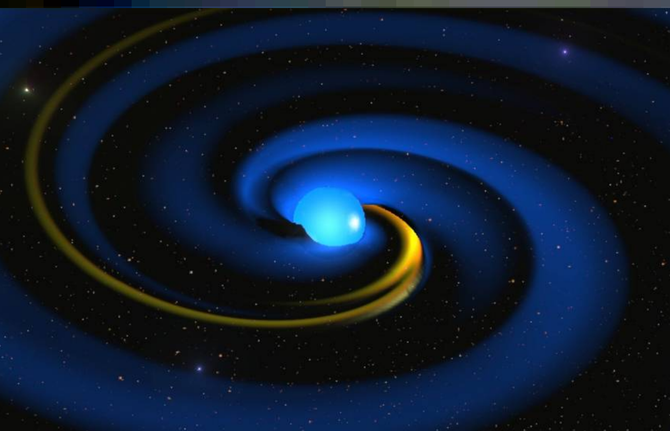
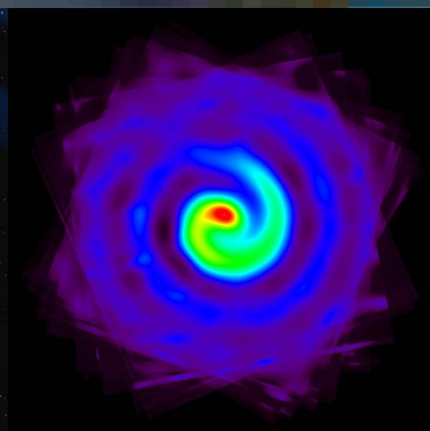
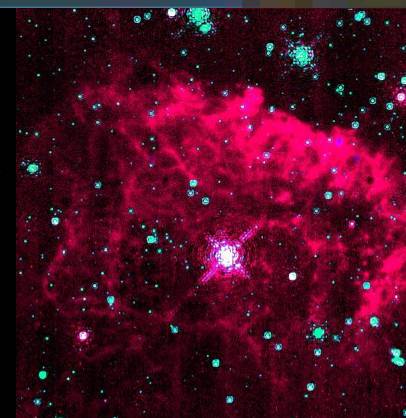
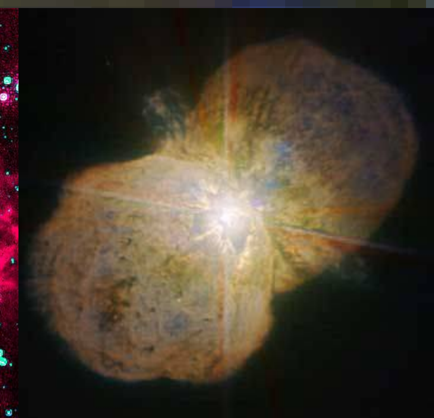
3-D Radiative Transfer Modeling of Structured Winds in Massive Hot Stars with Wind3D

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Wind Structure in Massive Hot Stars

- What physical mechanisms structure the winds of massive hot stars? Spectroscopic variability observed in massive hot stars is crucial for unraveling these mechanisms with detailed RT modeling of spectral lines.

- What is the physics of Discrete Absorption Components and Rotational Modulations prominently observed in UV wind lines of massive hot stars? What length scales of wind structures are involved? Are they the same for DACs and RMs?

- Detailed modeling requires spatial information about the wind structure at several tens of stellar radii. Clear indicators of wind structure & dynamics from optically thin wind regions are scarce and hard to model. “Multi-D” modeling is required.

Stellar and wind parameters of HD 64760 (B0.5 Ib)

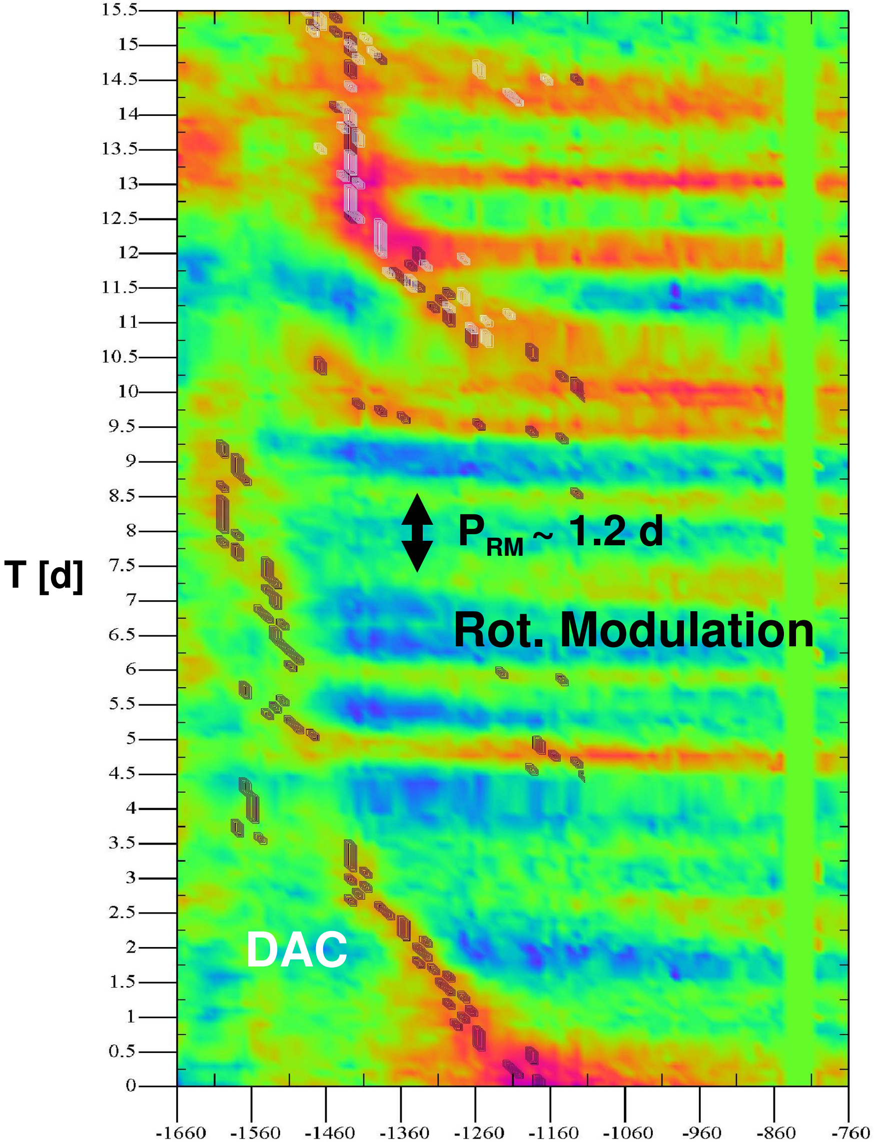
- T_{eff} = 24600 K
- $L_* = 1.55 \times 10^5\ L_\odot$
- $R_* = 22\ R_\odot$
- $M_* = 20\ M_\odot$
- Equatorial angular velocity

  $\omega = 1.763 \times 10^{-5}\ s^{-1}$

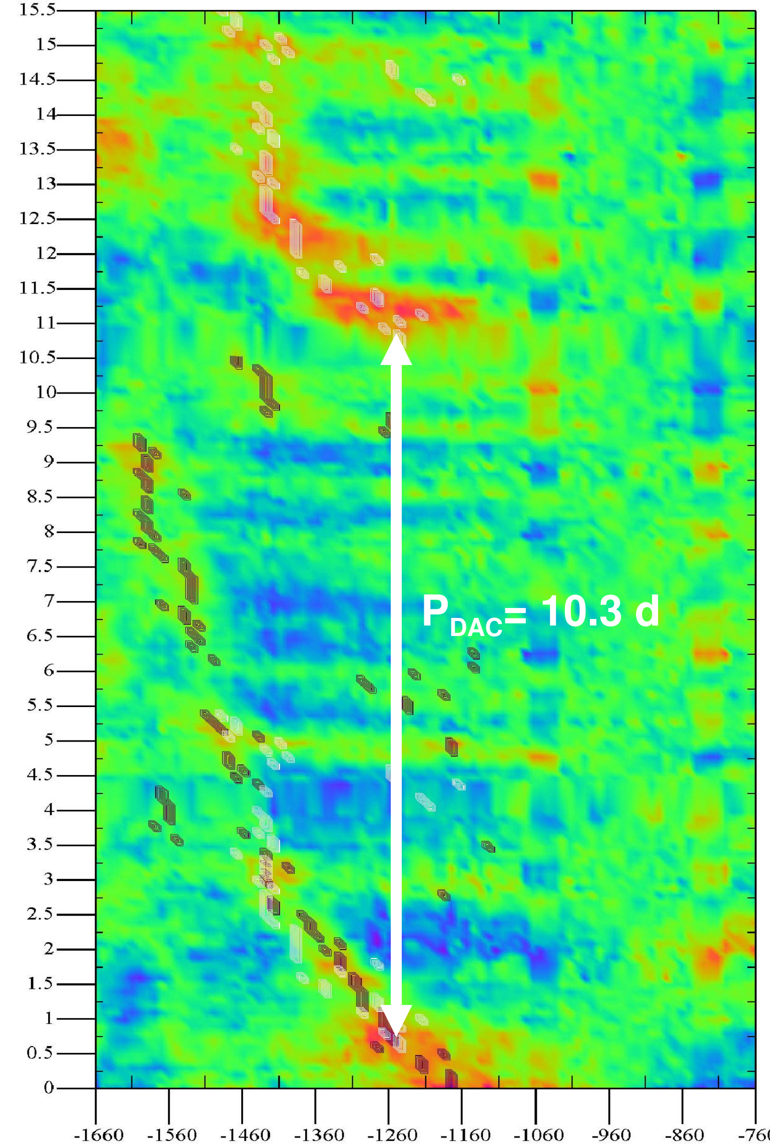
- $V_\infty = 1500\ km\ s^{-1}$
- $M_{dot} = 9 \times 10^{-7}\ M_\odot\ yr^{-1}$
- $V \sin i = 265\ km\ s^{-1}$
- $\sin i \sim 1$
- $P_{rot} = 4.12\ d$

HD 64760 IUE 1995 Si IV λ1394 line

Flux difference



Flux filter modulations



P_{DAC} = 10.3 ± 0.5 d is period between 2 spots at base of wind causing wind structures that produce DACs.
Since P_{rot} = 4.12 d for $V\sin i$ = 265 km s^{-1} & $\sin i$ = 1 ⇒ $V_{spot} = V_{rot} / 5$ or spots lag behind surface rotation

3-D Transfer Modeling Motivation

- Infer properties of Co-Rotating Interaction Regions from detailed UV wind line variability in DACs by combining 3-D RT and hydrodynamic models of structured winds. Include wind models with CIRs that do not co-rotate with the stellar surface.

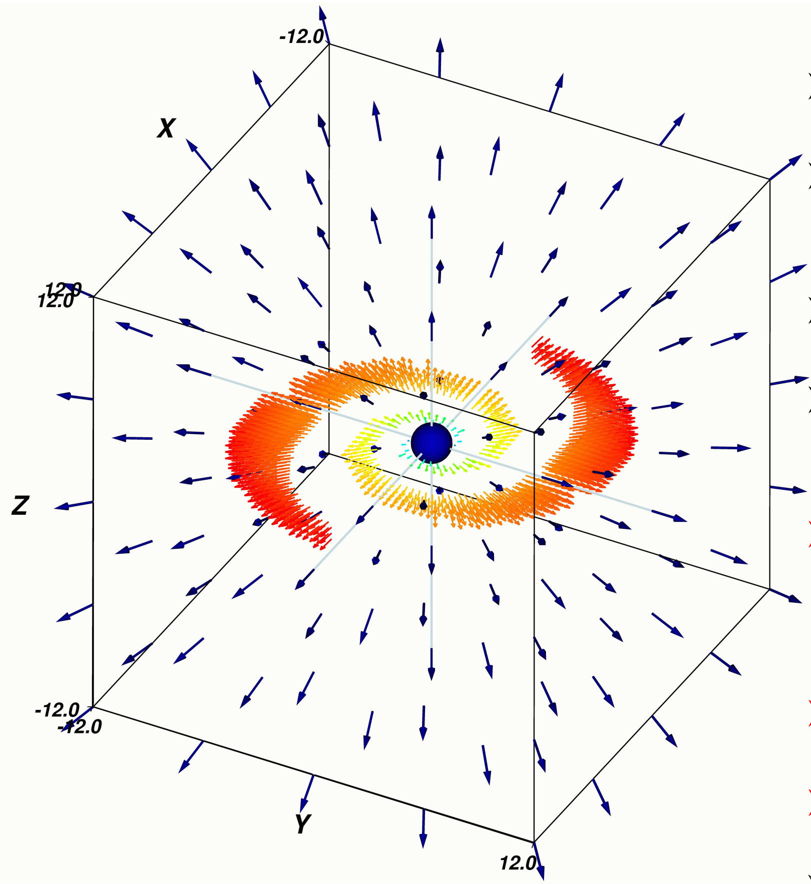
- Infer properties of Rotational Modulation Regions semi-empirically by combining 3-D RT and parametrized models of structured winds.

- Constrain wind density & velocity structures in CIRs and RMRs.

- What are the mass-loss rates of structured winds when they fit the time evolution of DACs and RMs?

- Develop versatile 3-D radiative transfer code that adequately and effectively handles Non-LTE wind line formation physics in asymmetric extended hot star winds. ApJ 2008, 678, 408.

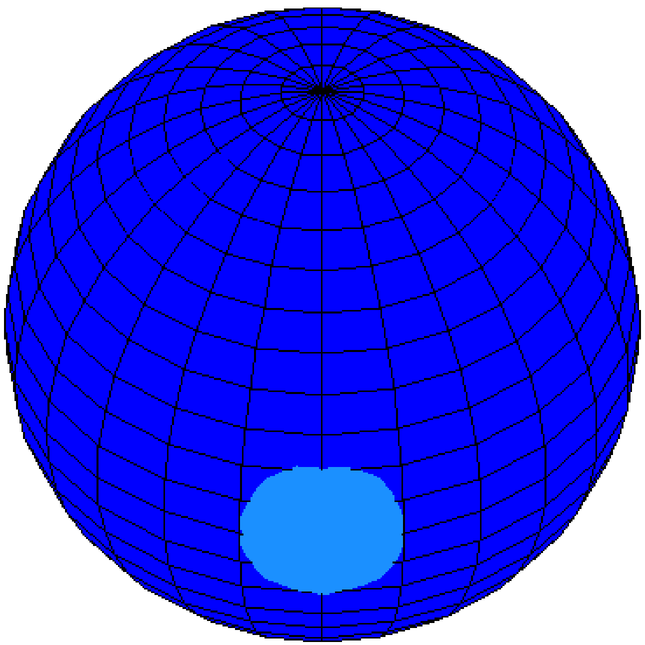
Development of 3-D radiation transport code Wind3D

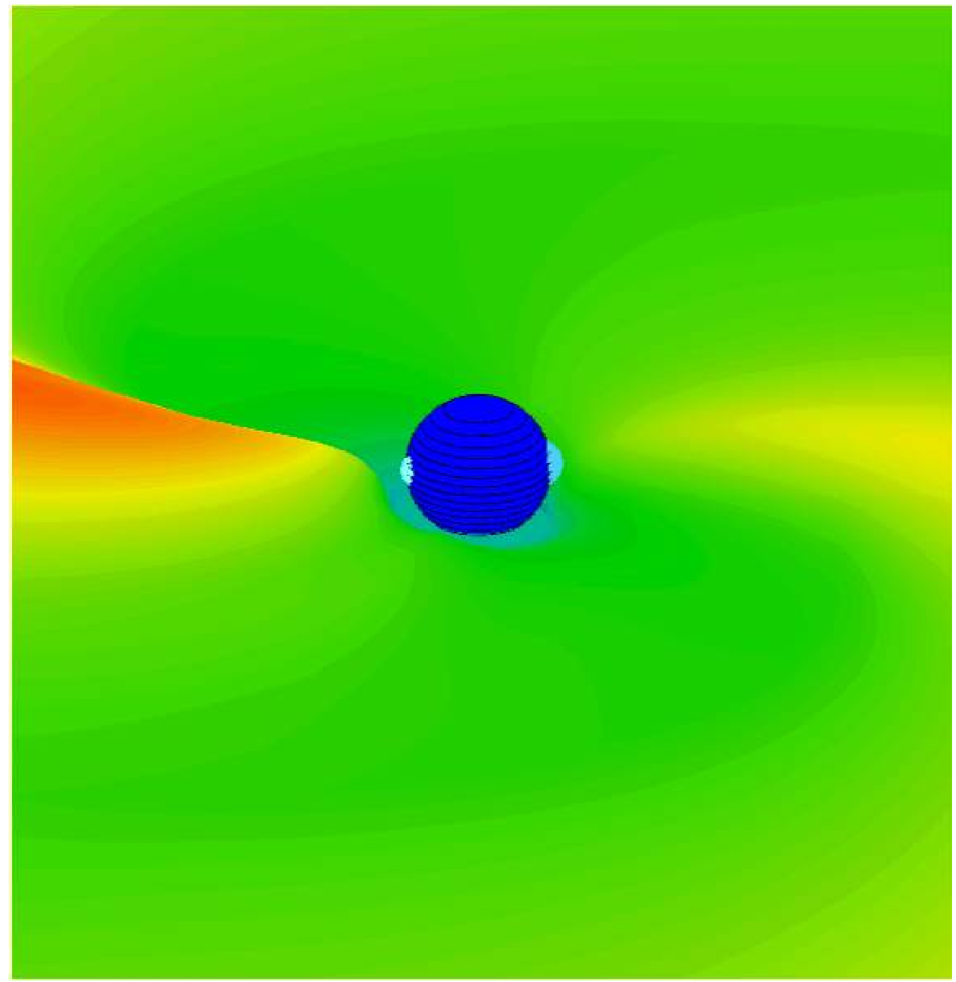


Hot star smooth wind with 'large scale' internal wind structures input for Wind3D

- implements Cartesian radiative transport scheme with short-characteristics method
- accepts arbitrary 3-D wind-density and -velocity structures
- exact lambda iteration of source function starting from Sobolev approximation in 3-D smooth wind model
- lambda iteration to non-Sobolev 3-D source function
- 71^3 source function points with 80^2 solid angles for 3-D intensity integral
- non-LTE radiative transfer equation is solved for 700^3 density and velocity points with 3-D source function interpolation technique
- two-level atom approx. for scattering dominated winds
- fully parallelized code with excellent load balancing
- 2008-2010: module implementation for parameterized structured wind input models based on CAK theory for radiatively-driven rotating winds (coll. w J. Toala UNAM)

HD 64760 hydrodynamic CIR model from Zeus3D





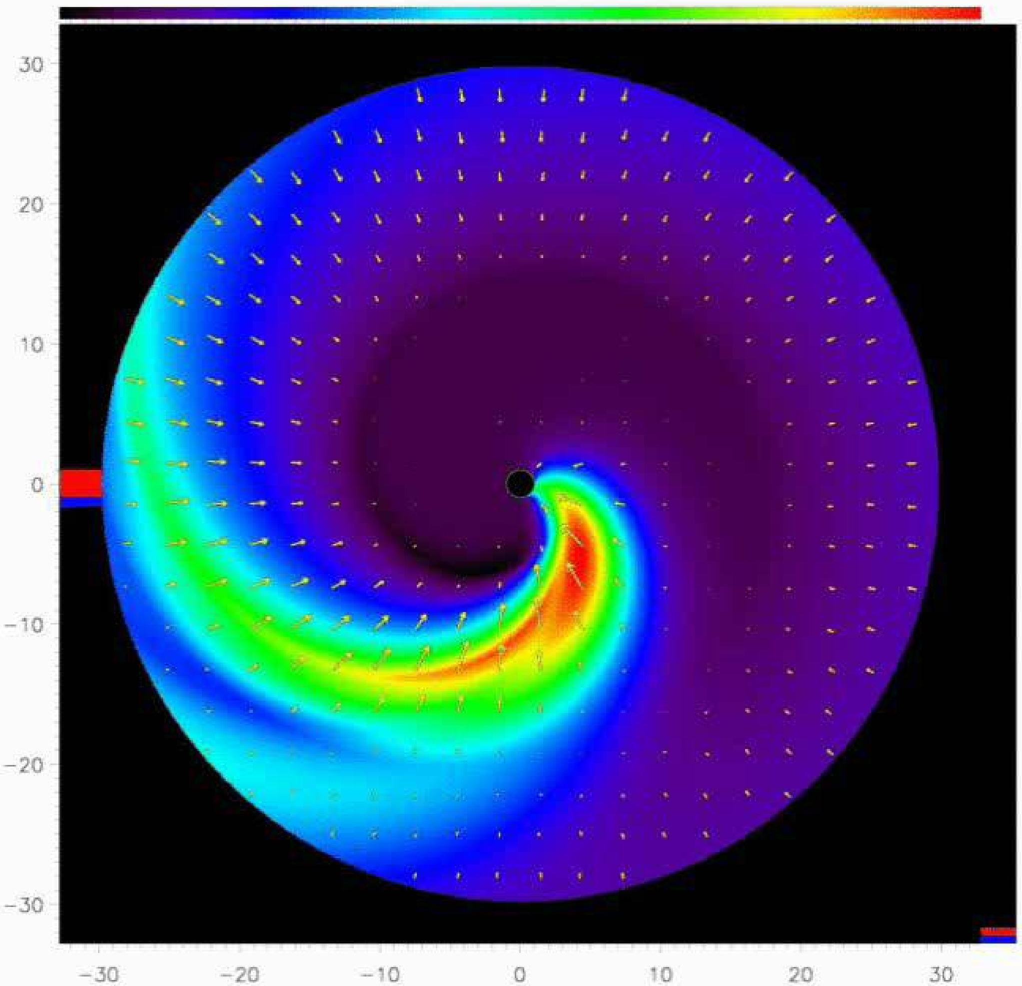
CIRs caused by 2 unequally bright equatorial spots that rotate 5 times slower than stellar surface rotation

$P_{rot} = 4.12$ d $\quad P_{spot} = 20.6$ d

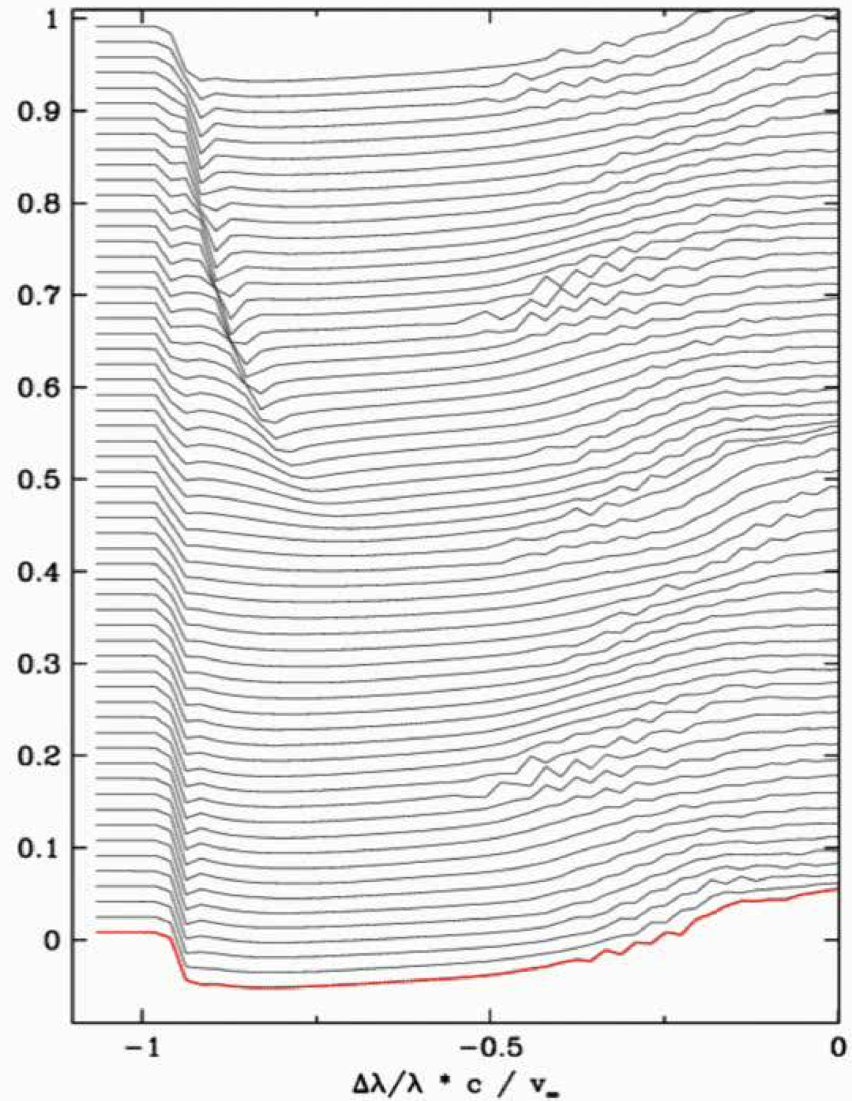
Hydrodynamic wind model with CIR lagging behind rotation of the stellar surface

Si IV λ1394 computed with Wind3D

$\rho / \rho_0 = 0.985$ Density contrast $\rho / \rho_0 = 1.2$



Normalized flux

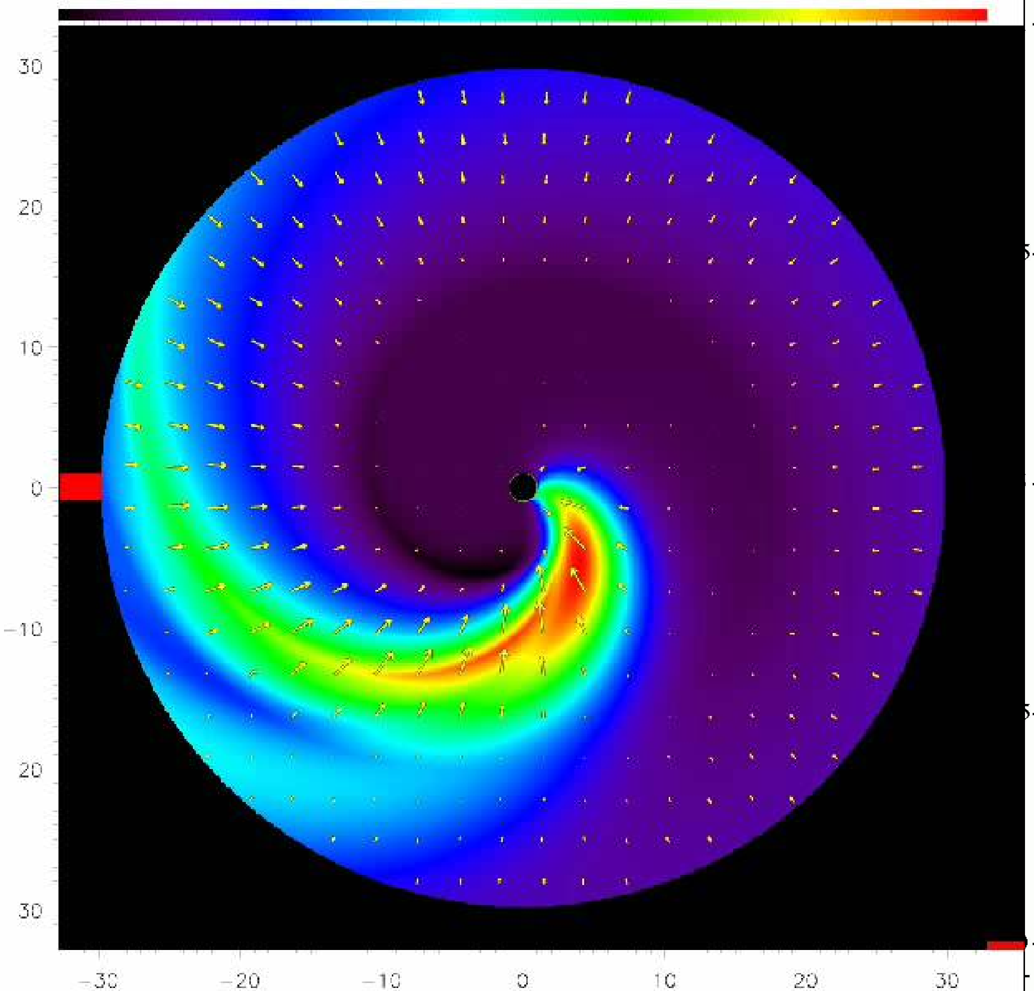


A_{sp}=0.1 Φ_{sp}=50^o $V_{spot} < V_{rot}$

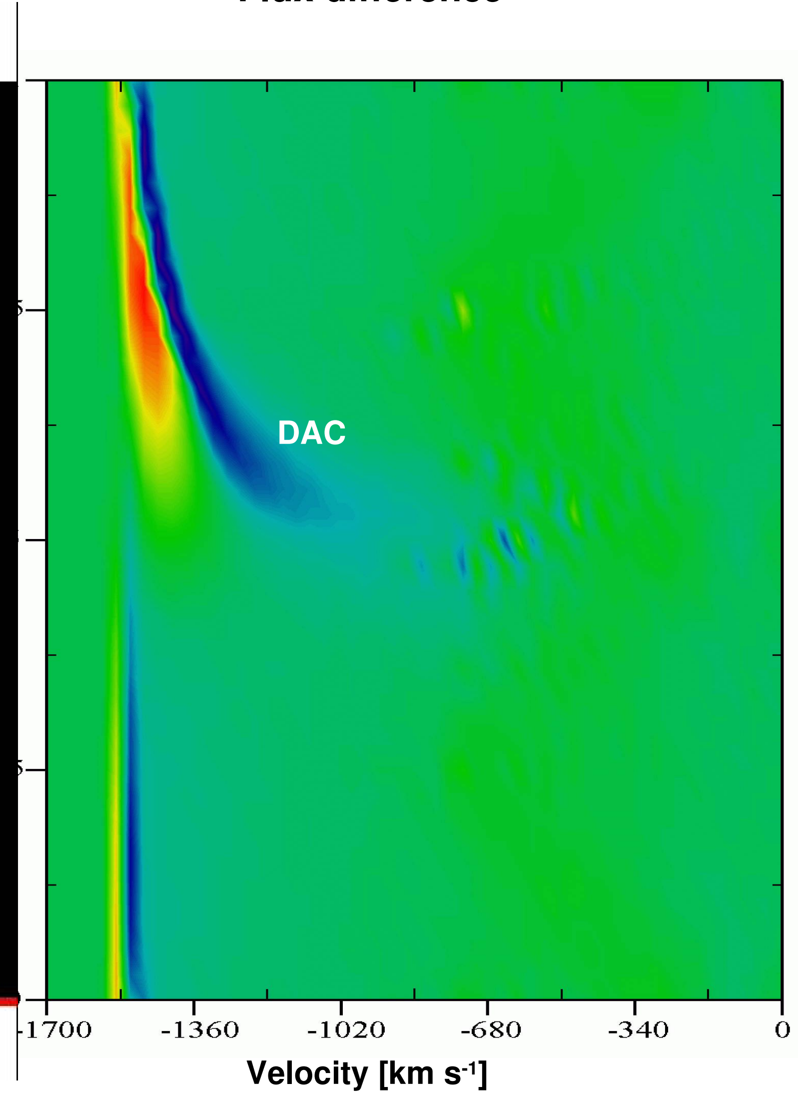
Hydrodynamic wind model with CIR lagging behind rotation of the stellar surface

Si IV λ1394 computed with Wind3D

$\rho / \rho_0 = 0.985$ **Density contrast** $\rho / \rho_0 = 1.2$



Flux difference



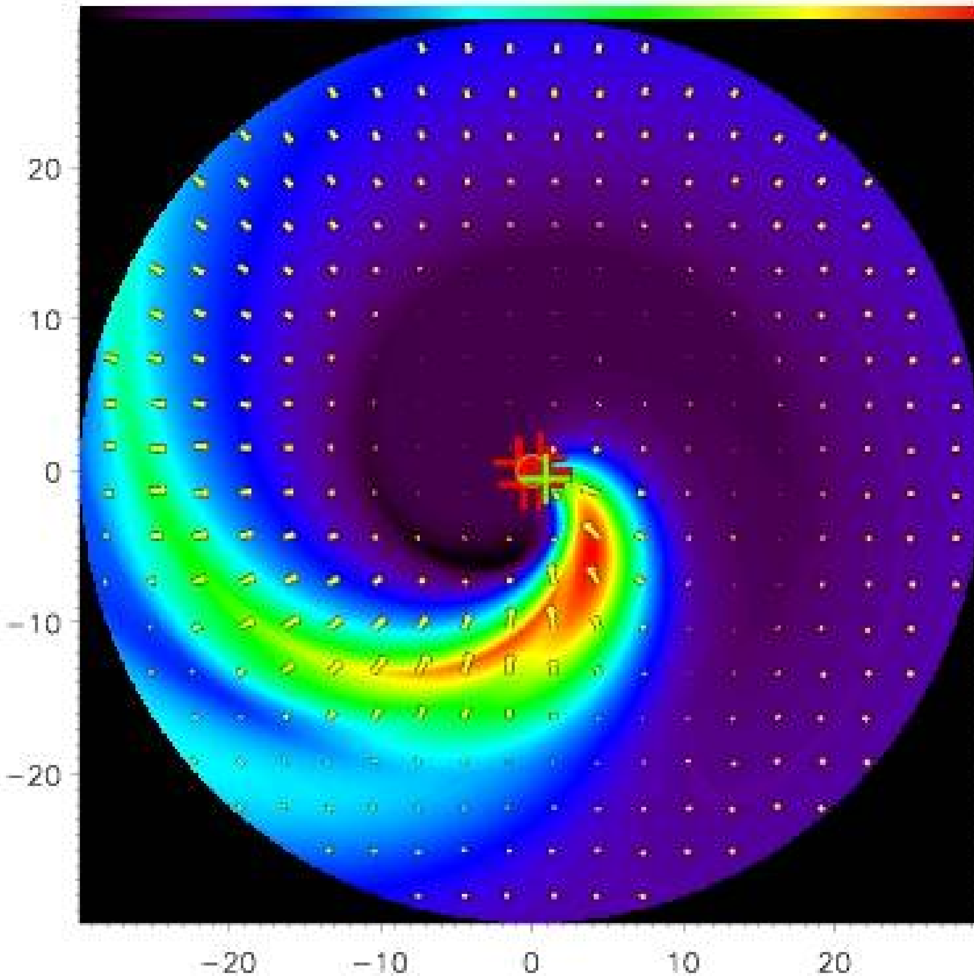
CIR causes DAC because of increased wind density contrasts and velocity plateaus

$A_{sp}=0.1 \quad \Phi_{sp}=50^o \quad V_{spot} < V_{rot}$

Structured wind hydrodynamics

1 rotating spot:

$A_{spot}=0.1 \quad \Phi_{spot}=50^o \quad V_{spot} = V_{rot}/2.5$

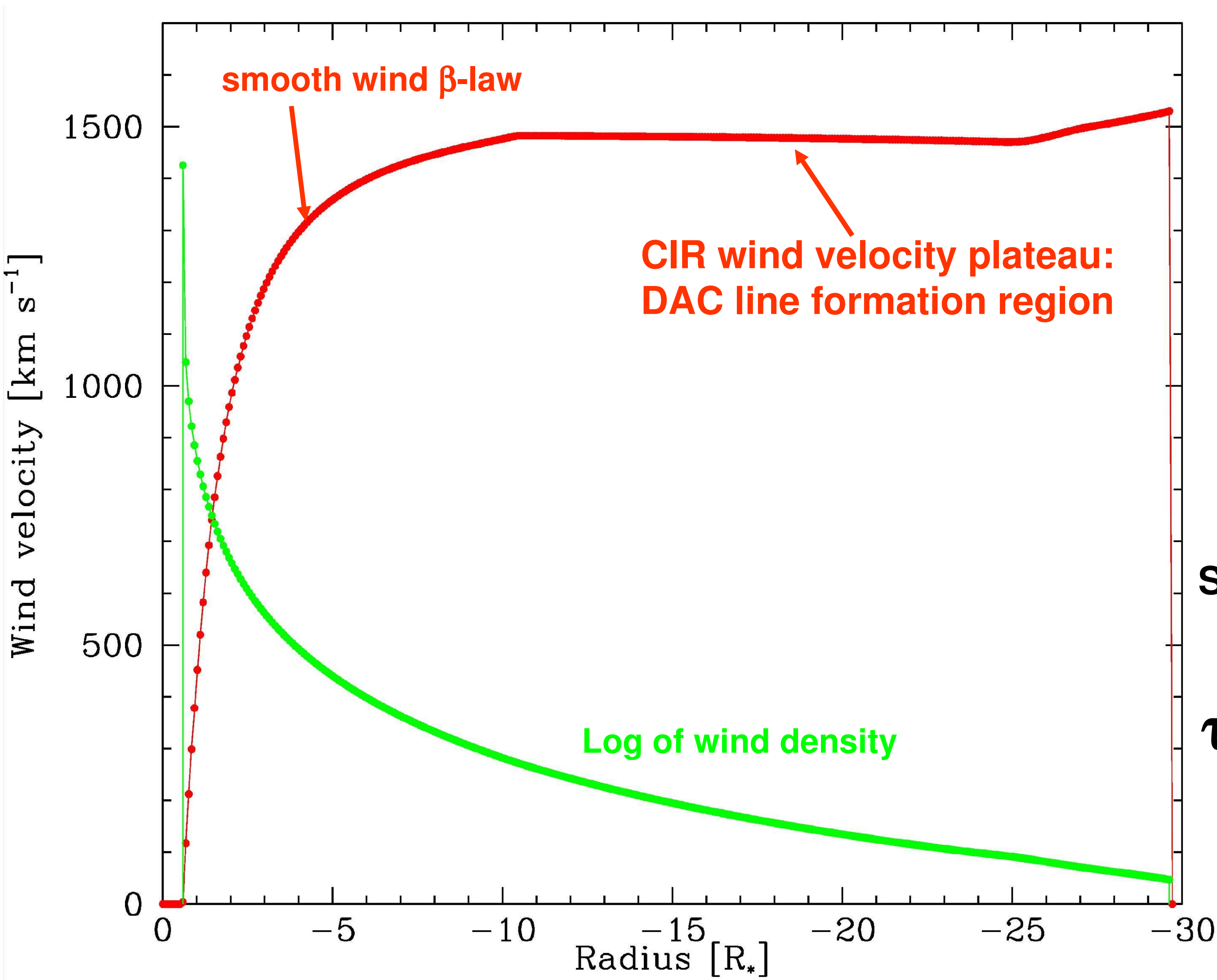


- Spiral shaped density enhancement (CIR)

- changes of wind velocity in the CIR

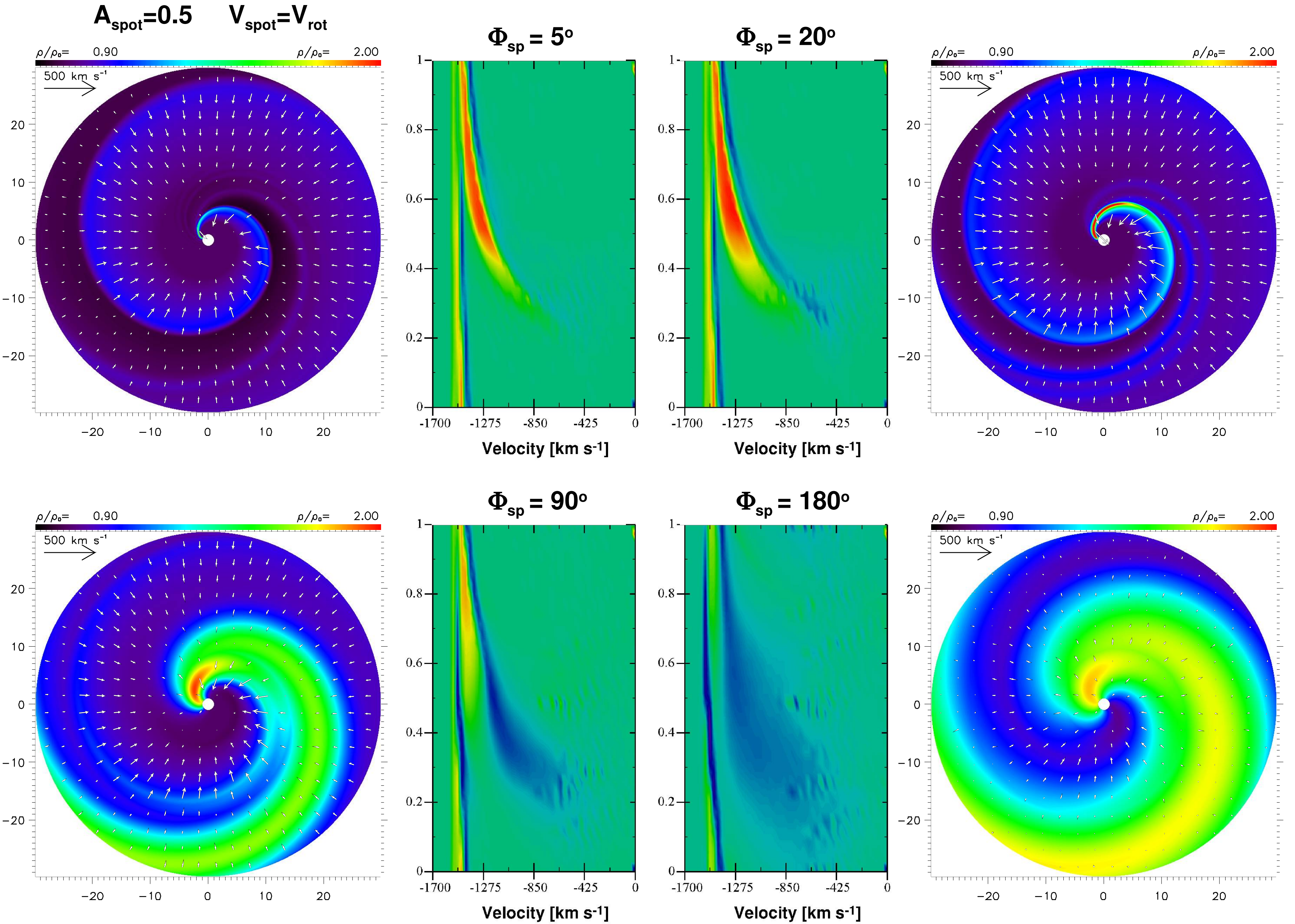
- CIR is a pattern; particles cross the CIR

Radial wind velocity structure



Sobolev optical depth:

$$\tau/\tau_0 \propto \frac{\rho \,/\, \rho_0}{\left|\frac{dv}{dr}\right| \Big/ \left|\frac{dv}{dr}\right|_0}$$



A_{spot}=0.5 V_{spot}=V_{rot}
Φ_{sp} = 5°
Φ_{sp} = 20°
Φ_{sp} = 90°
Φ_{sp} = 180°
ρ/ρ_0= 0.90
ρ/ρ_0= 2.00
500 km s^{-1}
Velocity [km s^{-1}]
-1700
-1275
-850
-425
0

Detailed best fit to DAC shapes with 2 unequal spots

2-spot model with

$V_{spot} = V_{rot} / 5$

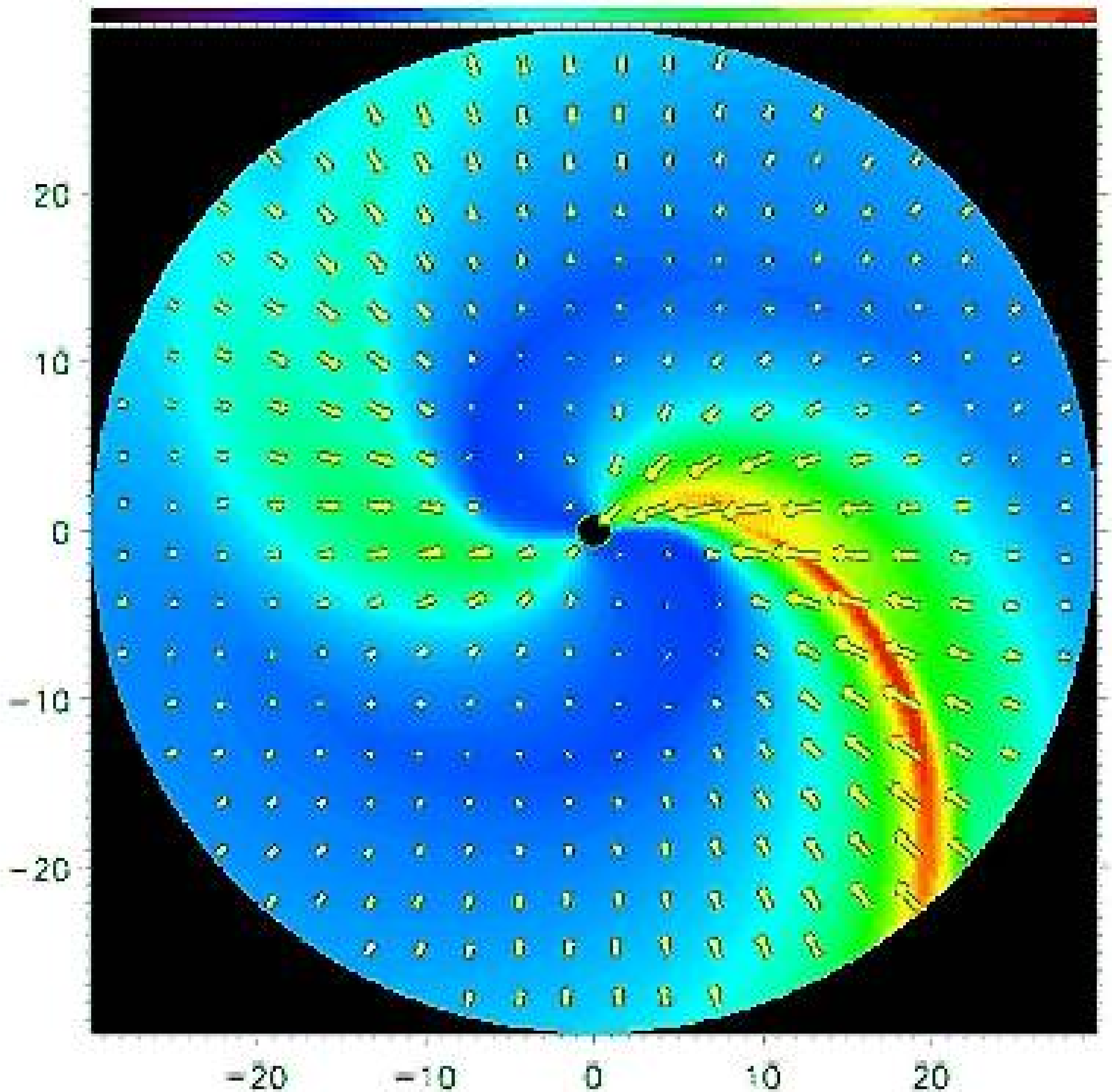
$A_{spot} = 0.2$ & $\Phi_{spot} = 20°$

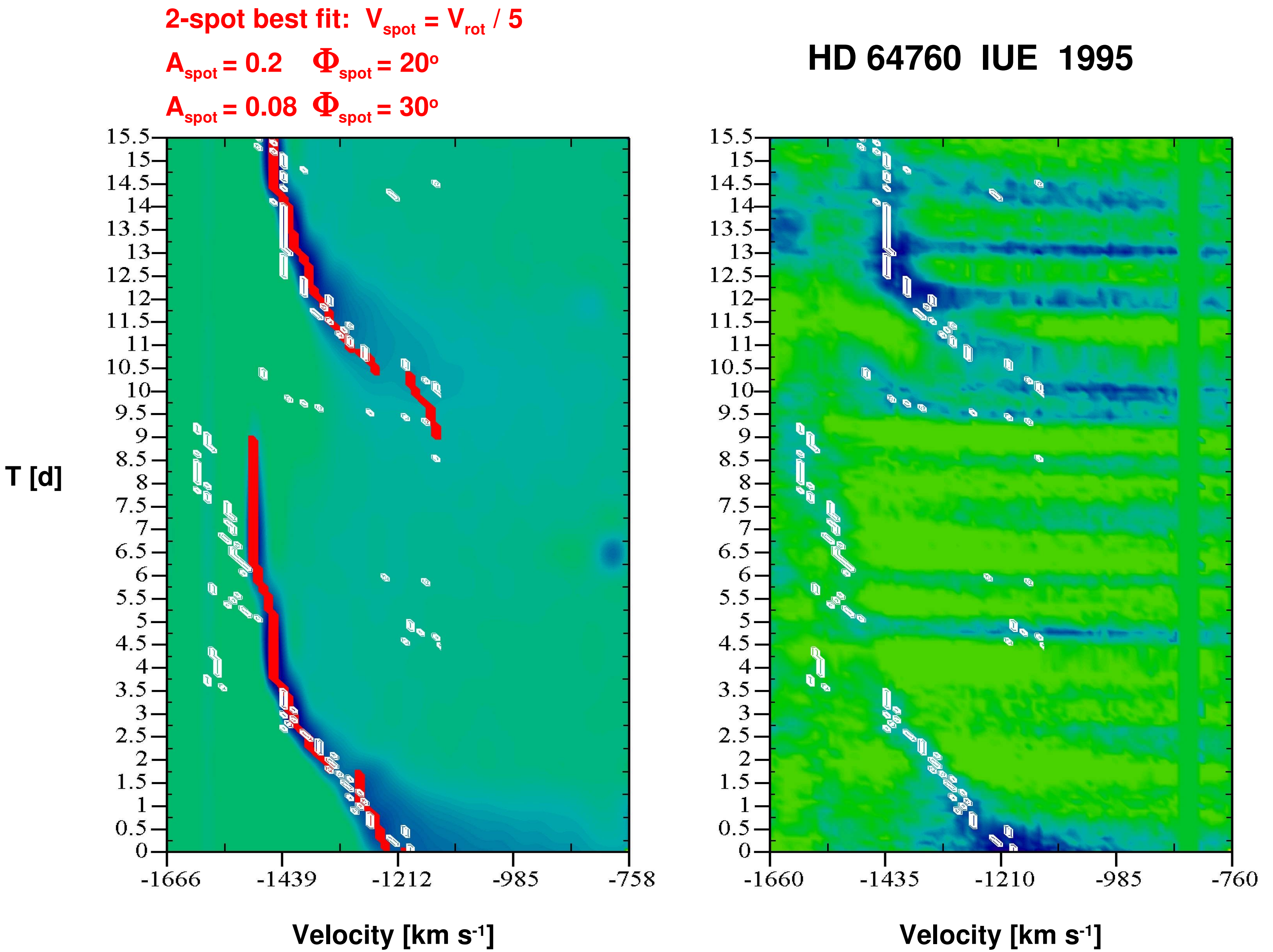
$A_{spot} = 0.08$ & $\Phi_{spot} = 30°$

Density contrast:

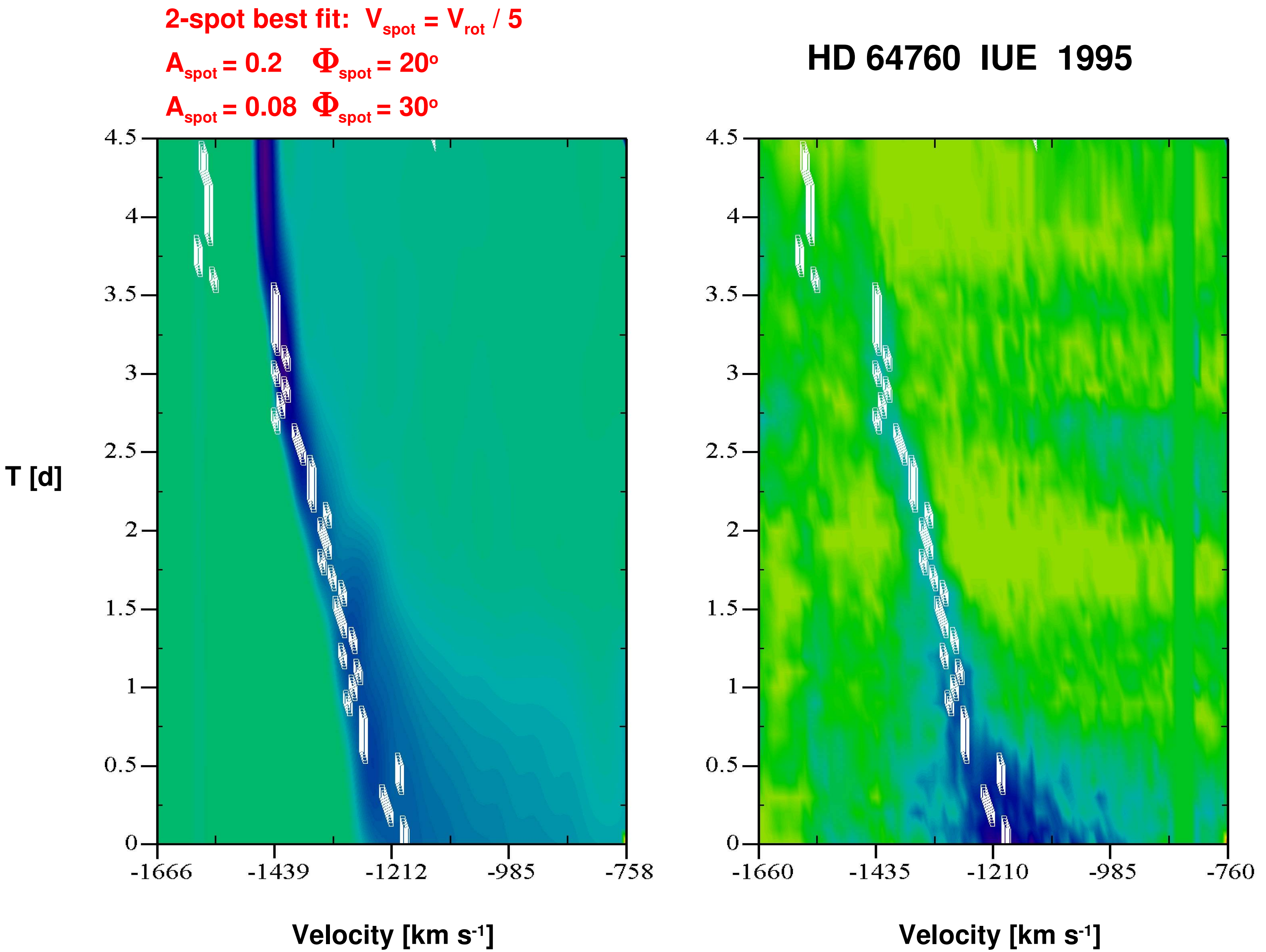
minimum $\rho / \rho_0 = 0.87$

maximum $\rho / \rho_0 = 1.31$





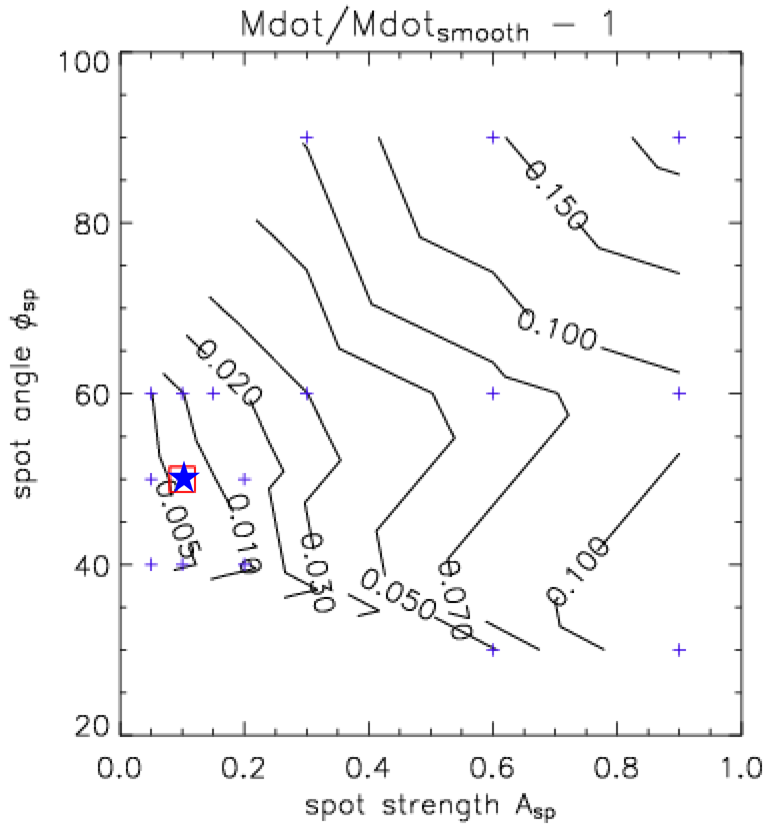
2-spot best fit: $V_{spot} = V_{rot} / 5$
$A_{spot} = 0.2$ $\Phi_{spot} = 20^o$
$A_{spot} = 0.08$ $\Phi_{spot} = 30^o$
HD 64760 IUE 1995
T [d]
15.5 15 14.5 14 13.5 13 12.5 12 11.5 11 10.5 10 9.5 9 8.5 8 7.5 7 6.5 6 5.5 5 4.5 4 3.5 3 2.5 2 1.5 1 0.5 0
-1666 -1439 -1212 -985 -758
-1660 -1435 -1210 -985 -760
Velocity [km s^{-1}]
Velocity [km s^{-1}]



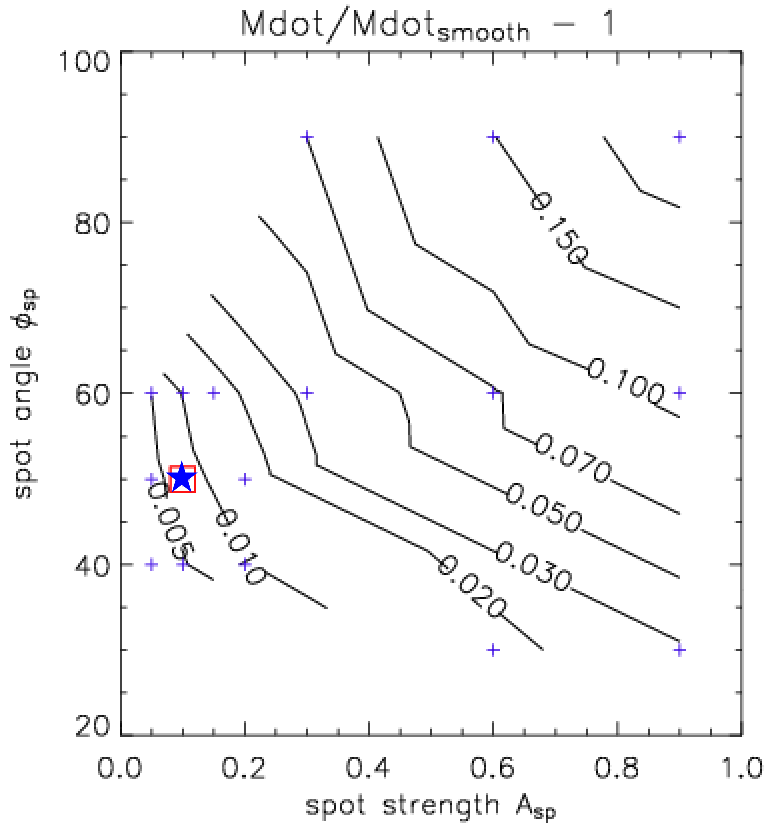
2-spot best fit: $V_{spot} = V_{rot} / 5$
$A_{spot} = 0.2$ $\Phi_{spot} = 20^o$
$A_{spot} = 0.08$ $\Phi_{spot} = 30^o$
HD 64760 IUE 1995
T [d]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-1666
-1439
-1212
-985
-758
-1660
-1435
-1210
-985
-760
Velocity [km s-1]
Velocity [km s-1]

CIR structured wind mass-loss rate of HD 64760

Exact integration



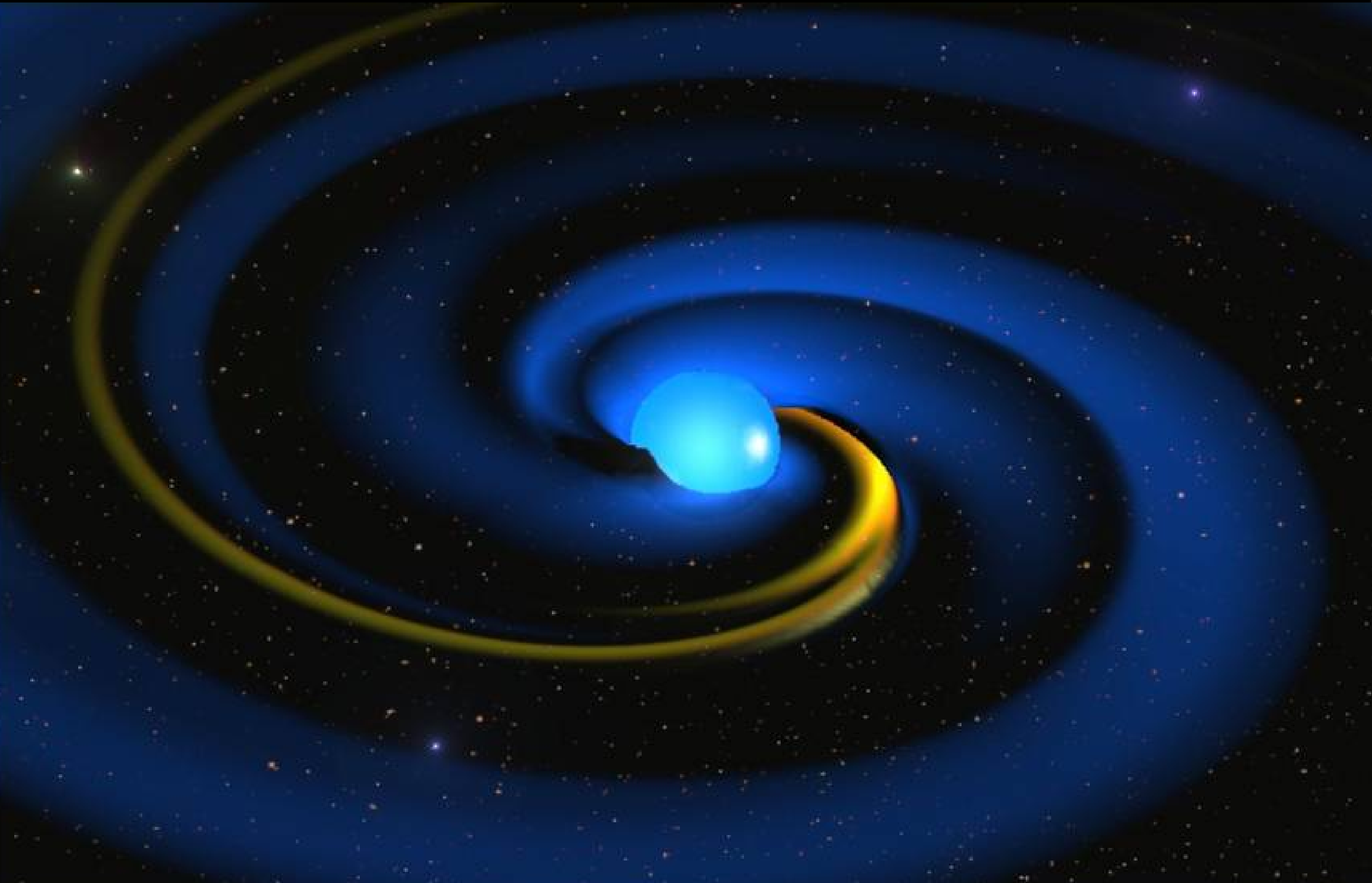
Approximation



Mdot of unstructured smooth wind model increases by only ~0.5 %

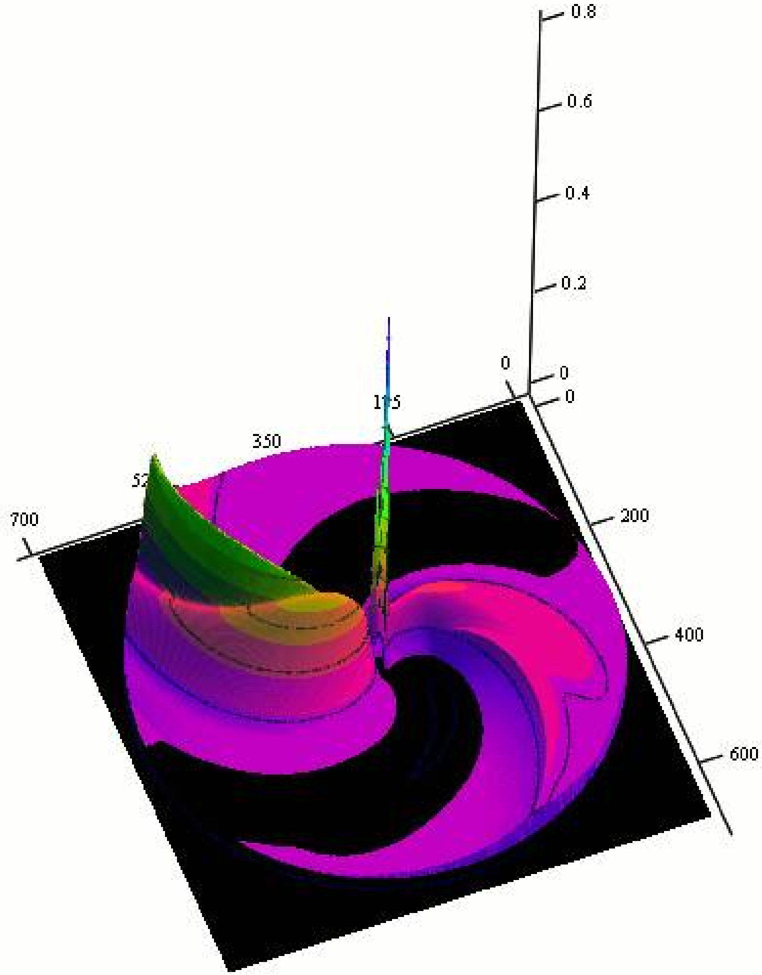
⇒ large-scale wind structures are ubiquitous

CIRs are rotating density waves in equatorial wind of massive hot stars

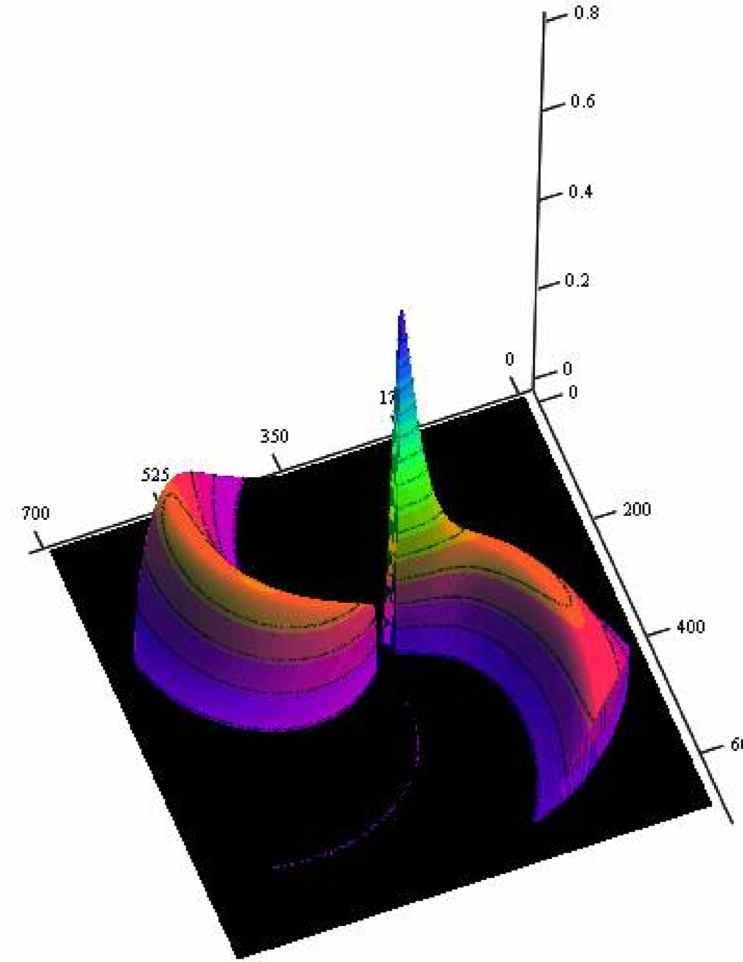


Parametrized structured wind modeling of CIRs

Equatorial wind density contrast out to 30 R_*



Best fit hydrodynamic wind model



Parametrized wind model

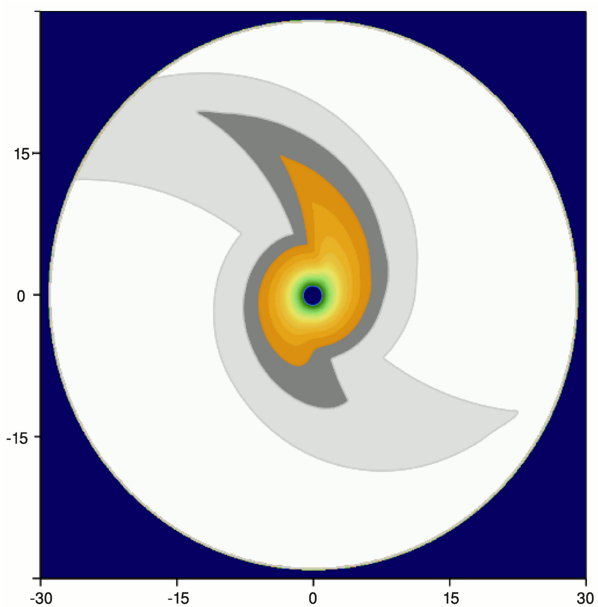
Parametrized structured wind modeling with Wind3D

- Wind3D integrates wind momentum balance equation for radiation-driven rotating wind using CAK theory.

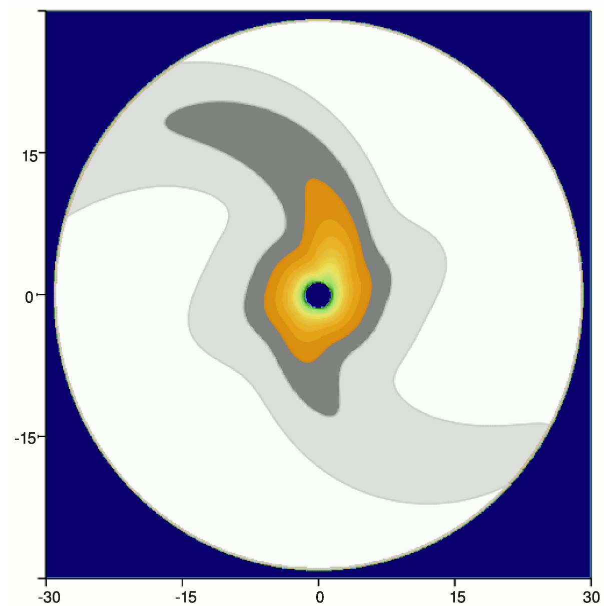
- Computes the radial wind velocity with α = ½ for an arbitrary (or semi-empiric) 2-D wind density structure.

- Tangential wind velocity approximated by V_{rot} / r

Equatorial radial wind velocity

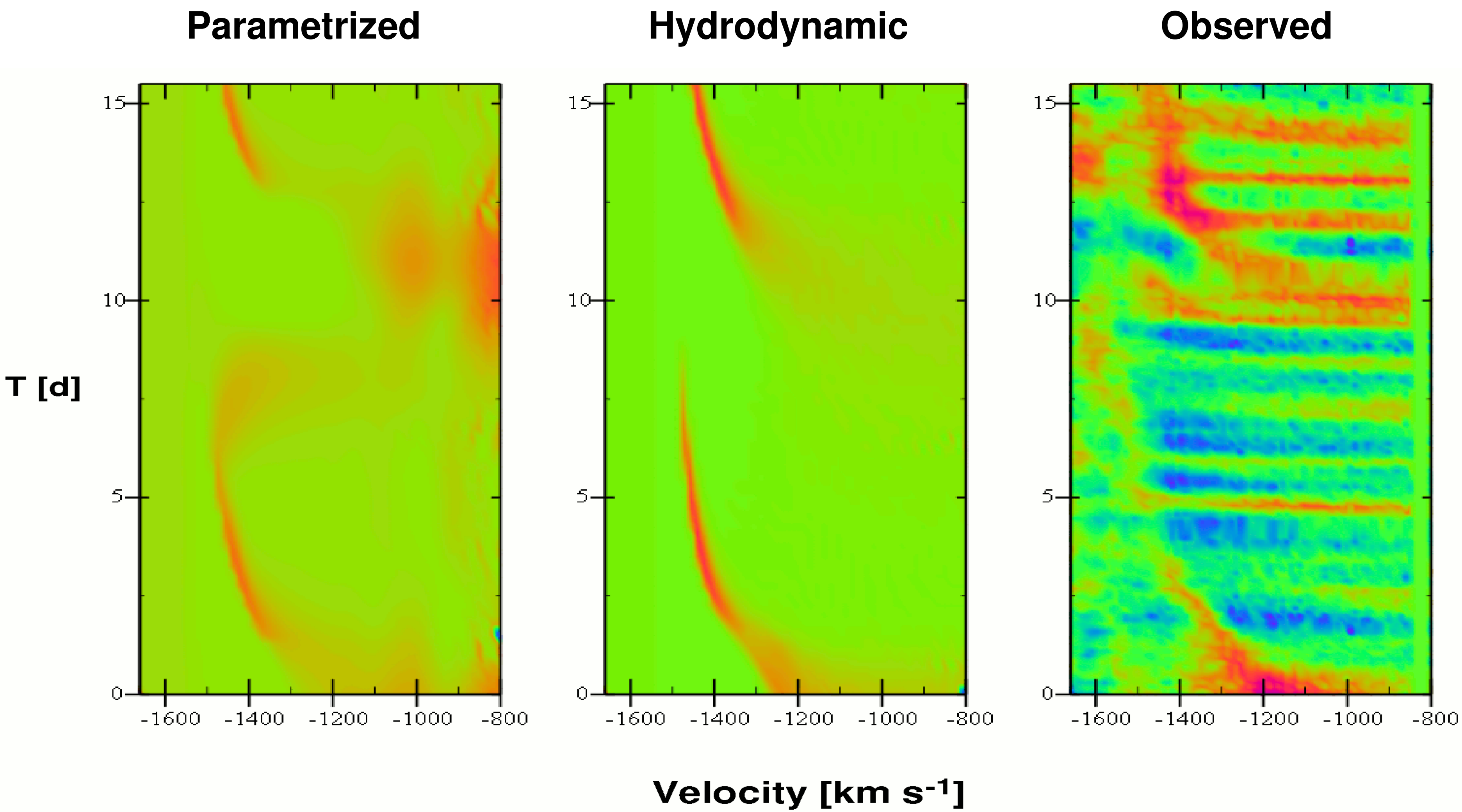


Hydrodynamic



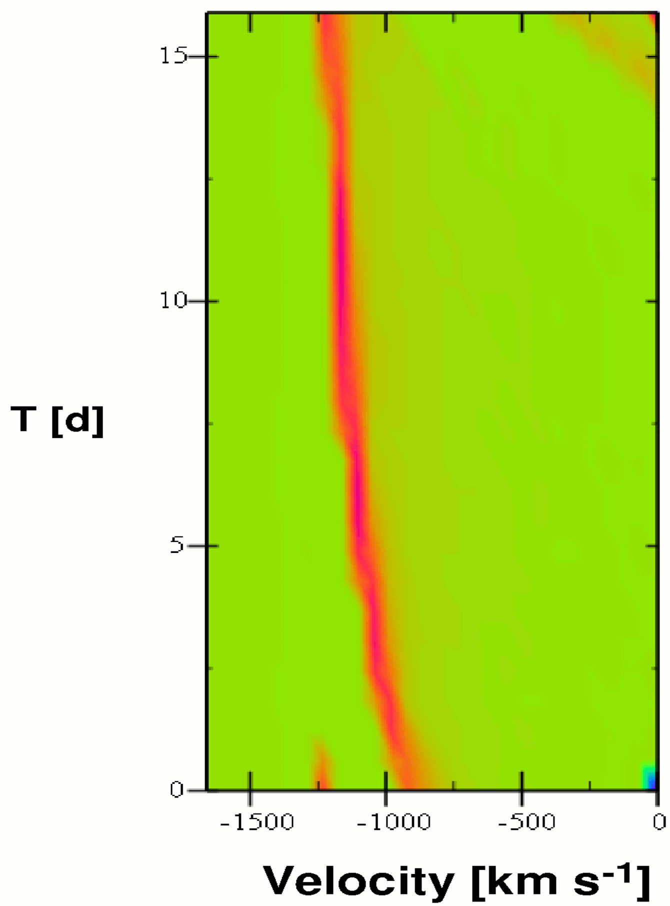
Parametrized

Comparison of parametrized and hydrodynamic DAC modeling with Wind3D

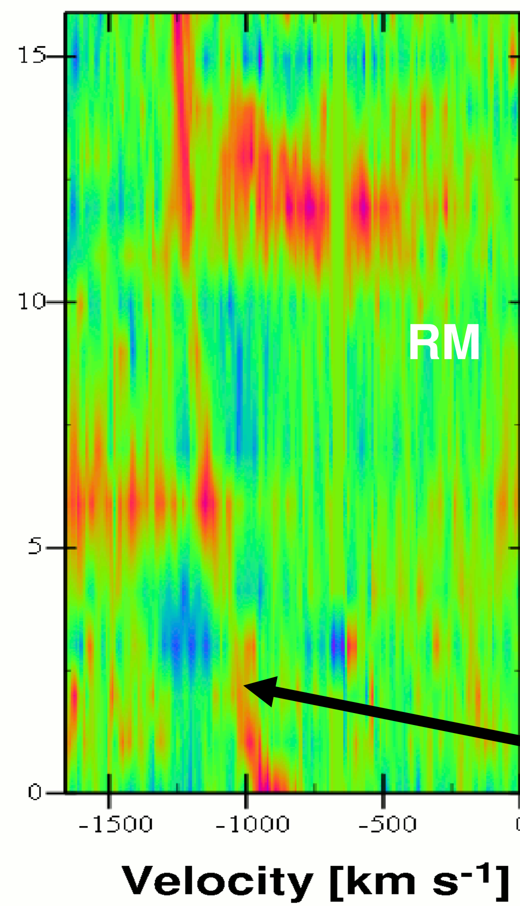


Semi-empiric DAC modeling of HD 164402

Best fit to DAC with parametrized model



IUE observed Si IV



T_{eff} = 28,500 K (B0 Ib)

R_* = 25 $R_\odot$

$V\sin i$ = 77 km s^{-1}

P_{rot} = 13.3 d

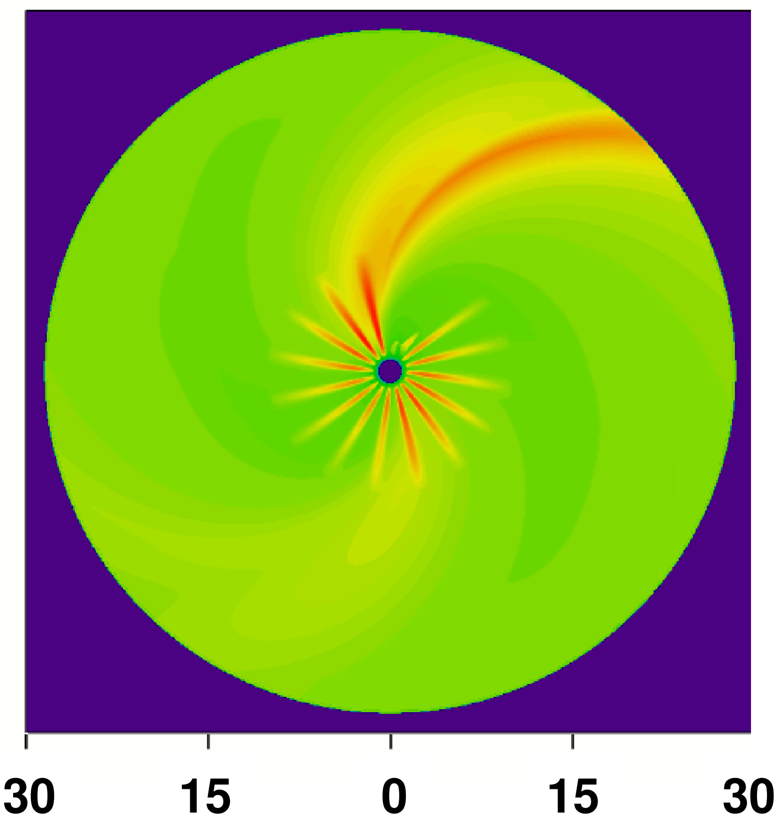
V_∞ = 1750 km s^{-1}

CIR model surrounds star before reaching V_∞

DAC width < 200 km s^{-1}

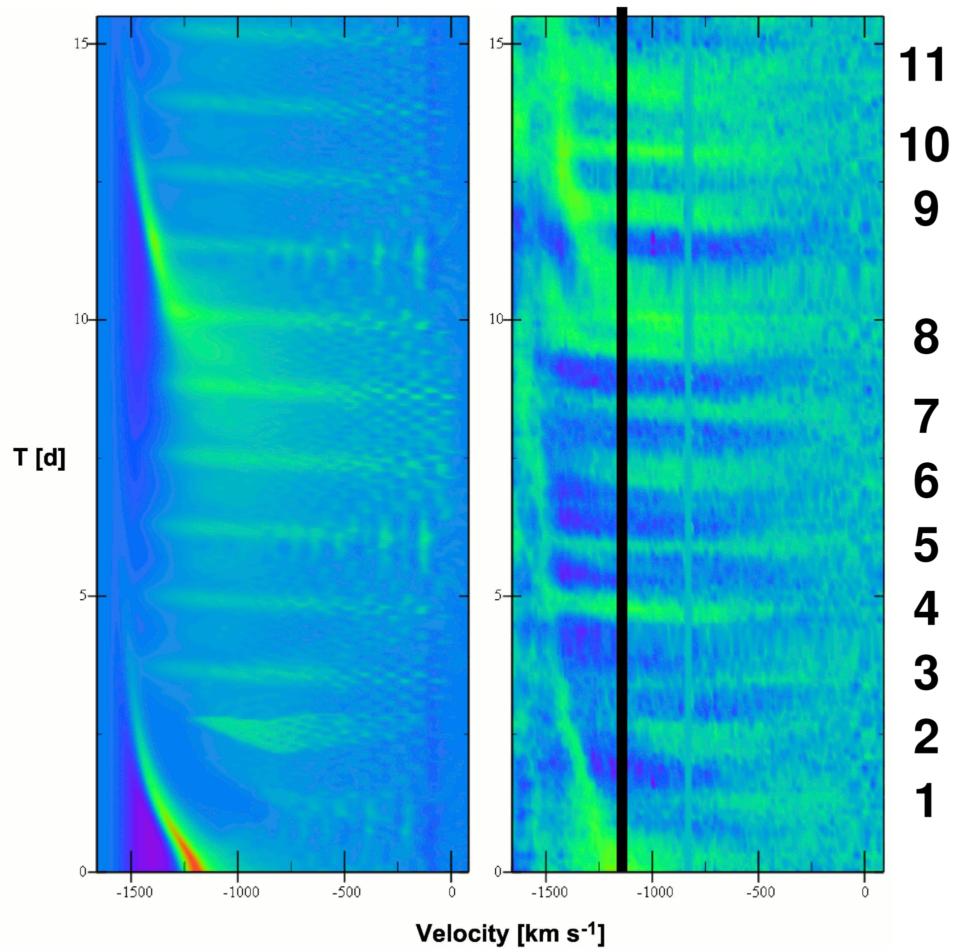
Parametrized model of DACs and RMs in HD 64760

Equatorial wind density contrast

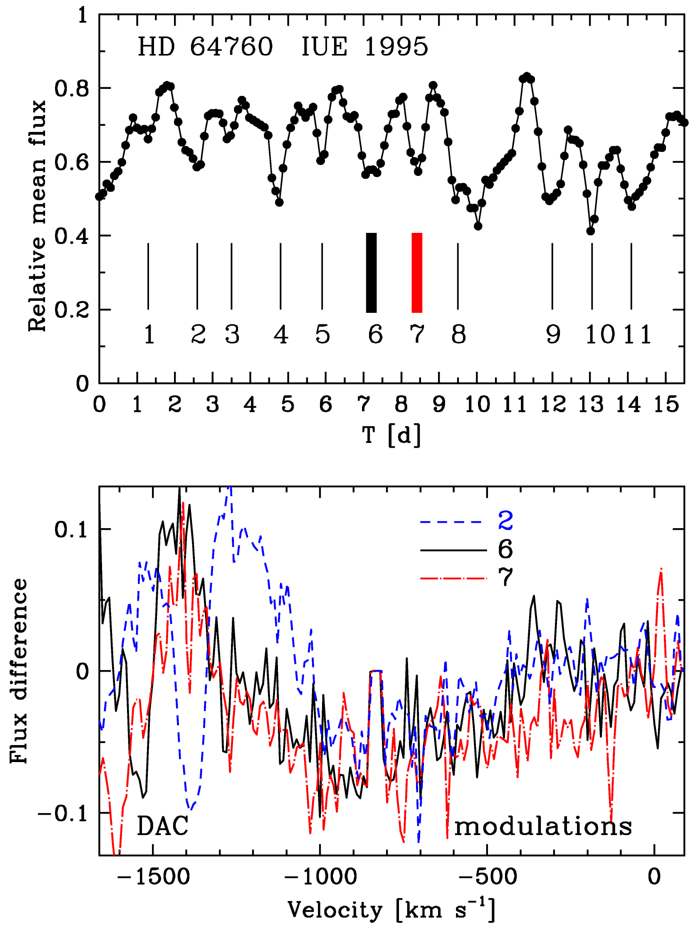


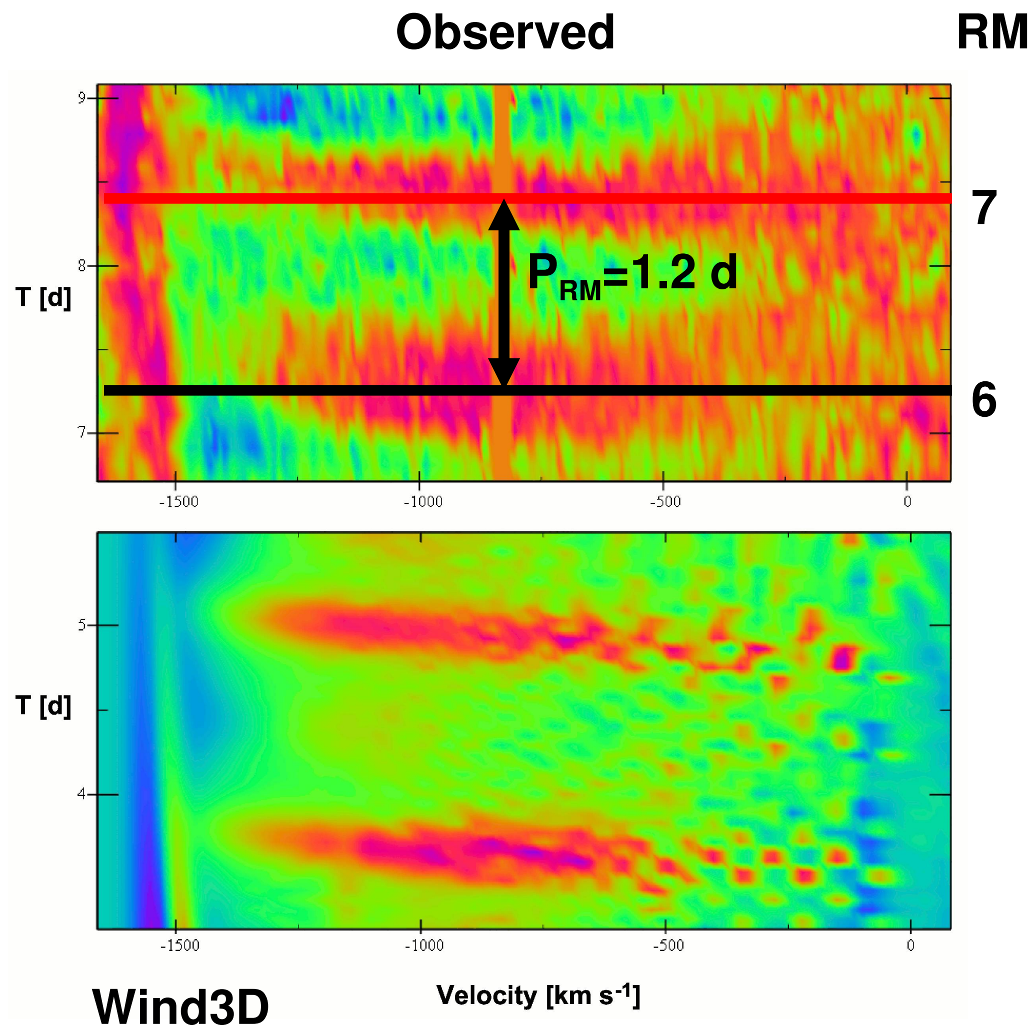
Co-rotating RMR is 'spoke-like' wind density pattern out to ~10 R_*

Wind3D Observed RM



Observed modulation flux profiles





RMs require density contrast of max. 17% above smooth wind density.

RT modeling of modulation properties

1. RM intensity

Radial and tangential wind density profile determines RM flux profile.
Radial distance in wind determines max. RM wind velocity.

2. RM frequency

Total number around star determines RM recurrence times.
Assumption: RMRs co-rotate with CIRs of P_{spot} = 20.6 d.

3. RM geometry

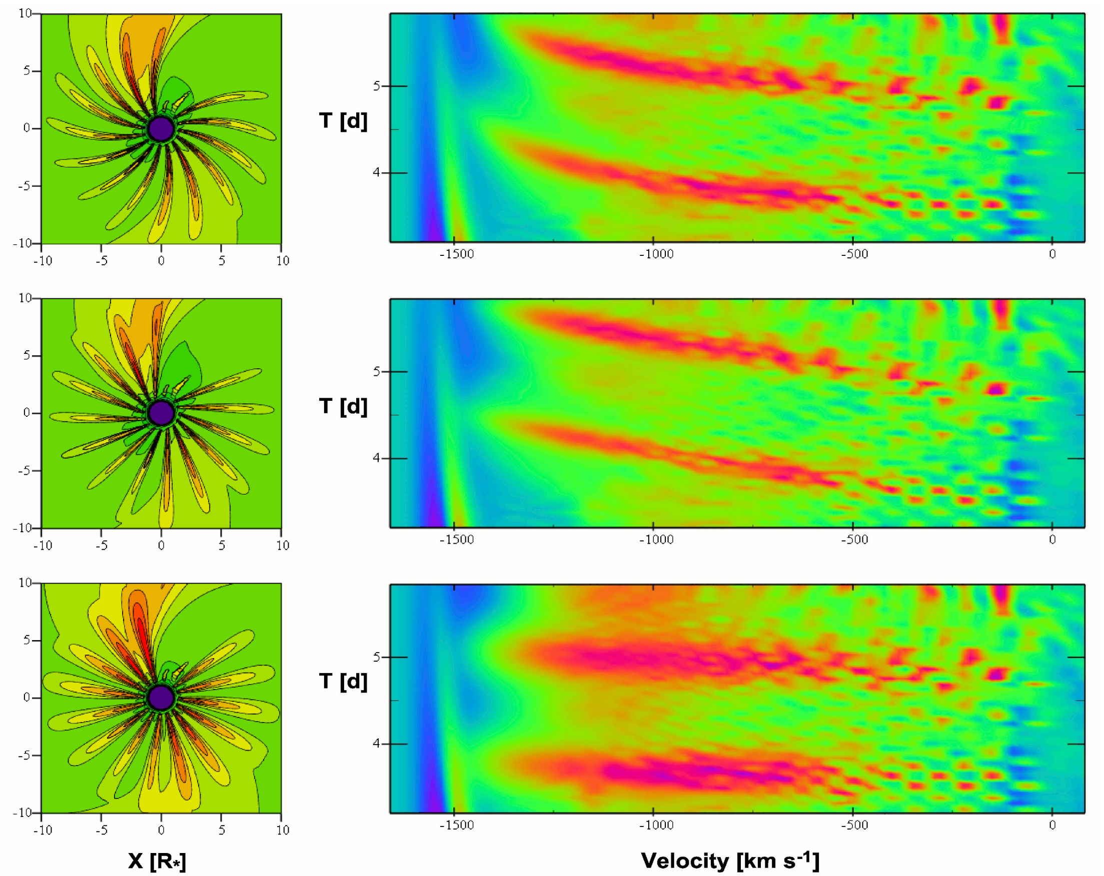
Radial curvature:

~linear below 10 R_*

RM acceleration

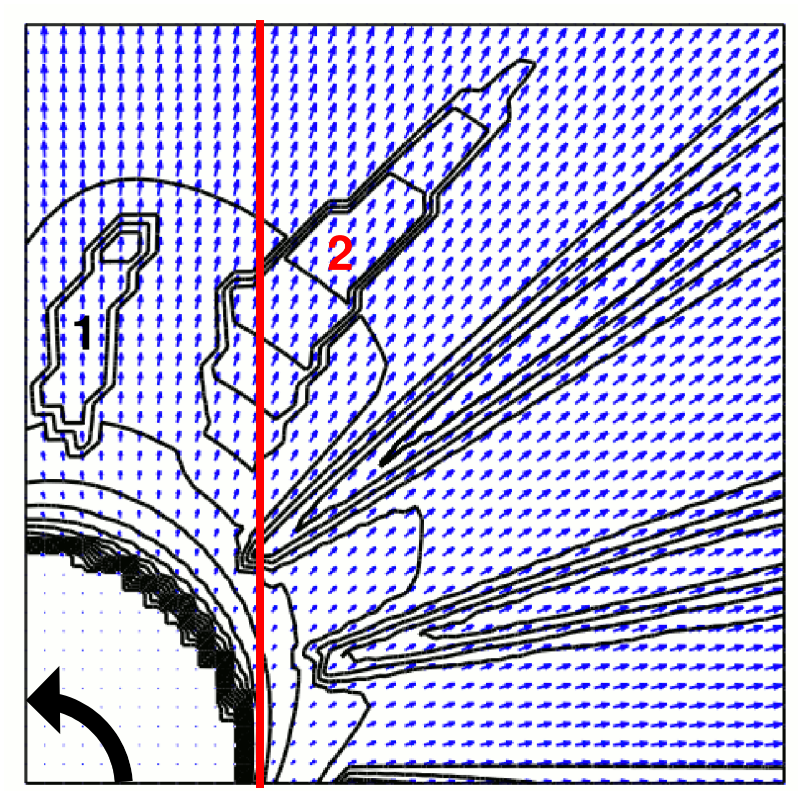
Surface incidence angle:
< 6 deg. from radial
RM inclination

Base opening angle:
~10 deg.
RM duration

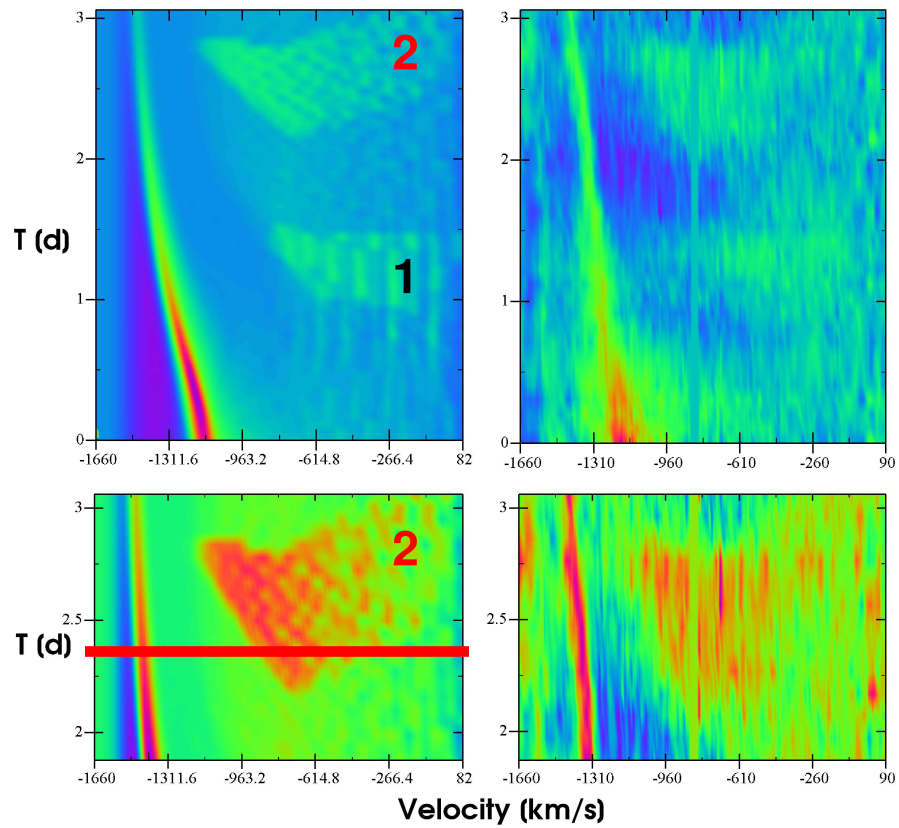


RT modeling of modulation ‘phase bowing’

Density contours parametrized model



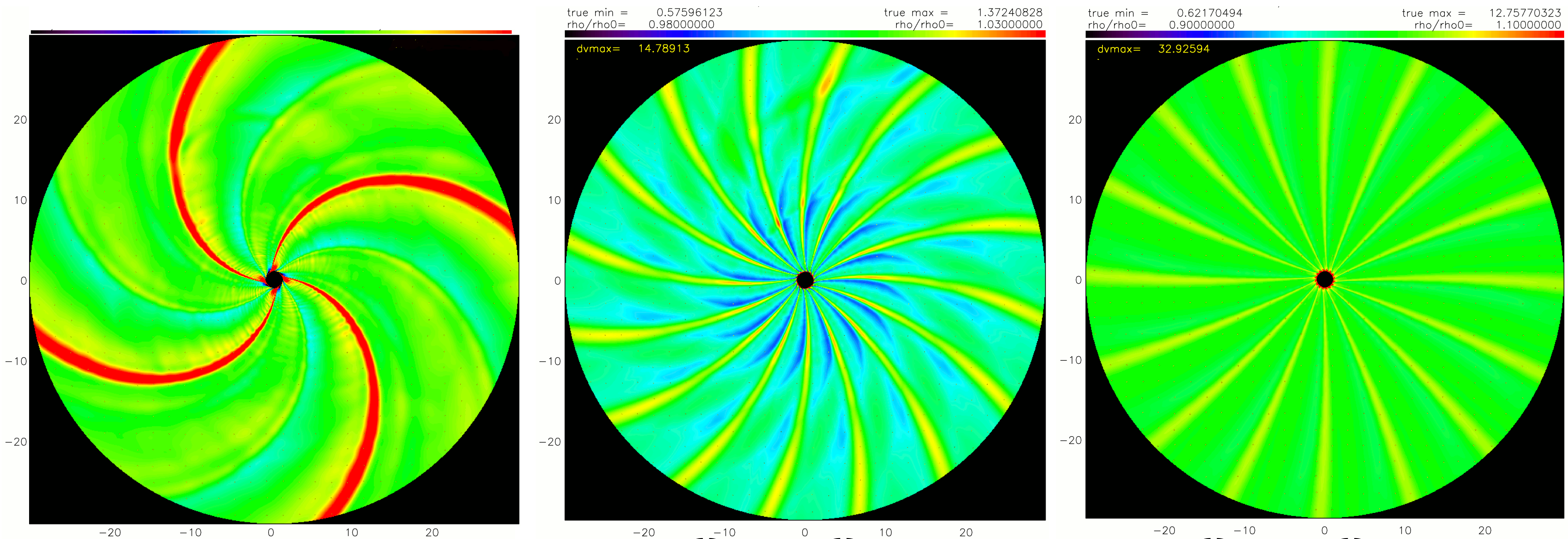
Wind3D **Observed**



Phase bowing of RM 2 is due to intrinsically curved shape of RMR base within ~2.5 R_* above the stellar surface.

Testing hydrodynamic wind models of modulations in HD 64760 with Zeus3D

Mechanical wave propagation at surface produces narrow spoke-like RMRs.

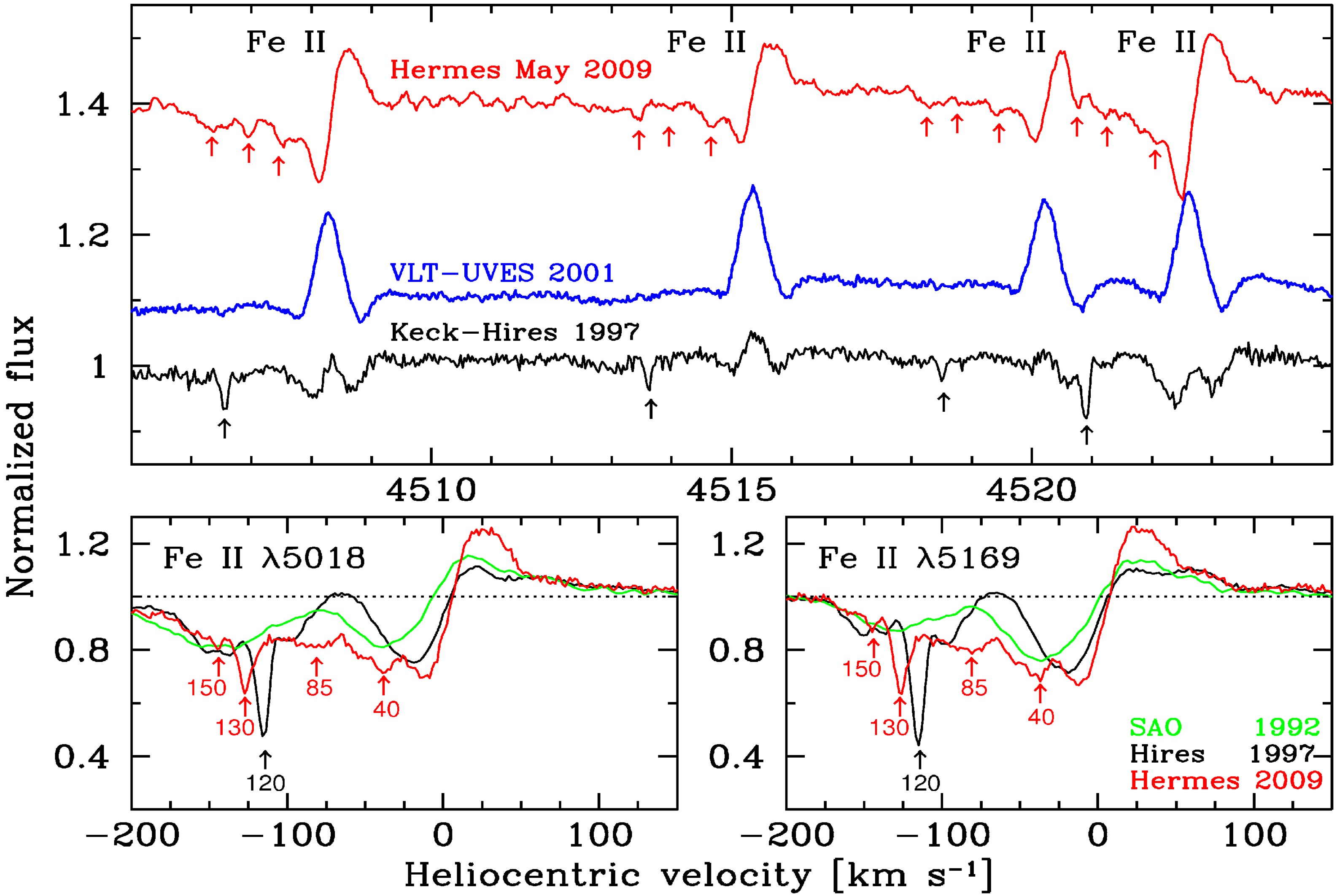


$\omega_{wave} = \omega_{star}$ $\omega_{wave} = \omega_{star}$ $\omega_{wave} = \omega_{star} / 5$

Density contrast too small below 10 R_* while ~17% is required to fit RM fluxes.

Reality of narrow spokes in hydrodynamic wind models is currently unclear.
Better understanding of hydrodynamic wave pattern formation physics needed.
Numerical artifacts observed in experiments without rotation?

Narrow Optical Absorption Components in LBV HD 168607 (B9.5 Ia+, S Dor Var)



Ongoing and future work: Monitoring and RT modeling of NOACs

Conclusions

- Shape and morphology of UV DACs observed in HD 64760 (B Ib) can be modeled in detail by combining hydro-dynamic and 3-D radiative transfer calculations. DACs are caused by large-scale density waves in hot star winds.
- Best fits to DAC evolution in HD 64760 signal sources at the base of the stellar wind that lag 5 times behind stellar surface rotation. 3-D radiative transfer fits require spot brightnesses of 20% ±5% & 8% ±5% above L_* and with spot diameters of 20°±5° & 30°±5°.
- Semi-empiric 3-D RT fits to RMs signal very regular ‘spoke-like’ equatorial wind density pattern. Maximum density of ~17% above smooth wind density up to ~10 R_*. Possibly caused by mechanical wave action at the surface? Is it a rotating wave interference pattern in the equatorial wind?
- Wind density enhancements due to large-scale CIRs and RMRs increase mass-loss rate of symmetric smooth wind model by ≈1%.