Methods for ultra-precise radial-velocity computation

Xavier Dumusque - Spectral Fidelity, Florence, 7.9.23

The signal of a planet in radial-velocity

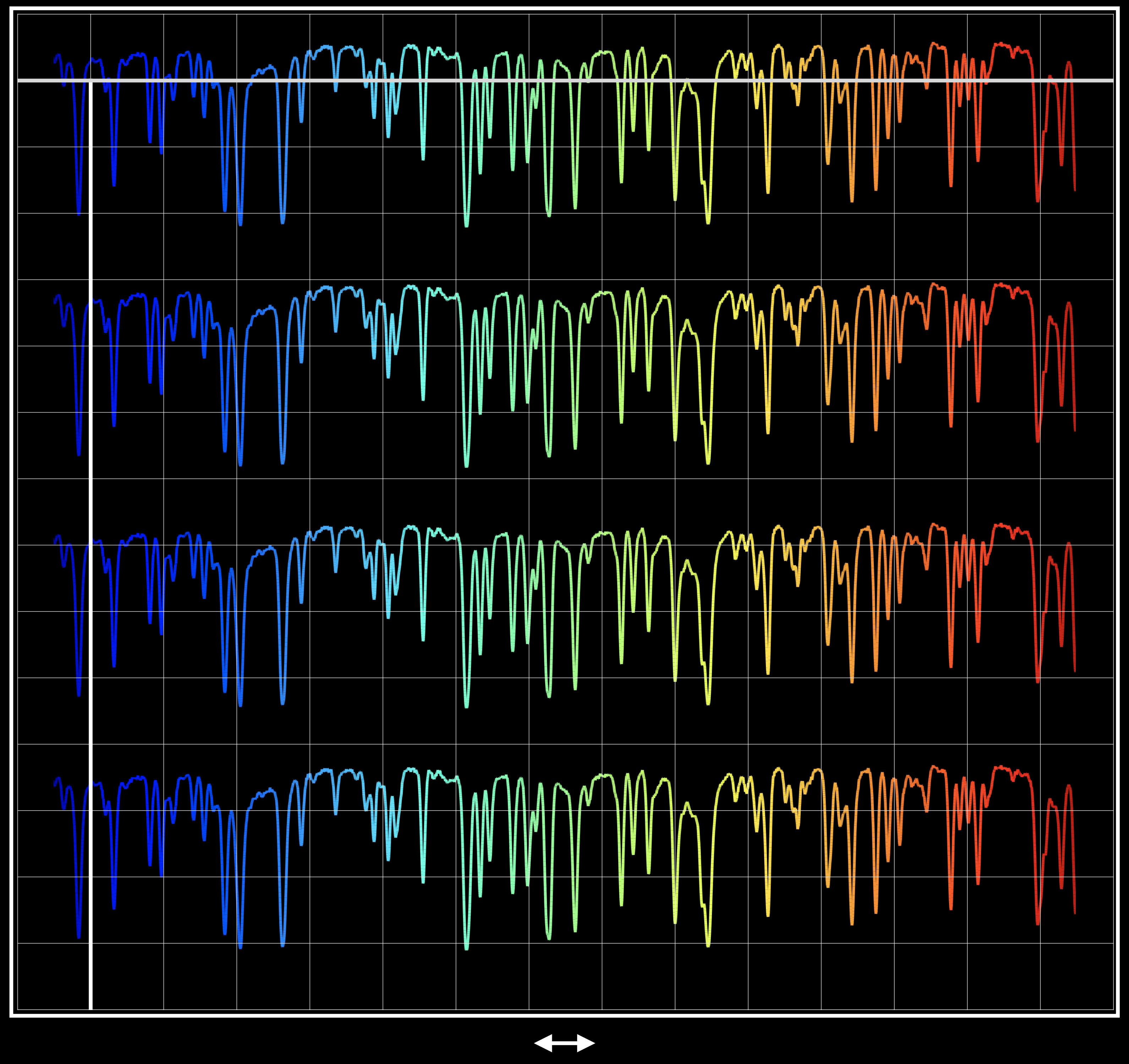
$$\text{Semi}-\text{amplitude} = K \propto \frac{m_{pl}\, sini}{P^{1/3}}$$

The RV method is sensitive to massive, close-in planets

	Semi major axis	Semi amplitude K
Jupiter	1 AU	28.4 m/s
Jupiter	5 AU	12.7 m/s
Super-Earth (5x Earth)	0.1 AU	1.4 m/s
Super-Earth (5x Earth)	1 AU	0.45 m/s
Earth	1 AU	0.09 m/s

The Challenge: measuring precise radial velocities

CCD Detector



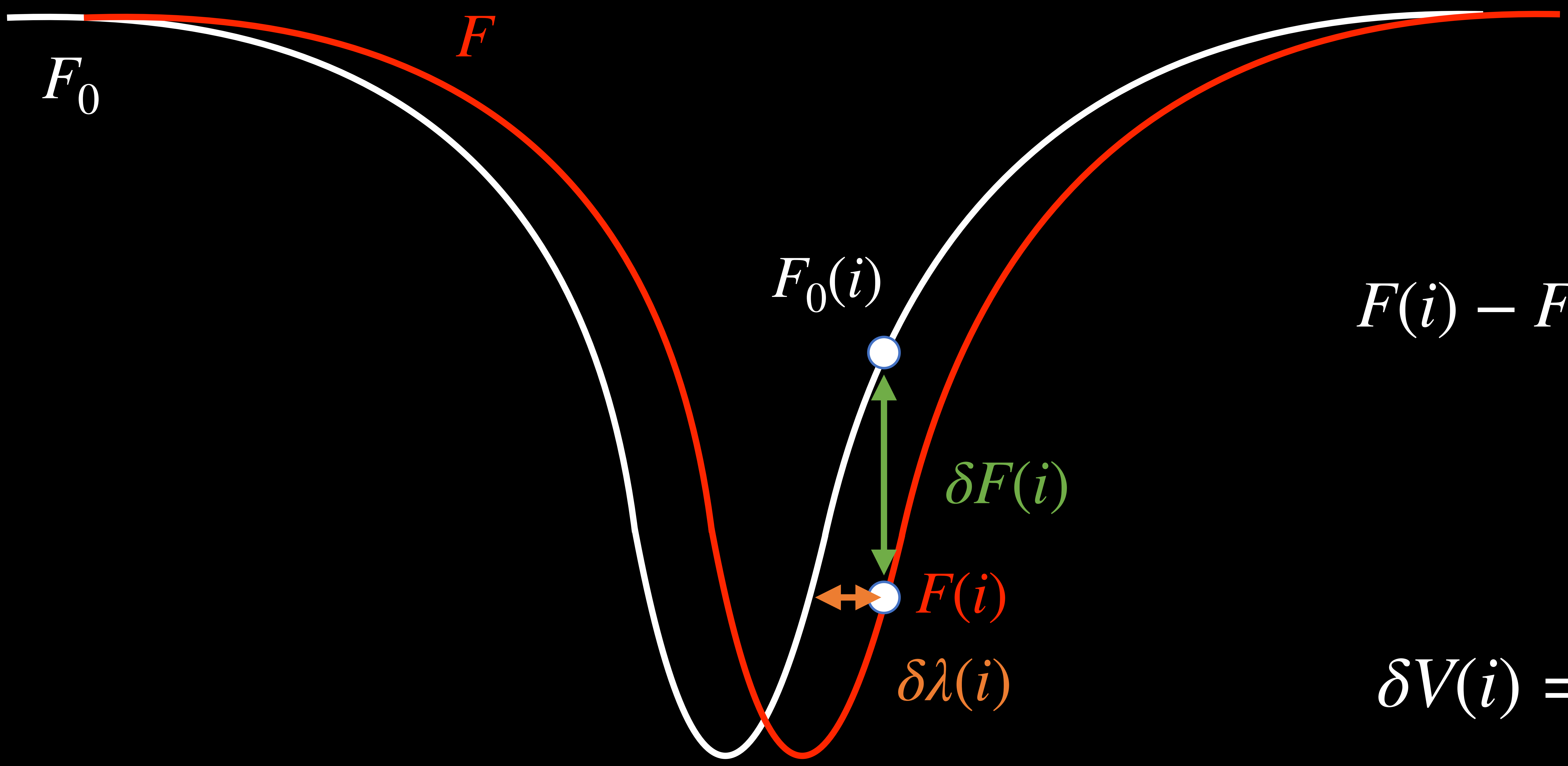
1 pixel ~ 500-800 m/s

Jupiter ~ 12 m/s - The Earth ~ 0.1 m/s

10^{-2} pixel 10^{-4} pixel

RV precision

For a small Doppler shift compared to the line width



For pixel i

$$F(i) - F_0(i) = \delta F(i) = \frac{\partial F_0(i)}{\partial \lambda(i)} \delta\lambda(i)$$

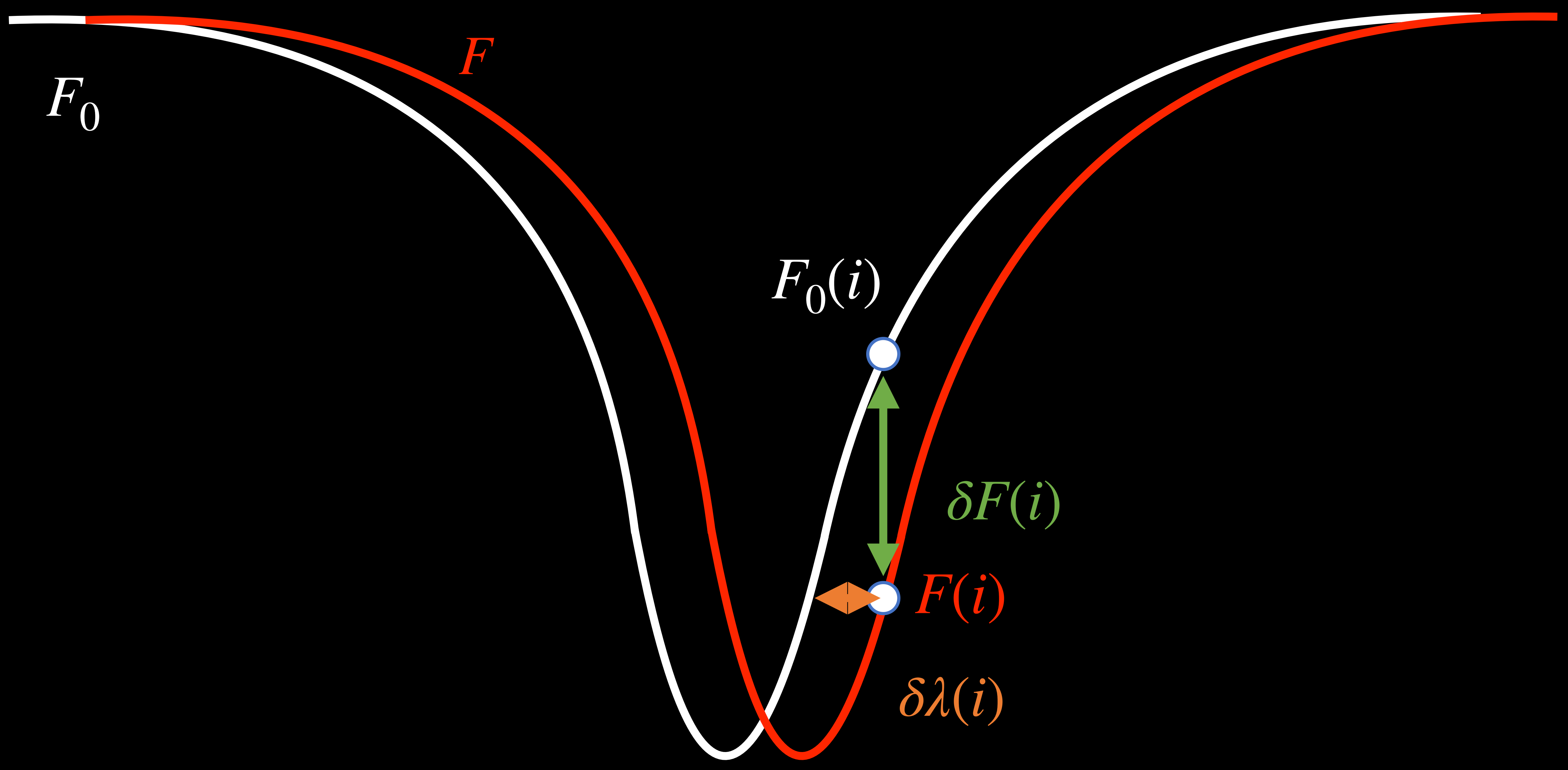
$$\frac{\delta\lambda}{\lambda} = \frac{\delta V}{c}$$

$$\delta V(i) = \frac{\delta F(i)}{\lambda(i)(\partial F_0(i)/\partial\lambda(i))} . c$$

Bouchy+ 01, Butler+ 96, Connes+ 96

RV precision

For a small Doppler shift compared to the line width



$$RV(i) \propto \frac{\text{Flux difference}(i)}{\text{Wavelength}(i)\,.\,\text{Slope}(i)}$$

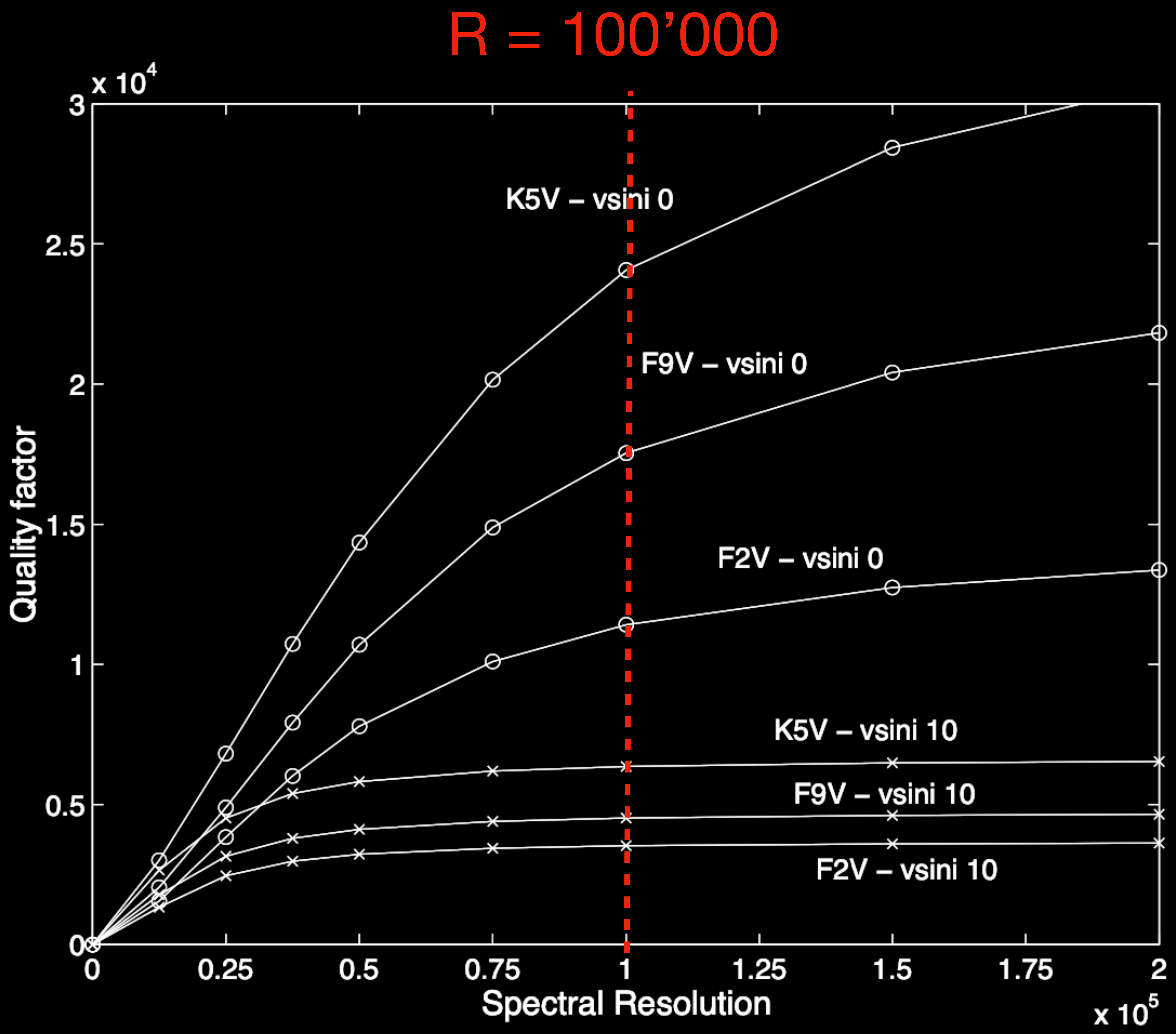
$$\sigma_{RV}(i) \propto \frac{S/N(i)}{\text{Wavelength}(i)\,.\,\text{Slope}(i)}$$

RV content

$$Q \propto \sum_i \frac{1}{\text{Wavelength}(i)\,.\,\text{Slope}(i)}$$

Bouchy+ 01, Connes+ 96

RV precision as a function of resolution

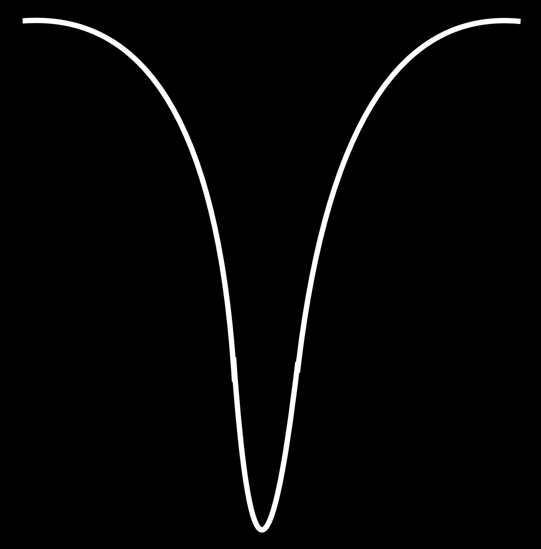


$$Q \propto \sum_i \frac{1}{\text{Wavelength}(i)\,.\,\text{Slope}(i)}$$

Bouchy+ 2001

RV precision by averaging over all the lines

$\sigma_{RV}(\text{line})$

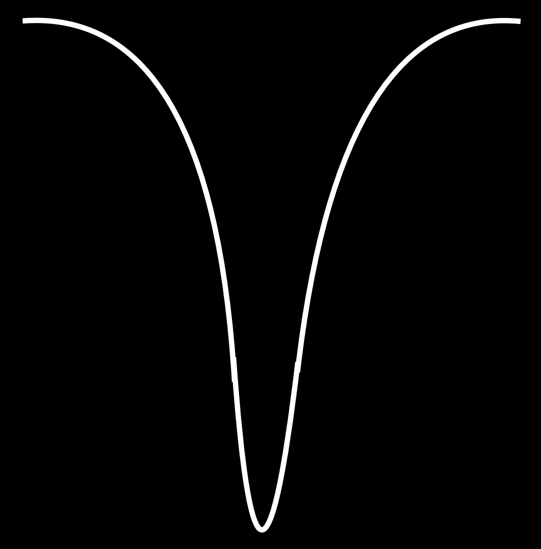


$S/N \sim 300$

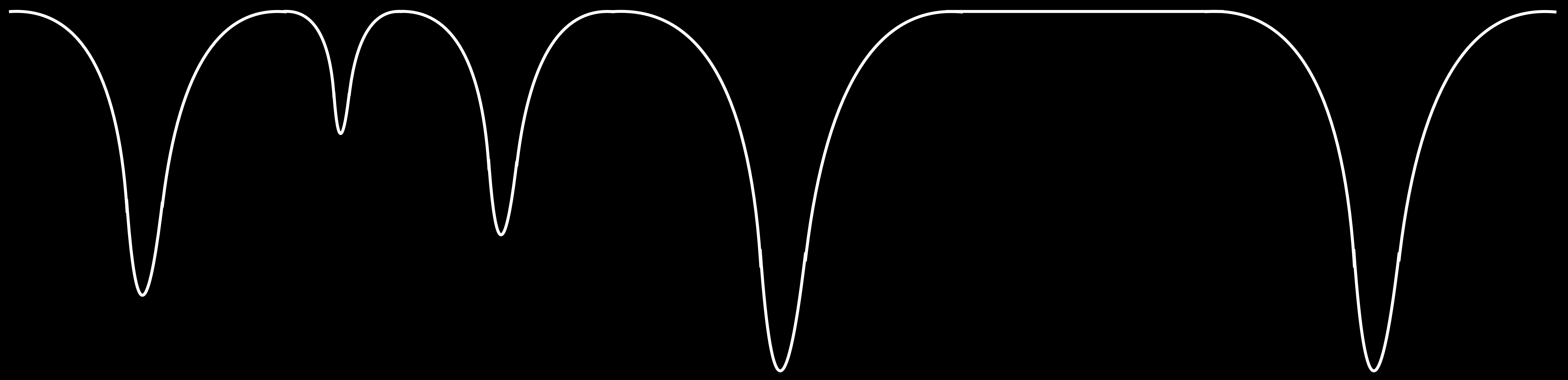
$\sim 20\, m/s$

RV precision by averaging over all the lines

$\sigma_{RV}(\text{line})$



$\sigma_{RV}(\text{spectrum})$



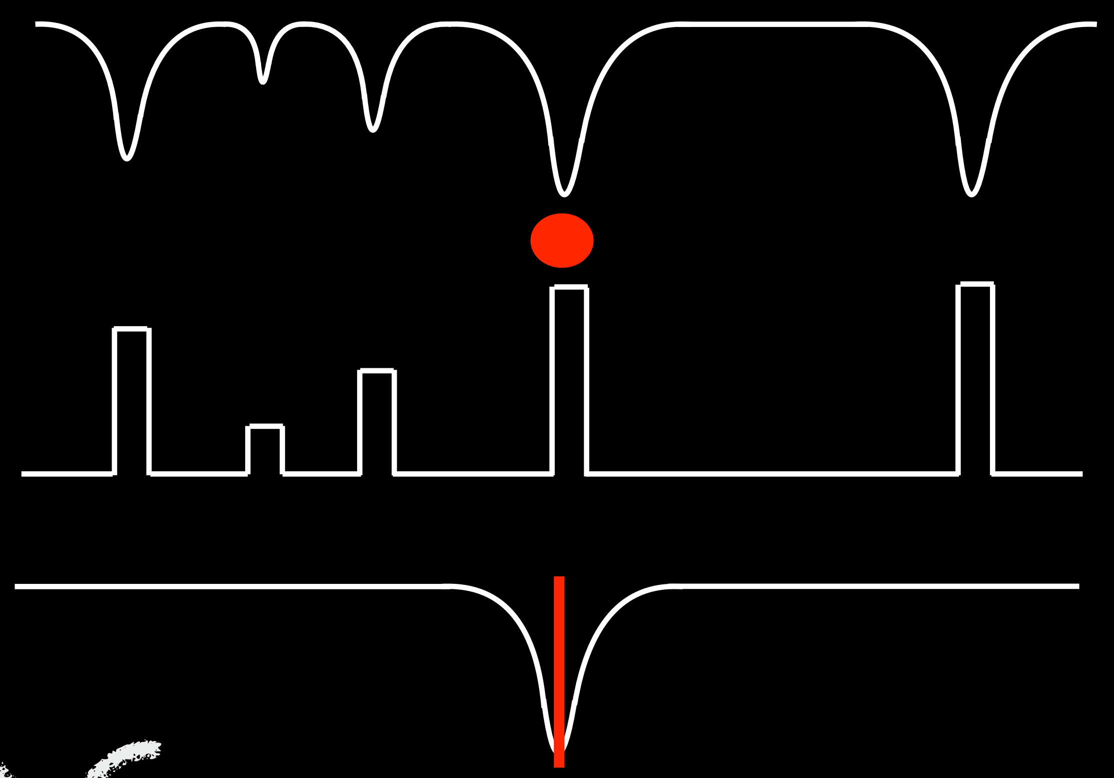
$S/N \sim 300$

$\sim 20\, m/s$

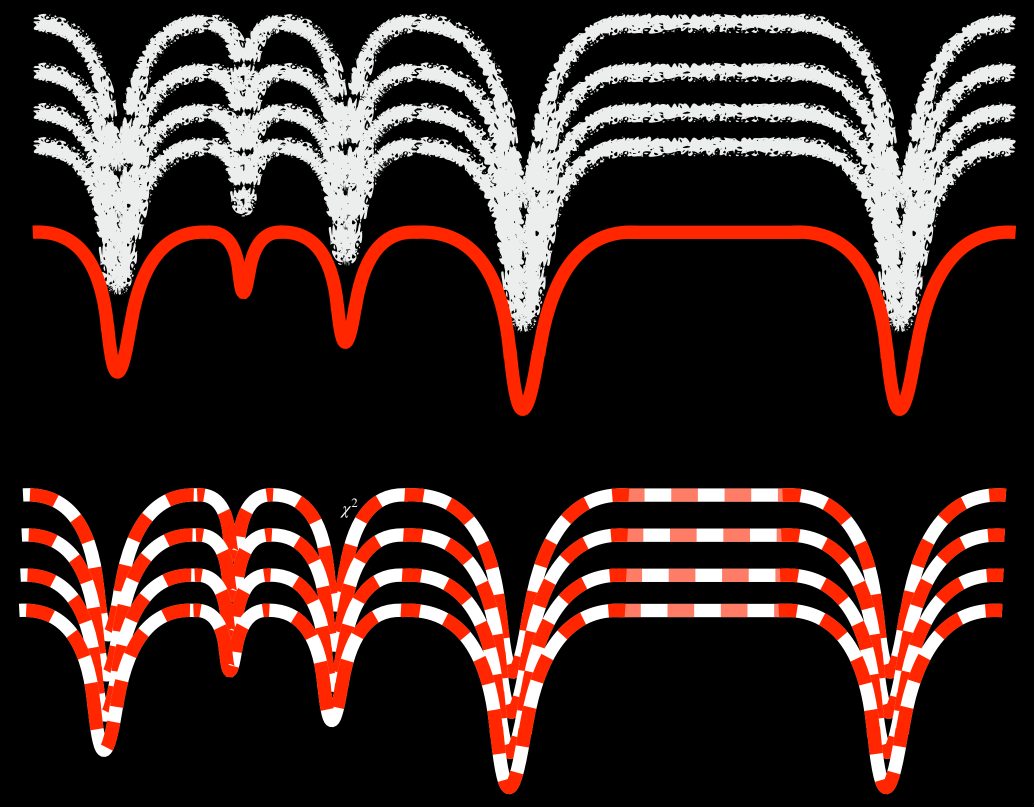
$\sim \sigma_{RV}(\text{line})/\sqrt{\#\,\text{line}} \sim \sigma_{RV}/\sqrt{4000} \sim 0.3\, m/s$

Different techniques to extract the RV

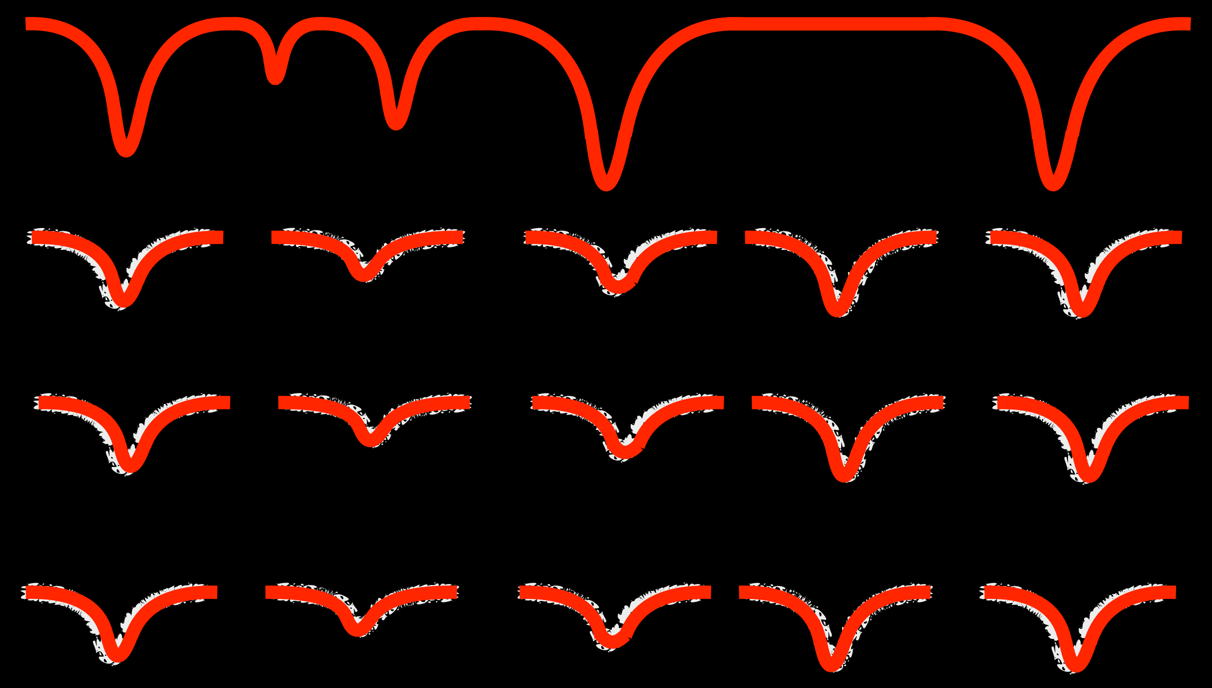
- Cross-correlation function (CCF)



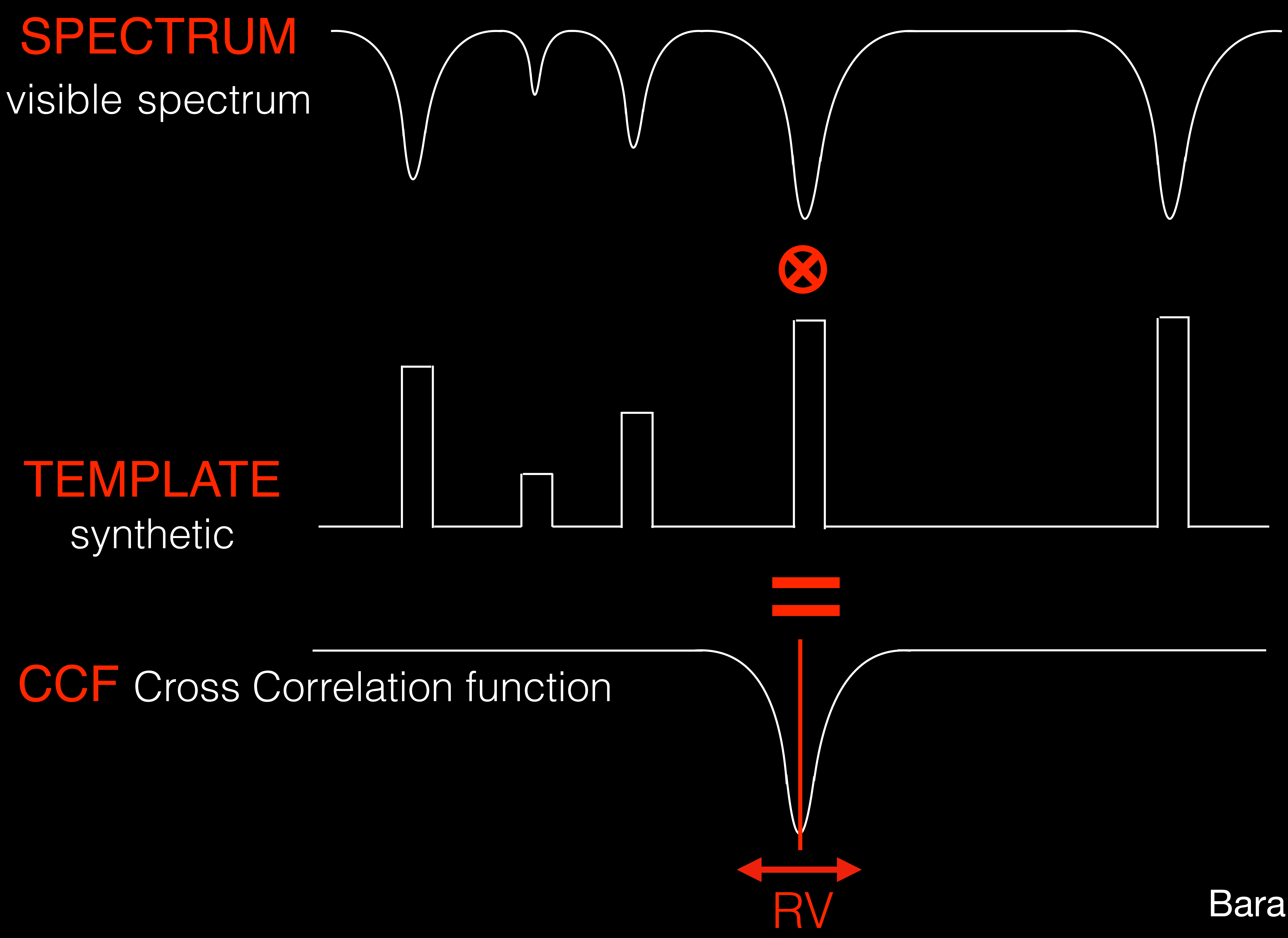
- Template matching



- Line-by-line (LBL) or chunk-by-chunk



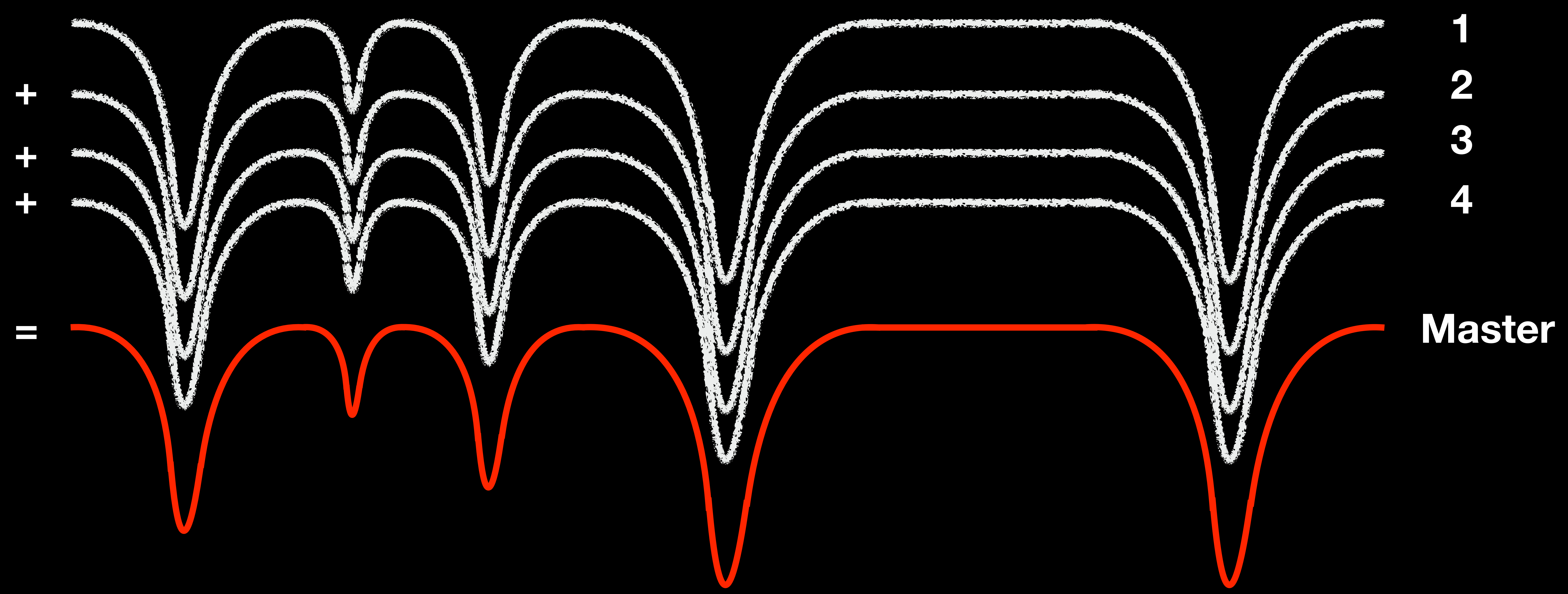
The cross-correlation technique



Baranne+ 96, Pepe+ 02

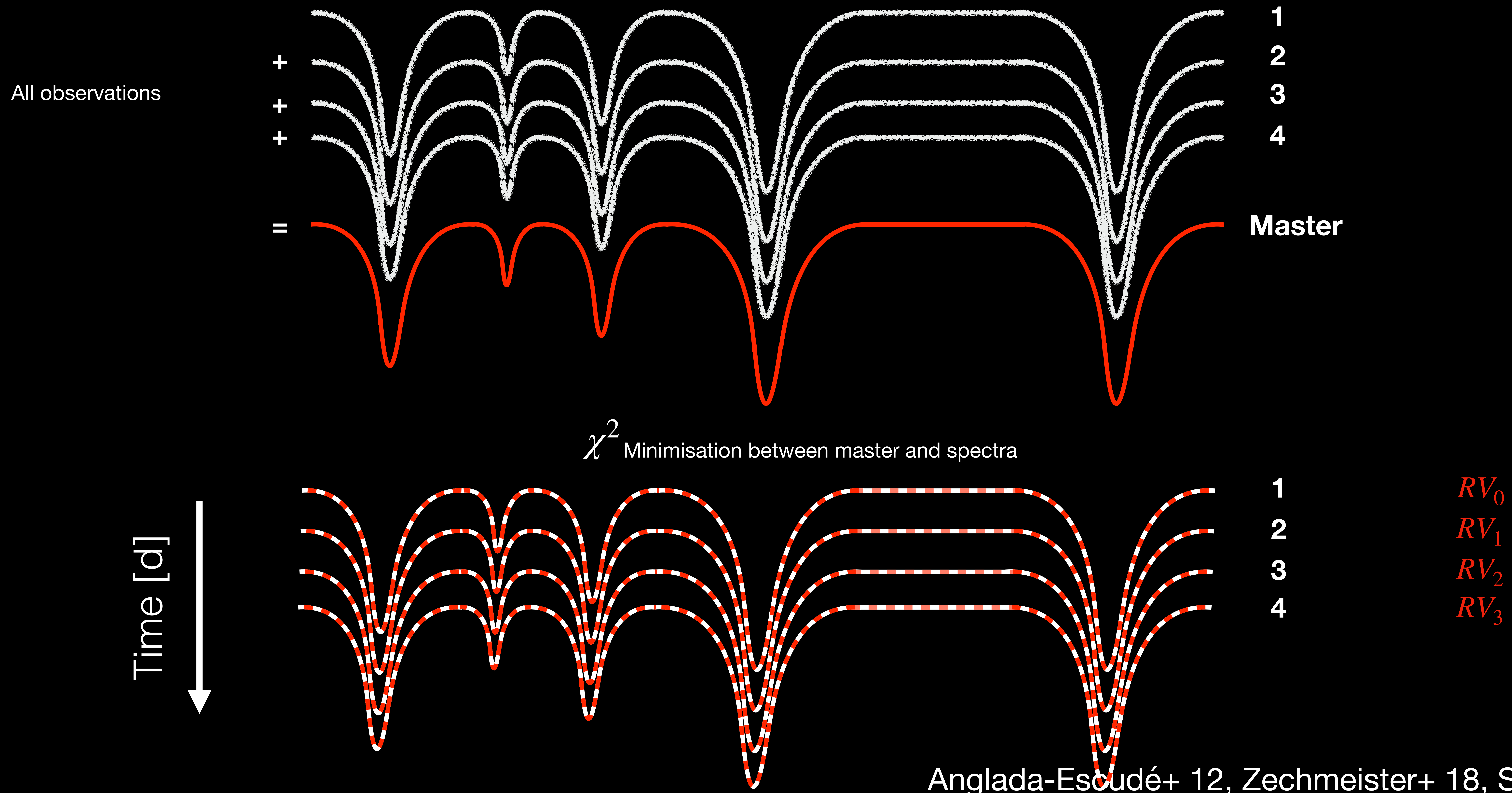
The template matching technique

All observations



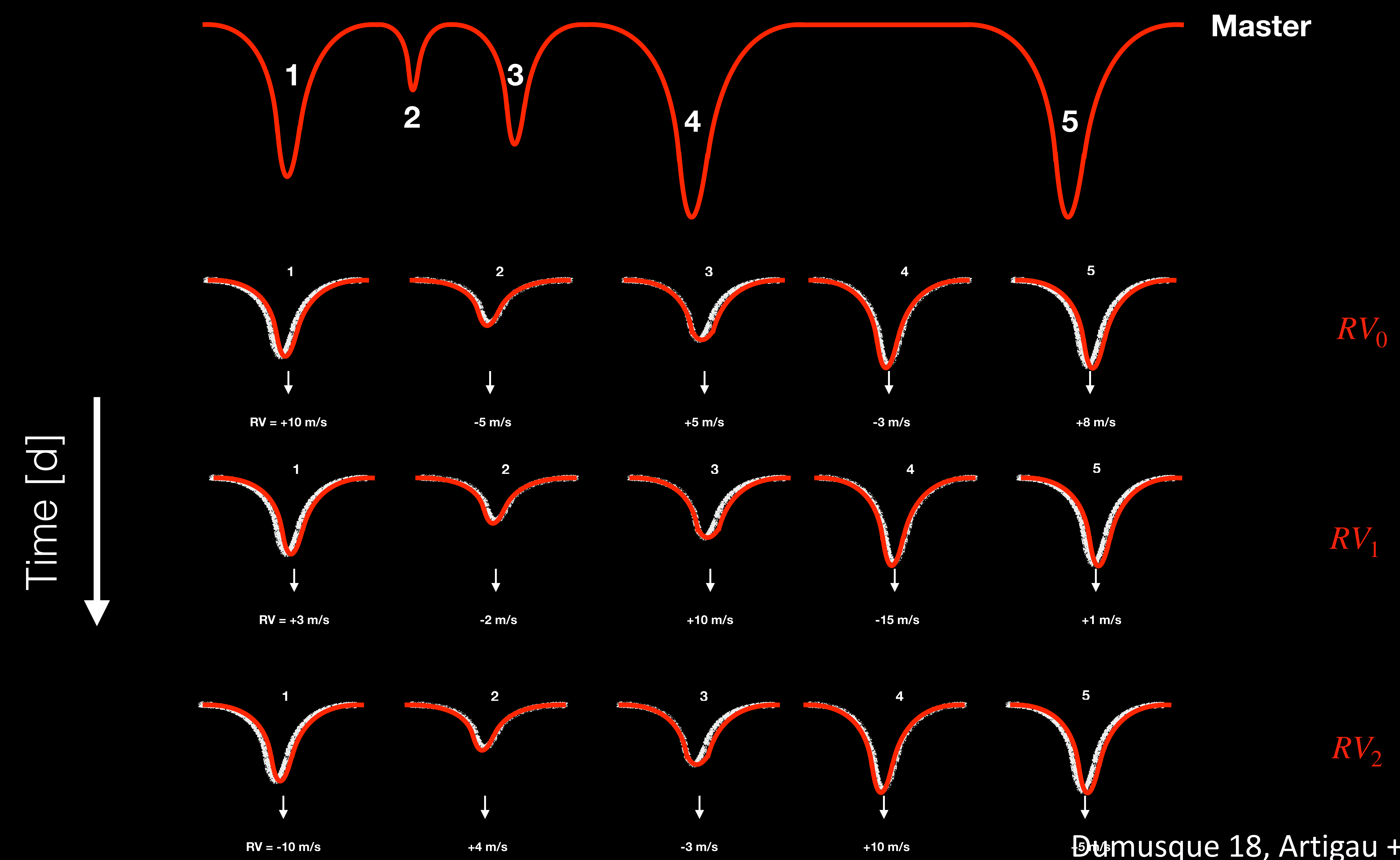
Anglada-Escudé+ 12, Zechmeister+ 18, Silva+ 22

The template matching technique



Anglada-Escudé+ 12, Zechmeister+ 18, Silva+ 22

The line-by-line (LBL) technique



Dumusque 18, Artigau +21 (Butler+ 96)

Cross-correlation functions

- Same template for different stars
- RV info with only one spectrum
- Measuring the systemic velocity
- Easy to implement

- Limited RV information for M dwarfs

Baranne+ 96, Pepe+ 02

Template matching

Maximum RV information for M dwarfs

Affected by instrument systematics and tellurics

Several spectra needed (10-20) to build a high S/N master

More difficult to implement than CCF

Anglada-Escudé+ 12, Zechmeister+ 18, Silva+ 22

Line-by-line (LBL) or chunck-by-chunck

Maximum RV information for M dwarfs

Detects telluric and instrumental systematics

Getting physical information

Affected by instrument systematics and tellurics

Several spectra needed (10-20) to build a high S/N master

More difficult to implement than CCF or template matching

Dumusque 18, Artigau +21 (Butler+ 96)

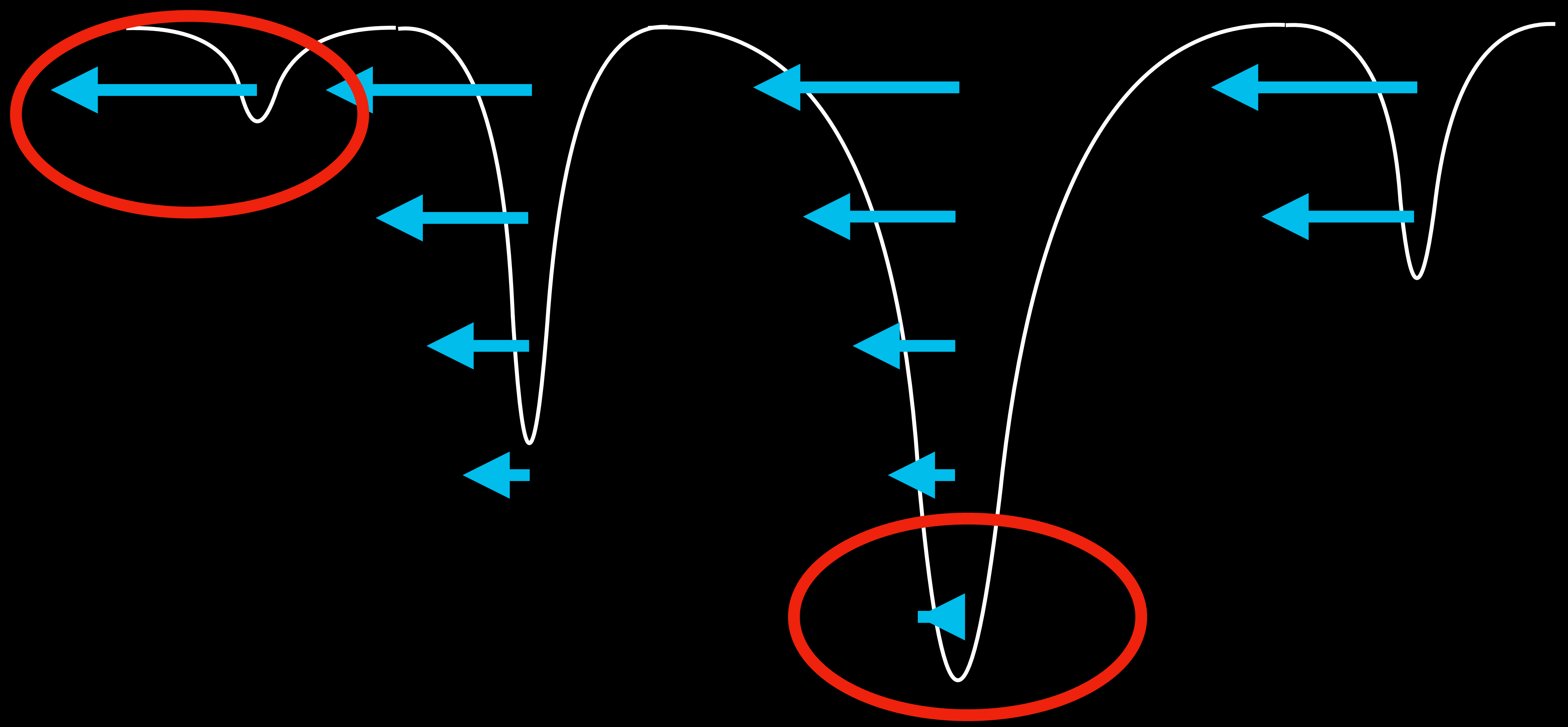
Getting physical information through LBL

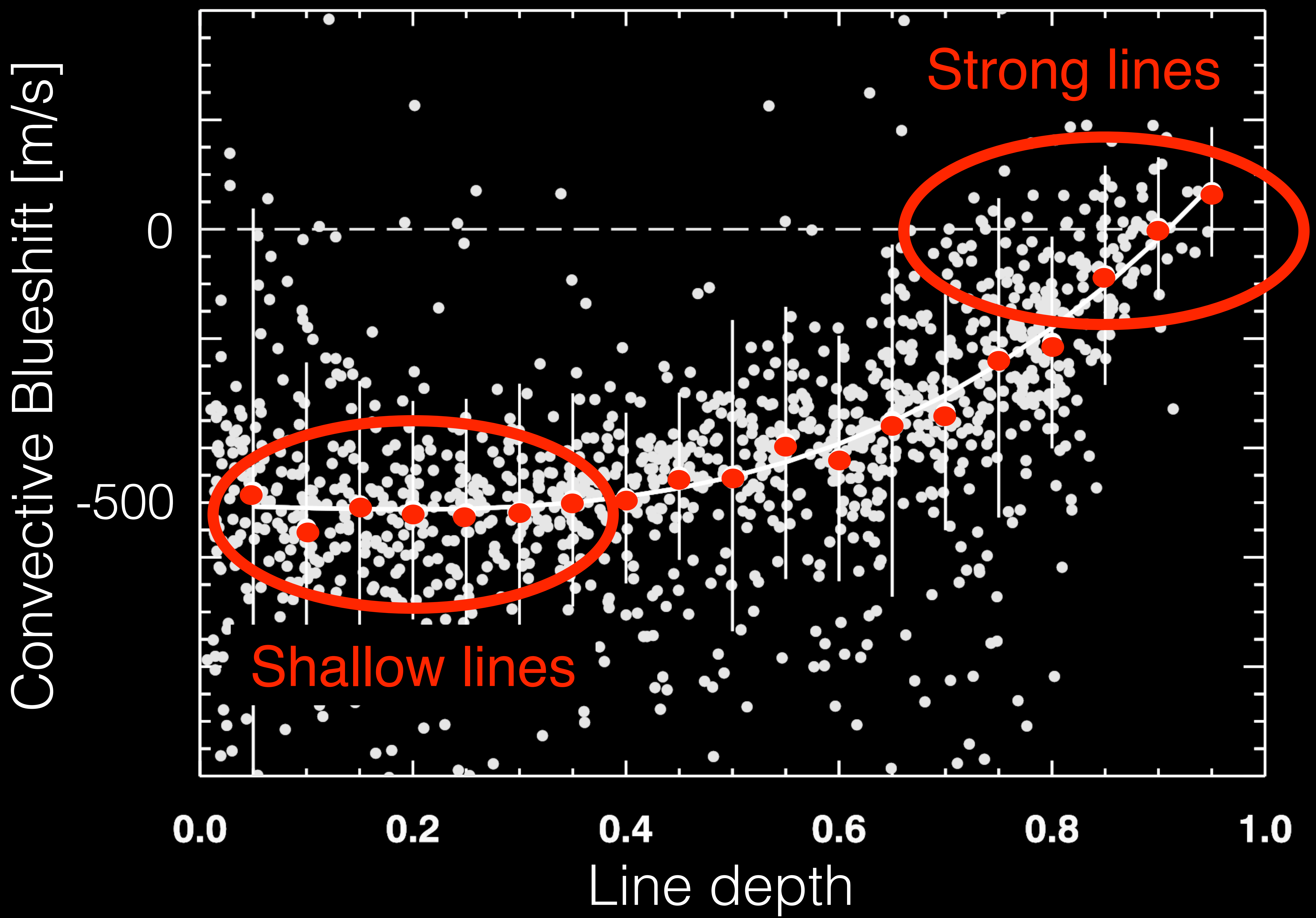
Spectral line formation


Credit: Vasco Henrique

Convective blueshift

Convective blueshift

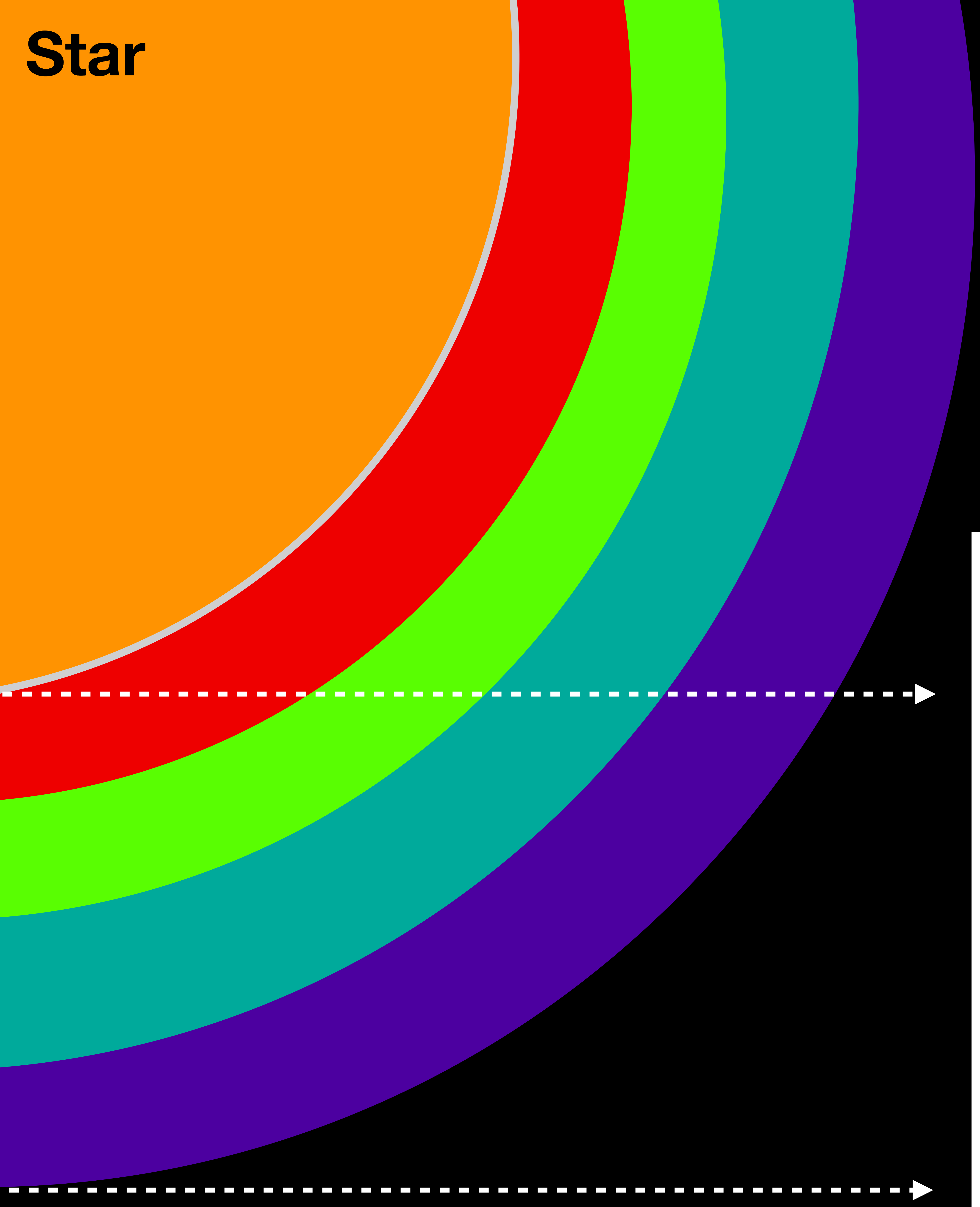




Reiners+ 16

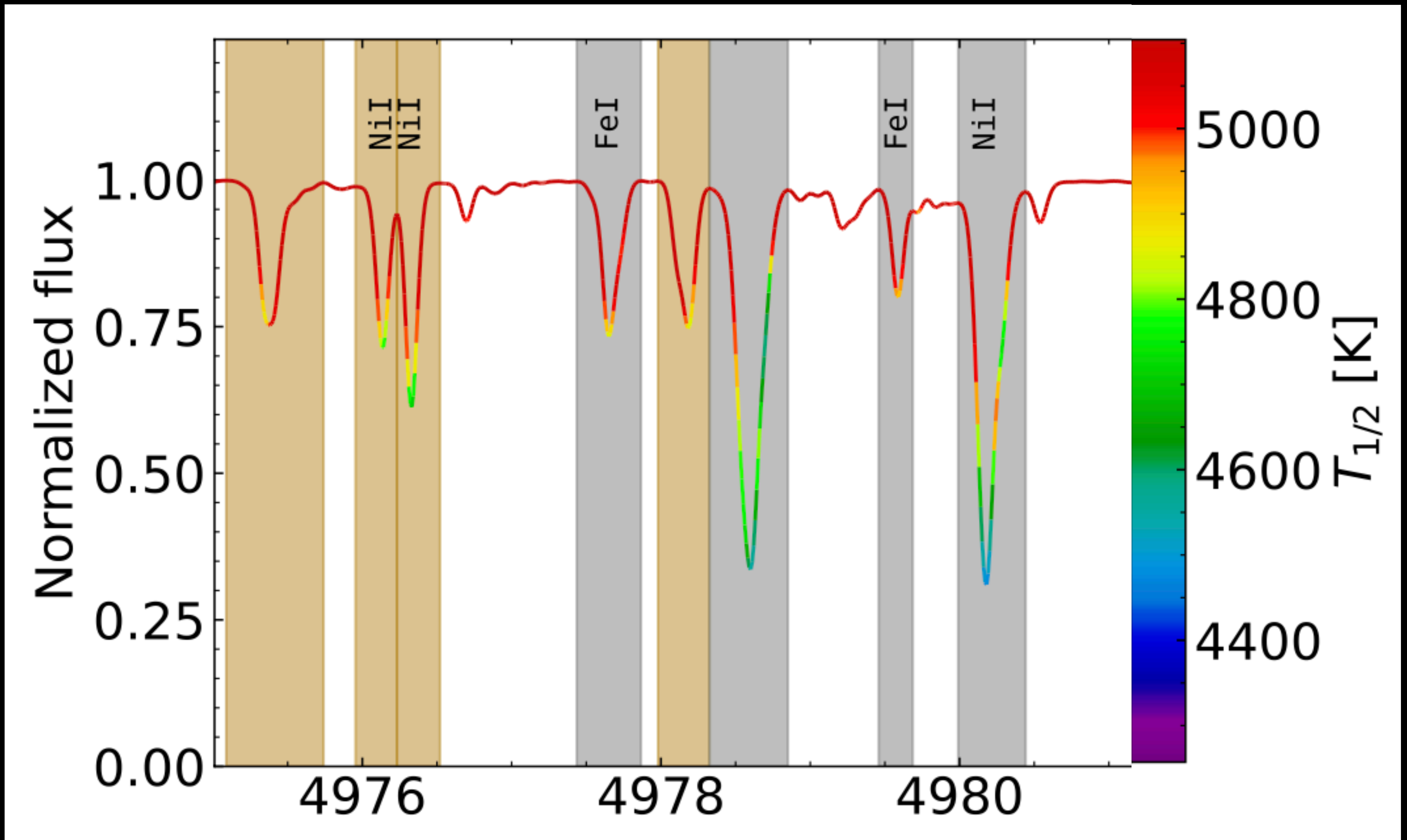
Stellar activity

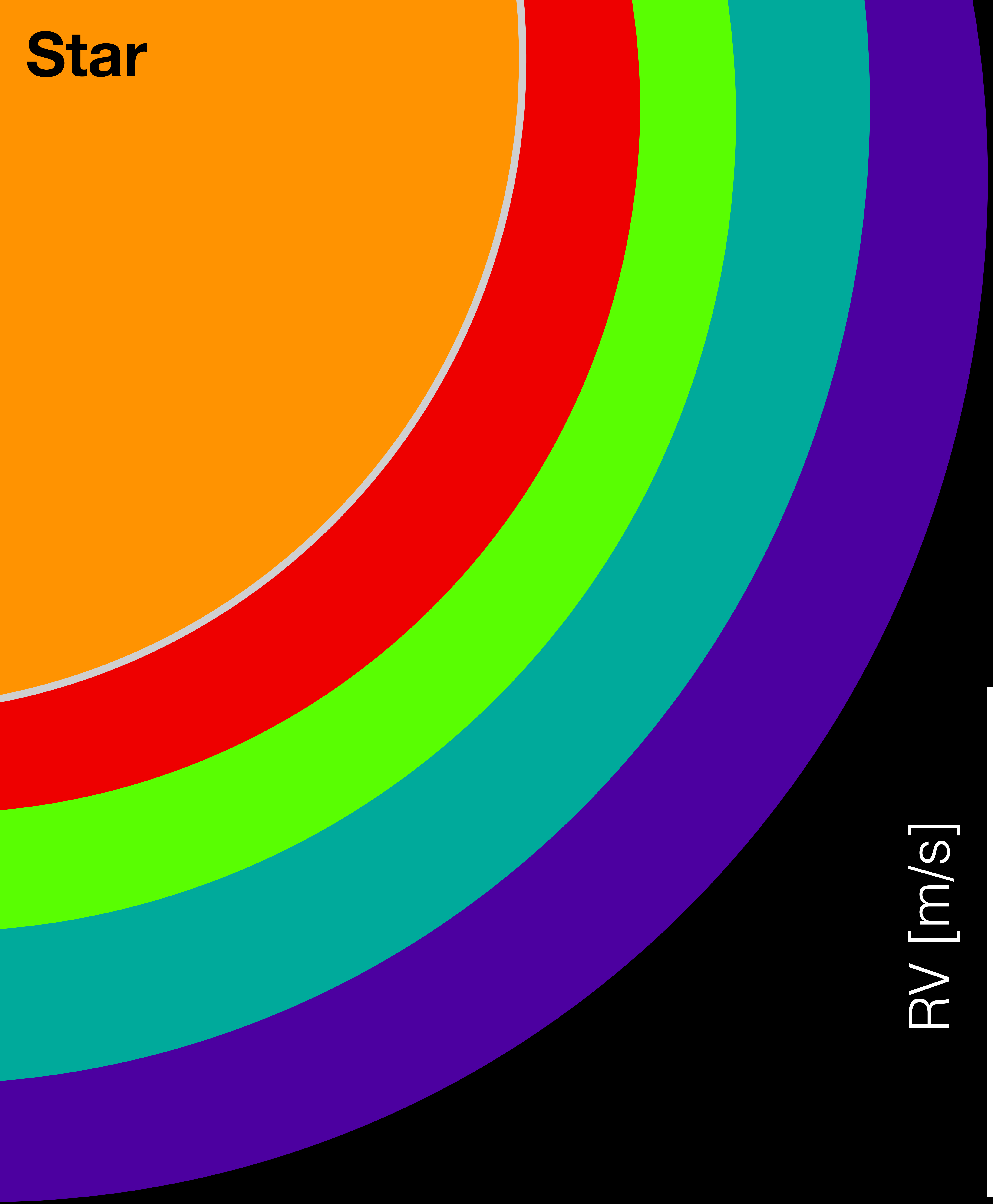
Stellar activity



Spectral synthesis

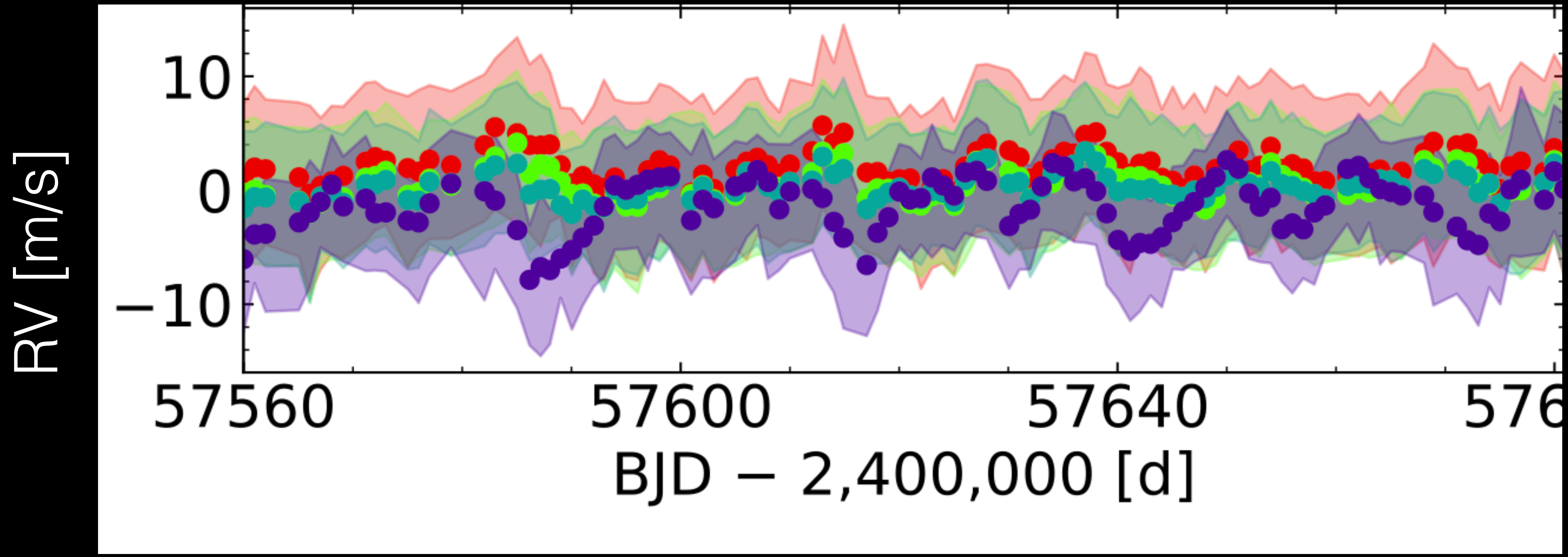
Khaled Al Moulla (PhD)





RV as a function of formation depth

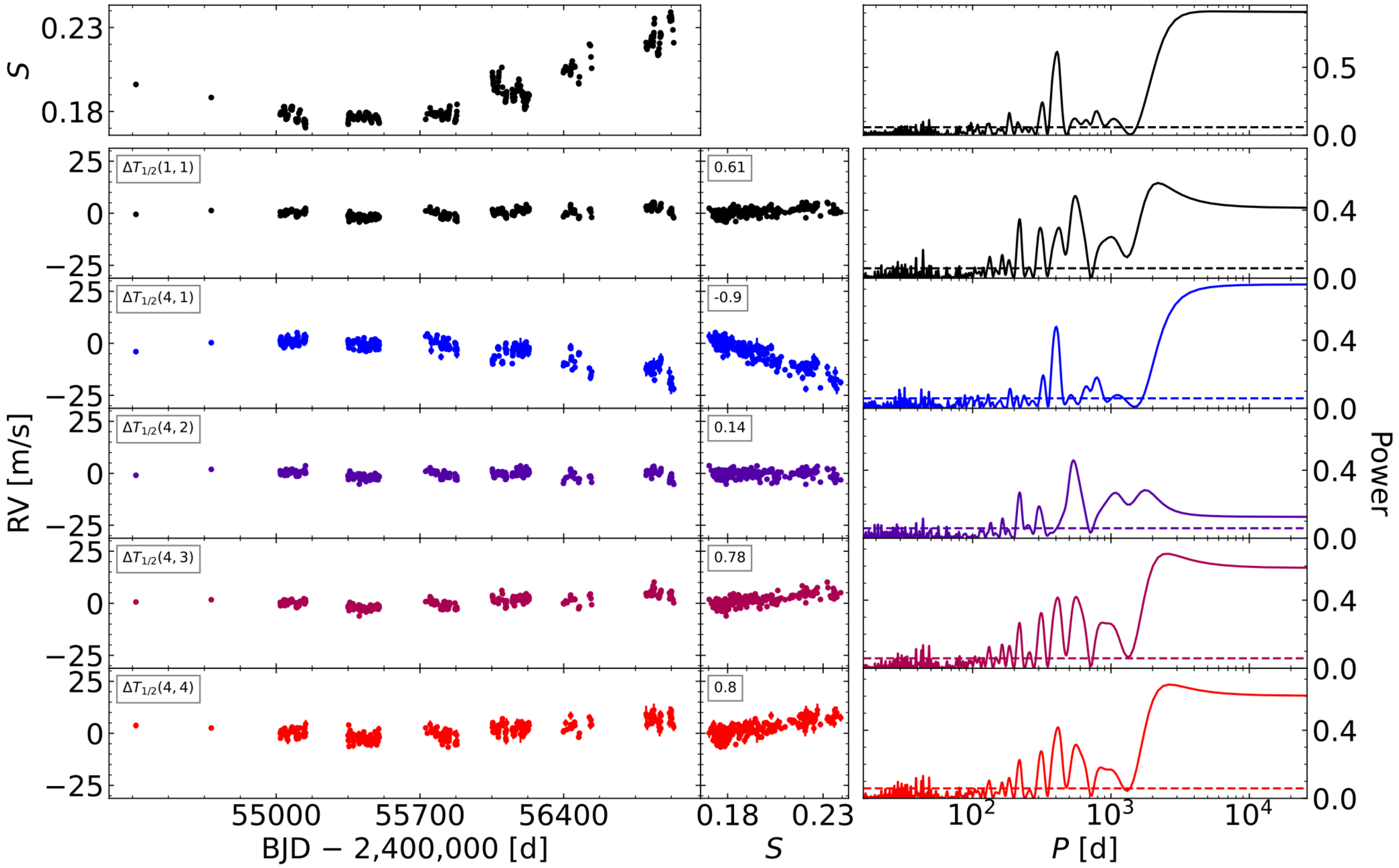
Khaled Al Moulla (PhD)



Al Moulla+ 22

RV as a function of formation depth

Detection for 20 stars observed by HARPS and HARPS-N

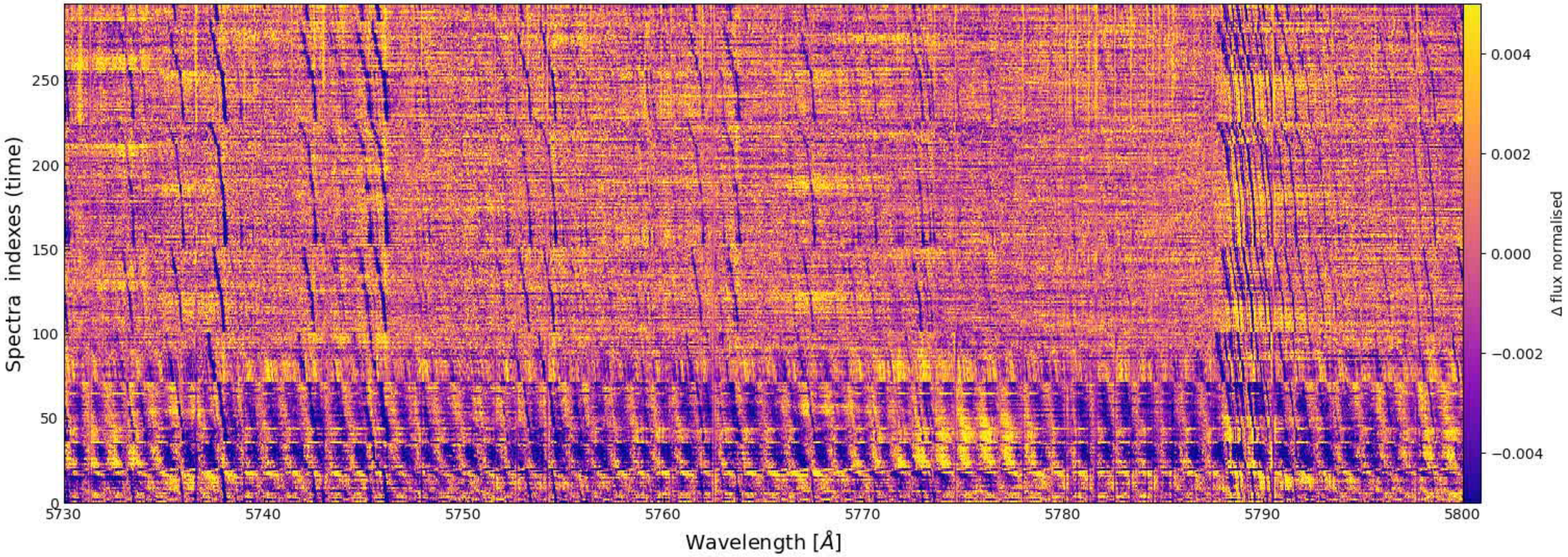


Al Moulla+ in prep.

Deriving more precise RVs using LBL

Correcting for instrument and telluric systematics

Implemented on :
HARPS, HARPN, ESPRESSO, EXPRES, CARMENES



- **Color correction**
- **Cosmics correction**
- **Water telluric correction**
- **Oxygen telluric correction**
- **Interference correction**
- **Stitchings correction**
- **Ghosts correction**
- **Activity-morphological correction**

Cretignier+ 21

Correcting for instrument and telluric systematics

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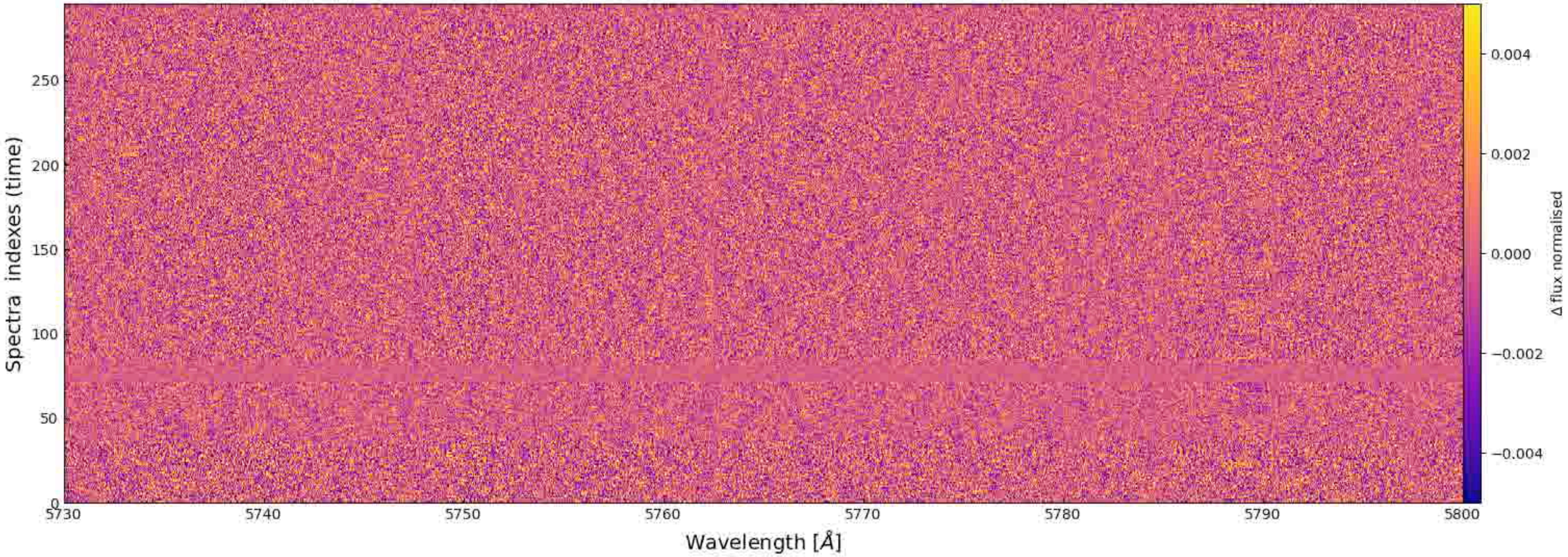

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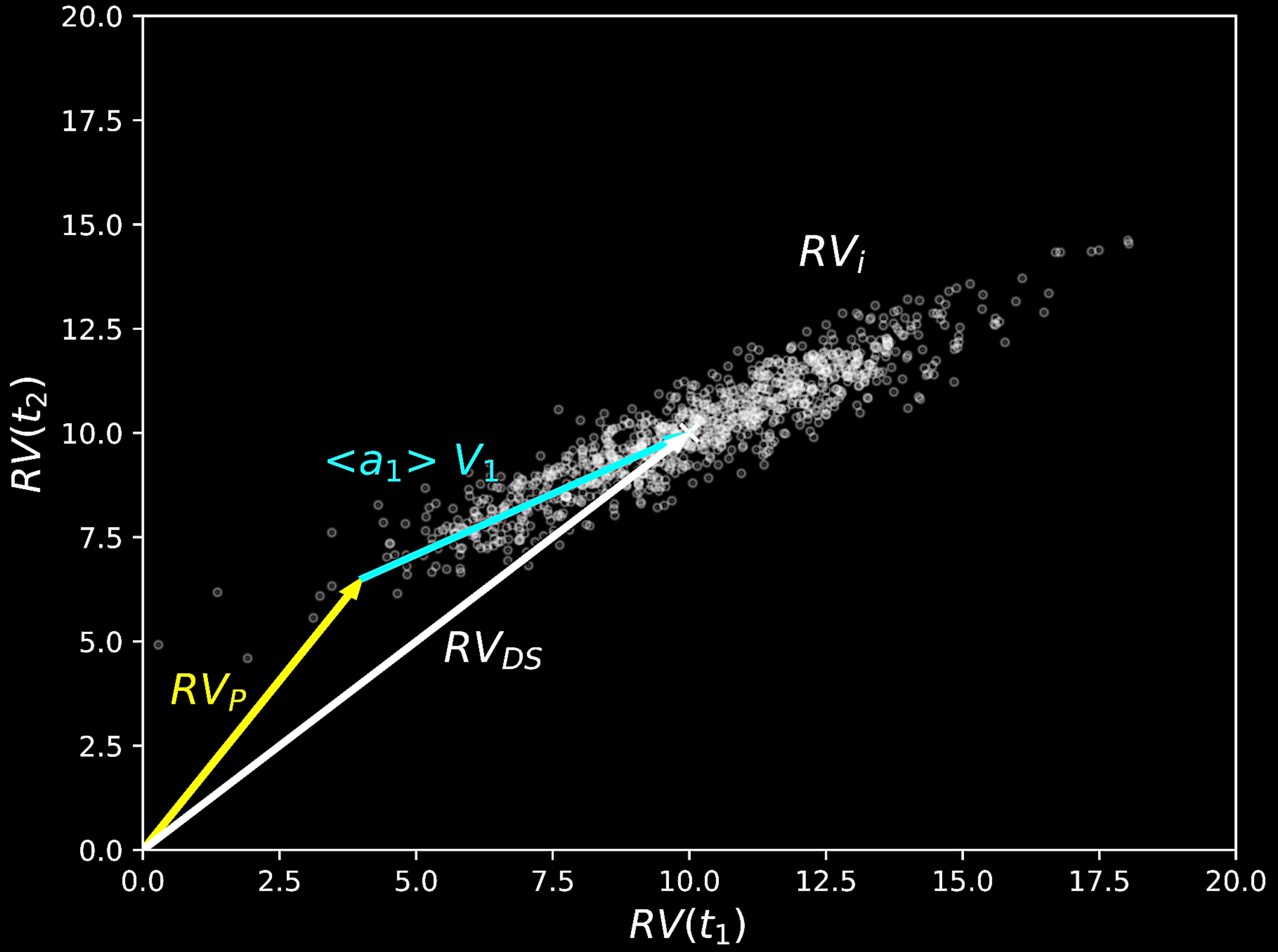
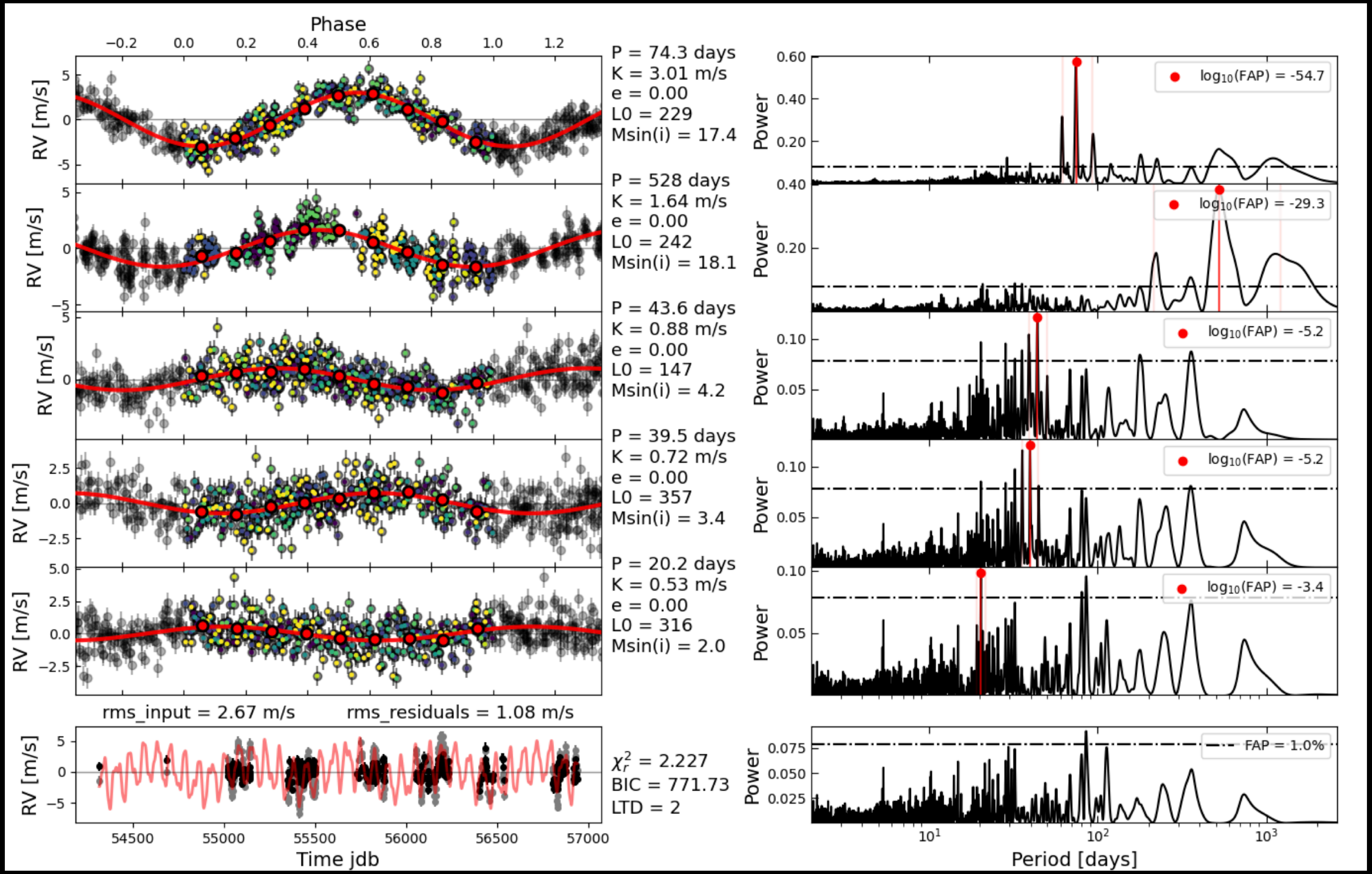
Cretignier+ 21

Line-by-line PCA



Cretignier+ 23, Ould-Elhkim+ 23

YARARA + LBL PCA on HD192310



Cretignier+ 23

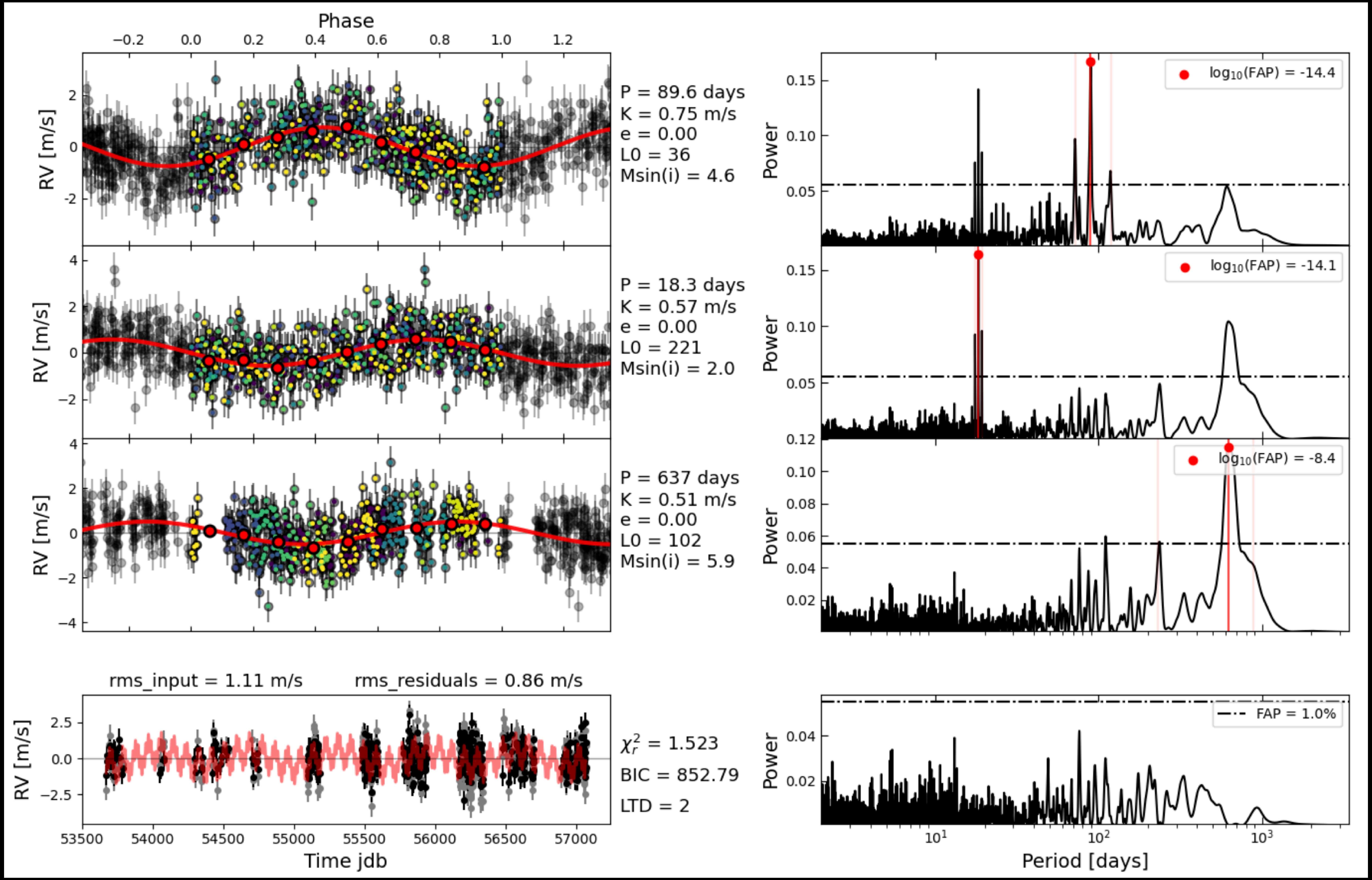
YARARA + LBL PCA on HD192310

Cretignier+ 23

YARARA + LBL PCA on HD192310

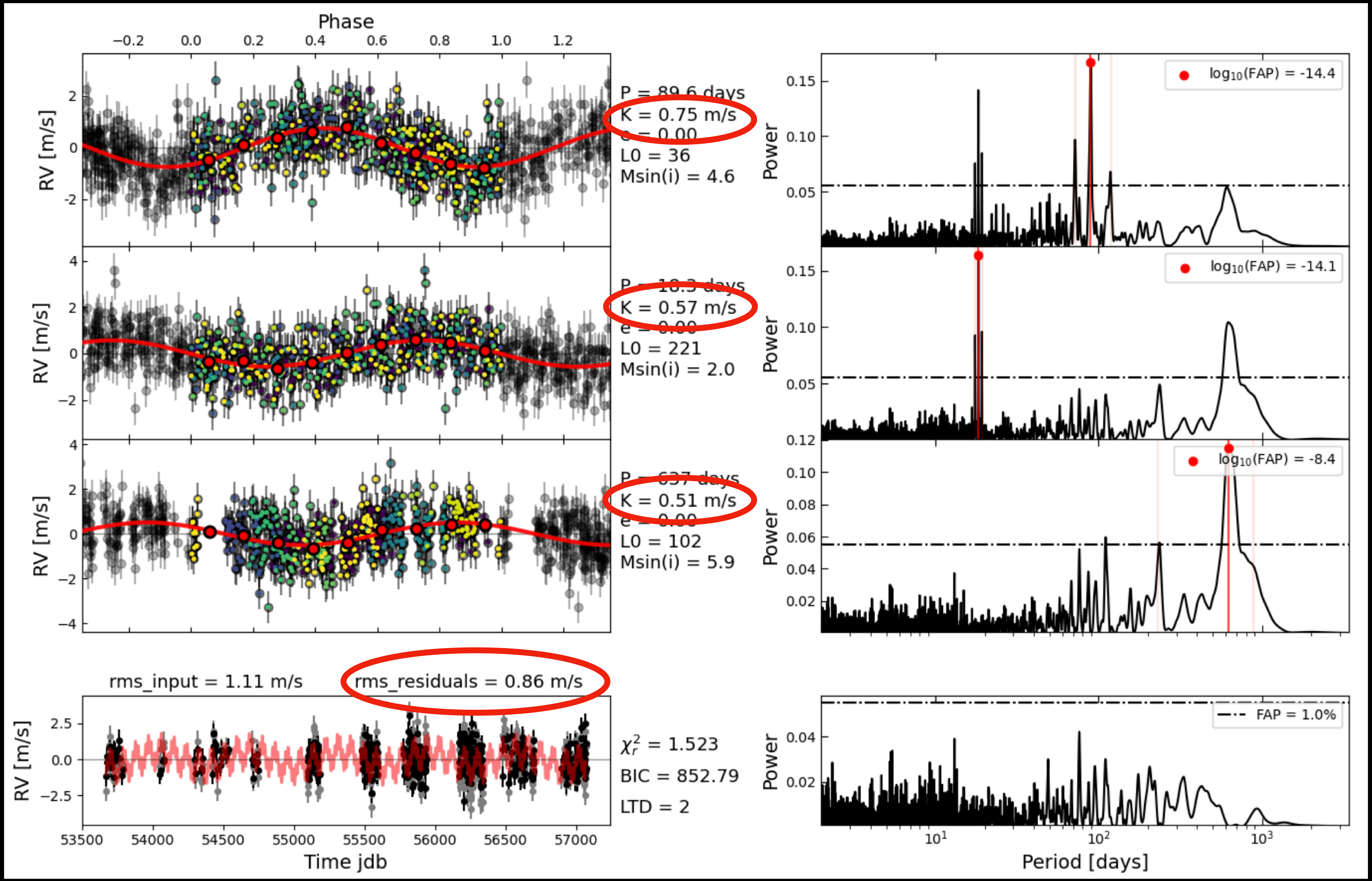
Cretignier+ 23

YARARA + LBL PCA on HD20794



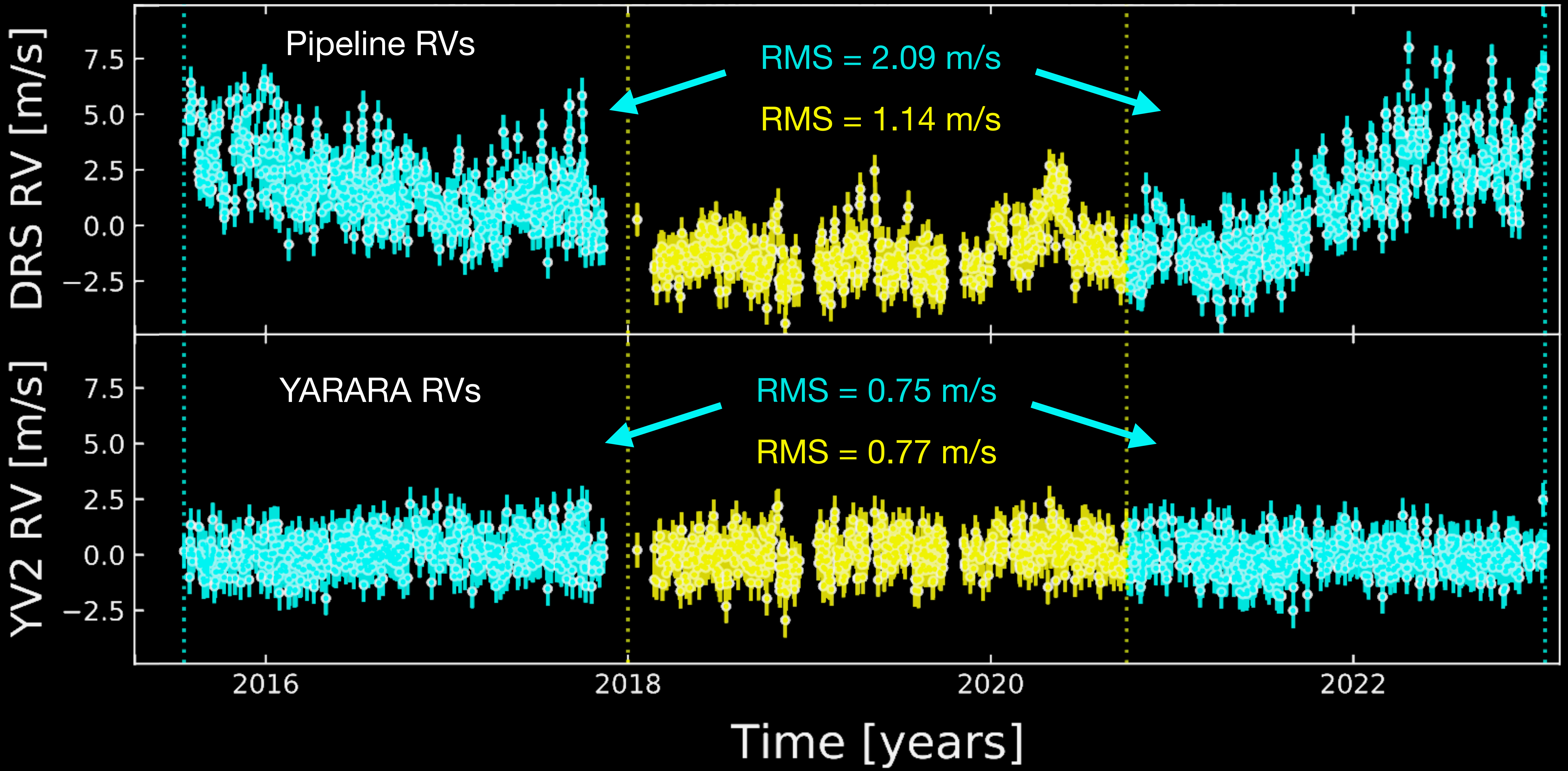
Cretignier+ 23

YARARA + LBL PCA on HD20794



Cretignier+ 23

YARARA + LBL PCA on the Sun



Take home message

- Cross correlation to measure RV is still very efficient to get to the m/s level
- Template matching helps in the M-dwarf regime, however a line-by-line technique is more robust thanks to outlier identification and rejection

  see Etienne Artigau’s talk

- Line-by-line helps us to understand the physics happening (stellar activity, granulation

  see Dainis Dravin’s talk

- We can use PCA approach on line-by-line to reject instrumental and activity signals
- HARPS can measure the velocity of stars to better than 1 m/s over 20 years