Spectro-Interferometric measurements of Massive Hot Stars

Anthony Meilland

What is the aim of this talk?

To show that spectro-interferometry is fun

To give you the urge to observe your favorite target with AMBER or VEGA right now

To persuade you (f needed) that hot stars are cool

What it is not

A lecture on hot star physics

A complete review of spectro-interferometric observation of hot massive stars

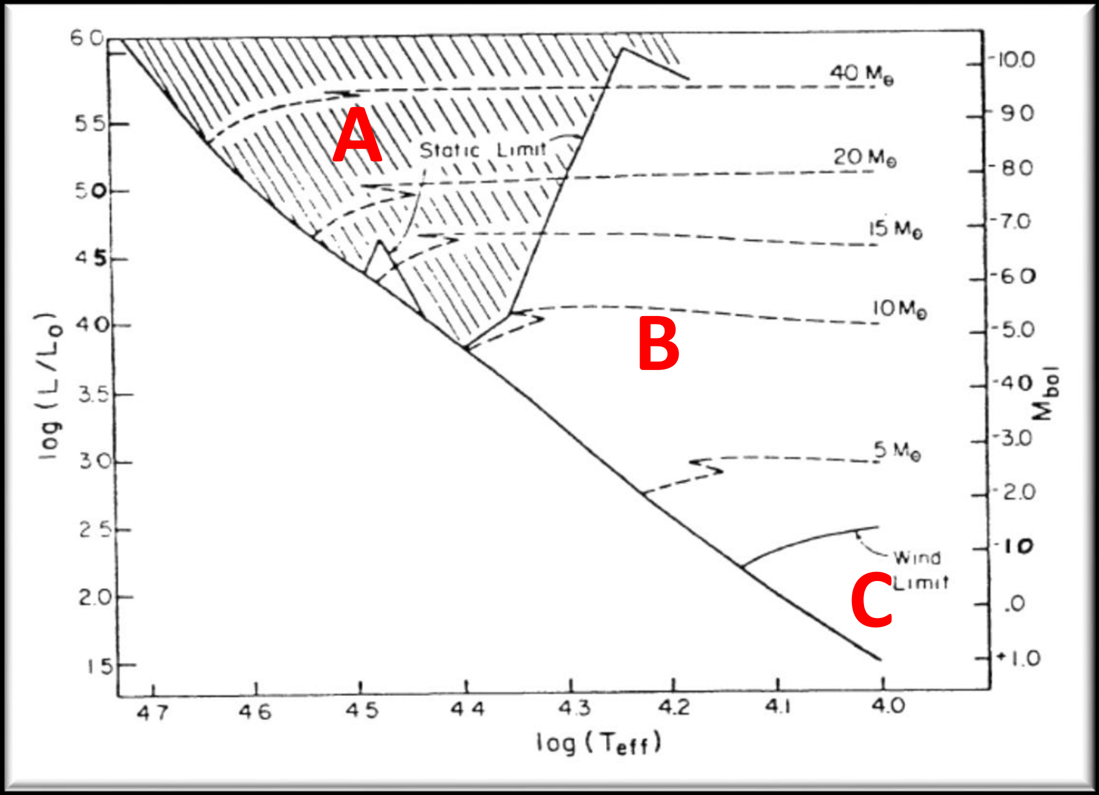
Massive stars show huge mass-loss at every stage of their evolution

This is mainly due to radiatively driven wind

Radiative pressure depends on the Luminosity and Temperature

Abbott (1979)

The domain of radiatively driven mass-loss in the H-R diagram



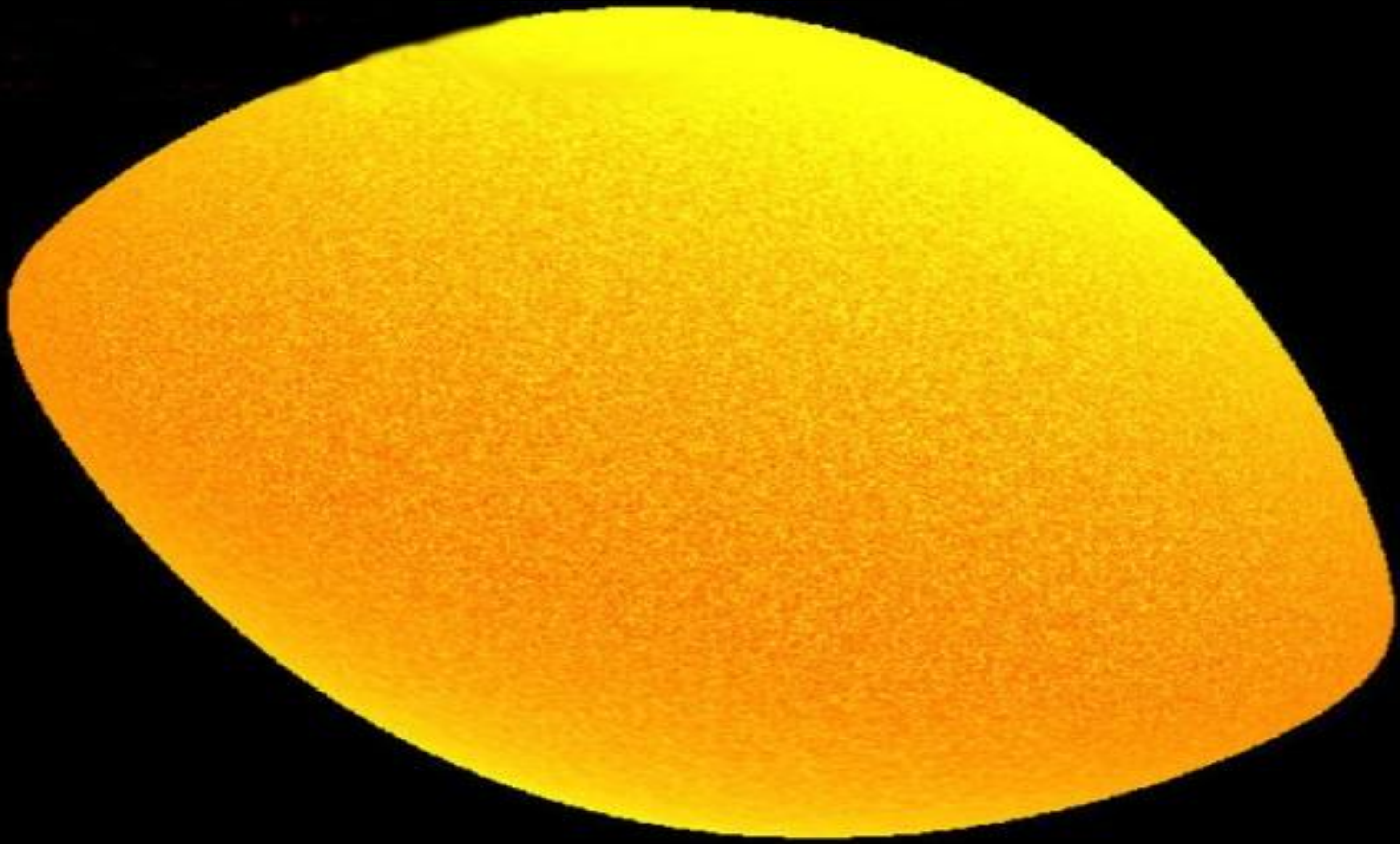
Three different regions

A - Wind wan be initiated (>B1V)

B – Wind can be sustained (> B8V)

C – No radiative wind possible (< B8V)

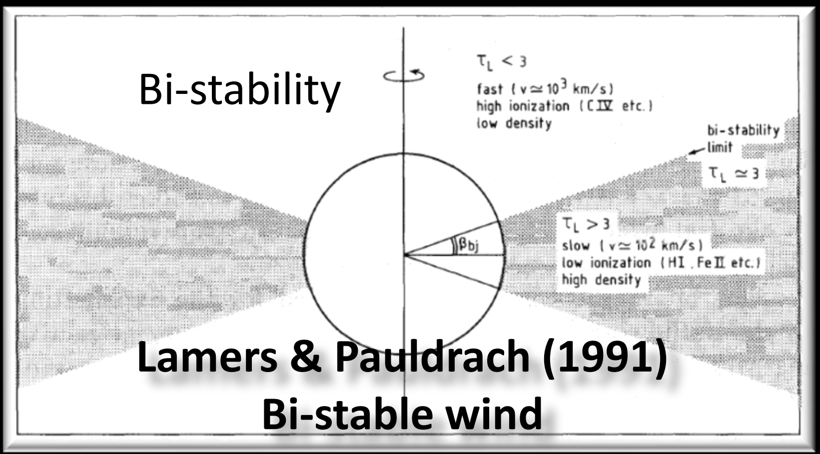
Massive are often fast rotators

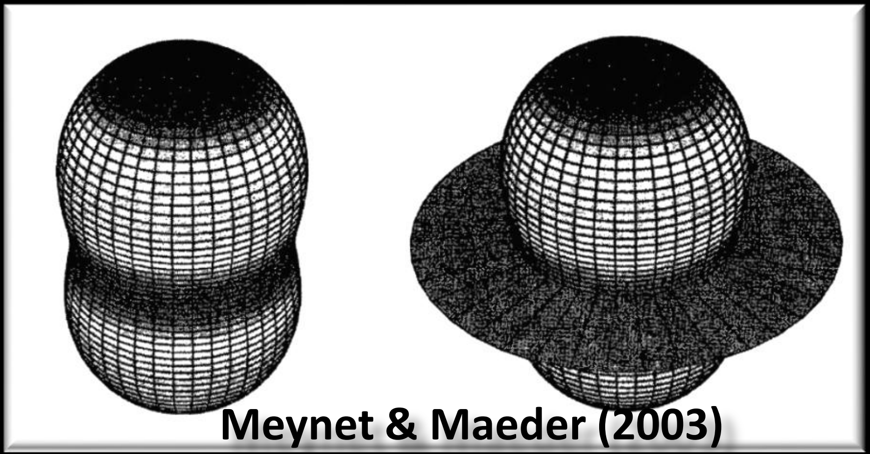


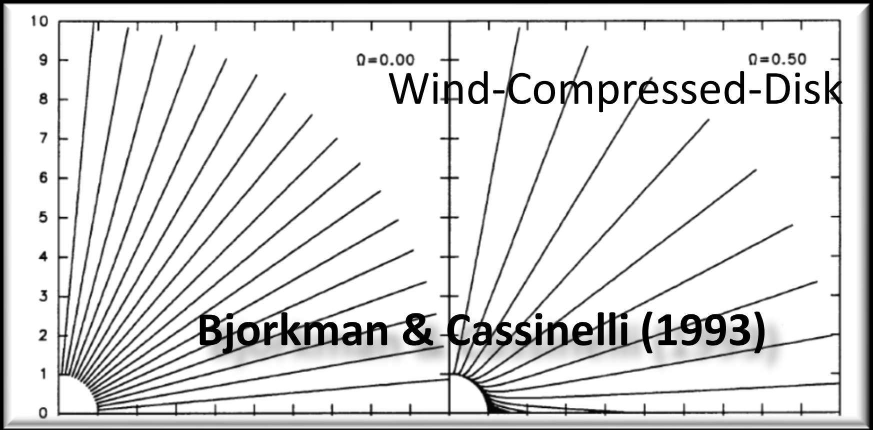
Surface deformation + Von Zeipel effect

Temperature and Gravity depends on the stellar latitude

Rotation influences the mass loss and its latitudinal dependence

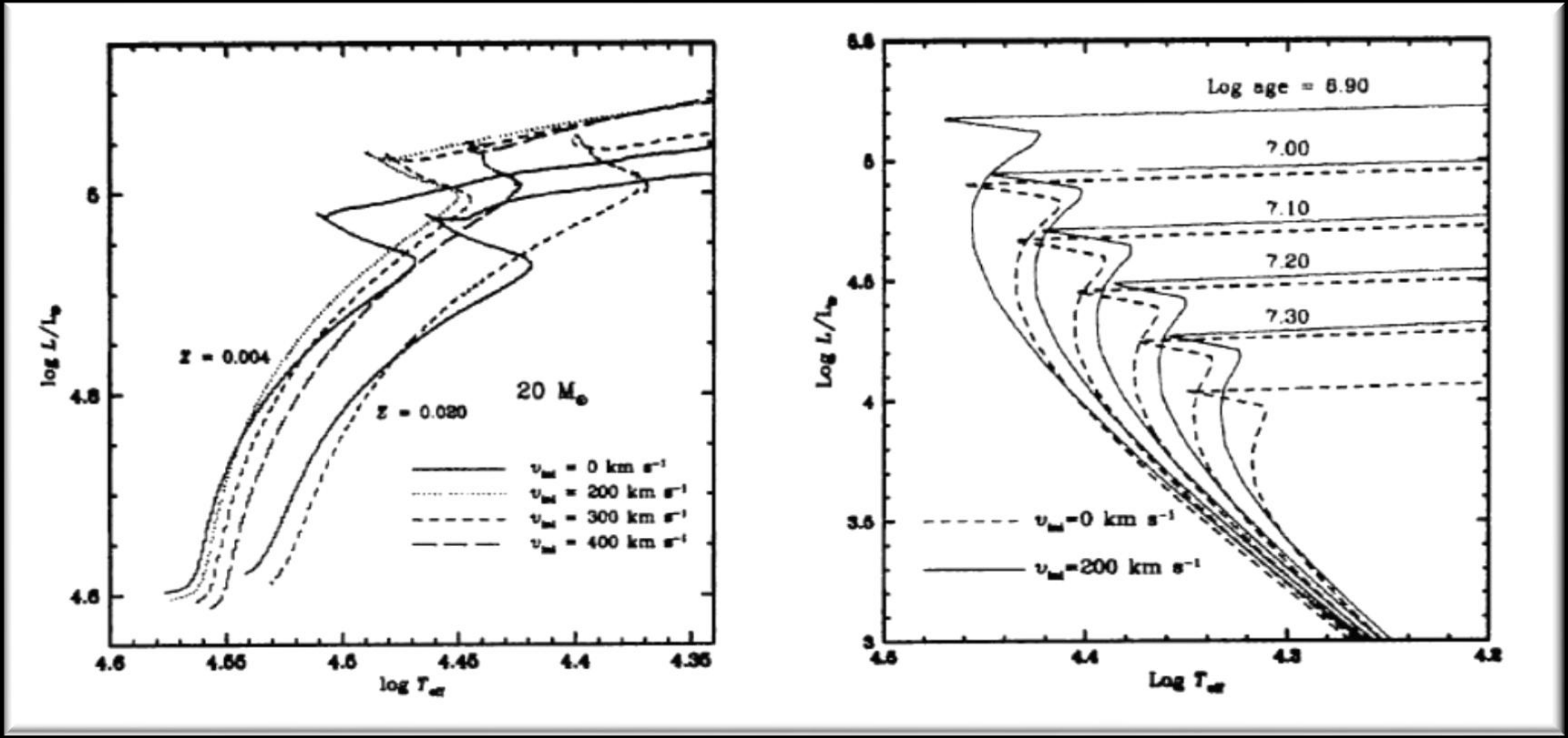






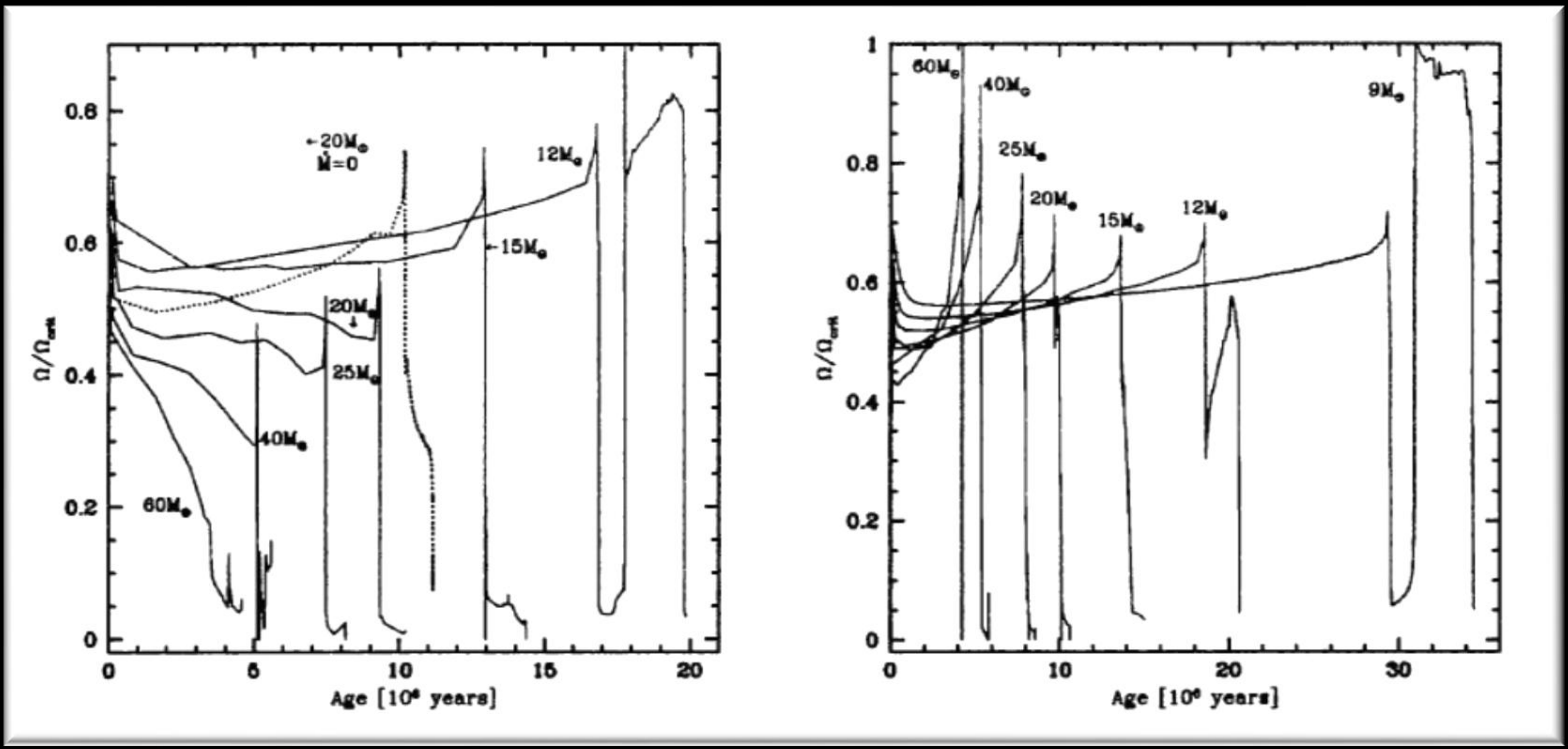
…Rotation can also initiate the mass-loss
When a star is close to critical rotation
« Mechanical » wind
Viscous excretion disk (Lee 1991)

Rotation and mass-loss influences each other and stellar evolution
Genova evolution models (Meynet, Maeder…)

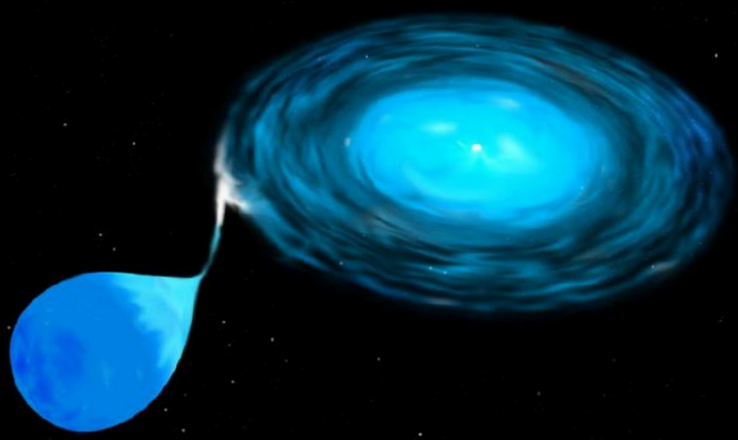


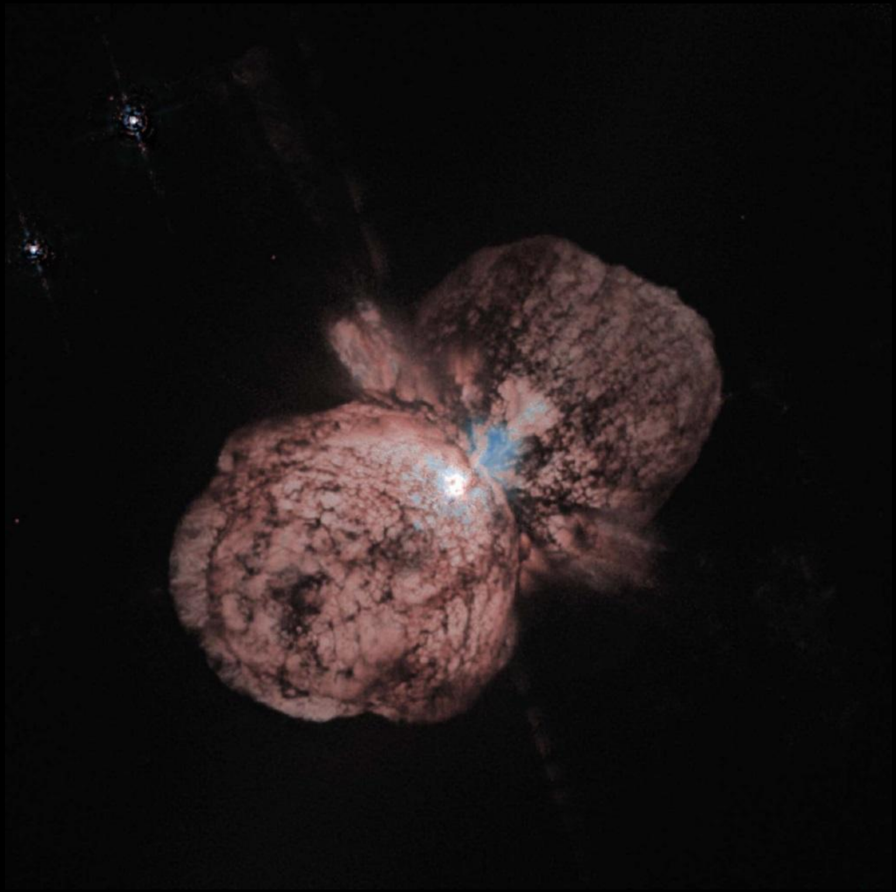
Rotation and mass-loss influences each other and stellar evolution

Genova evolution models (Meynet, Maeder…)



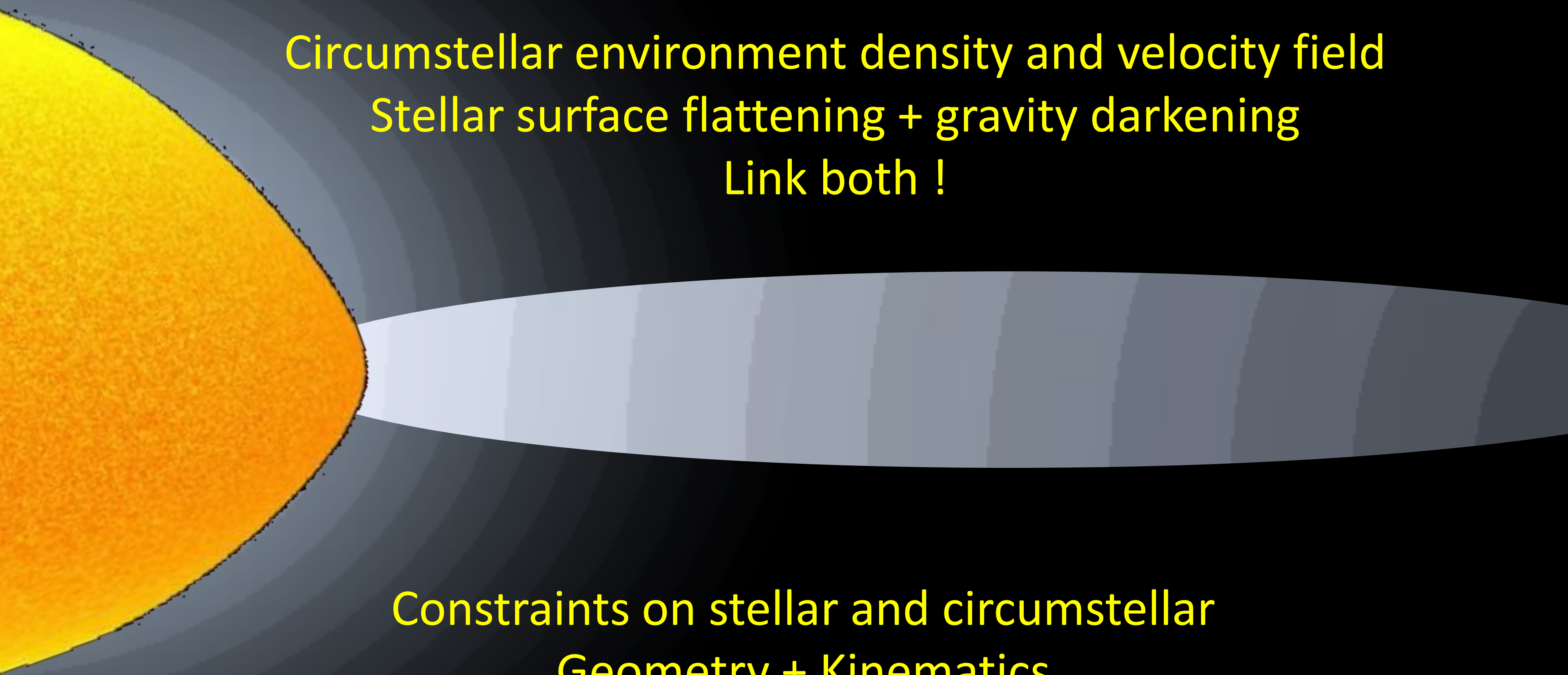
and I’m not talking of multiplicity!!!



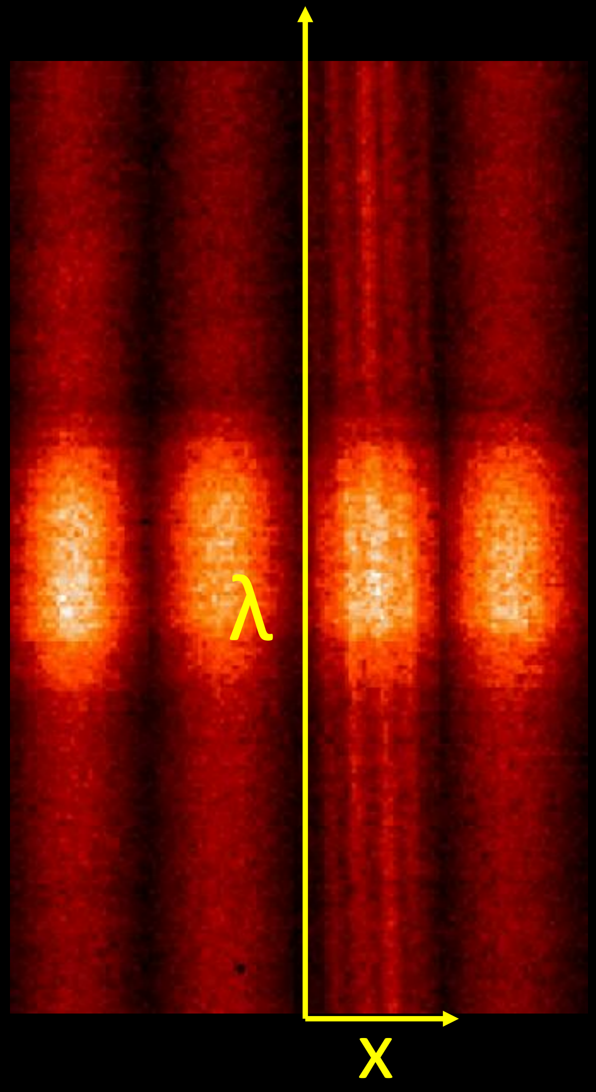


What do we need to disantangle all that mess?

Circumstellar environment density and velocity field
Stellar surface flattening + gravity darkening
Link both !



Constraints on stellar and circumstellar
Geometry + Kinematics
⇔
Spectro-interferometry



Dispersed fringes (in wavelength)

Variation of Constrast (visibility)
and
phase (= differential phase)
As a function
of the Wavelength

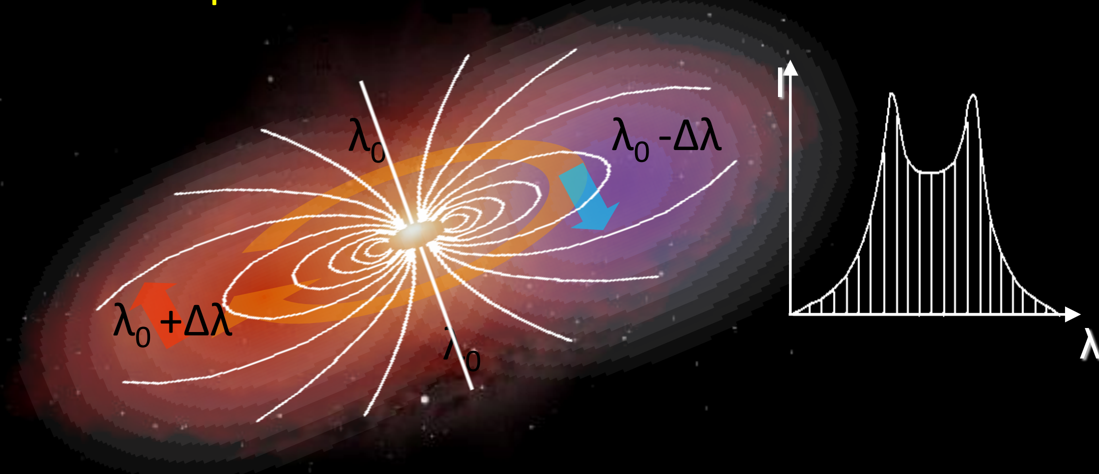
Localize

(Extension + position)

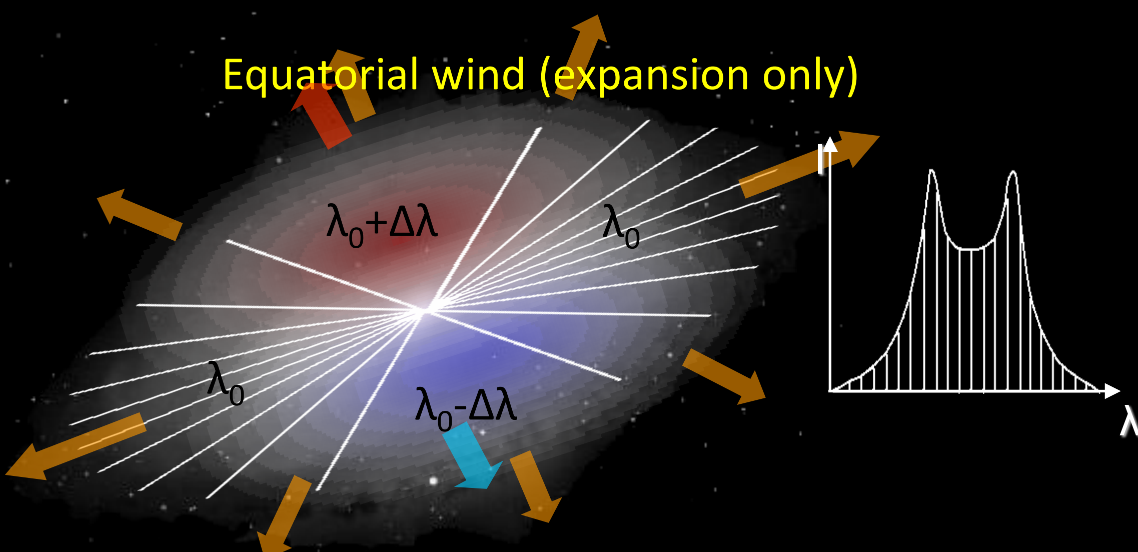
Chemical species
Physical Conditions in the medium
And iso-velocity zones (in spectral lines)

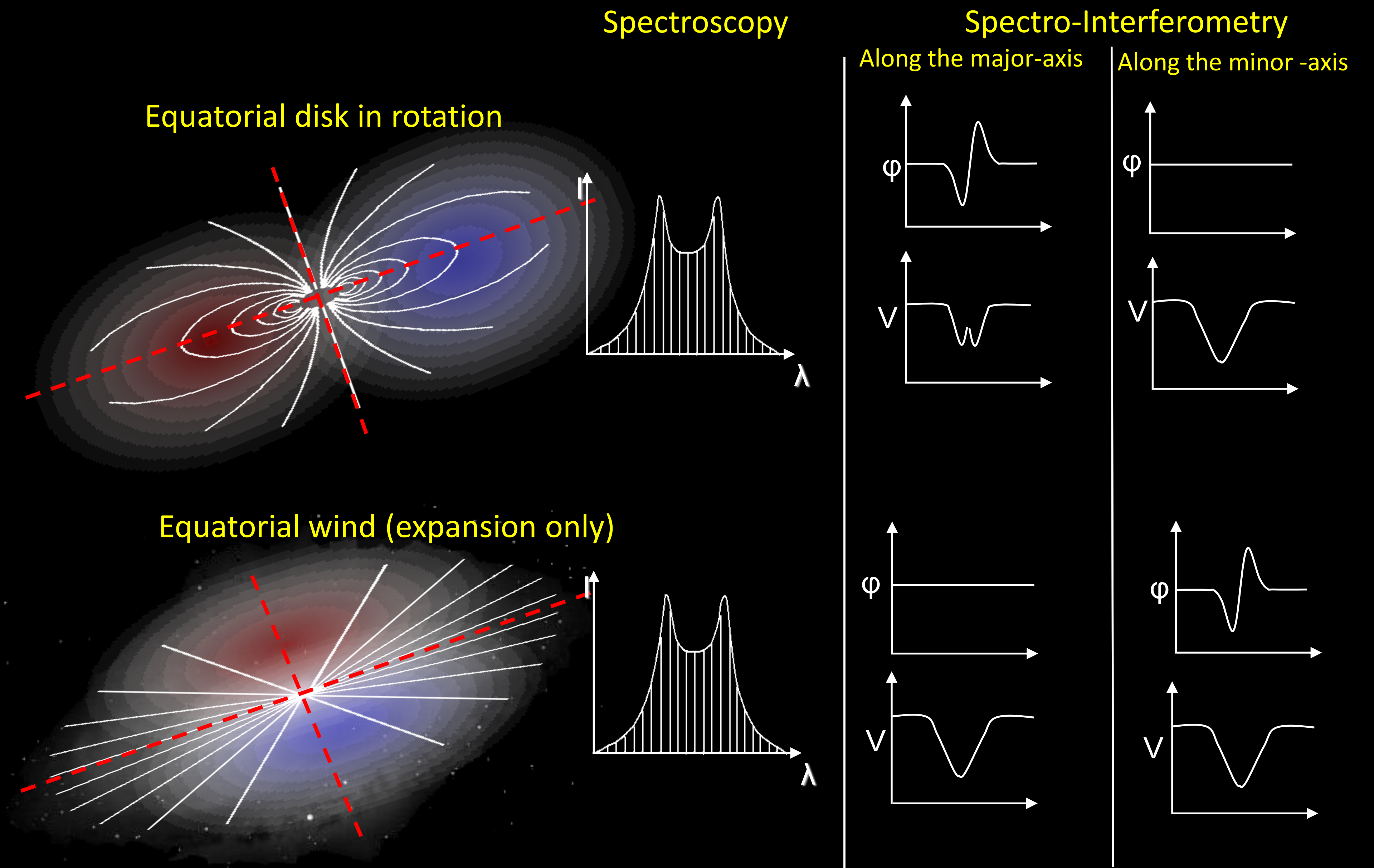
What about spectroscopy ?

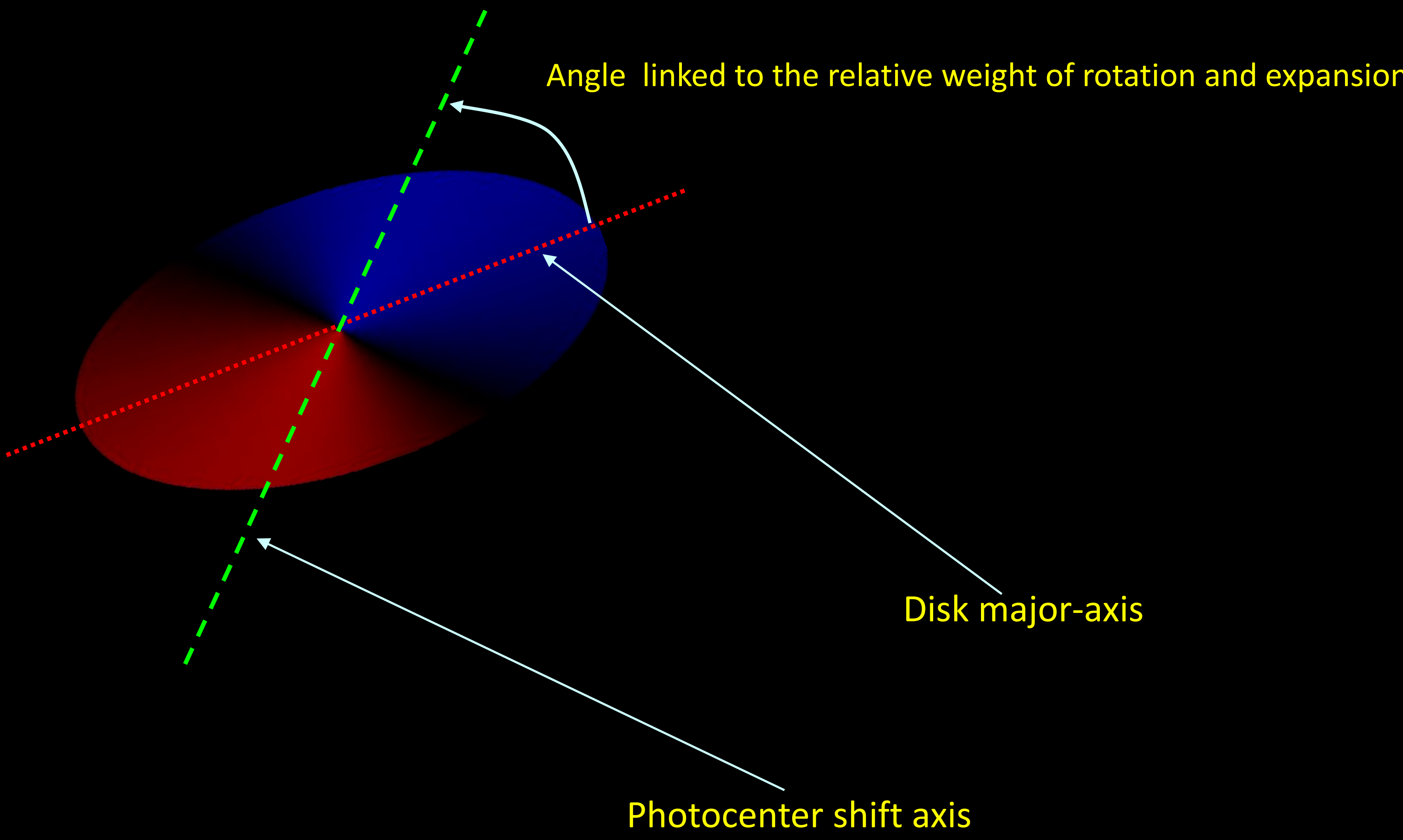
Equatorial disk in rotation

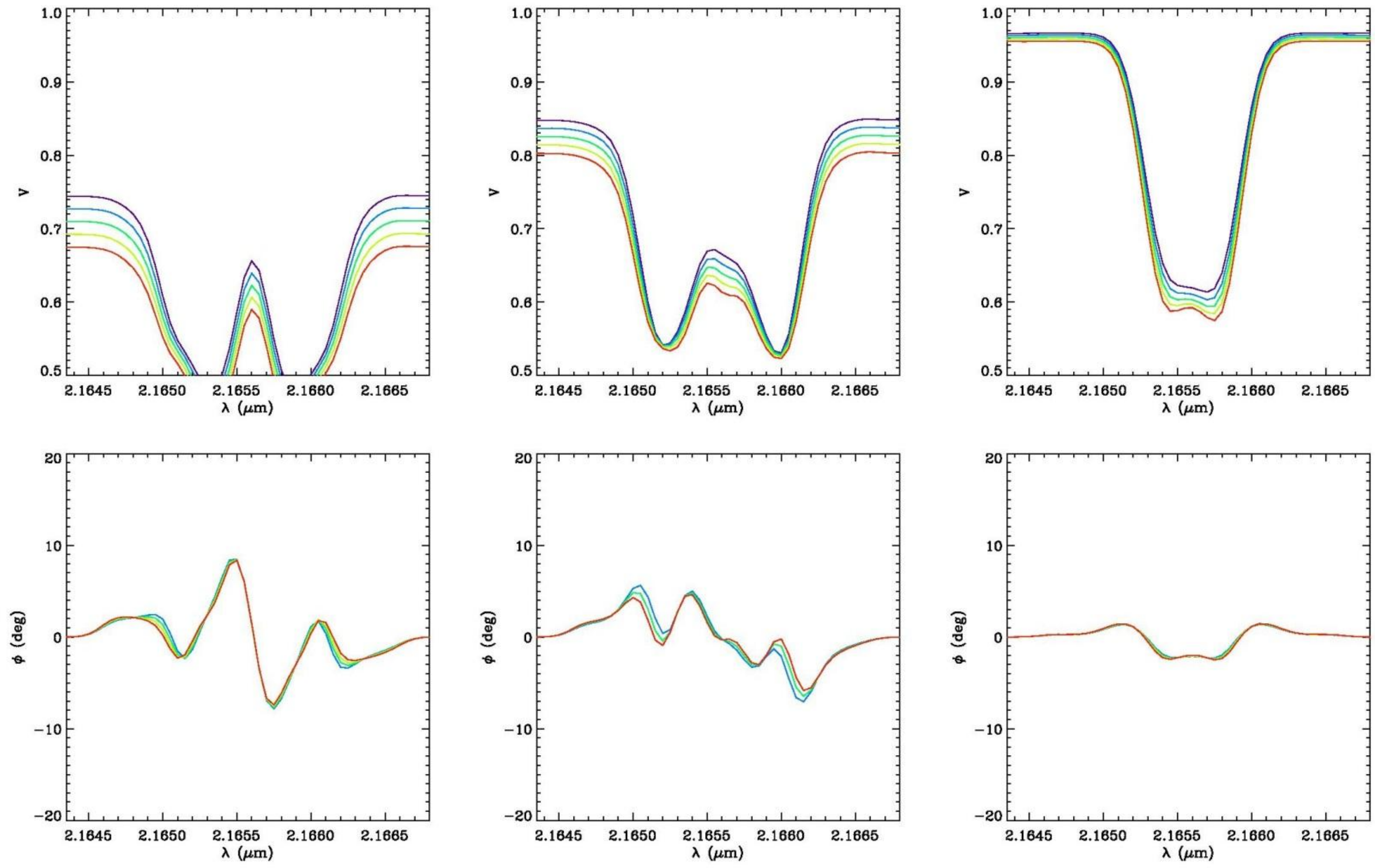


Equatorial wind (expansion only)




Spectroscopy
Spectro-Interferometry
Along the major-axis
Along the minor -axis
Equatorial disk in rotation
I
λ
φ
V
φ
V
Equatorial wind (expansion only)
I
λ
φ
V
φ
V


Angle linked to the relative weight of rotation and expansion
Disk major-axis
Photocenter shift axis

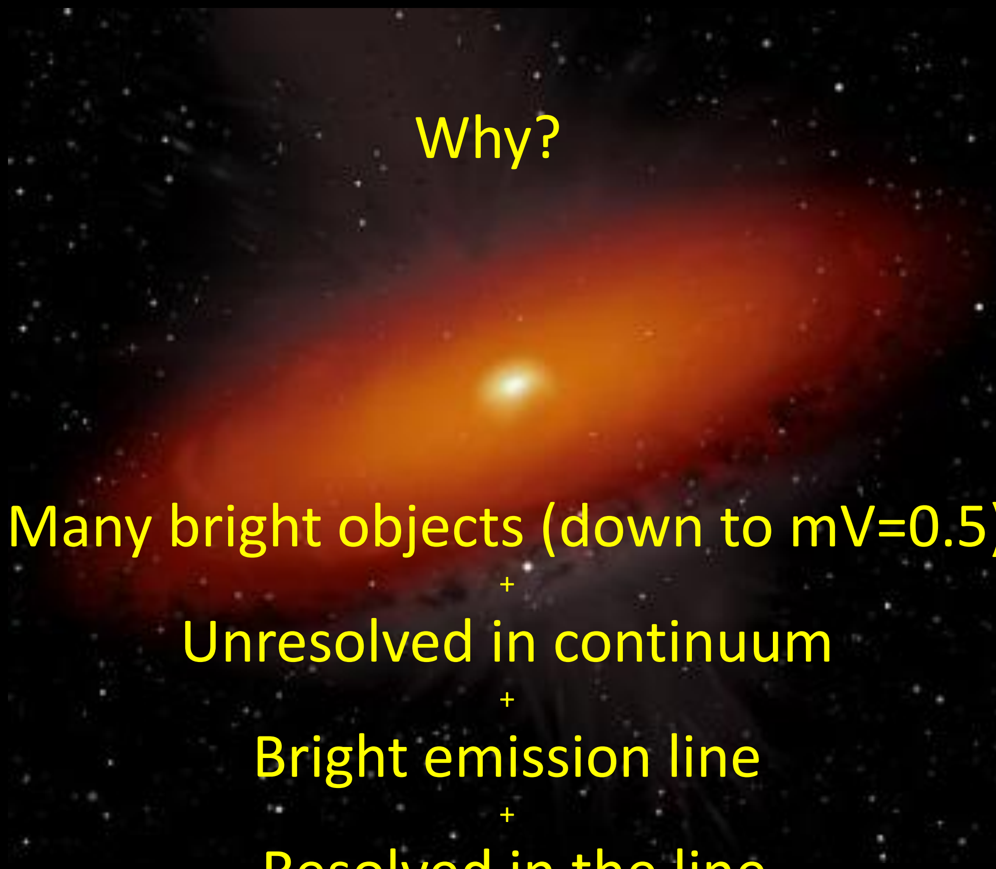

1.0
0.9
0.8
0.7
0.6
0.5
V
2.1645
2.1650
2.1655
2.1660
2.1665
λ (μm)
20
10
0
−10
−20
φ (deg)

Pioneers in spectro-interferometric observations

- Petrov (1987): differential-speckle interf. to measure rotation
- Mourard et al. (1989) The Be star Gamma Cas with GI2T
- Stee (1995), Berio (1998) & Vakili (1999) : More Be stars with GI2T

Their works leads to the development of AMBER and VEGA
The only instruments combining high spectral and spatial resolution

Classical Be stars and spectro-interferometry
And everlasting love story



Why?

Many bright objects (down to mV=0.5)

+

Unresolved in continuum

+

Bright emission line

+

Resolved in the line

+

Interesting physics and problematics

(not only because they were my PhD subject!)

Spectro-interferometry is a technique suitable for many objects :

- With Emission lines
  - Classical Be stars
  - Herbig Ae/Be stars
  - B[e] stars
  - Wolf-Rayet
  - LBV
  - Nova
  - AGNs…

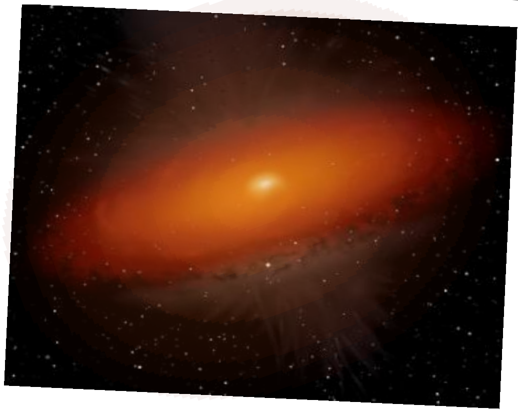
- With Absorption lines
  - Fast rotation in photosphere
  - Pulsating stars
  - Giants and Supergiants motion

The main limitation are the kinematic resolution you need

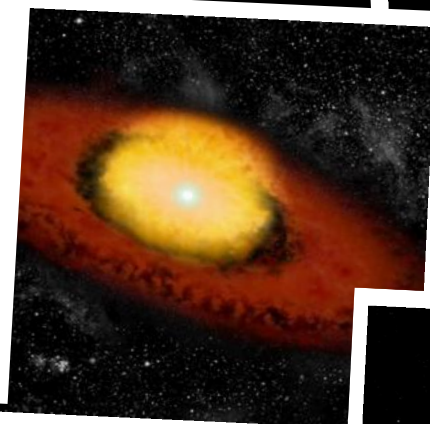
AMBER MR ⇔ dv = 200km/s
VEGA MR ⇔ dv = 60km/s
AMBER HR ⇔ 25km/s
VEGA HR ⇔ 10km/s

and the amplitude of the phenomena (errVis = 0.01 errPhi = 1°)

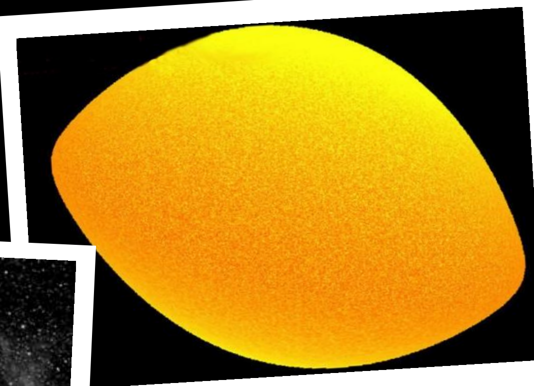
A few results from VLTI…



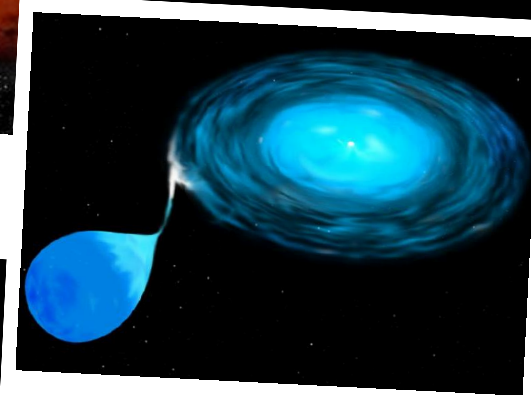
Classical Be stars



B[e] phenomenon



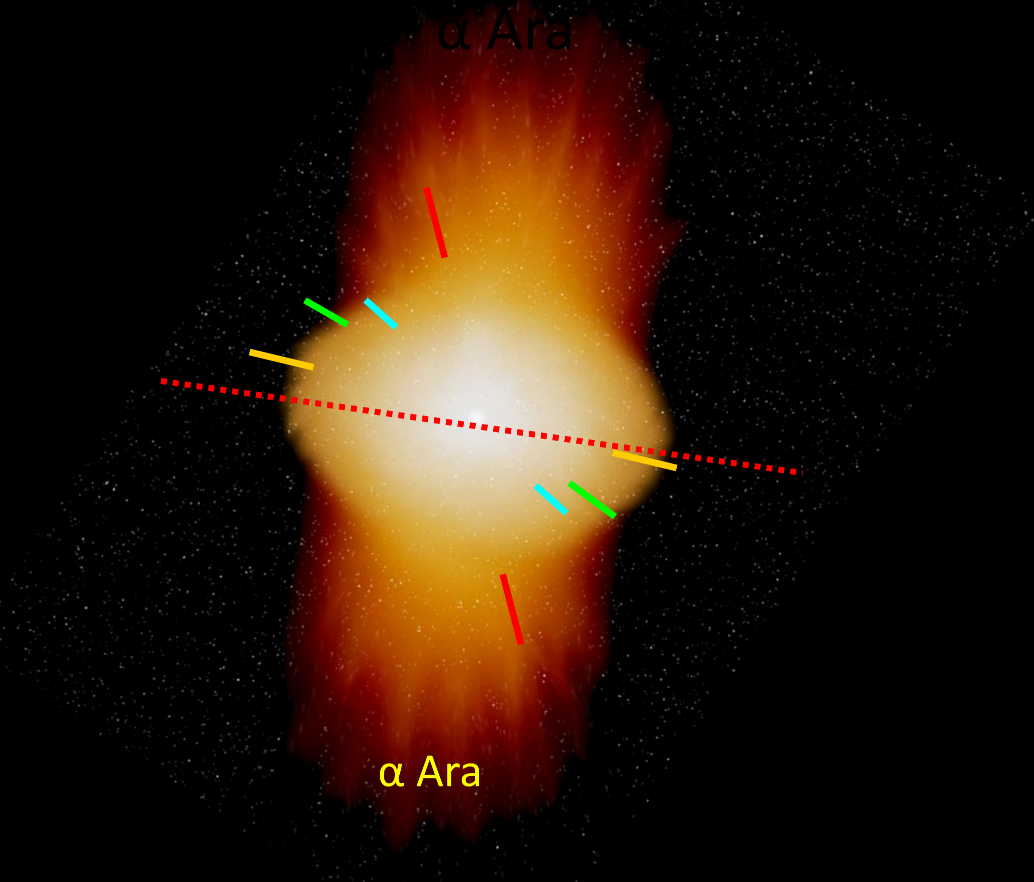
Rotation

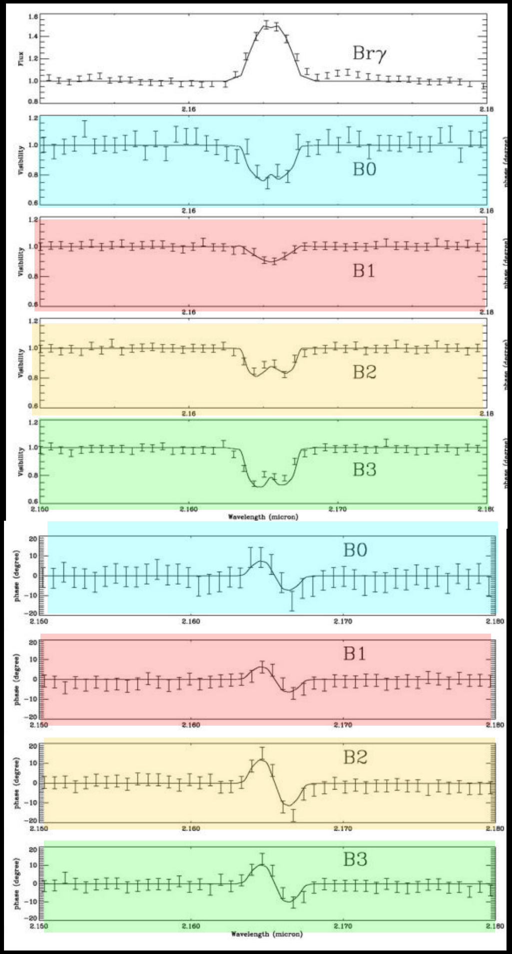


Binarity

Once again, this is not a review…
(and it's probably too much centered on my work)

Classical Be stars and spectro-interferometry
The love story is going on (AMBER 2005)

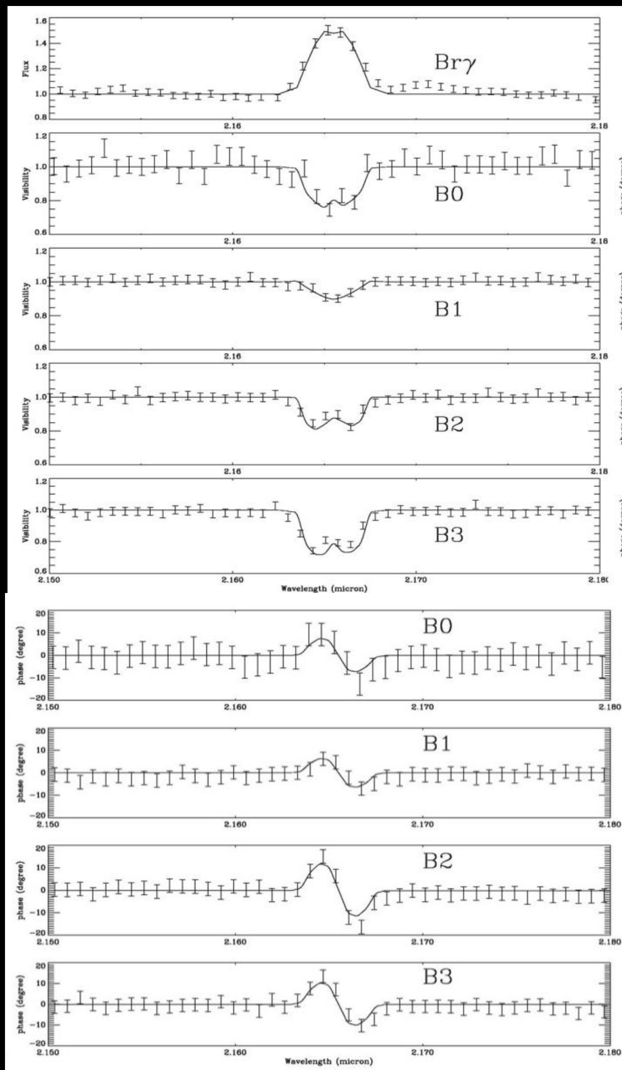




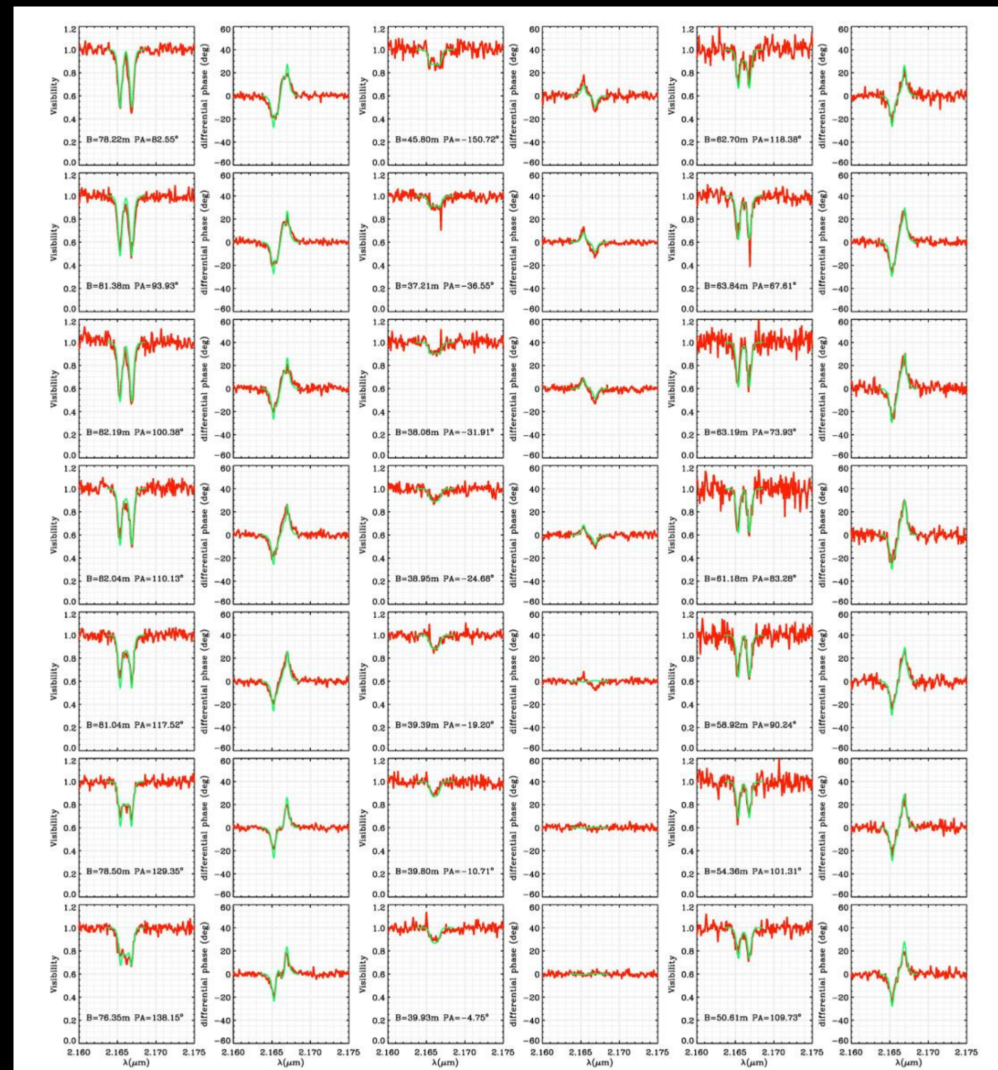
- Quasi-critical rotation
- Keplerian rotation
- No expansion (<10km/s)
- Clues of enhanced polar wind

Meilland et al. (2007)

From MR (R=1500) to HR (R=12000) with AMBER : Thank you FINITO!

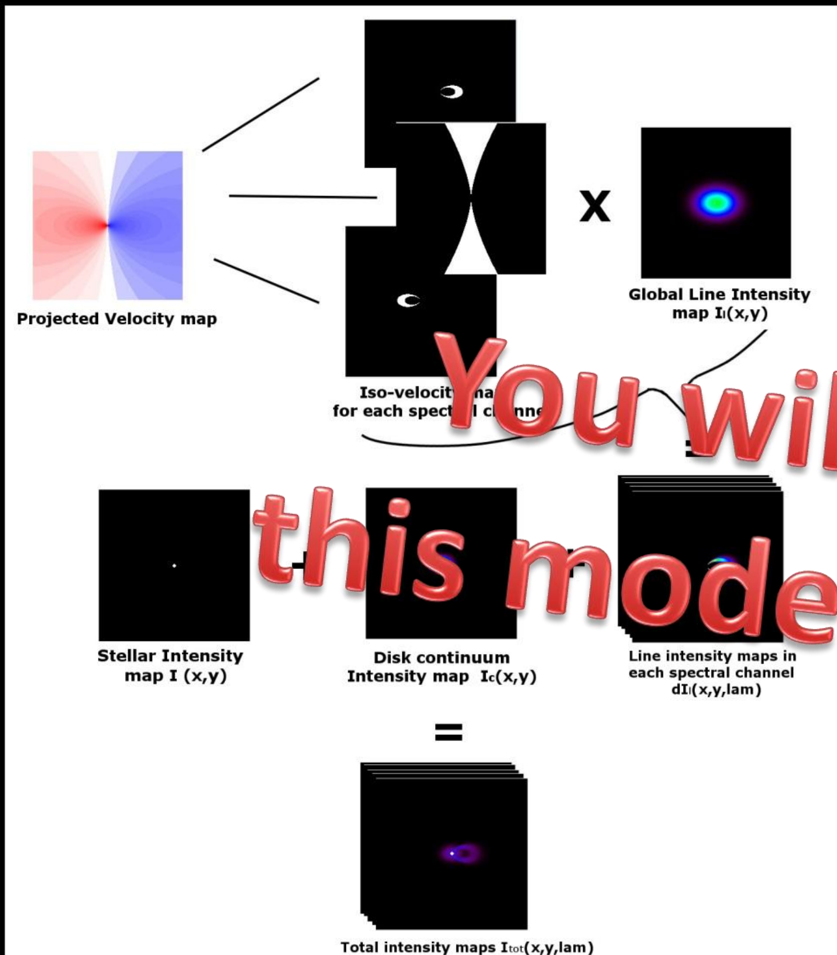


MR DIT=200ms



HR DIT= 7s

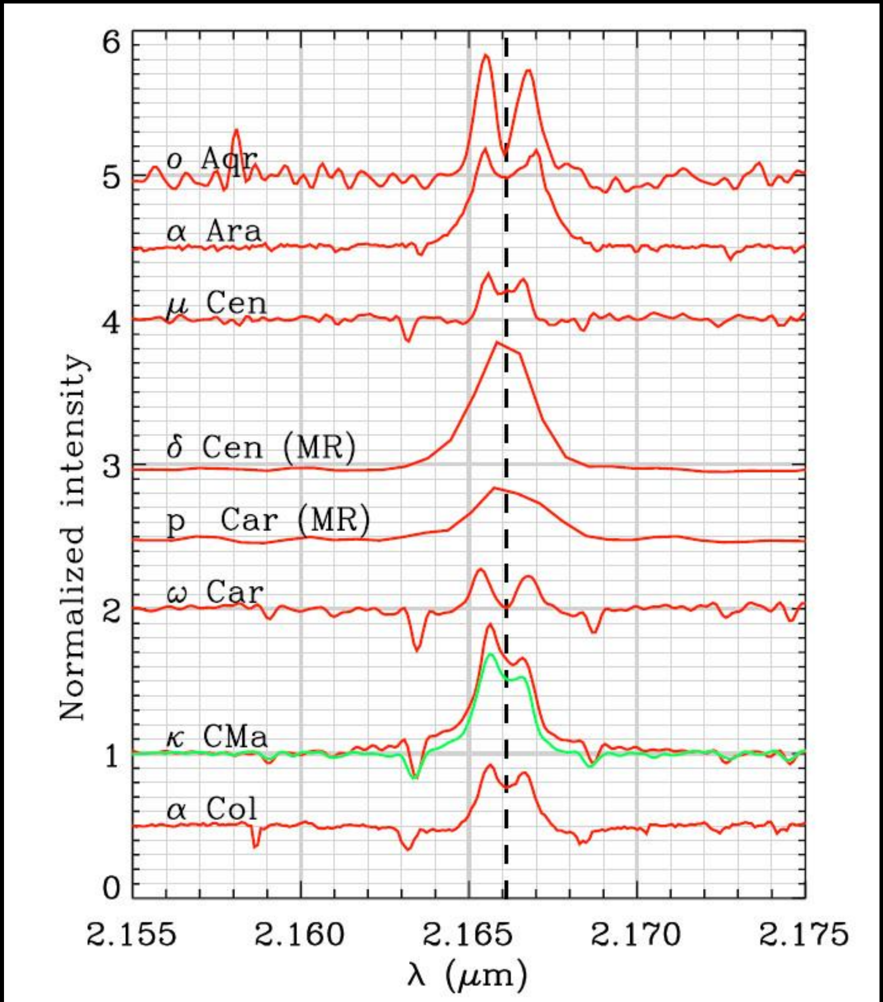
First mini-survey of Be stars in spectro-interferometry



You will play with this model on Thursday

Fit of the data with a geometric + kinematic model

First mini-survey of Be stars in spectro-interferometry



AMBER spectra on 8 stars
Meilland et al. (2012)

2013 VLTI School : High-angular resolution for stellar astrophysics

First mini-survey of Be stars in spectro-interferometry

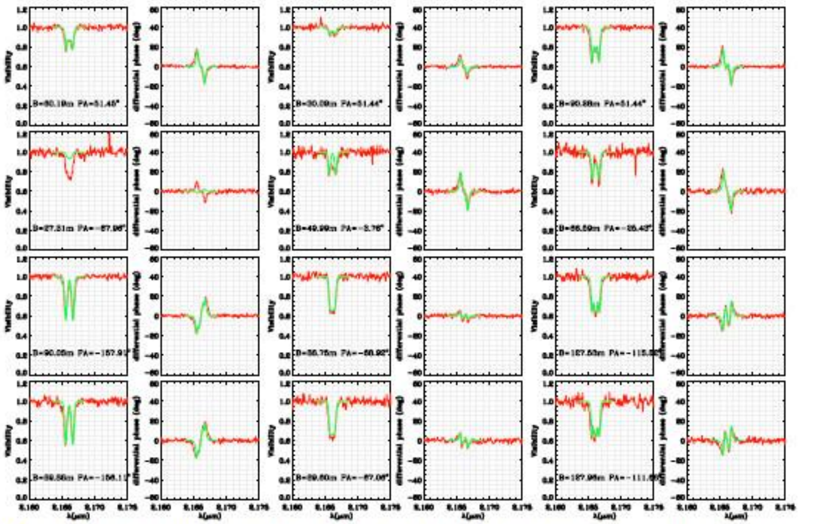


Fig. 3. α Col differential visibility and phase from our four VLTI/AMBER HR measurements (red line). Each row corresponds to one VLTI/AMBER measurement (three different baselines). The visibility and phase of the best-fit kinematics model is overplotted in green.

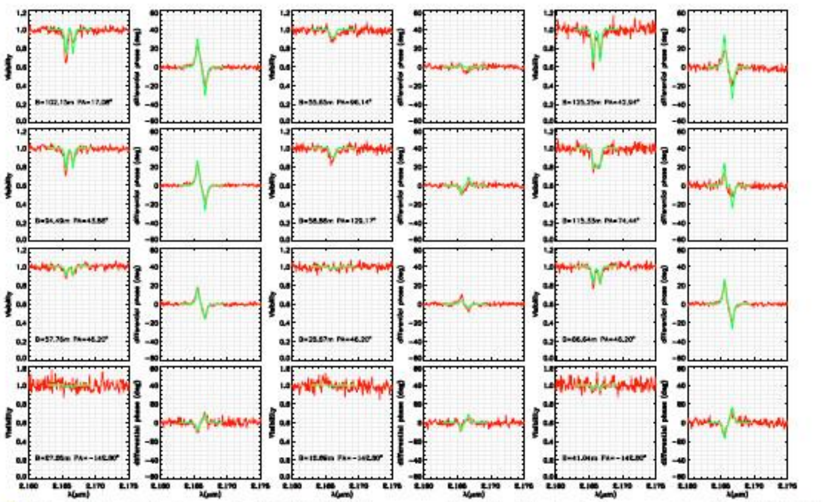


Fig. 4. κ CMa visibility and phase from our four VLTI/AMBER HR measurements (red line). The two first measurements are from 2008 (first two row) and the two other from 2010. The best-fit kinematics model is overplotted in green.

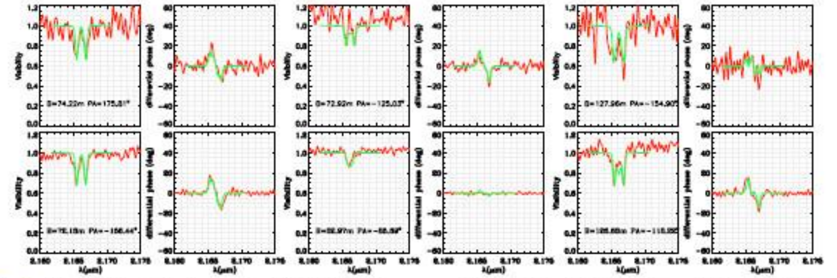


Fig. 5. ω Car visibility and phase from our two VLTI/AMBER HR measurements (red line). The best-fit kinematics model is overplotted in green.

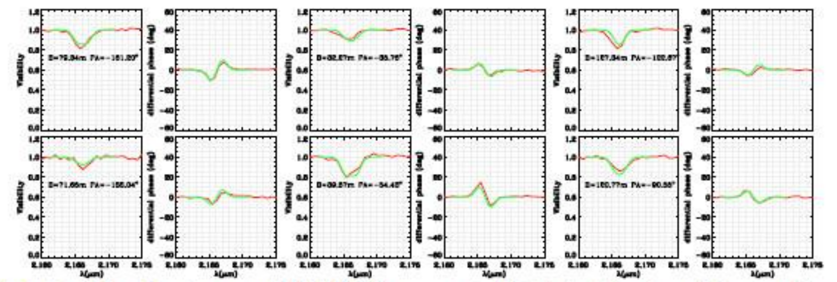


Fig. 6. p Car visibility and phase from our two VLTI/AMBER MR measurements (red line). The best-fit kinematics model is overplotted in green.

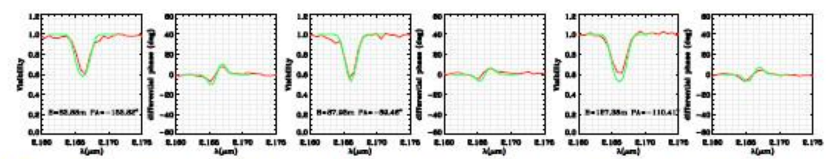


Fig. 7. δ Cen visibility and phase from our VLTI/AMBER HR measurement (red line). The best-fit kinematics model is overplotted in green.

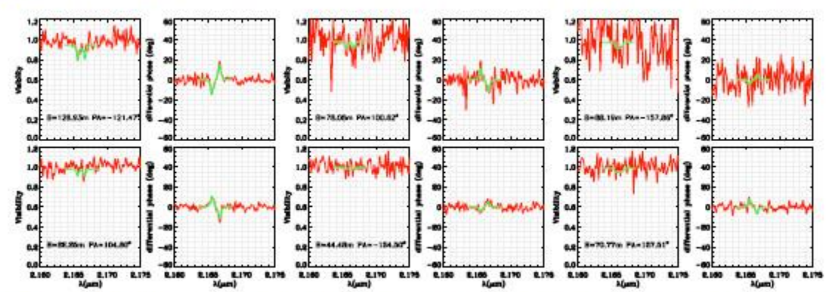
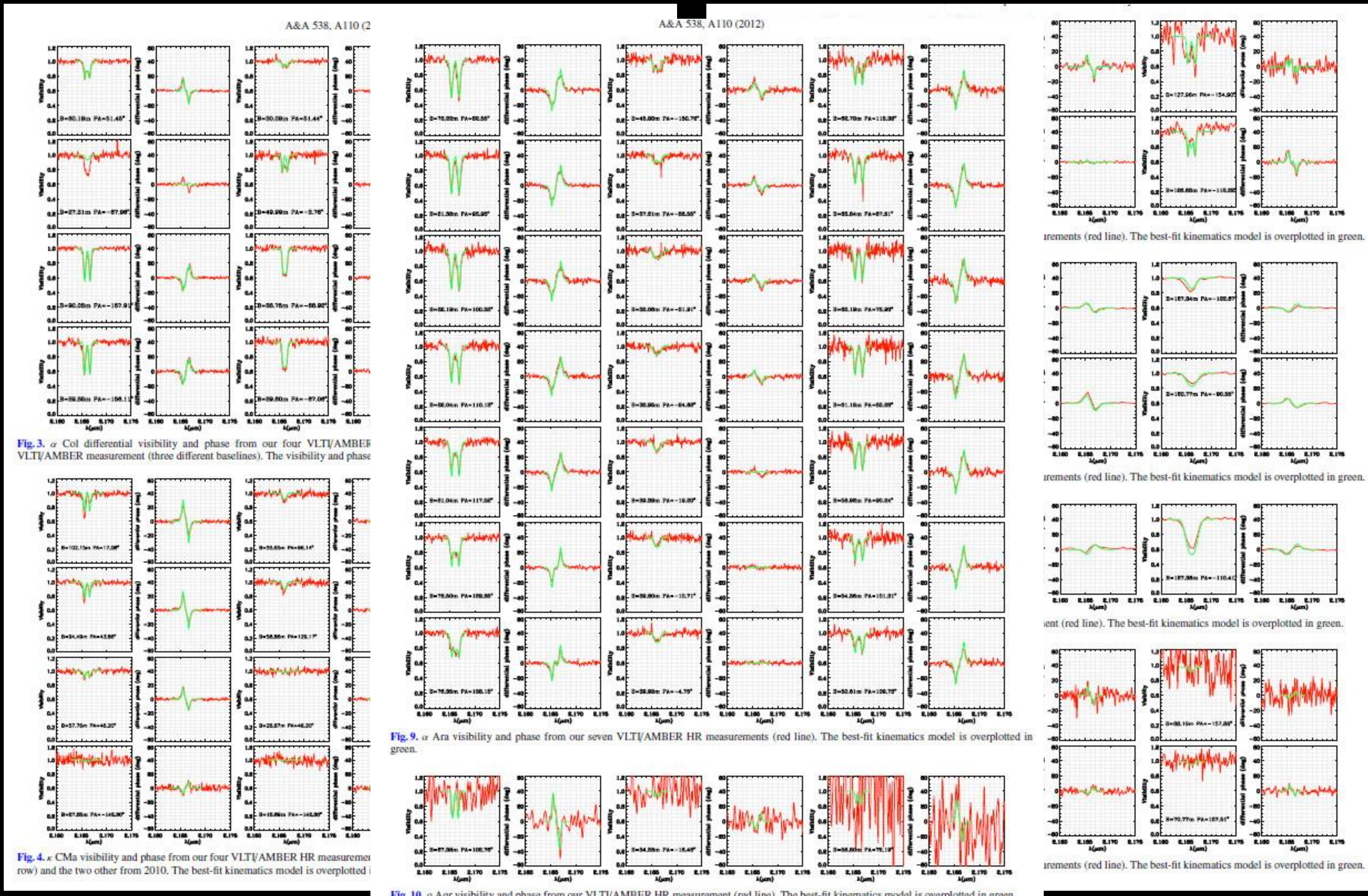


Fig. 8. μ Cen visibility and phase from our two VLTI/AMBER HR measurements (red line). The best-fit kinematics model is overplotted in green.

First mini-survey of Be stars in spectro-interferometry



First mini-survey of Be stars in spectro-interferometry

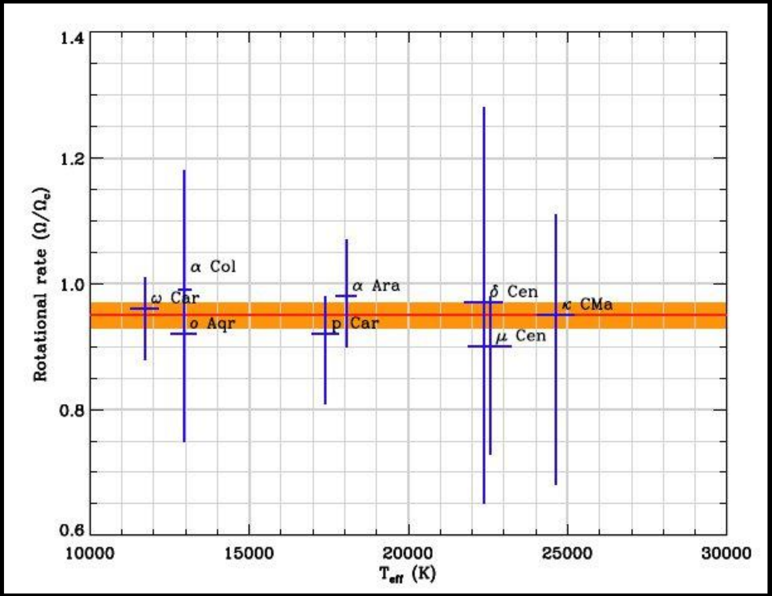
Star	V_c km s^{-1}	$V \sin i$ km s^{-1}	i deg	V/V_c	Ω/Ω_c
α Col	355 ± 23	192 ± 12	35 ± 5	0.95 ± 0.23	$0.99^{+0.19}_{-0.09}$
κ CMa	535 ± 39	244 ± 17	35 ± 10	0.80 ± 0.31	$0.95^{+0.16}_{-0.27}$
ω Car	320 ± 17	245 ± 13	65 ± 10	0.84 ± 0.16	$0.96^{+0.05}_{-0.08}$
p Car	401 ± 28	285 ± 20	70 ± 10	0.76 ± 0.15	$0.92^{+0.06}_{-0.11}$
δ Cen	527 ± 29	263 ± 14	35 ± 15	0.87 ± 0.41	$0.97^{+0.31}_{-0.32}$
μ Cen	508 ± 32	155 ± 4	25 ± 5	0.72 ± 0.20	$0.90^{+0.08}_{-0.17}$
α Ara	477 ± 24	305 ± 15	45 ± 5	0.90 ± 0.17	$0.98^{+0.09}_{-0.08}$
o Aqr	391 ± 27	282 ± 20	70 ± 20	0.77 ± 0.21	$0.93^{+0.06}_{-0.17}$

V/V_c = 0.82 0.08

Ω/Ω_c = 0.95 0.02

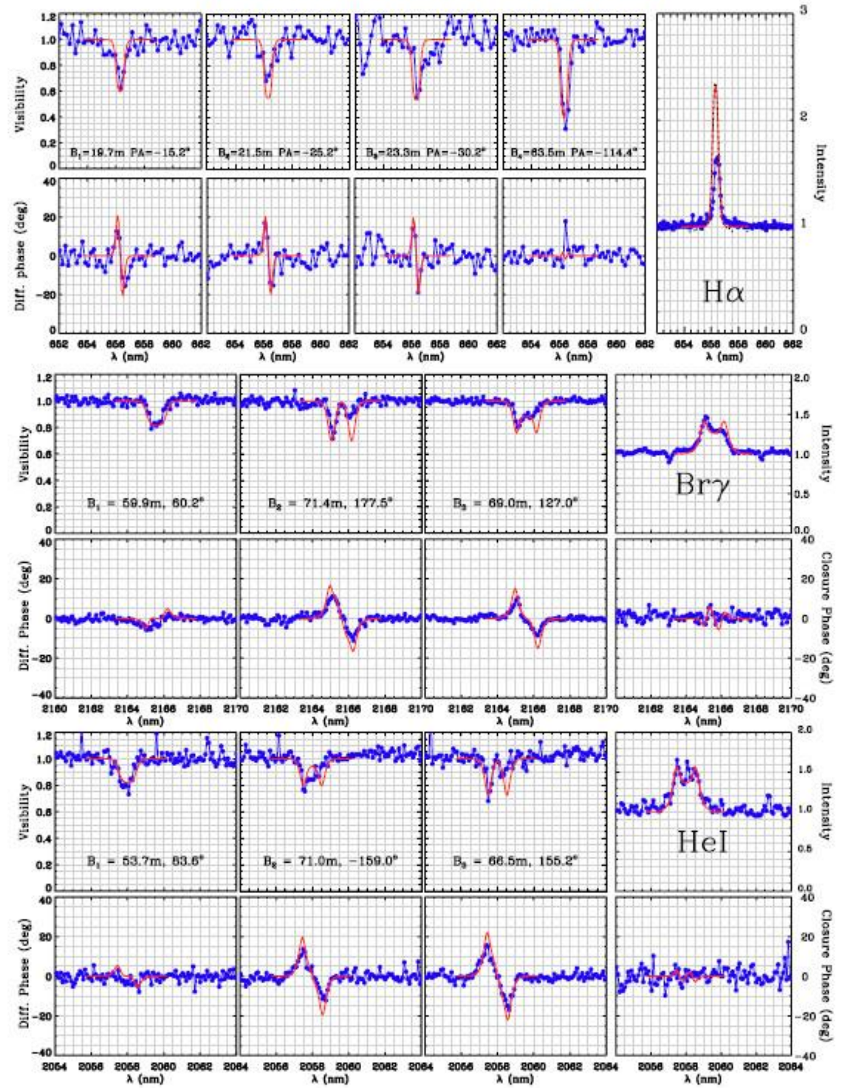
Rotation very close to critical

No clue of dependence on the stellar parameters



First multi-line study in spectro-interferometry (δ Sco)

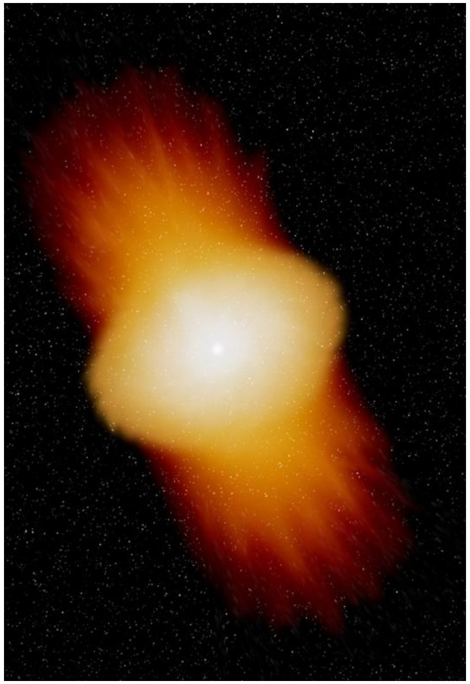
A. Meilland et al.: The binary Be star δ Sco at high spectral and spatial resolution. I.



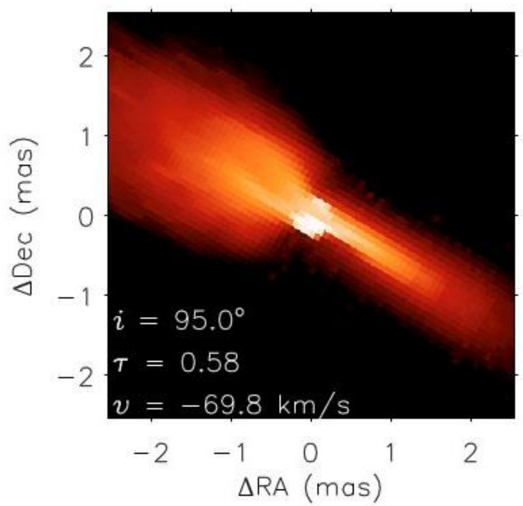
Parameter	Value	Remarks
Global geometric parameters		
$R_\star$	8.5 $R_\odot$	from the fit of the SED
d	150 pc	from von Leeuween (2007)
i	30 deg	from the fit of the binary
PA	−12 ± 7 deg	
Global kinematic parameters		
$V_{\rm rot}$	500 ± 50 km s^{-1}	$\approx V_c$
V_0	0 km s^{-1}	from Stee et al. (1995)
V_∞	0 km s^{-1}	<10 m s^{-1}
γ	0.86	from Stee et al. (1995)
β	0.5 ±0.1	Keplerian rotation
Hα disk geometry		
$a_{\rm H\alpha}$	9.0 ± 3.0 $R_\star$	= 4.8±1.5 mas
$EW_{\rm H\alpha}$	7.0 ± 1.0 Å	
Brγ disk geometry		
$a_{\rm Br\gamma}$	5.5 ± 1 $R_\star$	= 2.9 ± 0.5 mas
$EW_{\rm Br\gamma}$	6.5 ± 0.5 Å	
He I disk geometry		
$a_{\rm HeI}$	4.5 ± 0.5 $R_\star$	= 2.4 ± 0.3 mas
$EW_{\rm HeI}$	8.5 ± 0.5 Å	

Meilland et al. (2011)

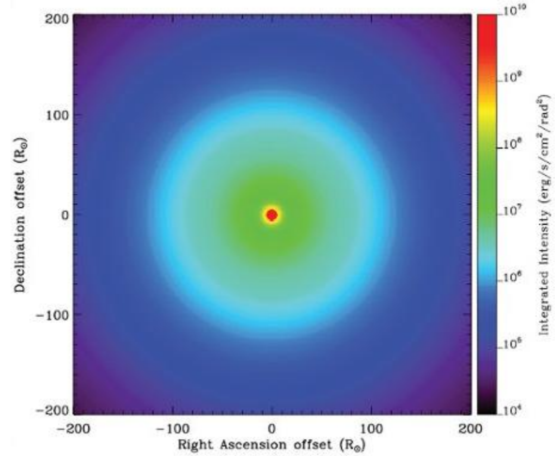
Spectro-interferometry + radiative transfer



SIMECA
(Stee et al. 1995)

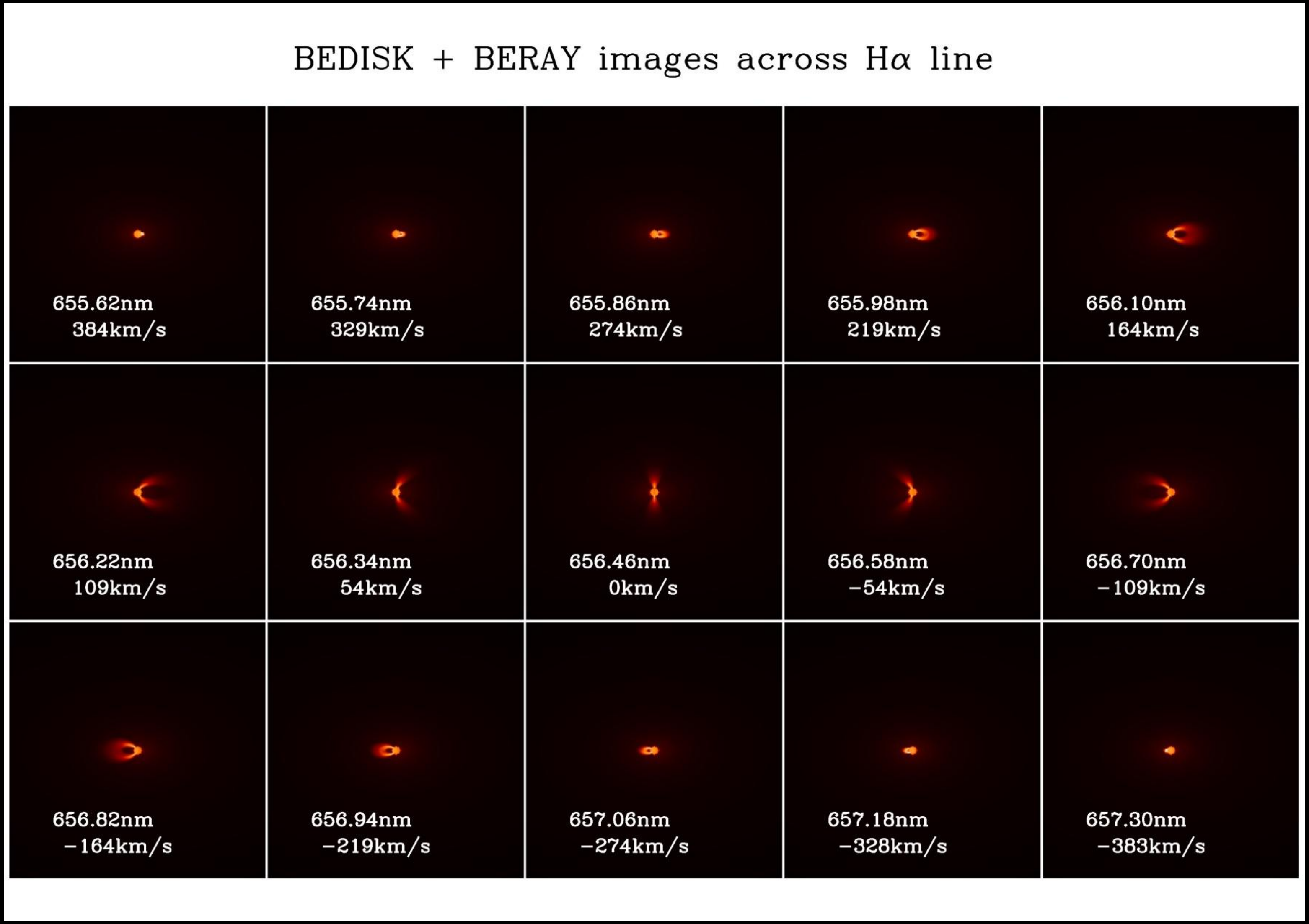


HDUST
(Carciofi et al. 2009)



BEDISK
(Sigut & Jones 2008?)

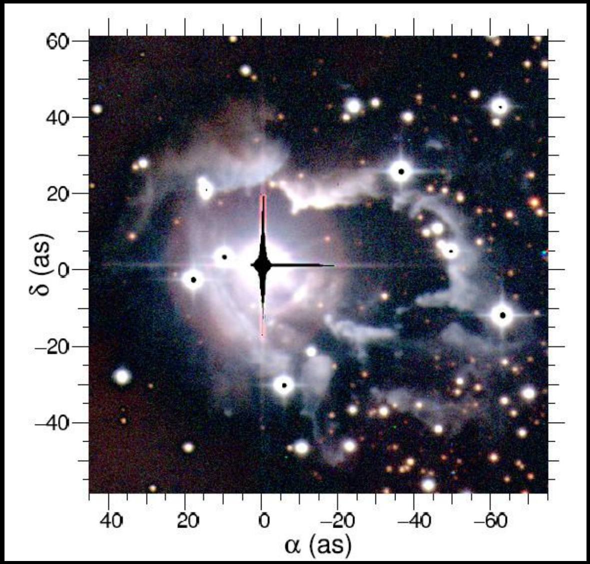
Spectro-interferometry + radiative transfer

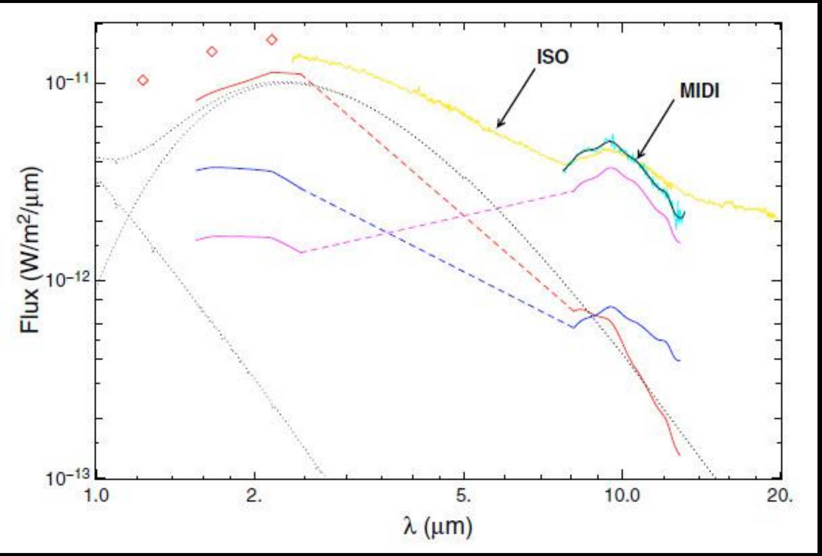


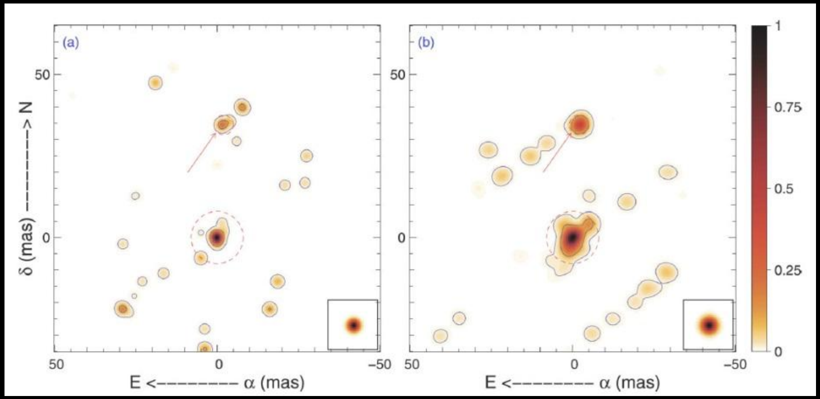
BEDISK + BERAY
(Sigut & Jones)

What about image reconstruction ?

B[e] star HD 87643 : AMBER + MIDI Observations





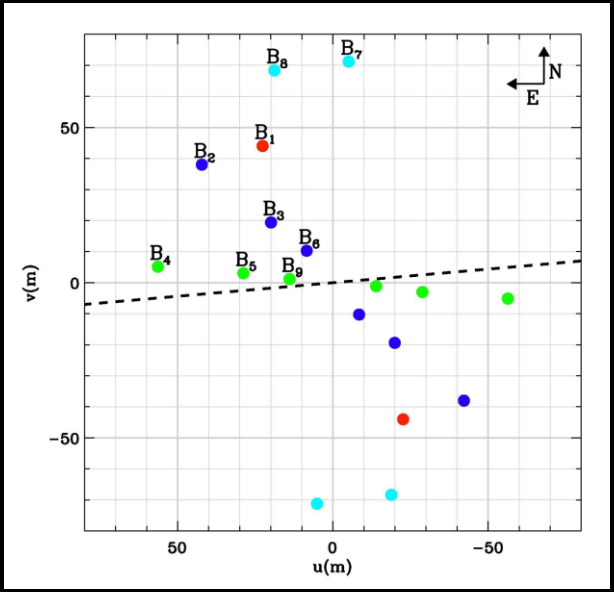


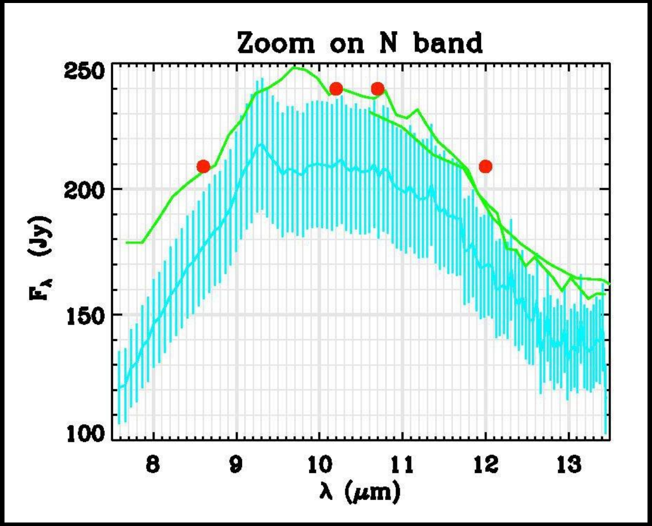
Discovery of the binary nature of this B[e] star

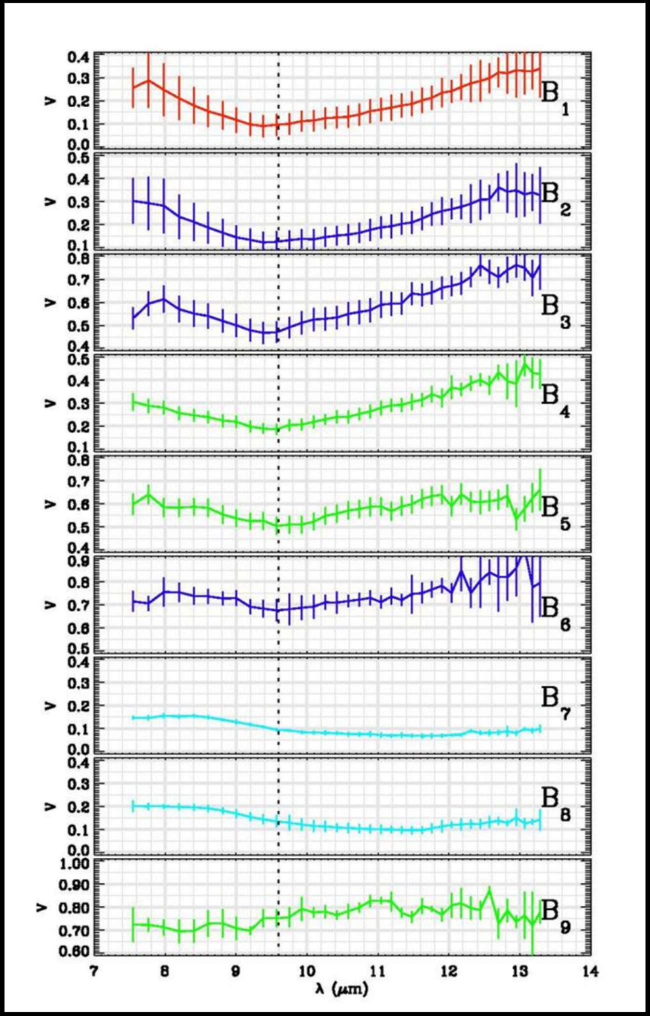
Contraints on the nature of the components:

- Hot central star
- Embedded companion (T=1300K)
- Circumbinary environment
  cold and emitting silicates bands

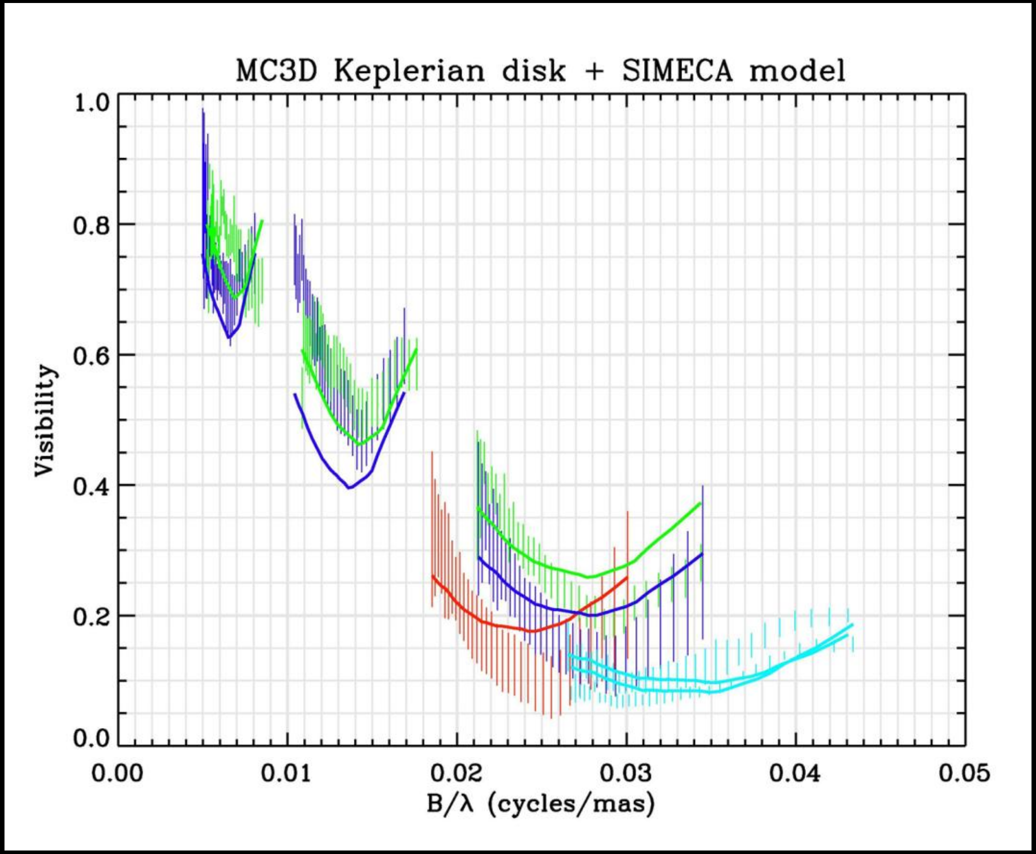
A[e] star HD62623 observed with MIDI

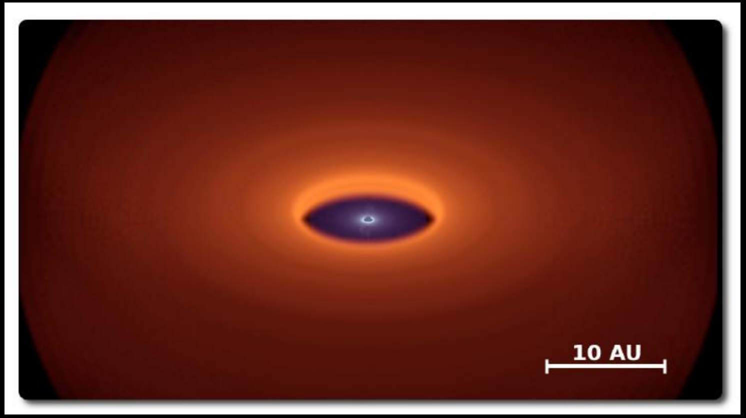




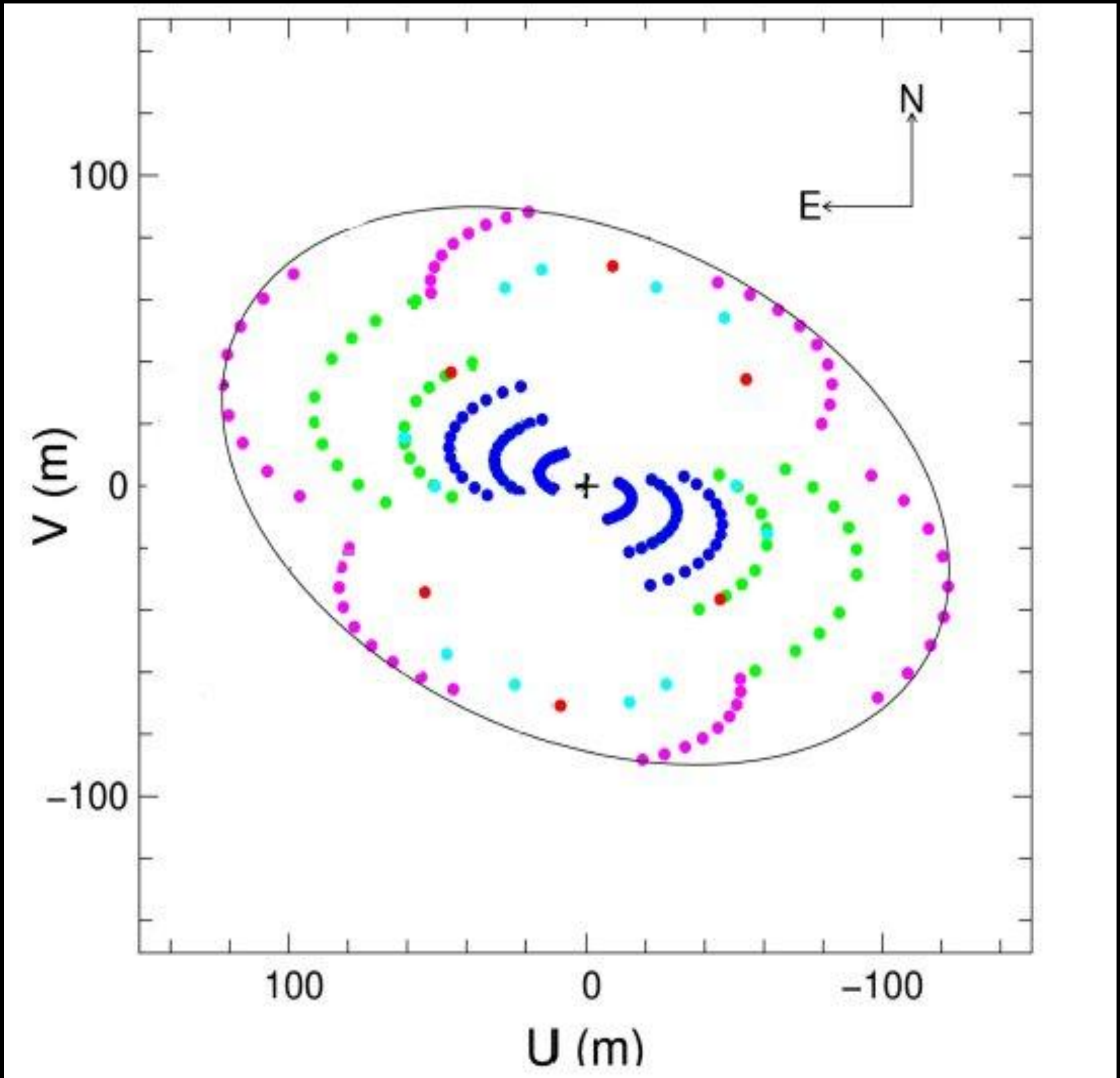


HD62623 observed with MIDI





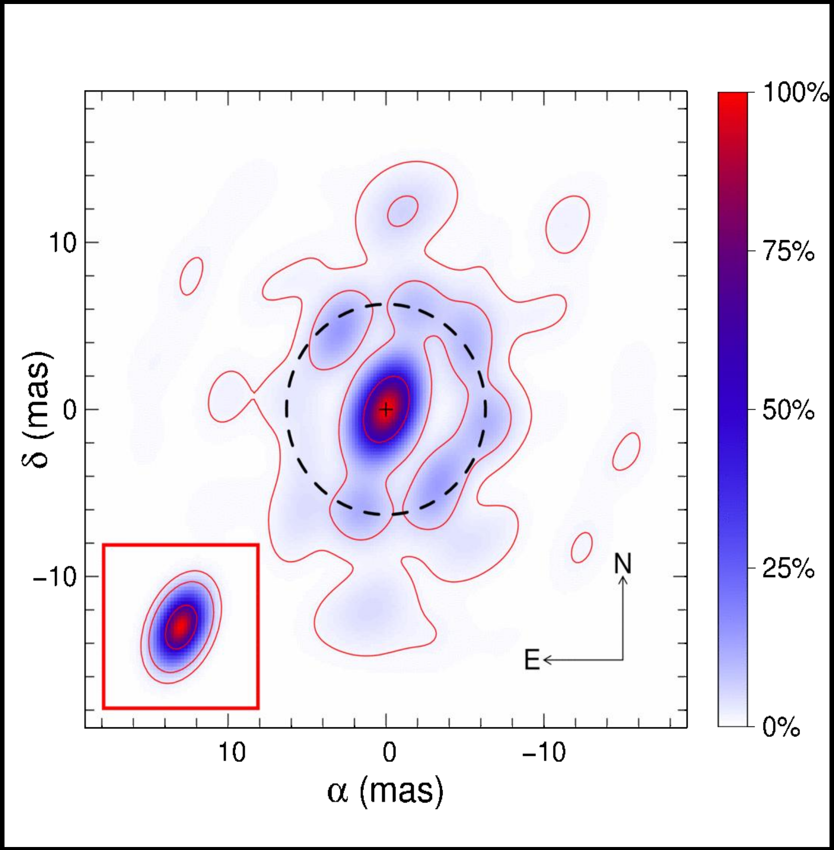
HD62623 observed with AMBER in HR mode (Br γ)

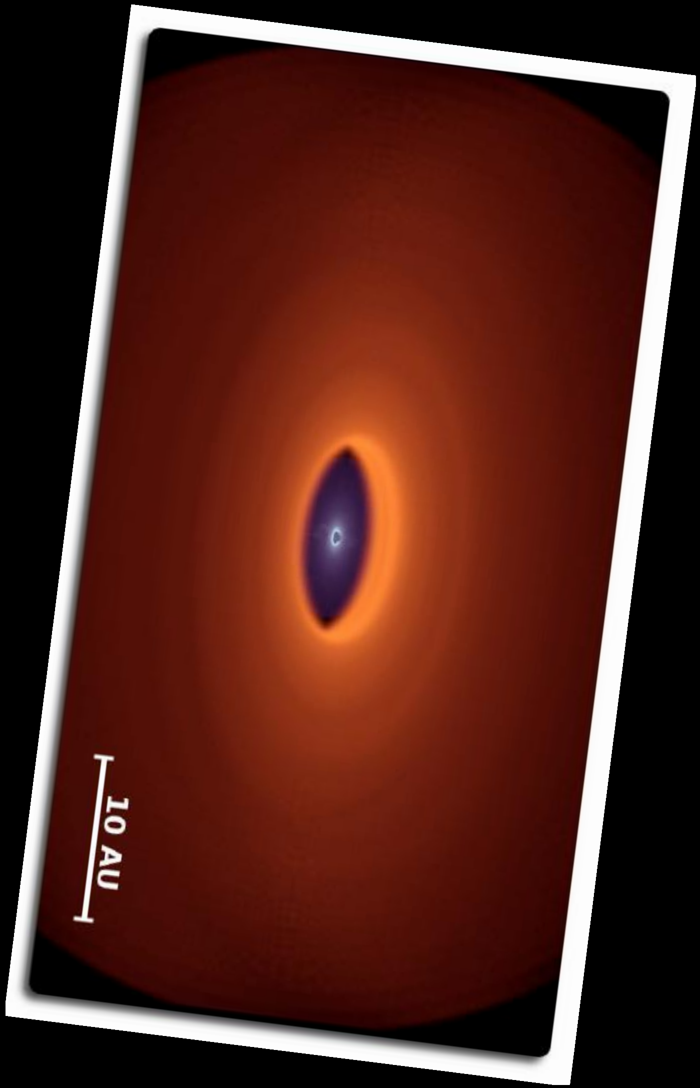


36 Measurements
=
108 Visibilities
+
36 closure phases

All in HR mode
R = 12000
High spatial and
spectral resolution

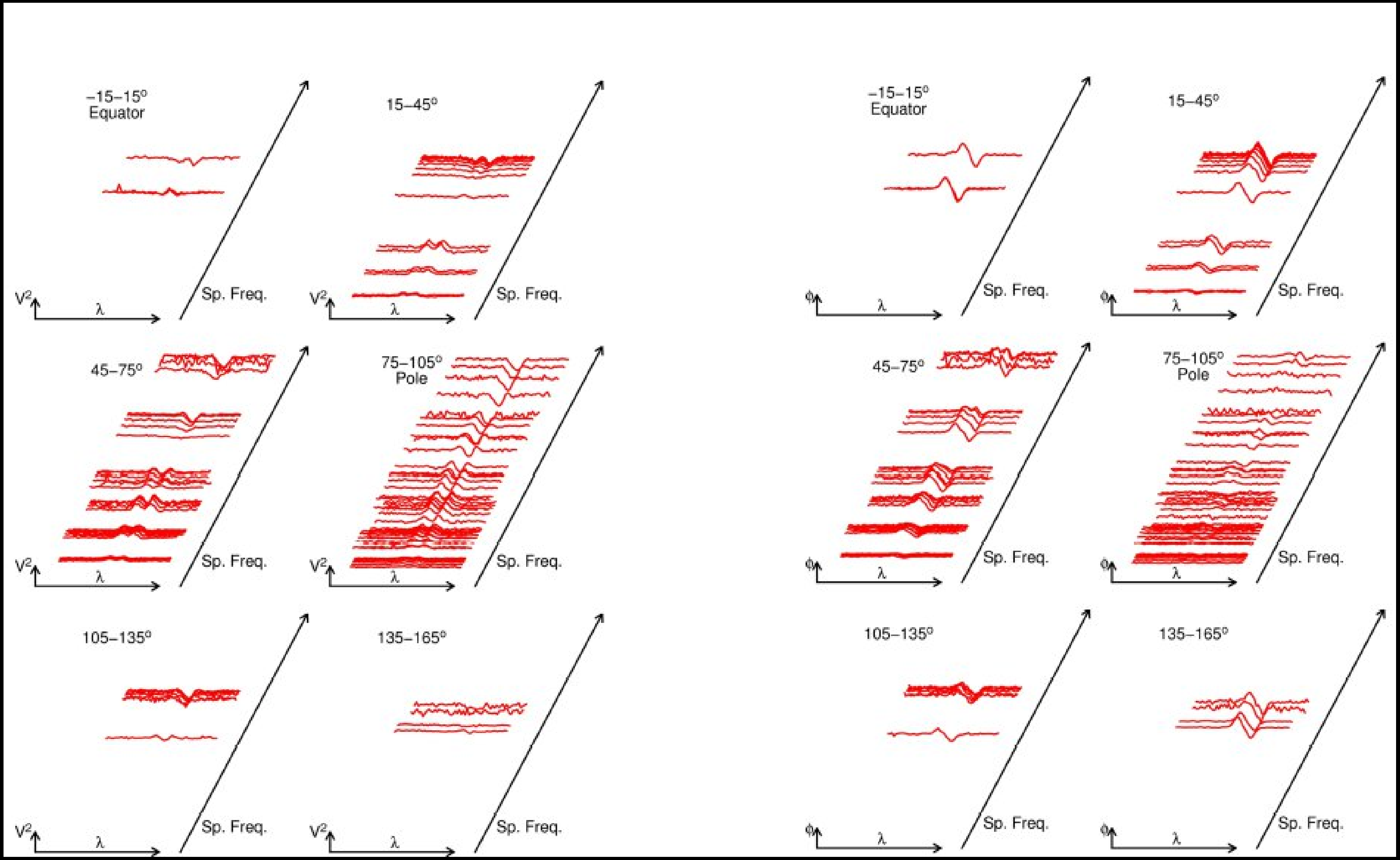
HD62623 observed with AMBER in HR mode (Br γ)



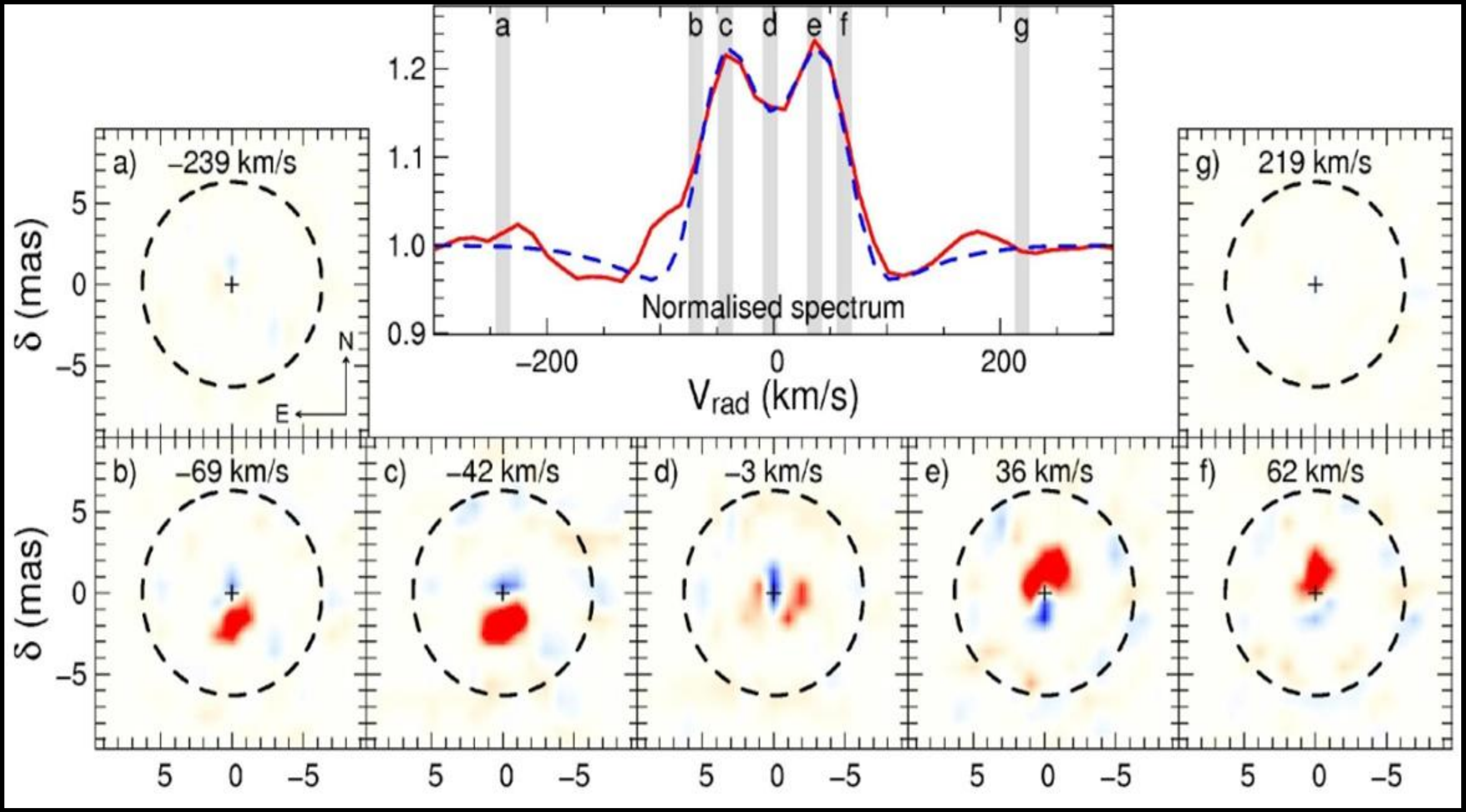


Compatible with SIMECA + MC3D MIDI data model

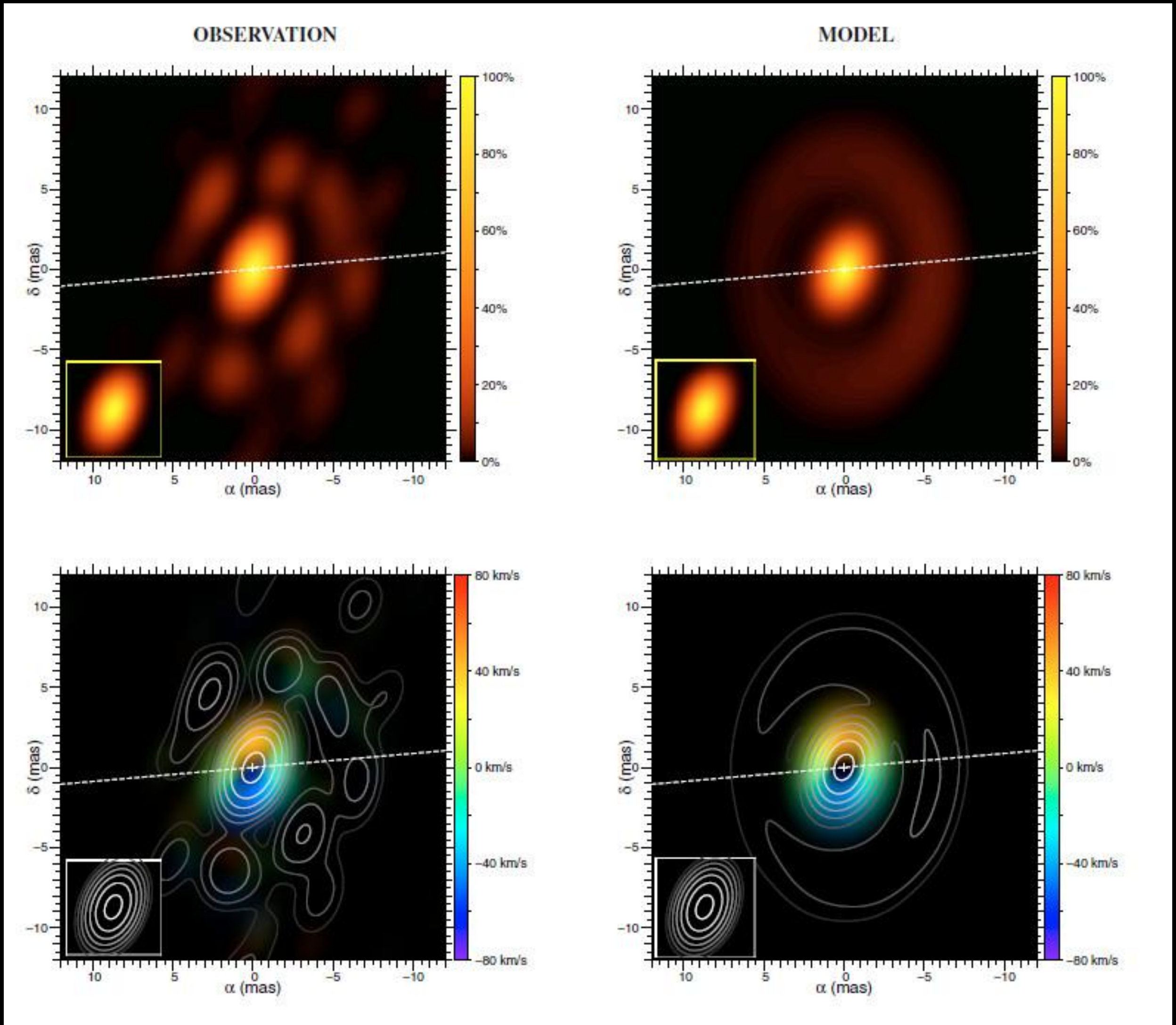
HD62623 observed with AMBER in HR mode (Br γ)



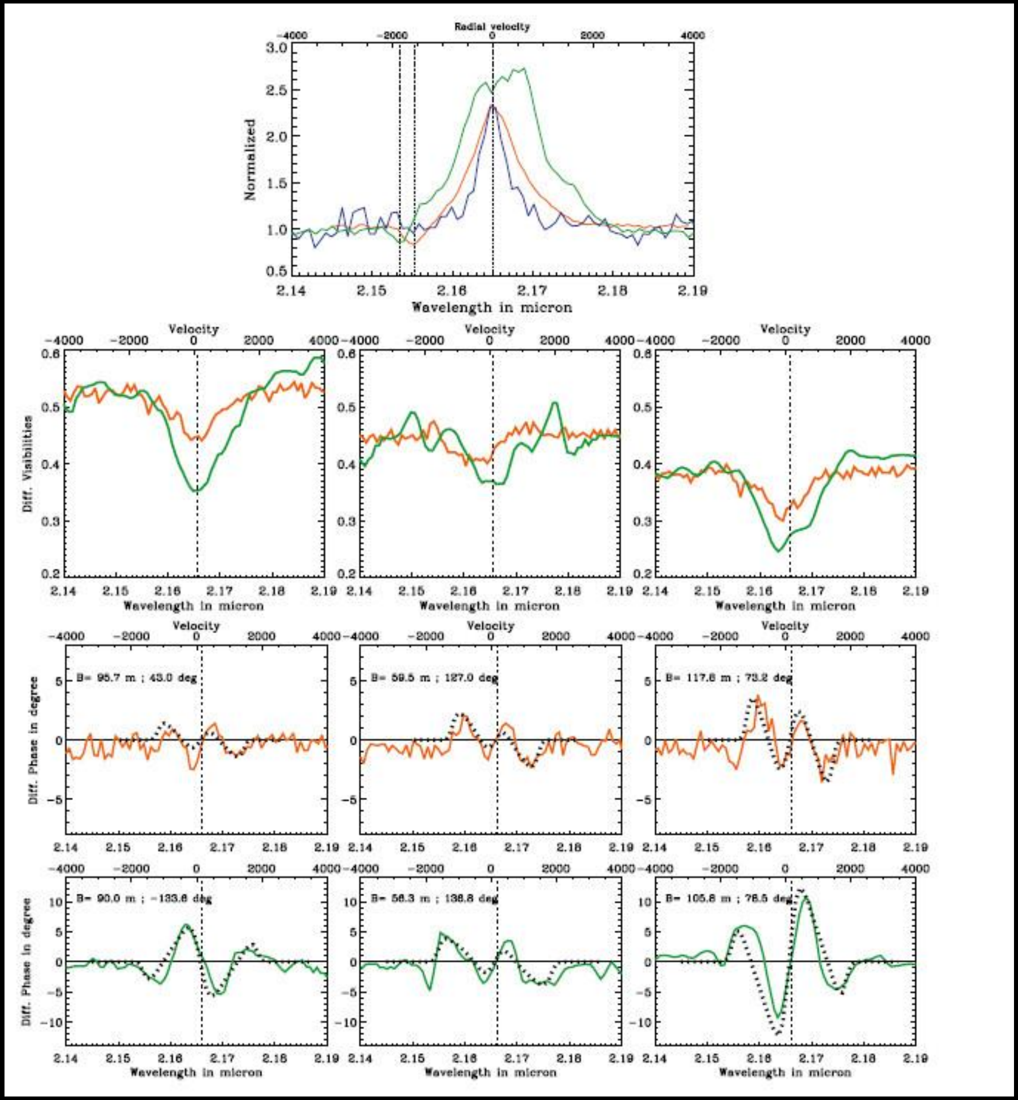
Self-calibrated reconstruted images

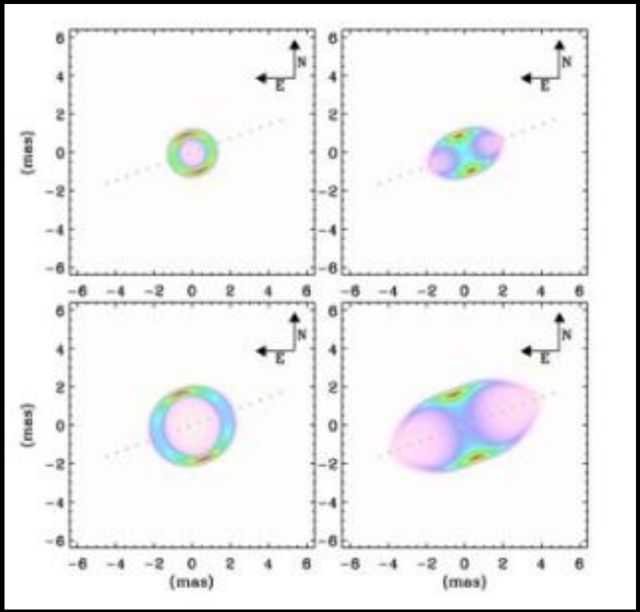


HD62623 observed with AMBER in HR mode (Br γ)



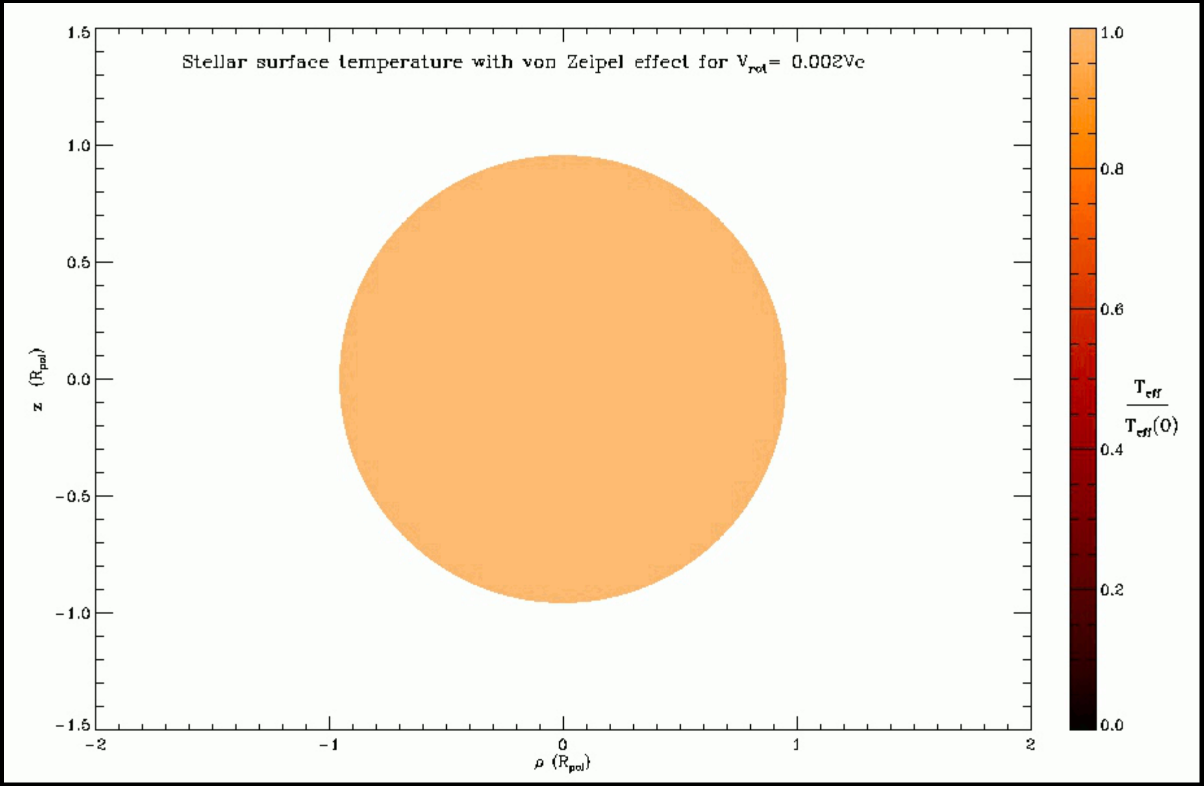
Not everything is dominated by rotation : the Nova T Pyx (AMBER)





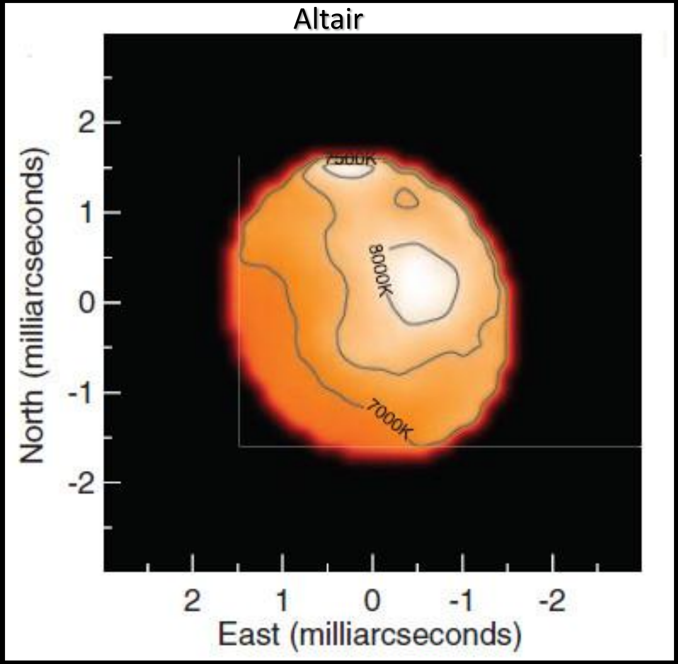
Chesneau et al. (2011)

and to finish (hope you're not too bored)
A few slides on stellar surfaces observed in spectro-interferometry

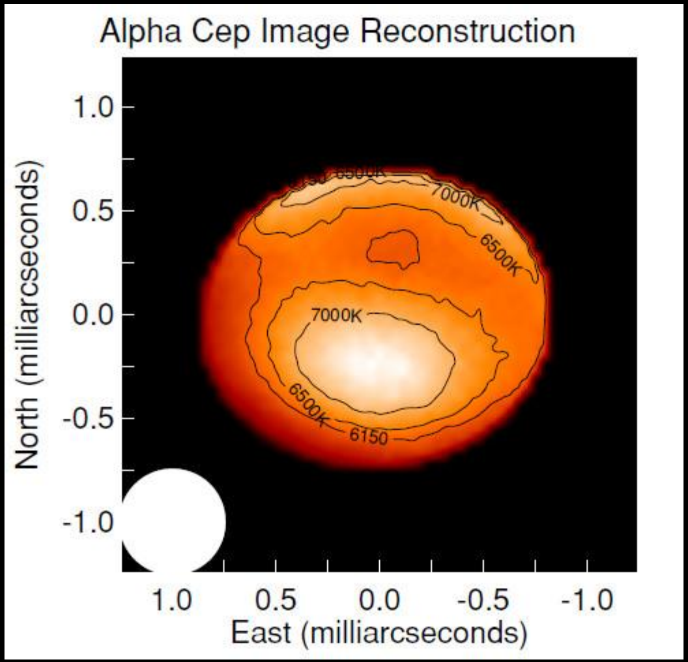


If you have questions don't ask me!
Ask Frascisco, Armando or even Massinissa (they are the specialists)

Stellar surface (in the continuum)



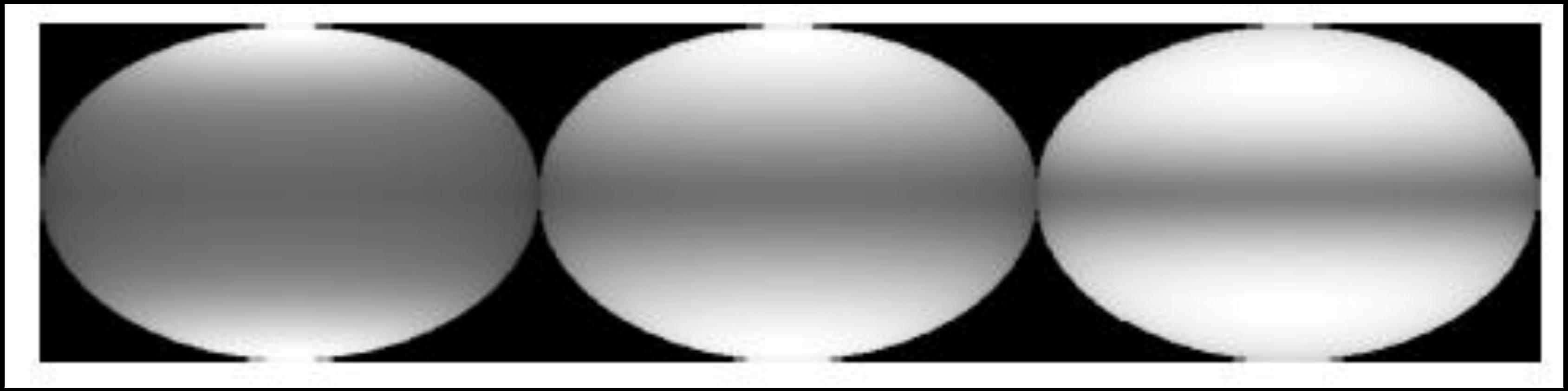
Monnier et al. (2007)



Zhao et al. (2009)

Determination of the β parameter of the gravity darkening

Stellar surface (in the continuum)



$\alpha = 0.5$
$\beta_{app} = 0.22$

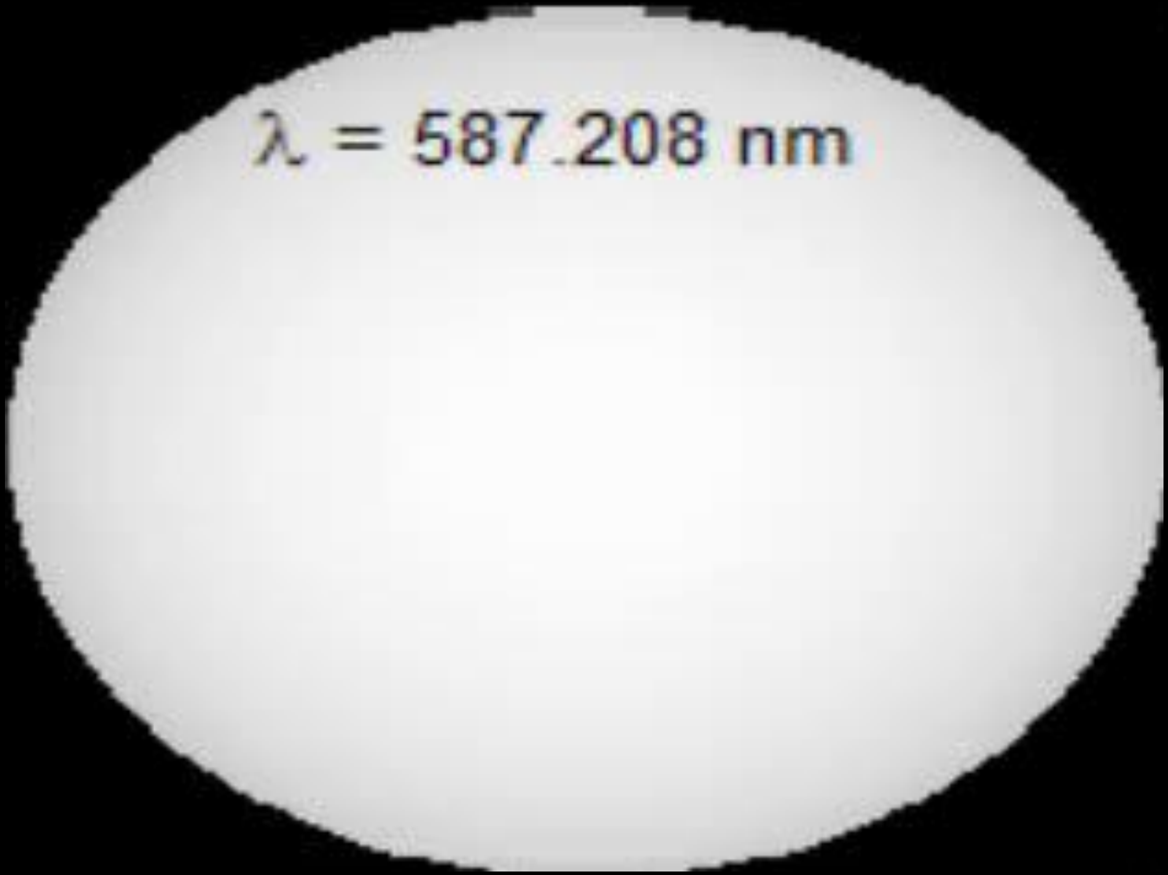
$\alpha = 0.0$
$\beta_{app} = 0.25$

$\alpha = -1,5$
$\beta_{app} = 0.30$

But apparent β might be affected by differential rotation

from Omar Delaa PhD thesis

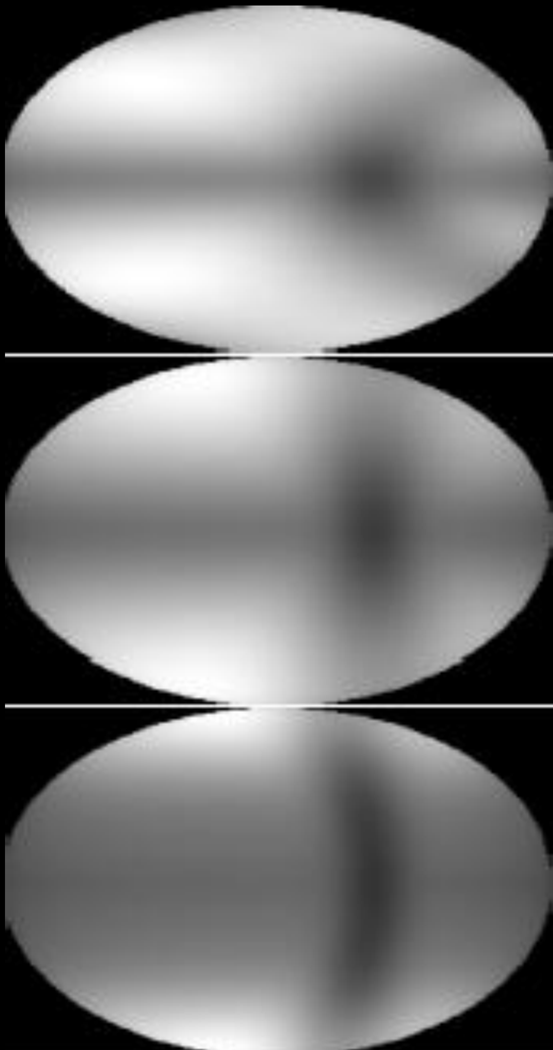
Stellar surface (in the line)



A little journey through a photospheric line...

From Massinissa code (SCIROCO)

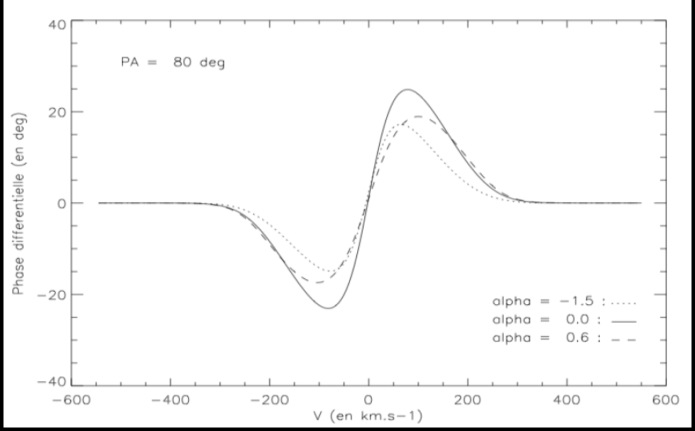
Stellar surface (in the line)



α = -1.5 : Equator faster than pole

α= 0 : Rigid rotation

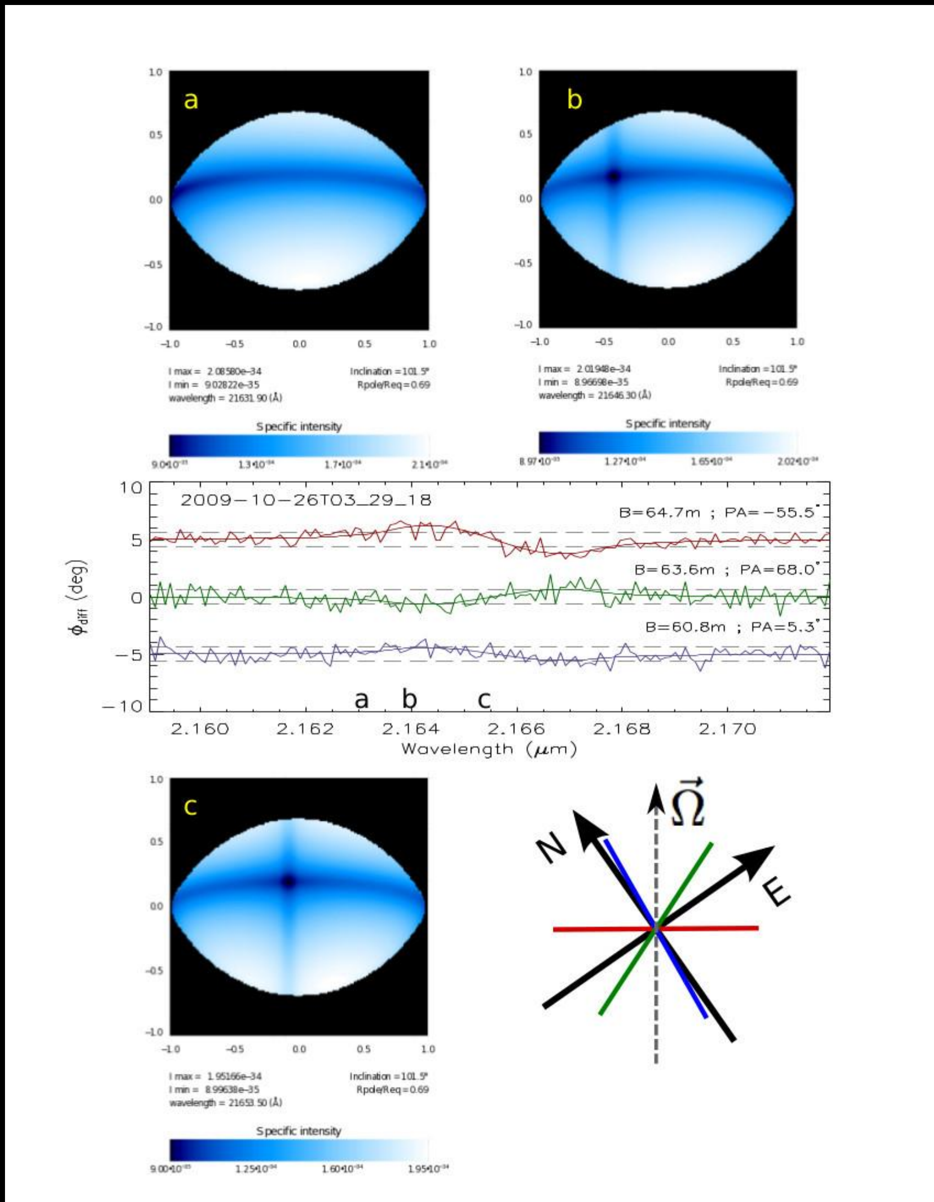
α =0.6 Pole faster than Equator



from Omar Delaa PhD thesis

2013 VLTI School : High-angular resolution for stellar astrophysics

Stellar surface (in the line)



Domiciano de Souza et al. (2012)

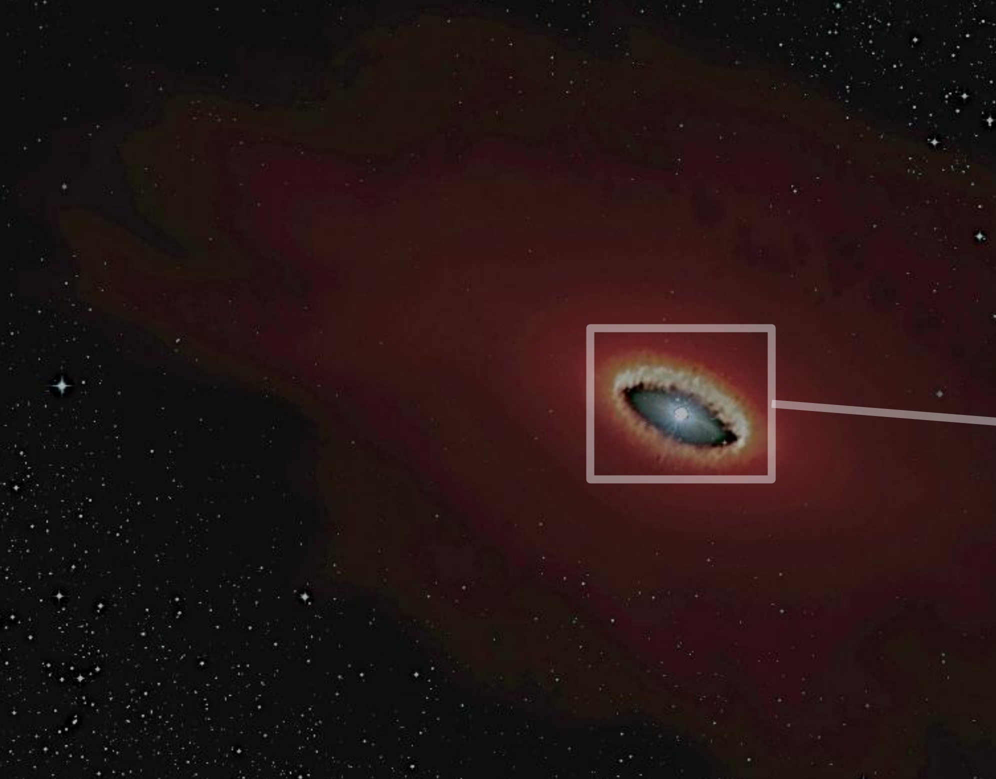
Measuring diameter an rotation
Using differential phase

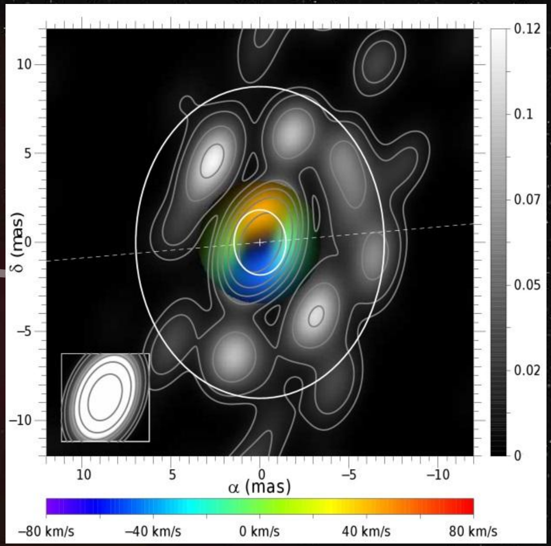
Table 2. Parameters and uncertainties estimated from a Levenberg-Marquardt fit of our model to the VLTI/AMBER ϕ_{diff} observed on Achernar.

Best-fit parameter	**Best-fit value and error**
Equatorial radius R_{eq}	$11.6 \pm 0.3\,R_\odot$
Equatorial rotation velocity V_{eq}	$298 \pm 9\,km\,s^{-1}$
Rotation-axis inclination angle i	$101.5 \pm 5.2°$
Rotation-axis position angle PA_{rot}	$34.9 \pm 1.6°$
Fixed parameter	**Value**
Distance d	44.1 pc
Mass M	$6.1\,M_\odot$
Surface mean temperature $\overline{T}_{eff}$	15 000 K
Gravity-darkening coefficient β	0.20
Derived parameter	**Value and error**
Equatorial angular diameter $⌀_{eq}$	2.45 ± 0.09 mas
Equatorial-to-polar radii R_{eq}/R_p	1.45 ± 0.04
$V_{eq} \sin i$	$292 \pm 10\,km\,s^{-1}$
V_{eq}/V_{crit}	0.96 ± 0.03
Polar temperature T_{pol}	$18\,013^{+141}_{-171}$ K
Equatorial temperature T_{eq}	9955^{+1115}_{-2339} K
Luminosity $\log L/L_\odot$	3.654 ± 0.028

Notes. The minimum reduced χ^2 of the fit is $\chi^2_{min\,r} = 1.22$. The Hipparcos distance $d = 44.1 \pm 1.1$ pc from Perryman et al. (1997) was adopted to convert from linear to angular sizes.

I might have talk too much but remember





Hot stars are cool !

And spectro-interferometry is what you want to do !

JOIN US NOW