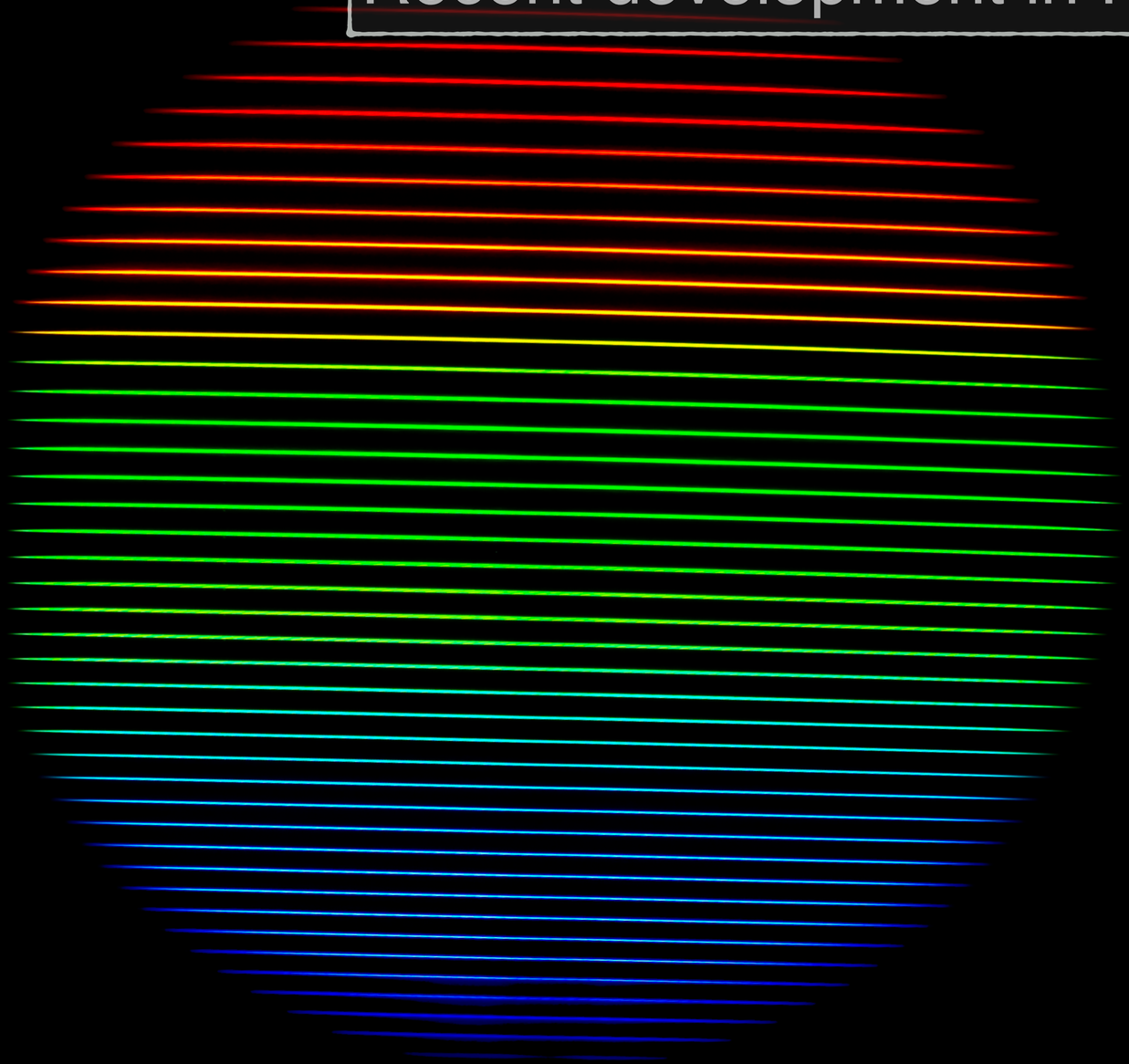
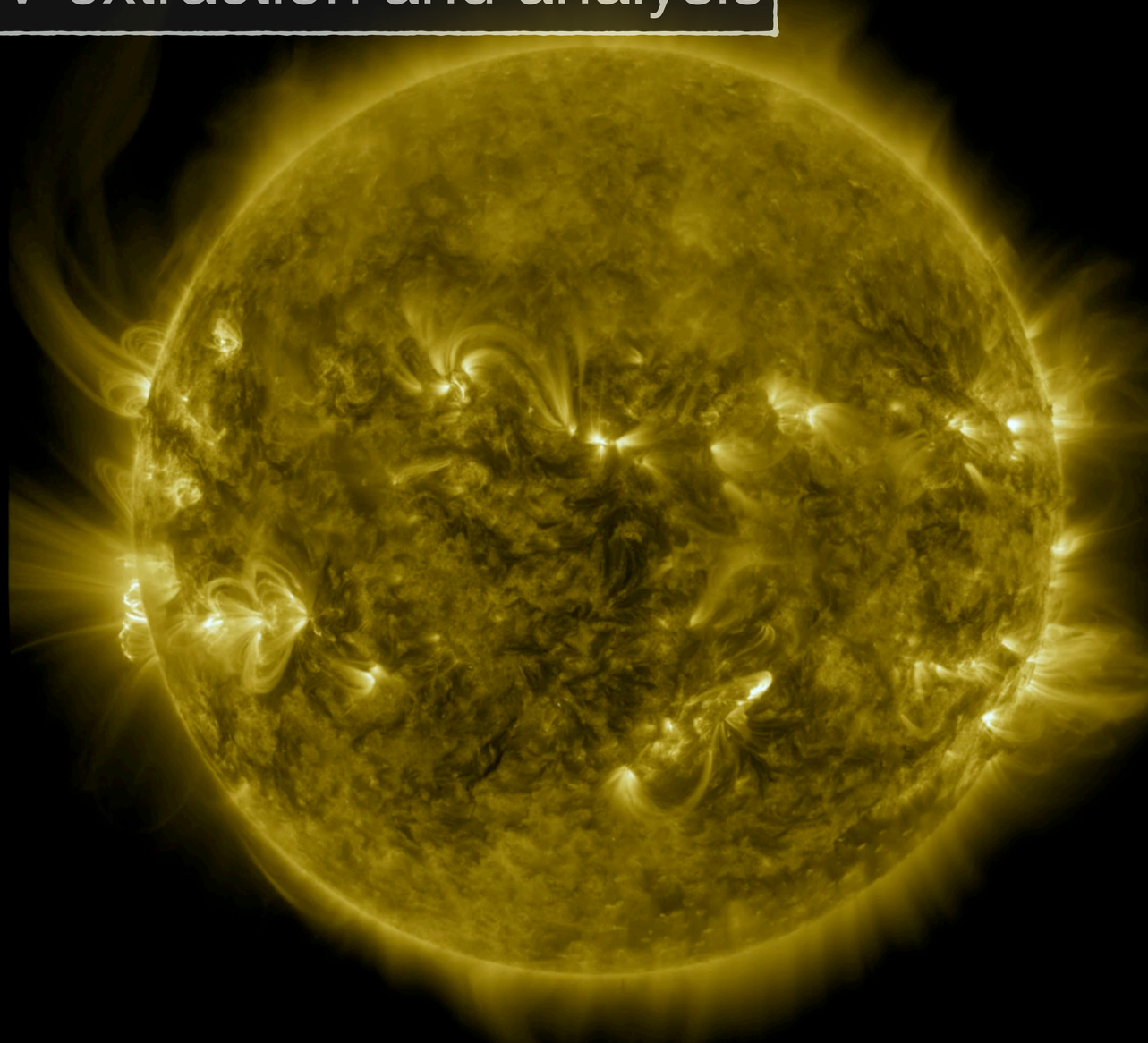
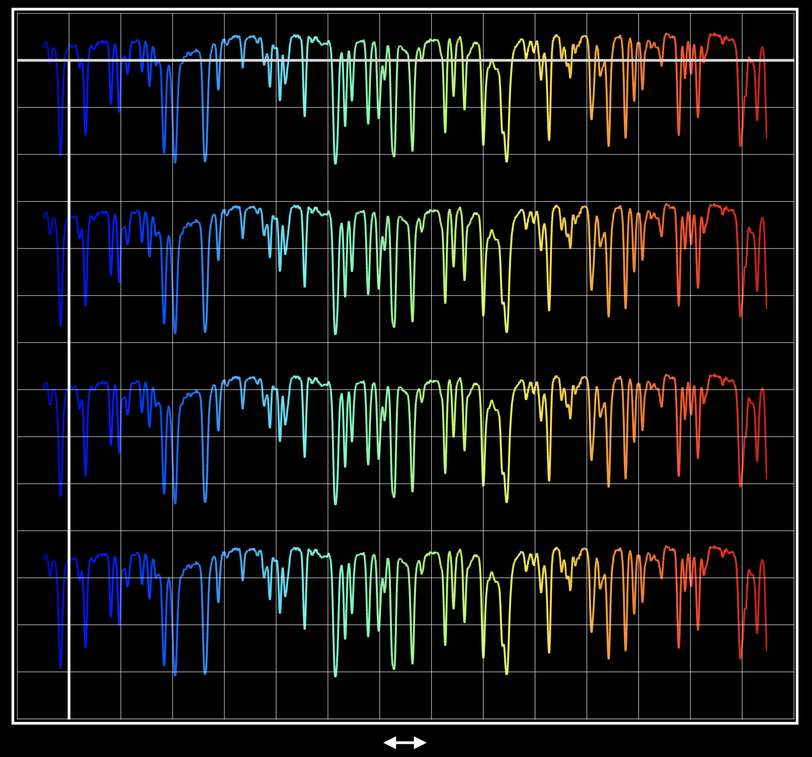
Recent development in RV extraction and analysis





The Challenge: measuring precise radial velocities

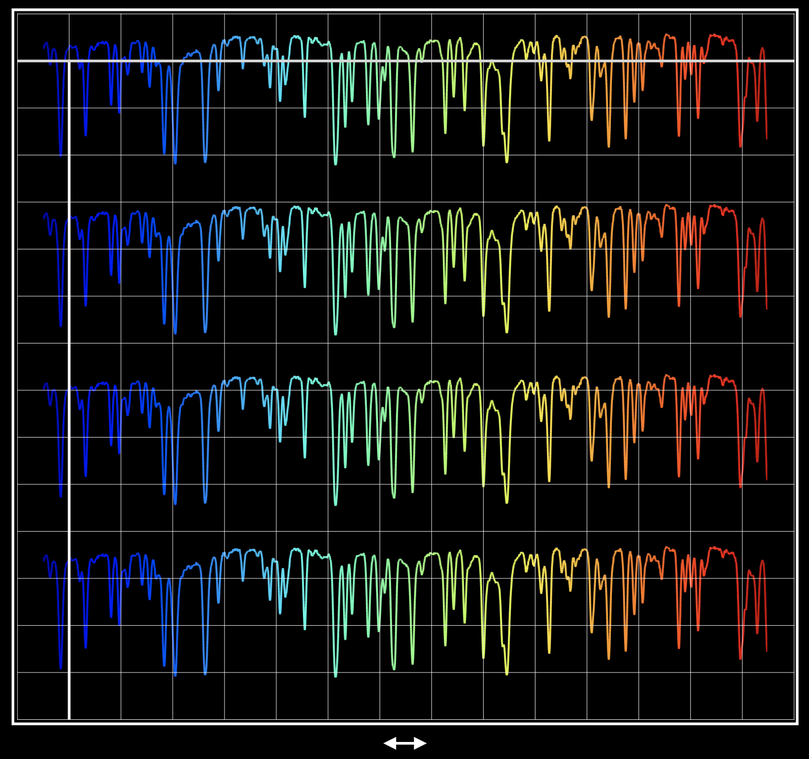
CCD Detector



1 pixel ~ 400-800 m/s

CCF or template matching to measure precise RVs

CCD Detector



1 pixel ~ 800 m/s

SPECTRUM

visible spectrum

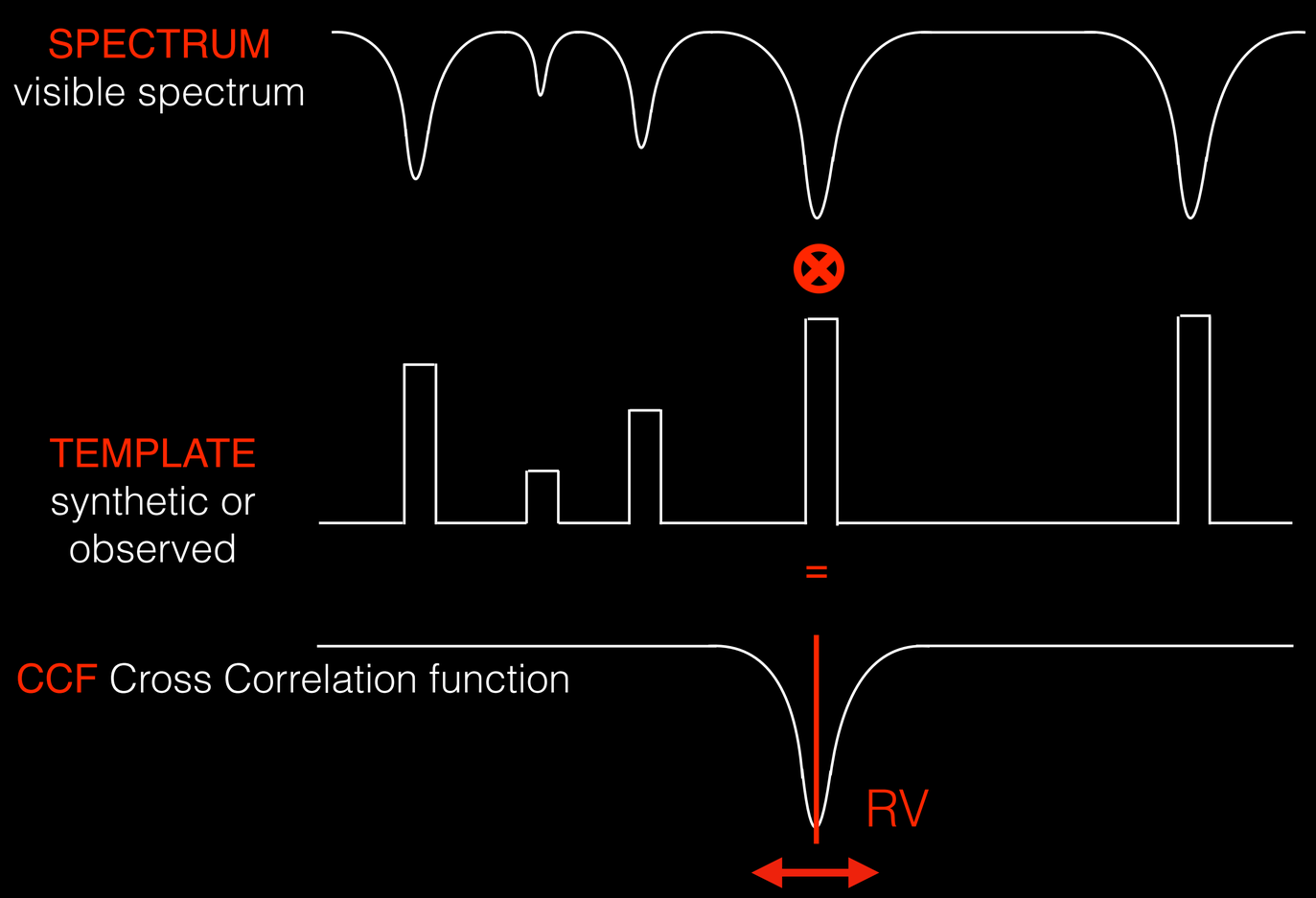
TEMPLATE

synthetic or observed

CCF Cross Correlation function

RV

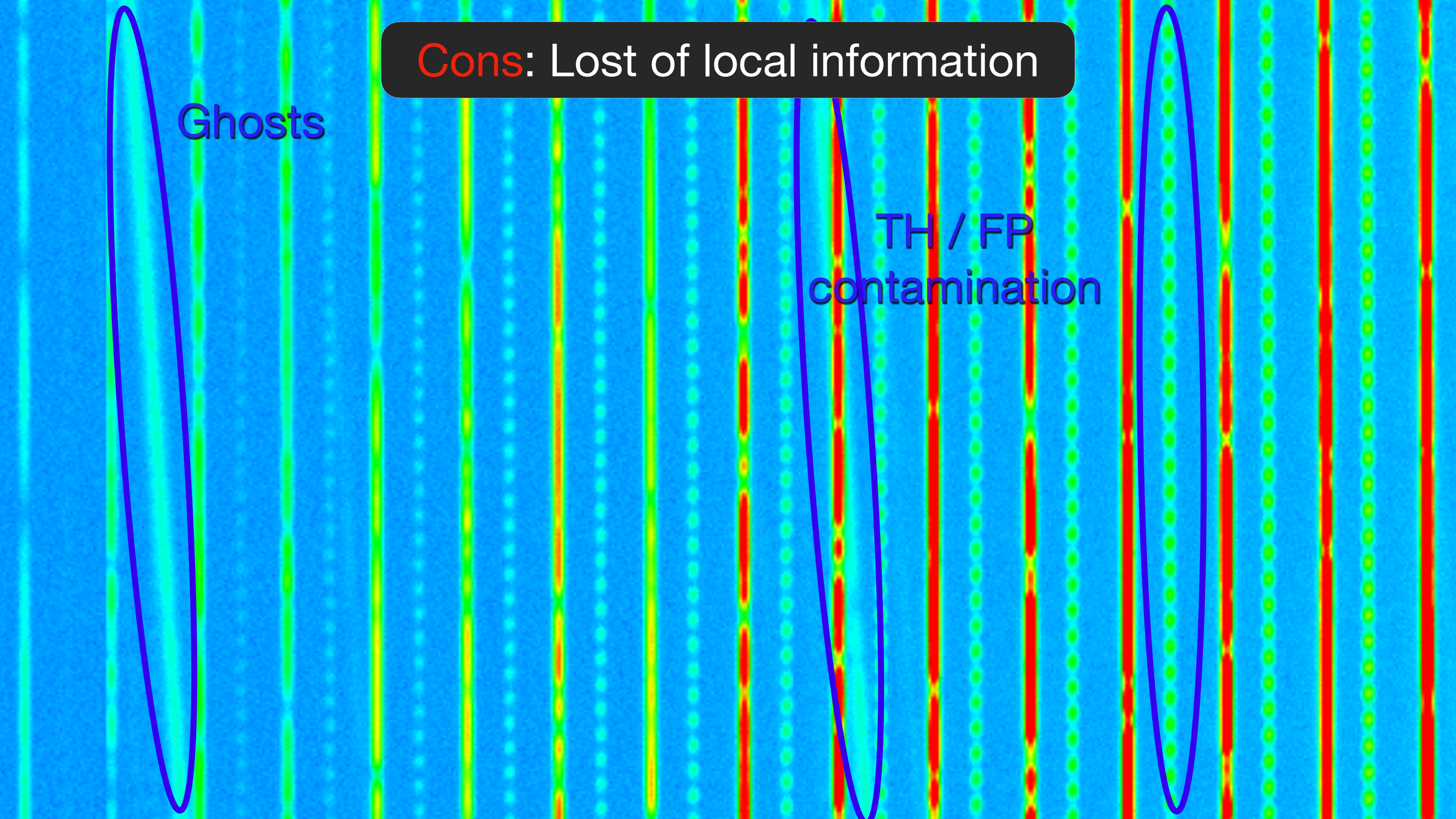
CCF or template matching to measure precise RVs



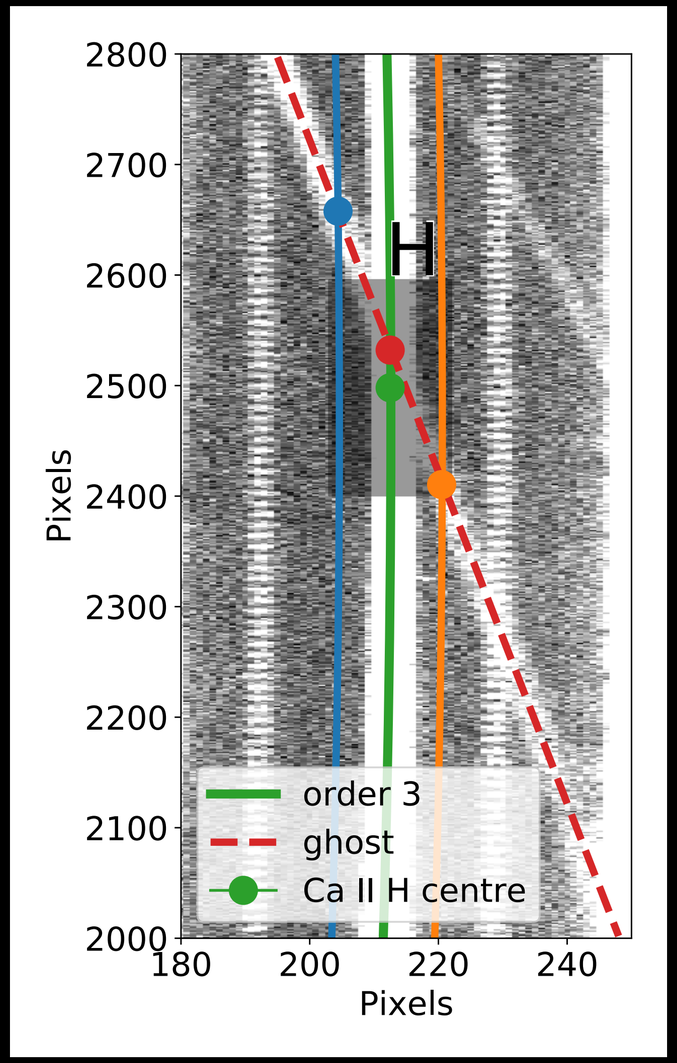
Pros / Cons

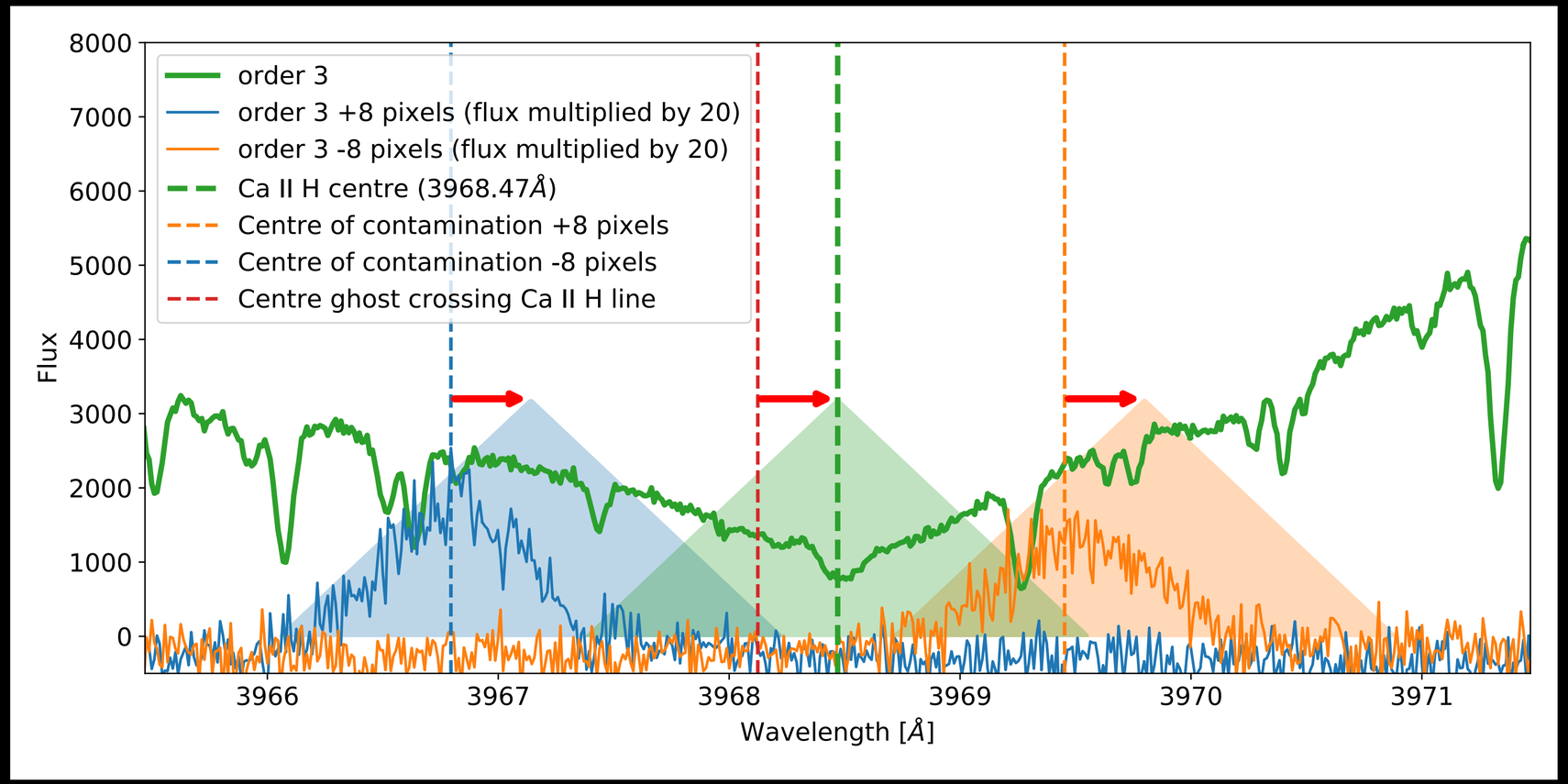
Average spectral lines using their RV content as weight

- Pros: SNR, RV precision
- Pros: Simplicity and robustness
- Pros: Mitigation of stellar and instrumental signals (but not all)
- Cons: Lost of local spectral information
- Cons: Mix physical information from spectral lines


Cons: Lost of local information
Ghosts
TH / FP
contamination

Ghosts





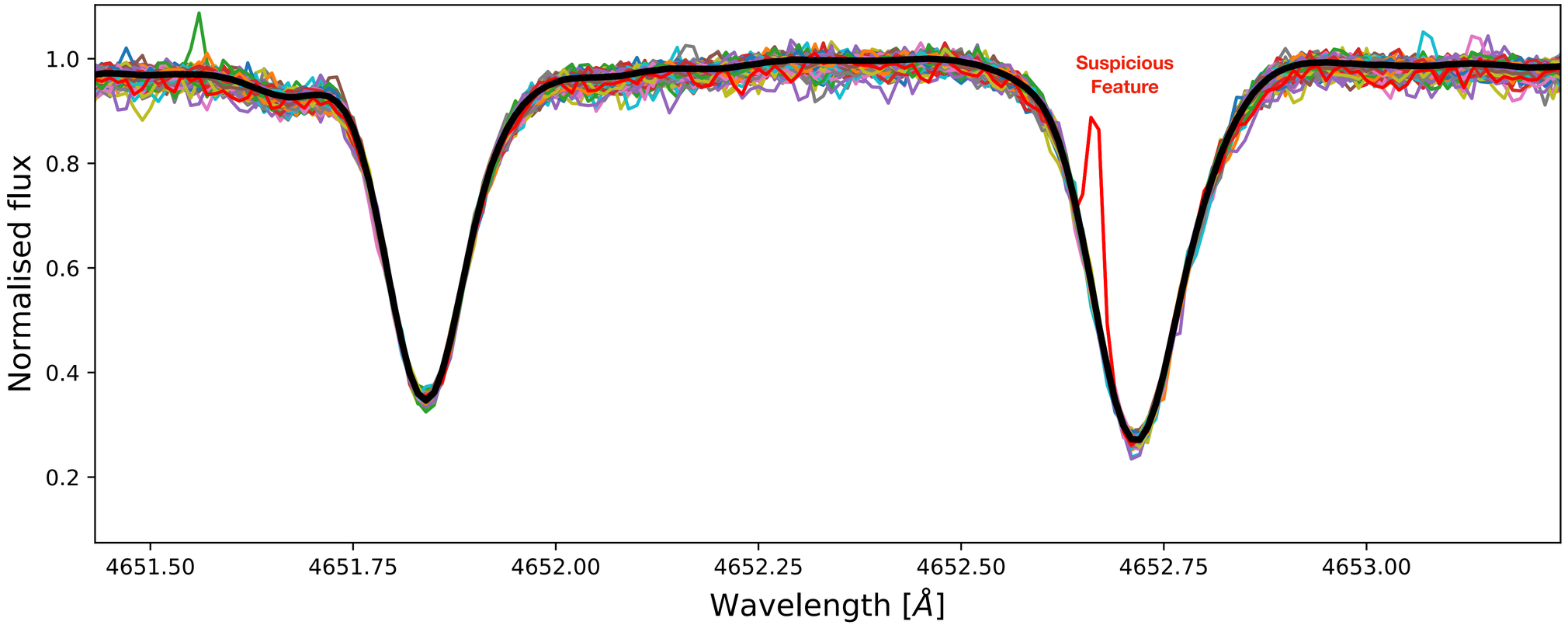
Dumusque+ 21

The problem due to loss of local information

Local effects can have 10-100 m/s effects, but when averaging all the lines together, only < 1-2 m/s effect

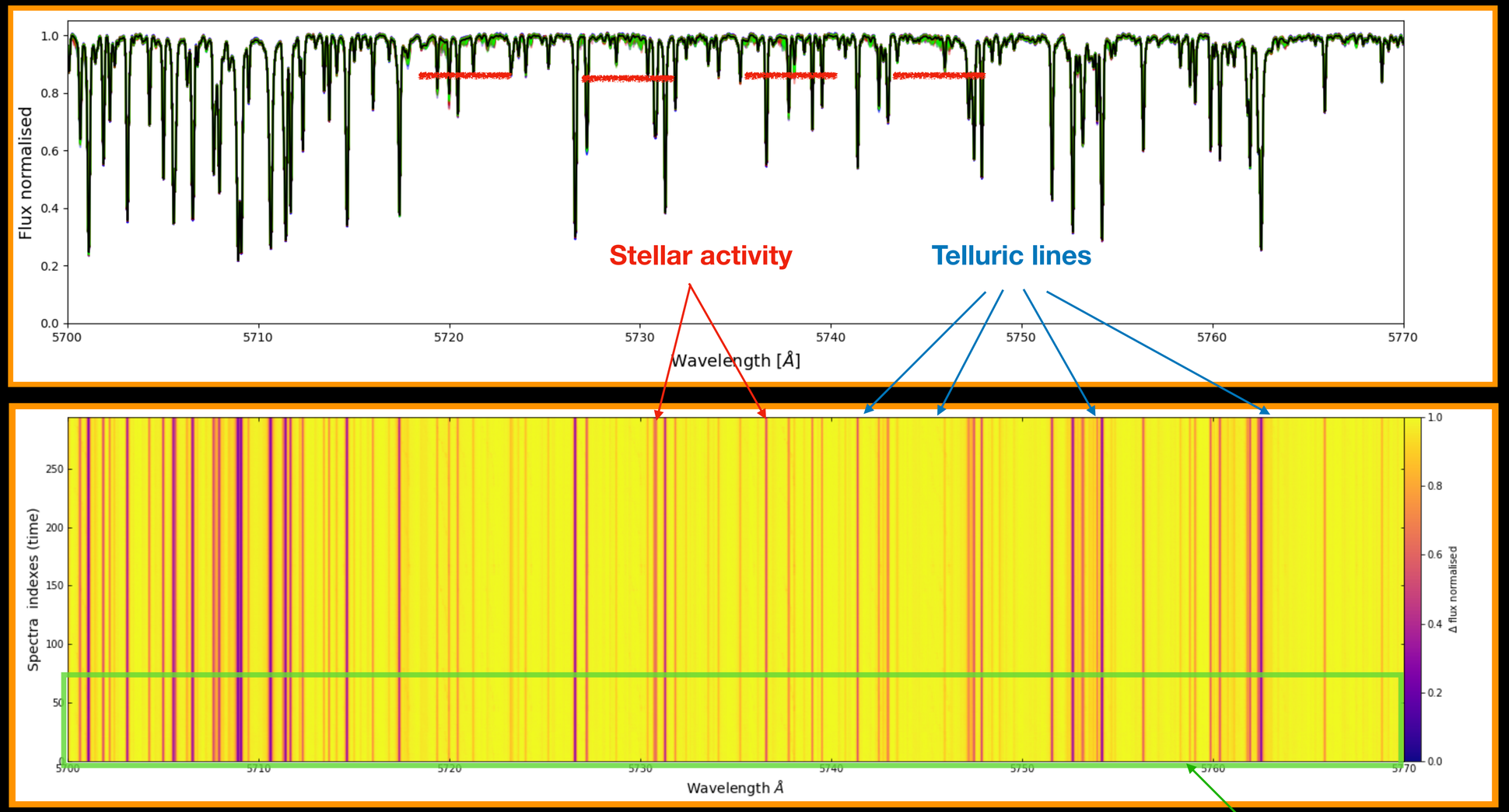
- Difficult to correct: low amplitude + mixing of information
- Reject the information from contaminated regions
    - physically
    - compute RV locally and then reject (downweighting large rms chunks)
- Correct at the spectrum level
    - no lost of RV information content

How to correct for spectral local systematics ?



Courtesy of Michael Cretignier

Using spectral time-series is the key



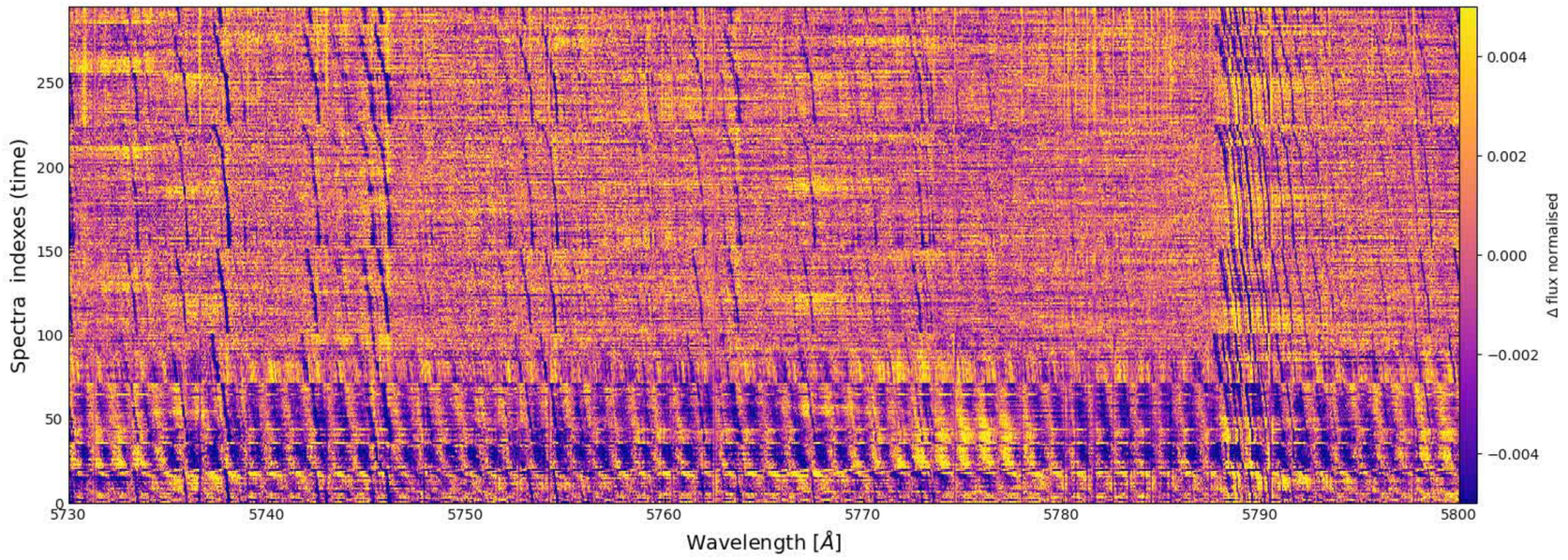
$$f(\lambda) - mean(f(\lambda))_{time}$$

Courtesy of Michael Cretignier

YARARA: a tool to remove instrumental systematics

YARARA, Cretignier+ 20, 21

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



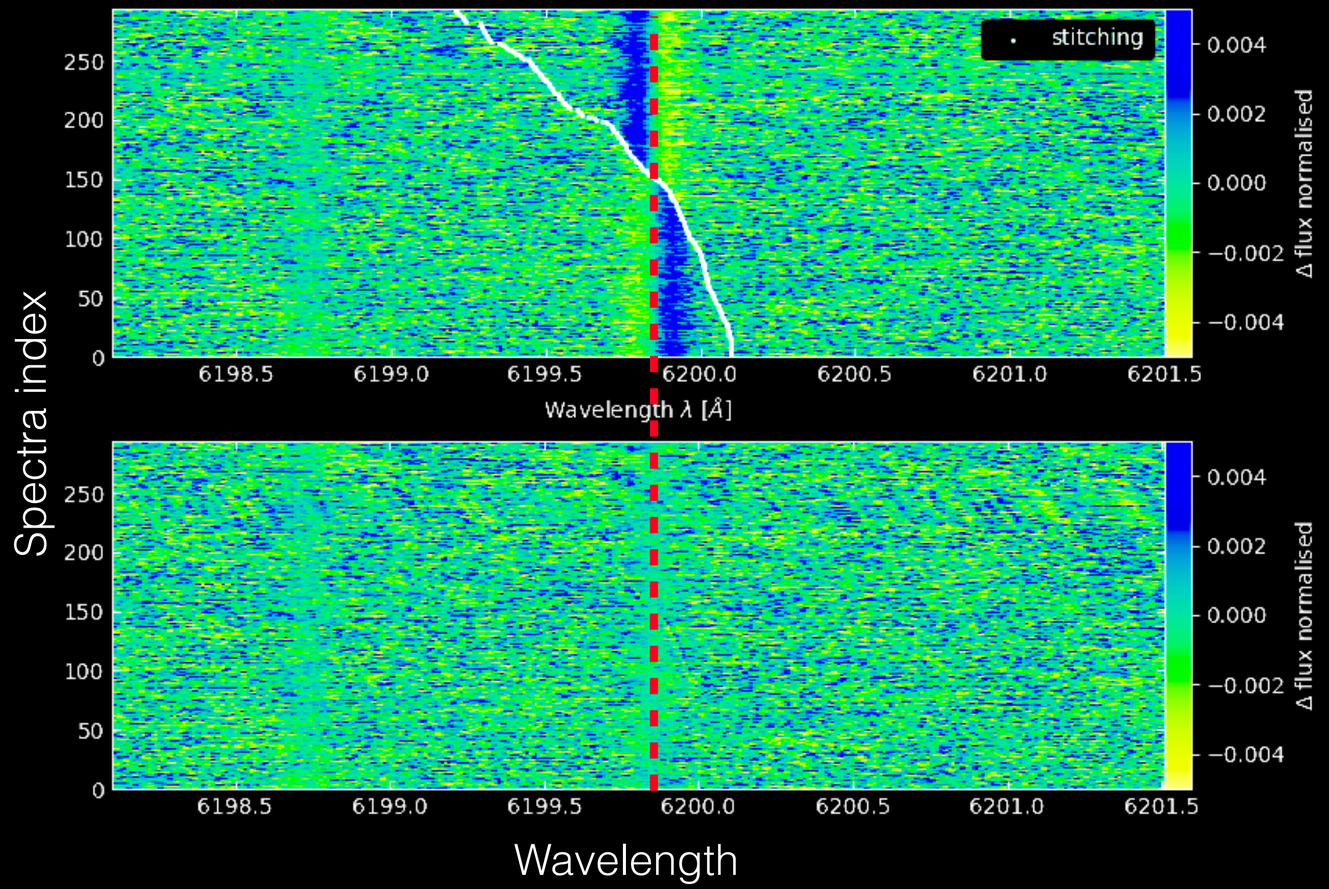
- **Color correction**
- **Cosmics correction**
- **Water telluric correction**
- **Oxygen telluric correction**
- **Interference correction**
- **Stitchings correction**
- **Ghosts correction**
- **Activity-morphological correction**

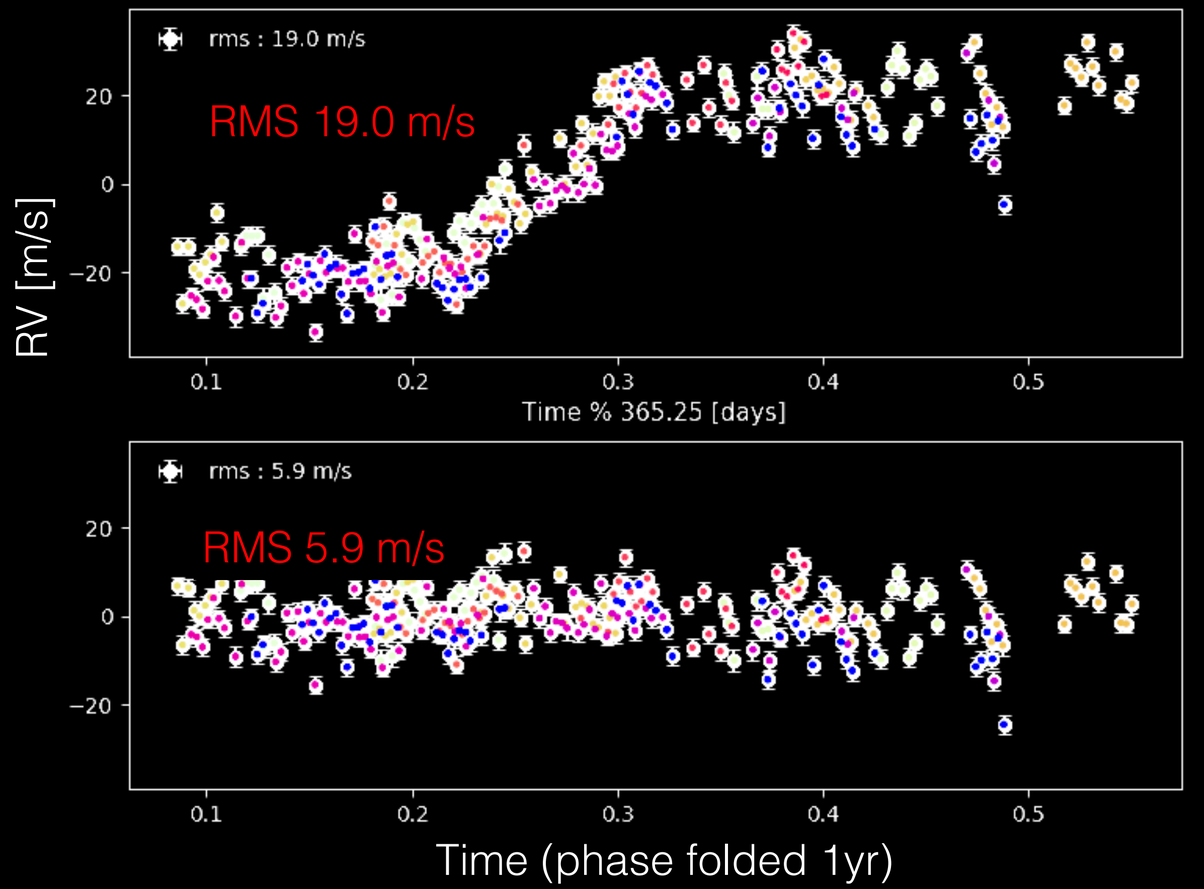
Courtesy of Michael Cretignier

Stitchings

Michael Cretignier (Doctor since 1 month)

Stellar line

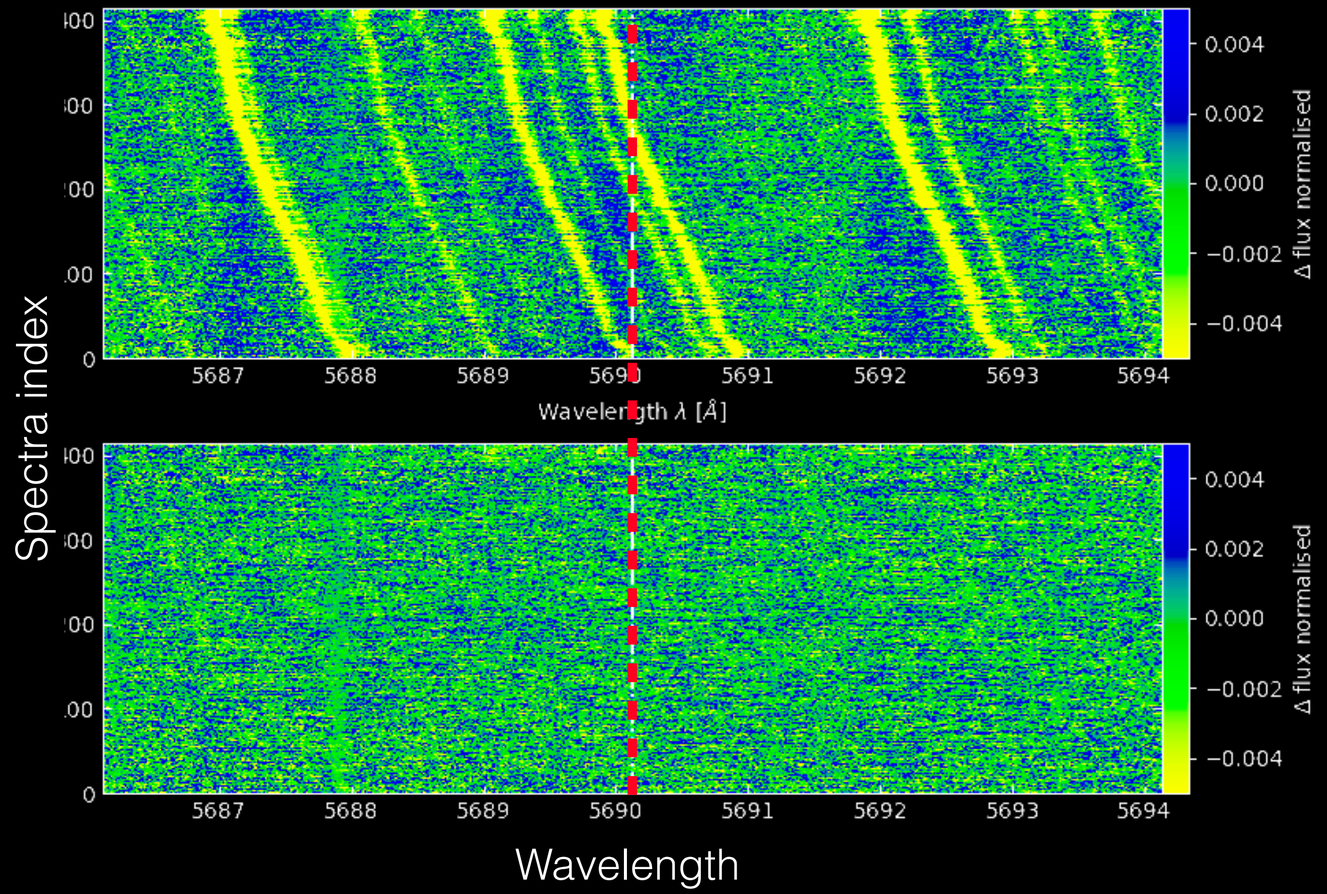


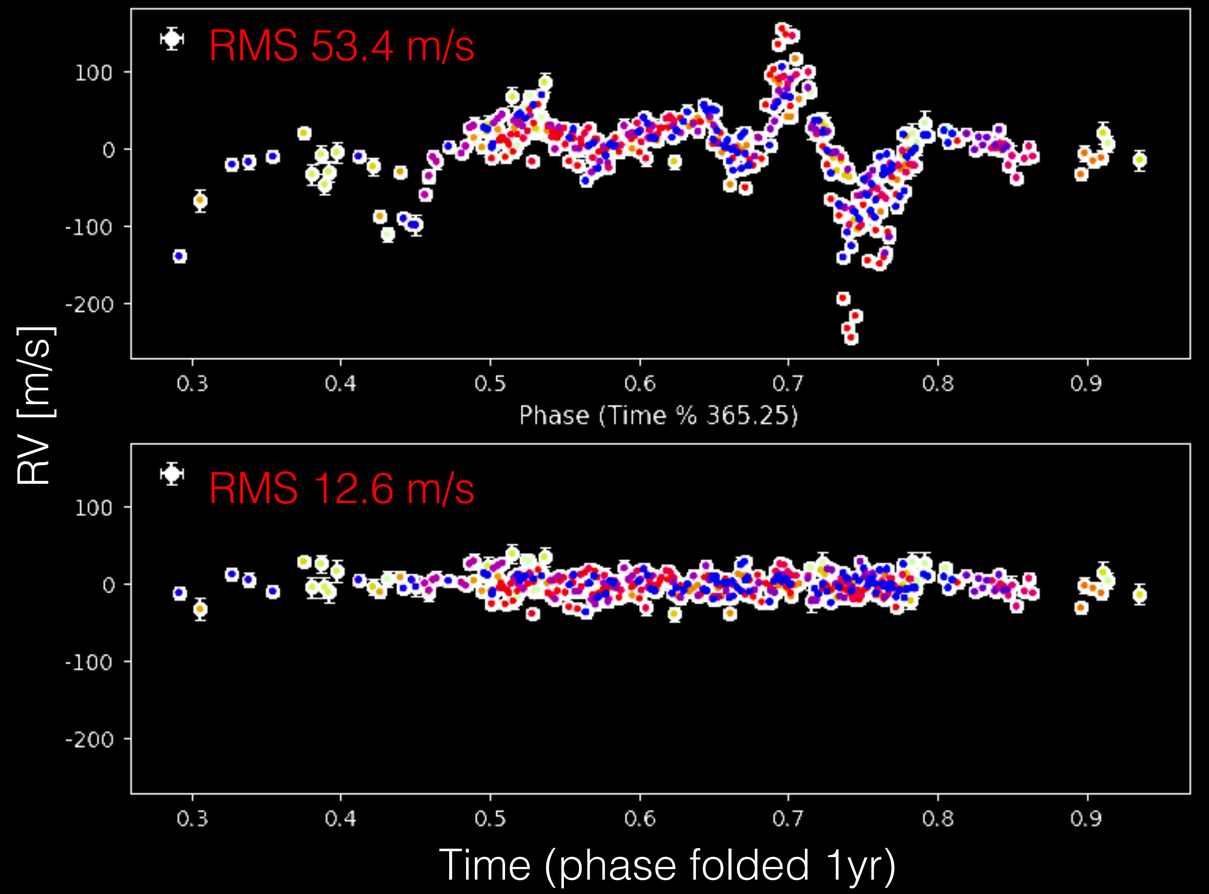


YARARA, Cretignier+ 20, 21

Tellurics

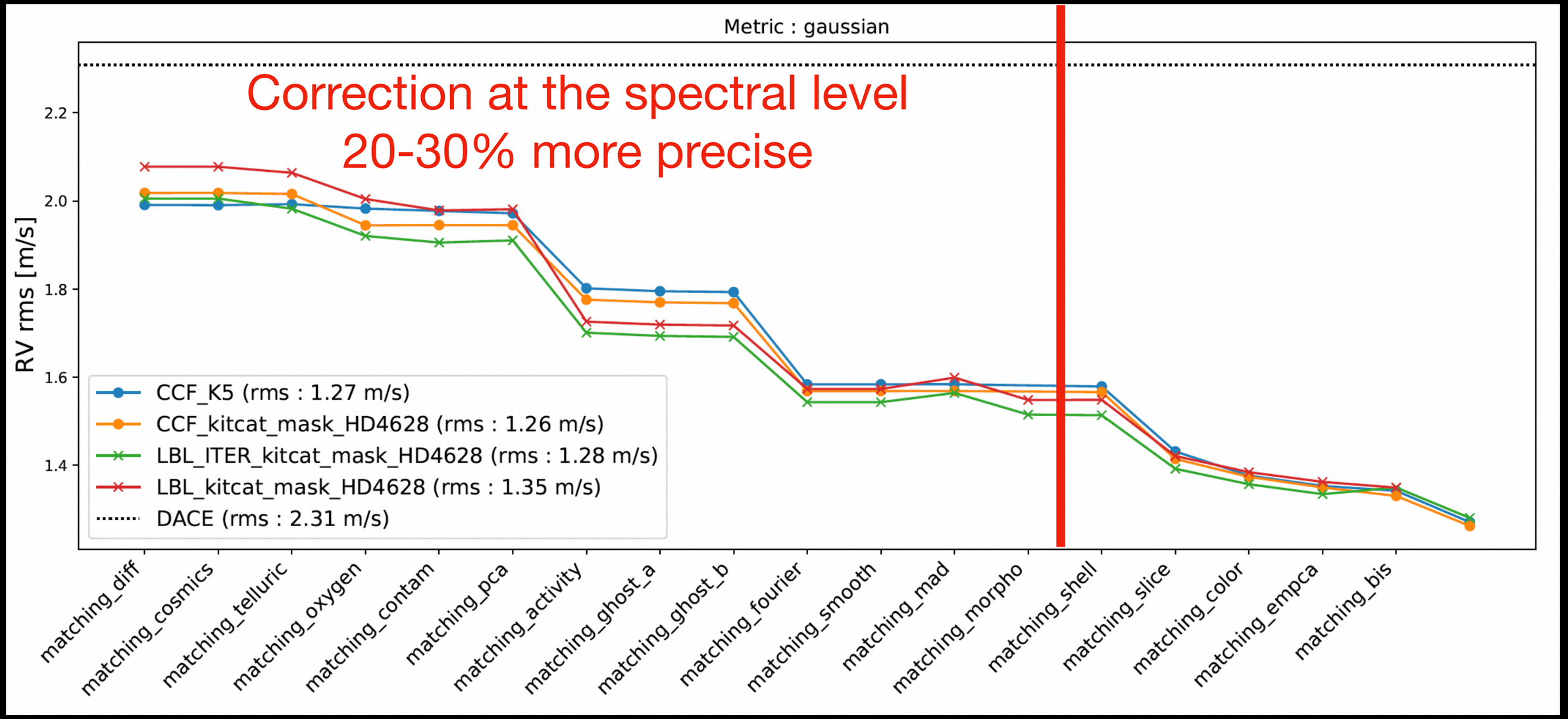
Stellar line





YARARA, Cretignier+ 20, 21

Benefits of correcting locally in the spectrum

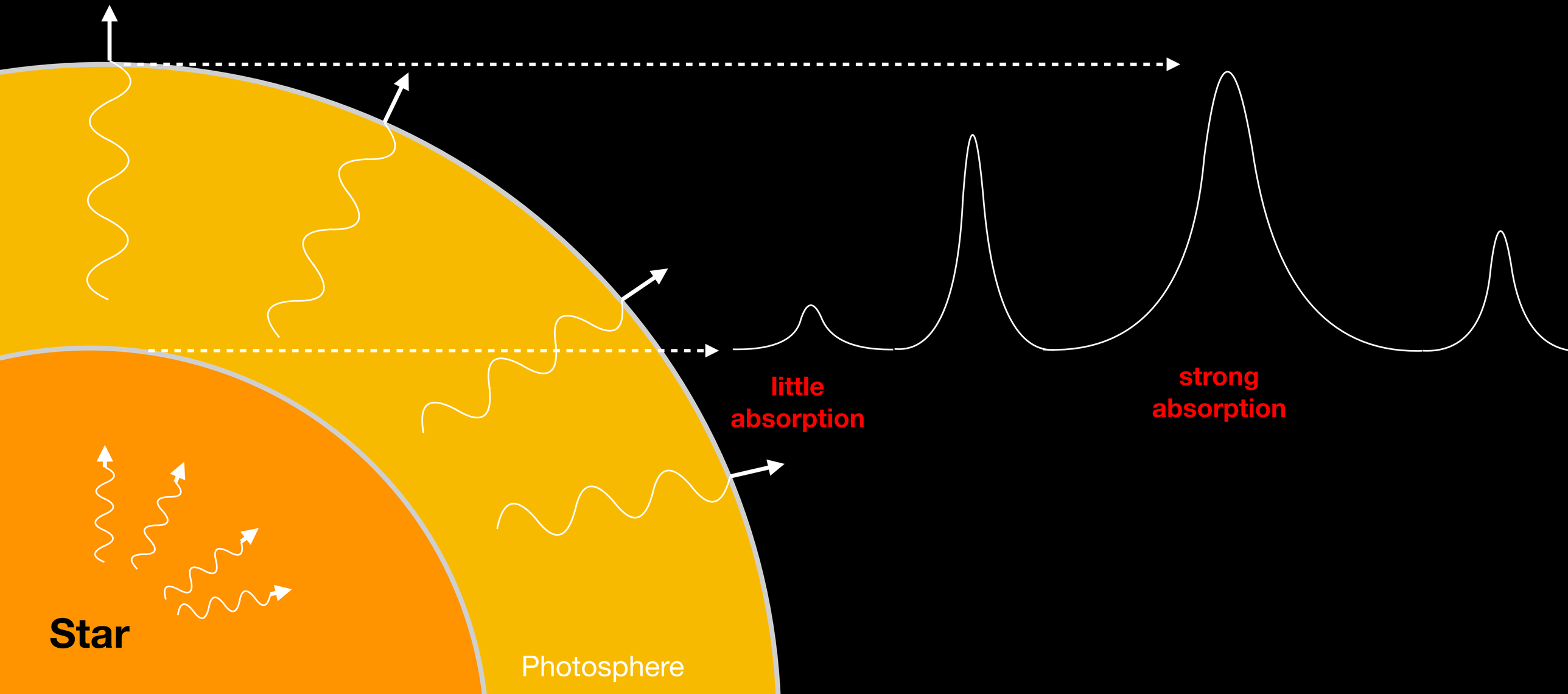


Cons: Mix physical information from spectral lines

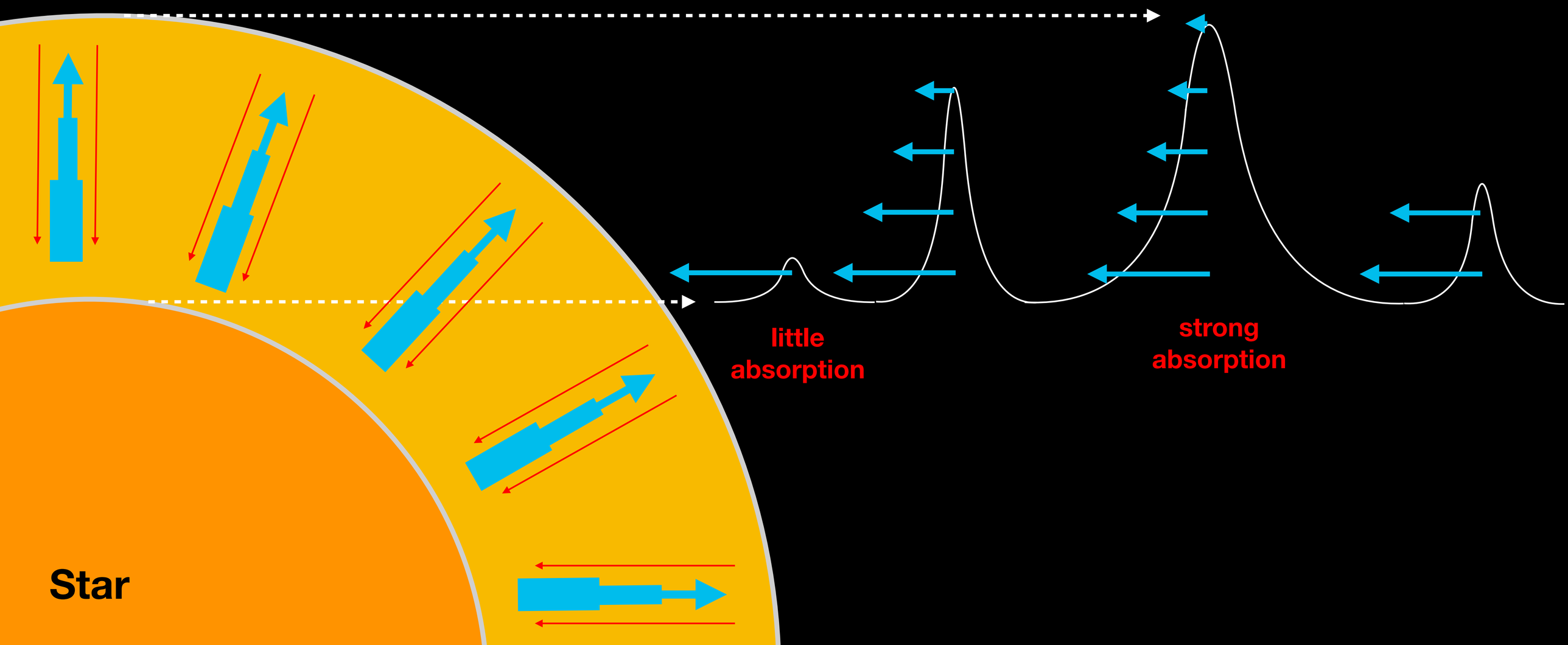
By doing CCF, template matching…

We are loosing physical information

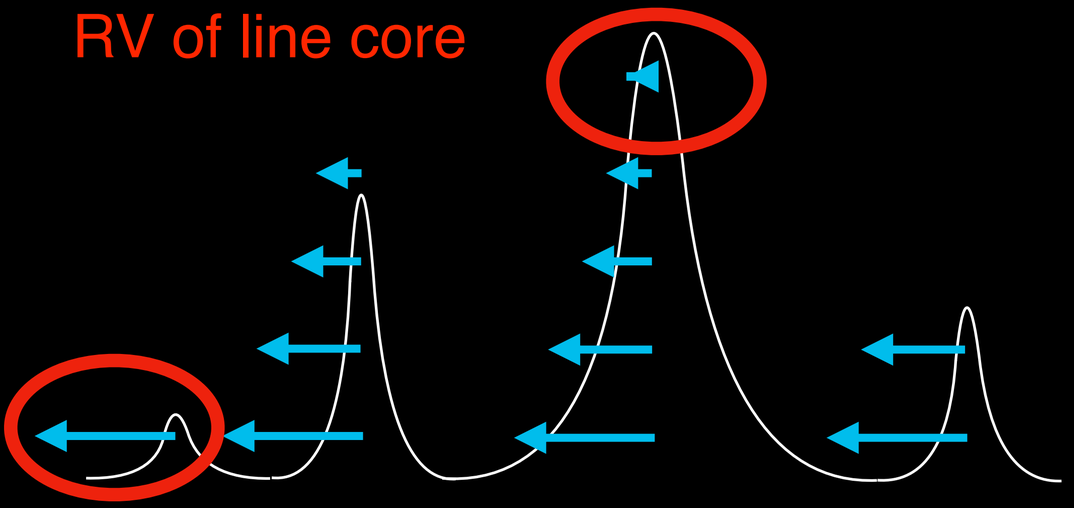
Formation of spectral lines 1.1

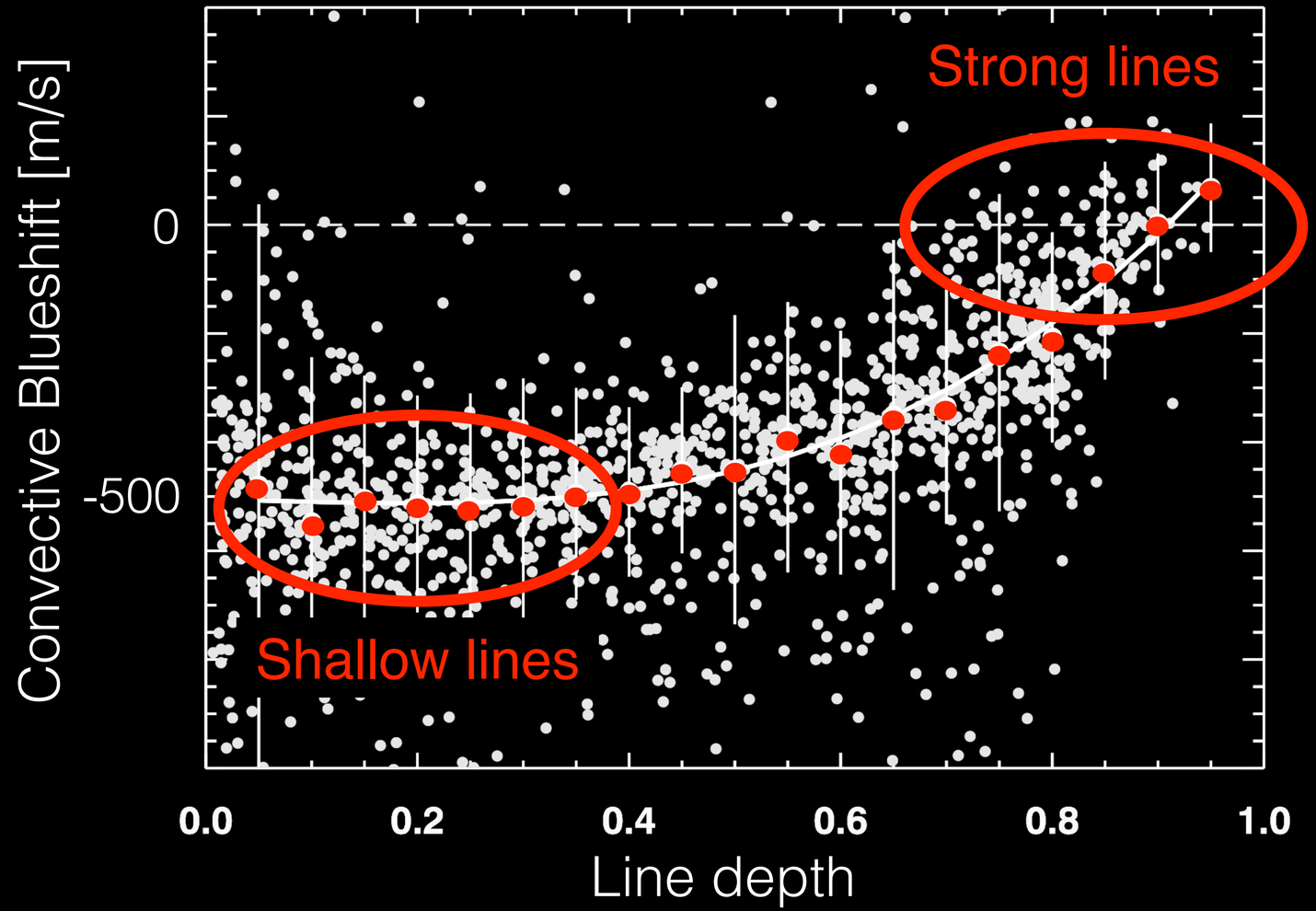


Convective blueshift



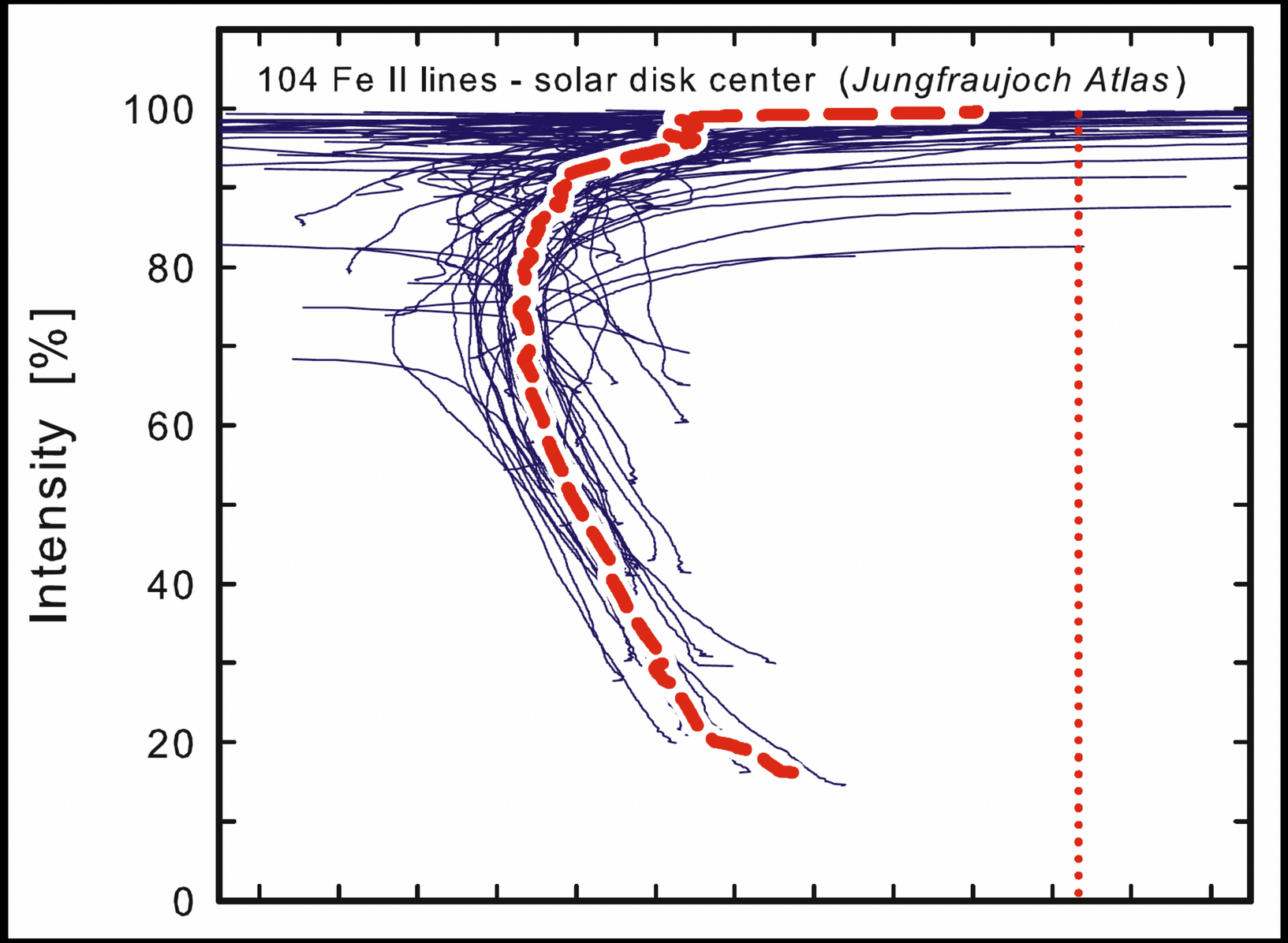
Convective blueshift



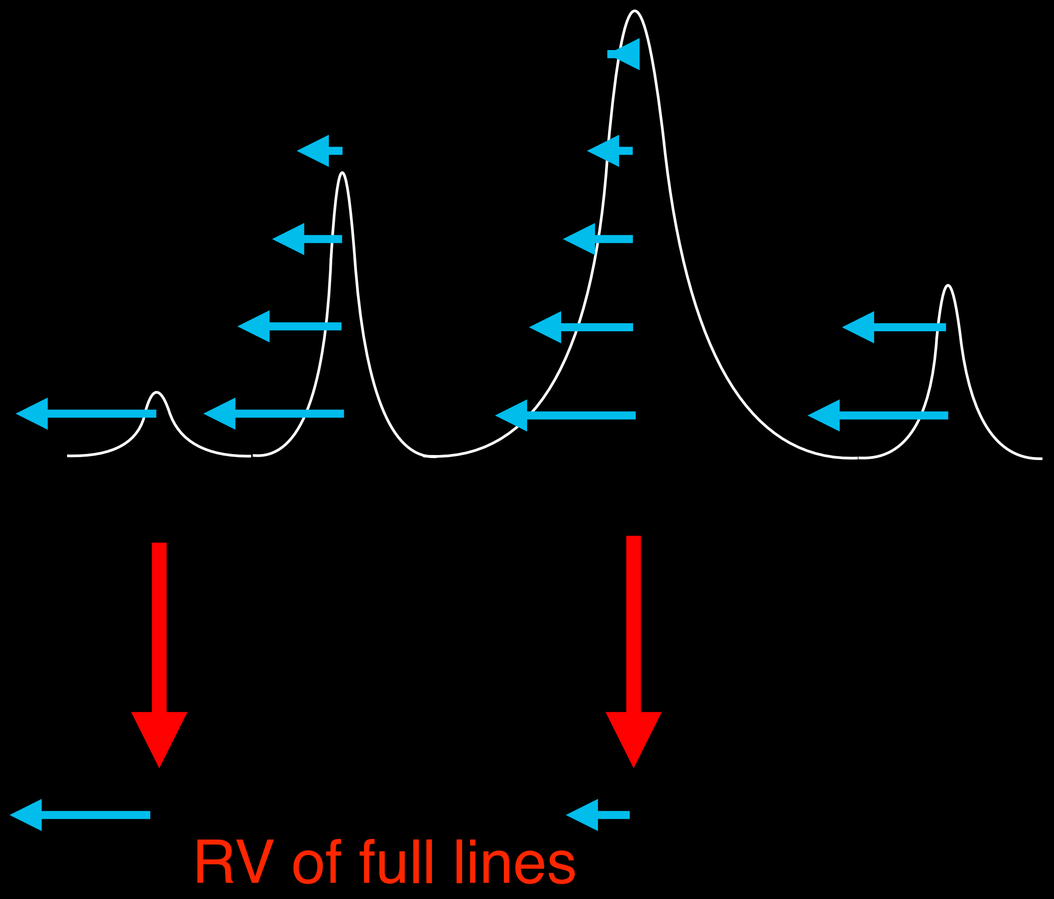


Reiners+ 16

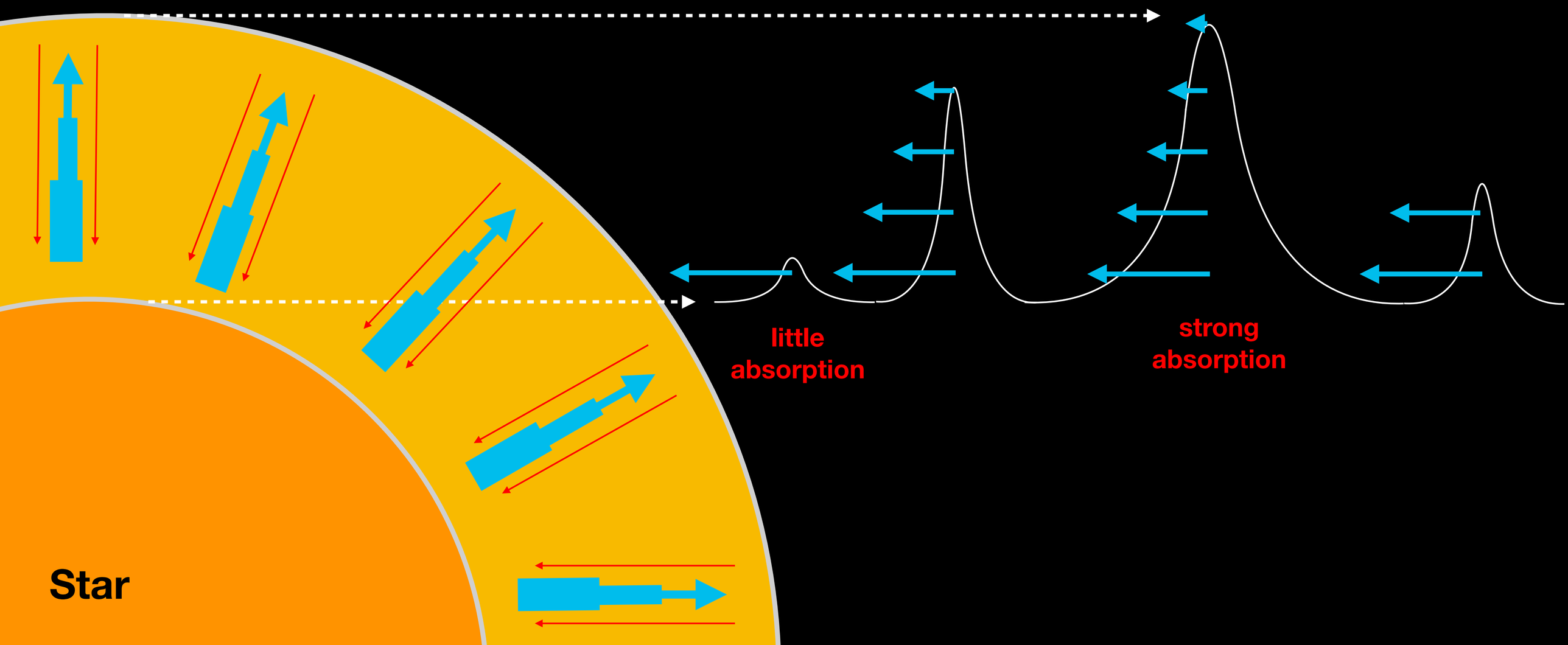
The C-shape of spectral lines



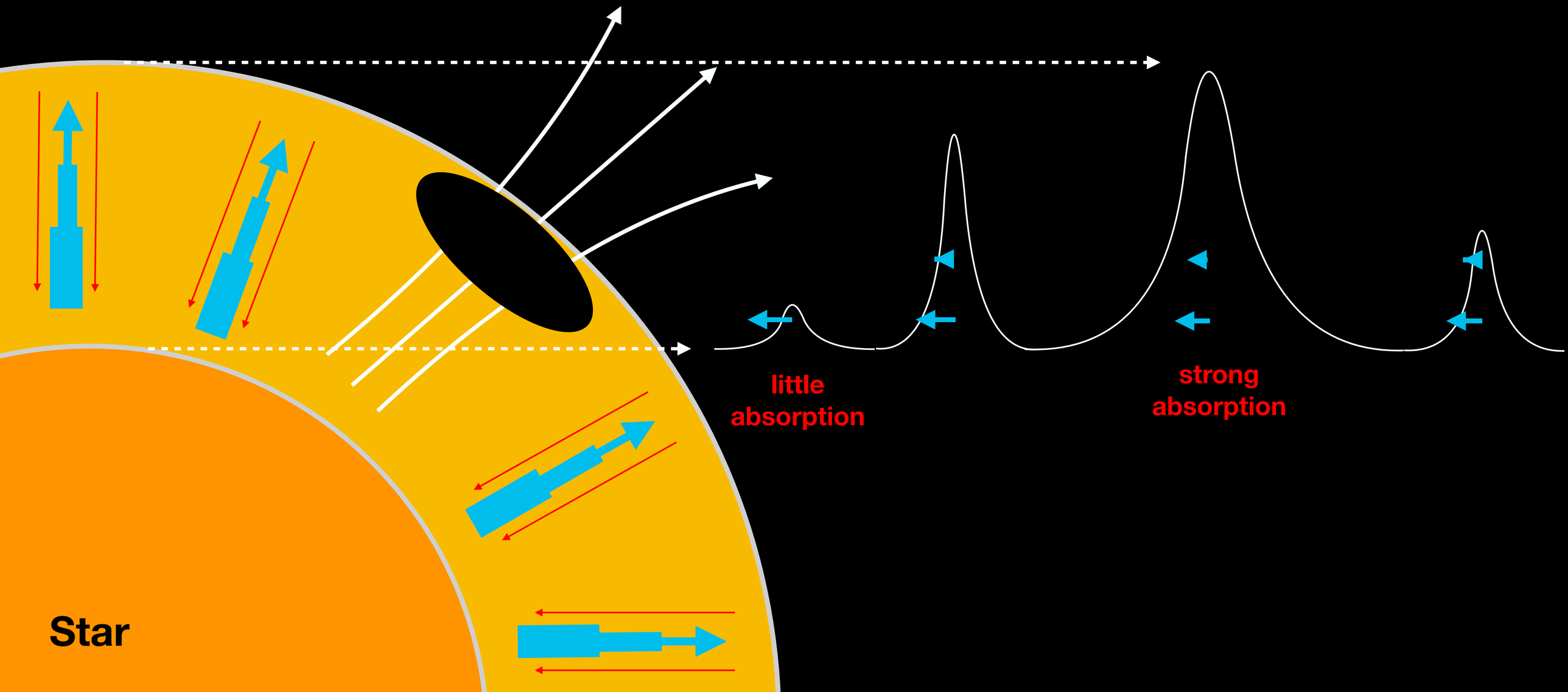
Convective blueshift



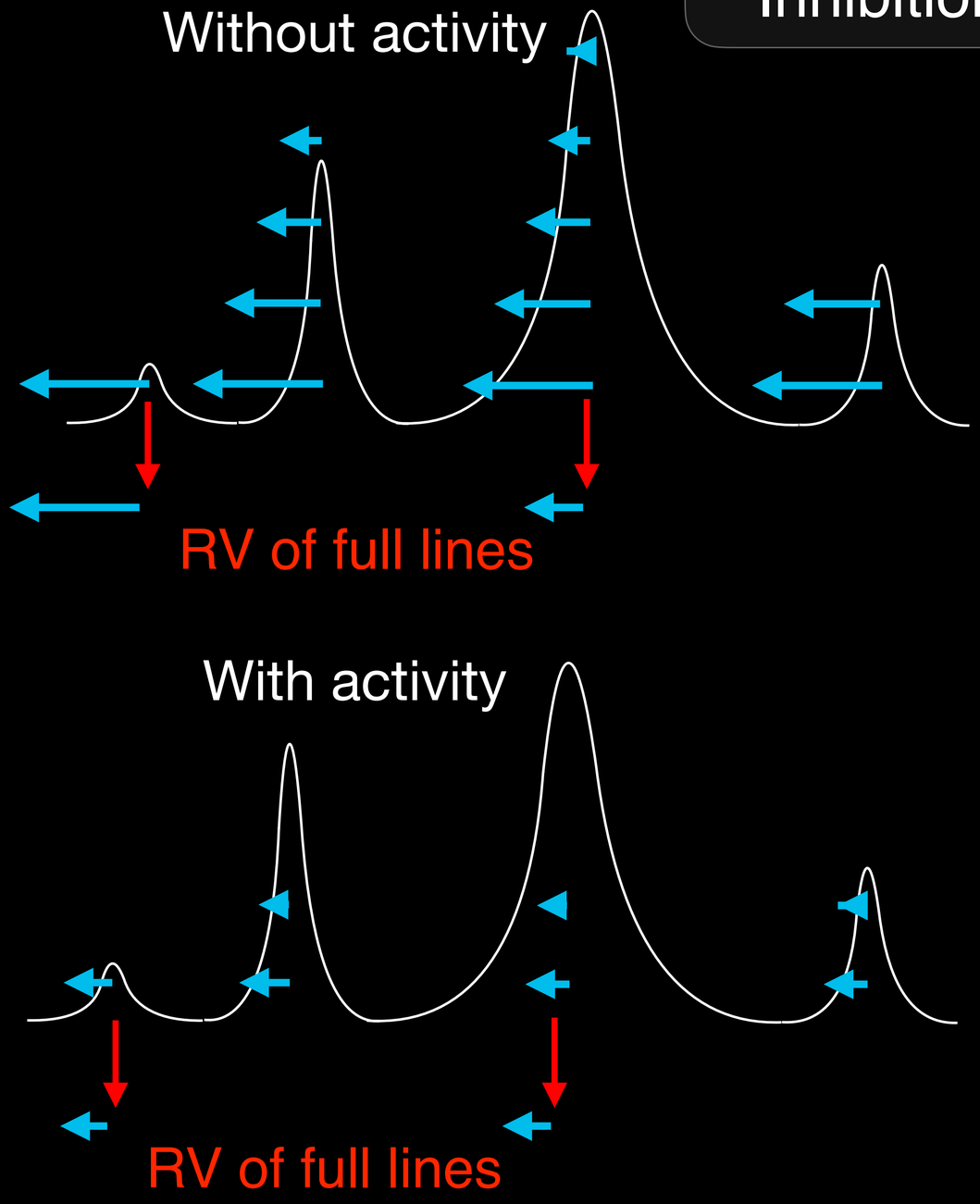
Convective blueshift

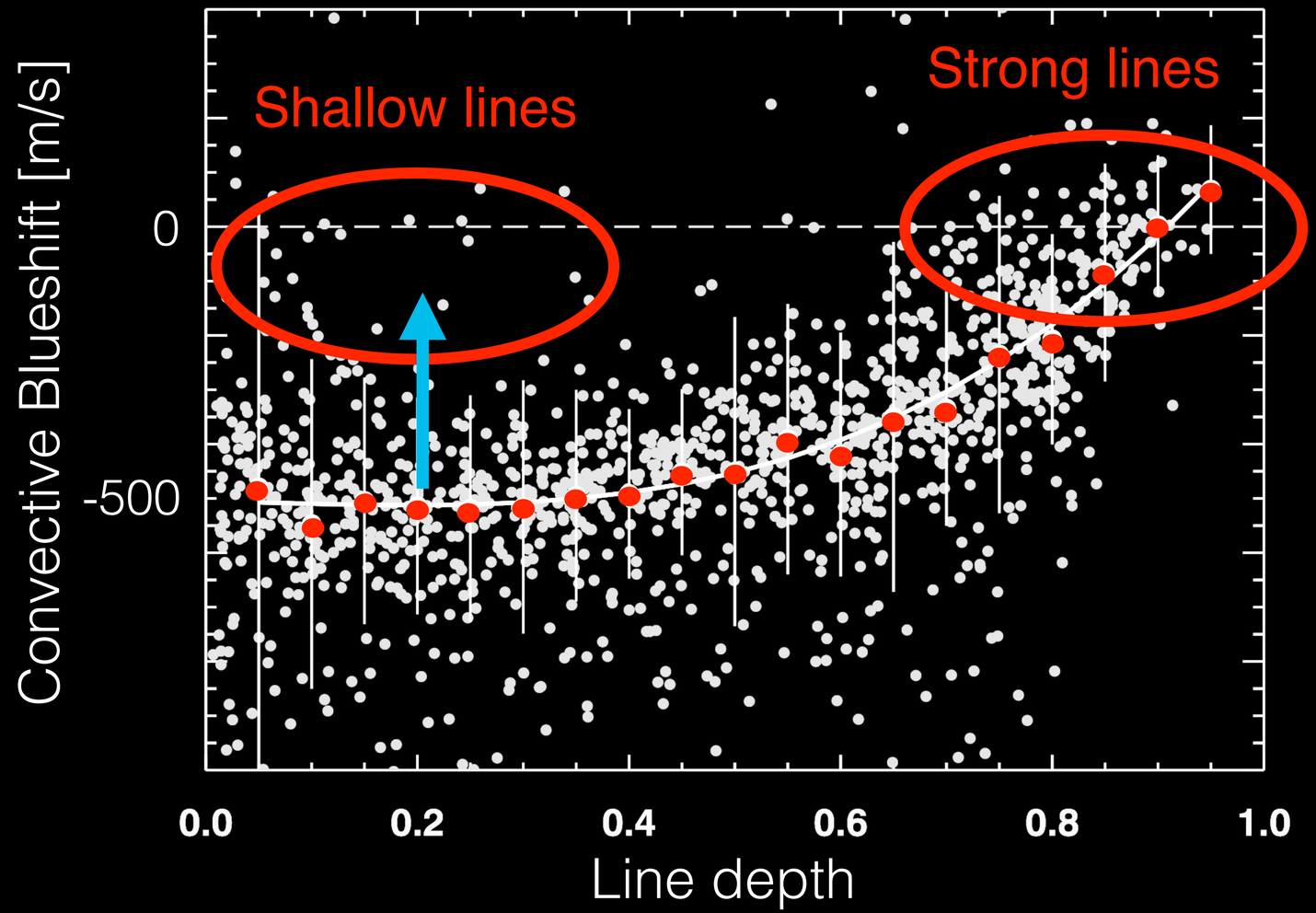


Inhibition of convective blueshift



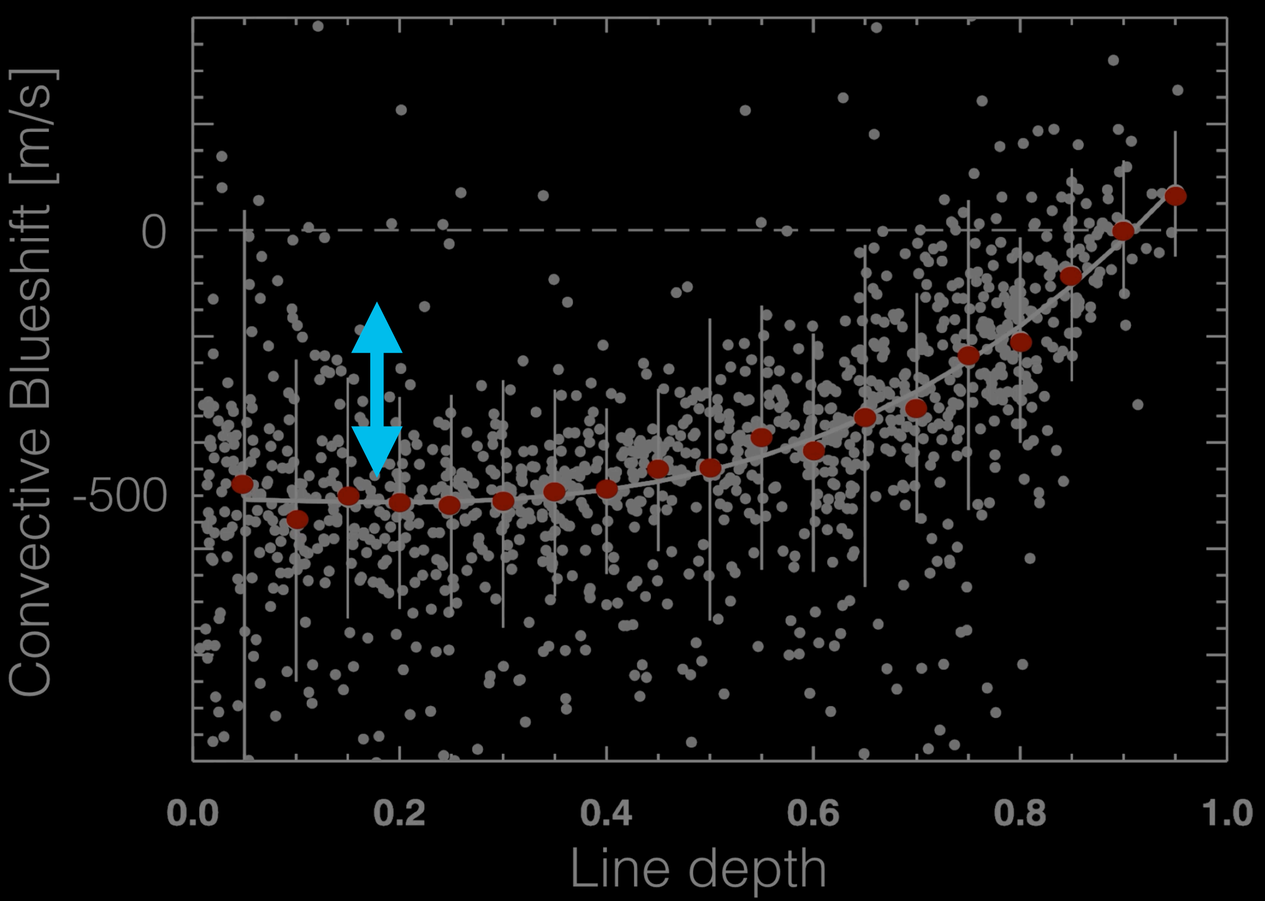
Inhibition of convective blueshift

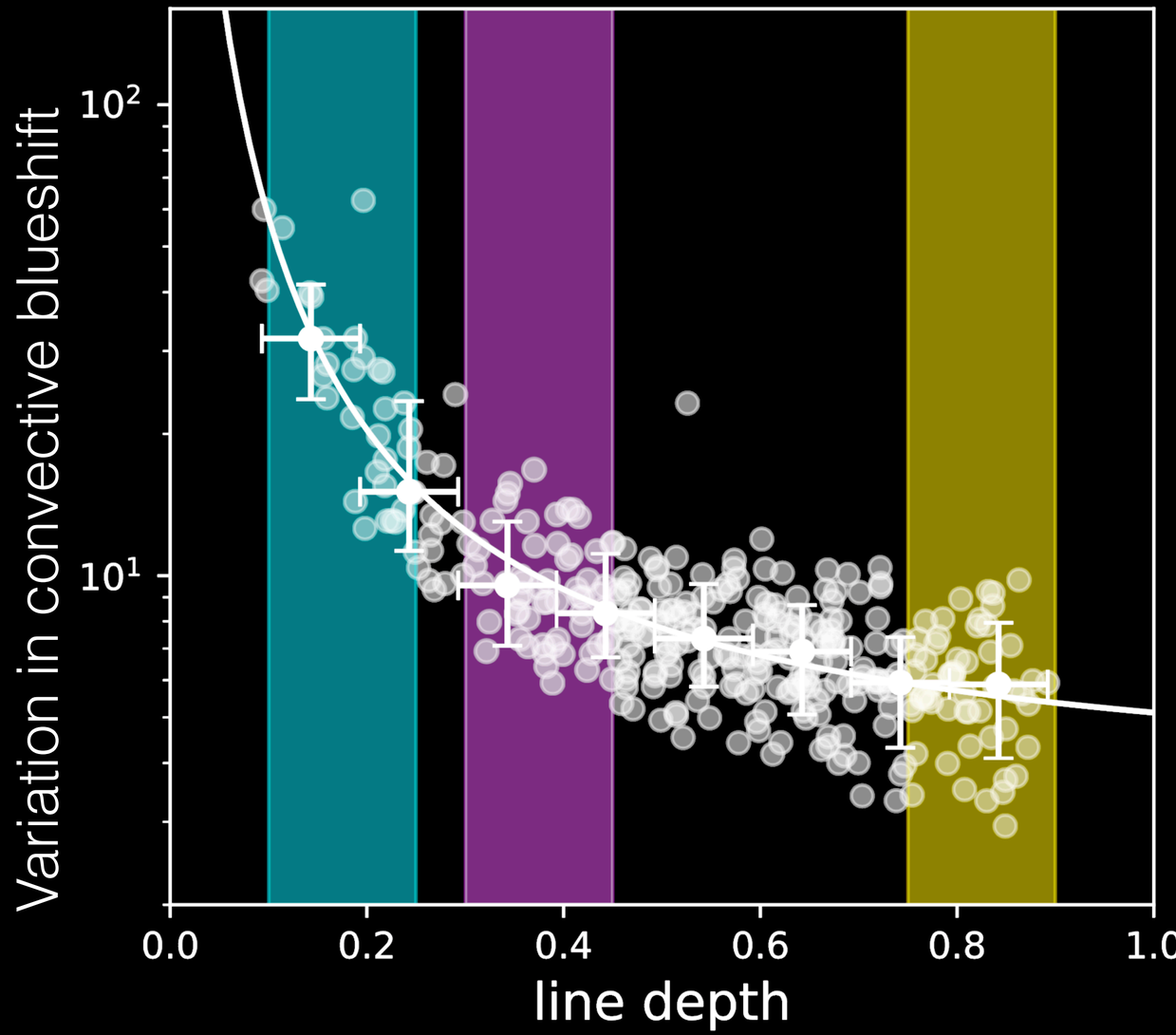




Reiners+ 16

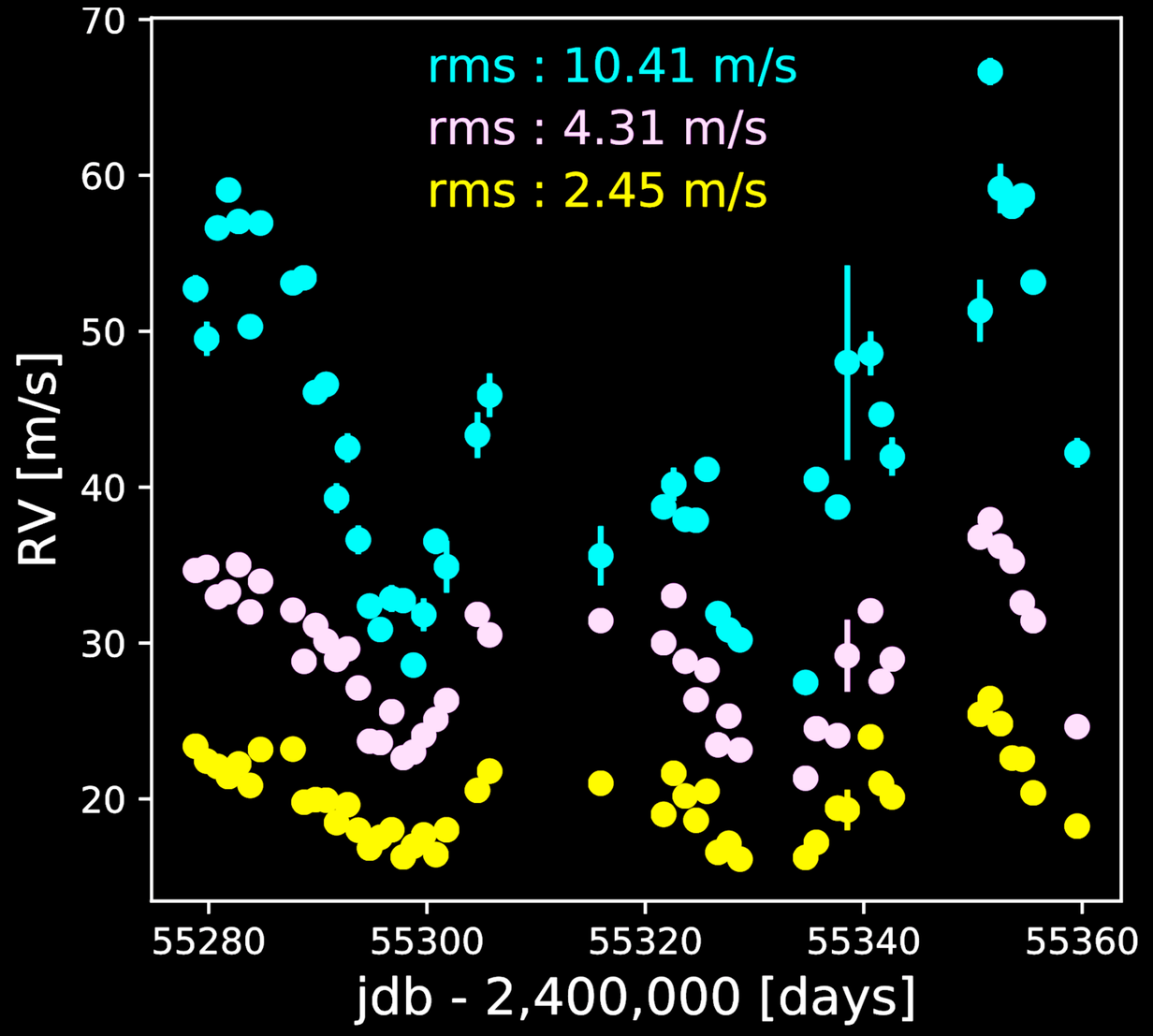
Stellar signal amplitude as a function of line depth

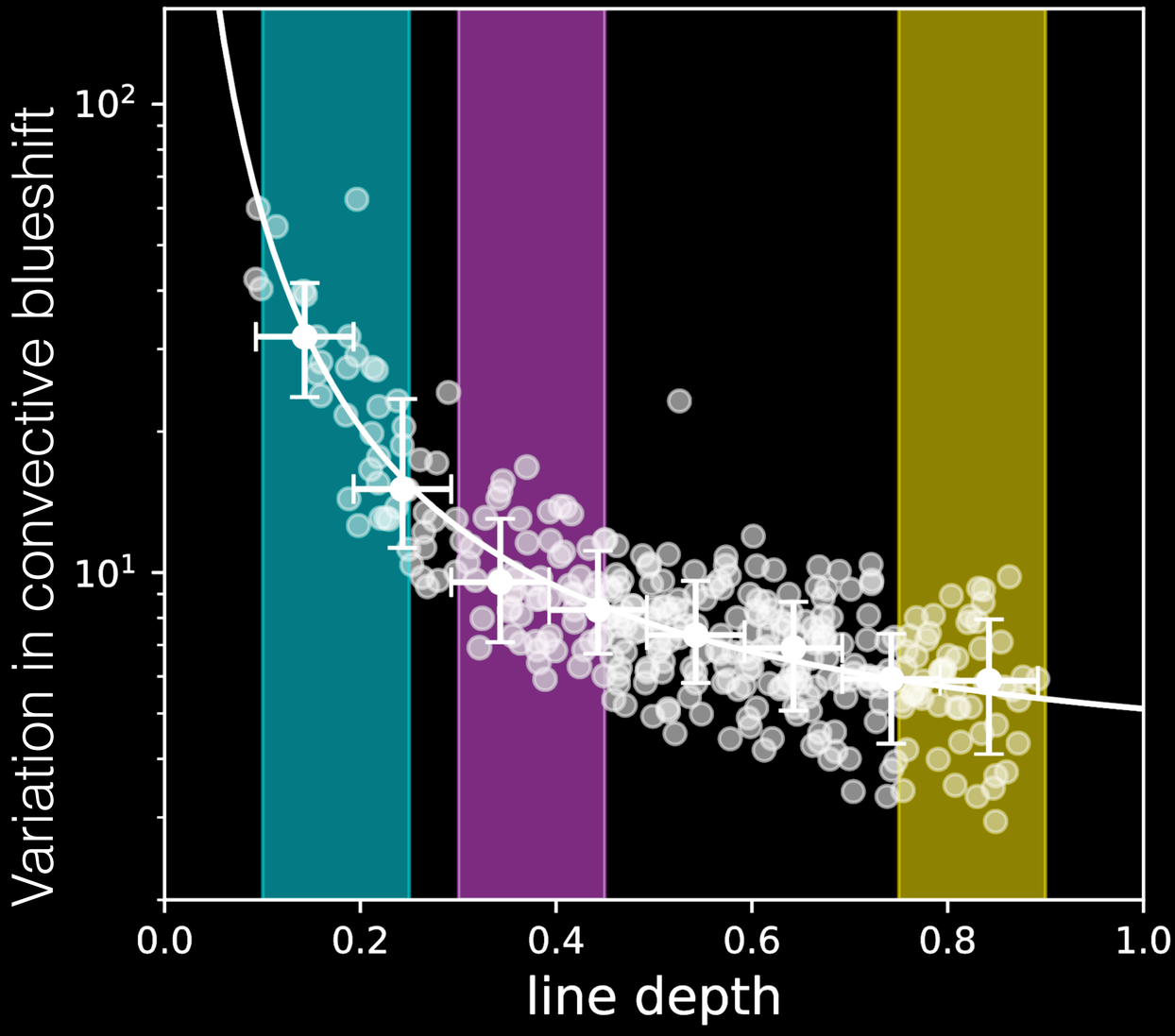




Cretignier+ 20, Al Moulla+ 22

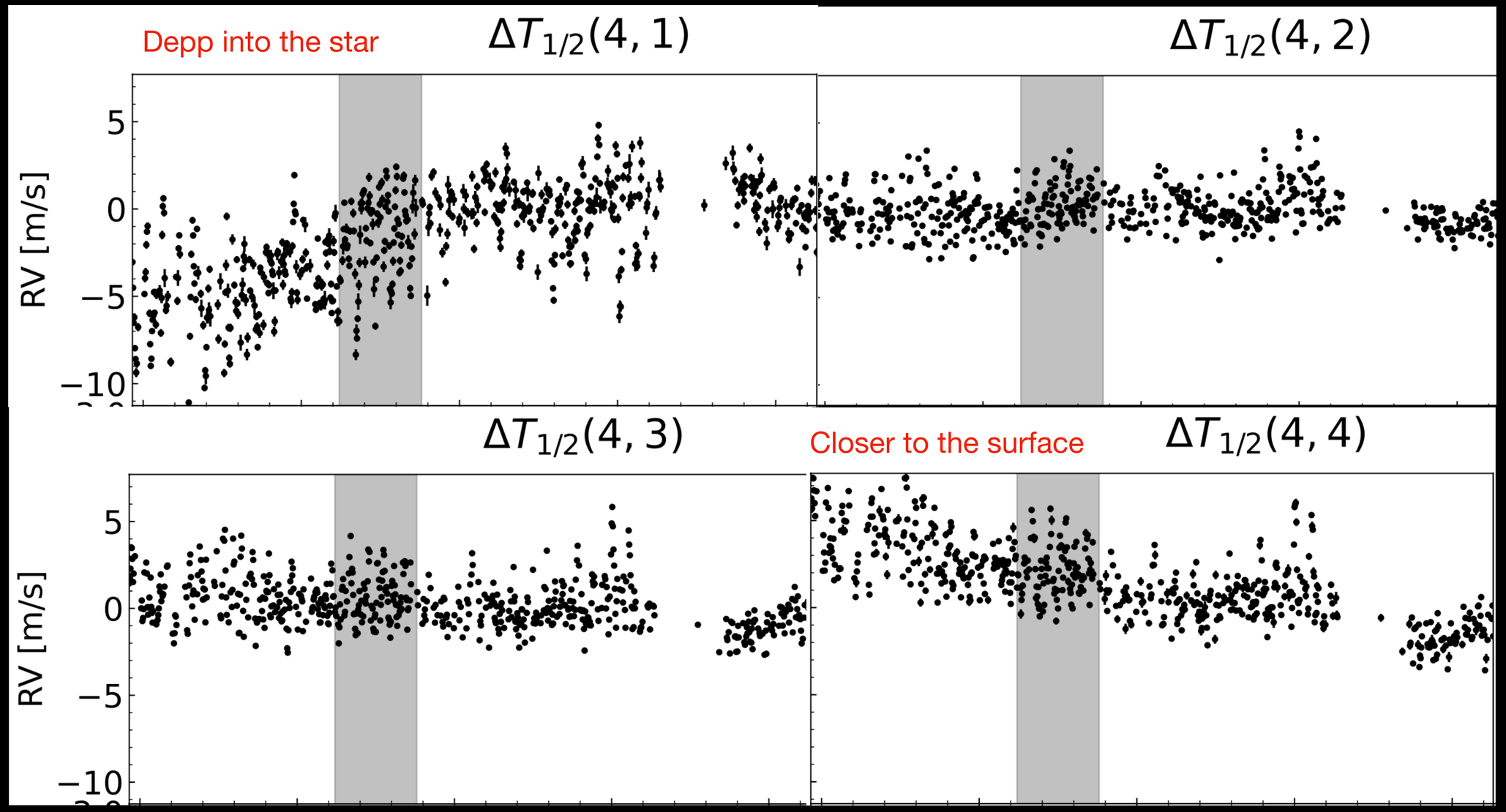
Stellar signal amplitude as a function of line depth





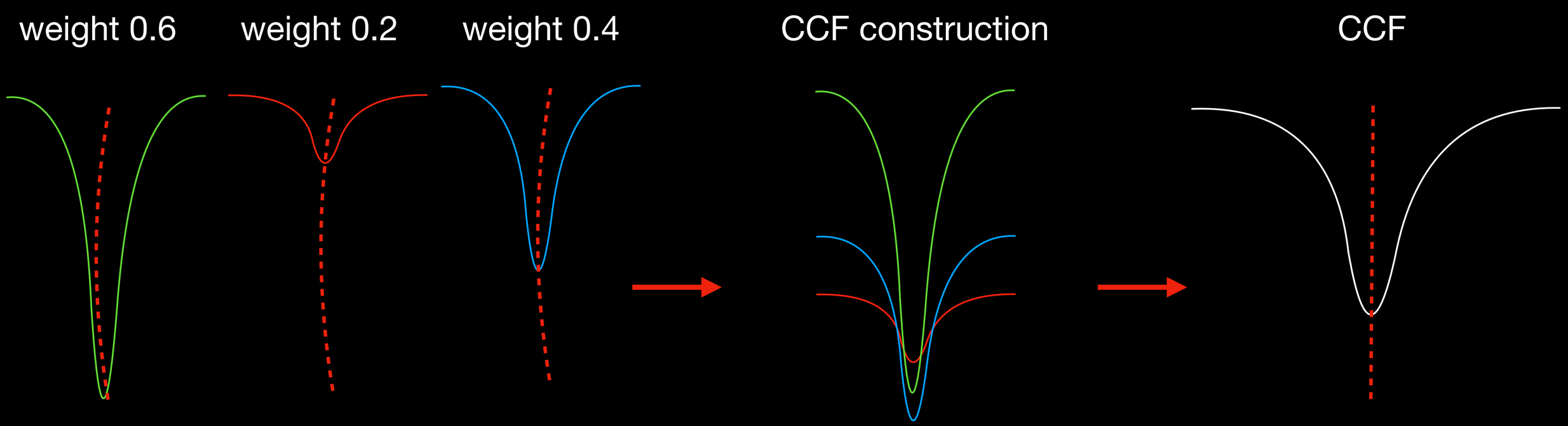
Cretignier+ 20, see also Thompson+17, Wise+ 18, 20

Stellar signal amplitude as a function of formation temperature



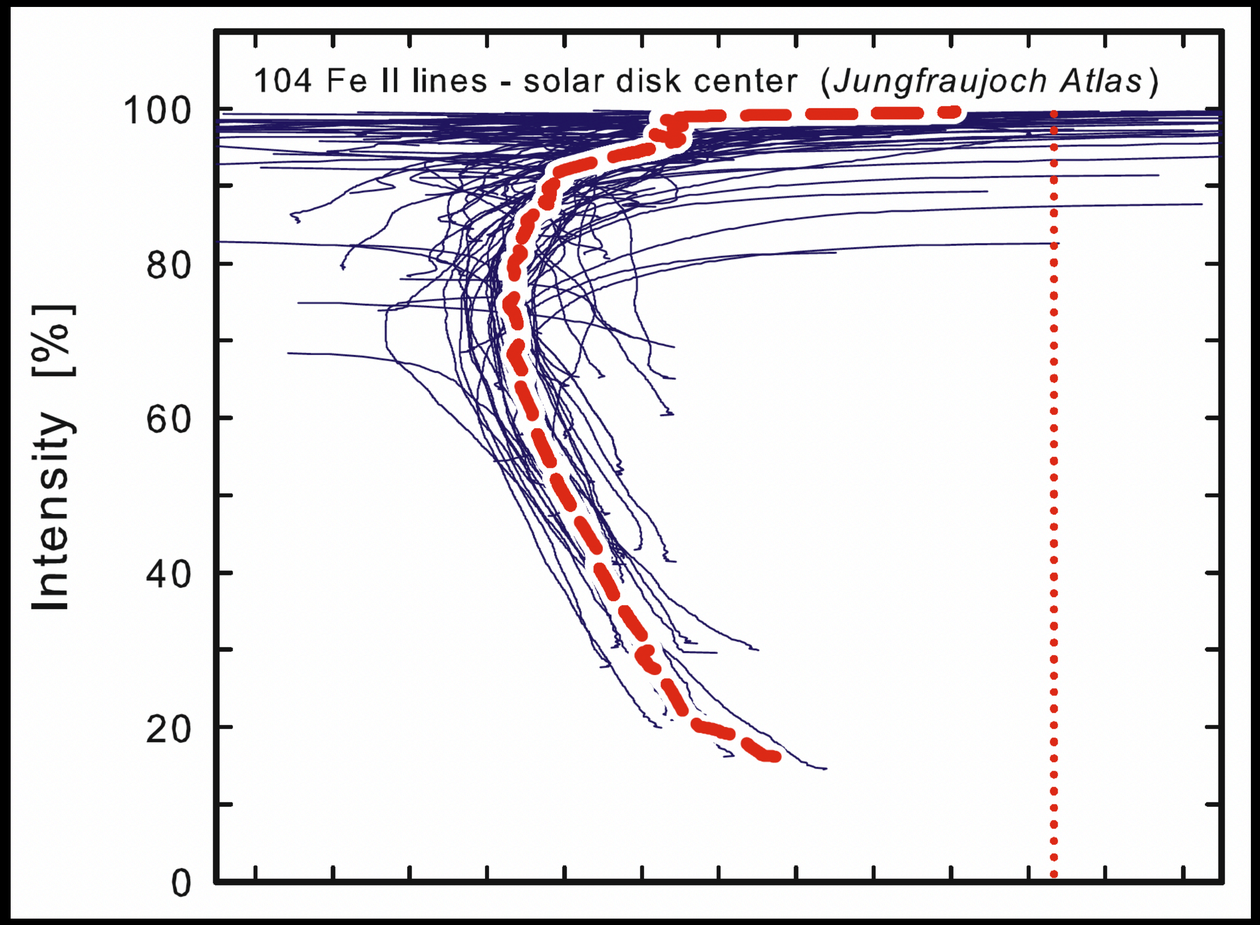
Al Moulla+ 22

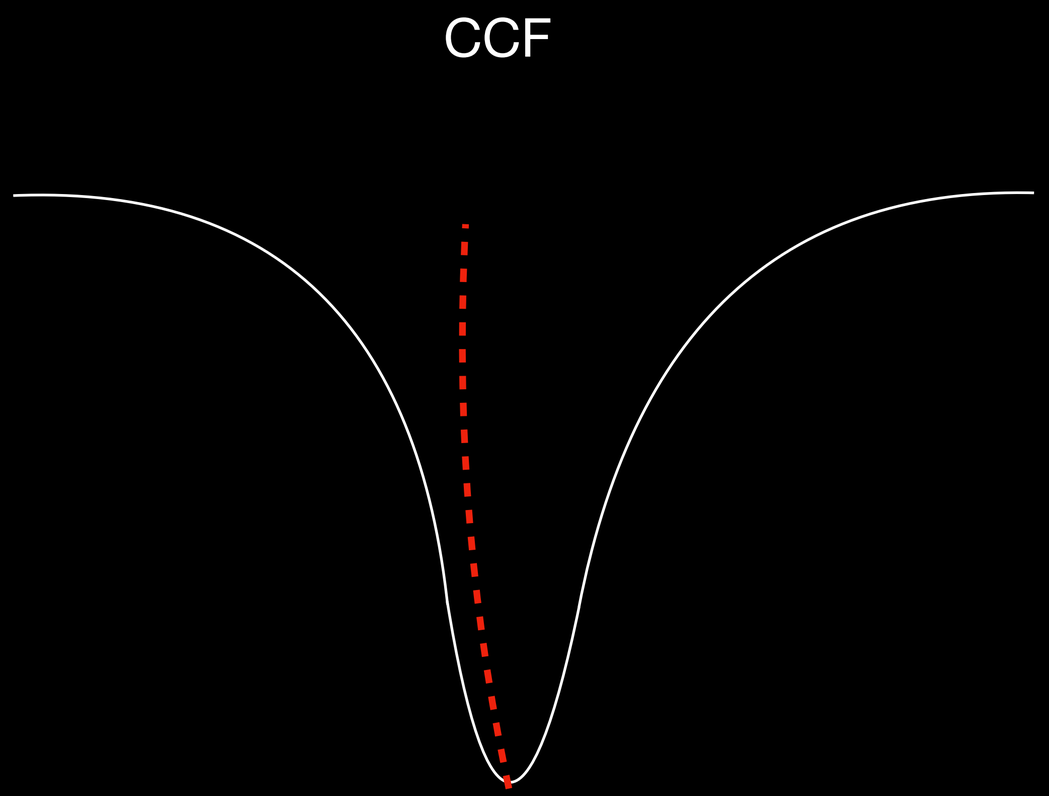
Cons: Mix physical information from spectral lines



Although line depth is a key parameter to understand stellar activity,
the CCF average out this information

The C-shape of spectral lines

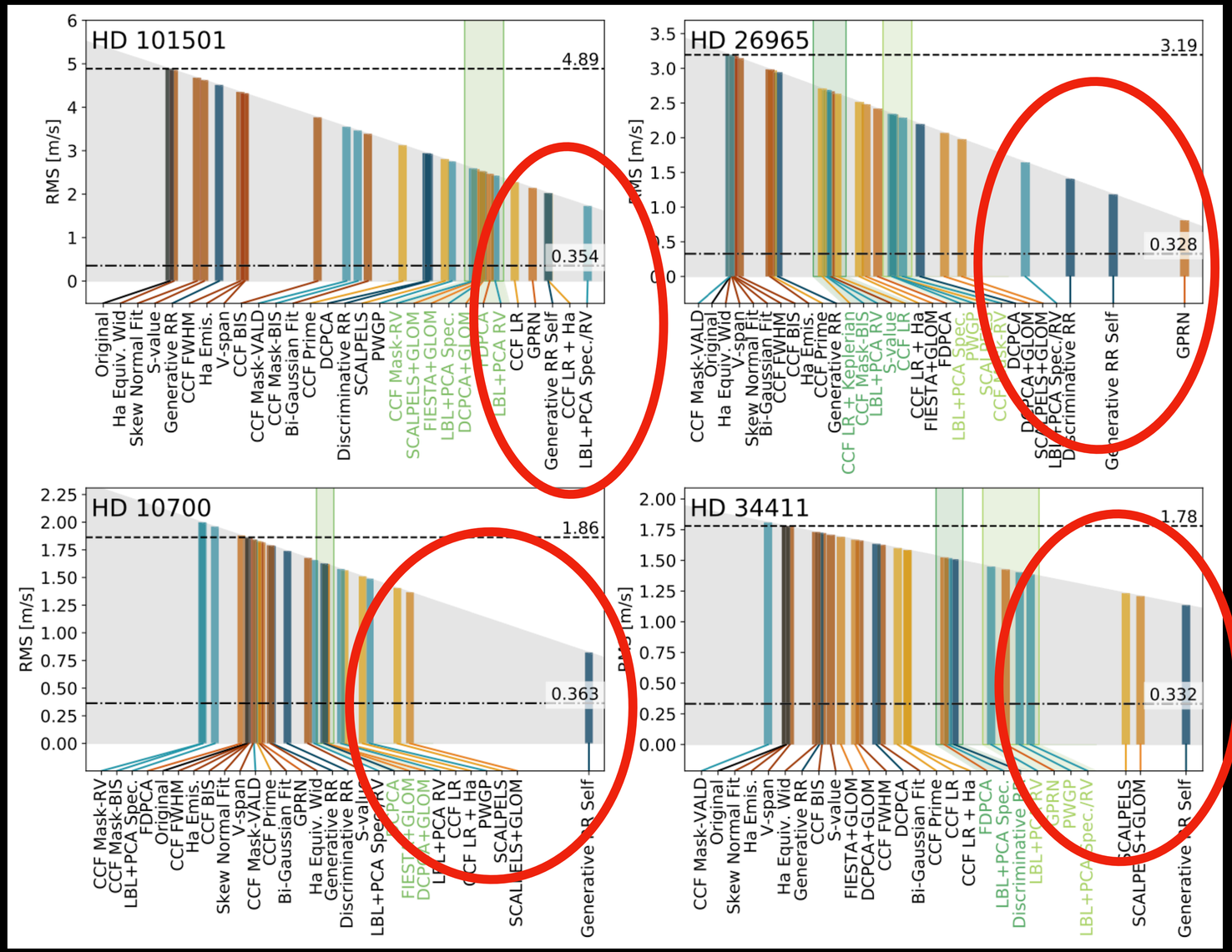




100-500 m/s (variations ~10 m/s)

10-50 m/s (variations ~1 m/s)

Techniques dealing with spectra (or CCF) mitigate better stellar signals



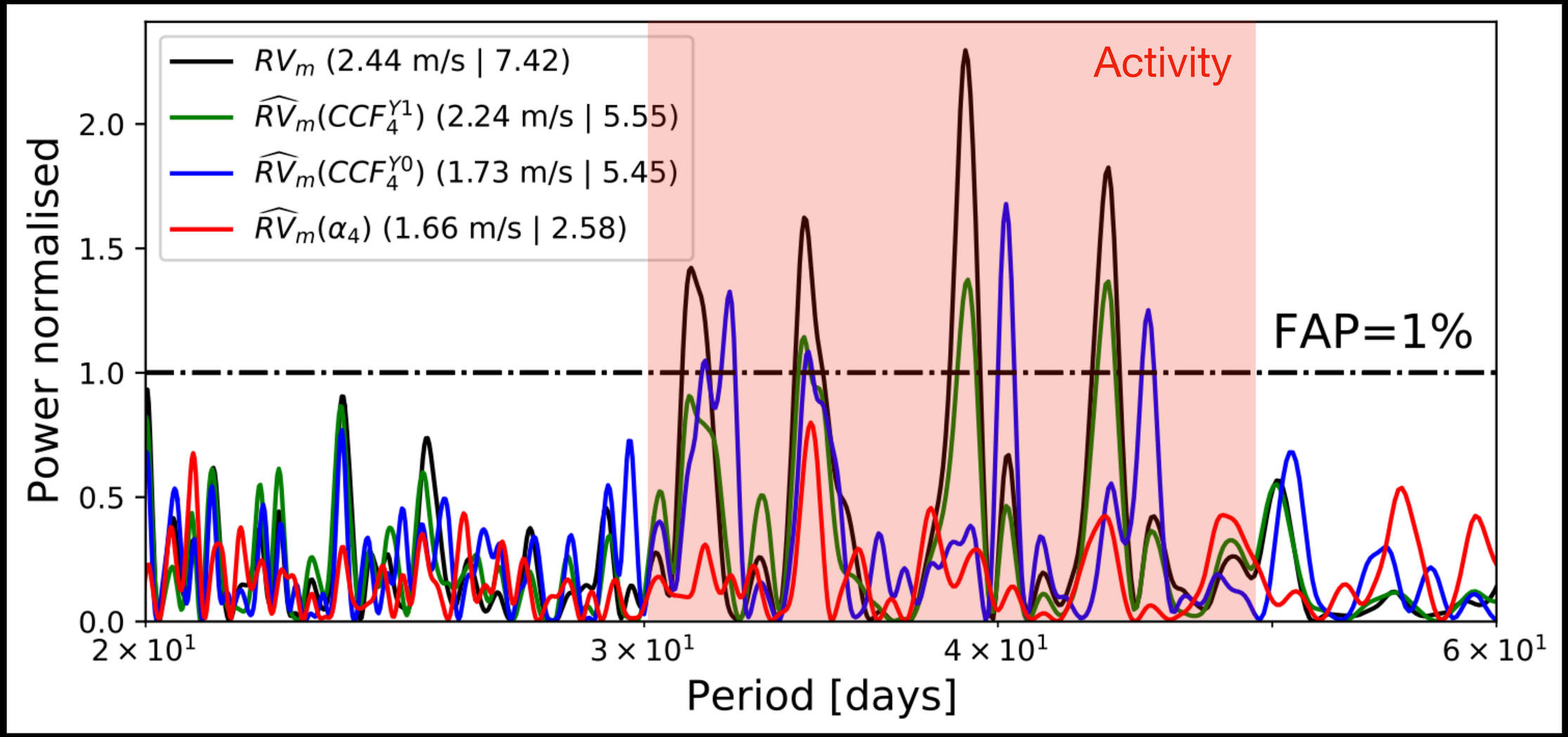
CCF or spectra techniques

Zhao+ 22

There is some hope !!!

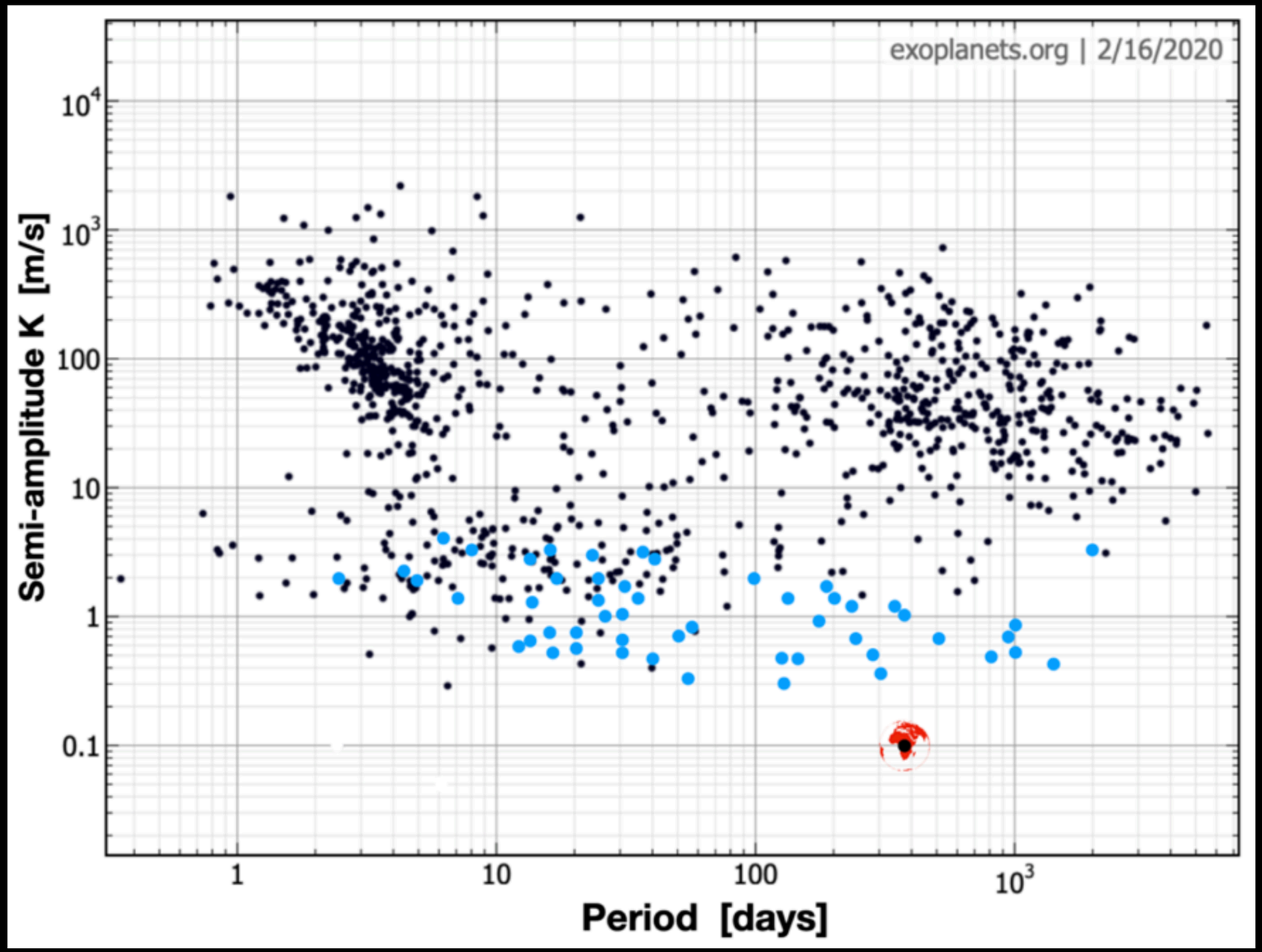
No or standard corrections

Spectral level corrections



Cretignier+ 22

There is some hope !!!



Cretignier+ in prep.

Take-home message

- Analysing spectral time-series is crucial to remove instrumental systematics
- Stellar activity leaves significant signals at the spectral level that we can measure, and that can be used to separate it from planetary signals

Developing techniques that works at the spectral level (or close to it) is key to reach 10 cm/s precision