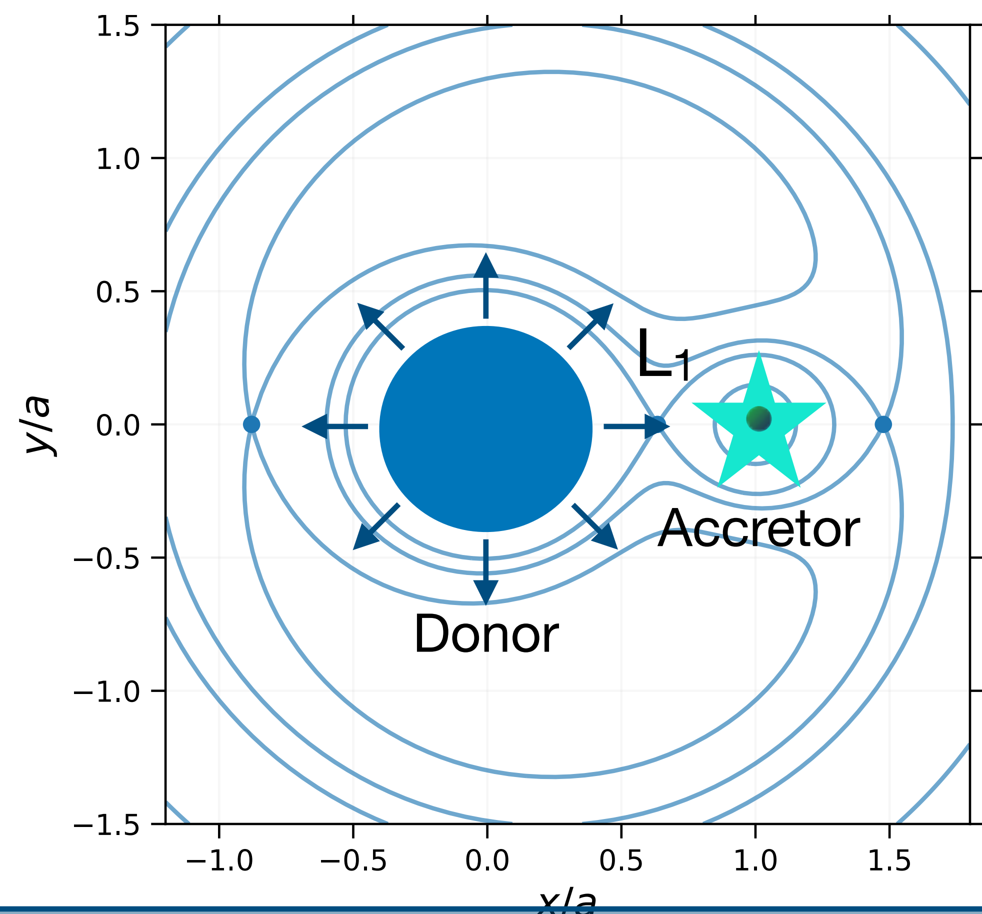


- Wind-fed accretion



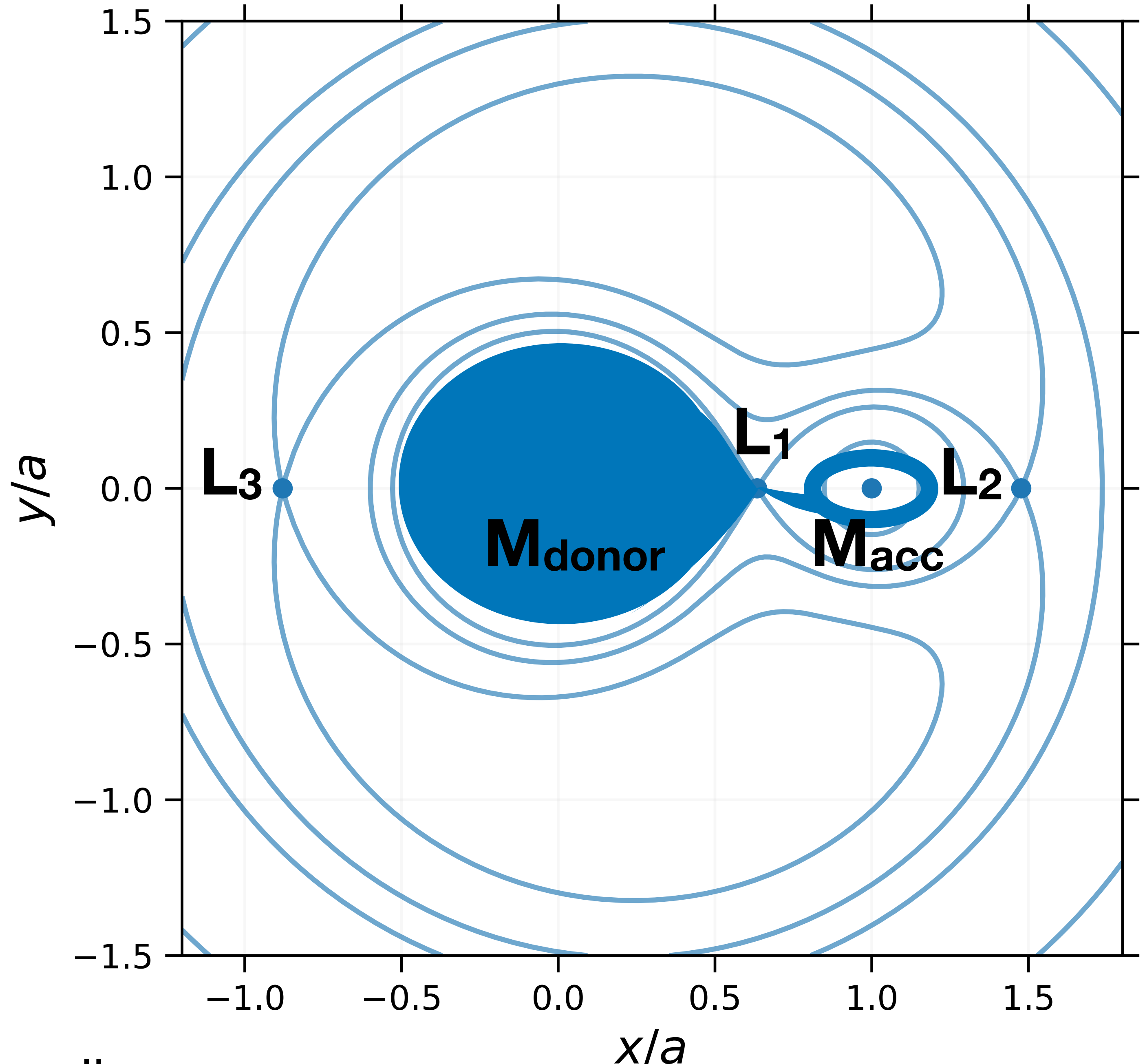
Calculating Roche-lobe overflow (RLO)

$$q = \frac{M_{\rm donor}}{M_{\rm accretor}}$$

Roche-lobe radius

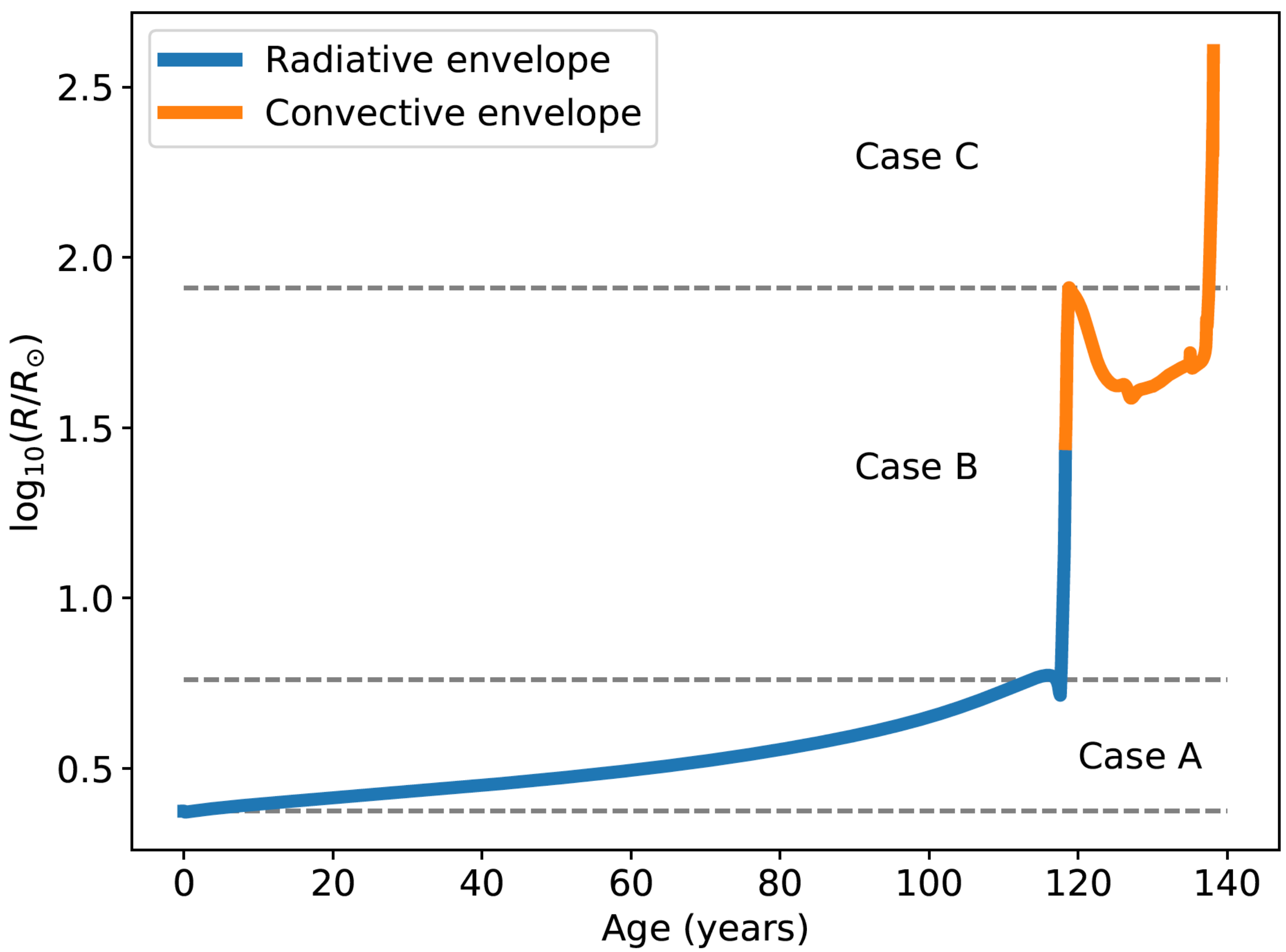
$$\frac{R_{\rm RL}}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$ [1]

[1] Eggleton (1983)

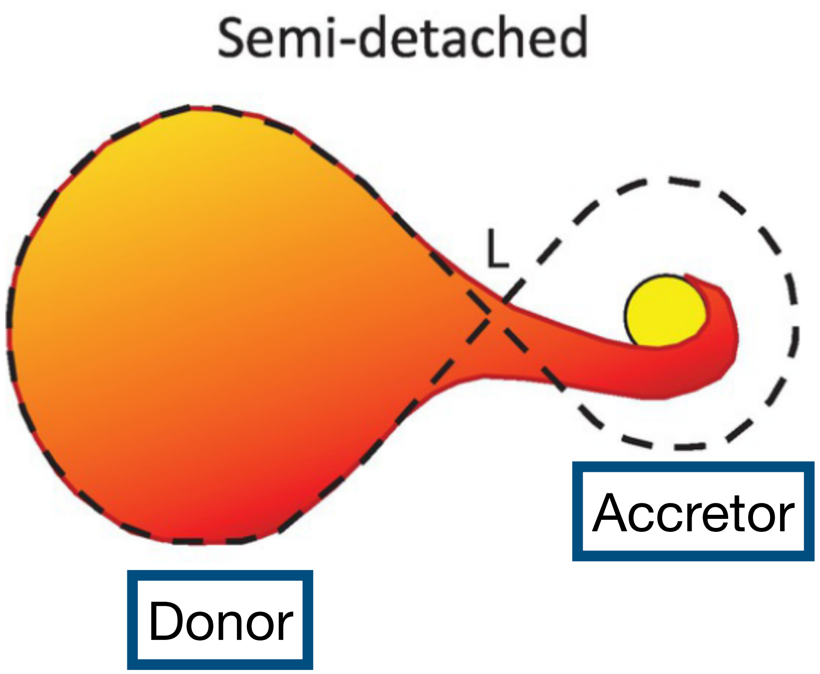


Mass transferred $\propto$ Overflow in radius

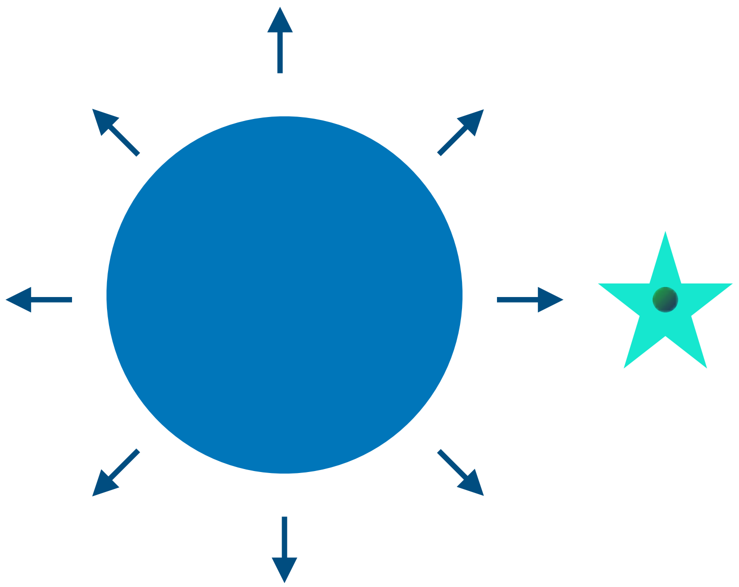
Roche-lobe overflow (RLO) cases



Case A: Donor on the Main Sequence
Case B: Donor in H-shell burning phase
Case C: Donor after core-He exhaustion



Types of XRBs



<u>High-mass X-ray binaries</u>

(HMXBs)

Donor masses $> 8\mathrm{M}_\odot$

Wind-fed accretion

Younger populations, $< 10^7$ yrs

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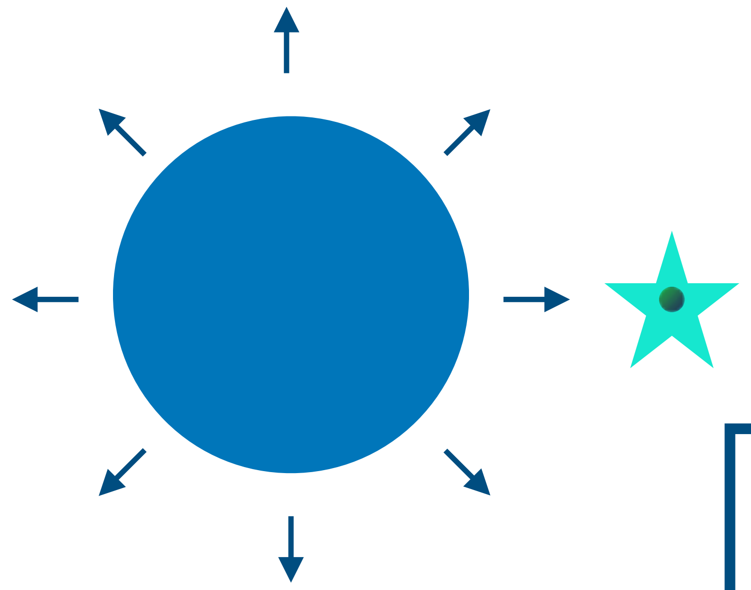

High-mass X-ray binaries

(HMXBs)

Donor masses $> 8M_\odot$

Wind-fed accretion

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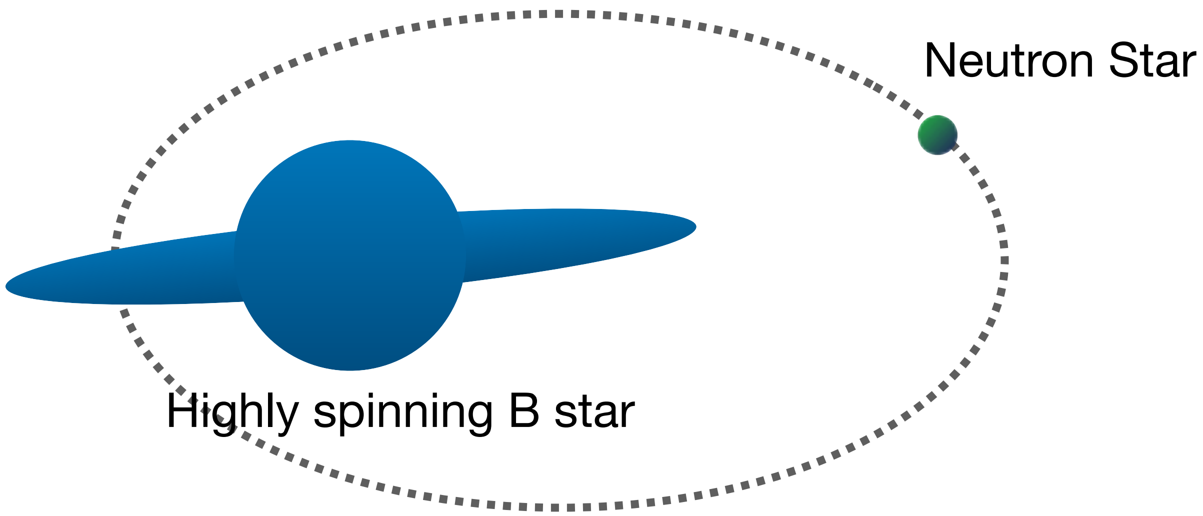
Be-XRBs

- Transient HMXBs, represent 2/3 of all HMXBs
- Highly spinning donor has a disc around it
- Interaction of compact object with the disc emits X-rays



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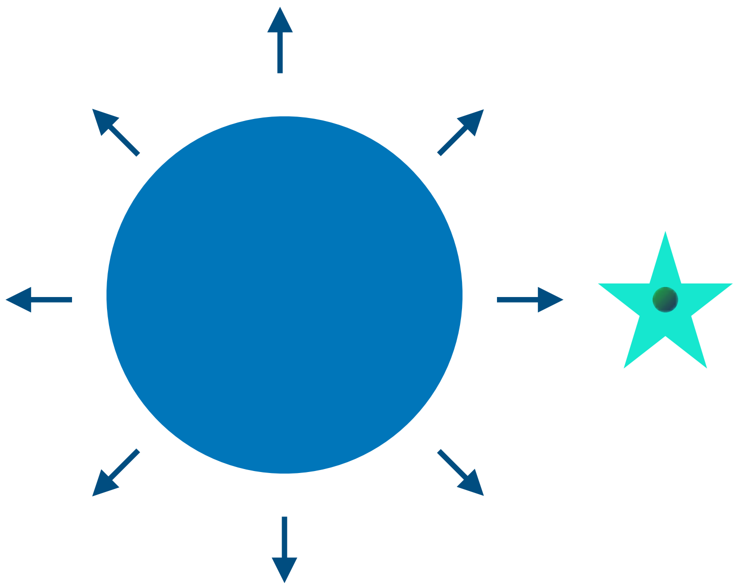

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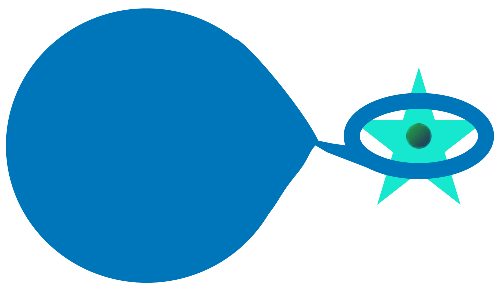


Low-mass X-ray binaries

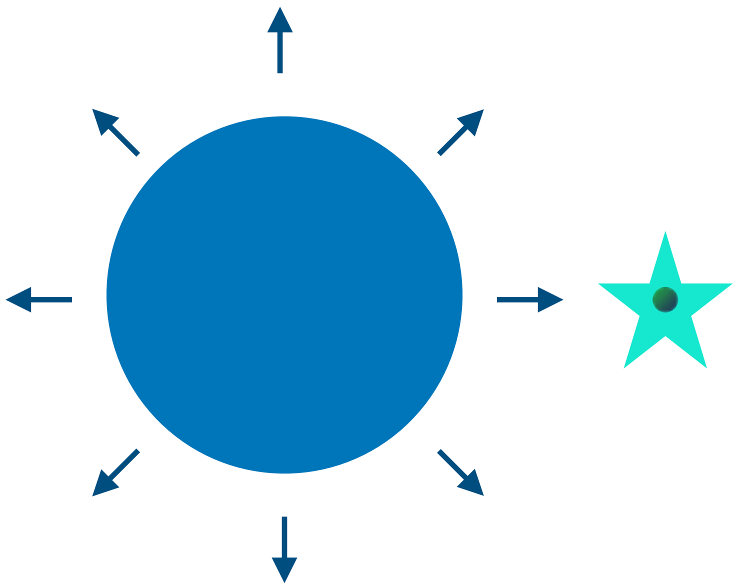
(LMXBs)

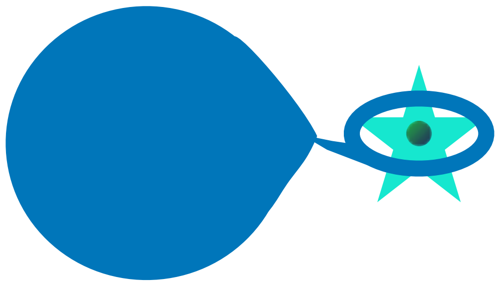
$2M_{\odot} <$ Donor masses

RLO

Older populations, $\gtrsim 10^9$ yrs

Types of XRBs





High-mass X-ray binaries

(HMXBs)

Donor masses $> 8M_\odot$

Wind-fed accretion

Younger populations, $< 10^7$ yrs

Intermediate-mass X-ray binaries

(IMXBs)

$2M_\odot \lesssim$ Donor masses $\lesssim 8M_\odot$

Stellar winds not strong enough [1]

RLO phase short lived and likely unstable [1,2]

Low-mass X-ray binaries

(LMXBs)

$2M_\odot <$ Donor masses

RLO

Older populations, $\gtrsim 10^9$ yrs

[1] van den Heuvel (1975)

[2] Tauris, van den Heuvel & Savonije (2000)

Ultra-luminous X-ray sources (ULXs)

[1]

10^{38} erg s^{-1} < L_X (> 10^{39} erg s^{-1}) < 10^{42} erg s^{-1}

(L_{XRB}) (L_{AGN})

Image: X-ray: NASA/CXC/Caltech/M. Brightman et al.; Optical: NASA/STScI

[1] Fabbiano et al. (1989)

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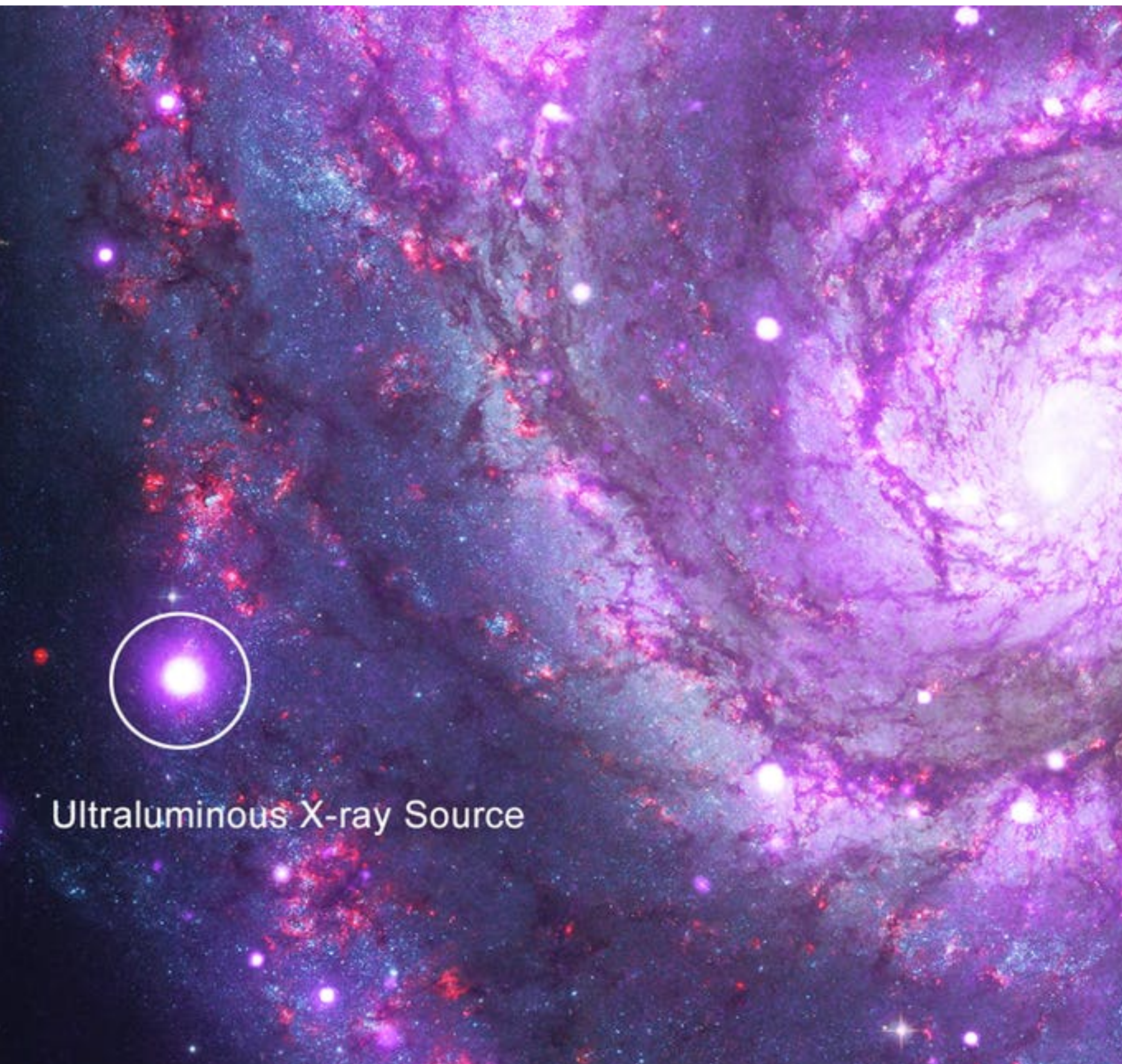


Eddington limit

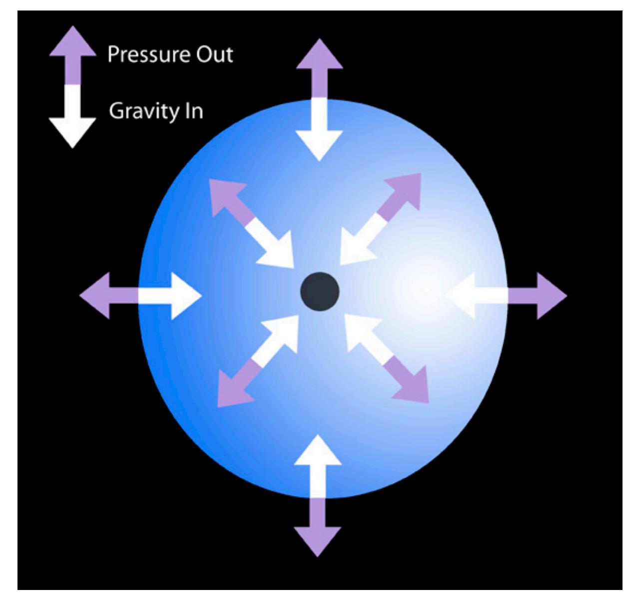


Image: NASA/STScI

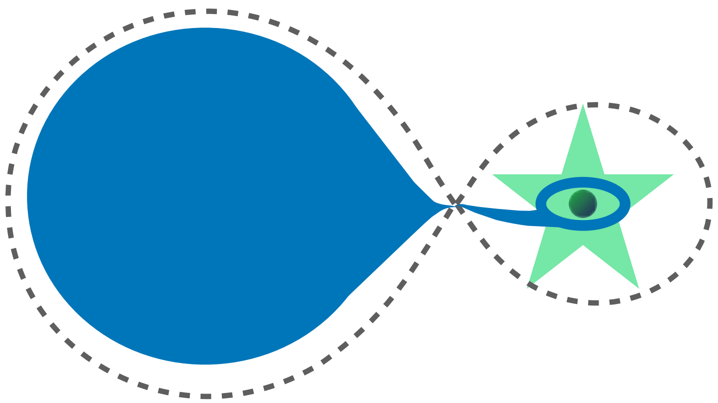
$$L_{\mathrm{Edd}} = \frac{4\pi G M c}{\kappa}$$

- $10M_\odot$ BH $\sim 10^{39}$erg s-1
- $1.4M_\odot$ NS $\sim 1.5 \times 10^{38}$erg s-1
- **Physical limit assuming spherical symmetry**

Ultra-luminous X-ray sources (ULXs)

Mass transfer nature?

Donor nature?



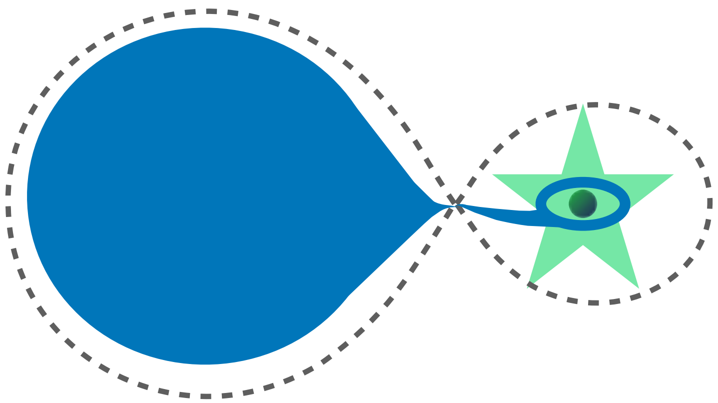
Accretor nature?

X-ray binary

Ultra-luminous X-ray sources (ULXs)

Mass transfer nature?

Donor nature?

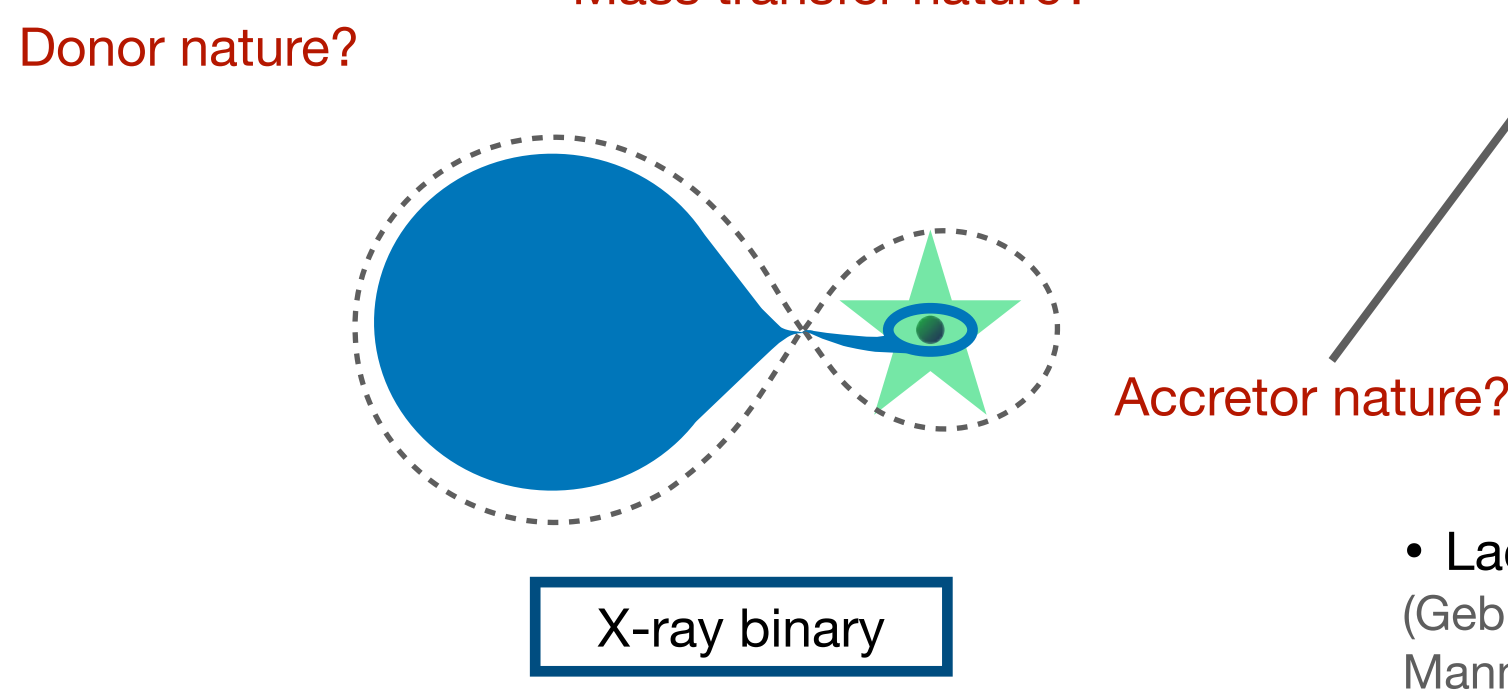


Accretor nature?

Intermediate-mass BH ($\gtrsim 100 \mathrm{M}_\odot$)
accreting at sub-Eddington rate

X-ray binary

Ultra-luminous X-ray sources (ULXs)



Intermediate-mass BH ($\gtrsim 100 M_\odot$)
accreting at sub-Eddington rate

- Lack of ample evidence
(Gebhardt et al. 2005; Gerssen et al. 2002; Mann et al. 2019; Miller-Jones et al. 2012; Perera et al. 2017; Tremou et al. 2018; Zocchi et al. 2019)

- GW evidence
(Abbott et al. 2020)

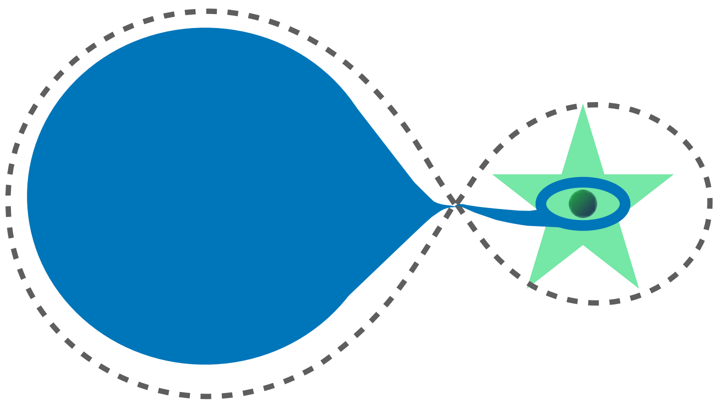
Ultra-luminous X-ray sources (ULXs)

NS / Stellar-mass BH in
a super-Eddington phase

Intermediate-mass BH ($\gtrsim 100 M_{\odot}$)
accreting at sub-Eddington rate

Mass transfer nature?

Donor nature?



Accretor nature?

X-ray binary

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Pulsating ULXs

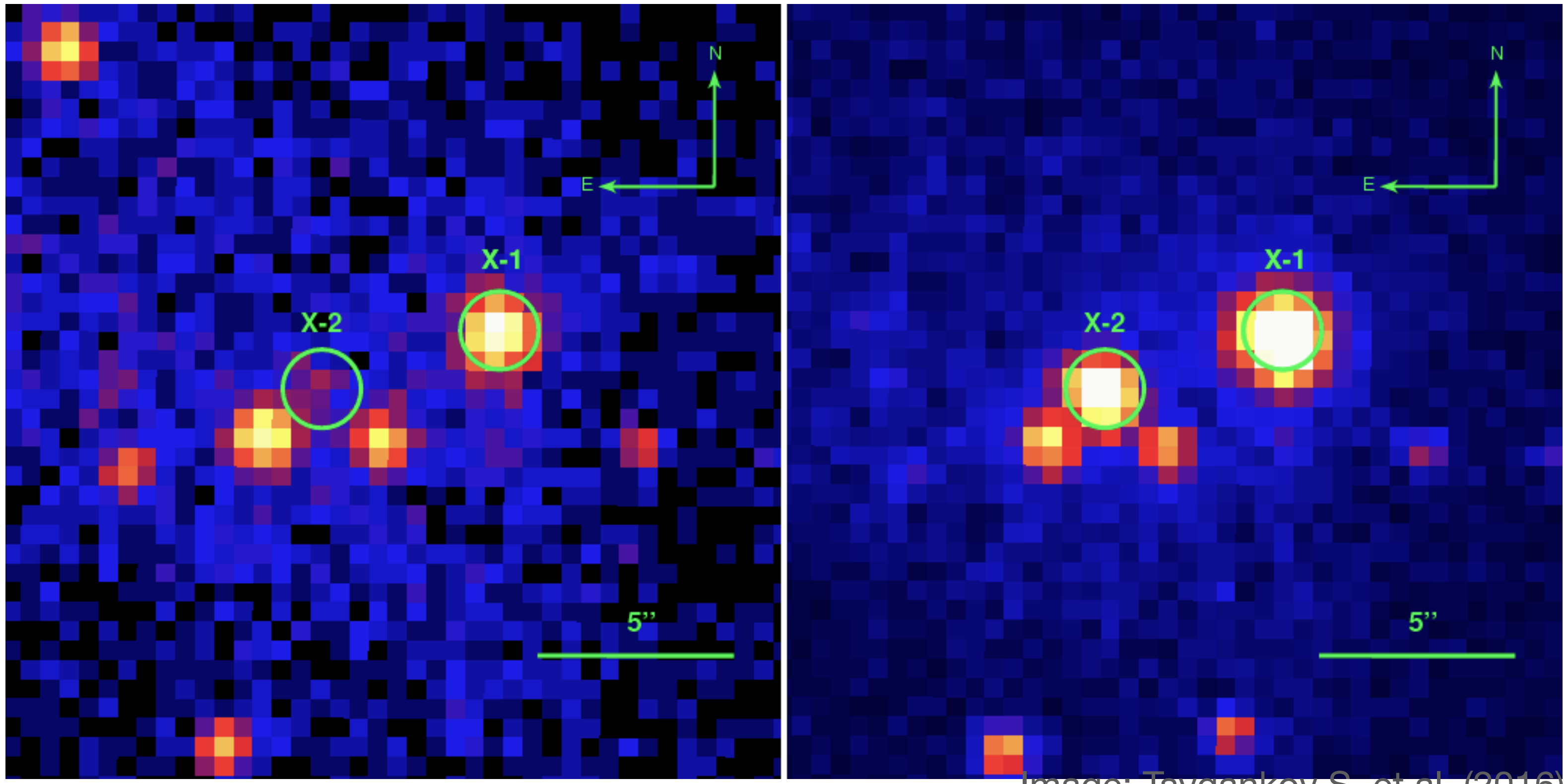
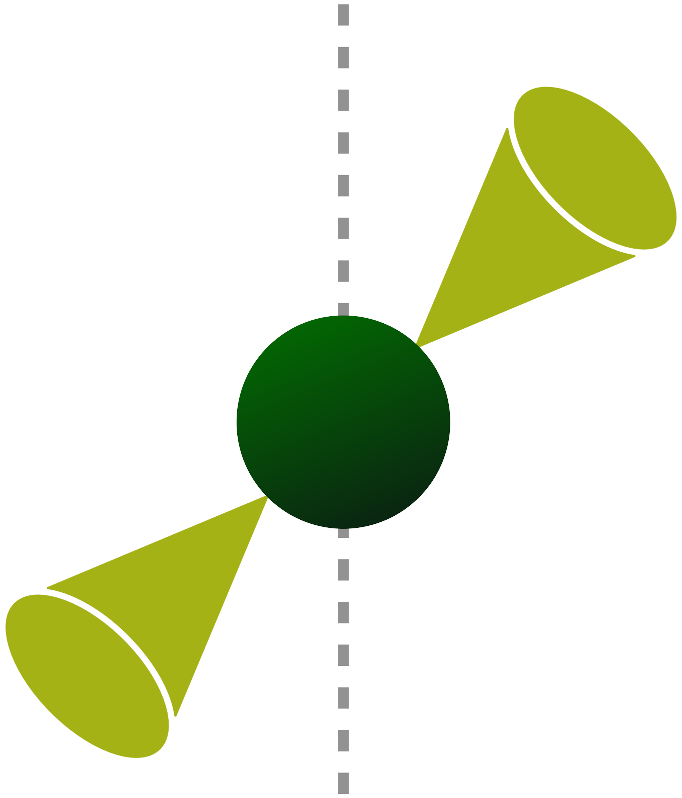


Image: Tsygankov S. et al. (2016)

- X-ray pulsations discovered in M82 X-2 [1]

$$L_{\rm Edd}(1.4{\rm M}_\odot \text{ NS}) \approx 10^{38} \text{ erg s}^{-1}$$



[1] Bachetti et al. (2014)

Pulsating ULXs

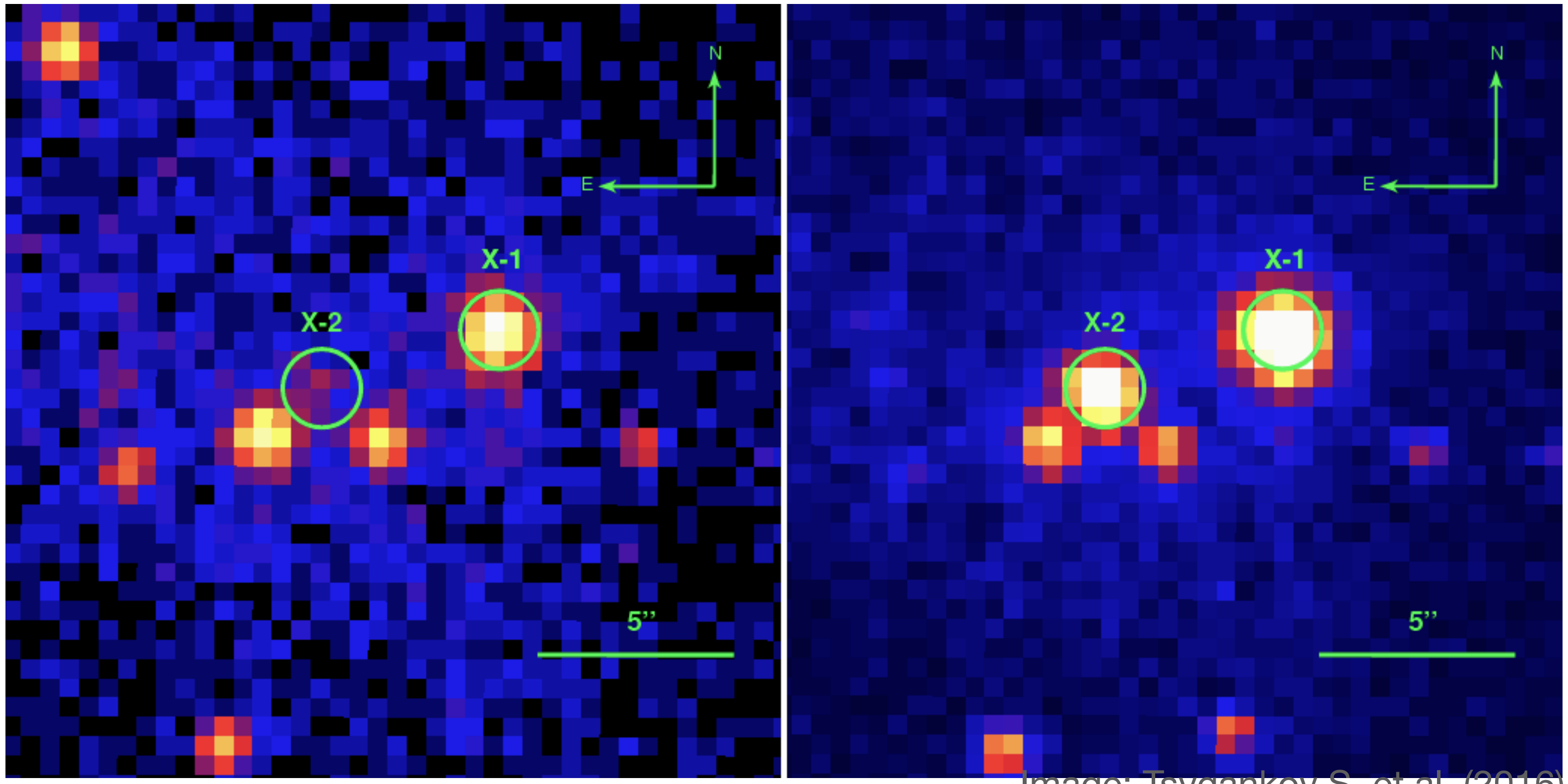


Image: Tsygankov S. et al. (2016)

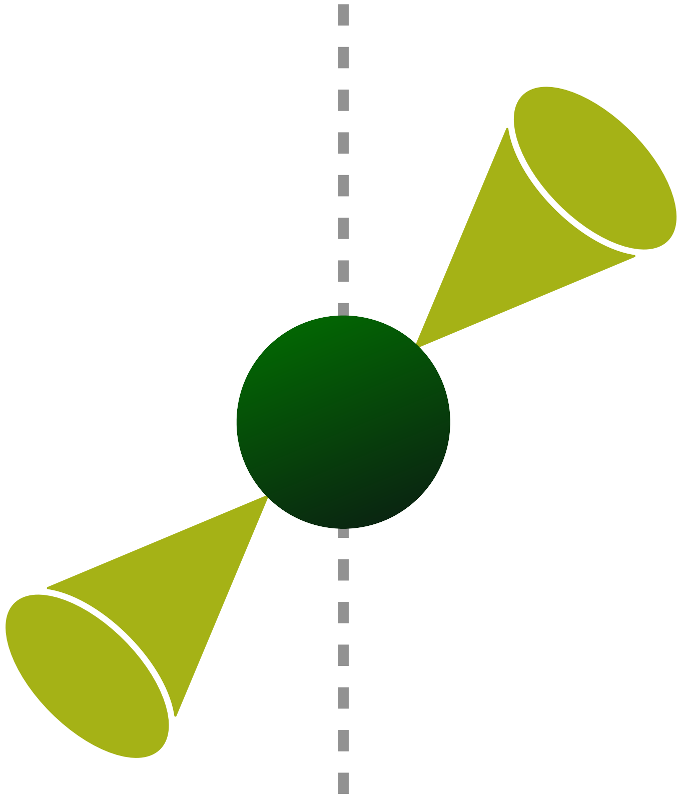
[1]

- X-ray pulsations discovered in M82 X-2

$L_{\mathrm{Edd}}(1.4\mathrm{M}_{\odot}\ \mathrm{NS}) \approx 10^{38}$ erg s^{-1}

- Since then more pulsating ULXs discovered

(Fürst et al. (2016); Israel et al. (2017b); Motch et al. (2011); Motch et al. (2014); Israel et al. (2017a), Carpano et al. (2018); Heida et al. (2019); Ray et al. (2019); Vasilopoulos et al. (2018); Brightman et al. (2018); Sathyaprakash et al. (2019); Grisé et al. (2008); Zhang et al. (2019b); Doroshenko et al. (2018); Ge et al. (2017); Jenke & Wilson-Hodge (2017); Kennea et al. (2017); Rodríguez Castillo et al. (2019)



[1] Bachetti et al. (2014)

Binary mass function

Starting from the Kepler's 3rd law $P_{\mathrm{orb}}^2 \propto a^3$

Radial velocity amplitude: $K_{\mathrm{x}} = \Omega a \sin i / \sqrt{1 - e^2}$

Orbital angular velocity: $\Omega = 2\pi / P_{\mathrm{orb}}$

Constrains the mass of the unseen component in a binary

$$f(\mathrm{M}) = \frac{M_{\mathrm{donor}}^3 \sin^3 i}{(M_{\mathrm{acc}} + M_{\mathrm{donor}})^2} = \frac{1}{2\pi G} K_{\mathrm{x}}^3 P_{\mathrm{orb}} (1 - e^2)^{3/2}$$

In solar mass units

Pulsating ULXs

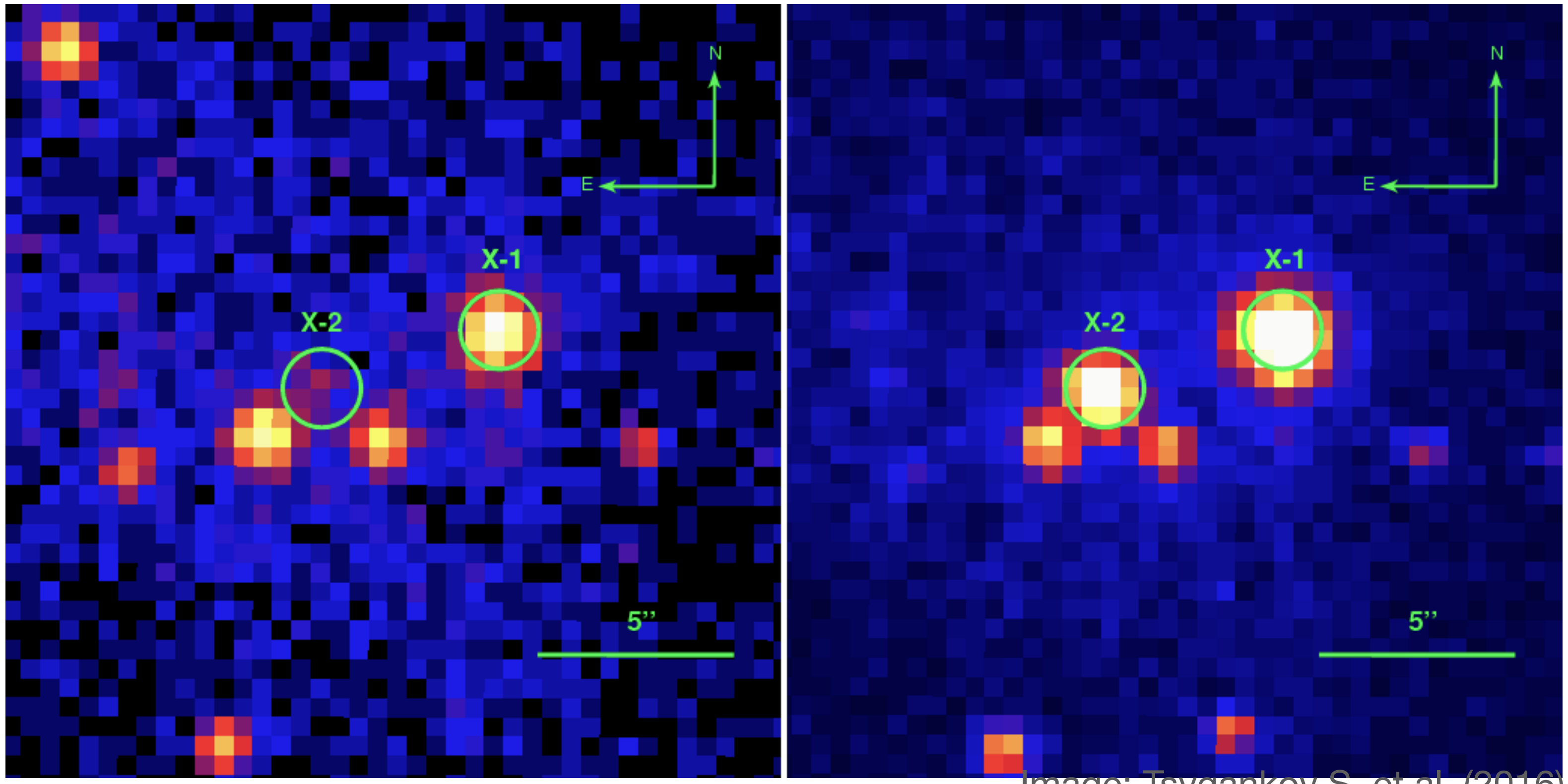
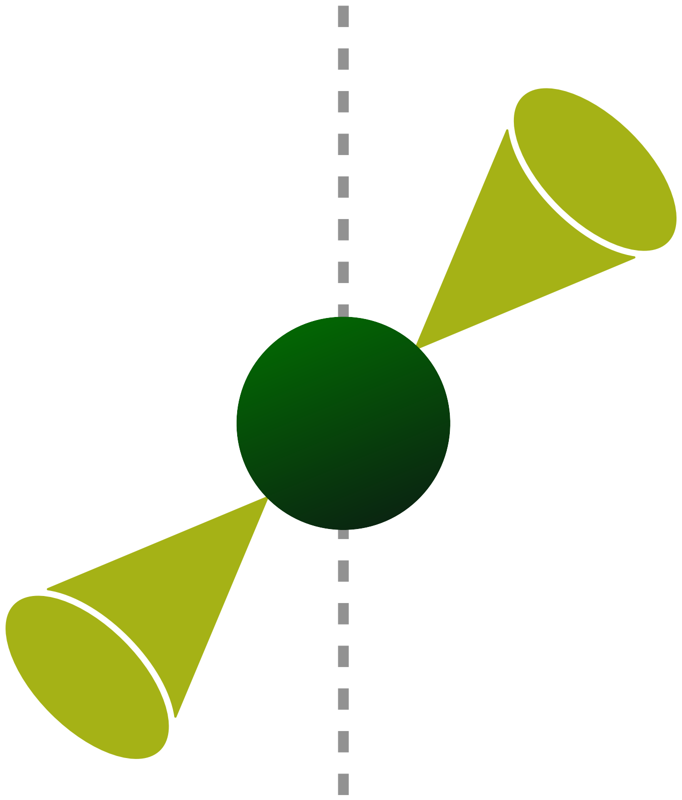


Image: Tsygankov S. et al. (2016)

- X-ray pulsations discovered in M82 X-2 [1]

$$f(M) = 2.1 M_\odot$$

L_X (erg s^{-1})	1.8×10^{40}
M_{acc} ($M_\odot$)	1.40
M_{donor} ($M_\odot$)	$\gtrsim 5.20$
P_{orb} (days)	2.52
P_{spin} (s)	1.37
i	$< 60°$



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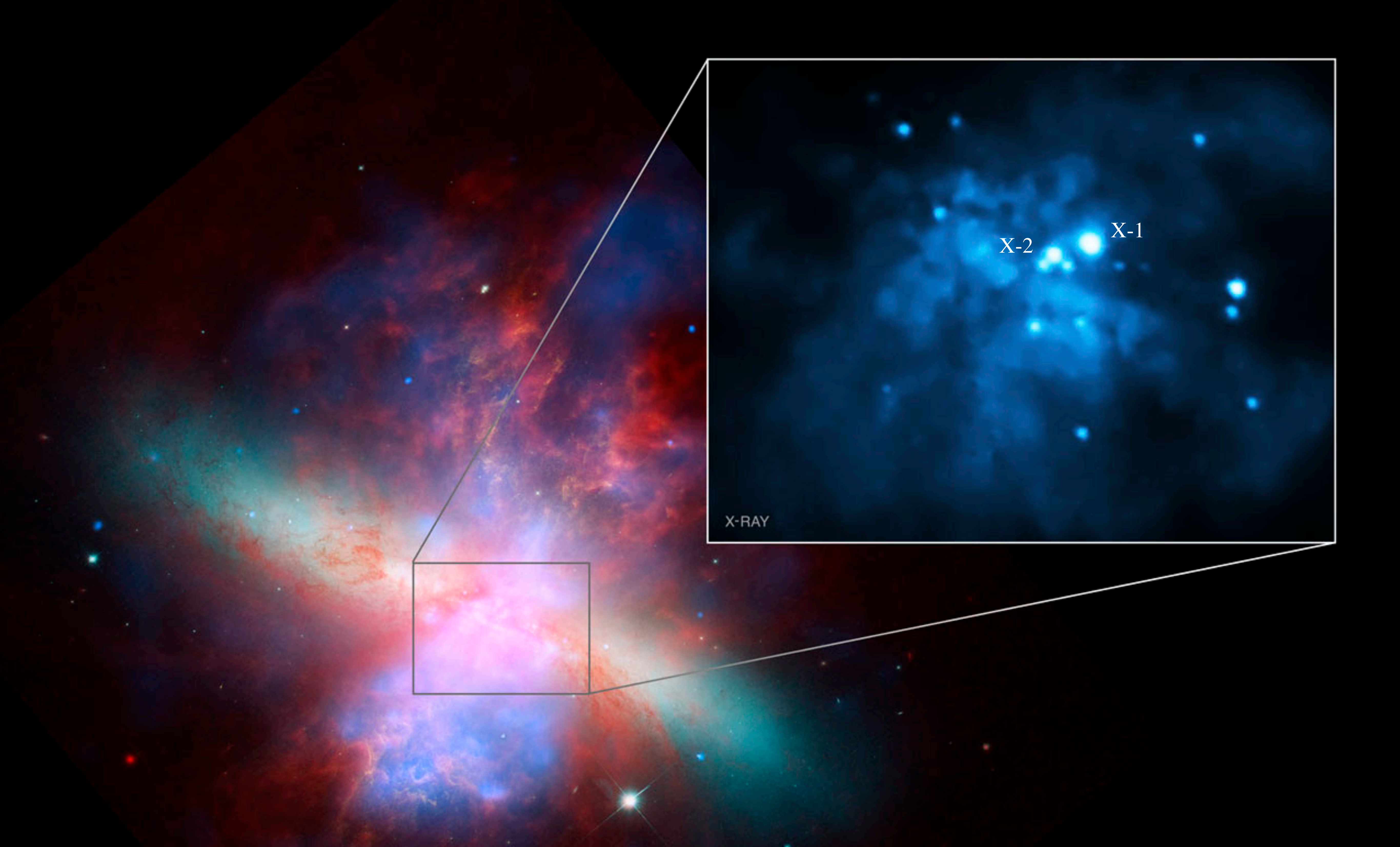


The origin of pulsating ULXs

Pulsating ultra-luminous X-ray sources as LMXBs/IMXBs

Image: NASA/H. Feng et al.
X-RAY, INFRARED & OPTICAL

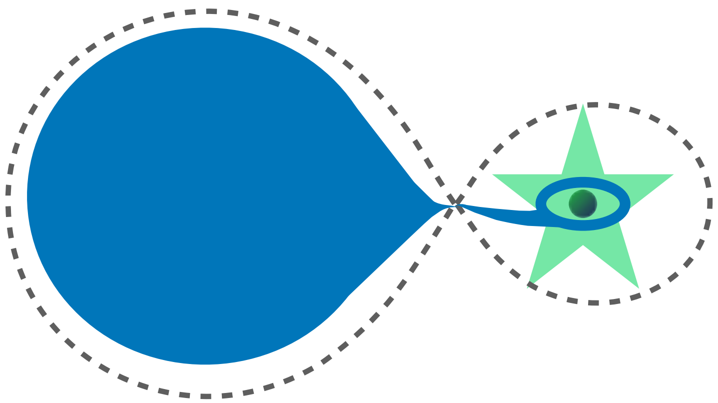
Ultra-luminous X-ray sources (ULXs)

NS / Stellar-mass BH in a super-Eddington phase

Intermediate-mass BH ($\gtrsim 100 M_\odot$) accreting at sub-Eddington rate

Mass transfer nature?

Donor nature?



Accretor nature?

X-ray binary

Ultra-luminous X-ray sources (ULXs)

NS / Stellar-mass BH in
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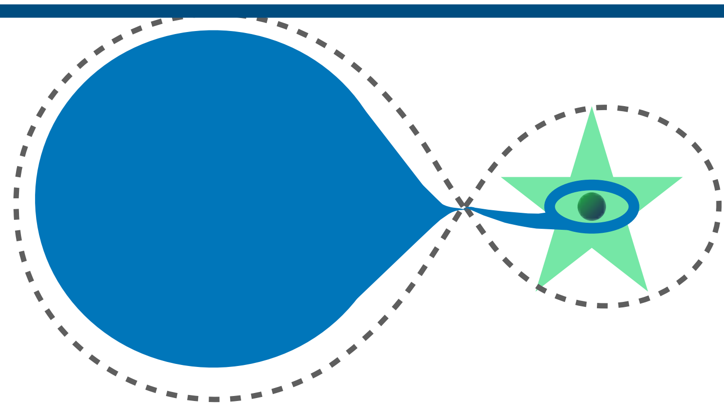
Low- and Intermediate-Mass X-ray binaries containing Neutron Star Accretors:
Donor masses $\lesssim 8M_{\odot}$ using detailed binary evolution calculations [1]



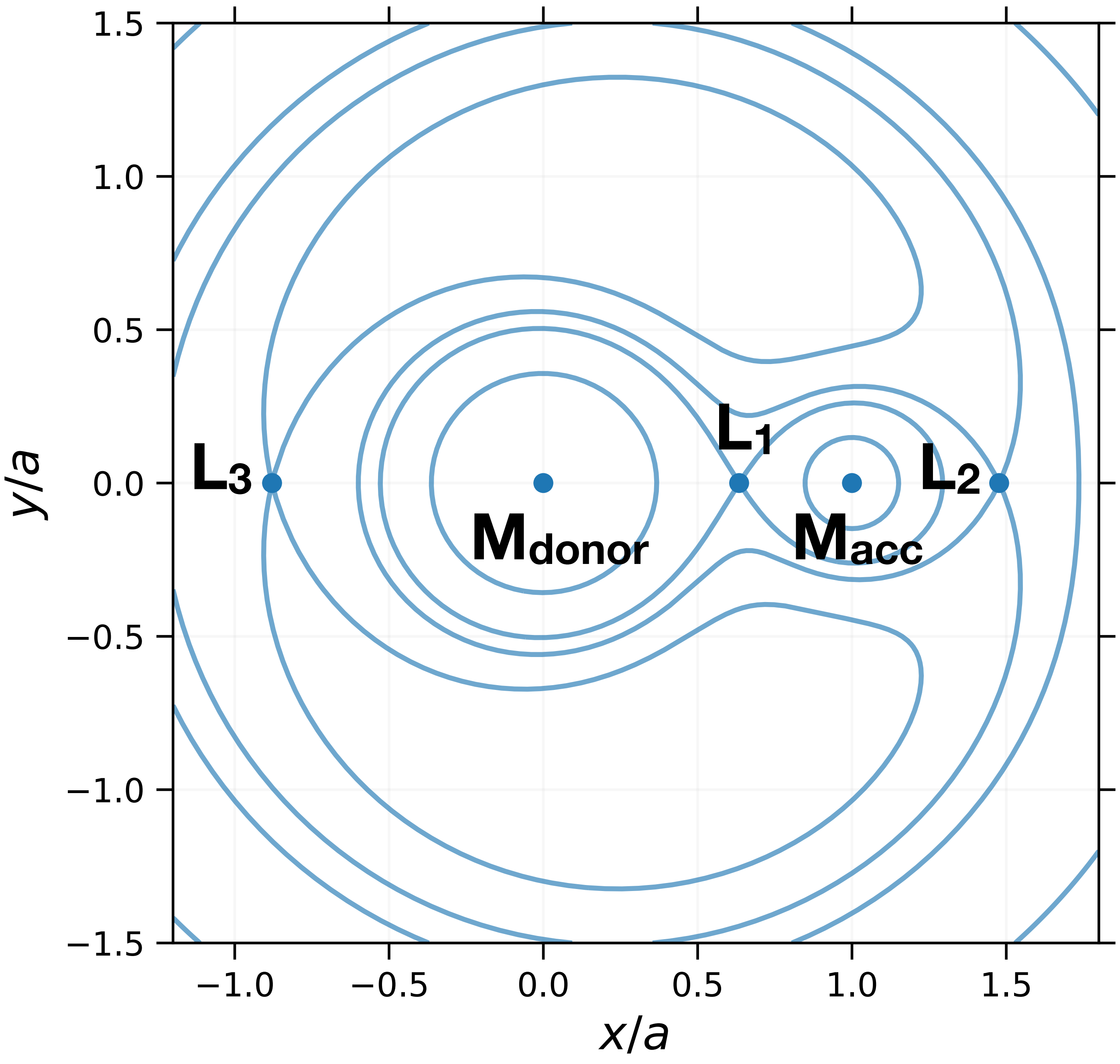
Accretor nature?

X-ray binary

[1] MESA

Paxton et al. (2011,2013,2015,2018,2019)

Stability of RLO mass transfer



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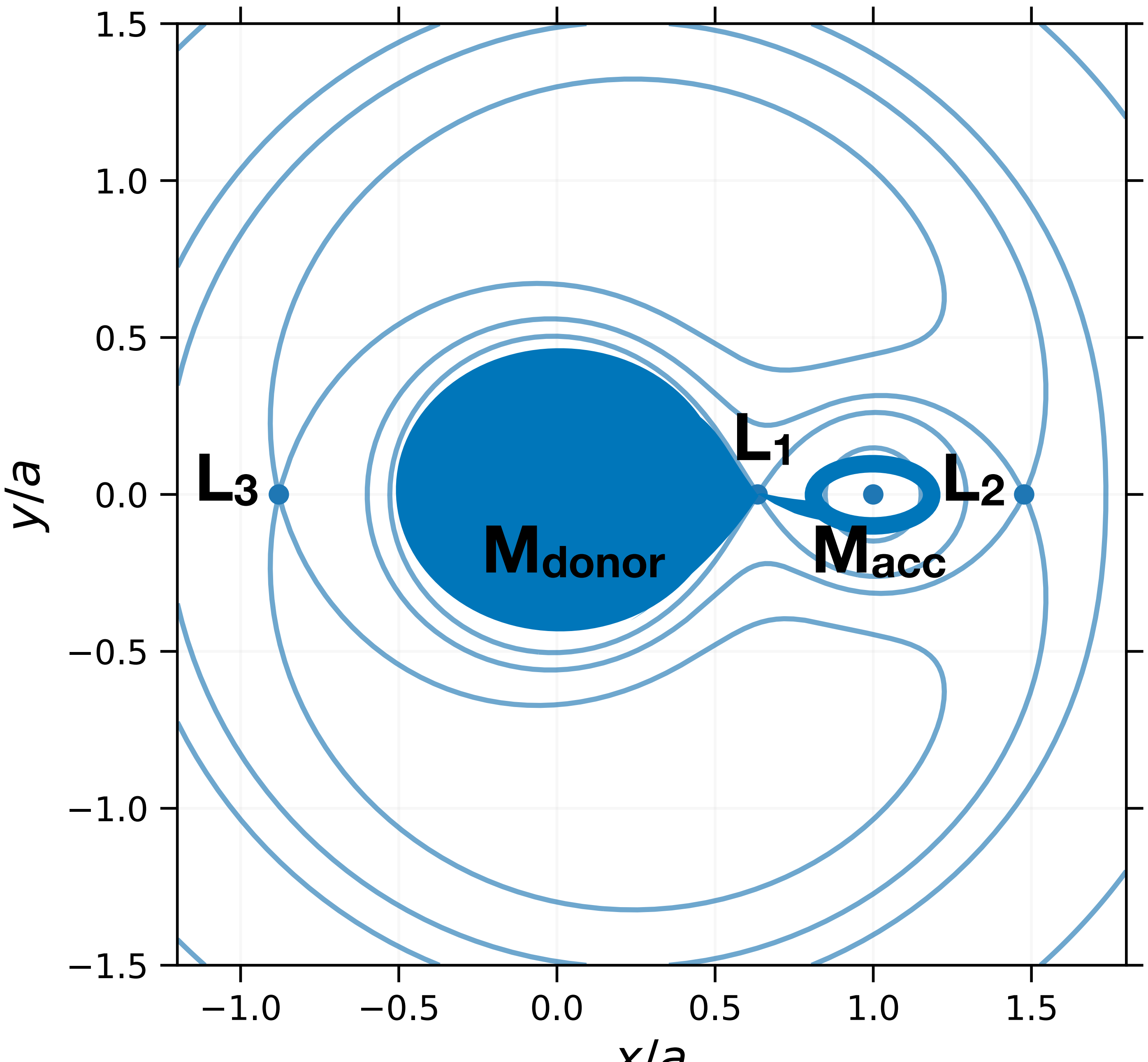

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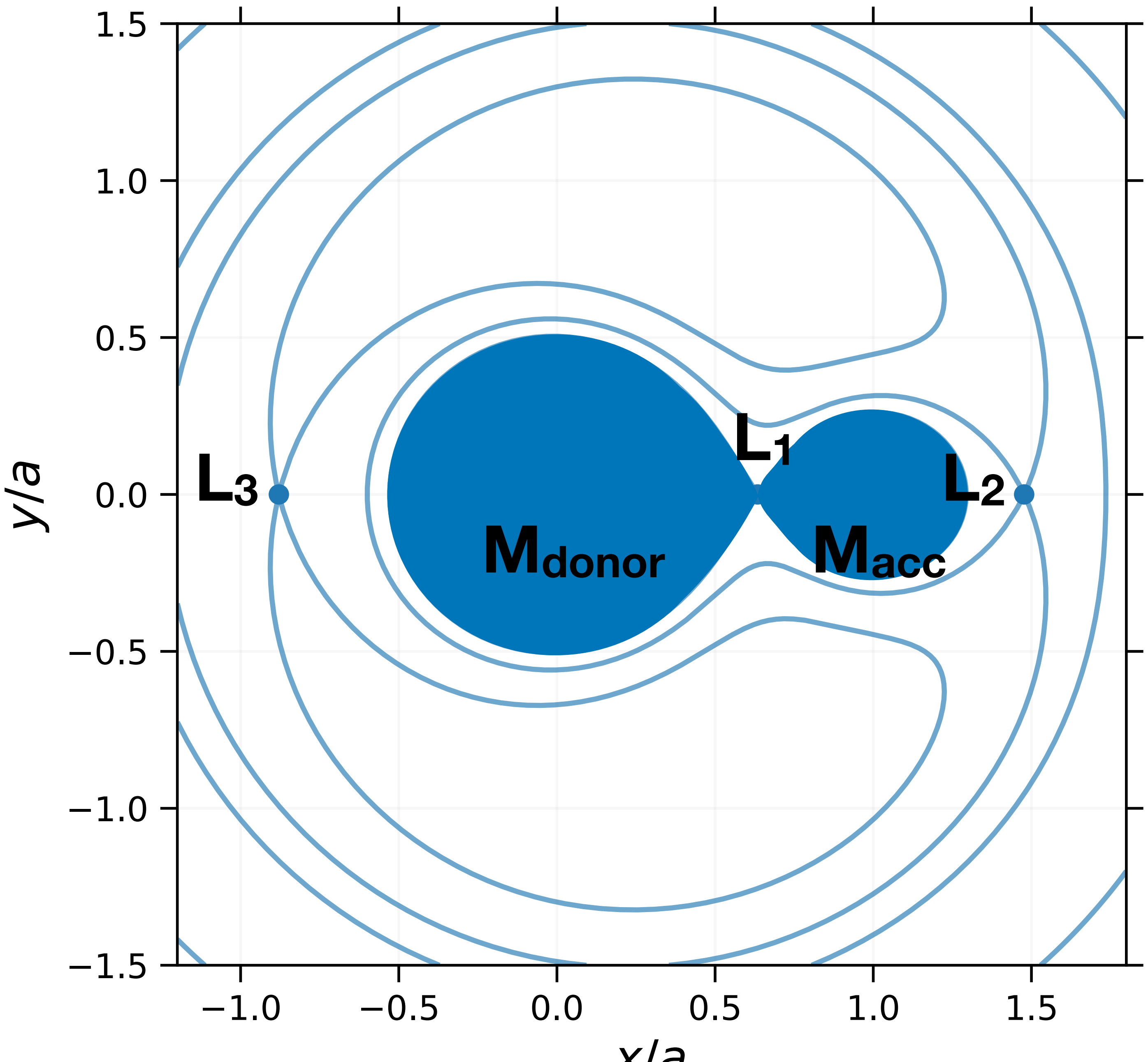

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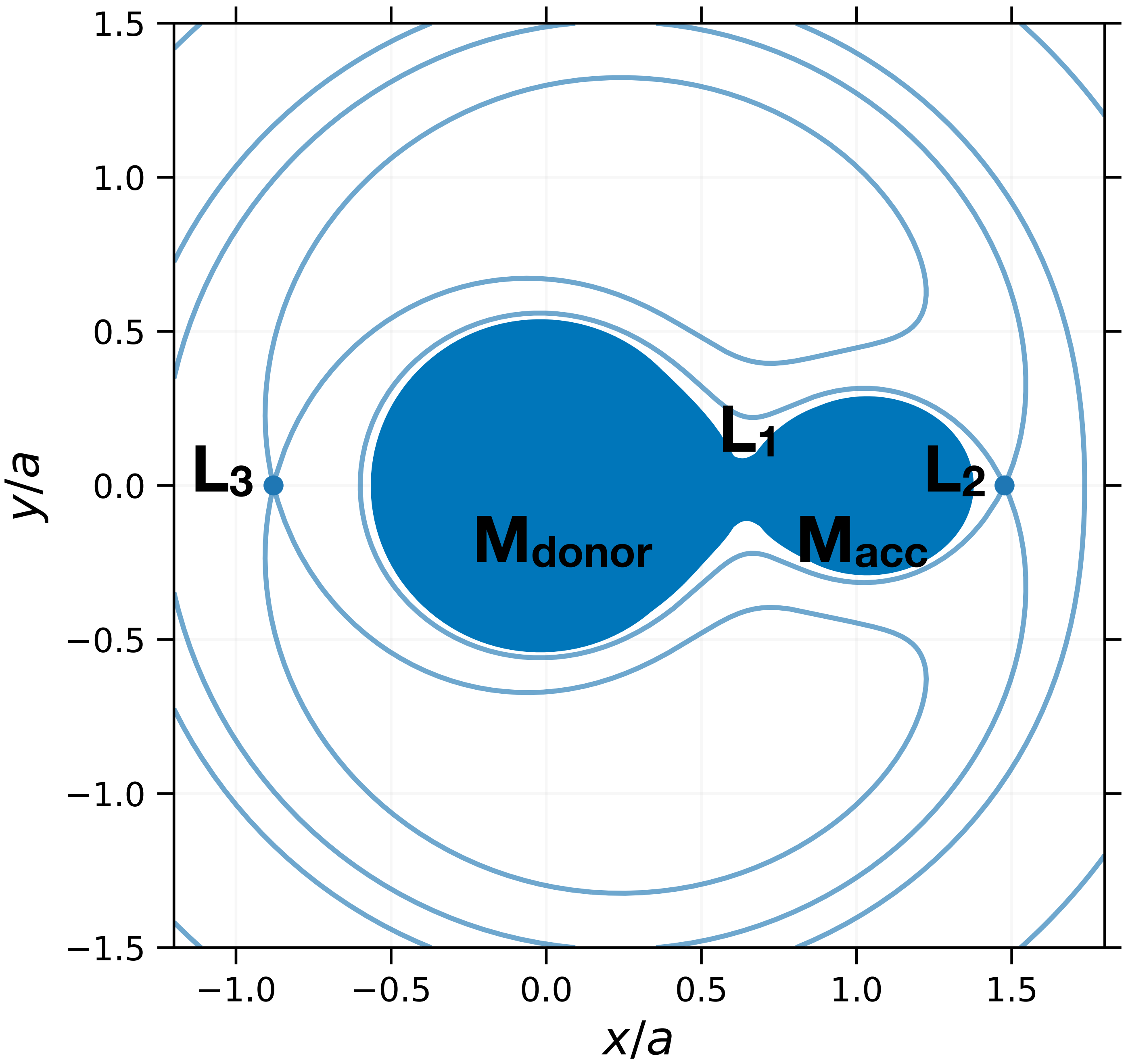

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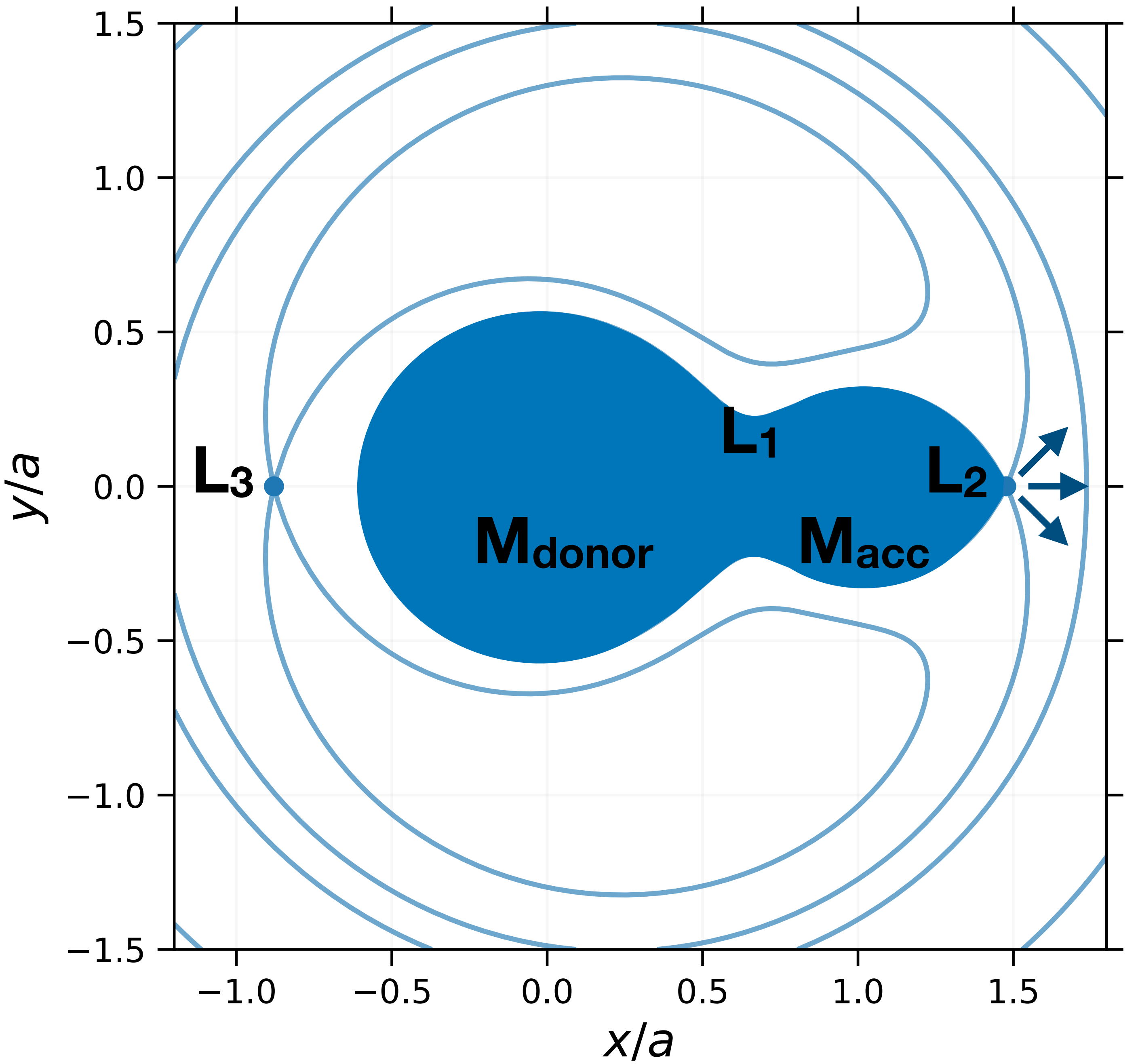
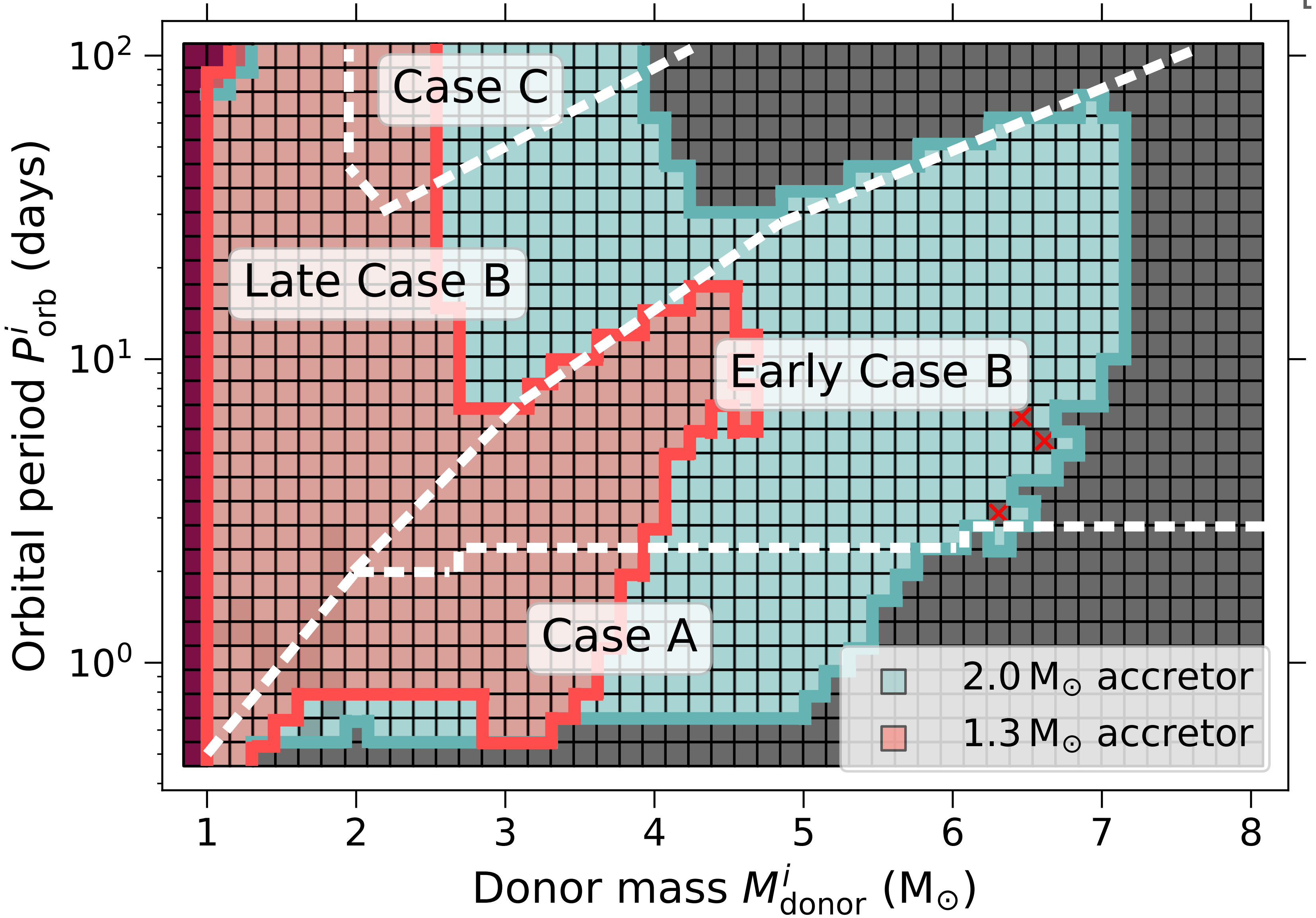


Unstable!

Stable mass transfer parameter space



[1]

Defining $q = \frac{M_{acc}}{M_{donor}}$

Case A: Donor on the Main Sequence

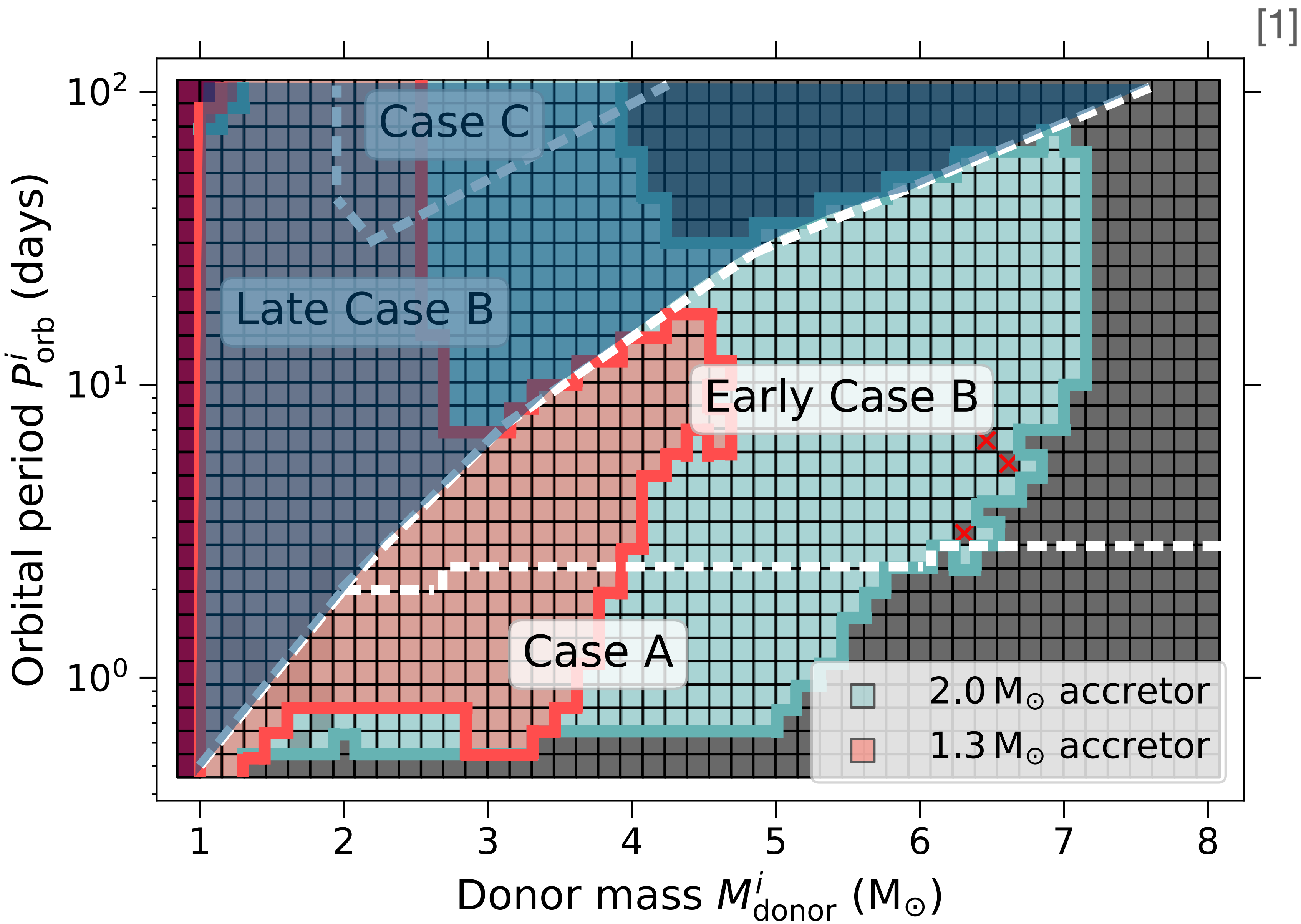
Case B: Donor in H-shell burning phase

Case C: Donor after core-He exhaustion

Qualitatively agrees with Tauris et al. (2000) and Shao & Li (2012)

[1] Misra et al. (2020)

Stable mass transfer parameter space



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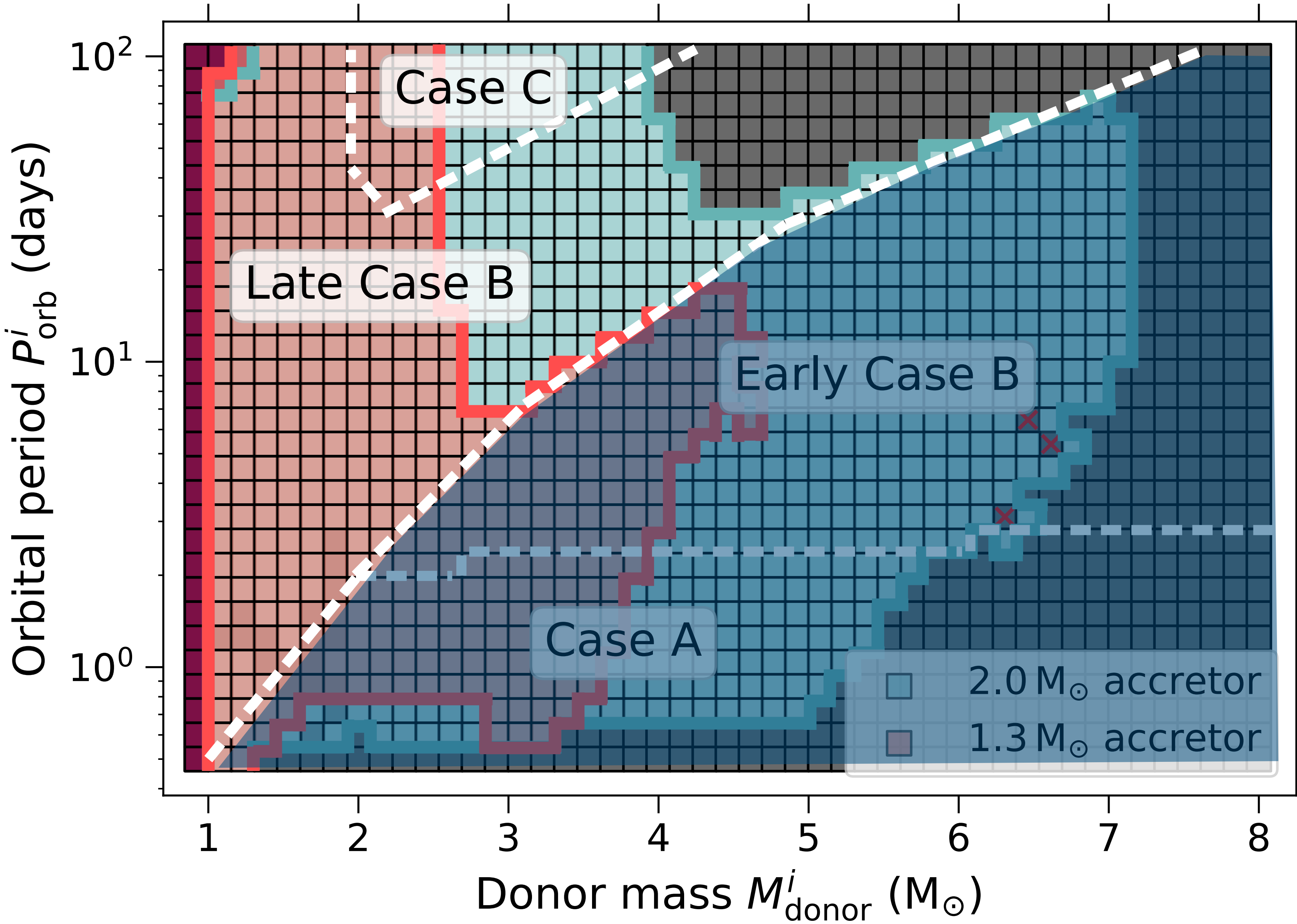

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Stability of mass transfer

- Response of donor to mass loss depends on its structure

Radiative envelopes → Contract

Convective envelopes → Expand or stay constant

Critical mass ratio for dynamical instability from analytical estimates:

Defining $q = \frac{M_{\rm donor}}{M_{\rm acc}}$

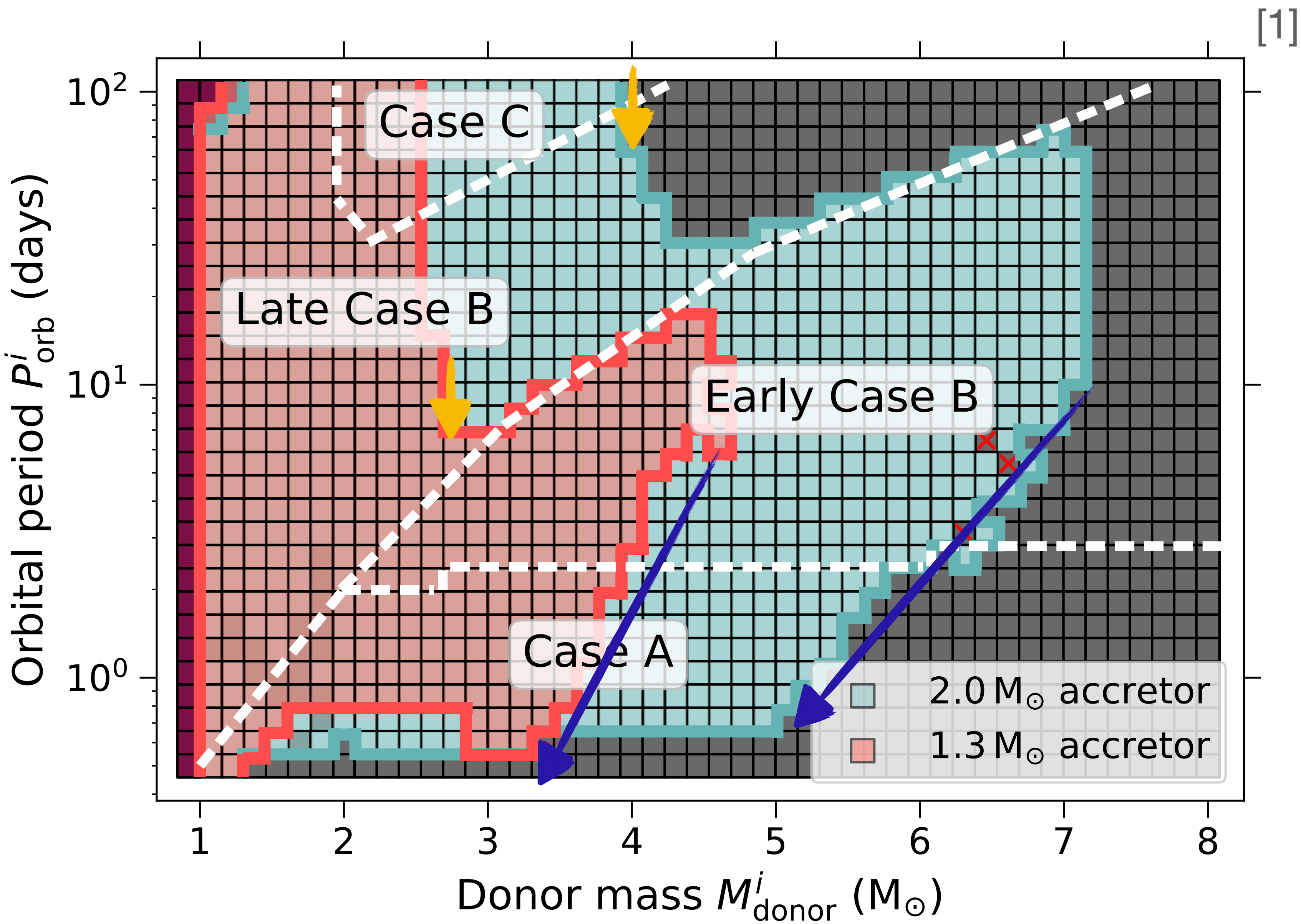
Fully conservative mass transfer with convective donor
(Hjellming & Webbink 1987; Soberman, Phinney & van den Heuvel 1997)

$q_{crit} \sim 0.78$

Mass transfer with radiative donor
(Ivanova & Taam 2004; Ge et al. 2010)

$q_{crit} \sim 3.5$

Stable mass transfer parameter space



Defining $q = \frac{M_{donor}}{M_{acc}}$

Radiative envelope:

q^{rad}_{crit}~[2.5, 3.5]

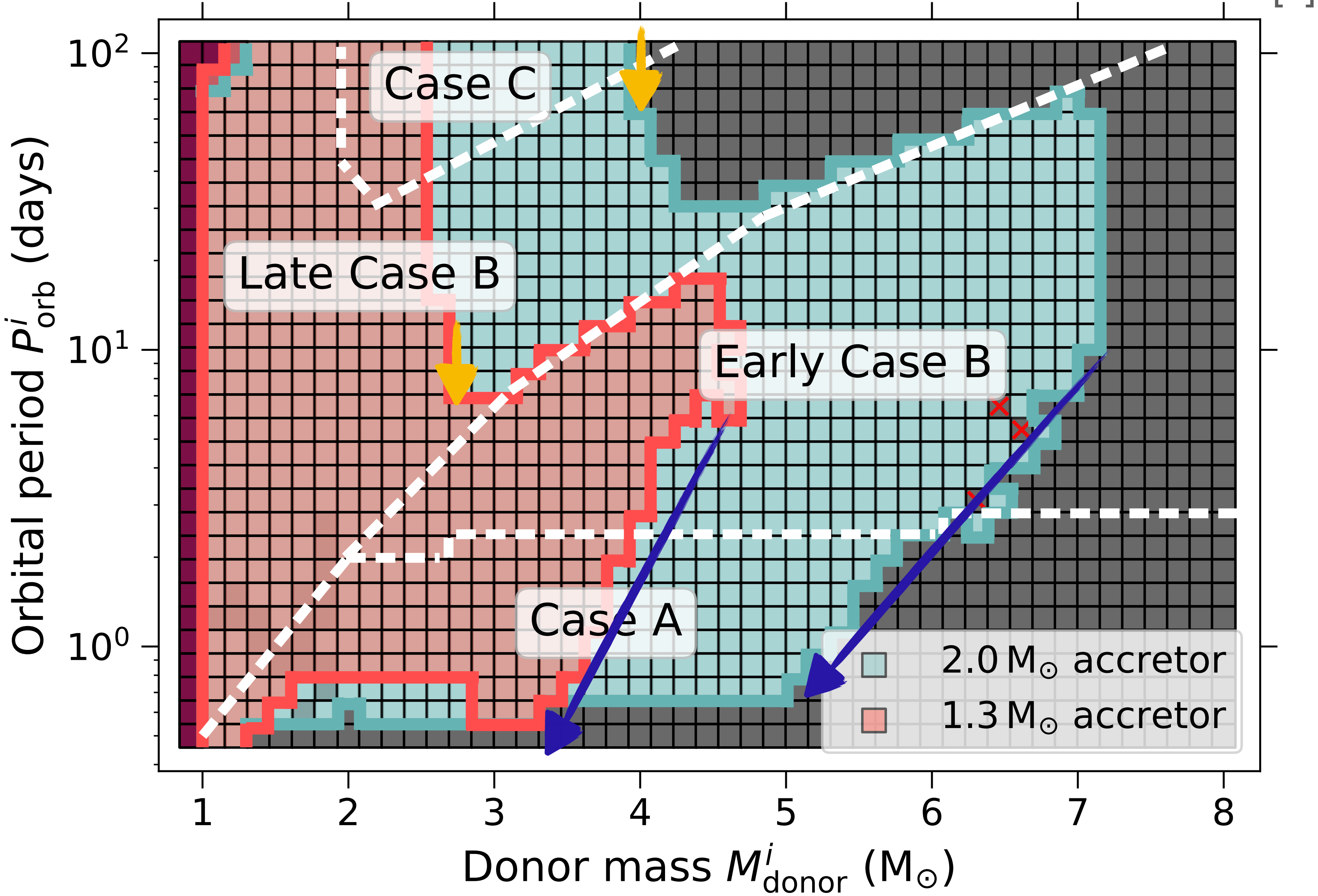
Convective envelope:

q^{conv}_{crit}~2.0

Qualitatively agrees with Tauris et al. (2000) and Shao & Li (2012)

[1] Misra et al. (2020)

Stable mass transfer parameter space



Defining $q = \frac{M_{donor}}{M_{acc}}$

Radiative envelope:

q^{rad}_{crit}~[2.5, 3.5]

Convective envelope:

q^{conv}_{crit}~2.0

Fully conservative mass transfer with convective donor

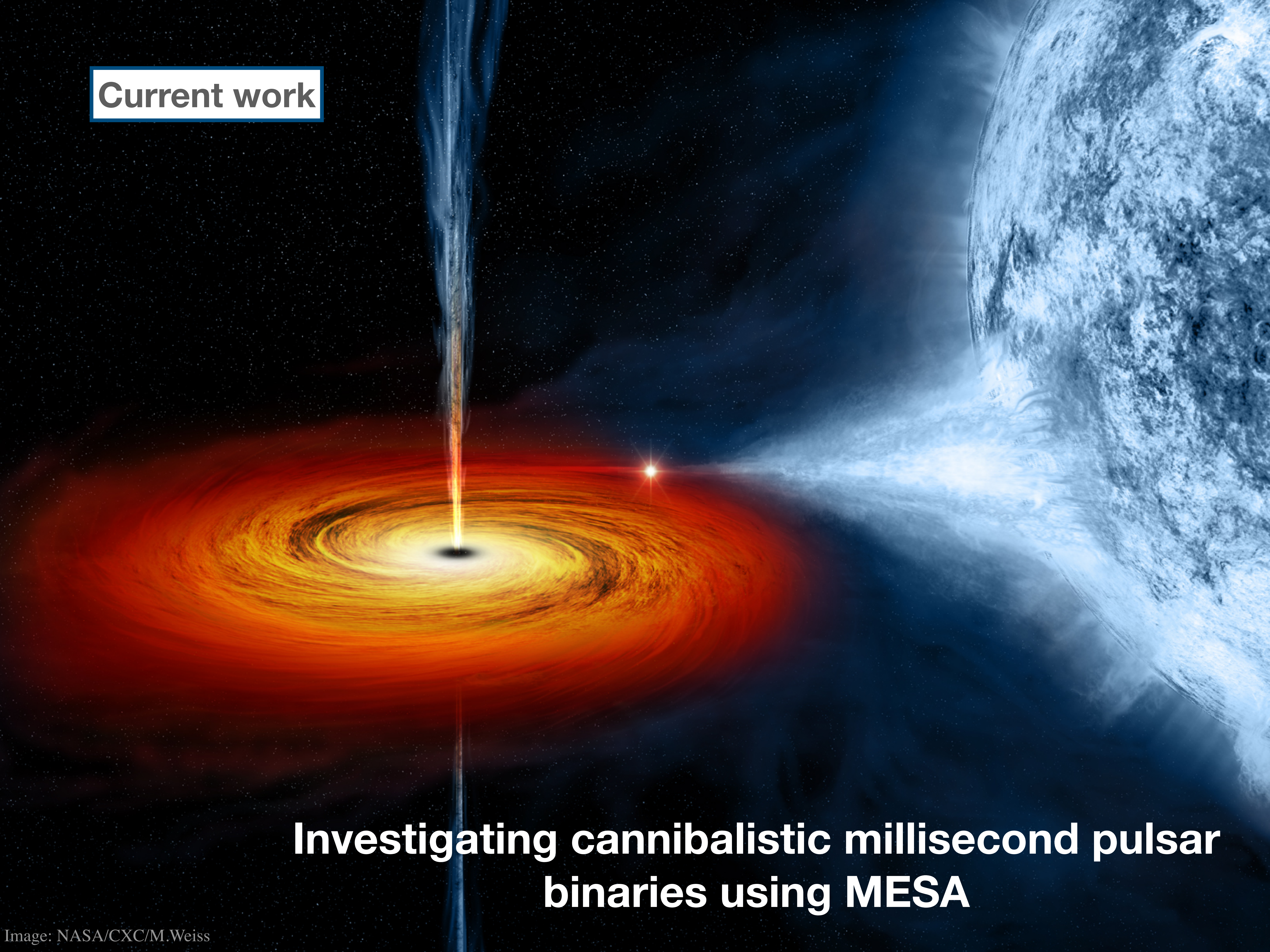
q_{crit} ~0.78

Mass transfer with radiative donor

q_{crit} ~ 3.5

Detailed modelling is critical!

[1] Misra et al. (2020)

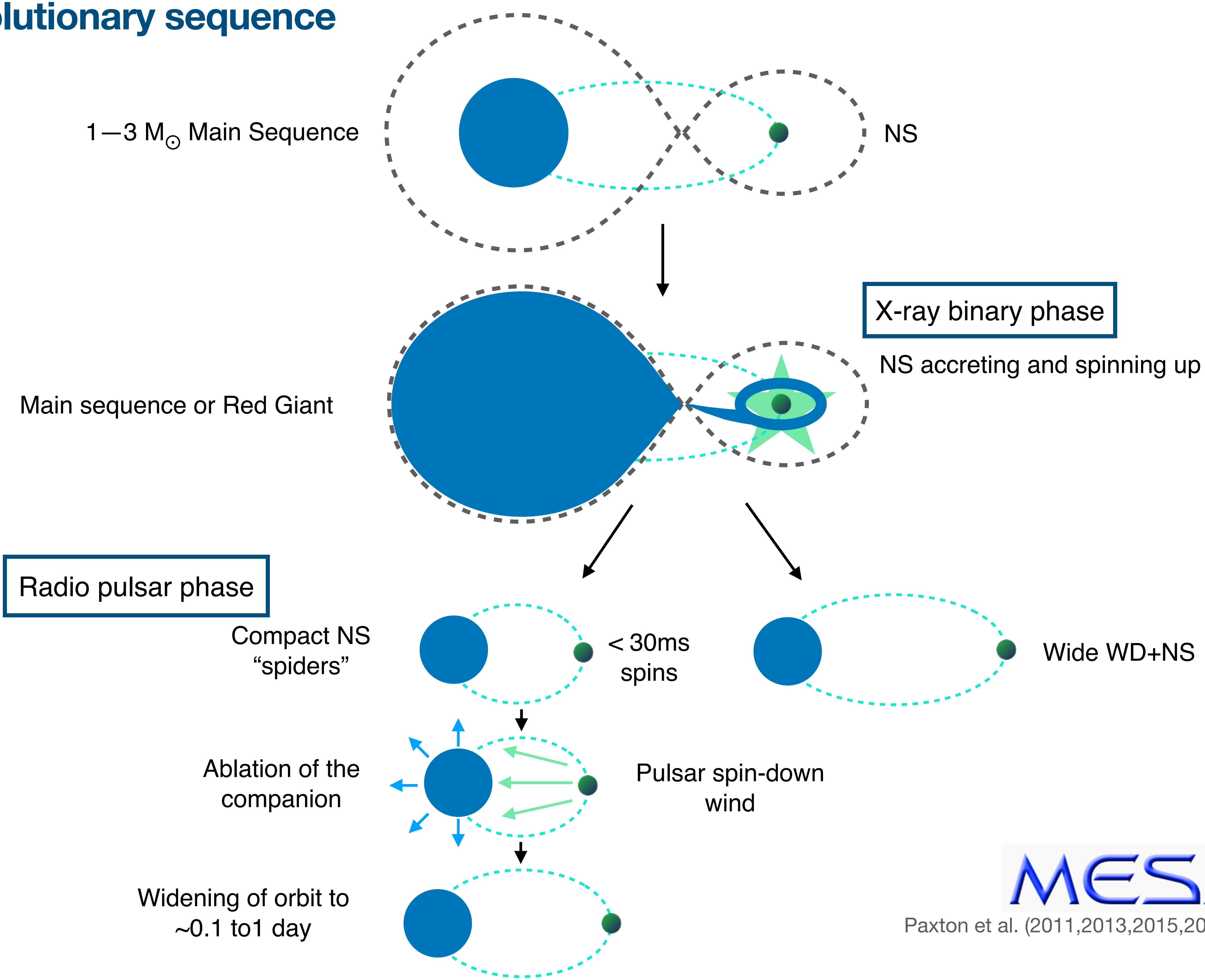


Current work

Investigating cannibalistic millisecond pulsar binaries using MESA

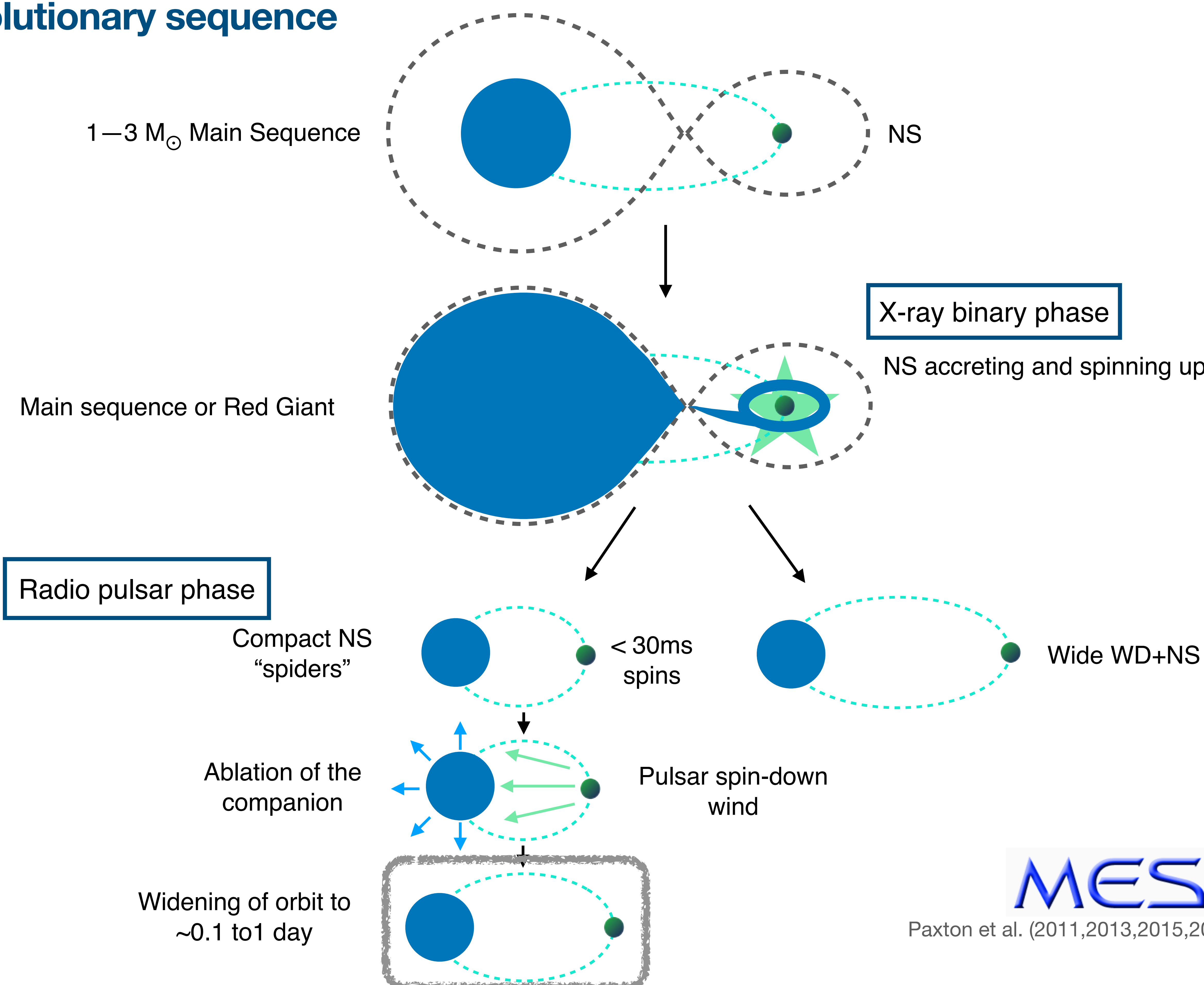
Image: NASA/CXC/M.Weiss

Evolutionary sequence



Paxton et al. (2011,2013,2015,2018,2019)

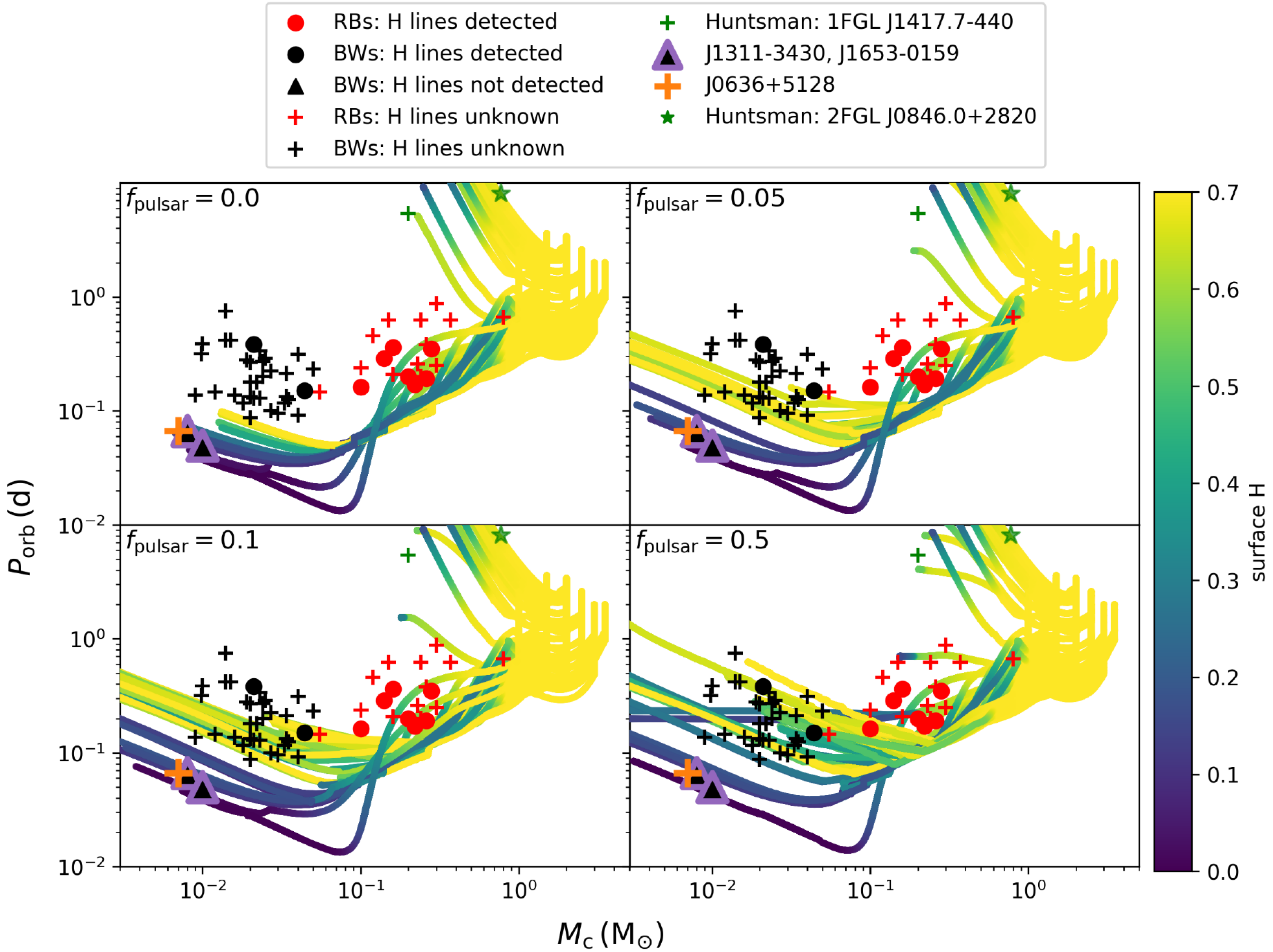
Evolutionary sequence



MESA

Paxton et al. (2011,2013,2015,2018,2019)

Evolution of spiders



Check here!

Misra et al. (2024) submitted

Binary evolution and X-ray binaries:
Theory and simulations

Image: NASA/CXC/M.Weiss

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