Broadening-function technique

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CCF technique

CORAVEL and CCF

- Analog cross-correlation (Griffin, 1967), using mask of stellar spectrum, RV precision of about 0.5 km/s achieved (e.g., DAO digital speedometer)
- CCF extracts information from the whole spectrum
- Numerical cross-correlation

$$ccf(x) = \int_{-\infty}^{\infty} f(k)\, g(k-x)\, dk$$

- Best match of spectra produces maximum of ccf(x) [x always in RV units]
- CCF is typically computed using FFT

BF technique

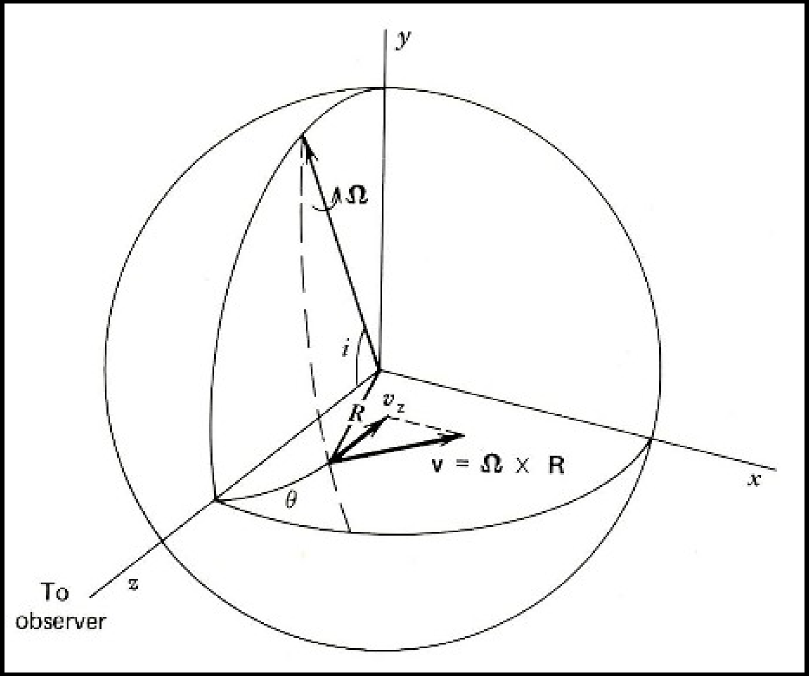
BF function basics

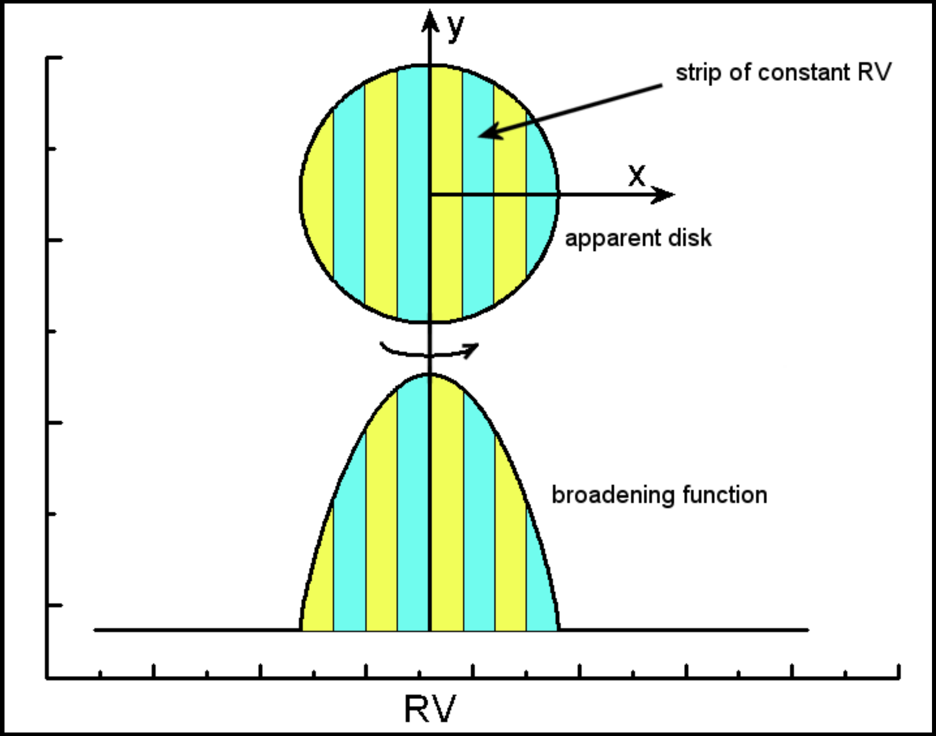
- BF originated & elaborated by Slavek M. Ruciński (DDO, UofT)
- BF is a function mapping sharp-line template spectrum to rotationally broadened spectrum
- Basic interpretation: BF is the Doppler image of star/stellar system: it gives dependence of flux on radial velocity
- In case of solid-body rotation (tidally-locked binaries also) BF is 1D image of star
- Similar to CCF, BF uses information from the whole spectrum

Solid-body rotation & BF

$$\vec{v} = \vec{\Omega} \times \vec{r}$$

$$\frac{\Delta\lambda c}{\lambda} = v_z = x \Omega \sin i$$



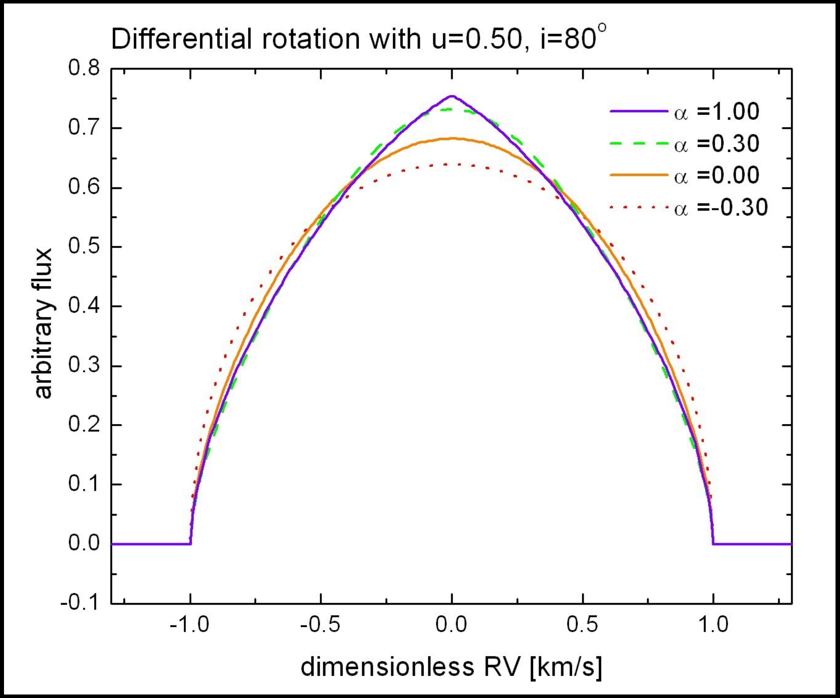


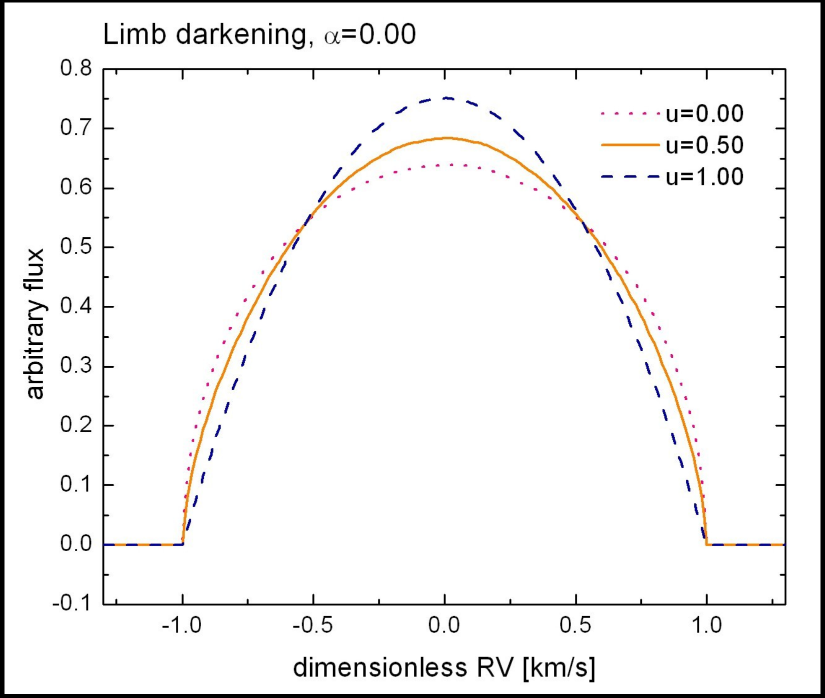
Concept of a rotational profile

$$I = I_0 + A\,\frac{(1-w)\sqrt{1-\frac{(x-x_0)^2}{R^2}} + \frac{1}{4}\pi w\left[1-\frac{(x-x_0)^2}{R^2}\right]}{(1-w)+\frac{1}{4}\pi w}$$

w – linear LD coefficient

R – projected rotational velocity



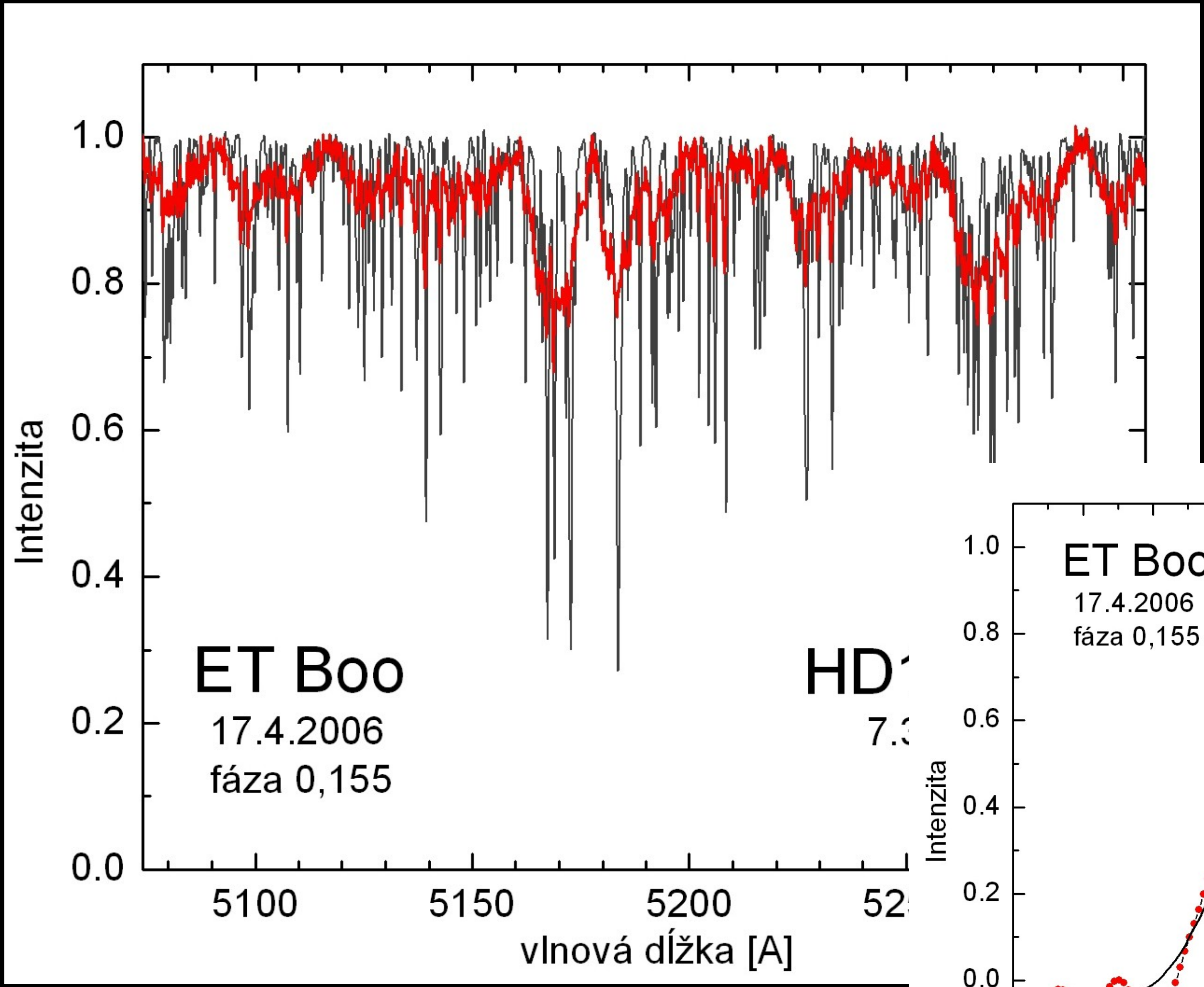


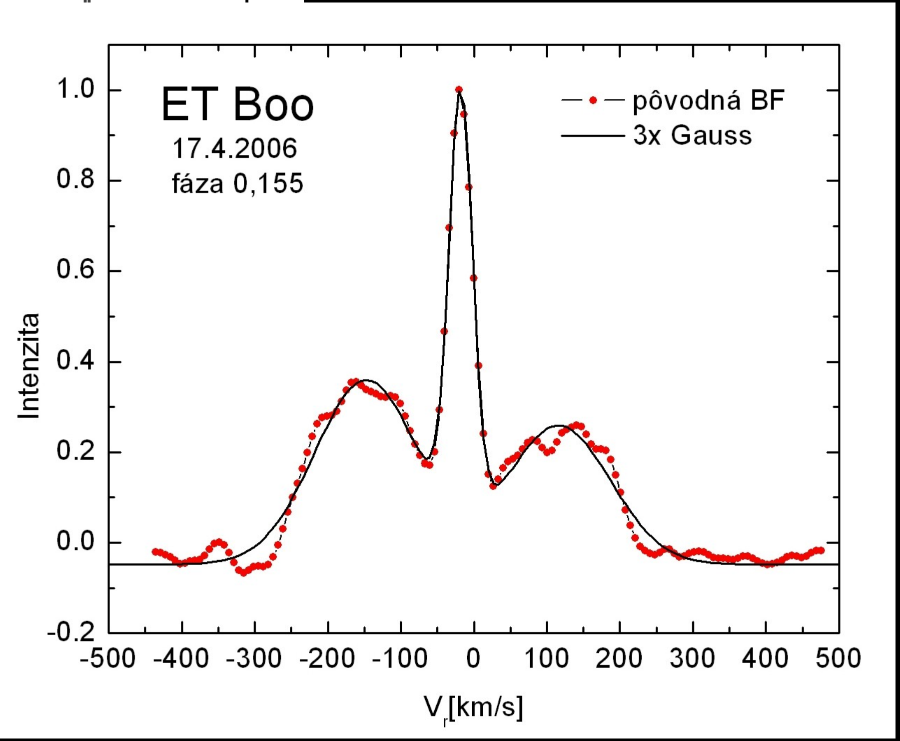
$$\Omega = \Omega_0\left(1-\alpha\sin^2\psi\right)$$

In case of differential rotation cannot be computed analytically, ψ - latitude

ET Boo

DDO, UofT





HD102870 template

Computing BF

- Having broadened spectrum and spectrum of slowly rotating template we look for the convolution kernel (bf) which maps the sharp-line spectrum (s) to the broadened spectrum (o)
- Both spectra must be expressed in constant step in radial velocity (the same requirement as in CCF)

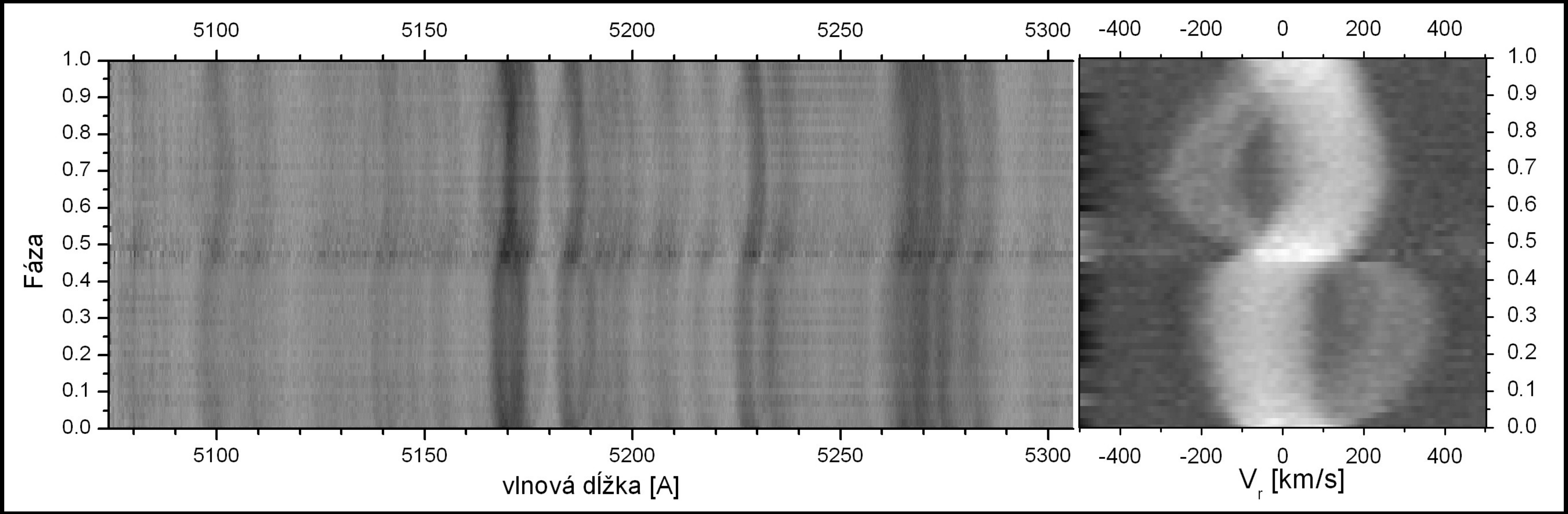
$$\lambda_i = \lambda_0 \left(1 + \Delta v / c \right)$$

$$o(x) = \int s(y)\, bf(y-x)\, dy$$

- In real and discrete data the last integral can be written as summation and results in MANY linear equations for BF
- (Only) theoretically deconvolution can be done in the Fourier space

Computing BF – II (SVD)

- Normally we have spectra >1000 elements long and want to extract BF with typically 100-200 elements
- For BF we have linear system of equations with each element as unknown !
- Can be solved conventionally but fails due to the normal equation being close to singular (numerically)
- The problem is elegantly solved by Singular Value Decomposition (SVD, chapter 2.6 in Numerical Recipes)



Comparison of CCF and BF

Cons and pros

CCF

-no easy interpretation

-indirect interpretation: bisector method

+no systematic errors if the average spectrum used as a template

-loses spectral resolution

BF

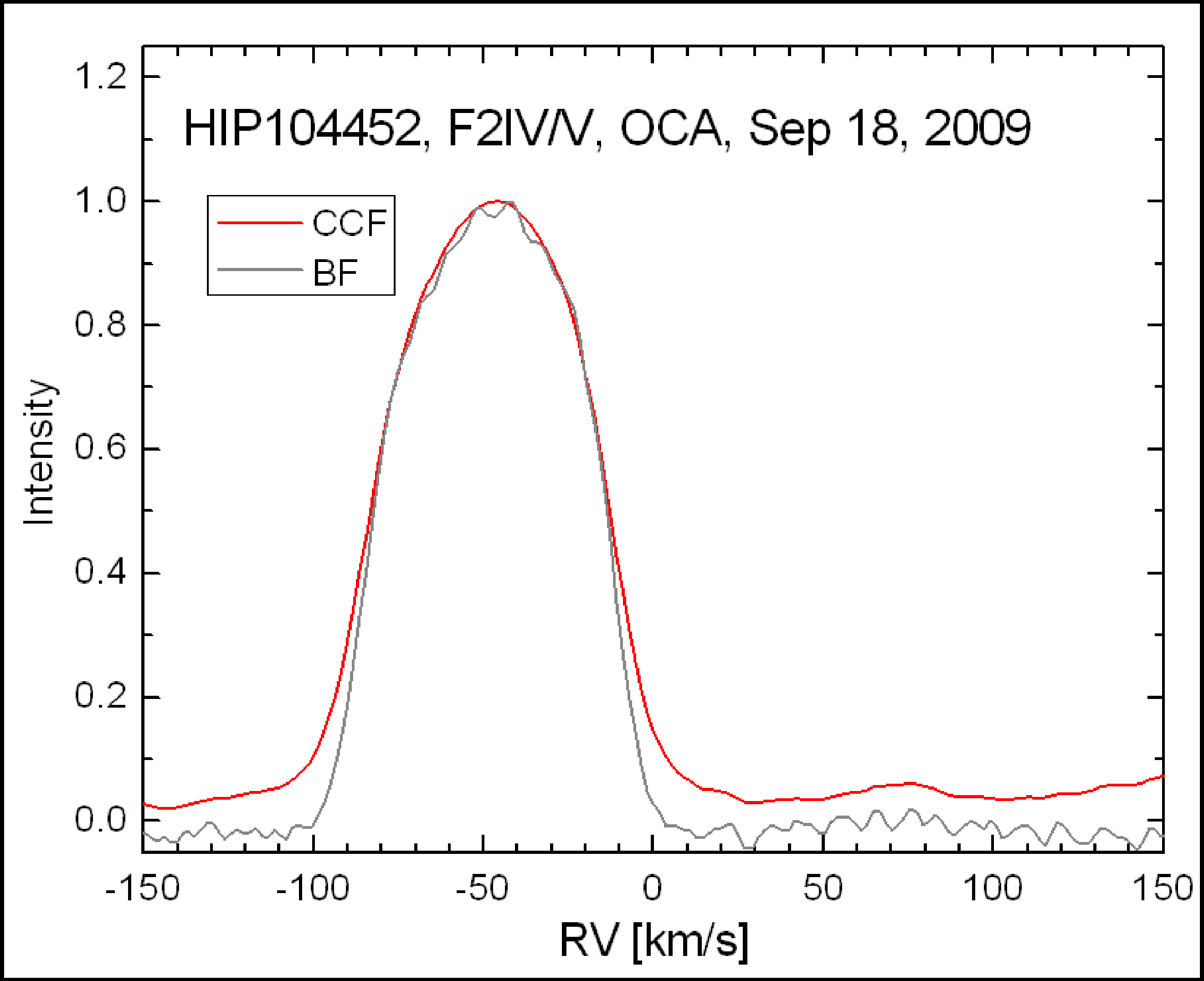
+straightforward interpretation and modeling

+ preserves spectral resolution ➔easy detection of spots, pulsations, asymmetries, multiplicity

-sensitive to proper rectification to continuum and reasonable selection of the template

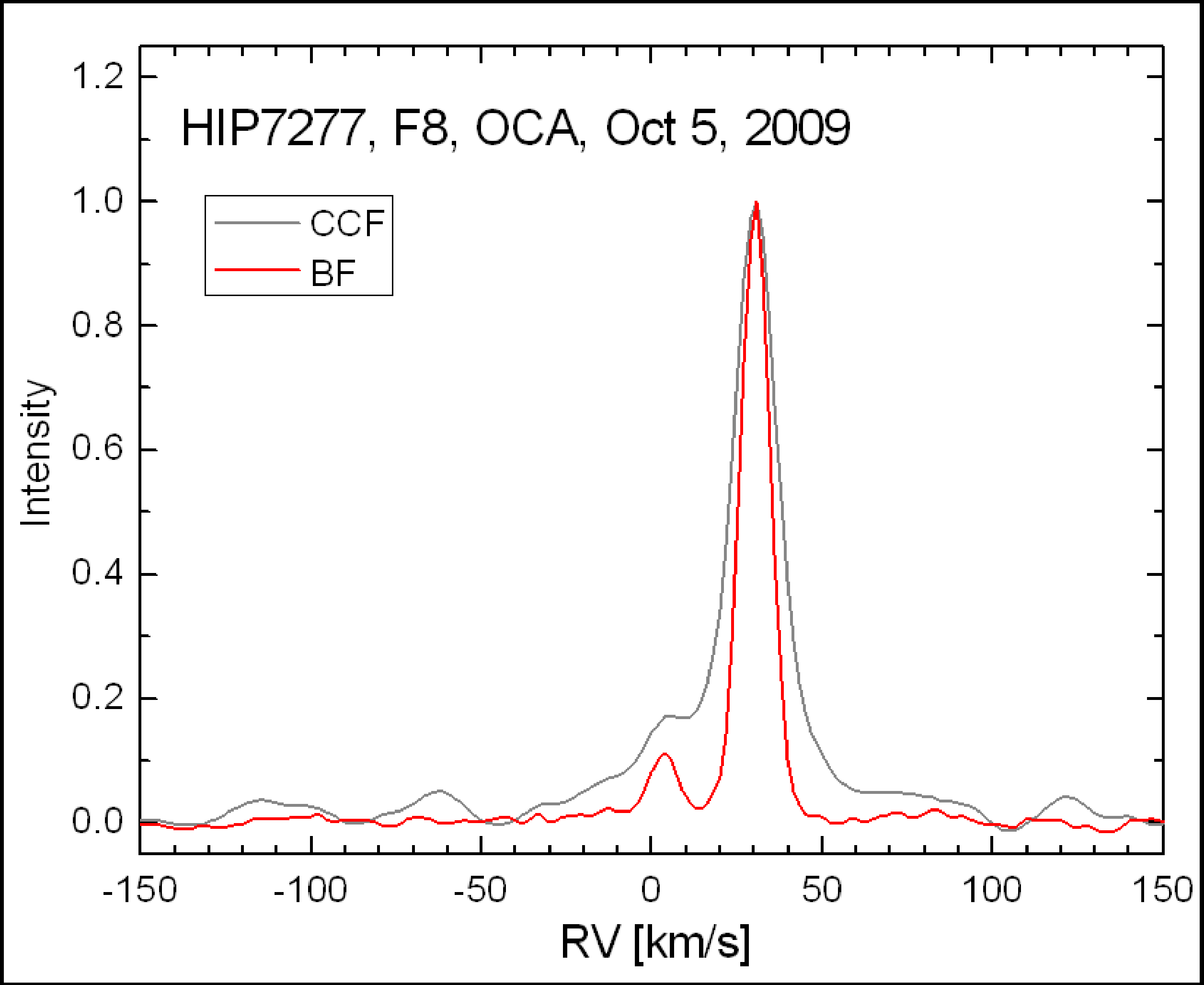
+enables simple spectral classification based on the BF integral

CCF and BF I



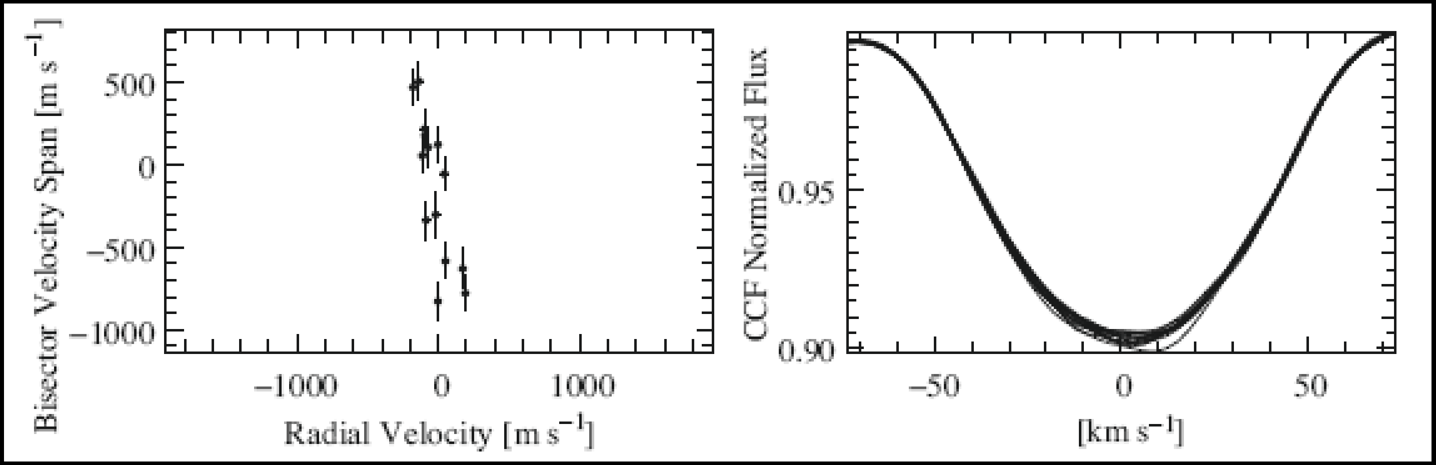
I. good case: rapidly rotating target: CCF is close to rotational profile

CCF and BF II



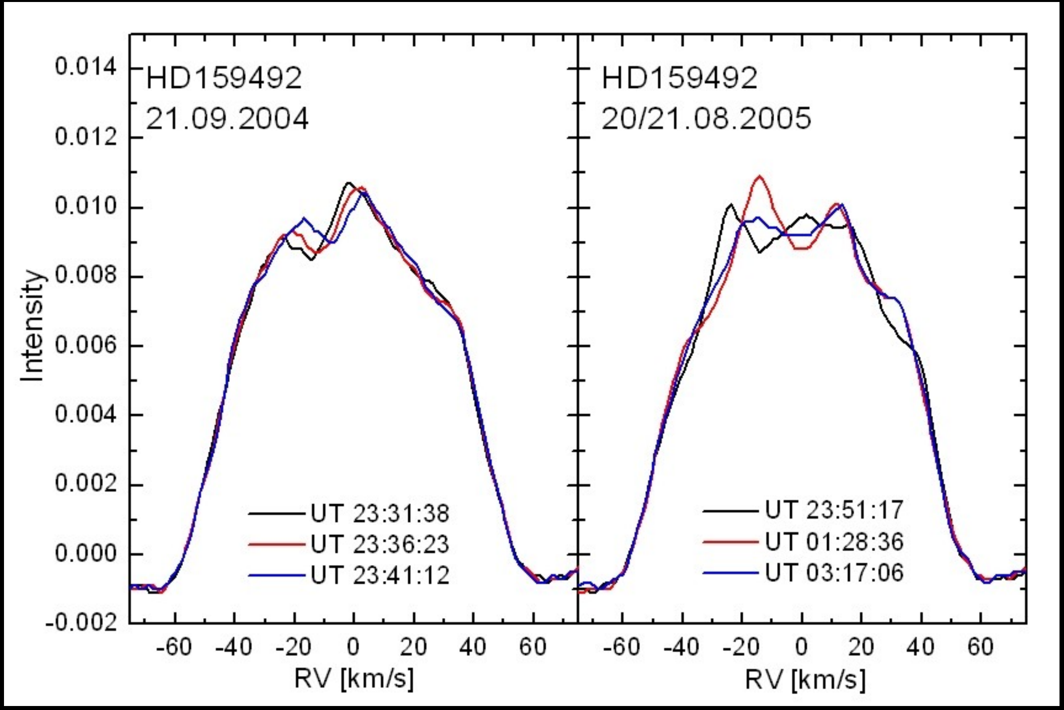
II. bad case: SB2 composed of two slowly rotating stars: CCF does not have sufficient resolution to analyze this SB2

Non-radial pulsations: CCF vs. BF (HARPS data)



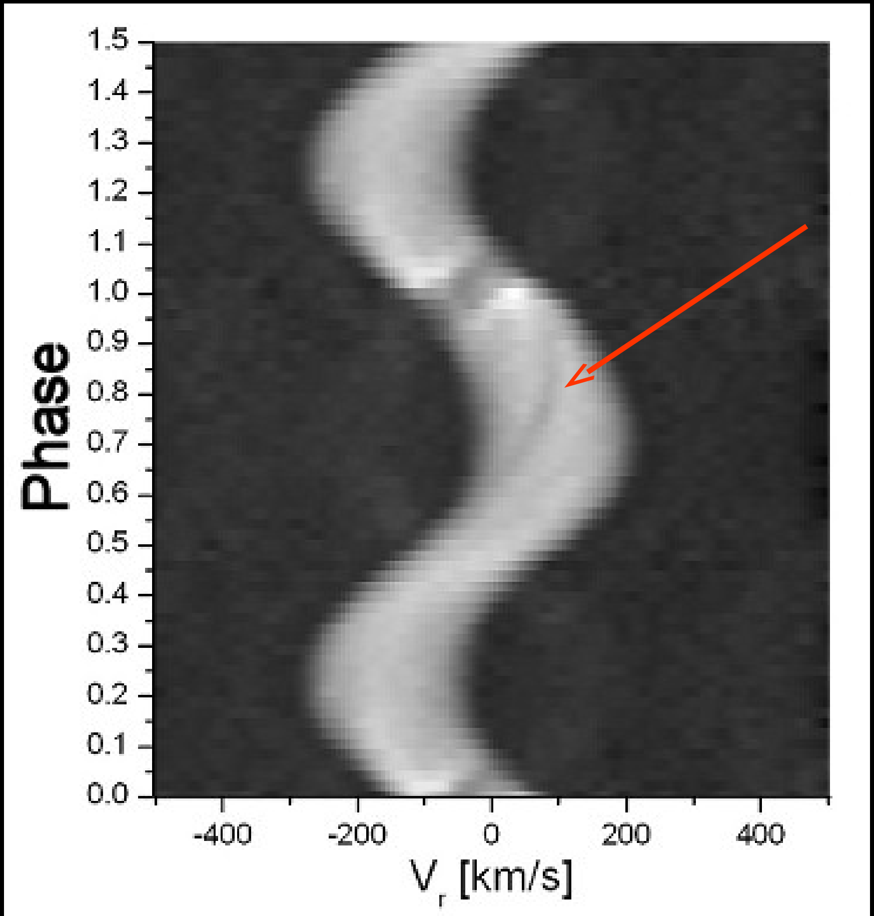
CCFs

BFs



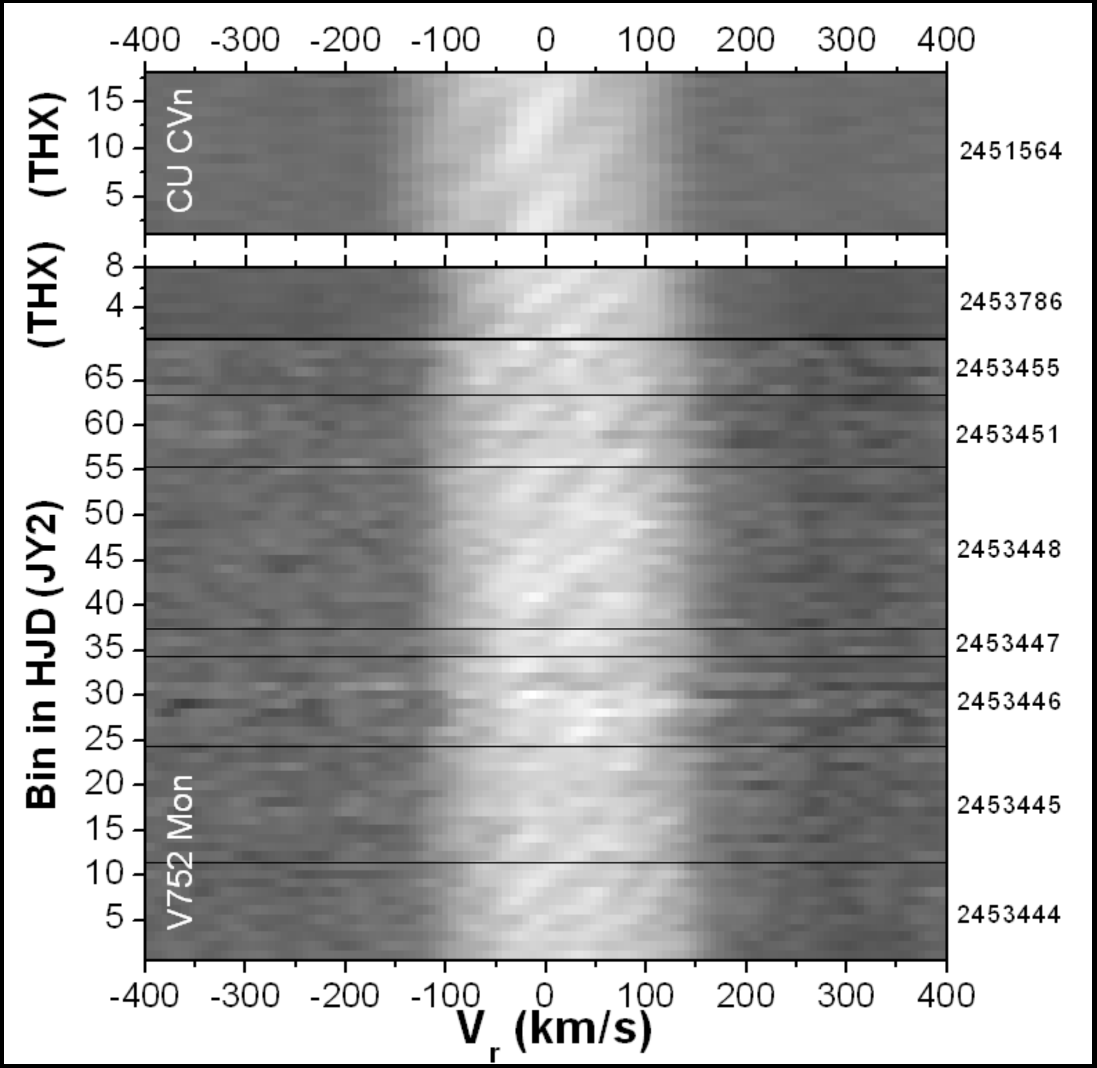
BF applications and capabilities

BF detection of spots



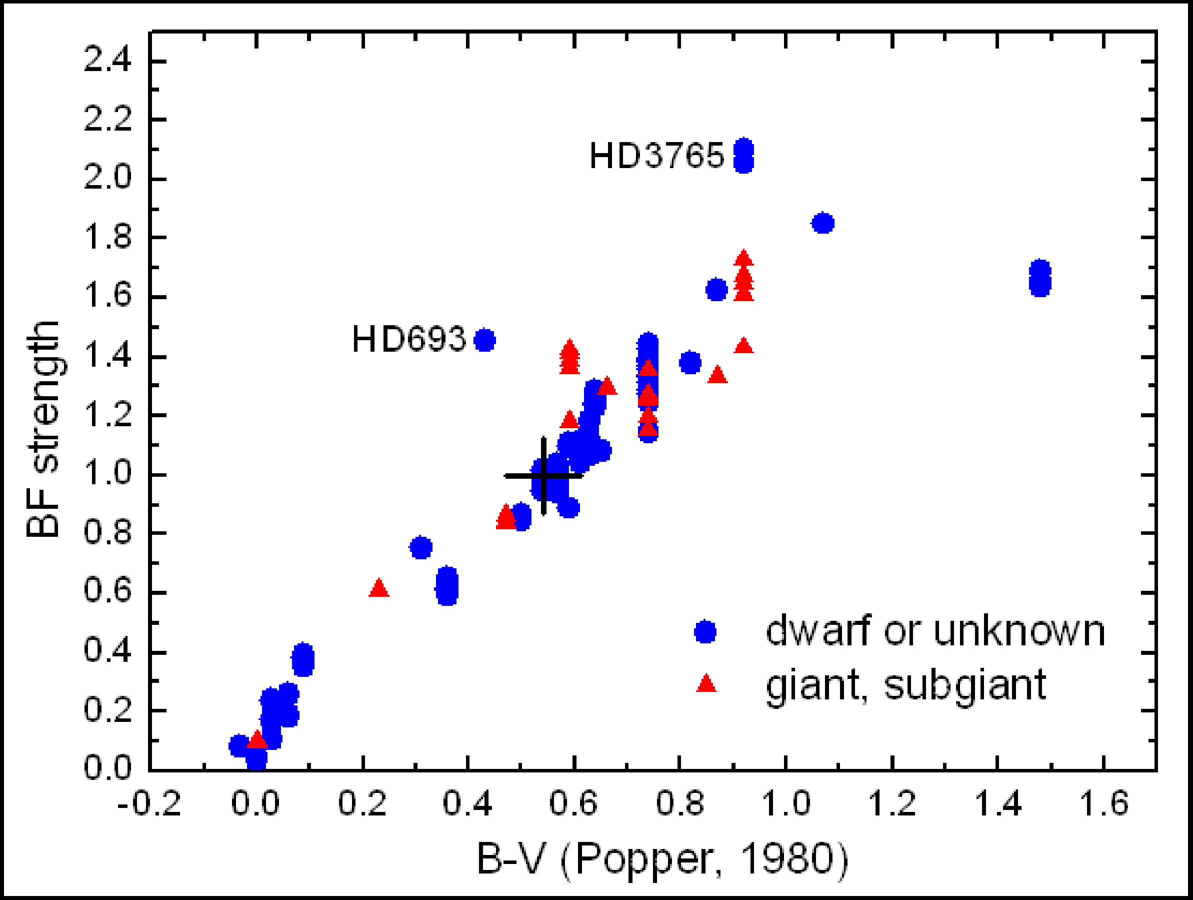
XY UMa, late-type spotted binary, DDO, UofT

BF detection of non-radial pulsations



Two late A-type non-radial pulsators detected at DDO

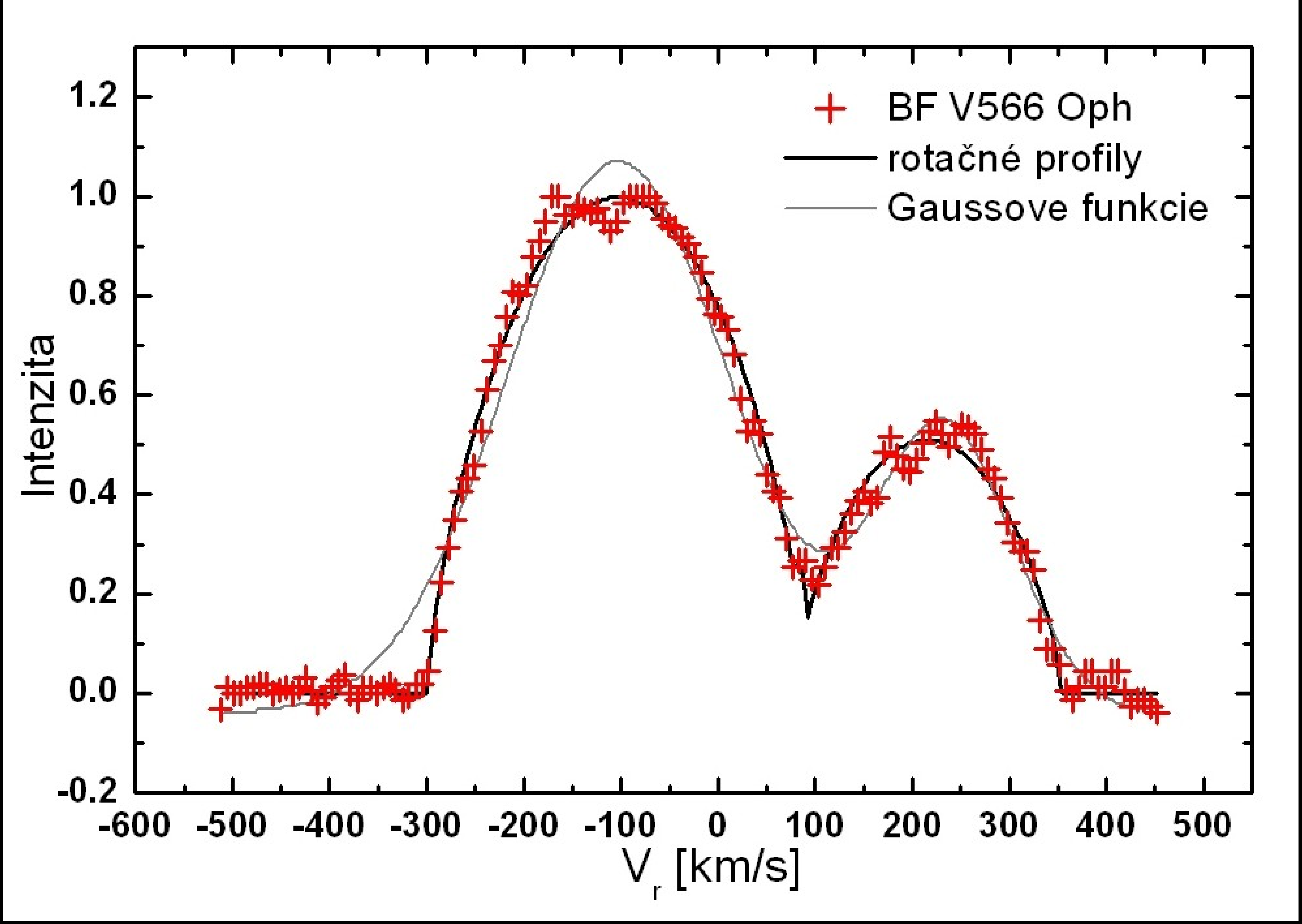
BF spectral type estimation



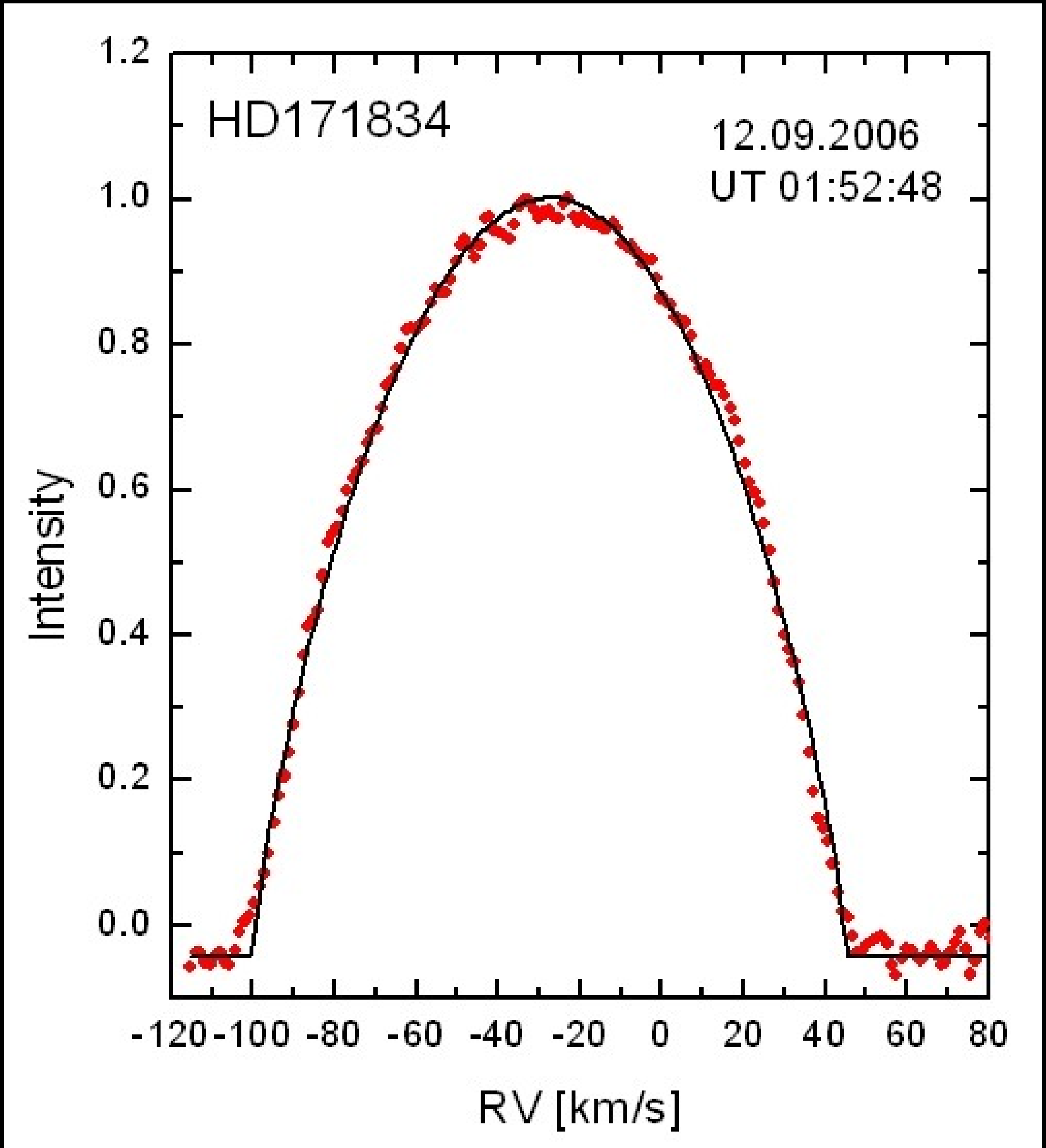
- Almost linear relation of the integral BF and *(B-V)* color index
- Good match of spectra results in BF integral = unity

Extracting Doppler information with BFs

Fitting rotational profiles to BF of a binary star



Fitting rotational profile to BF of a single star



BF extracted from an archive HARPS spectrum

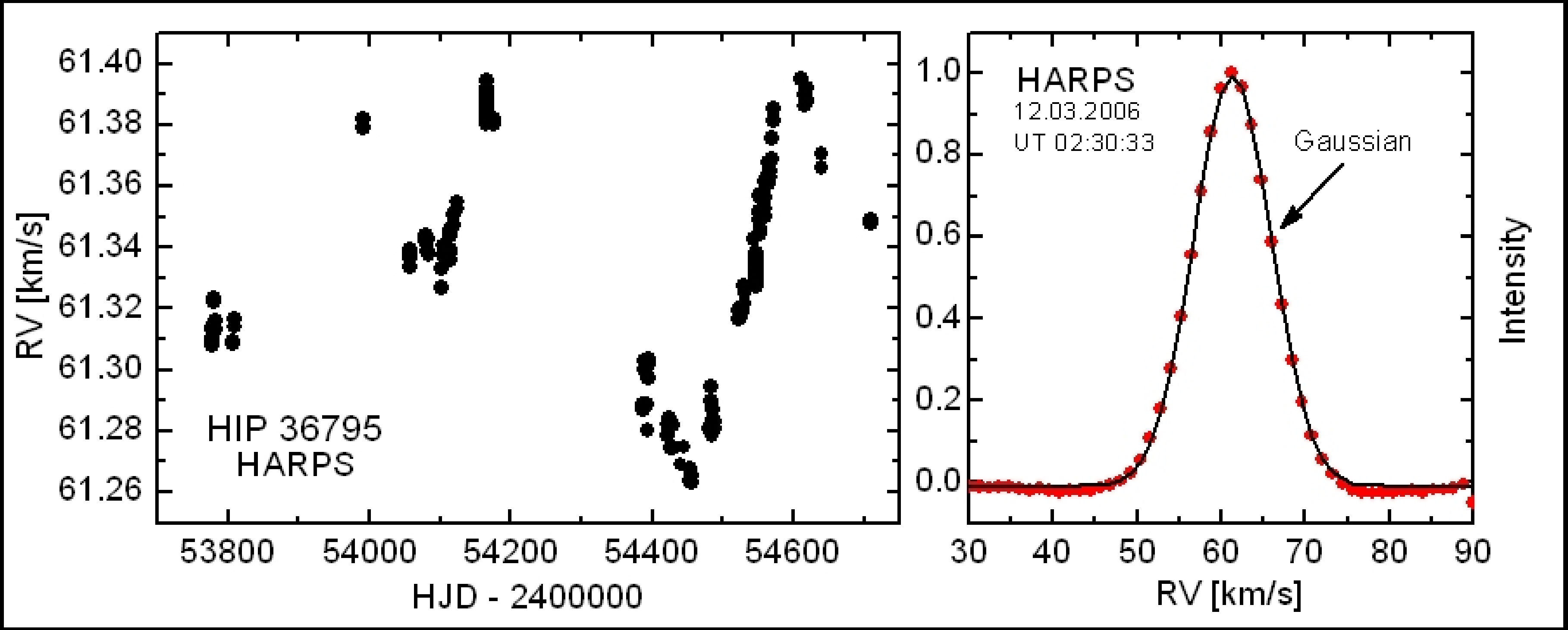
Limb-darkening coefficient u=0.75

Solid-body rotation

BF enables reliable determination of v sin i

precise RV for moderately to rapidly rotating stars

HIP 36795 (re-analysis with BFs)



HIP 36795 = slow rotator ➔ Gaussian fitting of BFs is appropriate, RV precision 2-3 m/s with BFs

Thank you !!!