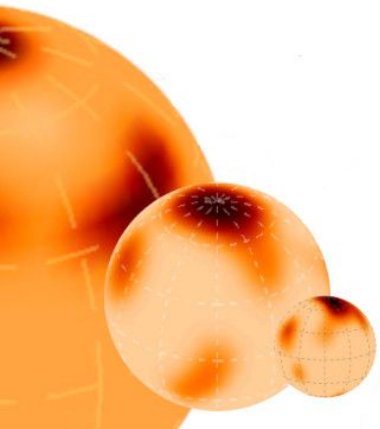
# Modeling stellar surface structures

## Theory and practice

20. 10. 2026

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Oláh, Katalin
Seli, Bálint
Van-Driel Gesztelyi, Lídia
Vida, Krisztián

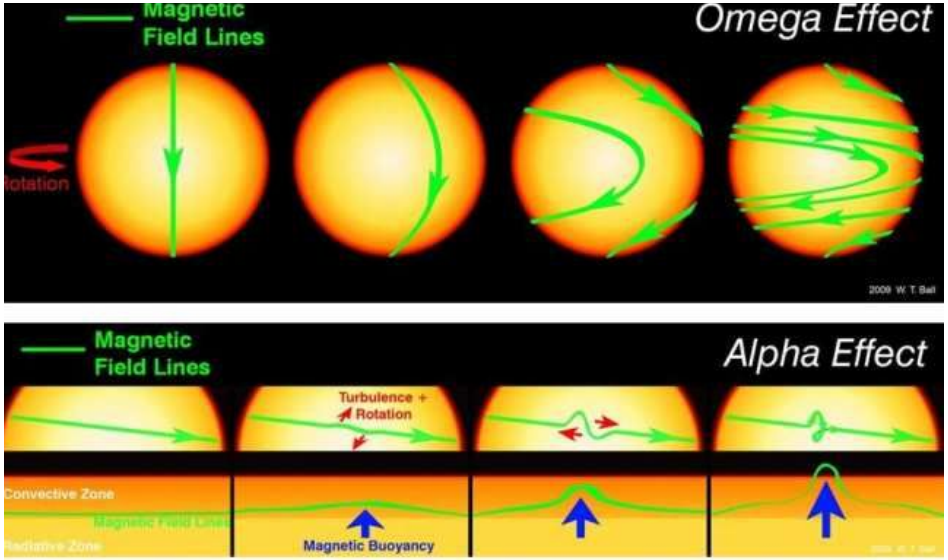


KONKOLY

CSFK

# Context, importance

- Stellar dynamos in late-type (G-K-M) stars generate magnetic fields which manifest in the observables of stellar activity, e.g. starpots
- (Differential rotation is of utmost importance in the regeneration of the toroidal field component during a dynamo cycle ( → Ω-effect))
- Dynamo action can differ on different types of stars
- Observing starspots is key in understanding how the underlying dynamos work



# Context – dynamo

Dynamo number: $$D = D_\alpha D_\Omega = \frac{\alpha_1 L}{\eta_t} \frac{\Delta\Omega L^2}{\eta_t}$$

$D_\alpha$, $D_\Omega$ – turbulent magnetic Reynolds-numbers

L – typical scale-length of the dynamo

$\eta_t$ – scalar turbulent diffusion

$\alpha_1$ – alpha-effect coeff.

$\Delta\Omega$ – difference between rotation rates

Sun: $|D_\alpha| \sim 2$, $D_\Omega \sim 10^3$ → typical for αΩ dynamo

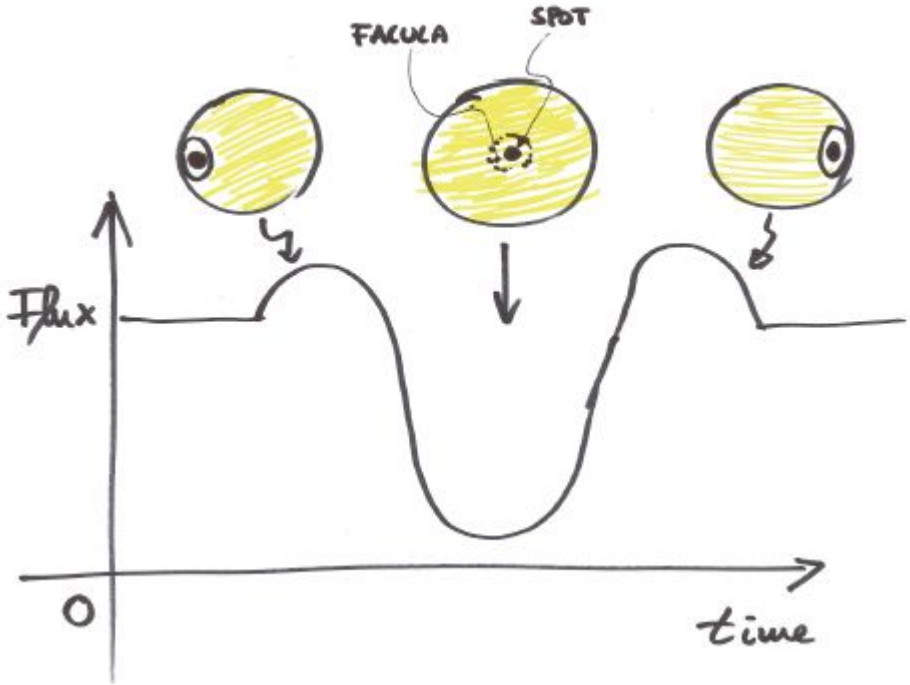
If $D_\alpha$ and $D_\Omega$ are in the same order of magnitude → $\alpha^2\Omega$ type dynamo, e.g. fast rotating, young MS stars

If $|D_\alpha| >> |D_\Omega|$ → $\alpha^2$ type dynamo, e.g. fully convective (~ cooler than M3.5-M4) dwarfs

Different types of dynamos can manifest different general spot configurations.

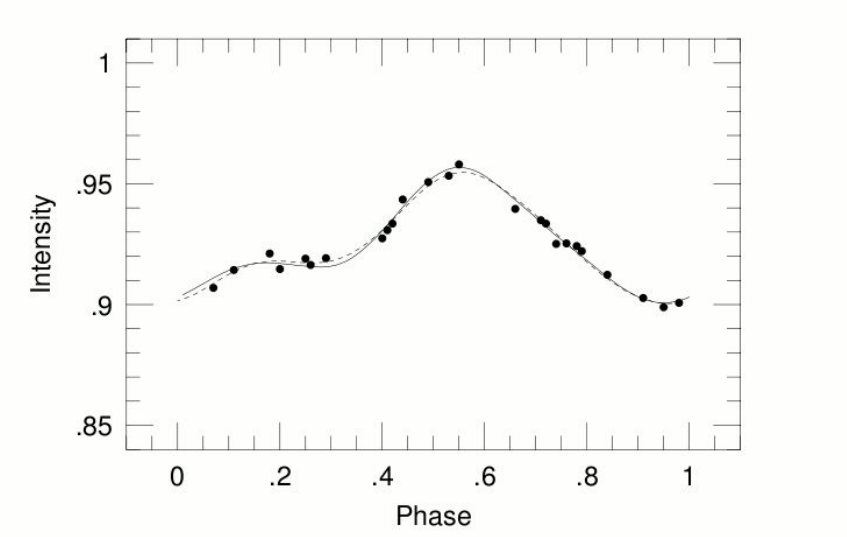
# Photometry – Analytic spot models

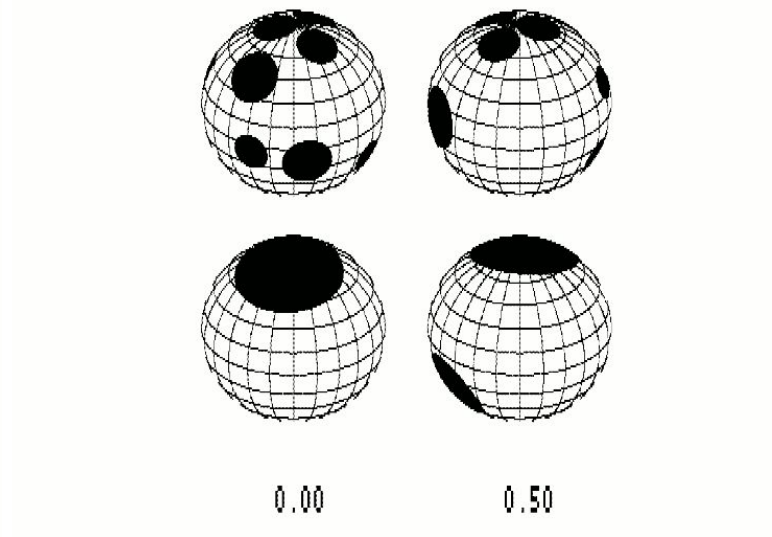
- 100% AI free plot of how an active region affects the light curve



# Photometry – Analytic spot models

- At an accuracy of about 0.01 magnitude, a few circular, homogeneous spots can describe the rotational modulation well, but this does not map the surface unambiguously.
- Two spots can be fitted with few parameters, yet the degeneracy between inclination, spot latitude, size and contrast is strong.
- The spot longitude can usually be constrained better than the latitude or the size.
- Without color information, the intensity ratio of the spot and the photosphere can only be fixed by assumption.



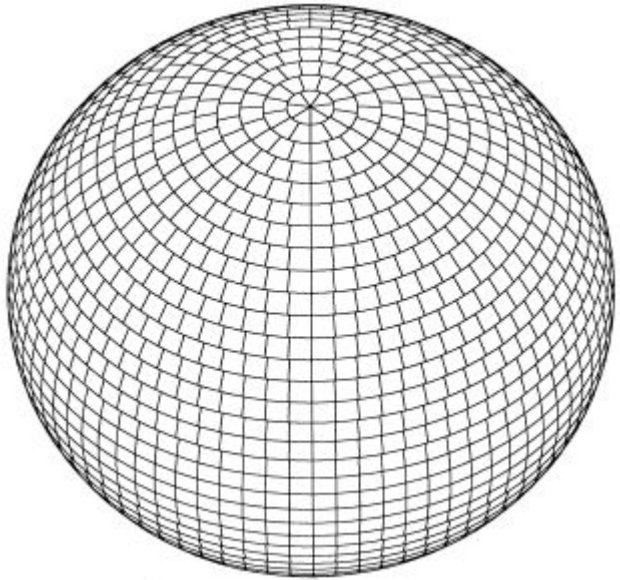



# Photometry – light curve inversion (“disco ball”)

- The surface is divided into many segments, which are fitted one by one.
- It builds a 2D model from roughly 1D information.
- The solution is often unstable (small changes in the data change the model a lot).
- This can be improved → regularization is needed, e.g. for a smoother spot distribution (see Doppler imaging, maximum entropy or Tikhonov).



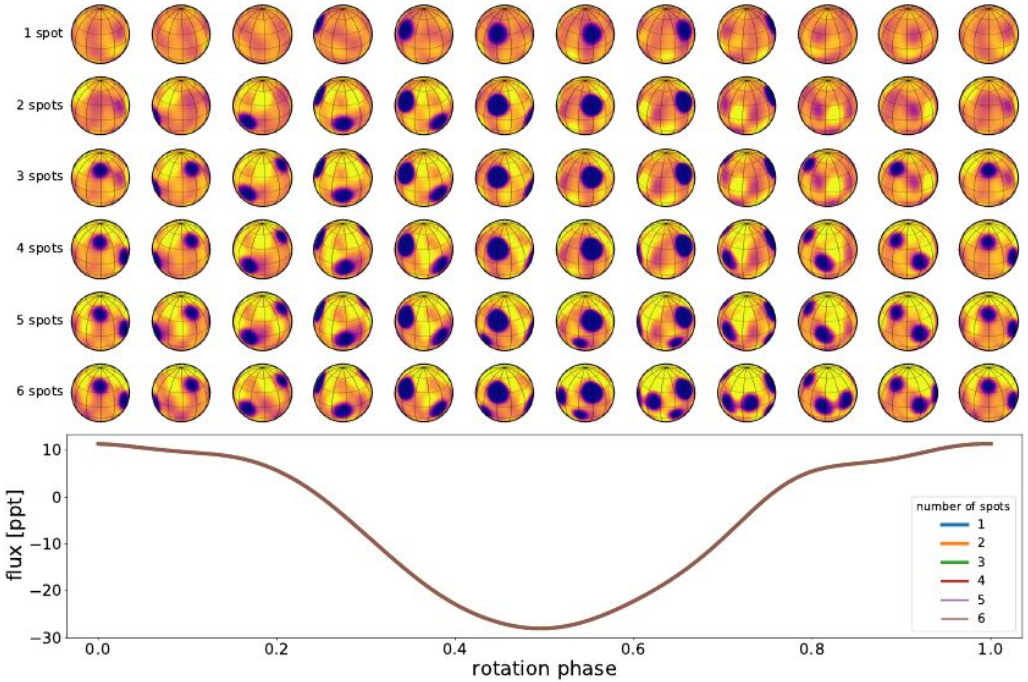




*Vogt+1987*

# Light curve inversion is not unique

- Anywhere from one to six spots can produce the same light curve, even with noise-free data.
- From a single photometric band, the total spot coverage and the number of spots cannot be determined without strong priors.



# Photometry vs spectroscopy

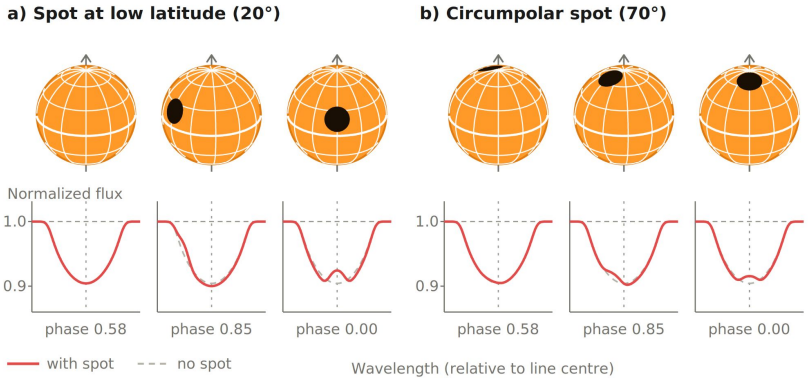
- Photometric spot modeling techniques are much “cheaper” than Doppler imaging
  - Can be applied in bulk especially in the space telescope era

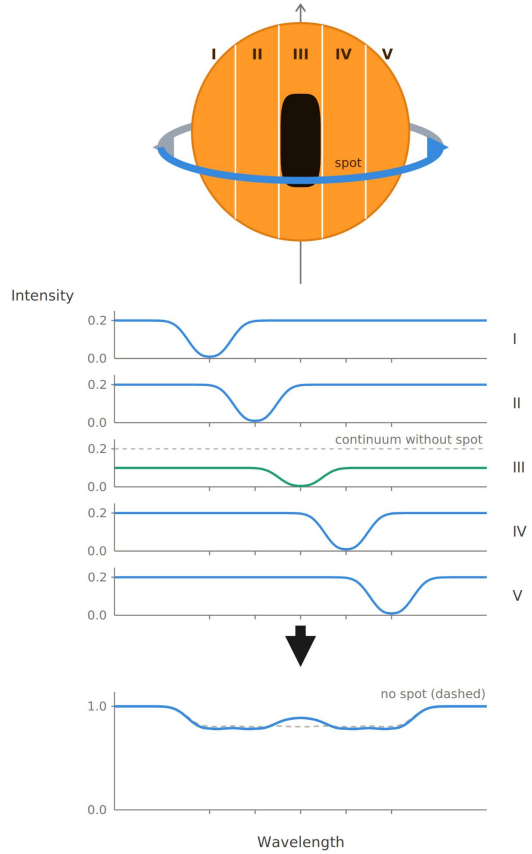
- Can only derive spot longitude reliably
  - Latitude, size and temperature are degenerate
  - Can only roughly estimate the absolute value of surface shear

- Doppler imaging requires much more resources but more accurate
  - Solution is unique (after regularization)
  - Spot parameters are reliably derived
  - Sign of differential rotation!

# Doppler imaging in theory

- the rotationally broadened line profiles are distorted due to starpots on the stellar surface
  - from the sector (III.) containing the spot, the measured continuum flux is significantly lower. This will appear on the profile as a “bump” (not an emisson core, just appears so!)
  - one profile is a one-dimensional imprint → time series spectra are required to create 2D maps (with the best possible phase coverage)
- the surface temperature distribution can be reconstructed (as



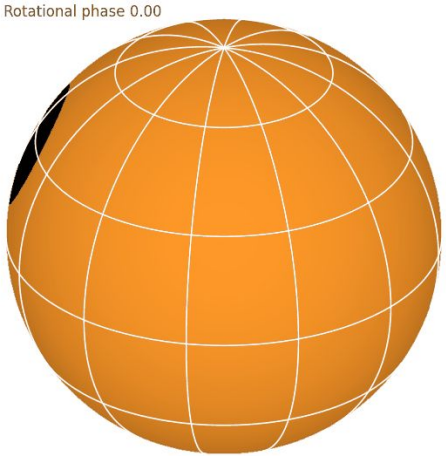



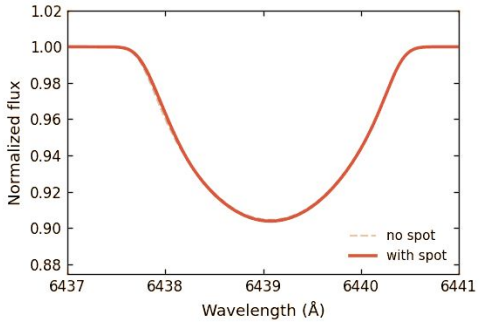
# Doppler imaging in theory

- The inversion can be carried out by calculating the local line profiles through solving the radiative transfer equation, and by minimizing this expression:

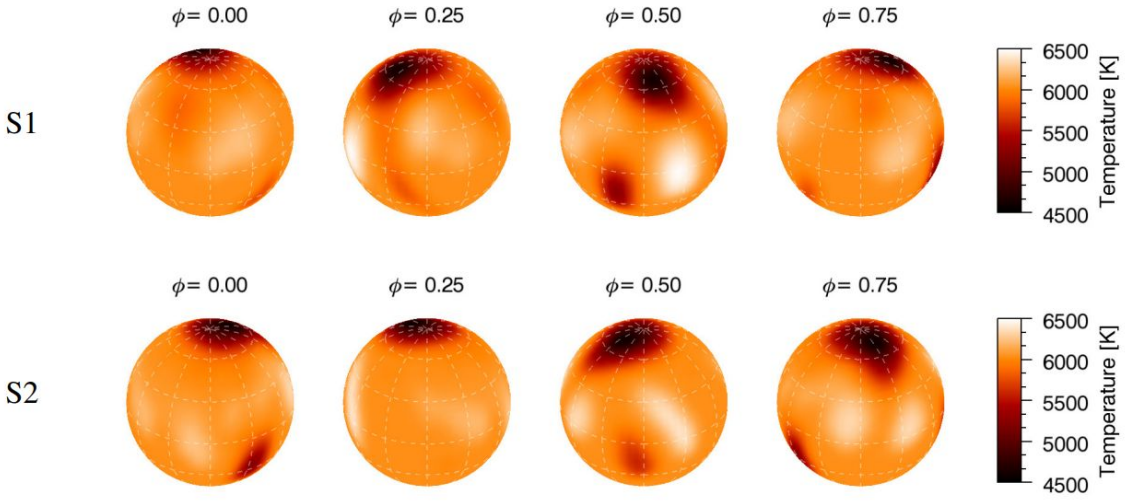
$$E = \sum_{\varphi}\sum_{\lambda} [R_{\mathrm{calc}}(\lambda,\varphi) - R_{\mathrm{obs}}(\lambda,\varphi)]^2 + f(M)$$

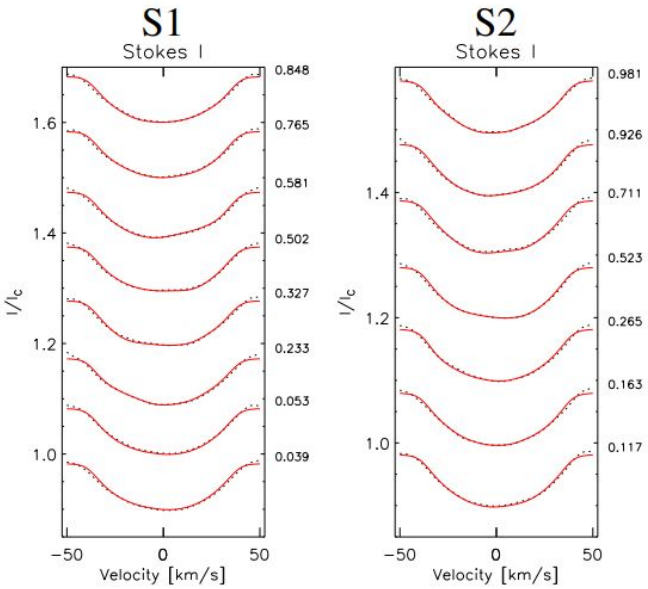
- the preliminary image is created by integrating over the surface, then through several iterative steps, the above expression is minimized, resulting in the final map
- regularization is necessary (maximum entropy, Tichonov-function, occamian approach...)
- applicational conditions:
  - (R~>20000-30000, S/N>100)
  - ~20<i<~70
  - 20 km/s<vsini<110 km/s
  - good phase-coverage
  - feasible mapping lines
- iMAP (*Carroll+2008,2012*)



# Doppler imaging – polar caps



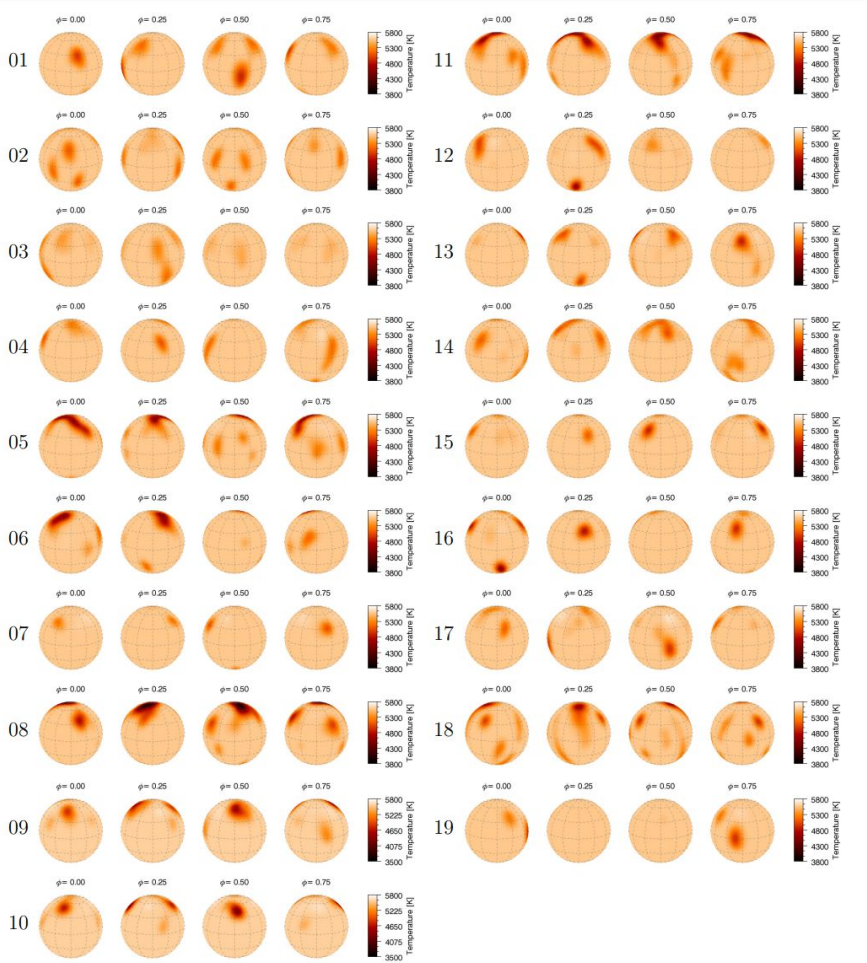




*V1358 Ori, Kriskovics+2019*

- Young G0 dwarf
- Strong polar features
- Typical on rapidly rotating solar likes: Coriolis-force carrying flux tubes towards the pole (*Isik+2018*)
- $\alpha^2\Omega$ dynamo?

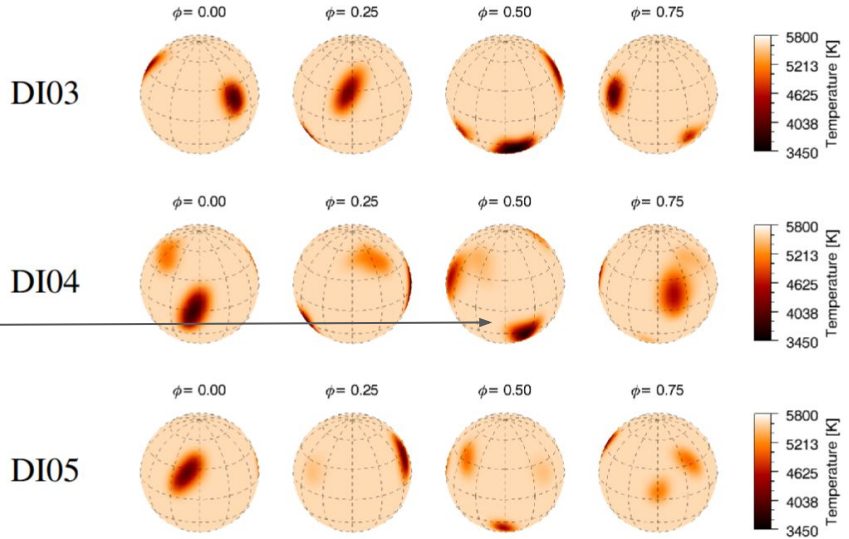
# Doppler imaging – cycles?

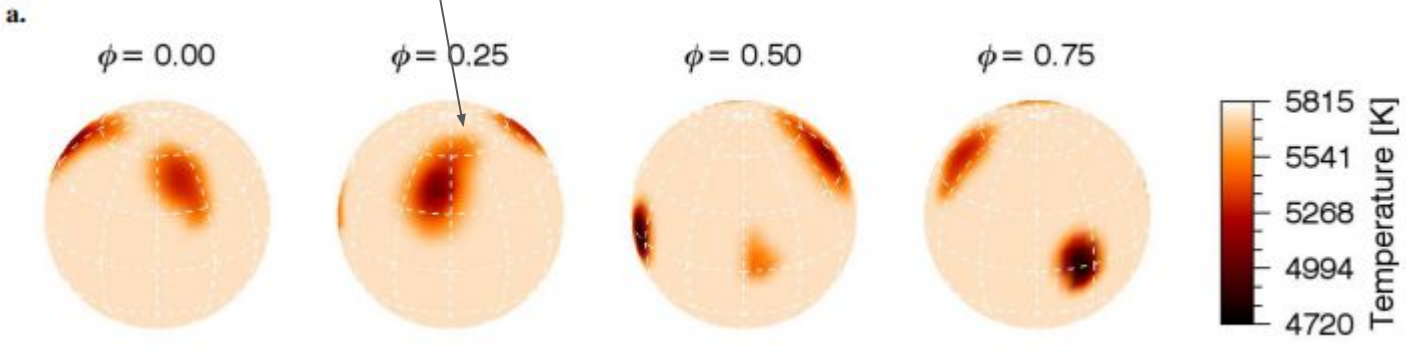
- V815 Her (*Kővári+2024*)
- Young G4 dwarf
- Drastically changing polar structures over ~1.5 years -> signs of magnetic cycles?



# Doppler imaging – cycles?

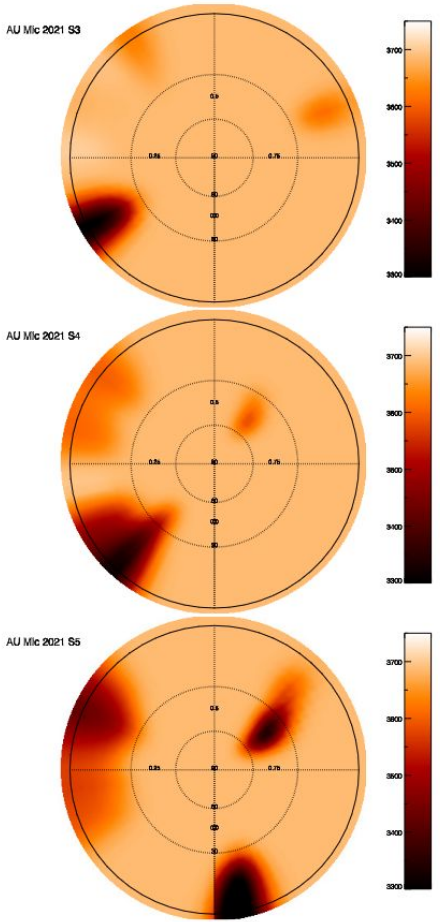
- EK Dra (*Järvinen+2018, Görgei+2026*)
- Young G3 dwarf
- Changing “leading hemisphere”?



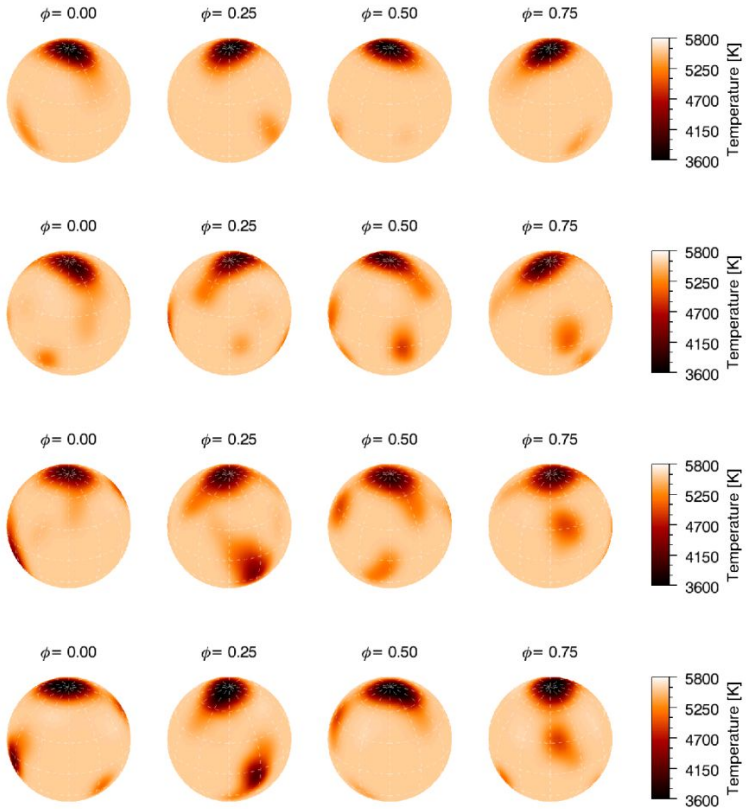
# Doppler imaging – slower rotation

- AU Mic (*Kriskovics+very close to be submitted, I swear*)
- M0 dwarf, not very fast rotator
- Inclination is almost 90 -> mirroring
- Spot evolution, but overall stucture is  more or less stable
- Not $\alpha^2$ but relatively close (dwarfs turn fully convective around M3.5-M4)



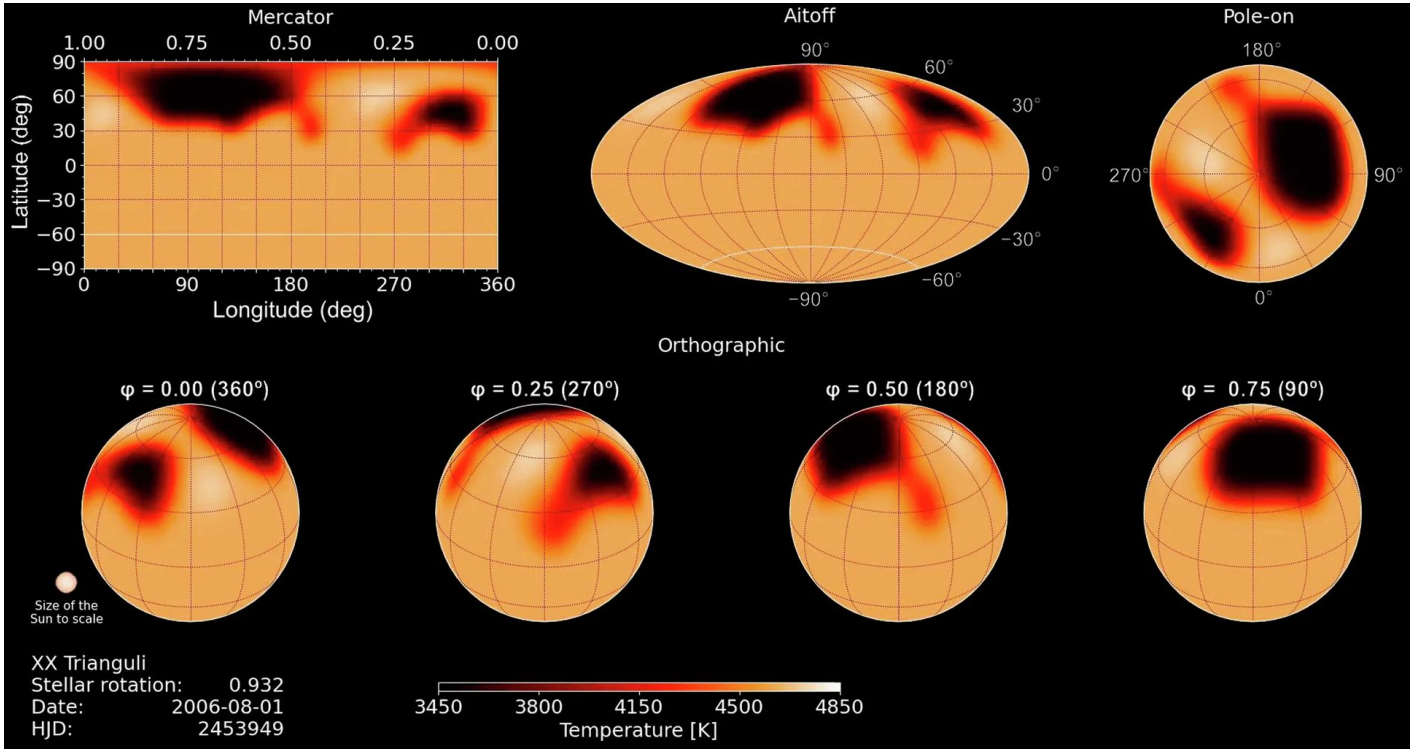
# Doppler imaging – rapid spot evolution

- EI Eri (*Kriskovics+2023*)
- G4IV rapid rotator, SB1
- Spot evolution on a very short scale (Days)
- Strong polar cap



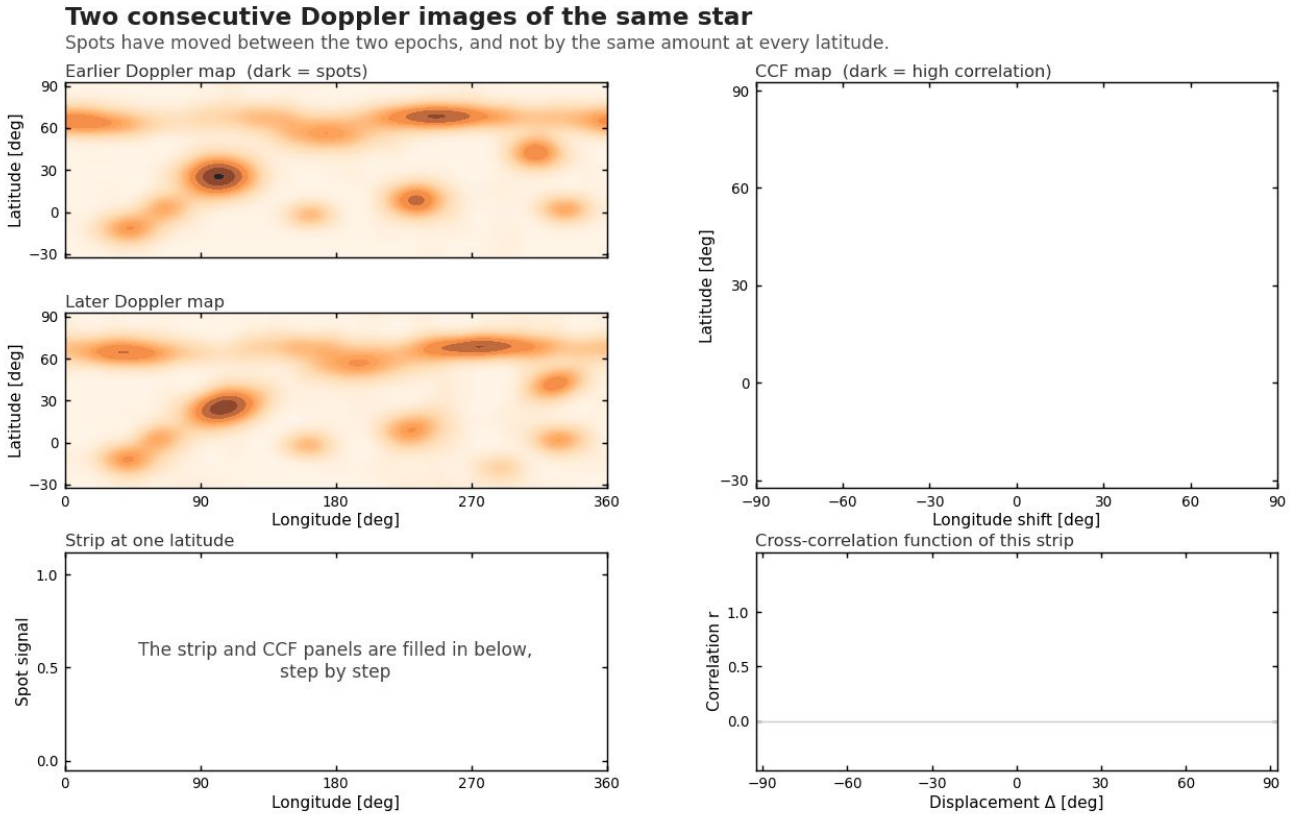
# Doppler imaging – heavy spottedness

- XX Tri (*Strassmeier+2025*)
- K1III rapid rotator, SB1
- Very heavy spottedness



# Doppler imaging – surface differential rotation

- Measuring differential rotation using cross-correlation: cross-correlating consecutive Doppler-maps



# Measuring surface differential rotation

**In case of stars**, surface differential rotation is generally expressed in a quadratic form:

$$\Omega(\beta) = \Omega_{eq}(1 - \alpha \sin^2 \beta)$$

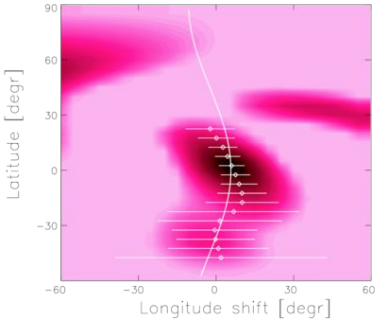
$\Omega(\beta)$: angular velocity at a given latitude $\beta$
$\Omega_{eq}$: equatorial angular velocity
**$\alpha = \Delta\Omega/\Omega = (\Omega_{eq} - \Omega_{pol})/\Omega_{eq}$**: dimensionless surface shear parameter

If $\alpha > 0$: solar type differential rotation – the angular velocity is maximal at the equator
If $\alpha < 0$: anti-solar type differential rotation – the angular velocity is minimal at the equator

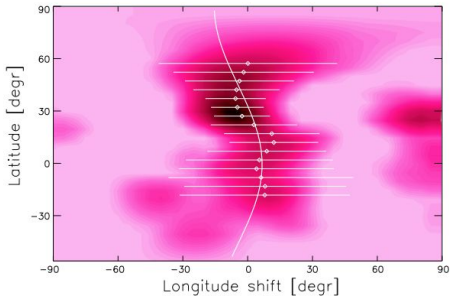
# Doppler imaging — surface differential rotation

- CCF (cross correlation function)-method:

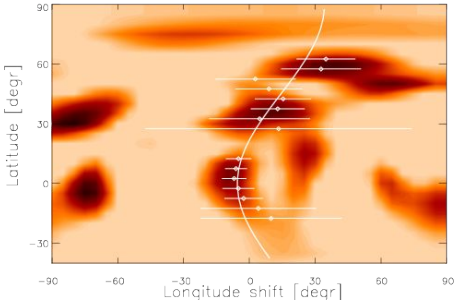
Cross-correlation of latitude strips on consecutive Doppler-maps



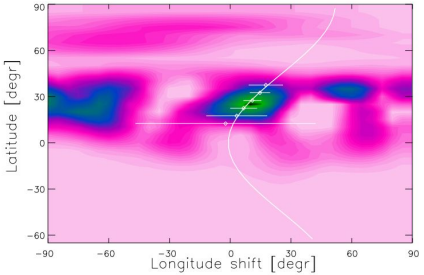

*V1358 Ori, Kriskovics+2019*




*EI Eri, Kriskovics+2023*




*DI Psc, Kriskovics+2014*




*V1192 Ori, Kővári+2017*

# Doppler imaging – surface differential rotation

## CCF

**Single Dwarfs**
AB Dor
LQ Hya
V1358 Ori
EK Dra

**Single Giants**
FK Com
DP CVn
DI Psc
KU Peg
V1192 Ori
IN Com

**Binary Subgiants**
EI Eri
UZ Lib
HU Vir
IL Hya

**Binary Dwarf**
V815 Her
V471 Tau

**Binary Giants**
ζ And
σ Gem
V2075 Cyg

## SIM

**Single Dwarfs**
BO Mic
LO Peg
HK Aqr
V557 Car
LQ Hya
61 Cyg A

**Single Giants**
V1794 Cyg

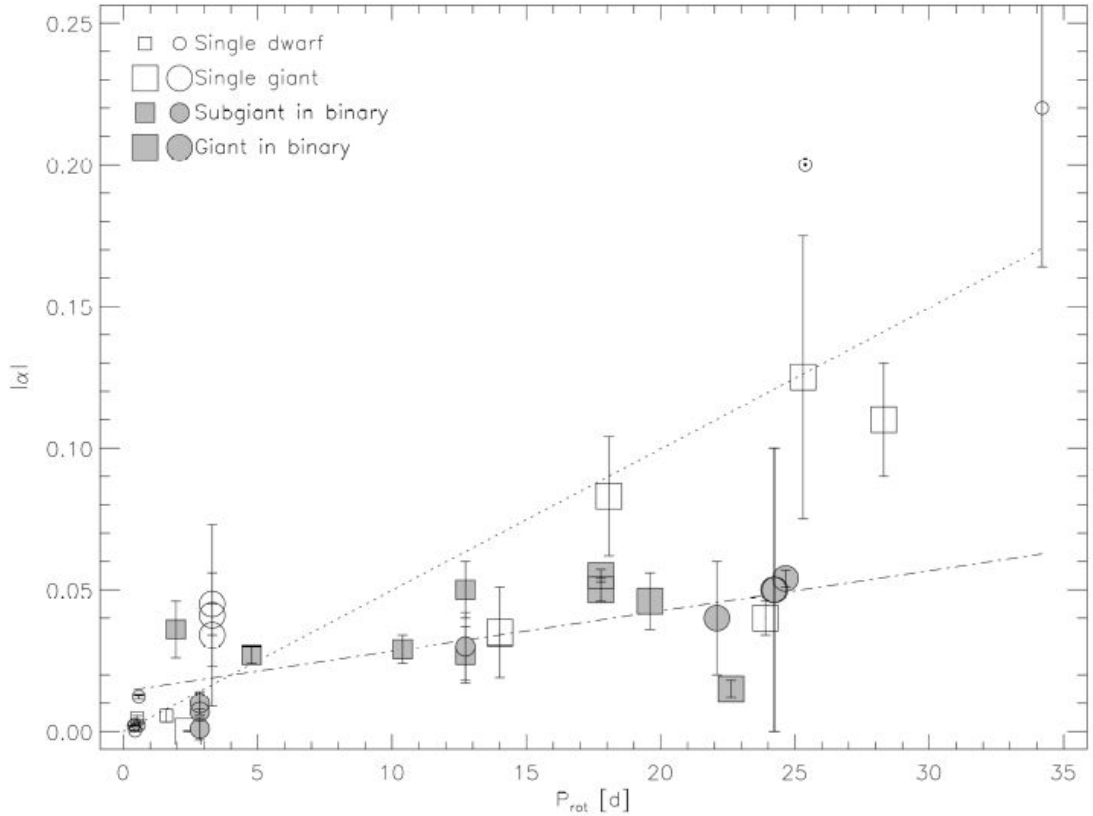
**Binary subgiants**
V711 Tau

**Binary Giants**
V2075 Cyg
HK Lac
IM Peg

Barnes+2005, Barnes+2005b, Barnes+2004, Donati+1997, Marsden+2005, Donati+2003, Petit+2004a, Kővári+2004, Kővári+2009, Korhonen+2000, Petit+2004b, Vida+2007b, Harutyunyan+2016, Kővári+2004b, Kővári+2014, Kővári+2013, Kővári+2007, Kővári et al+2012, Kriskovics+2013, Kriskovics+2014, Kővári+2015, Weber+2005, Özdarcan+2016, Kővári+2016, Marsden+2007, Strassmeier+2003, Kővári+2017, Balthasar+1986, Boro Saikia+2016,Kővári+2018, Kővári+2021, Kriskovics+2019, Kriskovics+2023, Kővári+2024, Görgei+2026

# Doppler imaging – surface differential rotation

- Differential rotation vs rotational period



# Doppler imaging – using lower spectral resolutions

*Kriskovics+2023,2024*
*Görgei+2026*
*Sági+in prep*

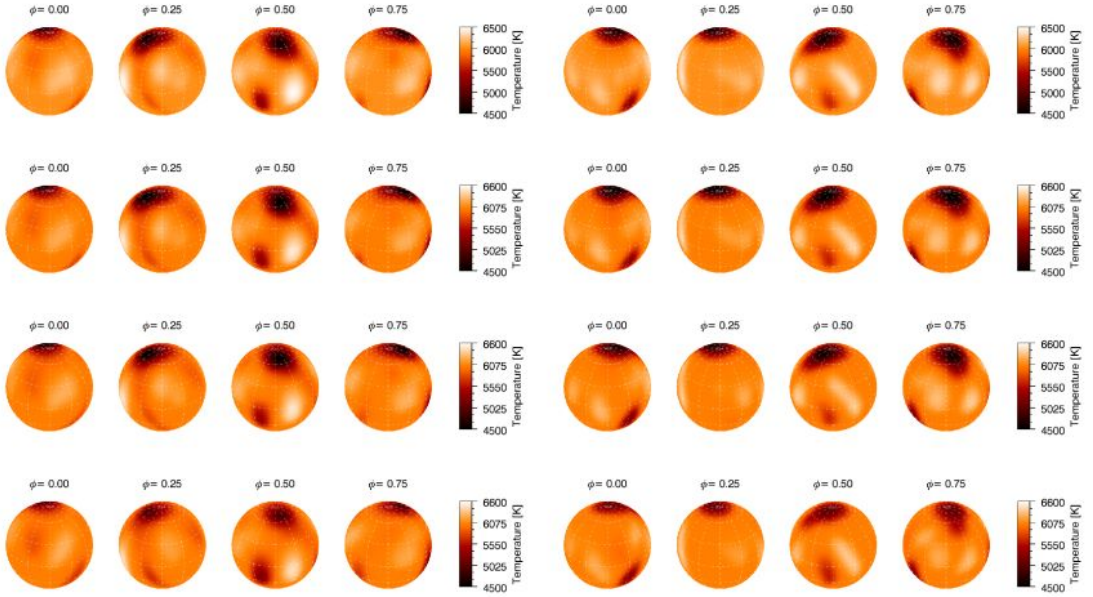



**Fig. A.1.** Doppler imaging test for two consecutive rotations of V1358 Ori. Images on the left correspond to the first rotation, while images on the right correspond to the second one. The four rows from top to bottom correspond to data of different spectral resolution: $R = 80\,000$ (original data taken from Kriskovics et al. 2019), and reduced levels of $R = 60\,000$, $R = 40\,000$, and $R = 20\,000$, respectively.

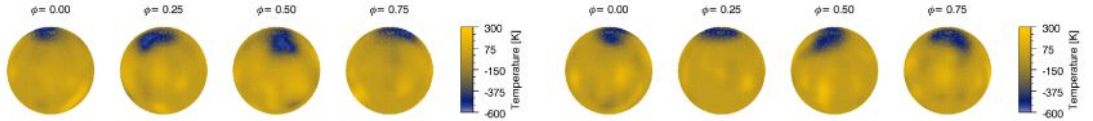
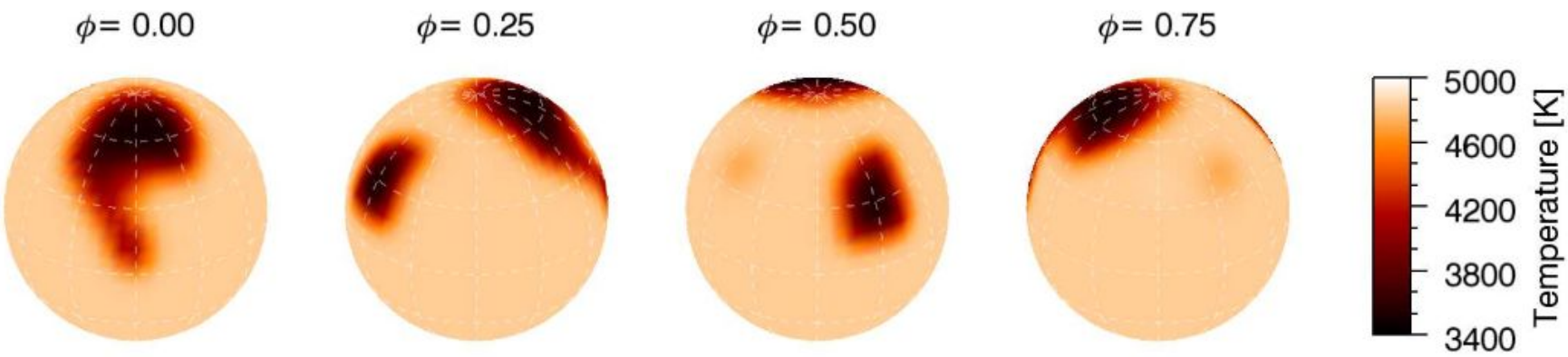
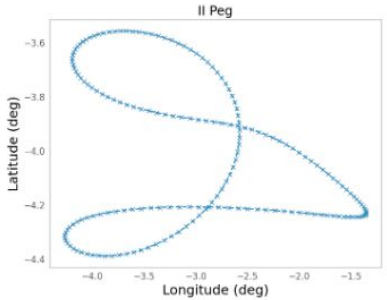



**Fig. A.2.** Difference images of the original V1358 Ori Doppler images (Kriskovics et al. 2019) and those that correspond to a spectral resolution reduced to $R$=20 000. The left panel corresponds to the first rotation and the right panel to the second; cf. Fig. A.1.

# Doppler imaging – photocentre

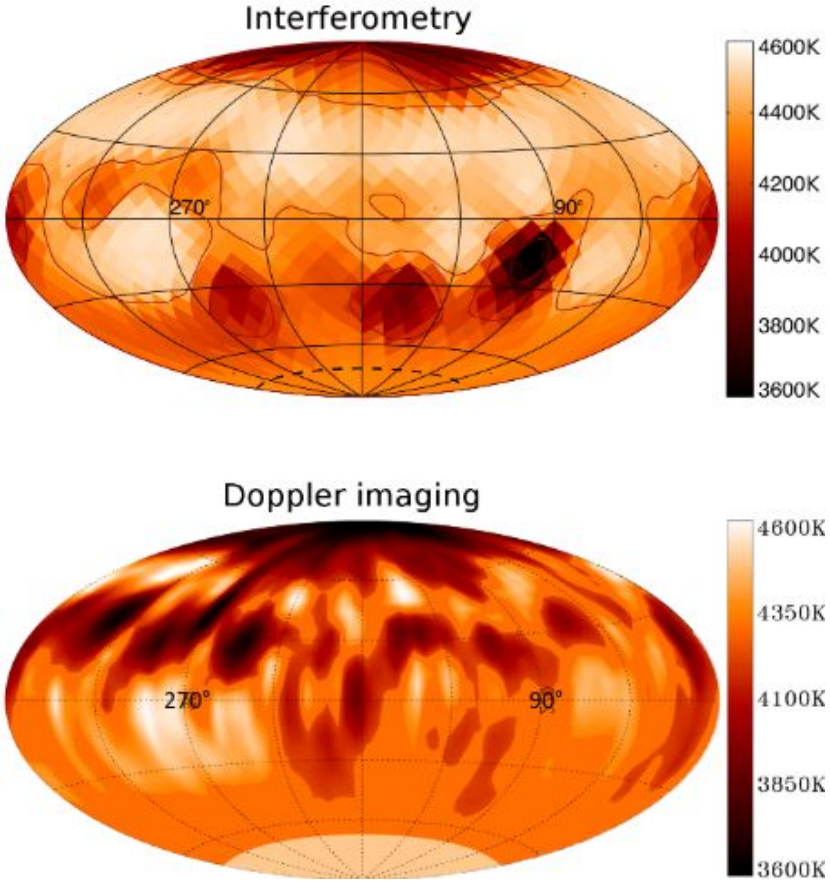



(d)

II Peg K1IV (and more)
*Ságí+in prep*

# Should we believe it? – comparison to interferometry




Thank you for your attention!

ζ And, K0III SB1
*(Roettenbacher+2018)*