Counterparts of X-ray and γ-ray binaries

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Plan de Recuperación, Transformación y Resiliencia

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ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Evidence of X-ray periodicity in LSI+61°303

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The distances to the X-ray binaries LSI +61° 303 and A0535+262

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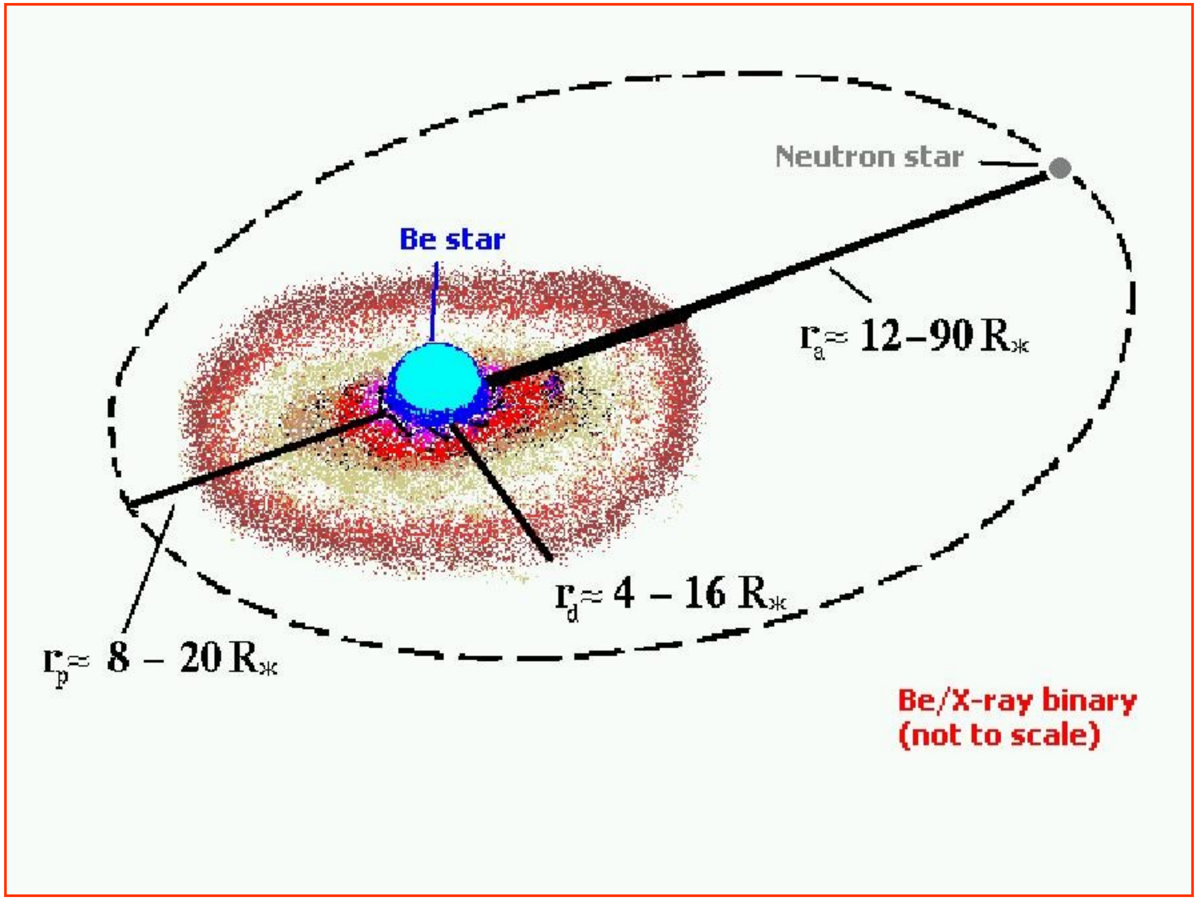
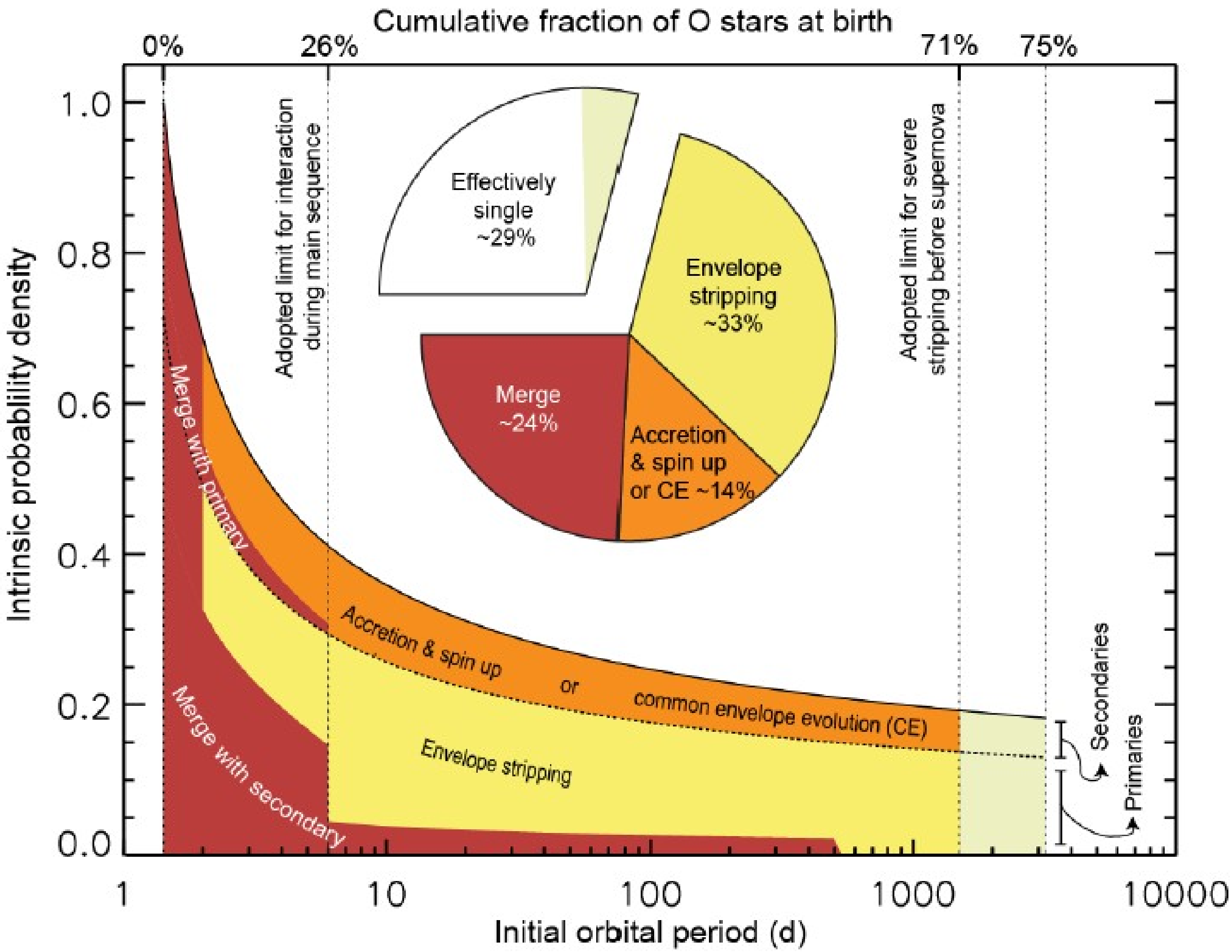
Be/X-ray binary



Okazaki & Negueruela 2001 (A&A 377, 161)

Binary interaction dominates the evolution of massive stars

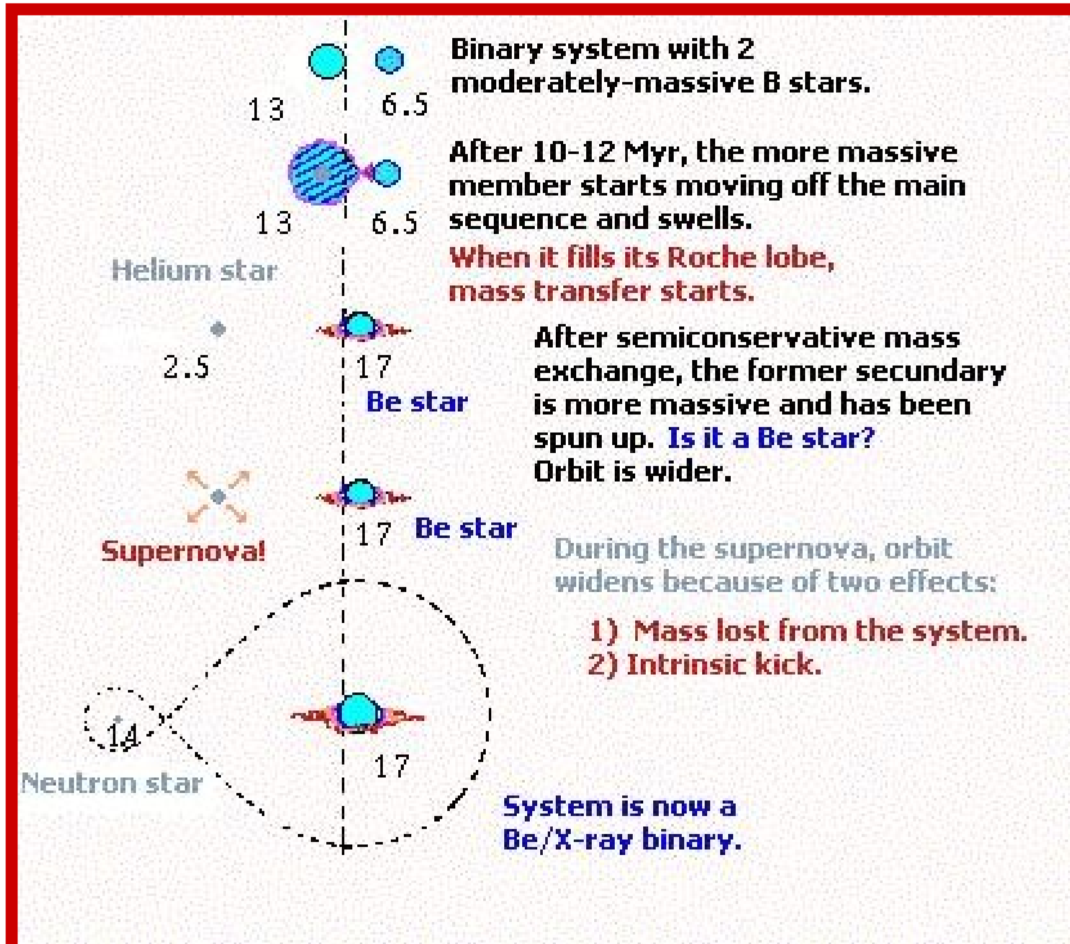


Estimated fraction of high-mass binaries obtained from the number of observed high-mass binaries (Sana et al. 2012, Science 337, 444**)**

The making of a Be/X-ray binary

Canonical model for the creation of Be/X-ray binaries:

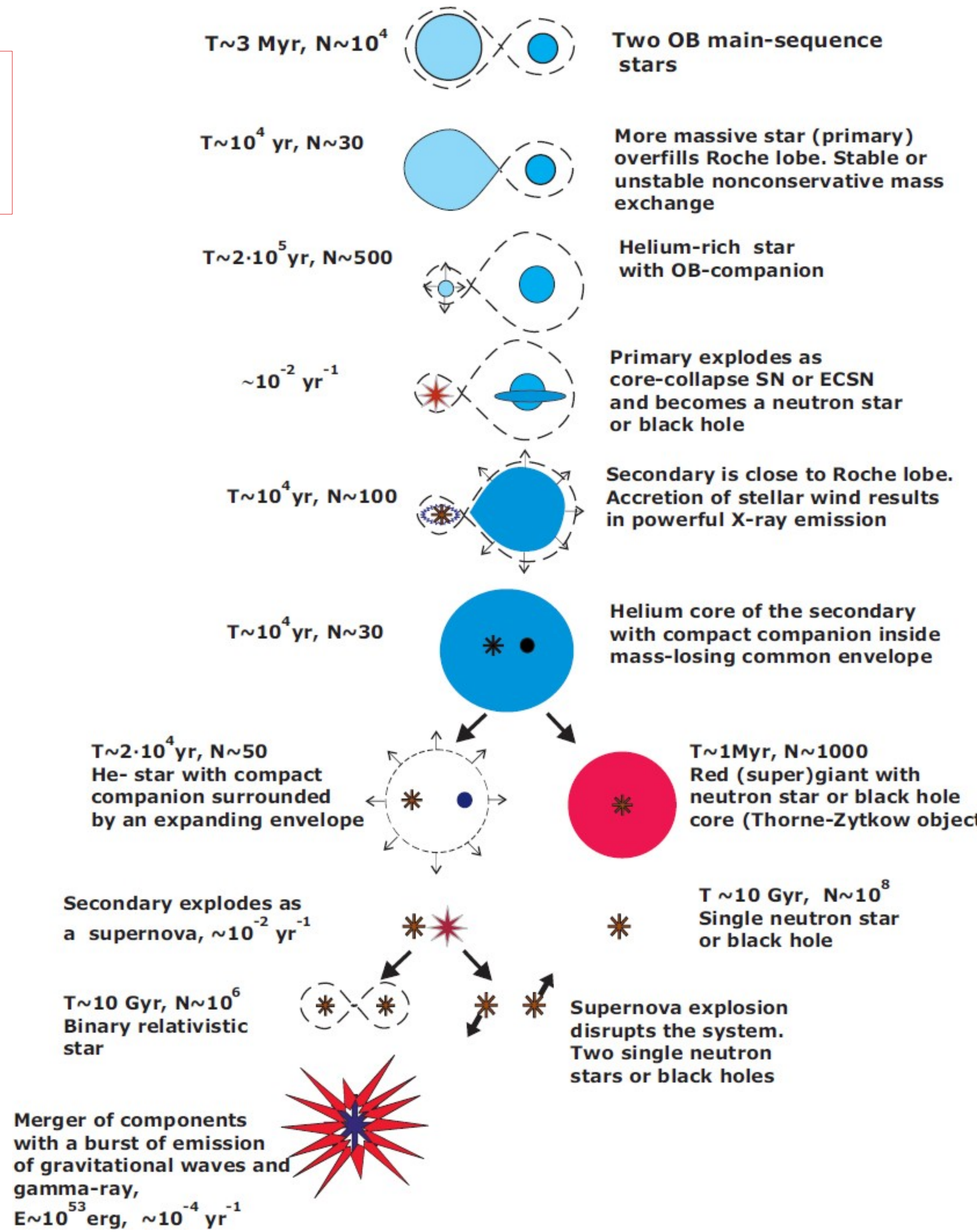
- Case B evolution
- (semi)conservative mass transfer
- q ≳ 0.5



After Rappaport & van den Heuvel (1982)

The road to GW

Postnov & Yungelson 2014 (LRR 17, 3)



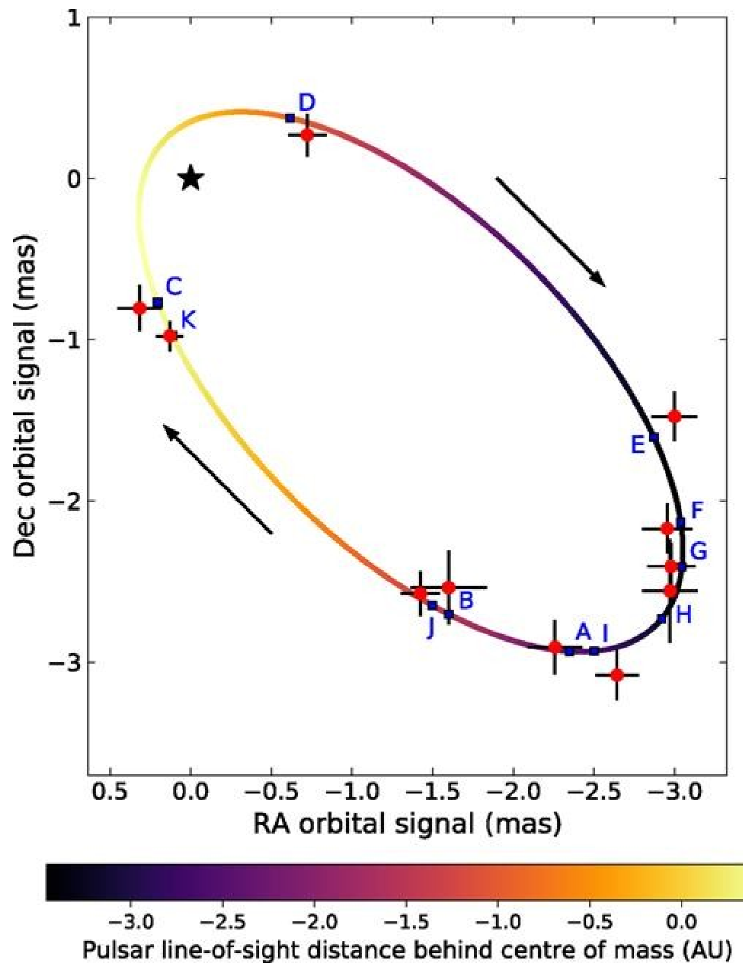
PSR B1259-63

Table 1
Fitted and Derived *Apparent* Stellar Parameters for LS 2883

Parameter	Value
$T_{\rm eff}$ (K)	32000^{+2000}_{-1000}
$\log g$	$3.80^{+0.30}_{-0.20}$
R_*[a] ($R_\odot$)	$9.0^{+1.8}_{-1.5}$
$\log(L_*/L_\odot)$[a]	$4.88^{+0.19}_{-0.17}$
M_*[a] ($M_\odot$)	$21.3^{+22.0}_{-9.0}$
M_*[a,b] ($M_\odot$)	$26.6^{+23.5}_{-10.5}$

Notes.
[a] Assuming $d = 2.3 \pm 0.4$ kpc and $E(B-V) = 0.85 \pm 0.05$.
[b] Deprojecting the rotational velocity with $i = 35°$, after applying the correction of Fremat et al. (2005).

Negueruela+ 2011 (ApJL 732, L11)

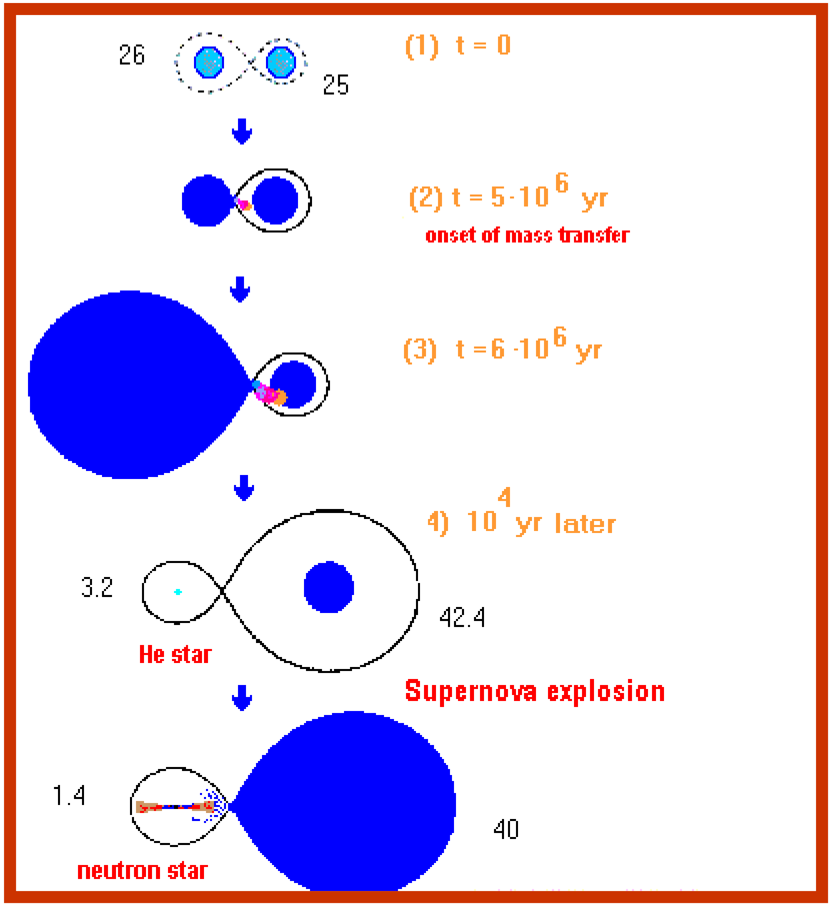


Miller-Jones+ 2018 (MNRAS 479, 4849)

PSR B1259-63

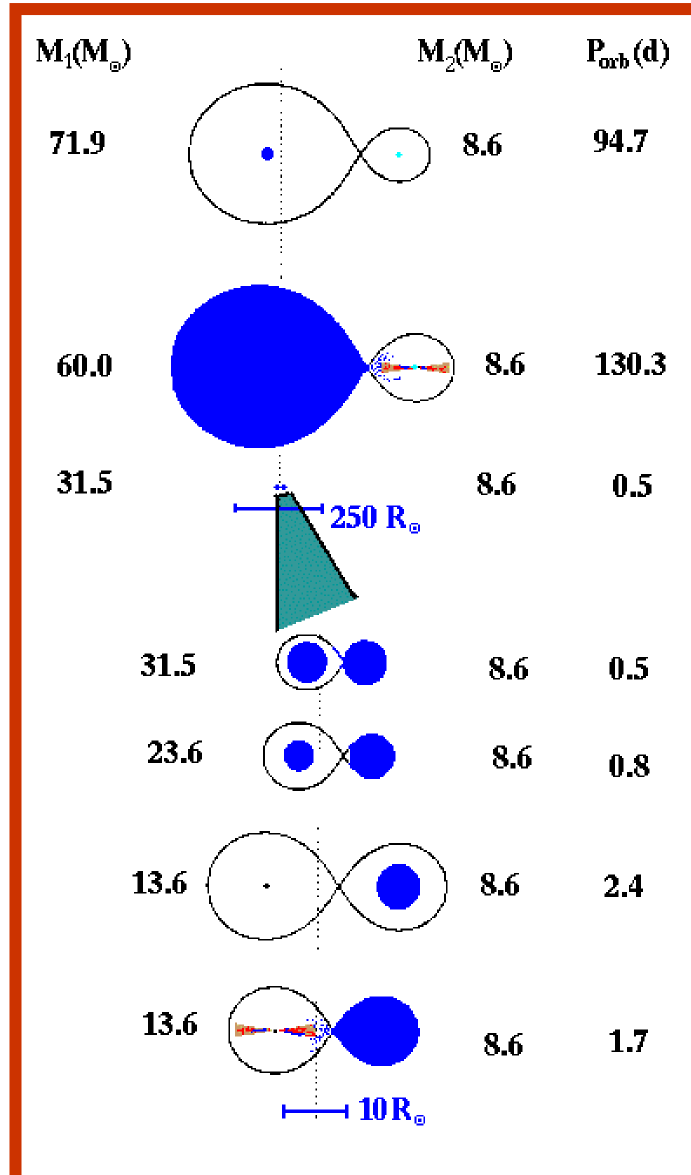
Conservative mass transfer

- Case A mass transfer
- $q \approx 1$
- Fully conservative evolution with two phases of mass transfer
- Produces SG+NS



Non-conservative mass transfer

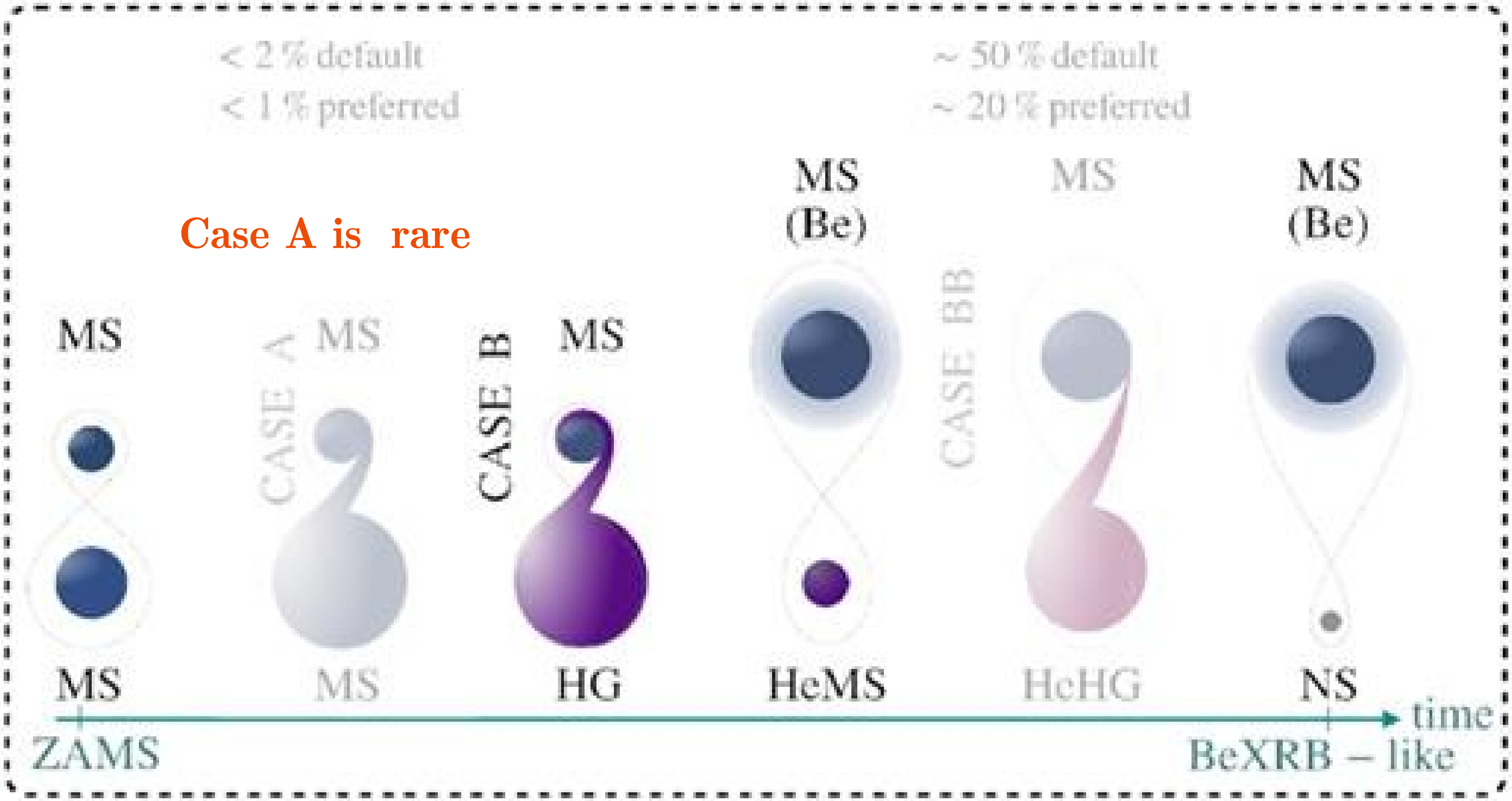
- Case C
- $q << 1$
- Fully non-conservative evolution via common envelope
- Produces SG+BH



$q > 0.3$ for stability

Case B at start of Hertzsprung gap greatly favoured

Significant mass transfer here results in ultrastripped He star → low kick



Vinciguerra+ 2020 (MNRAS 498, 4705)

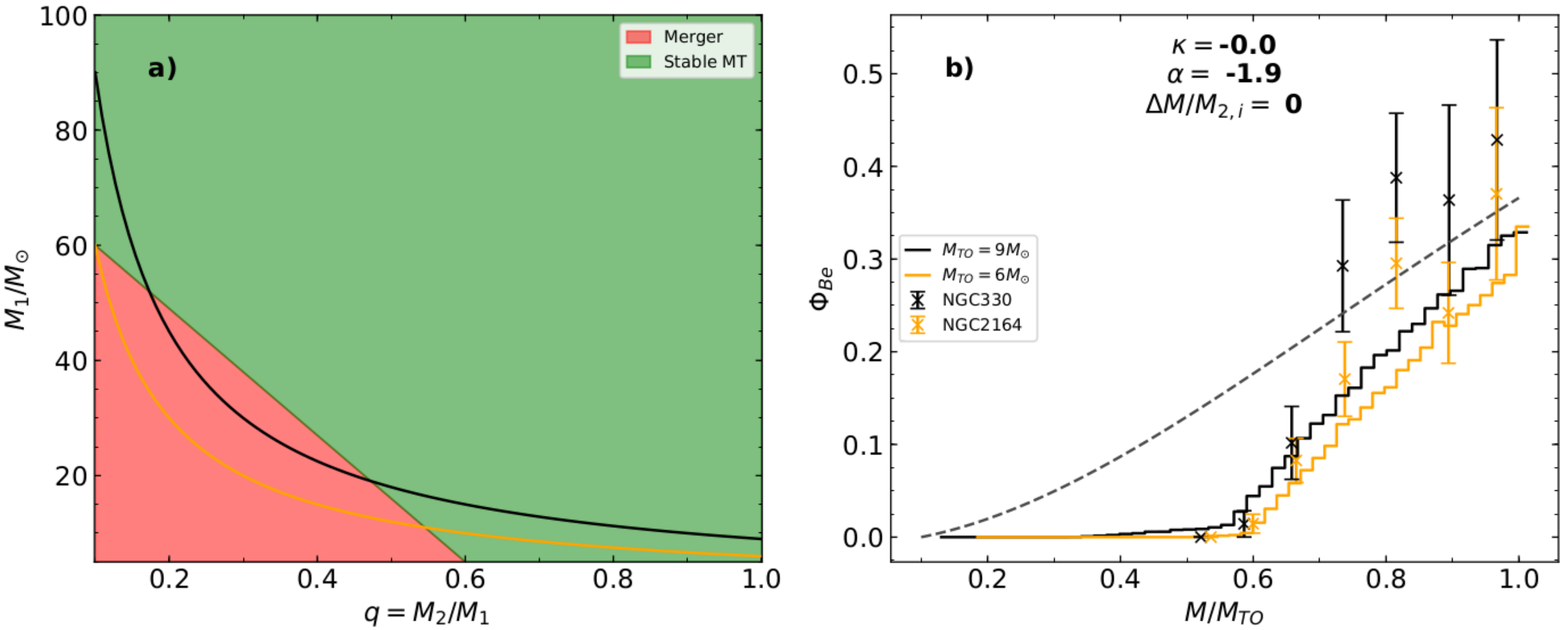


Fig. 5. (*a*) Adopted region of stable mass transfer in the primary mass-mass ratio plane. Regions coloured red experience unstable mass transfer and merge. For green regions, mass transfer is stable, and a Be star is formed. The black and orange lines show systems with secondary masses of 9 and 6 $M_\odot$, respectively. (*b*) Results of a Monte Carlo simulation showing the Be fraction, Φ_{Be}, when the stable mass-transfer region in (a) is applied. Binary systems have a flat mass-ratio distribution ($\kappa = 0$), a primary mass distribution $\xi(M_1) \propto M^{-1.9}$, and we have assumed inefficient accretion ($\Delta M/M_{2,i} = 0$). The black line shows a simulation with a turn-off mass of 9 $M_\odot$, and the orange line a turn-off mass of 6 $M_\odot$. The dashed grey line shows the theoretical upper limit, as given by Eq. (30). Measured Be fractions of NGC 330 and NGC 2164 according to Fig. 3 are plotted as black and orange crosses, respectively.

Hastings+ 2021 (A&A 653, A144)

Does mass transfer make a Be star?

O8V → B0 III

O9V → B1 III

Negueruela+ 2004 (AN 325, 749)

Does mass transfer make a Be star?

	Be fraction	Milky Way		Be fraction
O8V	$\sim 0\%$	→	B0III	$\sim 10\%$
O9V	$\sim 1\%$		B1III	$\sim 15\%$

Negueruela+ 2004 (AN 325, 749)

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Milky Way

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O8V	$\sim 0\%$	→	B0 III	$\sim 10\%$
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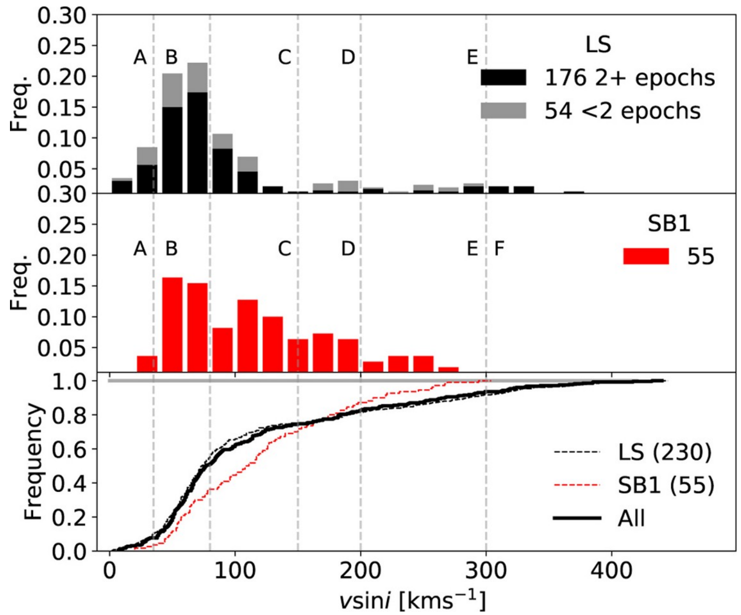

Holgado+ 2022 (A&A 665, A150)

Does mass transfer make a Be star?

Milky Way

	Be fraction			Be fraction
O8V	$\sim 0\%$	→	B0III	$\sim 10\%$
O9V	$\sim 1\%$		B1III	$\sim 15\%$

Ω/Ω_{crit}? Granada & Haemmerlé (2014)

Negueruela+ 2004 (AN 325, 749)

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$\Omega/\Omega_{\rm crit}$? Granada & Haemmerlé 2014

Wind properties?

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$\Omega/\Omega_{\rm crit}$? Granada & Haemmerlé 2014

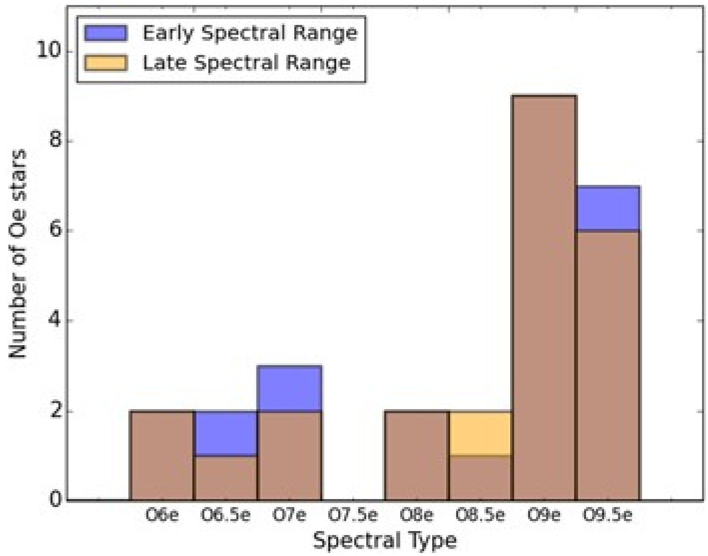
Wind properties?

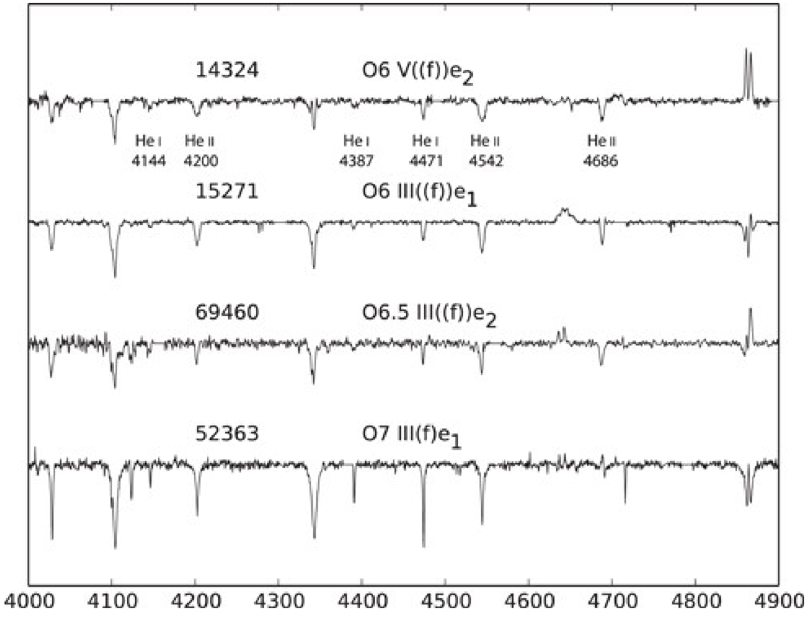
Non-radial pulsations?

Negueruela+ 2004 (AN 325, 749)

A dependence on metallicity

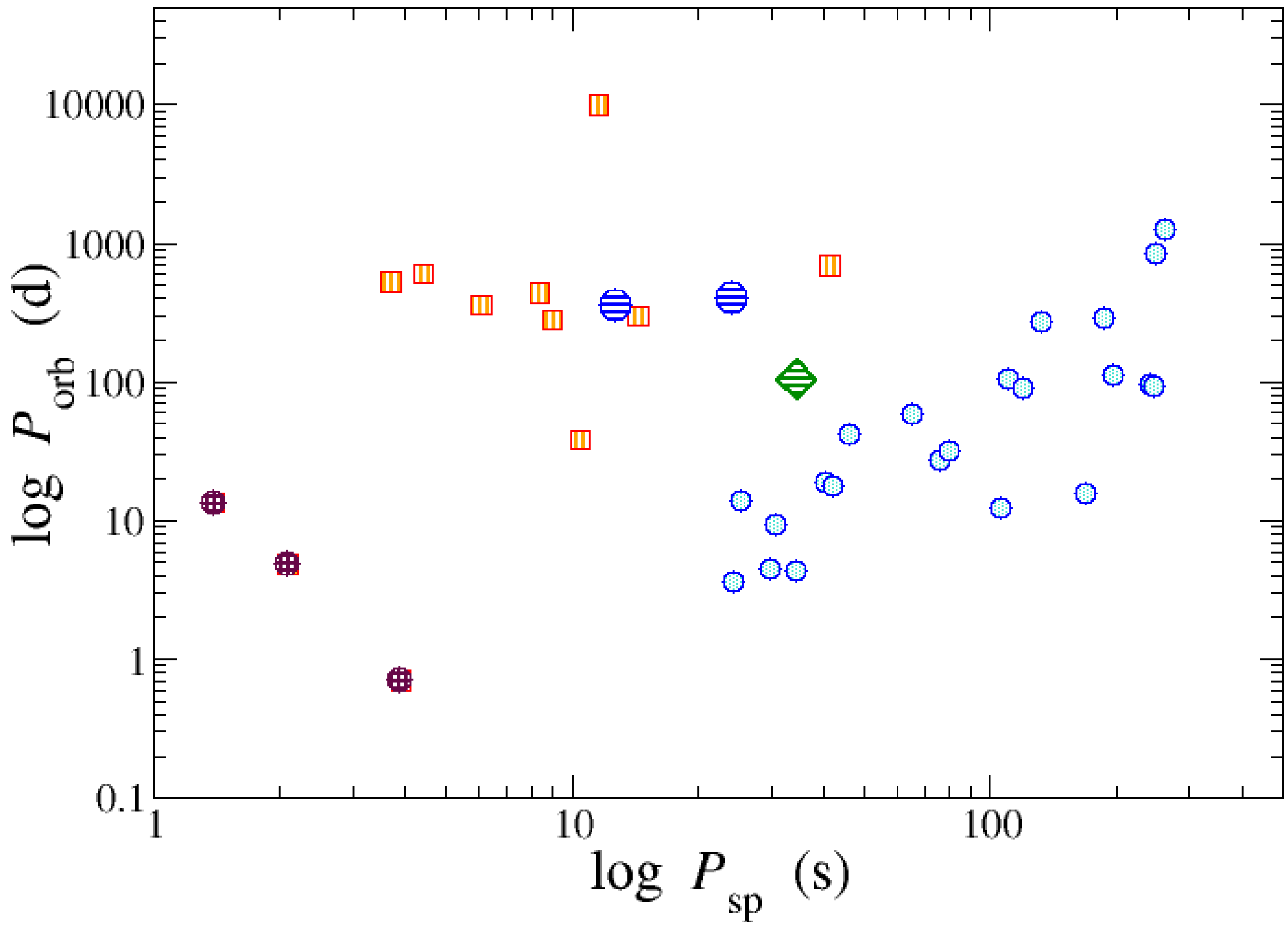
- Negueruela (2004) and Negueruela+ (2004) explored the edges of the Be phenomenon in the Milky Way.
- There are a few O9e stars, but only one known Be star earlier than O8.
- But it is very different in the SMC!





Golden-Marx+ (2016; ApJ 819, 55)

Corbet diagram



Object	P_s	Companion	P_{orb}	e
LS I +61 303	269 ms	O9.7 Ve	26.5 d	0.7
HESS J0632-057	??	B0.5 Ve	317 d	0.40
PSR B1259-63	48 ms	O9.5 Ve	1237 d	0.87
PSR J2032+4127	143 ms	B0 Ve	48 a	0.98

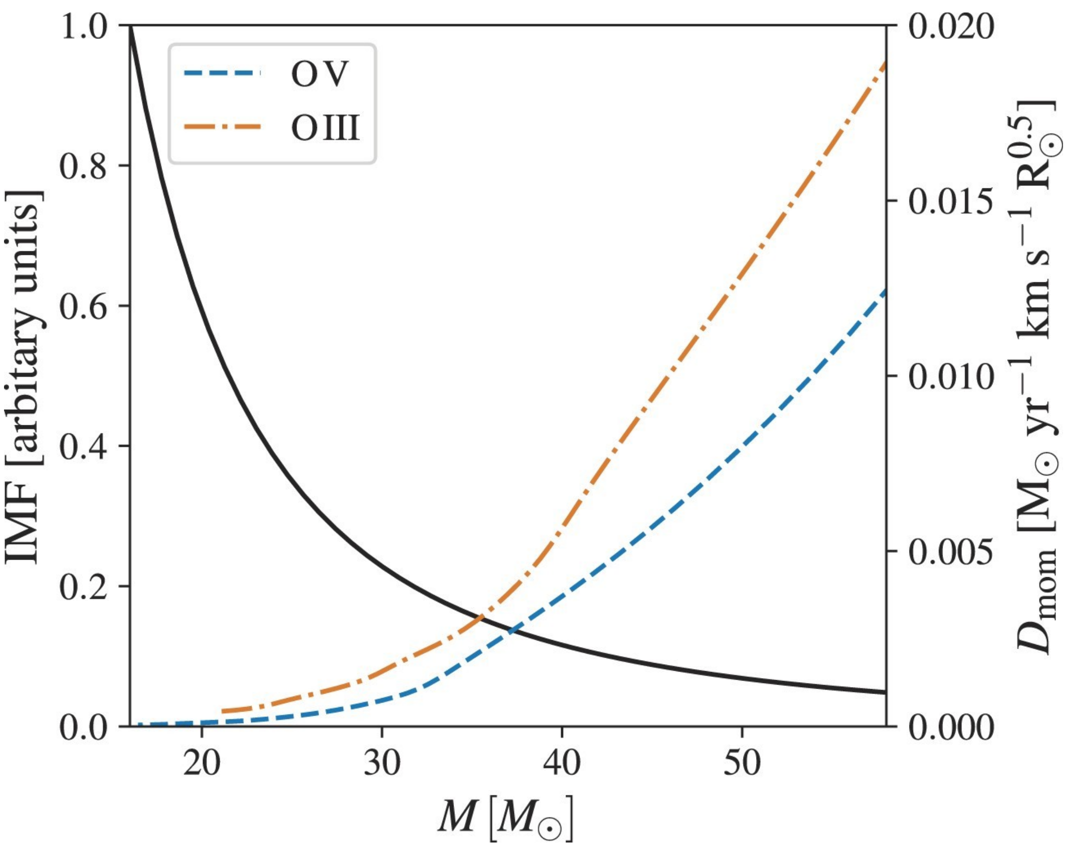
Object	P_s	Companion	P_{orb}	e
PSR J0045-17319	0.9 s	B1 V	51 d	0.8
PSR J1740-3052	570 ms	B	231 d	0.57
PSR J0210+5845	1.77 s	B6 V	~50 a	~0.45
PSR J1638−4725	0.76 s	B?		

Object	P_s	Companion	P_{orb}	e
4FGL J0535.2-6736	?	O5 III(f)	10.3 d	0.4
1FGLJ1018.6−5856	?	O6 V ((f))	16.5 d	0.53
4FGLJ1405.1−6119	?	~O6.5 III	13.7 d	?
1FGL J1826.2-1450	~9 s ??	ON6 V((f))z	3.9 d	0.3
HESS J1832-093	?	O6 V	~86 d	?

Object	P_s	**Companion**	P_{orb}	e
Cen X-3	4.8 s	O6-7 II-III	2.0 d	0.0
GX 301-2	680 s	B1.5 Ia+	41.5 d	0.46
OAO 1657-415	37 s	Ofpe/WN9	10.5 d	0.11
XTE J1739-302	?	O8 Iab(f)	51.5 d	?
AX J1845.0-0433	?	O9 Ia	4.7 d	0.34

And all the others?

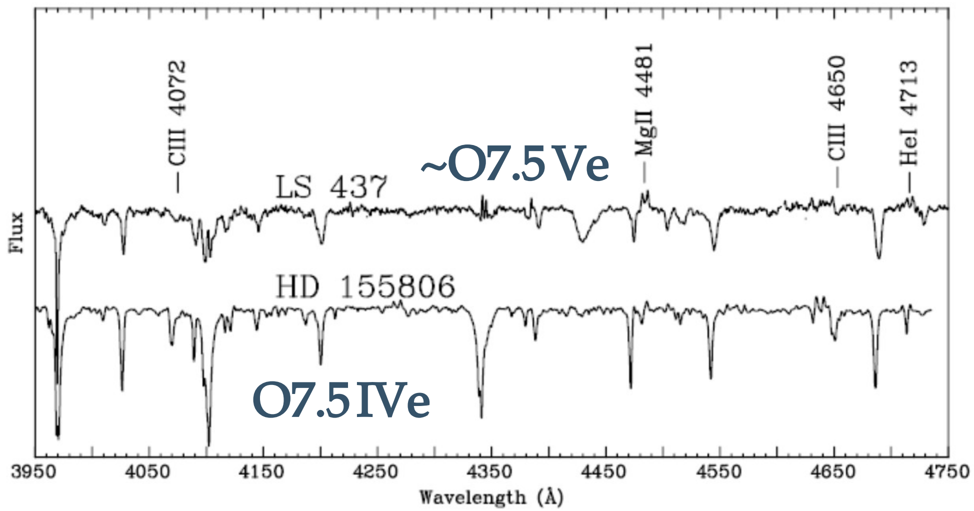
- O7V + ms pulsar
- O8V + ms pulsar



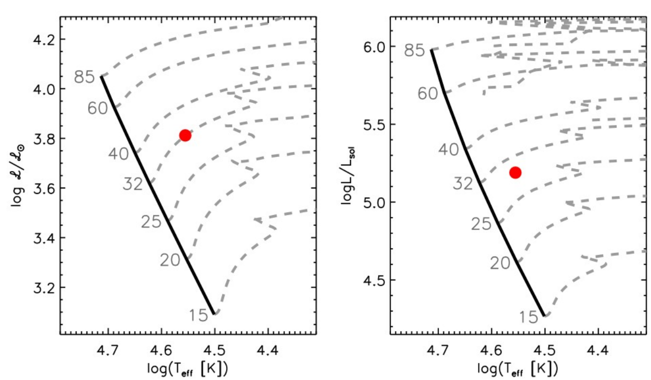
Van Soelen+ 2024 (MNRAS 529, L102)

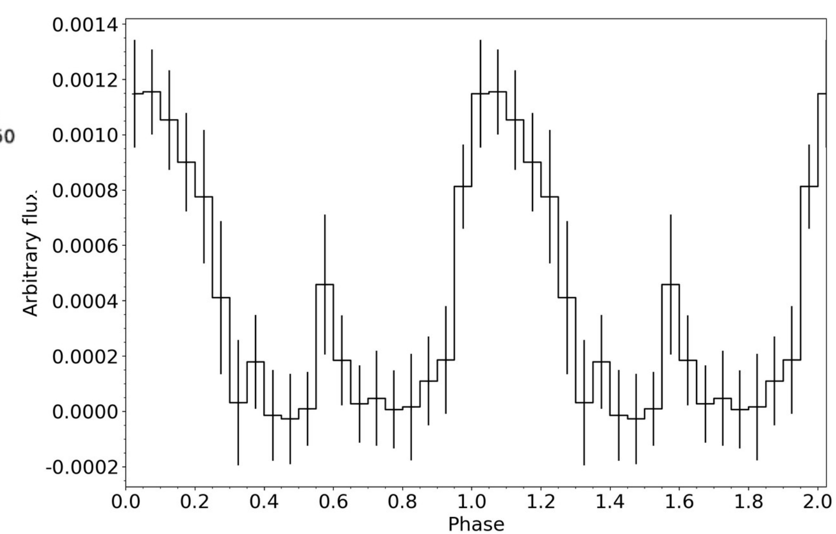
LS 437/ 4U0728-26

- Persistent intermediate-luminosity Be/X-ray binary with Oe companion (Negueruela+ 1996).

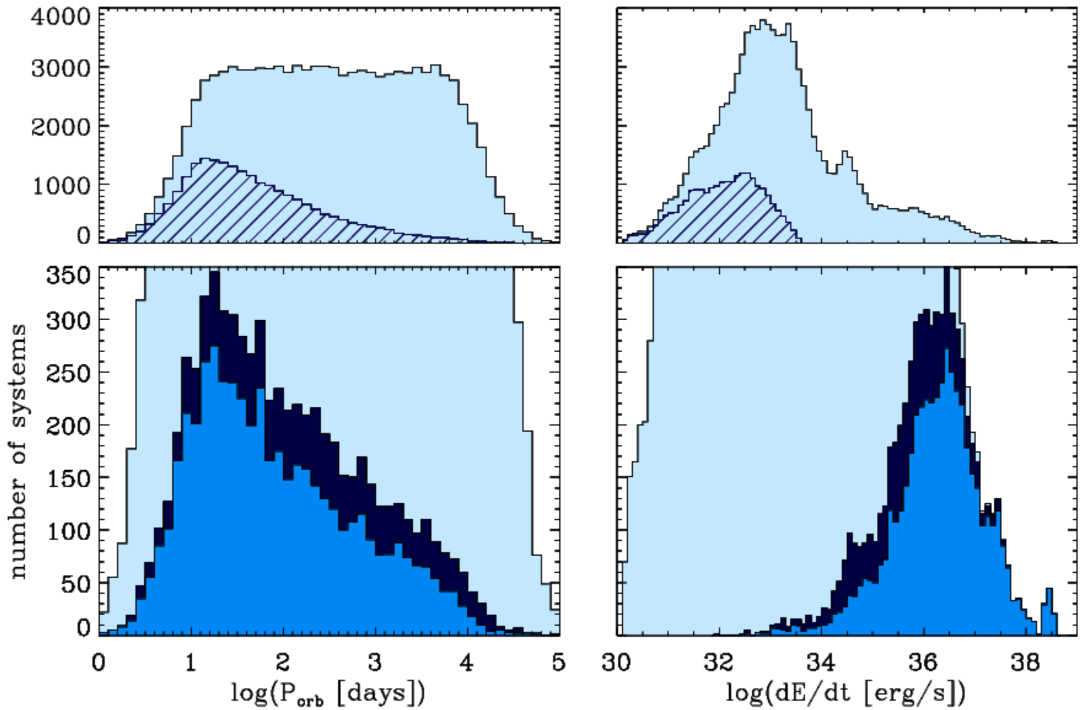


- A NS with P_{spin} = 103 s in a 34.5 d orbit (Corbet & Peele 1997)

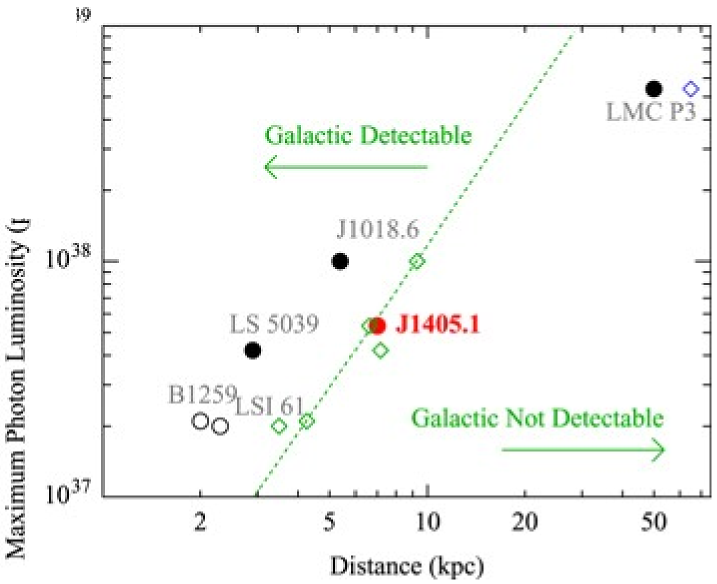




Gaia distance around 7.5 kpc

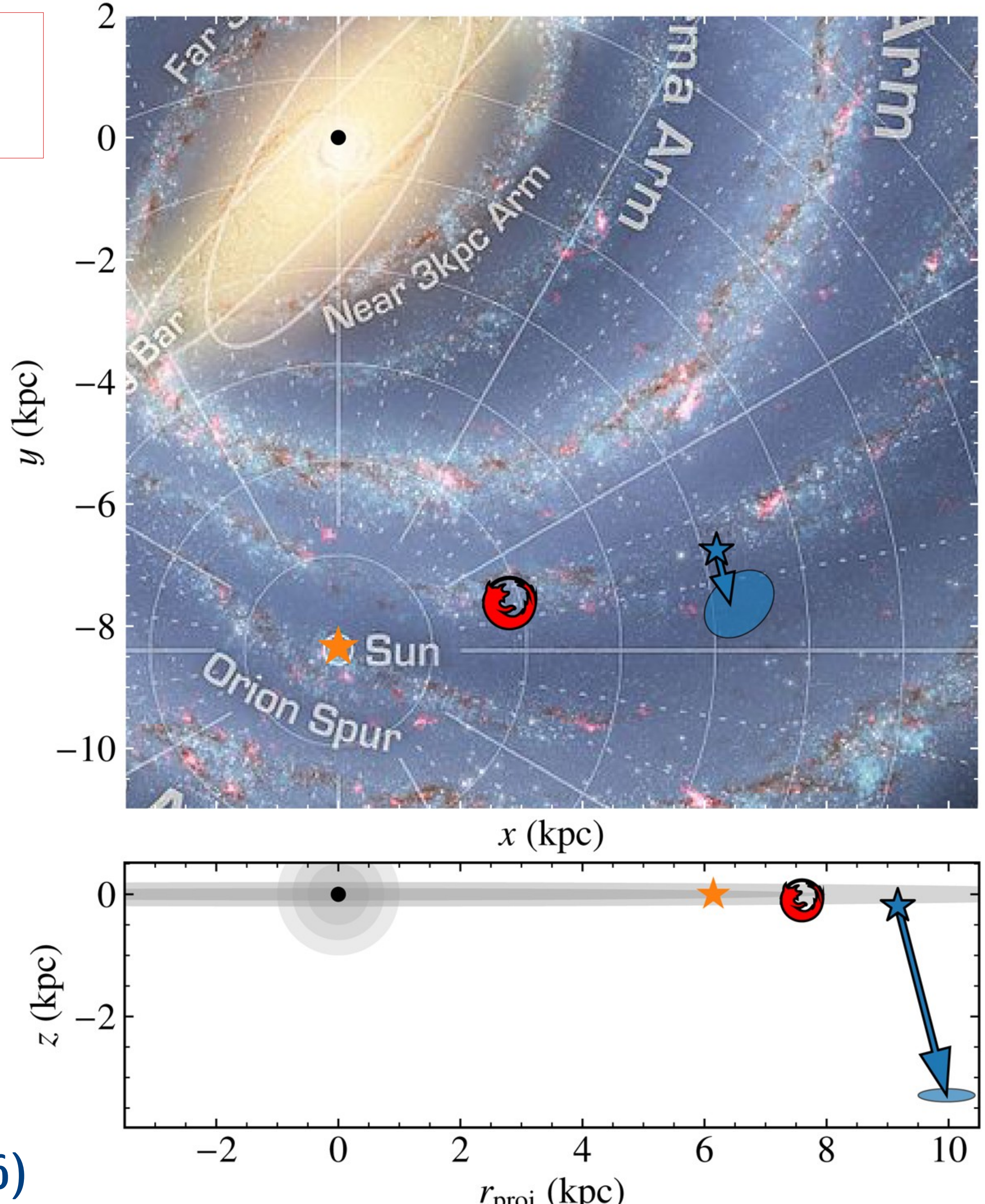


Dubus+ 2017 (A&A 608, A59)



Corbet+ 2019 (ApJ 884, id. 93)

1FGL J1018.6–5856



Marcote+ 2018 (A&A 619, A26)

HMXB	Cluster	Encounter age [Myr]	v_{pec} [km s^{-1}]	$M1_{ZAMS}$ [$M_{\odot}$]	$M2_{ZAMS}$ [$M_{\odot}$]	Xfer [$M_{\odot}$]
1A 0114+650	UBC 600	$-4.4^{+4.4}_{-3.4}$	37^{+11}_{-10}	13^{+1}_{-1}	12^{+2}_{-1}	4 ± 3
	NGC 457	-17^{+4}_{-4}	50^{+14}_{-11}	40^{+120}_{-12}	18^{+3}_{-2}	...
LS I+61 303	IC 1805	-5^{+5}_{-15}	9^{+13}_{-6}	$55^{+\infty}_{-30}$	31^{+11}_{-5}	...
	UBC 191	-16^{+6}_{-6}	12^{+5}_{-3}	39^{+120}_{-13}	19^{+2}_{-2}	...
	NGC 884	-15^{+4}_{-8}	14^{+3}_{-3}	51^{+110}_{-22}	20^{+3}_{-2}	...
	NGC 957	-15^{+7}_{-8}	18^{+4}_{-4}	15^{+2}_{-1}	12^{+5}_{-1}	1 ± 3
	ASCC 9	-10^{+5}_{-19}	33^{+30}_{-16}	18^{+10}_{-4}	15^{+2}_{-1}	...
X Per	ASCC 13	-24^{+8}_{-9}	33^{+4}_{-4}	28^{+120}_{-8}	15^{+2}_{-1}	1 ± 4
HD 259440	Stock 10	-38^{+4}_{-4}	31^{+1}_{-1}	$12.7^{+0.5}_{-0.5}$	10^{+1}_{-1}	6 ± 3
	COIN-*Gaia* 28	-47^{+32}_{-25}	11^{+4}_{-4}	28^{+130}_{-14}	15^{+2}_{-1}	4 ± 3
4U 1700-377	UBC 323	$-1.9^{+0.5}_{-0.5}$	110^{+26}_{-25}	31^{+1}_{-1}	27^{+4}_{-3}	19 ± 6
	NGC 6231	$-2.1^{+0.5}_{-0.7}$	62^{+12}_{-8}	$24.6^{+0.6}_{-0.6}$	23^{+3}_{-2}	23 ± 6
IGR J17544−2619	UBC 571	$-5.4^{+1.0}_{-0.8}$	37^{+3}_{-4}	$14.4^{+0.2}_{-0.1}$	14^{+2}_{-1}	10 ± 3
	UBC 540	-28^{+4}_{-8}	54^{+10}_{-10}	14^{+1}_{-1}	11^{+2}_{-1}	12 ± 3
Cyg X-1	NGC 6871	$-4.4^{+4.4}_{-8.0}$	26^{+16}_{-12}	56^{+110}_{-28}	32^{+4}_{-3}	...

Fortin+ 2022 (A&A 665, A69)

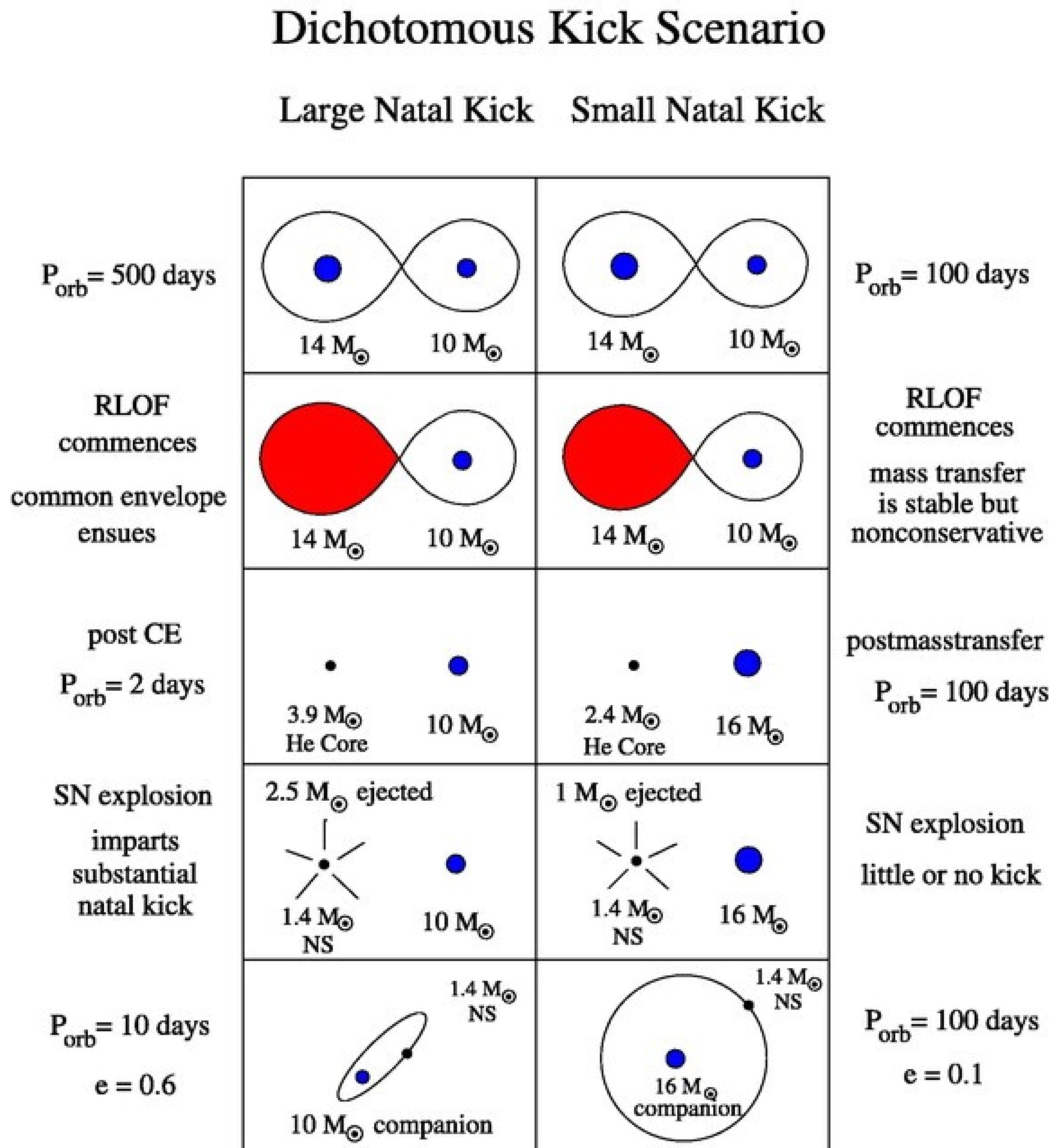
Be/X-ray binaries

Persistent sources

- Relatively low L_X ($\approx 10^{34}$ erg s^{-1}).
- Small intensity fluctuations (factor $\lesssim 10$) without an obvious temporal pattern.
- Lack of iron lines suggesting low-density environment.

Transients

- Quiescence: low ($\leq 10^{35}$ erg s^{-1}) or non-detectable L_X.
- Series of outbursts with relatively high X-ray luminosity ($L_x \lesssim 10^{37}$ erg s^{-1}), separated by the (suspected) orbital period (Type I or normal according to Stella et al. 1986, ApJ 308, 669).
- Larger outbursts with $L_x > 10^{37}$ erg s^{-1} ($L_x \approx L_{Edd}$), lasting several weeks and not showing modulation with the orbital period (giant or Type II) .



Podsiadlowski+ (2004; ApJ 612, 1044)

NGC 663

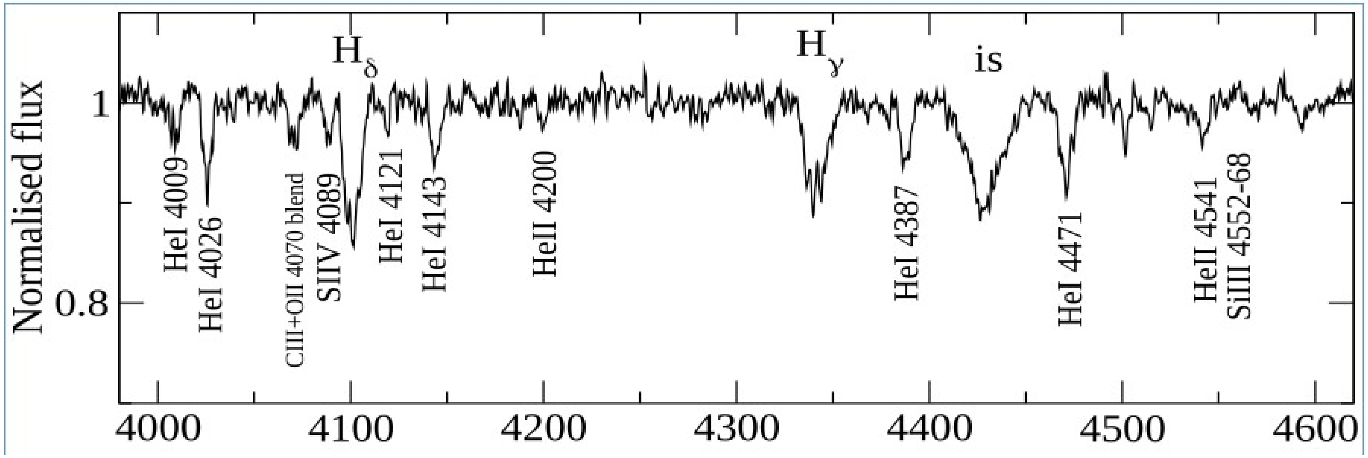
- Persistent low-luminosity Be/X-ray binary with Be shell companion (Reig+ 1997).
- Little X-ray variability.
- B0.7 IVe

Marco+ 2025 (MNRAS, submitted)

Swift J0243.6+6124

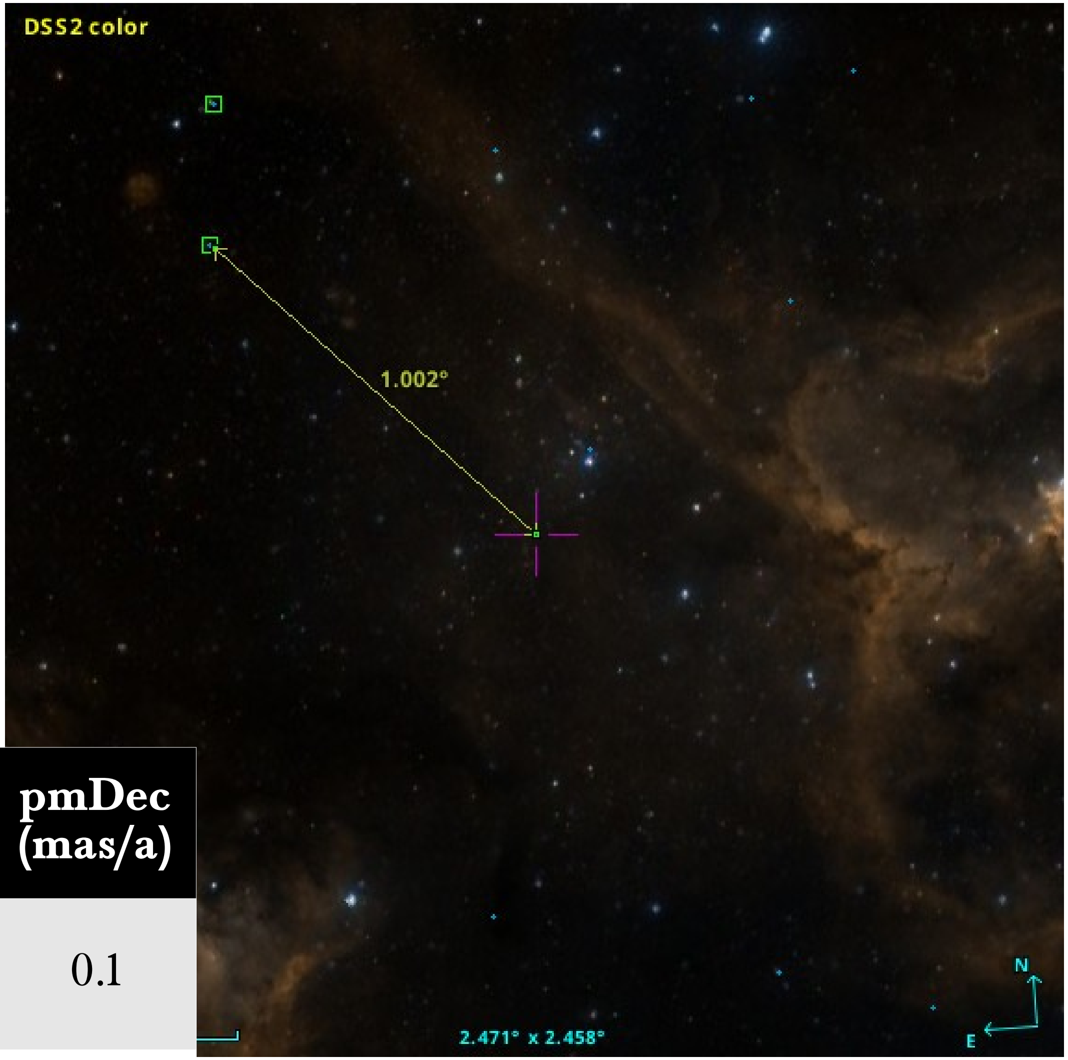
Parameter	Value
P_{orb}, d	28.3(2)
$a\sin(i)$, lt s	140(3)
e	0.092(7)
ω, deg	−76(4)
T_{PA}, MJD	58 019.2(4)
χ^2/dof	23.9/47
d_{GL}, kpc	6.60(5)
$B_{GL}/(10^{13}$ G)	1.08(6)

Doroshenko+ 2018 (A&A 613, A19)



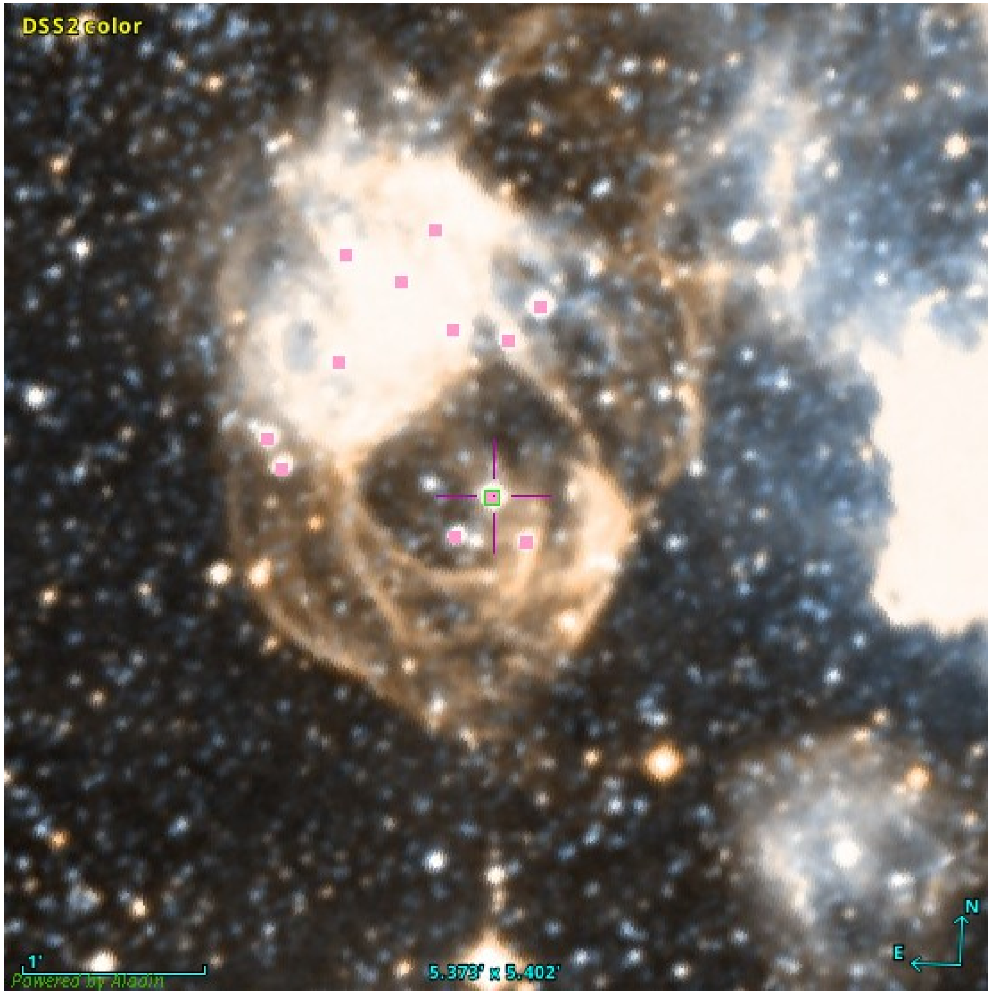
Reig+ 2020 (A&A 640, A35)

Swift J0243.6+6124



	Plx (mas)	pmRA (mas/a)	pmDec (mas/a)
J0243.6	0.18	-0.7	0.1
OC 254	0.18	-0.6	0.2
HSC 1108	0.17	-0.6	0.3

4FGL J0535.2-6736



$$P_{\mathrm{orb}} = 10.3\ \mathrm{d}$$
$$e = 0.4$$

Van Soelen+ 2019 (MNRAS 484, 4347)

Conclusions

- Over the past few years, our datasets have increased considerably.
- *Gaia* offers us a wealth of information that we could not have before.
- Gamma-ray binaries probe a very important point in the evolution of massive binaries.
- This is probably the best time to be working on these issues.

Counterparts of X-ray and γ-ray binaries

Ignacio Negueruela

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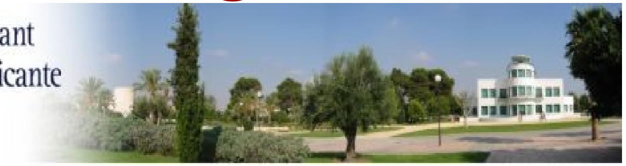

Barcelona, May 2025

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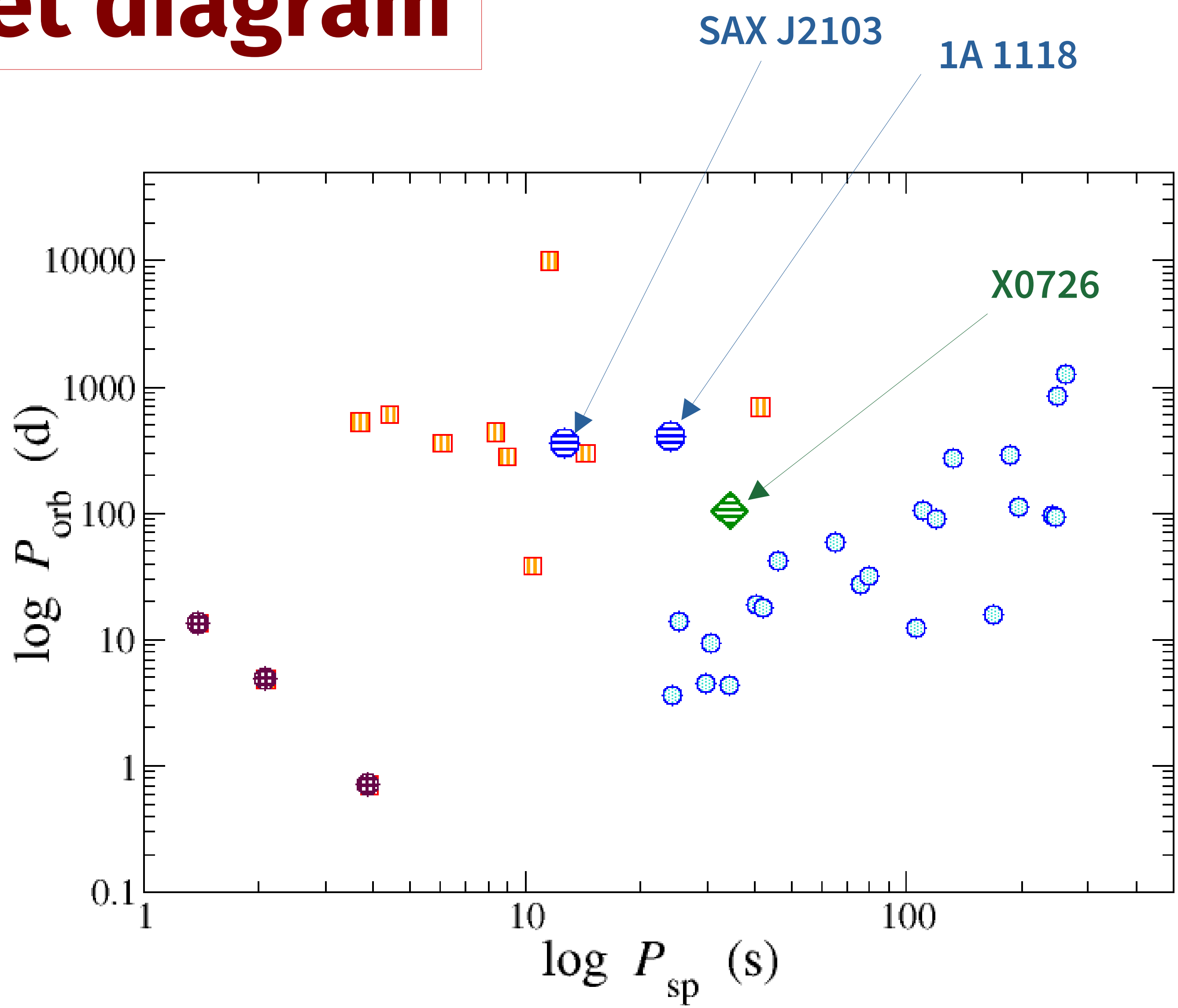
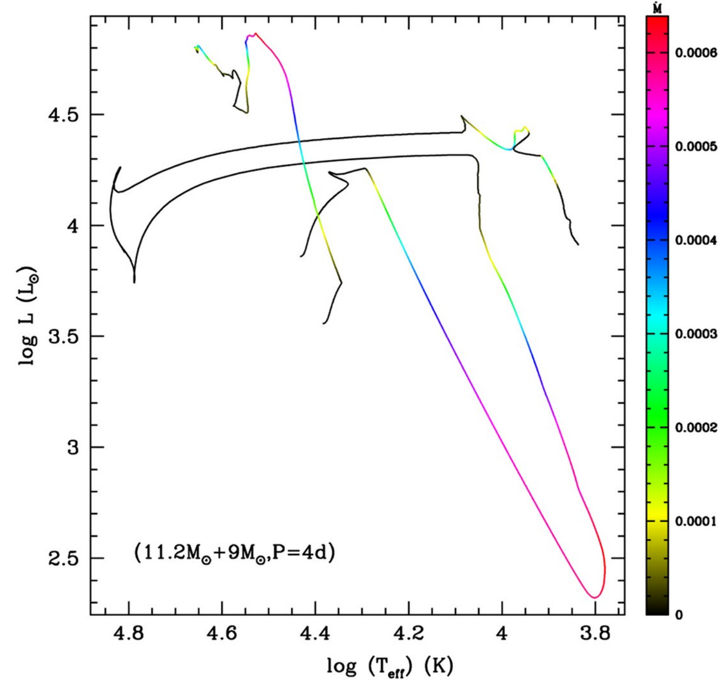
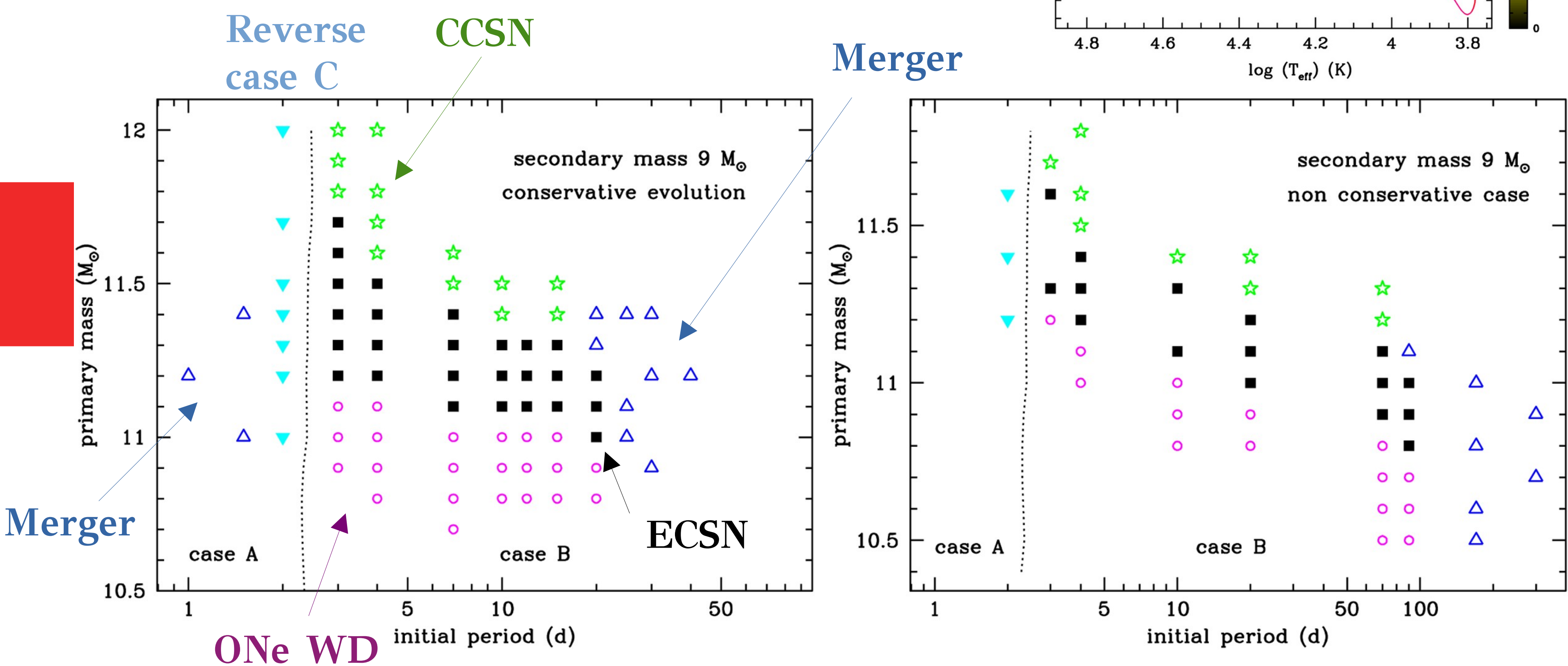
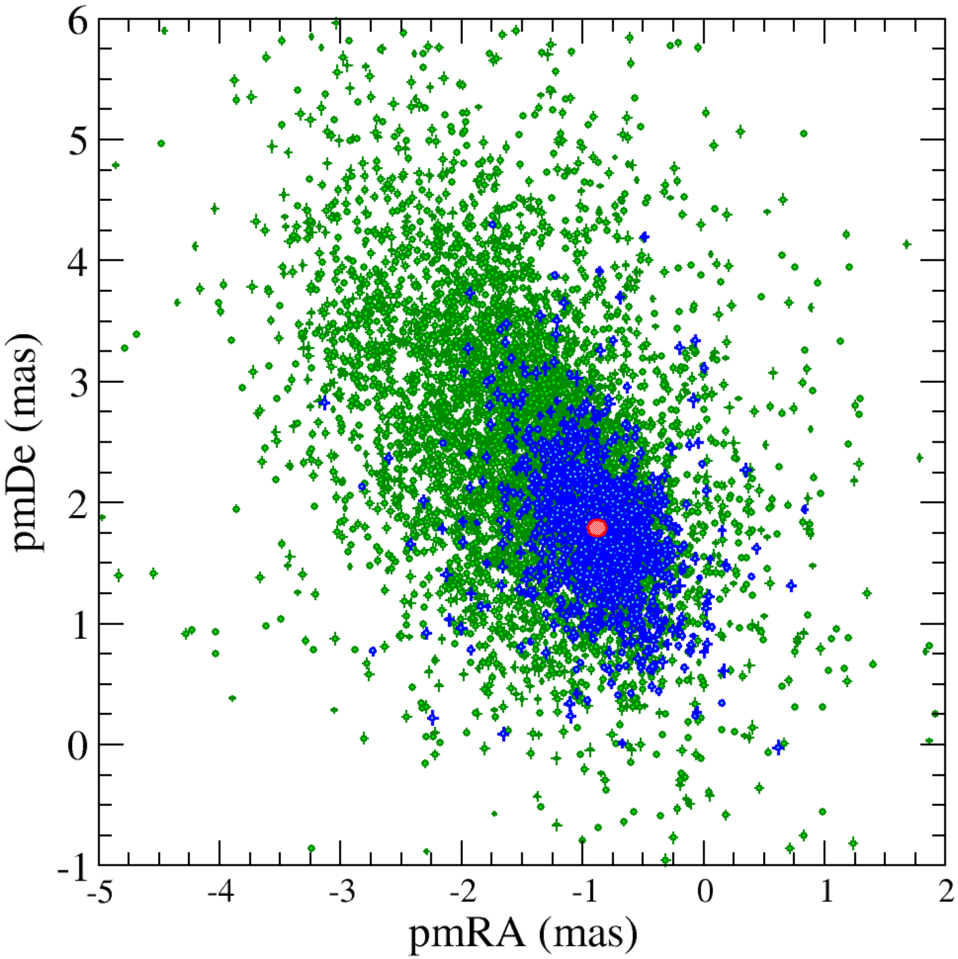
Corbet diagram



Siess & Lebreuilly 2018 (A&A 614, A99)







- A very massive Be star formed through binary interaction
- The progenitor of the NS was a pretty massive star (unless mass transfer was fully conservative).
- The supernova explosion did not disrupt the binary and imparted a moderate kick

Li 2020 (RAA 20, 162)