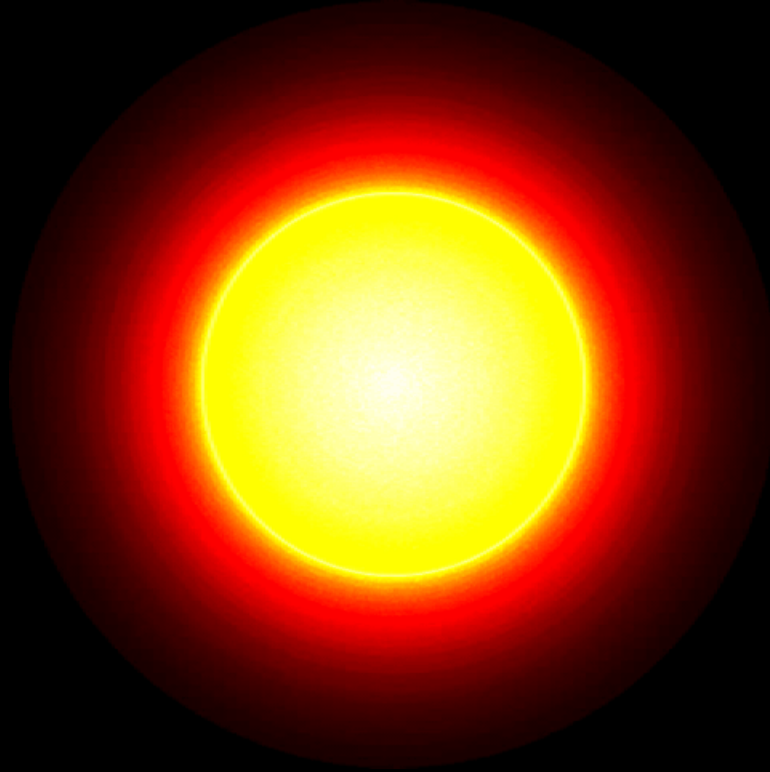


Binary and Multiple Stars
in the Era of Big Sky Surveys
2024 September 13
Litomyšl

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Be stars as post-mass-transfer binaries: *interferometric detections & orbits of stripped companions*

Thomas Rivinius
Dietrich Baade
Doug Gies
Antoine Mérand
Alex Carciofi



Credit: Faes & Carciofi

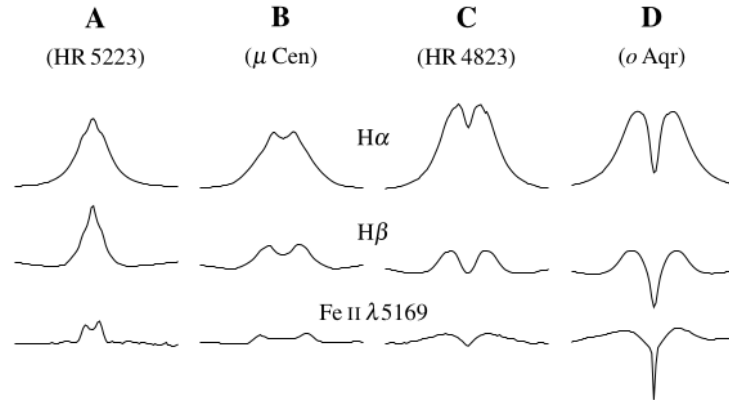
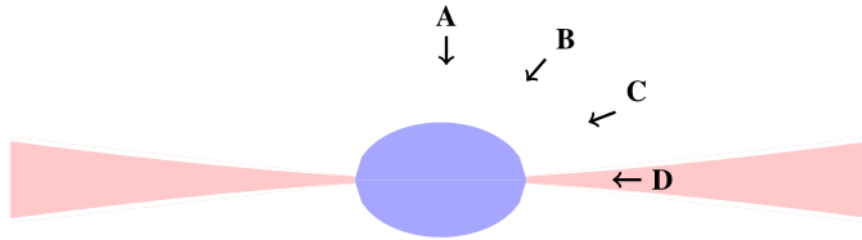


Pleione, Alkyone, Electra, Merope

Secchi 1866
 Struve 1931
 Underhill & Doazan 1982
 Slettebak 1988
 Porter & Rivinius 2003
 Reig+ 2011
 Rivinius+ 2013
 Smith+ 2016

Classical Be stars

Rapidly rotating and non-radially pulsating main-sequence **B-type** stars with ionized, gaseous **decretion disks** in Keplerian rotation



Struve 1931,
 Rivinius+ 2013

Formation:

B-type star acquires excess angular momentum \rightarrow
 Spins up and forms a viscous decretion disk to shed it

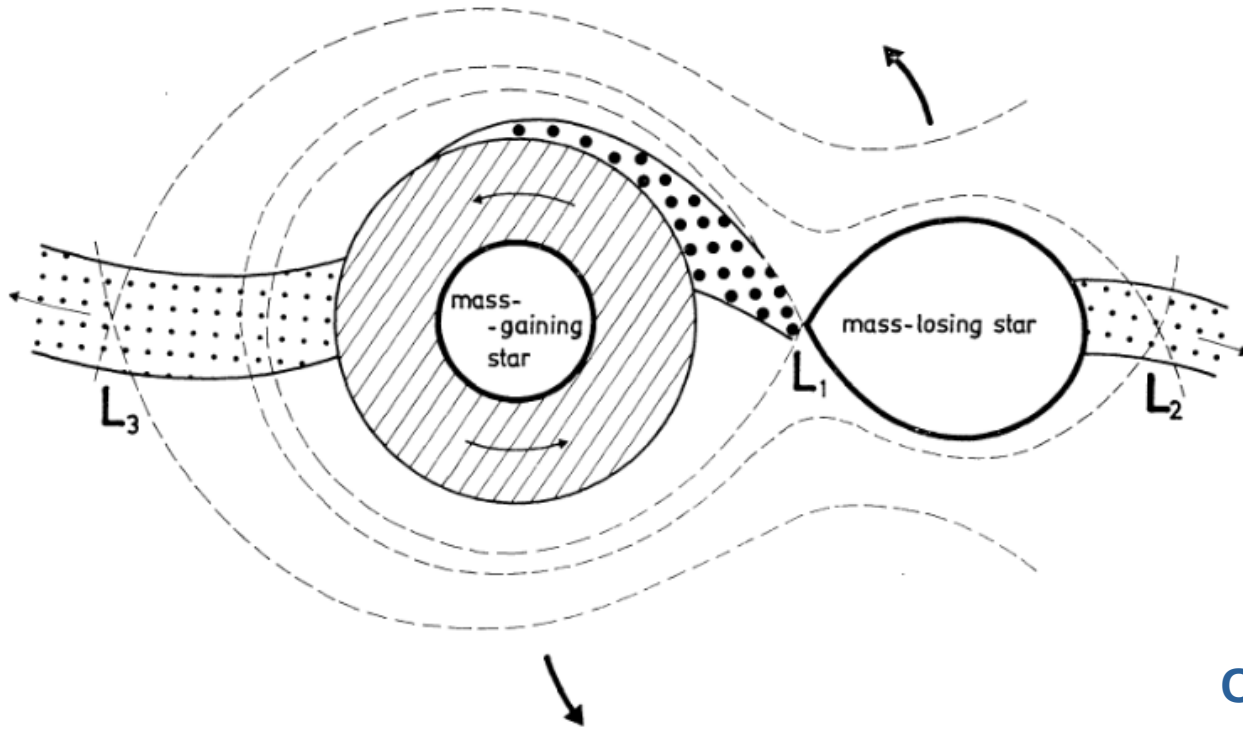
Excess angular momentum:

Single-star vs. **interacting binary evolution**

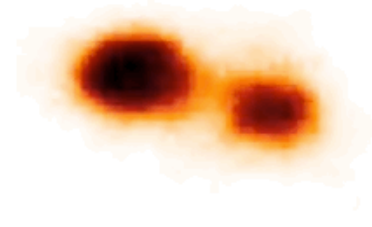
Close Be + MS binaries should
 be common but **observed**
binary fraction low

Be stars have faint, stripped companions
Also runaways, post-mergers (?)

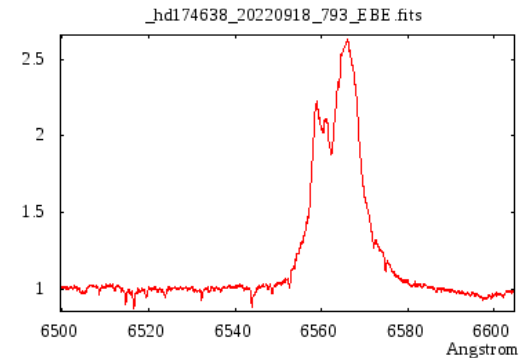
Be stars as Roche-lobe overflow mass-transferring binaries?



Kříž & Harmanec (1975)



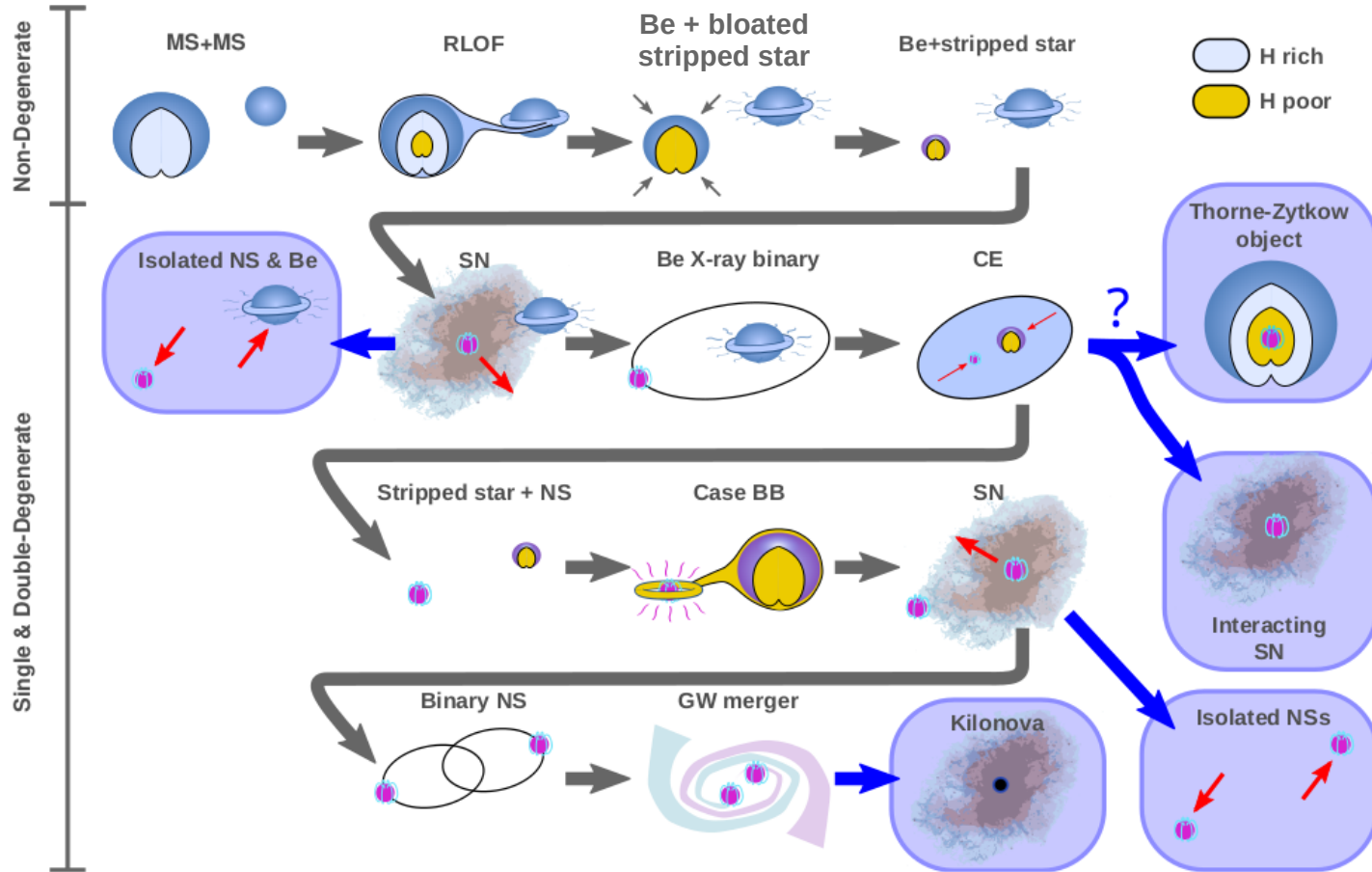
β Lyr CHARA H band image (Zhao+ 2008)



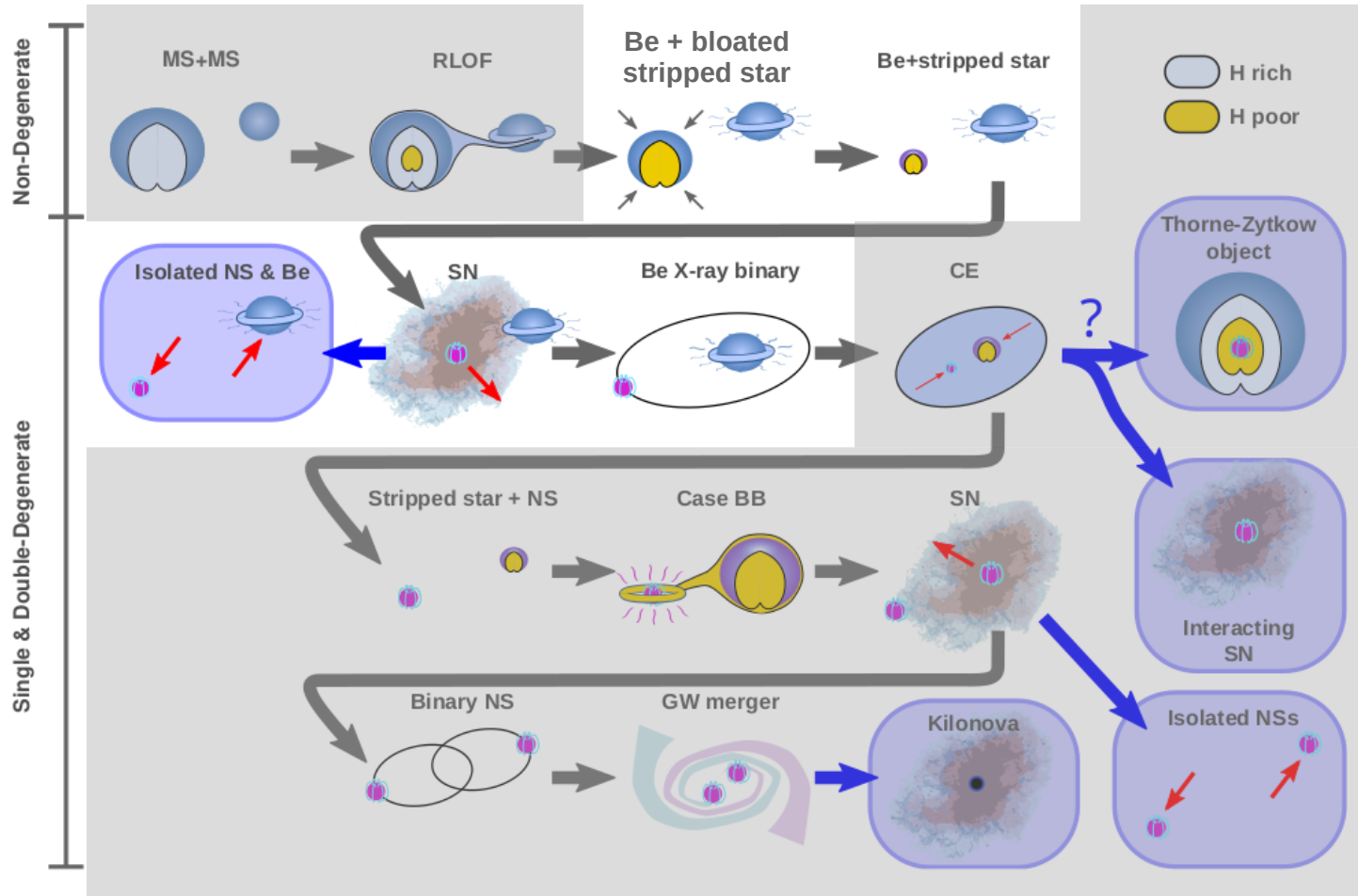
Classical Be (CBe)

- No Roche-lobe filling companions
- Decretion rather than accretion disks

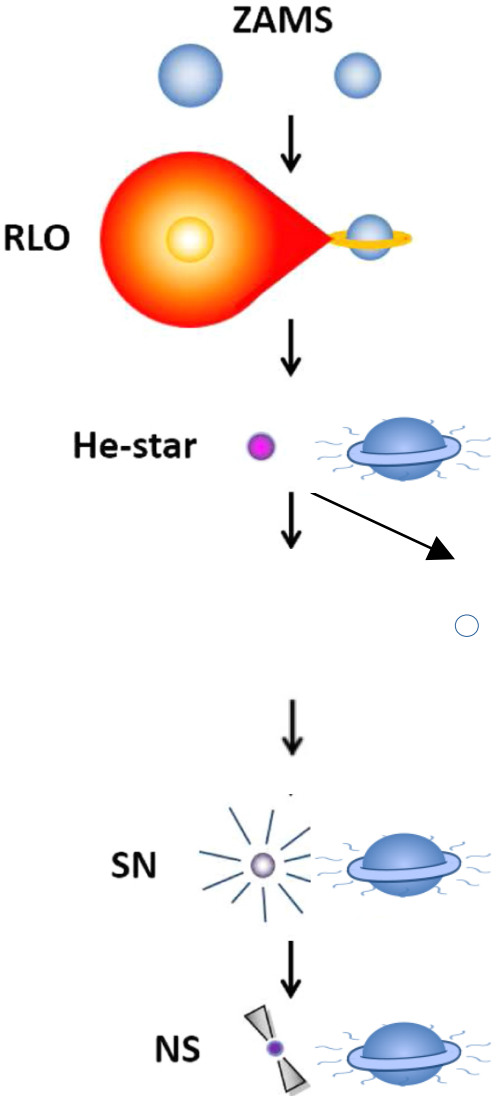
Massive (early-type) CBe stars



Massive (early-type) CBe stars



Formation of classical Be stars



CBe + bloated pre-sdOB (~1Myr)

CBe + sdOB

CBe + WD

CBe + NS

Several now confirmed

Frost+ 2022
Rivinius, Klement+ (submitted)

~20 confirmed in FUV
Gies+ 1998,
Wang+ 2018, 2021, 2023

Be with γ Cas-like X-rays?
Tsujimoto+ 2018, 2023,
Gies+ 2023 + *Spectroscopic companions around late-type Be stars?*
cf. Gies+ 2020

HMXRB
~150 Be X-ray binaries in MW, SMC, LMC
Rappaport & van den Heuvel 1982
Reig+ 2011

Runaway Be stars
~13% of Be stars?
Berger & Gies 2001
Boubert & Evans 2018

should be common

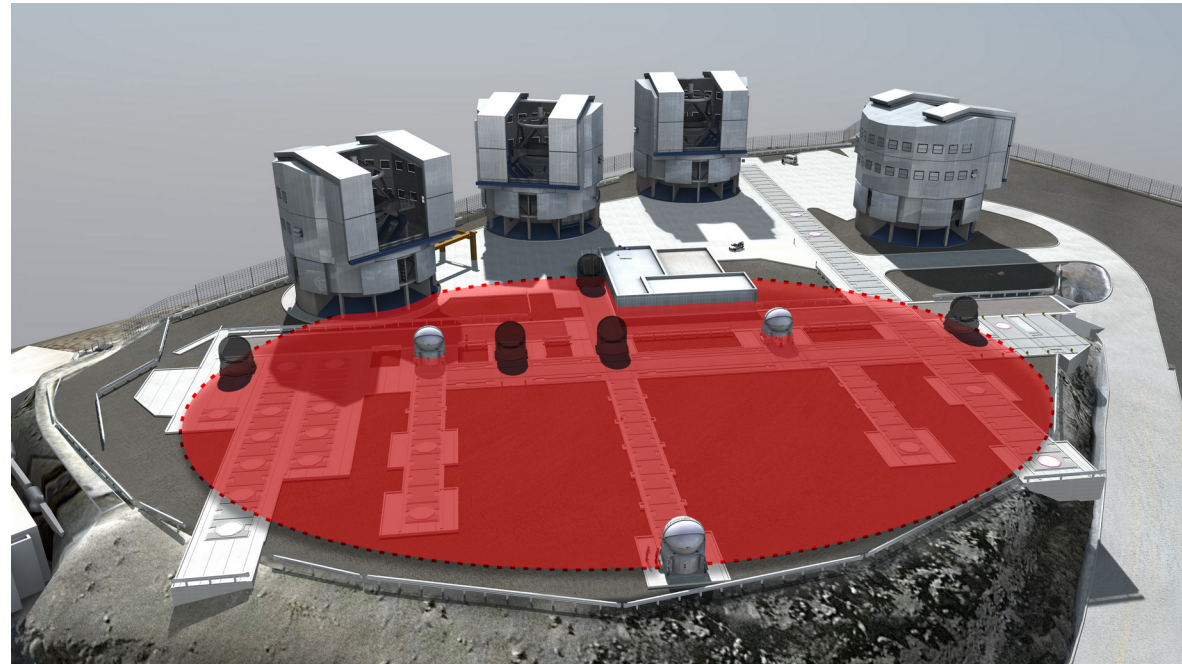
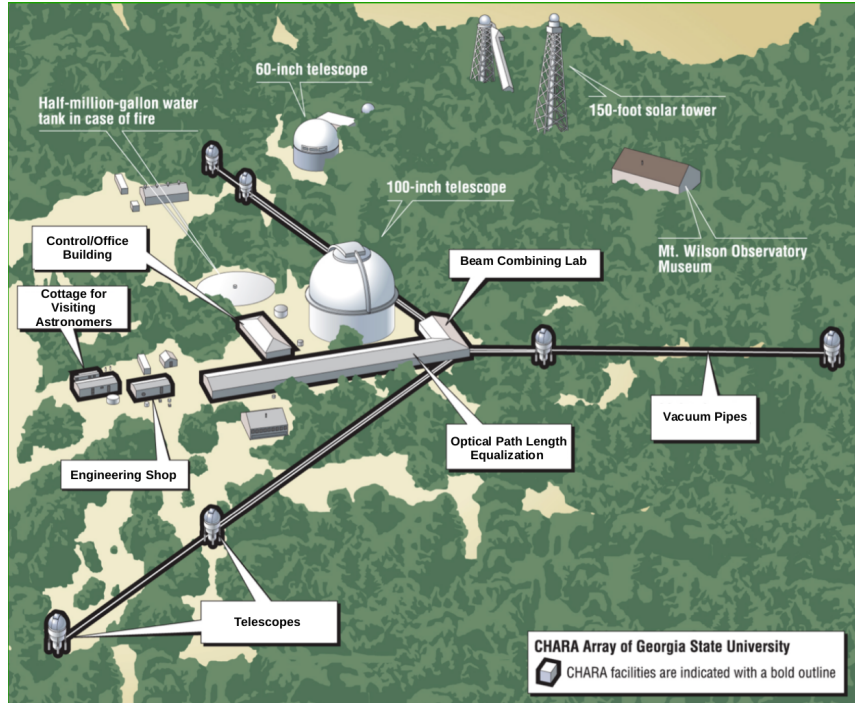
should be common

rare

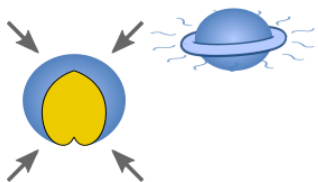
adapted from Tauris+ 2017

CHARA & VLTI near-IR interferometric program on the binarity of Be stars

- ~70 confirmed/candidate Be binaries observed
- at least **16 detections** of close companions (9 published) – faintest detection at $\Delta H = 5.3$ mag ($f = 0.76\%$)
- at least **14 SB1 + astrometric orbital solutions** (7 published)
- at least **12 dynamical masses for both components** (7 published) – mostly limited by RVs (and distances)

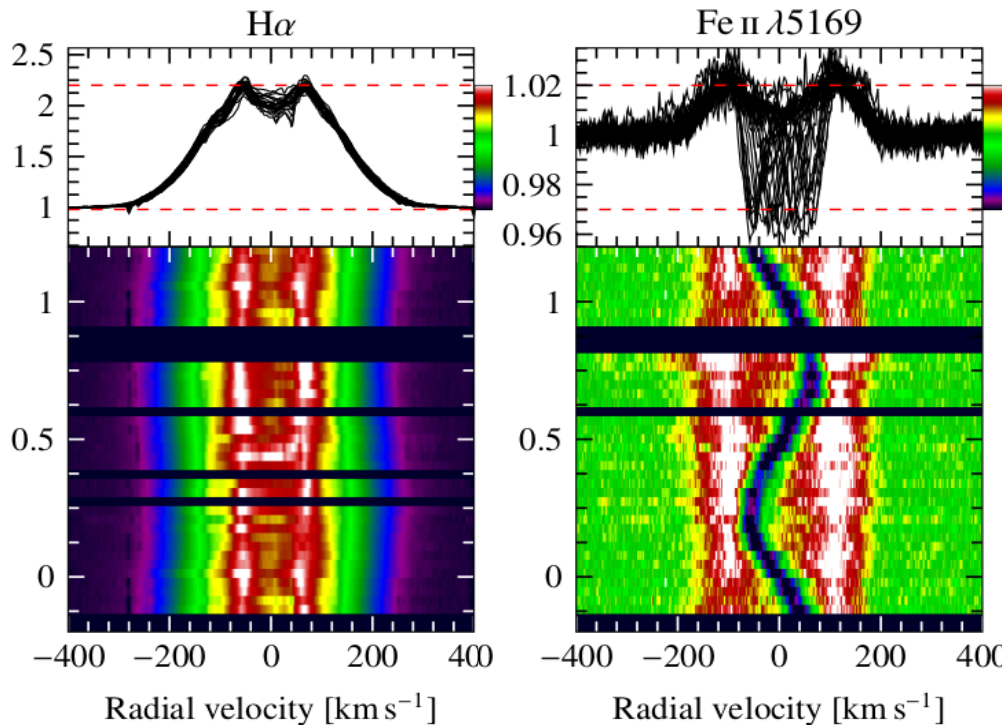


Be + bloated
stripped star



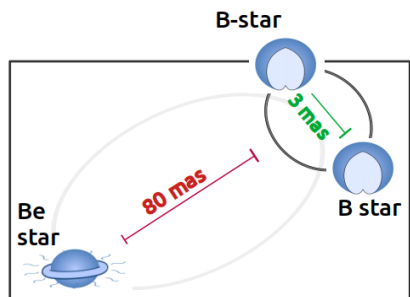
Be stars with bloated pre-sd companions

Extreme mass ratio but similar brightness



HR 6819 ($V = 5.4$)

$P = 40.3$ d

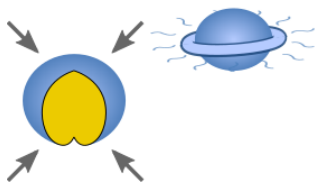


Rivinius+ 2020

Similar signature as Be stars in hierarchical triples such as ν Gem (Klement+ 2021)

Easily distinguished by interferometry

Be + bloated
stripped star

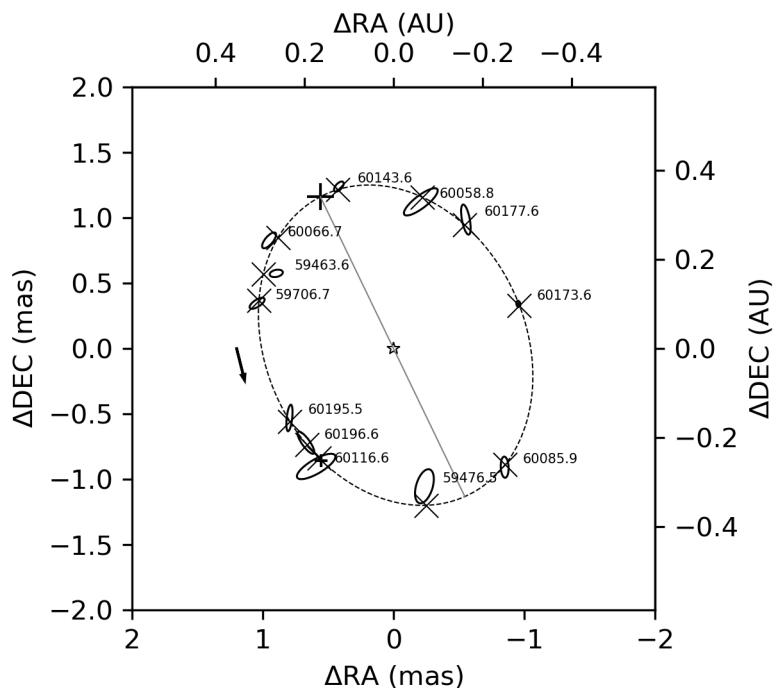


Be stars with bloated pre-sd companions

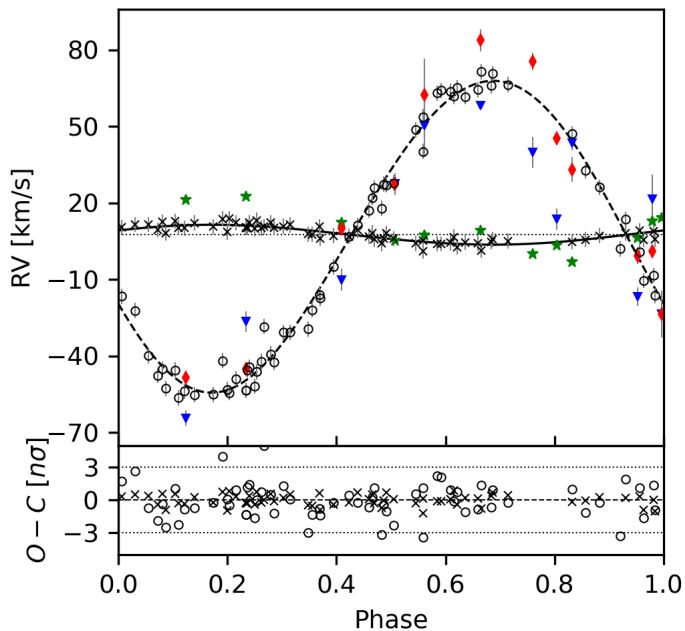
Extreme mass ratio but similar brightness

HR 6819 ($V = 5.4$)

Astrometric orbit from VLTI/GRAVITY



RV curve from FEROS & GRAVITY (colored)



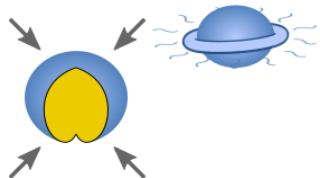
$P = 40.3$ d

First dynamical masses

- Gaia parallax biased by binary motion
- $M_{\text{Be}} = 4.2 \pm 0.5 M_{\odot}$
- $M_{\text{pre-sd}} = 0.271 \pm 0.064 M_{\odot}$
- $d = 294 \pm 14$ pc

Be + bloated stripped star

Be stars with bloated pre-sd companions



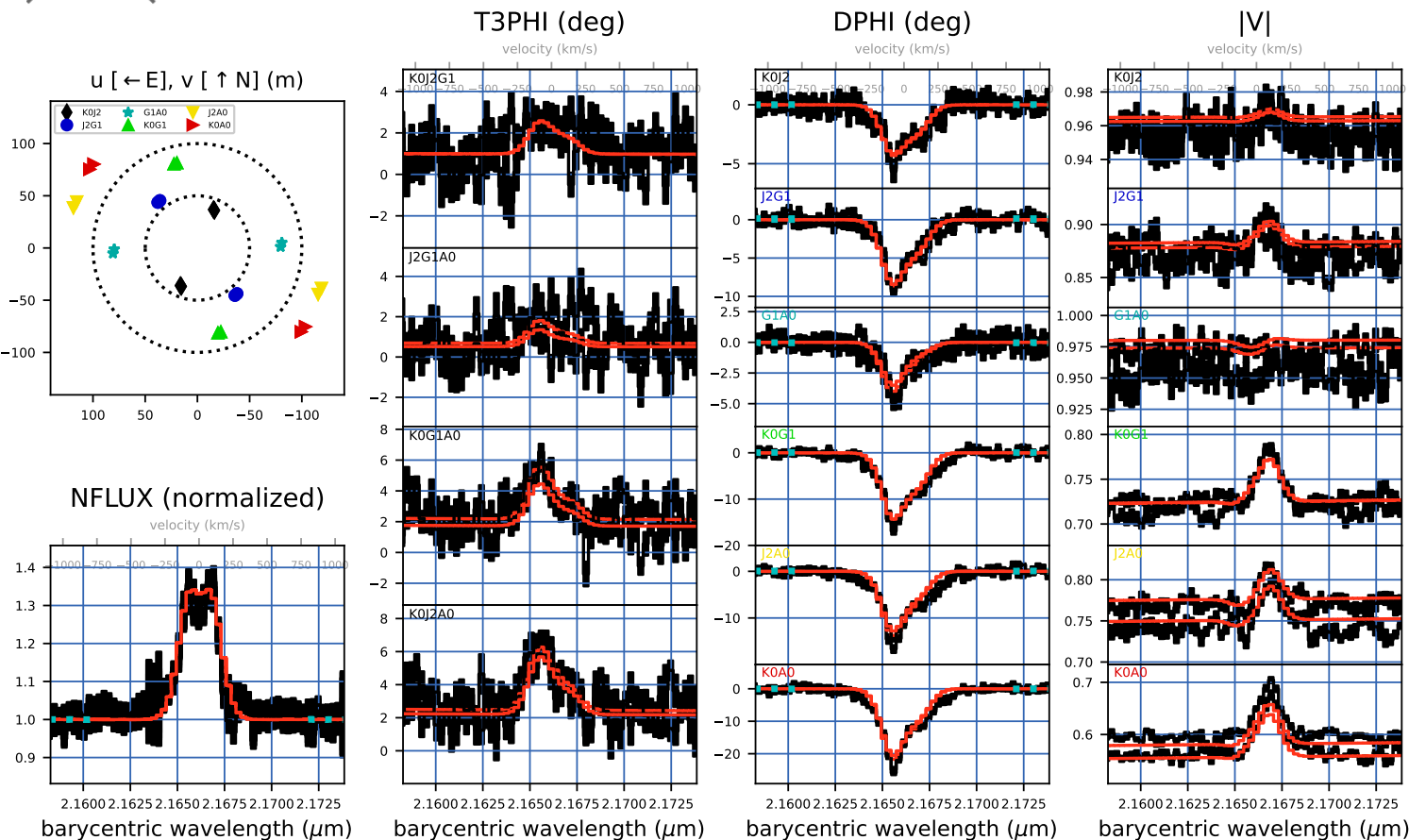
One of 12 GRAVITY snapshots – modeled by two stars (UD) + Keplerian disk

HR 6819 ($V = 5.4$)

$P = 40.3$ d

First dynamical masses

- Gaia parallax biased by binary motion
- $M_{\text{Be}} = 4.2 \pm 0.5 M_{\odot}$
- $M_{\text{pre-sd}} = 0.271 \pm 0.064 M_{\odot}$
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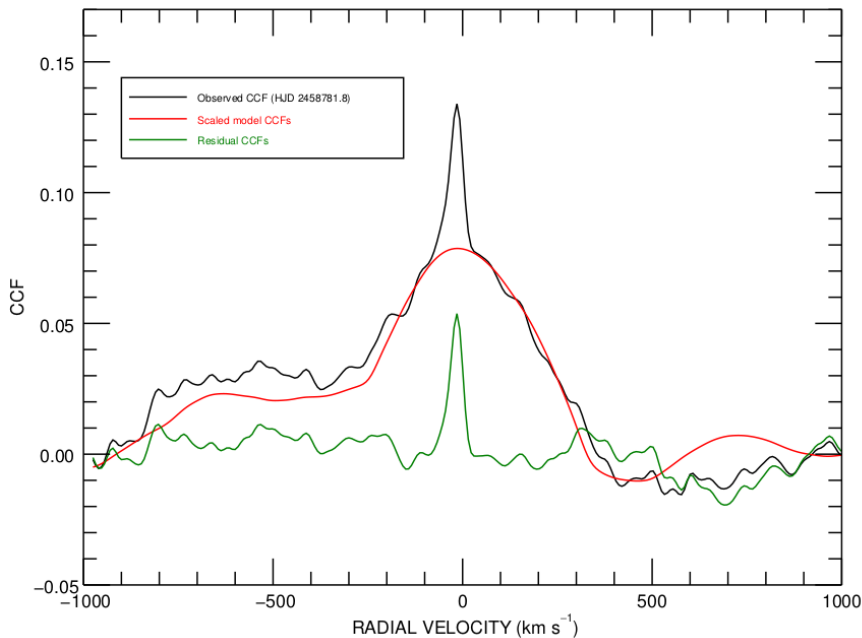


Be stars with sdOB companions

High mass and luminosity ratio but companion hotter than the Be star

sdOB detection in FUV spectra

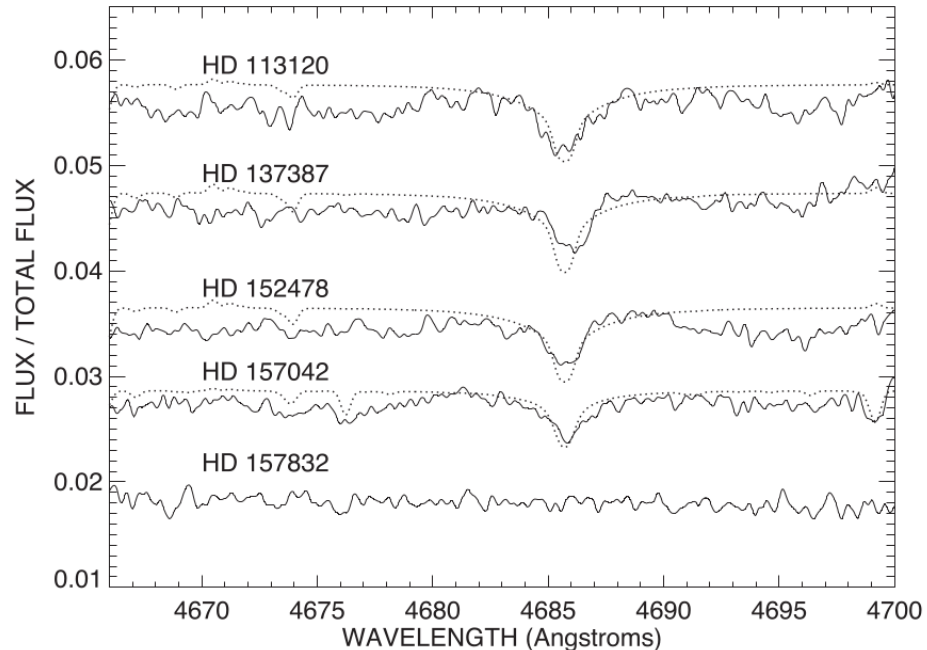
~20 confirmed & strong candidate Be+sdOB binaries



Wang+ 2021, HST

sdO Detection in optical spectra

He II 4686 profiles detected in cophased spectra



Wang+ 2023, APO/ARCES

Detectable by interferometry if

- ang. separation > 0.5 mas
- near-IR flux ratio > 0.5%

Be stars with sdOB companions

High mass and luminosity ratio but companion hotter than the Be star

κ Dra ($V = 3.9$)

$P = 61.5$ d

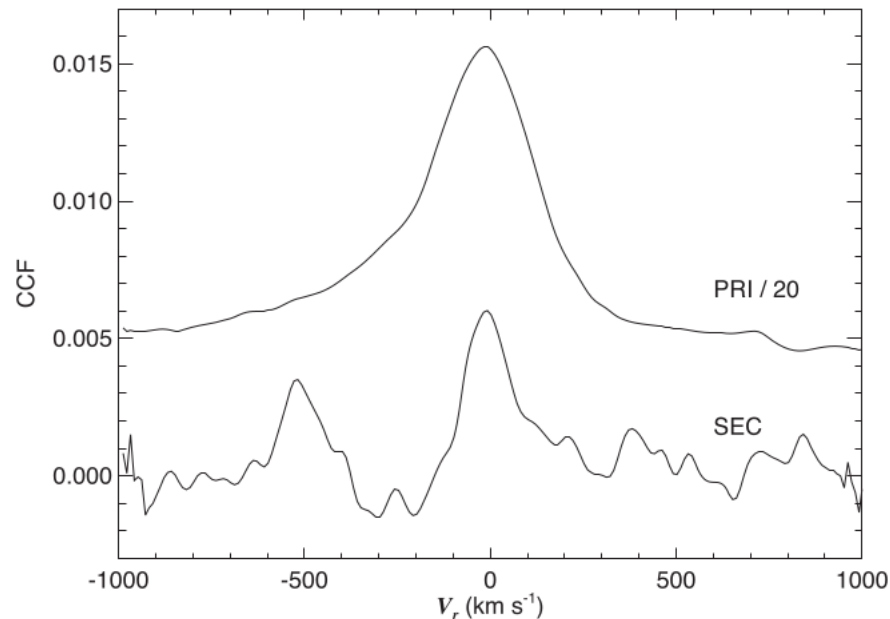
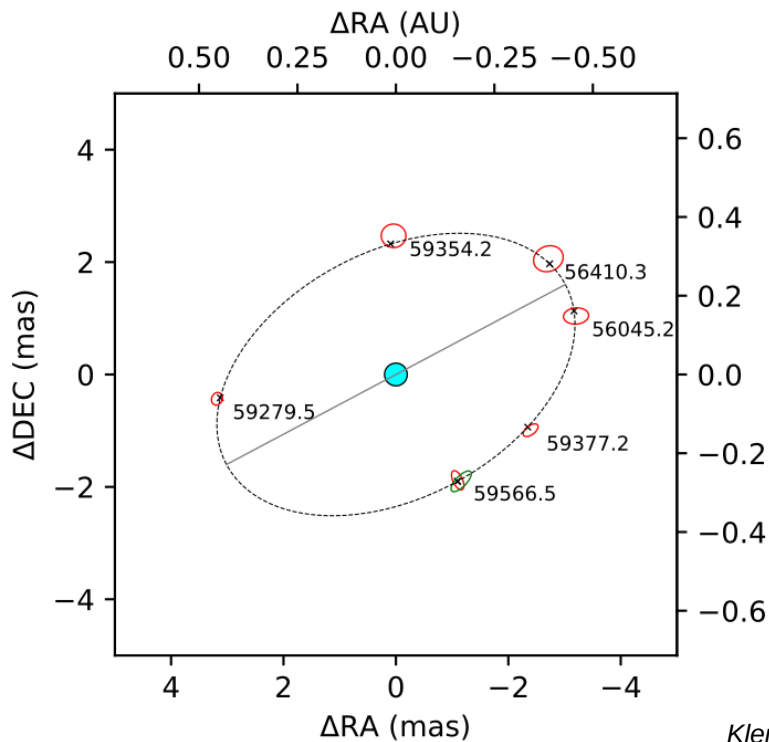
First confirmed sdB companion (cophased IUE spectra)

$M_{\text{Be}} = 3.65 \pm 0.48 M_{\odot}$

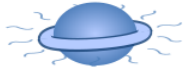
$M_{\text{sdB}} = 0.426 \pm 0.043 M_{\odot}$

$T_{\text{eff_Be}} = 14$ kK

$T_{\text{eff_sdB}} = 16.7$ kK



Be + WD



Be stars with γ Cas-like X-rays (Be + WD candidates)

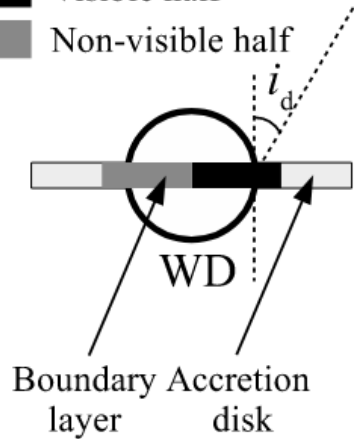
Single-lined spectroscopic binaries with **accreting WD?**

(a) Non-magnetic WD

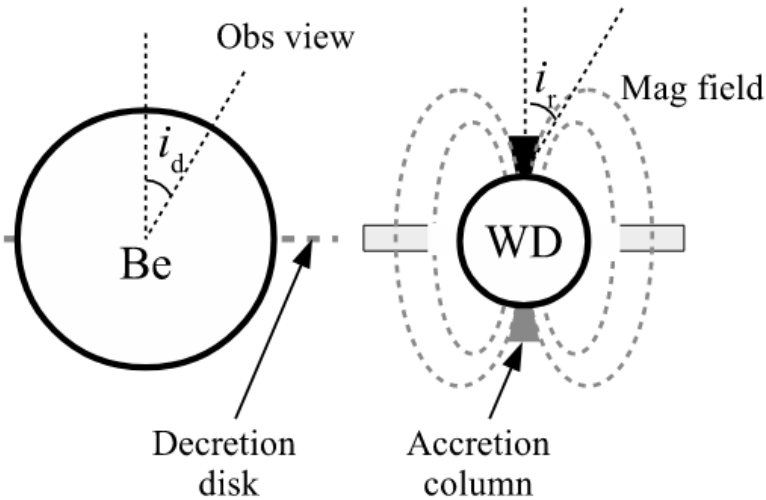
X-ray emitting region

■ Visible half

■ Non-visible half

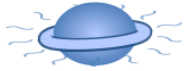


(b) Magnetic WD



Tsujimoto+ 2018

Not detectable by interferometry – but can be “confirmed” by ruling out sdOB or MS companion in SB1 Be binaries



Be stars with γ Cas-like X-rays (Be + WD candidates)

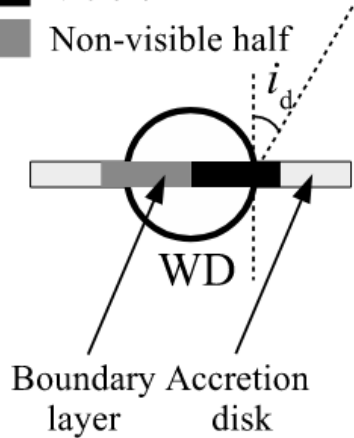
Single-lined spectroscopic binaries with **accreting WD?**

(a) Non-magnetic WD

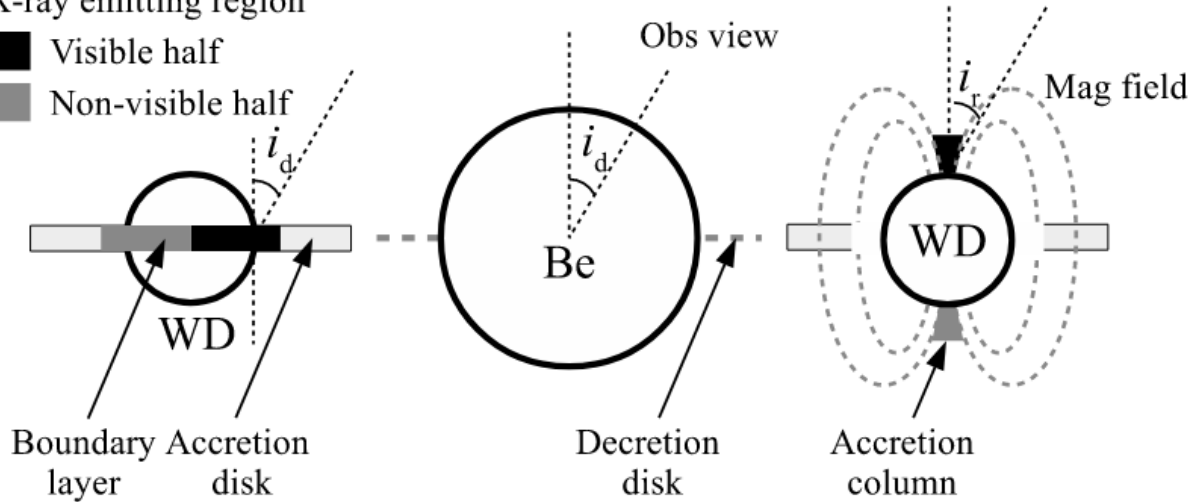
X-ray emitting region

■ Visible half

■ Non-visible half



(b) Magnetic WD



Tsujimoto+ 2018

No companions detected in SB1 systems by interferometry

$\Delta H_{\min} \sim 6-7$ mag for γ Cas and π Aqr

Expected mass of the spectroscopic companions for γ Cas and π Aqr is $\sim 1 M_{\odot}$ – should have been detected if sdOB or MS!

The only remaining option is WD companion

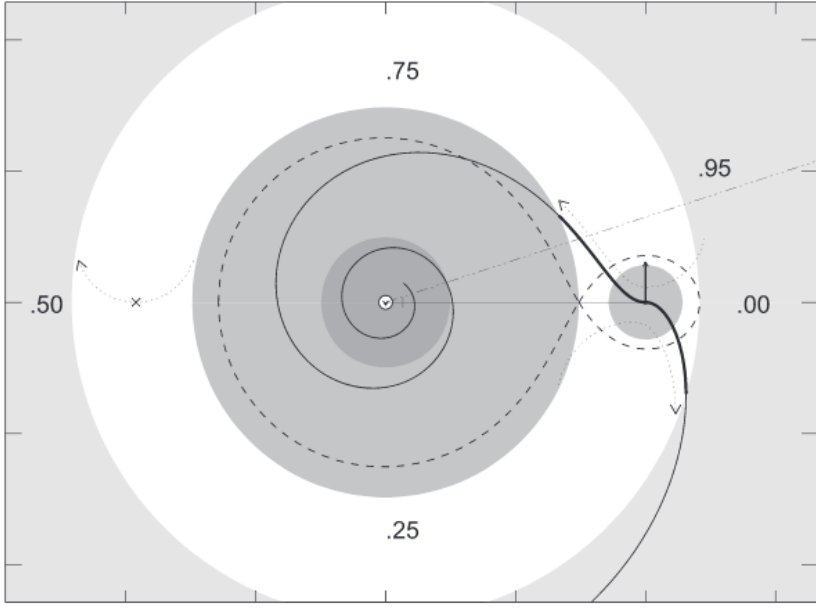
Not detectable by interferometry – but can be “confirmed” by ruling out sdOB or MS companion in SB1 Be binaries

Disk structure in binaries

New hydrodynamic (SPH) simulations now confirming what was suggested by observations

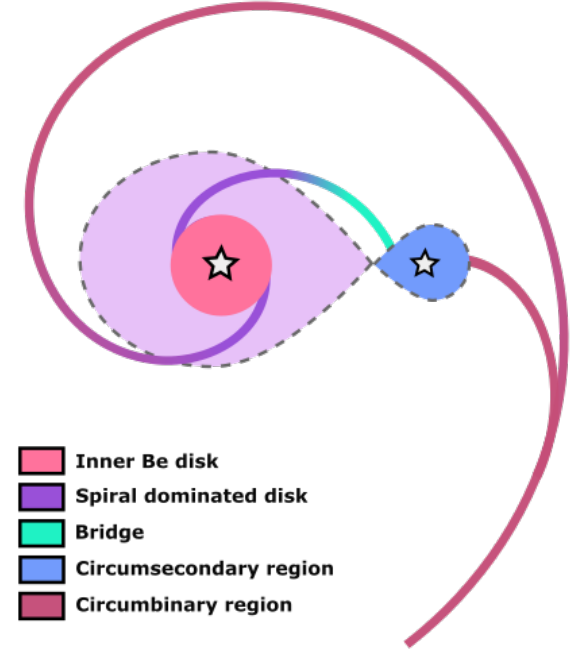
HR 2142 ($V = 5.2$)

HR 2142 - gas streams crossing gap between primary and secondary



Peters+ 2016

SPH simulation of a Be disk in a close binary

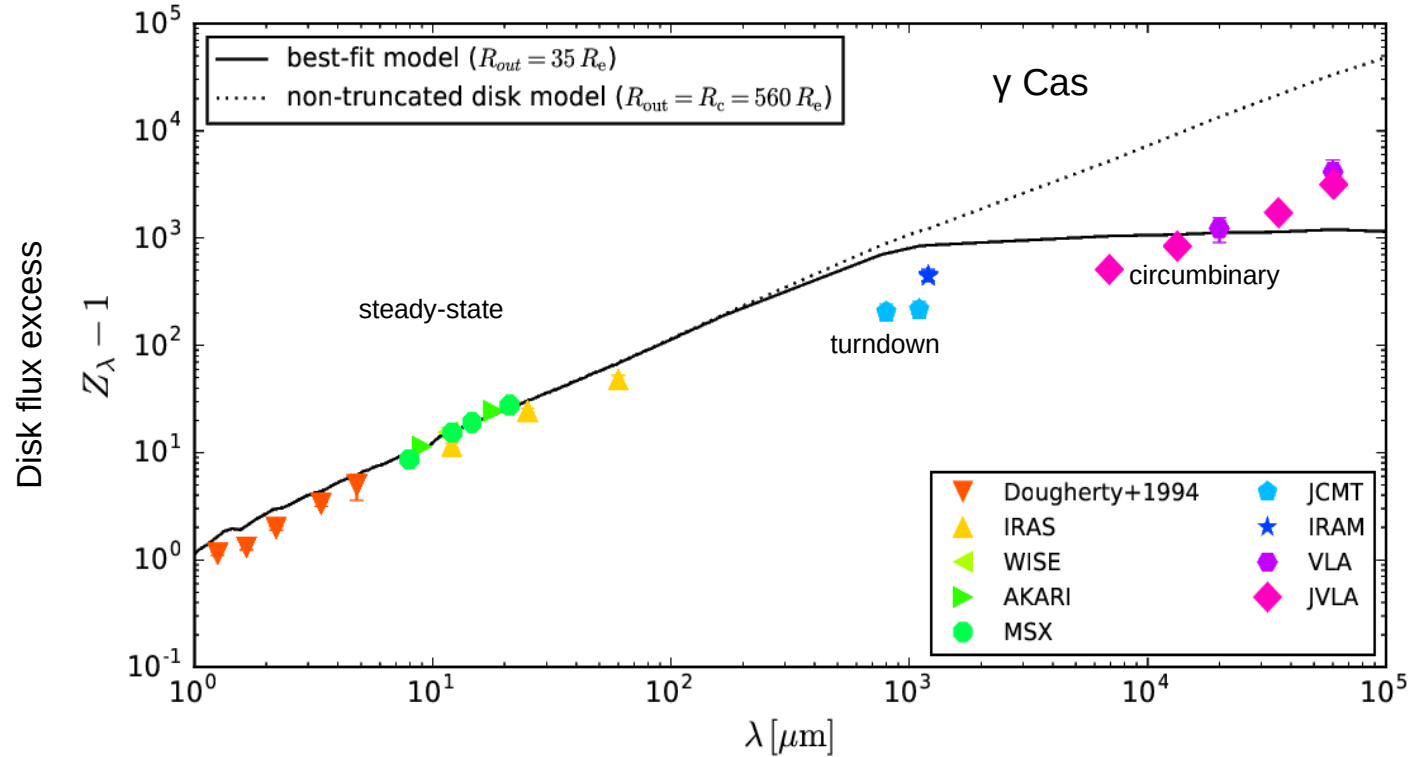


- Inner Be disk
- Spiral dominated disk
- Bridge
- Circumsecondary region
- Circumbinary region

Rubio+ submitted

Disk structure in binaries

SED of Be stars at radio wavelengths suggests the presence of extended circumbinary structures



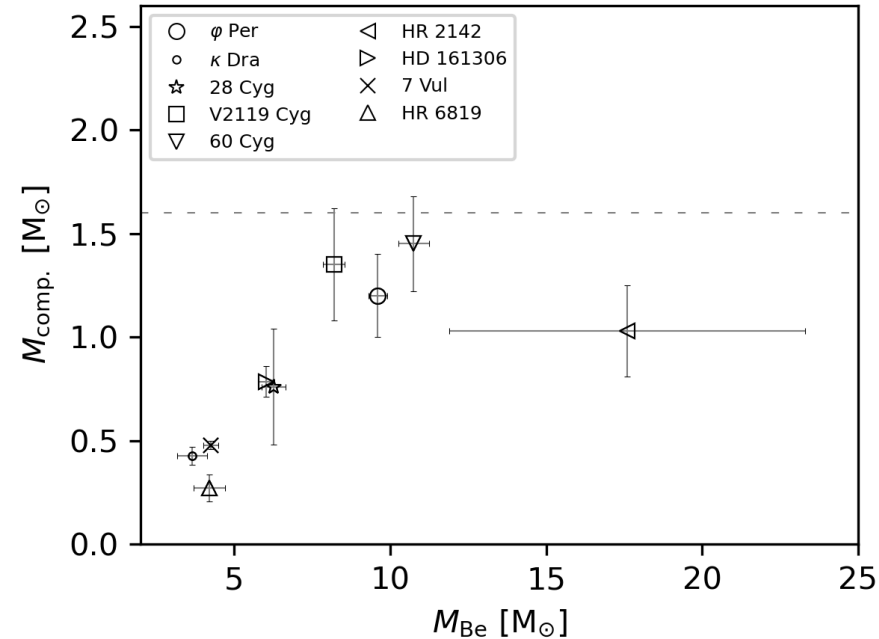
Klement+ 2019

Conclusions

Binary formation channel prominent for early types but confirmed to extend to at least mid-type Be stars (B6)

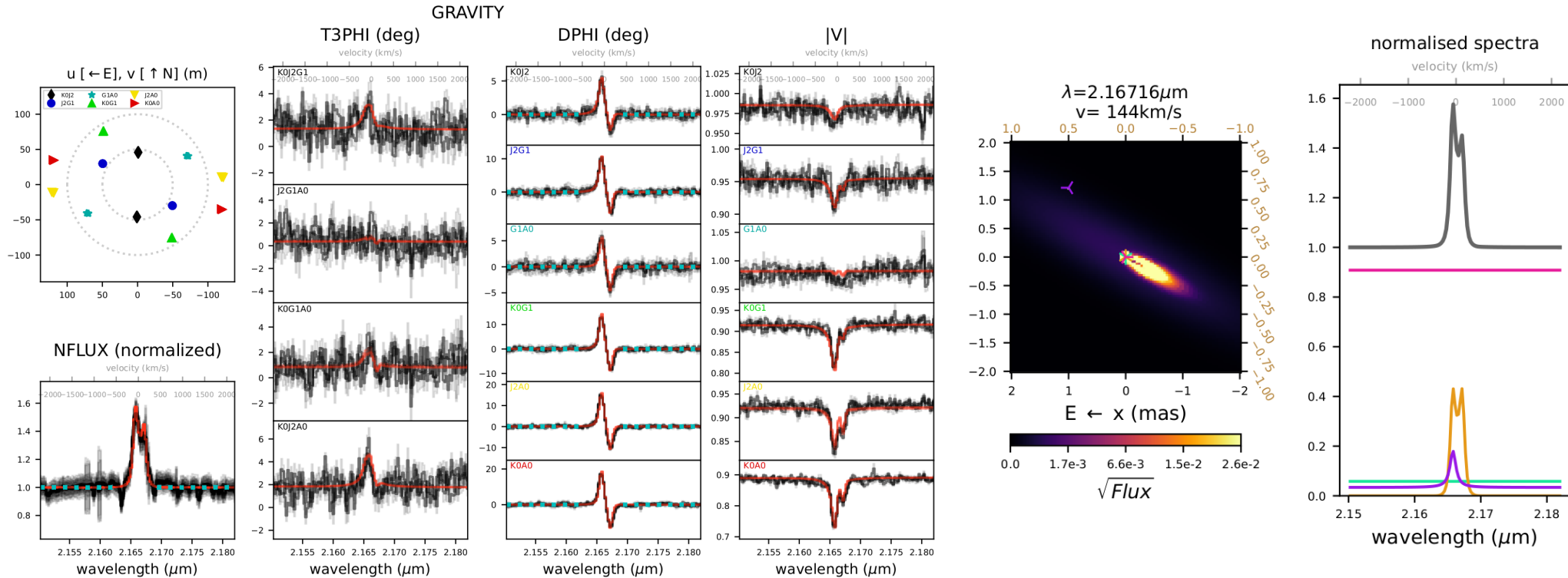
- Be + bloated pre-sd
 - **HR 6819 - dynamical masses and dynamical parallax**
 - Six now confirmed with interferometry
- Be + sdOB
 - Seven dynamical masses of both components published, more to come
 - **First sdB companion confirmed**
 - *No confirmed progenitor of Be X-ray binaries (Be + NS)*
- Be + WD
 - **WD companions the only option for X-ray sources γ Cas and π Aqr**
 - X-ray-faint WDs prominent around later types?
- Disk structure in binaries
 - Observations and simulations converging on complex structure including circumbinary spiral arms, circumcompanion gas, and streams

Dynamical masses of Be stars and stripped companions



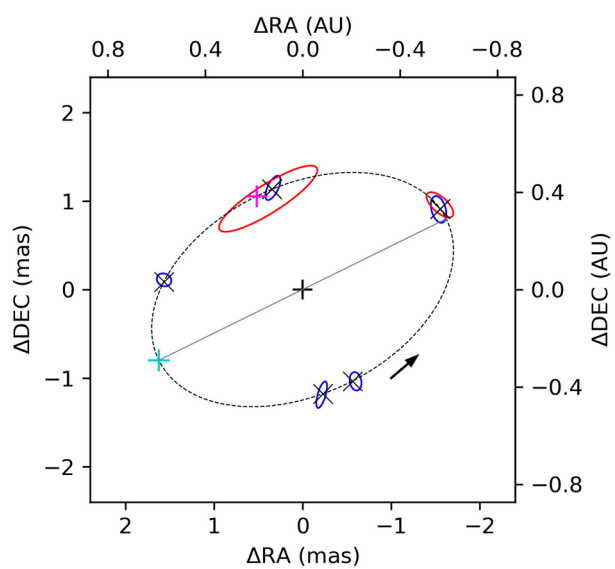
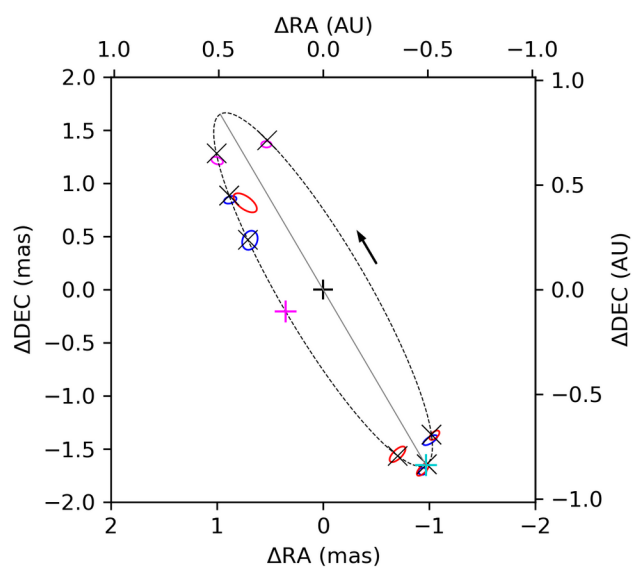
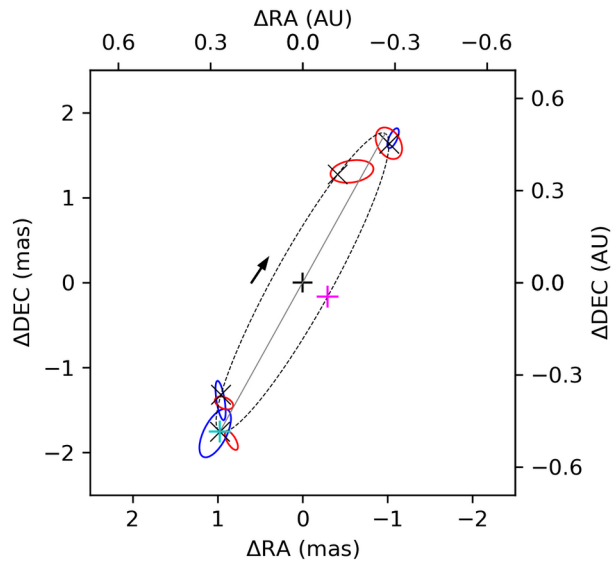
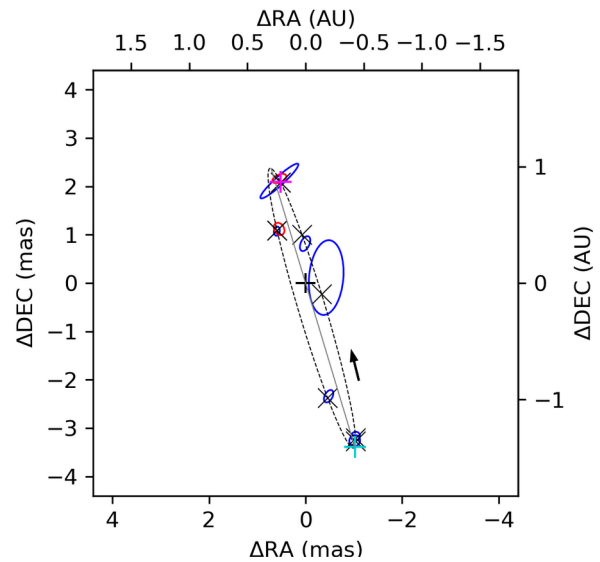
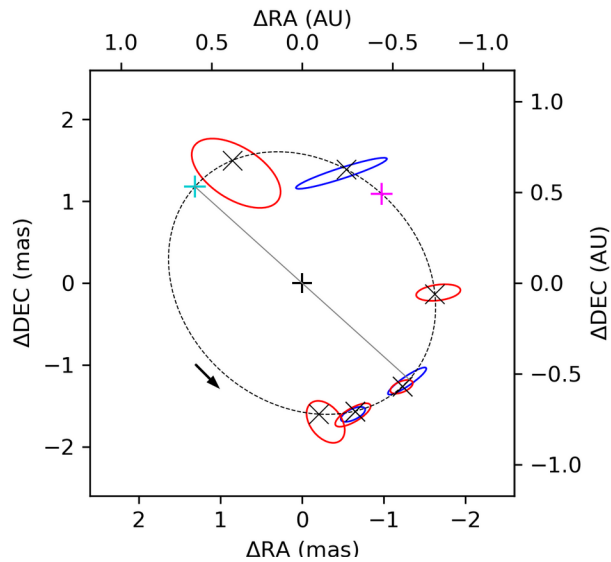
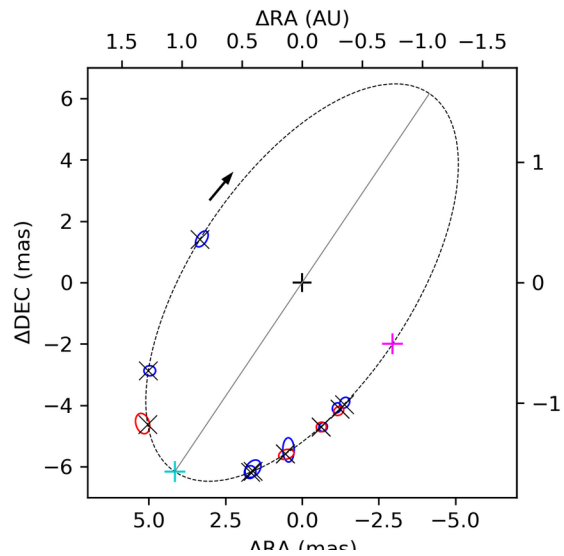
Disk structure in binaries

Interferometric Detection of circumcompanion gas in HR 2142



This is Bry line but similar emission also seen in He I 2058

Klement+ 2024

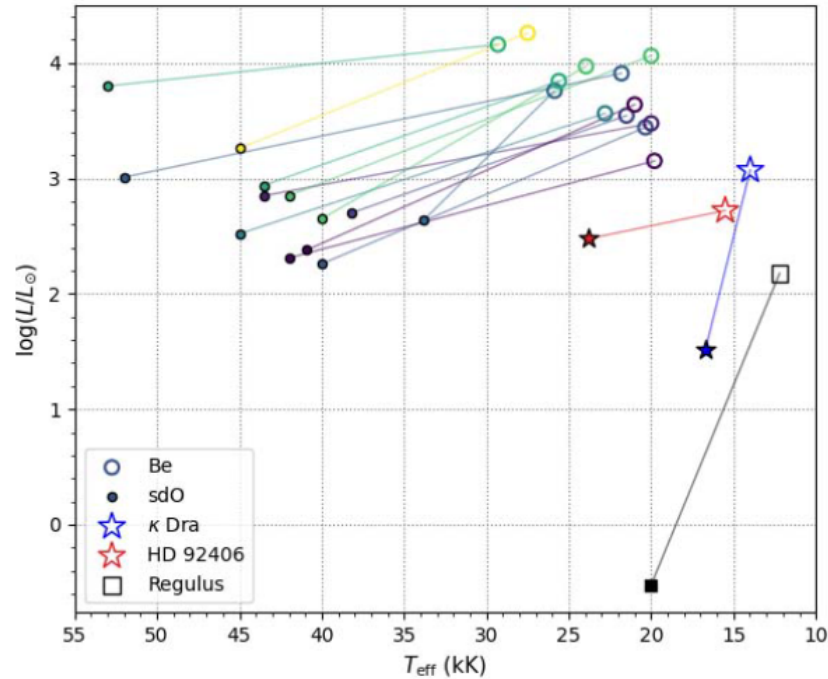


Next steps

- Be + bloated pre-sdOB
 - Spectroscopic analysis to determine abundances
 - Spectral disentangling to determine RVs of the Be stars → dynamical masses independent of biased parallaxes
- Be + sdOB
 - Expand FUV searches to cooler sdOB companions (thus far done assuming $T_{\text{eff}} \sim 45 \text{ kK}$)

Be + sdOB / (pre-)WD population

Be + sdOB systems
(Wang+ 2021, Klement+ 2022a)



κ Dra (B6 IIIe) + sdB (Klement+ 2022b)

V658 Car (mid-type Be) + late-type sdB (de Amorim+ 2023)

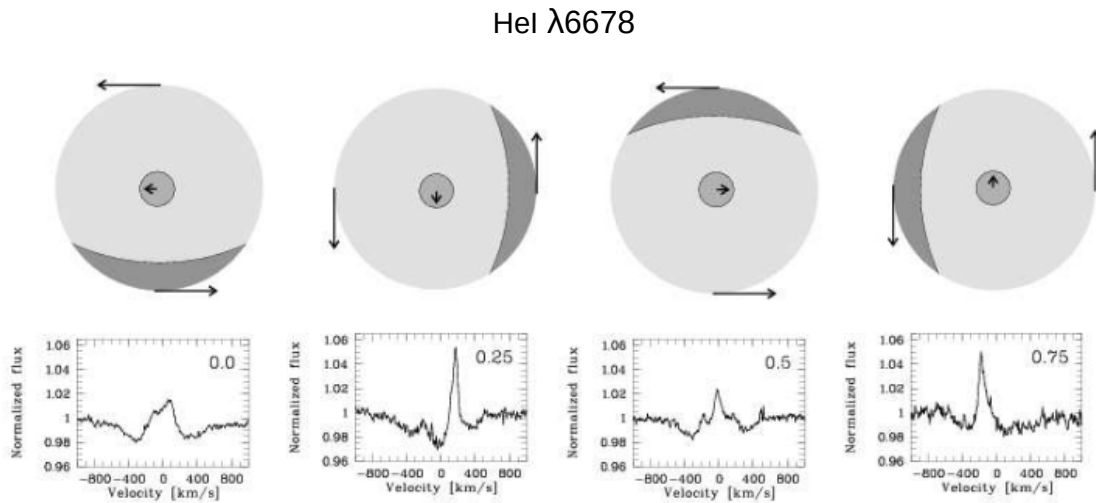
Regulus (B8 IVn) + pre-WD companion (Gies+ 2020)

sdOB companions – indirect detection

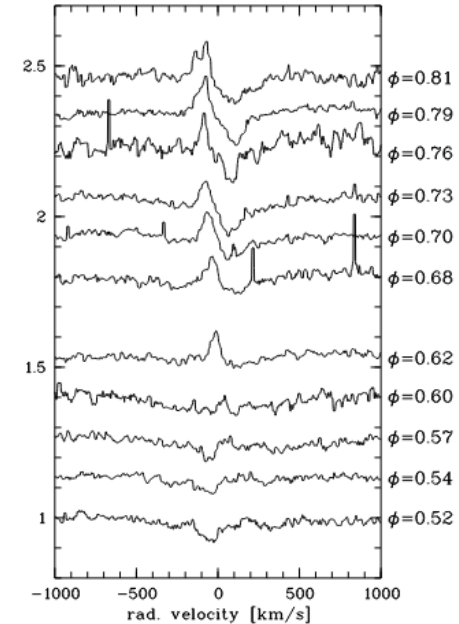
Evidence in optical spectra

variable emission components in HeI lines (*Rivinius & Štefl 2000 – 59 Cyg, Rivinius+ 2004 – FY CMa*)

HeI $\lambda 5016$



Maintz+ 2005



Rivinius+ 2004