Formation of millisecond pulsars with He WDs, ultra-compact X-ray binaries, and gravitational wave sources

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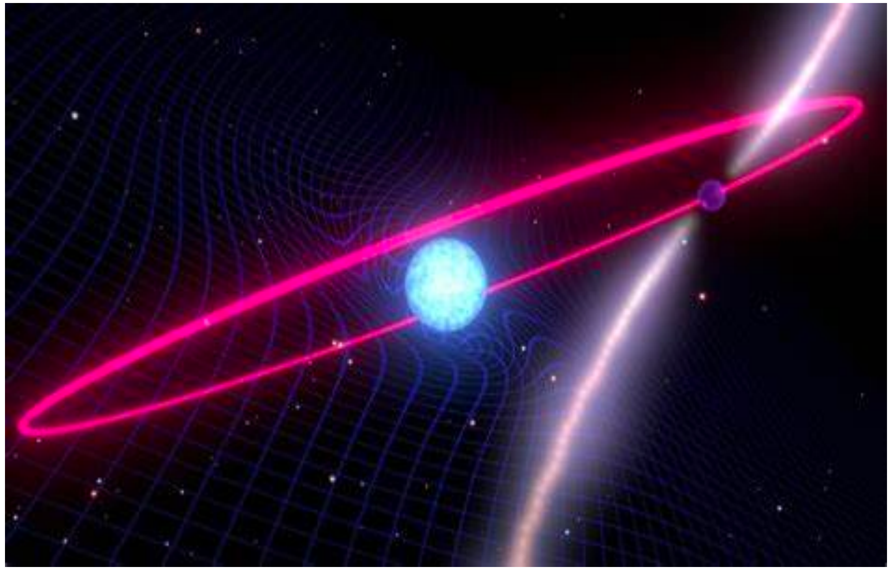
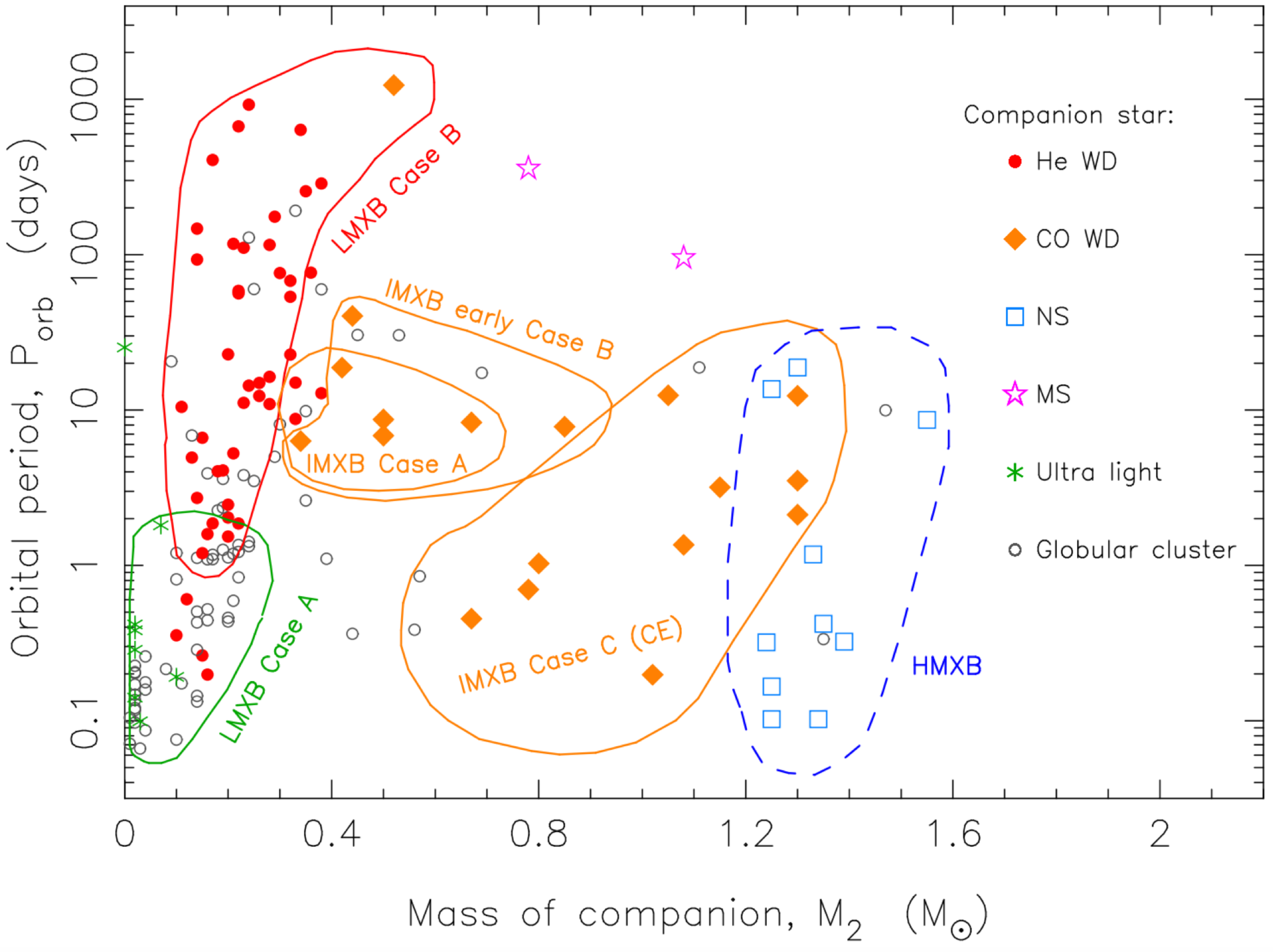
Binary millisecond pulsars

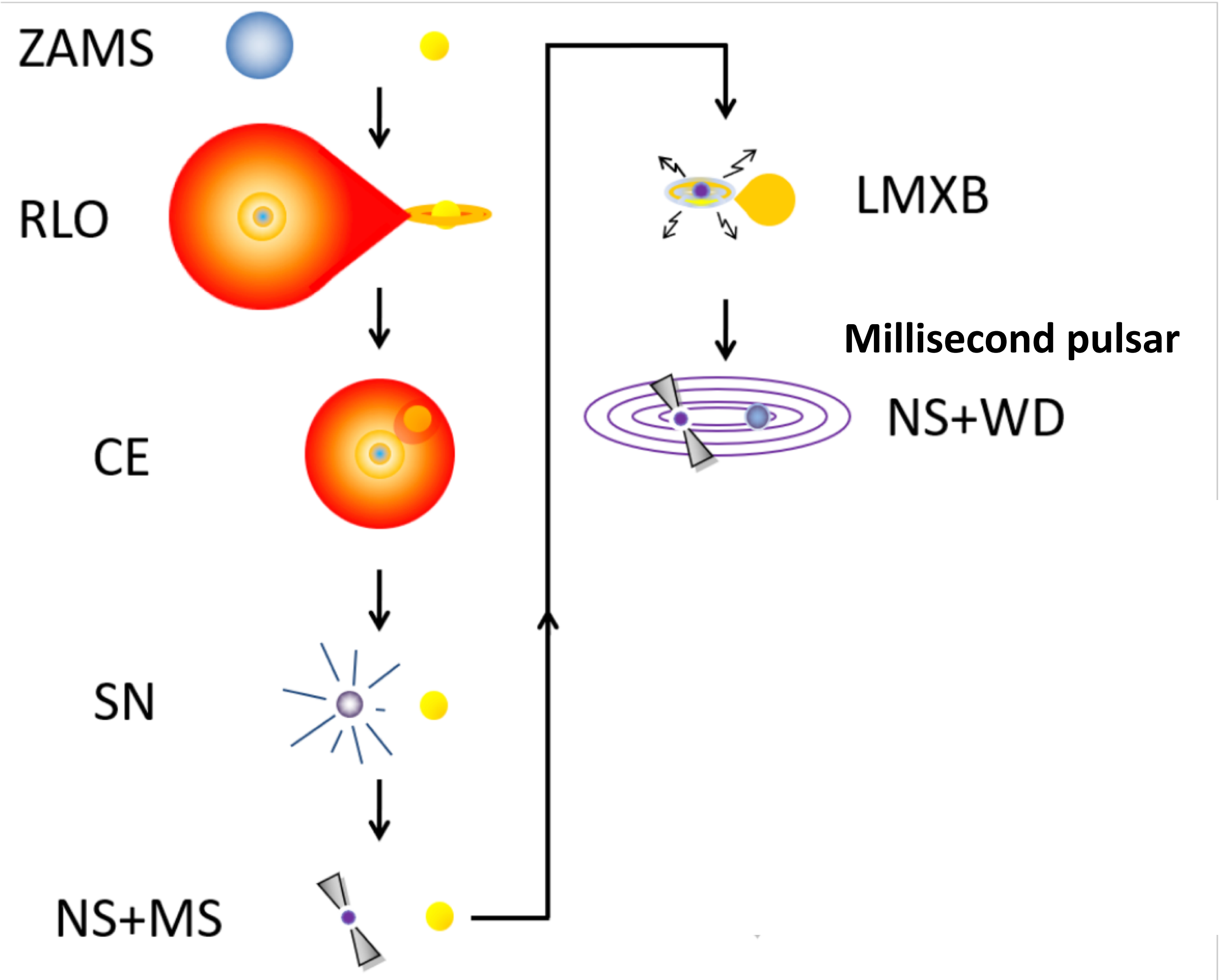


Different types of Companions



Credit: Thomas Tauris

Formation of MSP+He WD binaries



Tauris & van den Heuvel 2023

Binary millisecond pulsars with extremely low mass WDs

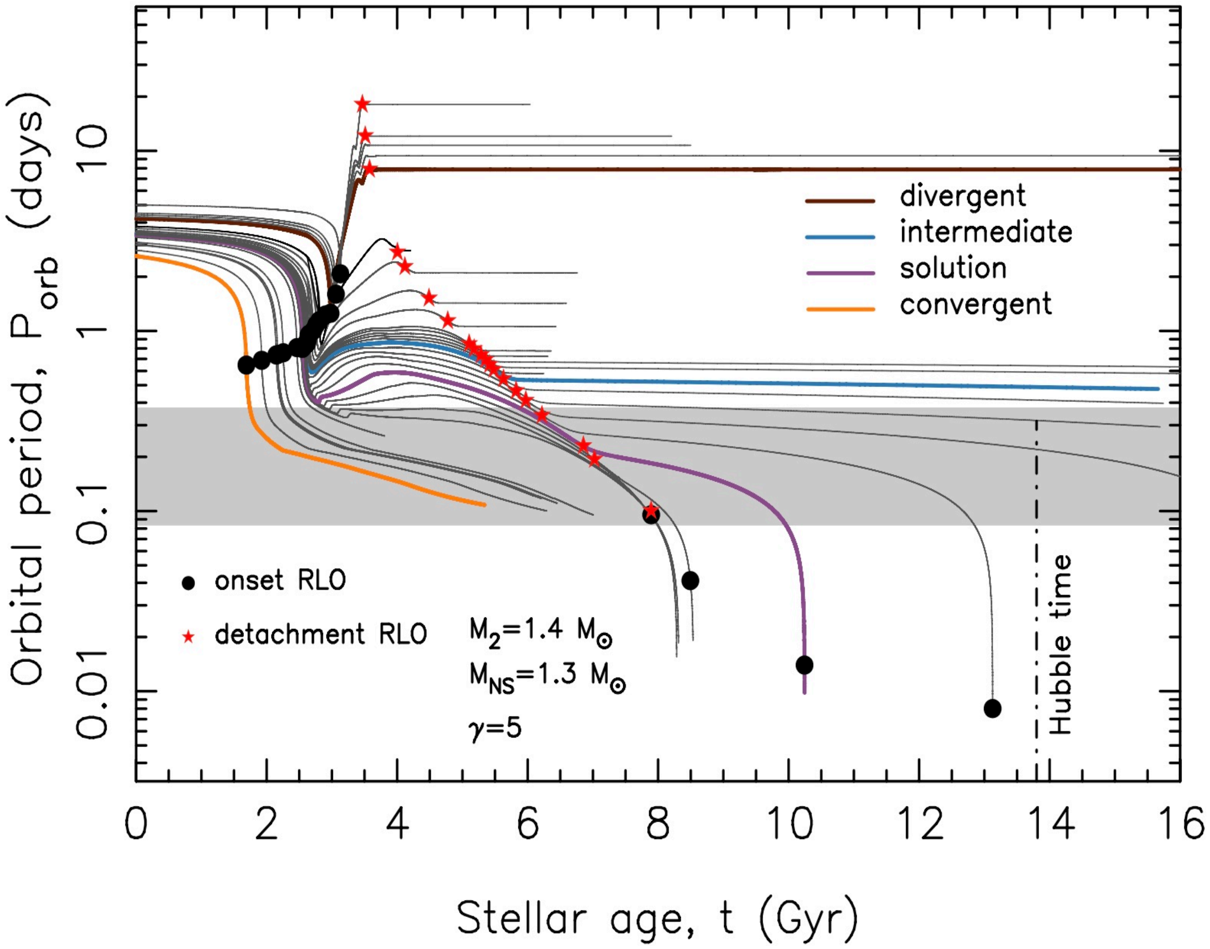
Pulsar name	P_{orb} (h)	M_{WD} ($M_\odot$)	M_{NS} ($M_\odot$)	Eccentricity	P_{spin} (ms)	$\dot{P}$ (s s^{-1})	WD age (Gyr)	Optical data reference
PSR J0348+0432	2.46	0.17	2.01	2.6×10^{-6}	39.1	2.41×10^{-19}	2.1 ± 0.5	Antoniadis et al. (2013)
PSR J0751+1807	6.31	0.14	1.34	7.1×10^{-7}	3.48	7.79×10^{-21}	–	Lundgren et al. (1995)
PSR J1738+0333	8.52	0.18	1.47	4.0×10^{-6}	5.85	2.41×10^{-19}	–	Antoniadis et al. (2012)
PSR J1816+4510	8.66	0.21[a]	2.0[a]	8×10^{-6}	3.19	4.31×10^{-20}	–	Kaplan et al. (2013)
PSR J0024−7204U	10.3	0.15[b]	1.5[b]	$<10^{-4}$	4.34	–	0.6	Edmonds et al. (2001)
PSR J1748−2446M	10.6	0.17[b]	1.5[b]	$<10^{-4}$	3.57	–	–	
PSR J1748−2446V	12.1	0.15[b]	1.5[b]	$<10^{-4}$	2.07	–	–	
PSR J0024−7204Y	12.5	0.17[b]	1.5[b]	$<10^{-4}$	2.20	–	–	
PSR J1641+3627D	14.2	0.22[b]	1.5[b]	$<10^{-4}$	3.12	–	–	
PSR J1012+5307	14.5	0.16	1.64	$<8.4\times10^{-7}$	5.26	1.71×10^{-20}	–	Callanan et al. (1998)

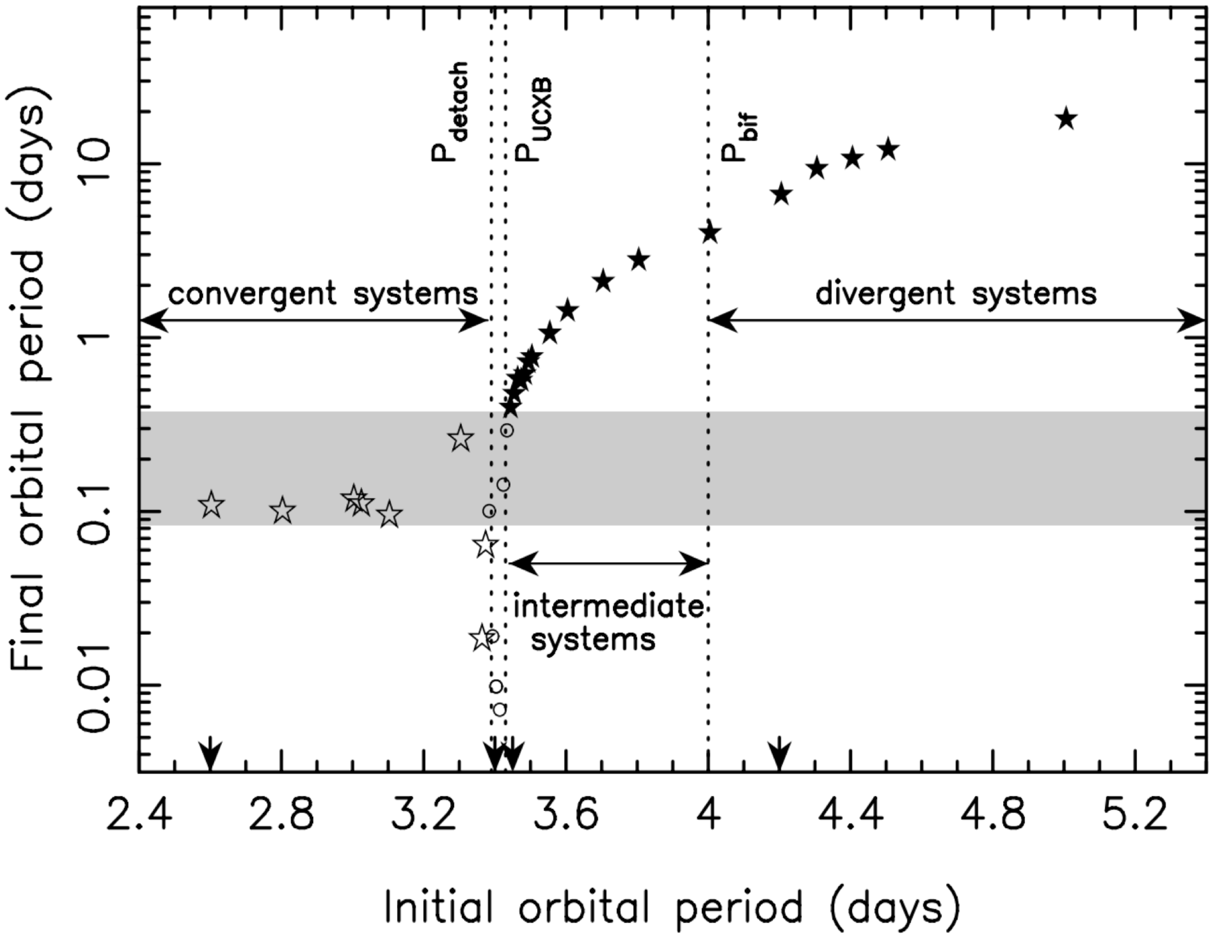
Porb: 2~14 hr; WD mass <= 0.22 Msun

Istrate et al. 2014

Fine-tuning Problem

Istrate et al. 2014





Convergent: $P_{orb}^{final} < P_{orb}^{initial}$

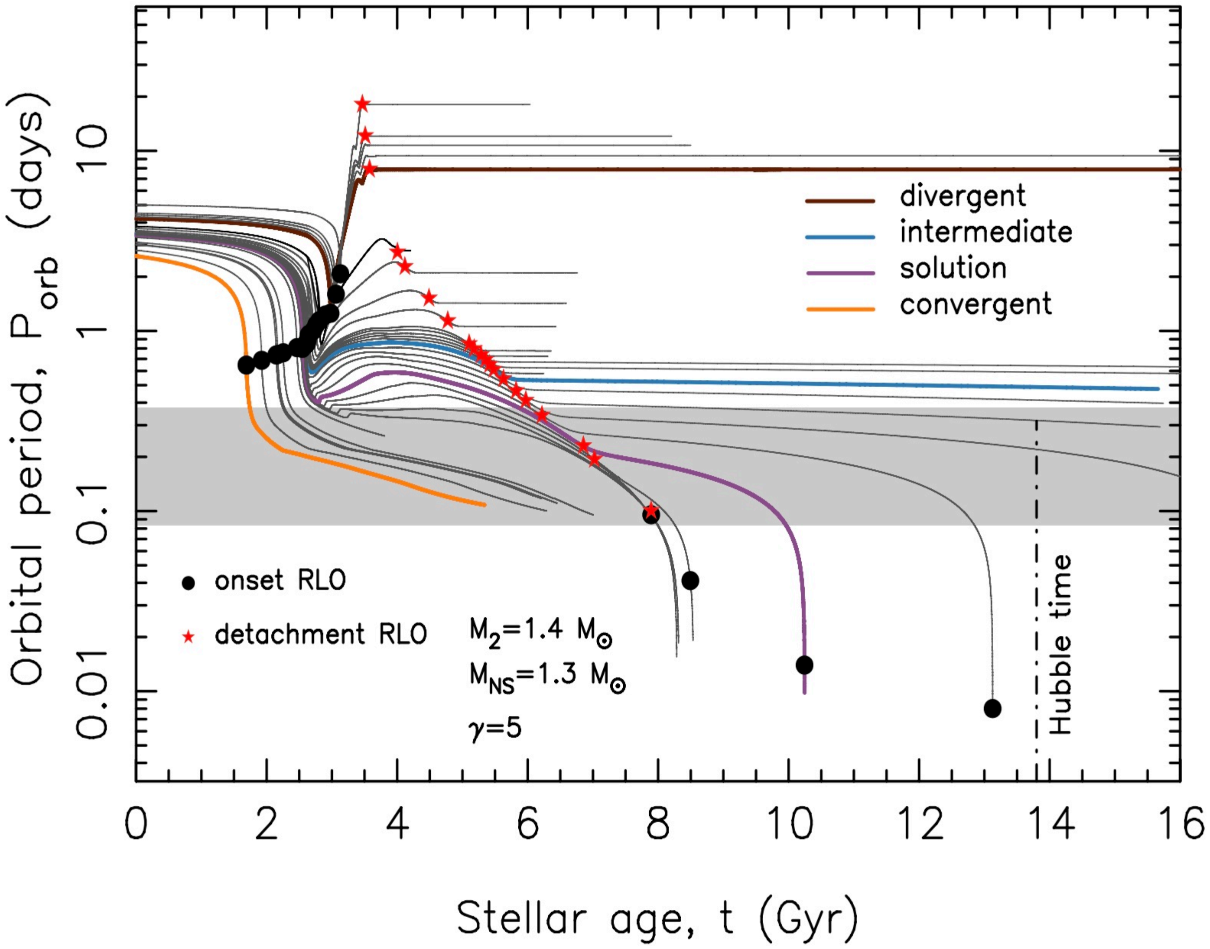
Divergent: $P_{orb}^{final} > P_{orb}^{initial}$

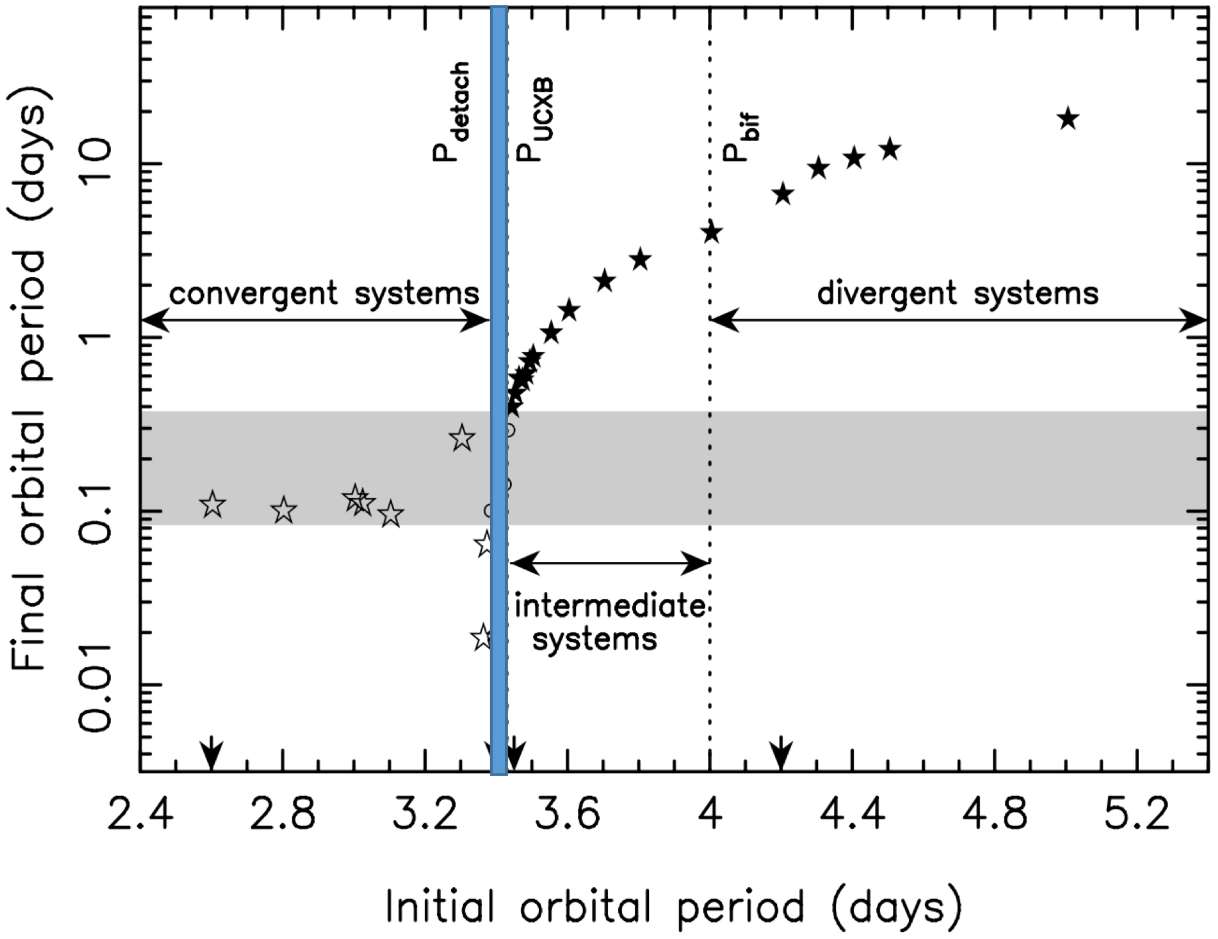
Intermediate: $9\ h < P_{orb}^{final} < P_{orb}^{initial}$

Grey Area:
Orbital period range of observed MSP+ ELM WDs

Fine-tuning Problem

Istrate et al. 2014





Initial orbital period: 3.39--3.43 days

Convergent: $P_{\rm orb}^{\rm final} < P_{\rm orb}^{\rm initial}$

Divergent: $P_{\rm orb}^{\rm final} > P_{\rm orb}^{\rm initial}$

Intermediate: $9\ {\rm h} < P_{\rm orb}^{\rm final} < P_{\rm orb}^{\rm initial}$

The parameter space of LMXBs for producing detached MSP - ELM WD is too small.

Binary evolution model

- NS mass: 1.3 Msun; Donor mass: 1.0 Msun ~ 4.0 Msun;

  Orbital Period: 0.40 ~ 1000 day
- Solar Metallicity
- Stellar Wind: Reimers (1975)
- Donor star: initially synchronized.
- Rotation:

  Chemical mixing: Secular shear instability, Eddington-sweet circulation, dynamical shear instability and Goldreich-Schubert-Fricke instability

  Transport of angular momentum: Spruit-Tayler dynamo

MESA

Stellar evolution code

Chen et al. MNRAS, 2021

Angular momentum loss

- Gravitational Wave Radiation

$$\frac{\mathrm{d}J_{\mathrm{gr}}}{\mathrm{d}t} = -\frac{32}{5}\frac{G^{7/2}}{c^5}\frac{M_{\mathrm{NS}}^2 M_2^2 (M_{\mathrm{NS}} + M_2)^{1/2}}{a^{7/2}}$$

- Mass loss

accretion efficiency: 30%

Eddington accretion rate:

$$\dot{M}_{\mathrm{Edd}} = \frac{4\pi G M_{\mathrm{NS}}}{c \cdot 0.20(1+X) \cdot \eta}$$

Material not accreted by NS takes away the specific angular momentum of NS.

- Spin-orbit coupling (Paxton et al. 2015)
- Magnetic braking

New magnetic braking prescription

Van et al. 2019

$$\frac{\mathrm{d}J_{\mathrm{mb}}}{\mathrm{d}t} = \frac{\mathrm{d}J_{\mathrm{mb,Sk}}}{\mathrm{d}t}\left(\frac{\omega}{\omega_{\odot}}\right)^{\beta}\left(\frac{\tau_{\mathrm{conv}}}{\tau_{\odot,\mathrm{conv}}}\right)^{\xi}\left(\frac{\dot{M}_{\mathrm{W}}}{\dot{M}_{\odot,\mathrm{W}}}\right)^{\alpha}$$

$$\frac{\mathrm{d}J_{\mathrm{mb,Sk}}}{\mathrm{d}t} = -3.8\times10^{-30} M_2 R_{\odot}^4 \left(\frac{R_2}{R_{\odot}}\right)^{\gamma_{\mathrm{mb}}} \omega^3 \mathrm{dyne\ cm}$$

- Reproduce the persistent LMXBs
- Improvements in reproducing transient LMXBs

New magnetic braking prescription

Van et al. 2019

$$\frac{dJ_{mb}}{dt} = \frac{dJ_{mb,Sk}}{dt}\left(\frac{\omega}{\omega_{\odot}}\right)^{\beta}\left(\frac{\tau_{conv}}{\tau_{\odot,conv}}\right)^{\xi}\left(\frac{\dot{M}_{W}}{\dot{M}_{\odot,W}}\right)^{\alpha}$$

$$\frac{dJ_{mb,Sk}}{dt} = -3.8\times10^{-30} M_2 R_{\odot}^{4}\left(\frac{R_2}{R_{\odot}}\right)^{\gamma_{mb}}\omega^{3}\,\text{dyne cm}$$

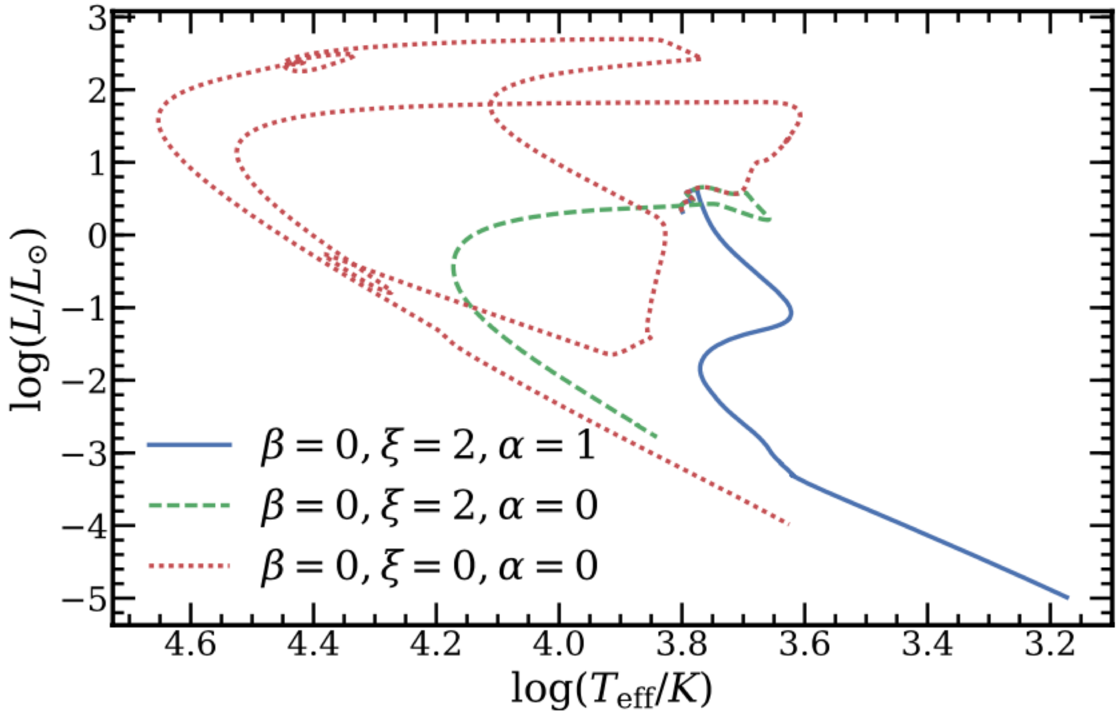
Case	β	ξ	α
1 – Default Skumanich	0	0	0
2 – Convection boosted	0	2	0
3 – Intermediate	0	2	1
4 – Wind boosted	2	4	1

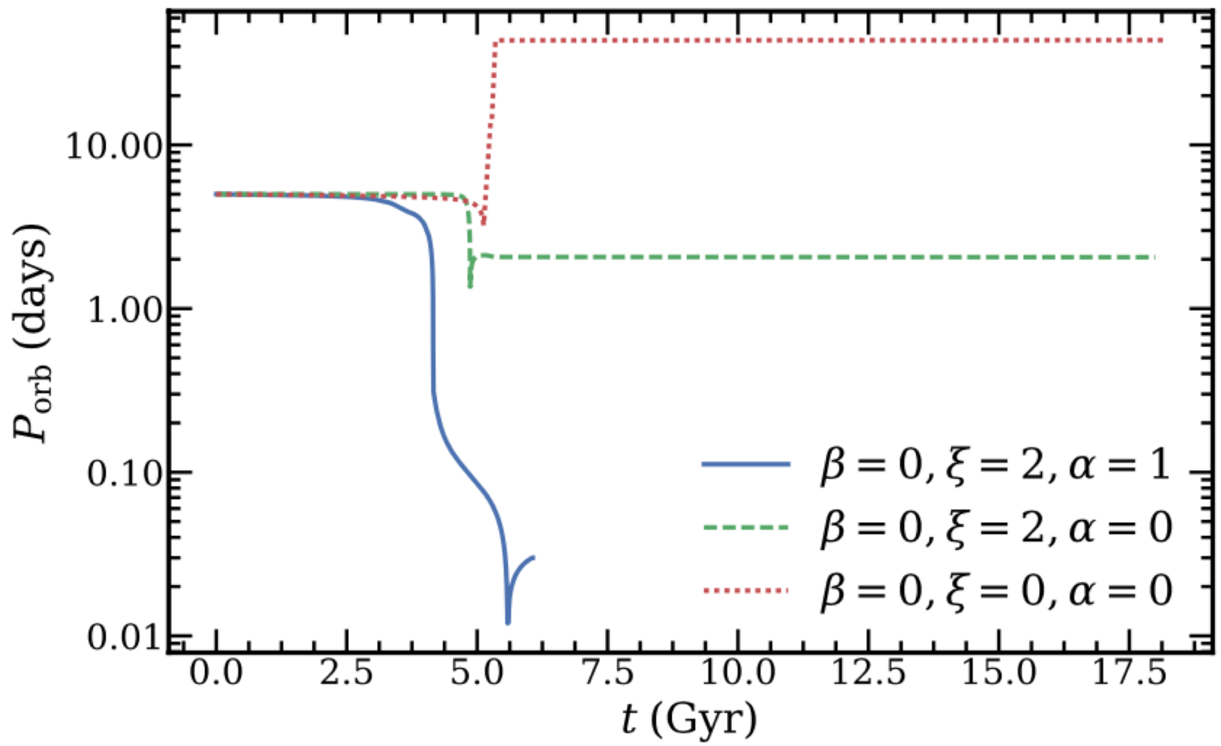
Models with β = 0, ξ = 2 and α = 1 can better reproduce the observed results of X-ray binaries (Van et al. 2019).

Influence of MB on binary evolution

NS mass: 1.30 Msun, Donor mass: 1.25 Msun, Orbital period: 5.0 d

Chen et al. MNRAS, 2021



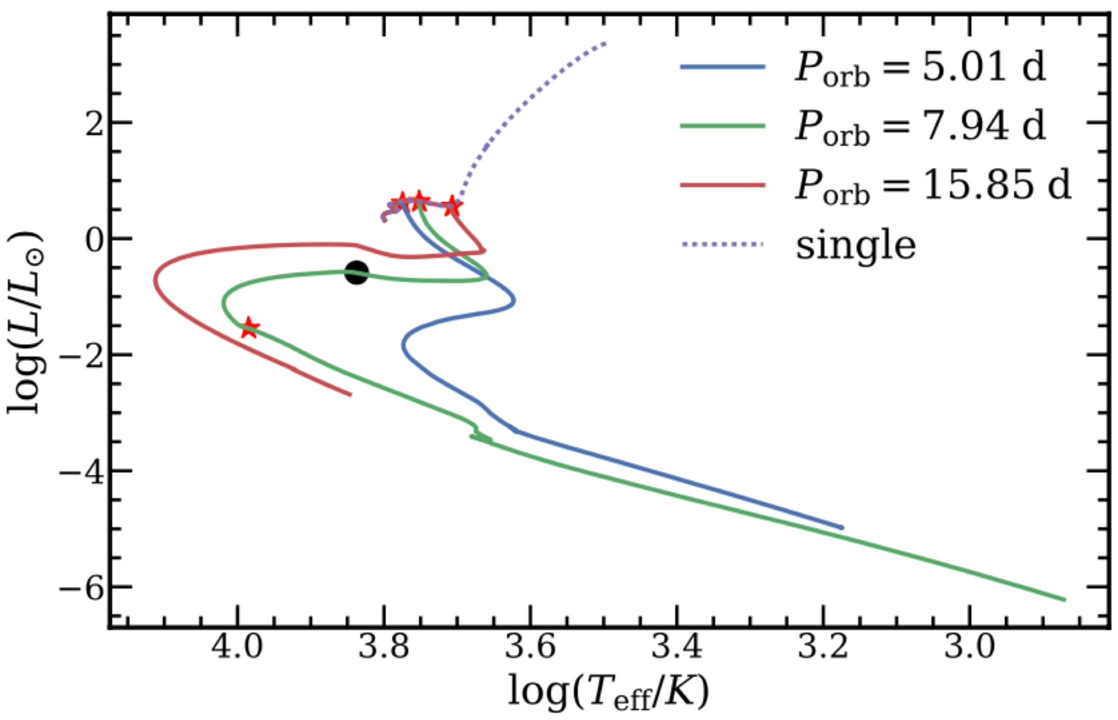


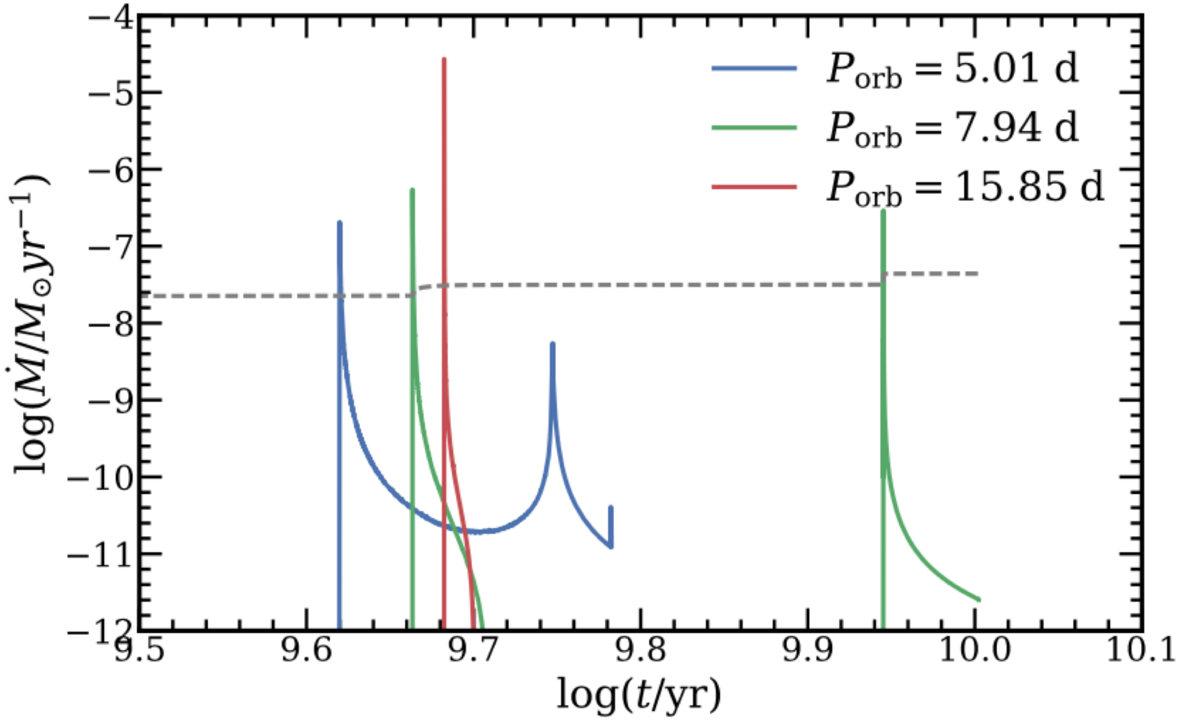
MB has an important influence on the evolution of LMXBs.

Examples of Binary evolution

Chen et al. MNRAS, 2021

NS mass: 1.30 Msun, Donor mass: 1.25 Msun, MB: intermediate

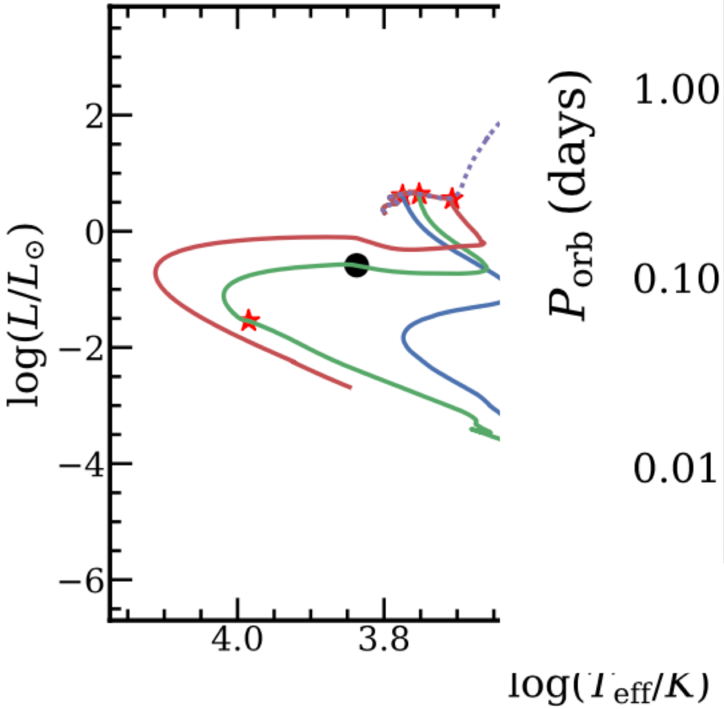


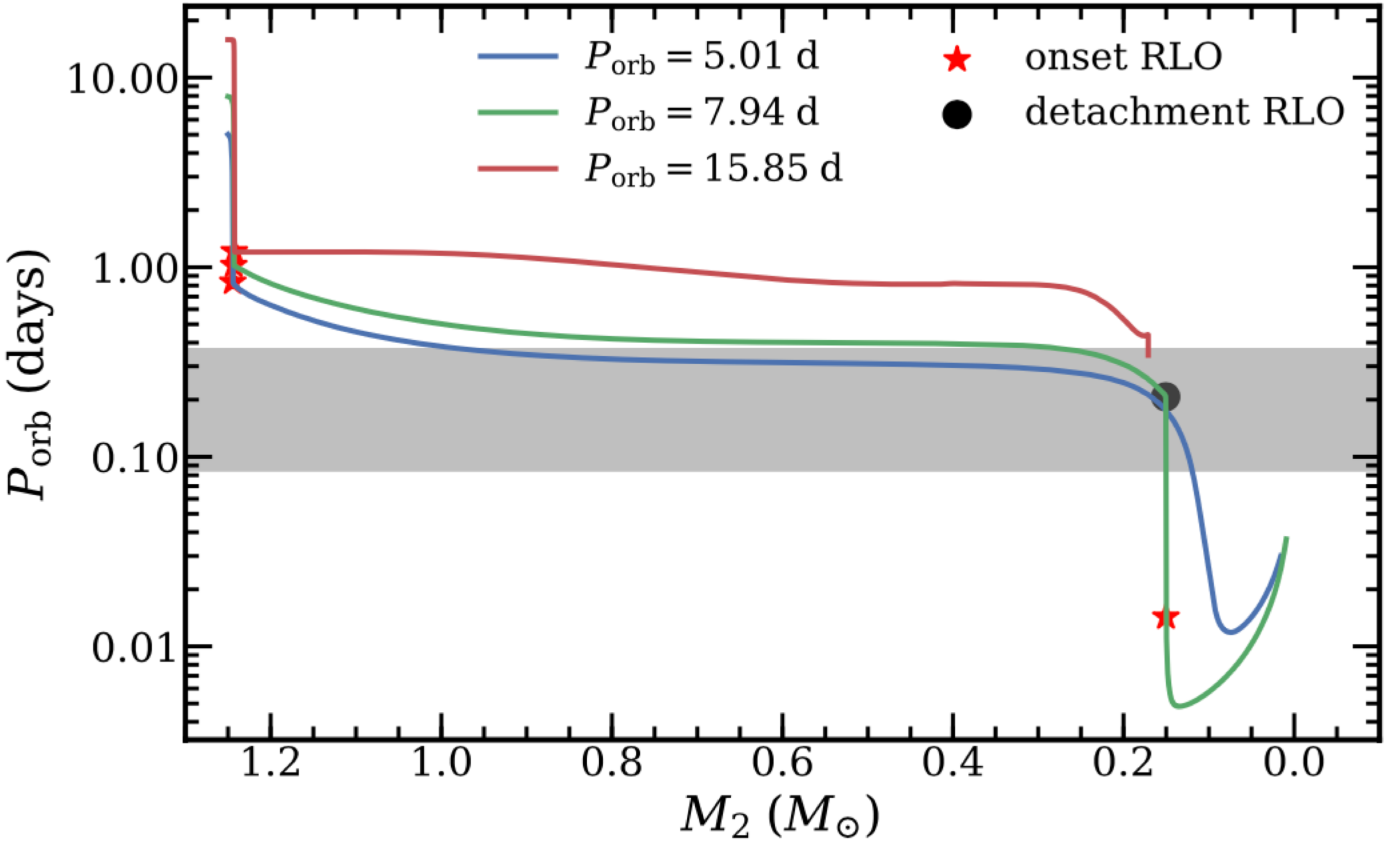


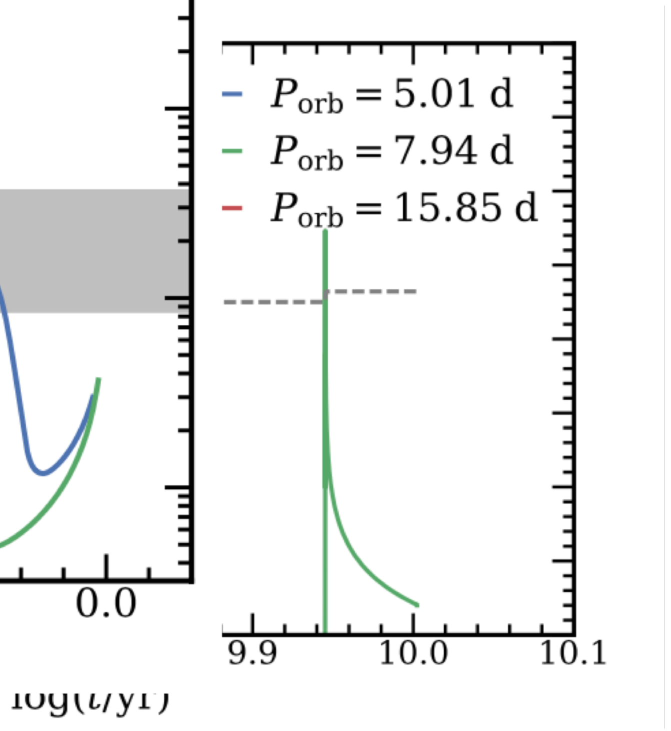
Examples of Binary evolution

Chen et al. MNRAS 2021

NS mass: 1.30 Ms

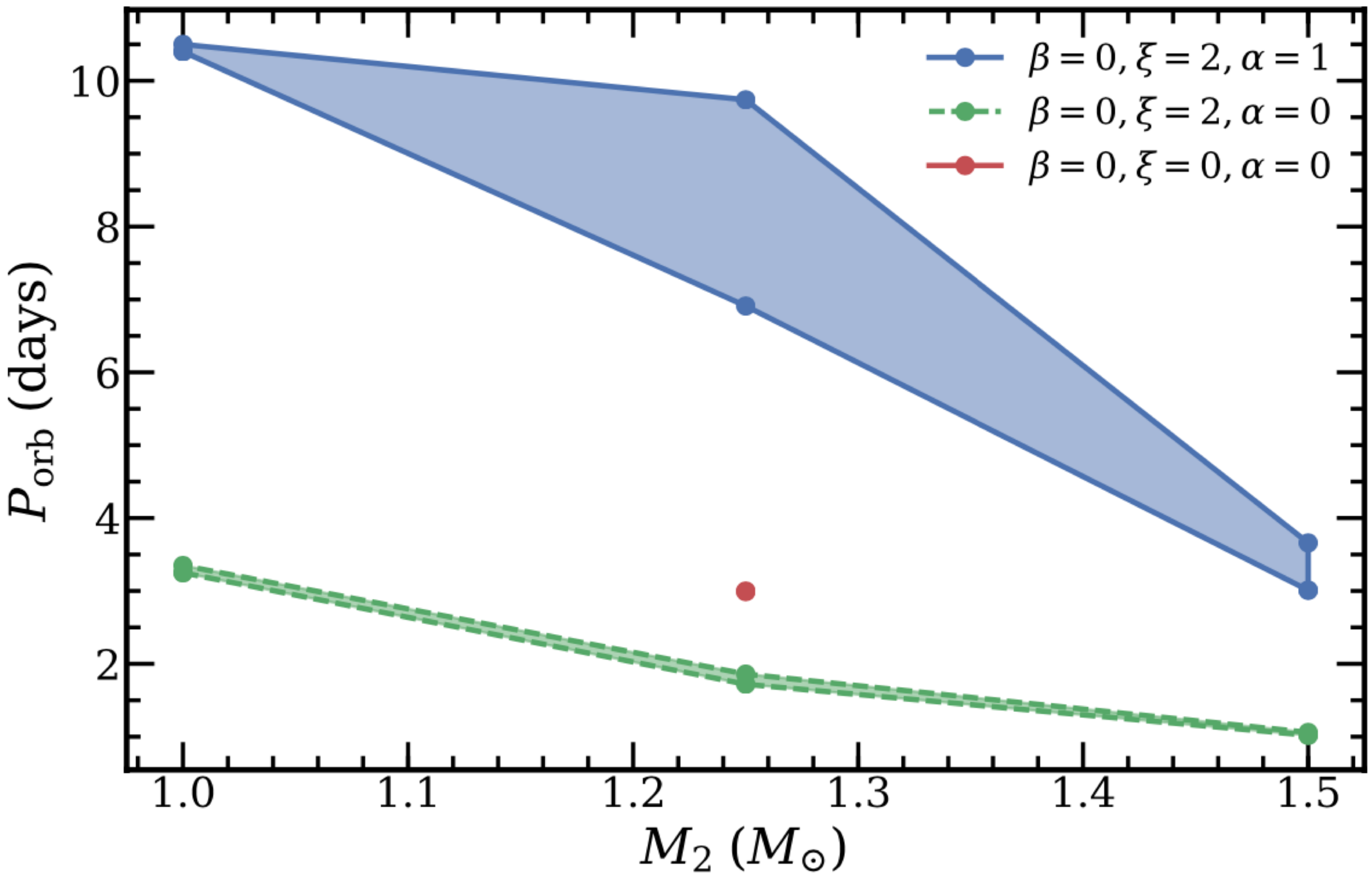






Grey Area:
Orbital period range of observed MSP+ ELM WDs

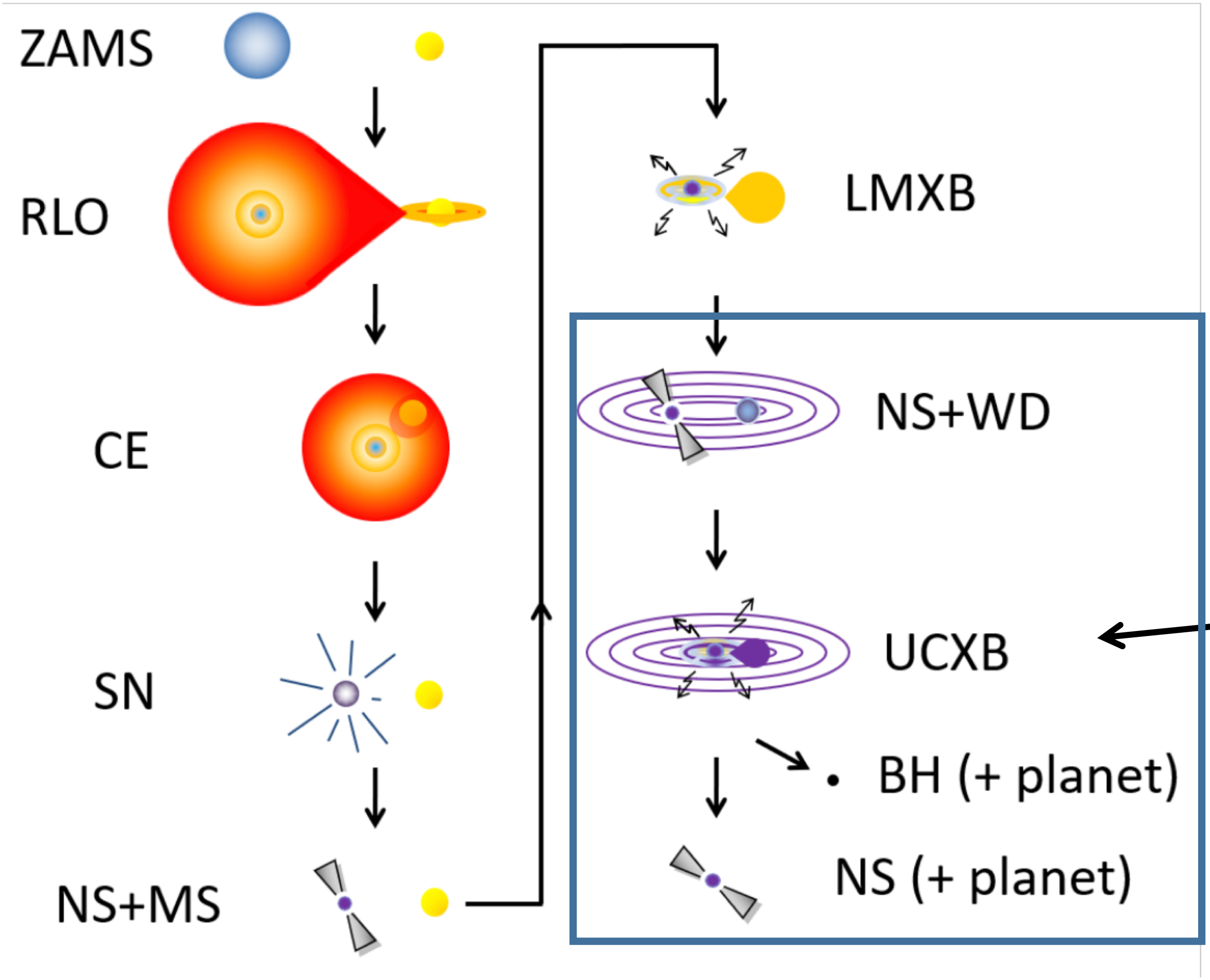
Initial Parameter Space

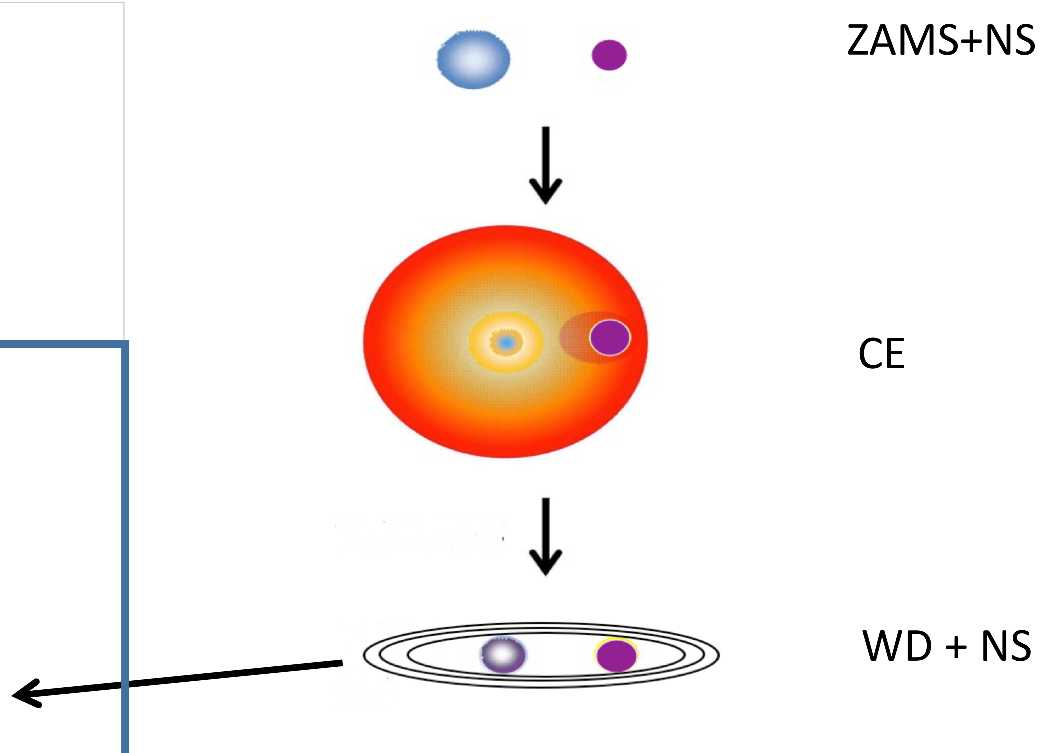


With the MB from Van et al. 2019, the parameter space for producing MSP-ELM WD and UCXBs becomes larger.

Chen et al. MNRAS, 2021

Evolution of NS+He WD binaries





Tauris & van den Heuvel 2023

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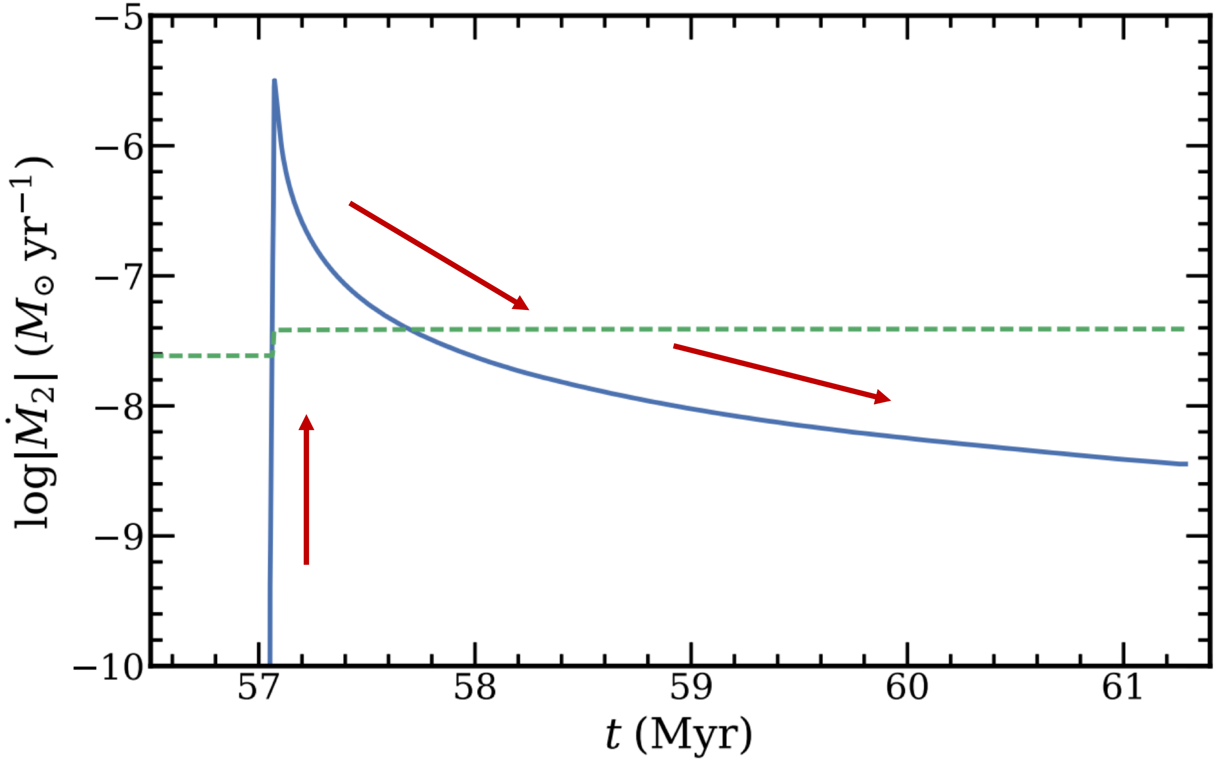
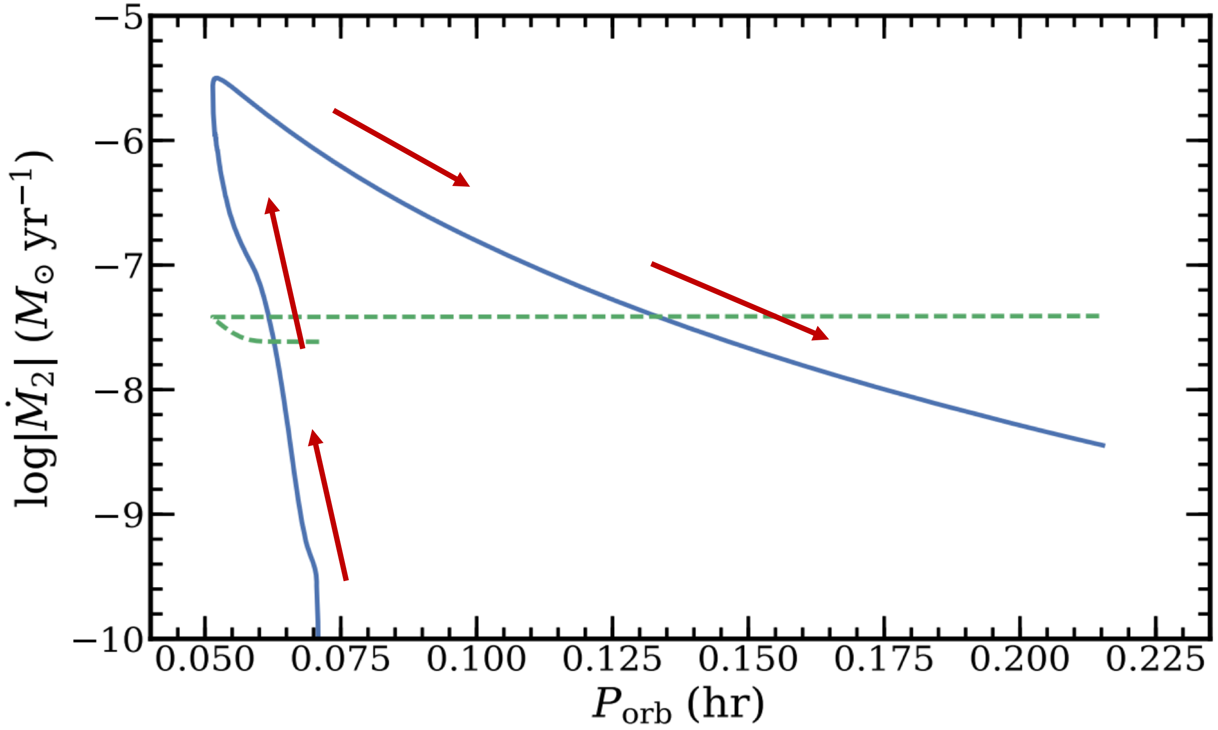
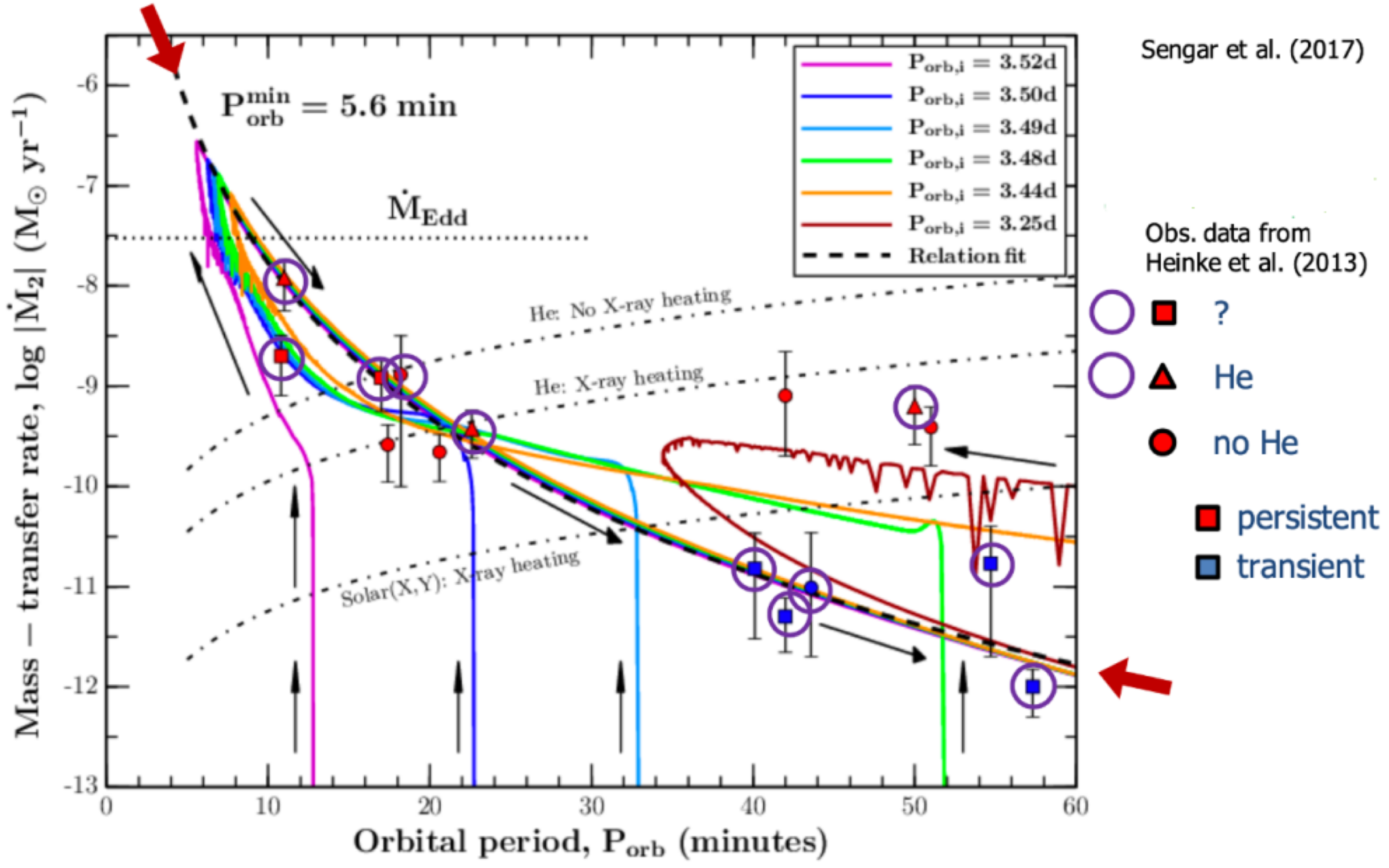
Chen et al. ApJ, 2022





M_{NS} = 1.30 Msun, M_2 = 0.25 Msun, P_{orb} = 0.05 days

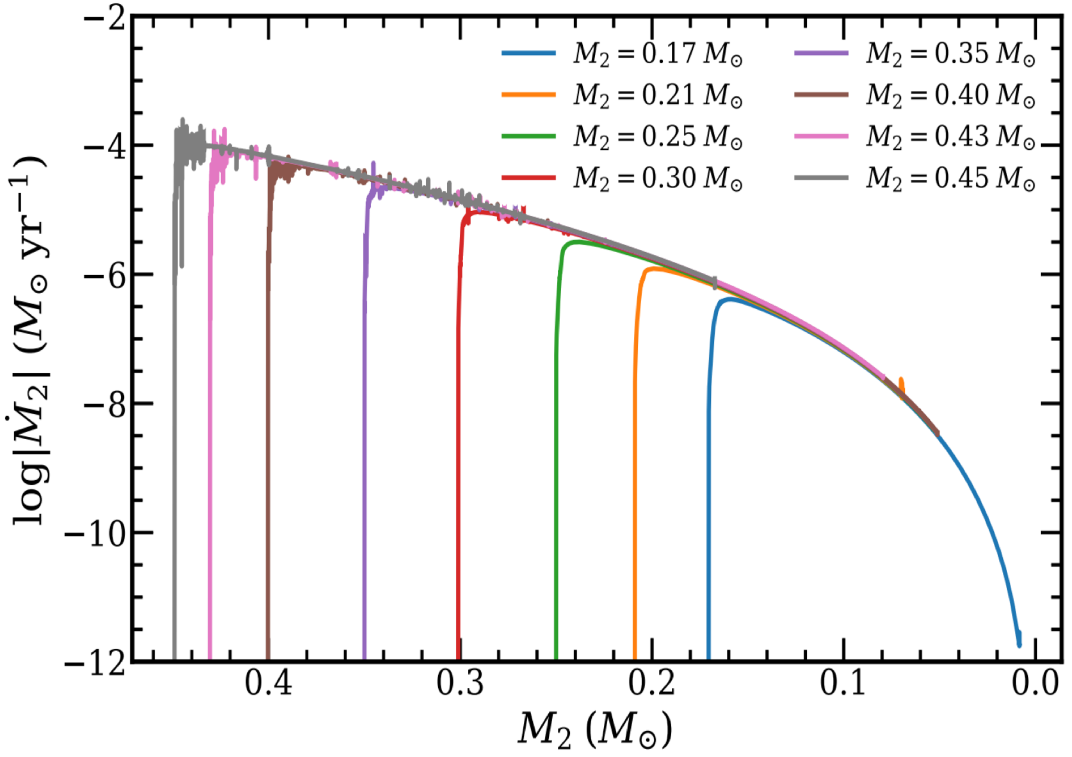
Evolution of NS+He WD binaries

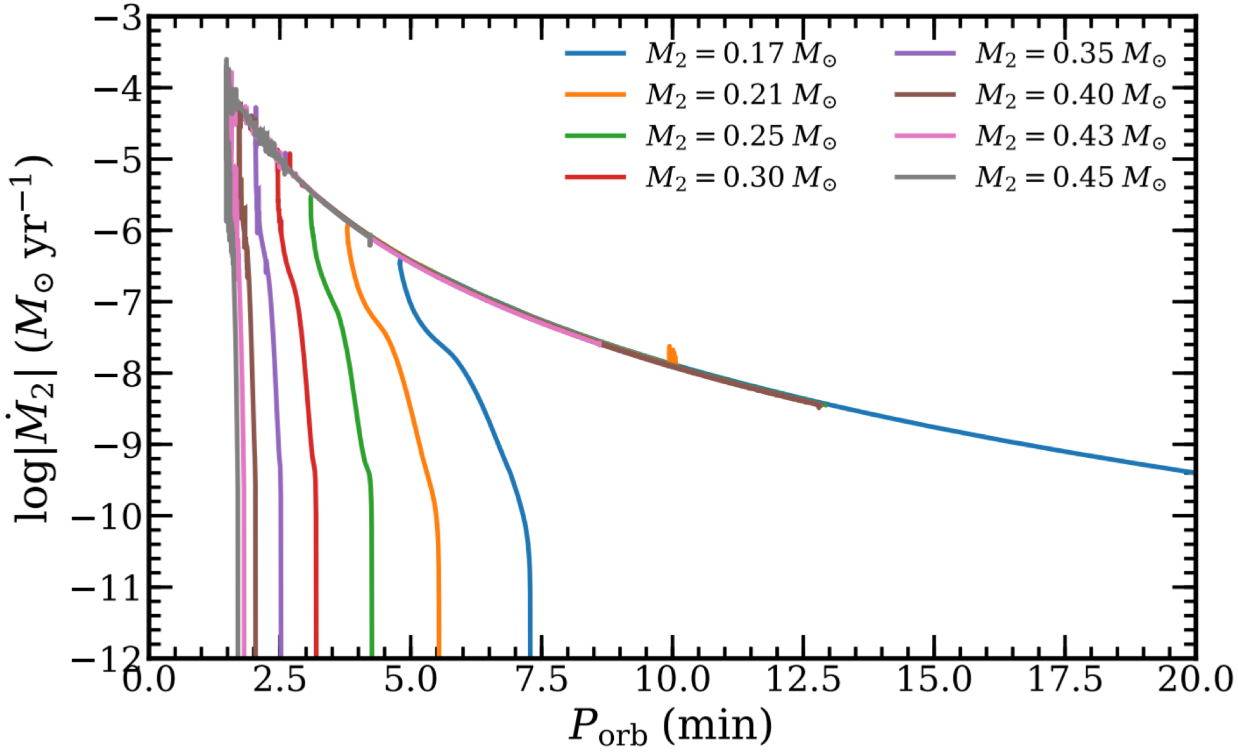


Common declining branch: $\log |\dot{M}/M_\odot \, \mathrm{yr}^{-1}| = -5.15 \, \log(P_{orb}/\mathrm{min}) - 2.62$

Stability of mass transfer of NS+He WDs

Chen et al. ApJ 2022

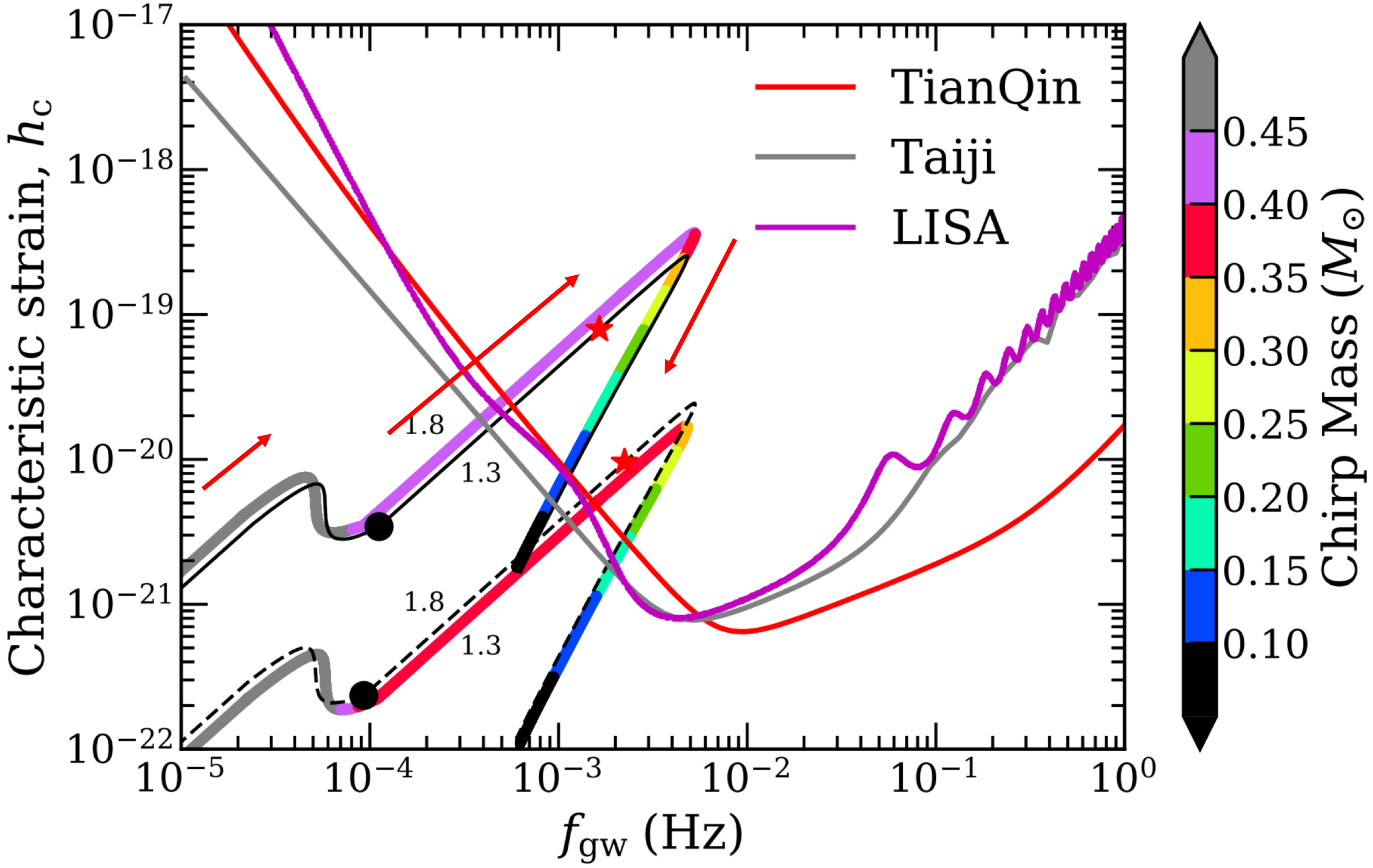




All NS+He WD binaries can have dynamically stable mass transfer.

minimum orbital period: 1.5-4.7min (GW frequency: 7.1-22mHz)

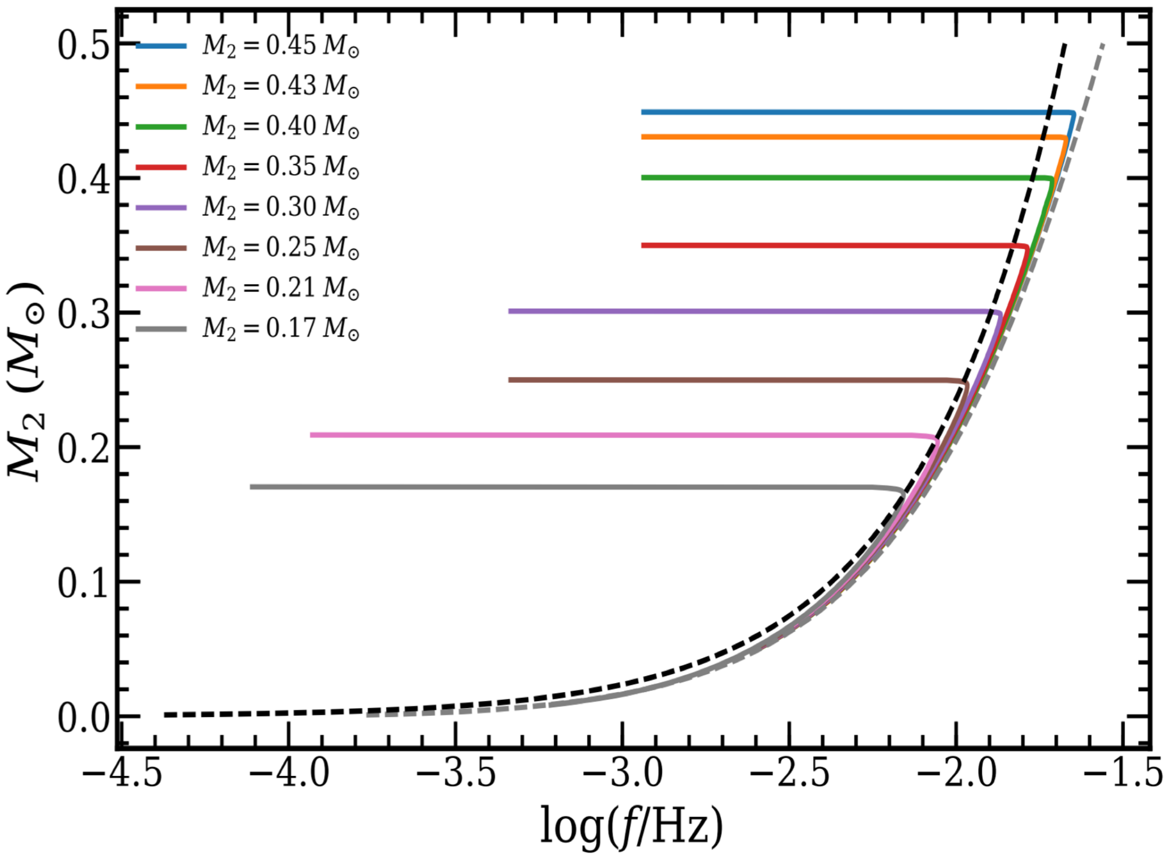
Properties as GW sources



UCXBs are important sources for TianQin, Taiji and LISA.

Properties as GW sources

Chen et al. ApJ, 2022



$$f = \frac{2}{P_{\rm orb}} = \frac{1}{\pi}\sqrt{\frac{G(M_{\rm NS}+M_2)}{a^3}}$$

$$\frac{R_{\rm rl}}{a} \simeq 0.462\left(\frac{M_2}{M_{\rm NS}+M_2}\right)^{1/3}$$

$$R_2 = 0.013\ R_\odot\left(\frac{M_2}{M_\odot}\right)^{-1/3}$$

$$R_2 = R_{\rm rl}.$$

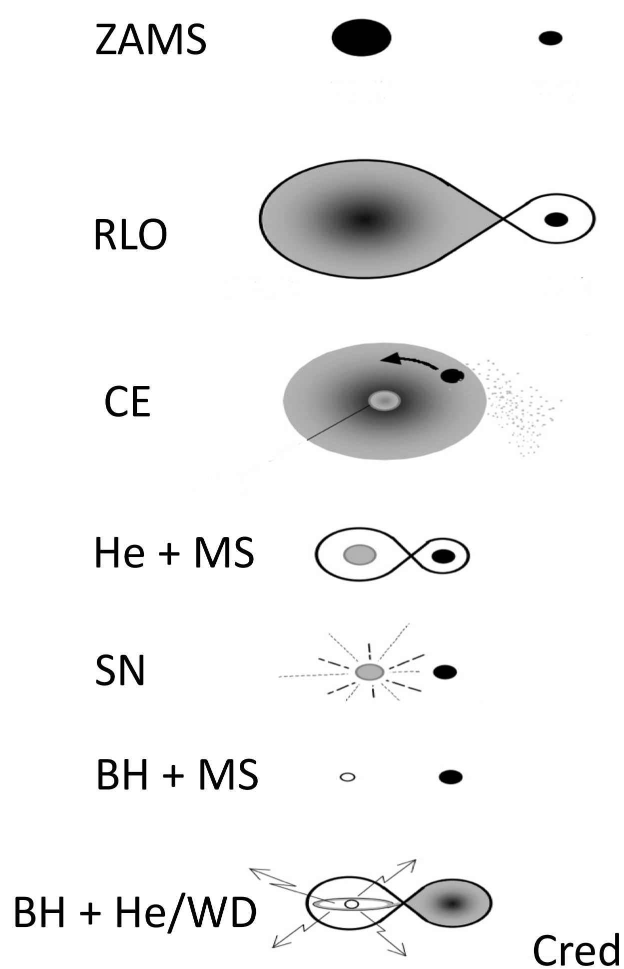
$$f = 4.23\ {\rm mHz}\ \left(\frac{M_2}{0.1\ M_\odot}\right)$$

The WD mass can be derived with this relation if the GW frequency is measured.

Formation of BH-UCXBs via accretion induced collapse of NSs

Chen et al. 2023, ApJ, accepted

Classical formation scenario



Problem:

The progenitor of BH is a massive star (> 25 Msun) and the donor is a low mass star (1 – 4 Msun).
It is hard to eject the envelope.

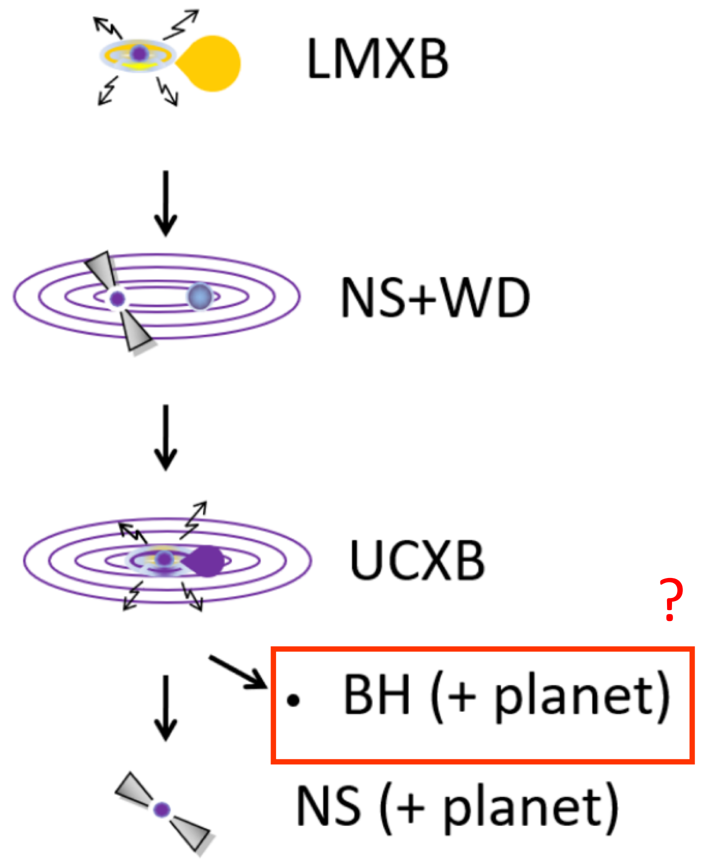
CE evolution:

$$\frac{m_1 m_{1,\mathrm{env}}}{\lambda R_1} = \alpha_{\mathrm{CE}}\left(-\frac{G m_1 m_2}{2a_\mathrm{i}} + \frac{G m_{1,\mathrm{c}} m_2}{2a_\mathrm{f}}\right)$$

Binding energy

orbital energy

Credit: Thomas Tauris



Maximum mass of NSs

NS mass from pulsar observations

PSR J1614-2230 1.908 ± 0.016 Msun (Demorest et al. 2010, Fonseca et al. 2016)

PSR J0348+0432 2.01 ± 0.04 Msun (Antoniadis et al. 2013)

PSR 0740+6620 2.14(+0.10/-0.09) Msun (Cromartie et al. 2020)

PSR 2215+5135 2.27 ± 0.17 Msun (Linares et al. 2018)

PSR 0952-0607 2.35 ± 0.17 Msun (Romani et al. 2022)

Constrain from GW 170817: Maximum mass 2.16 (+0.17/-0.15) Msun (Rezzolla et al. 2018)

The maximum mass of the NSs should be around 2.20 Msun.

During the evolution phase of LMXBs, little mass is accreted by NS.
Some NSs must be born with masses close to the maximum mass.

Kinematic effects of the AIC event

- During the collapse, we assume that an equivalent mass of 0.20 Msun is lost.
- The kick velocity of BH is assumed to be < 50 km/s.
- The binary separation after AIC

Tauris et al. 2013

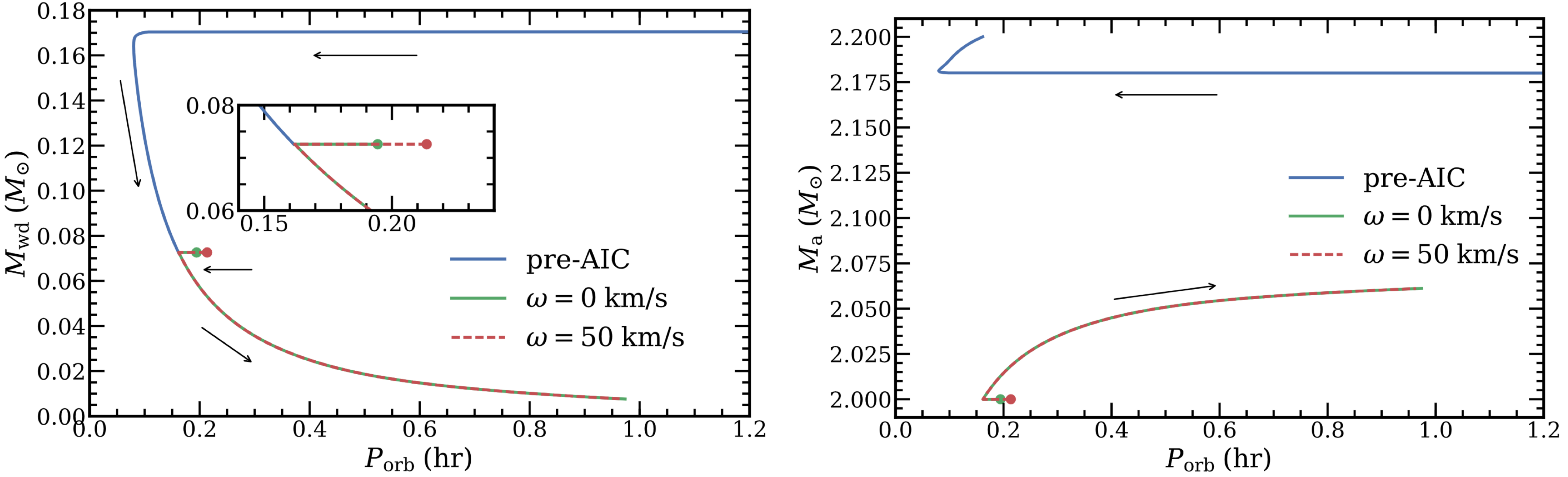
$$\frac{a}{a_0} = \left[\frac{1 - (\Delta M/M_0)}{1 - 2(\Delta M/M_0) - (w/v_c)^2 - 2\cos\theta\,(w/v_c)} \right]$$

- The eccentricity after AIC

$$e = \sqrt{1 + \frac{2E_{\rm orb}J_{\rm orb}^2}{\mu G^2 M_{\rm NS}^2 M_2^2}}$$

- the post-AIC orbit will be circularized due to the tidal interatction, binary separation: $a(1-e^2)$

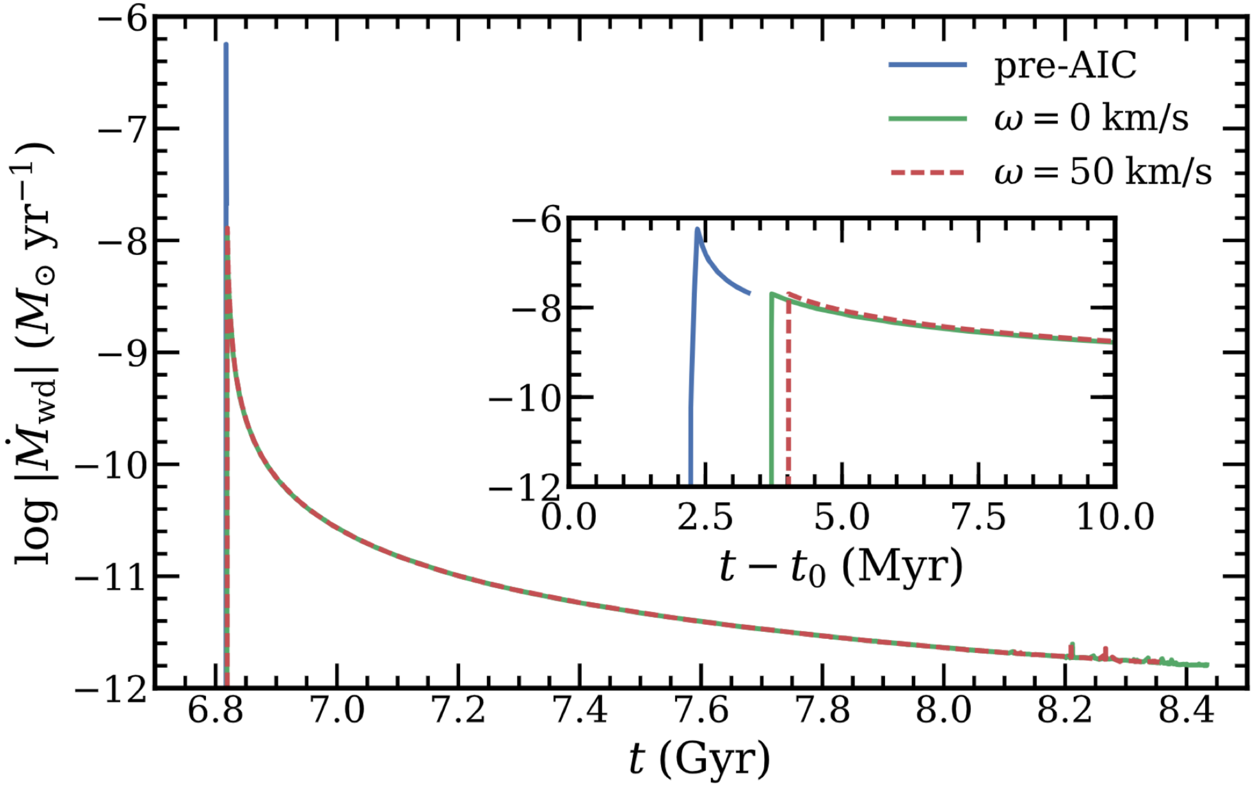
Binary evolution examples

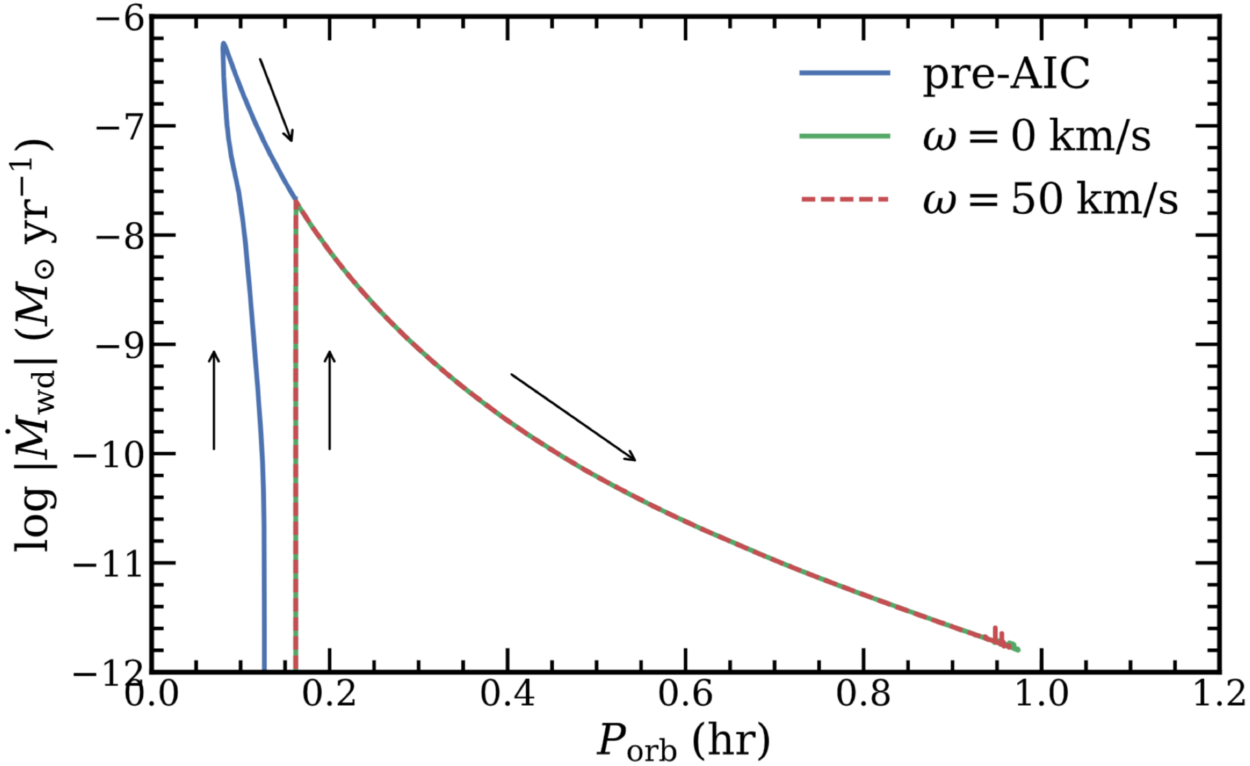


Initial binary parameters:

M_{NS} = 2.18 Msun, M_{wd} = 0.17 Msun, P_{orb} = 0.30 days

Binary evolution examples





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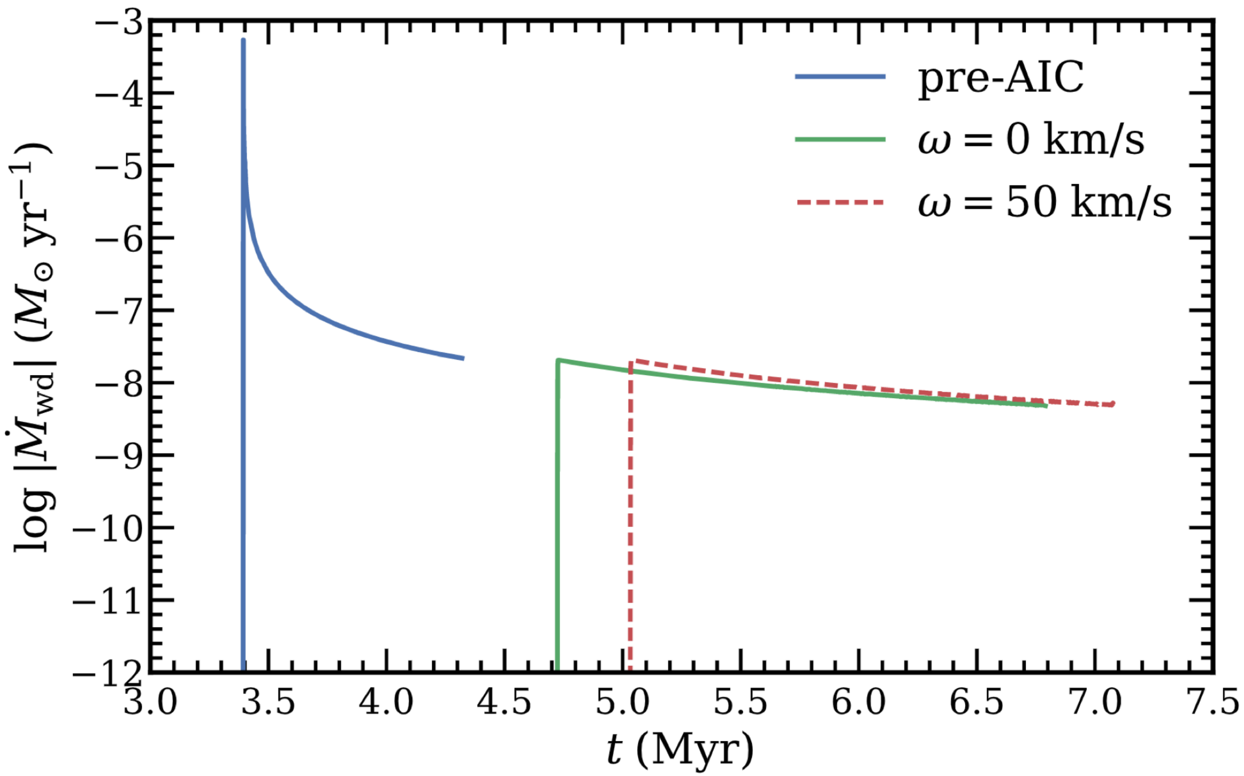
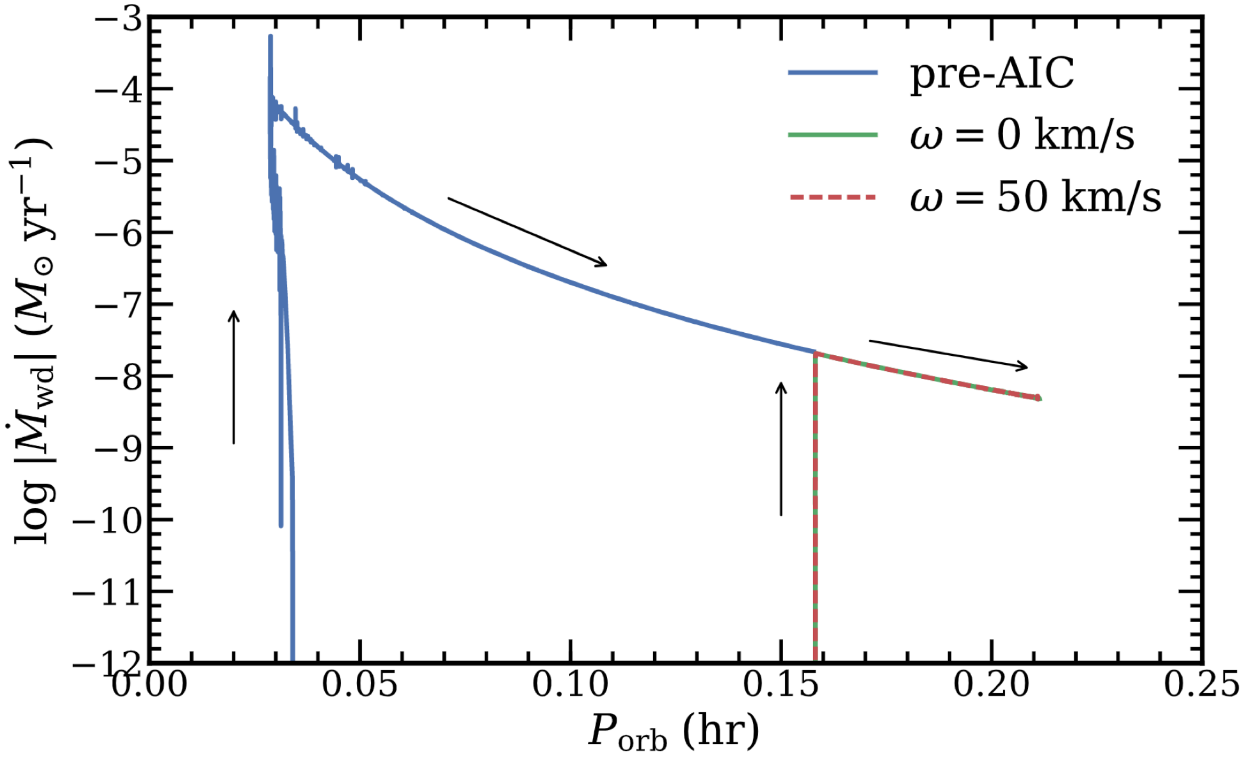
Binary evolution examples

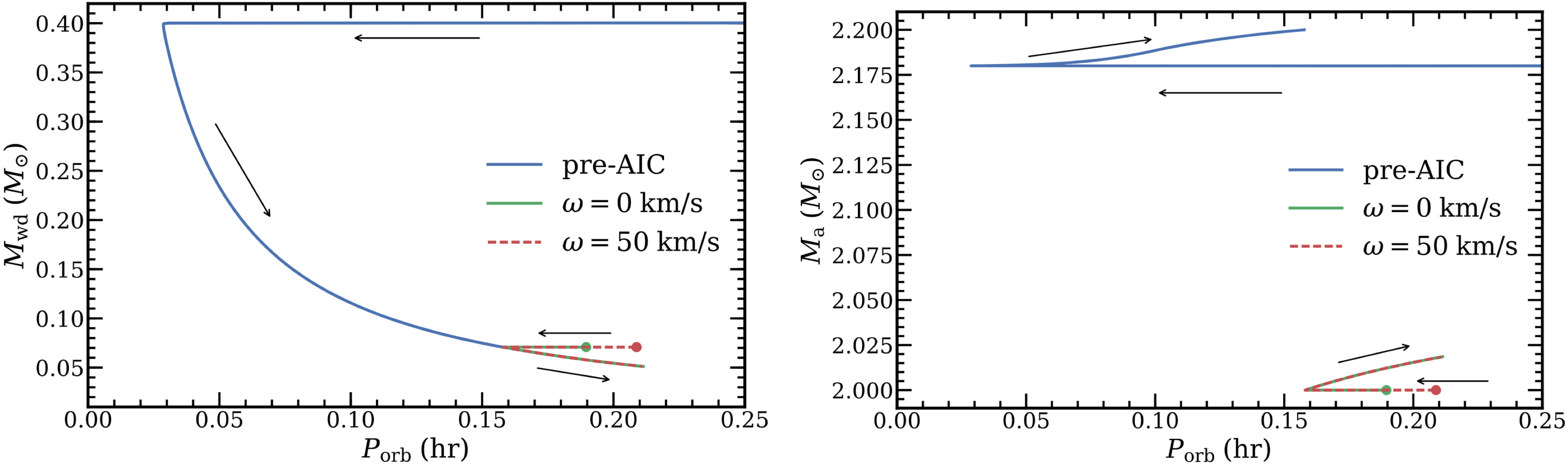




Initial binary parameters:

M_{NS} = 2.18 Msun, M_{wd} = 0.40 Msun, P_{orb} = 0.02 days

Binary evolution examples



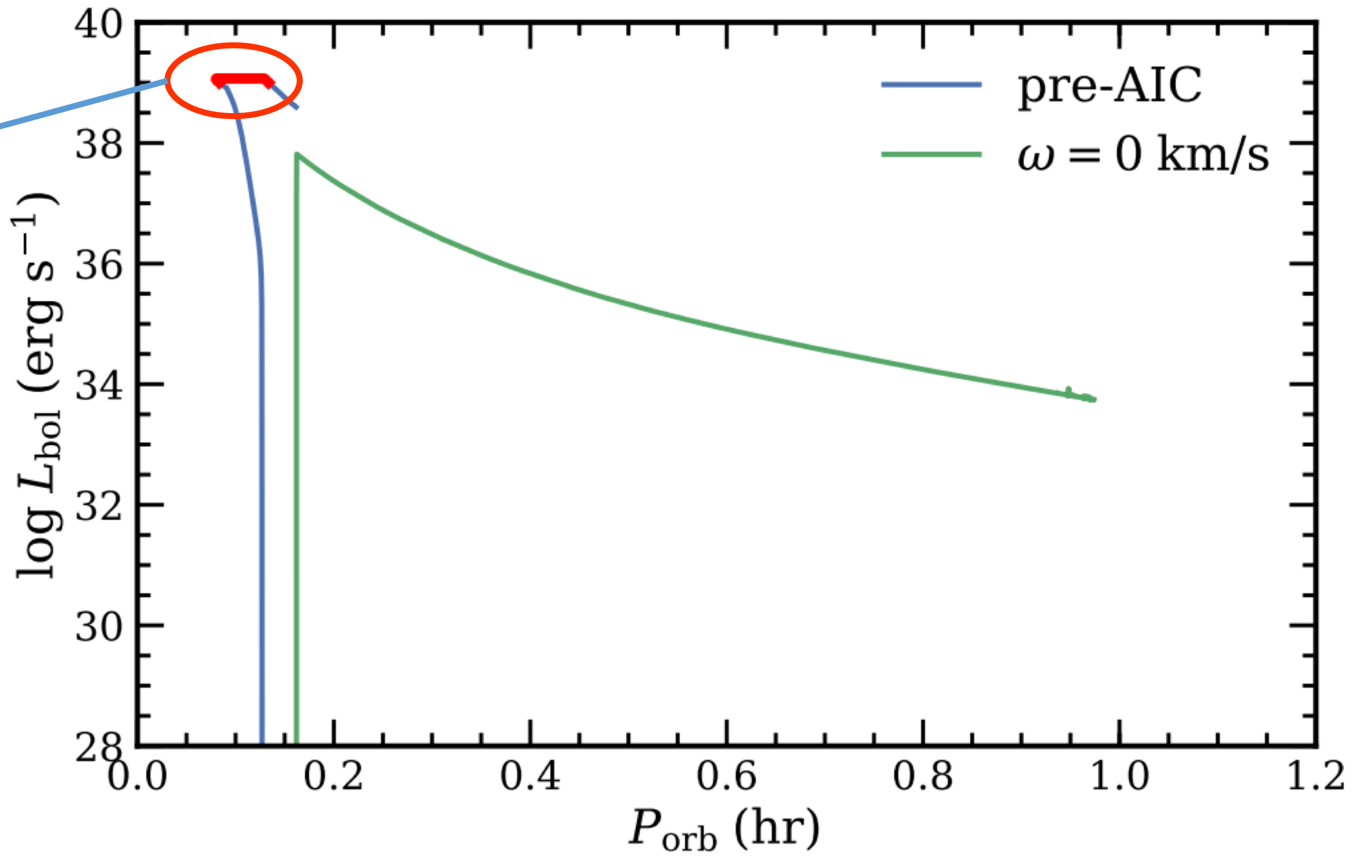
Initial binary parameters:

M_{NS} = 2.18 Msun, M_{wd} = 0.40 Msun, P_{orb} = 0.02 days

A new kind of ultra-luminous X-ray sources?

X-ray luminosity
Lx > 10^{39} erg/s

ultraluminous X-ray sources



This may be helpful to explain som of the ultraluminous X-ray sources observed in old stellar population environments (e.g. Irwin et al. 2004)

Summary

- With the MB prescription from Van et al. 2019, the fine-tuning problem is relieved.
- We found that all NS + He WD binaries can have dynamically stable mass transfer.
- The GW signal from NS + He WDs can be detected by LISA, TianQin and Taiji. There is a tight relation between the WD mass and GW frequency for UCXBs.
- We demonstrate that BH-UCXBs can be produced via accretion induced collapse of neutron stars.

Thank you !