Mass loss in Dwarf and Evolved B stars

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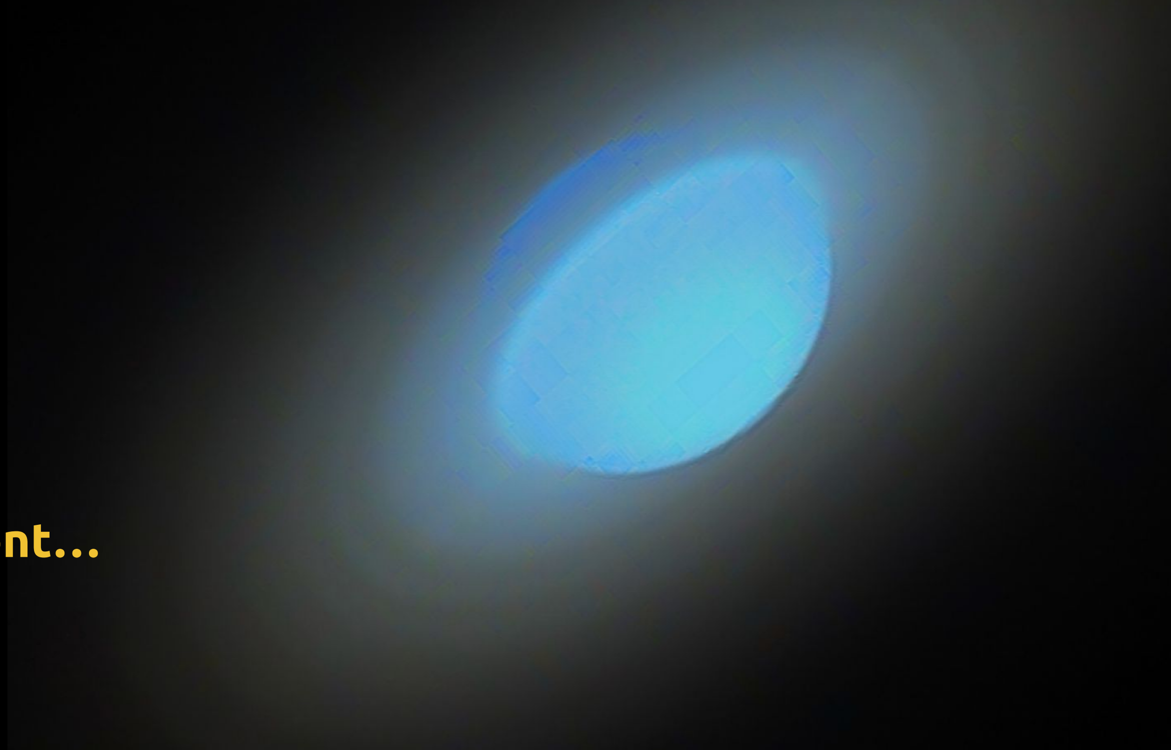
The Be star Achernar in true color (HDUST model)

~~Mass loss in Dwarf and Evolved B stars~~
Mass loss in Be stars

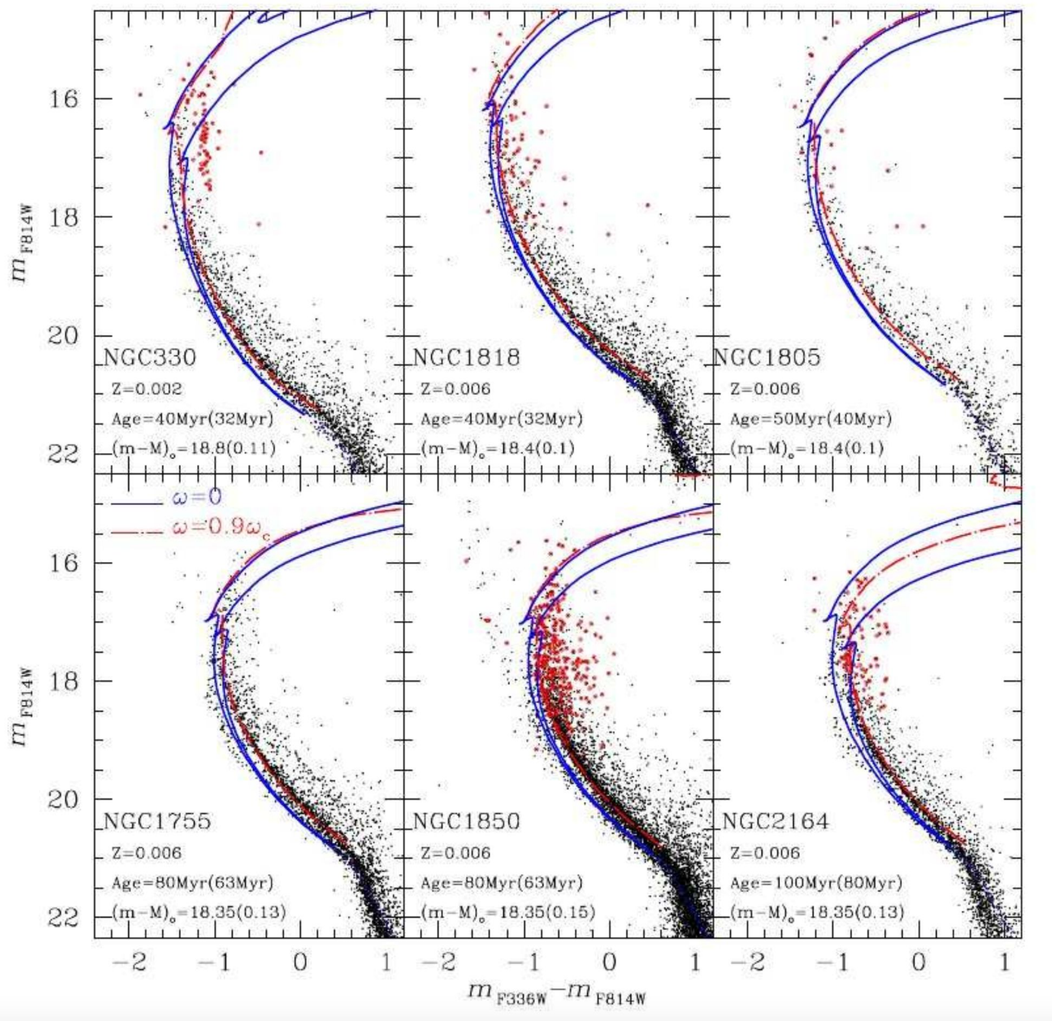


1) Be stars:
    - What are they?
    - Where they come from?
    - Why are they important?
2) News from the **mass loss front…**
3) News from the **disk front…**

The Be star Achernar in true color (HDUST model)

Young Open Clusters

- **Multiple** main sequences
- **Extended** main sequences
- **Uncertain** turn-off points
- What are the causes?
  - **Binarity**
  - **Fast rotation**, etc.
- **Be stars certainly are part of the explanation...**



The **black dots** represent normal stars

The **red dots** indicate Halpha emitters

(Milone+2018)

Be Stars: overview

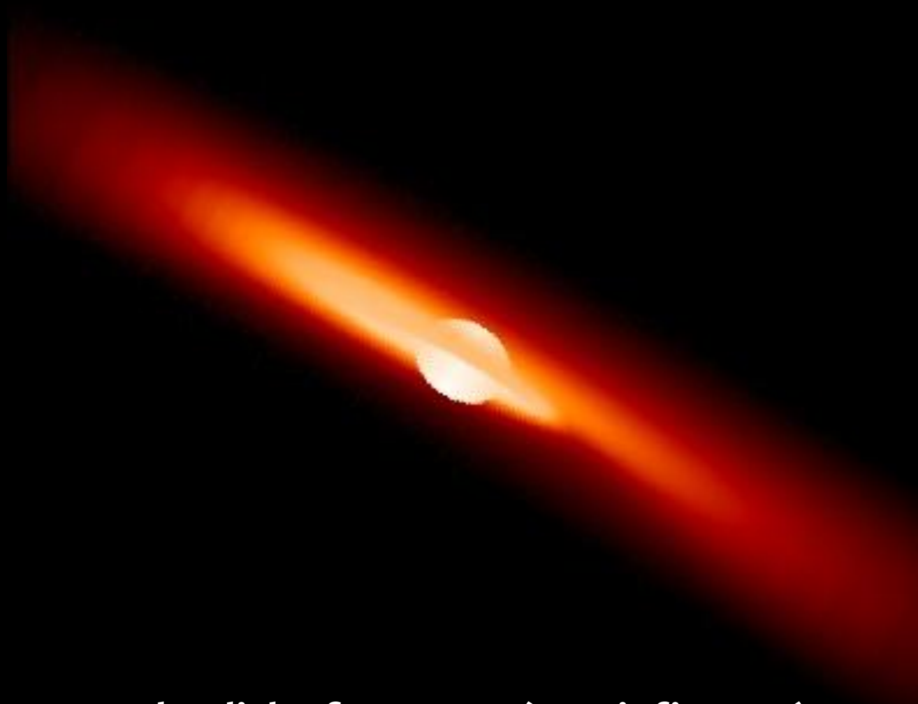
Three main characteristics:

1) They are **all fast rotators**
2) They sometimes possess a **circumstellar disk**
3) **All are non-radial pulsators**

Spectroscopy is historically (by very far) the main source of information about the central star and its disk

Polarization and **photometry** also important

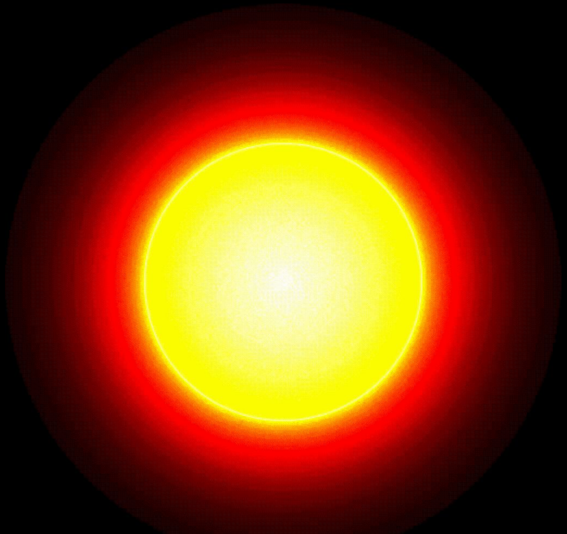
Recently, **space photometry** playing major role



The disk of zeta Tau (Carciofi+2009)

The Central Star

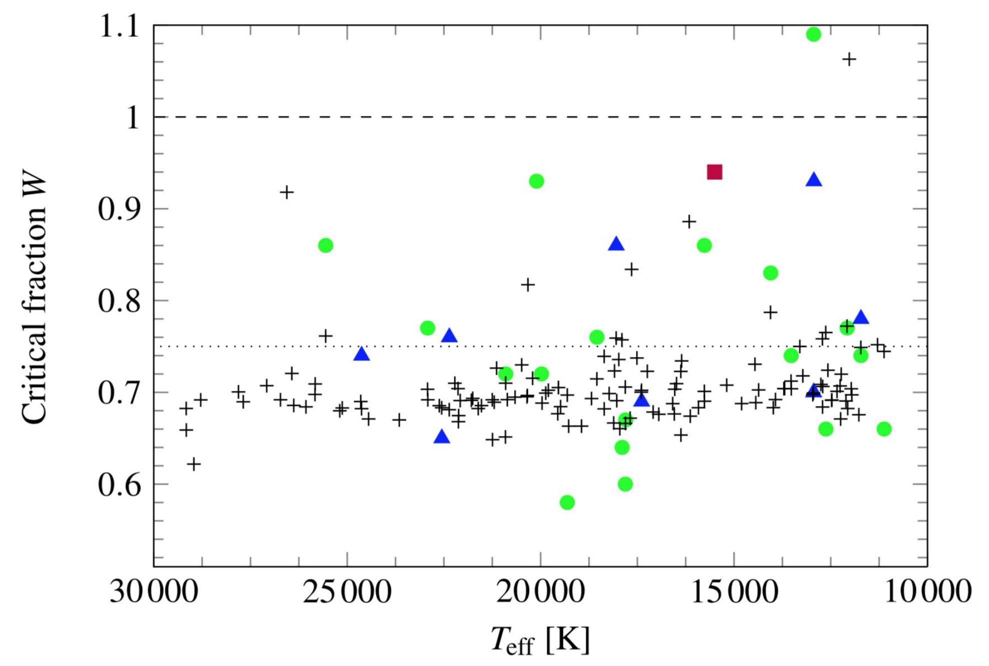
- **Main sequence** (or post-MS?)
- Most rapid massive rotators known to exist
  - **Geometrical flattening**
  - **Gravity darkening** ➜ poles are much hotter than the equator
  - **Internal coupling**
- Differences vs. slower rotators (normal B stars) in **structure**, **chemistry**, **evolution** etc.
- Be stars are key to models of fast-spinning stars



Achenar is estimated to be rotating at **88% of the critical velocity**

(shown are HDUST models)

The Central Star: rotation



Crosses (Fremat et al. 2005)

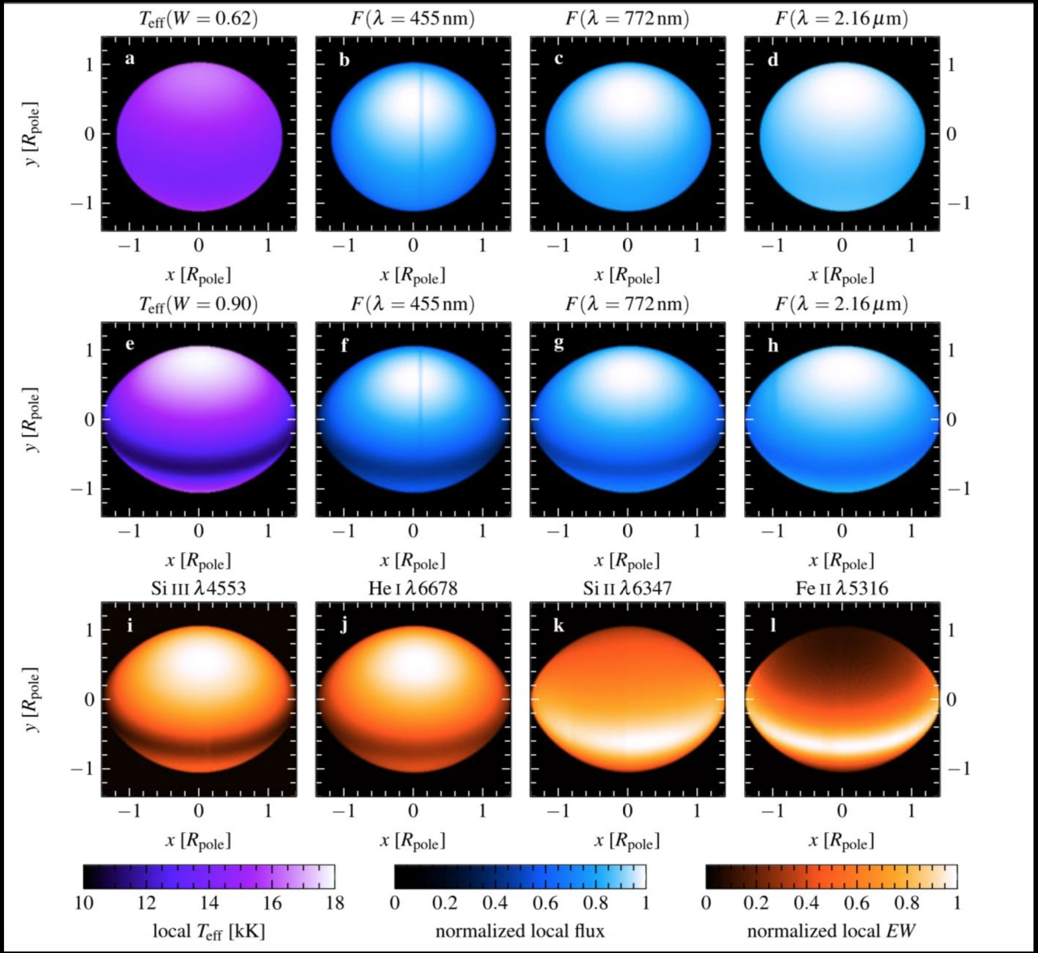
Green circles - shell stars
(Rivinius et al. 2006)

Blue Triangles - interferometry
(Meilland et al. 2012)

Achernar (Domiciano de Souza et al. 2014)

Rotational rates of Be stars derived from different techniques
(Rivinius, Carciofi and Martayan 2013)

The Central Star: rotation



W = 0.62

W = 0.90

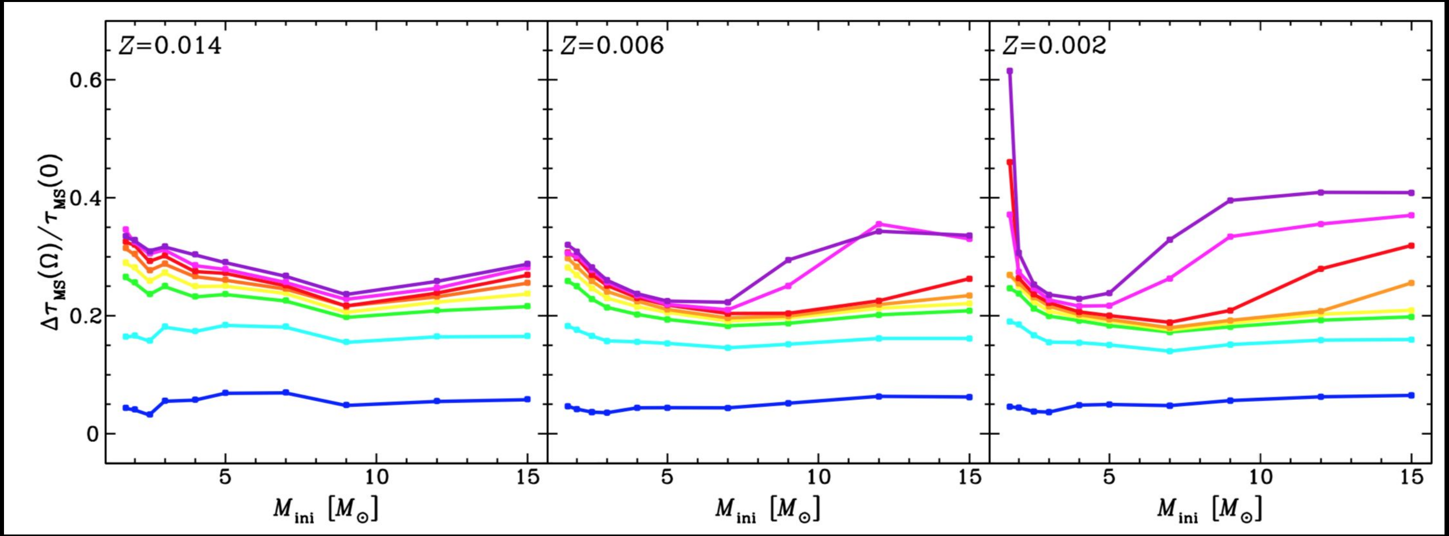
Surface Temperature

Line absorption

(Rivinius, Carciofi and Martayan 2013)

The Central Star: rotation

(Georgy et al. 2013)

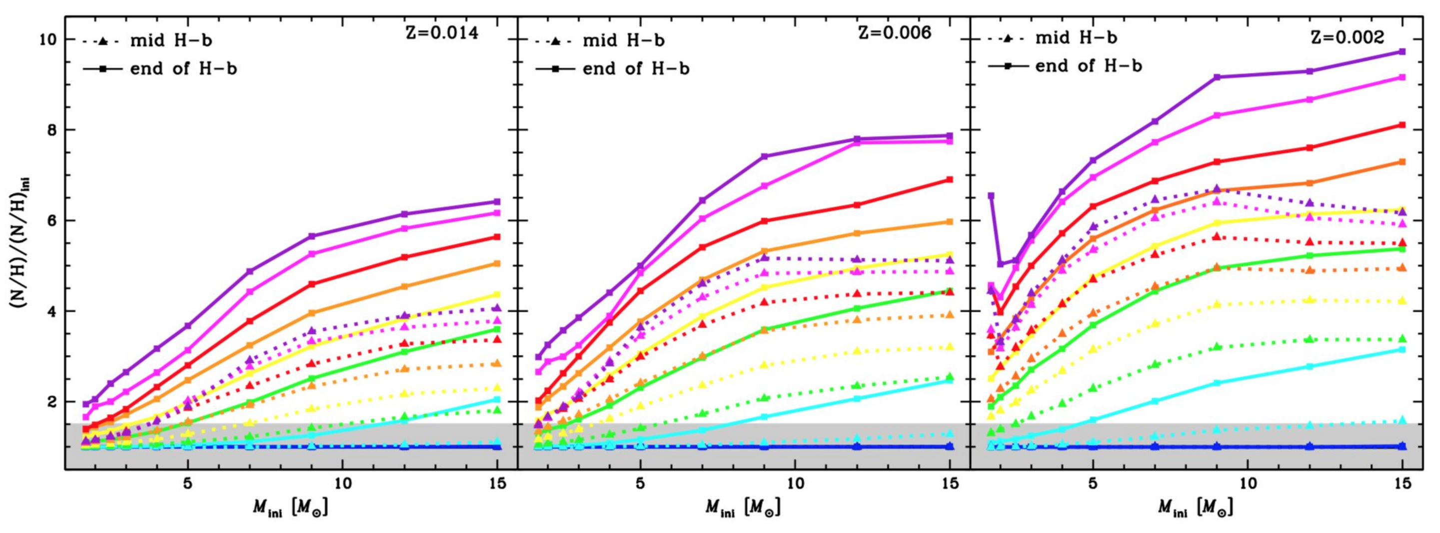


MS lifetime enhancement as a function of mass & for different metallicities

Different colors indicate different rotation rates, from ***W = 0.1*** to **W = 0.95**

The Central Star: rotation

(Georgy et al. 2013)



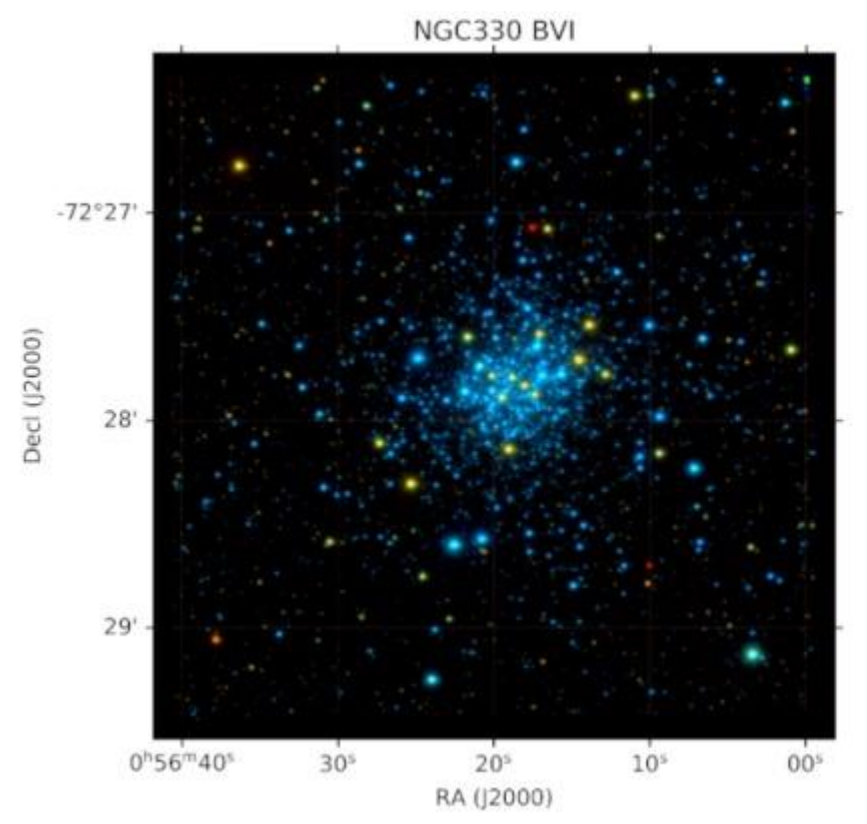
Chemical enrichment at the surface as a function of mass & for different metallicities

Different colors indicate different rotation rates, from ***W* = 0.1** to ***W* = 0.95**

Be Stars: incidence

- Be stars are **quite common**
  - 5-20% of all B stars in the Galaxy
  - Up to 50% (or more) in the SMC
  - Recent results indicate ~ 60% in some spectral subtypes in the SMC! (Navarete et al. 2024)

Right: composite **BVI image** of the young stellar cluster NGC 330



Navarete et al. (2024)

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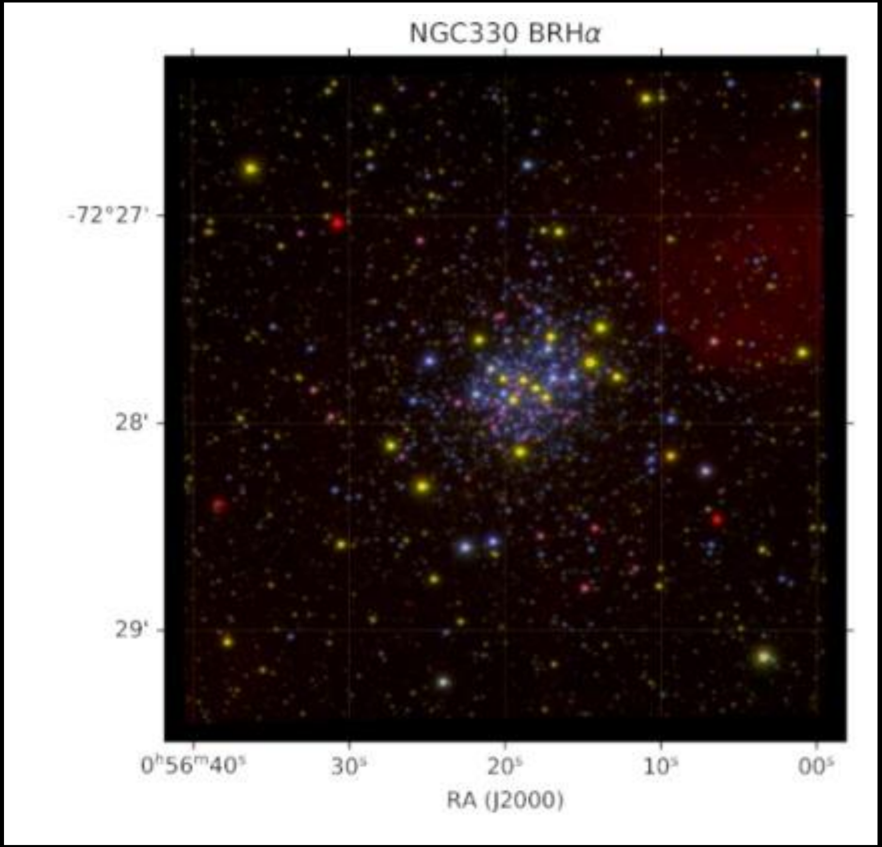
Right: composite **BVI image** of the young stellar cluster NGC 330

Red/pink are almost all Be stars!



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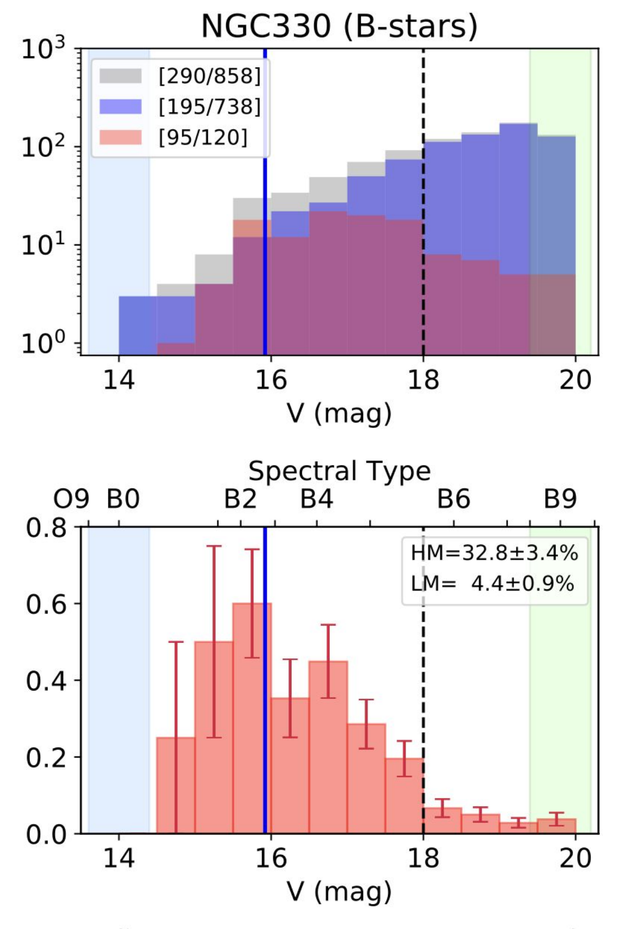


Navarete et al. (2024)

Be Stars: formation scenarios

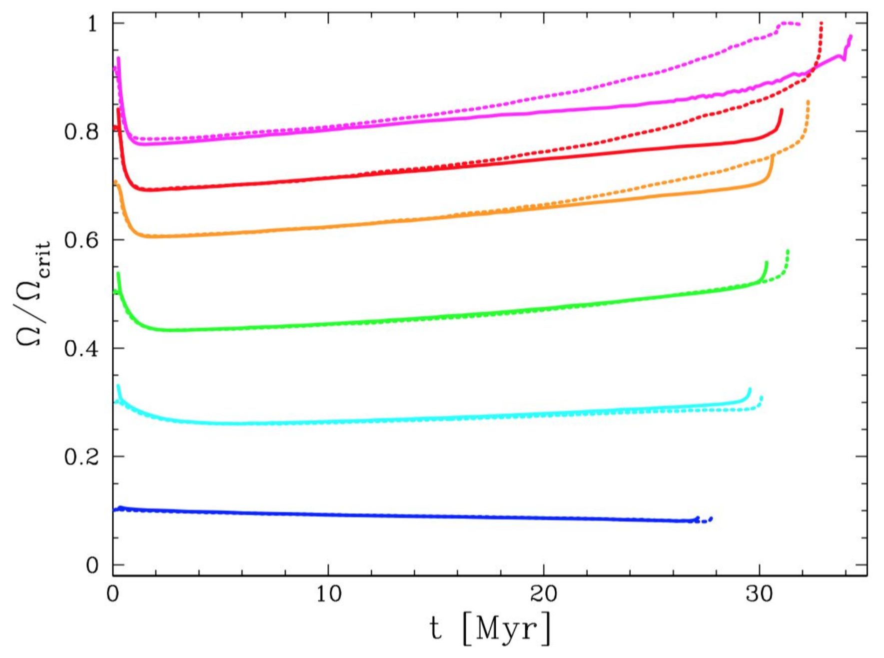
1) Be stars are born as rapid rotators

- Both models and observations still quite uncertain
- Key point: there exists Be stars even in the youngest YOCs known

2) Evolutionary spin-up

- Fast rotation already at $t = 0$
- **Angular momentum is transferred from the contracting core to the surface**

(Granada et al. 2013)



Evolution of the **rotational velocity vs. time**, for stars with different velocities at the ZAMS

Be Stars: formation scenarios

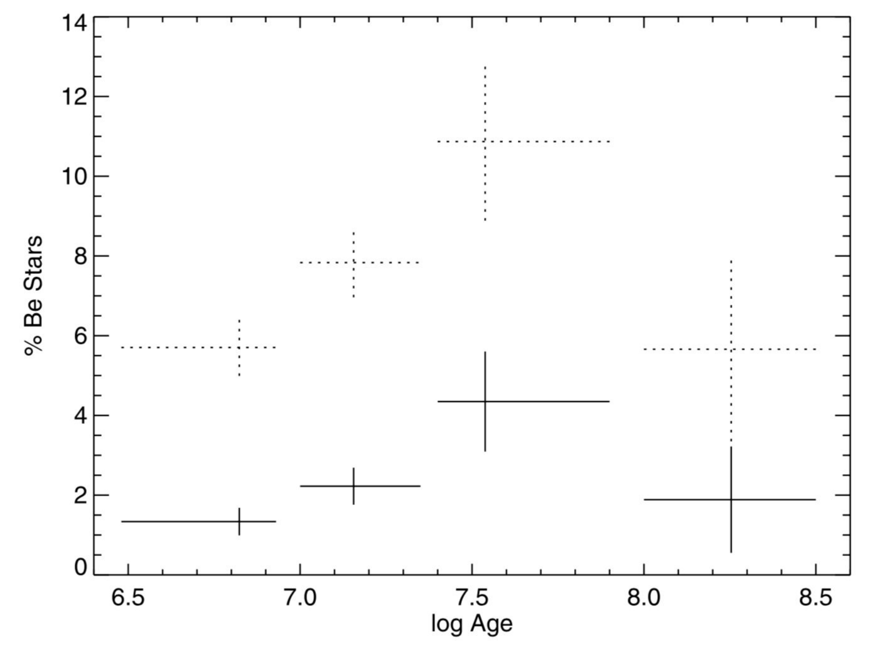
(McSwain & Gies 2005)

2) Evolutionary spin-up

One of the predictions of the evolutionary spin-up scenario is that **once a Be star reaches the critical limit, it stays there until the end of the MS**

However, cluster studies suggests that the Be/(B+Be) fraction **does not peak at the TAMS**

What is causing this? Unclear at the moment…

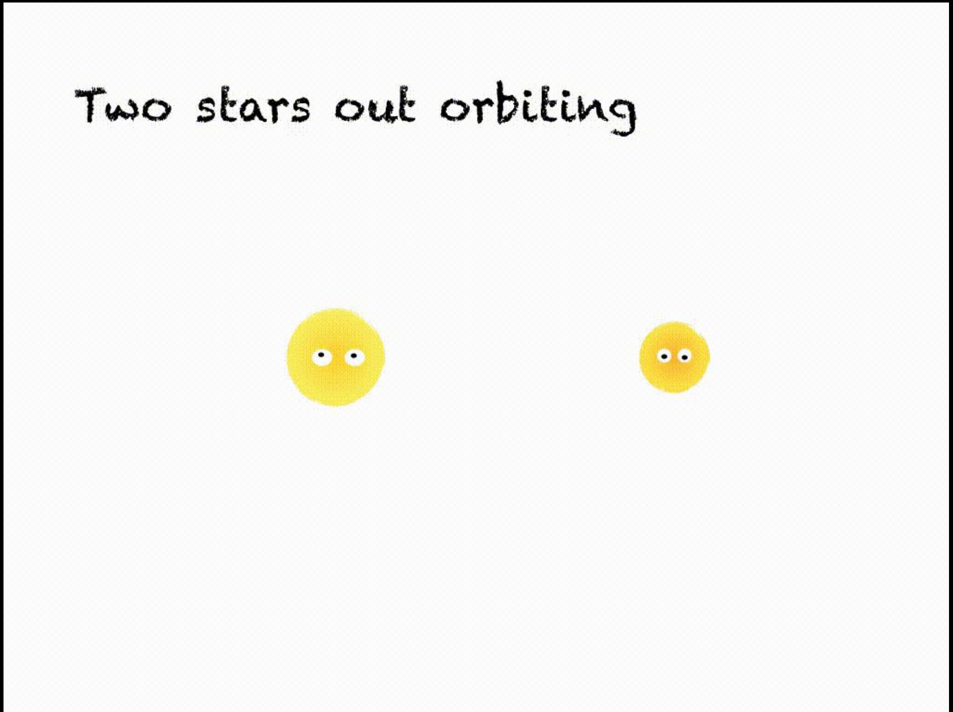


Be/(B+Be) as a function of age

Be Stars: formation scenarios

3) Binary evolution

- Star was spun up in a past mass & angular momentum exchange phase
- **Primary (mass & AM donor)** evolves to become a sdO or sdB star
- **Secondary (mass & AM gainer)** evolves to become a fast-spinning B star
- End system in **nearly circular orbit**
- Wang+2018 and others: over 20 systems Be+sdOB known ➜ **why so few?**



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Where do Be stars come from?

Born as fast rotators

vs.

Evolutionary spin-up

vs.

Binary evolution

IMPORTANT: At least some AM transfer is necessary
to counteract the spin-down as the star expands during the MS

**The truth likely is a
combination of the processes…**

Recent spur of interest in the literature

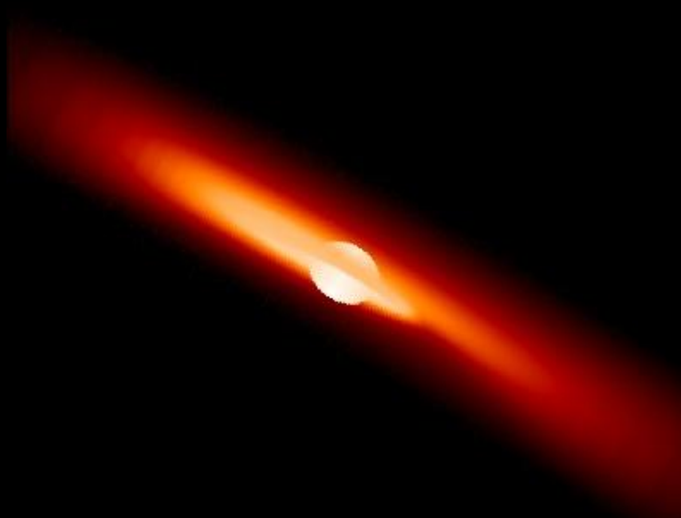
Be Stars: the disk

(Carciofi et al. 2009)

- **Brightest example pieces to study disk physics**, with impacts on all scales
- Created by the star through **mass loss**
  - Matter is <u>somehow</u> ejected from the star
  - **Viscous diffusion transports matter and AM outwards**
- Viscous Decretion Disk (**VDD**) Model. Ingredients:

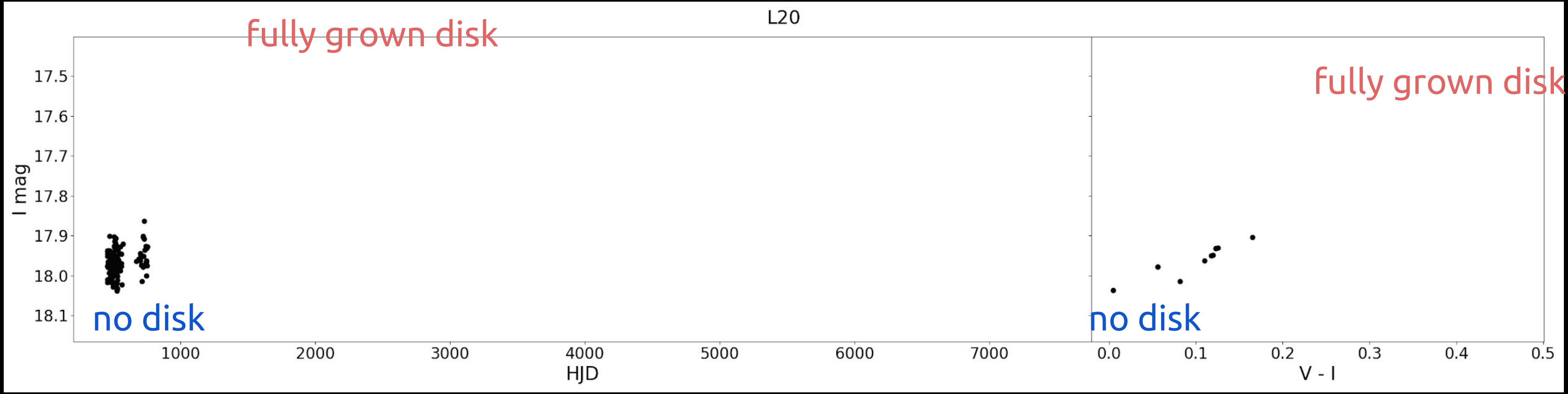
  1) **Viscosity** (alpha disk)

  2) **Mass** and **angular momentum injection rate**
- **Intrinsically variable** on several timescales



Model image of zeta Tau's disk showing a one-armed density wave

Disk variability



Mass loss in action…

Lightcurve of Be star SMC_SC5_32652

Outburst stars at HJD~1600, building in a disk that makes the system **brighter and redder**

Dissipation begins at HDJ~2500. System goes back to baseline along 14+ years!

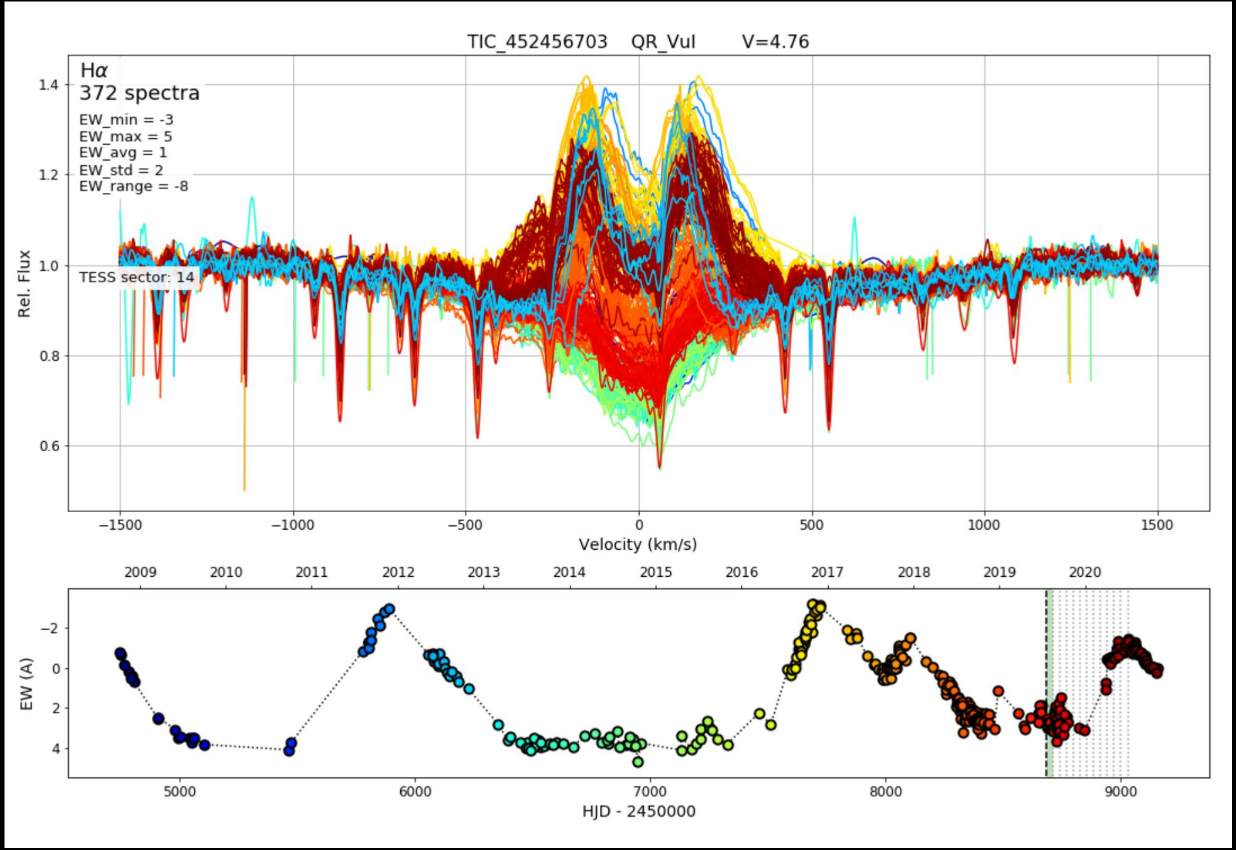
Disk variability

Spectroscopic variability of the Be star QR Vul

(data BESS database)

At least two complete cycles of disk formation/dissipation

Third one ongoing



How a Be disk is formed?

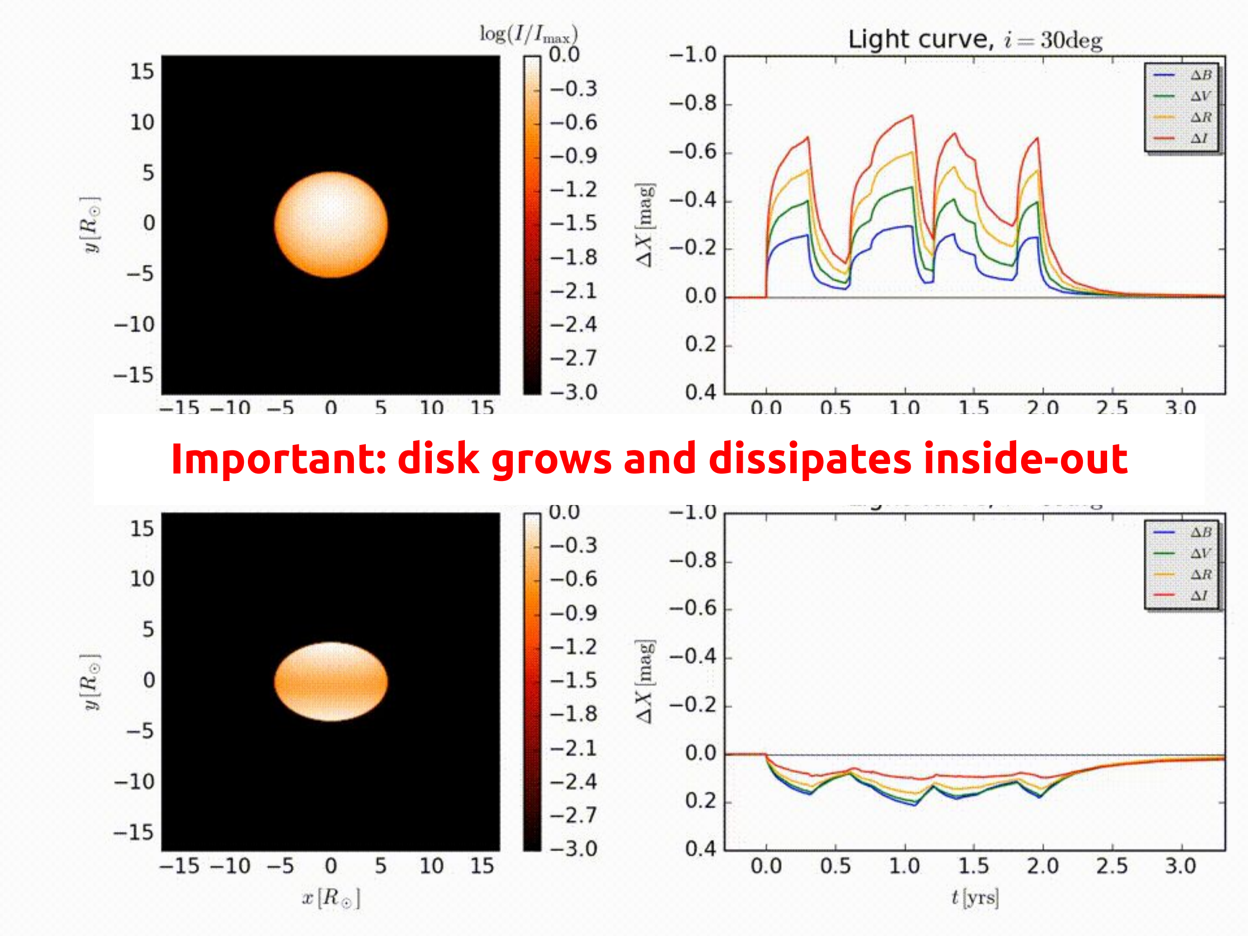
Main ingredients:

1) Material is **ejected from the star**, most likely close to the equator
2) Part of the material acts like a **donor of AM momentum**, falling back to the star. In typical models, 99.9% of the ejected mass falls in this category
3) The material that gains sufficient angular momentum attains progressively larger orbits, making the disk grow ➜ **disk grows inside out**
4) When mass loss is interrupted, **the star no longer supports the disk**, and its inner part is reaccreted back to the star
   ➜ **disk dissipates inside out**

Disk growth and dissipation

Pole-on case

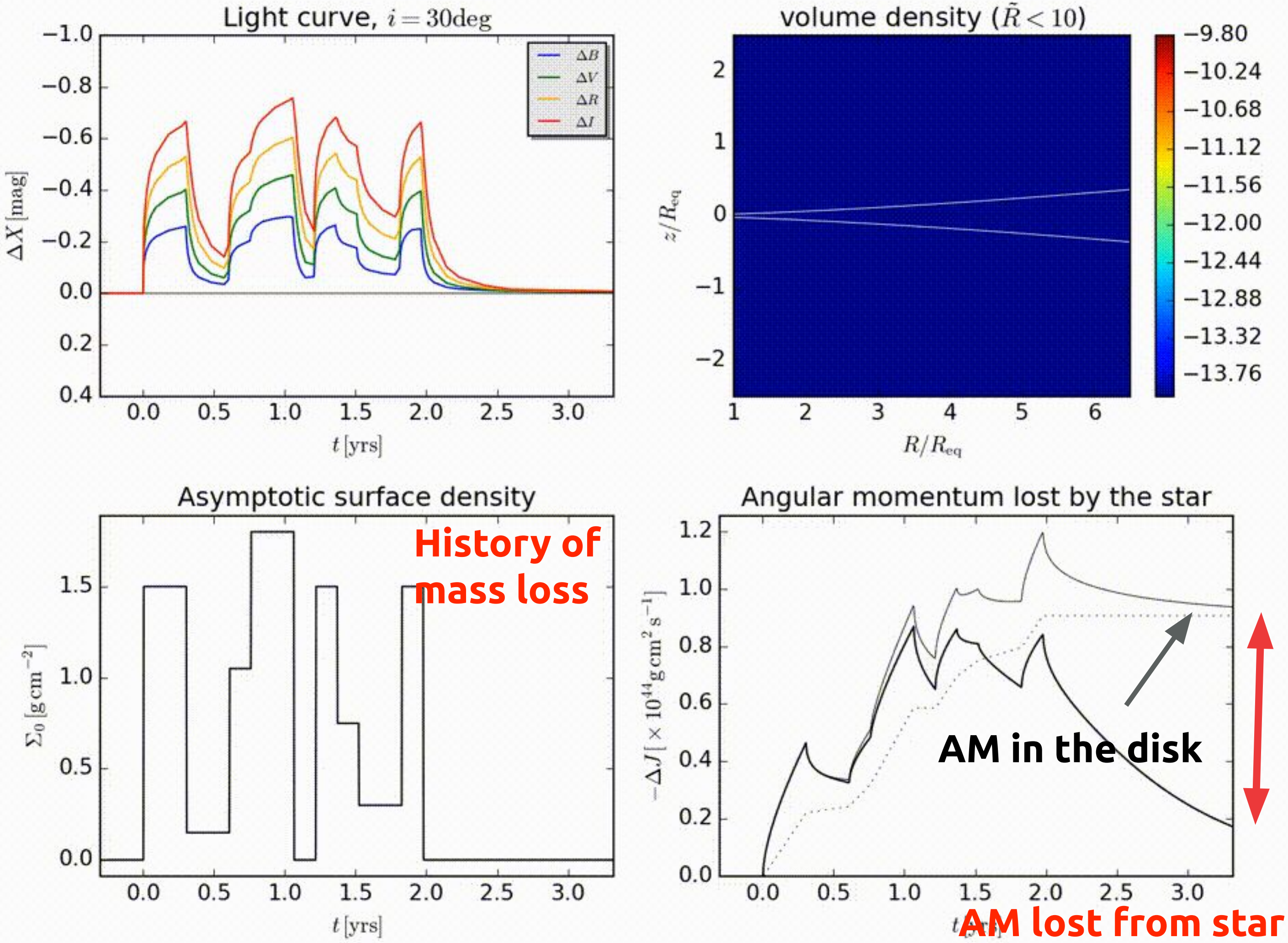
Edge-on case (shell star)



Important: disk grows and dissipates inside-out

Calculations using the HDUST & SingleBe codes

Disk growth and dissipation



History of mass loss

AM in the disk

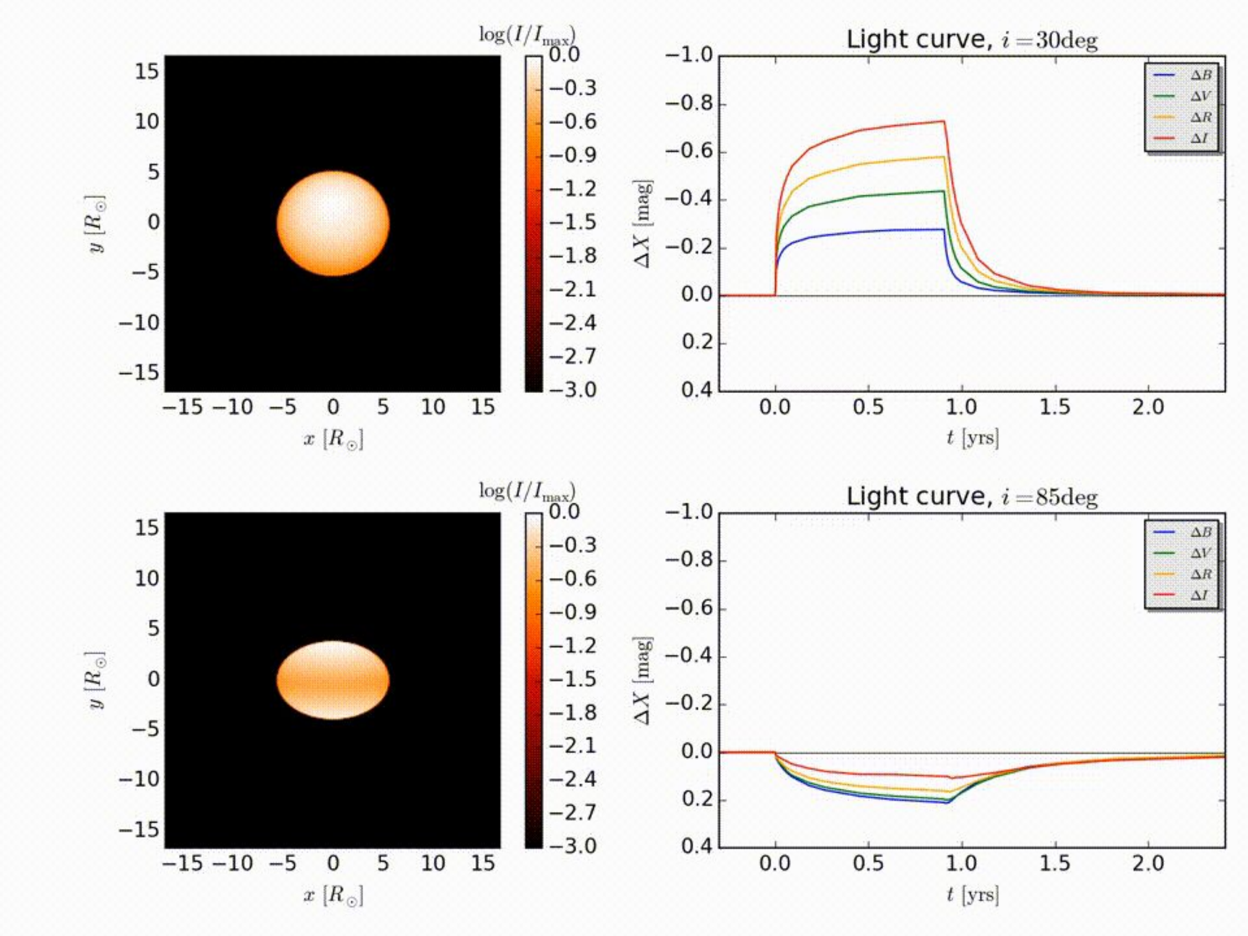
AM lost from star

Calculations using the HDUST & SingleBe codes

Isolated disk events

Pole-on case

Edge-on case
(shell star)



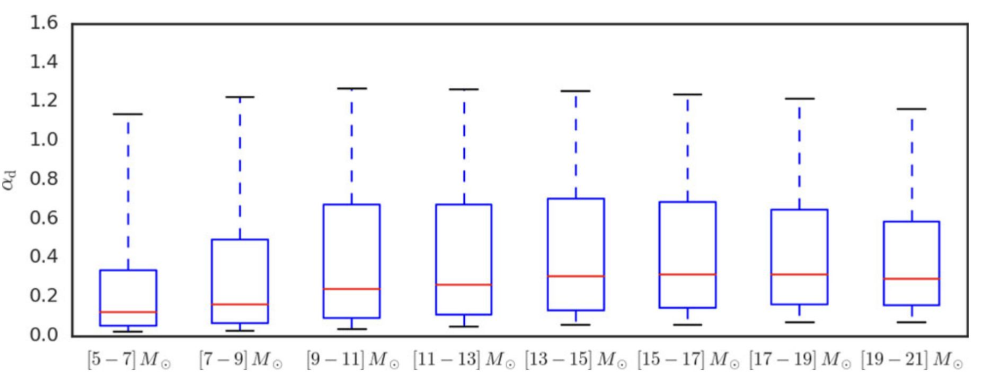
Fitting disk events

Rímulo, Carciofi et al. (2018)

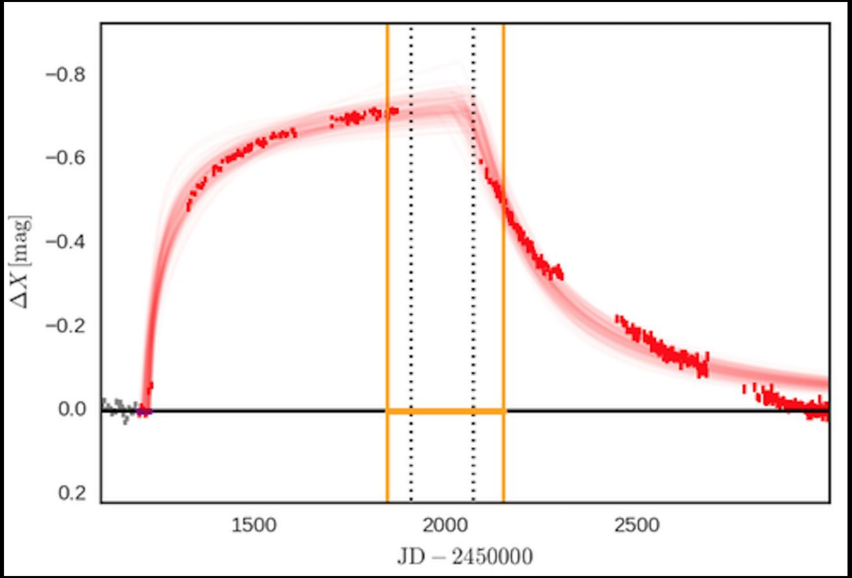
By modeling a disk event we can obtain

- The viscosity of the disk
- The rate of AM & mass loss

(Granada+2013, Ghoreyshi+2022)



Estimated values of the viscosity parameter for a sample of 54 SMC stars



Red dots: observations

Red lines: models

Mass loss in Be stars

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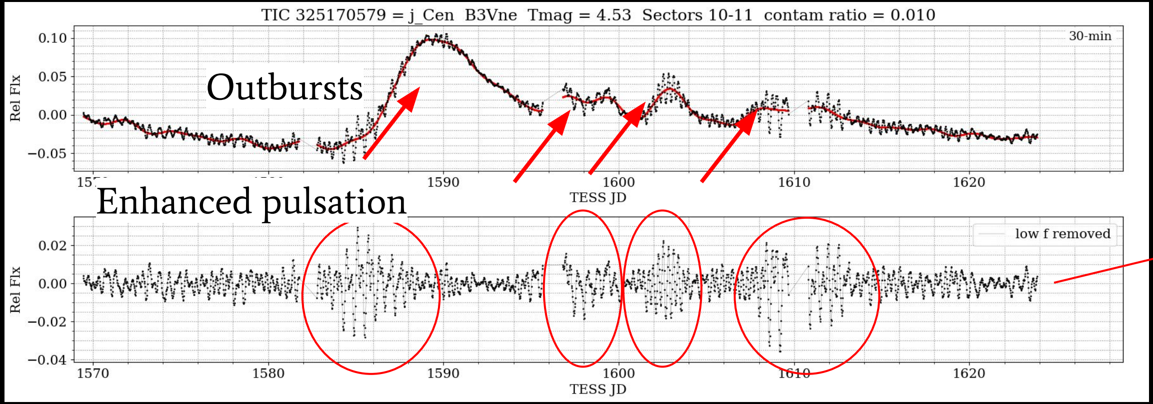
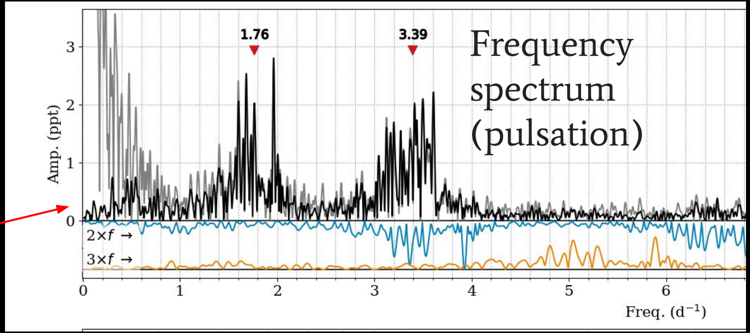
The Be star Achernar in true color (D. M. Faes)

The disk: mass injection



TESS photometry of j Cen



Asteroseismology : determines interior stellar properties by quantifying pulsation

~500 stars observed by TESS (Labadie-Bartz+2022)

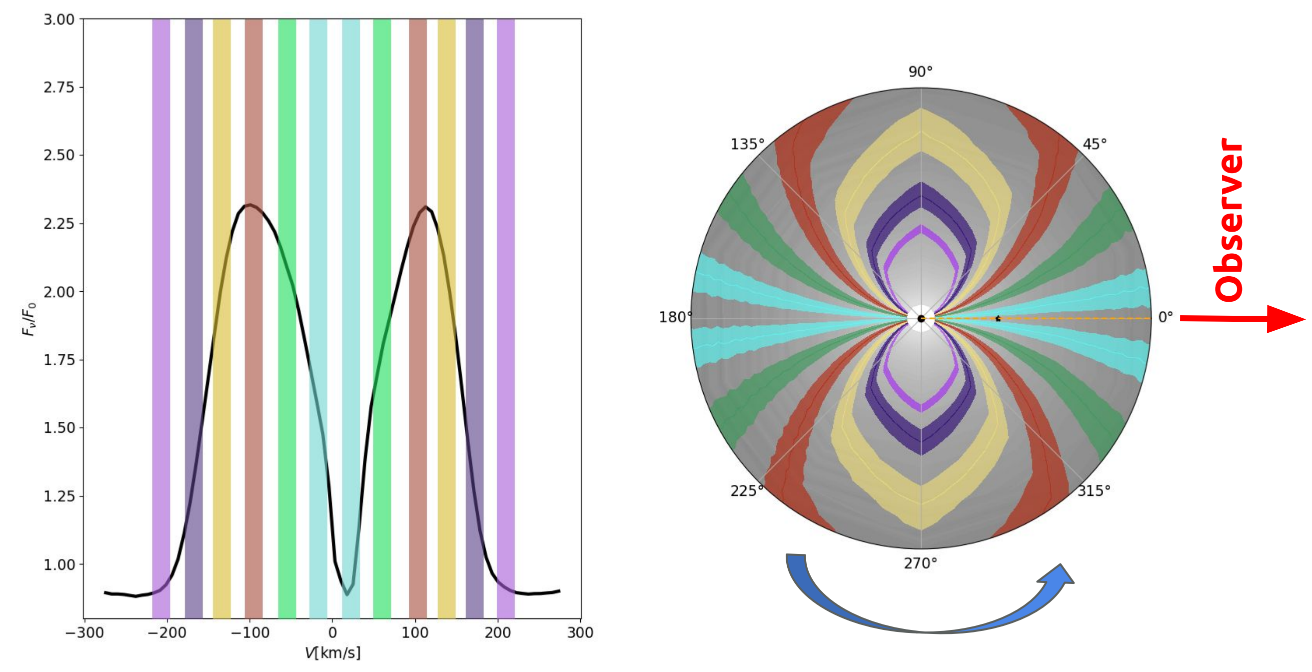
- 97% have **detectable pulsation**
- 87% have **frequency groups**
- 18% (31% of early-type) show 1+ mass outburst
- 83% **increase pulsation amplitude during outburst**
- 15% have high-frequency pulsation (p modes)

Main result: mass loss (or mass injection into the disk) is **unequivocally** related to pulsation

KEY POINT: Space photometry is quite sensitive to small mass ejection events, however it is (almost) **completely blind to the geometry of ejecta**

Solution: **simultaneous high-cadence, high-resolution spectroscopy!**

In a rotating disk (or ring), **different spectral channels map different disk positions**



The FRISBEEE project

The FRISBEEE project

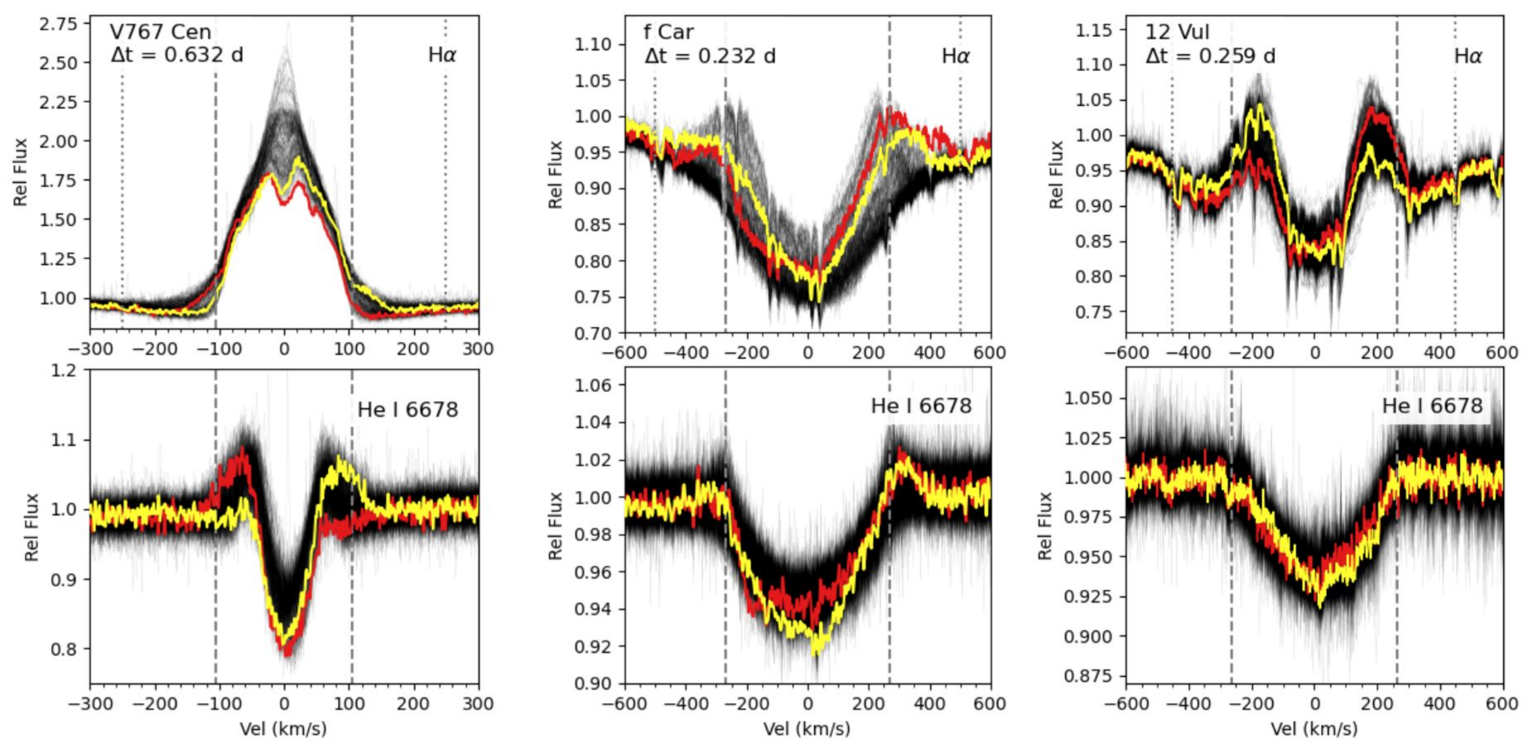
Following **R**eally **I**ntensively with **S**pectroscopy: **B**e **E**mission **E**vents

Strategy:

- Tabulate when TESS will observe **every known bright Be star**
- **Select Be stars that are likely to eject mass** during TESS observations (based on archival data, previous monitoring, etc.)
- Monitor every night with spectroscopy; **analyze data immediately**
- When spectra show mass ejection, **increase cadence**

Results:

- After a **4-yr long effort** we have **13 well-documented cases of mass ejection both from TESS and spectroscopy** (+ another 7 from literature)



V767 Cen: star with a strong pre-existing disk, well-defined outbursts

CLEAR

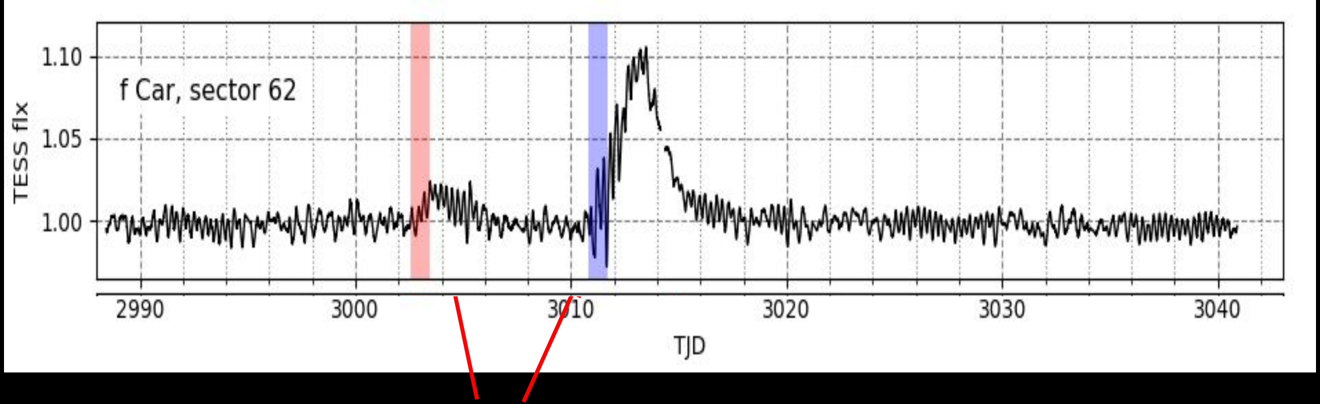
f Car: star without a pre-existing disk, well-defined outbursts

PRISTINE

12 Vul: complex variability, frequent (overlapping) outbursts

COMPLEX

f Car (B3Ve)
(PRISTINE)



2 mass outbursts (**flickers**) in 50 days of TESS

No disk prior to these events ➜ **pristine environment for disk formation**

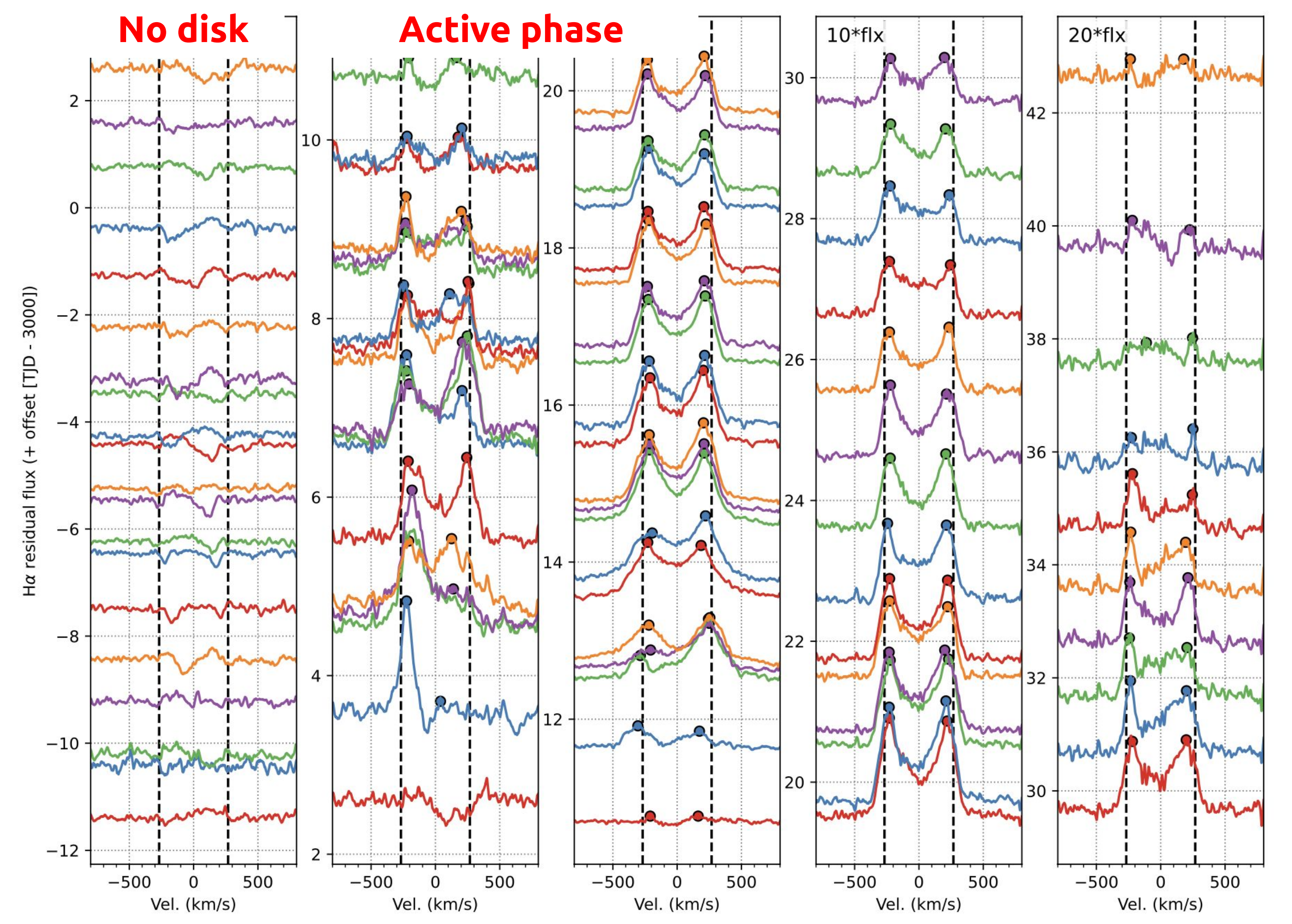
f Car (B3Ve)

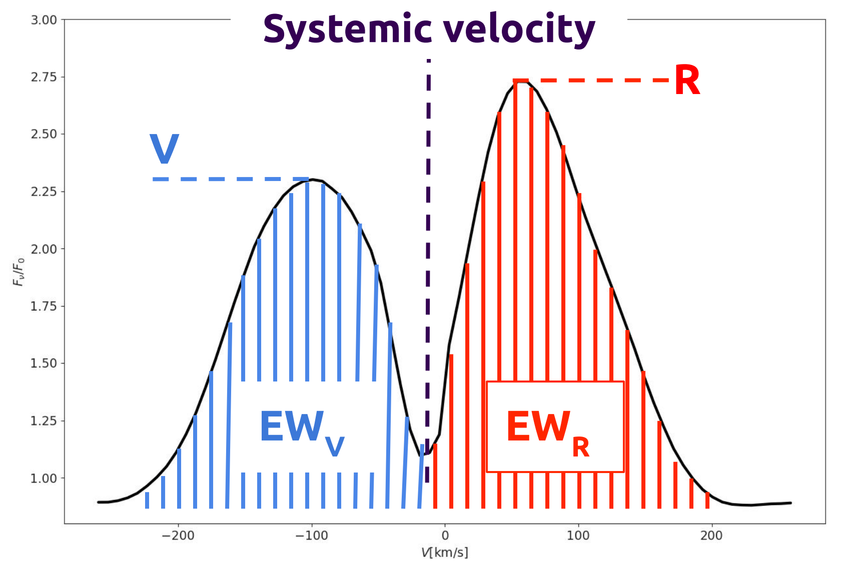
* Short-term temporal variability, in timescales of **hours**

* Shown are **emission spectra**, i.e., with the photospheric profile subtracted

* **First panel** ➜ Initially no disk

*** Second panel on** ➜ disk starts to form





Line measurements:

- **Equivalent Width** ➜ measure of total emission
- **V/R ratio** ➜ measure of asymmetry (what to do with more than 2 peaks?)
- **EW_V / EW_R** ➜ measure of asymmetry (deals well with complex profiles)

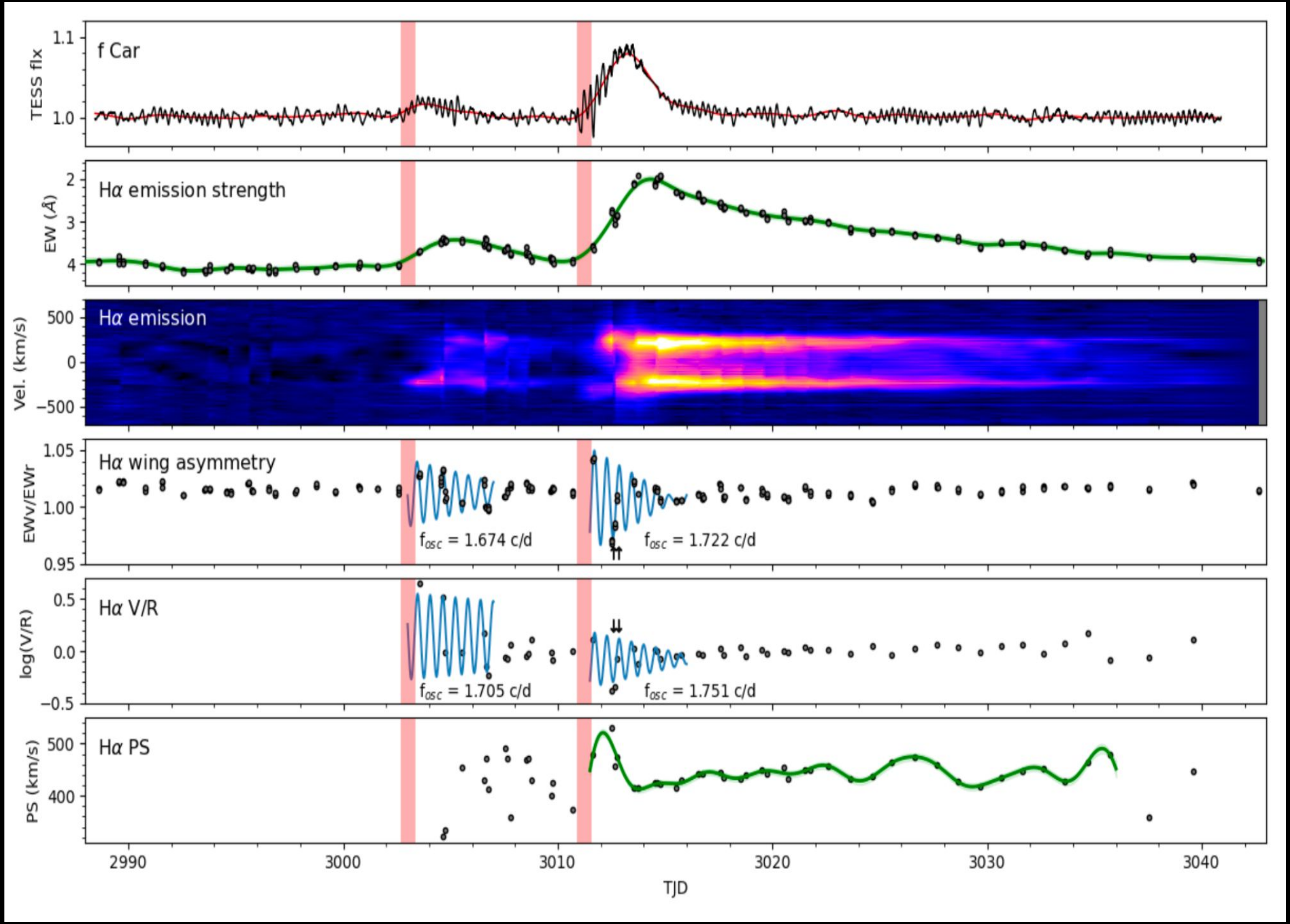
f Car (B3Ve)

- **Two flickers** during the TESS observations

- Photometric flicker evolves **much faster** than the Halpha EW

- Halpha profiles are **highly asymmetrical** and vary with a **period of ~ 1.7 c/d**

- Asymmetries are **maximum at the earliest stages** and dampens out slowly



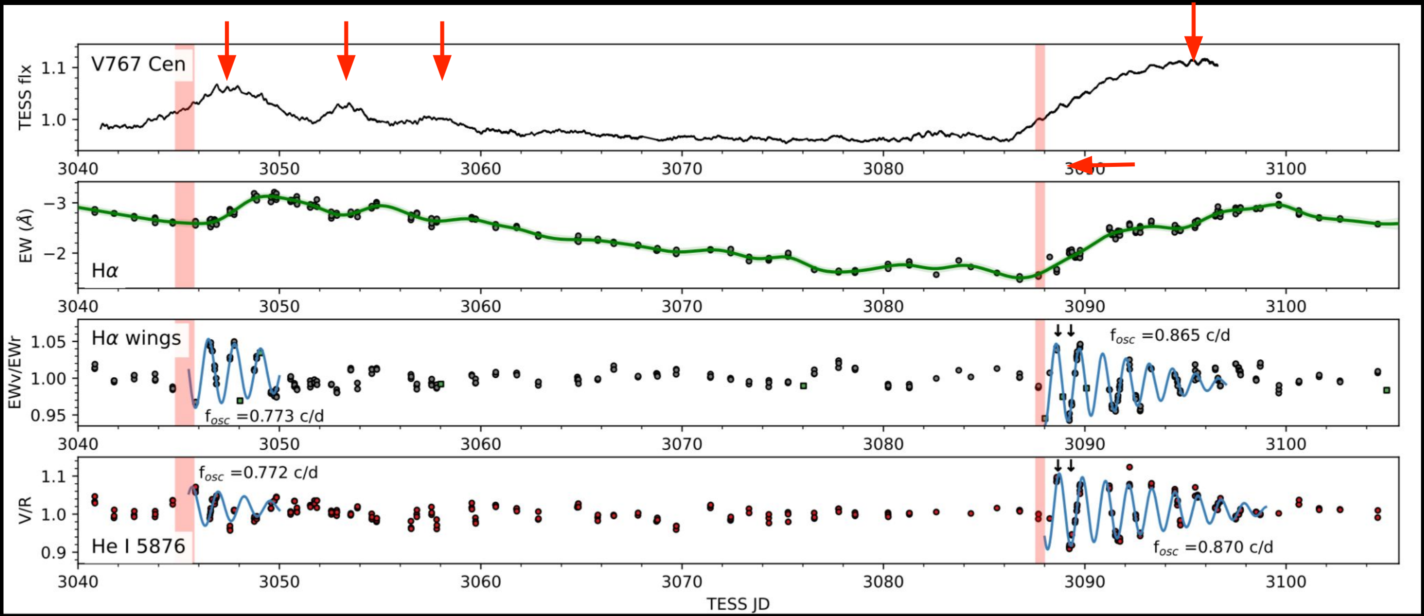
V 767 Cen (B2Ve) (CLEAR)

* gamma Cas analog (X-ray emission)

* The star **had a disk prior to TESS**

* Several small outbursts and a large one starting at the end of the TESS window

* **Halpha asymmetry also cyclic** with much shorter periods **(0.77 - 0.87 c/d)**



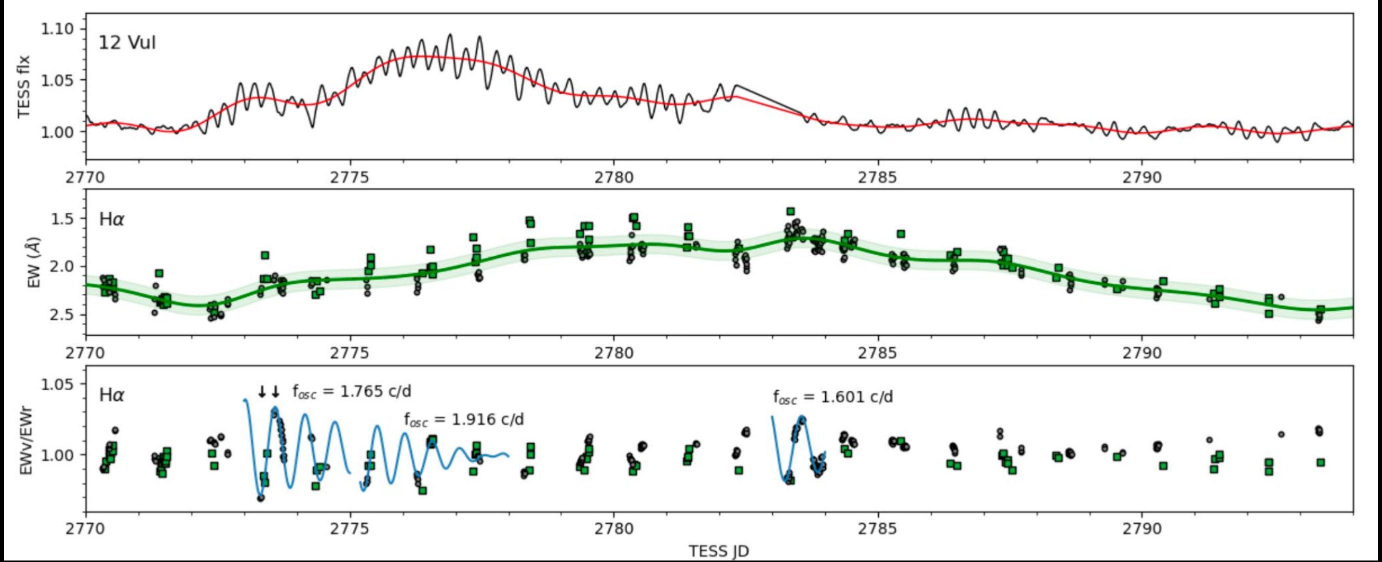
12 Vul (B2.5Ve)
(COMPLEX)

Permanently active?

Several overlapping outbursts?

Halpha asymmetry also cyclic

Periods vary from **1.6 to 1.9 c/d**

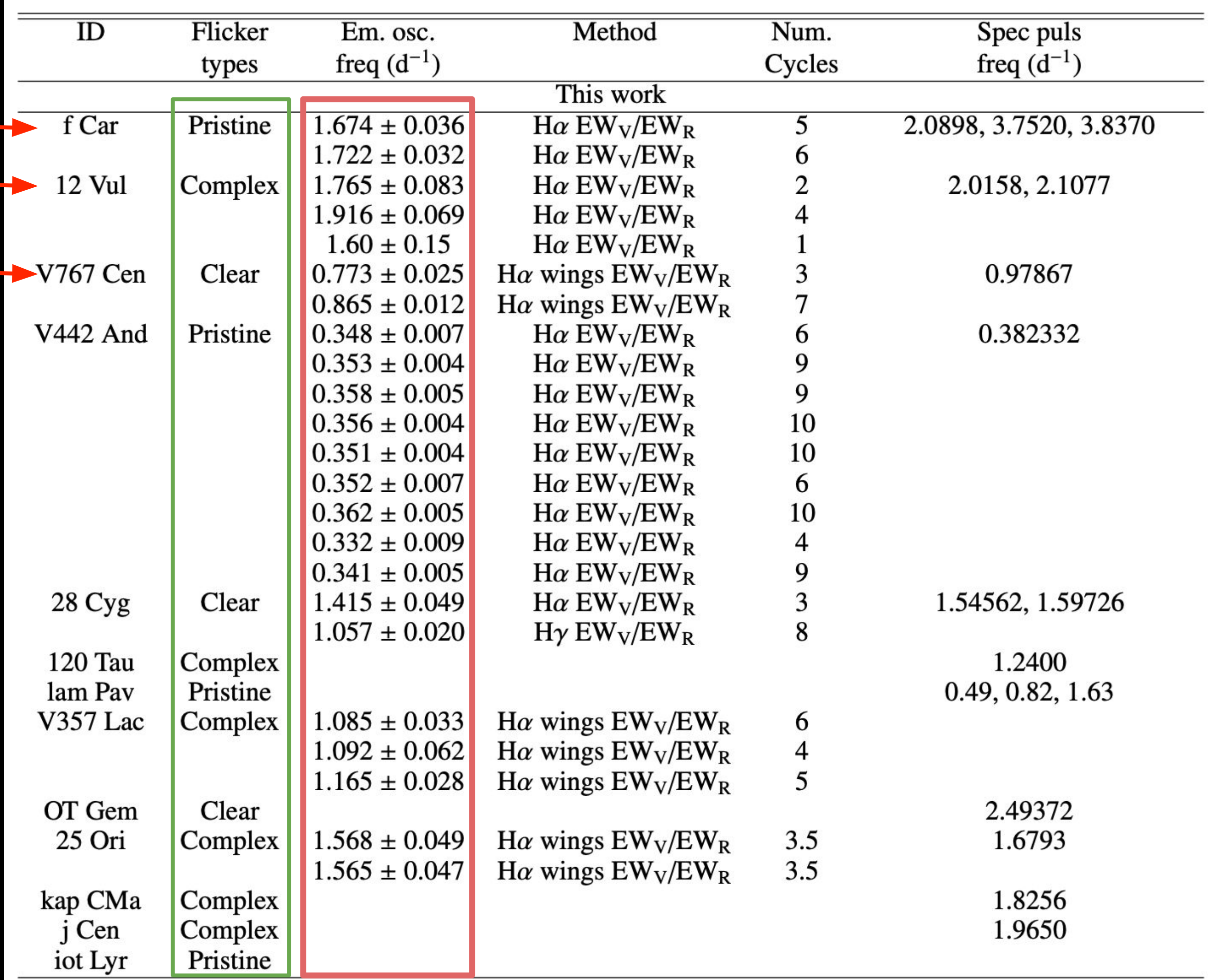


The full sample

Mix of pristine, clear and complex cases

EW_V / EW_R ranging between 0.3 – 1.9 c/d

Stars with multiple flickers always present similar EW_V / EW_R periods

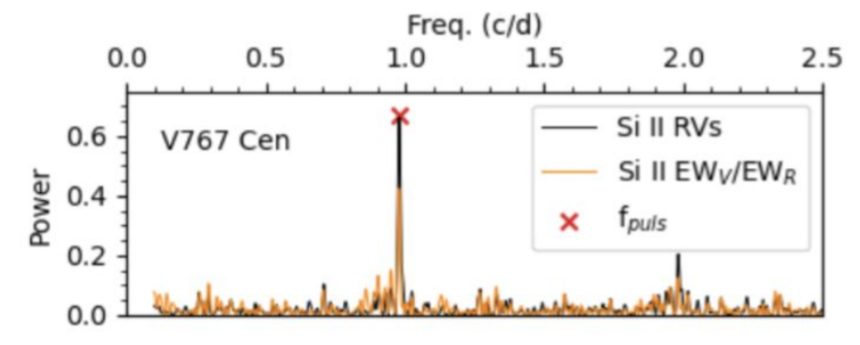


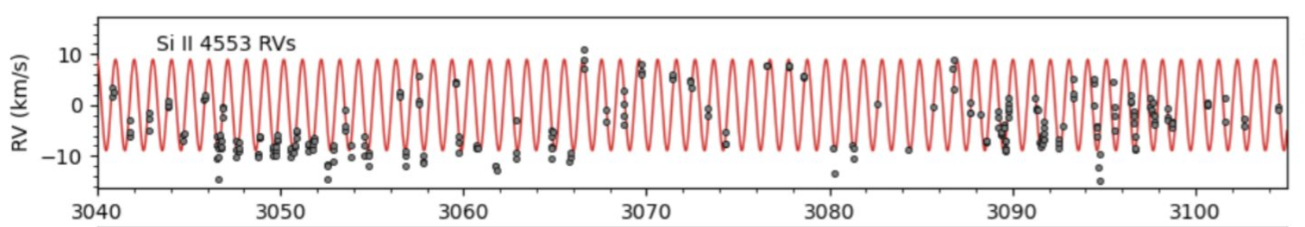
ID	Flicker types	Em. osc. freq (d^{-1})	Method	Num. Cycles	Spec puls freq (d^{-1})
			This work		
f Car	Pristine	1.674 ± 0.036	Hα EW_V/EW_R	5	2.0898, 3.7520, 3.8370
		1.722 ± 0.032	Hα EW_V/EW_R	6	
12 Vul	Complex	1.765 ± 0.083	Hα EW_V/EW_R	2	2.0158, 2.1077
		1.916 ± 0.069	Hα EW_V/EW_R	4	
		1.60 ± 0.15	Hα EW_V/EW_R	1	
V767 Cen	Clear	0.773 ± 0.025	Hα wings EW_V/EW_R	3	0.97867
		0.865 ± 0.012	Hα wings EW_V/EW_R	7	
V442 And	Pristine	0.348 ± 0.007	Hα EW_V/EW_R	6	0.382332
		0.353 ± 0.004	Hα EW_V/EW_R	9	
		0.358 ± 0.005	Hα EW_V/EW_R	9	
		0.356 ± 0.004	Hα EW_V/EW_R	10	
		0.351 ± 0.004	Hα EW_V/EW_R	10	
		0.352 ± 0.007	Hα EW_V/EW_R	6	
		0.362 ± 0.005	Hα EW_V/EW_R	10	
		0.332 ± 0.009	Hα EW_V/EW_R	4	
		0.341 ± 0.005	Hα EW_V/EW_R	9	
28 Cyg	Clear	1.415 ± 0.049	Hα EW_V/EW_R	3	1.54562, 1.59726
		1.057 ± 0.020	Hγ EW_V/EW_R	8	
120 Tau	Complex				1.2400
lam Pav	Pristine				0.49, 0.82, 1.63
V357 Lac	Complex	1.085 ± 0.033	Hα wings EW_V/EW_R	6	
		1.092 ± 0.062	Hα wings EW_V/EW_R	4	
		1.165 ± 0.028	Hα wings EW_V/EW_R	5	
OT Gem	Clear				2.49372
25 Ori	Complex	1.568 ± 0.049	Hα wings EW_V/EW_R	3.5	1.6793
		1.565 ± 0.047	Hα wings EW_V/EW_R	3.5	
kap CMa	Complex				1.8256
j Cen	Complex				1.9650
iot Lyr	Pristine				

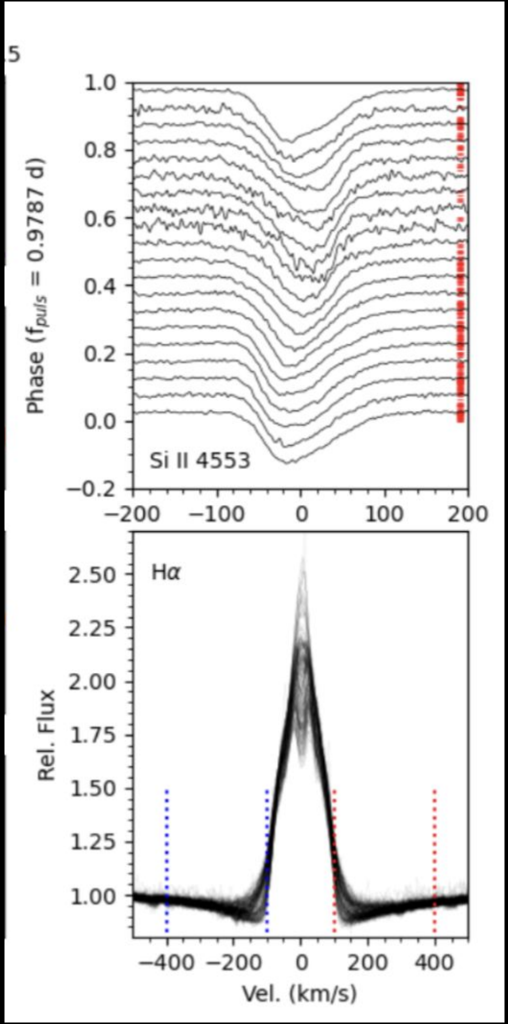
Pulsational frequencies

All stars in the sample have clear NRP frequencies

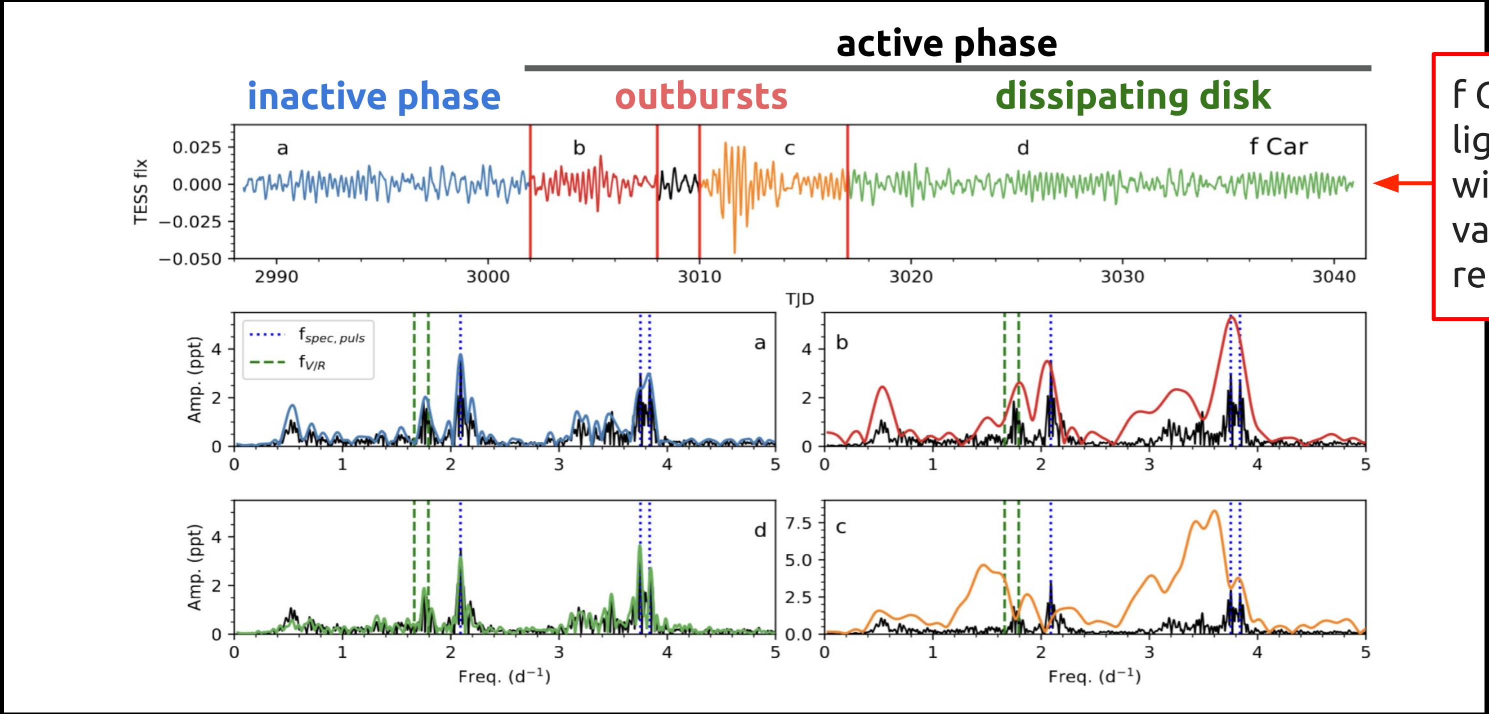
Ex: V767 Cen has a mode with a frequency of 0,979 c/d







Pulsation and mass loss



f Car's lightcurve with low-freq. variations removed

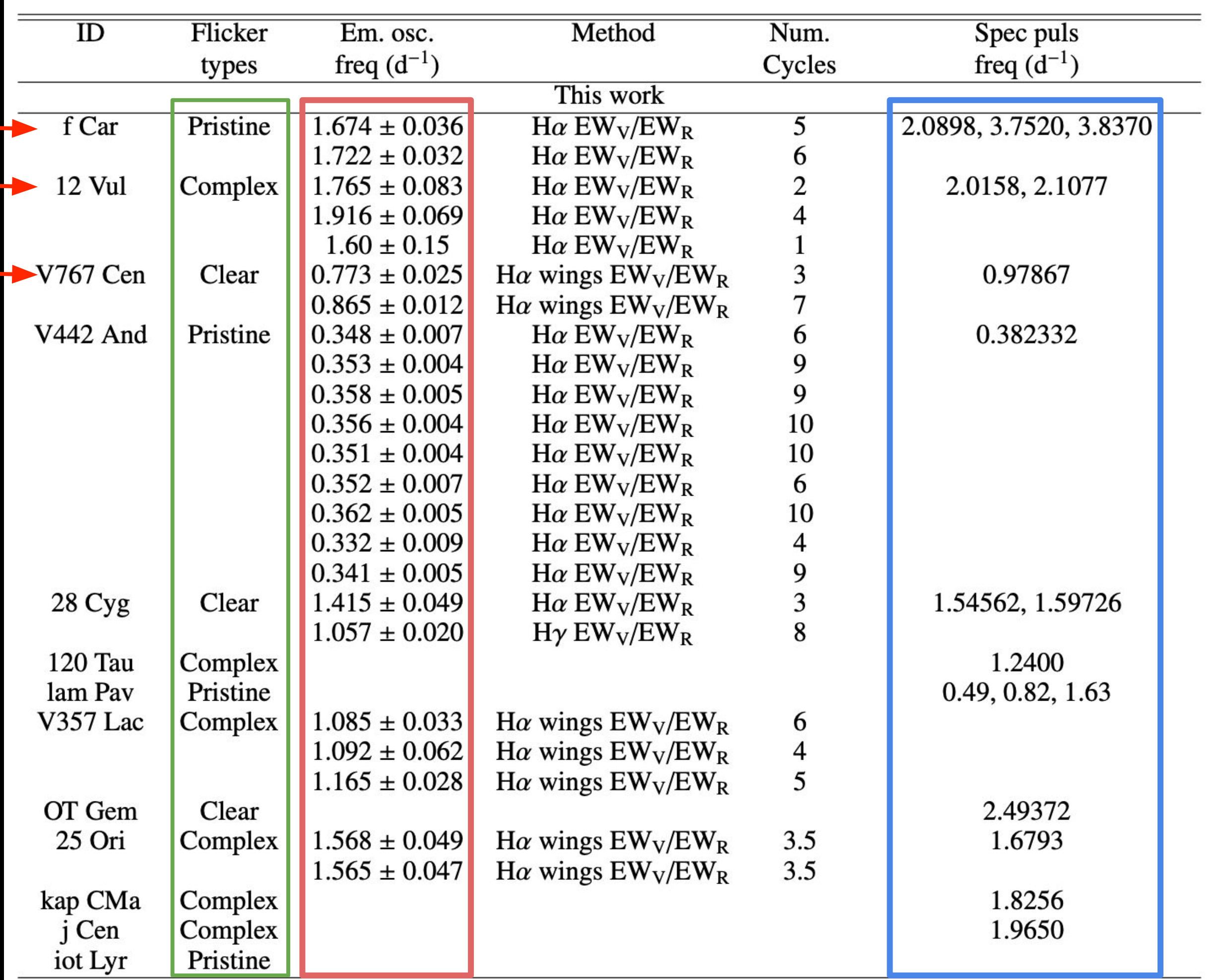
For **all** flickers observed, there is an **increase in the pulsation power during the outburst**

The full sample

Mix of pristine, clear and complex cases

EW_V / EW_R ranging between 0.3 – 1.9 c/d

All stars have spectroscopic frequencies measured. They are always larger than the EW_V / EW_R frequencies



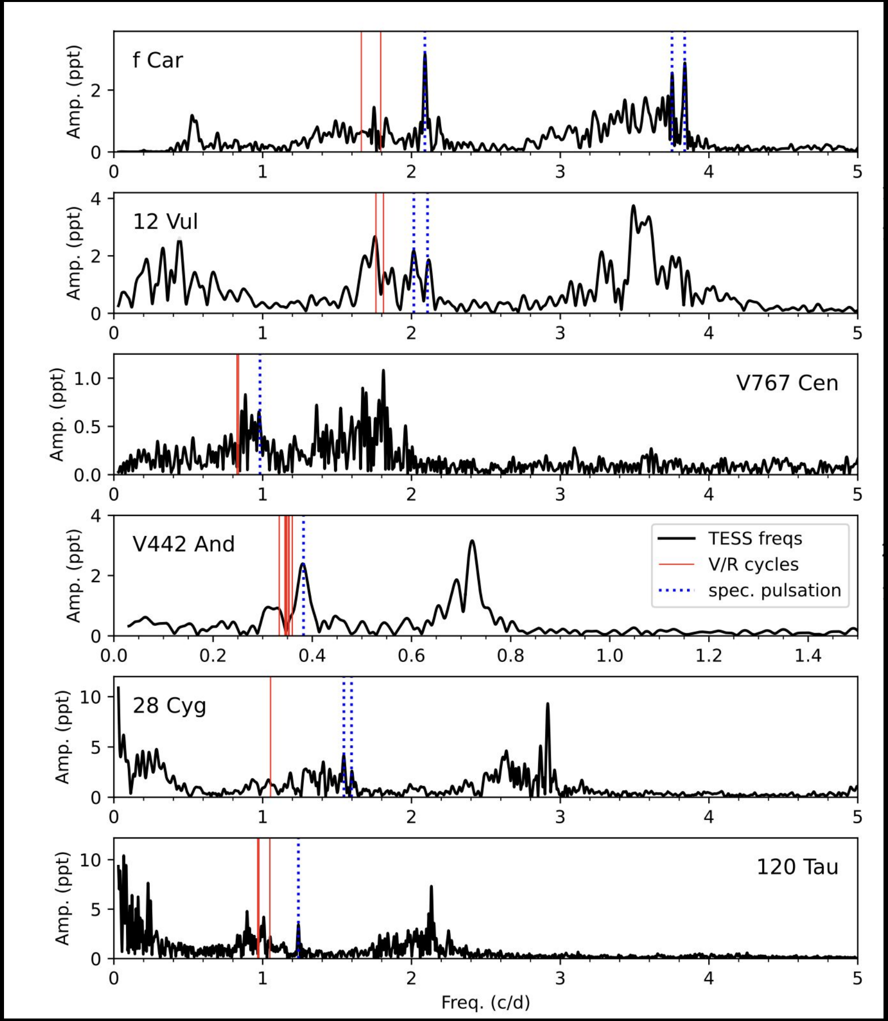
ID	Flicker types	Em. osc. freq (d^{-1})	Method	Num. Cycles	Spec puls freq (d^{-1})
			This work		
f Car	Pristine	1.674 ± 0.036	Hα EW_V/EW_R	5	2.0898, 3.7520, 3.8370
		1.722 ± 0.032	Hα EW_V/EW_R	6	
12 Vul	Complex	1.765 ± 0.083	Hα EW_V/EW_R	2	2.0158, 2.1077
		1.916 ± 0.069	Hα EW_V/EW_R	4	
		1.60 ± 0.15	Hα EW_V/EW_R	1	
V767 Cen	Clear	0.773 ± 0.025	Hα wings EW_V/EW_R	3	0.97867
		0.865 ± 0.012	Hα wings EW_V/EW_R	7	
V442 And	Pristine	0.348 ± 0.007	Hα EW_V/EW_R	6	0.382332
		0.353 ± 0.004	Hα EW_V/EW_R	9	
		0.358 ± 0.005	Hα EW_V/EW_R	9	
		0.356 ± 0.004	Hα EW_V/EW_R	10	
		0.351 ± 0.004	Hα EW_V/EW_R	10	
		0.352 ± 0.007	Hα EW_V/EW_R	6	
		0.362 ± 0.005	Hα EW_V/EW_R	10	
		0.332 ± 0.009	Hα EW_V/EW_R	4	
		0.341 ± 0.005	Hα EW_V/EW_R	9	
28 Cyg	Clear	1.415 ± 0.049	Hα EW_V/EW_R	3	1.54562, 1.59726
		1.057 ± 0.020	Hγ EW_V/EW_R	8	
120 Tau	Complex				1.2400
lam Pav	Pristine				0.49, 0.82, 1.63
V357 Lac	Complex	1.085 ± 0.033	Hα wings EW_V/EW_R	6	
		1.092 ± 0.062	Hα wings EW_V/EW_R	4	
		1.165 ± 0.028	Hα wings EW_V/EW_R	5	
OT Gem	Clear				2.49372
25 Ori	Complex	1.568 ± 0.049	Hα wings EW_V/EW_R	3.5	1.6793
		1.565 ± 0.047	Hα wings EW_V/EW_R	3.5	
kap CMa	Complex				1.8256
j Cen	Complex				1.9650
iot Lyr	Pristine				

The full sample

Frequency spectra of all 13 stars are **typical of Be stars**

- Frequency groups
- Spec. frequencies (**blue**) always on the large frequency side of group

Halpha asymmetry frequencies (**red**) are **always shorter than the spectroscopic frequencies**



Comparing frequencies

How the observed **EW_V / EW_R** compares with the **characteristic frequencies** of the system?

- **Orbital frequency at stellar equator (*W* < 1)**

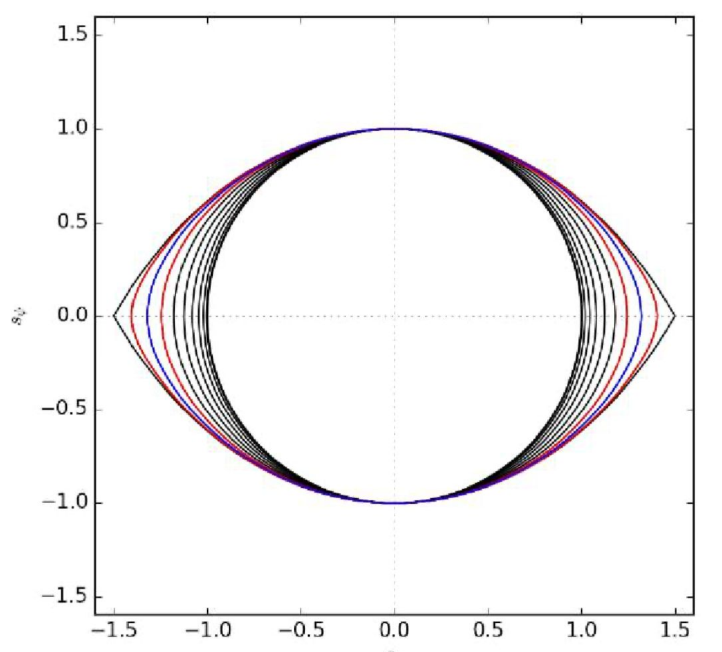
$$\omega = \frac{1}{2\pi}\sqrt{\frac{GM}{R_{\mathrm{eq}}^3}}$$

- **Critical frequency (orbital freq. for *W* = 1)**

$$\omega = \frac{1}{2\pi}\sqrt{\frac{GM}{(1.5R_{\mathrm{pole}})^3}}$$

- **Rotational frequency**

$$\omega = \frac{V_{\mathrm{eq}}}{2\pi R_{\mathrm{eq}}}$$



Shape of star for different values of *W*

Comparing frequencies

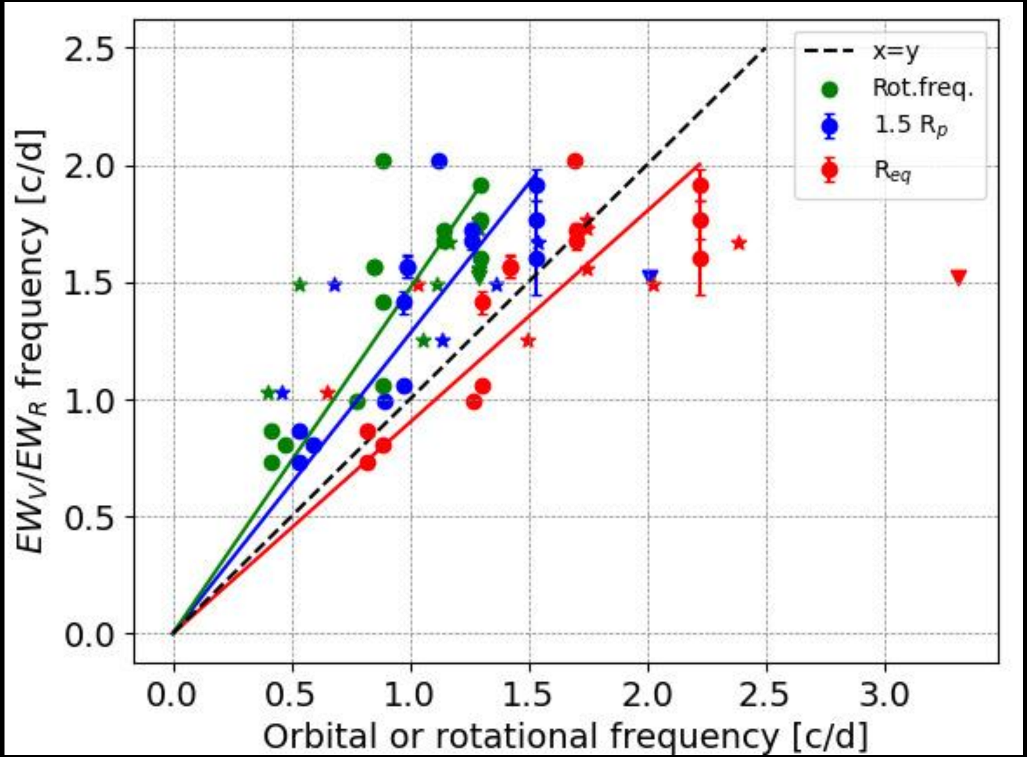
Red - orbital frequency

Blue - critical frequency

Green - rotational frequency

Important conclusion: what is causing the line asymmetries is **material orbiting very close to the stellar surface**

Seemingly obvious, but not quite so…



Stellar parameters from Fremat et al. (2016)

The full sample: conclusions from the FRISBEE project

1) We identified about **50 flickers in 13 targets** for which we had simultaneous TESS and high-resolution, high-cadence spectroscopy
2) 100% of them showed **strong EW_V / EW_R asymmetries,** with similar behavior (cyclic variation that dampens out after a few cycles)
3) Therefore, **in ALL cases, mass loss was highly asymmetrical**
4) Material orbits **very close to the stellar surface. How close?**

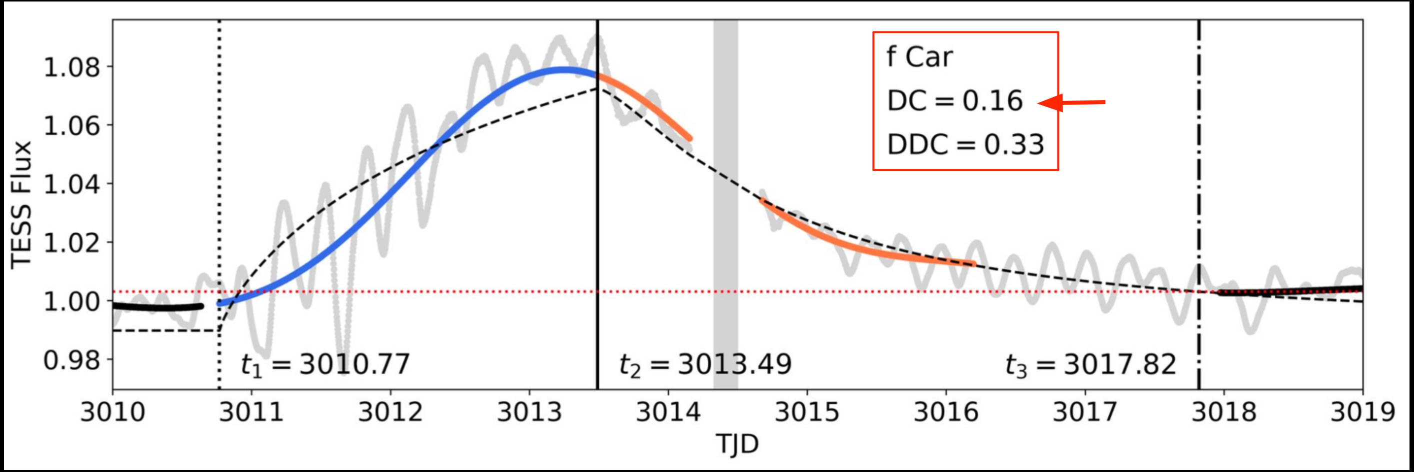
Labadie-Bartz, Carciofi et al. (in preparation)

Flicker analysis

* We measure the length of the outburst (**blue**) and the length of the dissipation (**orange**)

* From that we can estimate the **duty cycle**, the **fraction of time the star is actively losing mass**

f Car



$$\Delta X(t) = \Delta X_{\rm bu}^{\infty} \begin{cases} \left(1 - \frac{1}{1+[C_{\rm bu}(t-t_1)]^{\eta_{\rm bu}}}\right), & t_1 \leq t < t_2 \\ \left(1 - \frac{1}{1+[C_{\rm bu}(t_2-t_1)]^{\eta_{\rm bu}}}\right) \frac{1}{1+[C_{\rm d}(t-t_2)]^{\eta_{\rm d}}} \, . & t \geq t_2 \end{cases}$$

Rímulo et al. (2018)

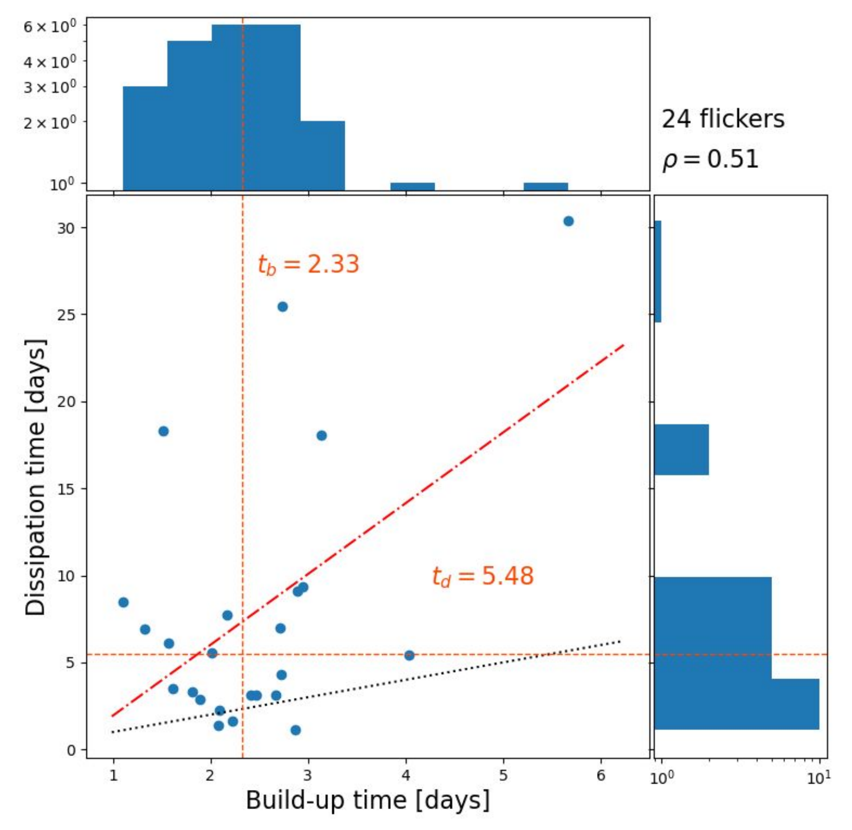
Flicker analysis

* **Sample of 54 flickers for 11 stars**

* Dissipation is **typically 2 times longer** than formation

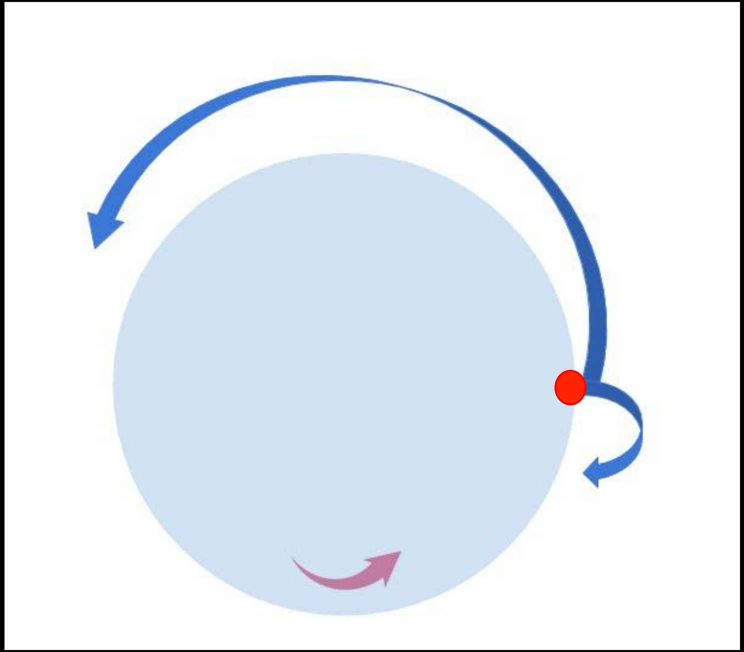
* Similar to models and observations of large scale disk formation ➜ **mass reservoir effect**

* **Flickers are also controlled by viscosity** (?)



SPH models of localized ejecta

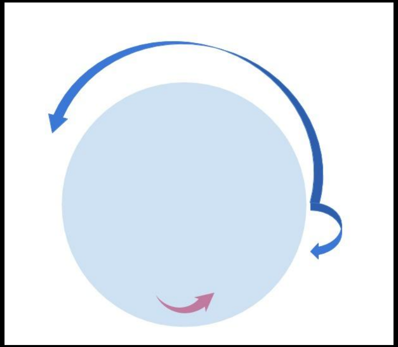
- Define **ejection region** with given size and rotational frequency
    - **NOT the orbital frequency**
    - **NOT the stellar rotational frequency**
- **Create particles** in this region at a given rate
- Sample random (Gaussian) speeds with random (outward) directions
- Define **duration** of outburst
- Let **ejecta evolve under action of gravity and viscosity**

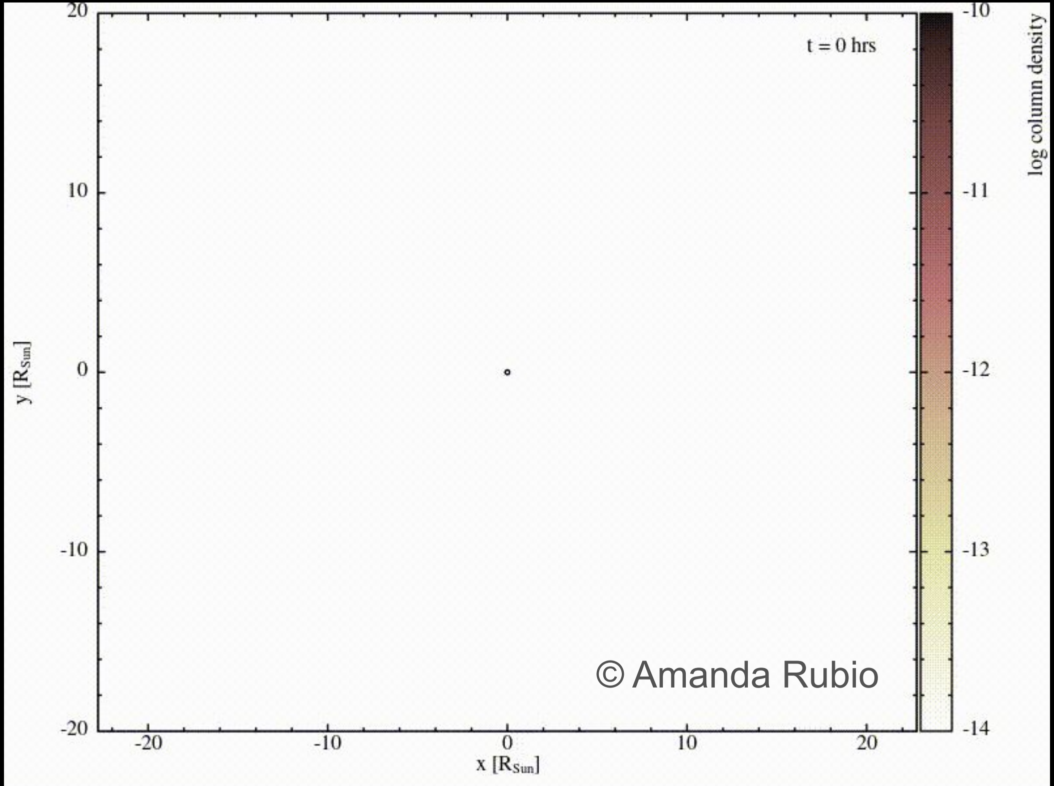


Kroll's gravity filter

SPH models of localized mass ejection

- Duration of mass injection: **30h**
- Average speed (local frame): **20 km/s**
- alpha = 1
- Mdot = **1.E-7 Msol/year**
- Rotation frequency of **hot spot** = Orbital frequency

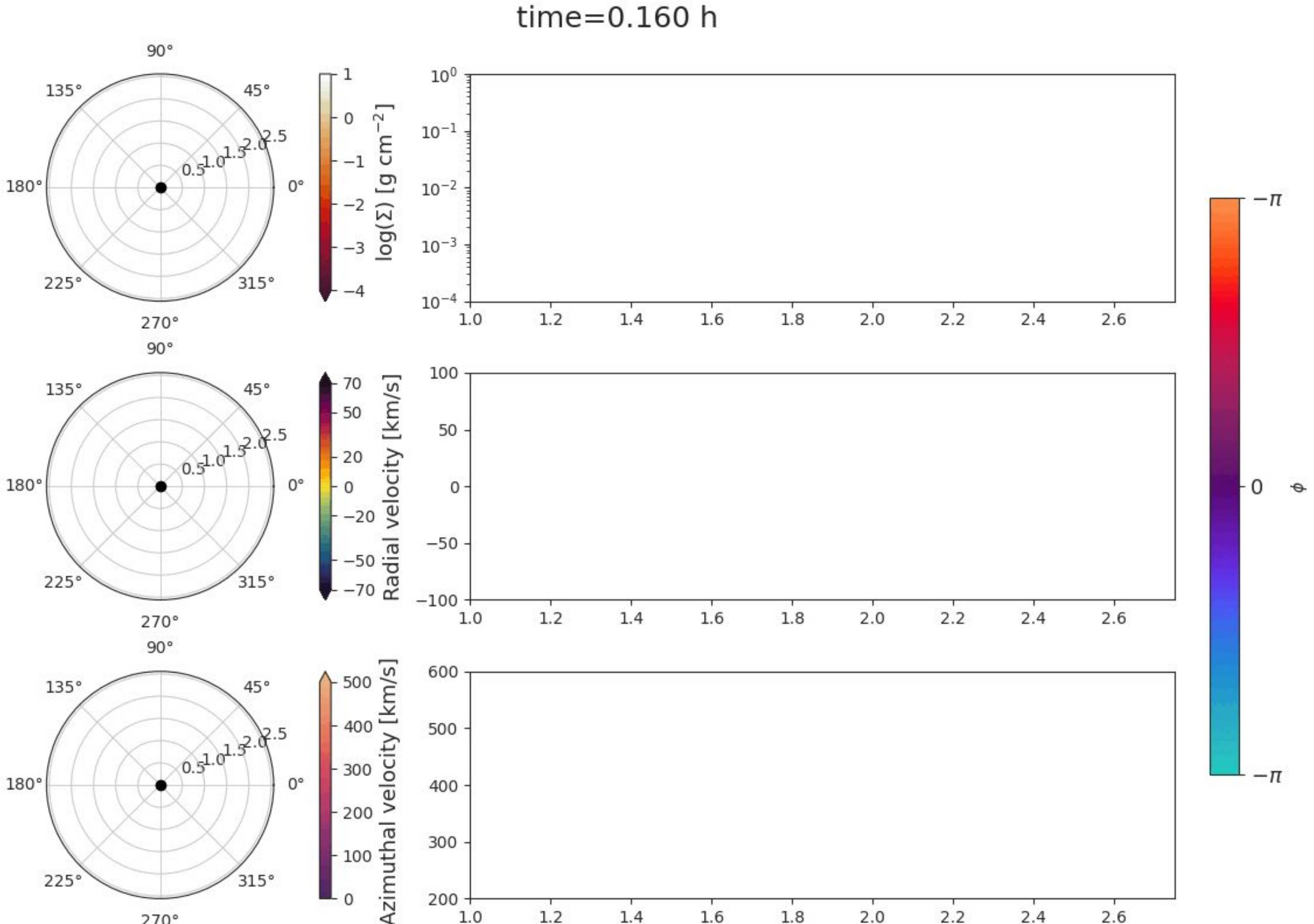




density

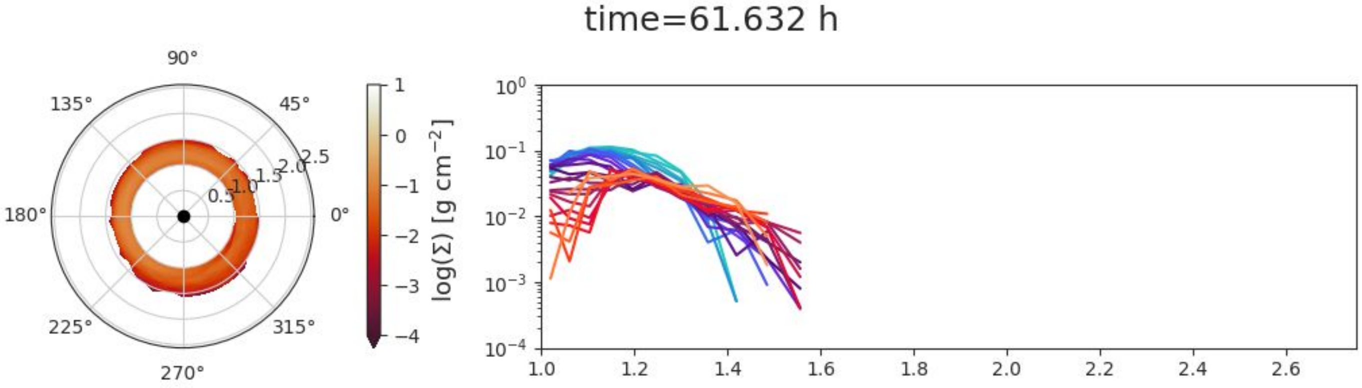
radial velocity

azimuthal velocity

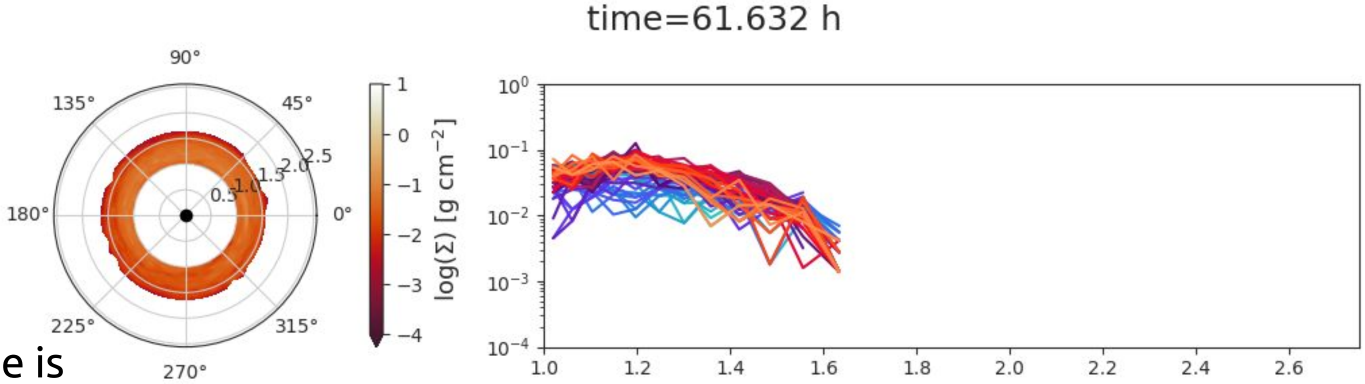


Effects of viscosity

high viscosity



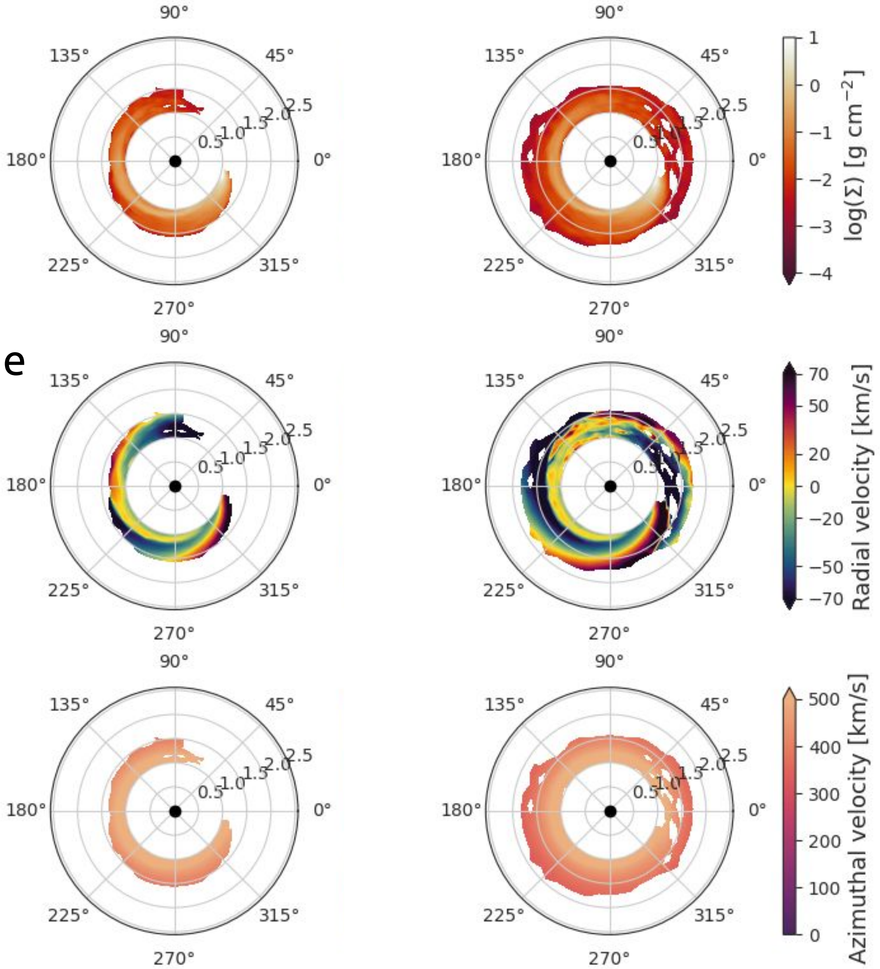
low viscosity



Circularization timescale is longer por low viscosity model

Effects of ejection speed

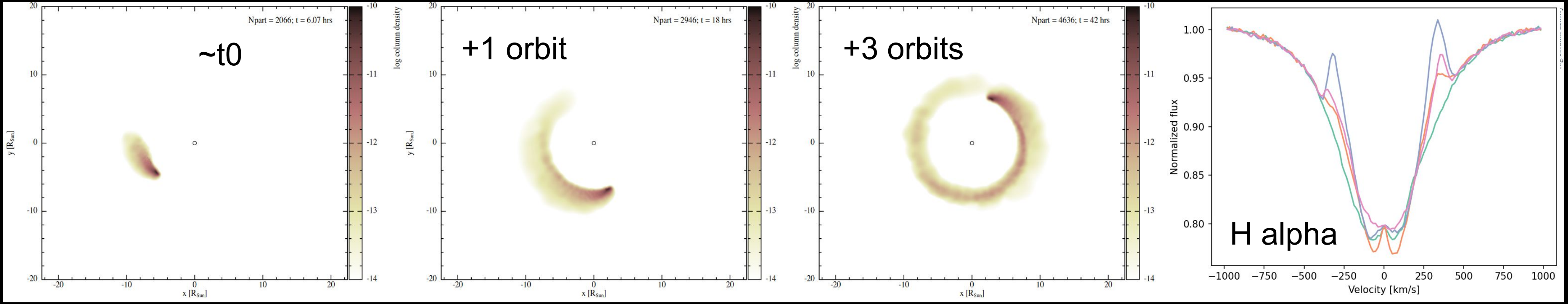
20 km/s



50 km/s

Snapshots at the end of the outburst show that larger ejection speed produce larger disks

SPH models of localized mass ejection



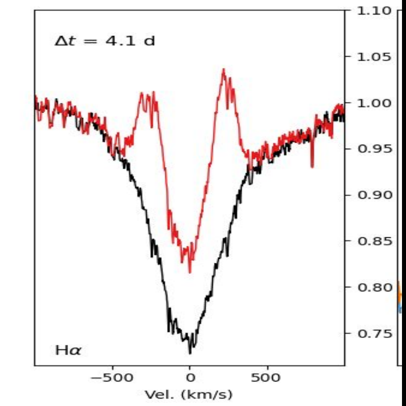
(preliminary) model for f Car

- For the first time we have the **ability to model mass loss in a physically realistic way**

AND

- We **have the data to compare** with…
- Rubio, Carciofi, Baade et al. (in preparation)

Observations of f Car



Mass loss in Be stars

1) Be stars:
   - What are they?
   - Where they come from?
   - Why are they important?
2) News from the **mass loss front…**
3) News from the **disk front…**

The Be star Achernar in true color (D. M. Faes)

Mass loss in Be stars

1) Be stars:
   - What are they?
   - Where they come from?
   - Why are they important?
2) News from the **mass loss front…**
3) News from the **disk front…**

Most Be disks are quite different from this!

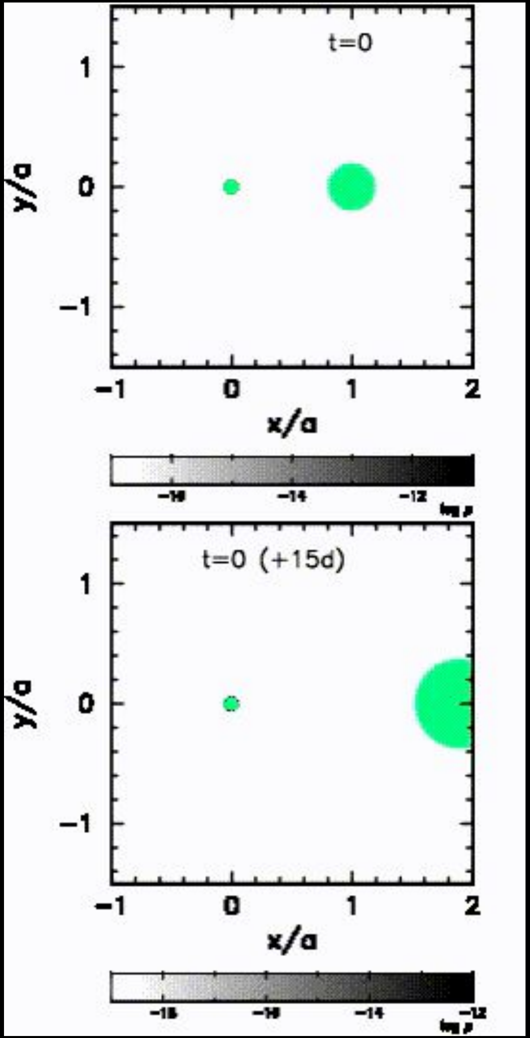
The Be star Achernar in true color (D. M. Faes)

Be disks in binary systems

SPH studies of Be disks in binary systems revealed that the secondary perturbs the disk in many ways:

1) **Density waves**
in the disk, that **leads to V/R variations of emission lines** (Okazaki+2002, Panoglou+2016,2018)

2) **Disk truncation**
as the resonant torque exerted by the companion removes momentum from the disk (Okazaki, Panoglou+2016, Cyr+2017)



circular orbit

eccentric orbit

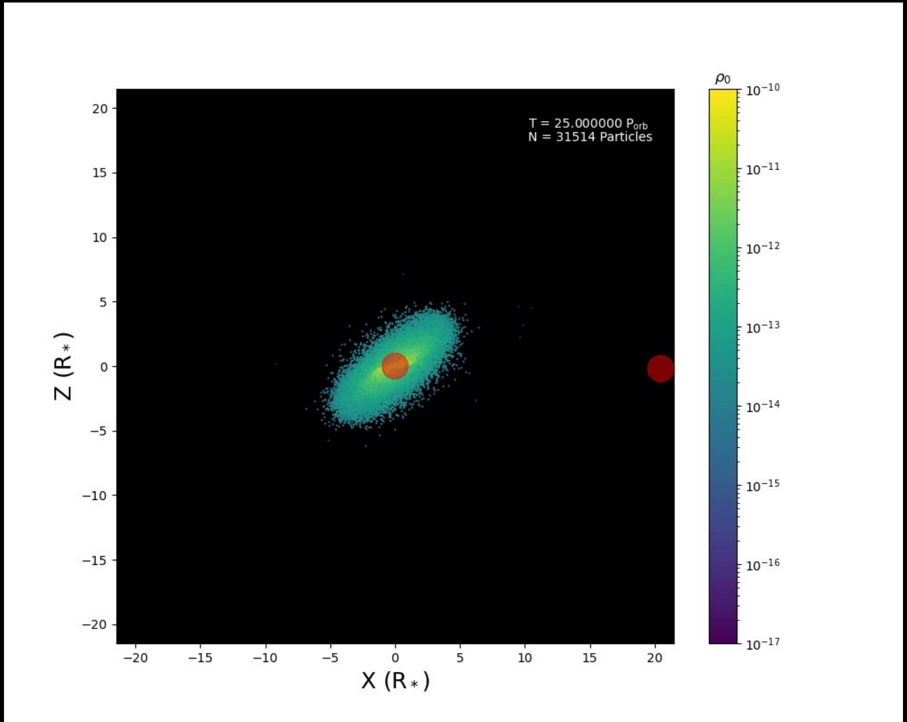
Panoglou+2016

Be disks in binary systems

3) Disk tilting/warping/tearing

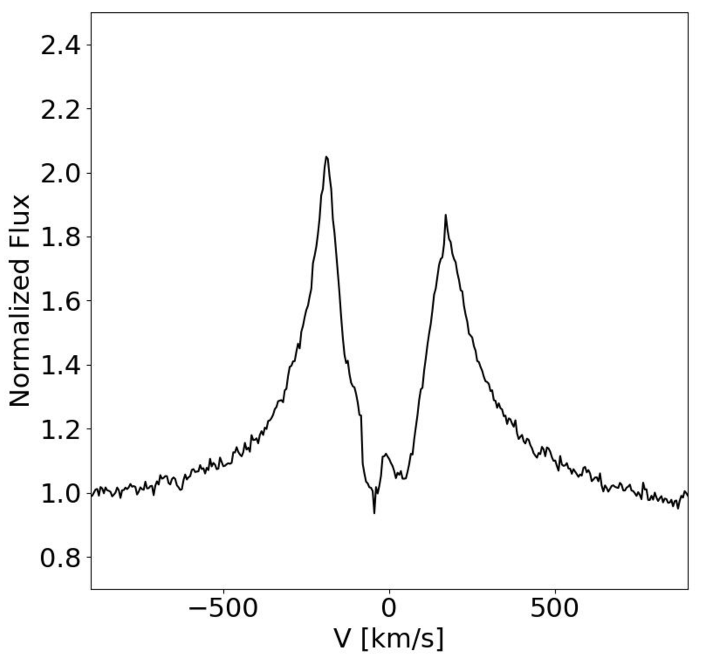
Happens when there is a misalignment between the disk and the orbital plane of the secondary (Suffak+2021)

Disk tearing, for instance, was shown to **occur in the disk of Pleione** (Marr+2022)



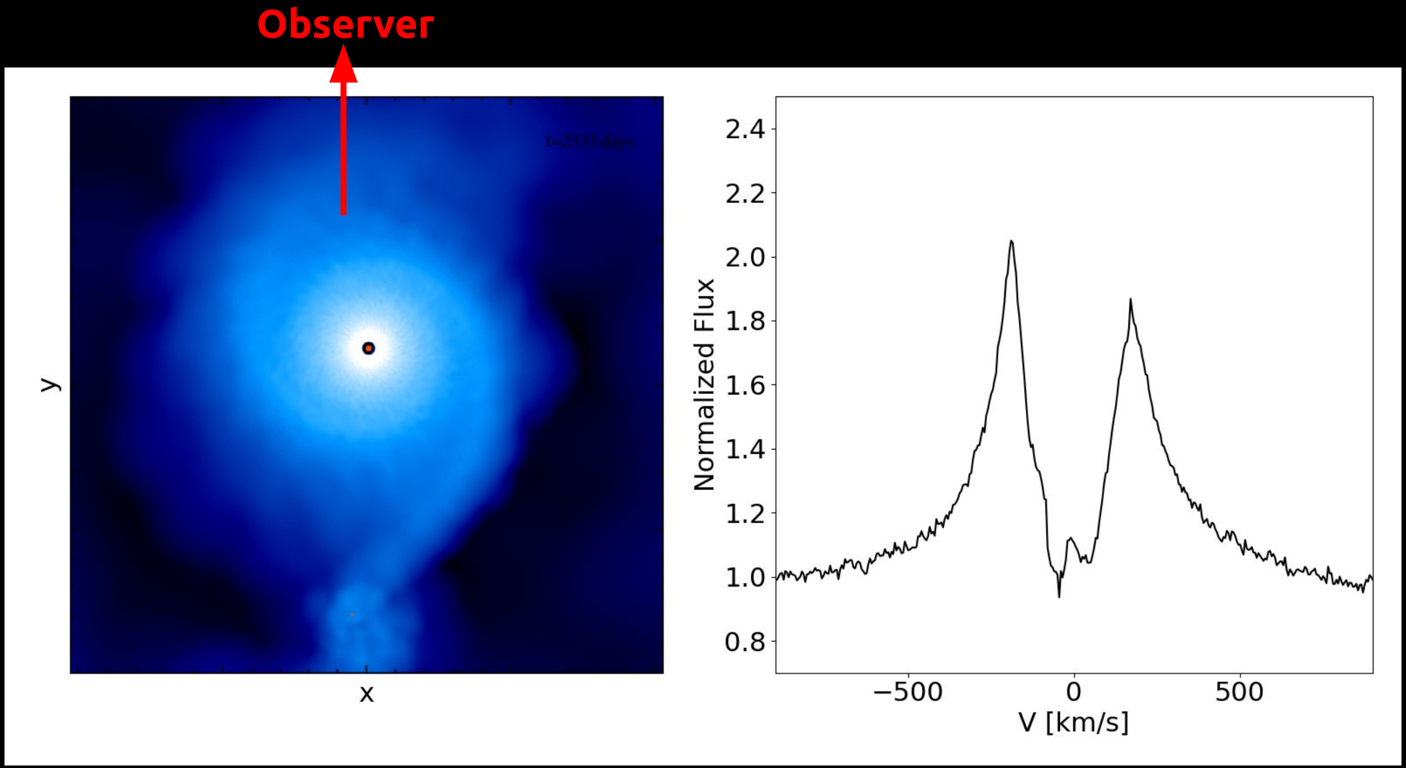
Be disks in binary systems

- "Messed up" profiles
- Triple or even multiple peaks
- Shell vs non-shell phases
- **What is going on here?**



Data: binary Be star **V658 Car** over an orbital period ($P = 32$ d)

Be disks in binary systems



Model: **SPH simulation** reveals the formation of complex structures

Data: binary Be star **V658 Car** over an orbital period ($P = 32$ d)

Be disks in binary systems

New simulations with **two important updates**

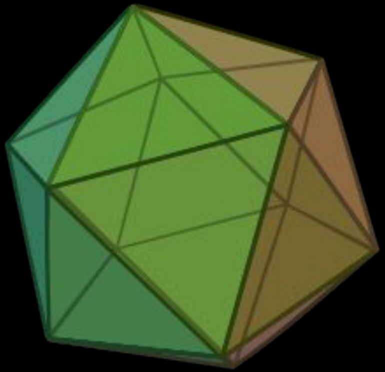
1) **Particle splitting**

   When certain criteria are met, one particle is **split in 13 daughter particles**, maintaining the velocity, AM and total mass of the original particle

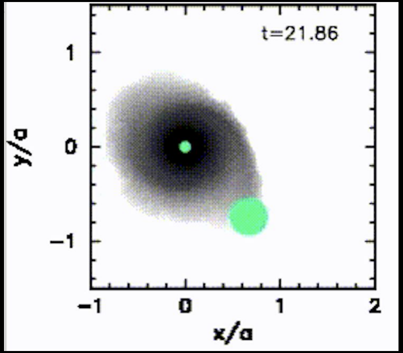
2) **Correct outer boundary conditions**

   Radius of the 2nd sink particle is the radius of the secondary star (before: radius of Roche lobe)

These allowed us resolve the outer disk structure and track material as it leaves the system



The new positions of the particles are in **each of the 12 vertices plus the center of a icosahedron**

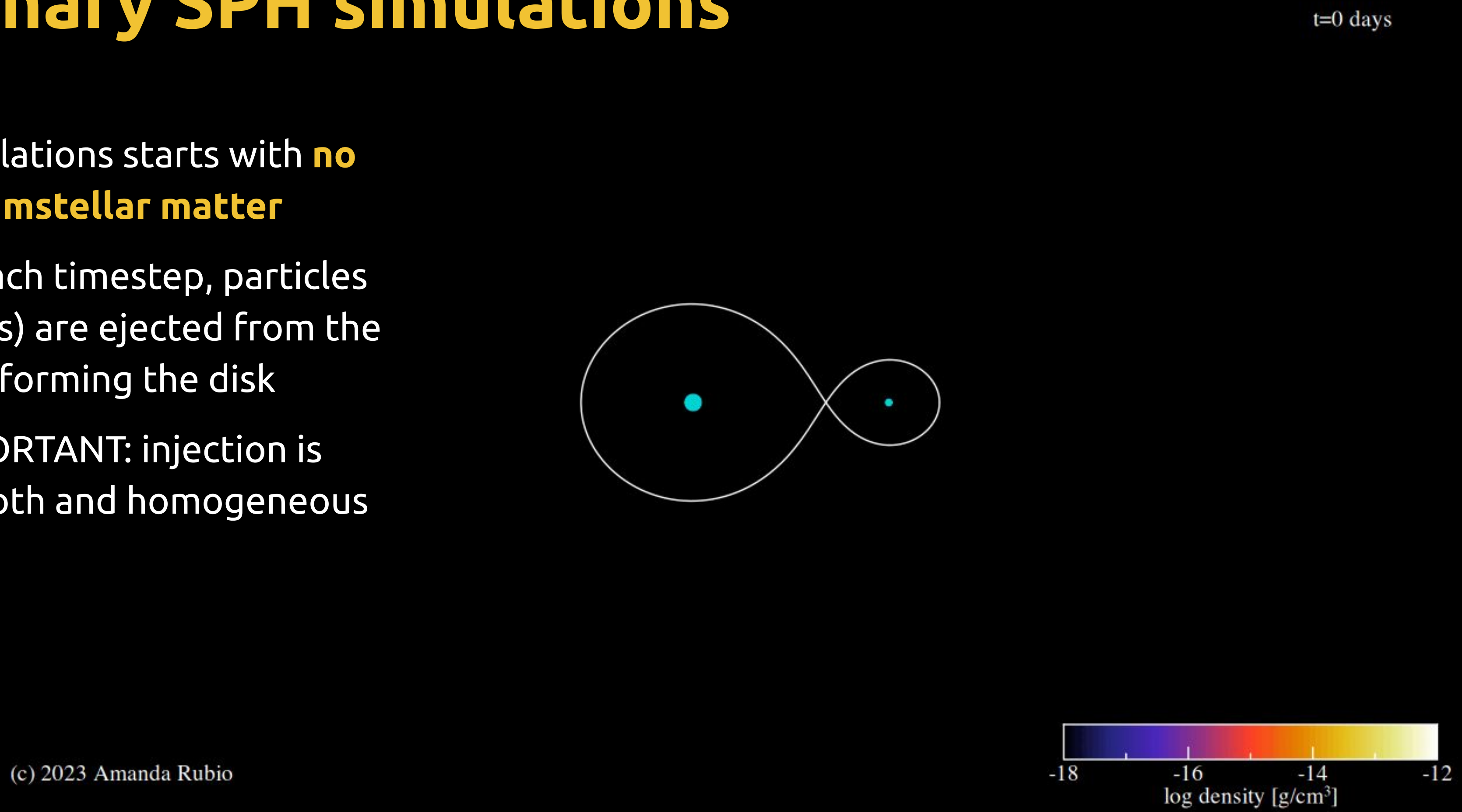


Binary SPH simulations

Simulations starts with **no circumstellar matter**

At each timestep, particles (mass) are ejected from the star, forming the disk

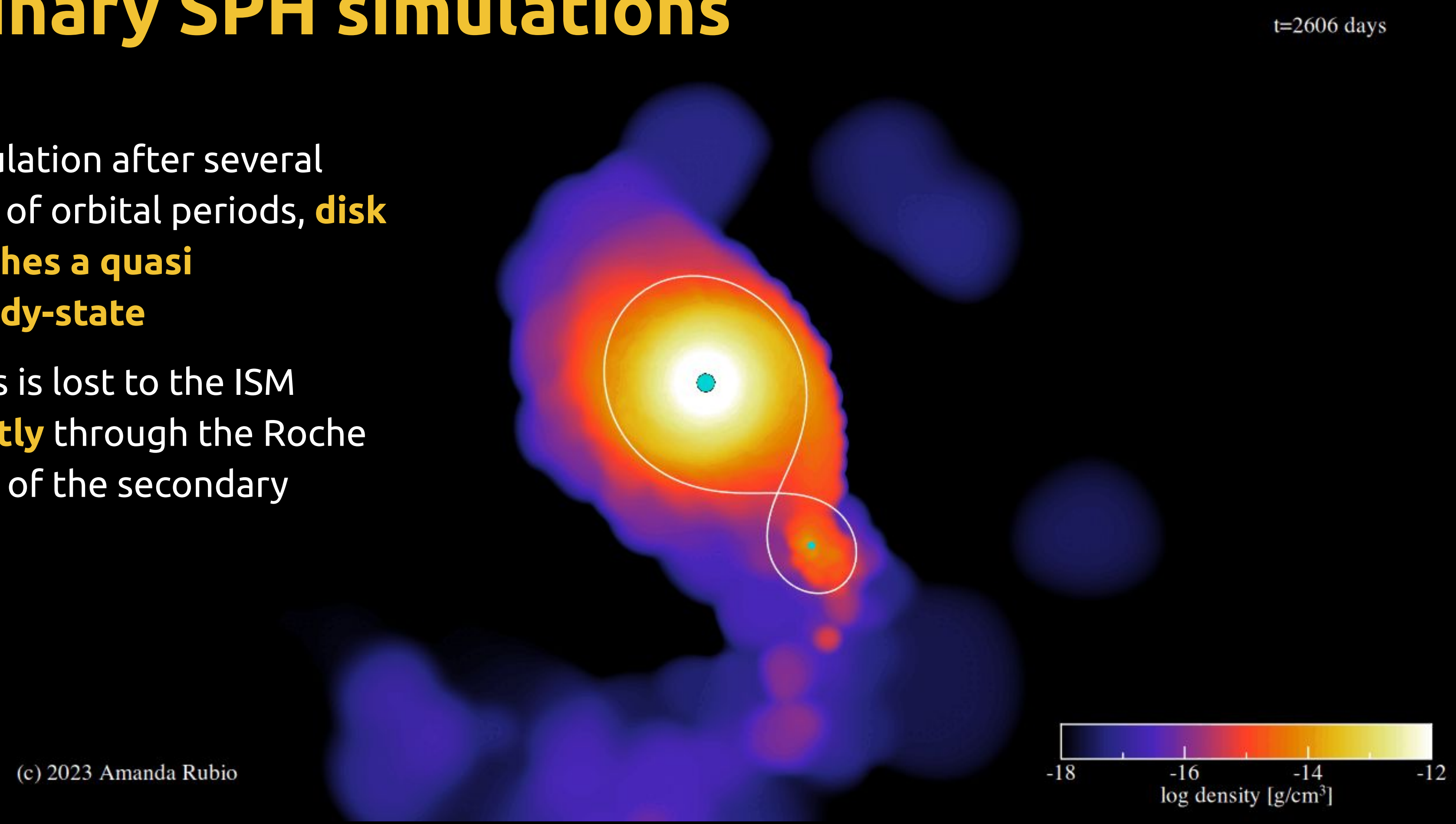
IMPORTANT: injection is smooth and homogeneous



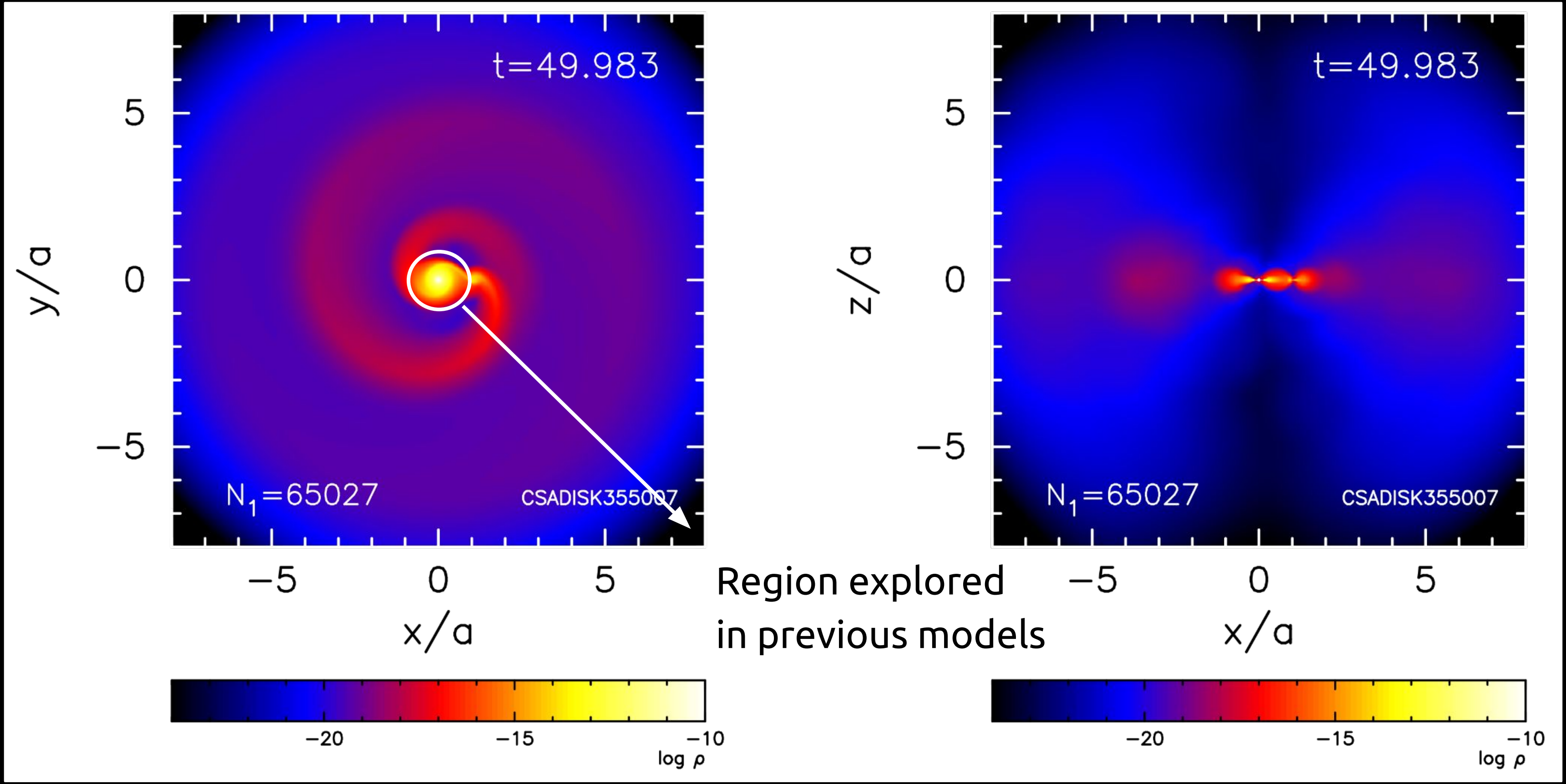
Binary SPH simulations

Simulation after several tens of orbital periods, **disk reaches a quasi steady-state**

Mass is lost to the ISM **mostly** through the Roche lobe of the secondary

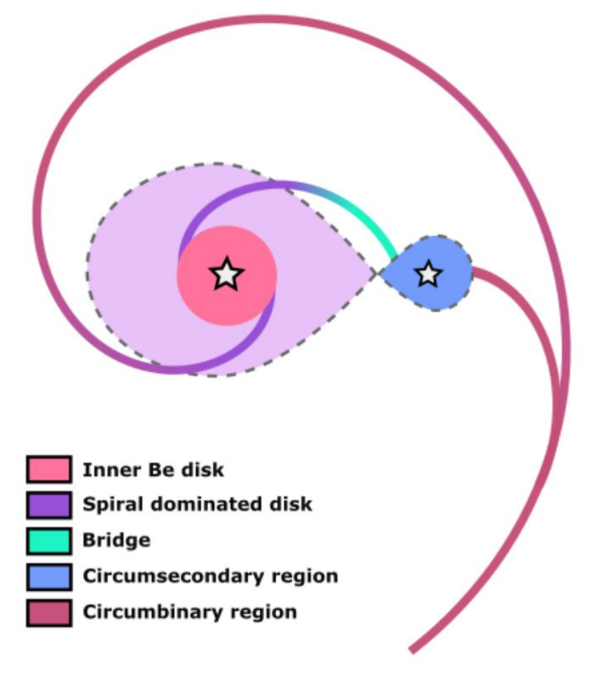


Binary SPH simulations

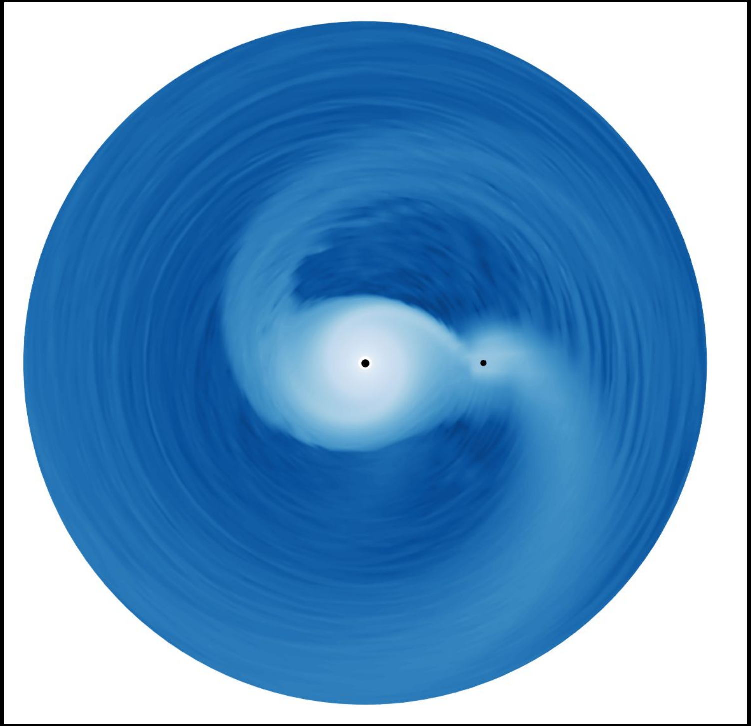


Region explored in previous models

Binary SPH simulations

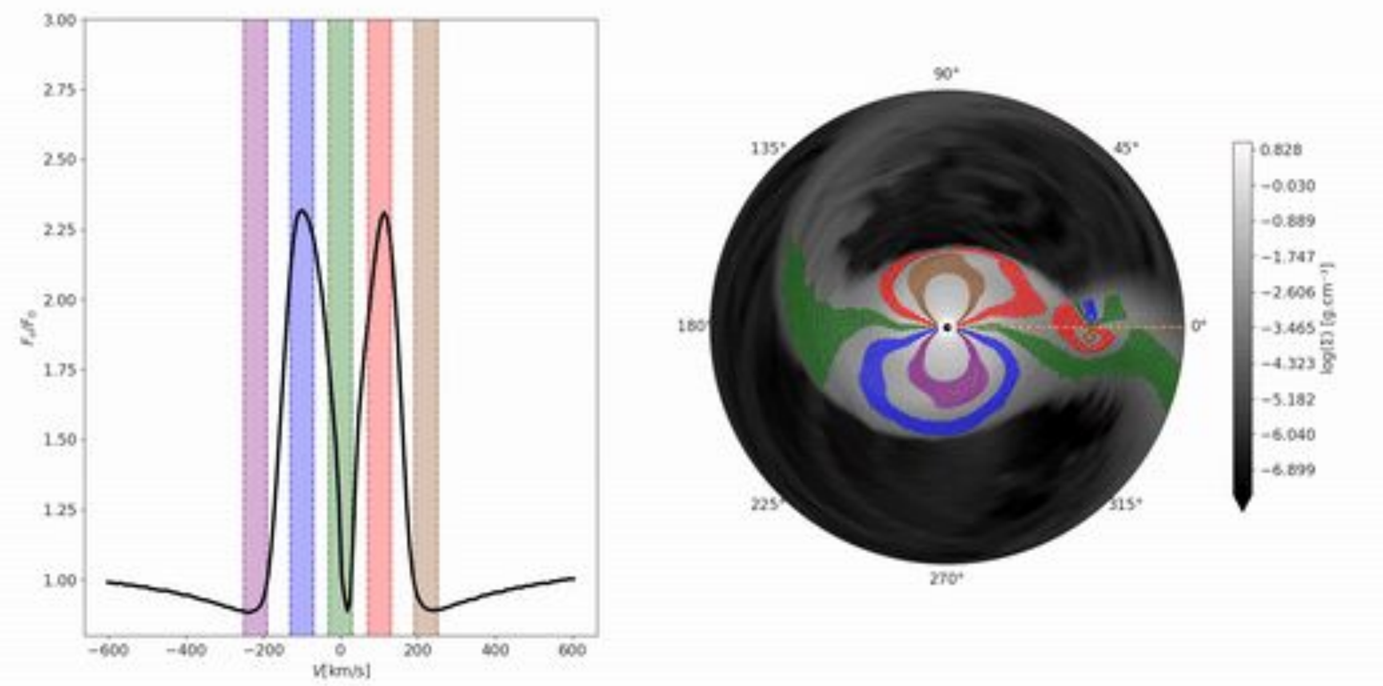


Simplified sketch with **5 regions with distinct properties**



Surface density map predicted for a binary Be star with P = 30 days

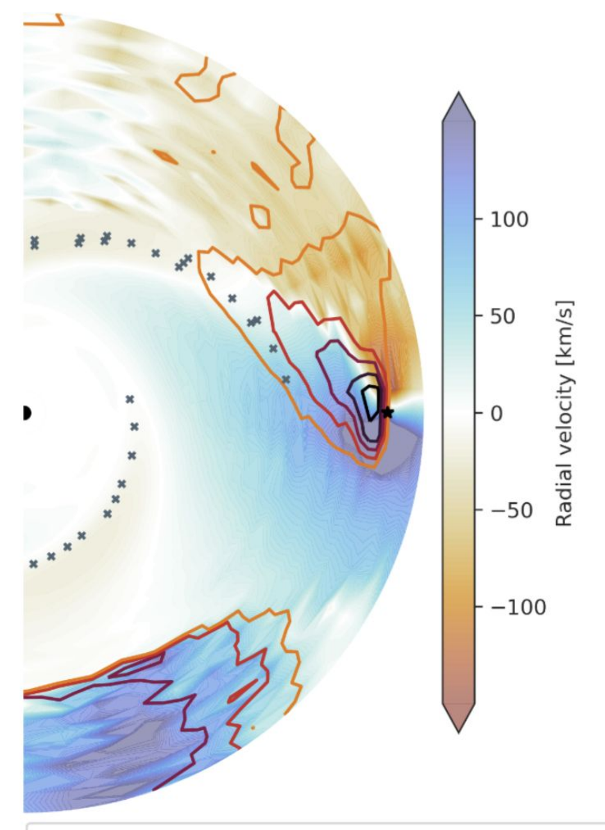
Binary SPH simulations



SPH + HDUST simulations of a 30d period binary Be star

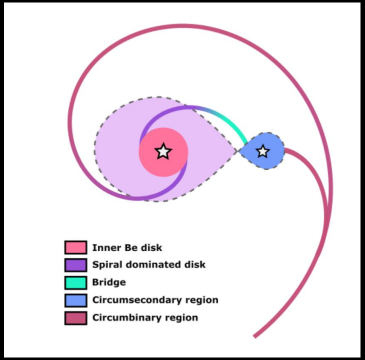
If the disk is asymmetric, this will cause line asymmetries
(e.g., different ratios between the V and R peaks ➔ **V/R variations**

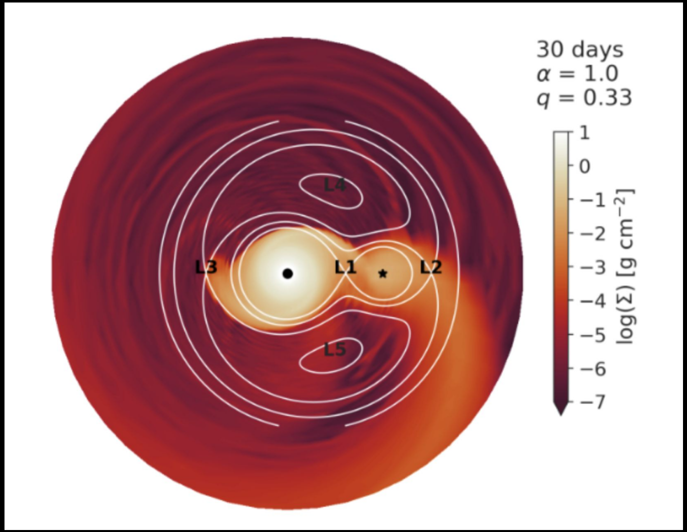
Binary SPH simulations



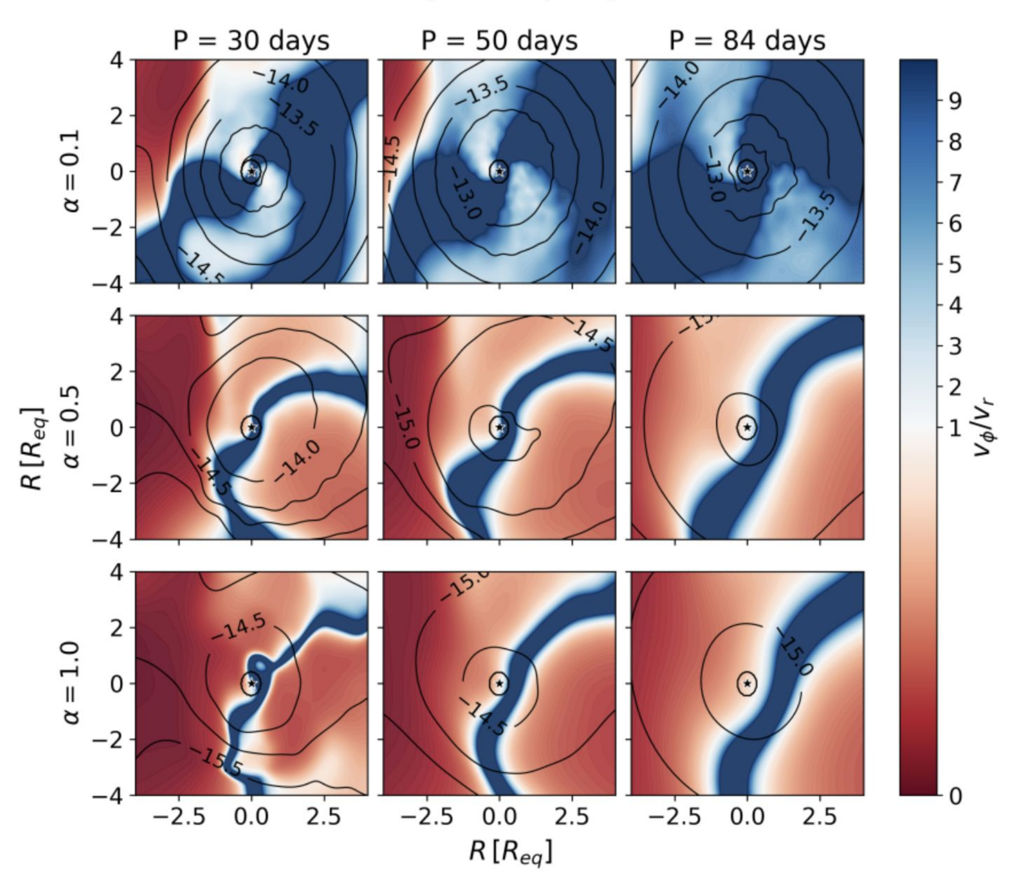
Material flows through the bridge is **dumped into the Roche lobe of the secondary at large speeds**

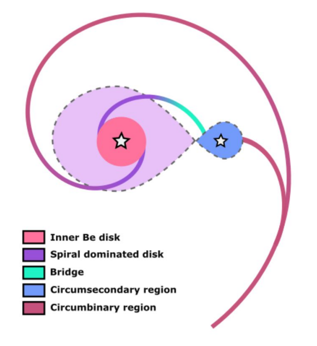
Part of this material is accreted onto the secondary, and part flows out through L2





Is it a disk?





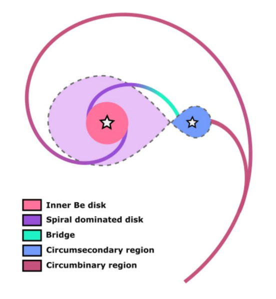
Depending on the model parameters, the structure around the secondary is either

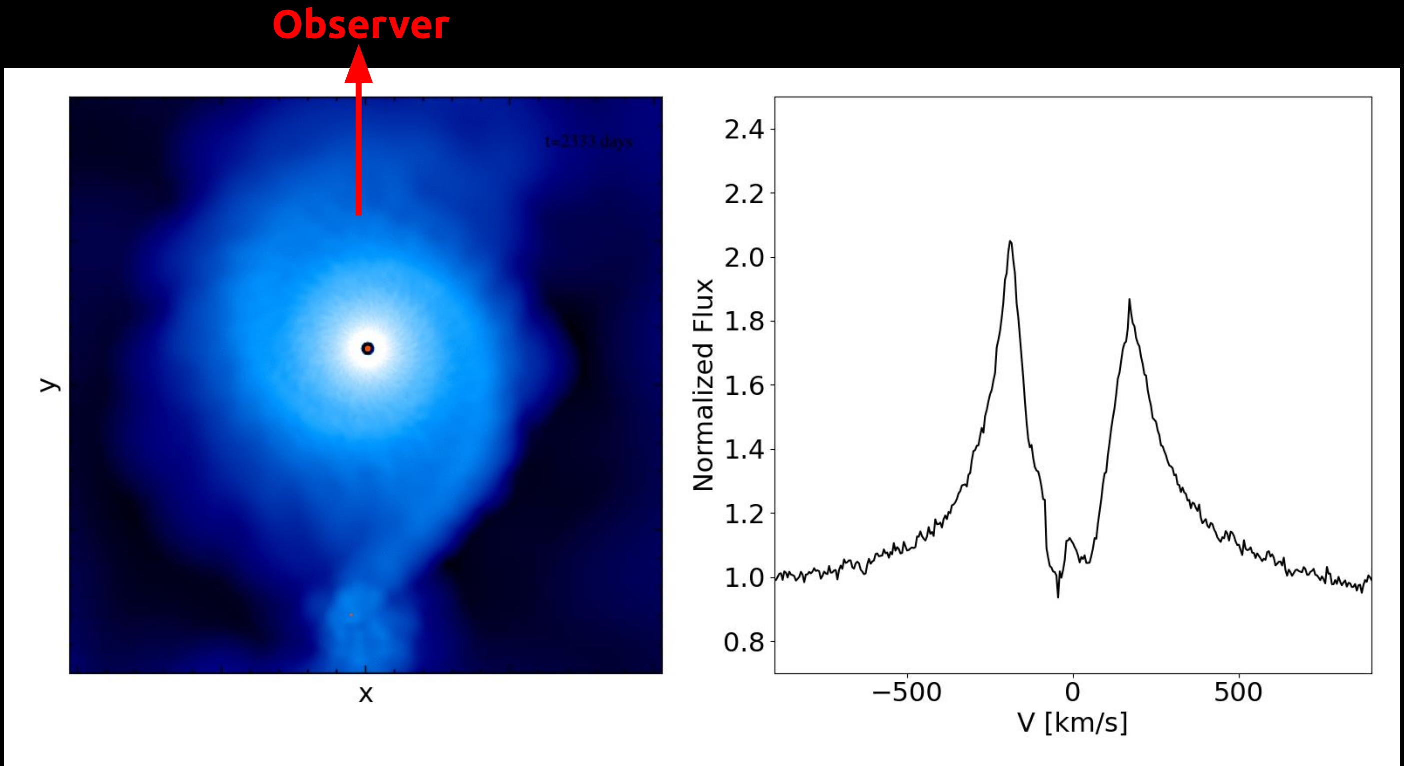
1) A **rotationally supported, accretion disk** (when vphi >> vr)

2) An **outflowing structure** (vr >~ vphi)

These will likely have different spectroscopic signatures

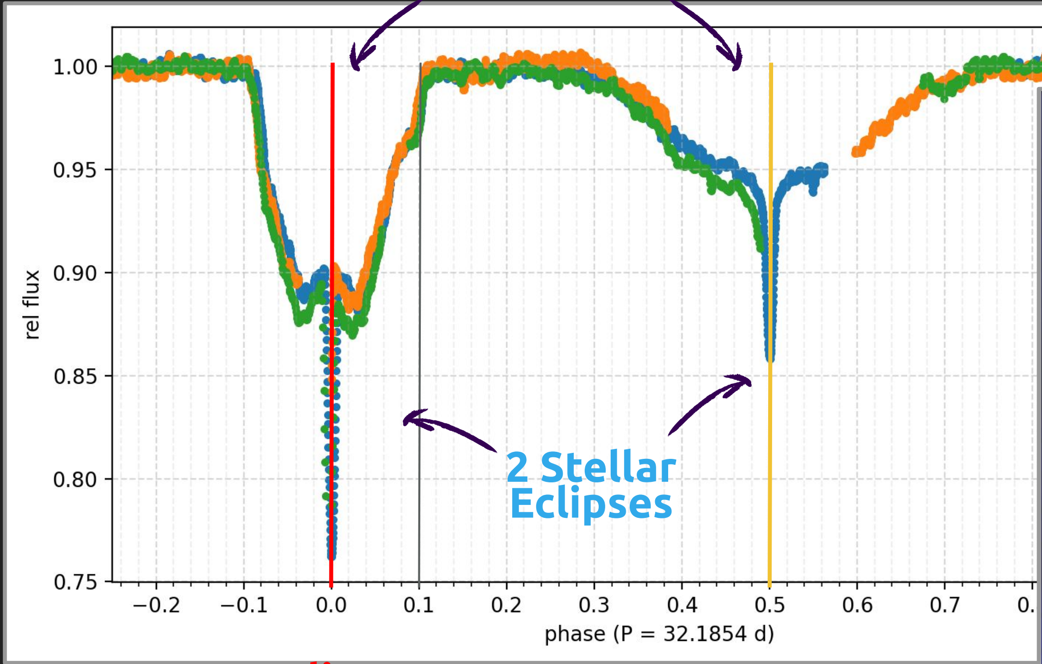
Binary SPH simulations





Ongoing: what is the role of each part of the disk in shaping the spectroscopic appearance of the star?

V658 Car: the first eclipsing binary Be star

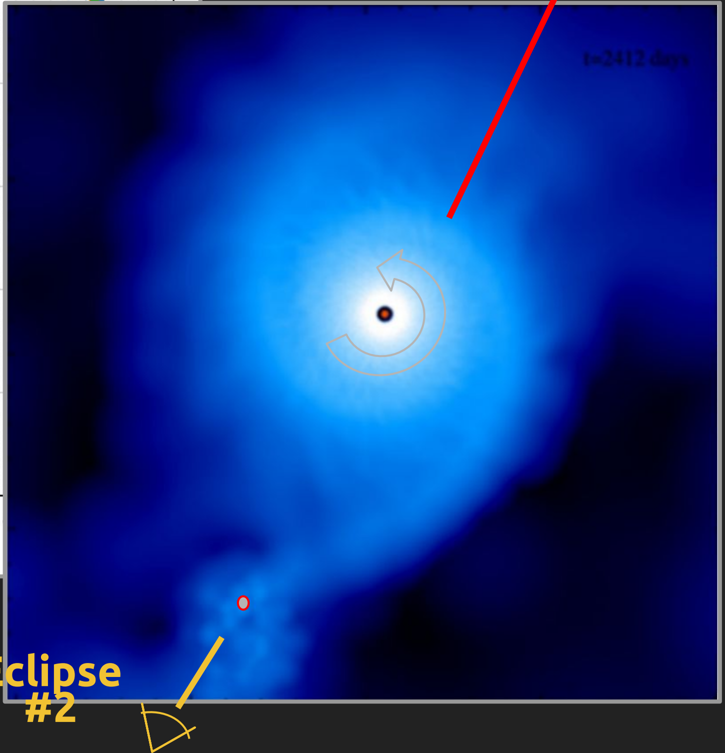


2 Broad Eclipses

2 Stellar Eclipses

Eclipse #1

Eclipse #2

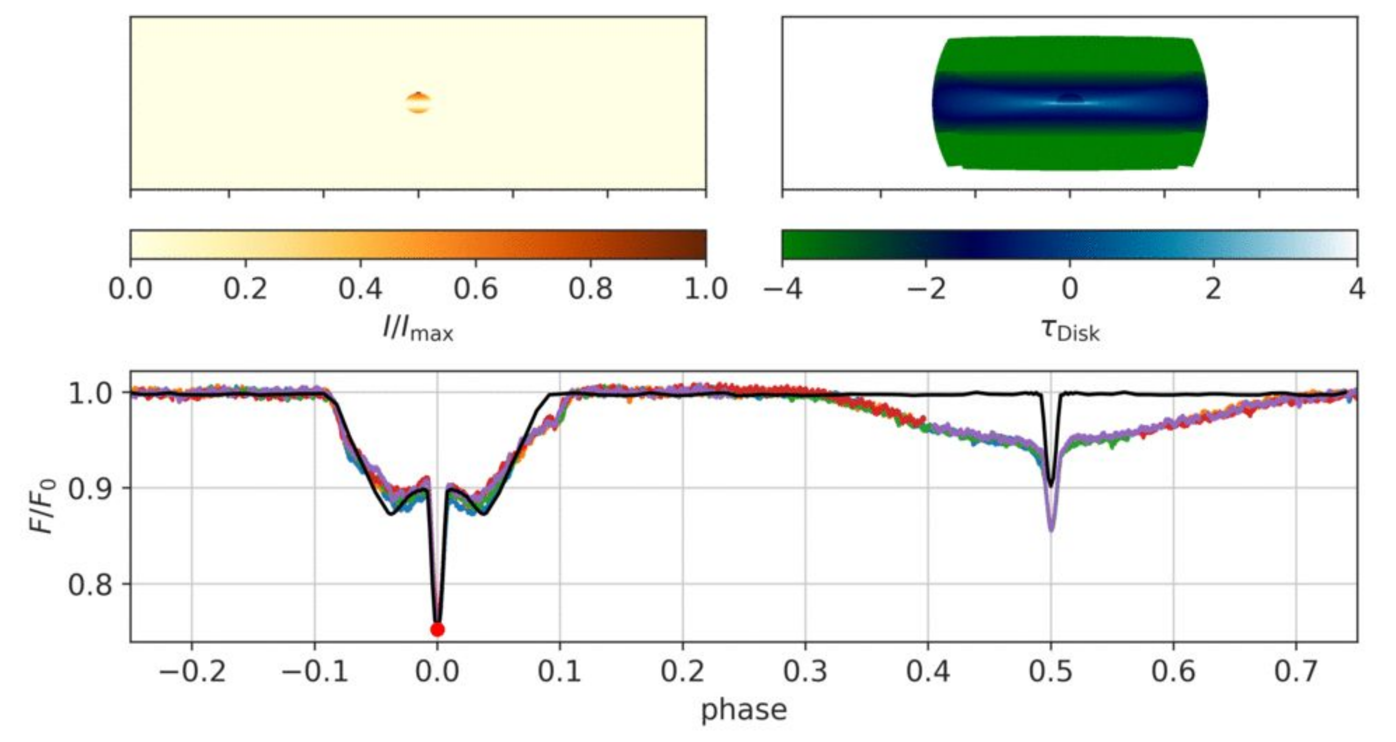


Eclipse #1

Eclipse #2

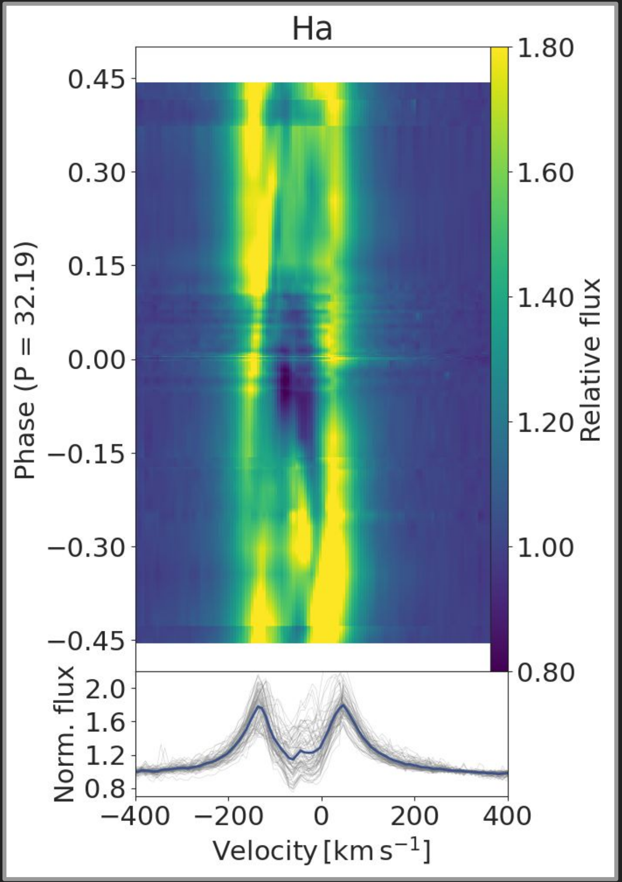
TESS lightcurve of V658 Car

Ongoing modeling effort

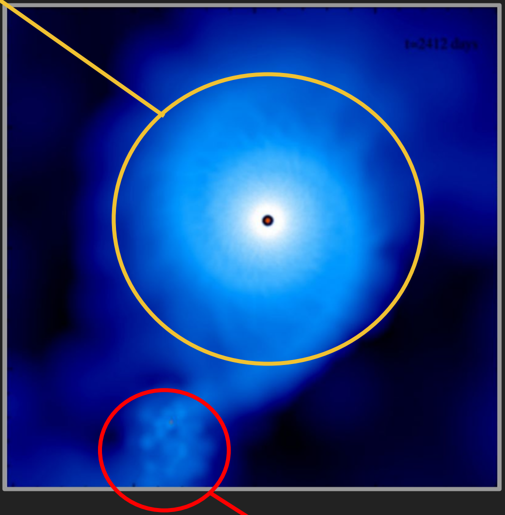


de Amorim, Carciofi et al. (in preparation)

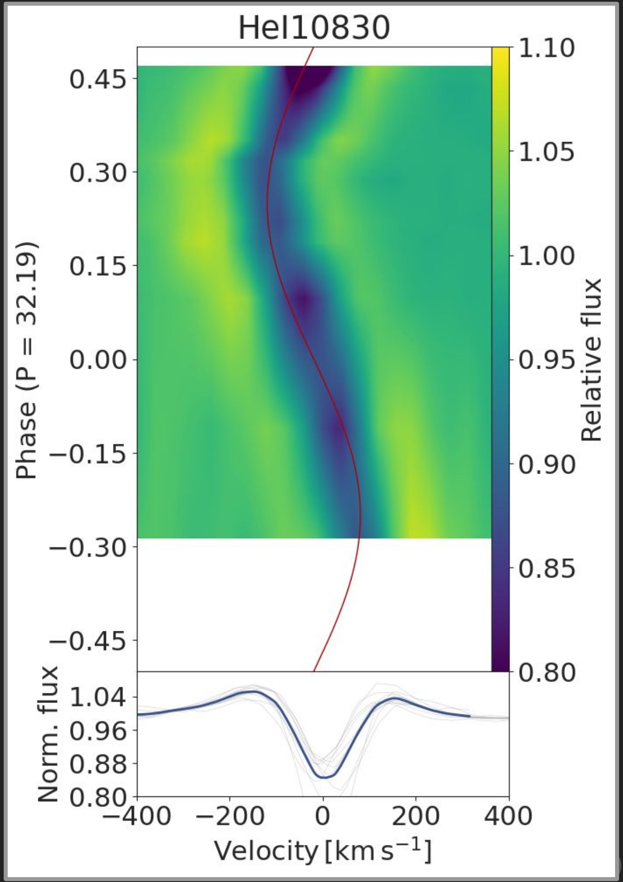
Two Disks!



Disk around the Be star



Disk around the secondary



Takeaways from part 2

- New particle-splitting SPH simulations provide a **complete view of Be star disks for the first time**

- They reveal the fate of the material as it escapes from the Be disk: most **material escapes through L2** (in some models part also leaves through L3)

- Simulations predict the **formation of a circumsecondary disk** under certain conditions

-
- Those are now being detected (5 known cases so far, Carciofi+ in preparation)