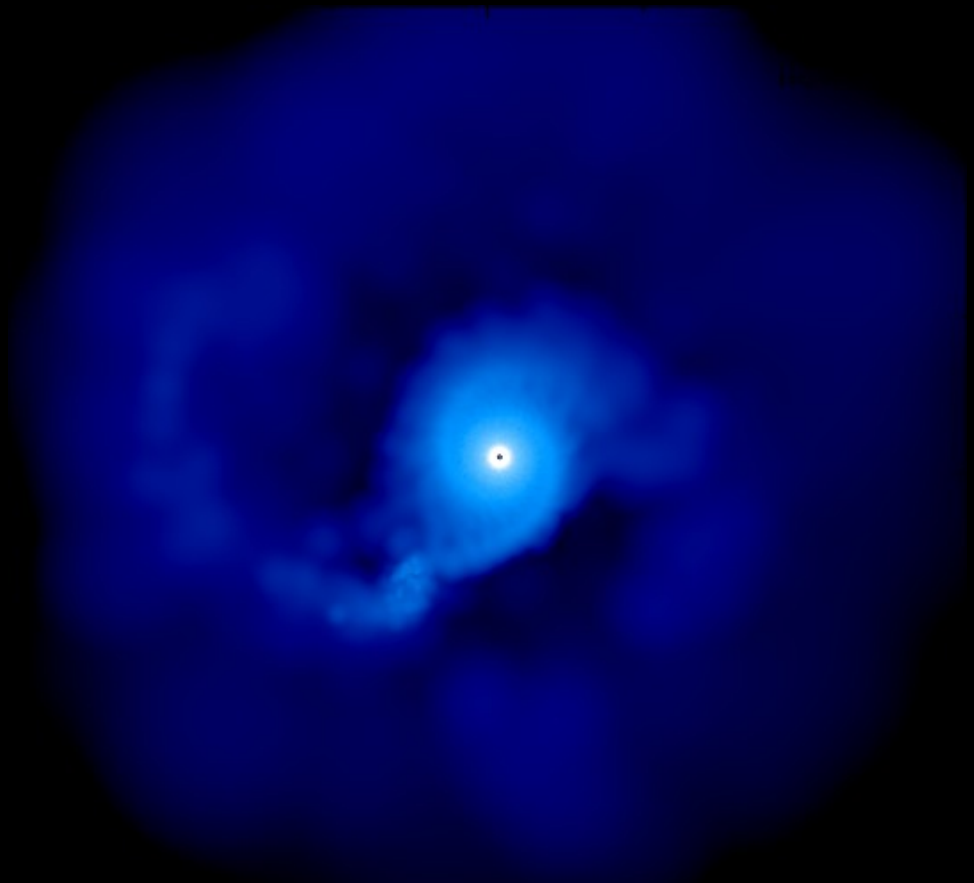


Physics of Extreme Massive Stars
2024 June 28
Rio de Janeiro

Interferometric program on the multiplicity of Be stars: *new detections & orbits of stripped subdwarf companions*

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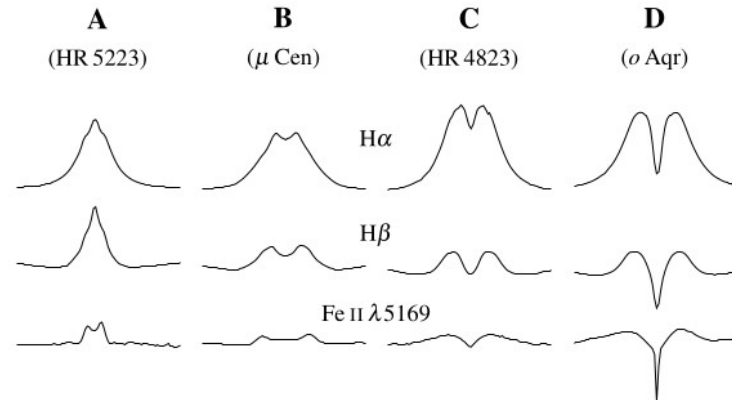
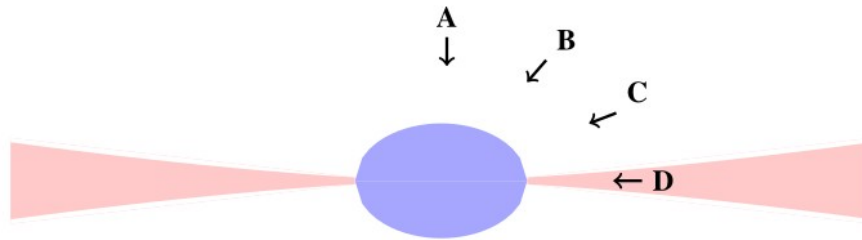


Rubio, Carciofi+ (in prep.)

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



Rivinius+ 2013

Formation of classical Be stars:

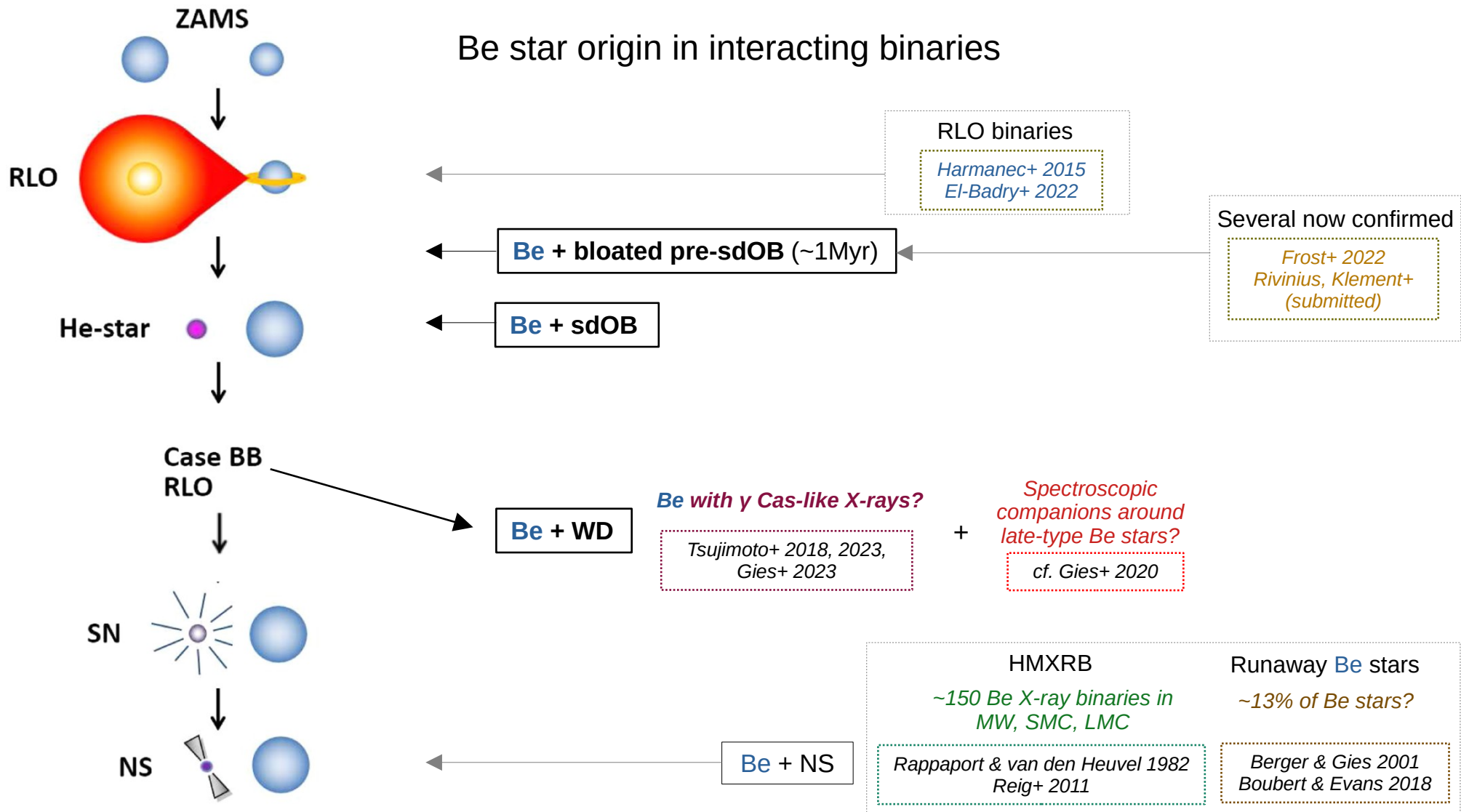
B-type star acquires excess angular momentum \rightarrow
Viscous decretion disk formed to shed it

Origin of excess AM:

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

No confirmed Be stars with MS companions
BUT
many Be stars with stripped companions

Be star origin in interacting binaries

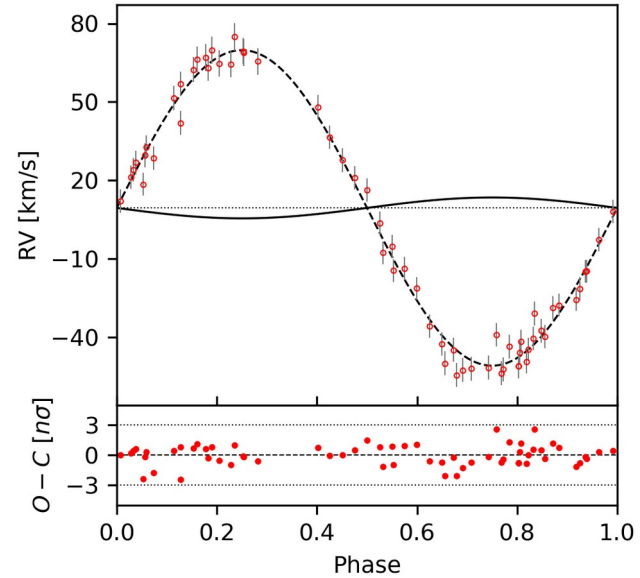
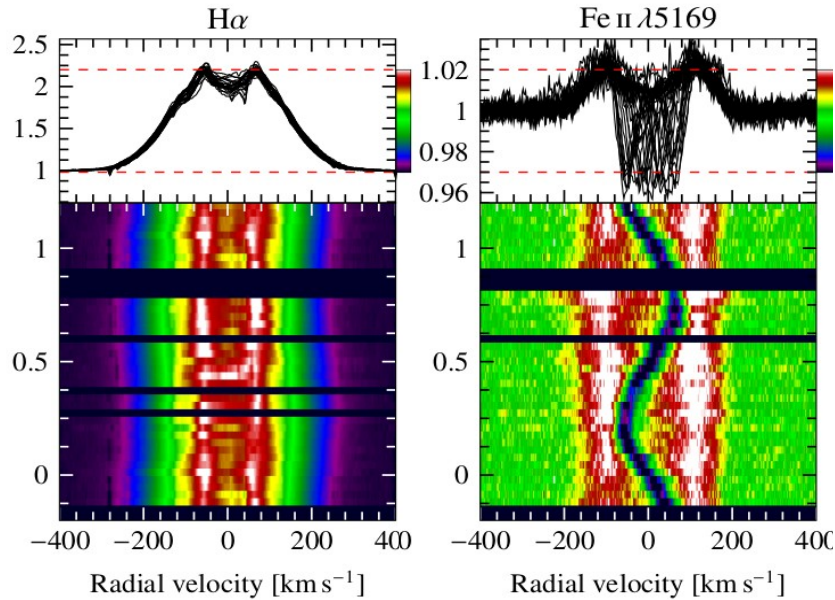


Be stars with bloated pre-sdOB companions

High mass ratio but comparable luminosities

HR 6819 (B2Ve)

P = 40.3 d



Rivinius+ 2020

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

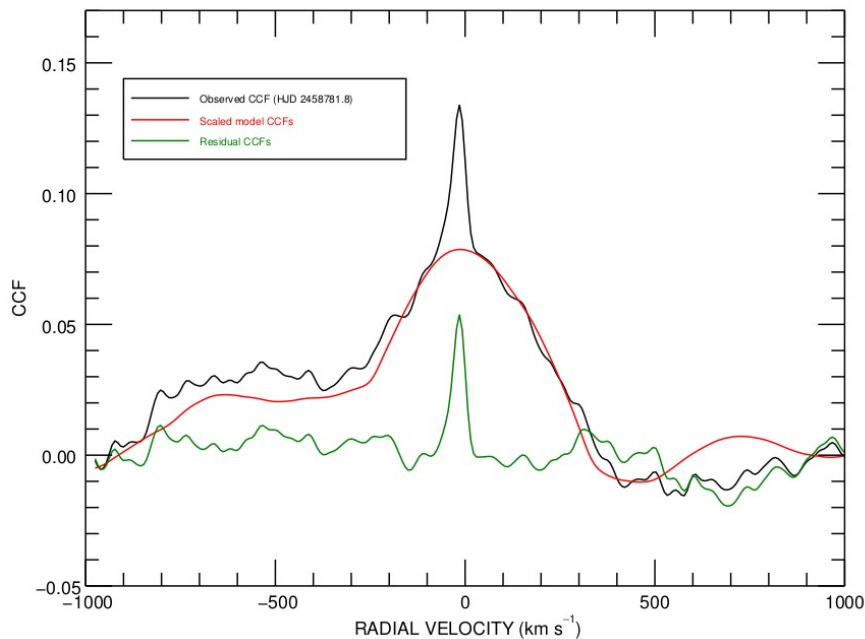
Easily confirmed by interferometry

Be stars with sdOB companions

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

sdOB detection in FUV spectra

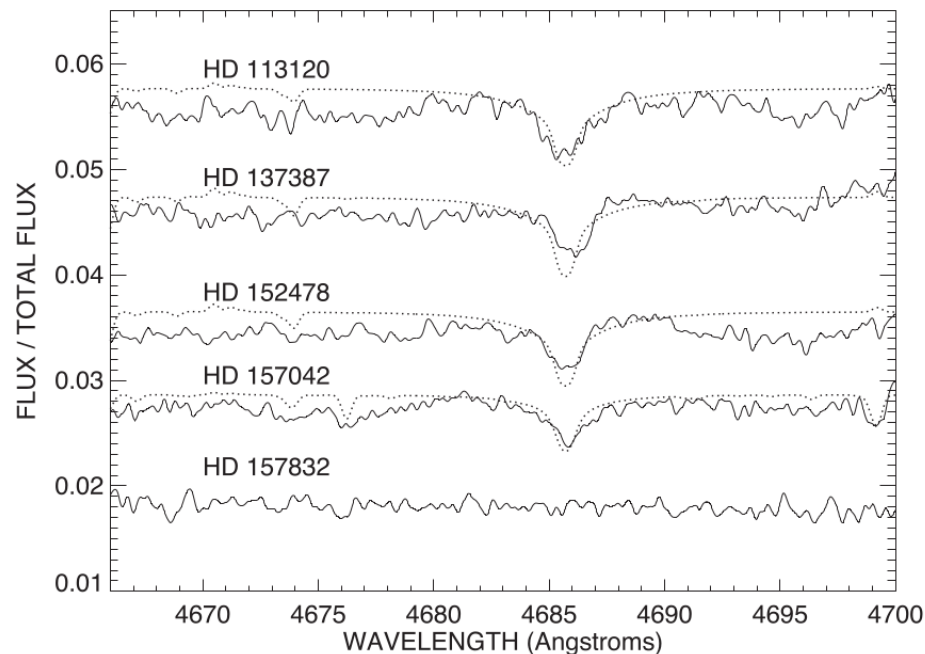
~20 confirmed & strong candidate Be+sdOB binaries



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 γ Cas-like X-rays (early Be + accreting WD candidates)

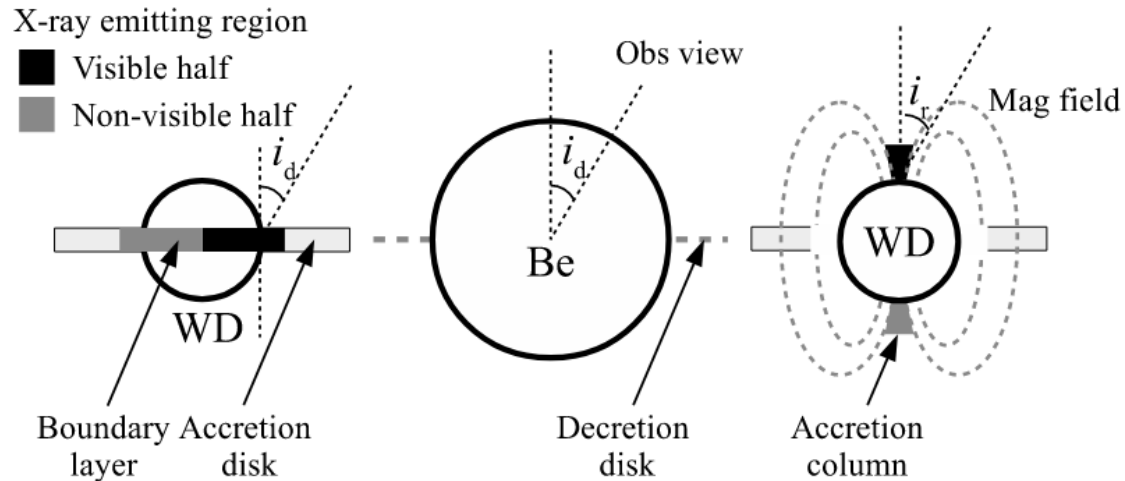
Single-lined spectroscopic binaries with companions detectable only via **peculiar X-ray properties?**

γ Cas & π Aqr

Consistent with accretion of Be disk material onto WD companion

(a) Non-magnetic WD

(b) Magnetic WD



Tsujimoto+ 2018

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

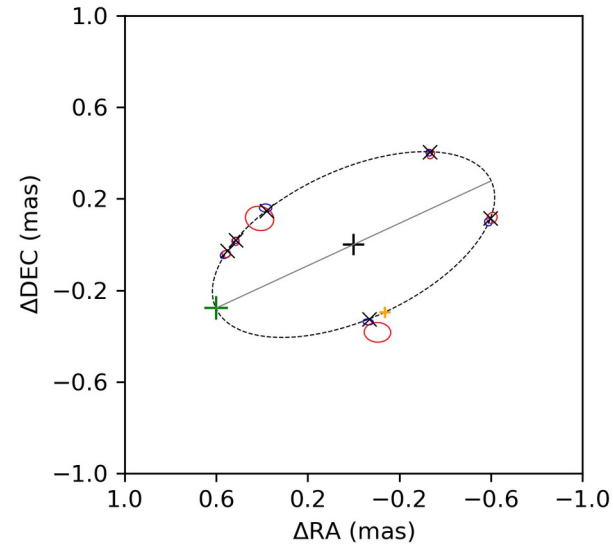
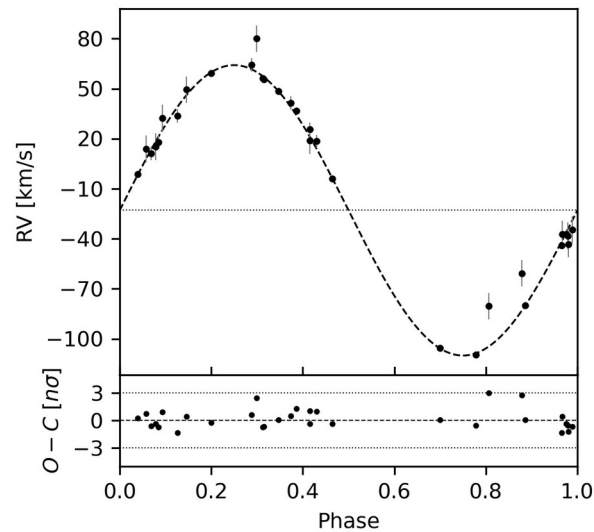
CHARA & VLTI near-IR interferometric program on the binarity of Be stars

- ~70 confirmed/candidate Be + sdOB 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)

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5 newly confirmed Be + bloated pre-sdOB binaries



V742 Cas (B7e)

P = 40.3 d

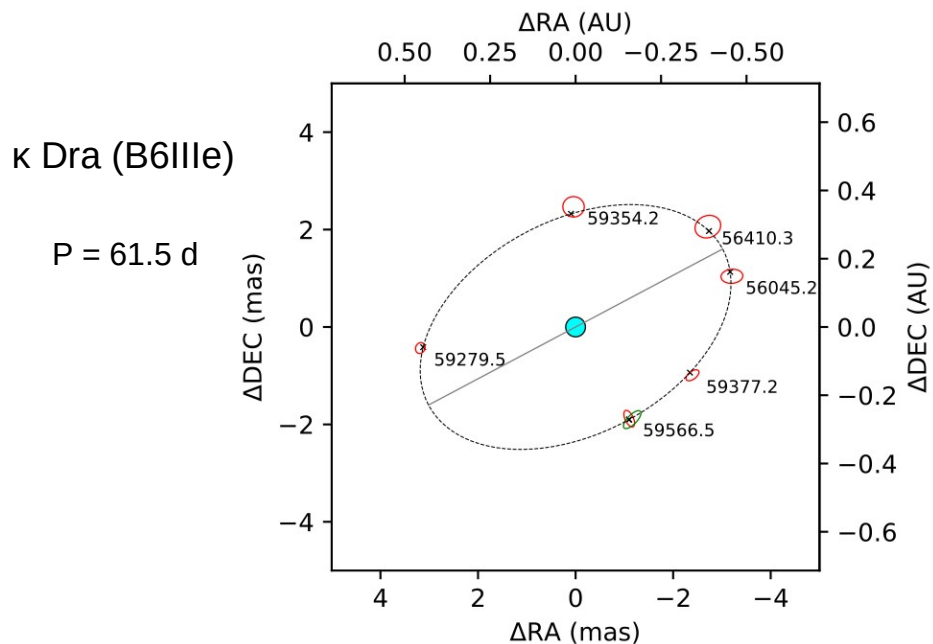
The smallest measured orbit?
 $a = 0.663 \pm 0.003$ mas

Biased parallax due to the low-contrast binary → uncertain masses :(

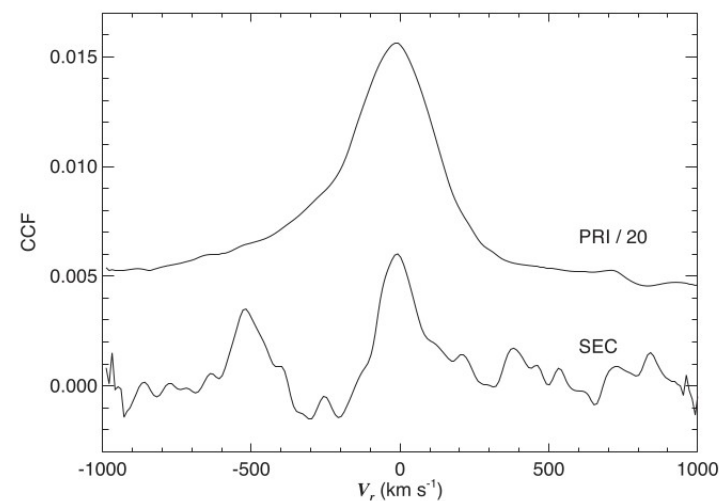
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New combined orbital solutions and dynamical masses for Be + sdOBs



First confirmed sdB companion (cophased IUE spectra)

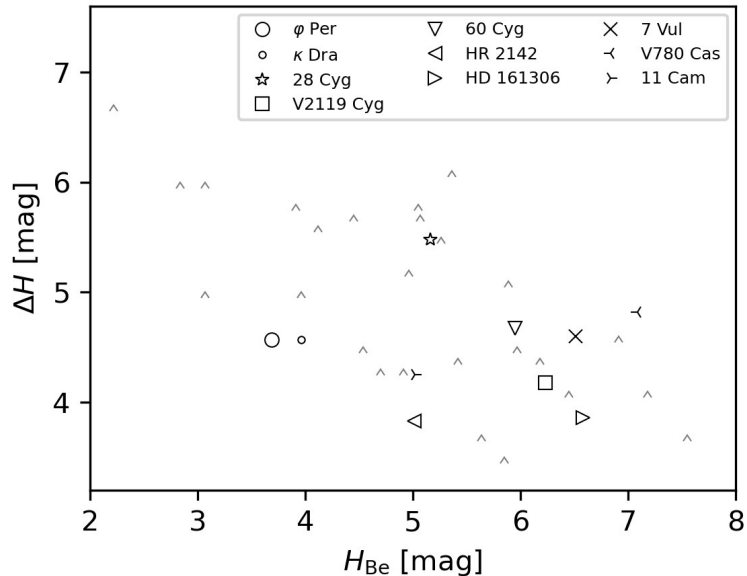


$M_{\text{Be}} = 3.65 \pm 0.48 M_{\odot}$
 $M_{\text{sdB}} = 0.426 \pm 0.043 M_{\odot}$

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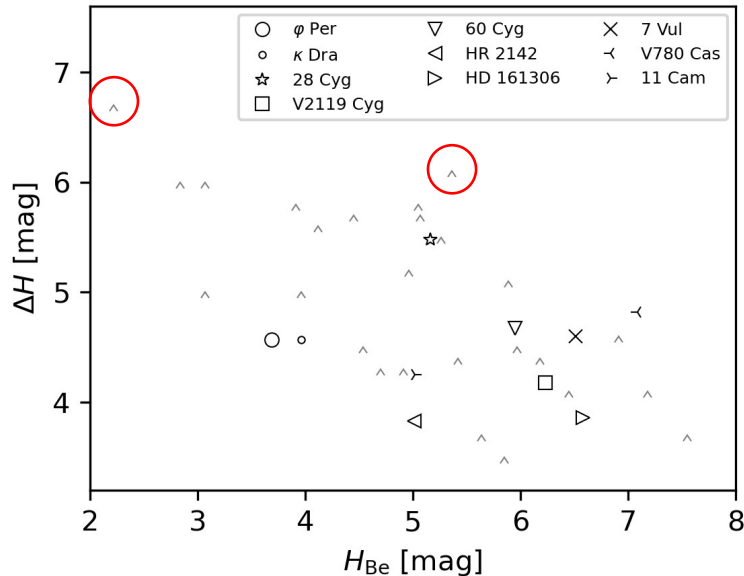
No companions detected for stars with γ Cas-like X-rays (Be + WD candidates)



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No companions detected for stars with γ Cas-like X-rays (Be + WD candidates)



- $\Delta H_{\min} \sim 6-7$ mag for γ Cas and π Aqr
- $\Delta H_{\min} \sim 4-5$ mag for four others

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!

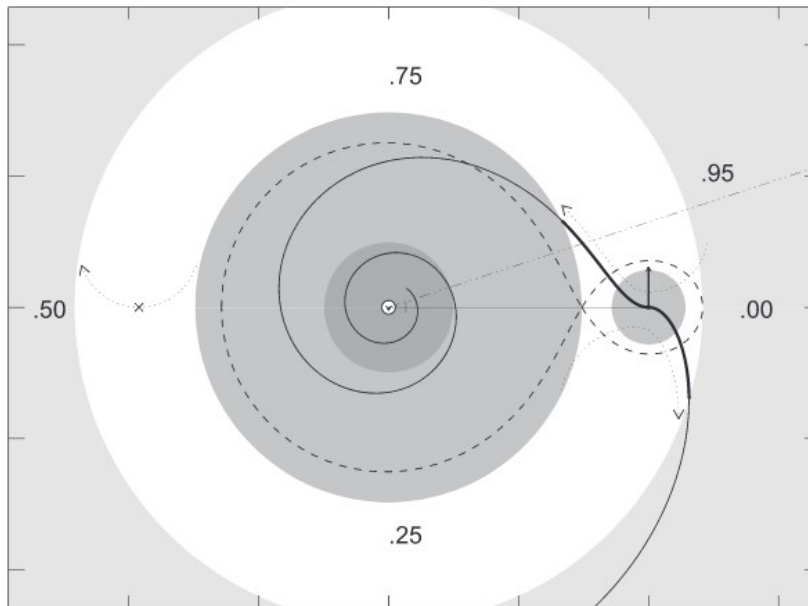
The only remaining option is WD companion

Presence of circumcompanion gas

- Spectroscopic evidence for HD 55606 (Chojnowski+ 2018), **HR 2142** (Peters+ 2016), and probably π Aqr (Bjorkman+ 2002)
- Photometric evidence for the eclipsing binary V658 Car (de Amorim+ 2023)

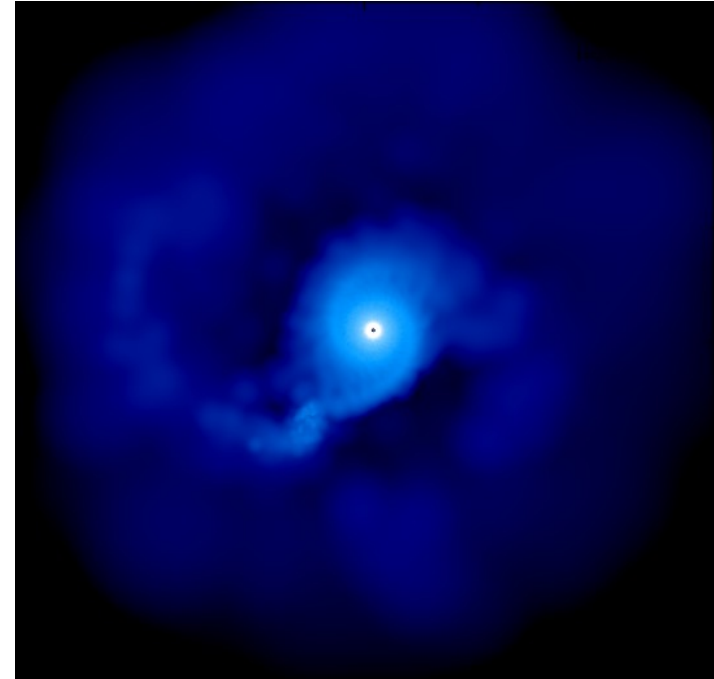
HR 2142 (B1Ve)

HR 2142 - gas streams crossing gap between primary and secondary



Peters+ 2016

SPH simulation of a Be disk in a close binary

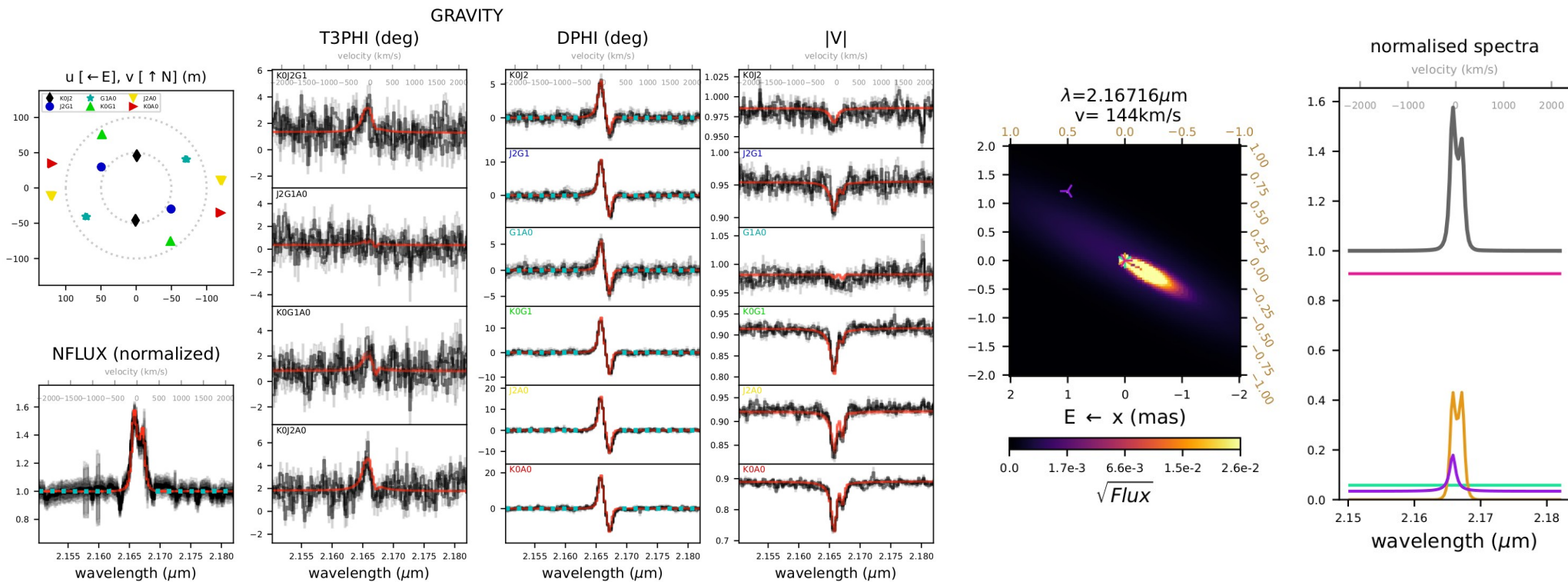


Rubio, Carciofi+ in prep.

Presence of circumcompanion gas

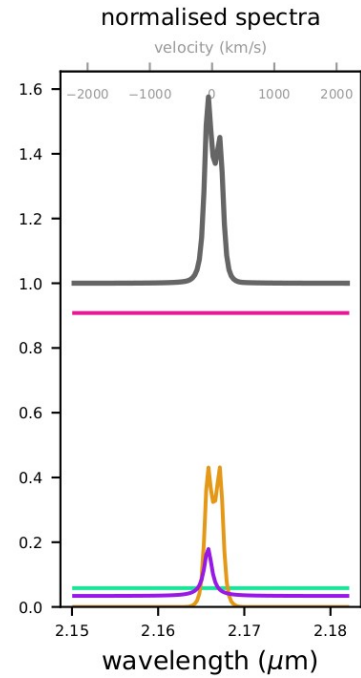
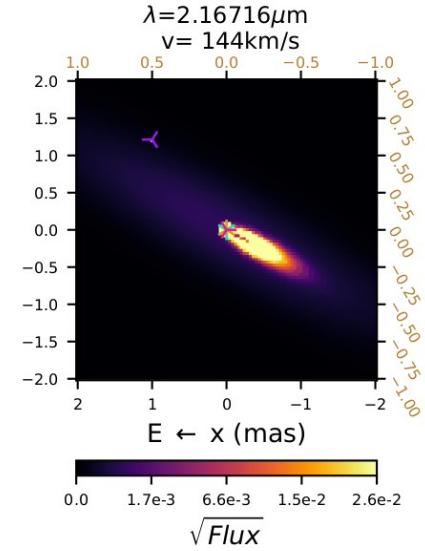
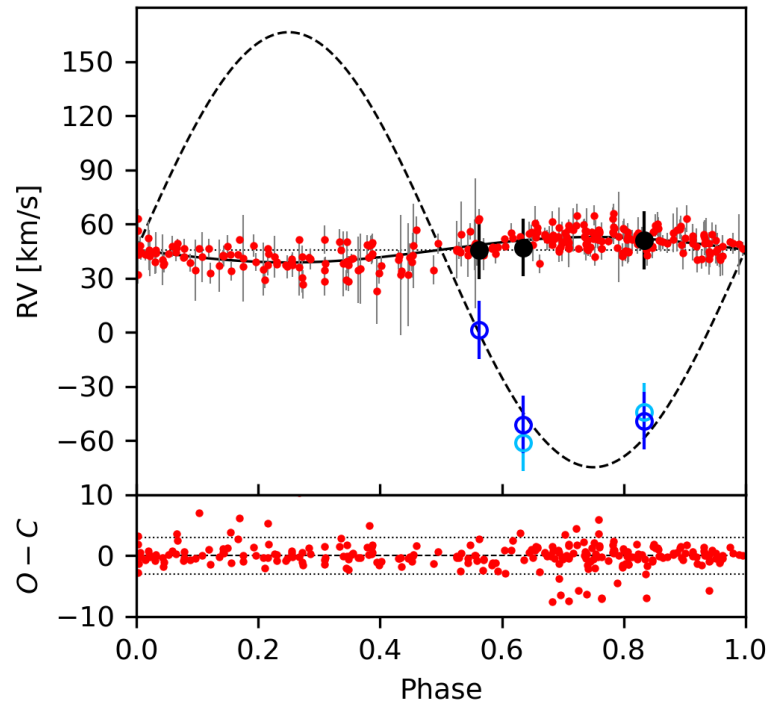
Interferometric Detection of circumcompanion gas in HR 2142

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



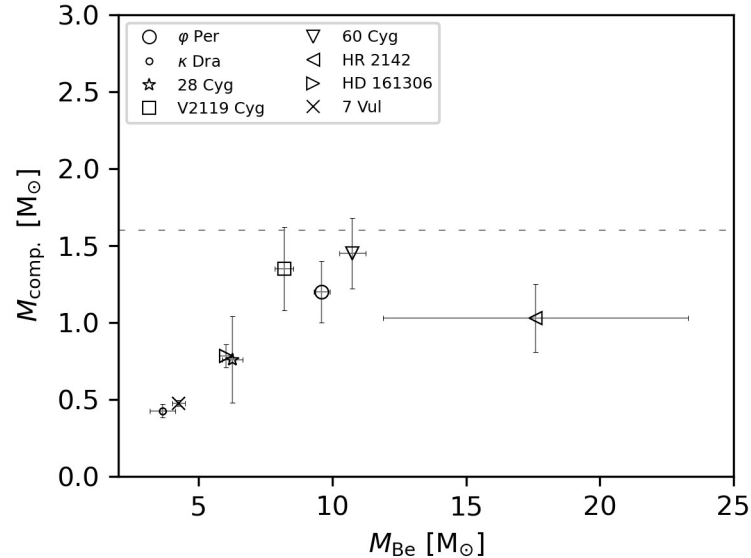
Presence of circumcompanion gas

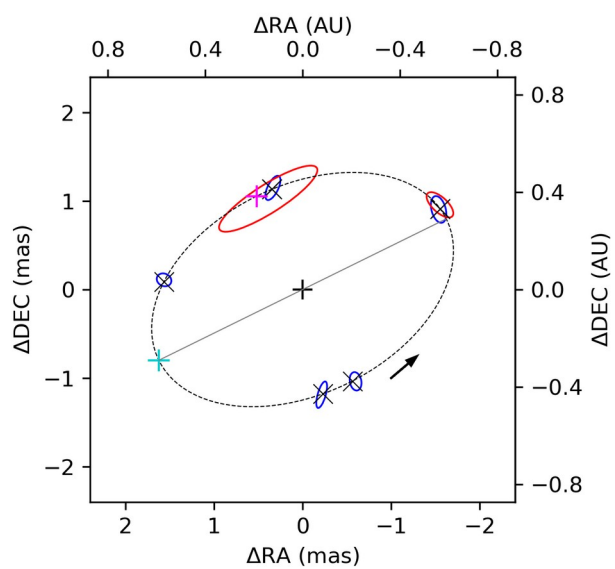
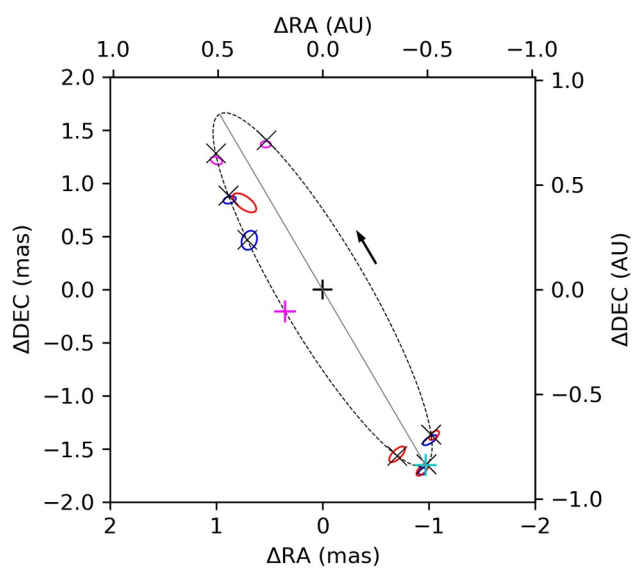
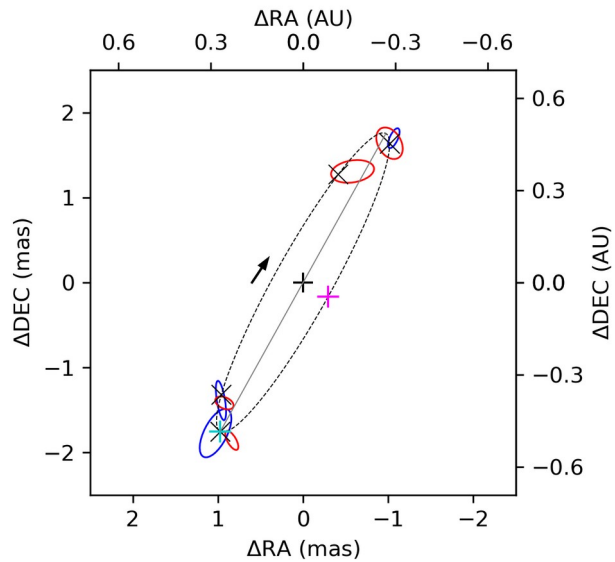
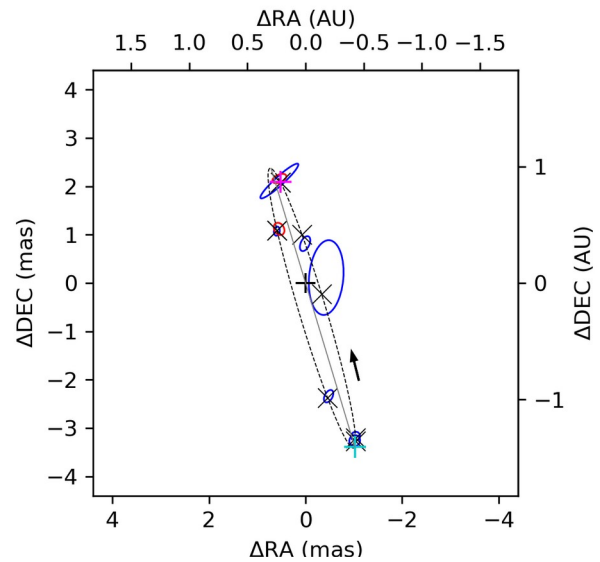
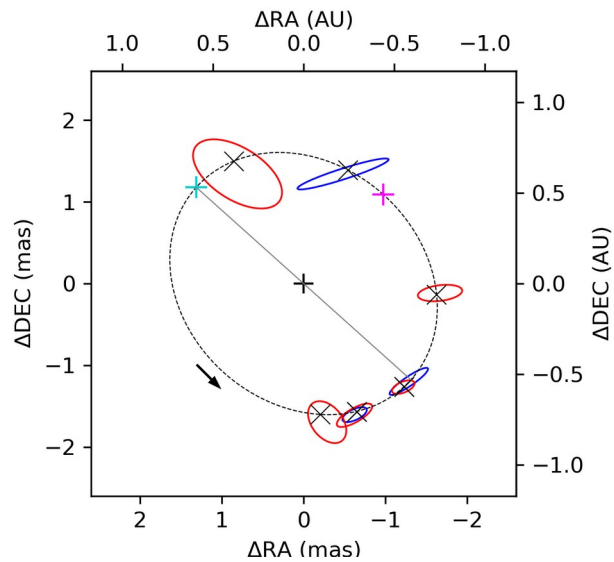
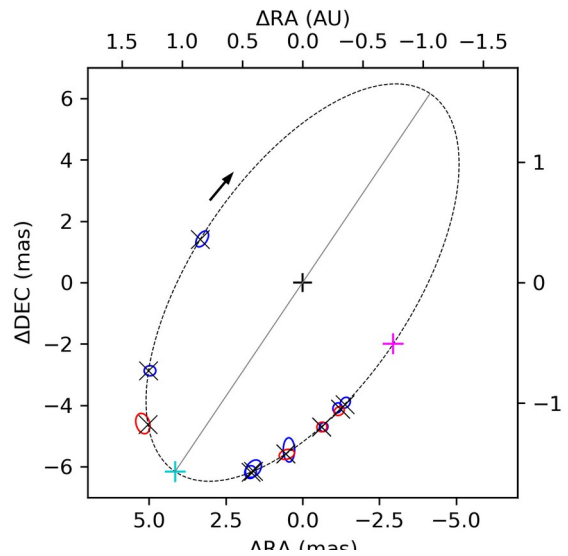
GRAVITY Detection of circumcompanion gas in HR 2142



Conclusions

- **Be + bloated pre-sdOB** - $\sim 1\%$ of Be stars in magnitude-limited sample (1% also for hierarchical triples)
 - Six now confirmed with interferometry & several more candidates
- **Be + sdOB** – $\sim 5\%$ of Be stars - *incomplete*
 - Seven well-constrained dynamical masses of both components published - *no confirmed progenitor of Be X-ray binaries (Be + NS)*
 - **Binary formation channel prominent for early types** but confirmed to extend to at least mid-type Be stars (B6)
- **Be with γ Cas-like X-rays** (Be + accreting WD candidates) – $\sim 2\%$ of Be stars
 - Strong evidence against sdOB or MS companions in γ Cas and π Aqr → WD companions
 - These are early-type Be stars – X-ray-faint WDs prominent around later types? Evolutionary spin-up for later types?



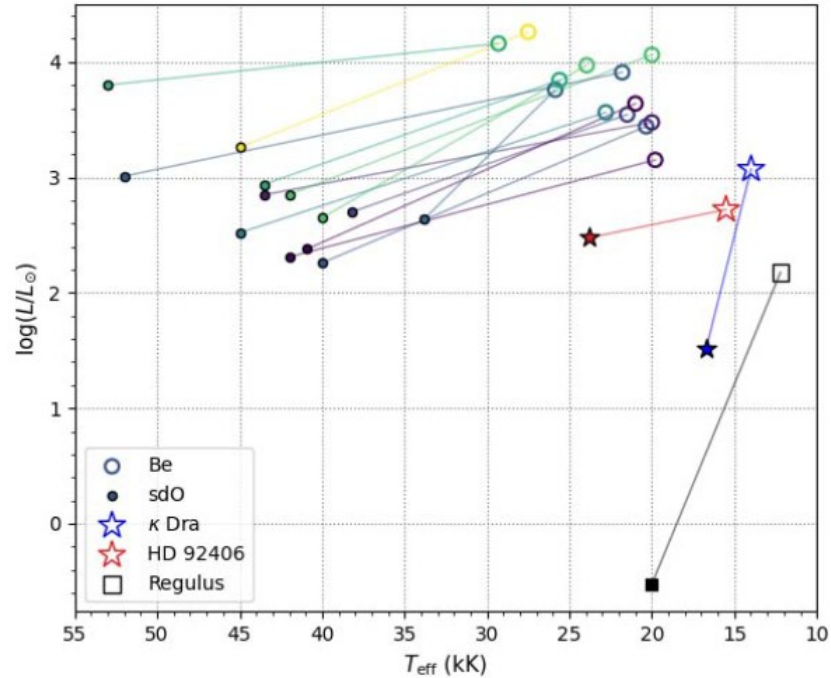


Next steps

- 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)

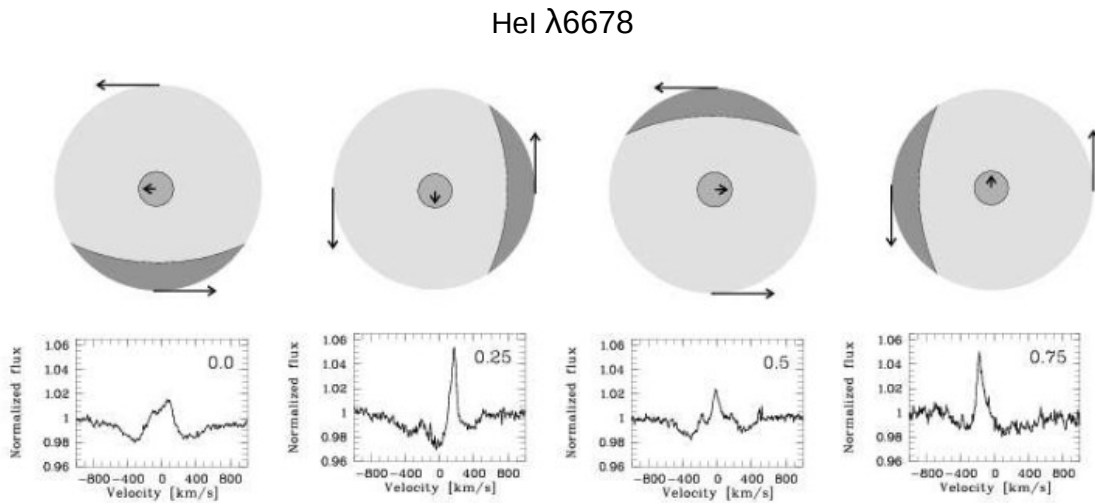
V658 Car (mid-type Be) + late-type sdB (de Amorim+ 2023)

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

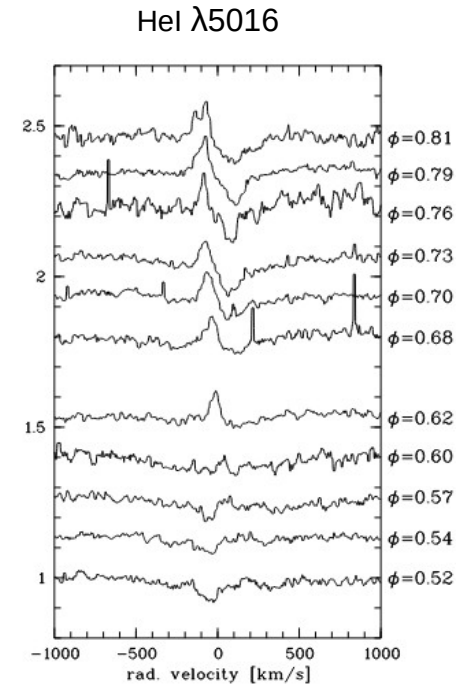
sdOB companions – indirect detection

Evidence in optical spectra

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



Maintz+ 2005



Rivinius+ 2004