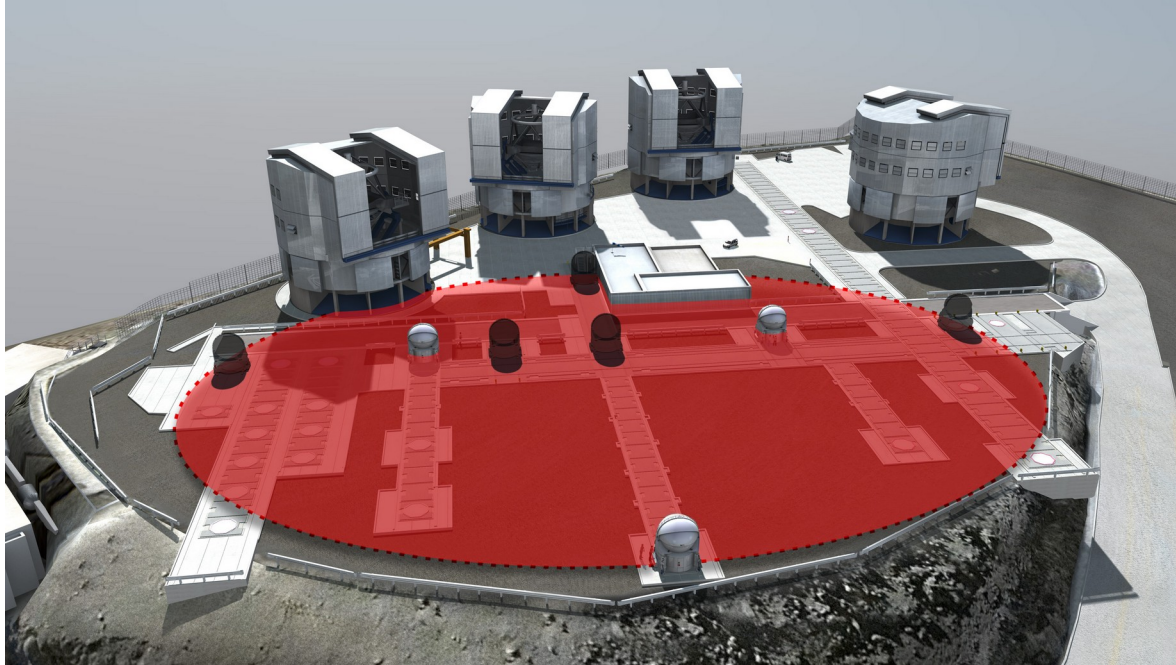


Subdwarf companions and the origin of Be stars_s

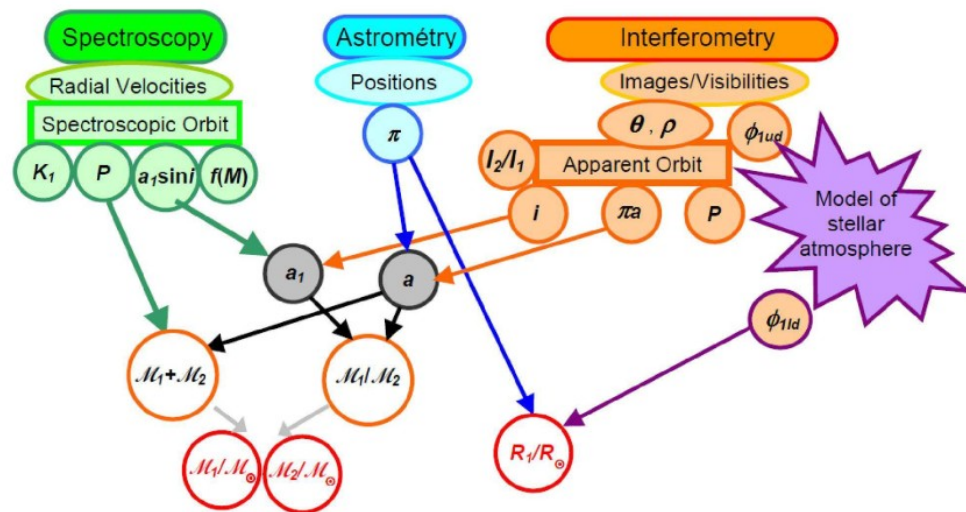
R. Klement, Th. Rivinius, D. Gies, A. Merand, CHARA team



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Interferometric detection of companions

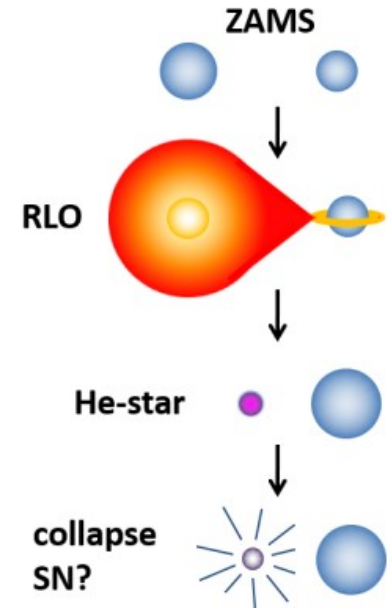
- Close, short-period binaries detected as (single-lined) spectroscopic binaries
- Interferometric detection → angular separation and flux ratio
- Astrometric orbit → i and a''
 - Astrometric + SB1 orbit – need d for orbit size and masses – but parallax may be biased!
 - Astrometric + SB2 orbit – d obtained independently
- Dynamical masses for both components
 - Calibration of evolutionary and population synthesis models



SB1 case, (Bonneau+ 2014)

Binarity among classical Be stars

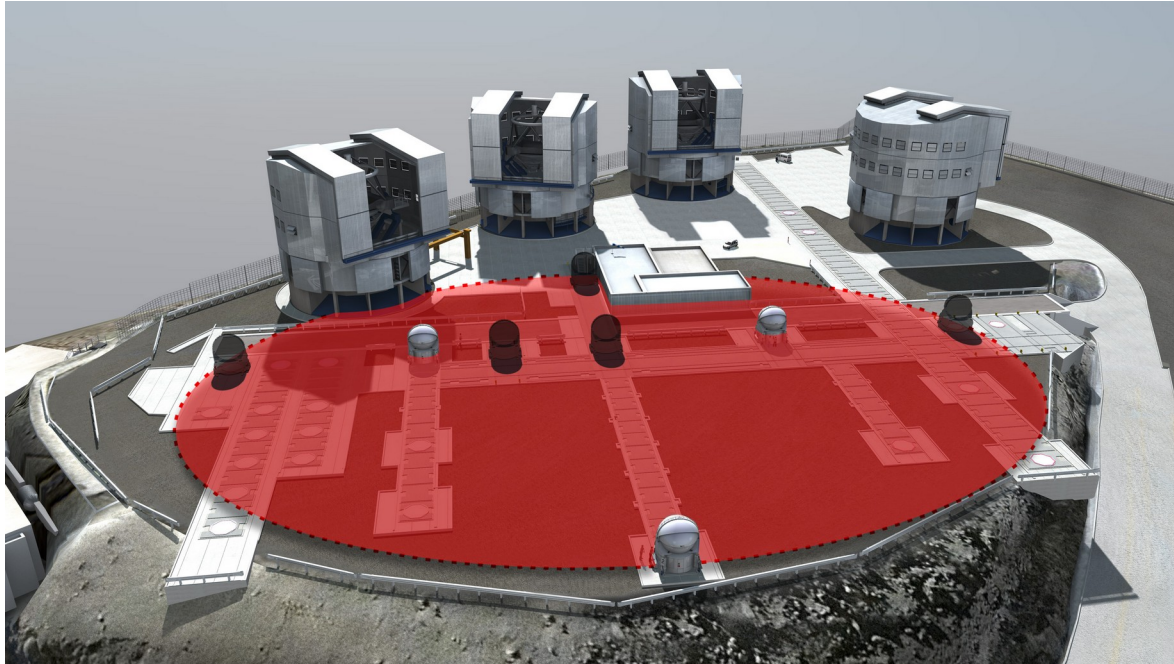
- *Classical Be stars are rapid rotators with self-ejected Keplerian disks (15-40% of B-stars)*
- Mass-transferring B-type binaries – progenitors of (most?) classical Be stars
 - Examples: HD 15214 (El-Badry+ 2022) - semidetached binary (P = 5.47 d)
- Classical Be stars right after mass transfer – **bloated pre-subdwarf companions**
 - Examples: HR 6819 (Frost+ 2022), LB-1, ... (Rivinius+ in prep.)
- Classical Be stars longer after mass transfer
 - Neutron-star companions in Be/X-Ray binaries - ~70 in the Galaxy (<http://xray.sai.msu.ru/~raguzova/BeXcat/>)
 - **Stripped subdwarf OB** (He star) **companions** around early and mid-type Be stars
 - White-dwarf companions in γ Cas stars (?) – after case BB mass transfer (Gies+ 2023)
- Be stars as a result of single-star evolution?
 - Achernar (Kervella+ 2022)
 - Several Be stars are the outer components in hierarchical triples (Klement+ 2021, in prep.)



Langer+ 2020

Subdwarf companions and the origin of Be stars

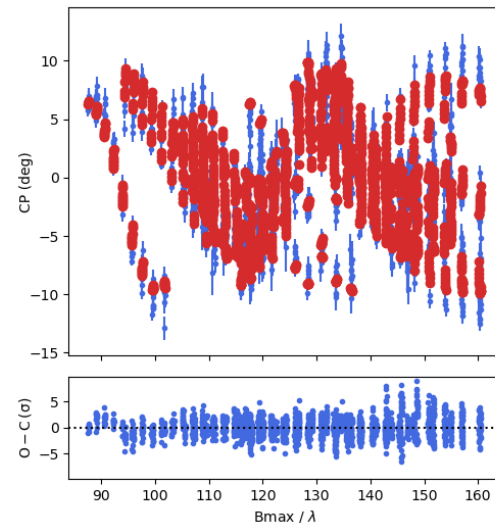
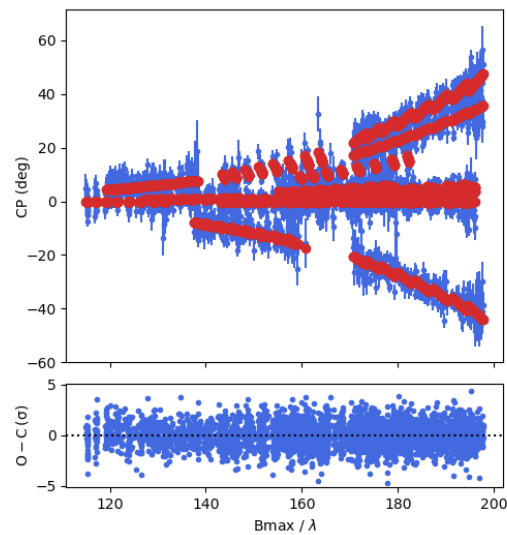
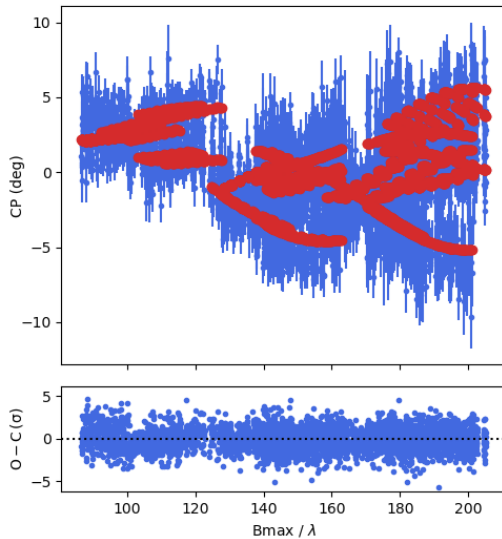
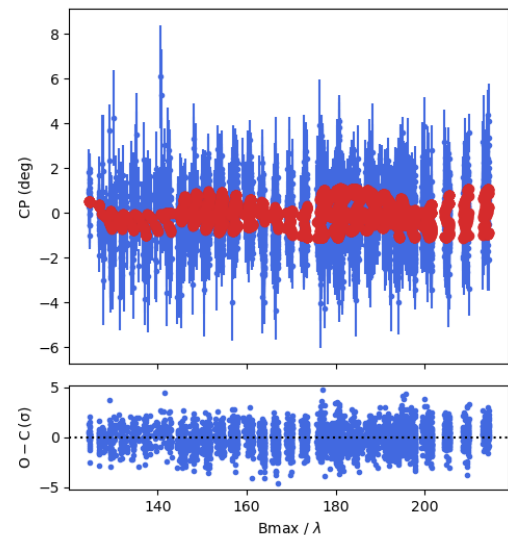
R. Klement, Th. Rivinius, CHARA team, D. Baade, A. Merand



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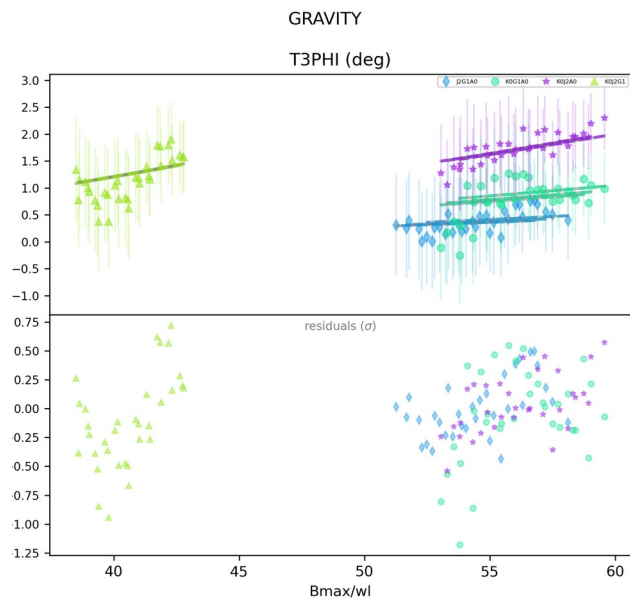
Interferometric detection of companions

- CHARA MIRC-X/MYSTIC campaign 2020-2022 - **45 Be stars with snapshot observations**
 - 3 Be/pre-subdwarf spectroscopic binary candidates confirmed – 1 orbit mapped (but parallax wrong)
 - 7 Be/sdOB detections and mapped orbits → first dynamical masses!
 - 7 γ Cas stars observed → no detections
 - 8 Be stars with detections of wide companions – hierarchical triples with the Be star as the outer component

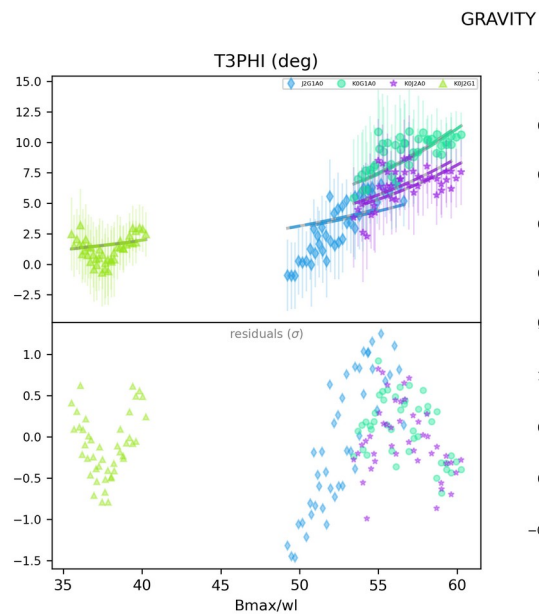


Interferometric detection of companions

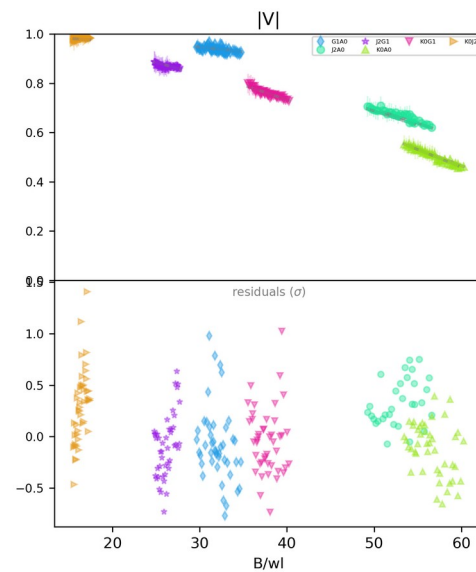
- VLT/IRGRAVITY campaign 2022-2023 - **40 Be stars with snapshot observations** by the end of 2023
 - 1 Be/pre-subdwarf spectroscopic binary candidate confirmed, 3 others ruled out
 - 5 Be/sdOB detections – follow-up mapping of the orbit proposal to be submitted



sep ~ 1.5 mas; f ~3.5%

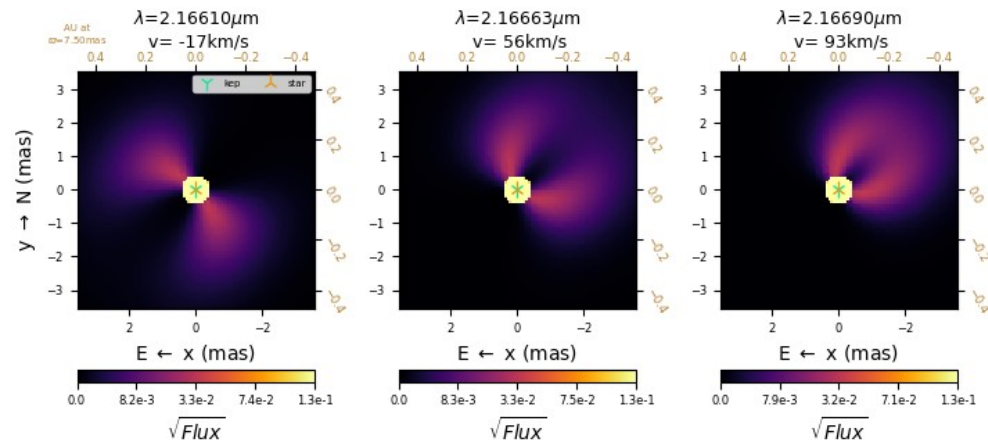
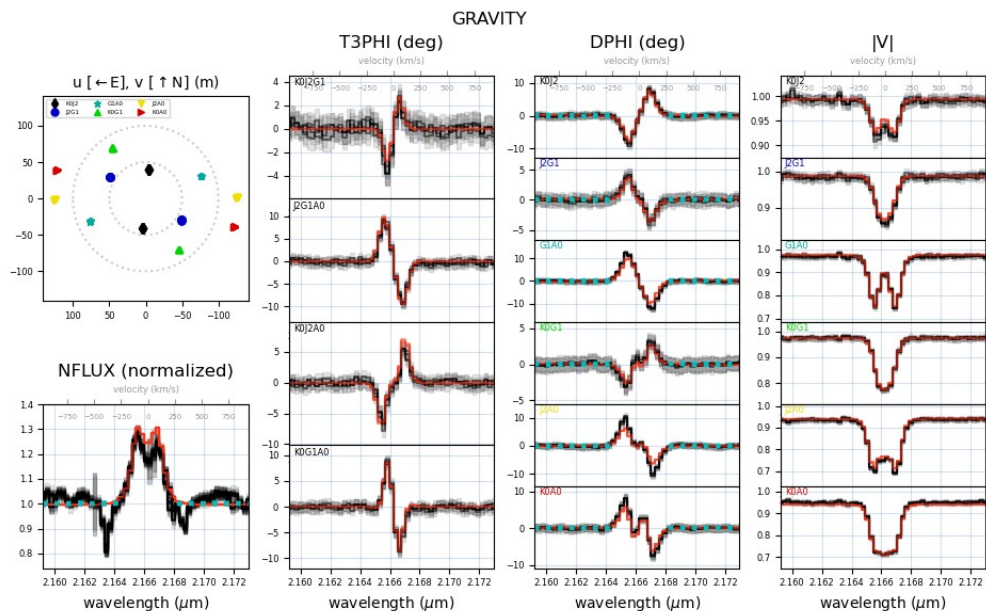


sep ~ 1.5 mas; f ~62%



Interferometric detection of companions

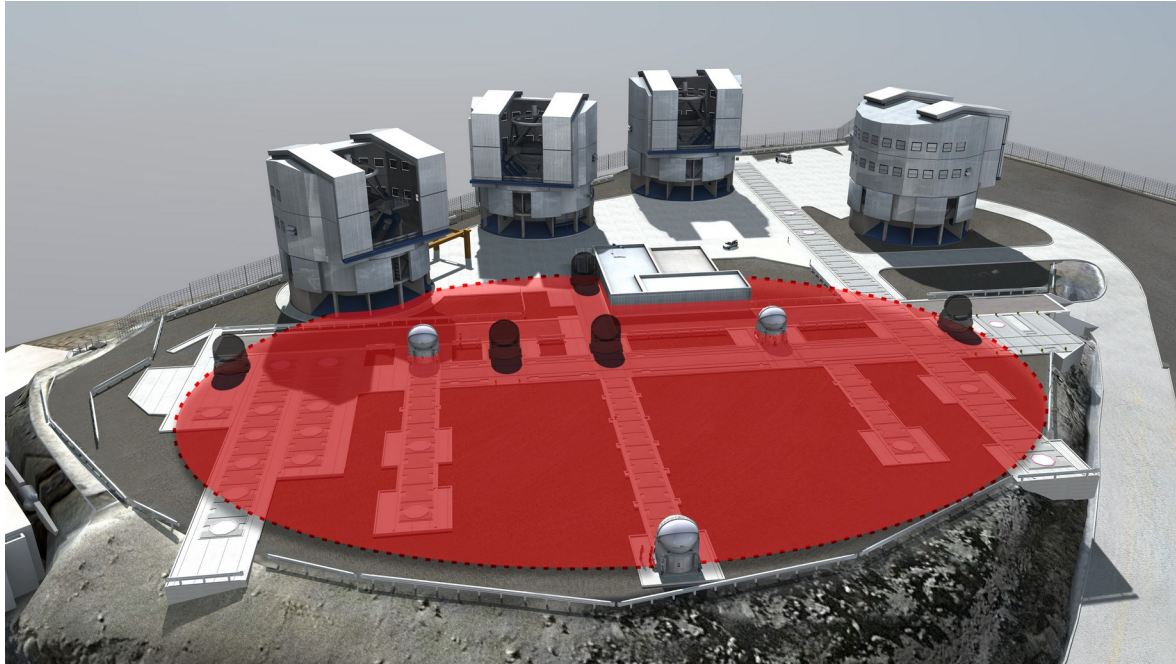
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Keplerian disk modeling with PMOIRE2 (A. Merand)

Subdwarf companions and the origin of Be stars

R. Klement, Th. Rivinius, CHARA team, D. Baade, A. Merand

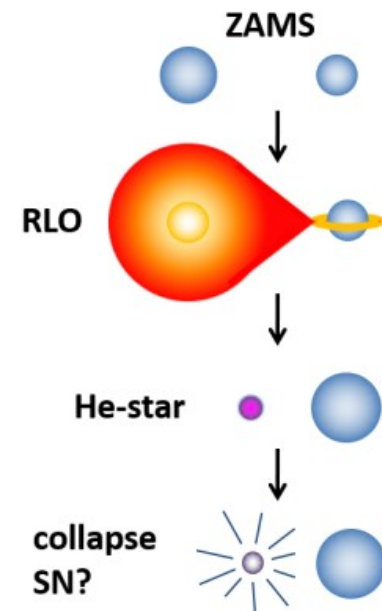


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- **Binary statistics**
- Be/sdOB systems – HR 2142
- Be/pre-subdwarf systems

Binarity among classical Be stars

- ~22 confirmed or strong candidate Be/sdO binaries + 1 confirmed Be/sdB binary
 - Elusive in spectroscopy and interferometry
 - ~5% of a magnitude-limited sample (~300 Be stars) from BeSS - **incomplete**

HD	Name	Type	P	ΔH	a''	a	M Be	M sdO
			[d]	[mag]	[mas]	[AU]	[Msun]	[Msun]
10516	ϕ Per	B1.5V:e-shell	126.7	4.6	5.9	1.1	9.6 ± 0.3	1.2 ± 0.2
41335	HR 2142	B3/5Vnne	80.9	3.8	1.9	1.0	18.0 ± 5.1	0.68 ± 0.13
109387	κ Dra	B6IIIe	61.5	4.5	3.4	0.5	3.65 ± 0.48	0.426 ± 0.043
161306	HD 161306	B3/5Vnne	99.3	3.9	1.8	0.8	6.316 ± 0.250	0.806 ± 0.086
183537	7 Vul	B5Vn	69.5	4.6	2.0	0.6	4.35 ± 0.20	0.485 ± 0.018
191610	28 Cyg	B2.5Ve	359.1	5.2	7.4	1.9	5.20 ± 1.16	1.98 ± 1.17
194335	V2119 Cyg	B2IIIe	63.1	4.1	1.8	0.7	8.42 ± 0.36	1.51 ± 0.30
200310	60 Cyg	B1Ve	147.6	4.8	3.0	1.1	7.93 ± 1.19	1.10 ± 0.24
55606	HD 55606	B0.5Vnnpe	93.8		~ 0.77	~ 0.78	~ 6.2	~ 0.9
58978	FY CMa	B0.5IVe	37.3		0.88-0.93	0.49-0.53	10 – 13	1.1 – 1.5
63462	σ Pup	B1IVe	28.9		1.36	0.45	13.85	0.89
200120	59 Cyg	B1.5Vnne	28.2		0.51-0.59	0.35-0.40	6.3 – 9.4	0.62 – 0.91



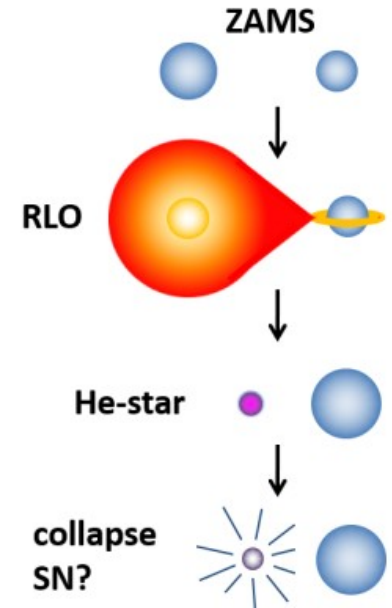
Langer+ 2020

Binarity among classical Be stars

- ~22 confirmed or strong candidate Be/sdO binaries + 1 confirmed Be/sdB binary
- ~25 γ Cas stars (Be/WD systems?) including 8 binaries and 5 candidates
 - Second (case BB) mass transfer from a massive sdO
 - 2% of mag-limited BeSS sample – incomplete?

Name	P (d)	e	Be Sp.type	$M(\text{Be})$ (M_{\odot})	M_{comp} (M_{\odot})	i ($^{\circ}$)	Reference
<i>γ Cas stars</i>							
γ Cas	203.6	0	B0IV	13	0.98*	45	Nemravová et al. (2012)
V782 Cas	122.0	0	B2.5III	9	0.6–0.7*	60–90	this work
HD 45995	103.1	0	B2V	10	1.0±0.1*	46.8	this work
V558 Lyr	83.3	0	B3V	8	0.7–0.8*	60–90	this work
SAO 49725	26.11	0	B0.5III	13	0.2–0.5*	30–90	this work
	137.0	0			0.4–0.7*	30–90	this work
V2156 Cyg	126.6	0	B1.5V	11	0.7–0.8*	60–90	this work
π Aqr	84.1	0	B1V	15	2.4±0.5	70	Bjorkman et al. (2002)
V810 Cas	75.8	0	B1	12.5	0.7–0.8*	60–90	this work

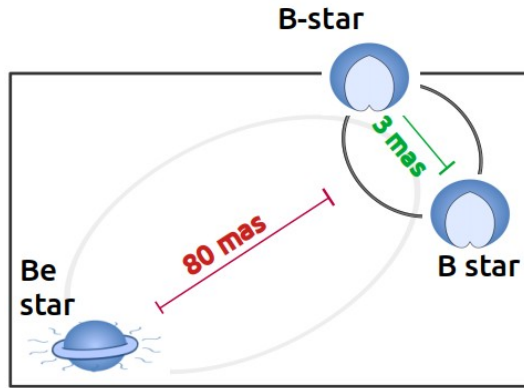
Naze+ 2022



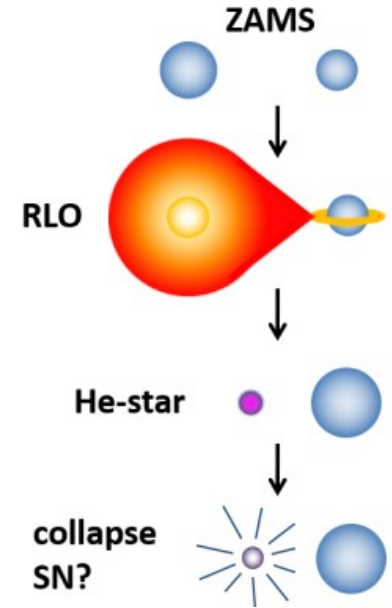
Langer+ 2020

Binarity among classical Be stars

- ~22 confirmed or strong candidate Be/sdO binaries + 1 confirmed Be/sdB binary
- ~25 γ Cas stars (Be/WD systems?) including 8 binaries and 5 candidates
- ~10 Be stars are the outer components in hierarchical triples
 - ~ 1% of BeSS sample – complete?



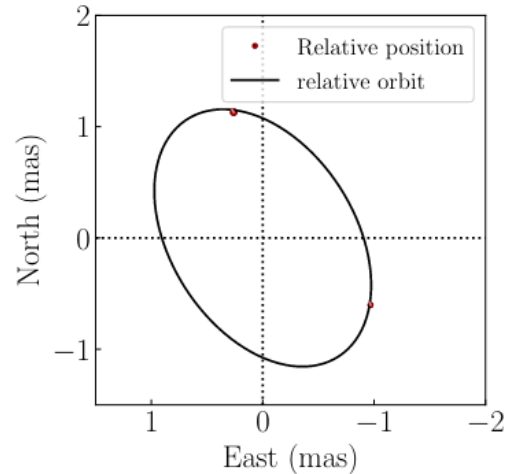
v Gem (Klement+ 2021)



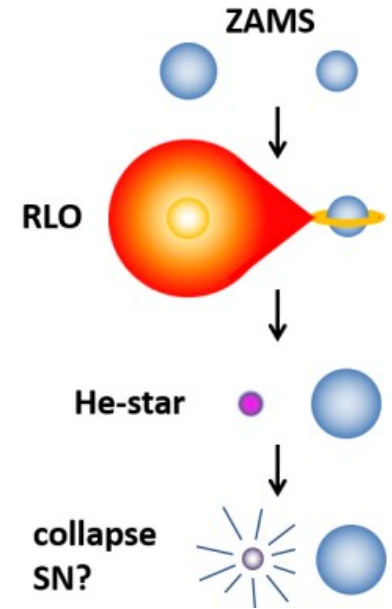
Langer+ 2020

Binarity among classical Be stars

- ~22 confirmed or strong candidate Be/sdO binaries + 1 confirmed Be/sdB binary
- ~25 γ Cas stars (Be/WD systems?) including 8 binaries and 5 candidates
- ~10 Be stars are the outer components in hierarchical triples
- ~7 Be/pre-subdwarf binaries
 - ~ 1% of BeSS sample – complete?



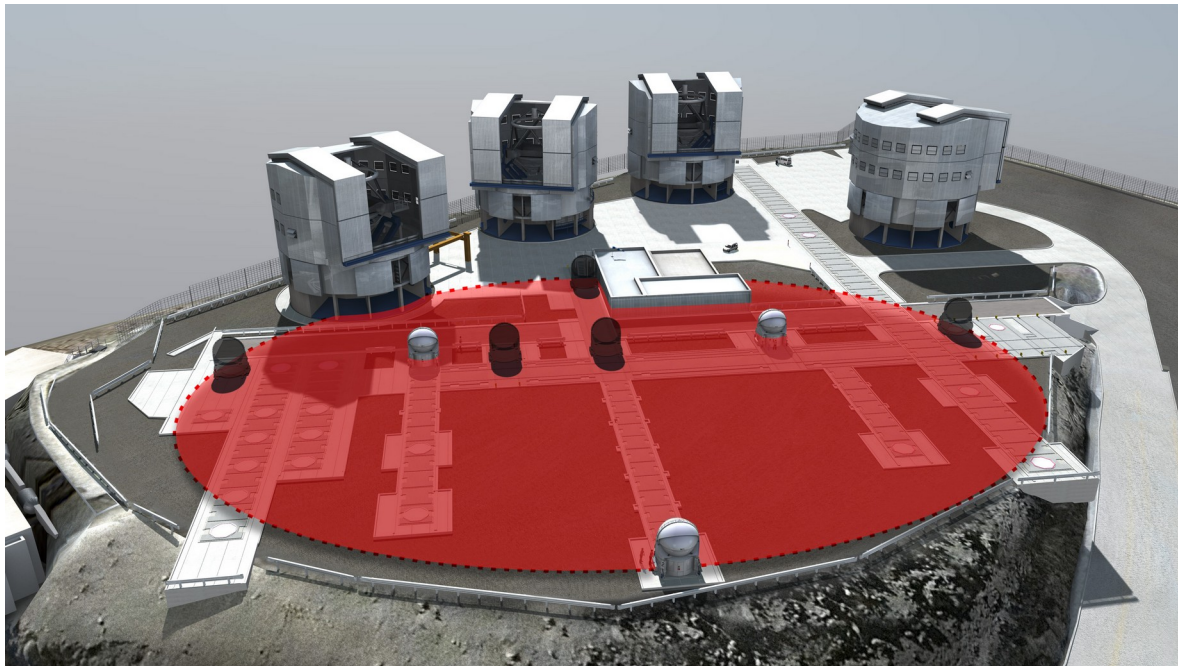
HR 6819 (Frost+ 2022)



Langer+ 2020

Subdwarf companions and the origin of Be stars

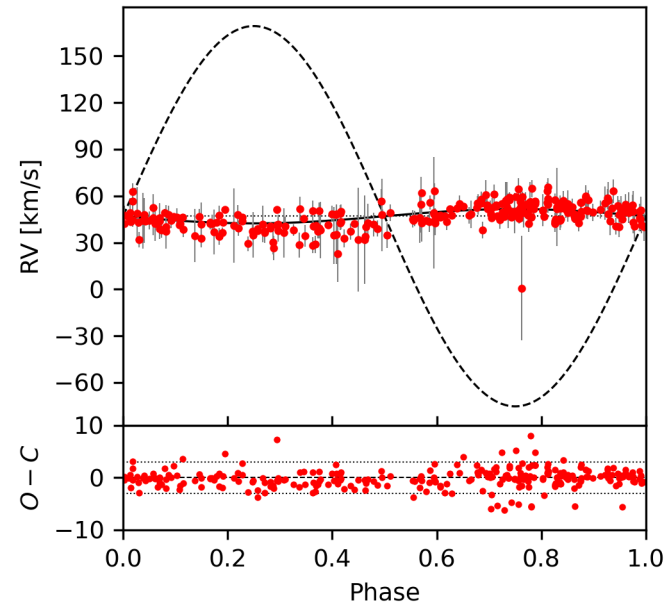
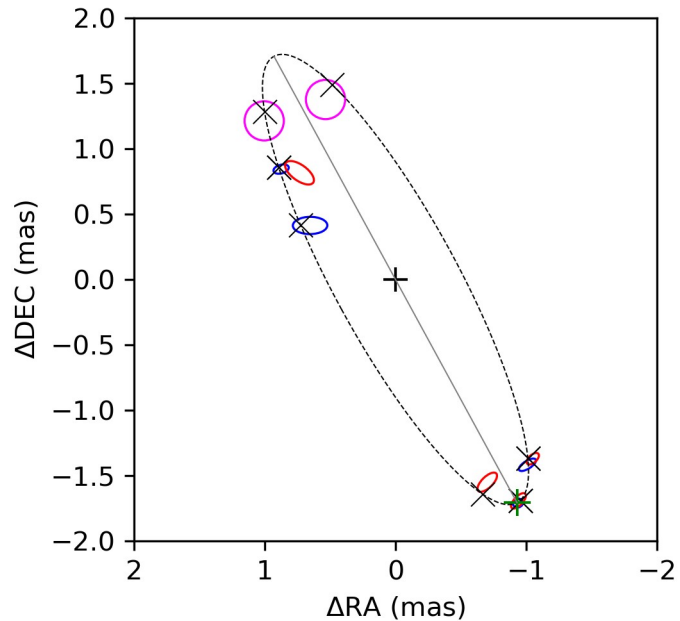
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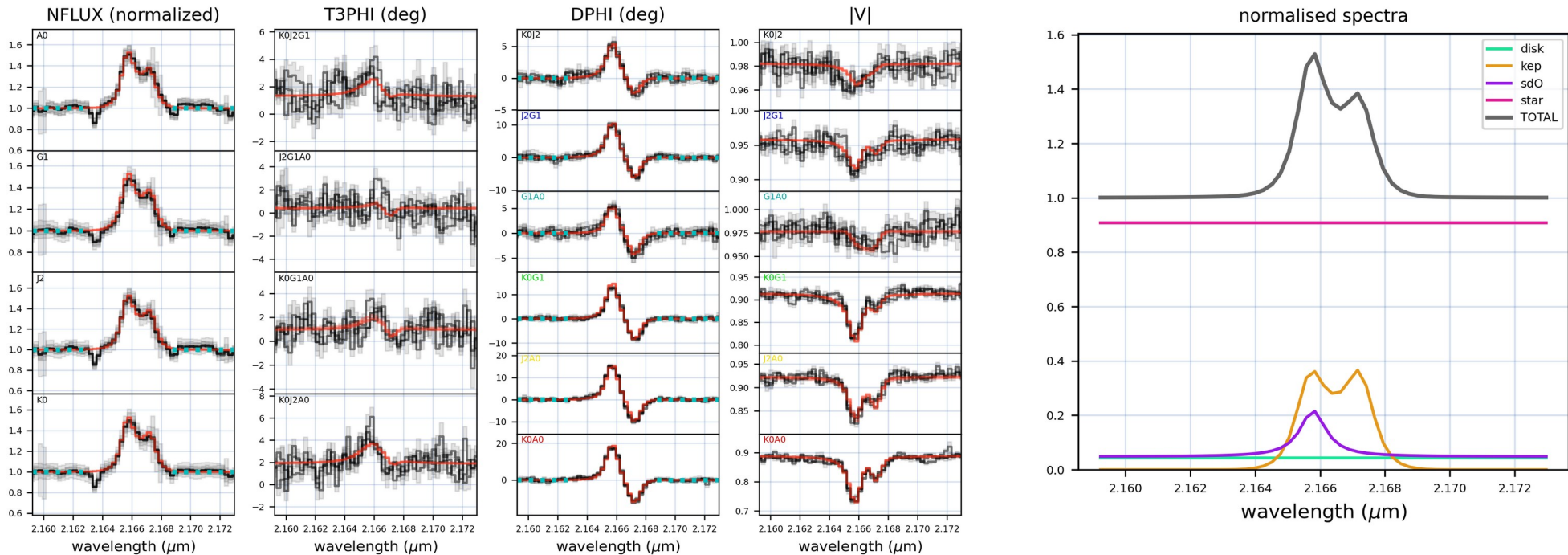
Be/sdOB systems – HR 2142

- Both CHARA and VLTI data
 - CHARA enables easier orbit mapping – better angular resolution, better uv-coverage
 - VLTI enables spectro-interferometry in Bry and HeI 2058 ($R \sim 4000$ across K -band)



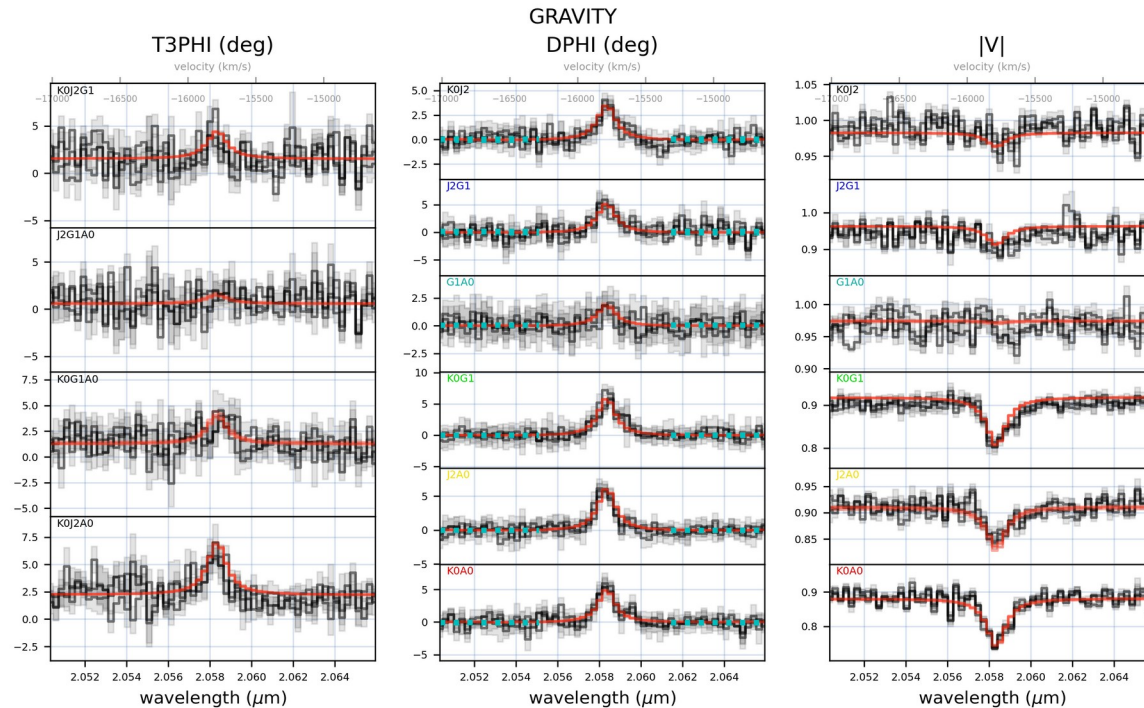
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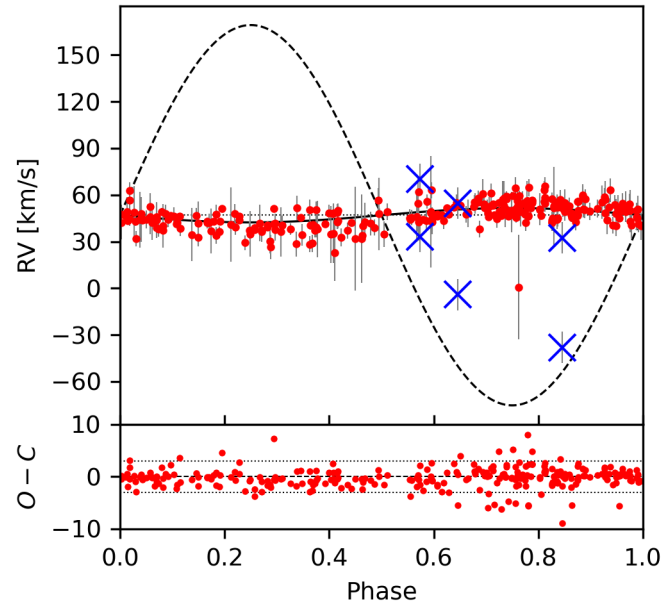
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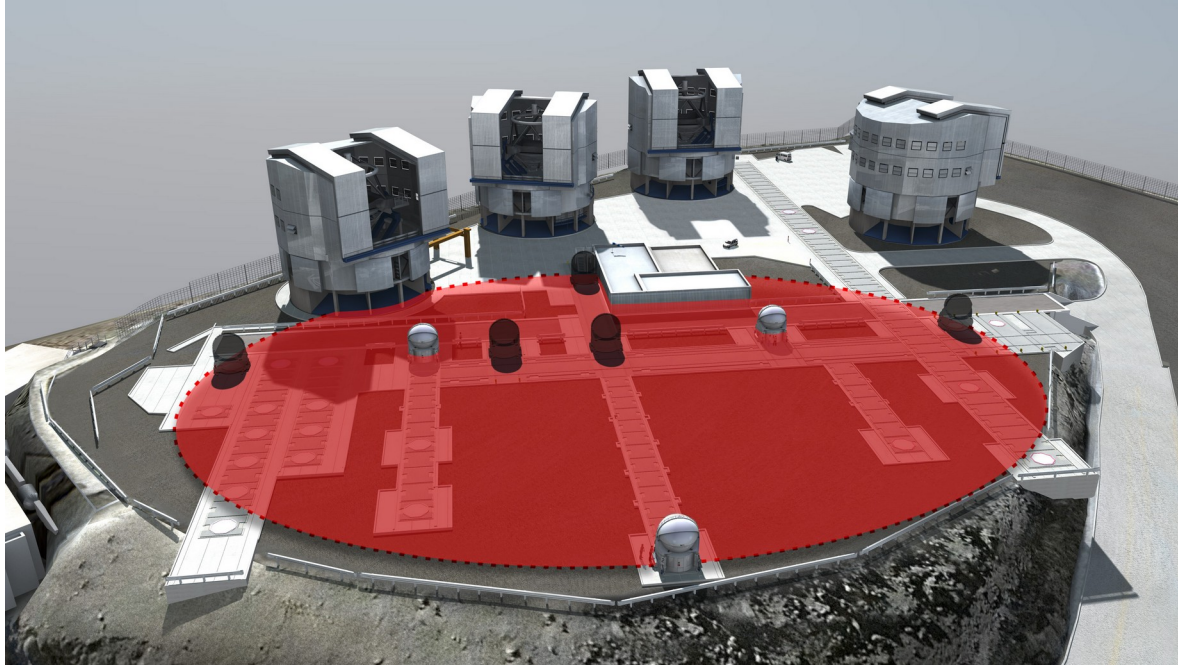
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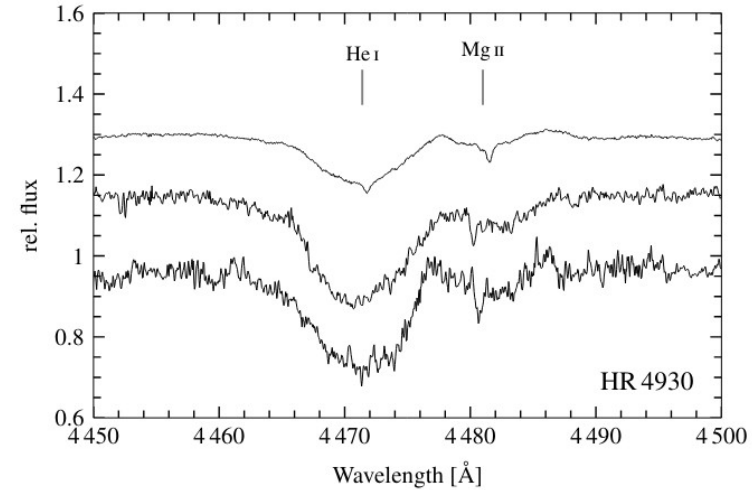
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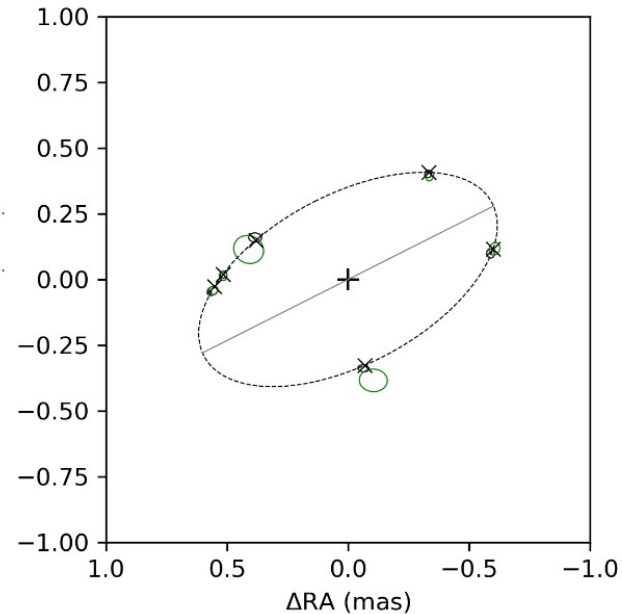
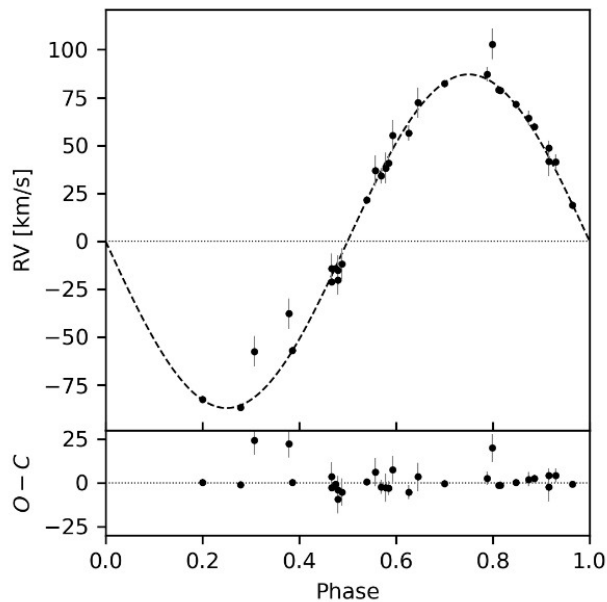
Be hierarchical triples vs. Be/pre-subdwarf binaries

- Quasi-static broad (emission) lines from Be star + narrow periodically moving absorption lines
- The two scenarios can only be distinguished with interferometry
 - Be/pre-subdwarf – *direct detection of the close binary or lack of detection of the wide component*
 - Hierarchical triple with outer Be star – *detection of the wide binary*



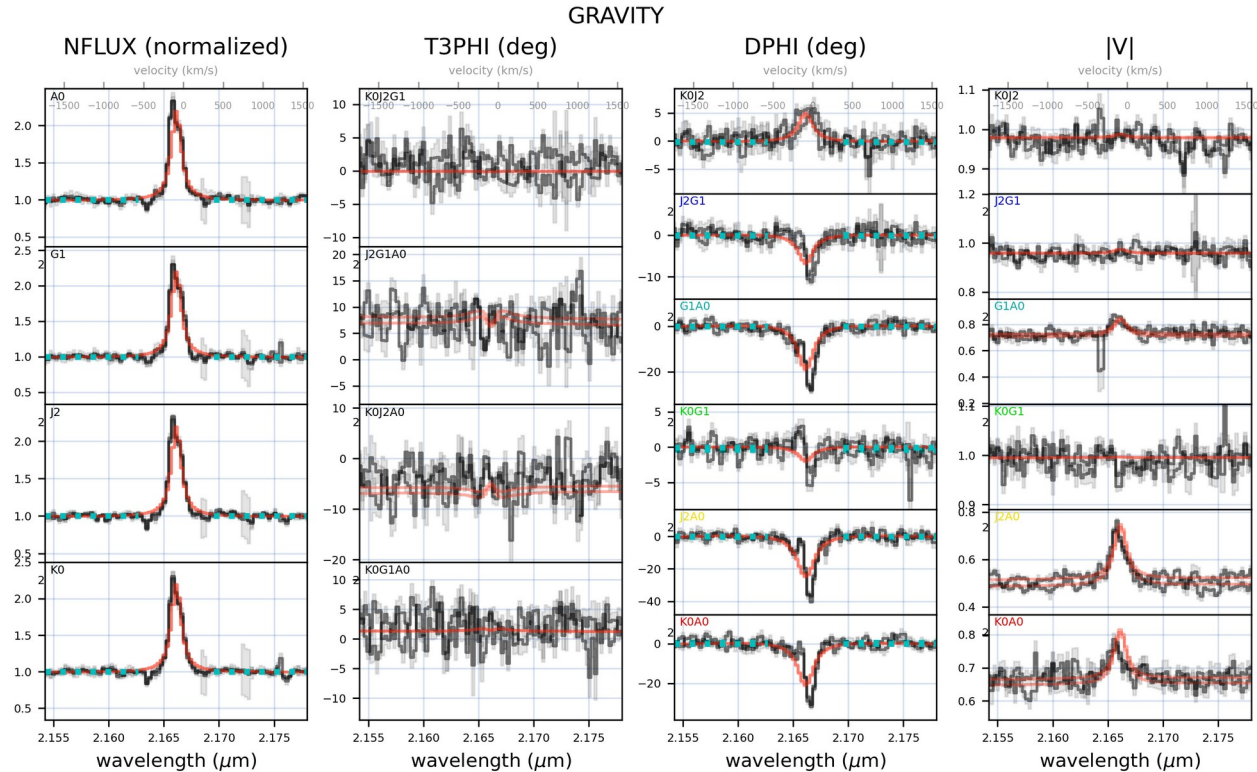
Be/pre-subdwarf systems – V742 Cas

- RVs of narrow-lined component from APO/ARCES spectra (observed by K. Shepard)
- Astrometric orbit mapped with MIRC-X and MYSTIC
- Flux ratio 1:2 – **unclear which component is which**
- Dynamical masses dependent on parallax – but that results in non-physical masses



Be/pre-subdwarf systems – HD 44637

- Emission line from the newly formed Be star – with GRAVITY data we can tell which one is which



Conclusions

- Zoo of multiple systems with a classical Be star
 - Be/pre-subdwarf binaries – of great astrophysical interest
 - Be/sdOB binaries – progenitors of Be/WD binaries?
 - Be/WD binaries – identifiable as BeXRBs of gam-Cas type? Also 4 Be/WD candidates in the SMC
 - Be/NS binaries = BeXRBs
 - Be stars in hierarchical triples, merger products, runaways
 - Other Be binaries – Achernar, delta Sco, Pleione, ...
- First dynamical masses for a sample of Be stars and sdOB companions
 - Only one distance-independent solution – ϕ Per (Mourard+ 2015)
 - At least seven more + several new detections
- Be/pre-subdwarf binaries
 - First representative sample to be published soon

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