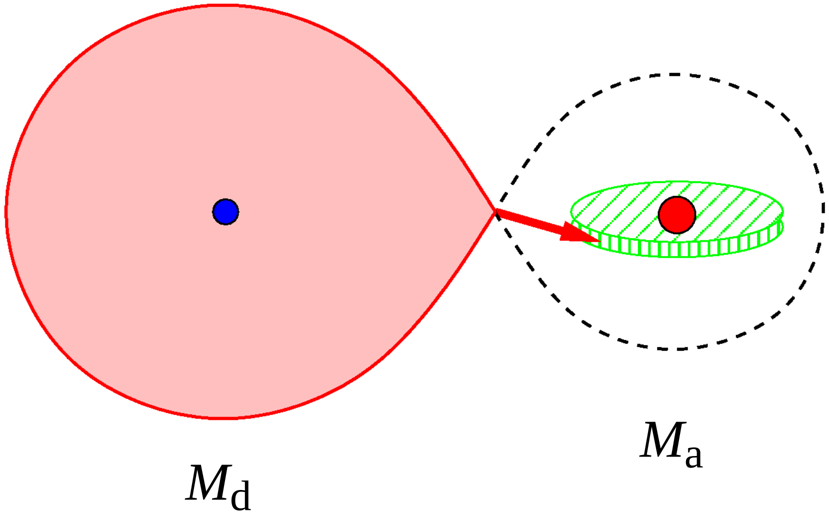
lecture 11:

stable mass transfer & evolution of massive binaries

response of mass-accreting star

- mass transfer stream from donor star:
  - direct impact if $d_{min} < R_a$
  - accretion disk if $d_{min} > R_a$

minimum distance of stream to accretor's centre of mass ($d_{min} \propto a$)



response of mass-accreting star

- effects of mass accretion on companion (MS) star:
  - kinetic energy of accretion flow ⇒ accretion luminosity, dissipated locally (hot spot or accretion disk)
  - transfer of angular momentum ⇒ spin-up of mass gainer (accretion of ~0.1 M_a may already lead to break-up rotation) ⇒

    this may lead to *non-conservative mass transfer*

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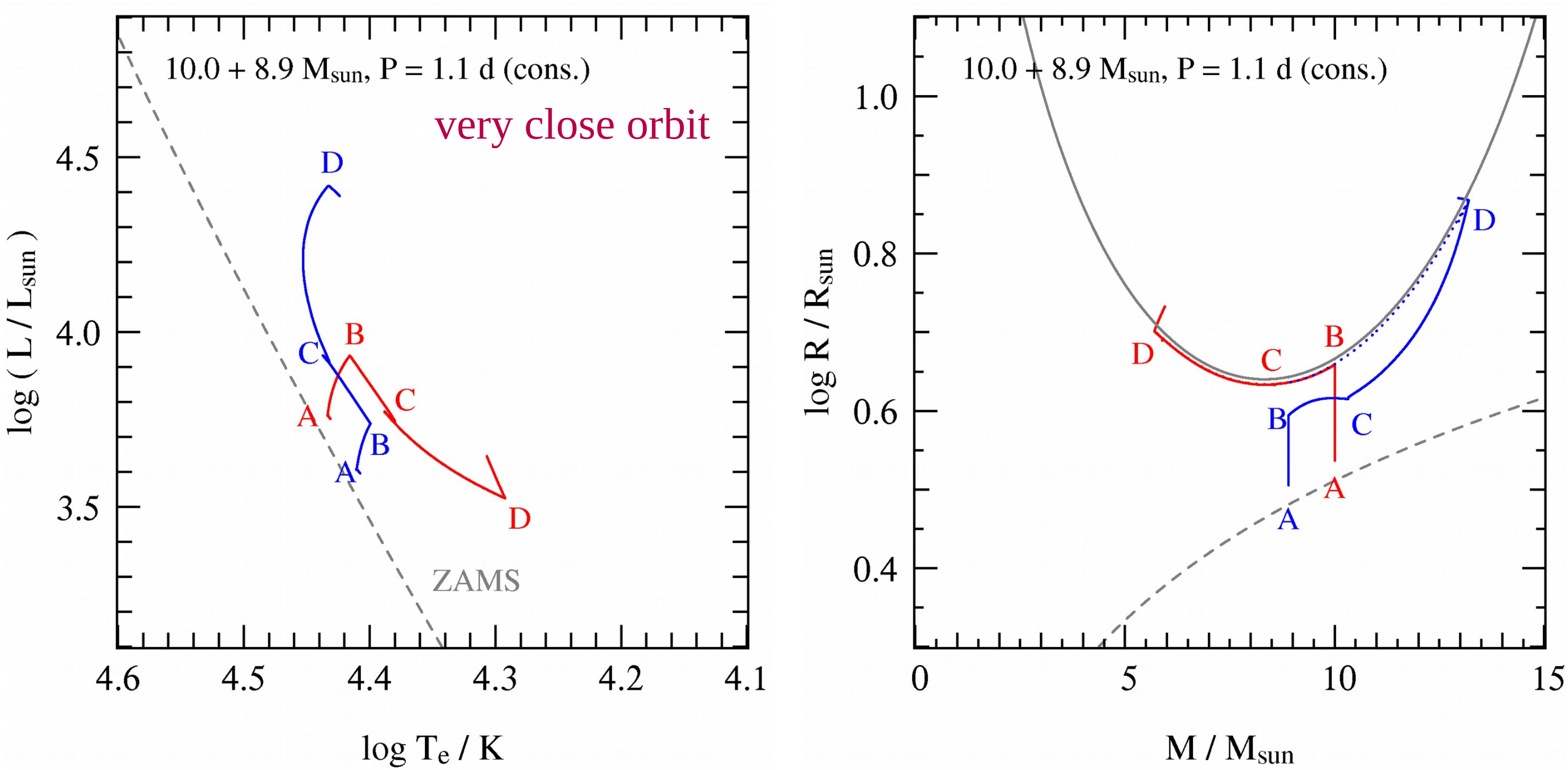
- further effects, to be illustrated next:
  - thermal readjustment of mass gainer ⇒ over-luminosity and expansion (when accretion occurs faster than gainer's thermal timescale) ⇒ *contact binary?*
  - if substantial accretion occurs: rejuvenation of mass gainer (due to larger convective core)
  - but also: higher mass causes increased rate of nuclear evolution ⇒ secondary can overtake evolution of primary ⇒ *contact binary*

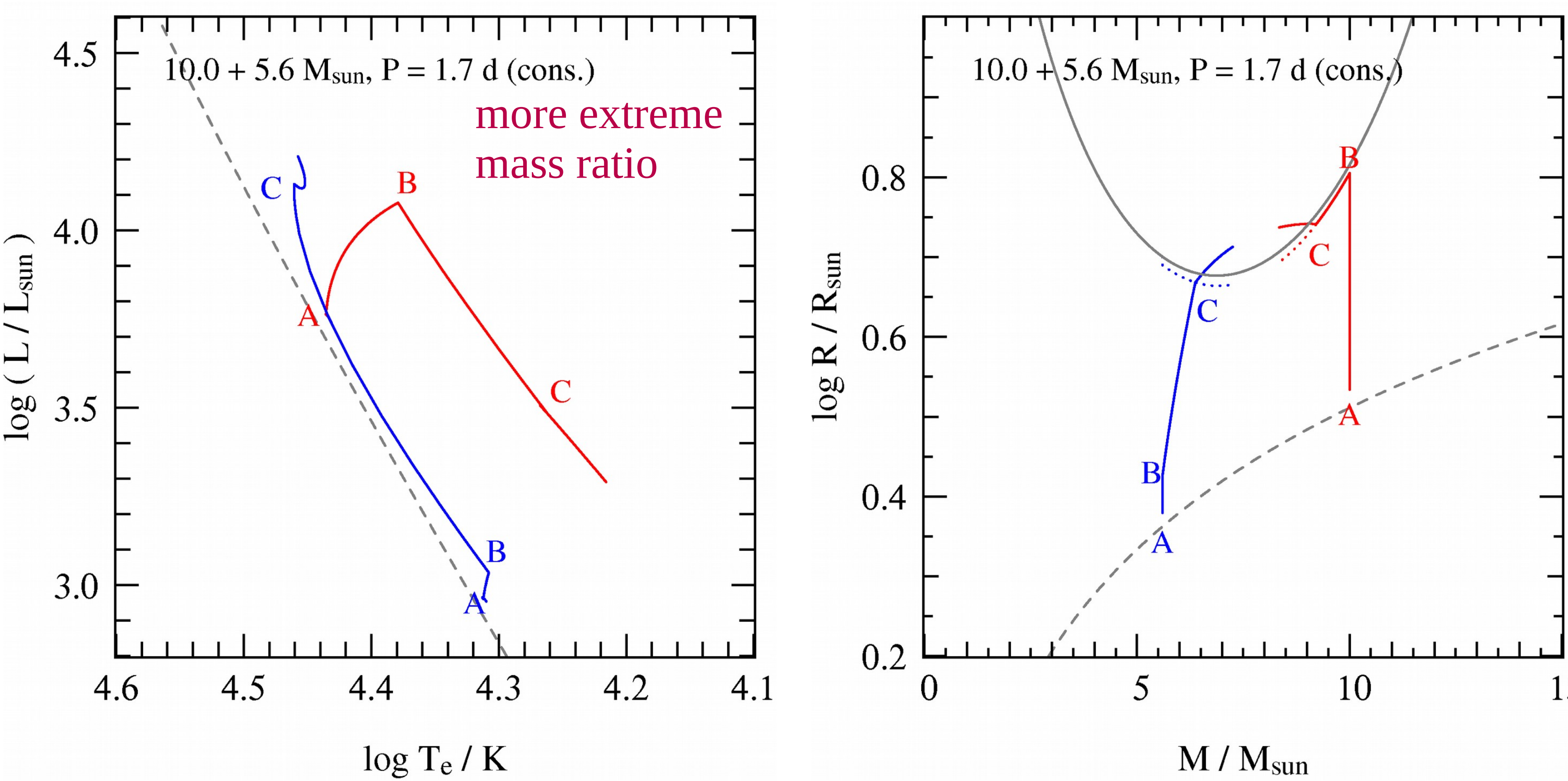
case A: slow evolution into contact



example of *secondary overtaking primary*

- B – C: thermal-timescale mass transfer
- C – D: nuclear-timescale mass transfer ⇒ Algol-type binaries
- beyond D: both stars overfill RL ⇒ long-lived contact binaries

case A: rapid evolution into contact



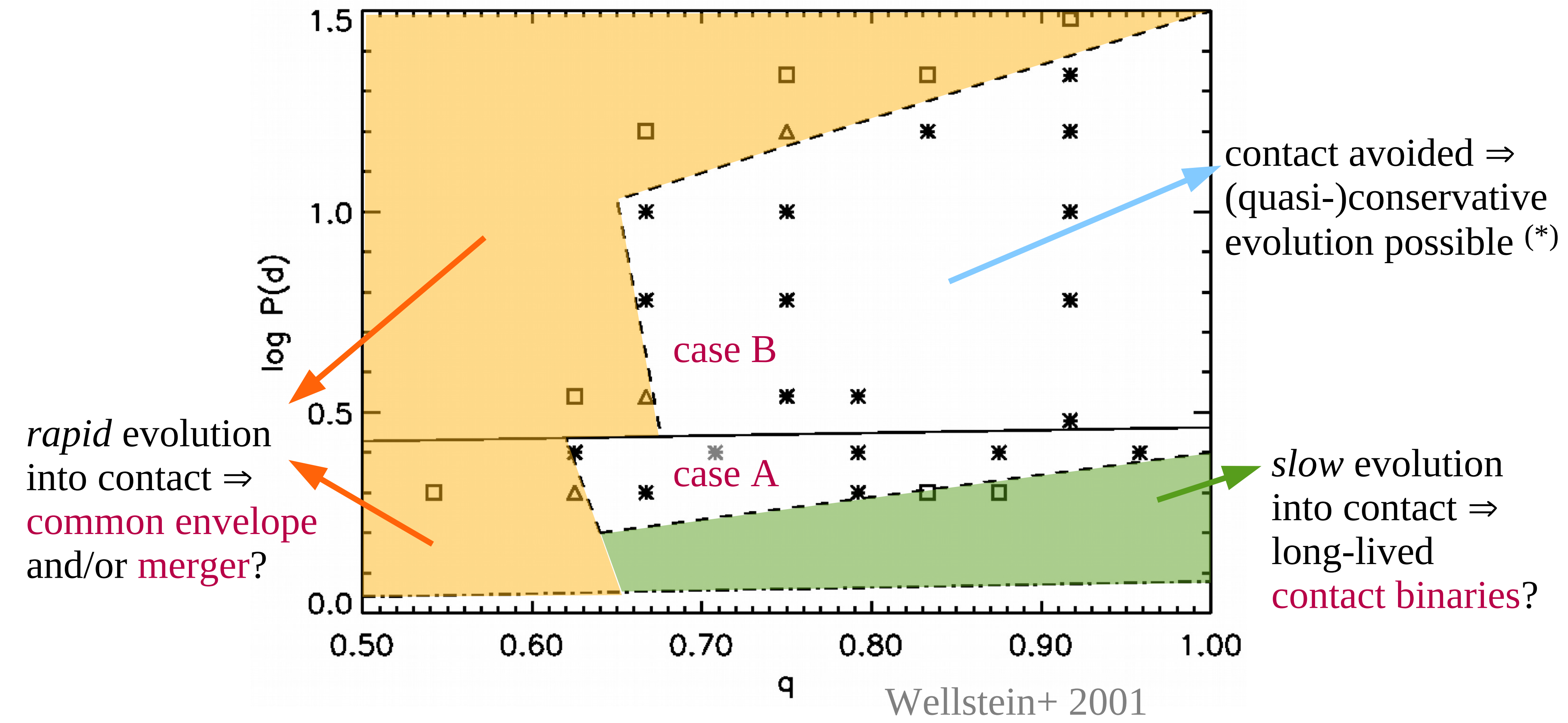
example of *secondary accreting too fast to thermally readjust*

- B – C: thermal-timescale mass transfer, but $\tau_{KH,acc} \gg \tau_{KH,don} \sim \tau_{mass\text{-}transfer}$
- beyond C: both stars overfill RL during rapid mass transfer

$\Rightarrow$ outcome uncertain, likely binary merger $\Rightarrow$ single star?

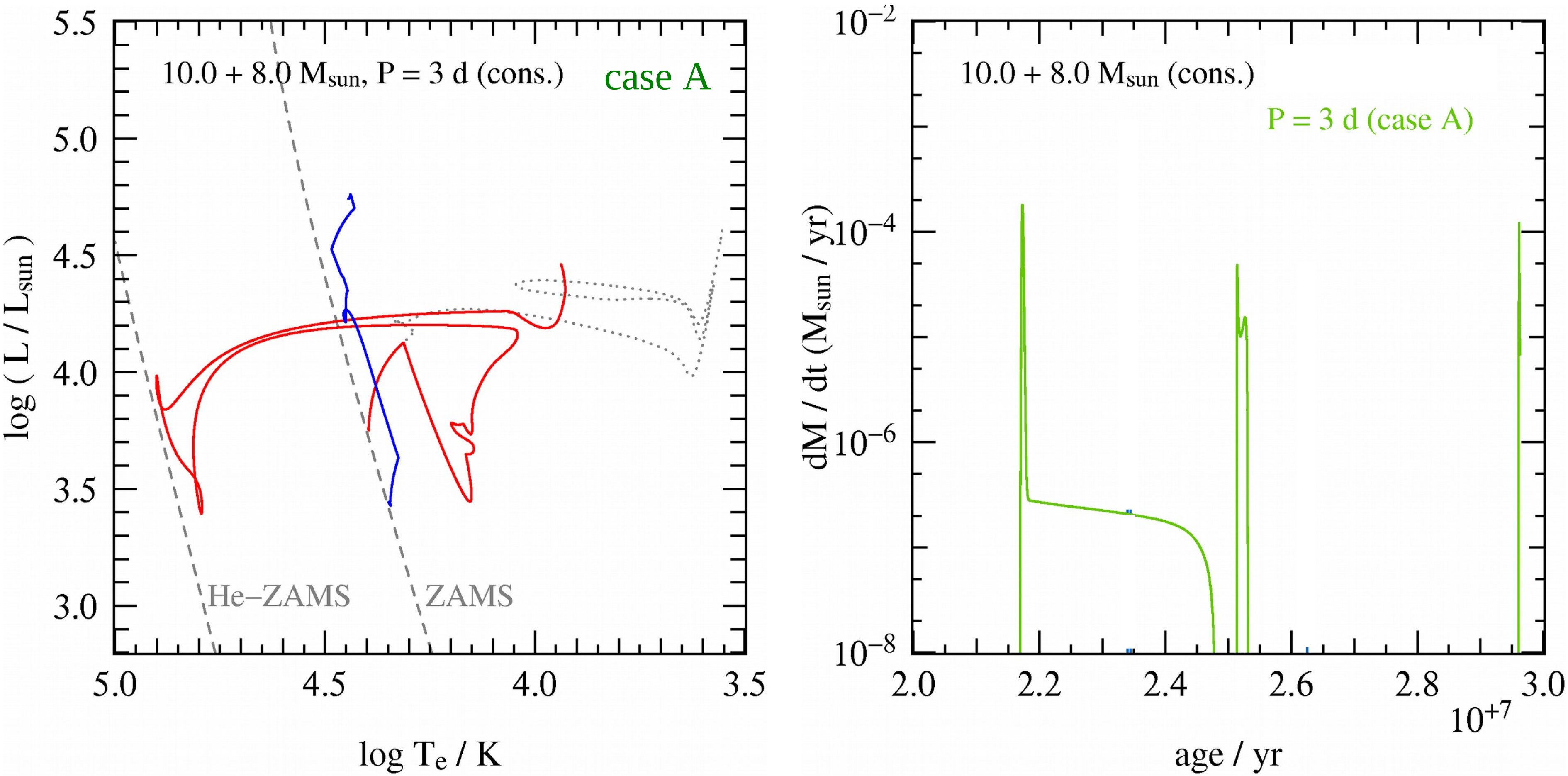
evolution into contact

- binary parameters for which contact occurs (example: $M_{1,i} = 12\ M_{sun}$)



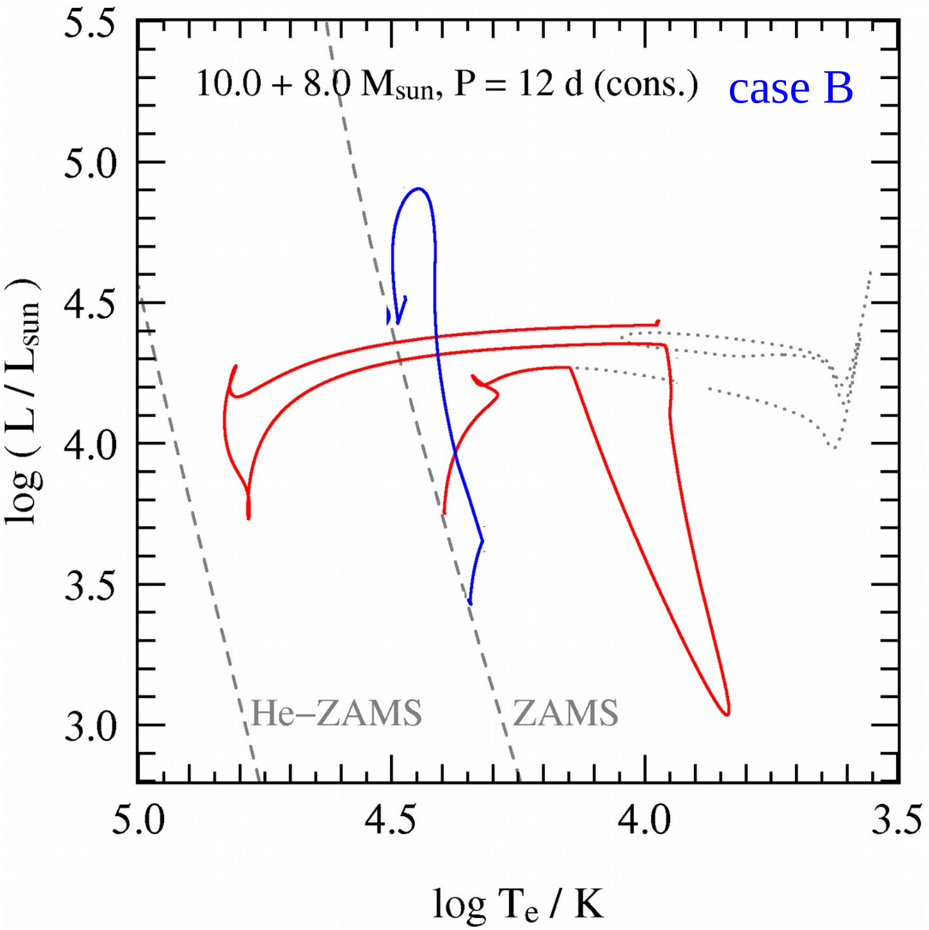
(*) if *spin-up of mass gainer* (see later) does not prevent accretion...

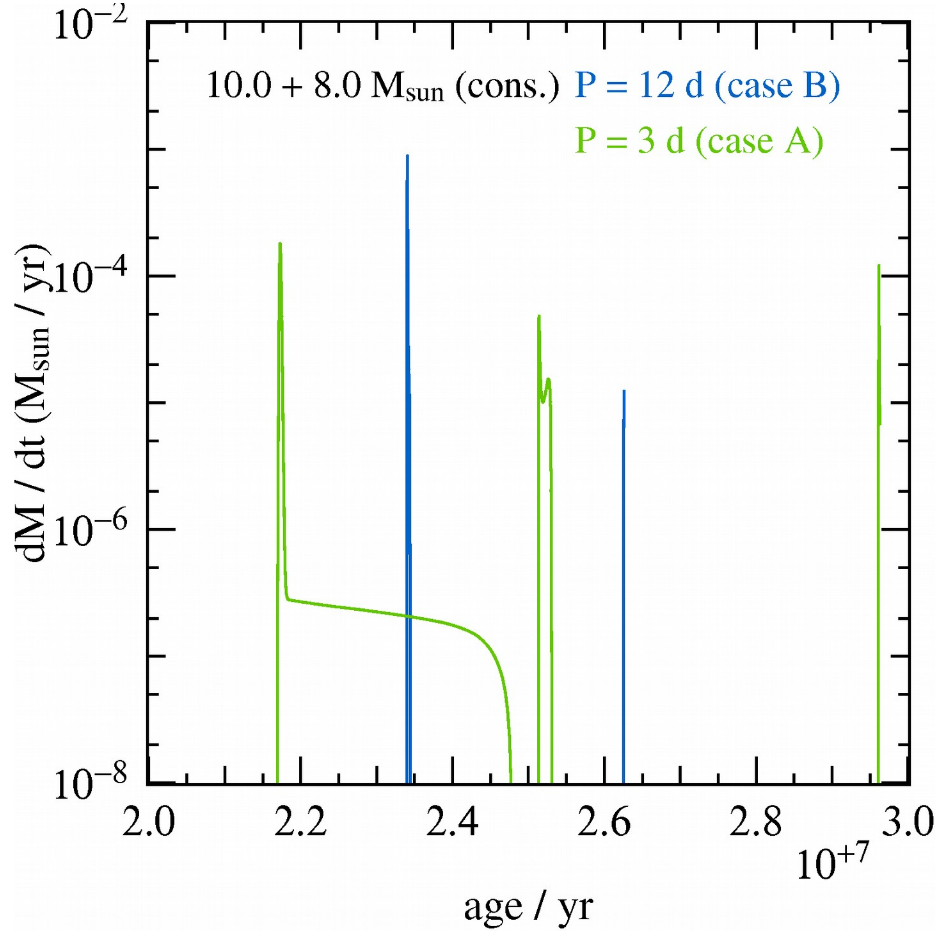
case A versus case B



- **case A**: rapid + slow phase of mass transfer during donor's MS phase
- mass transfer resumes after MS ("case AB"): remainder of donor's H-envelope transferred, remnant is an almost naked helium star (as in case B)

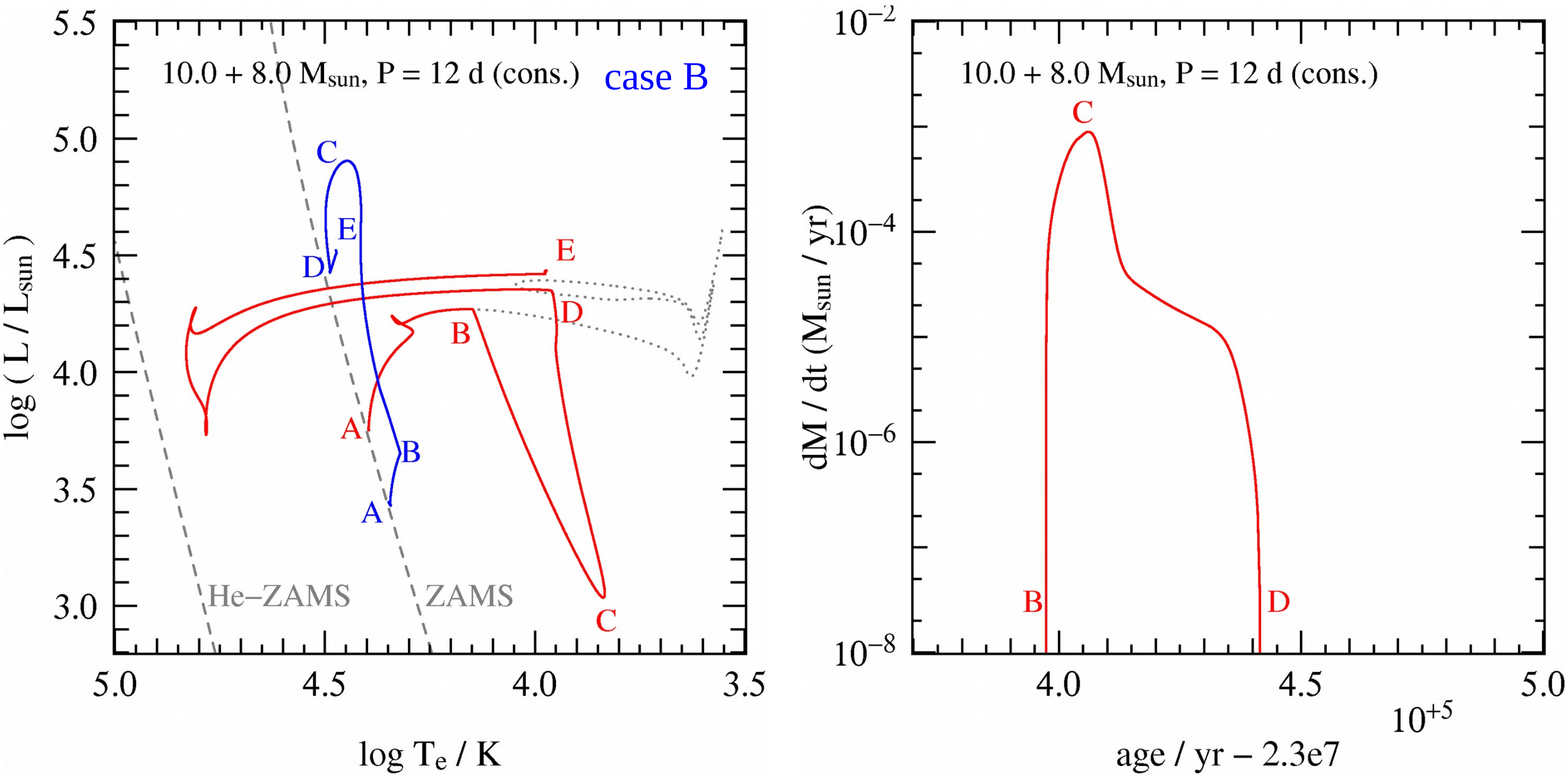
case A versus case B





- **case B**: mass transfer starts after MS phase *1
  - shorter thermal timescale ⇒ rapid mass transfer with higher dM/dt
  - rapid expansion during Hertzsprung gap ⇒ no long-lived, slow phase of mass transfer

case A versus case B



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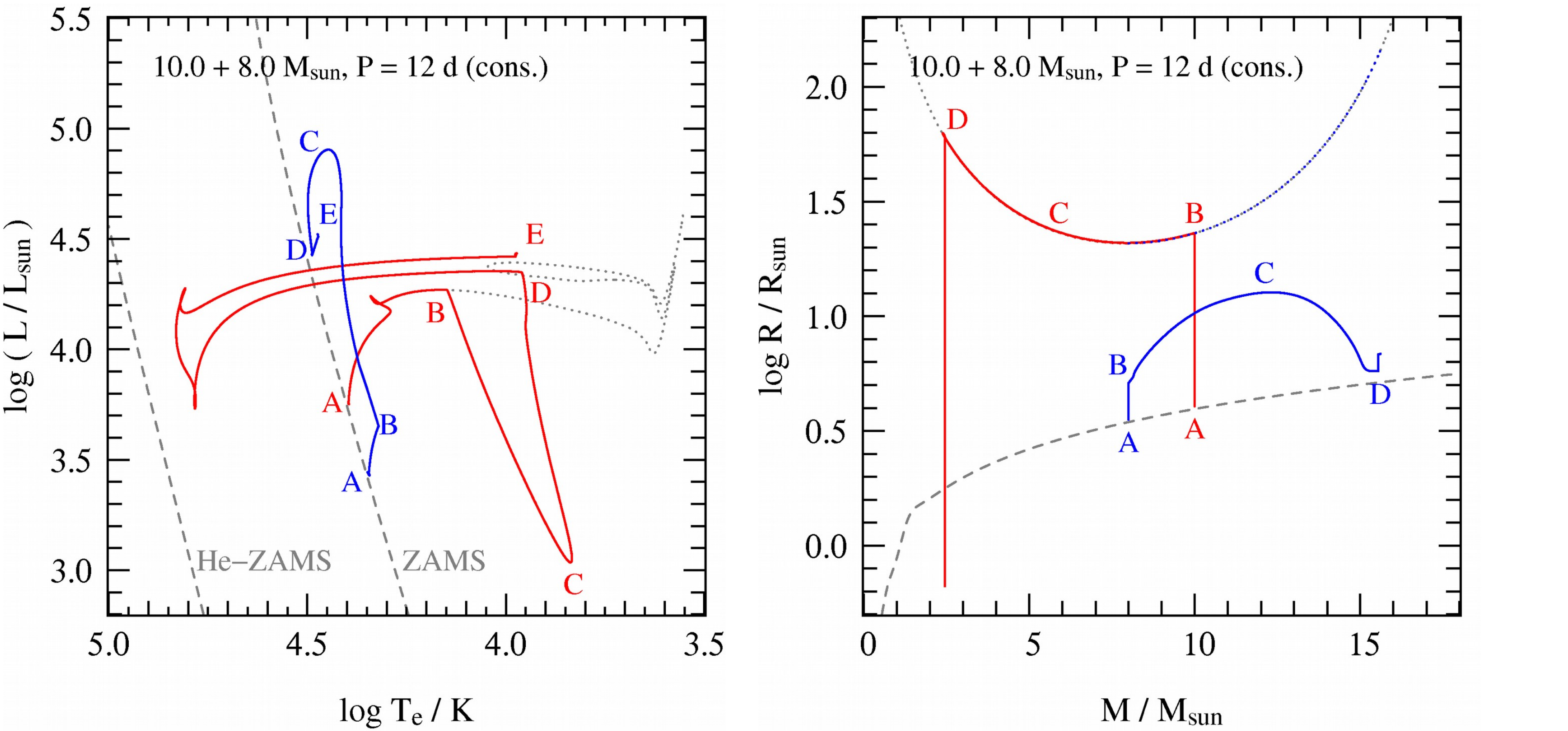
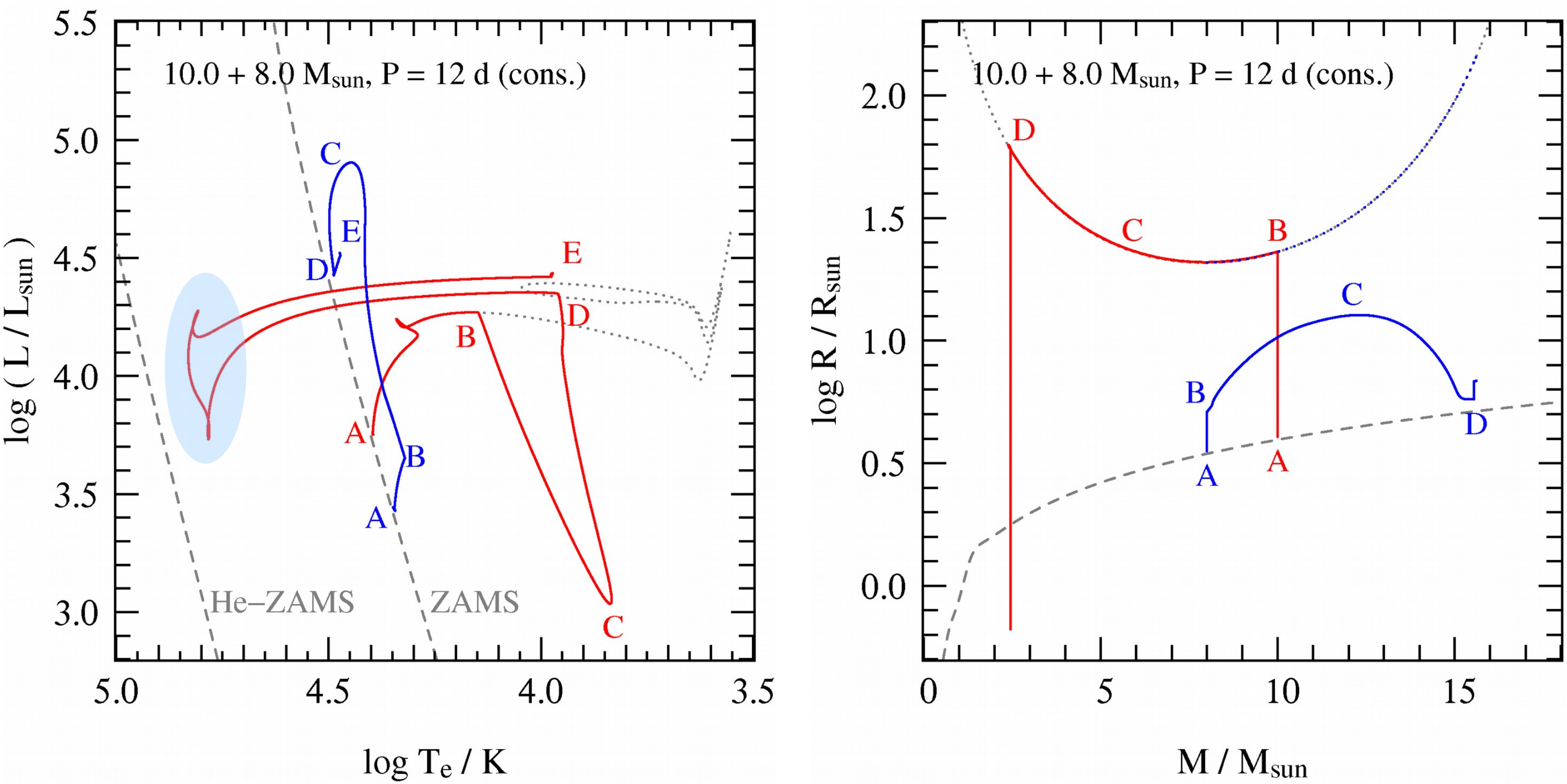
case A versus case B

case B evolution example



- orbit expands during (conservative) case B mass transfer (B–D)
  in this example (B–D): as $M_1 = 10\ M_{sun} \rightarrow 2.5\ M_{sun} \quad \Rightarrow \quad P = 12\text{ d} \rightarrow 105\text{ d}$

case B evolution example



- B – D: thermal timescale (rapid) mass transfer ⇒ few obs. counterparts
- D – E: detached, He-burning *1 (nuclear timescale)
  ⇒ expect many observed counterparts
- E: end He-burning *1, further RLOF phase possible

post-mass transfer binaries

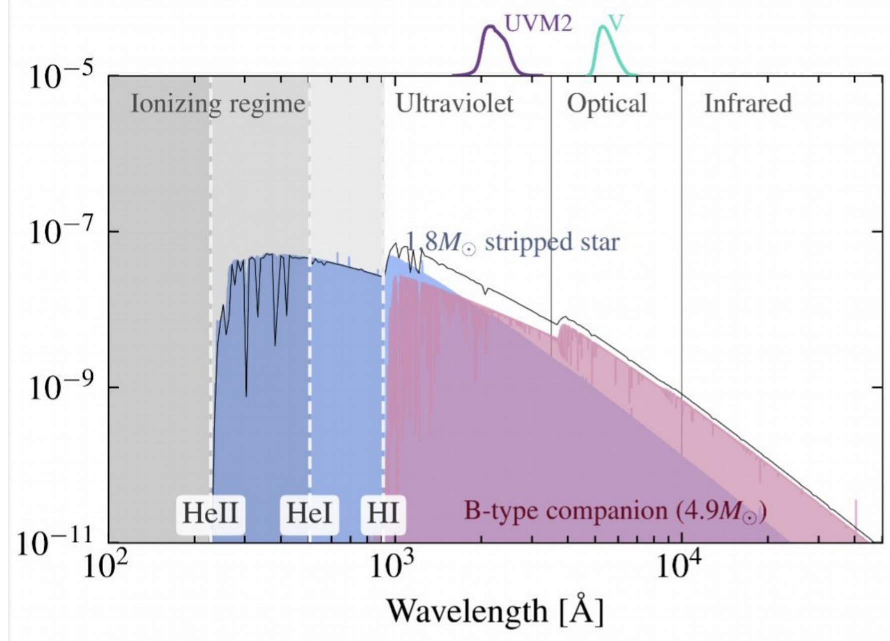
- *1 stripped down to its (almost) bare He core:
  - a He star in long-lived He-burning state
  - if massive enough: He star appears as a Wolf-Rayet star
- *2 is still a MS star (O- or B-type)
- when $M_1 \ll M_2$ and large $P_{\rm orb}$ $\Rightarrow$ sign of conservative mass transfer (e.g. ϕ Per)
- however, many WR+O binaries with short $P_{\rm orb}$ and $M_1 \sim M_2$ $\Rightarrow$ must have lost substantial mass and AM

name	spectra	P (d)	M_1	M_2	R_1	R_2
CQ Cep	WN7 + O6	1.64	24	30	8.8	7.9
V398 Car	WN4 + O4-6	8.26	19	37		
GP Cep	WN6/WC + O3-6	6.69	15	27		
CV Ser	WC8 + O8-9	29.7	13	27		
V444 Cyg	WN5 + O6	4.21	9.3	28	2.9	8.5
ϕ Per	HeI em + B1IIIe	127	1.15	9.3	1.3:	5.5–8

post-mass transfer binaries

- in binaries like ϕ Per, the more massive mass gainer outshines the He star, which is hard to detect

  ⇒ mass gainers in massive binaries often appear to be single stars



Götberg+ 2022

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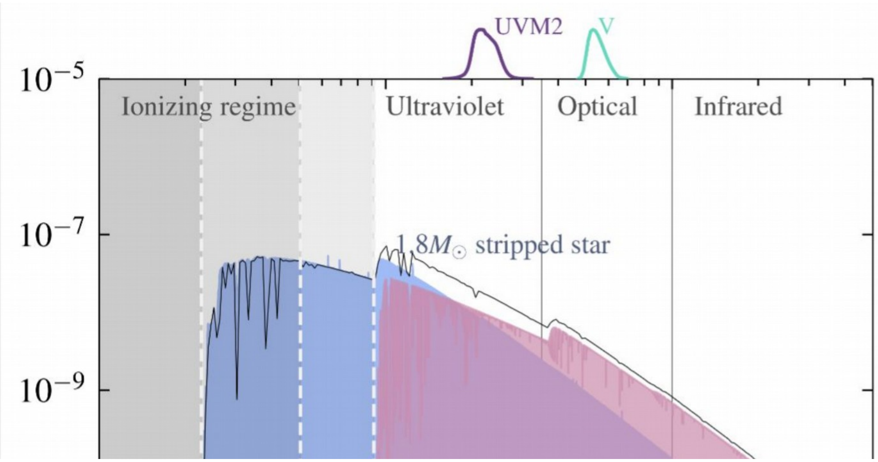
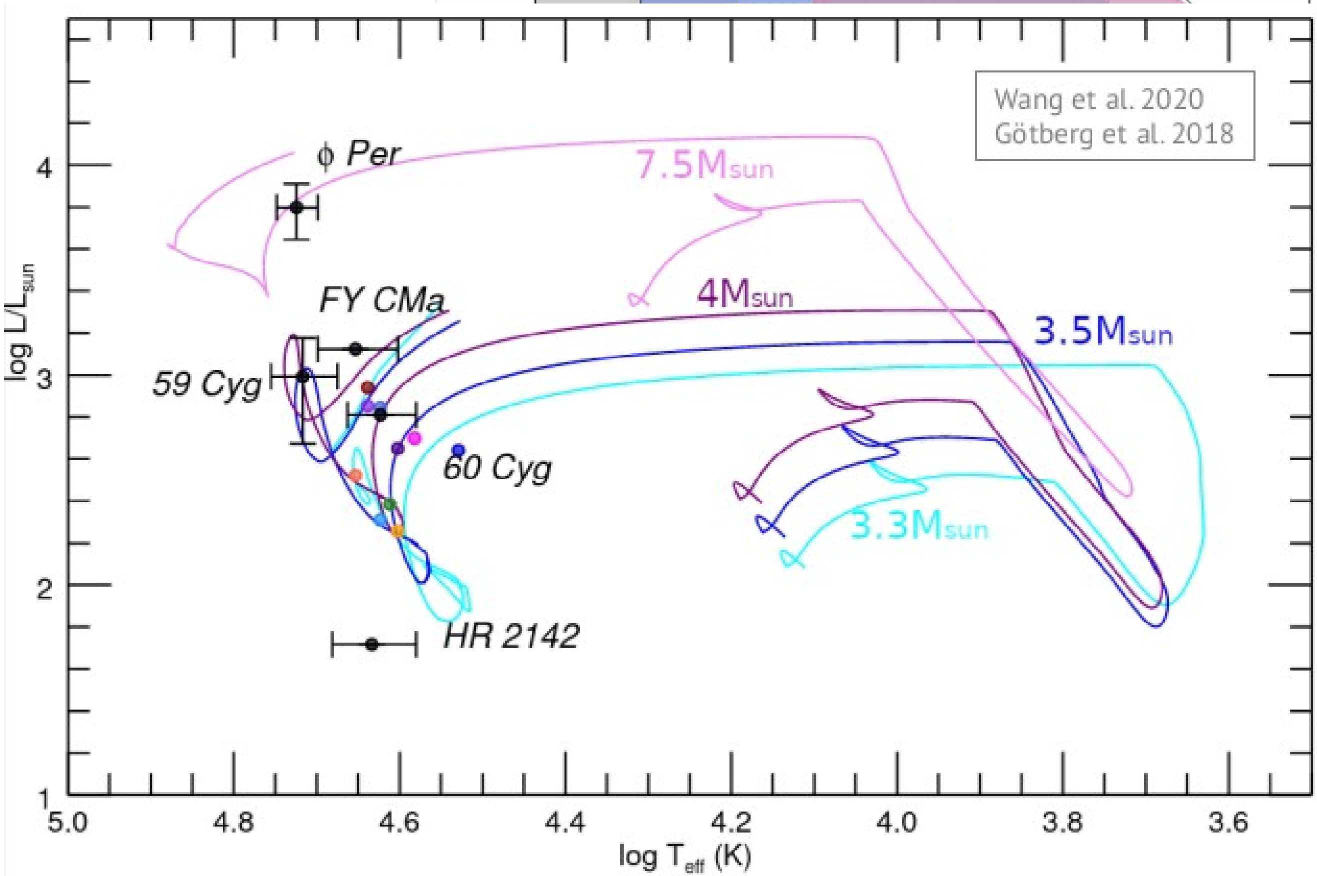


- recently more such companions have been discovered using far-UV observations:



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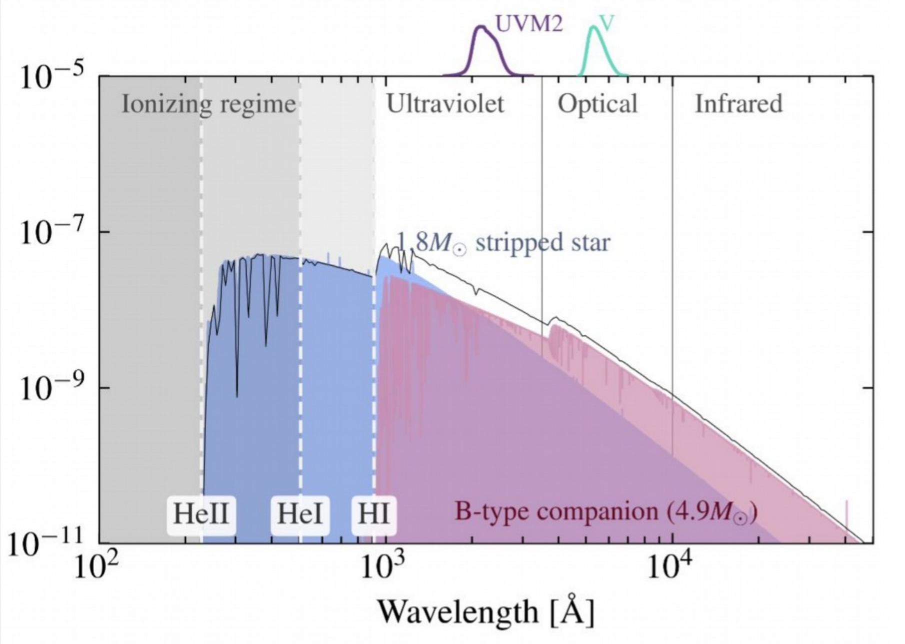

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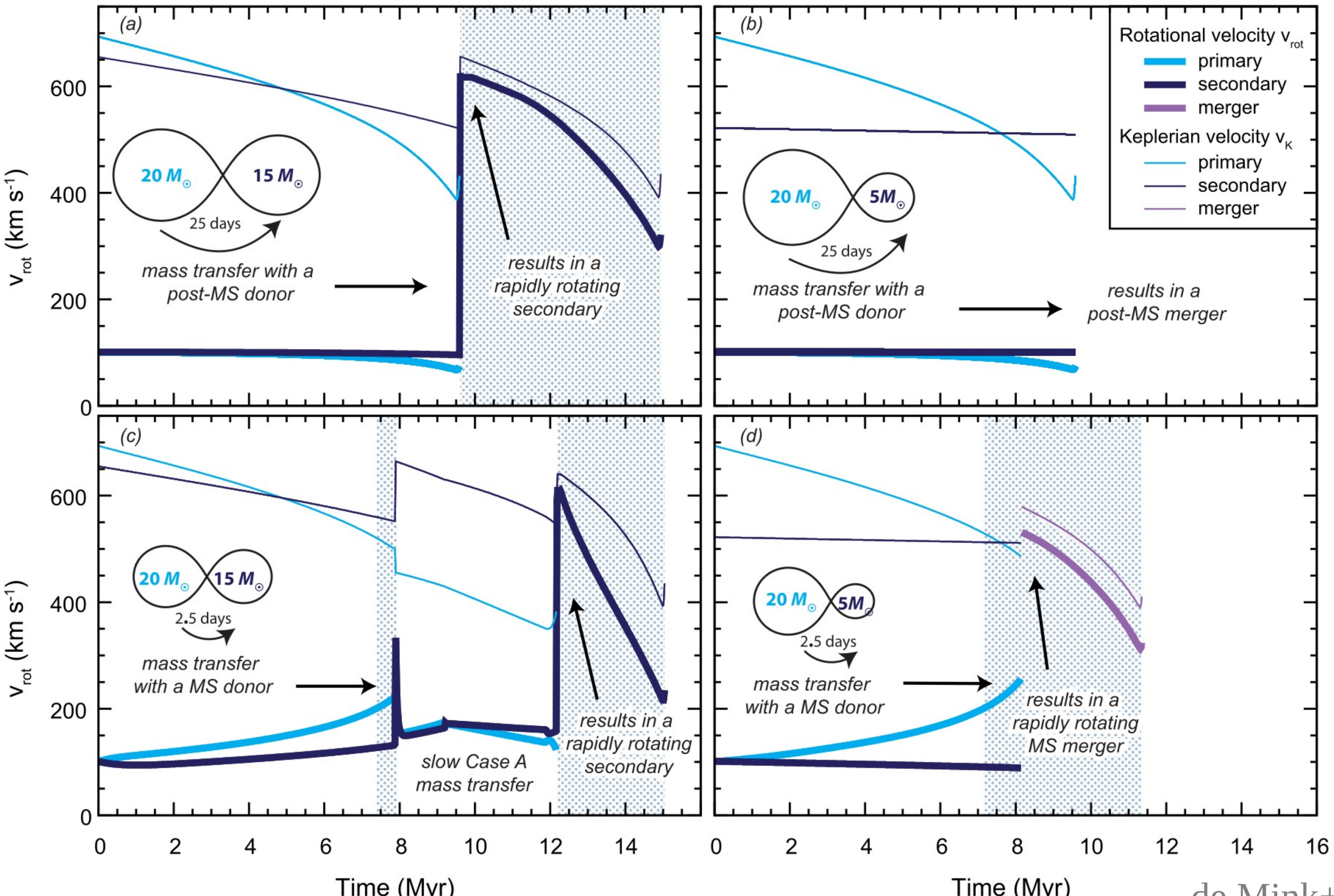
effects on the mass gainer:

- as a result of mass transfer, the mass gaining star is expected to:
  - rotate very rapidly
  - have modified surface abundances
- (qualitatively) similar effects expected for MS binary mergers

effects on the mass gainer

- evolution of rotation velocities of massive binaries:



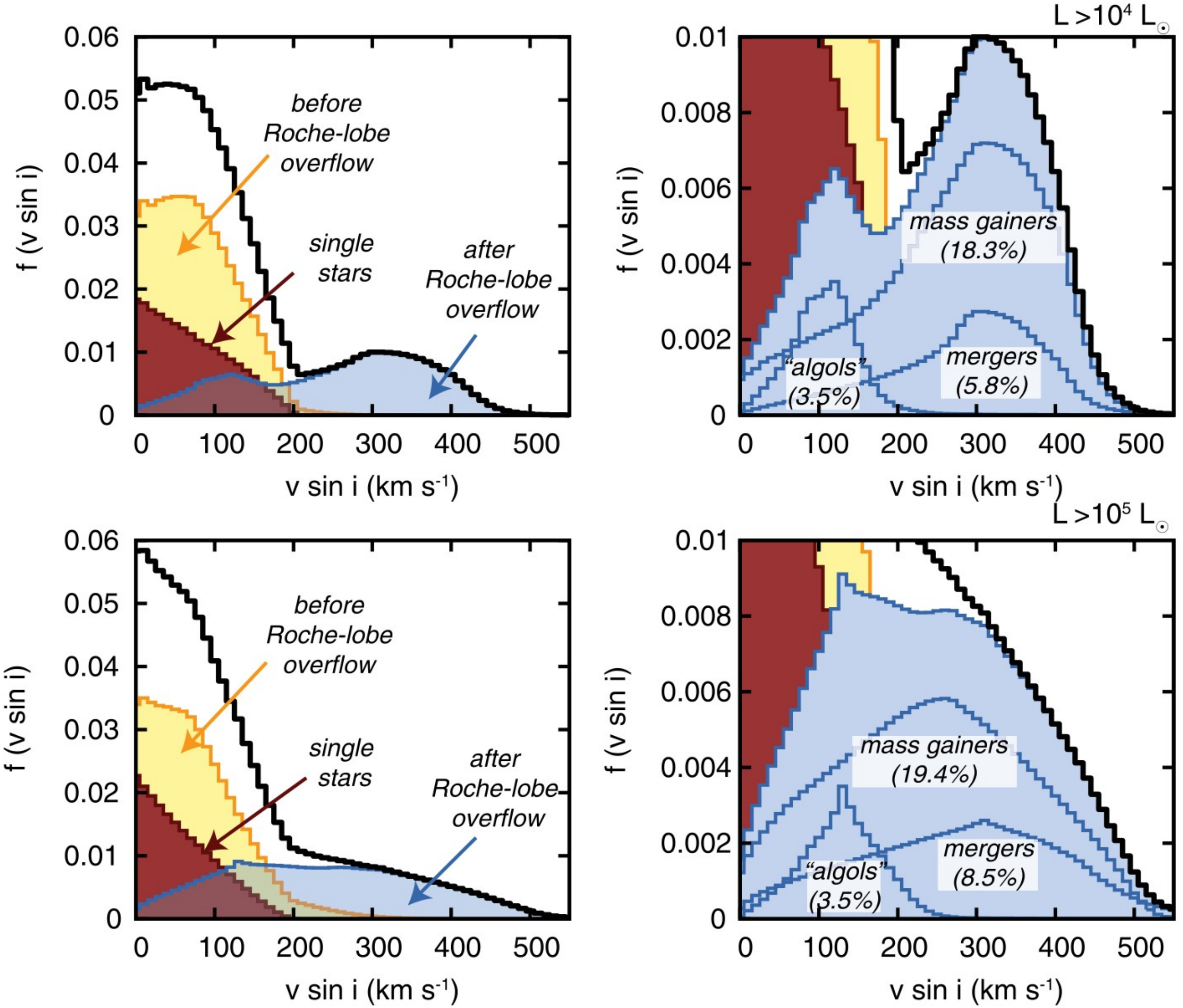
case B

case A

de Mink+ 2013

effects on the mass gainer

- predicted distribution of rotation velocities:



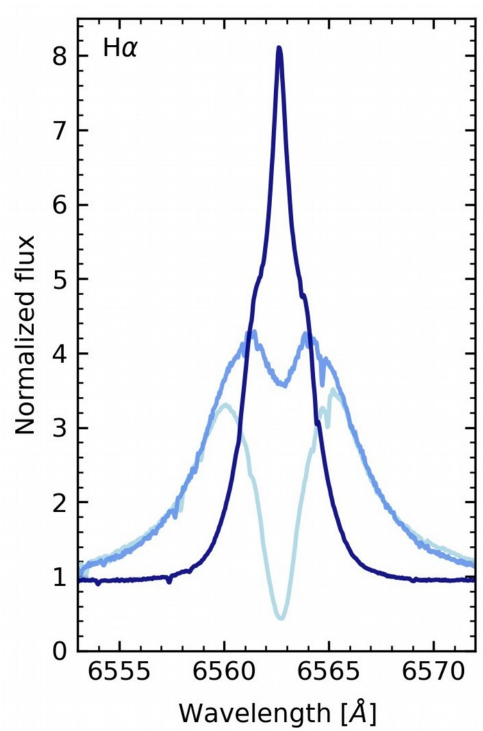
stars with
$L > 10^4\ L_{sun}$

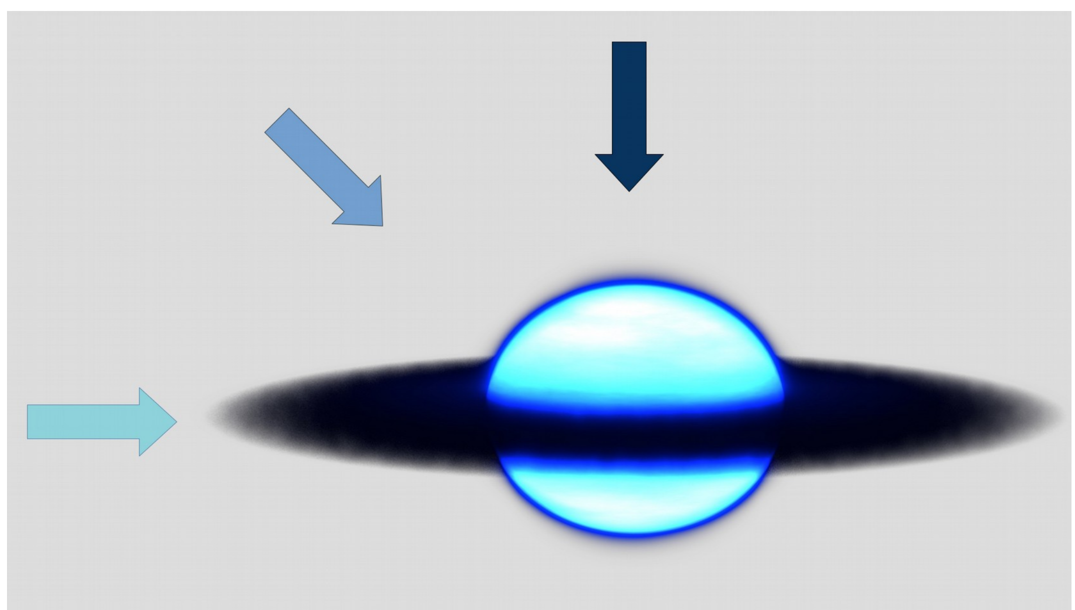
stars with
$L > 10^5\ L_{sun}$

de Mink+ 2013

effects on the mass gainer

- a (likely) manifestation of spin-up by accretion or merger: Be stars
    - ~20% of B-type stars (3 – 20 M_{sun}), rapidly rotating
    - equatorial mass loss into circumstellar disk (transient phenomenon)
  - some Be stars have stripped He-star companions (e.g. ϕ Per) or compact companions (Be/X-ray binaries)
  - ***no*** Be stars have normal B-star companions

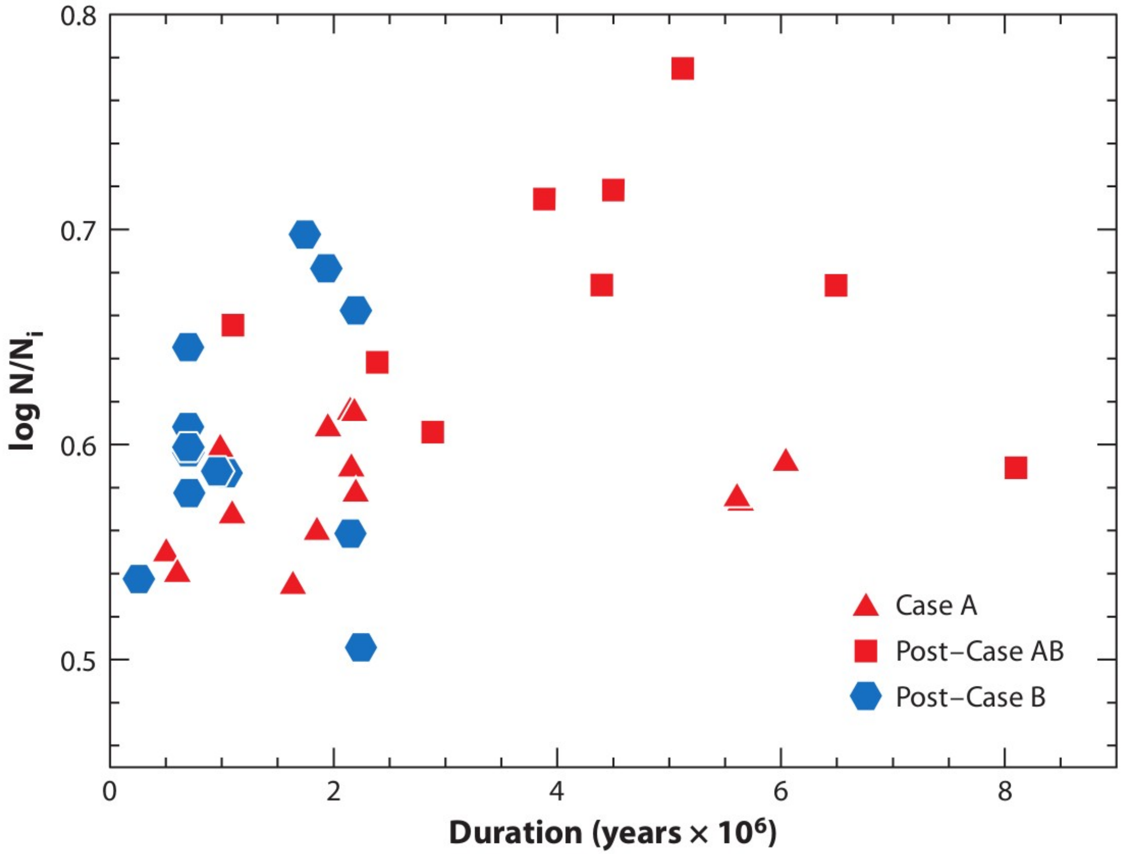




credit: J. Bodensteiner

effects on the mass gainer

- predicted nitrogen abundances after mass accretion ($M_i = 16 + 12\ M_{sun}$)



Wellstein+ 2001, Langer 2012

- mass transfer results in similar properties (N enrichment + rapid rotation) as expected from rotational mixing in single stars
- effects are very hard to disentangle...

effects of SN explosion

- next stage in the evolution of a massive binary: core collapse of the stripped primary star (if M_{He} >~ 2 M_{sun})
- resulting supernova explosion leads to sudden mass loss, and a possible "kick" imparted to the remnant (NS or BH)

  ⇒ both effects change the binary orbit (and possibly disrupt the binary)

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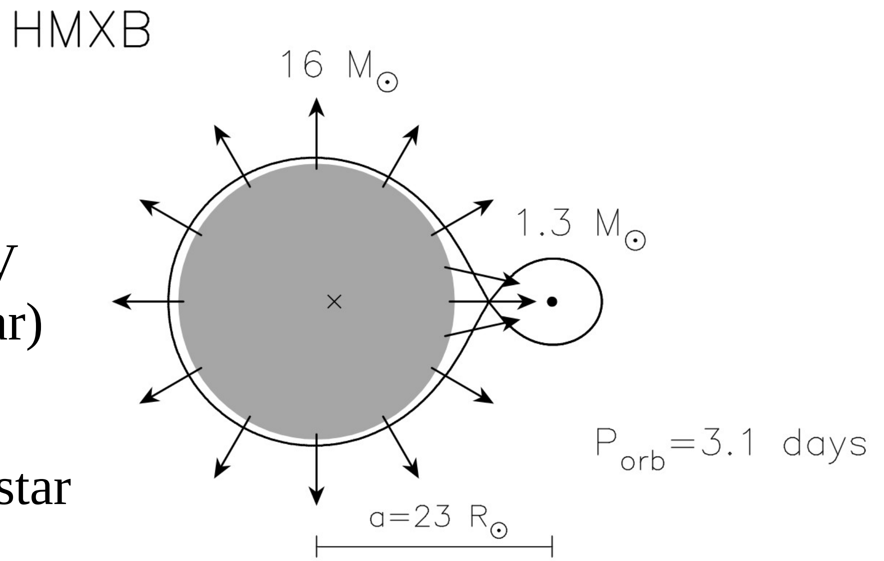
- resulting systems may be observed as
  - X-ray binaries: NS or BH accreting gas from a normal (MS, RG) companion star
  - binary radio pulsars: non-accreting NS with a stellar companion
  - normal stars with an unseen, very massive (non-accreting BH) companion

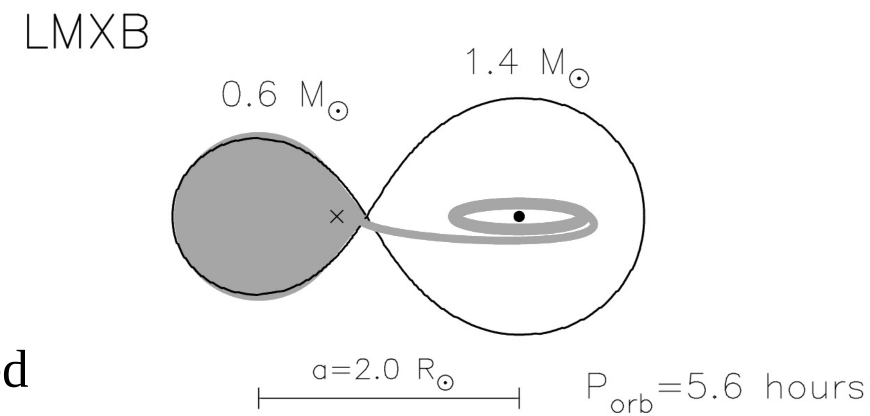
… and some of these eventually evolve into double NS, double BH or NS-BH binaries (GW sources)

X-ray binaries

- high-mass X-ray binaries:
  OB-star + NS/BH
  - often: X-ray pulsations ⇒ rotating, magnetized NS (allows measuring orbital RV variations of NS ⇒ mass function of OB star)
  - OB-companion easily detectable
  - eclipses of X-source + RV variations of OB star ⇒ measure mass of compact object



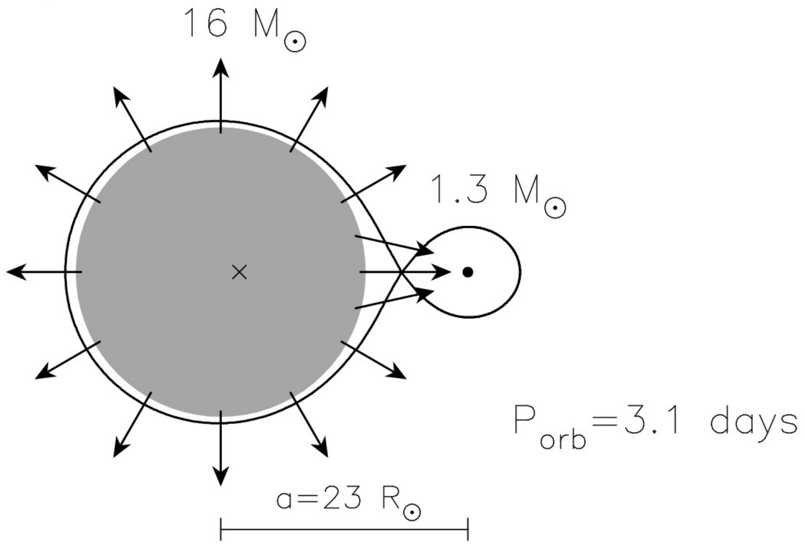
- low-mass X-ray binaries:
  G/K-star + NS/BH
  - no X-ray pulsations, but often X-ray bursts (thermonuclear flashes of accreted gas on NS surface)
  - companion often not observed (*L* is dominated by reprocessed X-rays in accretion disk), unless X-ray emission is transient



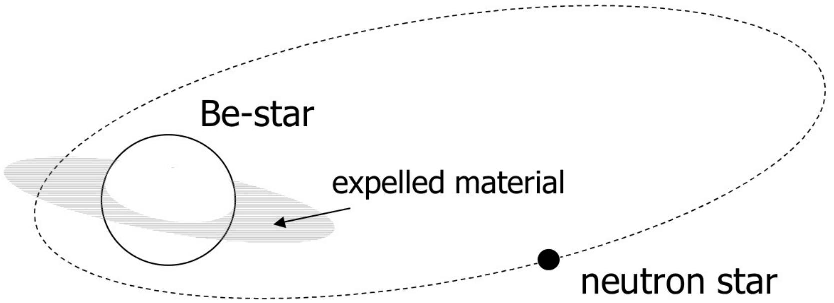
X-ray binaries

two main sub-groups of HMXBs:

- 'standard' HMXBs:
  O-star + NS/BH, P <~ 10 d, e <~ 0.1
  - O-star (> ~20 M_{sun}) often close to filling Roche lobe
  - persistent X-ray emission
  - accretion from stellar wind or beginning RLOF



- Be/X-ray binaries:
  Be-star + NS, P ~ 15–300 d, e <~ 0.5
  - weak stellar winds, far from RLOF
  - accretion from equatorial mass ejections of Be star (~8–20 M_{sun})
  - transient X-ray emission (known population is incomplete)



mass loss in supernova

- special case: symmetric explosion (instantaneous, isotropic mass loss ΔM) in circular orbit $\Rightarrow$ produces a wider, eccentric orbit with

$$e = \Delta M \,/\, M_{\mathrm{tot,f}}$$

$$a_{\mathrm{f}} = a_{\mathrm{i}} \,/\, (1 - e)$$

  - binary is disrupted if $\Delta M > 0.5\, M_{\mathrm{tot,i}}$

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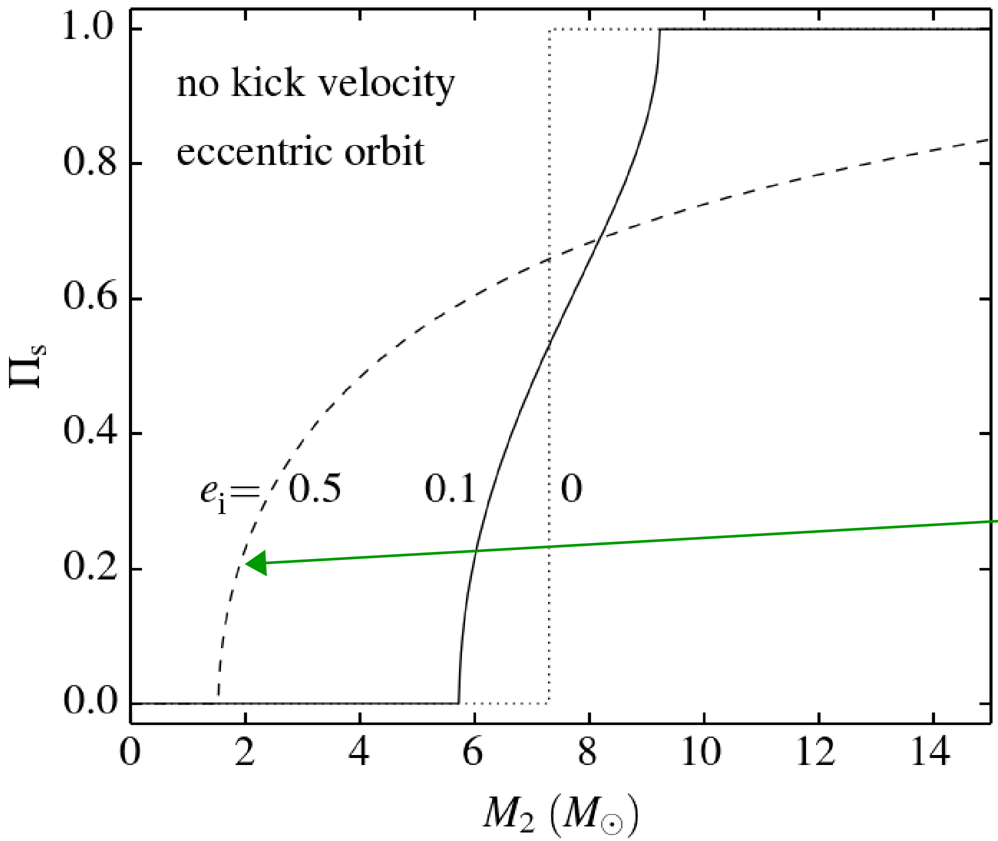
- general case:
  - initial orbit may be eccentric (if wide enough to avoid strong tides)
  - SN explosion likely to be slightly asymmetric $\Rightarrow$ compact remnant receives a kick (recoil) velocity, up to few 100 km/s

- both introduce a random effect:
  - explosion may occur at any point on eccentric orbit
  - kick velocity can have an arbitrary direction
  - result is unpredictable, can only compute probabilities

mass loss in supernova

effect of supernova explosion

- probability that binary remains bound after SN explosion
- example: $M_1 = 10\ M_{sun} \Rightarrow$ SN $\Rightarrow M_{1f} = 1.35\ M_{sun}$ (NS)
  - symmetric explosion in circular orbit: bound orbit if $M_2 > 7.3\ M_{sun}$
  - eccentric orbit and/or SN kick: survival probability depends on M_2



finite probability of survival even for small M_2, if explosion occurs near apastron

effect of supernova explosion

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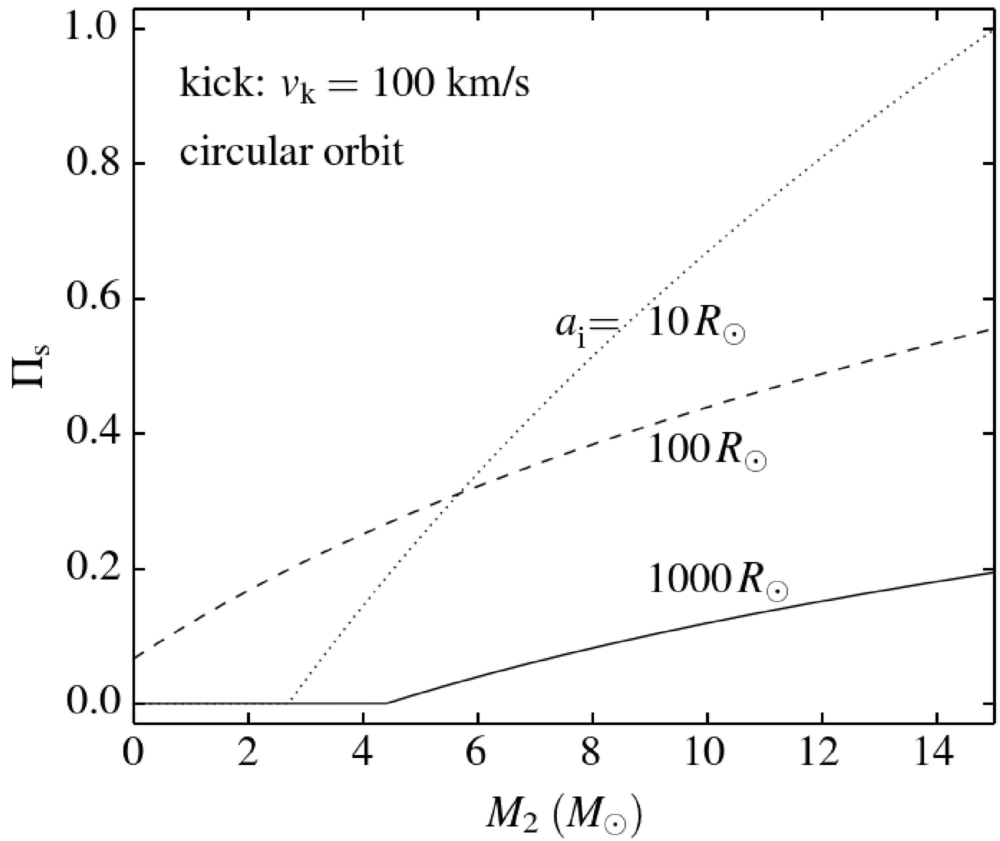
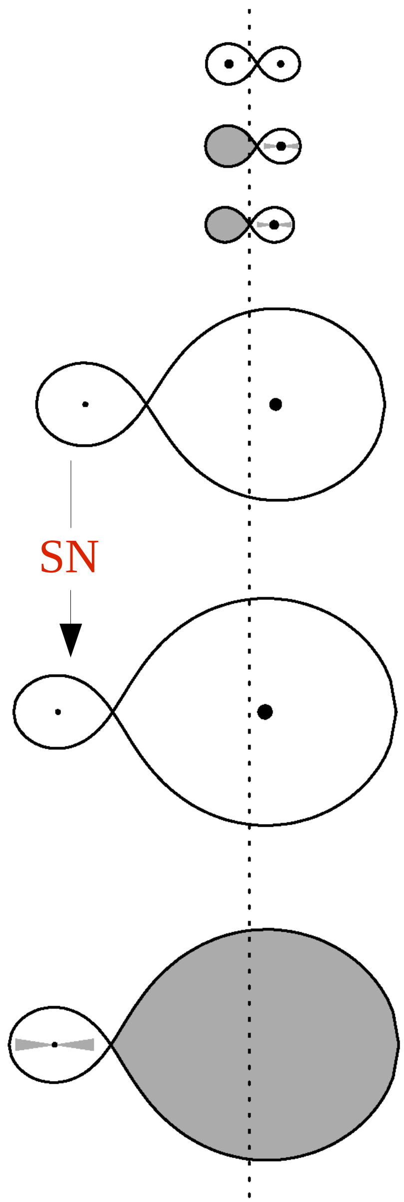
SN kick in circular orbit:

- larger effect in wider orbits
- if $v_k \sim v_{orb}$, even a very small M_2 can remain bound if kick is opposite to orbital motion



formation scenario of HMXB

Age (Myr)	$M_1 (M_\odot)$	$M_2 (M_\odot)$	P_{orb}(d)
0.00	12.00	8.00	10.0
17.92	11.80	8.00	10.3
17.93	9.90	9.90	9.2
17.96	2.70	17.10	71.0
21.01	1.35	17.00	83.6 e=0.06
26.21	1.35	16.60	87.0



in case of symmetric SN

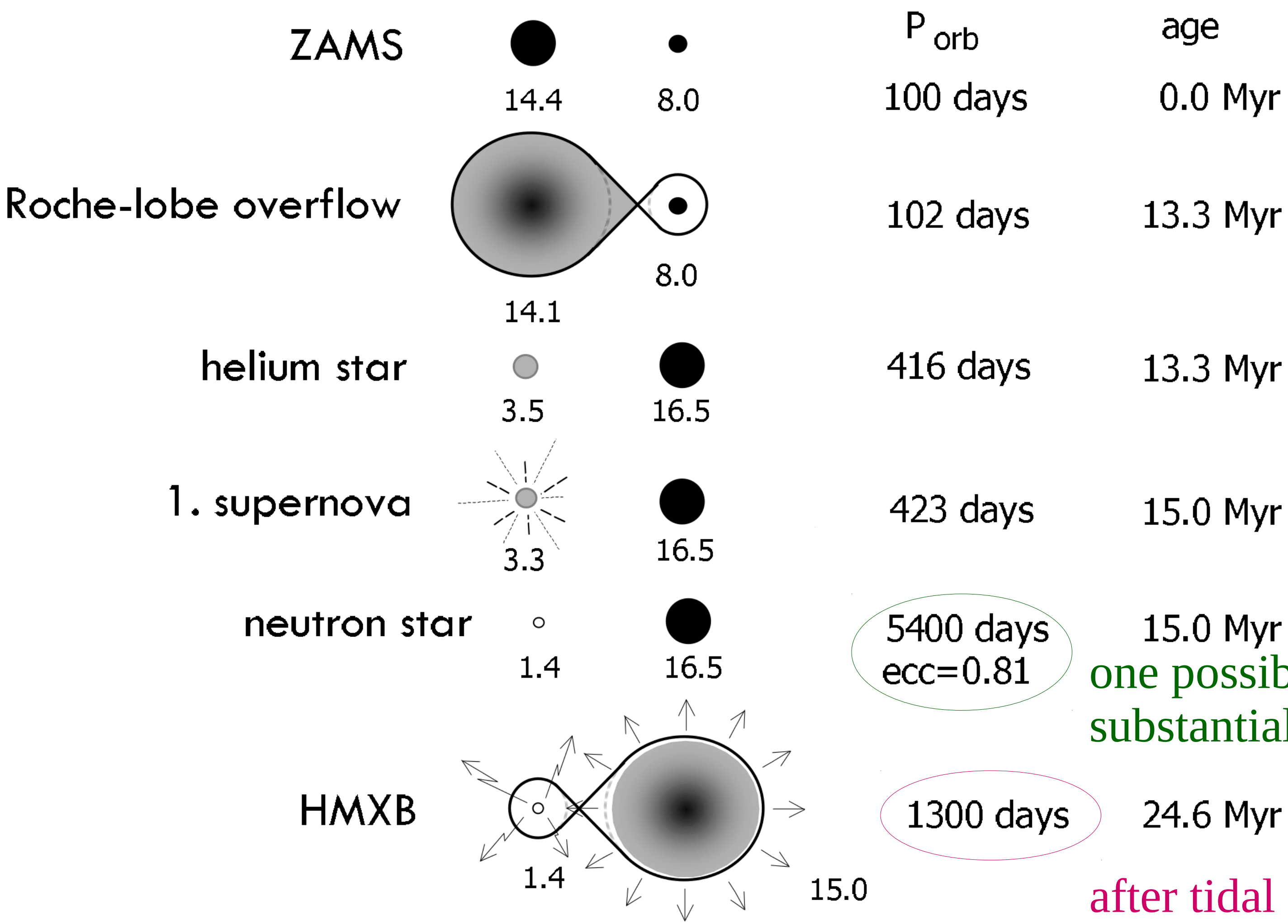
example:

<u>conservative case B evolution</u>

- MS + MS: detached binary
- start of RLOF
- minimum $P_{\rm orb}$
- He-star + MS (Be star)
  ϕ Per-like binary
- NS + MS (Be star)
  Be/X-ray binary
- start of RLOF from *2 (unstable)

formation and evolution of a HMXB

<u>another possible scenario</u>, starting from a wider orbit:



one possible outcome, in case of substantial SN kick

after tidal circularization:

$a_f = a_i\,(1 - e^2)$