Exploring the nature of ultra-luminous X-ray sources across stellar population ages using detailed binary evolution calculations

Devina Misra

NTNU
Norwegian University of Science and Technology

Observatoire de Genève
Fondé en 1772

Image: NASA/CXC/M.Weiss

Ultra-luminous X-ray sources (ULXs)

10^{38} erg s^{-1} < L_X (> 10^{39} erg s^{-1}) < 10^{42} erg s^{-1} [1]
(L_{XRB}) (L_{AGN})

Eddington limit

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

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

[1] Fabbiano et al. (1989)

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

Pulsating ULXs

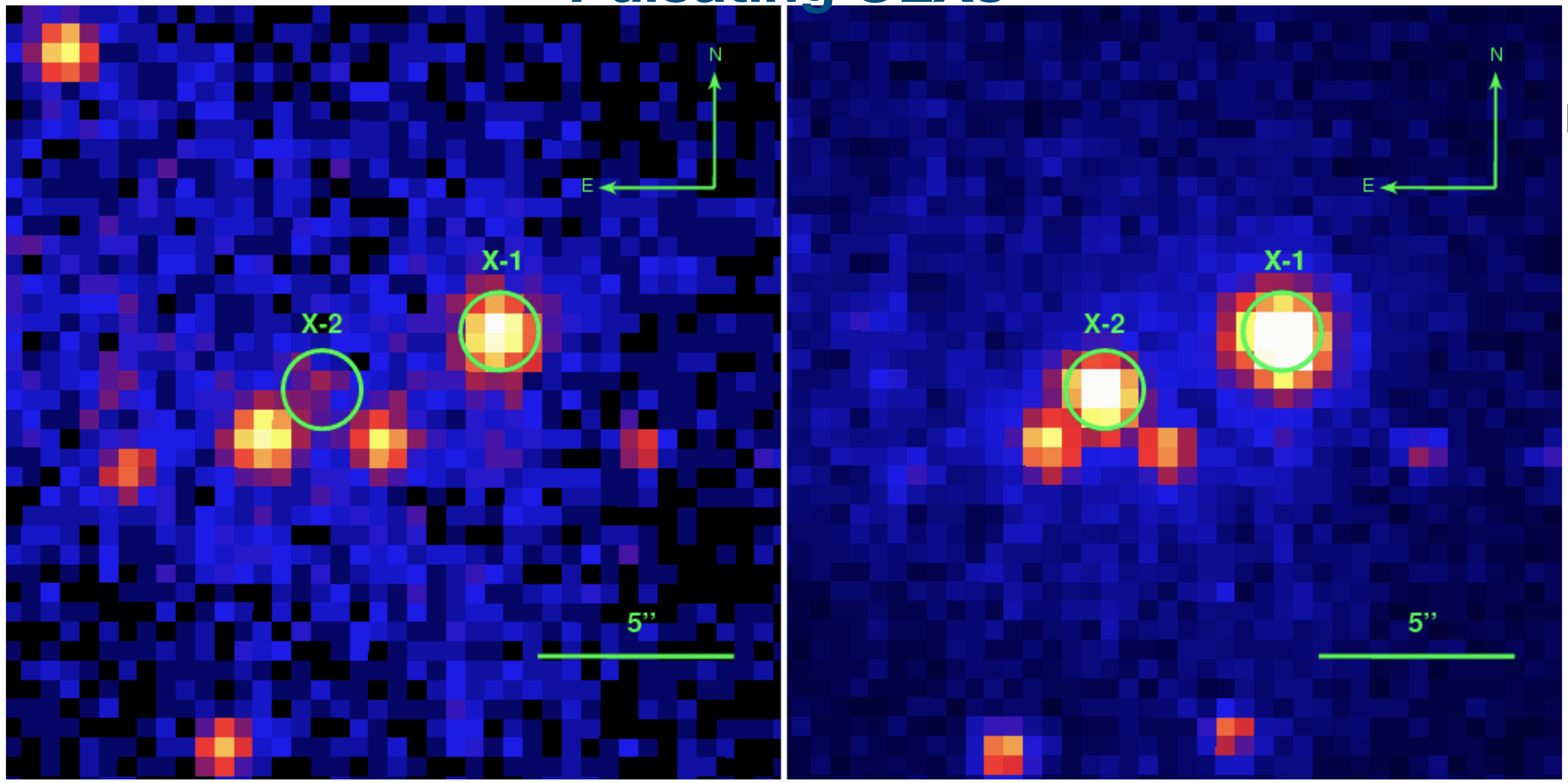
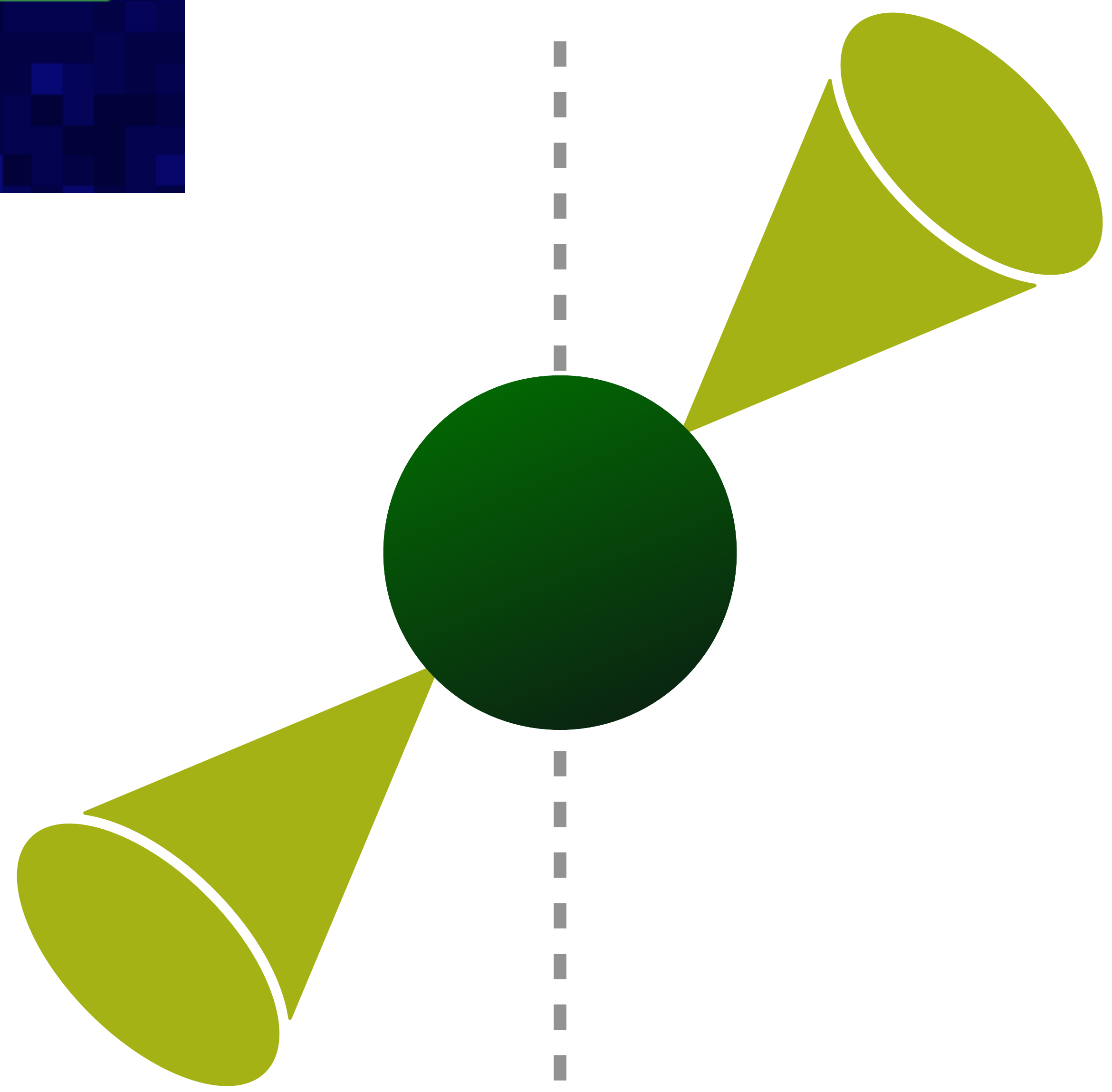


Image: Tsygankov S. et al. (2016)

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

$L_{\mathrm{Edd}}(1.4 M_{\odot}$ NS) ≈ 10^{38} erg s^{-1}



[1] Bachetti et al. (2014)

Pulsating ULXs

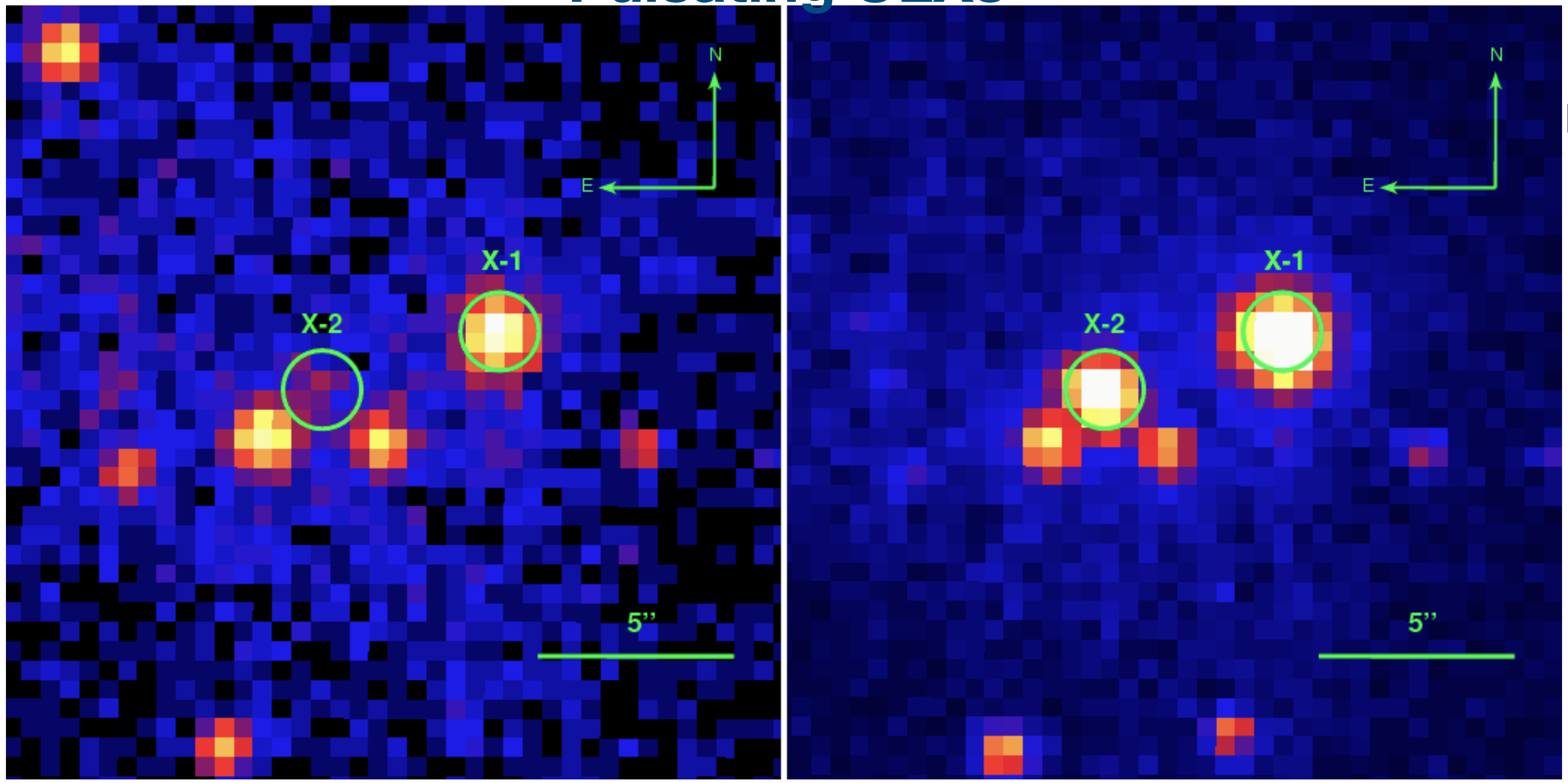
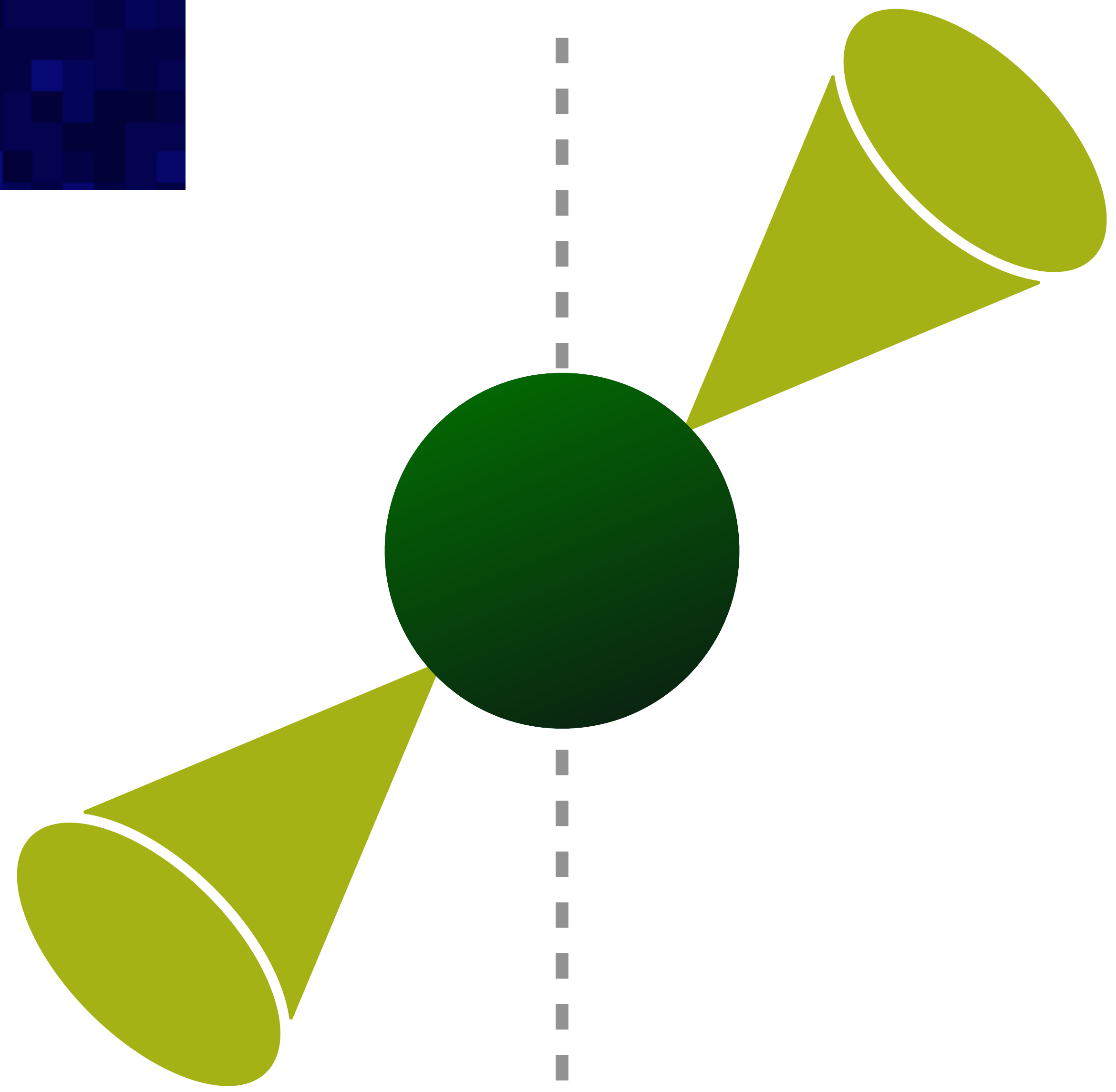


Image: Tsygankov S. et al. (2016)

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

$L_{Edd}(1.4M_{\odot}$ NS) ≈ 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)

=> Part of ULX have NS accretors

[1] Bachetti et al. (2014)

Populations synthesis study of ULXs [2]

Fragos et al. (2023)

- 10^7 initial ZAMS binaries
- Instantaneous burst star formation ages of 5, 10, 40, 100, 300, and 1000 Myr

[1]

Parameters	Model A	Model B
Remnant mass prescription	Patton & Sukhbold (2020)	Patton & Sukhbold (2020)
Natal kick normalization	BH mass normalized kicks	No kick normalization
Orbit circularization at RLO	Conserved angular momentum	Conserved angular momentum
CE efficiency (α_{CE}).	1.0	0.3
CE core-envelope boundary	At $X_H = 0.30$	At $X_H = 0.30$
Observable wind-fed disk	Hirai & Mandel (2021)	No criterion

[1] Misra et al. (2023)

[2] Misra et al. (2024)

Populations synthesis study of ULXs [2]

POSEIDON

Fragos et al. (2023)

- 10^7 initial ZAMS binaries
- Instantaneous burst star formation ages of 5, 10, 40, 100, 300, and 1000 Myr

[1]

Parameters	Model A	Model B
Remnant mass prescription	Patton & Sukhbold (2020)	Patton & Sukhbold (2020)
Natal kick normalization	BH mass normalized kicks	No kick normalization
Orbit circularization at RLO	Conserved angular momentum	Conserved angular momentum
CE efficiency (α_{CE}).	1.0	0.3
CE core-envelope boundary	At $X_H = 0.30$	At $X_H = 0.30$
Observable wind-fed disk	Hirai & Mandel (2021)	No criterion

⇨ **Check out my poster!!!**
No. 17

[1] Misra et al. (2023)
[2] Misra et al. (2024)

Populations synthesis study of ULXs [2]

POSEIDON

Fragos et al. (2023)

- 10^7 initial ZAMS binaries
- Instantaneous burst star formation ages of 5, 10, 40, 100, 300, and 1000 Myr

[1]

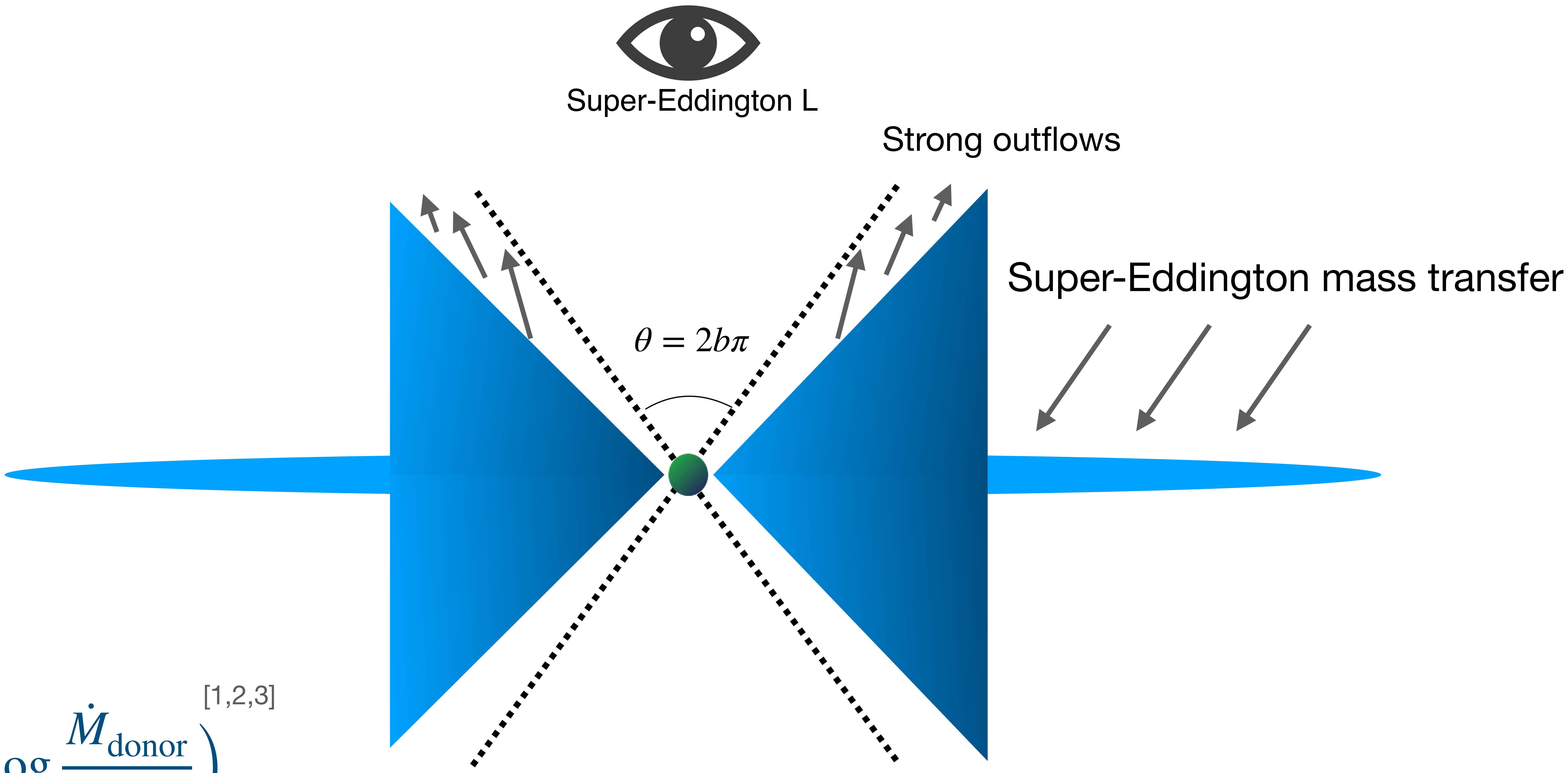
Parameters	Model A	Model B
Remnant mass prescription	Patton & Sukhbold (2020)	Patton & Sukhbold (2020)
Natal kick normalization	BH mass normalized kicks	No kick normalization
Orbit circularization at RLO	Conserved angular momentum	Conserved angular momentum
CE efficiency (α_{CE}).	1.0	0.3
CE core-envelope boundary	At $X_H = 0.30$	At $X_H = 0.30$
Observable wind-fed disk	Hirai & Mandel (2021)	No criterion

- The magnitude of the NS kicks imparted are drawn from a Maxwellian distribution with σ = 265.0 km s^{-1}, based on pulsar observations (Hobbs et al. 2005)

[1] Misra et al. (2023)

[2] Misra et al. (2024)

Super-Eddington Accretion Disc



$$L_{\rm acc}^{\rm iso} = \frac{L_{\rm Edd}}{b}\left(1 + \log\frac{\dot{M}_{\rm donor}}{\dot{M}_{\rm Edd}}\right)$$ [1,2,3]

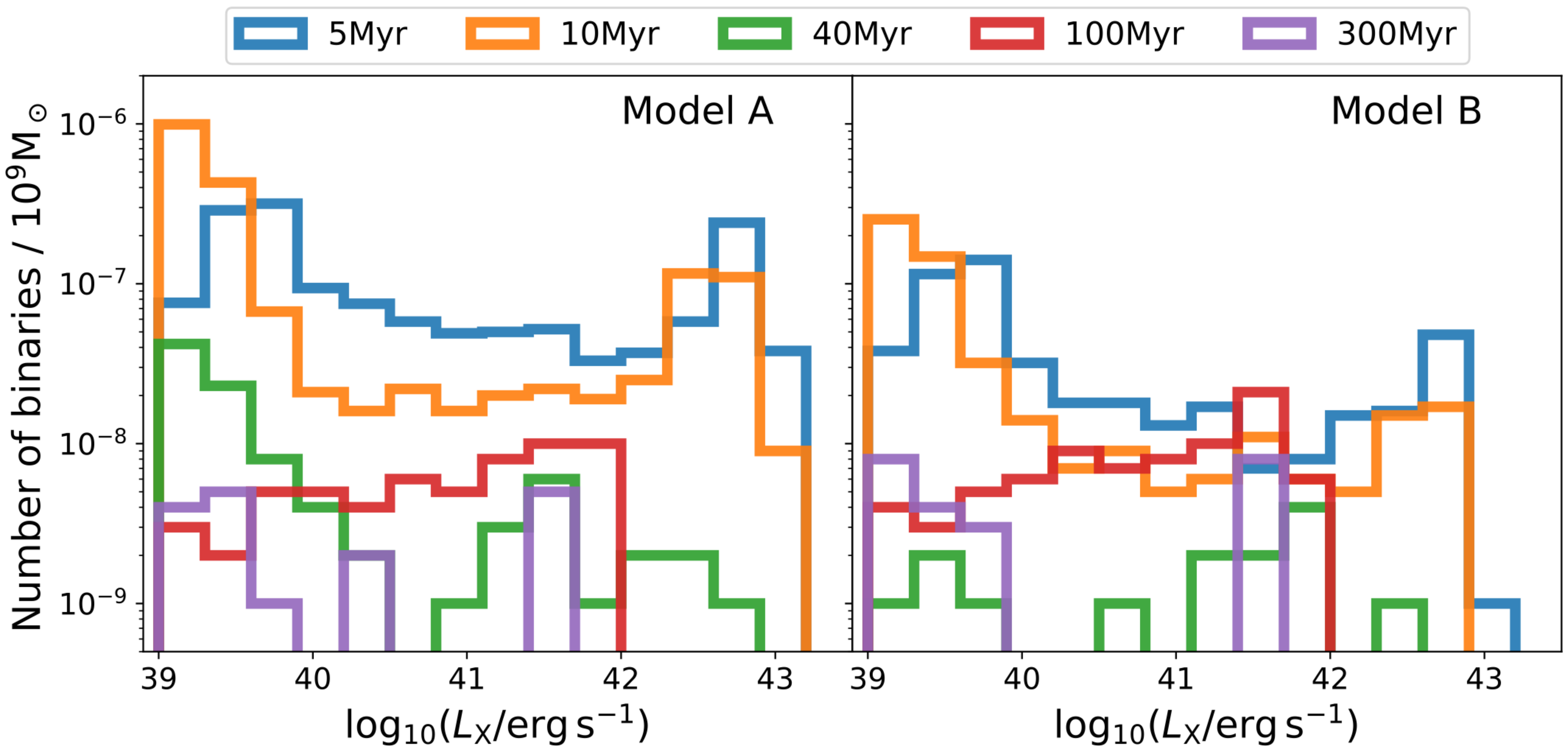
$$\dot{M}_{\rm donor} > 8.5 \times \dot{M}_{\rm Edd} \implies b < 1$$

[1] Shakura & Sunyaev (1973)

[2] King et al. (2001)

[3] King (2009)

Populations synthesis study of ULXs [1]

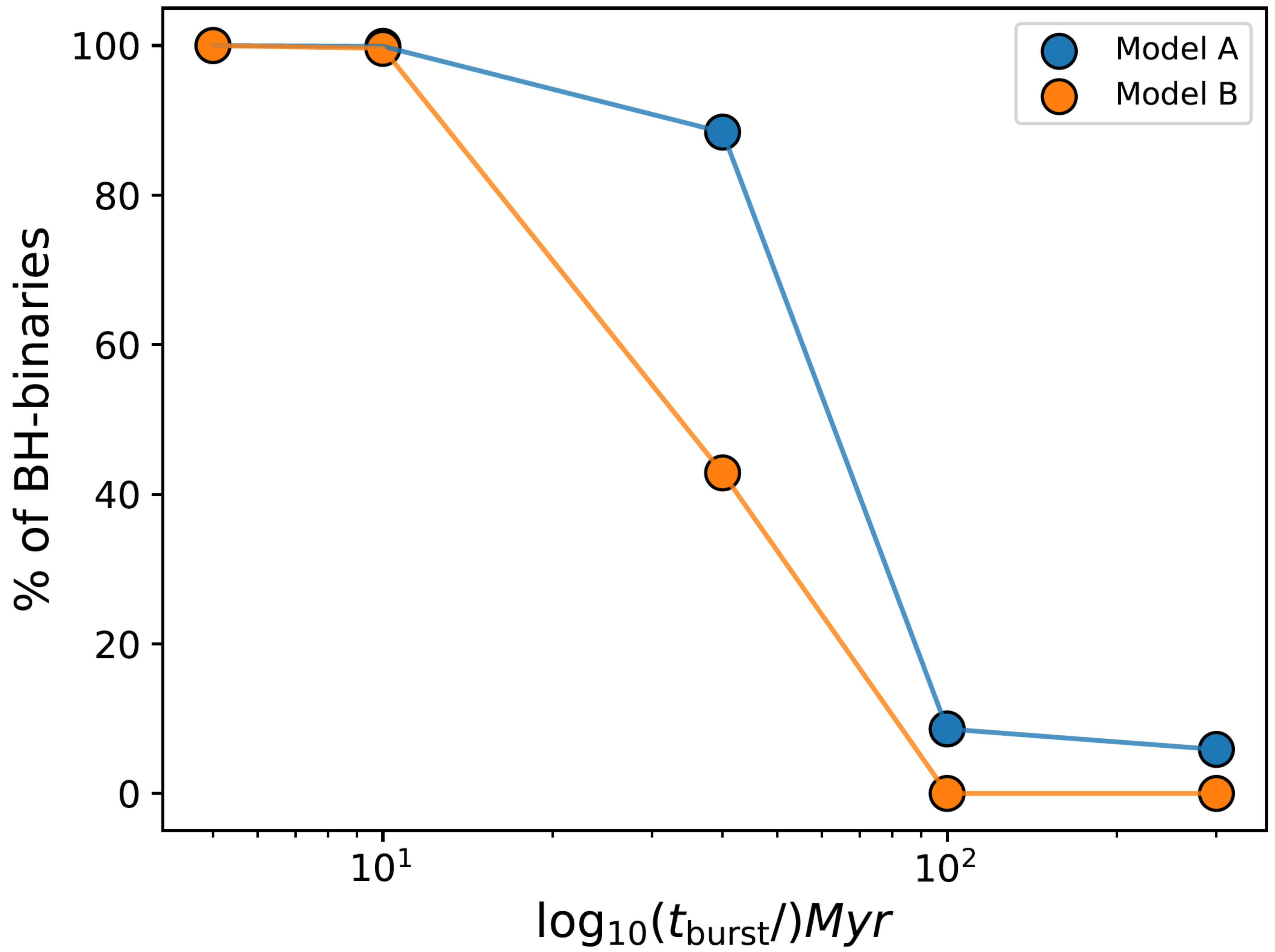


HMXB ---> LMXB

Parameters	Model A	Model B
Natal kick normalization	BH mass normalized kicks	No kick normalization
CE efficiency (α_{CE}).	1.0	0.3

[1] Misra et al. (2024)

Populations synthesis study of ULXs [1]



Nature of the accretors

- BHs decrease with age and NSs start to dominate around 100 Myr
- Model B has less BH binaries due to stronger kicks

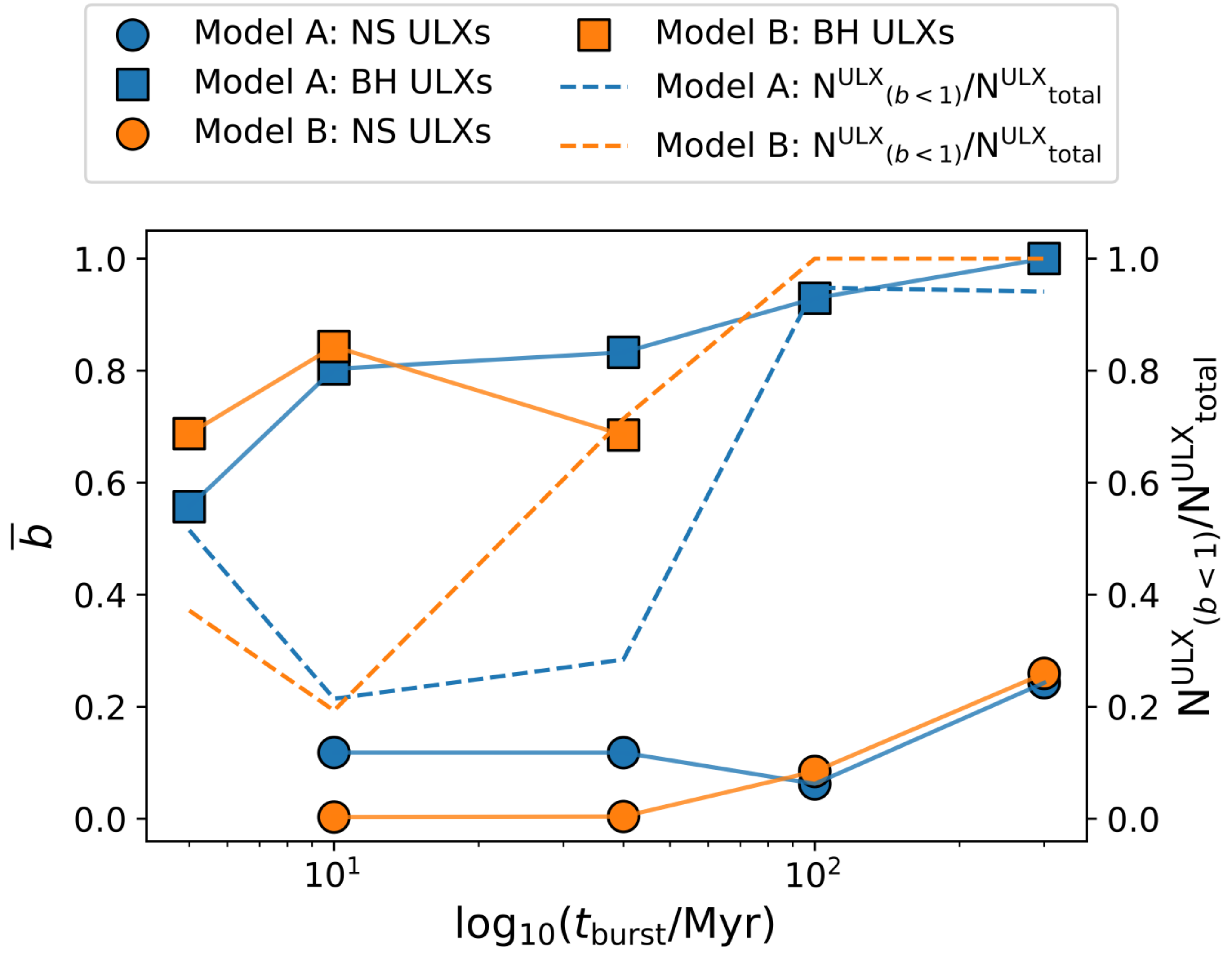
Parameters	Model A	Model B
Natal kick normalization	BH mass normalized kicks	No kick normalization
CE efficiency ($\alpha_{\rm CE}$).	1.0	0.3

[1] Misra et al. (2024)

Populations synthesis study of ULXs [1]

Geometrically beamed emission

- Mean beaming factor denotes the fraction of observed ULXs
- NSs more strongly beamed than BHs



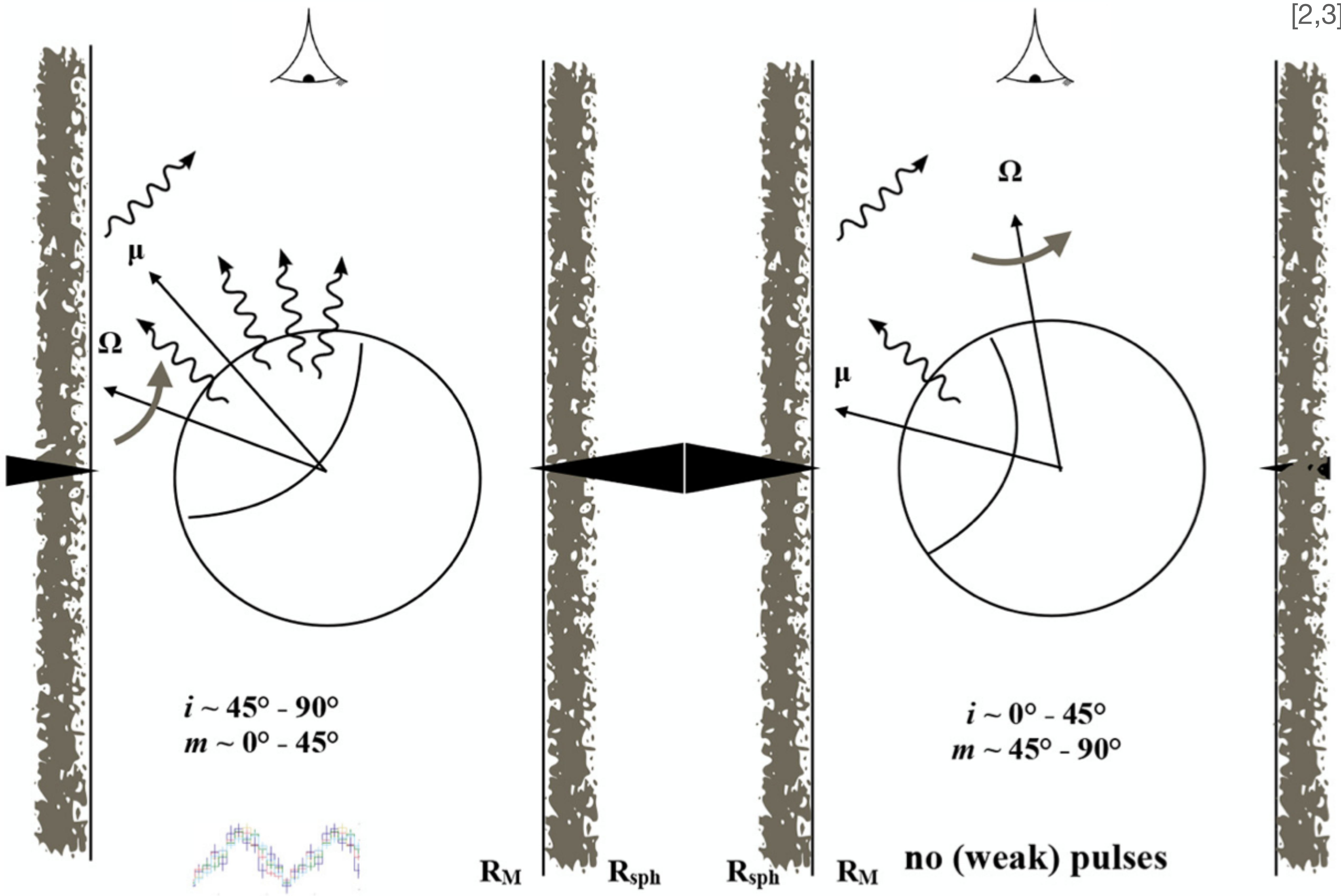
Parameters	Model A	Model B
Natal kick normalization	BH mass normalized kicks	No kick normalization
CE efficiency (α_{CE}).	1.0	0.3

[1] Misra et al. (2024)

Observable pulses in NS-ULXs [1]

- King & Lasota (2020) proposed the suppression of X-ray pulses in NS binaries

[2,3]



[1] Misra et al. (2024)

[2] King and Lasota (2020)

[3] King and Shaviv (1984)

Observable pulses in NS-ULXs [1]

Limits of accreting specific angular momentum

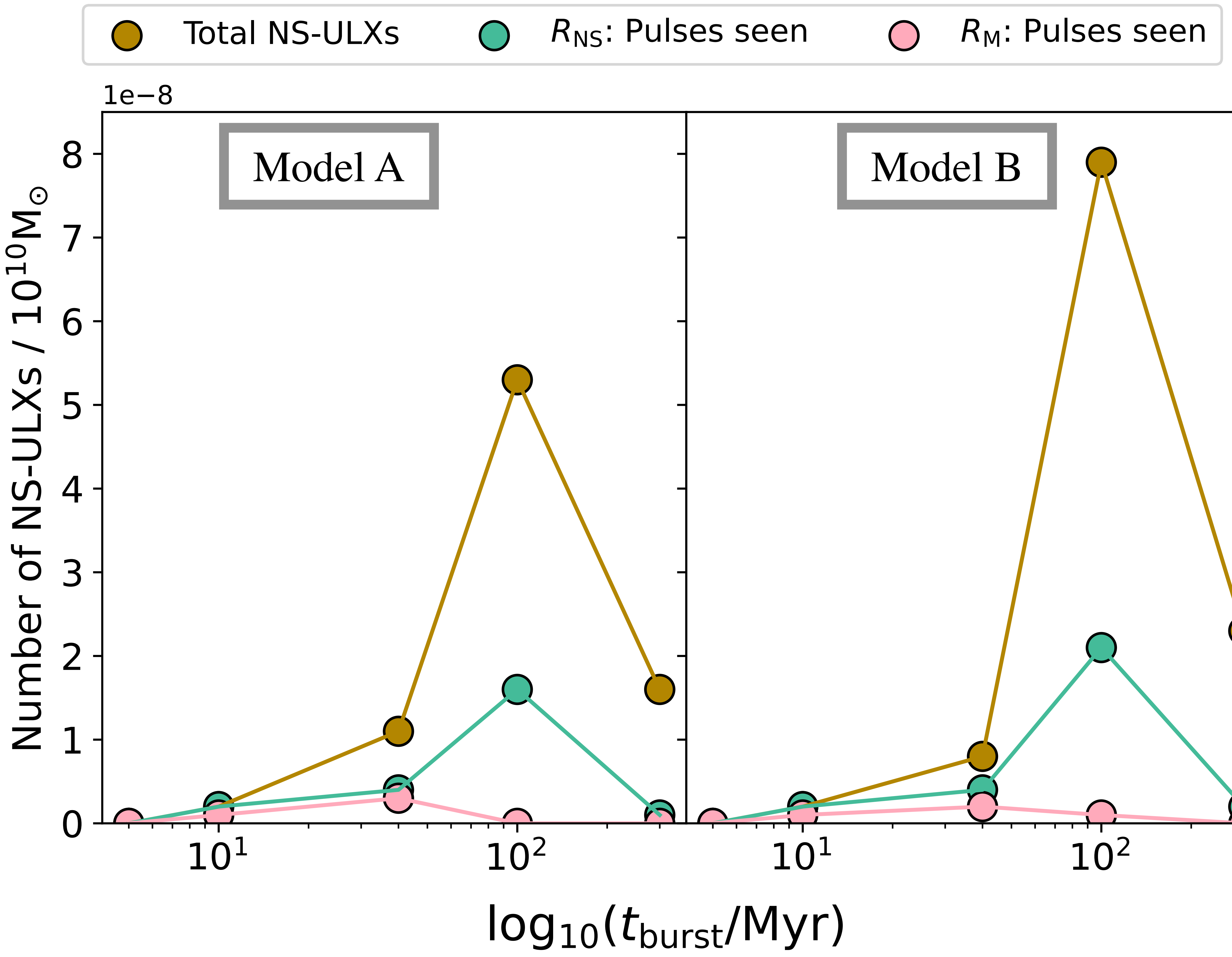
- At the NS radius (12.5km)
  (Most et al. 2018; Riley et al. 2019; Miller et al. 2019; Abbott et al.2020; Landry et al. 2020; Biswas 2021; Kim et al. 2021; Raaijmakers et al. 2021)
- At the magnetospheric radius for a NS with 10^{12} G
  (Frank et al. 2002)

[1] Misra et al. (2024)

Observable pulses in NS-ULXs [1]

Limits of accreting specific angular momentum

- At the NS radius (12.5km)
  (Most et al. 2018; Riley et al. 2019; Miller et al. 2019; Abbott et al.2020; Landry et al. 2020; Biswas 2021; Kim et al. 2021; Raaijmakers et al. 2021)
- At the magnetospheric radius for a NS with 10^{12} G
  (Frank et al. 2002)



[1] Misra et al. (2024)

Exploring the nature of ultra-luminous X-ray sources across stellar population ages using detailed binary evolution calculations

https://arxiv.org/abs/2309.15904

Key takeaway

ULX populations depend on the assumptions of physics and age, affecting various aspects of ULXs like properties of accretors, beamed emission, and observations of pulses

Thank you for your attention!

Devina Misra

NTNU
Norwegian University of Science and Technology

OBSERVATOIRE DE GENÈVE
FONDÉ EN 1772

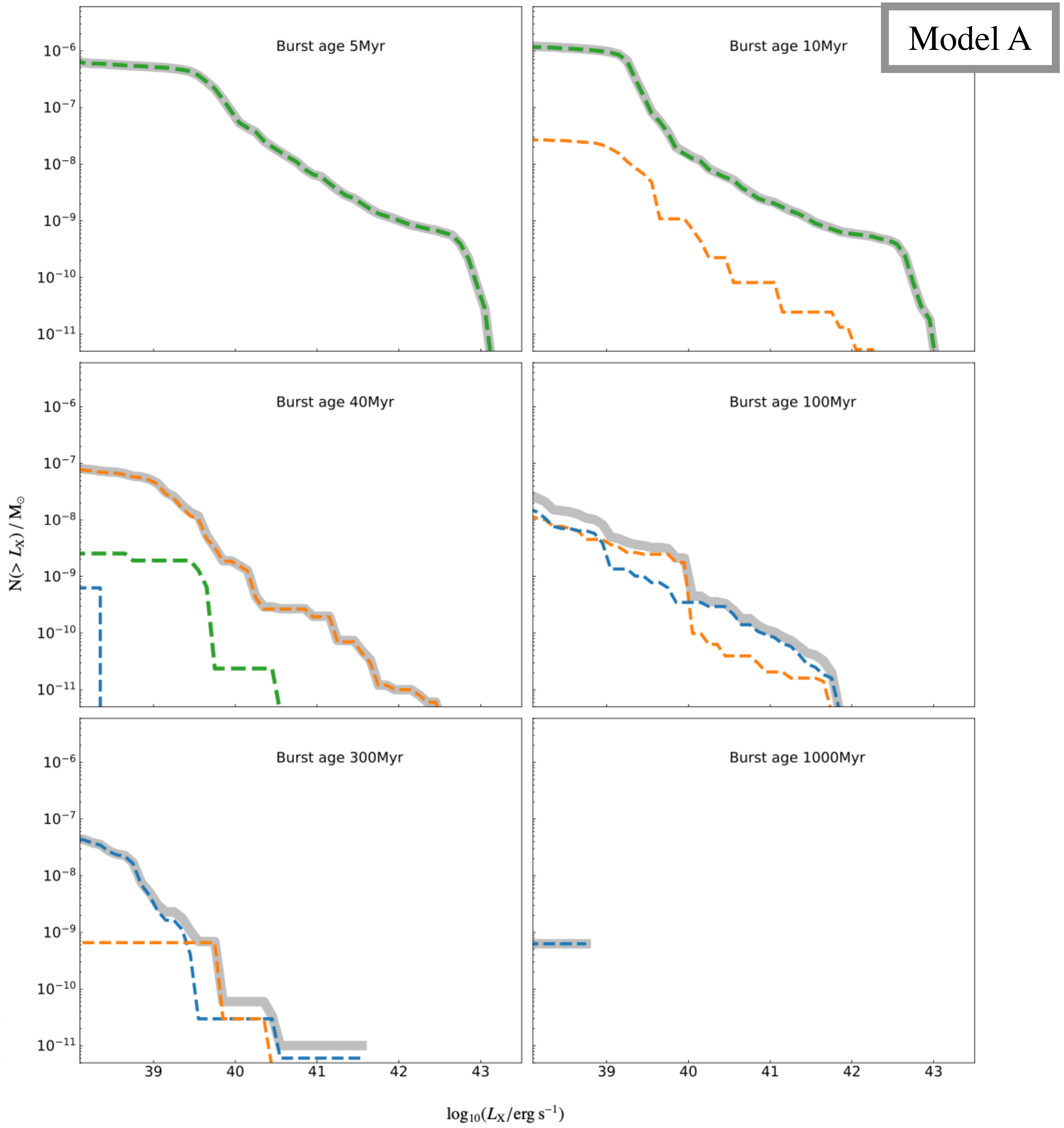
Image: NASA/CXC/M.Weiss

Populations synthesis study of ULXs [1]

- Intermediate mass stars in the range of 2 to 8 $M_{\odot}$

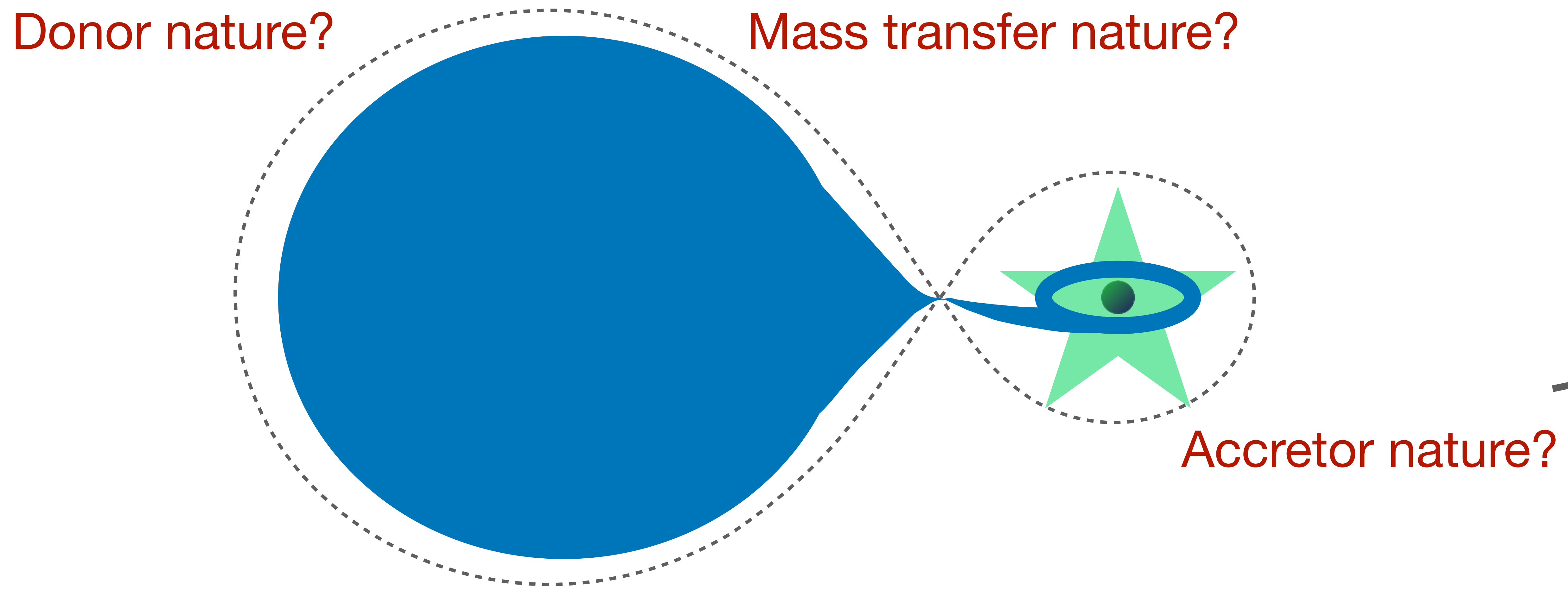
M82 X-2

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	$< 60^{\circ}$



[1] Misra et al. (2024)

Ultra-luminous X-ray sources (ULXs)

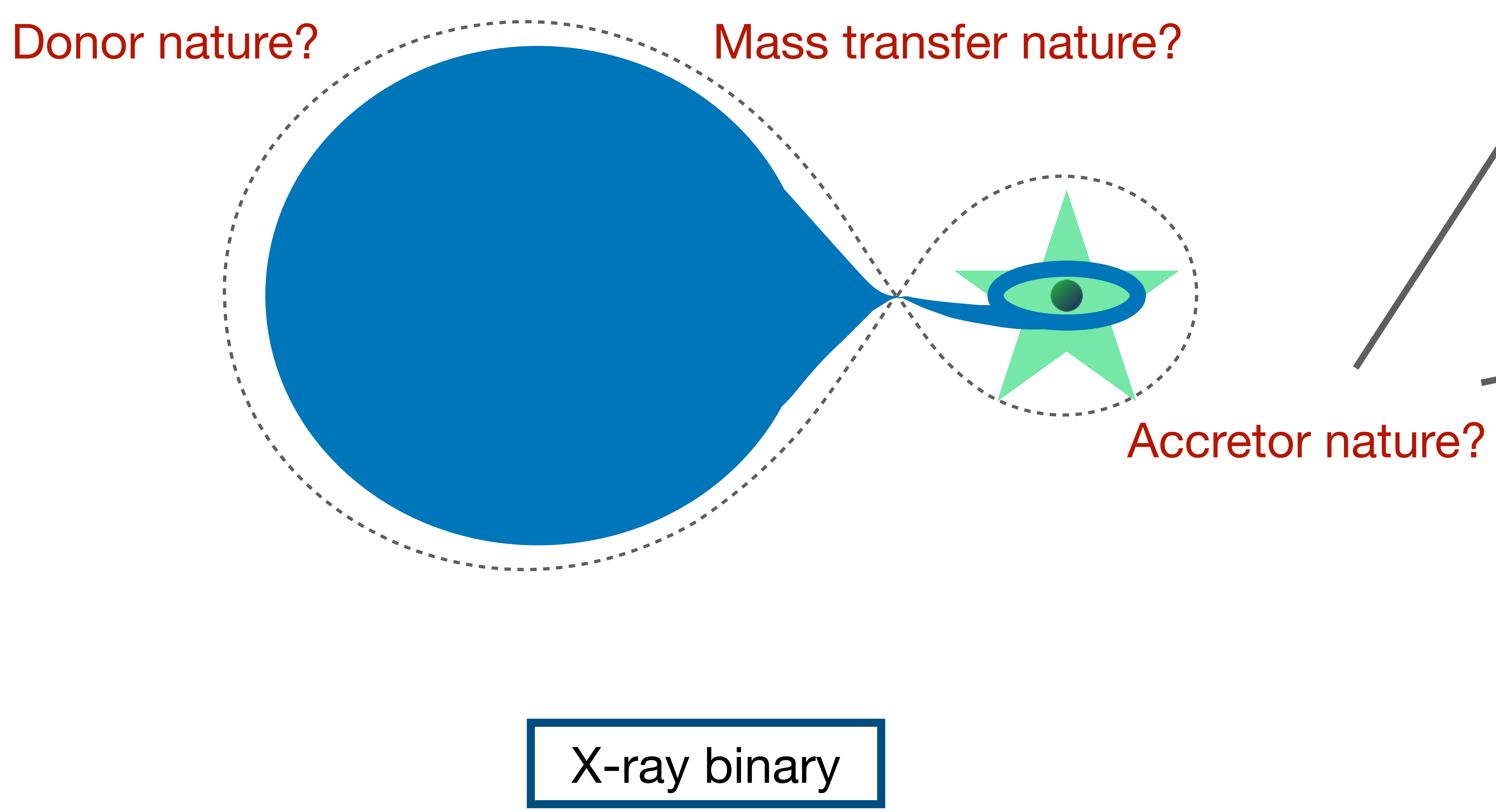


X-ray binary

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)
- GW190521 (Abbott et al. 2020)

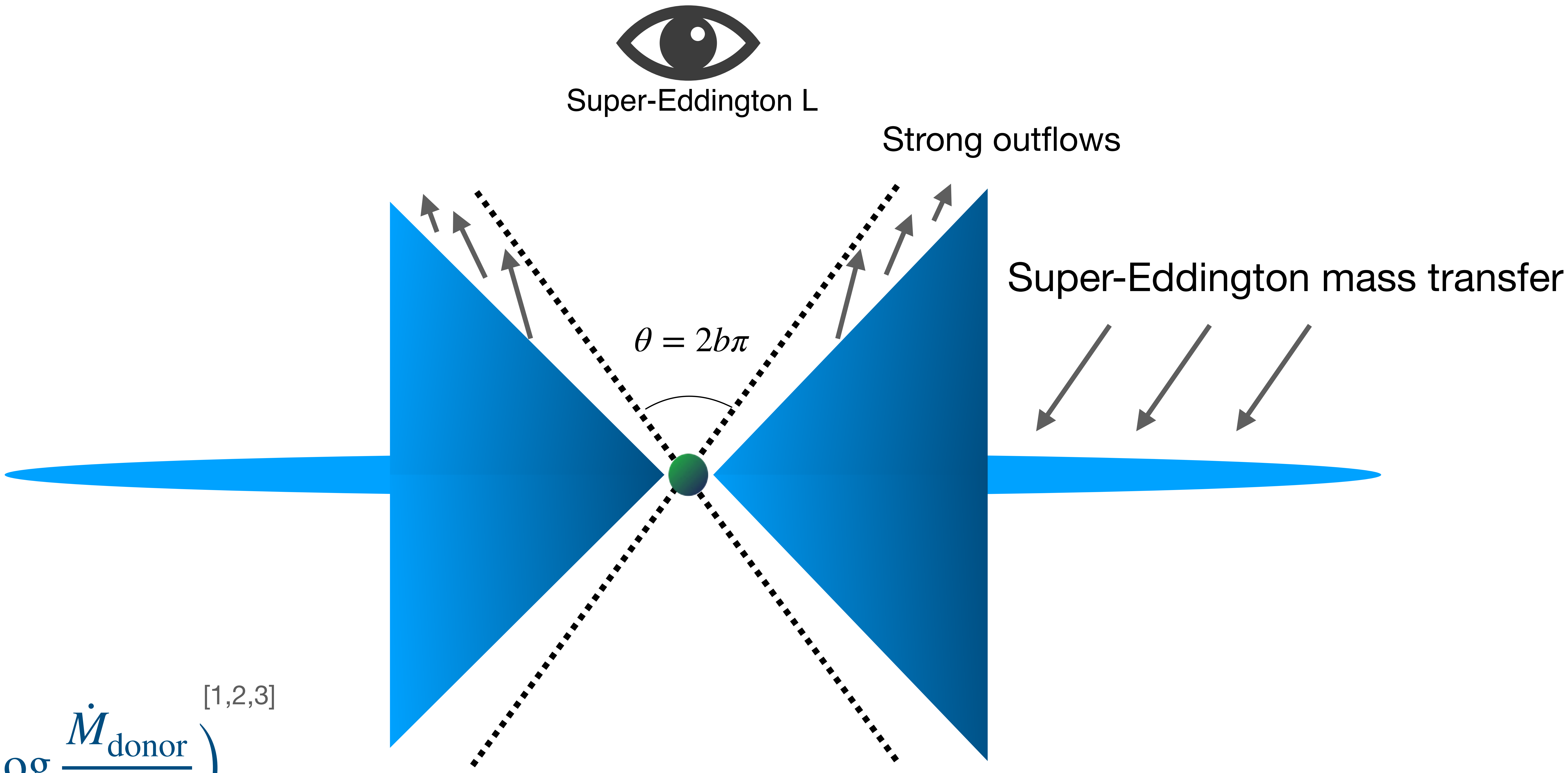
Ultra-luminous X-ray sources (ULXs)



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

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

Super-Eddington Accretion Disc

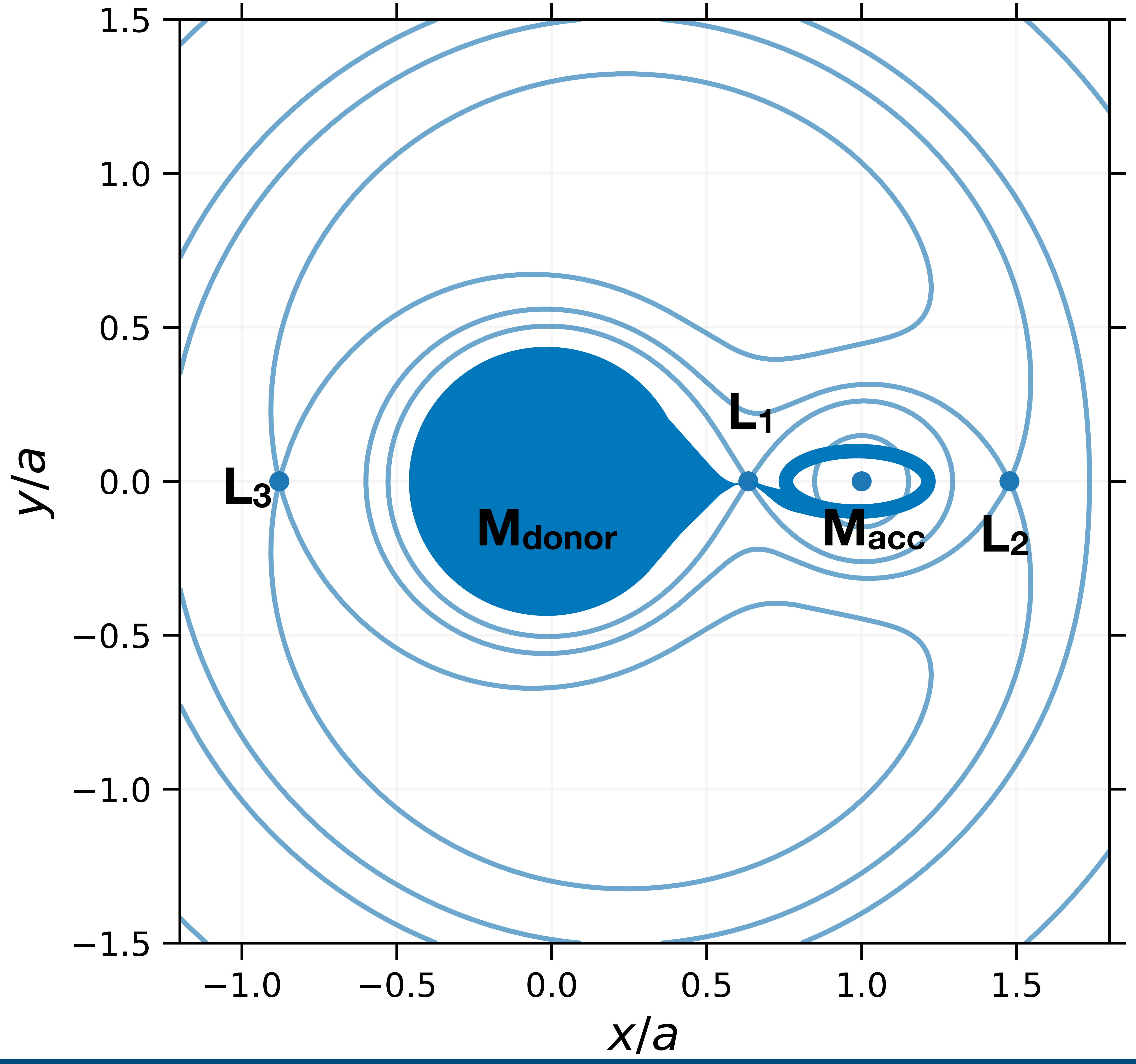


$$L_{\rm acc}^{\rm iso} = \frac{L_{\rm Edd}}{b}\left(1 + \log\frac{\dot{M}_{\rm donor}}{\dot{M}_{\rm Edd}}\right)$$ [1,2,3]

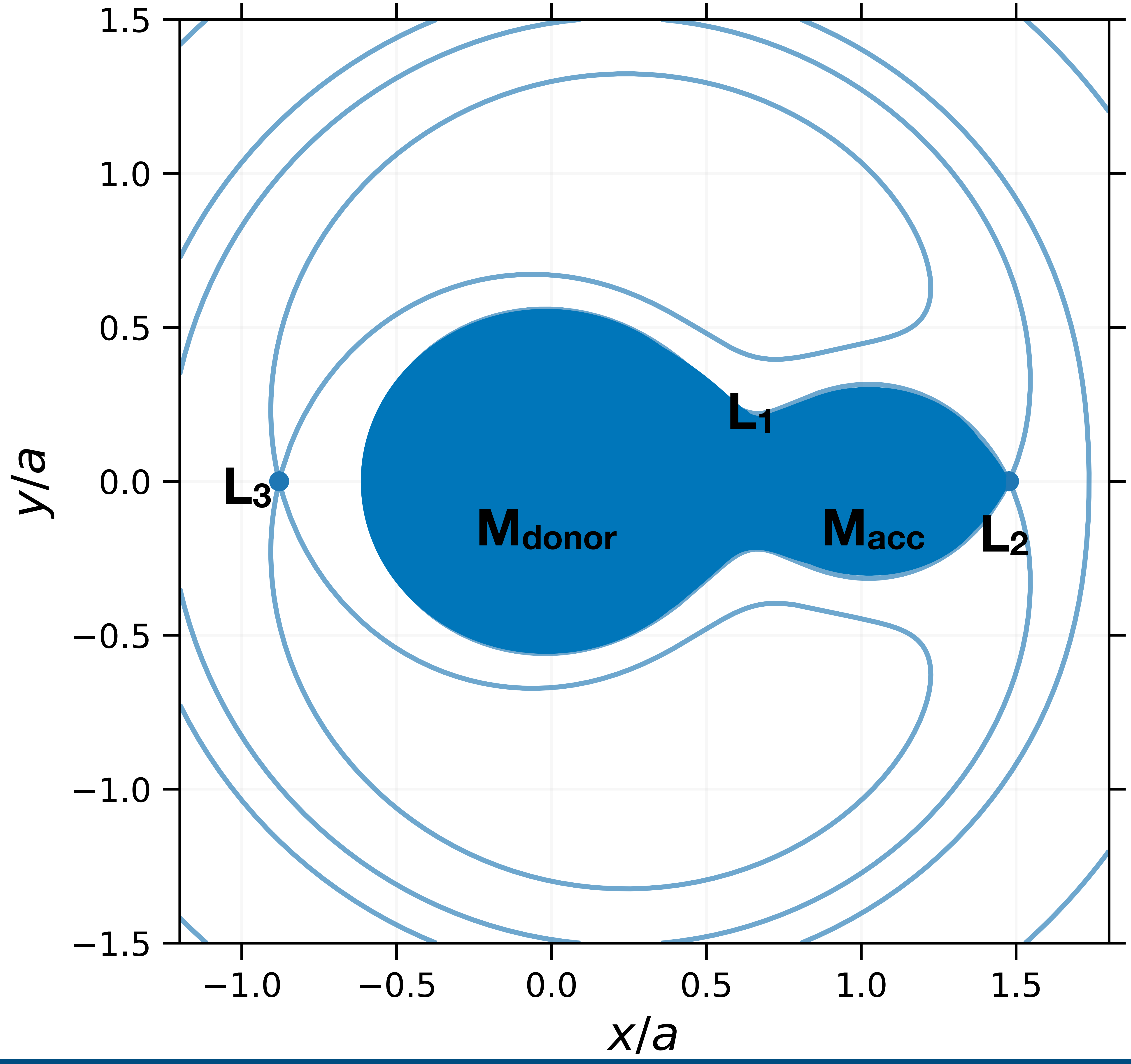
$$\dot{M}_{\rm donor} > 8.5 \times \dot{M}_{\rm Edd} \implies b < 1$$

[1] Shakura & Sunyaev (1973)
[2] King et al. (2001)
[3] King (2009)

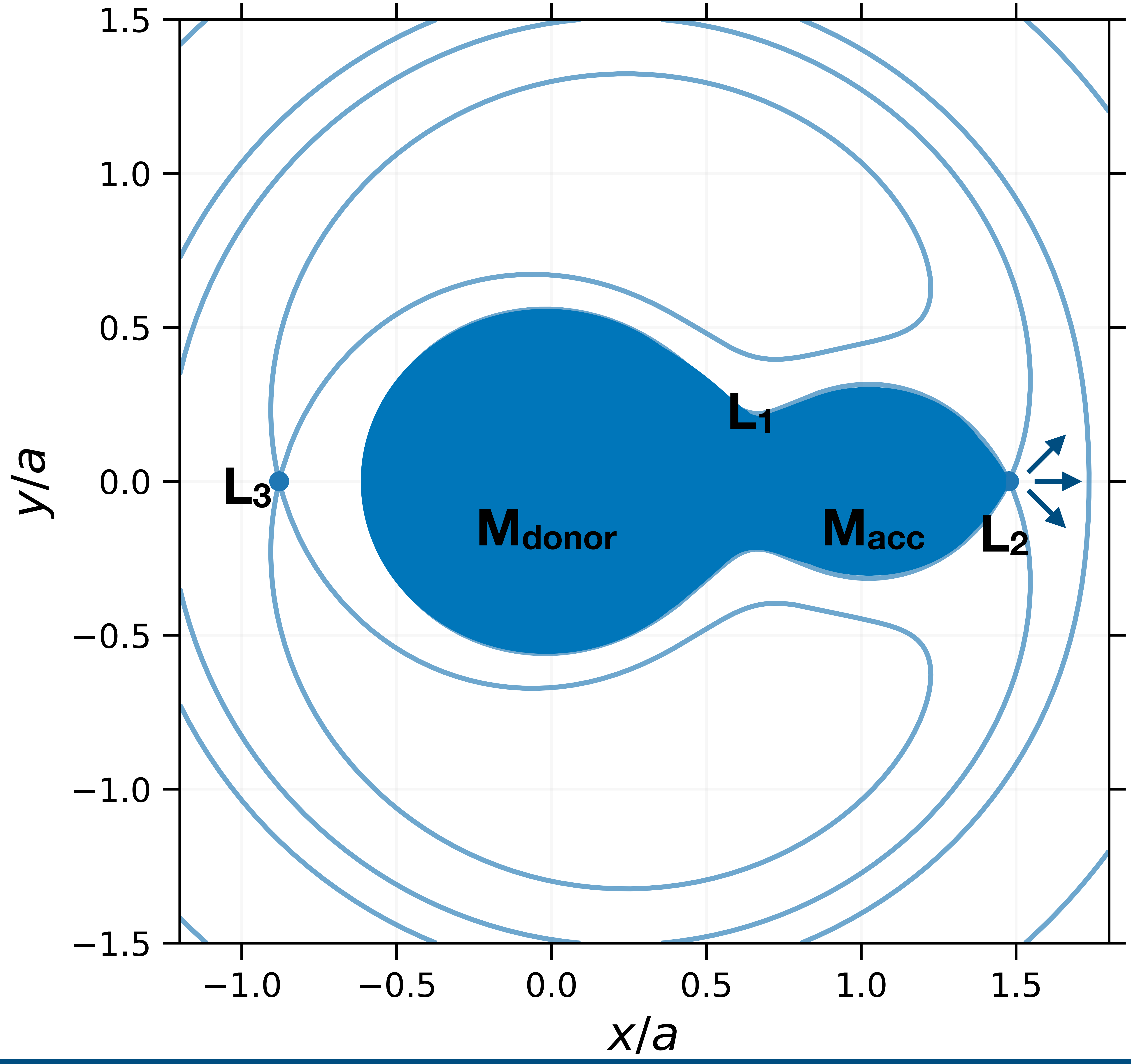
Stability of RLO mass transfer



Stability of RLO mass transfer



Stability of RLO mass transfer



Ultra-luminous X-ray sources (ULXs)

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

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

How do they attain their bright luminosities?

How were they formed?

[1] Fabbiano et al. (1989)

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

Pulsating ULXs

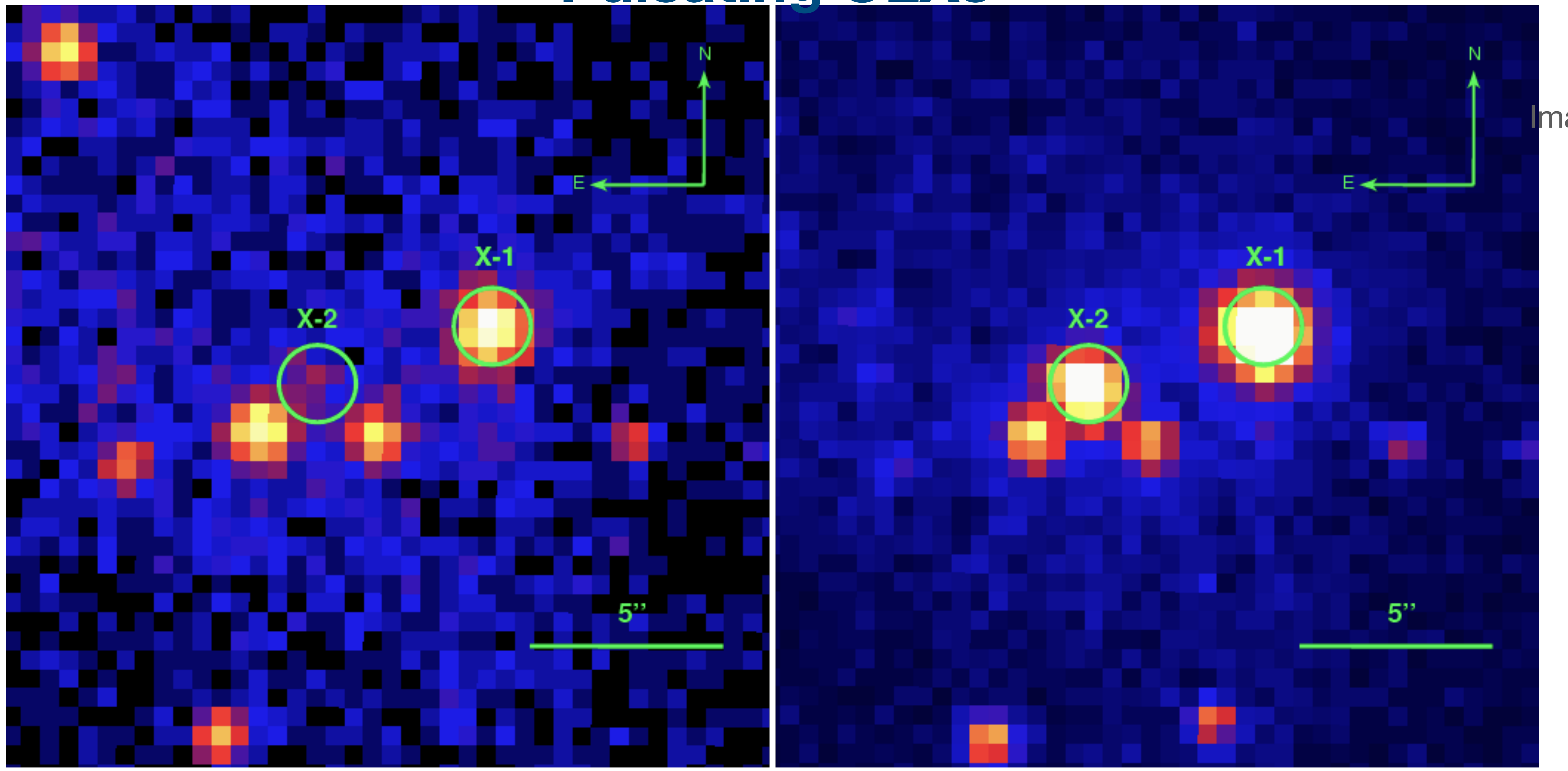
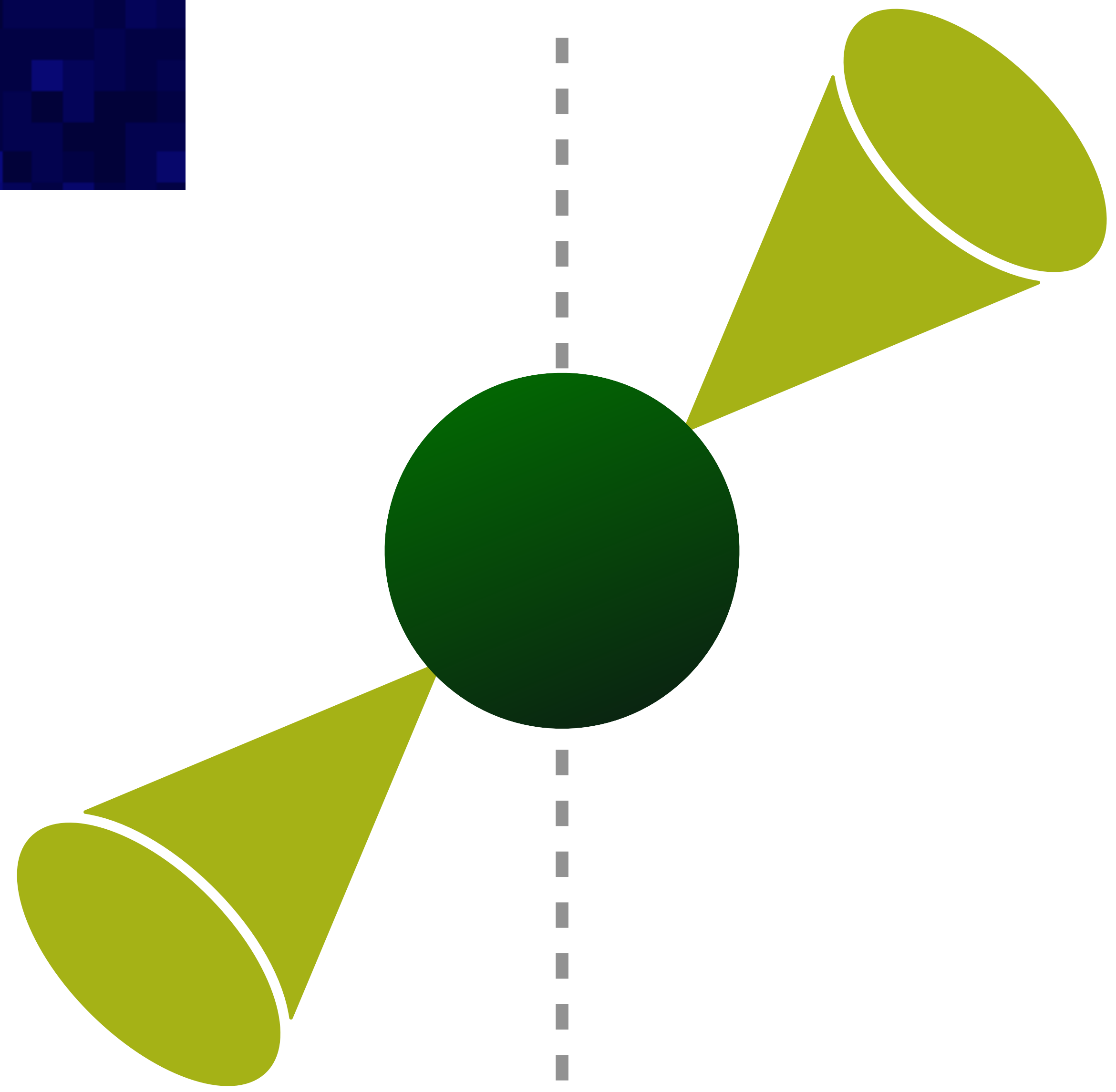


Image: Tsygankov S. et al. (2016)

[1]

- X-ray pulsations discovered in M82 X-2

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

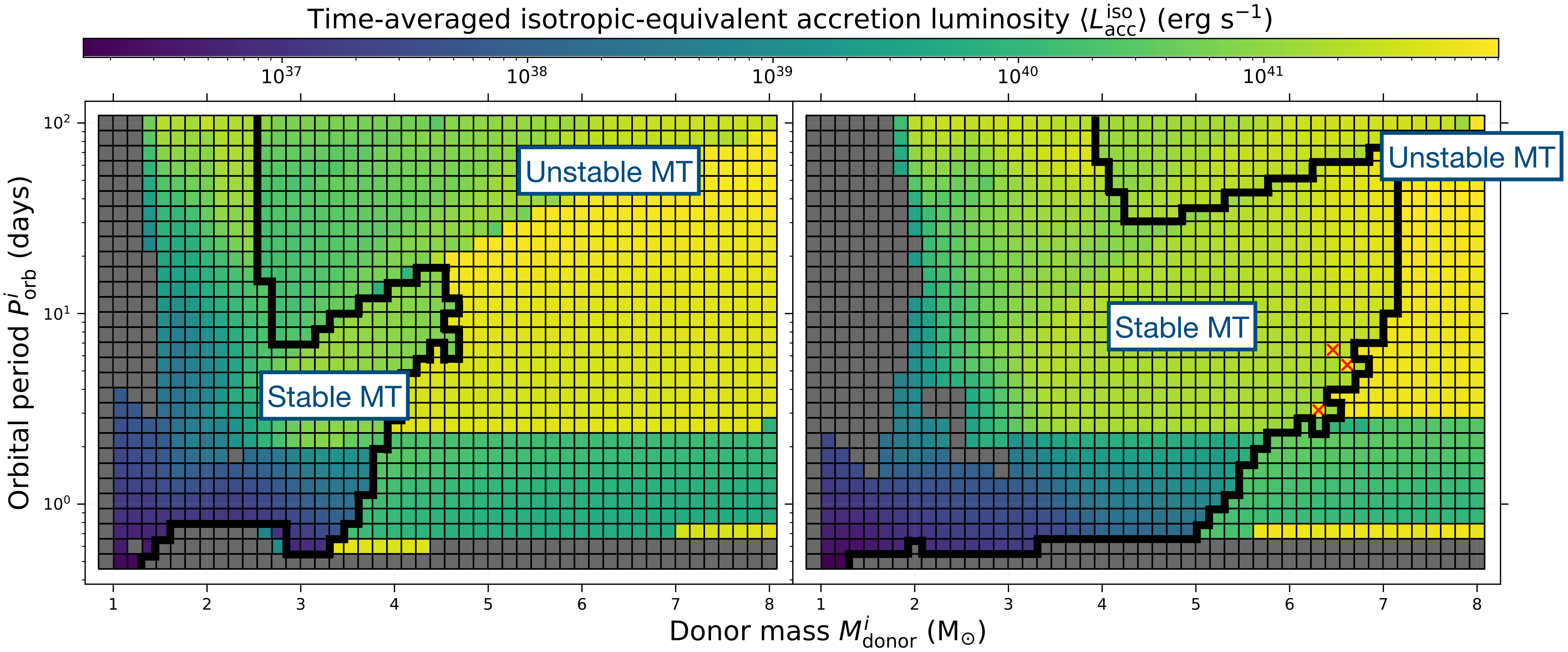


M82 X-2

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

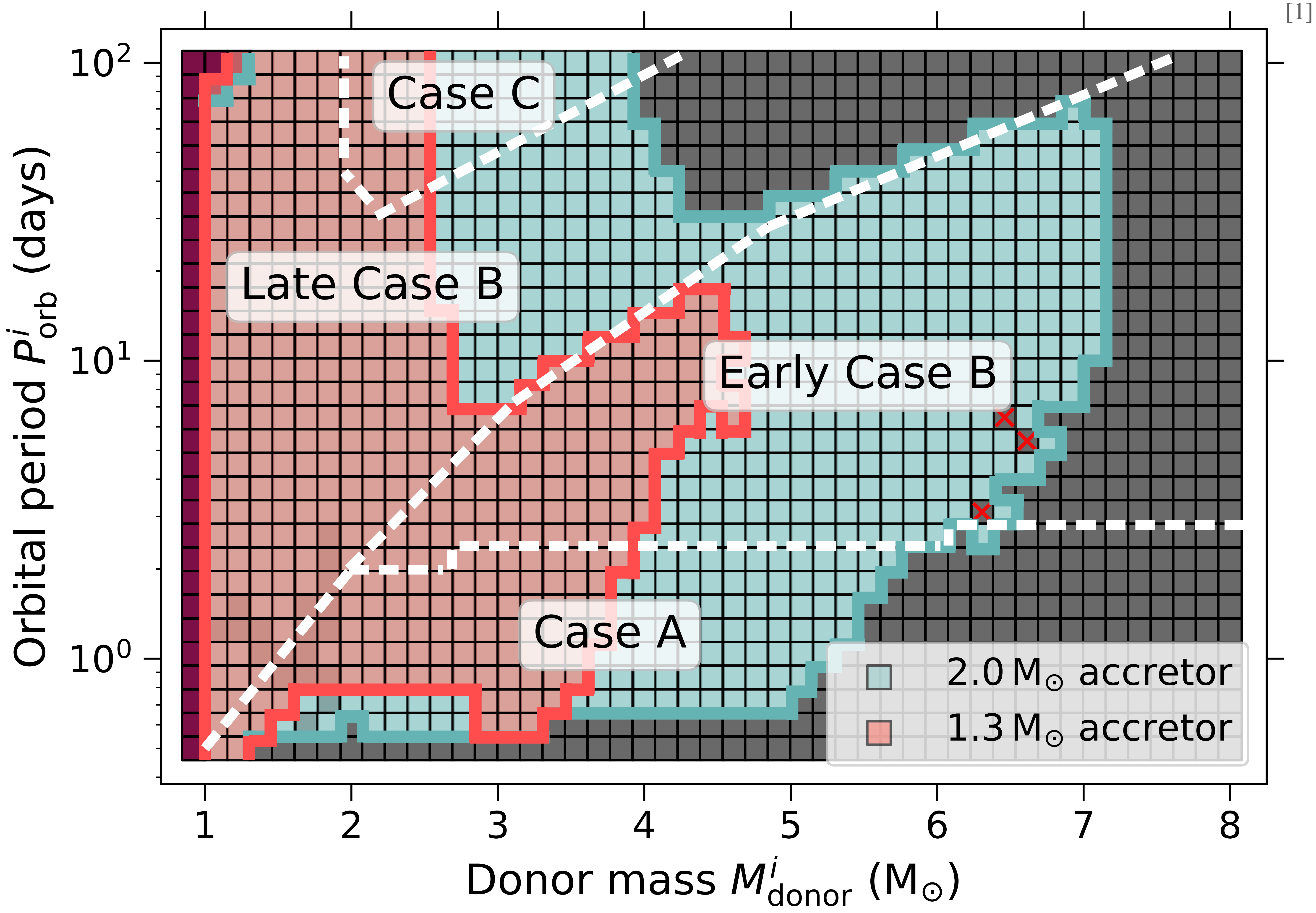
[1] Bachetti et al. (2014)

Time averaged accretion luminosity



[1] Misra et al. (2020)

Stable mass transfer parameter space



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

Case A: Donor on the MS

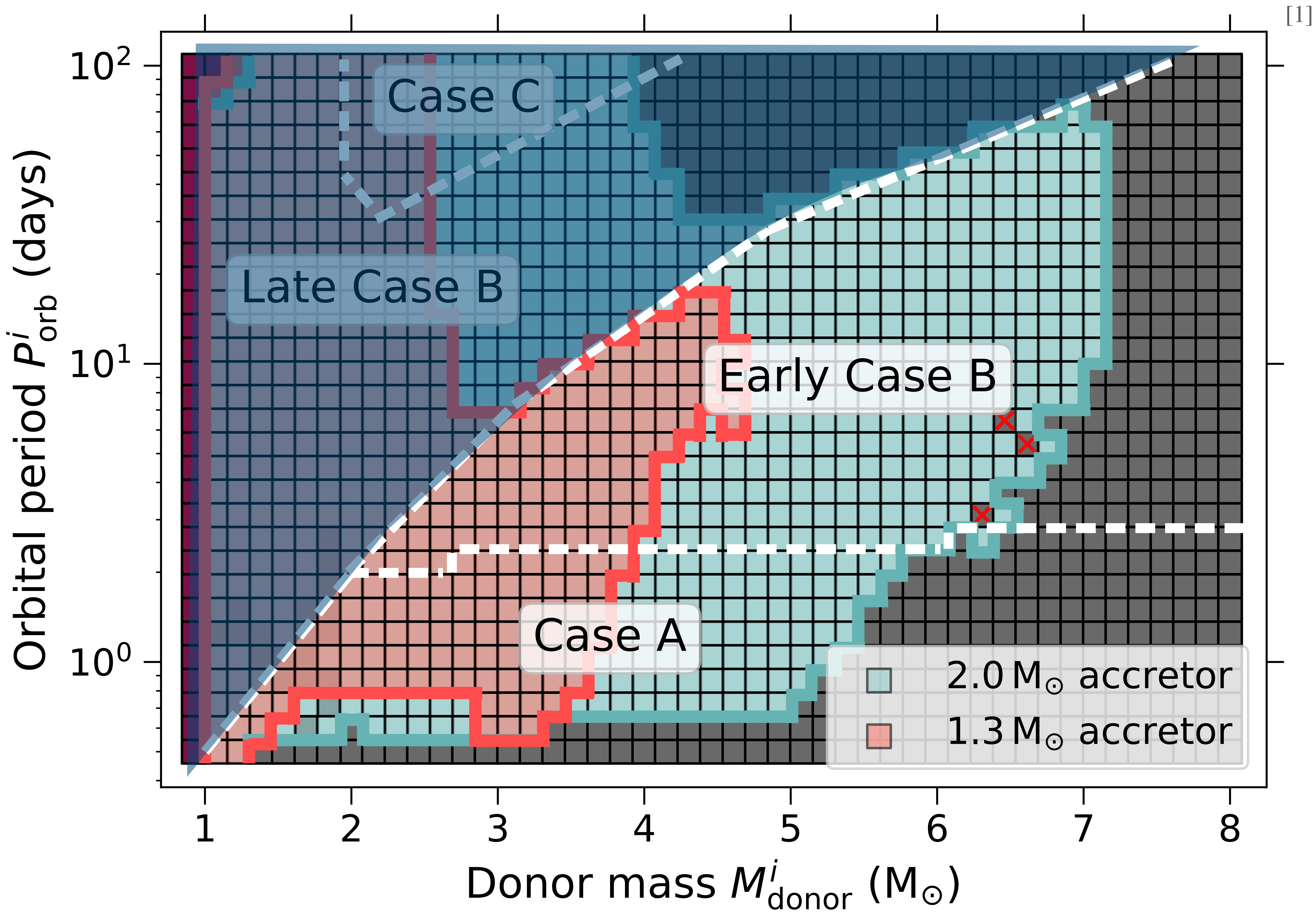
Case B: Donor in H-shell burning phase

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



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

Case A: Donor on the MS

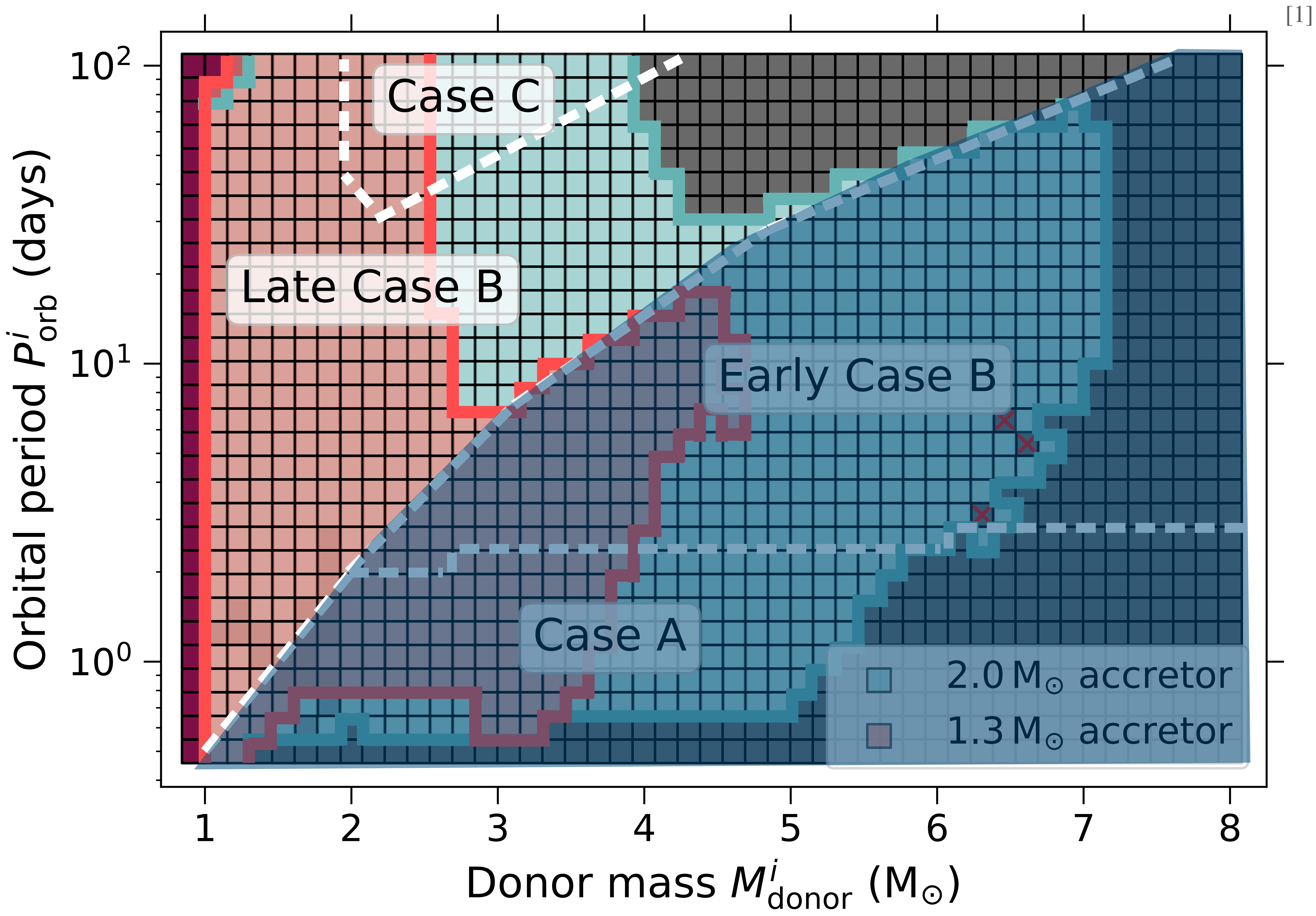
Case B: Donor in H-shell burning phase

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



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

Case A: Donor on the MS

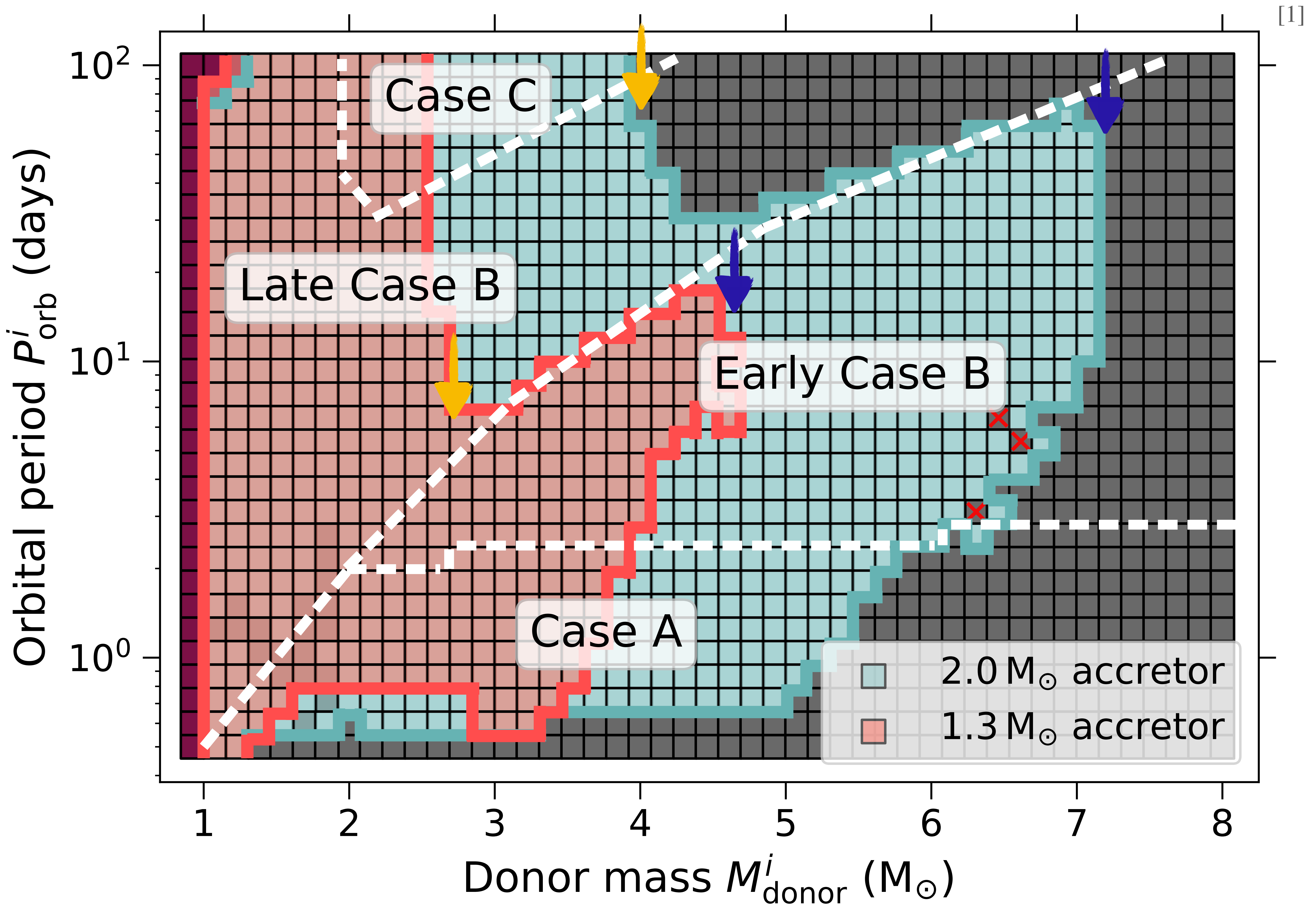
Case B: Donor in H-shell burning phase

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



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

Radiative envelope:

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

Convective envelope:

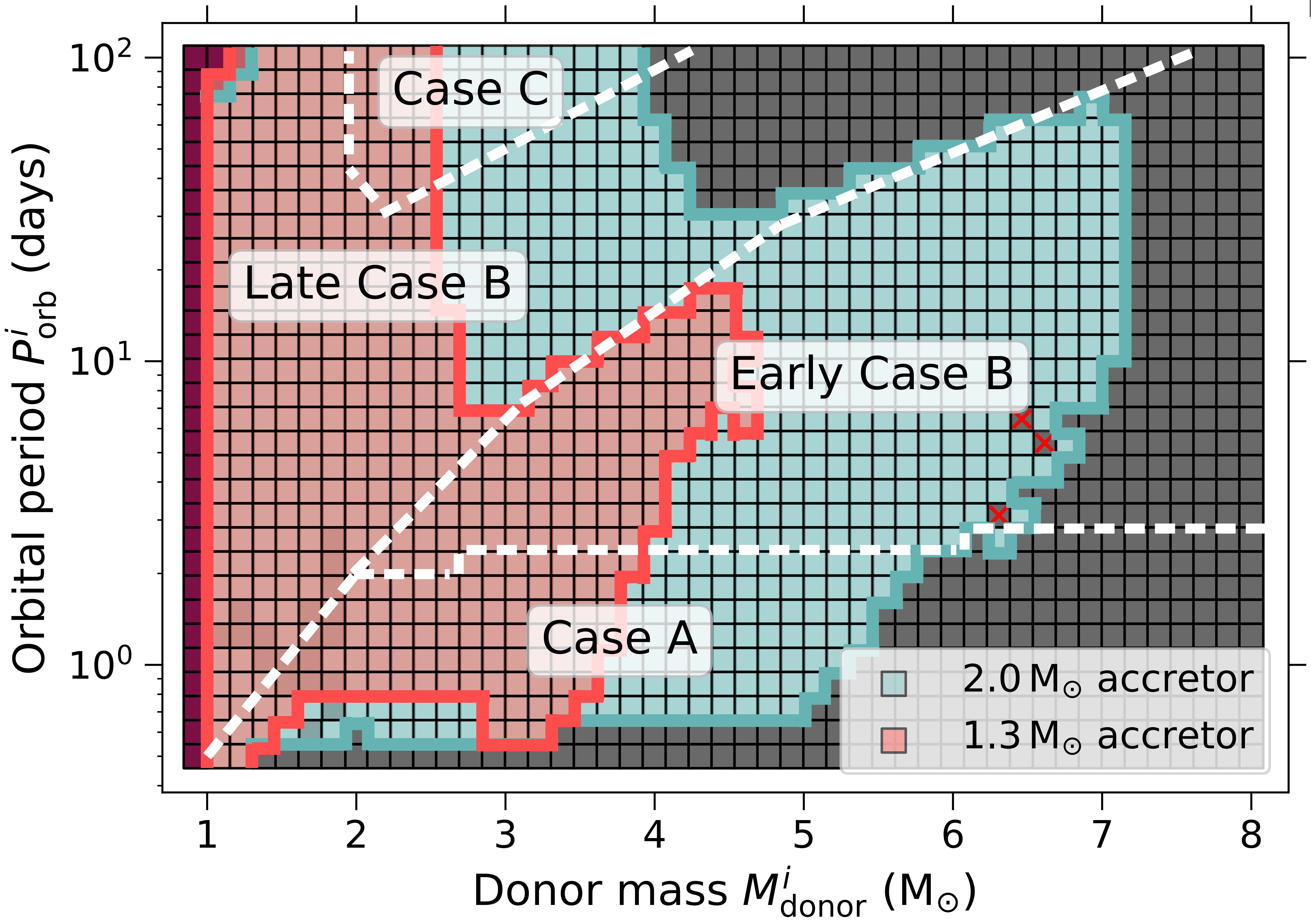
q^{conv}_{crit}~2.0

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

[1] Misra et al. (2020)

Stable mass transfer parameter space

[1]



M82 X-2

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	$< 60°$

For 2.0 $M_\odot$, Mdonor $\geq 5.83 M_\odot$

[1] Misra et al. (2020)