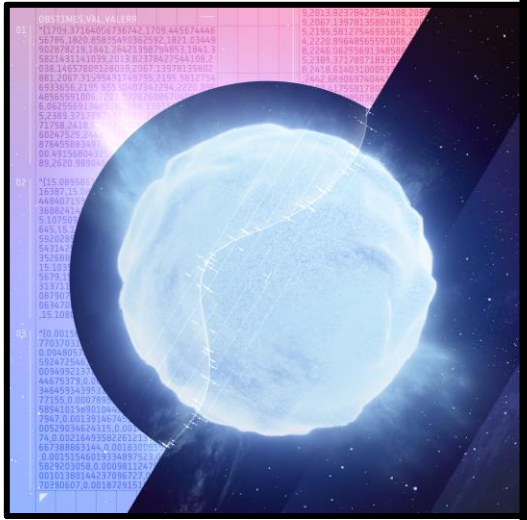
EPFL



Periodicities of binary Cepheids
-
Exploring a novel approach based on distance correlation

K. Barbey[1*], G. Viviani[1], R.I. Anderson[1]

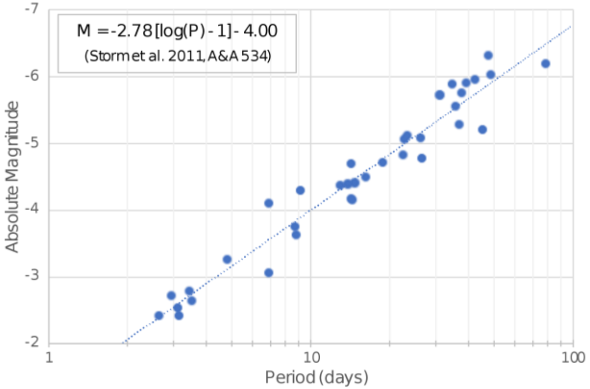
[1] Institute of Physics, EPFL, Chemin Peg 51b, CH-1290 Versoix

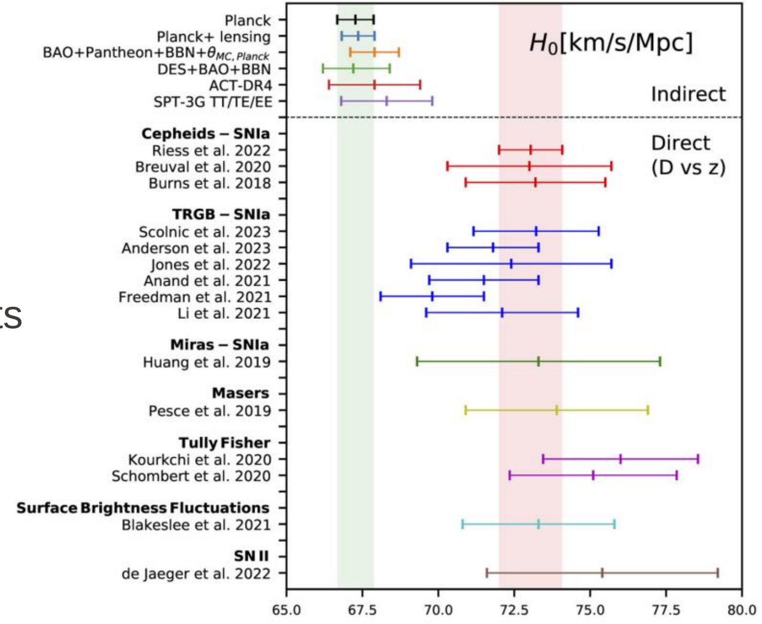
[*] kent.barbey@epfl.ch

Photo Credits: GAIA Vari Citizen Science Project

Context I
Period, Luminosity and the Hubble Constant

- **H_0**: Local expansion rate of the universe
  - How do we compute it: early vs late universe
  - PL relation
- **Hubble tension**
  - Early universe: 67.4 ± 0.5 [km/s/Mpc]
  - Late universe: 73.04 ± 1.04 [km/s/Mpc]
  - Two possible causes: distance measurements or cosmological model

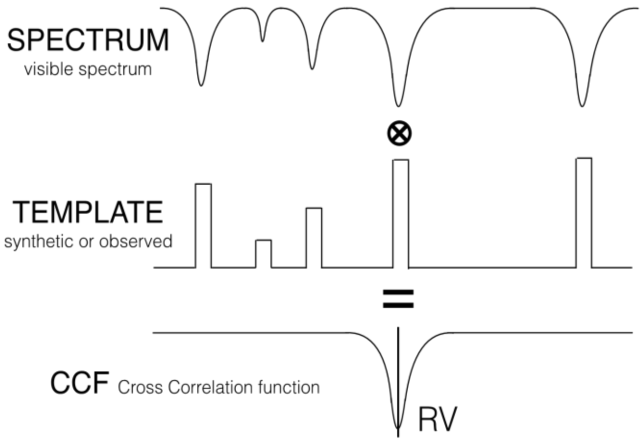




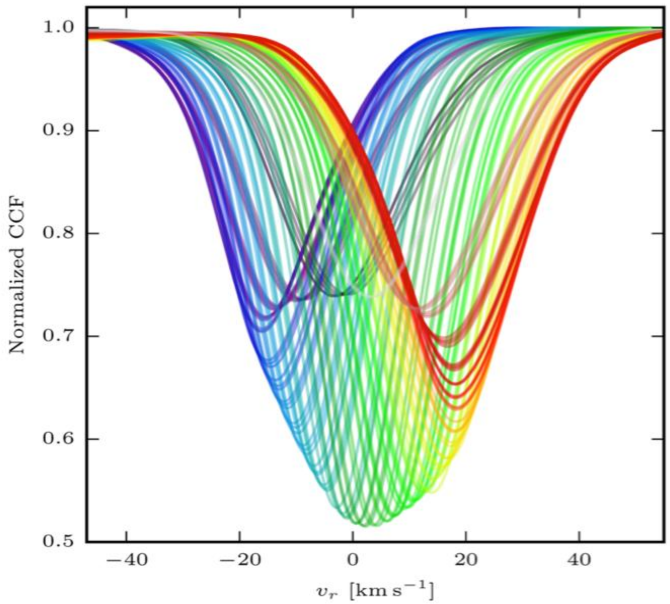
Credits: Riess (2023)

Context II
Radial velocities and periodicities

- **Radial velocity(RV):** velocity of a star to an observer projected on the line-of-sight.
  - Causes: orbital motion(~10-20 [km/s]) + pulsation of the star.
  - How do we find it: 1d-CCF for example.



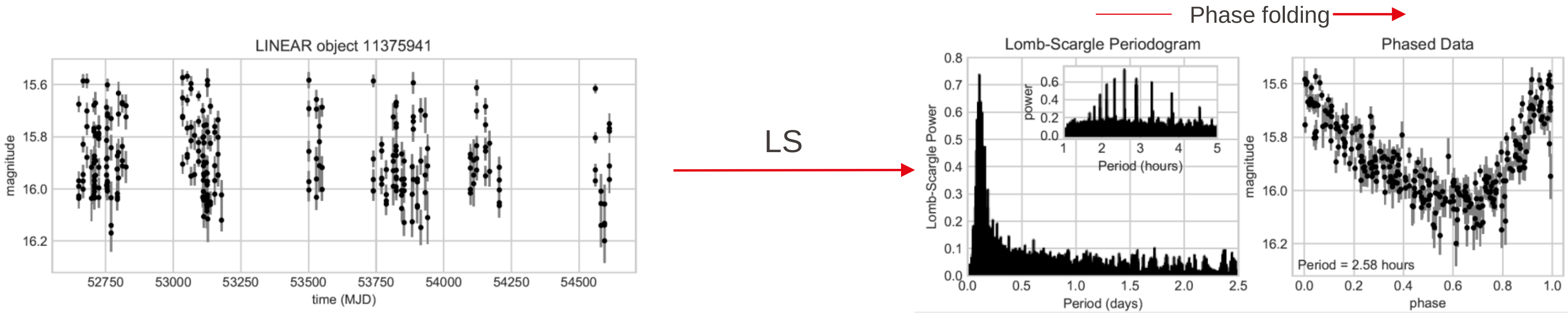
Credits: X. Dumusque



Credits: R.I. Anderson+2016

Finding periodicities with RVs.

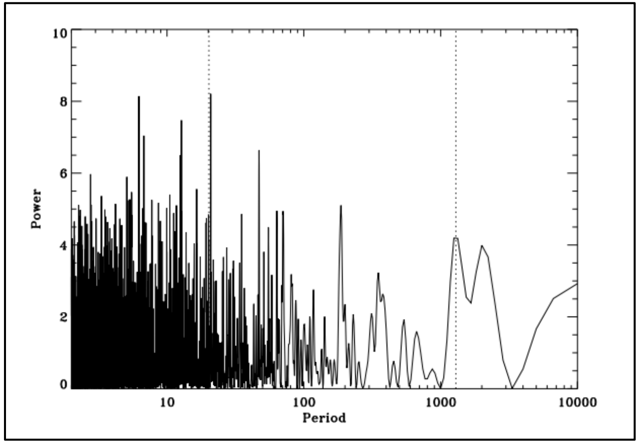
- **Phase-folding methods**: frequency that optimises a cost function
- **Least-squares methods**: frequency that maximises the likelihood of the fit.
- **Bayesian approaches**.
- **Fourier methods**: Schuster, *Lomb-Scargle(LS)* etc…



Credits: J. VanderPlas (2018)

Motivation I
Why is the LS periodogram not always enough ?

- The case of Classical Cepheid variable stars.
  - Radial velocity: up to ~60 [km/s].
  - Often in binary systems.
  - Effects of pulsation: shift + shape variation of spectrum.
- What is the problem then ?
  - Time-varying shape modulations can
    - Induce errors in shift measurement
    - Mimic exoplanet reflex motion



Credits: Carolo et al. (2014)

Motivation II
Why this new approach and what does it do?

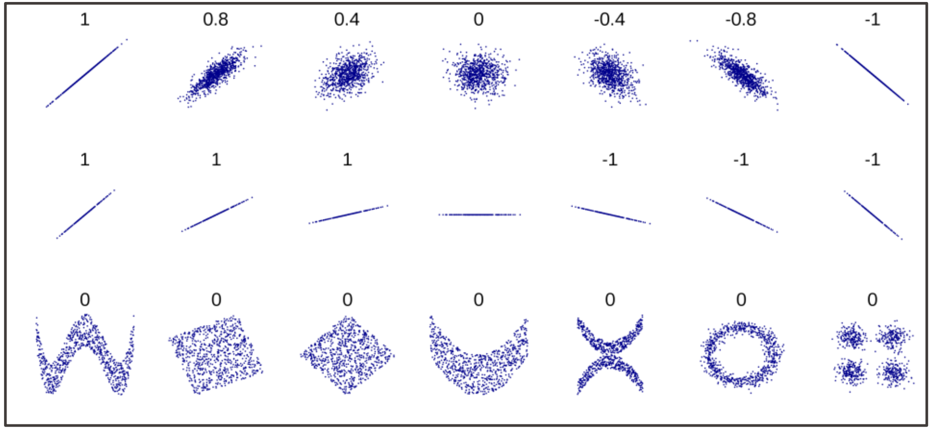
- Important to distinguish orbital from pulsational(stellar activity) motions.
  - Find companions to Cepheid binaries.
  - Uncover presence of non-radial pulsations.
  - Confirm older methods’ results.
  - Find something else?
- Distance correlation-based periodograms:
  - No sinusoidal assumption
  - Shift: shape variations influence is controlled
    - Sensitive to line displacements.
  - Shape: shift variations influence is controlled
    - Sensitive to shape variations.

Two periodograms for the price of one

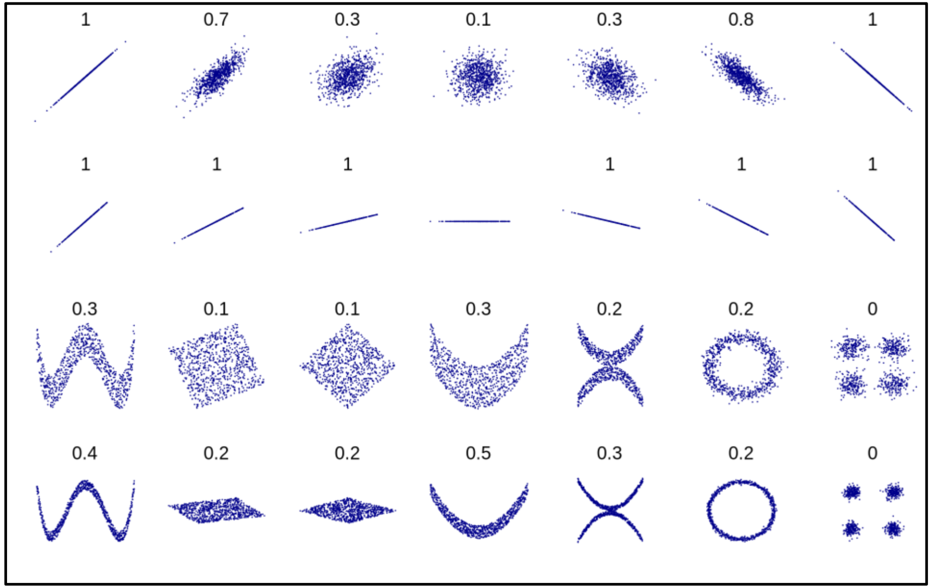
Mathematical framework I
Semi-partial distance correlation: A didactic example

- **Pearson's correlation**: measure of linear statistical relationship between two random variables → linear dependence
- **Distance correlation(Szèkely, 2005)**: measure of both linear and non linear relationships between two random variables.

  → General dependence



Correlation coefficient:
$Cor(X, Y)$



Distance correlation coefficient:
$dCor(X, Y)$

Mathematical framework II
Semi-partial distance correlation: A didactic example

- **Experiment:**
  - **GOAL** : Assess the relation between color($\boldsymbol{x}$) and effective temperature($\boldsymbol{y}$) for stars.
  - Take n stars and measurements of color, T_{eff} and line-of-sight dust column density($\boldsymbol{z}$).

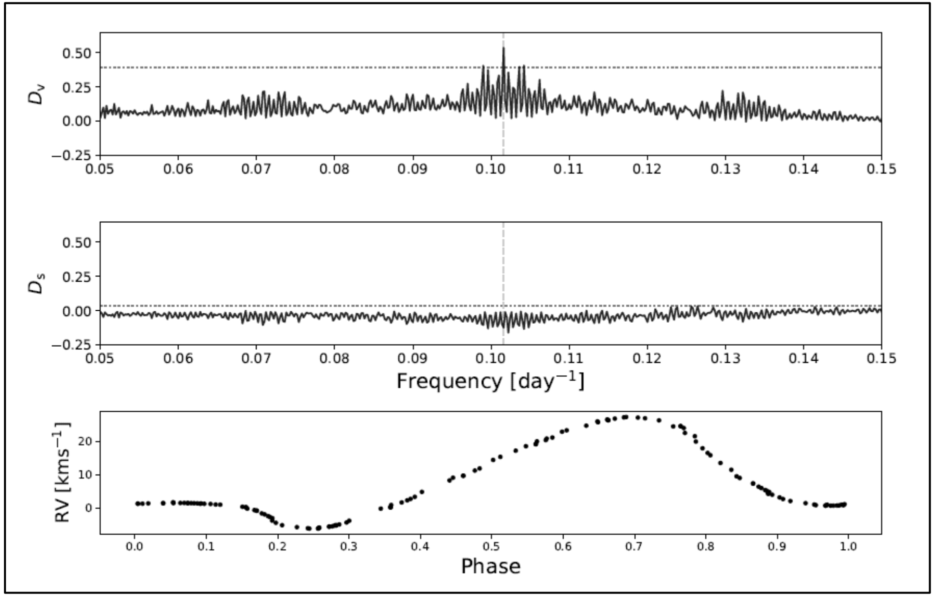
$$\boldsymbol{x} = \begin{pmatrix} x_1 - \overline{x} \\ \vdots \\ x_n - \overline{x} \end{pmatrix}, \quad \boldsymbol{y} = \begin{pmatrix} y_1 - \overline{y} \\ \vdots \\ y_n - \overline{y} \end{pmatrix}, \quad \boldsymbol{z} = \begin{pmatrix} z_1 - \overline{z} \\ \vdots \\ z_n - \overline{z} \end{pmatrix}$$

  - Naive idea: compute $Cor(x, y) = \frac{1}{\mathrm{n}} \frac{\langle x,y \rangle}{\boldsymbol{\sigma_x \sigma_y}}$. Problem: **x** and **y** may be correlated with **z**!

    → **z**: nuisance parameter.
  - Solution: Partial correlation: $pCor(x, y) = \frac{1}{n} \frac{\langle \boldsymbol{e_x}, \boldsymbol{e_y} \rangle}{\boldsymbol{\sigma_{e_x} \sigma_{e_y}}}$ or semi-partial: $\frac{1}{n} \frac{\langle \boldsymbol{e_x}, \boldsymbol{y} \rangle}{\boldsymbol{\sigma_{e_x} \sigma_y}}$
  - From correlation to distance correlation: **x, y, z** → $\overline{\overline{\boldsymbol{x}}}$, $\overline{\overline{\boldsymbol{y}}}$, $\overline{\overline{\boldsymbol{z}}}$ (distance matrices)
- **For us:** $\overline{\overline{\boldsymbol{\phi}}}$: phase, $\overline{\overline{\boldsymbol{v}}}$: RV, $\overline{\overline{\boldsymbol{s}}}$: shape(spectra)
  - **One distance metric per matrix:** $\boldsymbol{d_\phi = \phi_{ij}(P - \phi_{ij}), d_v = |v_i - v_j|, d_s = (1 - C_{ij})^{\frac{1}{2}}}$
  - **Constructing the periodograms:** $\boldsymbol{D_{\phi v}, D_{\phi s}}$

Some examples: β Doradus

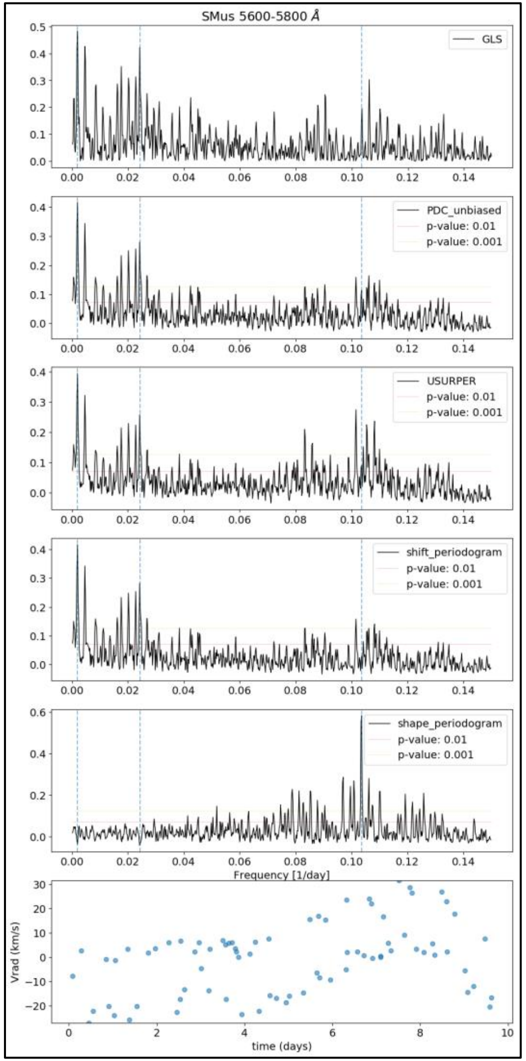
- Classical Cepheid(no known companion)
- 135 CORALIE observations
- Range tested: 4900-5150 Å
- Periods recovered:
  - Radial pulsation periodicity: ~9.84 days



Credits: Binnenfeld et al.(2021) (badly labeled)

Some examples: S Muscae

- Binary classical Cepheid
- 60 CORALIE observations: 01.2012 → 05.2018
- Range tested: 5600-5800 Å
- Periods recovered:
  - Radial pulsation periodicity: ~9.66 days
  - Orbital periodicity: ~505 days
  - Window function: 40 days

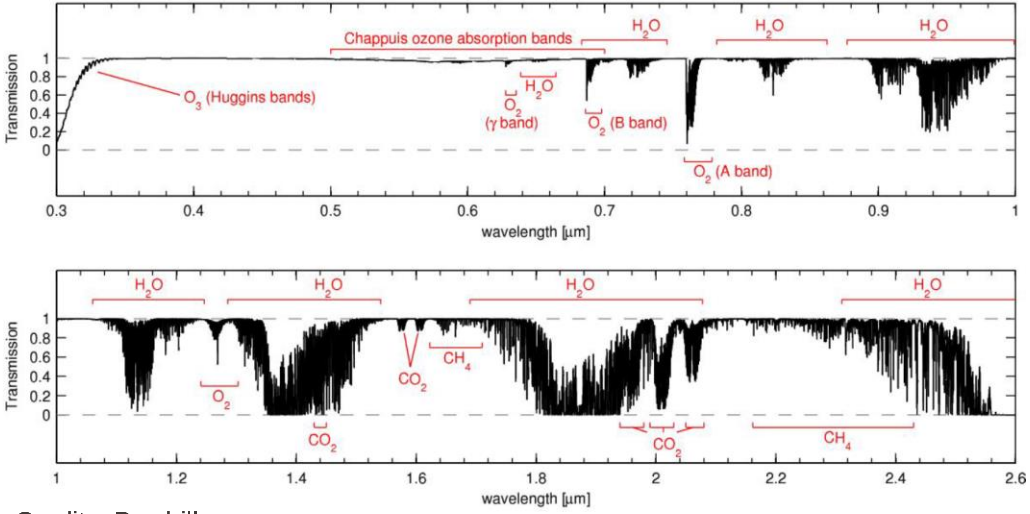


What have I been doing apart from calcetto and cycling?

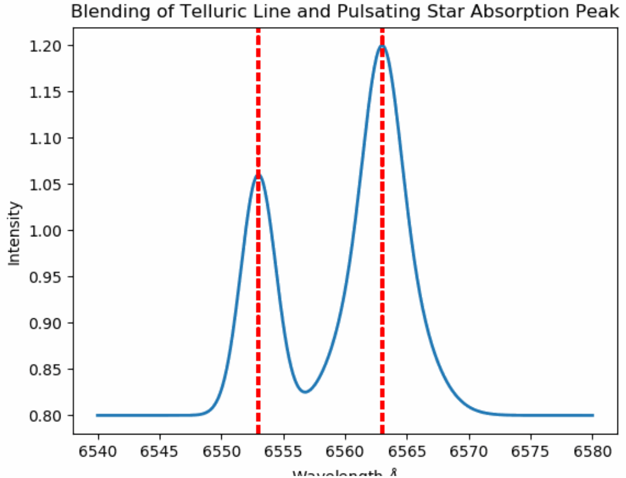
- Finding the right peak
  - Harmonics, aliases, window function.
- What wavelength ranges should be avoided?
  - Impact of tellurics (« high-frequencies » of Earth’s atmosphere)
- What range size should be used?
  - Low frequency variation of earth’s atmosphere.
  - Preprocessing
- What range gives the best results?
- Asserting the statistical significance of a peak.
  - Can a FAP be computed without implementing bootstrap?

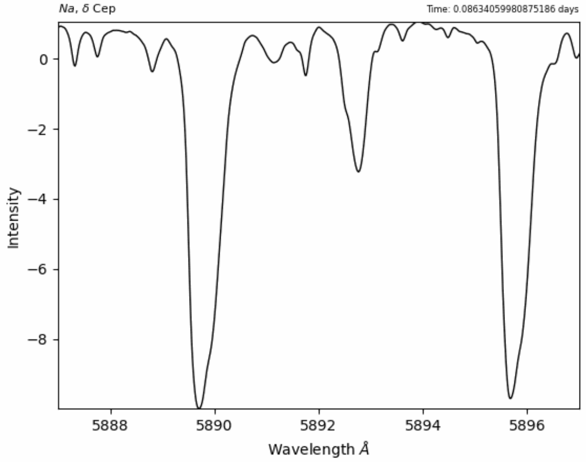
Tellurics
The sky is a limit

- Question
- Goal: : finding the right wavelength ranges

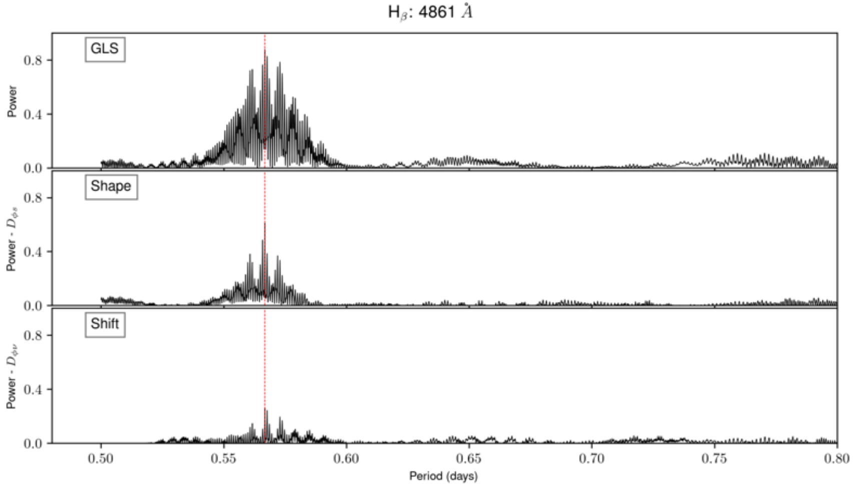


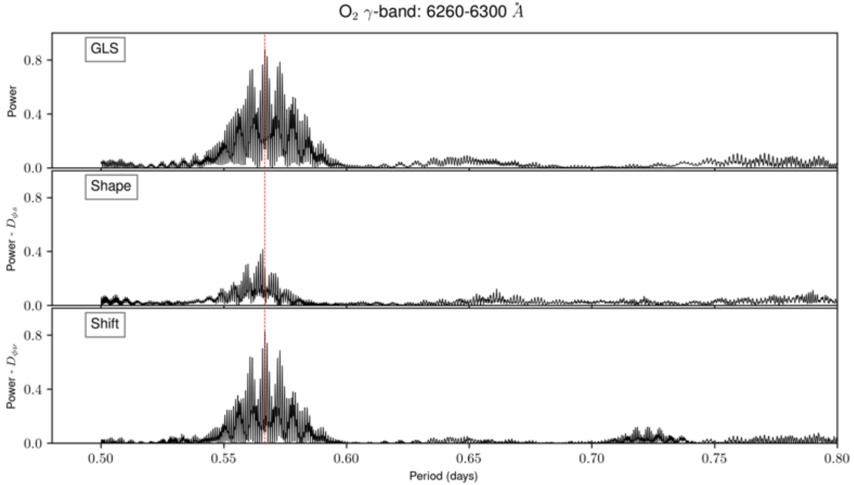
Credits: Przybilla



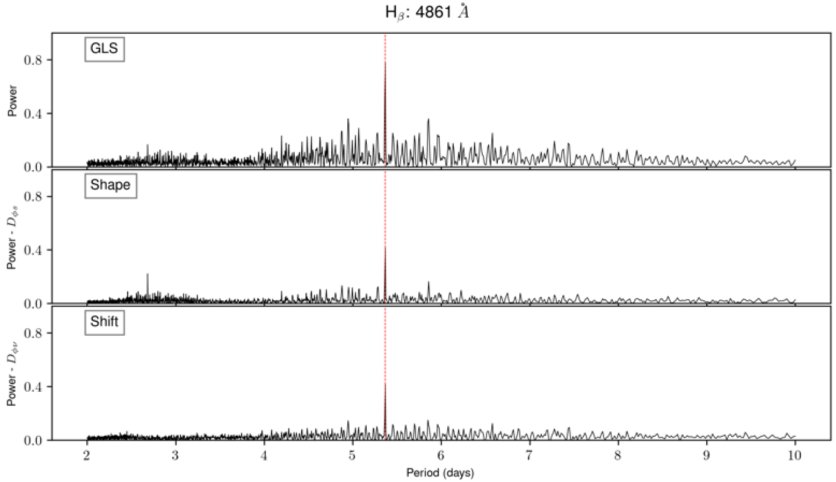


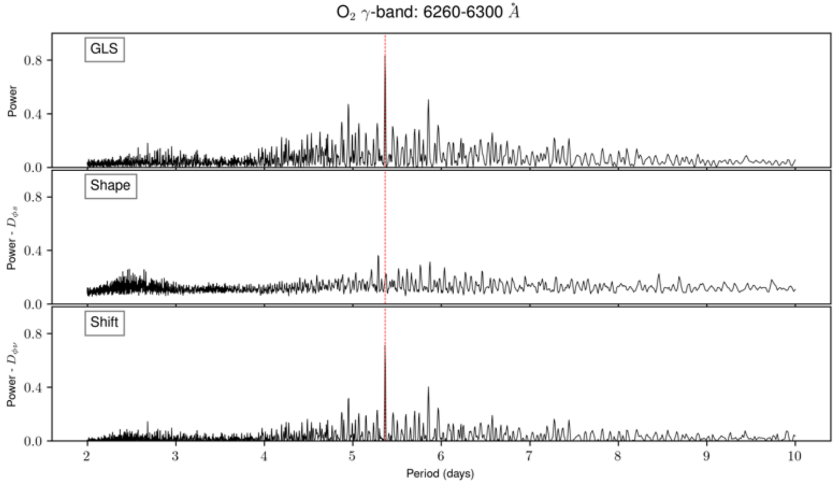
RR Lyrae



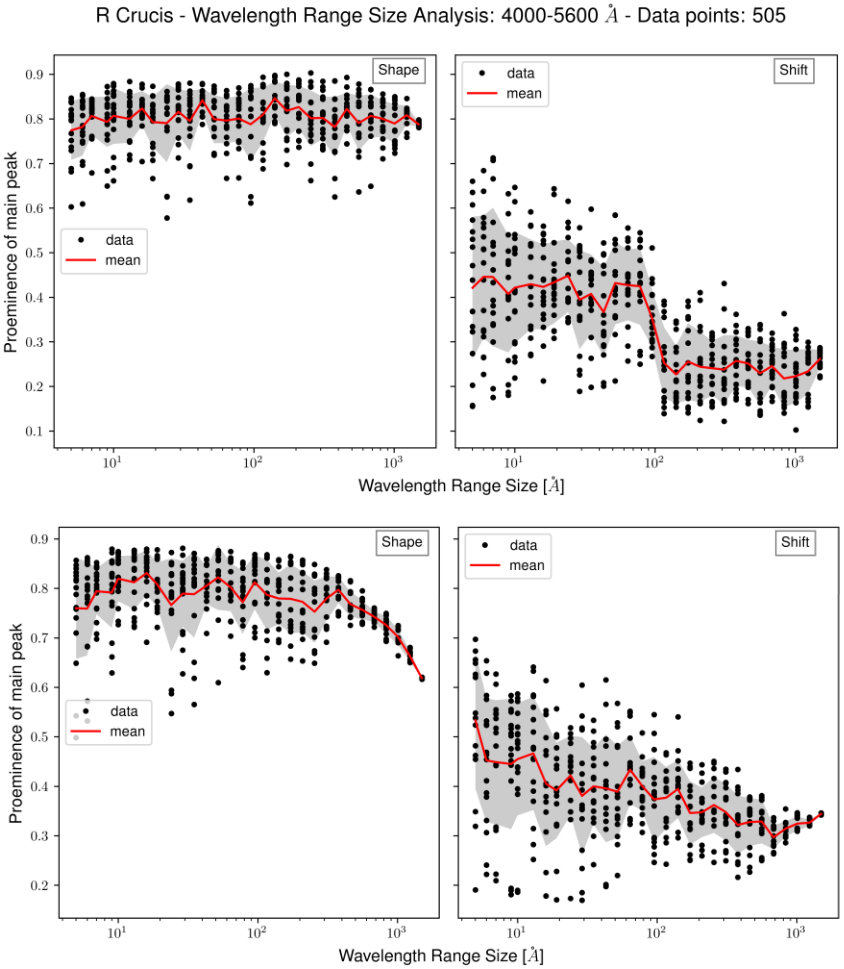


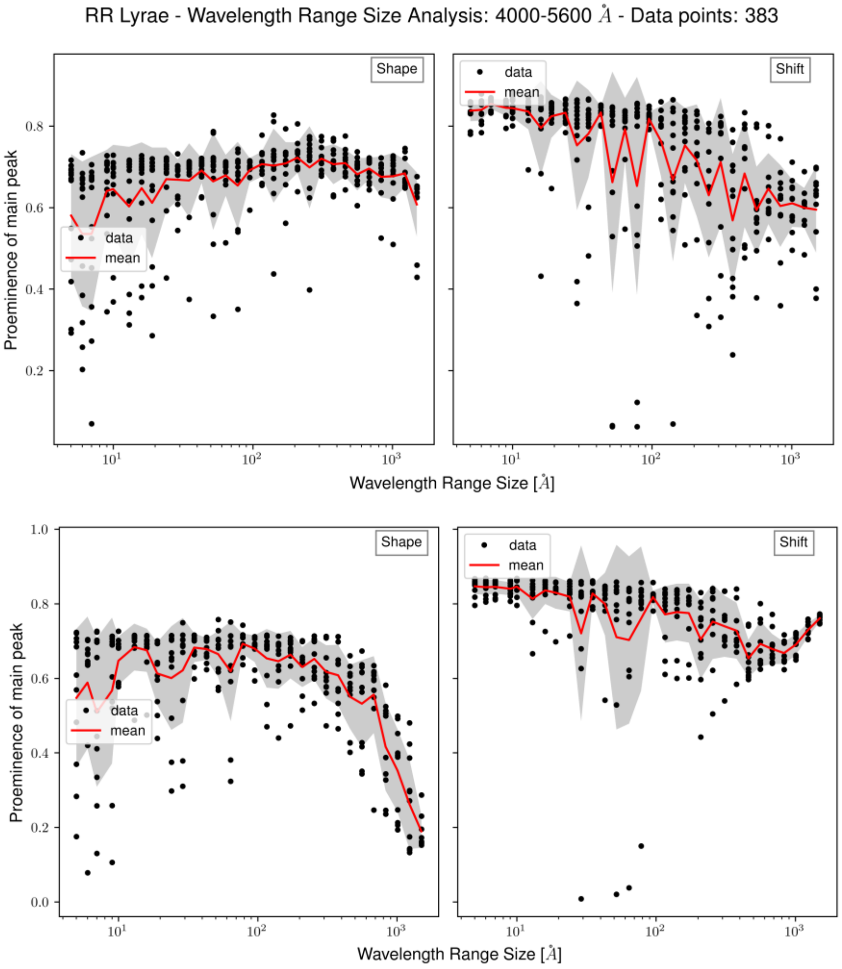
δ Cephei



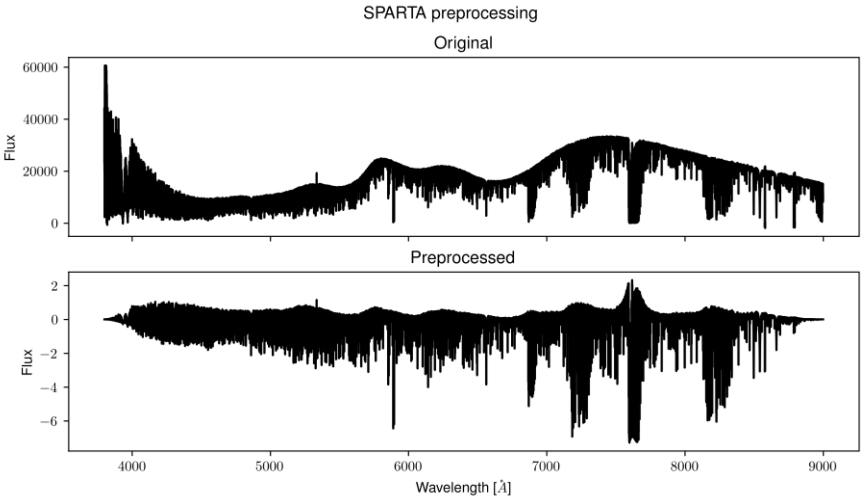


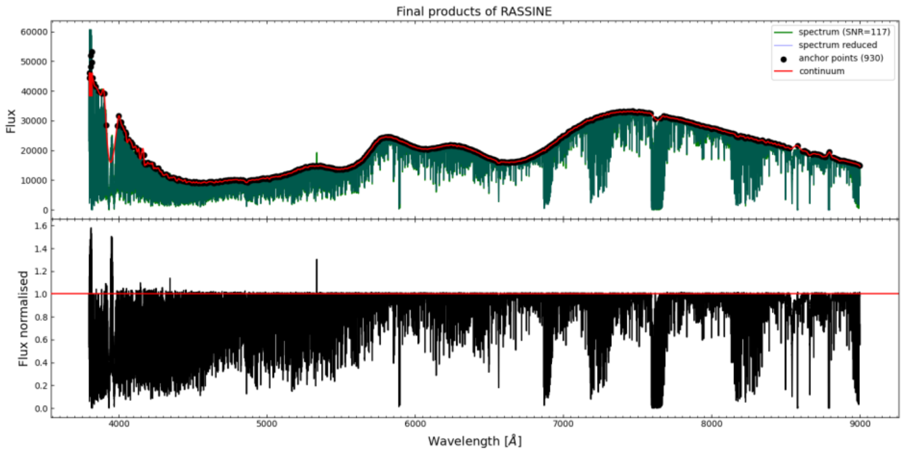
Finding the right wavelength range: The effect of preprocessing





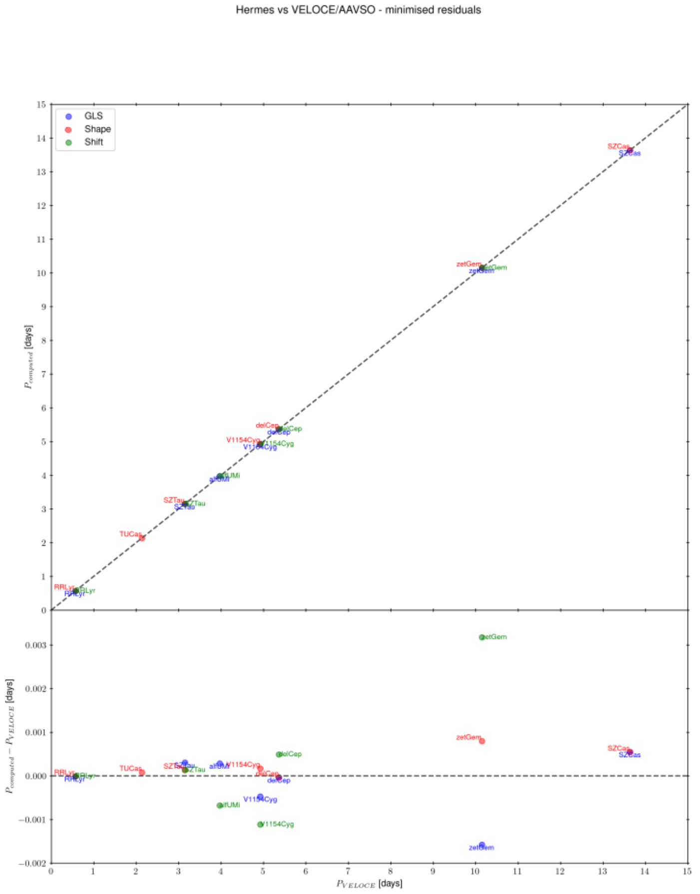
Finding the right wavelength range: The effect of preprocessing

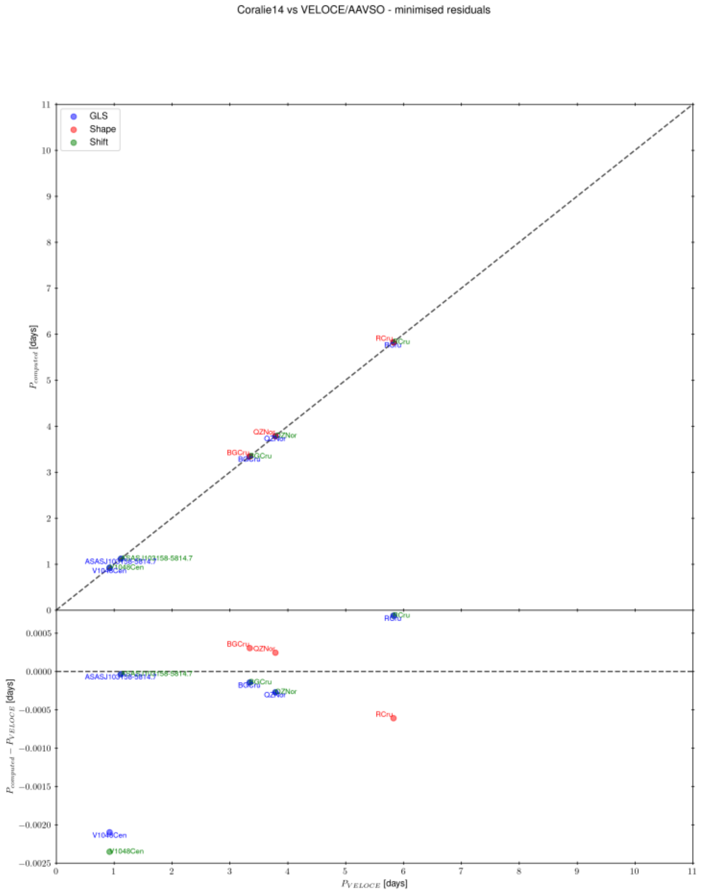




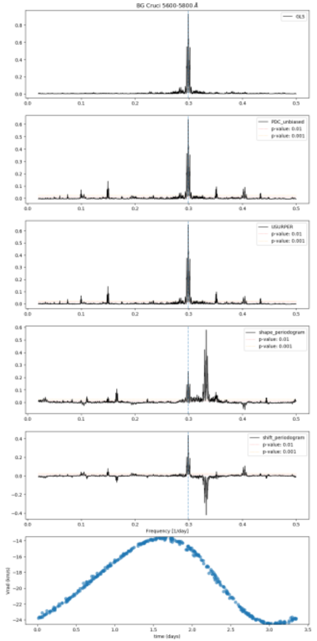
- Hopes
  - Get cleaner periodograms(avoiding Earth’s atmosphere low-frequencies)
  - Enable bigger wavelength ranges

Results on a dataset of 13 stars: Hermes + Coralie14





For the future



- Complete Polaris data set.
- RASSINE time series preprocessing.
- Error analysis on periodicities found
- Detecting new periodicities: from the variable star and from companions
  - BG Cru: stability of the 3.00 days additional periodicity
  - R Cru: orbital periodicity
  - ASAS: orbital periodicity
- Shift periodogram showing a peak at the pulsational frequency.
  - RV signal not properly removed.
  - Estimating the accuracy of the RV?
- Asserting the statistical significance of a peak
  - Spurious peaks: harmonics and aliases.
  - Implement bootstrap? Is there another way?
  - Baluev, Davies, Süveges not applicable(or so I think)
- Which range should be used?
- Optimisation the computation of multiple periodograms at the same time(see with Giordano and Mauricio for multiprocessing).
- $O(nlog(n))$

Conclusion

- **Goal of the algorithm**:
  Separately identify Doppler and spectral-shape modulations.
- **Results**:
  - Avoid tellurics
  - Use wavelength ranges of ~100-200 angströms with original preprocessing.
  - All Hermes except Polaris stars have their main period found with the shape periodogram at max power
  - For Coralie14, only R Cru, BG Cru and QZ Nor have their main period found with the shape periodogram at max power.
  - Shift periodogram shouldn't show a peak at the shape periodogram's stellar pulsation peaks -> could be a way to know if the RVs a accurately measured.
- **Questions on my mind**:
  - Does this shift problem pose a problem to finding orbital companions?
  - Does it make the shape periodogram less efficient?
  - Why does BG Cru's second periodicity show a hole in the shift periodogram and its main periodicity don't even though it has a higher power?
  - Why is ASAS' shape periodogram flat?
  - Polaris/BG Cru/zetGem: upward, downward trend.

References

- A. Binnenfeld, S. Shahaf, R. I. Anderson and S. Zucker.
  New Periodograms Separating Orbital Radial Velocities and Spectral Shape Variations.
  A&A 659 A189 (2022)
- J. T. VanderPlas.
  Understanding the Lomb-Scargle Periodogram.
  ApJS 236 16 (2018)
- R. I. Anderson, G. Viviani et al.
  VELOCE I. High-Precision Radial Velocities of Cepheids.
  [Manuscript submitted for publication], IPHYS EPFL Switzerland.
- M. Cretignier, J. Francfort, X. Dumusque, R. Allart and F. Pepe.
  RASSINE: Interactive Tool for Normalising Stellar Spectra.
  A&A 640 A42 (2020)

RR Lyrae shockwaves on H_β