# Reducing stellar noise in exoplanet observables using machine learning

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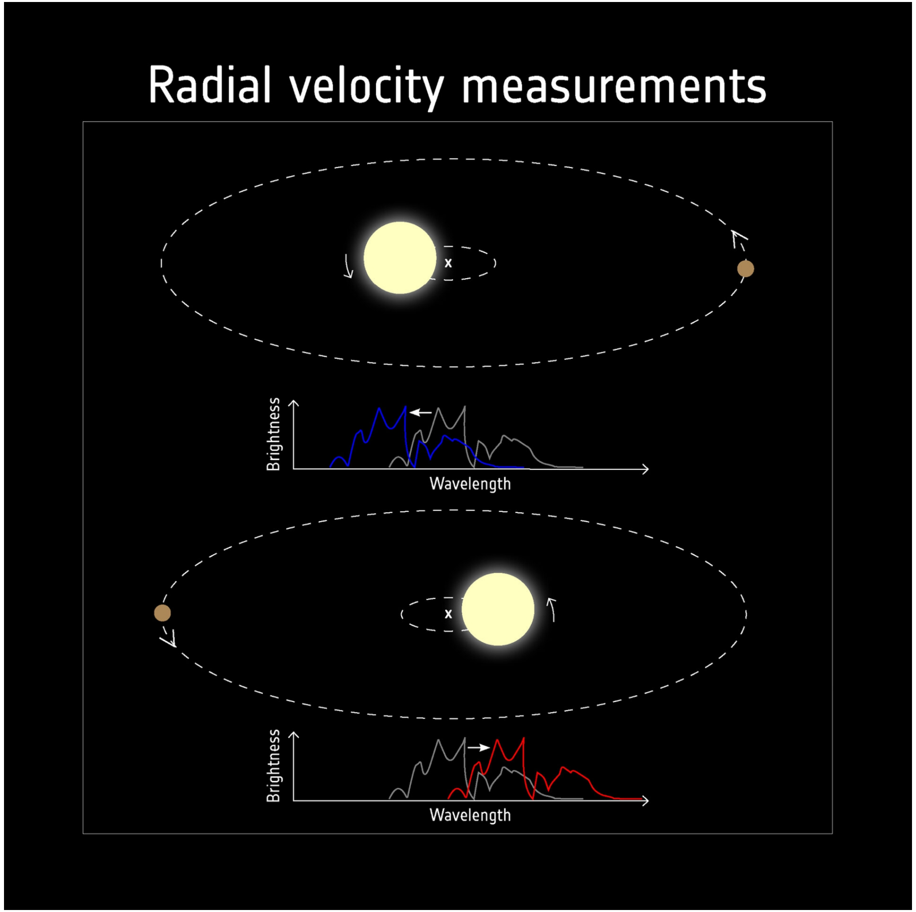
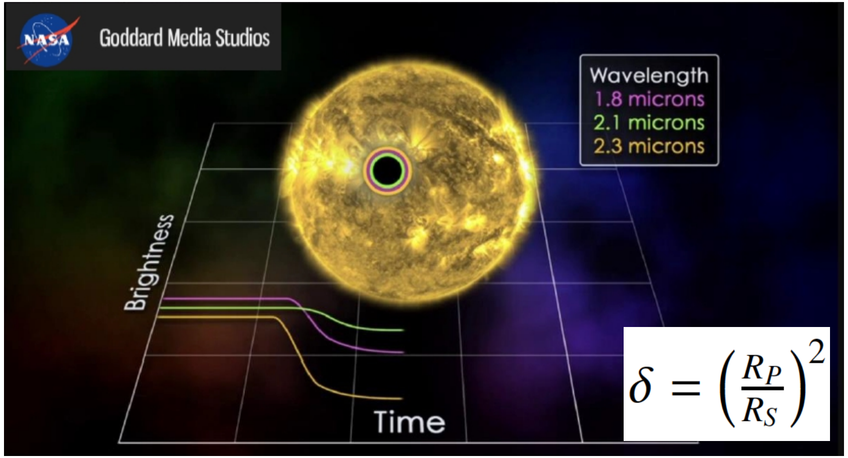
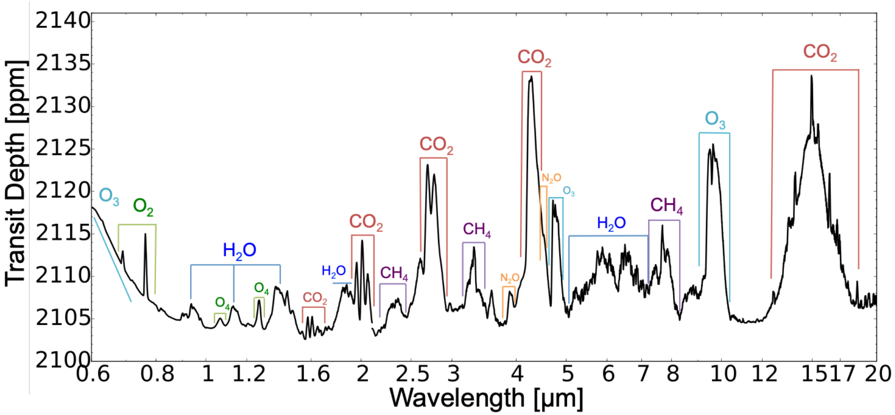
# Radial velocities, planetary transits, transmission spectra



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# Stellar phenomena affecting observations

**oscillations**: min; cm/s

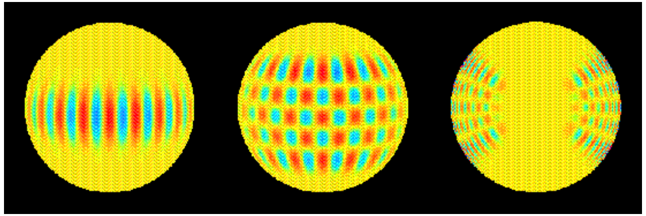
**convection/granulation/flares**
min to hrs; m/s

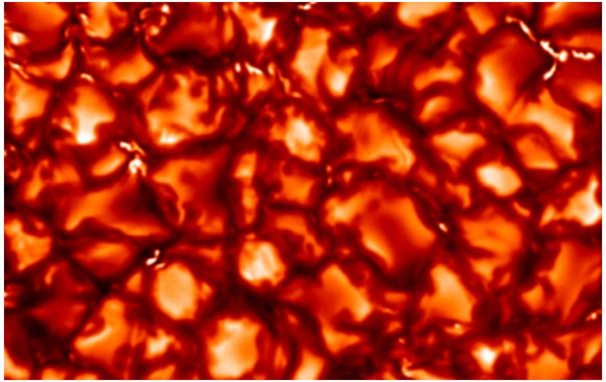
**spots/faculae/plagues**
several rotation periods
m/s to km/s

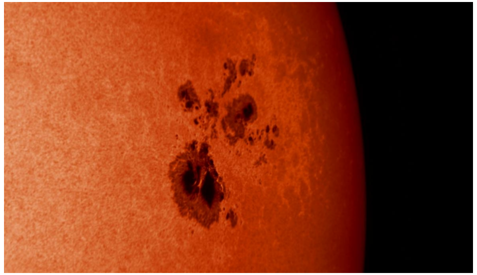
**magnetic cycle**
spot evolution, number and
position, years

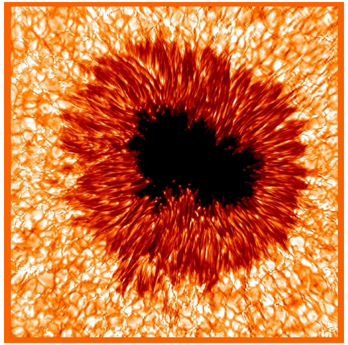
**instrumental precisions ~1 m/s**
**stellar activity >2-3 m/s**
**Earth twin RV 9 cm/s**

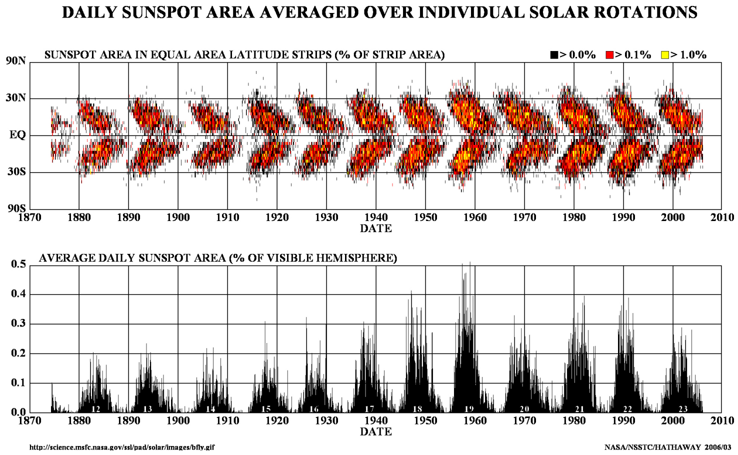
**JWST precision ~20 ppm**
**stellar activity >100 ppm**
**Earth twin ~50 ppm**











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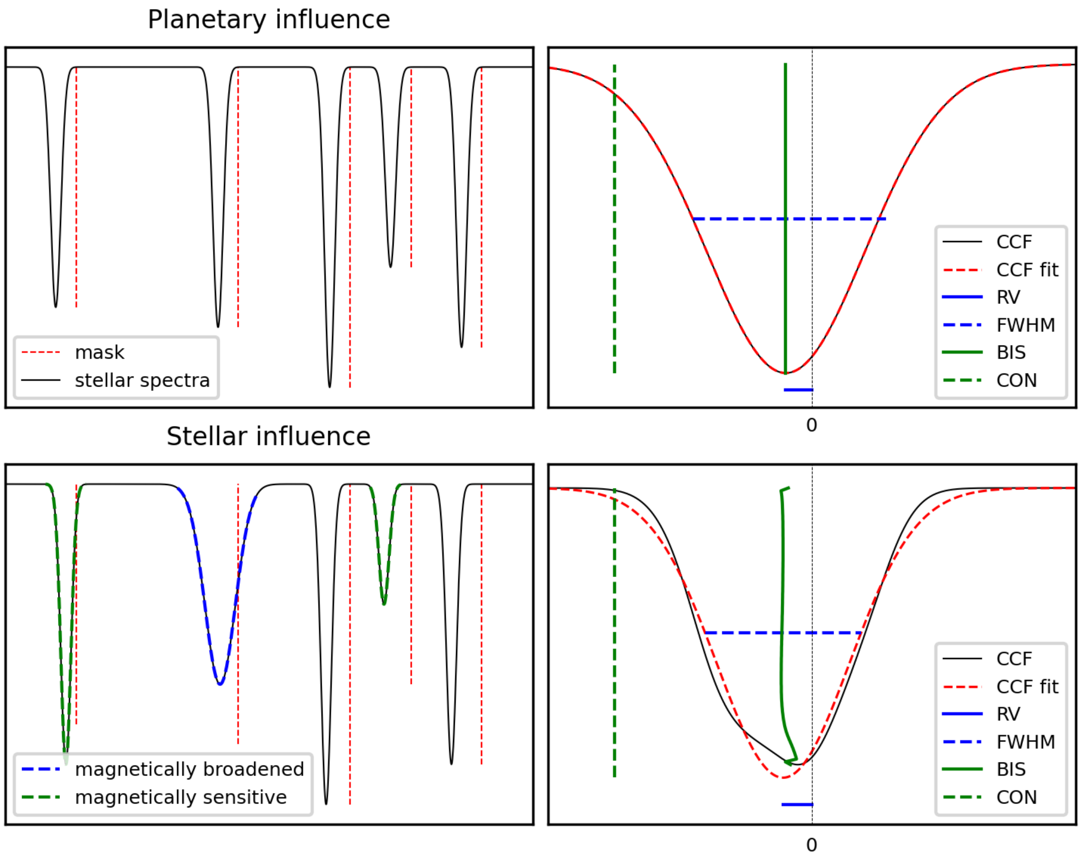
# Magnetic activity affecting stellar spectra

Parameterization with Cross - Correlation Function (**CCF**) and its *moments* (**activity indices**)

Doppler shift induced by a **planetary companion** is achromatic and is an actual translational shift.

Shifts induced by **magnetic effects** (e.g., spots & faculae) depend on wavelength and are only due to asymetries and shape changes of the lines/CCF.

line features can be (more or less) **sensitive to magnetism** – Zeeman effect, line broadening, varying absorption level, etc.



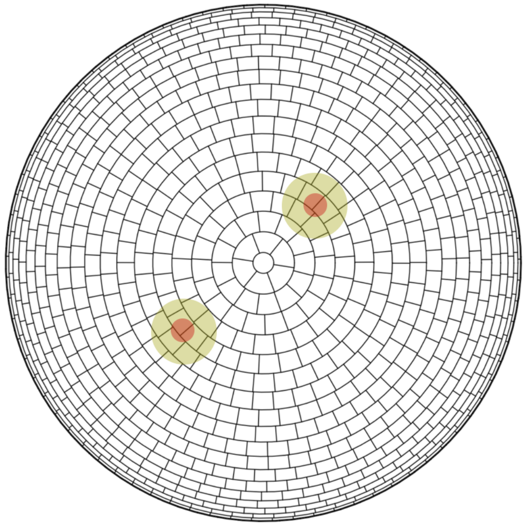
# **StarSim** forward and inverse modelling

## Synthetic observables of a spotted rotating star

Forward modellling of radial velocities and light curves

### Modes

RV: CCF of high resolution spectra
Photometry: low-resolution spectra
Phoenix spetra models (Husser et al. 2013)
500 to 50000 nm



### Stellar parameters

Teff = Tphot = 2600 – 12000 K
logg 3.5 – 5.0
Metallicity -4.0 – 1.0
Radius
Mass
Rotation period
Inclination
Differential rotation
Limb darkening laws
Convective shift & Center-to-limb
Bisector (CIFIST models,
Ludwig et al. 2009)

### Evolving spot map

date of appearance
lifetime of spot
latitude
longitude
Radius
Evolution law
N spots
Spot ΔT = Tphot - Tspot
Facula ΔT = Tfac - Tphot

**Herrero et al. (2016)**
**Rosich et al. (2020)**
**ICE team (in prep.)**

**https://github.com/dbarochlopez/starsim**

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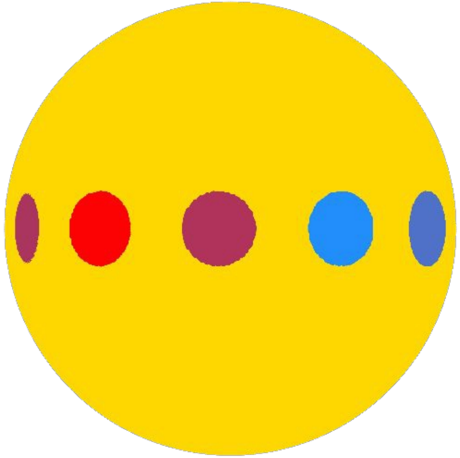
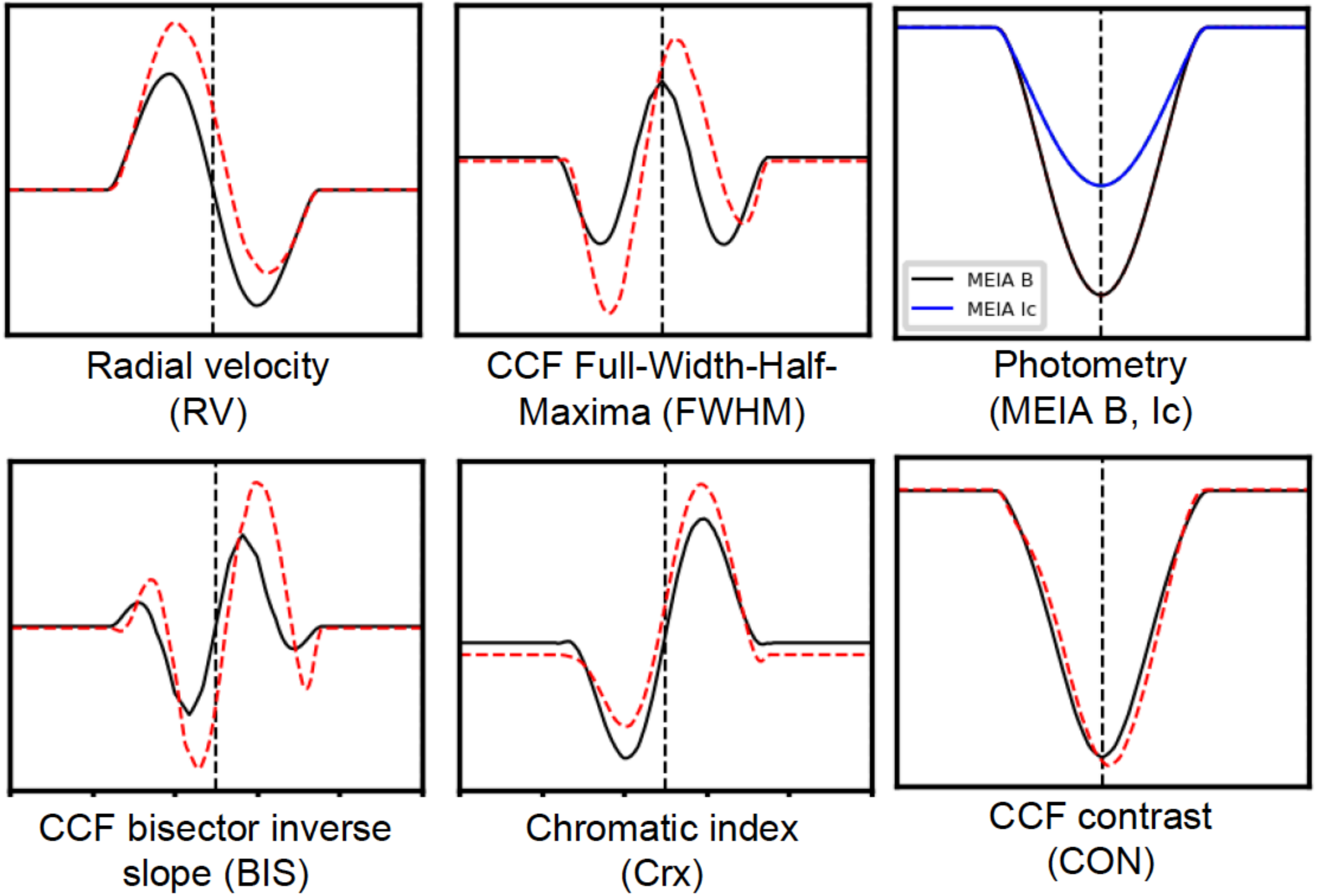
# **StarSim** time-series data products






## **Other modelling code**

SOAP (Boisse et al. 2012)
SOAP-T (Oshagh et al. 2013)
SOAP2.0 (Dumusque et al. 2014)
SOAP-GPU (Zhao & Dumusque 2023)

# Sun-as-a-star time-series data

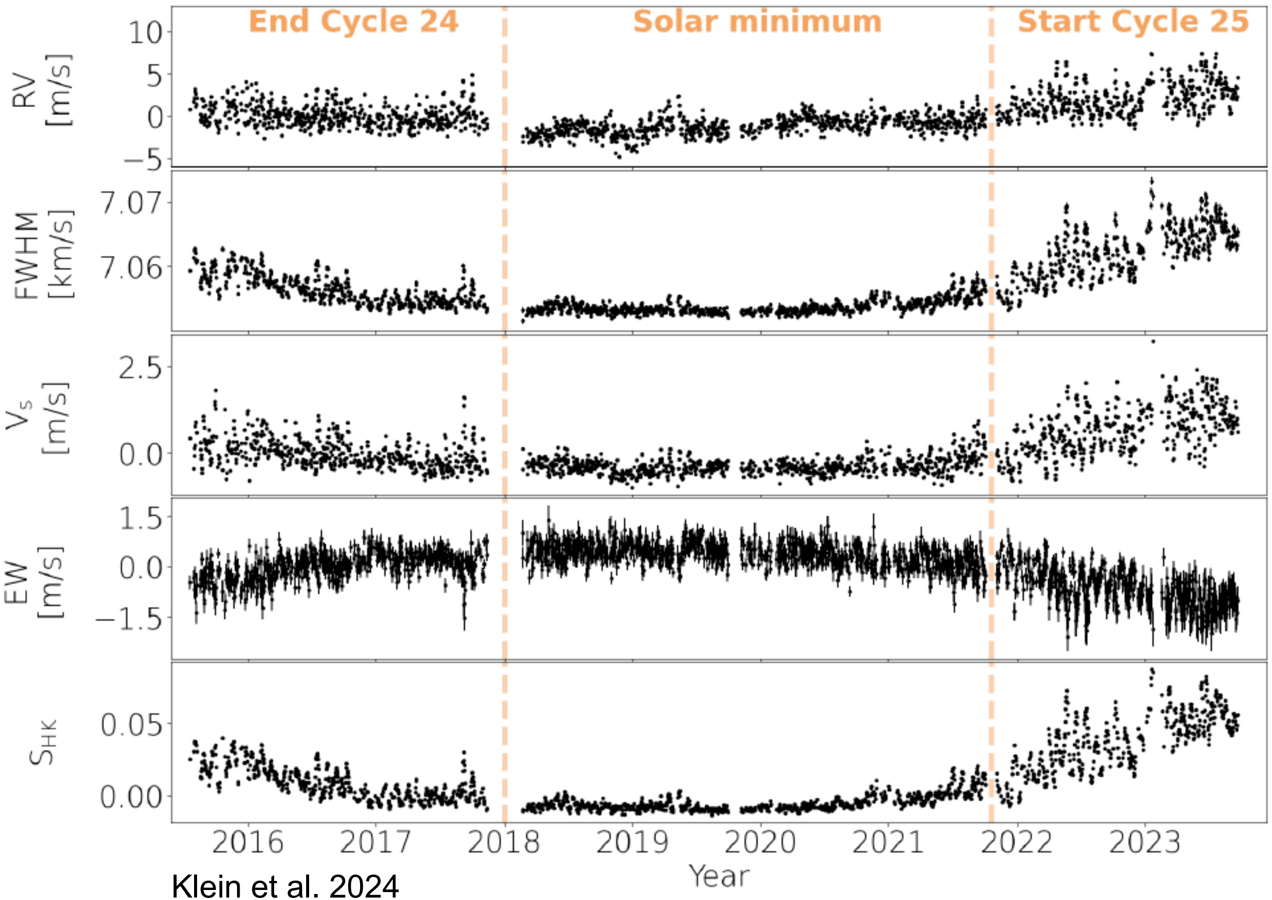
## HARPS-N spectrograph

- **H**igh **A**ccuracy **R**adial velocity **P**lanetary **S**earch project
- stabilised cross-dispersed échelle spectrograph
- Roque de Los Muchachos observatory (La Palma, Spain)
- 3.58-m Telescopio Nazionale Galileo (TNG)
- High resolution R=115 000
- Optical wavelength: 383 to 690 nm

## Solar observations

- Since 2015
- 5-min cadence (averaging out oscillations)
- 150 000 disk integrated spectra (8000 nightly-binned)
- Median SNR =350

**Dumusque et al. (2020)**
https://dace.unige.ch/sun/?




Klein et al. 2024

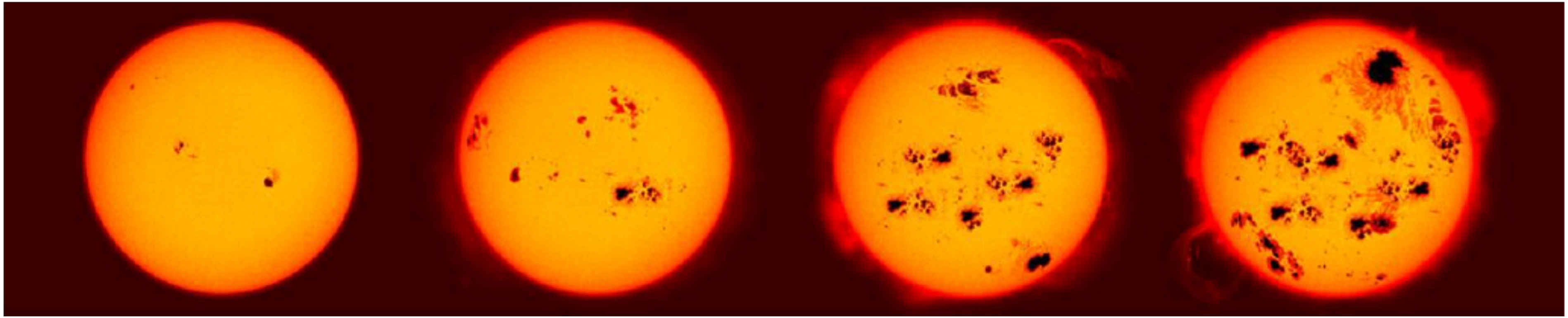
# Problem set

## Problem
- Stellar phenomena have to be mitigated in all exoplanet observations

## Input data
- Test star data (e.g. Sun), model data (StarSim)
- High-resolution spectra, CCF, activity indices time series, temporal correlation
- (*Data contemporaneous to transit event*)

## Output data
- Radial velocity data
- (*Transmission spectrum*)

## Results
- Model data shows good capabilities of the method (down to 2% rms reduction)
- Test star data can be reduced from 10% (AU Mic, active star) to 50% (Sun)
- Better modelling (StarSim3)
- Different (better) spectral parameterization



# Papers on radial velocities

## A machine learning approach for correcting radial velocities using physical observables

M. Perger[1,2], G. Anglada-Escudé[1,2], D. Baroch[1,2], M. Lafarga[3], I. Ribas[1,2], J. C. Morales[1,2], E. Herrero[1,2], P. J. Amado[4], J. R. Barnes[5], J. A. Caballero[6], S. V. Jeffers[7], A. Quirrenbach[8], and A. Reiners[9]

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8
9 Institut für Astrophysik, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

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|---|---|
| De Beurs et al. (2022) | https://iopscience.iop.org/article/10.3847/1538-3881/ac738e/pdf |
| **Perger et al. (2023)** | https://www.aanda.org/articles/aa/pdf/2023/04/aa45092-22.pdf |
| Liang et al. (2023) | https://iopscience.iop.org/article/10.3847/1538-3881/ad0e01/pdf |
| Colwell et al. (subm.) | https://arxiv.org/pdf/2304.04807 |
| Zhao et al. (subm.) | https://arxiv.org/pdf/2405.13247 |

# StarSim input data modelling

## Different spot maps

600000 EpsEri
1000000 AUMic

| | |
|---|---|
| Number of spots | 25 to 40 |
| Appearance | -lifetime to 100 |
| Lifetime | 5 to 100 days |
| Colatitude | 0 to 180 deg |
| Longitude | 0 to 360 deg |
| Radius | 2.5 to 4 deg |

## Different time samplings

100 time stamps
0<t<100 days
all sets simultaneous
1 x uniformely distributed
2 x randomly distributed
2 x seasonal gap
observed sampling

## Input time-series data

photometric light curves in *VBI* filters
CCF activity indicators: FWHM, BIS and CON
uncertainties extracted from observed data
- AU Mic 30 to 60%
- Eps Eri 17 to 25%

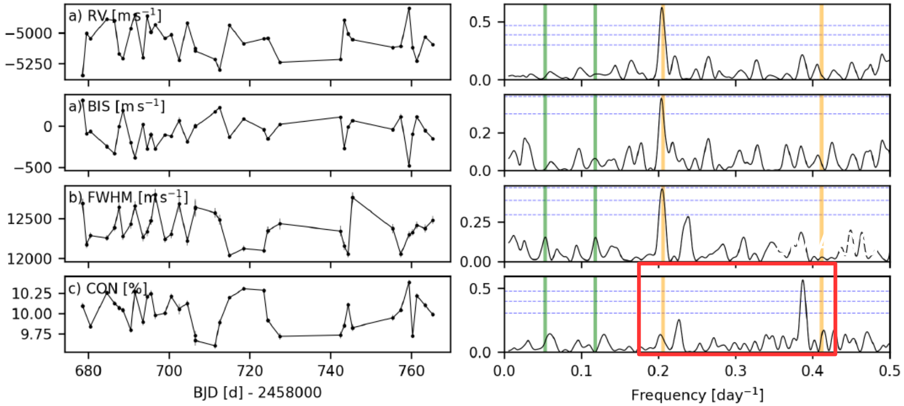
## Output data StarSim models (labels)

radial velocities
90 % training data
10 % test data
observed data is test data

# Test stars and neural network

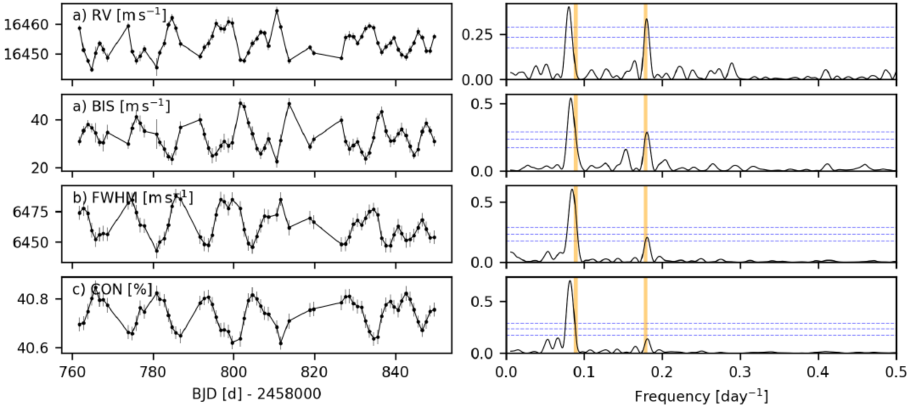
## AU Microscopii

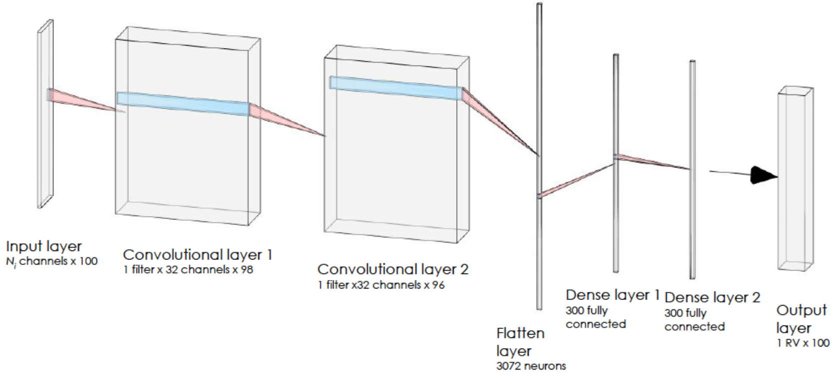
Active M1-type star with 2 planets




## Epsilon Eridani

Young K2-type star with one long-period planet




- $N_i$ channels: number of input activity indices
- kernelsize 3
- default 50 epochs

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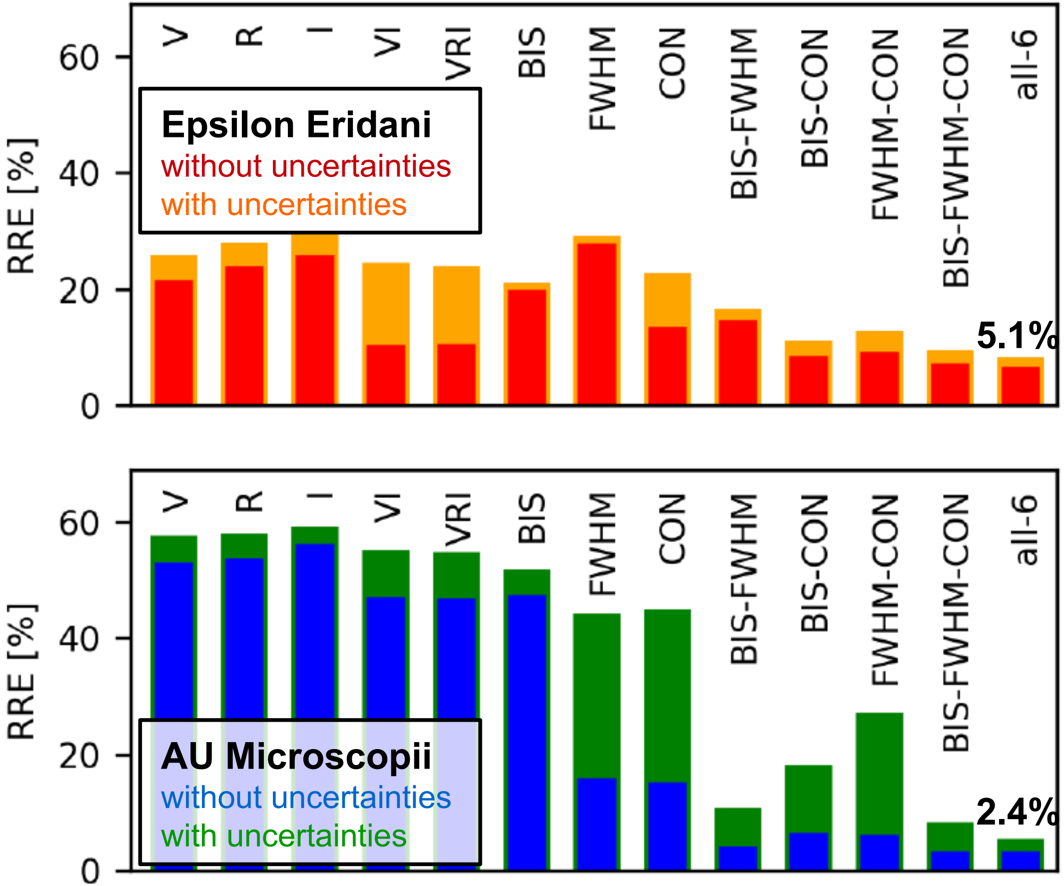
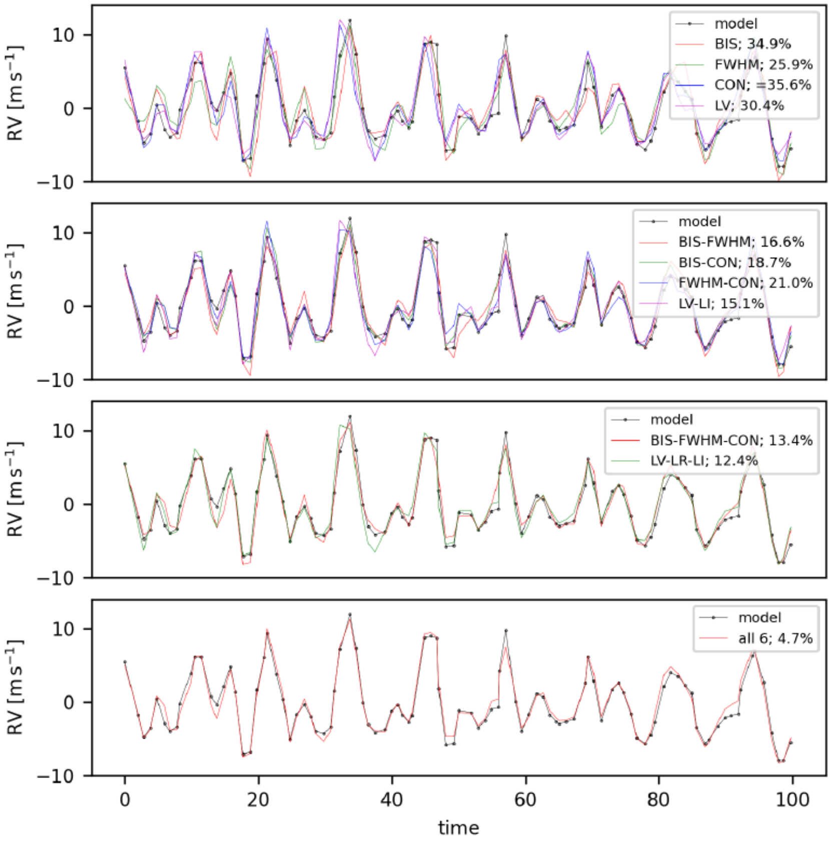
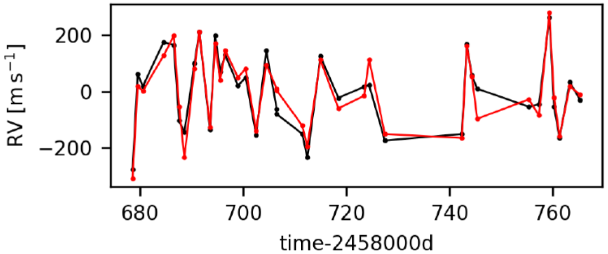
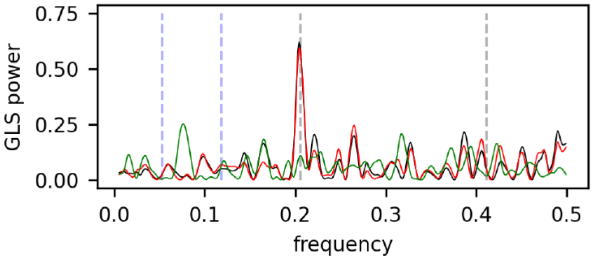
# Results on StarSim models

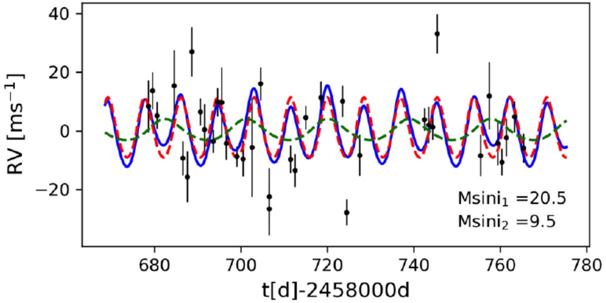


# Results on test stars

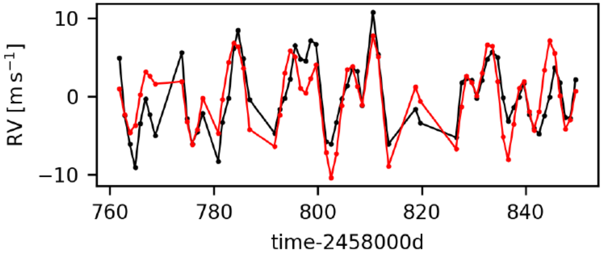


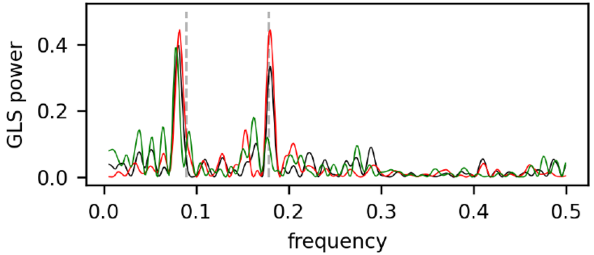




## AU Microscopii

- observed time stamps
- 400000 simulation
- Input: FWHM, and BIS
- Output: RV
- Reduced rms from 132.2 to 13.0 ms-1 (10%)




## Epsilon Eridani

- observed time stamps
- 100000 simulation
- Input: FWHM, BIS, and CON
- Output: RV
- Reduced rms from 4.4 to 2.0 m/s (45%)

# Study on different input data

**CCF decomposition**:

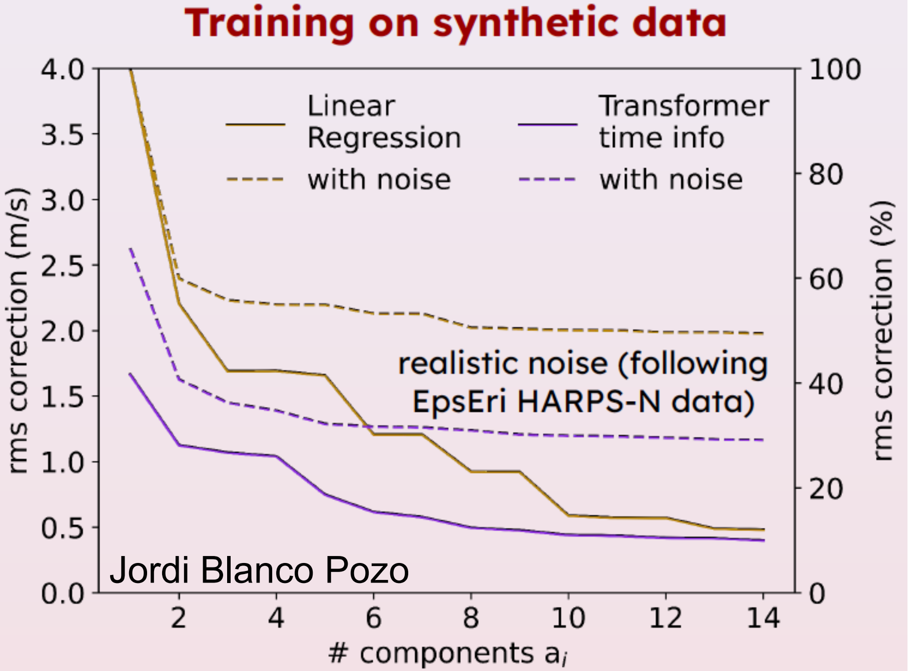
- Auto correlation function (ACF)
  shift invariant
- Moments
  similar to FWHM, BIS, contrast
- CCF principal component analysis (PCA)
  Eigenvectors
- Autoencoder latent space analysis
- Orthonormal functions
  base function G, orthonormalized to CCF'
  G from PCA or Gaussian fit
  $a_0$: output, stellar activity induced RV
  $a_i$: input, show line distortions perpendicular to CCF'

**Transformer models**
include time problem through positional embedding

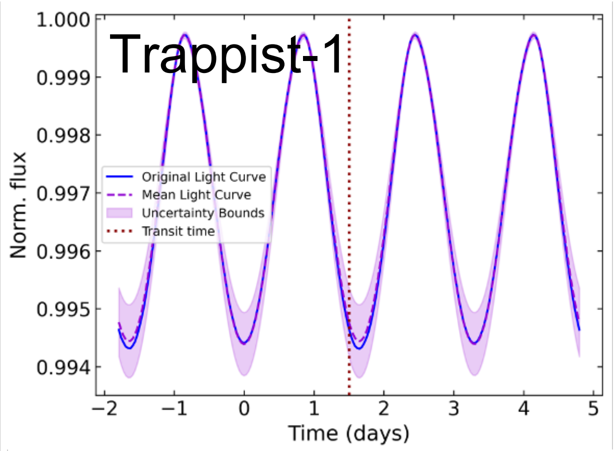
**Test stars**: AU Microscopii, Epsilon Eridani, Sun, etc.

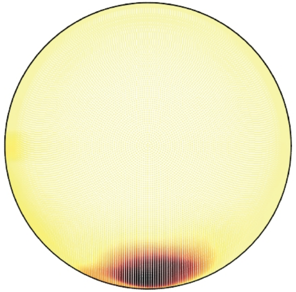
$$\mathbf{F}(v,t) = \langle \mathbf{F}(v) \rangle + \underbrace{(\epsilon(t) + a_0(t))}_{RV_{obs}} \langle \mathbf{F}'(v) \rangle + \sum_{i=1}^{N} a_i(t)\mathbf{G_i}(v)$$

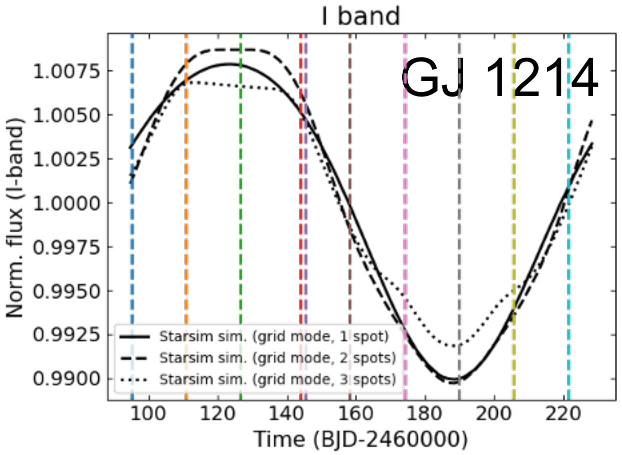


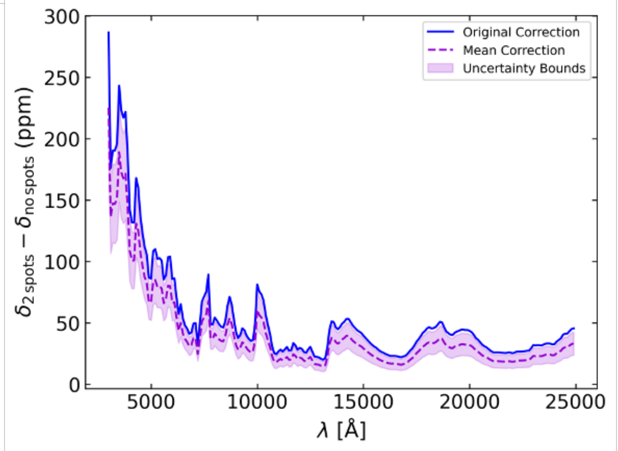


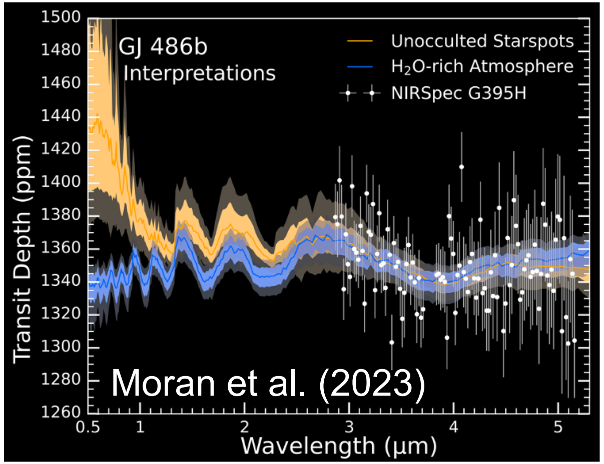
# First results on transmission spectra

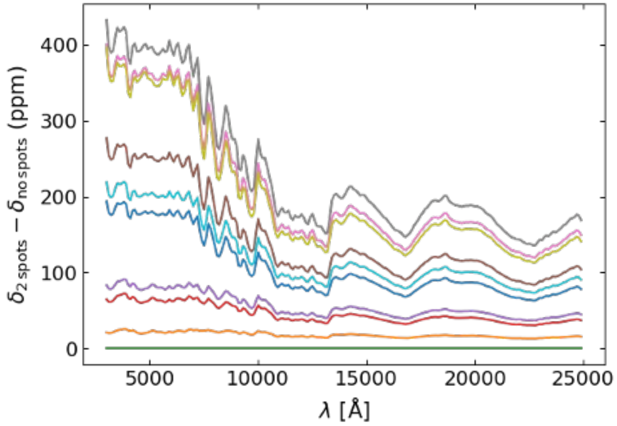




# ERC (European Research Council) Advanced Grant
# Ignasi Ribas

- Detecting ExoEarths
- Starsim3 development
- Stellar data modelling
- General Machine Learning algorithms
- RV variations down to 10 cm/s
- Transit spectroscopy down to 10 ppm

https://www.ieec.cat/en/ieec/job-offers/

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