The Evolution of
Massive Binaries

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Carnegie Observatories

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Illustration: ESO Kornmesser & de Mink

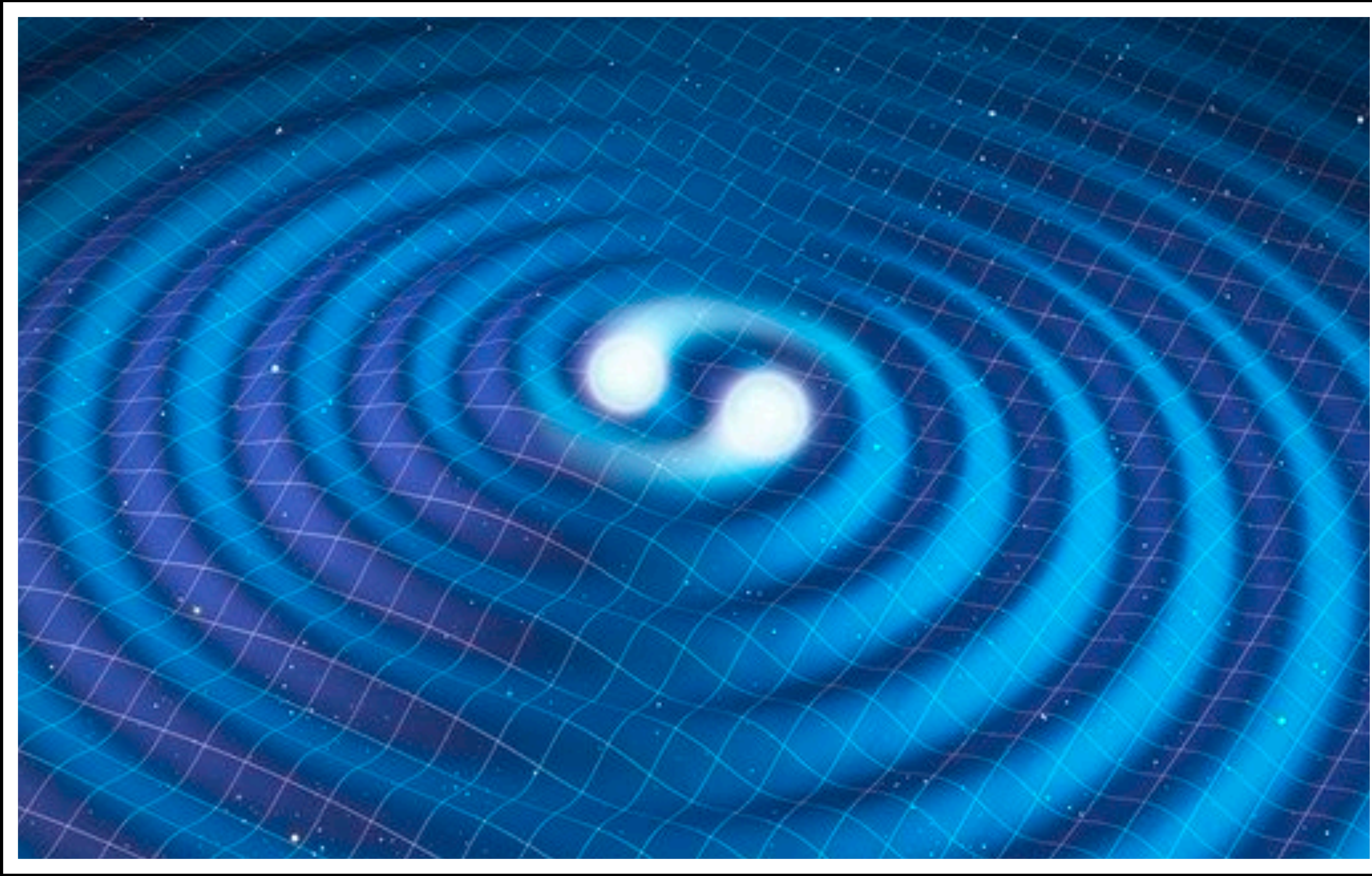
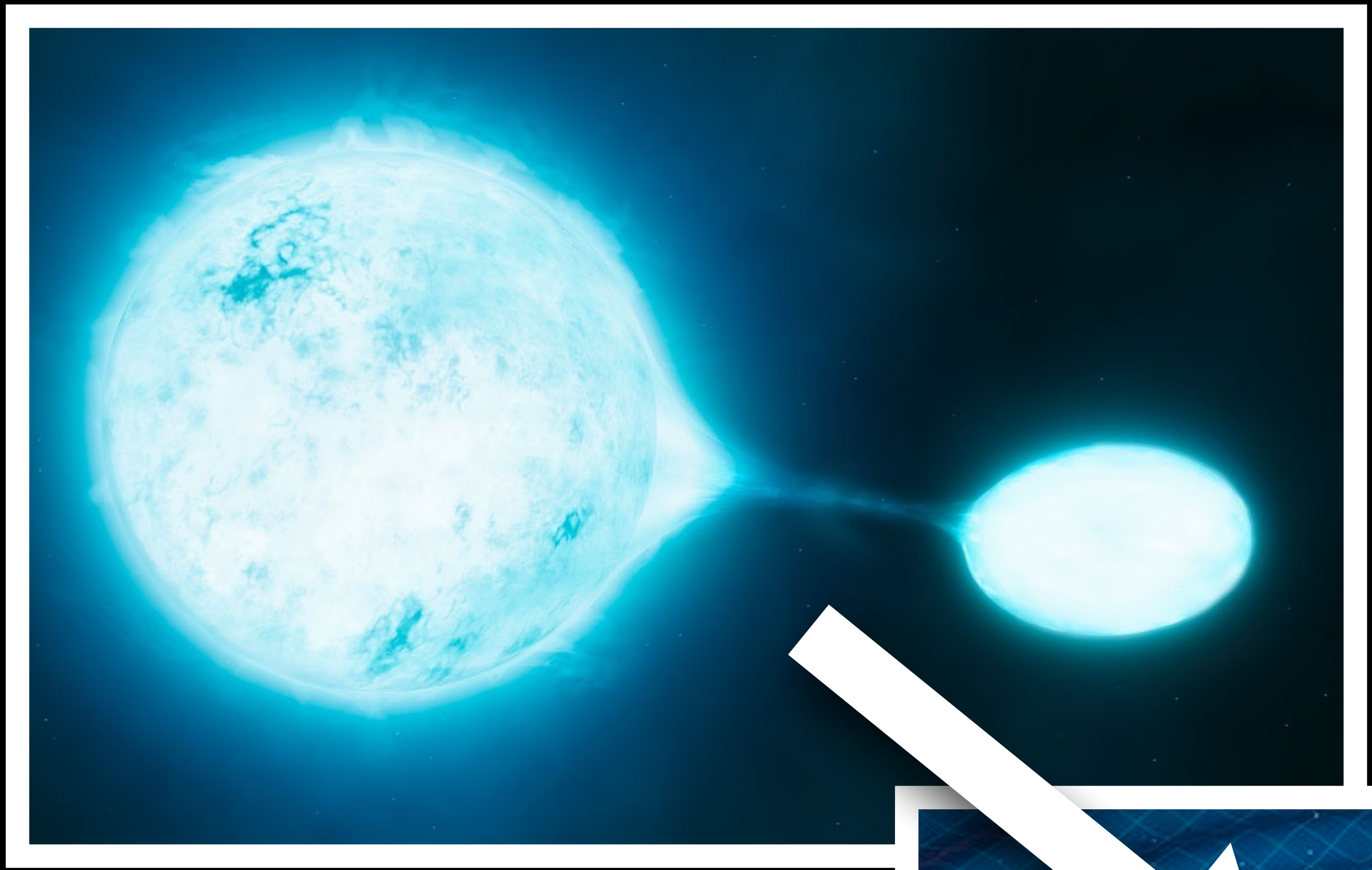


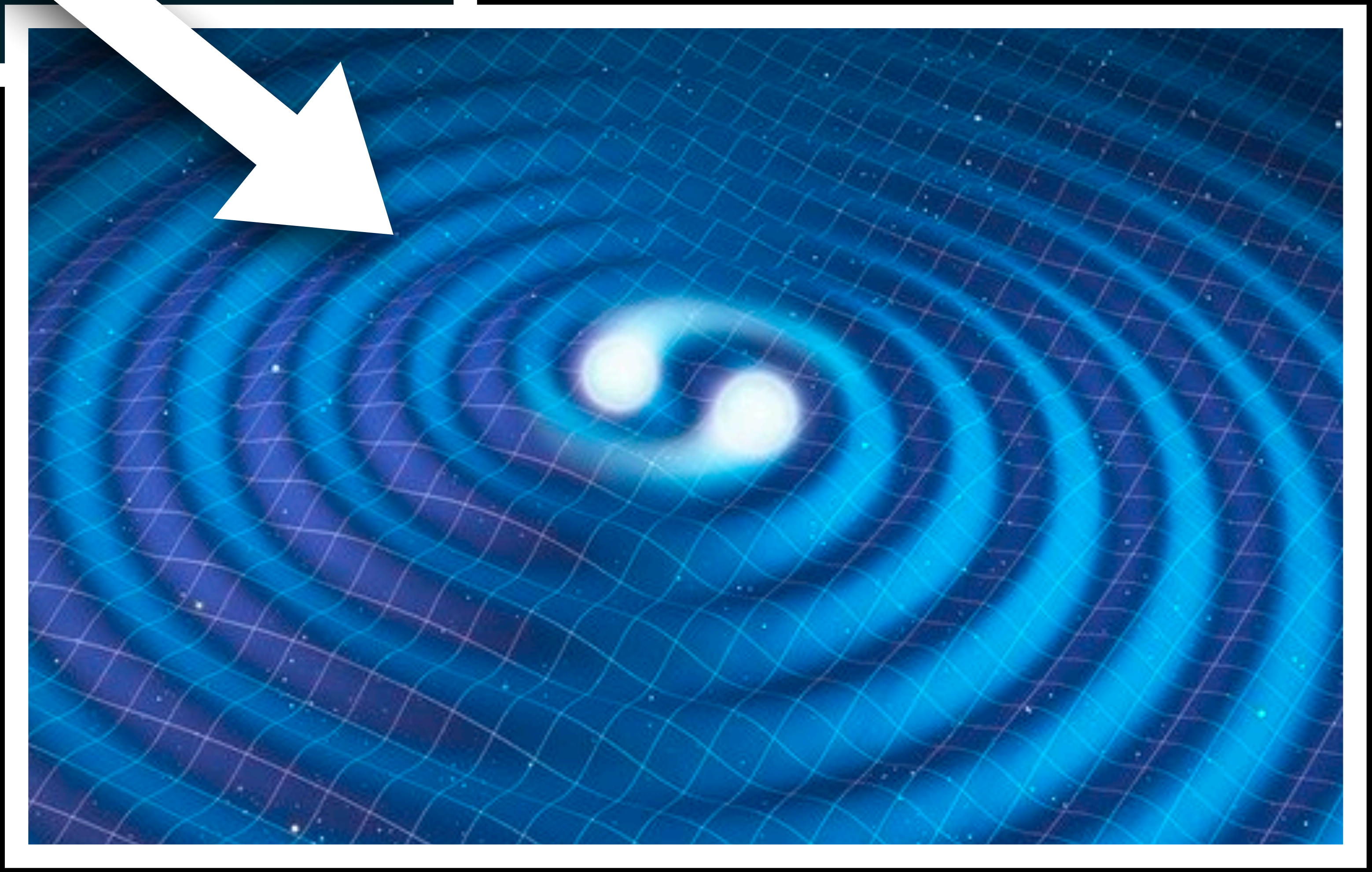
Illustration: Mark Garlick/Science Photo Library



*How did the system become so **tight**?*

*How did the binary stay **bound**?*

***How often** does binary evolution lead to GWs?*



*Are GW progenitors **unique** systems?*

Evolution of Massive Binaries

1 From binary star to gravitational waves

2 Relevant evolutionary processes for GW events

3 The uncertainties in binary evolution models

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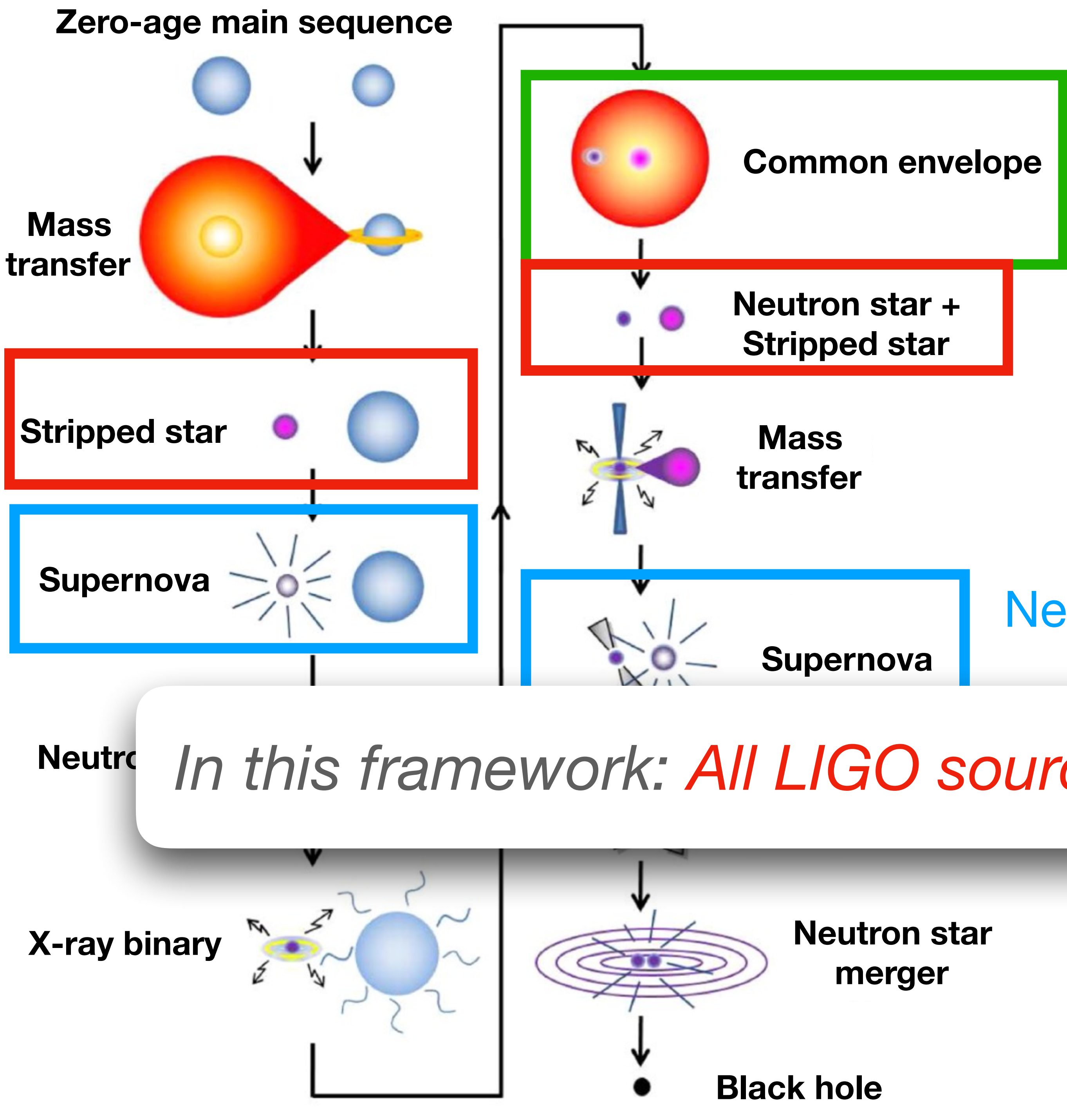
From binary star to gravitational waves

Zero-age main sequence

Figure credit: Tauris et al. (2017)

From binary star to gravitational waves



Common envelope
assumed to tighten the binary!

First binary interaction:
a stripped star is formed

Need to survive two **SN kicks**

In this framework: All LIGO sources had a stripped progenitor

Figure credit: Tauris et al. (2017)

Two stars out orbiting

BinCosmos

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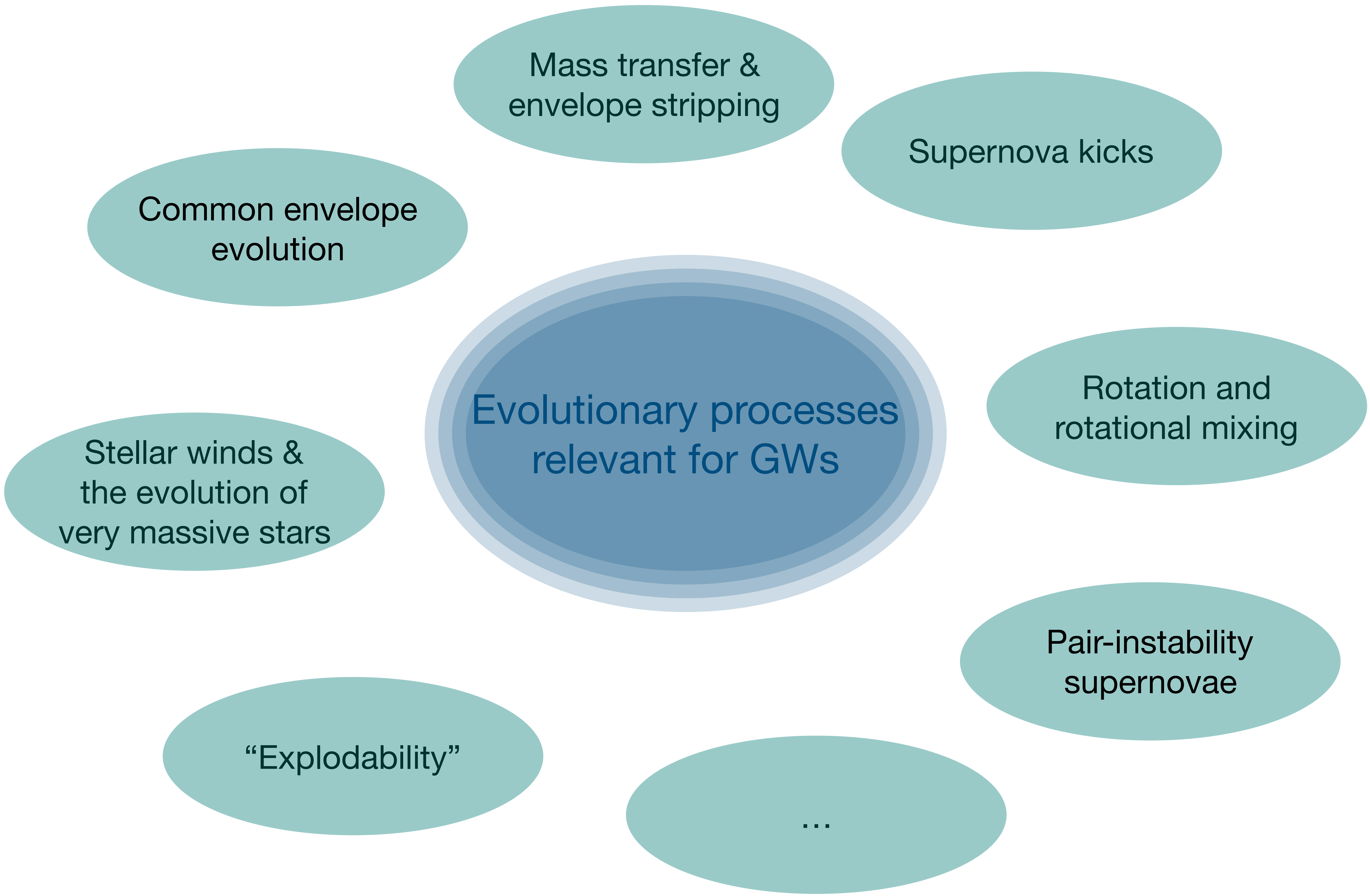
Mass transfer &
envelope stripping
Supernova kicks
Common envelope
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Evolutionary processes
relevant for GWs
Rotation and
rotational mixing
Stellar winds &
the evolution of
very massive stars
Pair-instability
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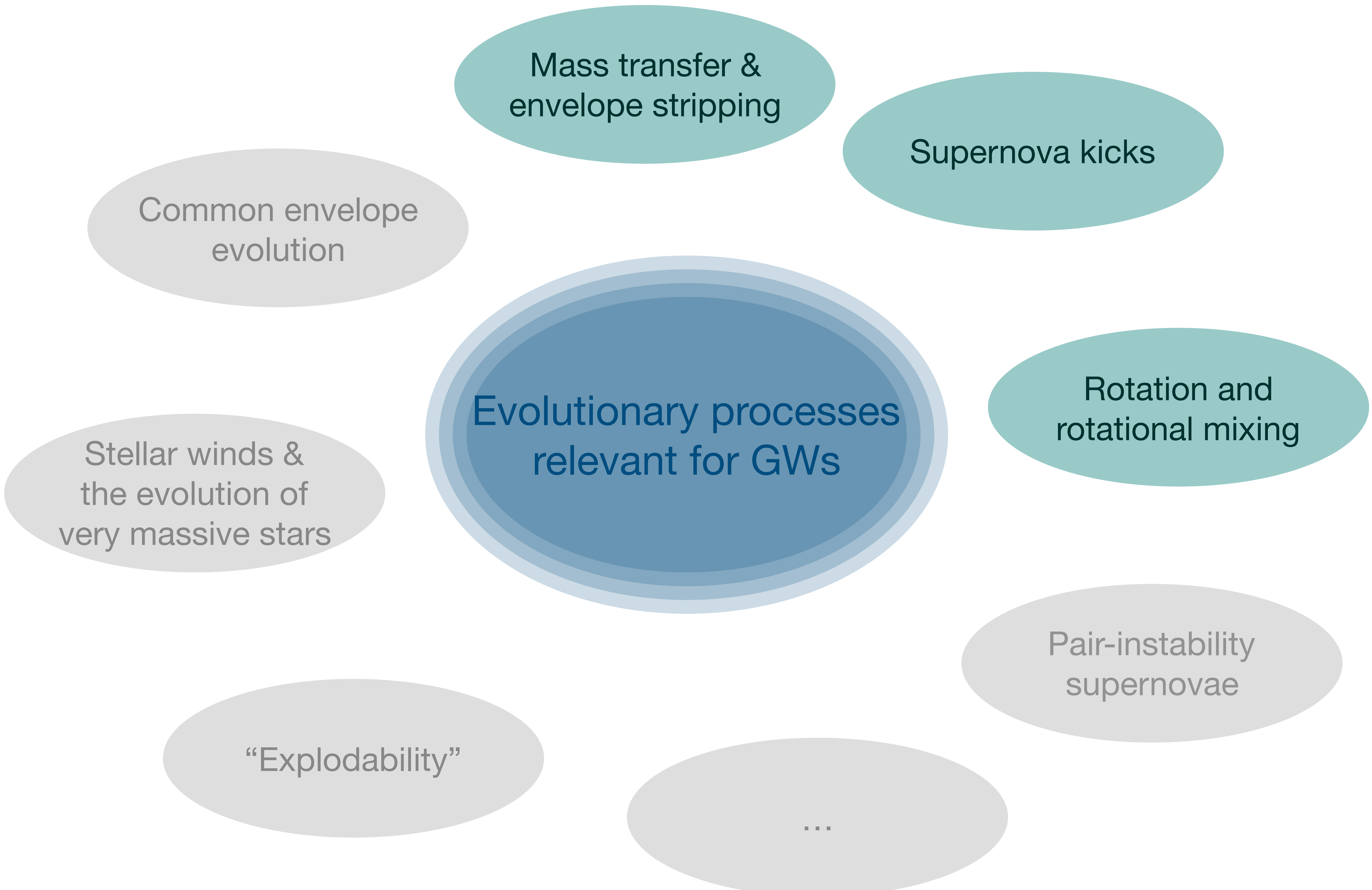
“Explodability”
…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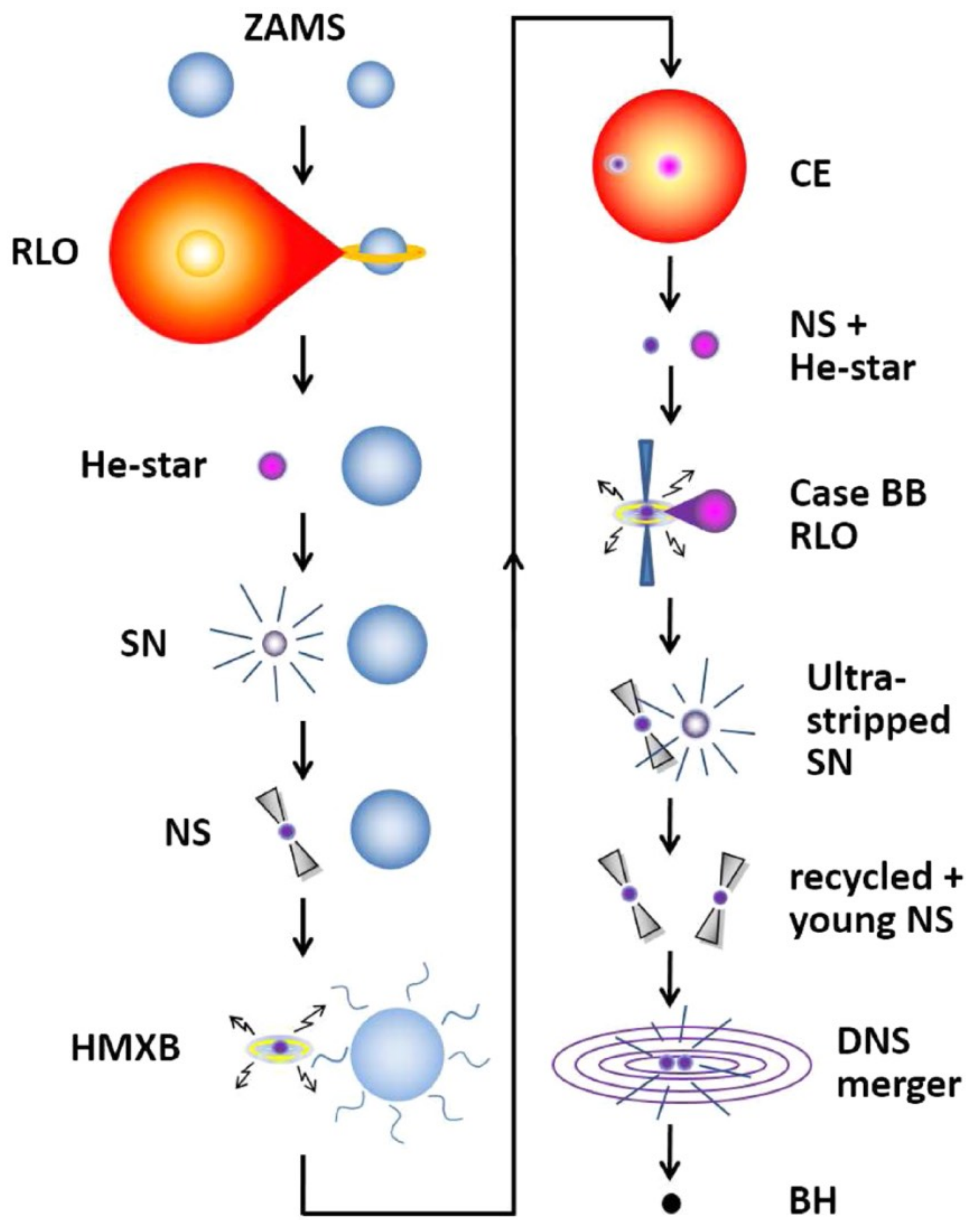
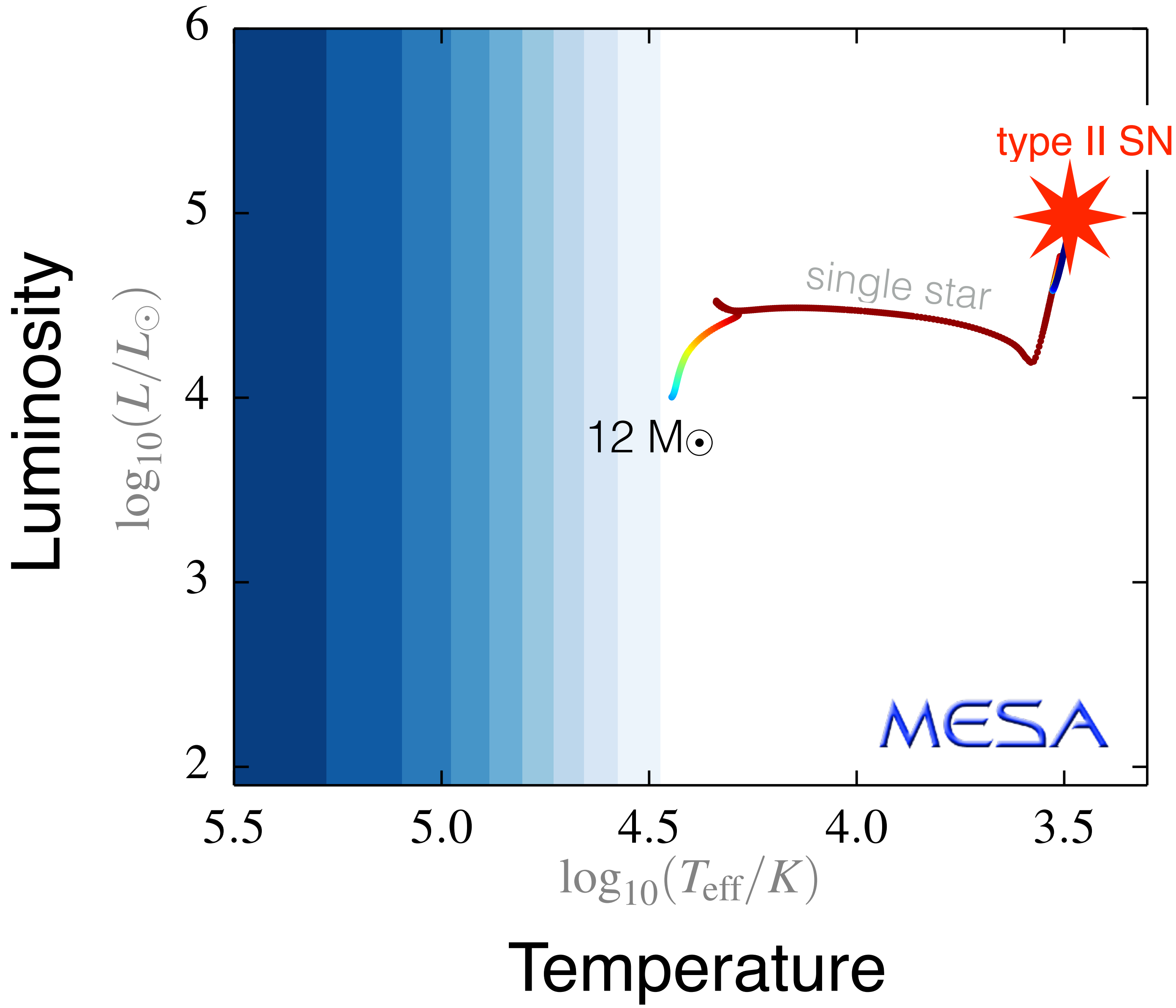
Radius evolution of stripped stars





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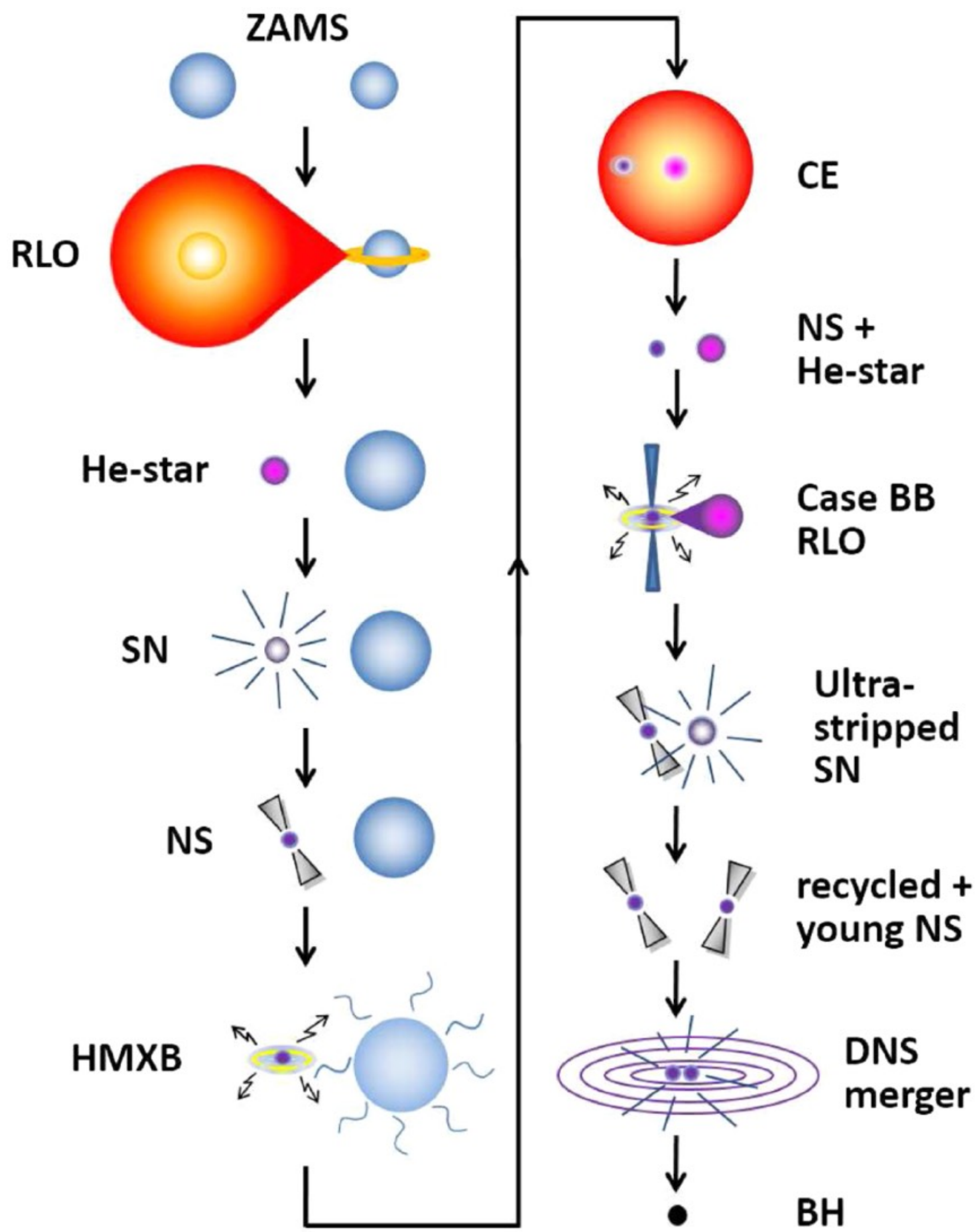
(cf. Kippenhahn & Weigert 1967, Paczyński 1971, Podsiadlowski et al. 1992)

Radius evolution of stripped stars



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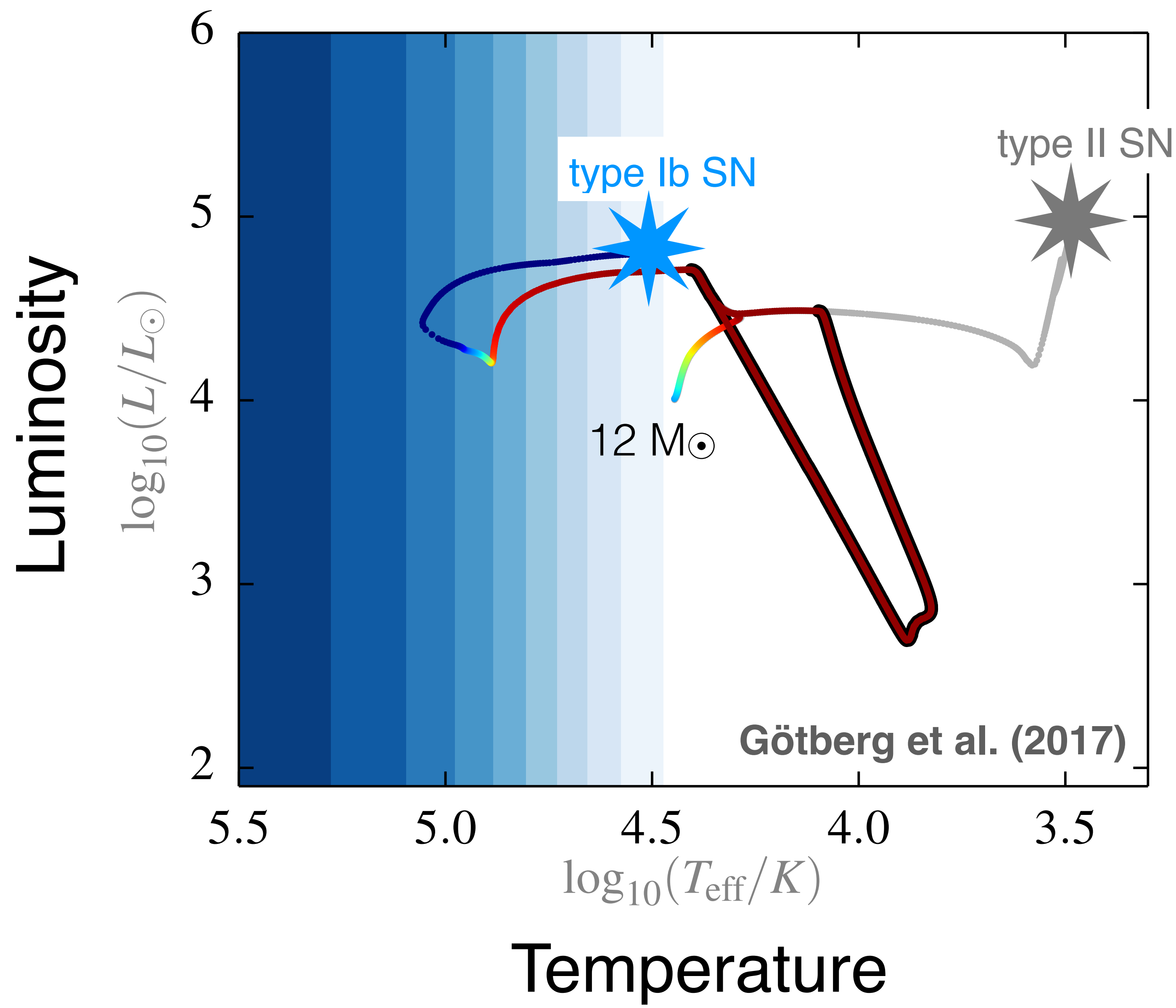
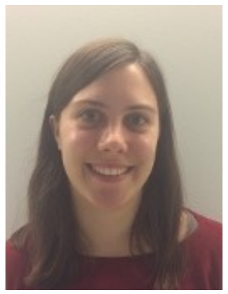


(cf. Kippenhahn & Weigert 1967, Paczyński 1971, Podsiadlowski et al. 1992)

Radius evolution of stripped stars

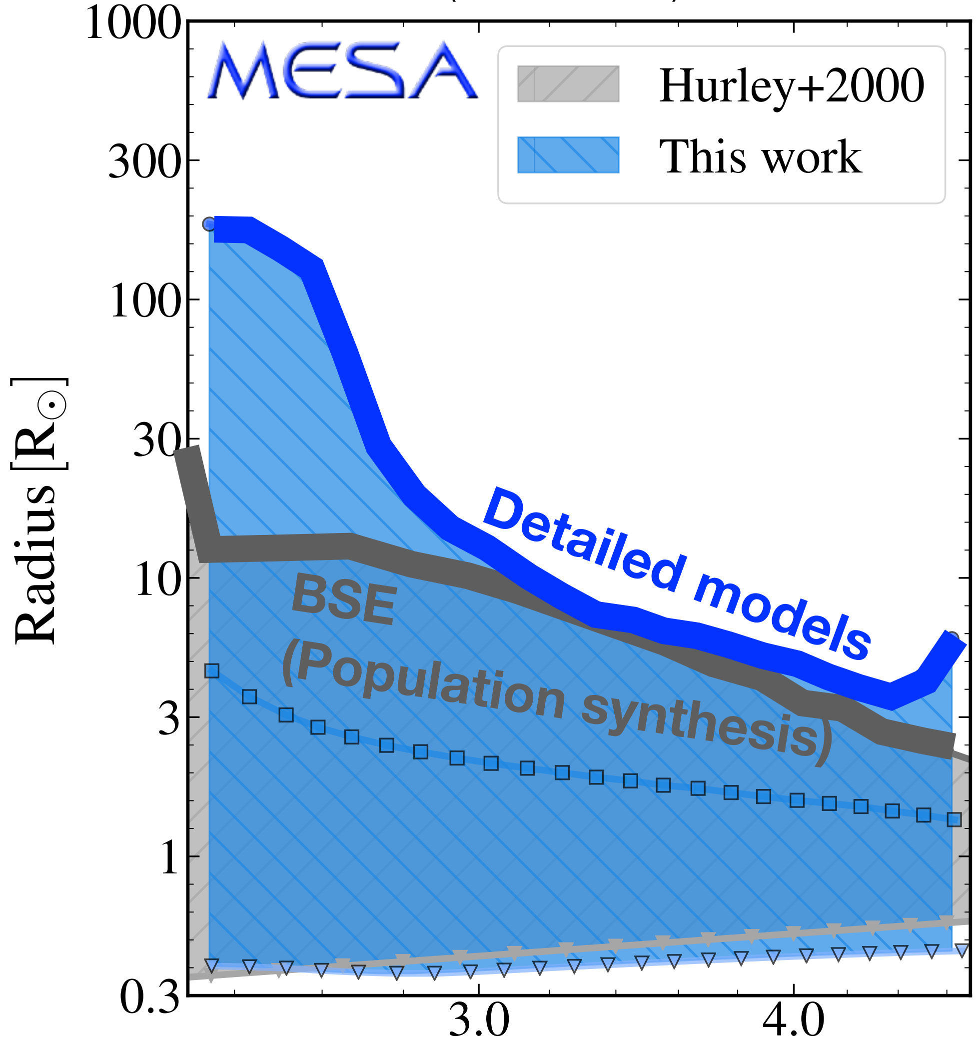


Eva Laplace

(Laplace et al., incl. Götberg in prep.)

Interaction more common at low metallicity

Solar metallicity
(Z = 0.014)

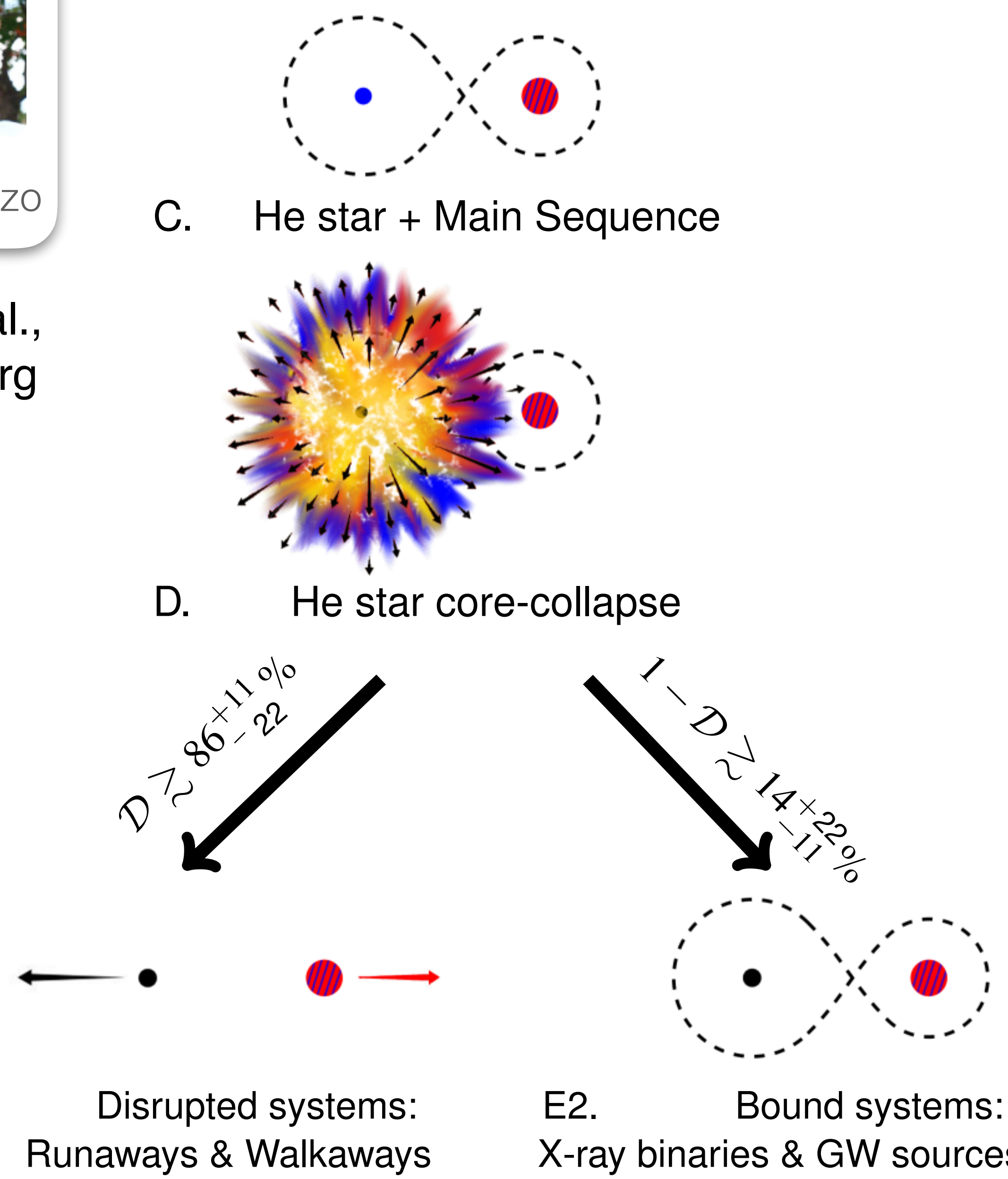


Stripped star mass

(cf. Yoon et al. 2017, Sravan et al. 2018)

Supernova kicks and runaway stars

(Renzo et al., incl. Götberg 2019)



Most systems are disrupted after a supernova (86%)

Runaway stars → understanding GW progenitors

Models predict fewer runaways than observations show → impact on GW rate?

(see Blaauw 1961, Hoogerwerf et al. 2001, Eldridge et al. 2011, Kochanek 2018, and also Katz 1975, Cordes 1993, Janka 2012, 2013, 2017, Wongwathanarat et al. 2013)

Chemically homogeneous evolution towards GWs

Rotational mixing can cause stars to evolve completely into helium
(e.g., Brott et al. 2011)

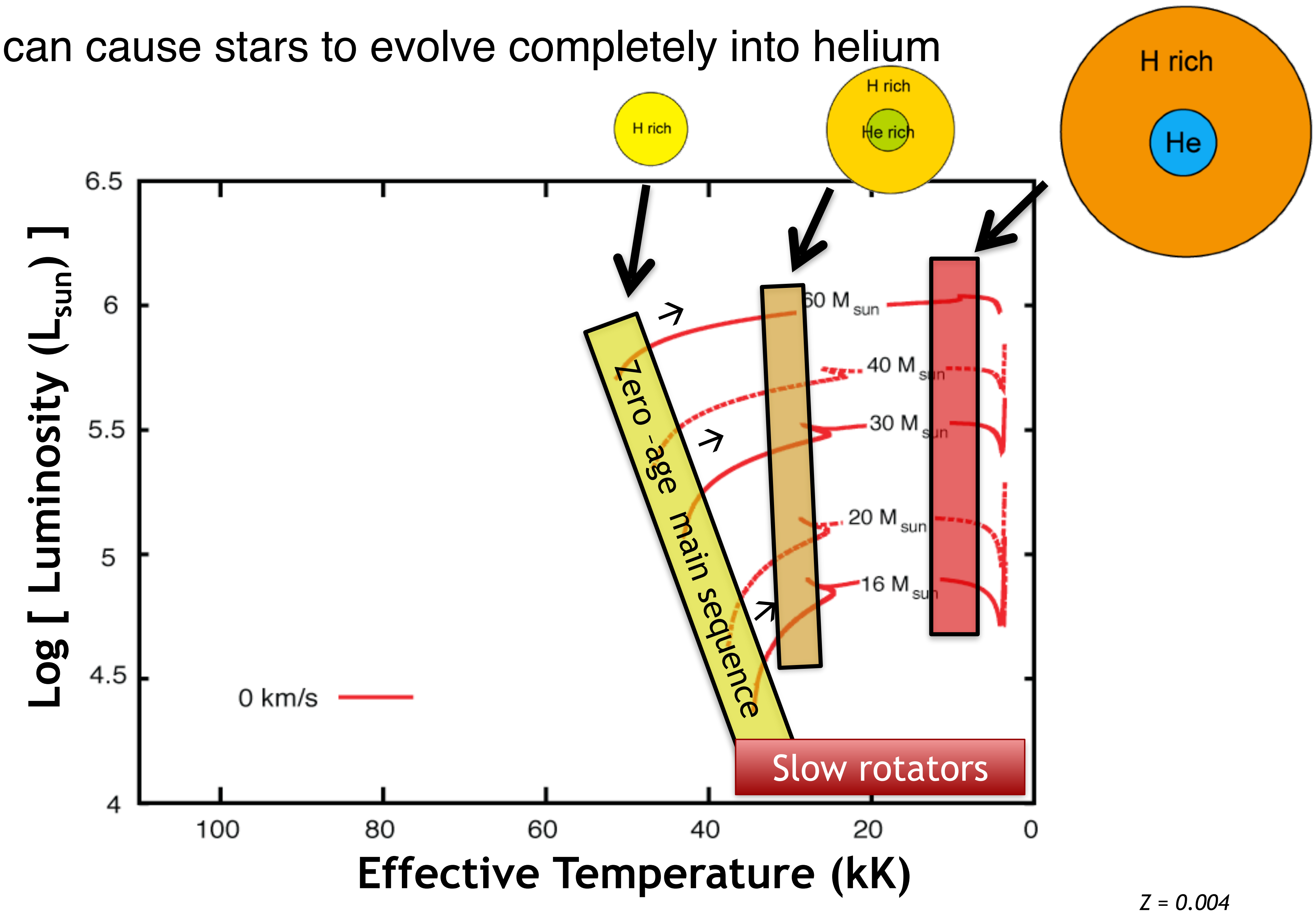


Figure credit: S.E. de Mink
(see also De Mink & Mandel 2016, Mandel & De Mink 2016, Marchant et al. 2016, Szecsi et al. 2015, Kubatova et al. 2019)

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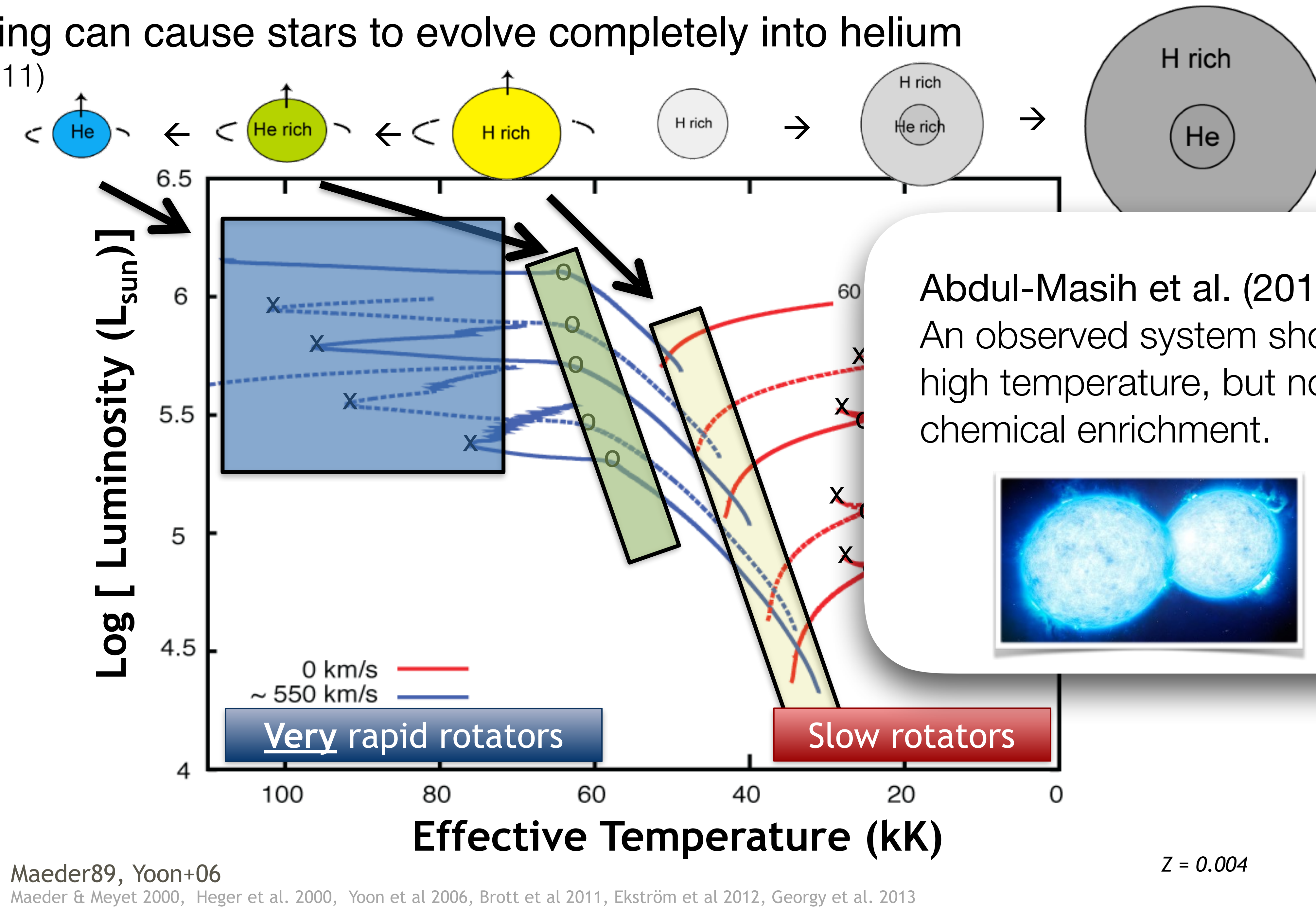

Abdul-Masih et al. (2019):
An observed system shows high temperature, but no chemical enrichment.

Figure credit: S.E. de Mink
(see also De Mink & Mandel 2016, Mandel & De Mink 2016, Marchant et al. 2016, Szecsi et al. 2015, Kubatova et al. 2019)

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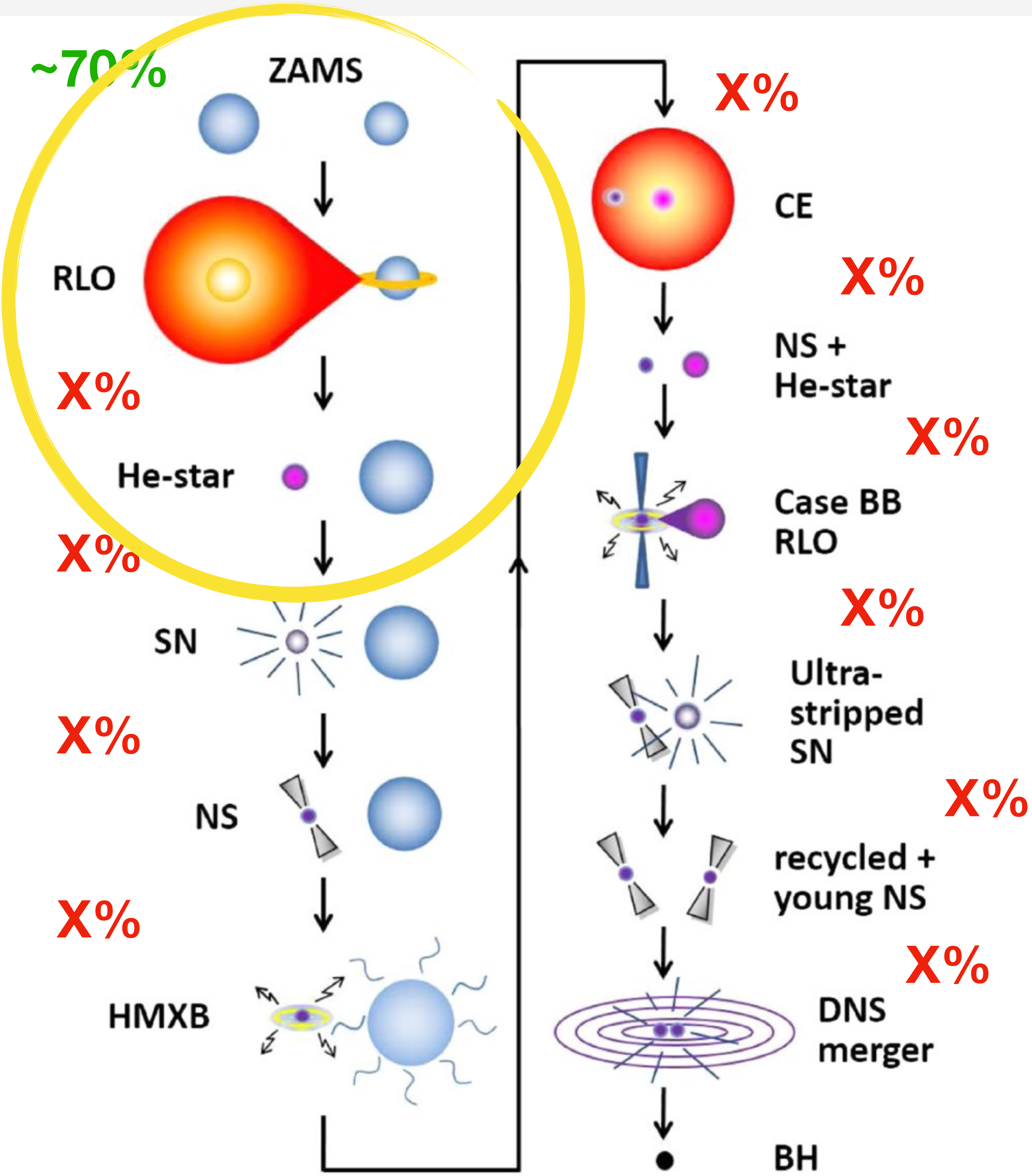
The uncertainties in binary evolution



Tauris et al. (2017)

What fraction of binaries are GW progenitors?

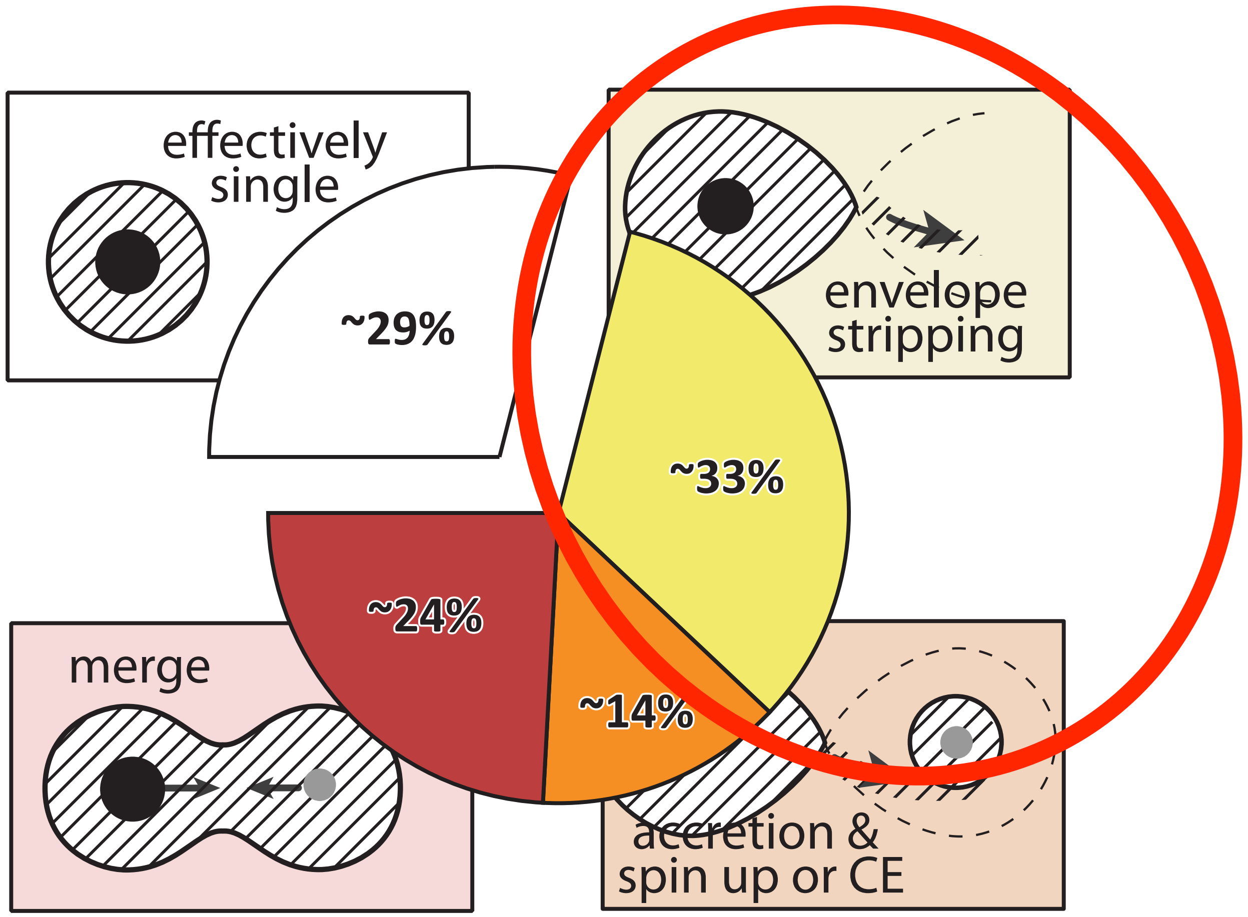
Initial conditions are best constrained (IMF, fbin, P, q)

Models unconstrained observationally!

(cf. Sana et al. 2012, Chini et al. 2012, Kobulnicky et al. 2014, Moe & DiStefano 2017, de Mink et al. 2007, Hurley et al. 2000, 2002, Renzo et al. 2019)

The paradox of the missing stripped stars

Theory: A third of all massive stars strip
(Sana et al. 2012)



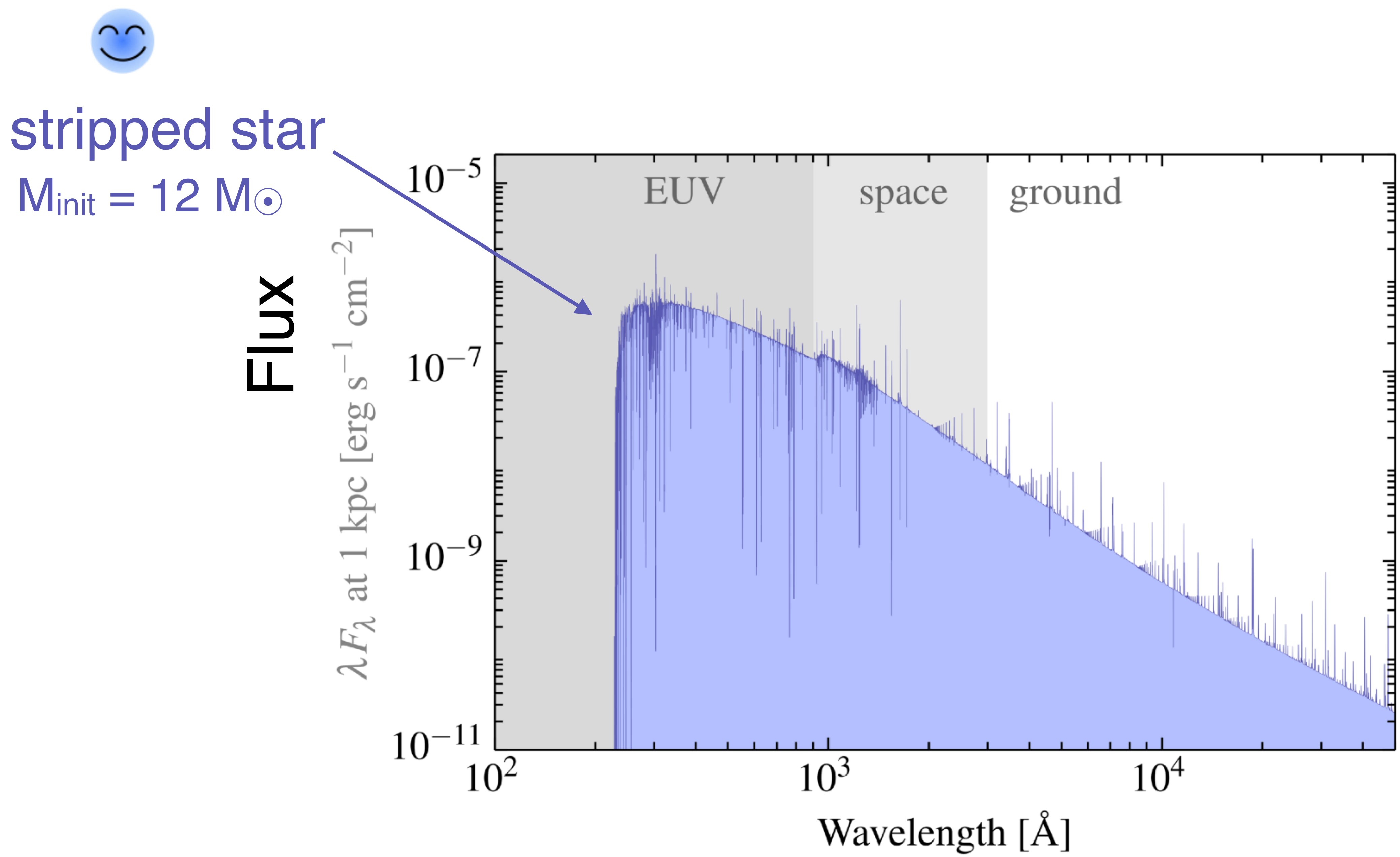
Observations: A dozen of stripped massive stars found
(Gies et al. 1998, Steiner & Oliveira 2005, Groh et al. 2008, Peters et al. 2008/13, Wang et al. 2017/18, Schootemeijer et al. 2018)

Star	SpT	M_{strip}	M_{comp}	confirmed
φ Persei	B1.5Ve:shell +sdO	1.2	9.6	✓
FY CMa	B0.5IVe+ sdO	1.3	12.5	✓
59 Cyg	B1Ve+sdO	0.75	8	✓
60 Cyg	B1Ve+sdO	1.7	11.8	✓
HD 45166	B8V+qWR	4.2	4.8	✓
V378 Pup	B3IV			
LS Mus	B2IVne			
κ[1] Aps	B2Vnpe			
V846 Ara	B3Vnpe			
ι Ara	B2.5IVe			
28 Cyg	B3IVe			
V2119 Cyg	B2IIIe			
8 Lac B	B1IVe			

(Only systems with massive MS companions, see also Shara et al. 2017)

Stripped stars likely hidden by companions

Götberg et al. (2017)



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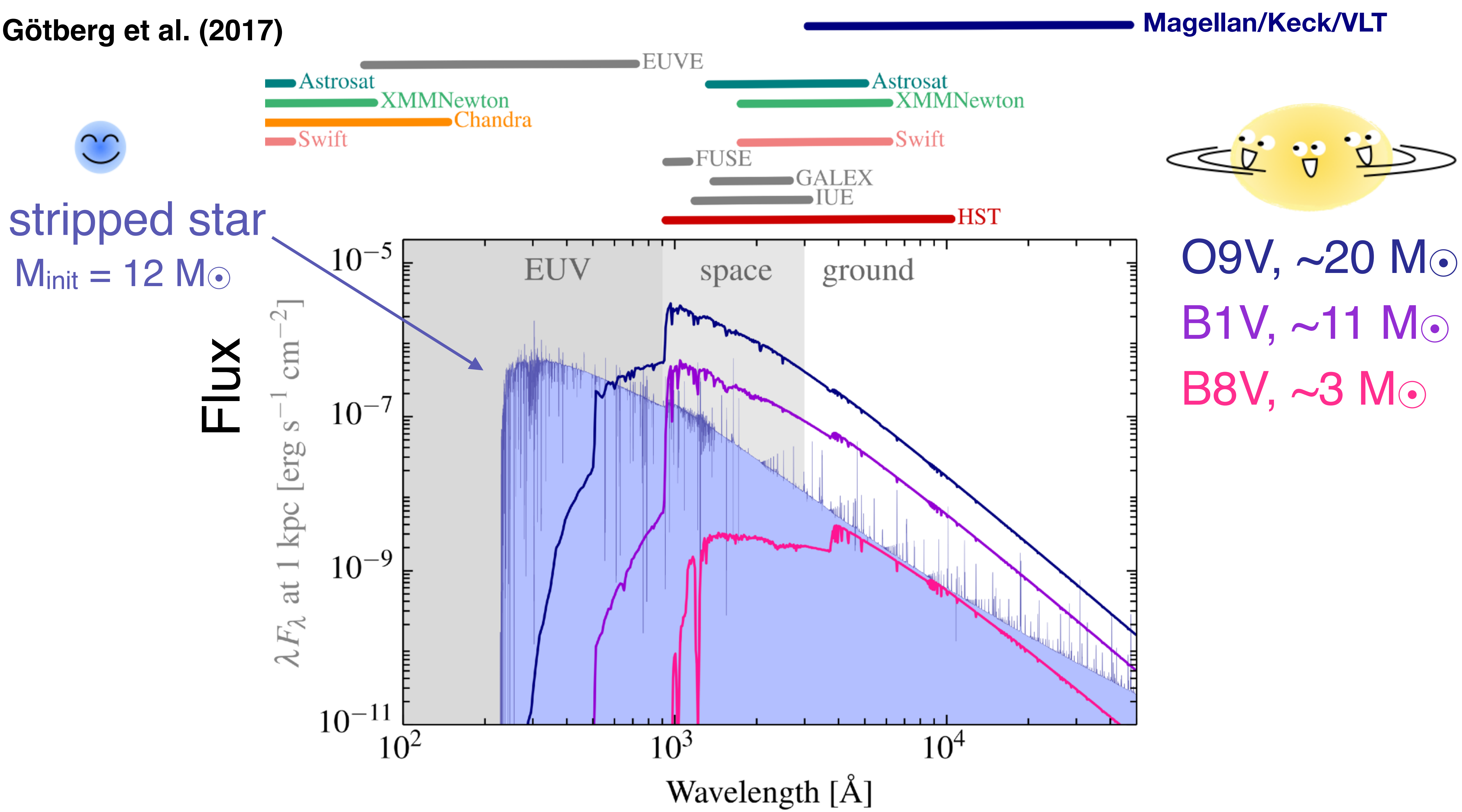

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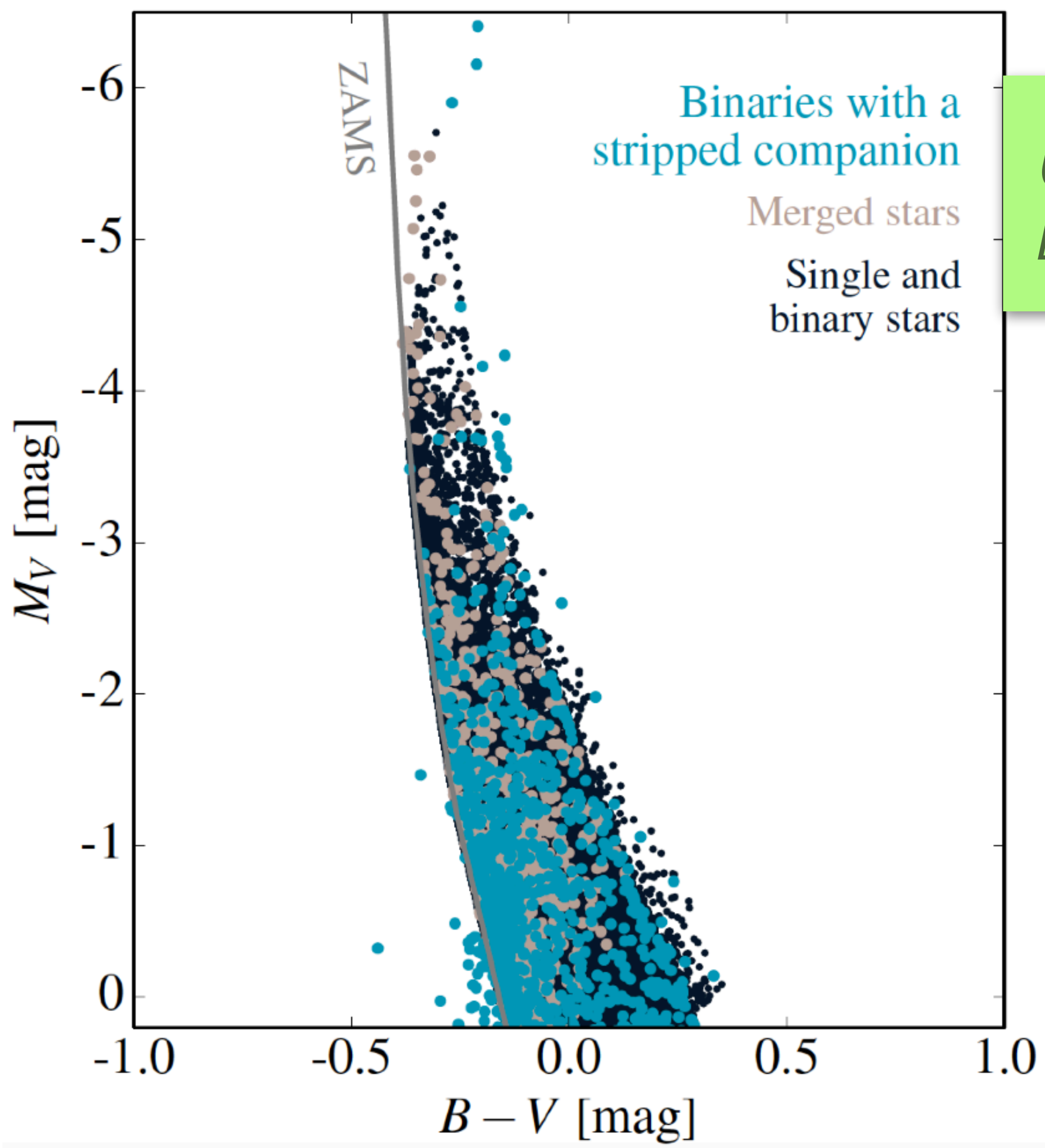
The treasure trove of stripped stars

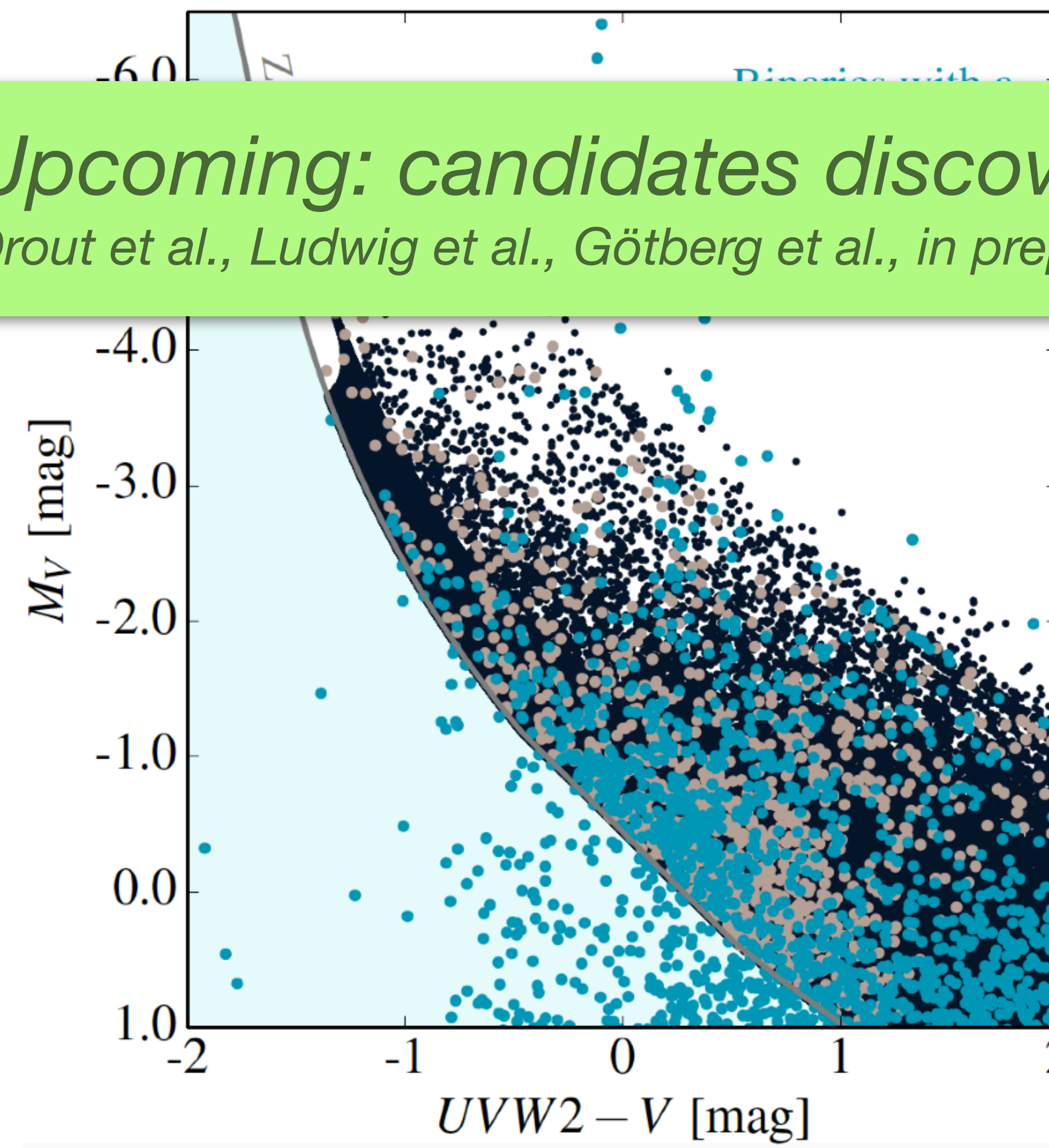
Preliminary

Bethany Ludwig

Maria Drout

How to identify the stripped stars?





Upcoming: candidates discovered!

Drout et al., Ludwig et al., Götberg et al., in prep.

Continuous SFR, 0.005 $M_\odot$/yr, 1 Gyr

(see also Pols & Marinus 1994 and Schneider et al., 2014)

Summary

Stripped stars — the progenitors for all types of GW events

Expansion of stripped stars — more interaction — more GWs?

Runaway stars — better understanding of period evolution needed

Chemically homogeneous evolution — does rotational mixing lead to GW events?

GW progenitor evolution — all but the first step are unconstrained by observations