Mysteries in the formation of chemically polluted binaries

Onno Pols
Dept. of Astrophysics/IMAPP, Radboud Universiteit Nijmegen

chemically polluted binaries

- binaries with an unevolved (MS, RG) star showing signs of advanced (AGB) nucleosynthesis:

  enhanced abundances of C and s-process elements (Ba, La, Zr, Sr, Pb, …)

	Ba stars	**CH stars**	**CEMP-s stars**
- population:	Galactic disk		halo
- metallicity:	~0.5 Z_{sun}	~0.1 Z_{sun}	$< 0.01\ Z_{sun}$
- fraction (RG):	~1%	~2%	6–20% (!)
- duplicity:	100%	100%	100%?

- probes of AGB nucleosynthesis
- probes of binary interaction processes at low/intermediate stellar mass: *focus of this talk*

binary evolution scenario

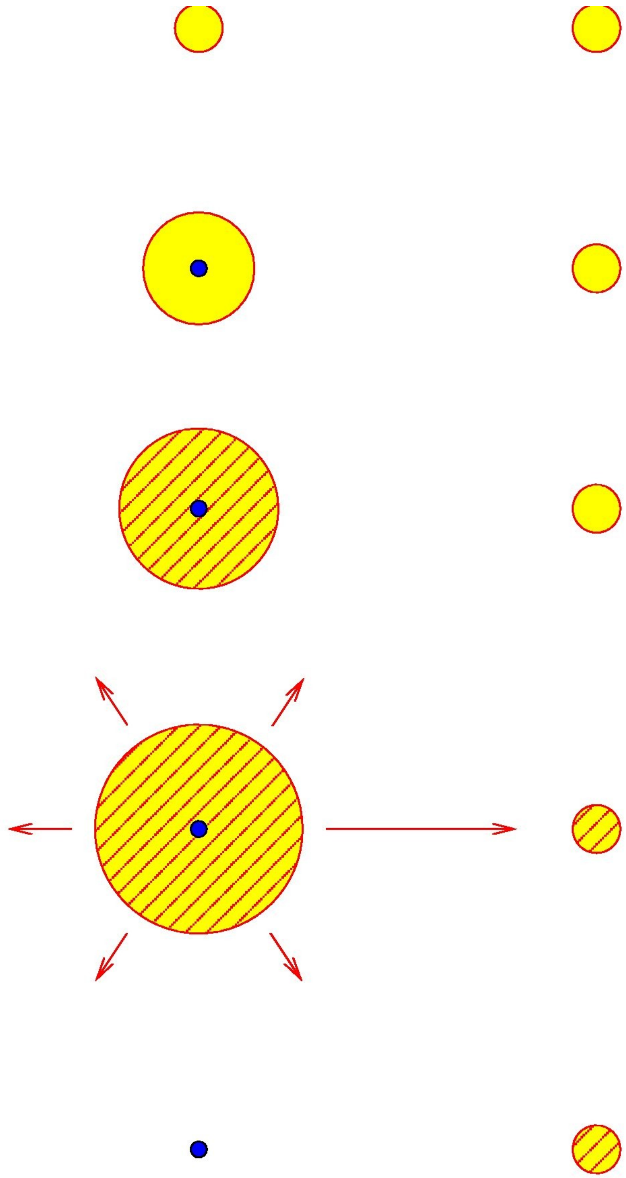
MS $(M_1 > 0.9\text{–}1.5\ M_\odot)$ — MS $(M_2 < M_1)$

first giant branch

AGB: surface C ↑ s ↑

mass loss (wind, RLOF) — accretion: C ↑ s ↑

white dwarf — Ba star / CH star / CEMP-s star



carbon-enhanced metal-poor stars

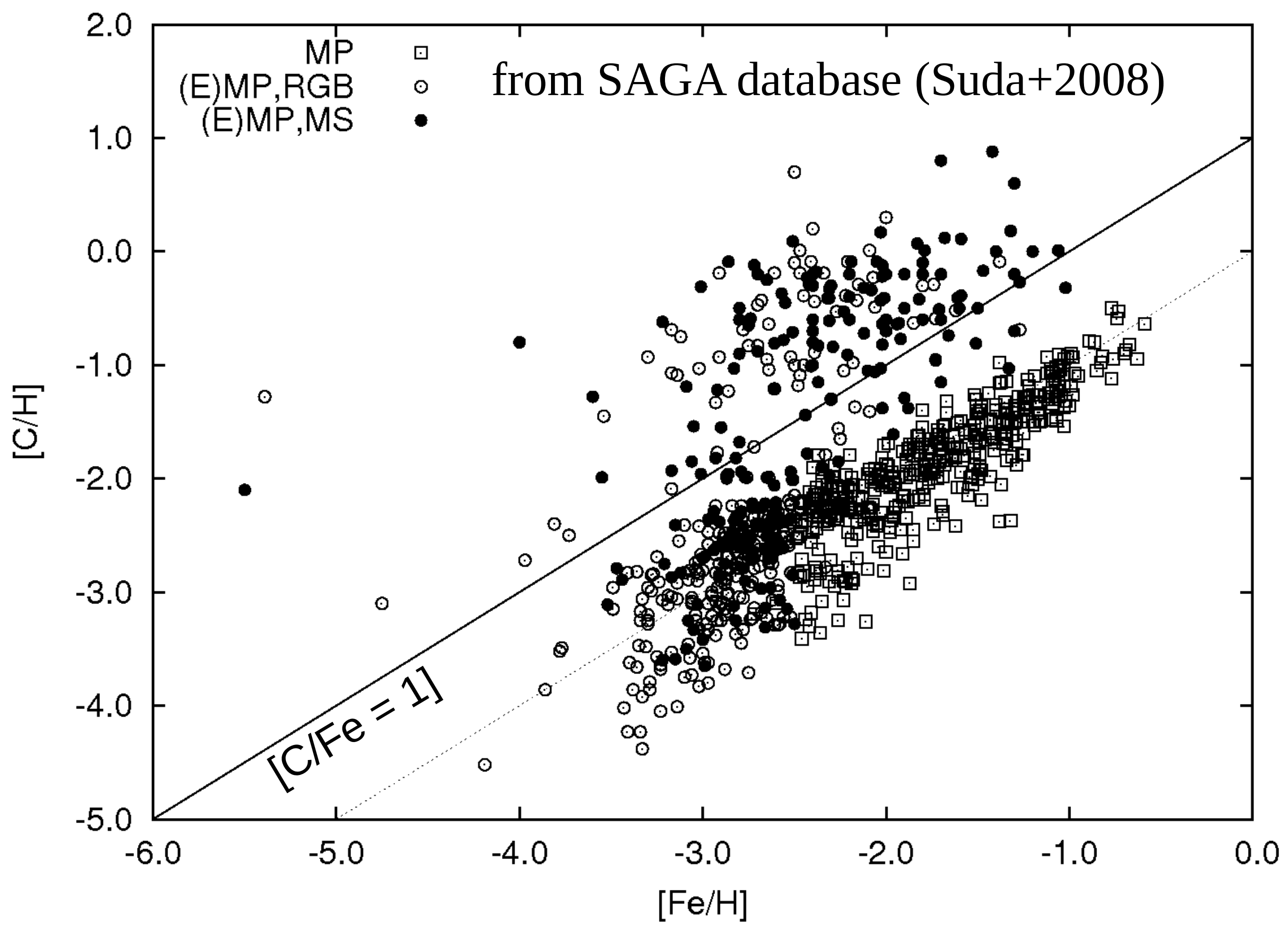
- 6–25% of halo stars with [Fe/H] < −2 have [C/Fe] > 1
  Lucatello+2006, Lee+2013

- ~80% also enhanced in s-process elements: **CEMP-s** stars
  ⇒ AGB nucleosynthesis

- some also appear r-process enriched: CEMP-r/s

- probably all binaries
  Lucatello+2005, Starkenburg+2014

- similar origin to Ba and CH stars



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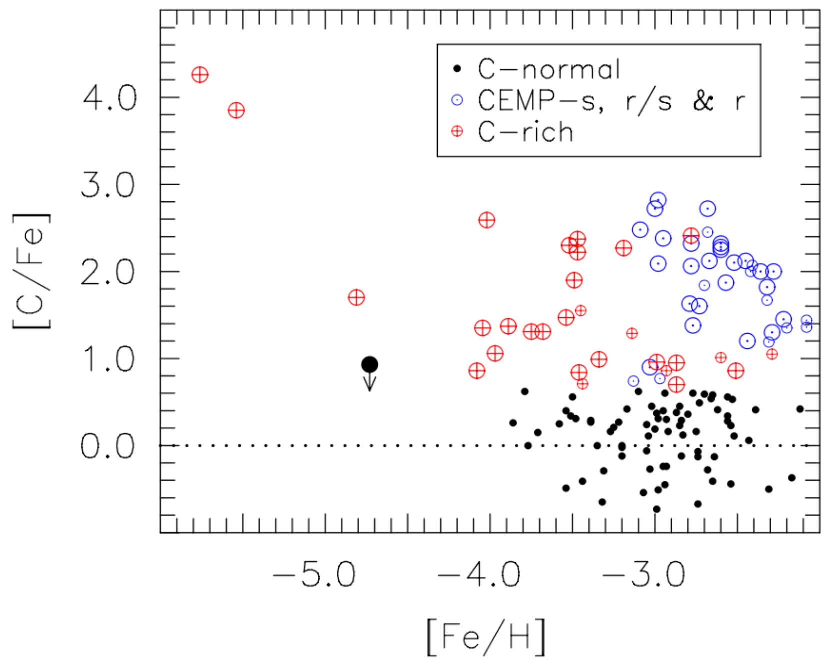
- similar origin to Ba and CH stars

- **CEMP-no** stars: no heavy-element enhancements
- dominate at [Fe/H] < −3
- normal (field) binary properties
  Starkenburg+2014, Hansen+2015
- probably entirely different origin

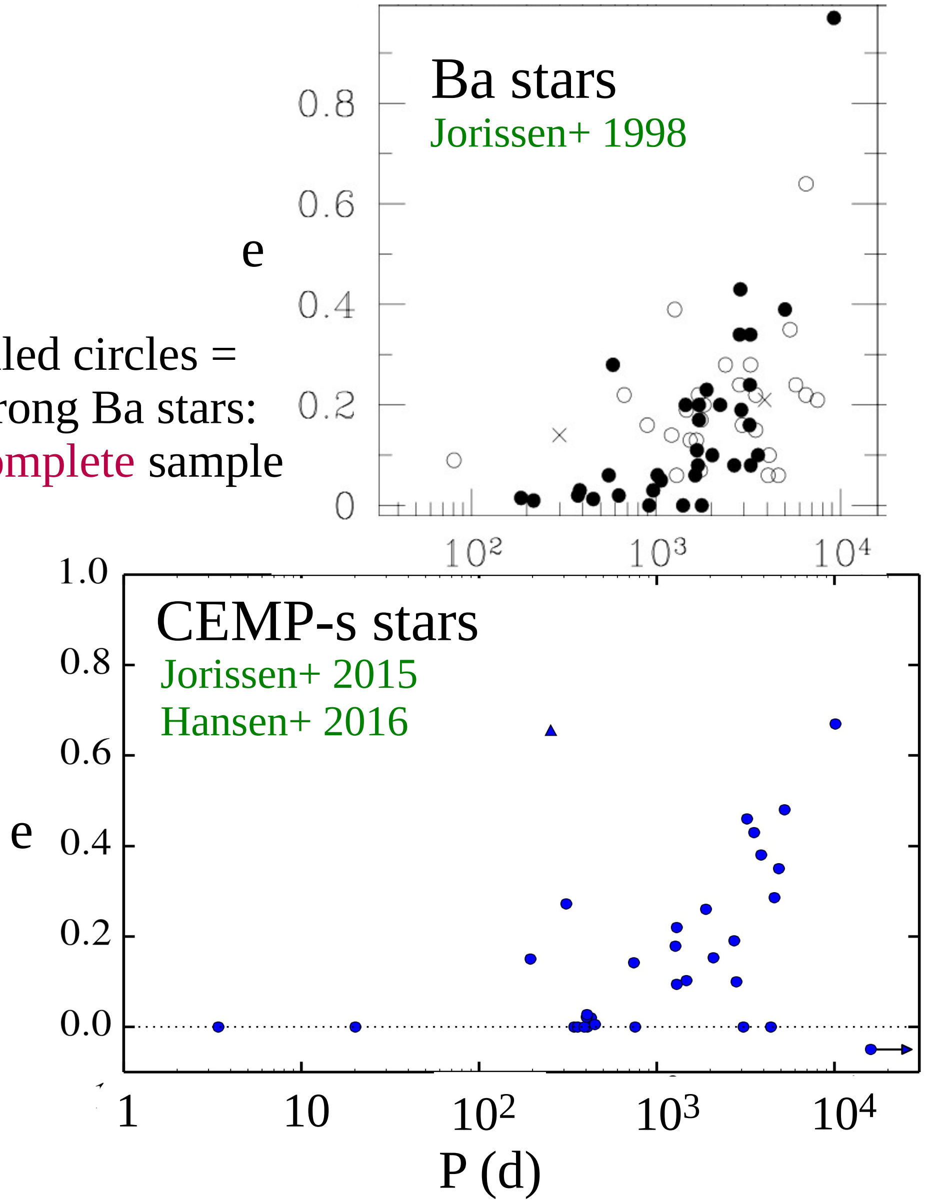


Norris+2013

orbits of AGB descendants

eccentricity versus orbital period

filled circles = strong Ba stars: complete sample

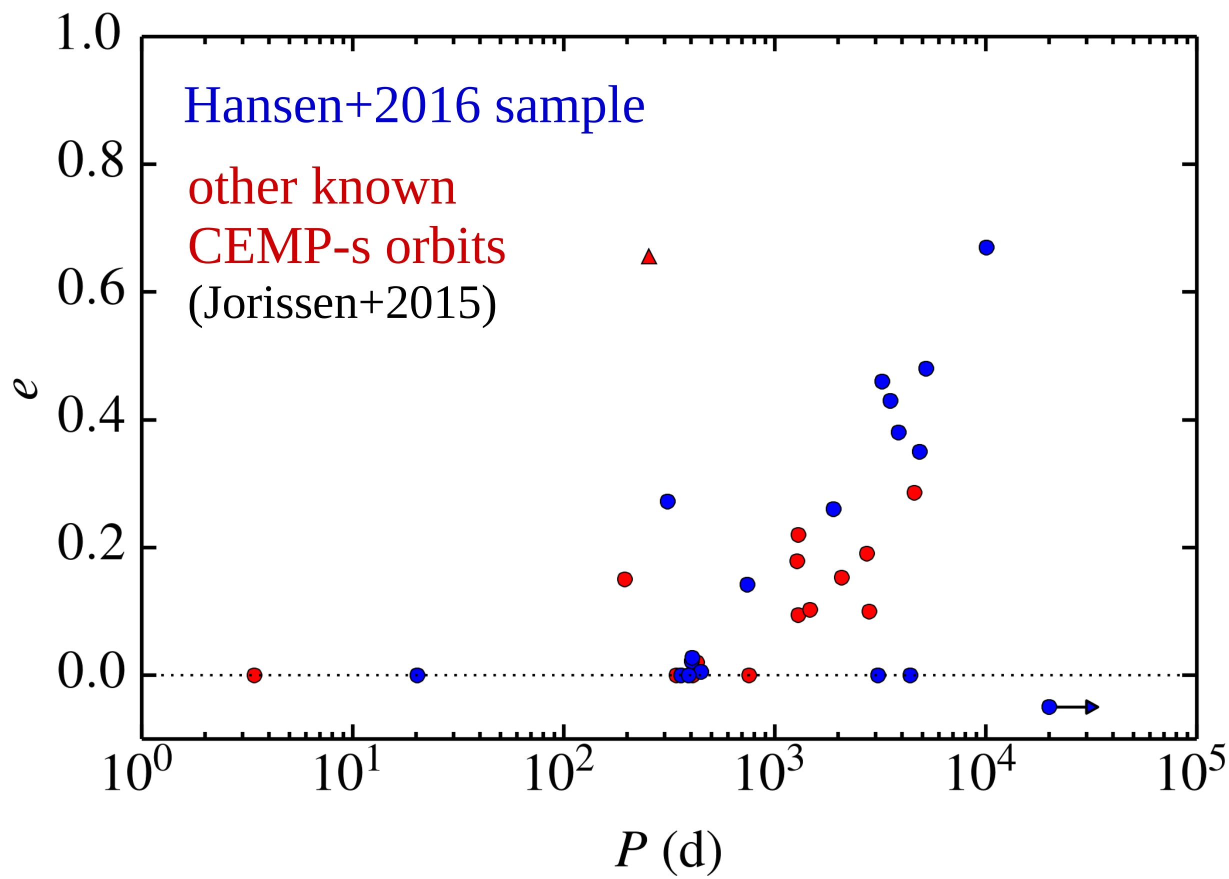


- periods mostly $10^2 - 10^4$ days
- substantially eccentric (but less so than unevolved binaries at same *P*)
- mass functions consistent with WD companions

CEMP-s binary properties

- Hansen+2016: high-precision RV monitoring of 22 CEMP-s stars over 8 years:
  - 18 show orbital motion (17 orbits determined)
  - 4 constant RV, apparently *single* (~80% binary frequency?)

(N.B. also some Ba-rich blue stragglers appear to be single... Milliman+ 2015)

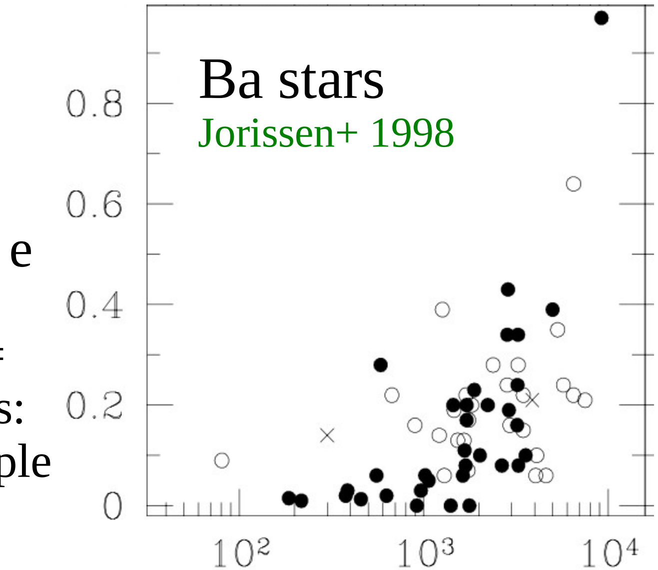


lack of orbital periods > 10^4 d is *not* a selection effect (cf. Starkenburg+ 2014)

consistent with Ba star orbits Jorissen+ 1998

orbits of AGB descendants

eccentricity versus orbital period



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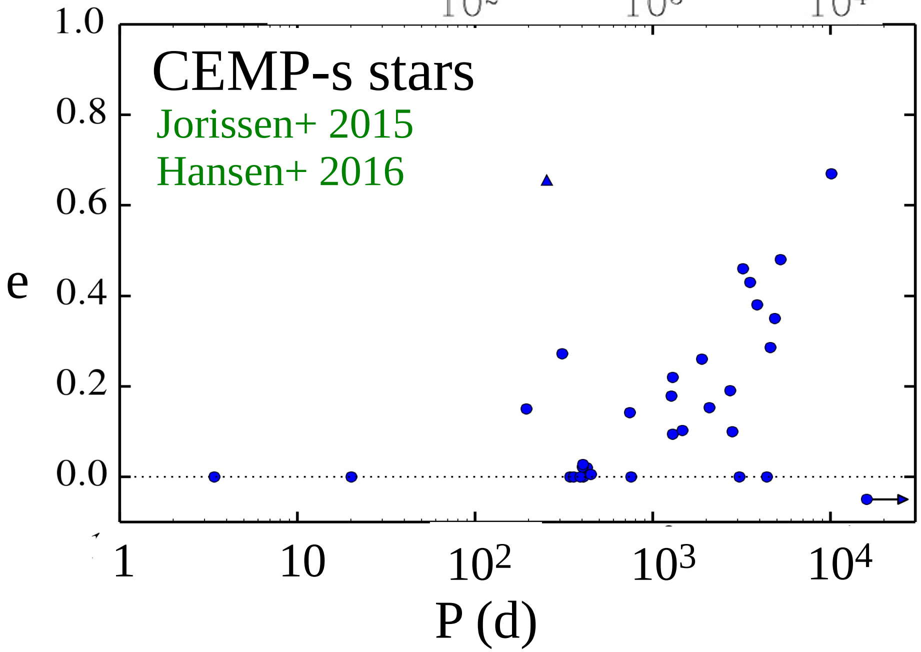

- periods mostly 10^2 – 10^4 days
- substantially eccentric (but less so than unevolved binaries at same *P*)
- mass functions consistent with WD companions
- very similar *e*-*P* distributions found among many classes of post-AGB/RGB binaries:
  - extrinsic S stars (without Tc)
  - post-AGB stars in binaries
  - S-type symbiotics
  - blue stragglers in old populations
  - sdB+MS binaries

orbits of AGB descendants

eccentricity versus orbital period

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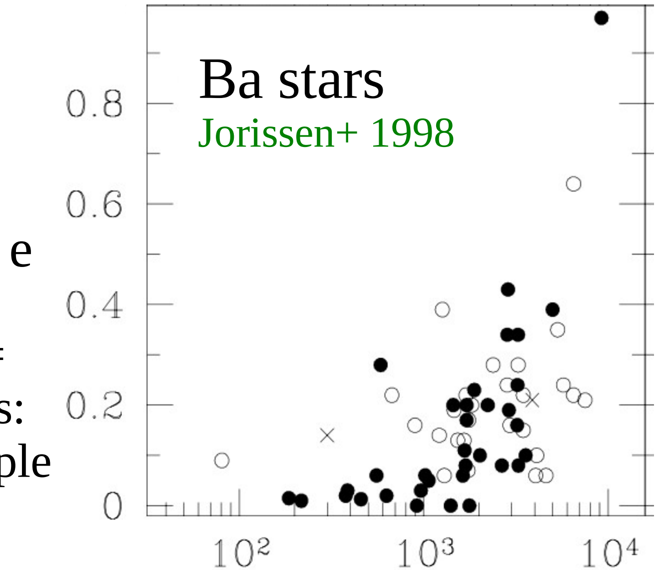
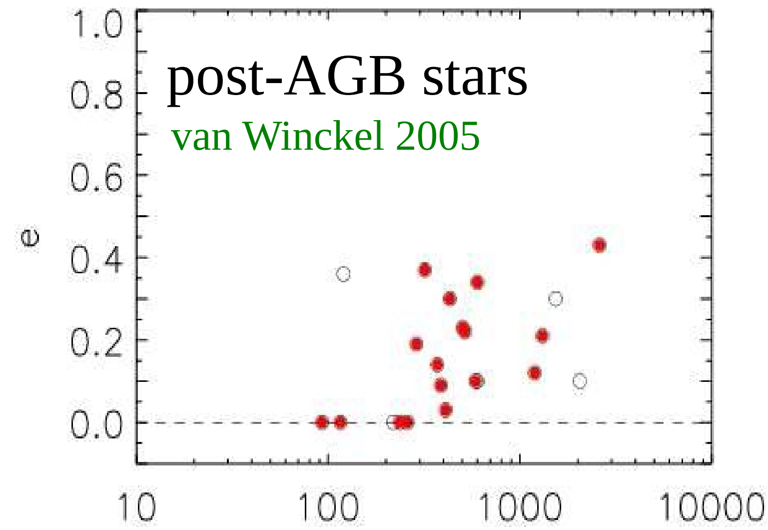
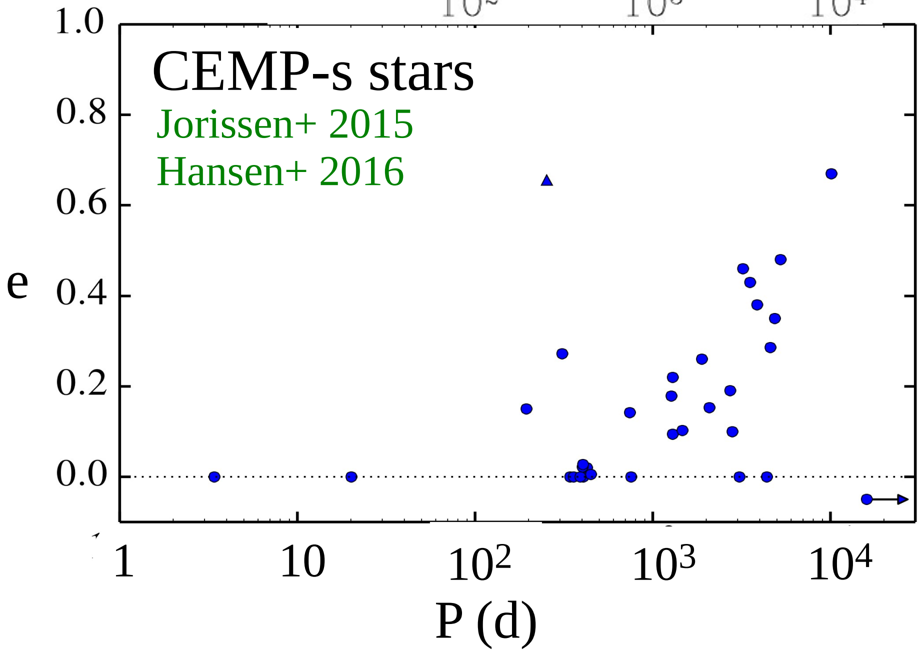
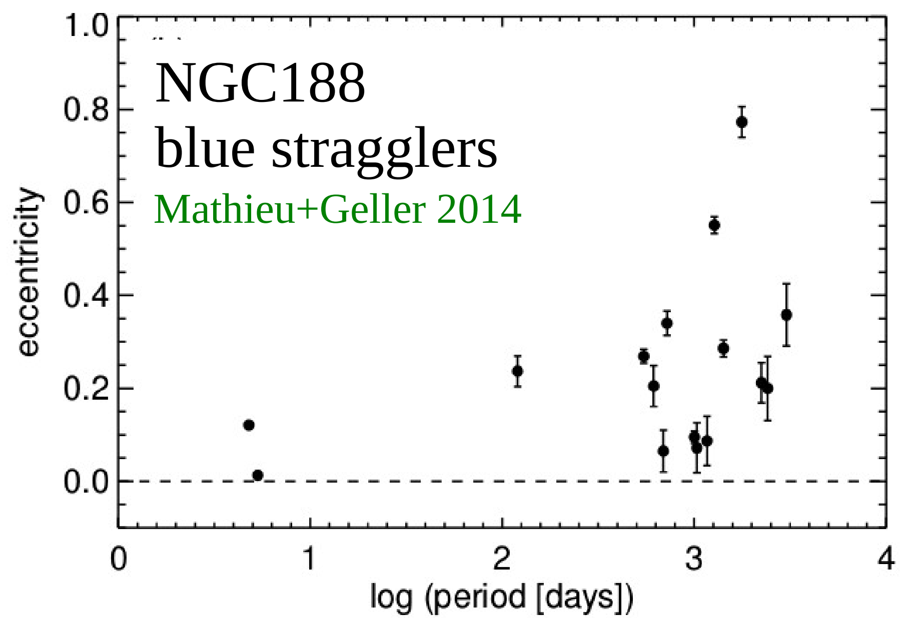


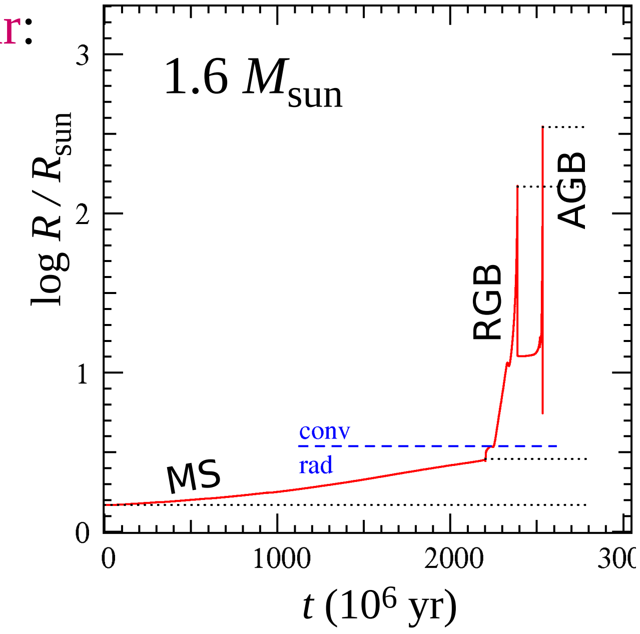




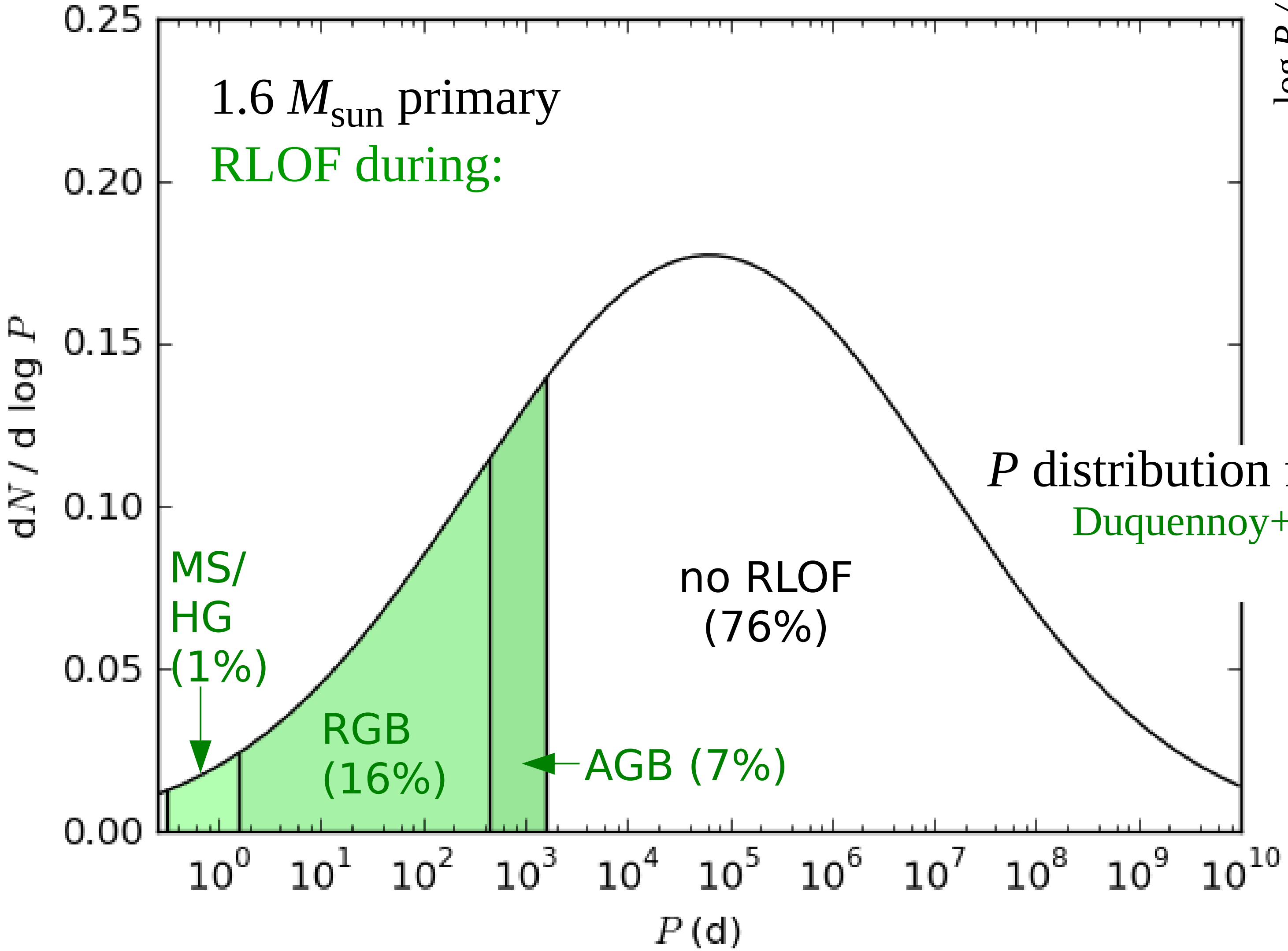


close binaries

stellar radius increase of a low-mass star:



- ~25% of low-mass binaries undergo RLOF

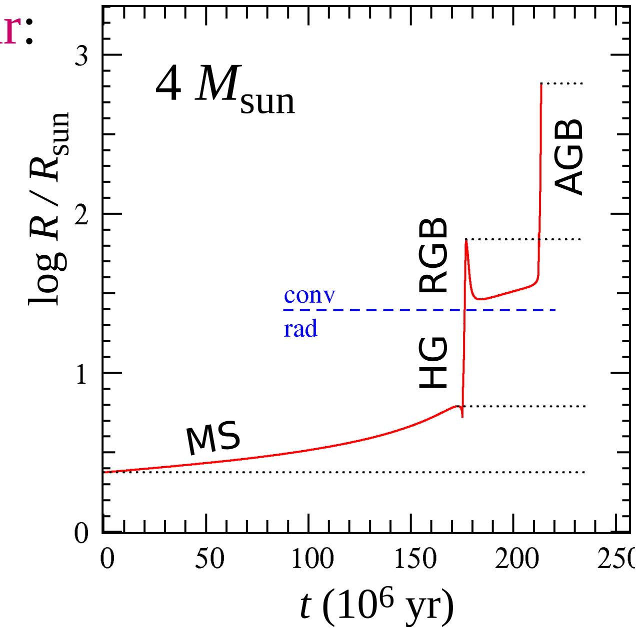


P distribution for G dwarfs
Duquennoy+Mayor 1991, Raghavan+2010

46% of G dwarfs are multiple systems (of which 13% triple, quadruple, …)
Tokovinin 2014

close binaries

radius increase of an intermediate-mass star:



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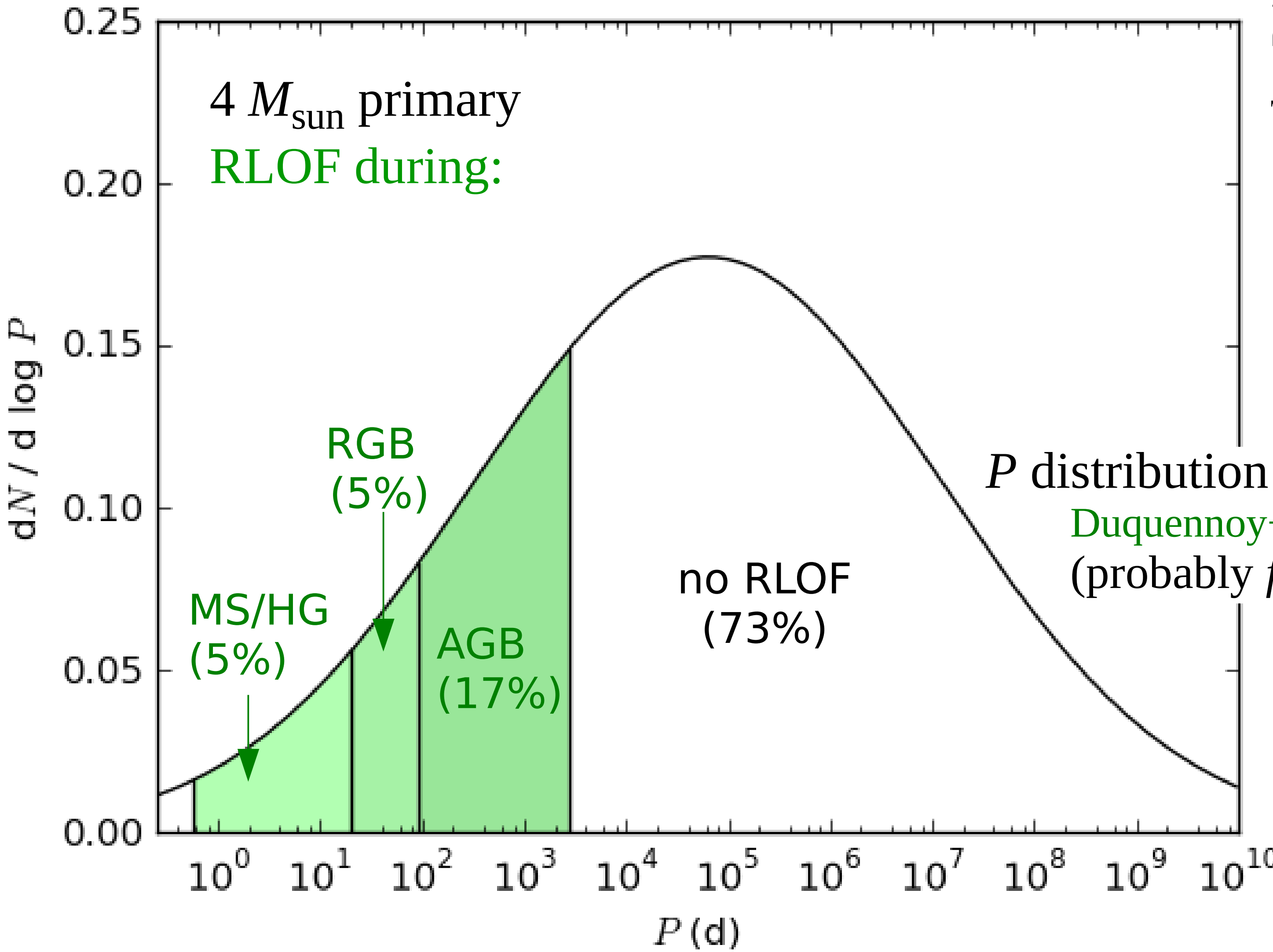
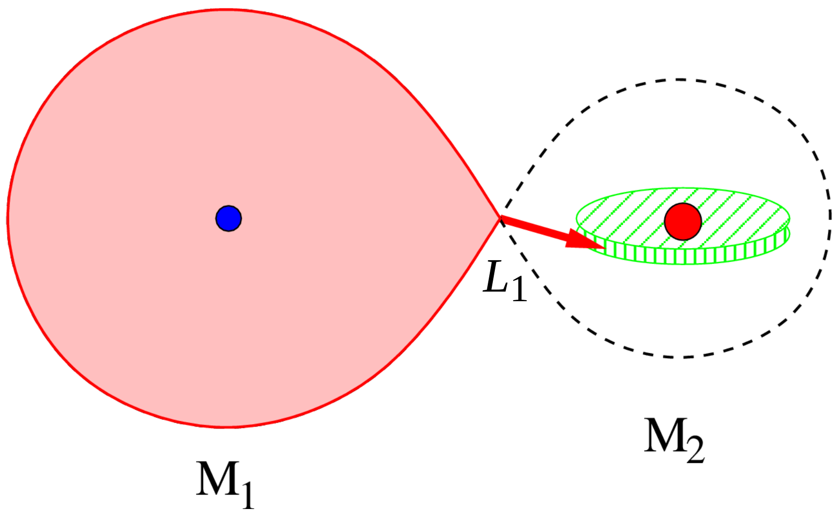


P distribution for G dwarfs
Duquennoy+Mayor 1991, Raghavan+2010
(probably *flatter* for IM stars)

multiplicity fractions increase with mass
Duchene+Kraus 2013, Moe+DiStefano 2016

Roche-lobe overflow

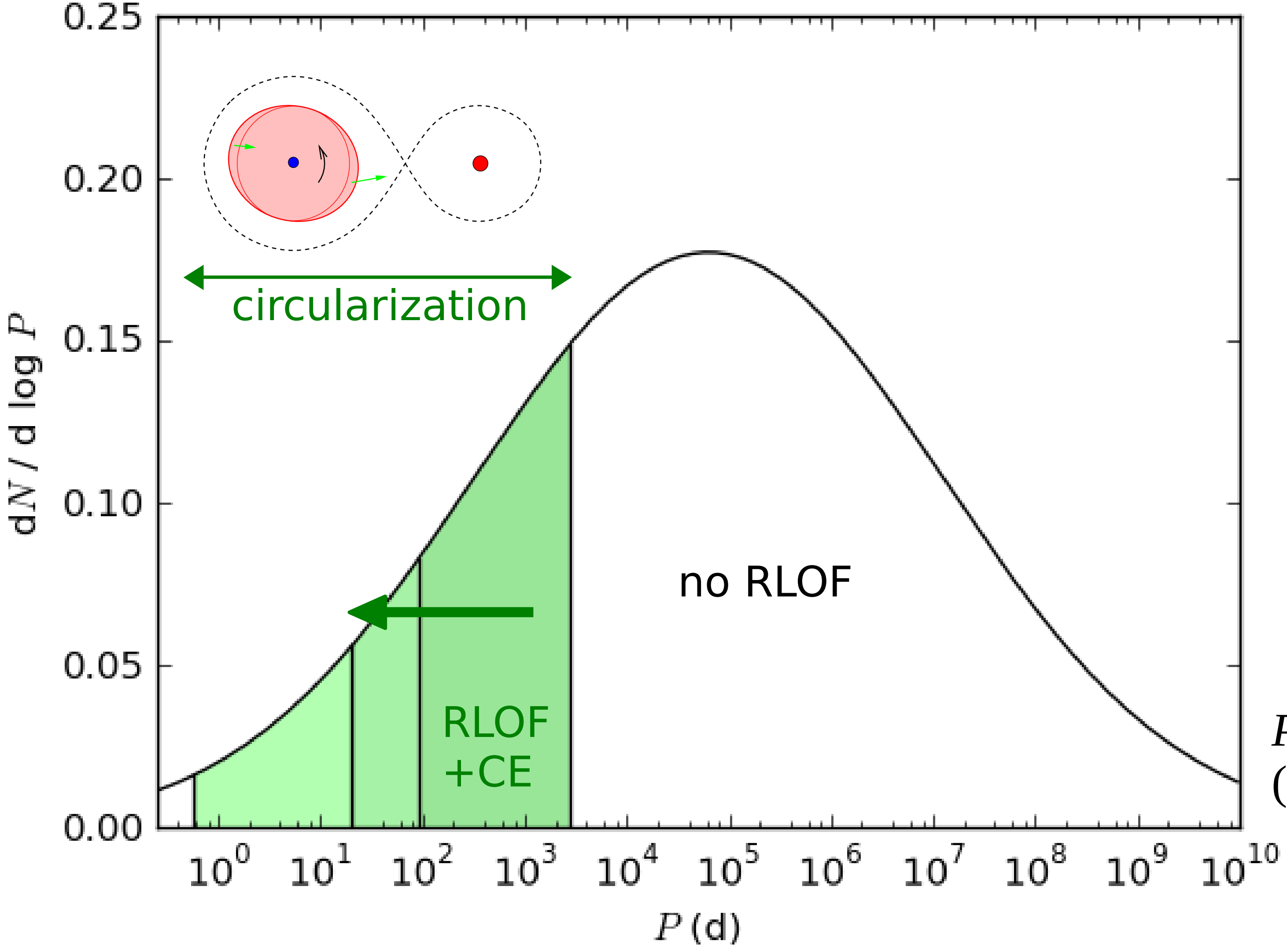


- close binaries with MS and HG primaries ⇒ stable and efficient RLOF (provided $M_1/M_2 < \sim 4$)

- red giant (RGB or AGB) primaries ⇒ RLOF is usually unstable, unless $M_1/M_2 < q_{cr} \sim 0.8$
- typical outcome: dynamical mass transfer and formation of common envelope, with almost no accretion and strong spiral-in
- complications:
  - luminous RGB/AGB stars have (very) extended atmospheres
  - radiation pressure may deform Roche lobes Schuerman 1972, Dermine+2009
  - q_{cr} may be > 1 in some cases Chen+Han 2008, Woods+ 2011, Pavlovskii+Ivanova 2014

close binaries

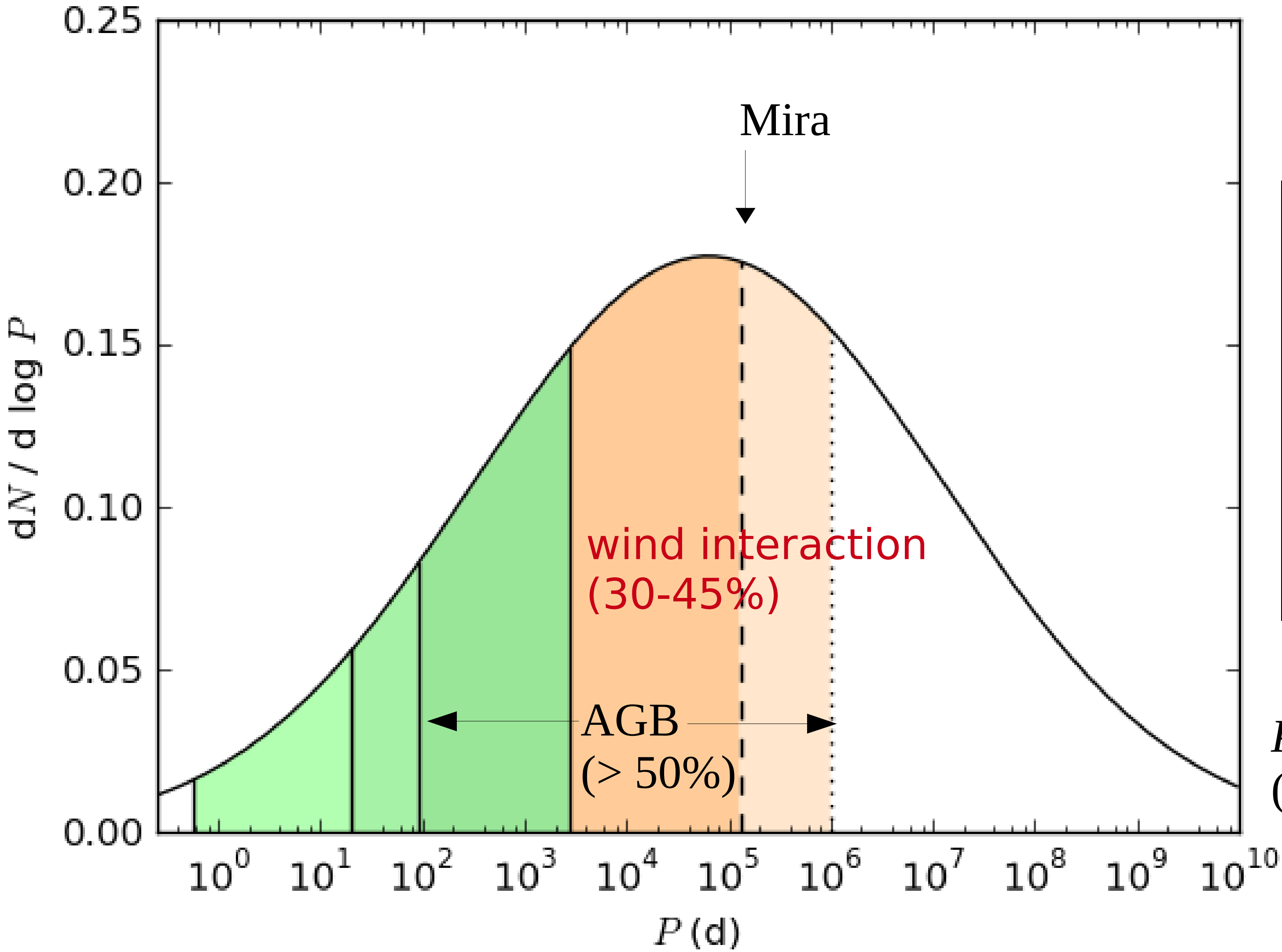
- close binaries tend to circularize due to tidal interactions
- most red-giant binaries expected to spiral-in to closer orbits



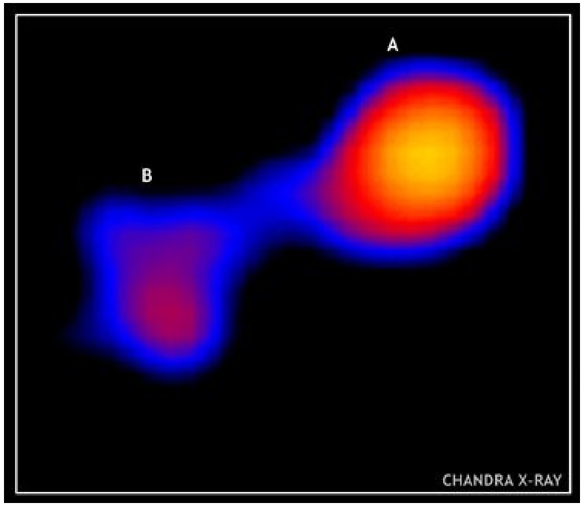
P distribution for G dwarfs
(may be flatter for IM stars)

wide binaries

- wide binaries can also interact by their stellar winds, especially on the AGB where the bulk of mass loss occurs (slow, dense winds)



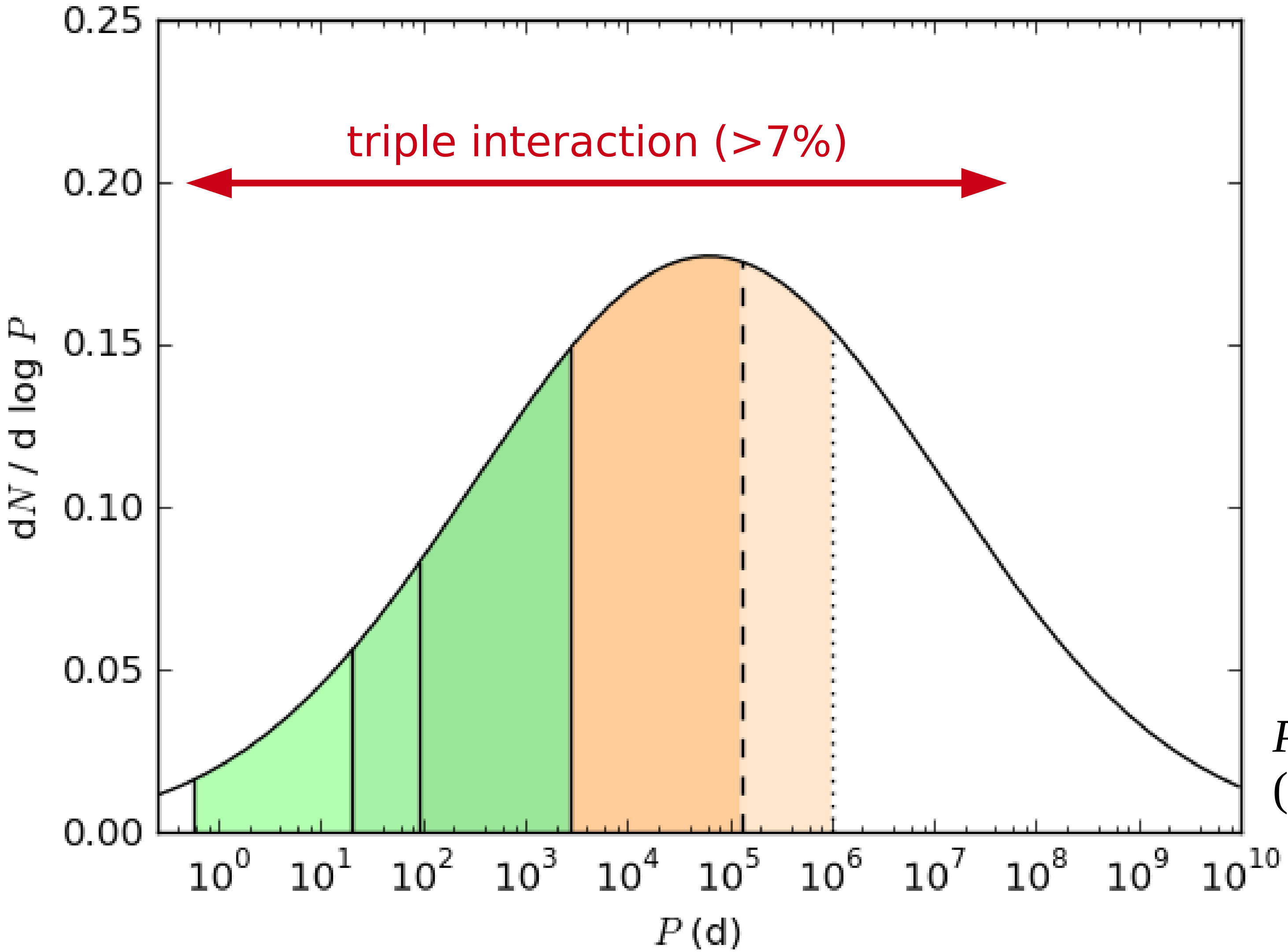
example: Mira AB, a wide symbiotic binary
Karovska+ 2005

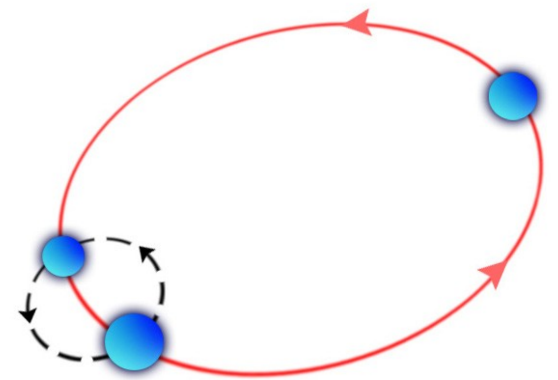


P distribution for G dwarfs (may be flatter for IM stars)

wide binaries

- orbits of all these binaries may also be affected by an outer triple component in suitably inclined orbit (see talk by S. Toonen)





P distribution for G dwarfs
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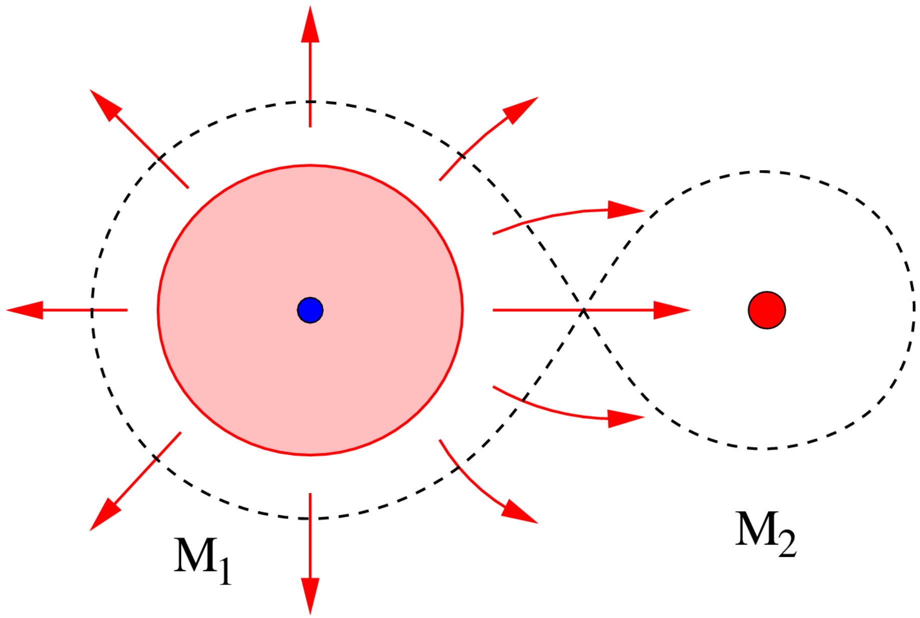
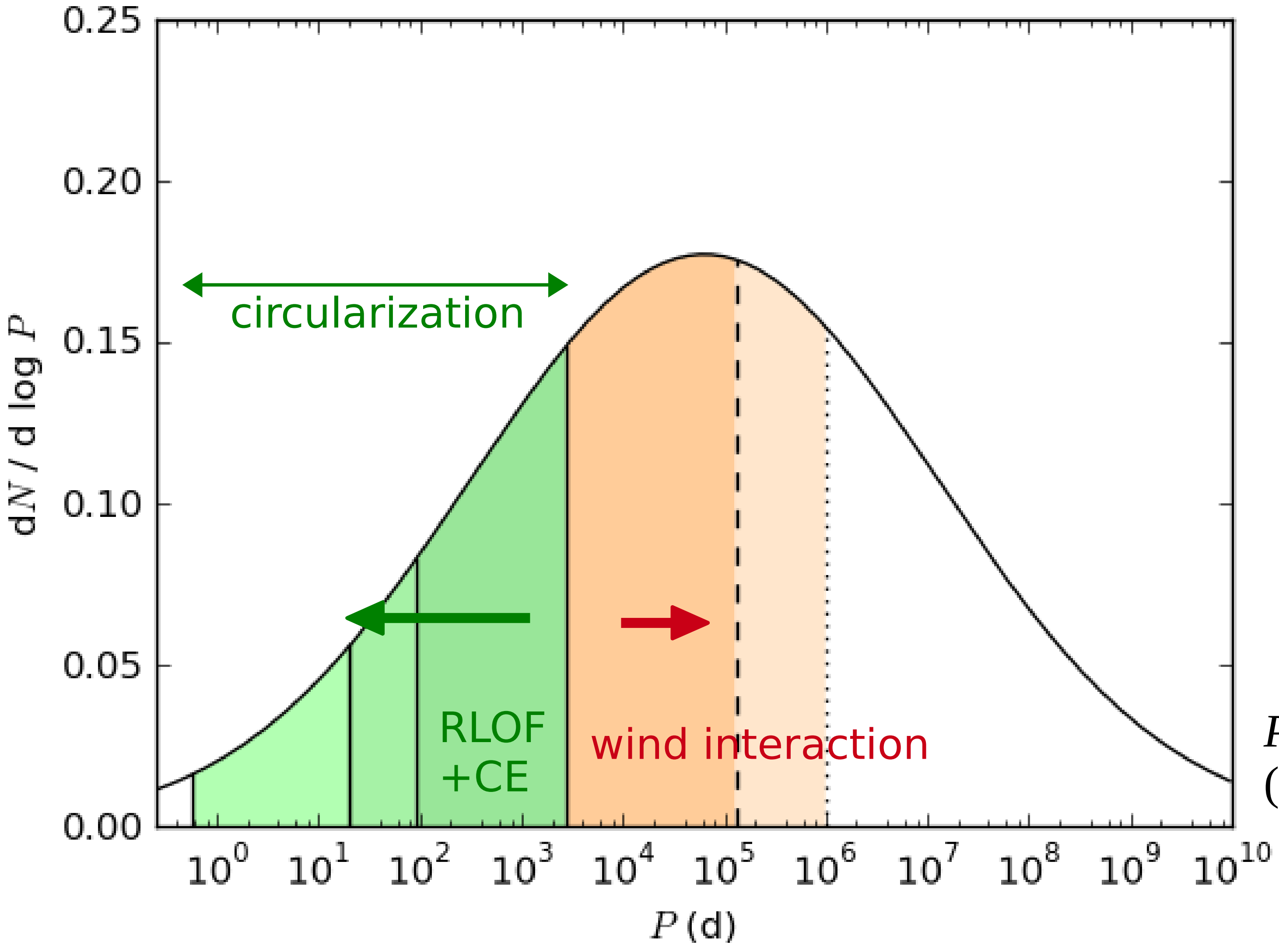
wind interaction and accretion



- stellar wind outflow is modified by companion $\Rightarrow$ may affect shape of circumstellar envelope and produce asymmetric PNe
  e.g. Soker 1998, De Marco 2009
- companion captures part of the stellar wind $\Rightarrow$ wind accretion
- if outflow is roughly isotropic and mostly lost from binary system $\Rightarrow$ expansion of the orbit ($P \propto M_{\rm tot}^{-2}$)

descendants of AGB binaries

- expectations from canonical binary evolution:
  close binaries should tighten and circularize, wide binaries should widen



P distribution for G dwarfs
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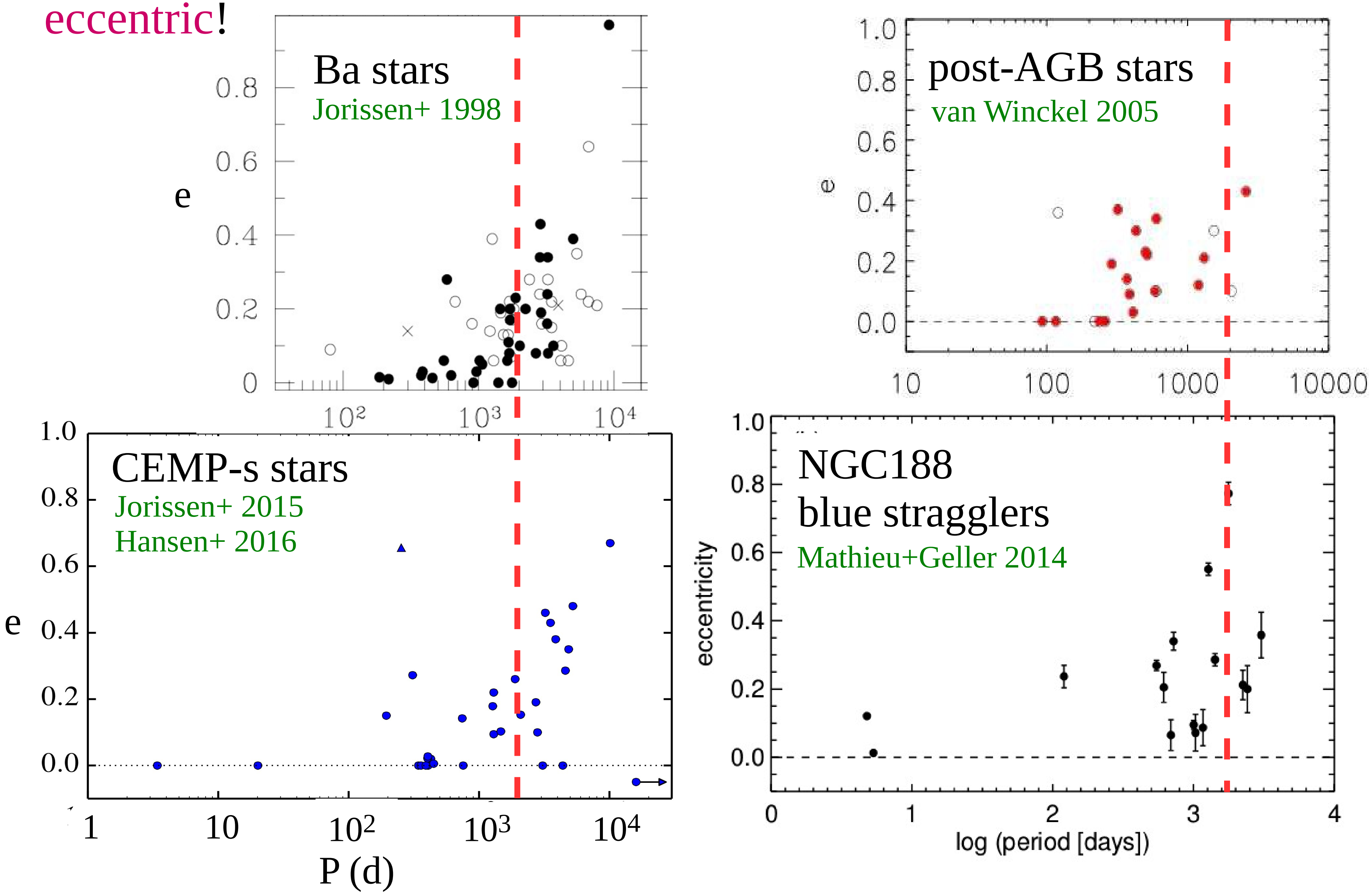
descendants of AGB binaries

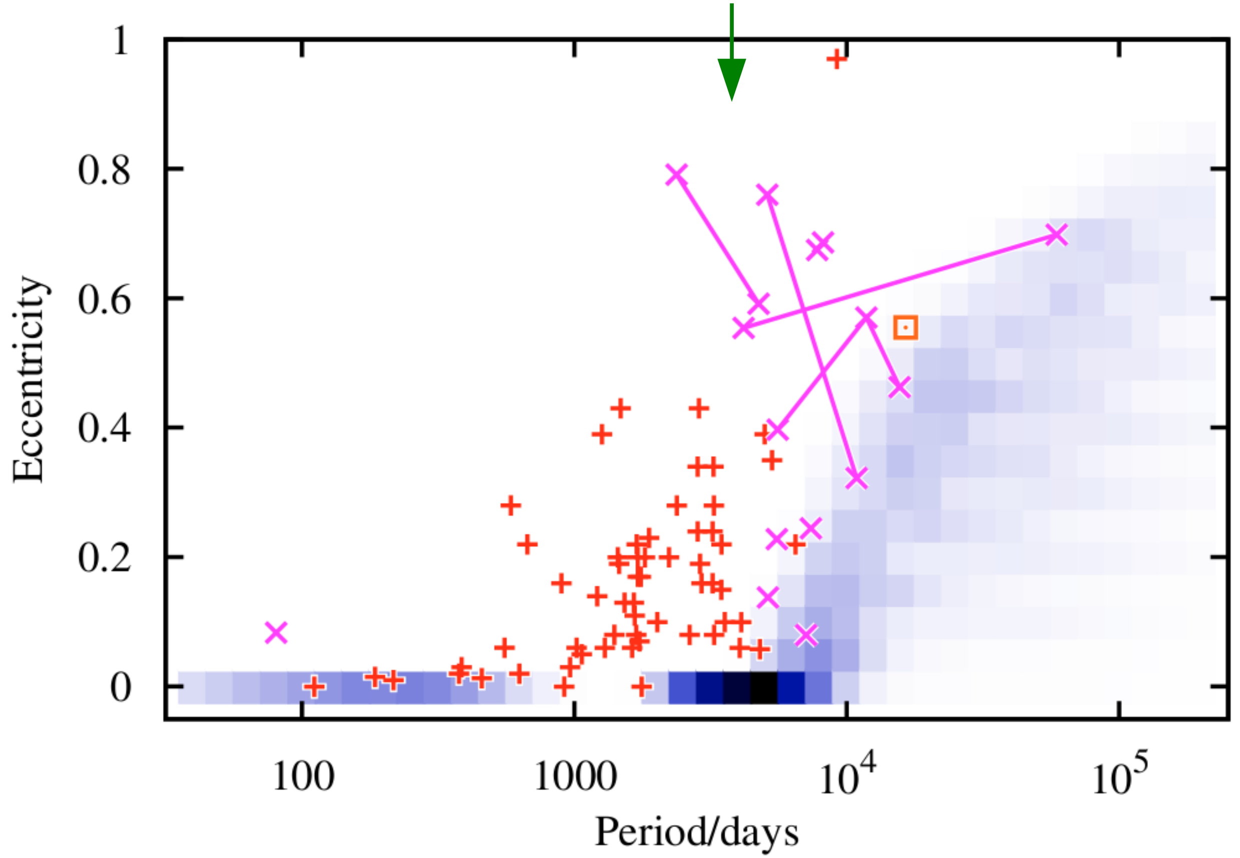
- … but known post-AGB binaires are right in the expected *P* gap, and often eccentric!



barium star orbits

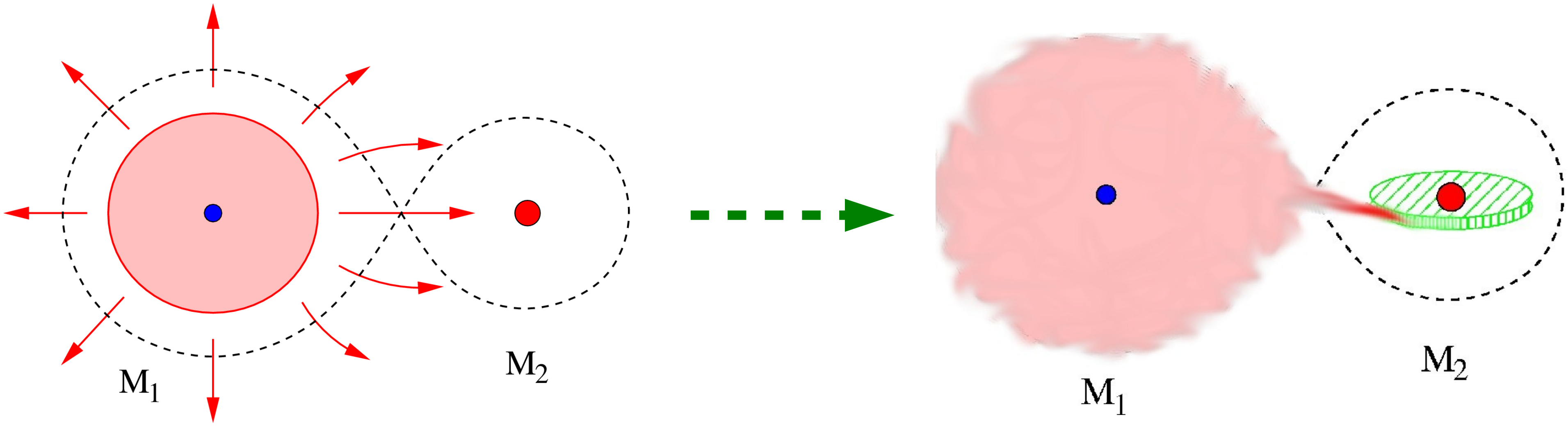
- standard binary evolution models cannot reproduce the *e*-*P* distribution
  - RLOF and tides circularize Ba star orbits with $P < 3000$ d
  - most Ba stars found in *P* gap predicted by binary population synthesis
  - many stars predicted at $P > 10^4$ d, but not observed

Pols+ 2003, Frankowski 2004, **Izzard+ 2010** (also see poster by G.-M. Oomen)



wind interaction revisited

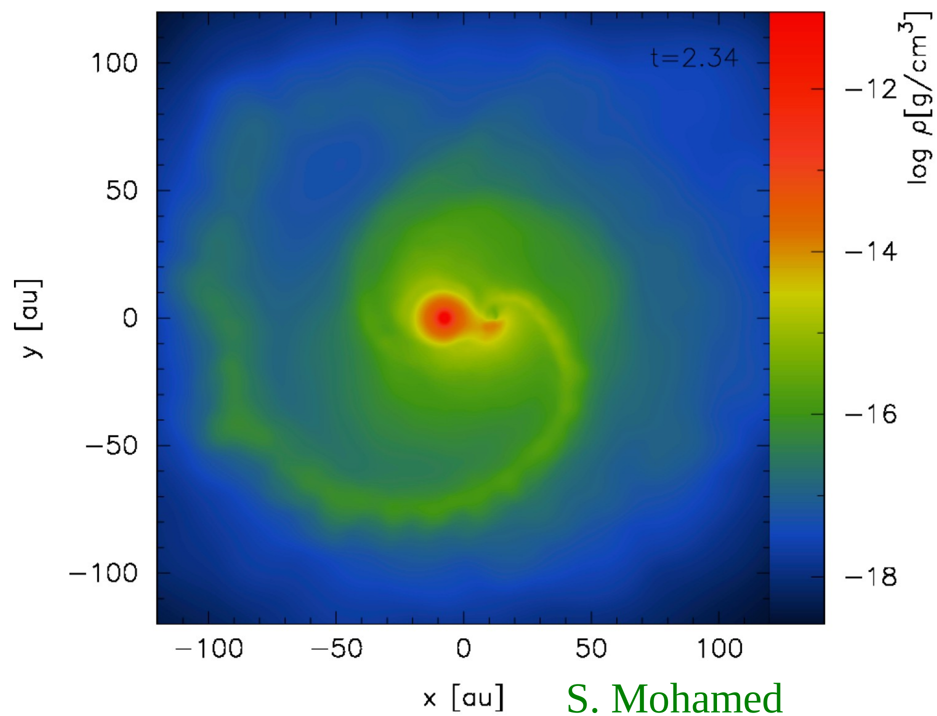
- usually described as Bondi-Hoyle-Lyttleton accretion (isotropic flow, $v_{wind} \gg v_{orb}$) $\Rightarrow$ small accretion efficiencies, orbital expansion
- … but conditions for BHL accretion do not hold for AGB binaries with slow, dense winds
- extended atmospheres, strong radiation pressure $\Rightarrow$ blurs distinction with RLOF
  e.g. Dermine+ 2009
- possibility of wind-RLOF: slow wind fills Roche lobe, highly distorted outflow
  Mohamed+Podsiadlowski 2007



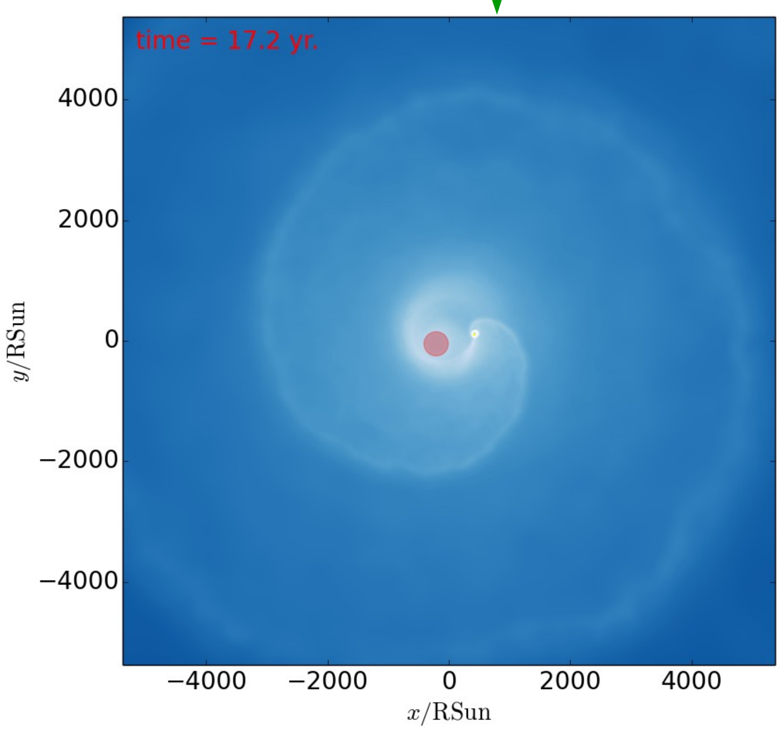
wind mass transfer simulations

- confirmed by hydro simulations of AGB wind mass transfer:
  - larger accretion efficiencies (compared to BHL) e.g. Mohamed 2010
  - formation of circumbinary discs e.g. Chen+ 2017
  - enhanced angular momentum loss (compared to isotropic wind) Jahanara+ 2005, Chen+ 2017, Saladino+ 2017

$\Rightarrow$ possibility of orbital shrinkage (see talk by M. Saladino)

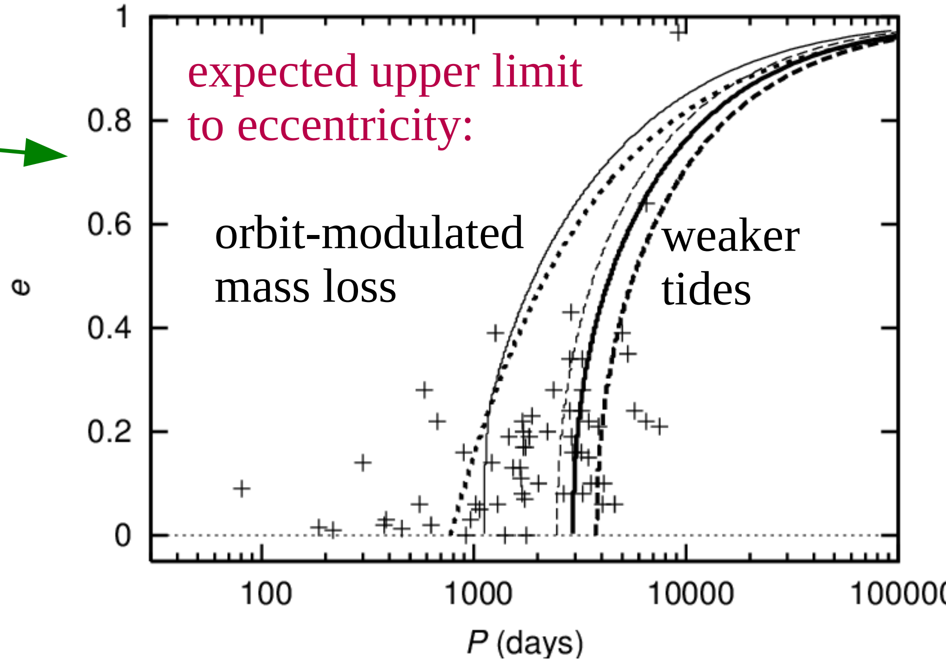


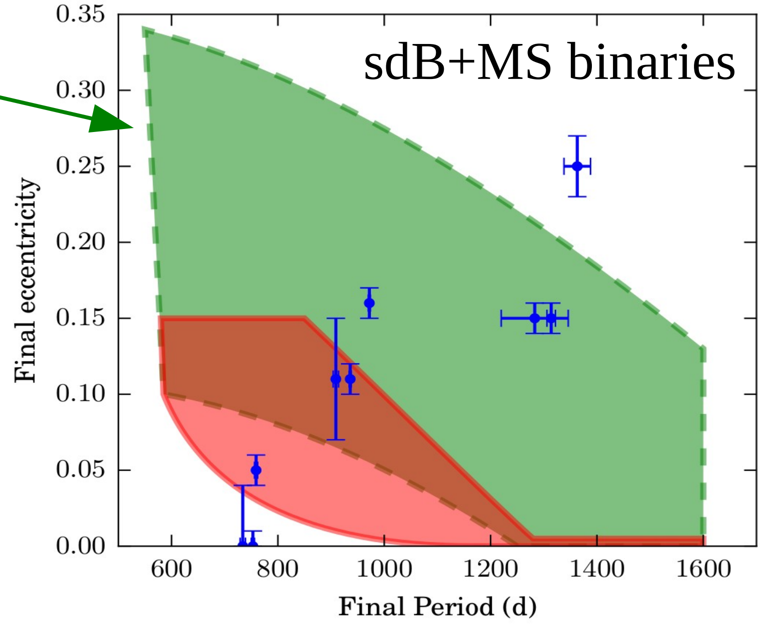
S. Mohamed



possible *e*-pumping mechanisms

- enhanced wind mass loss at periastron
  van Winckel+ 1995, **Bonacic+ 2008**
  (Ba stars; also explains orbit of Sirius)
- RLOF at periastron
  Soker+ 2000, **Vos+ 2015**
- circumbinary disks (formed from ejected envelope)
  as seen in post-AGB-star binaries
  Waelkens+ 1996, Dermine+ 2013, **Vos+ 2015**





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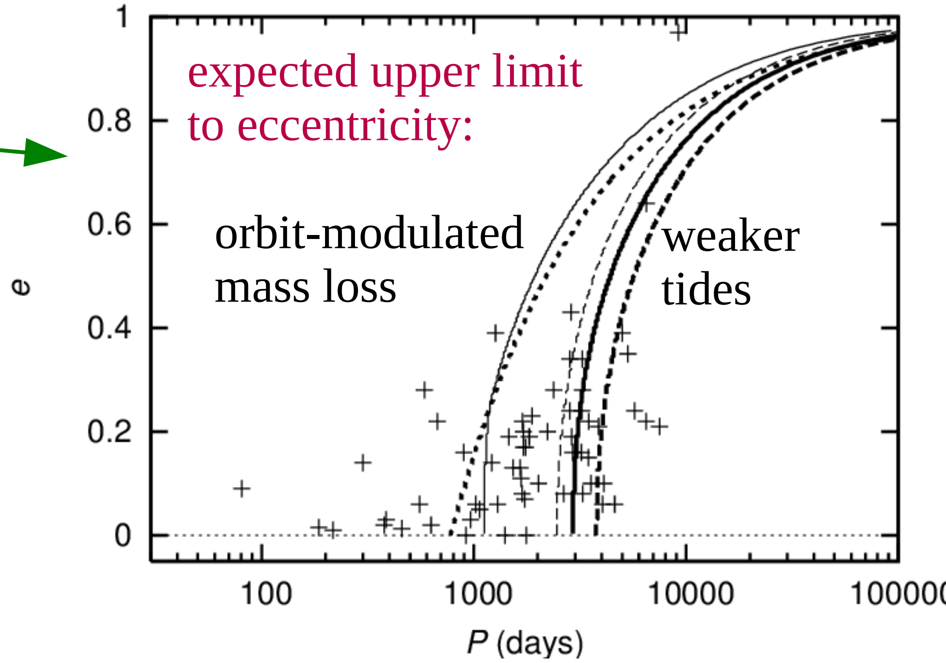
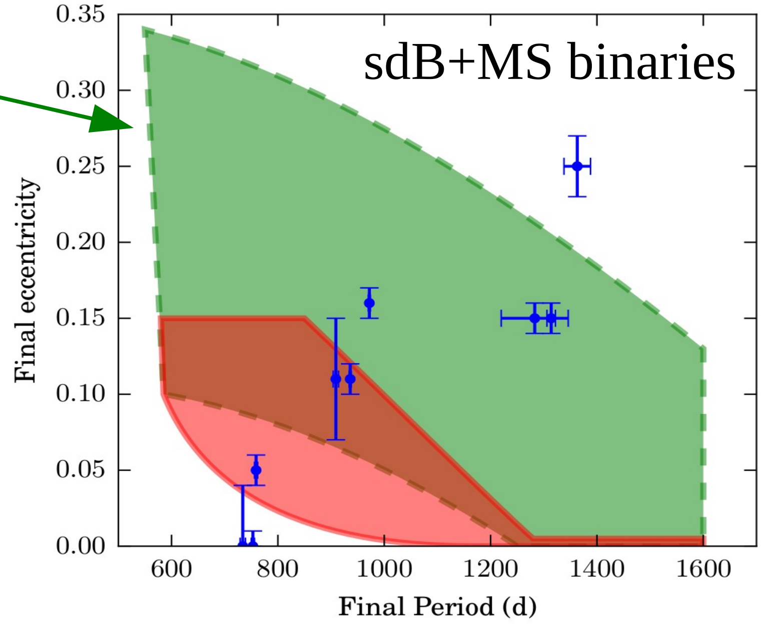
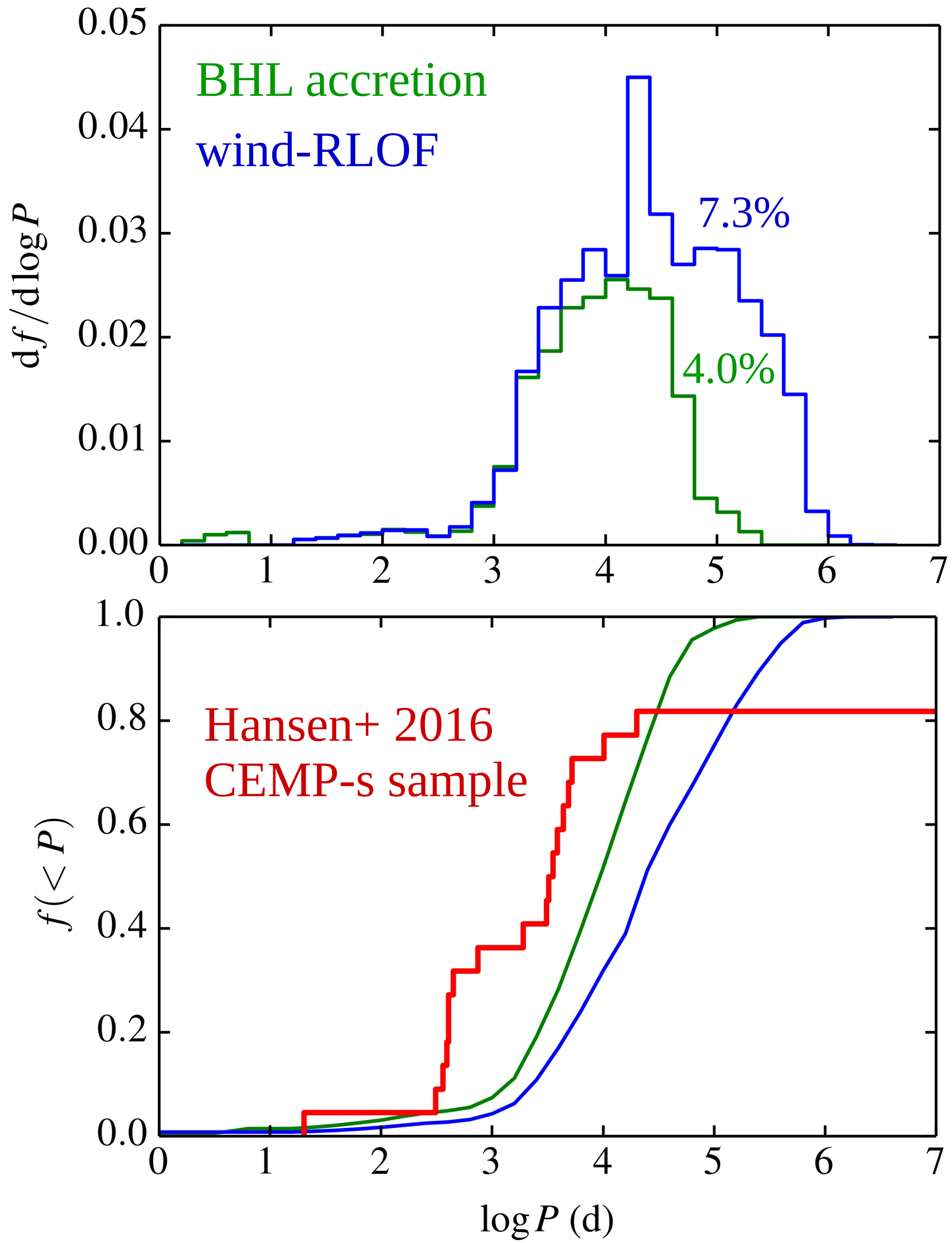
  Waelkens+ 1996, Dermine+ 2013, **Vos+ 2015**
- outer triple companion
  Perets+Kratter 2012
- WD birth "kicks"??
  Izzard+ 2010
- tides-pulsation interaction?





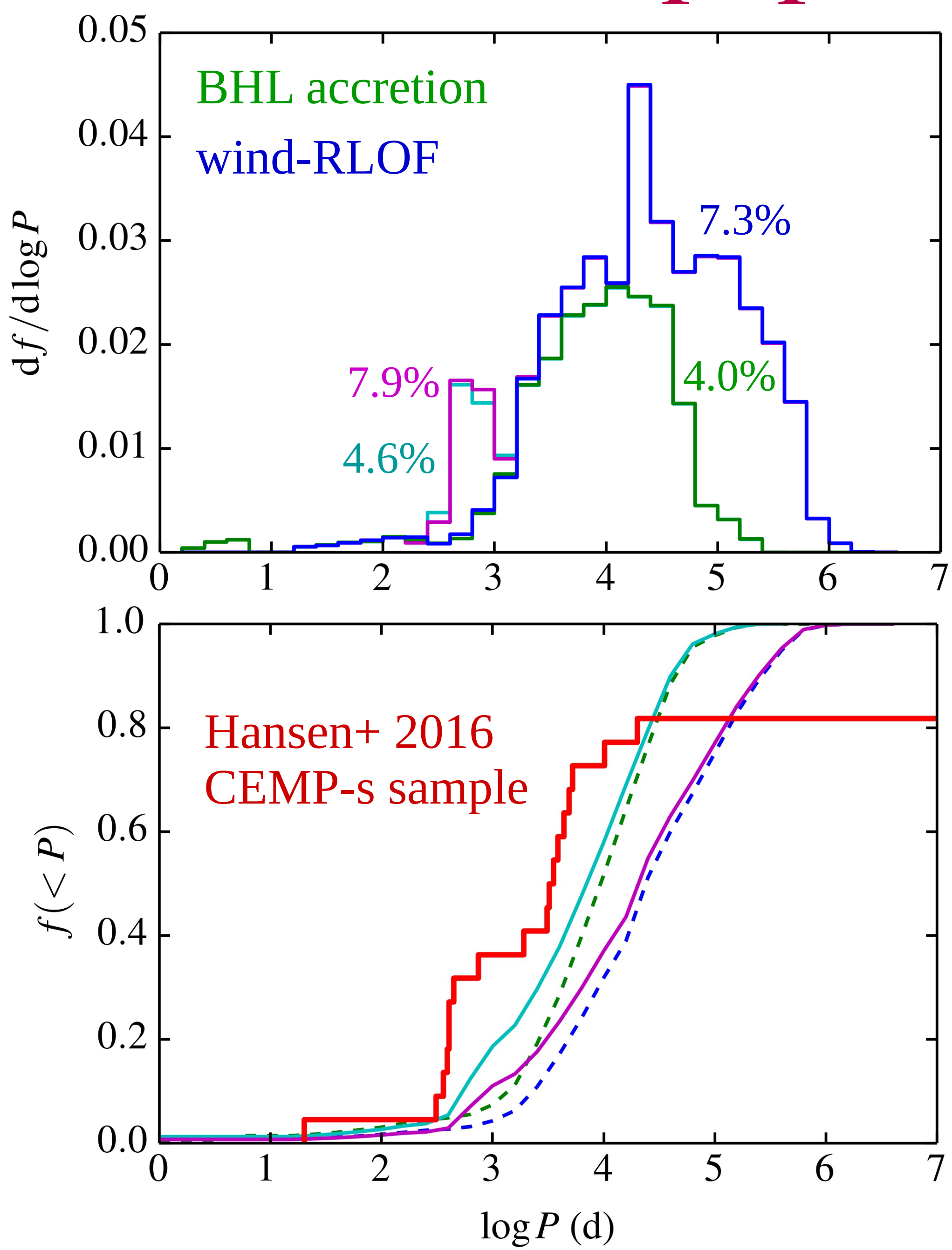
CEMP-s population synthesis



binary population synthesis of CEMP-s stars: Abate+ 2015

- disregard eccentricities
- can reproduce observed CEMP-s fraction of ≈ 6% at [Fe/H] > –2.8 (SDSS/SEGUE, Lee+2014)
- mostly resulting from wind mass transfer, which needs to be very efficient (wind-RLOF)
- requires wide range of initial orbits ($P \sim 10^3 - 10^6$ d)
- isotropic wind assumption ⇒ final periods are too wide

CEMP-s population synthesis



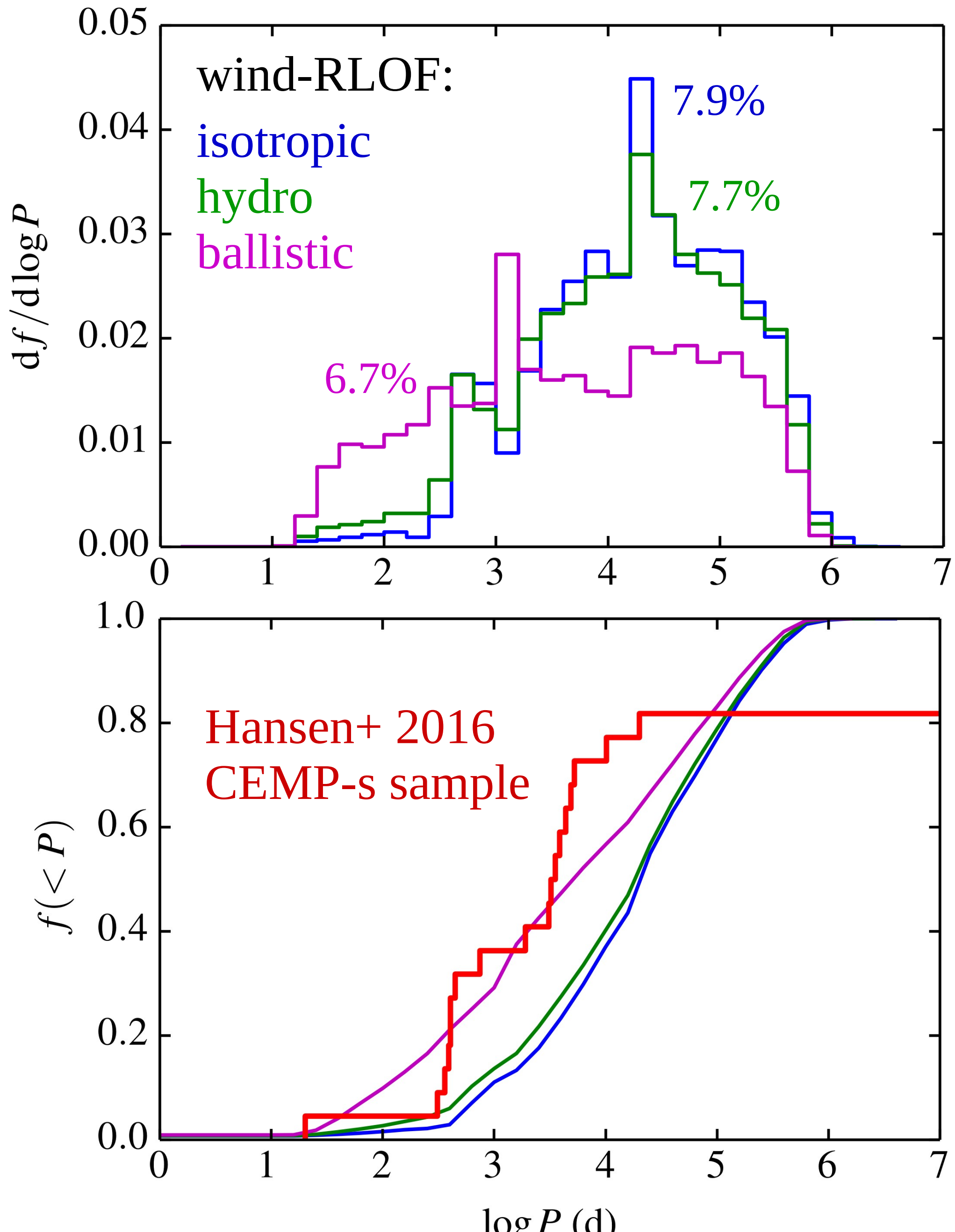
contribution from stable RLOF?

Abate+2017, in prep.

- revised RLOF stability criterion for red giants (Chen+Han 2008)

  ⇒ modest effect on *P* distribution

CEMP-s population synthesis



enhanced angular momentum loss?

Abate+2017, in prep.

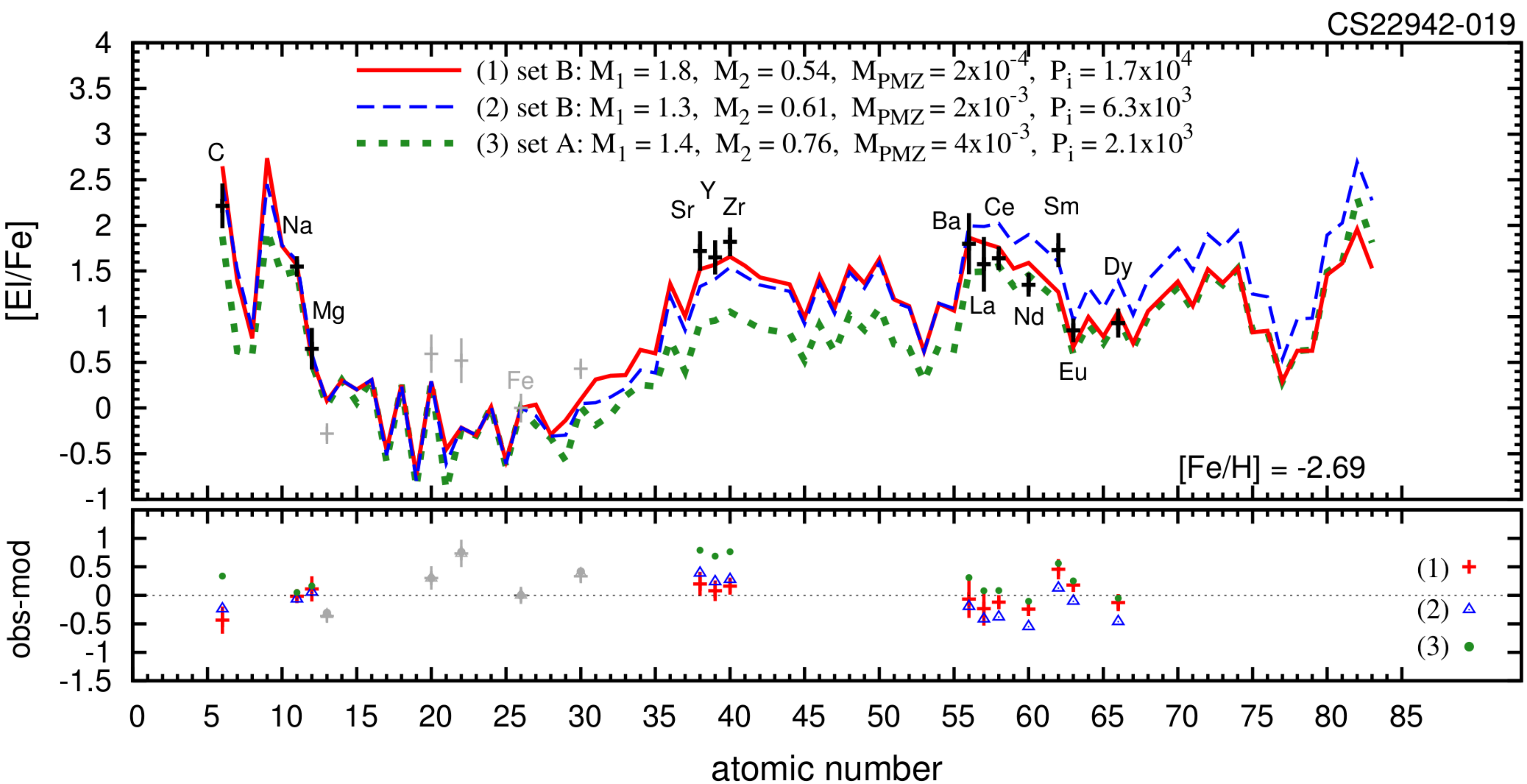
- parameterized AM loss, compared to isotropic wind:
  - hydro models of wind transfer
    Jahanara+2005
  - ballistic "wind" transfer models
    Brookshaw+Tavani 1993

⇒ strong orbital AM loss helps producing close CEMP-s orbits

… but still too many wide binaries ($P > 10^4$ d)

modelling CEMP-s binaries

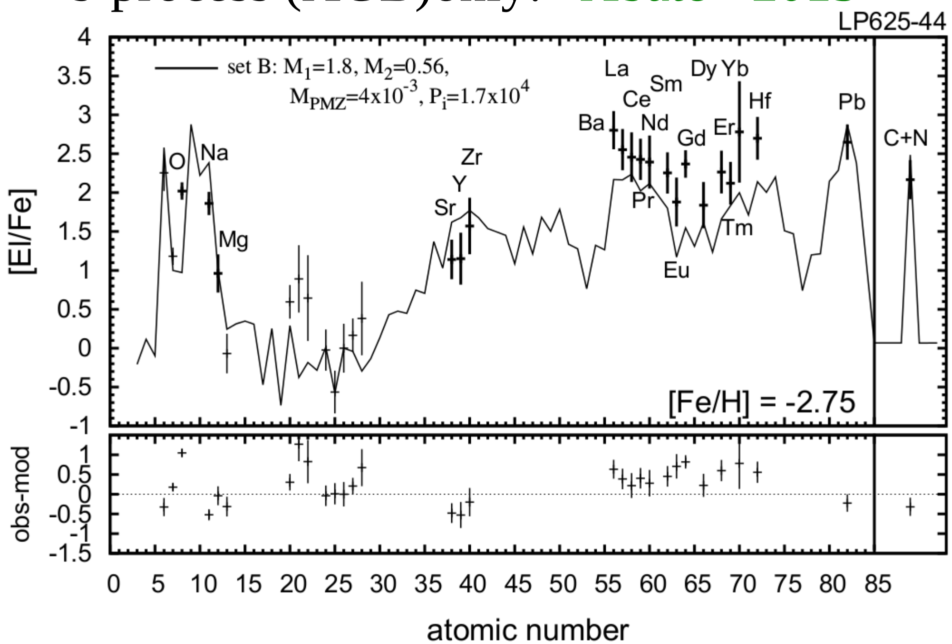
- Abate+ 2015: 14 CEMP-s binaries with known orbits:
  - fit measured abundances, surface gravity and orbital period
  - find best-fitting binary model, using recent AGB nucleosynthesis models
    Karakas+2010, Lugaro+2012
  - generally good fit to CEMP-s abundance patterns



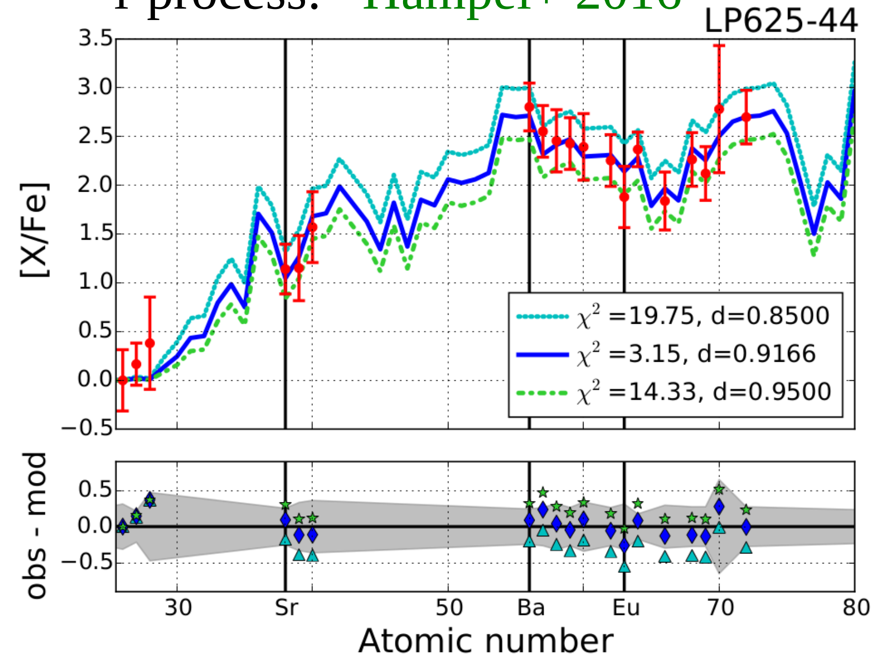
modelling CEMP-r/s binaries

- CEMP-r/s stars: overabundances of typical r-process elements (Eu, etc)
- can not be reproduced by current AGB (s-process) nucleosynthesis
- models invoking separate s- and r-processes component also fail!
  Abate+2016
- a single nucleosynthesis process with intermediate neutron densities (i-process, ~10^{15} cm^{-3}) can produce observed abundance patterns
  Hampel+ 2016

s-process (AGB)only: Abate+ 2015

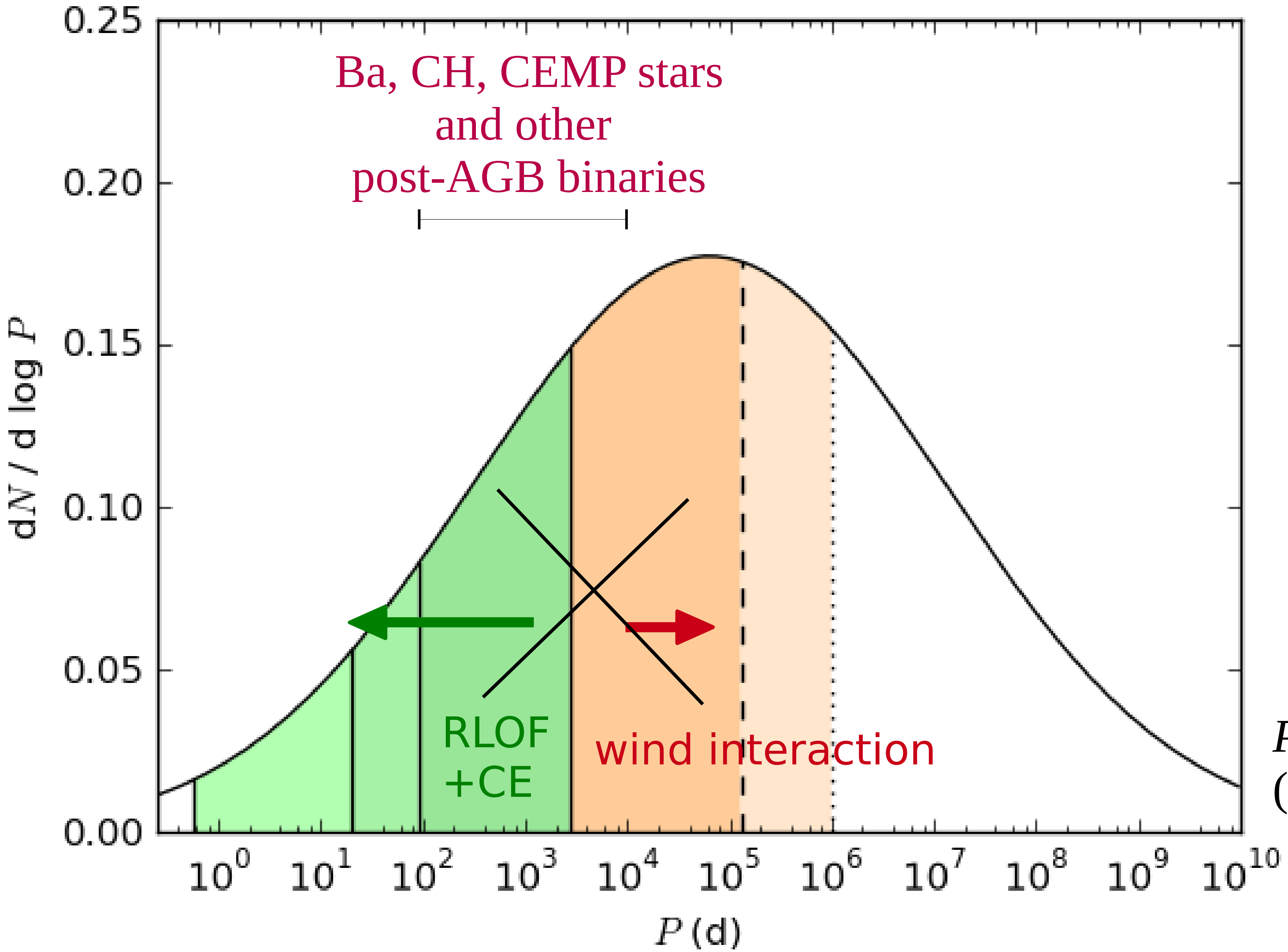


i-process: Hampel+ 2016



descendants of AGB binaries

- observational evidence: efficient mass transfer + a continuity of orbital properties across close/wide-binary boundary



P distribution for G dwarfs (may be flatter for IM stars)

descendants of AGB binaries

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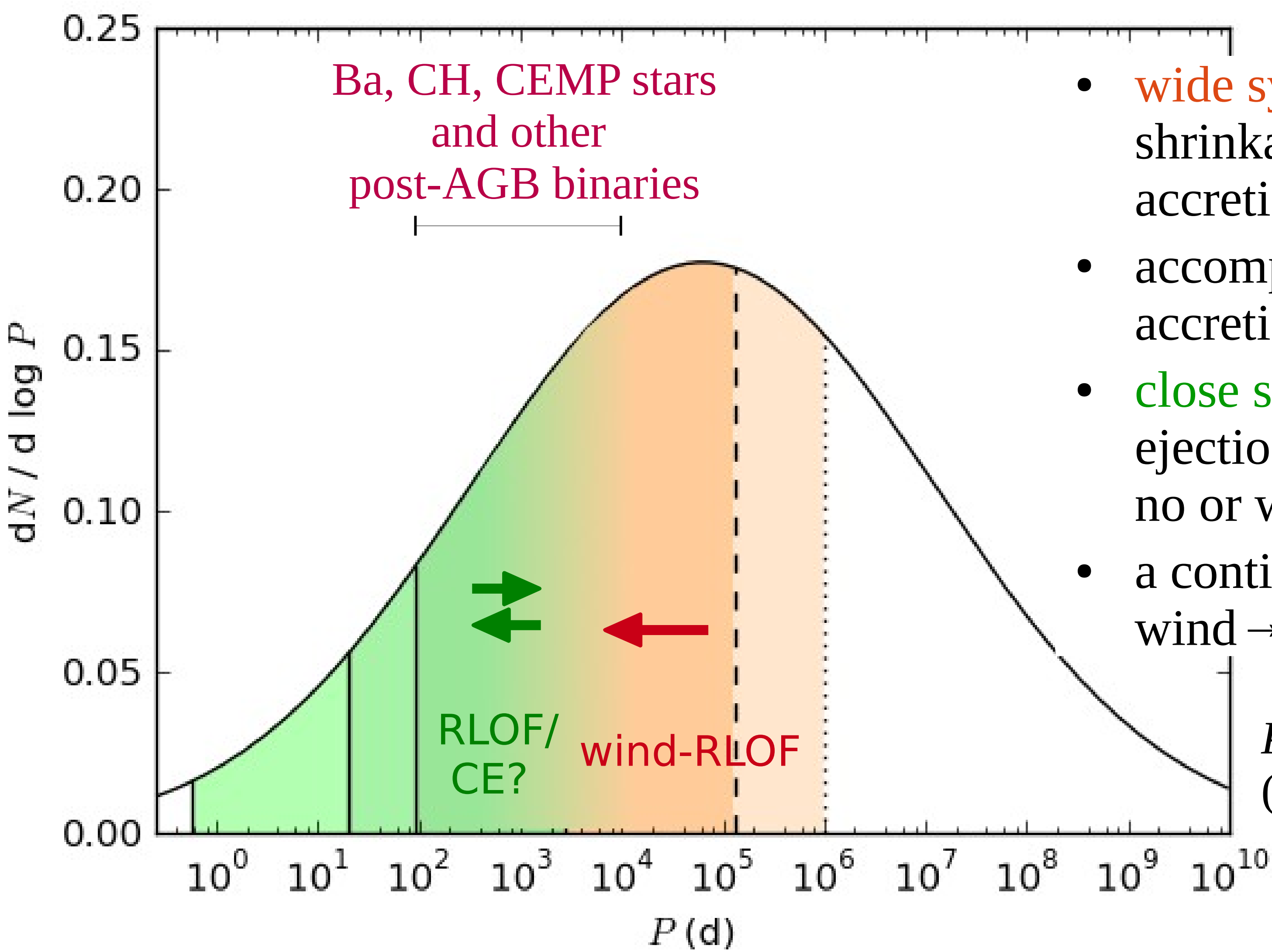

- wide systems: strong orbital shrinkage during wind accretion
- accompanied by efficient accretion (wind-RLOF)
- close systems: efficient “CE” ejection or stable RLOF, no or weak orbital shrinkage
- a continuous process? wind → RLOF → CE

P distribution for G dwarfs (may be flatter for IM stars)

summary

- >50% of low- and intermediate-mass binaries undergo their main interaction during the AGB phase
  - provides interesting tests of both AGB nucleosynthesis and binary interaction processes
- combination of wind interaction, RLOF and common envelopes: far from being well understood
- evidence from Ba, CH and CEMP stars, as well as many other post-AGB binaries:
  - efficient wind accretion (wind-RLOF) with strong orbital shrinkage
  - stable RLOF or CE ejection *without* strong orbital shrinkage
  - pumping of eccentricity during interaction
  - continuity of properties across types of interaction