Detecting targets with radial velocities for their atmospheric characterisation with the next flagship instruments

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Sf2A 2023, breakout session *Origin of water and life: What astrophysical and instrumental challenges for tomorrow?*
21 June 2023

Key message

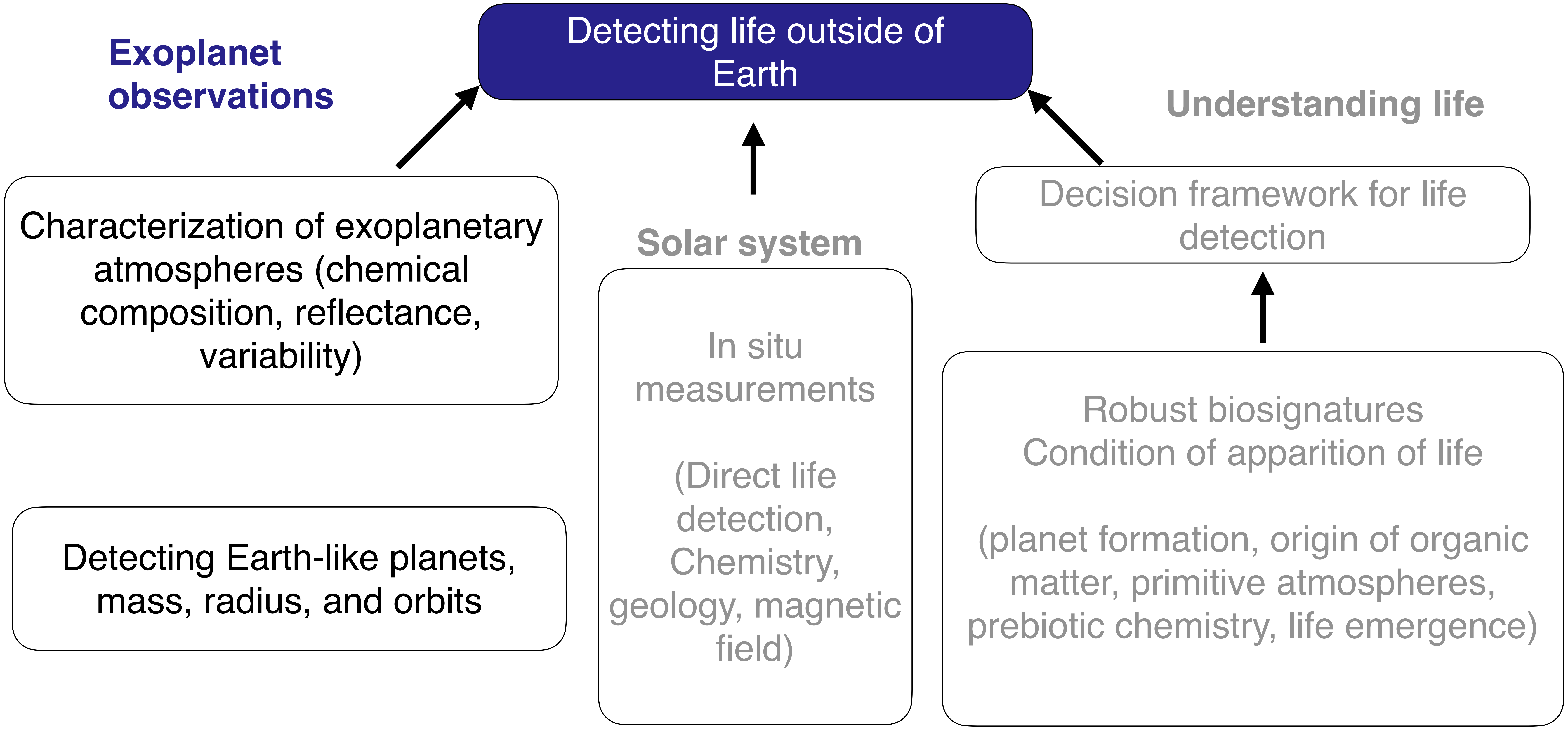
A core objective of flagship ESA and NASA mission at the 2050 horizon is to characterise the atmosphere of Earth-like exoplanets

Radial velocity measurements can pre-detect Earth-like targets and will be essential in any case to measure planetary mass

The radial velocity signal of the Earth on the Sun is 9 cm/s and current instruments are limited at ~ 1 m/s because of complex noises

Reaching 9 cm/s precision is the primary goal of the radial velocity community, it is largely a data analysis problem, and there has been recent progress

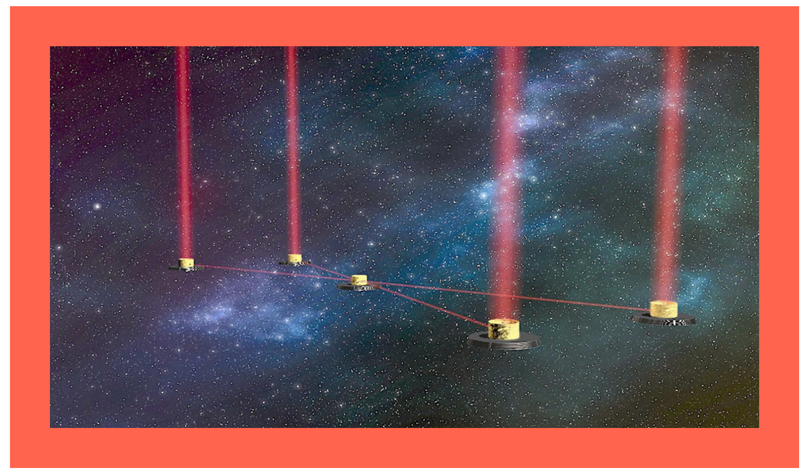
Objectives

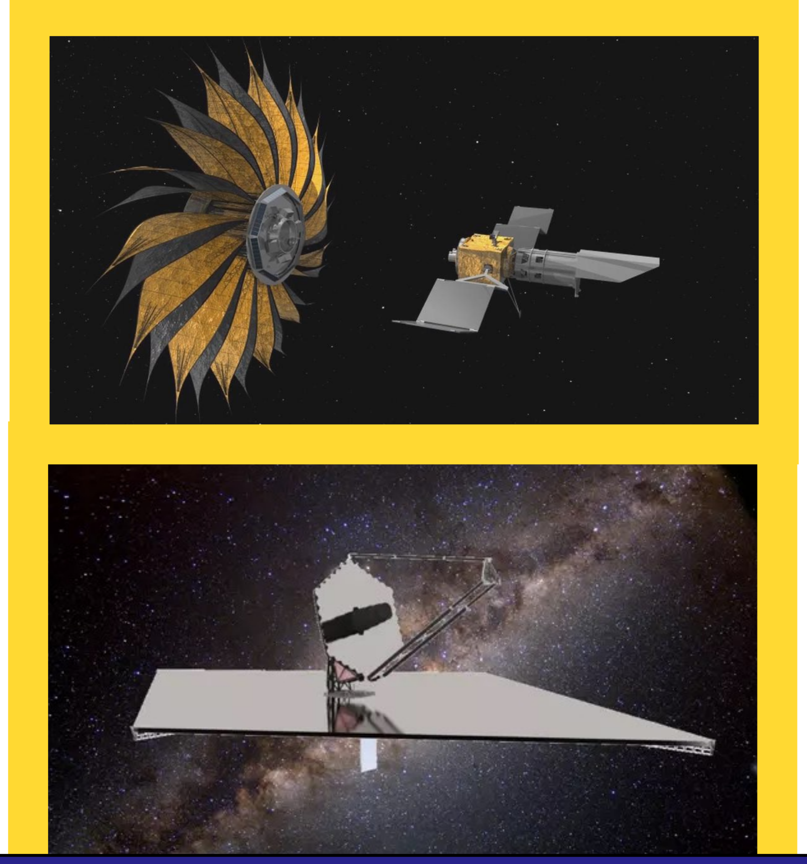

Exoplanet observations
Detecting life outside of Earth
Understanding life
Characterization of exoplanetary atmospheres (chemical composition, reflectance, variability)
Solar system
Decision framework for life detection
In situ measurements
(Direct life detection, Chemistry, geology, magnetic field)
Robust biosignatures
Condition of apparition of life
(planet formation, origin of organic matter, primitive atmospheres, prebiotic chemistry, life emergence)
Detecting Earth-like planets, mass, radius, and orbits

Objectives

Exploplanet observations

Characterizing Earth-analogs
Detecting life outside of Earth

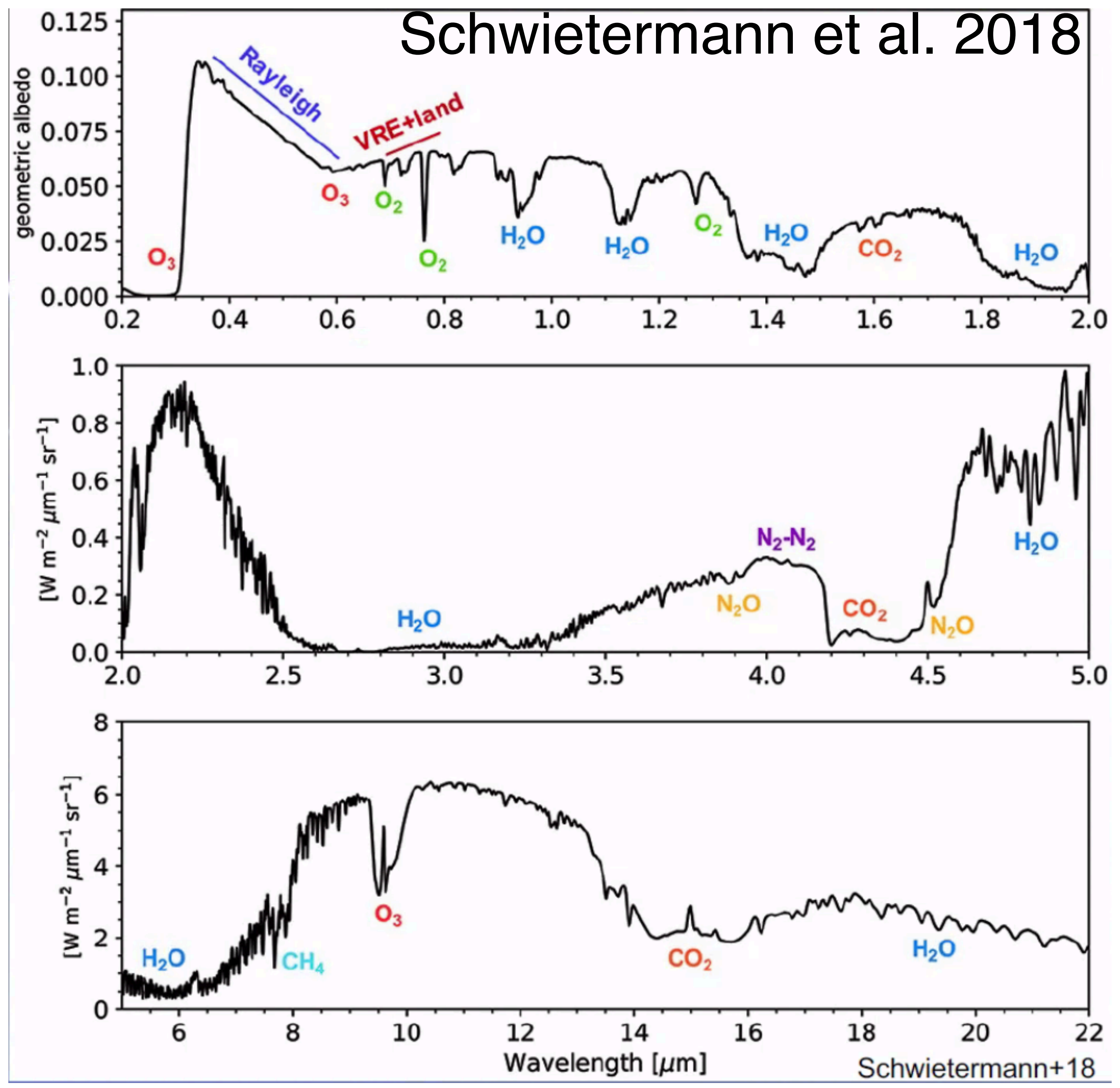


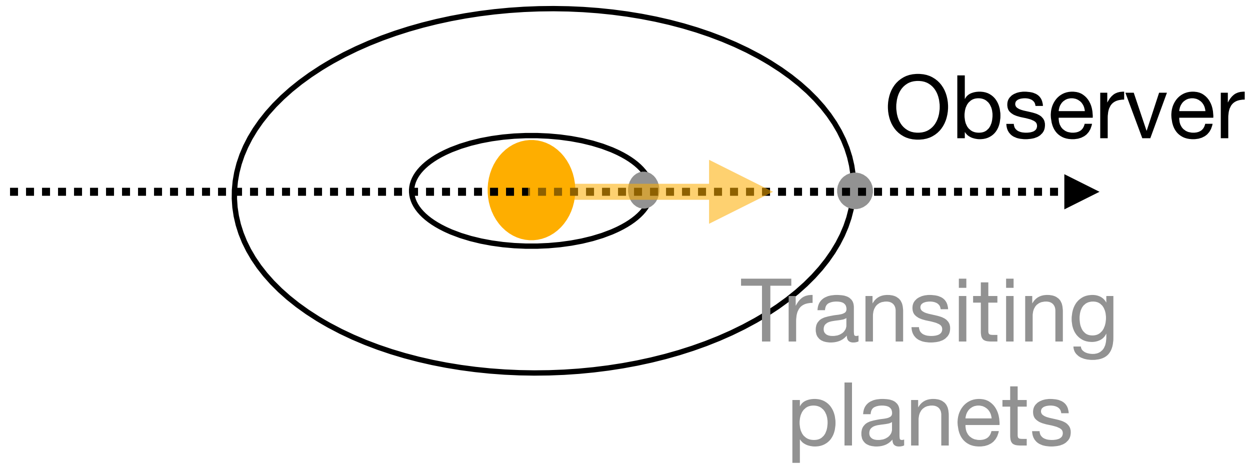


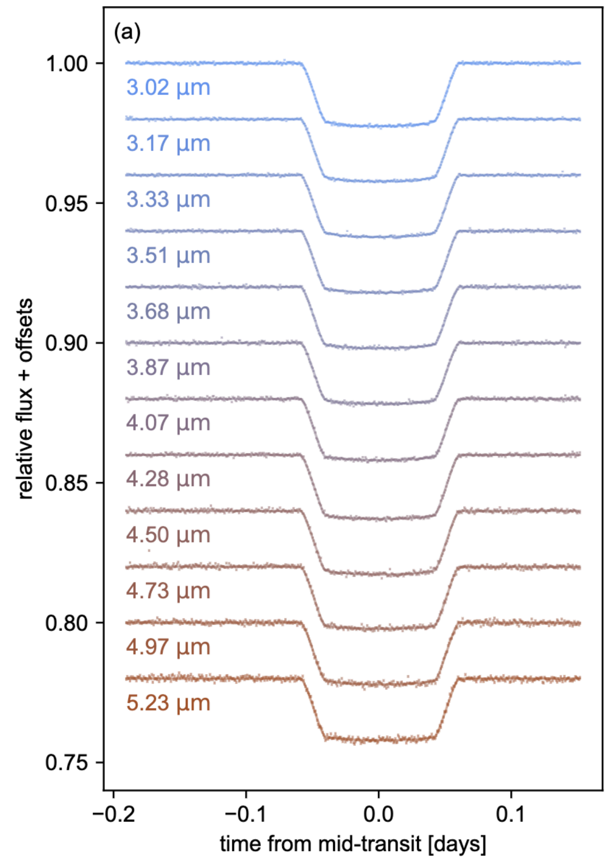
Characterization of exoplanetary atmospheres (chemical composition, reflectance, variability)

Transmission spectroscopy: Ariel, ANDES@ELT, ESPRESSO

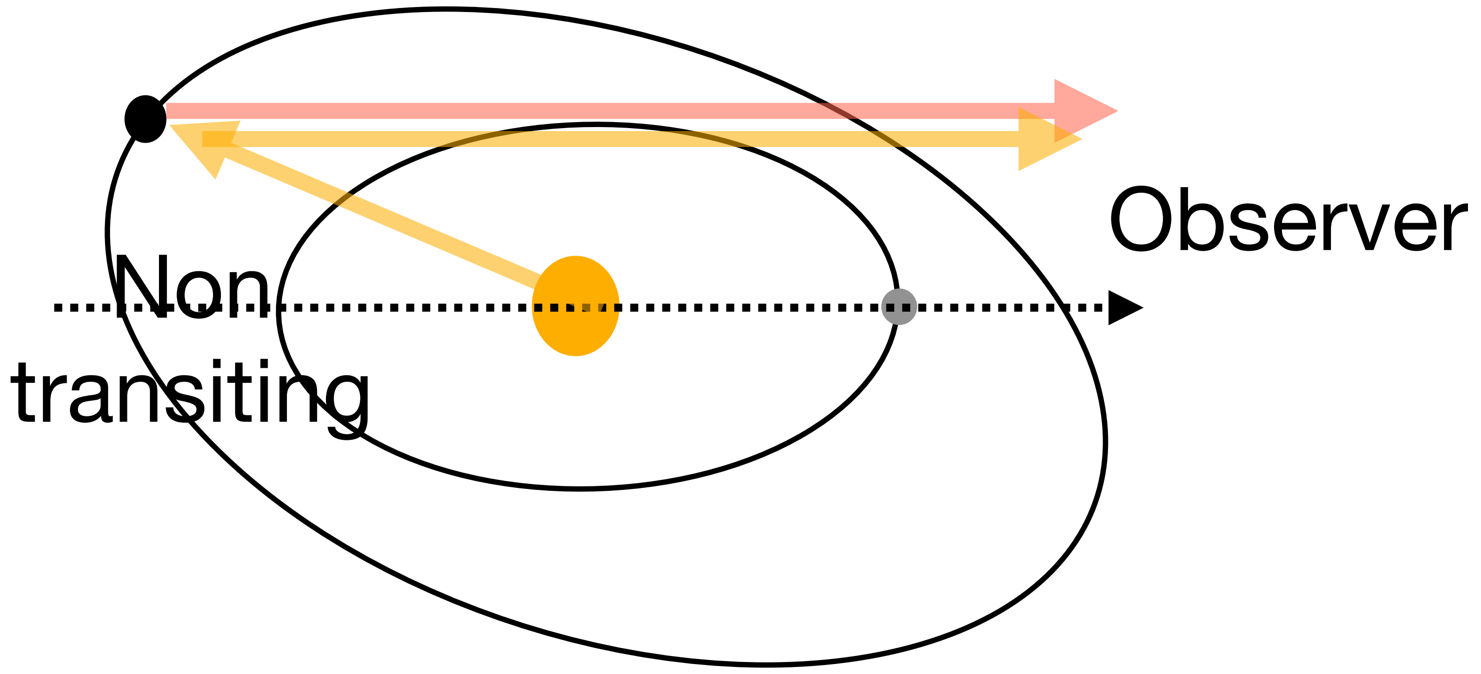
JWST, PCS@ELT
LIFE (ESA), ***HWO*** (NASA),





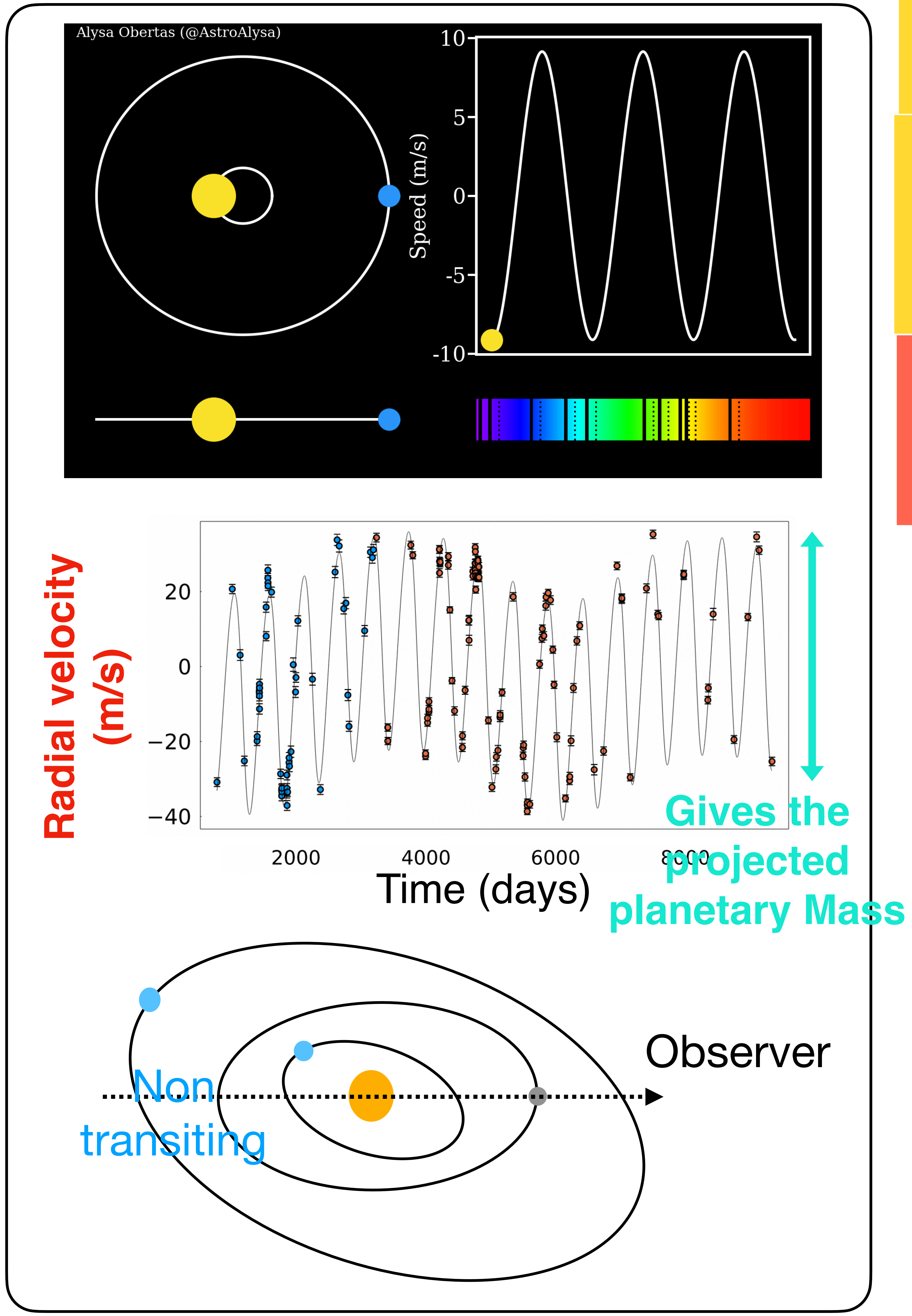


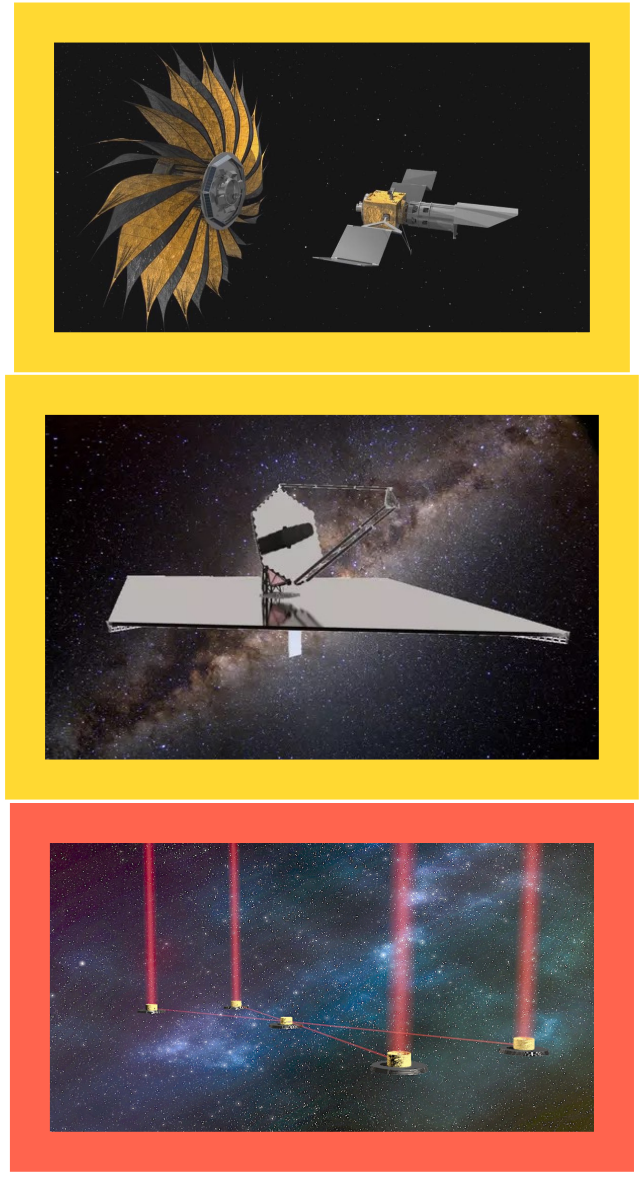
From JWST Transiting Exoplanet Community Early Release Science Team et al. 2022



Characterizing the atmosphere of **Earth-analogs** from space: priority for the horizon 2050

Radial velocites are key

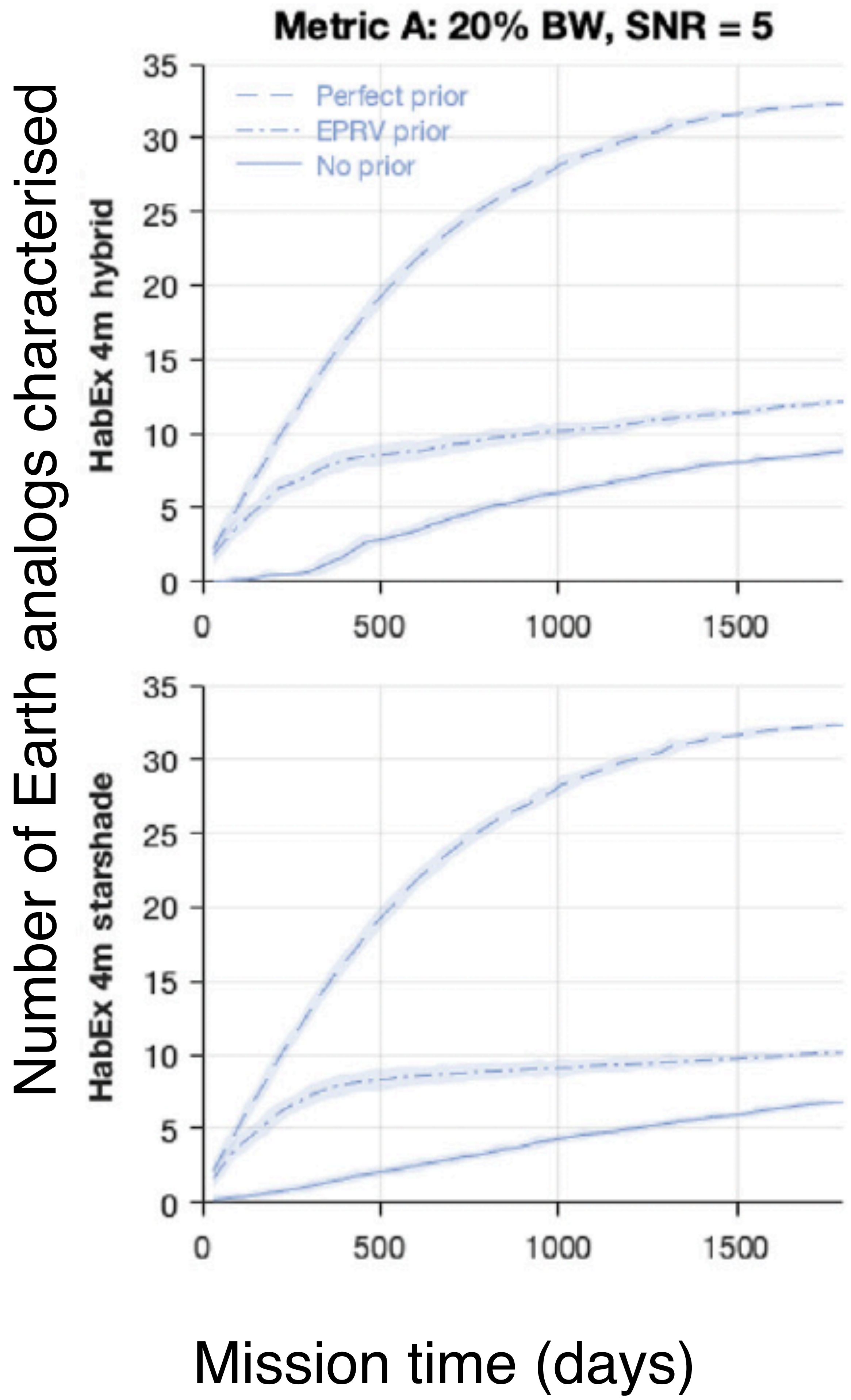




Mass is essential to interpret spectroscopic observations of atmospheres (Batalha et al. 2017, 2019)

The yield of atmospheric characterization is greatly improved if Earth like planets are detected in advance, **require targets $\lesssim$ 20 parsec**

+ **Results obtained faster, more time for characterisation**
+ **Mitigates the risk of the missions**
+ **True for other kinds of planets**



Morgan et al. 2021

NASA Extreme precision radial velocity report Crass et al. 2021

Roadmap to the detection of Earth-like planets with radial velocities to prepare HWO

« Musts » = requirements

- Determine by 2025 the **feasibility** to detect Earth-mass planets in the habitable zone of solar-type stars
- Demonstrate by 2025 **on sky** precision of 30 cm/s
- Conduct precursor survey: now-2035 on 100 stars on the « green target list »

« Wants »

- Survey as many stars as possible (« Yellow list: 100 stars »)
- Least estimated cost

Green target list (106 stars)

- Spectral types F7–K9 and
- vsin(i) < 5 km/s

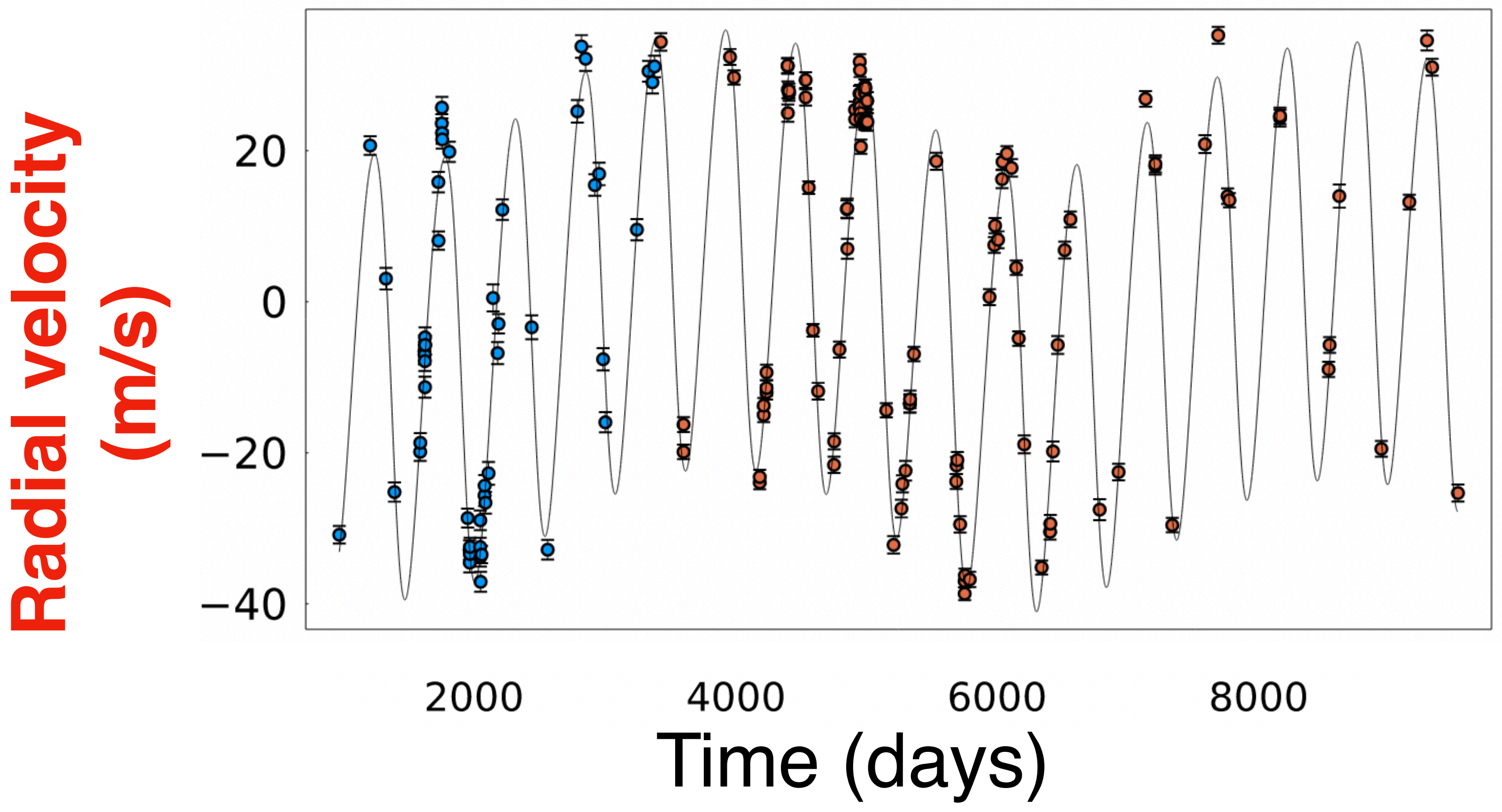
- Close (On the HabEx 'deep survey' or '50 highest priority stars' lists (Gaudi et al. 2020), or on at least 2 other mission concept target lists (including LUVOIR-A, LUVOIR-B, HabEx 'master list,' Starshade Rendezvous)

NASA Extreme precision radial velocity report

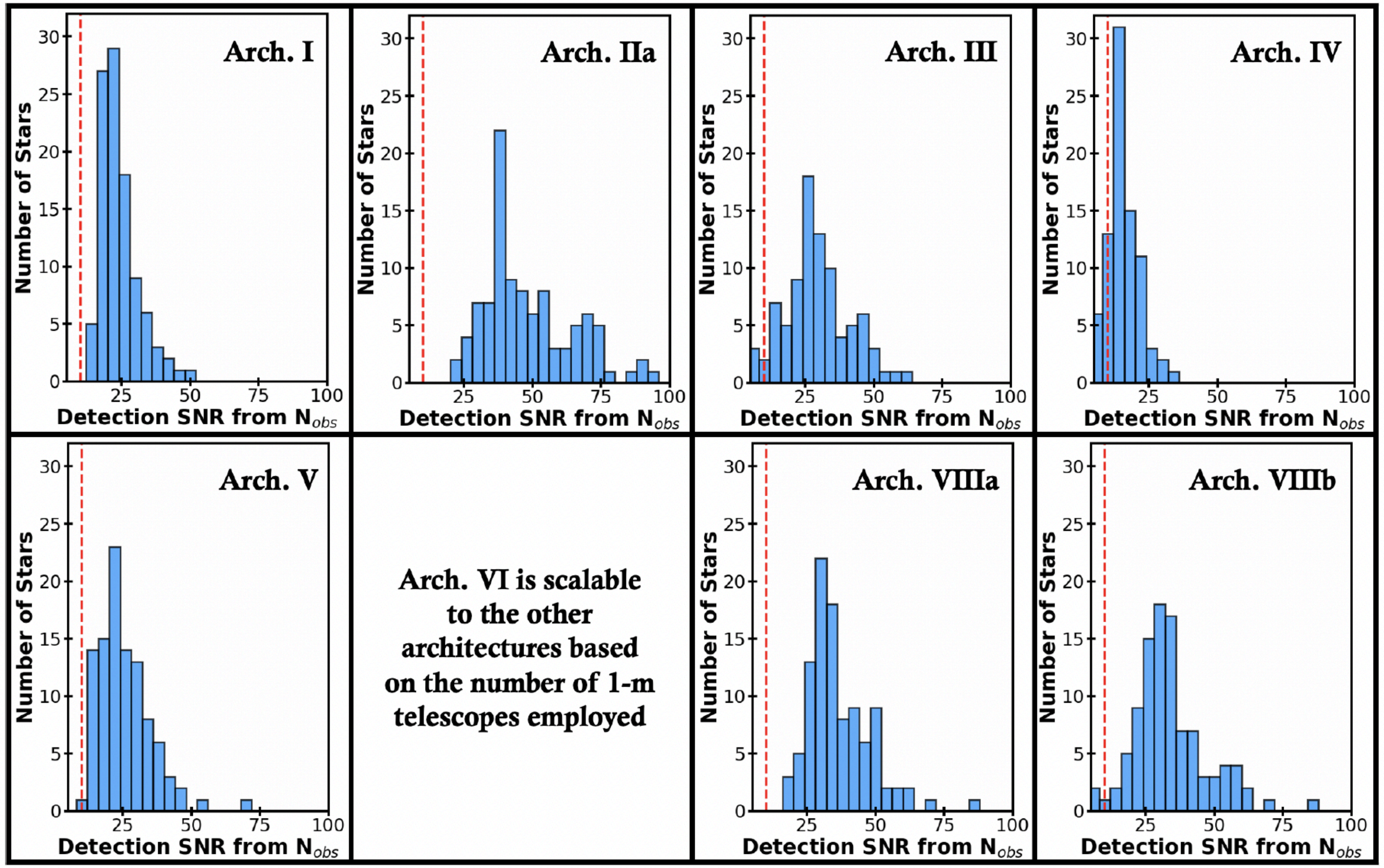
Simulation with different telescope/instrument associations

In principle the 100 prioritised targets can all be characterised

Simulation done in the best case scenario: White noise



Histogram of obtained signal to noise ratio for 100 priority stars assuming they all have an Earth



Crass et al. 2021

Excerpts from the EPRV report

Telluric line contamination is assumed to be limited and correctable

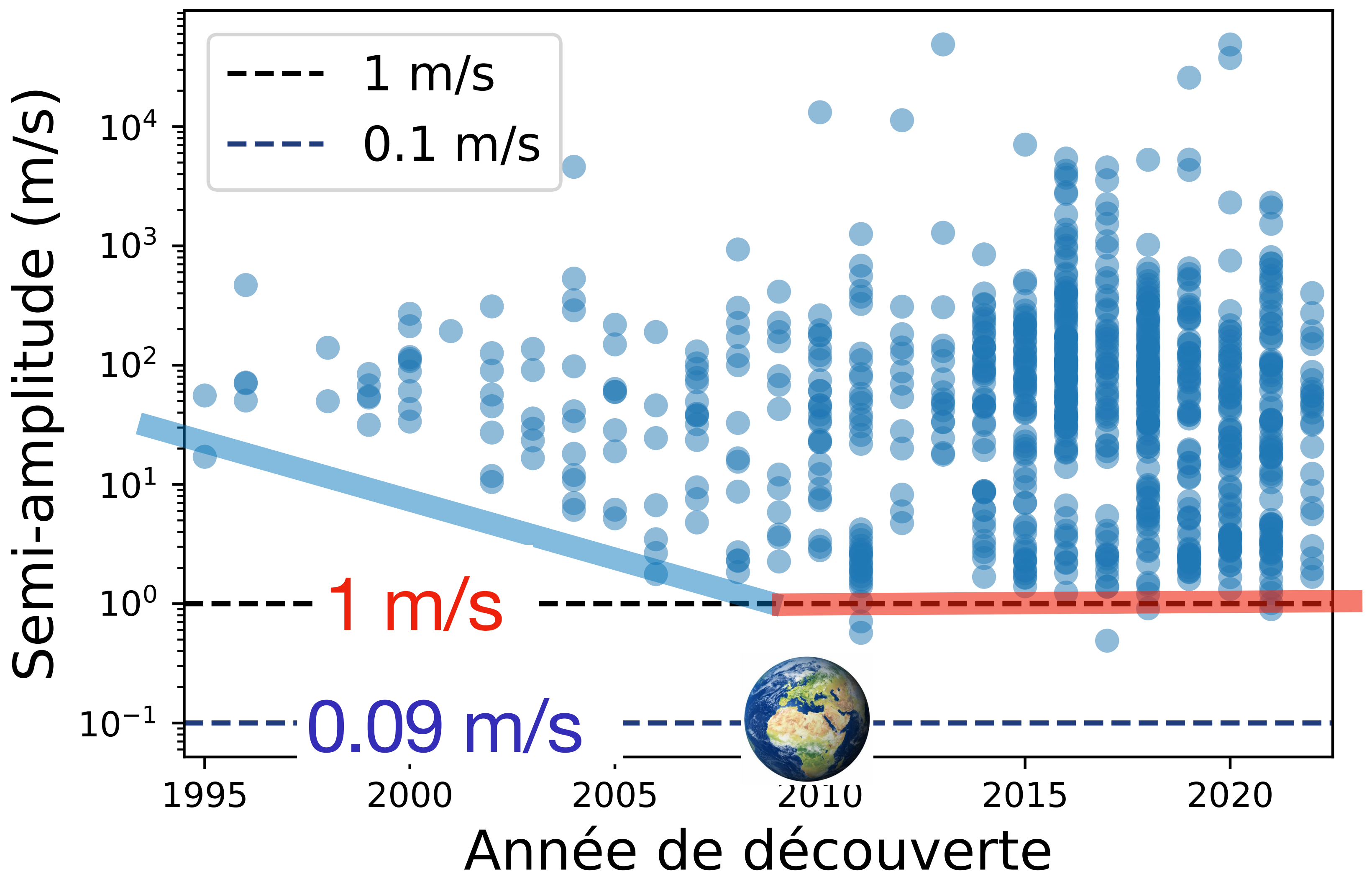
Weather conditions are uncorrelated.

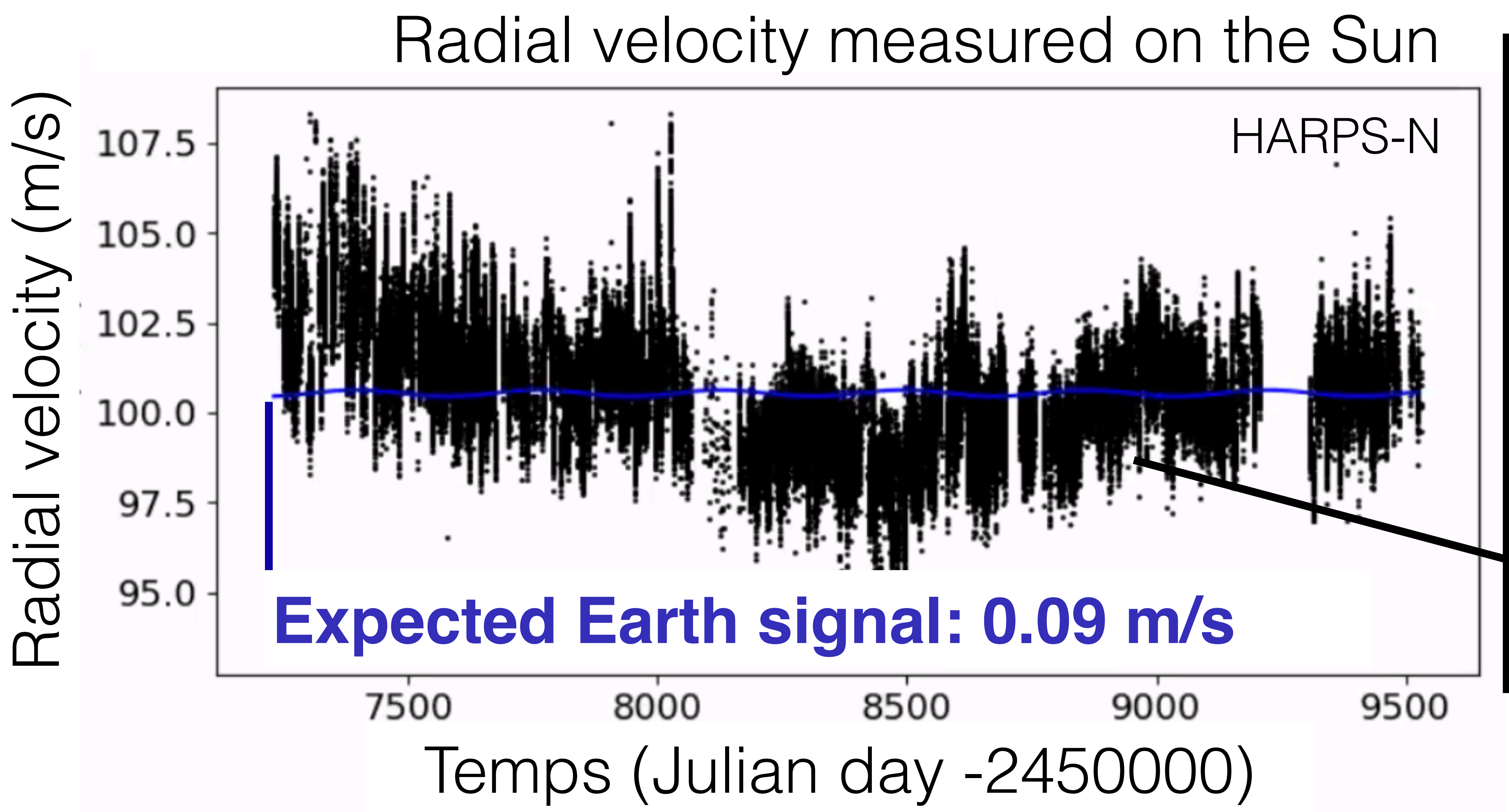
We do not account for errors due to RV contamination from additional planets in the same planetary system

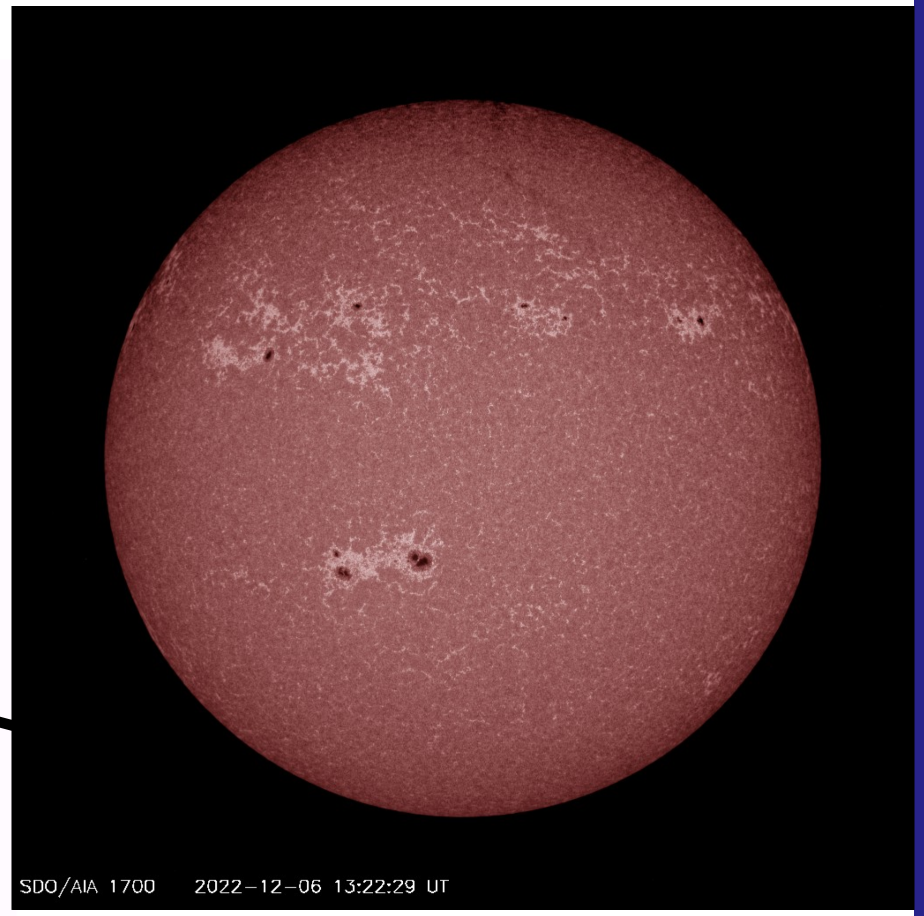
Stellar variability is assumed to be adequately characterized and mitigated during the data extraction of RV signals such that the remaining signal due to stellar variability is uncorrelated in time.

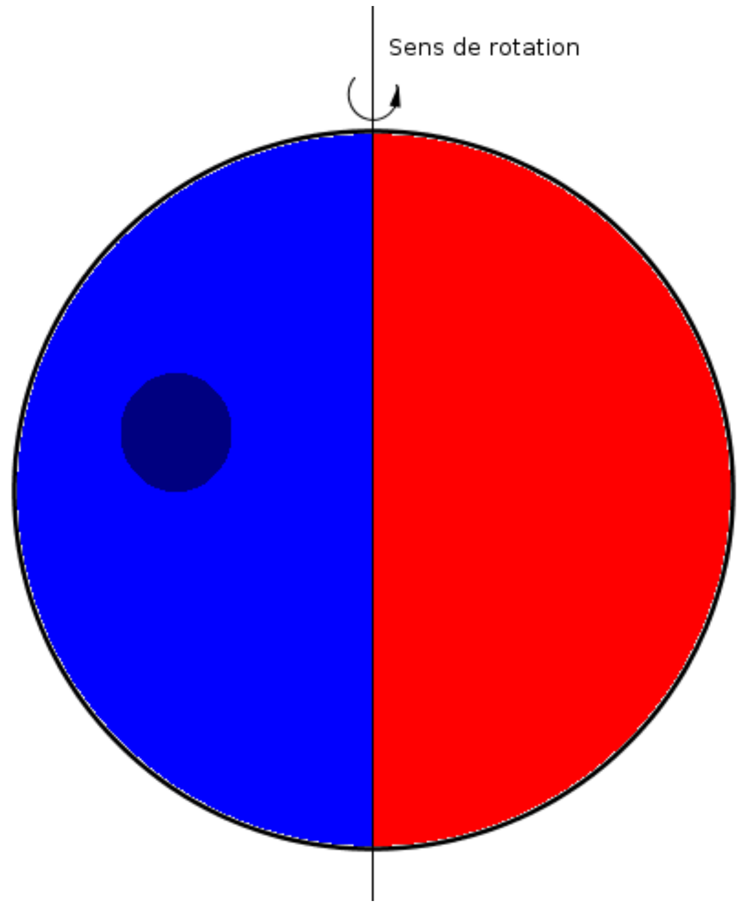
Extreme precision radial velocity is very useful **if these problems can be mitigated**

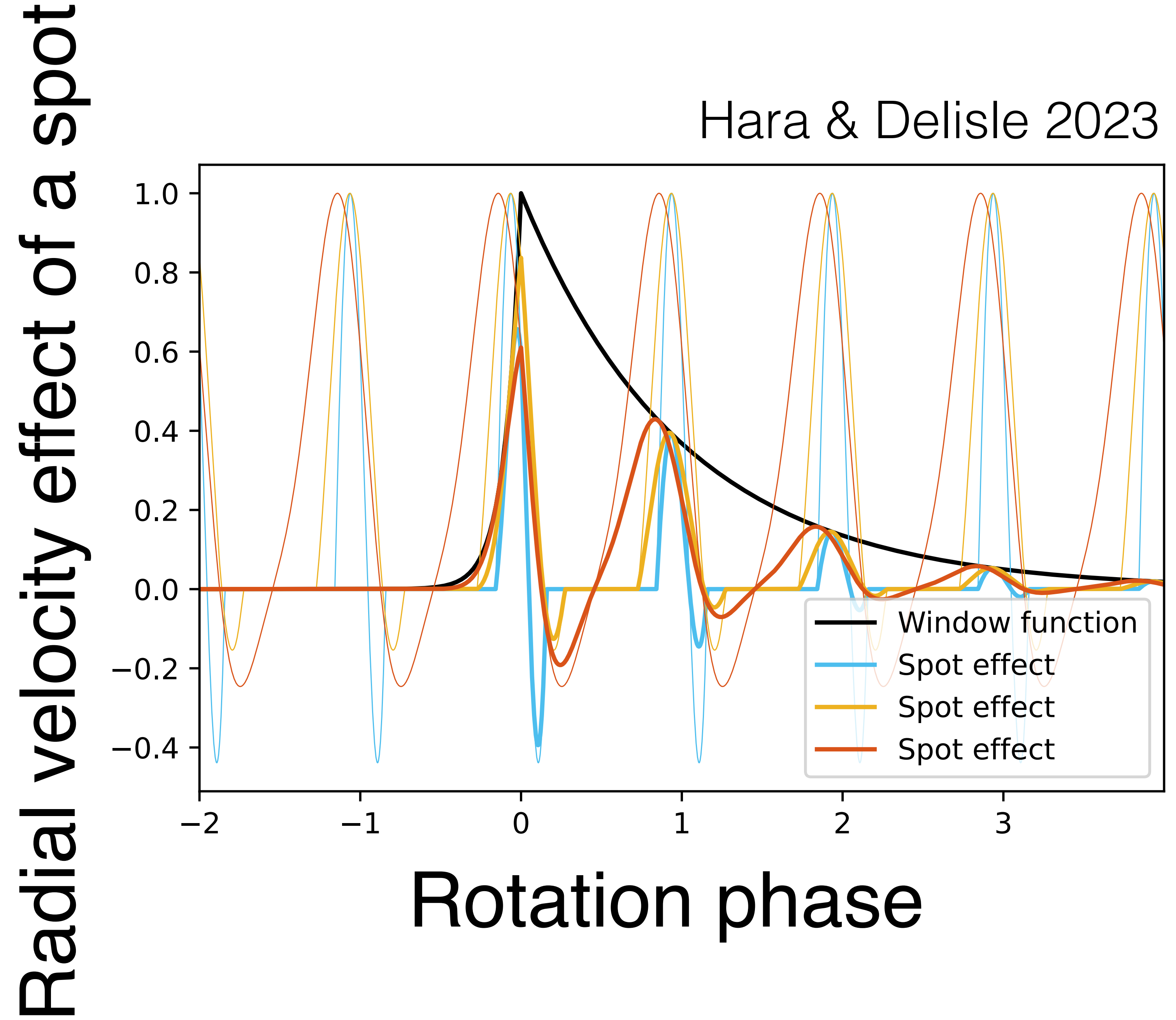
Noise in radial velocities is not white









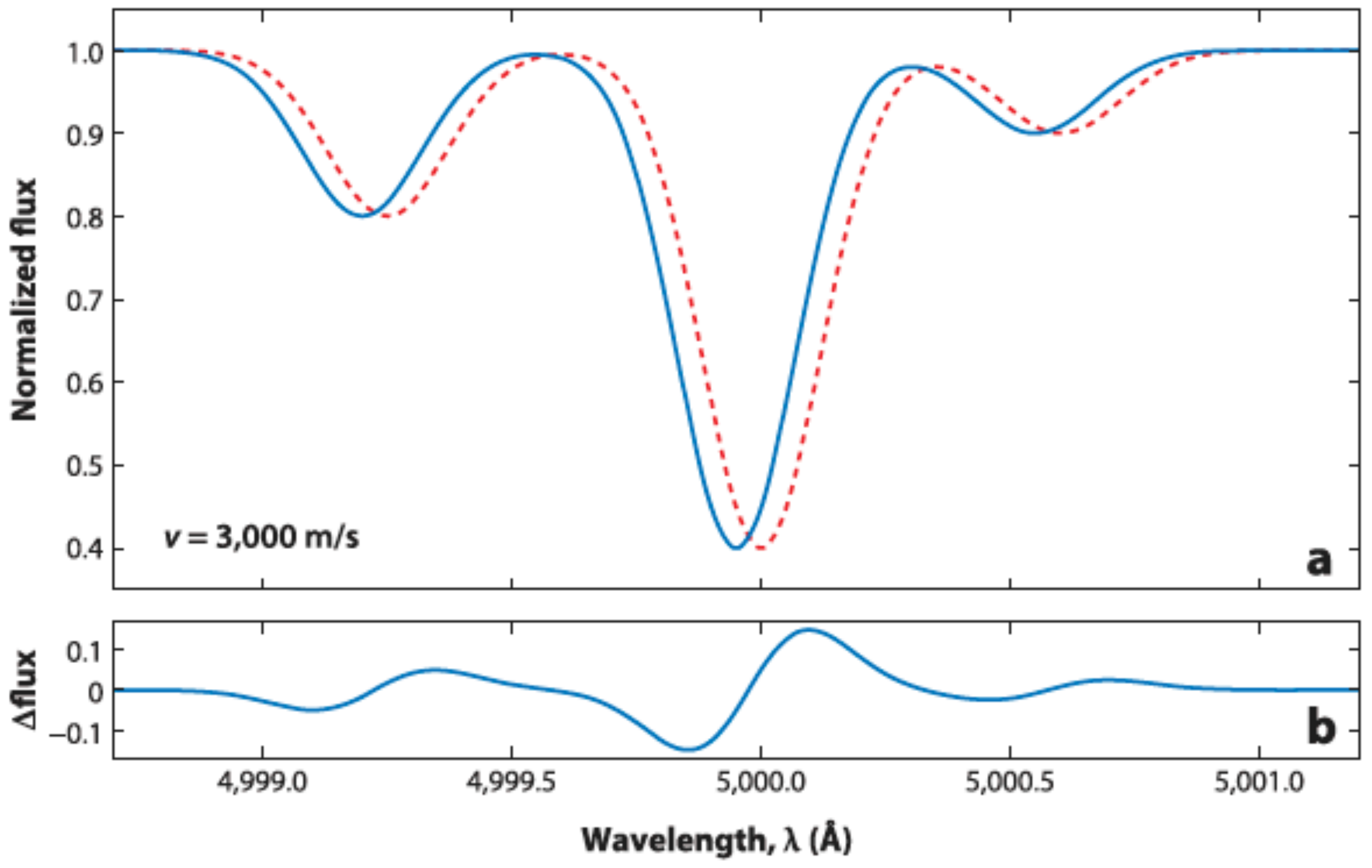


Stellar variability (magnetic activity, granulation, oscillations, meridional winds…) + systematics + telluric lines absorption

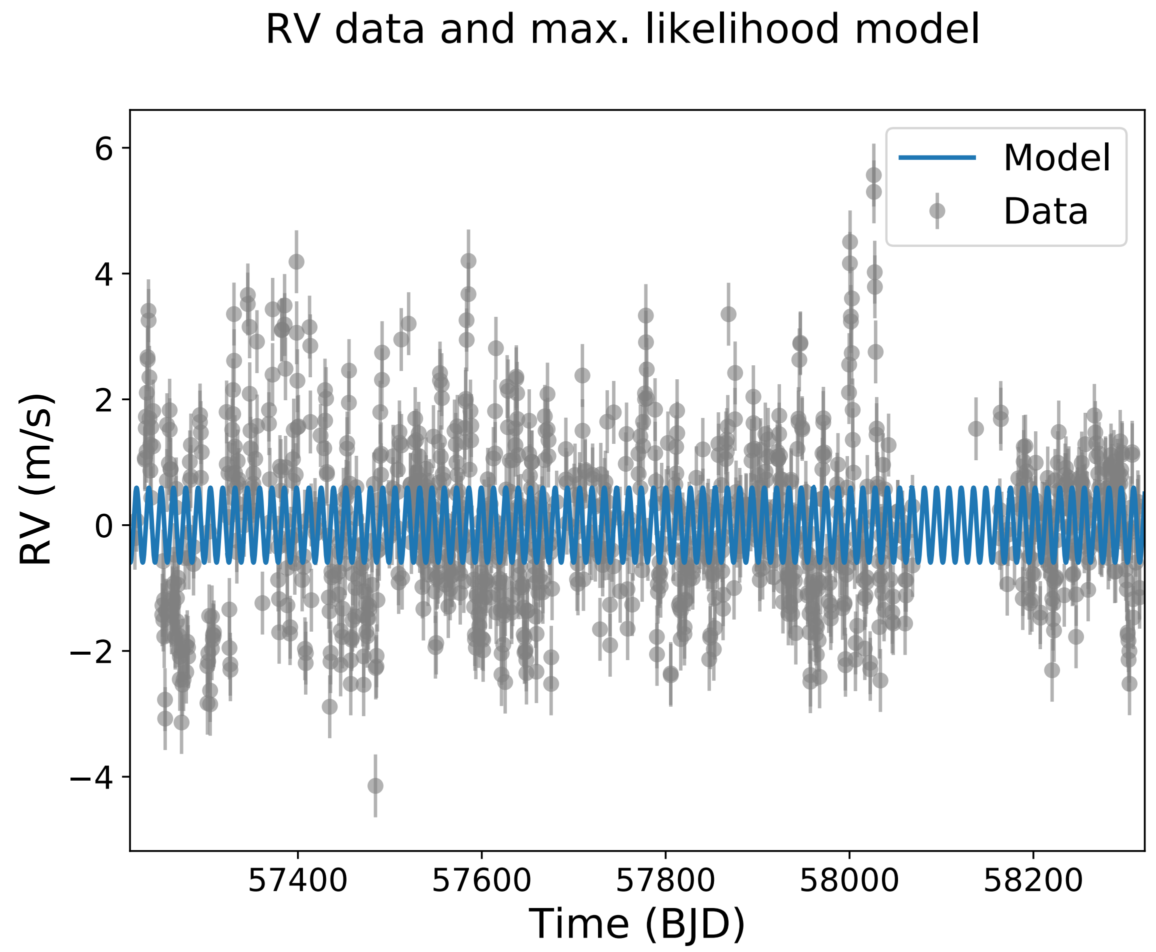
understanding and correcting these signals is crucial, data analysis methods play a key role

Key ideas

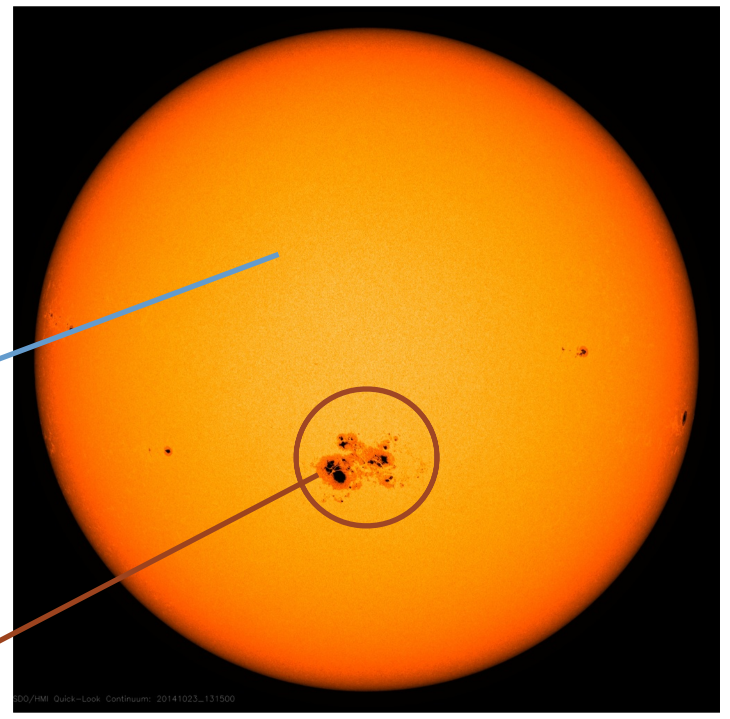
Planets induce a pure Doppler shift

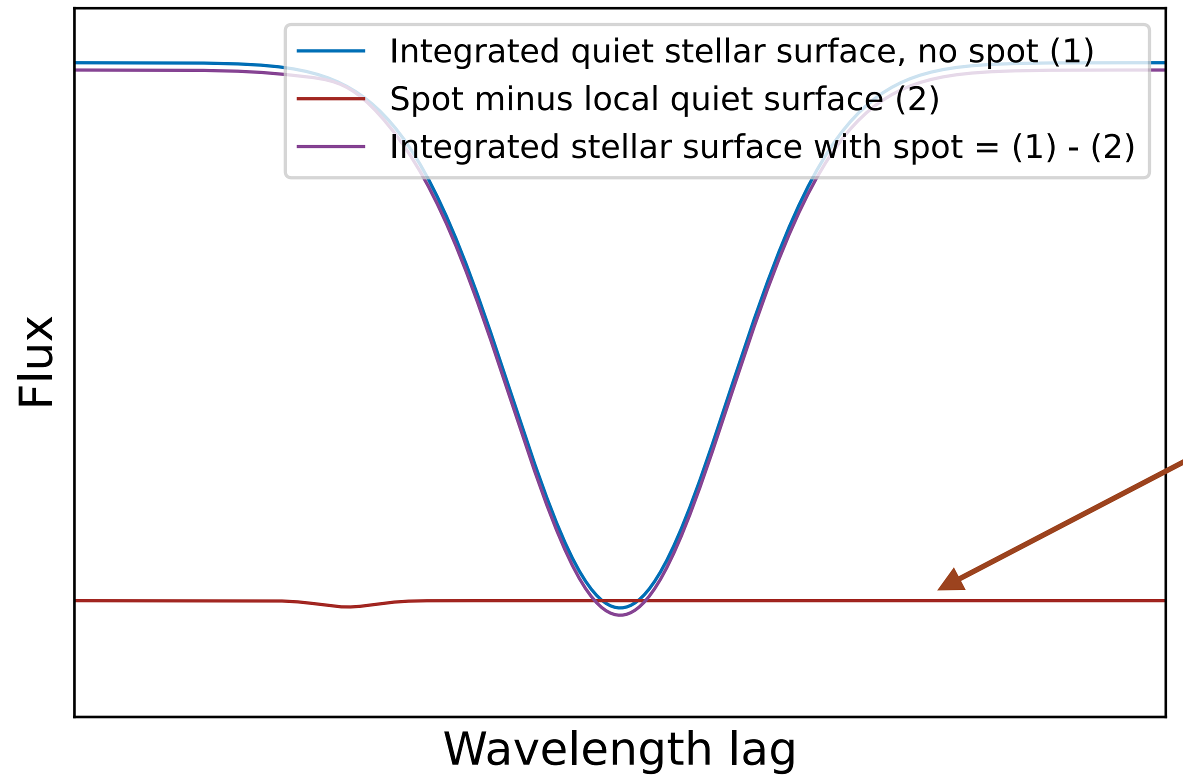


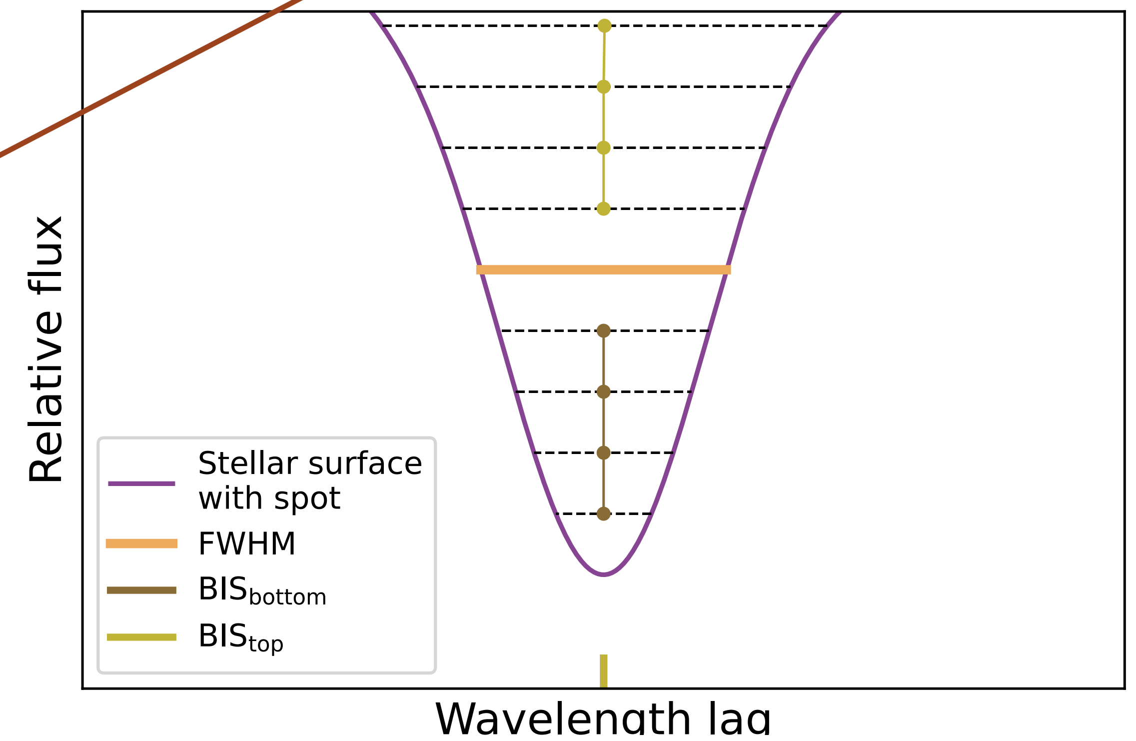
Planets induce a periodic signal



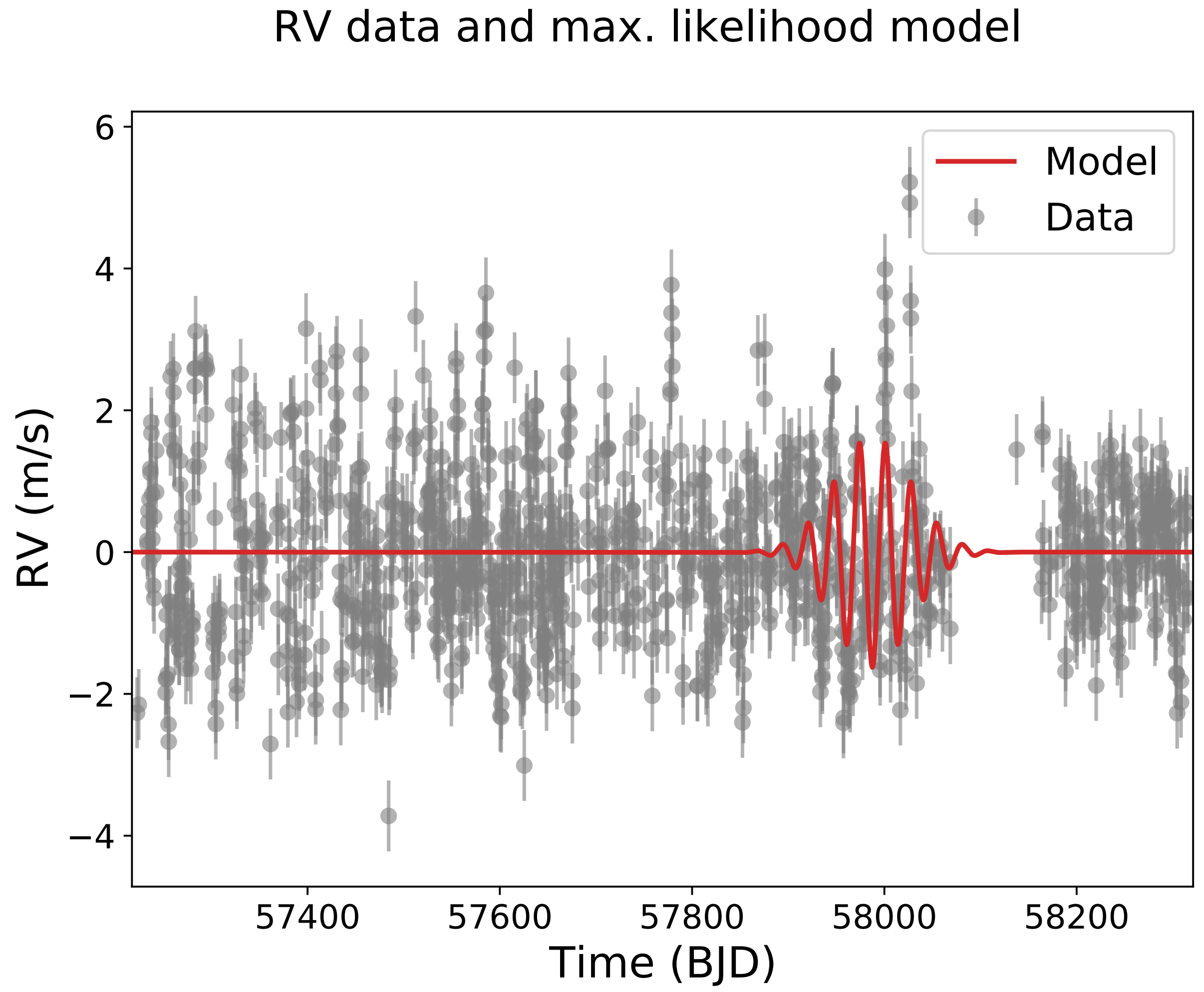
stellar and instrumental effects change the shape of the spectrum







Stellar and instrumental effects are (usually) not strictly periodic

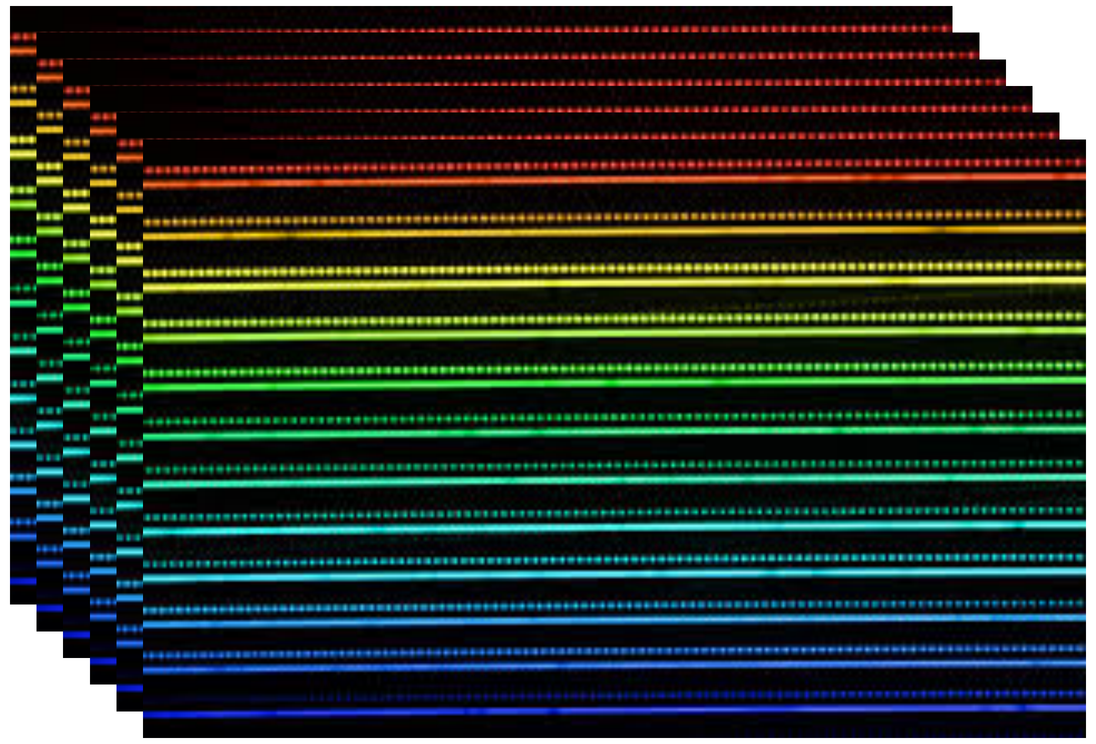


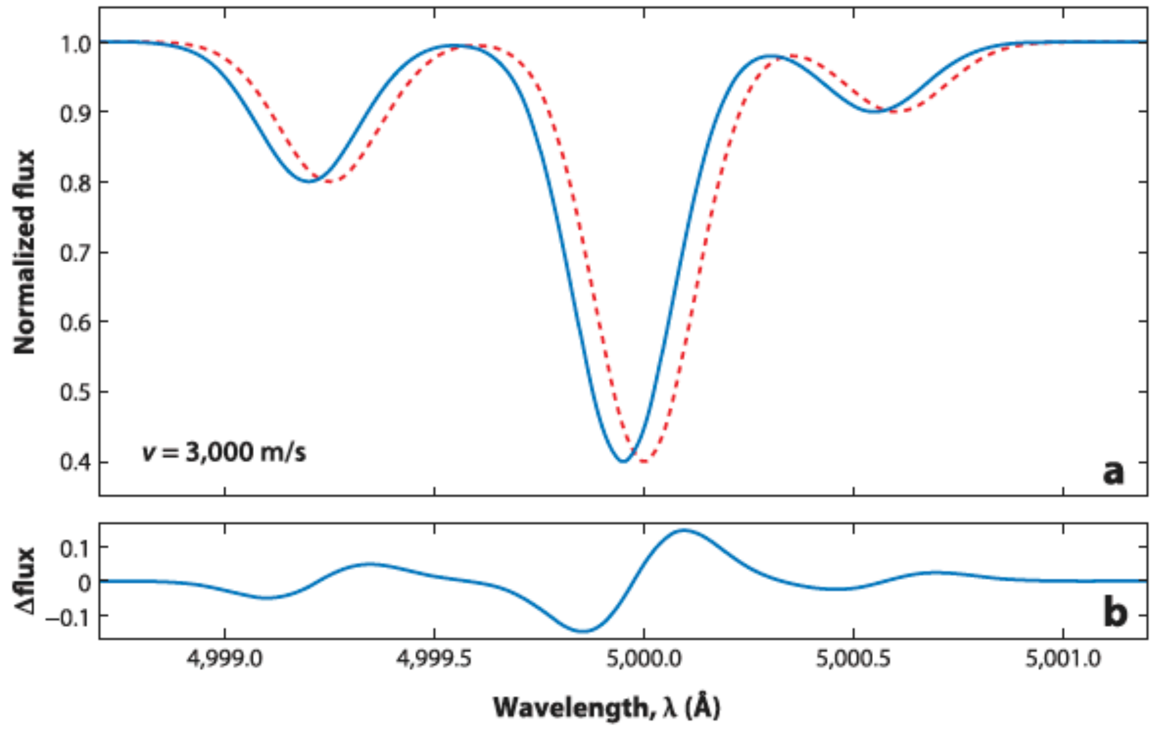
Steps of RV analysis

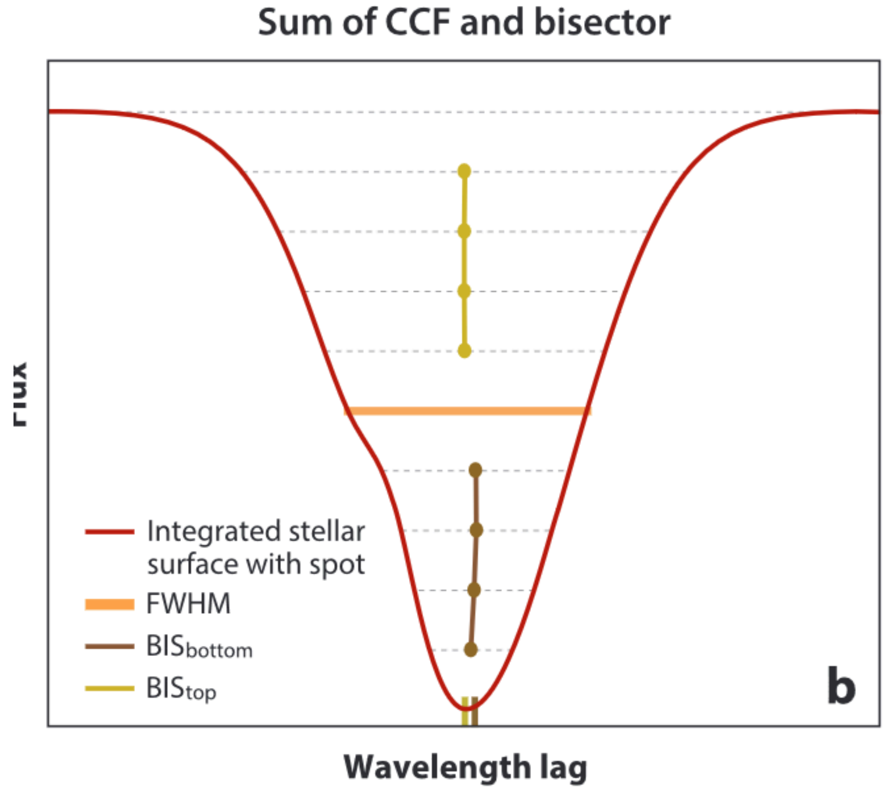
Time series of Raw spectra

Reduce to 1 dimensional spectrum

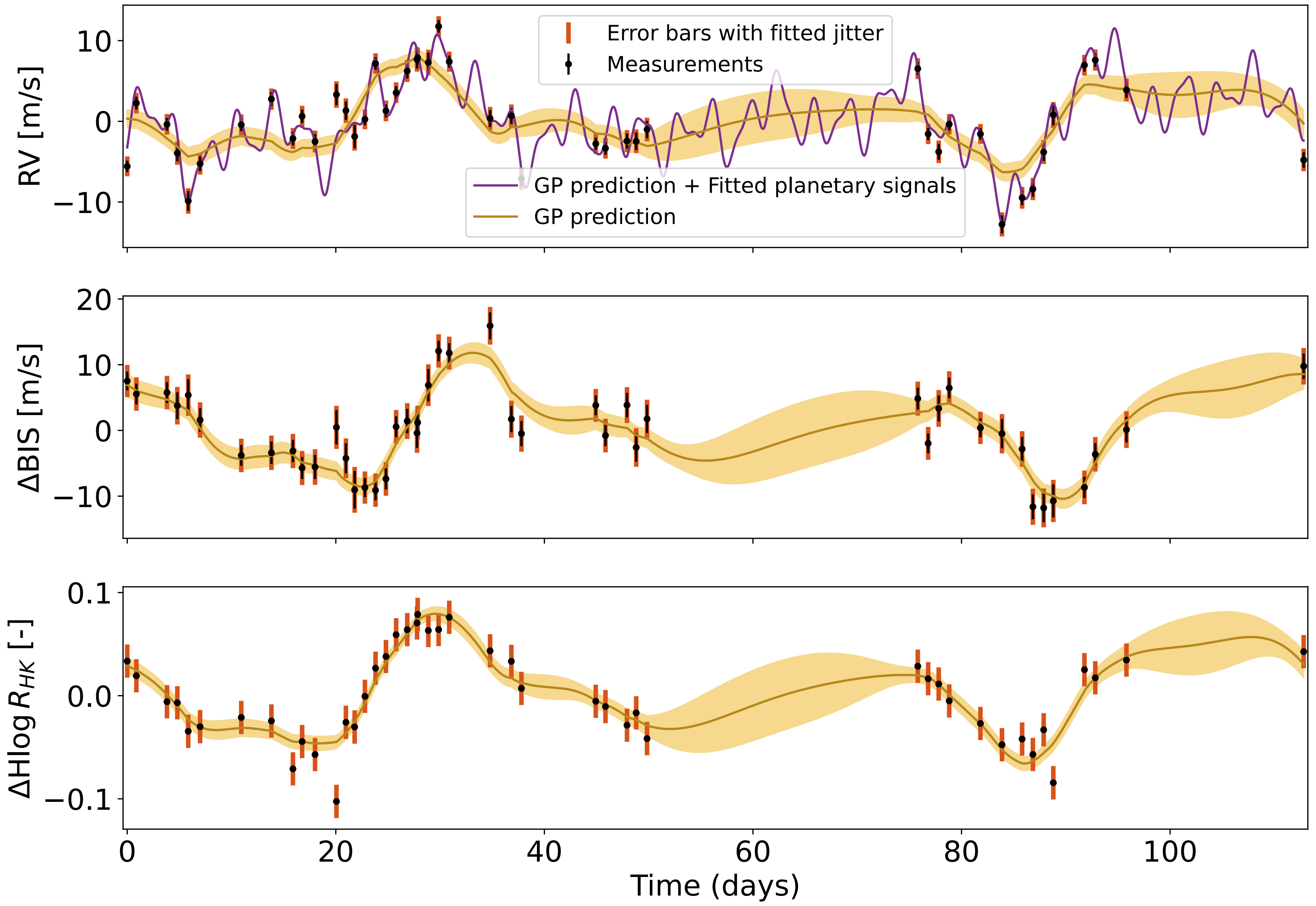
Extract Radial velocity Indicators



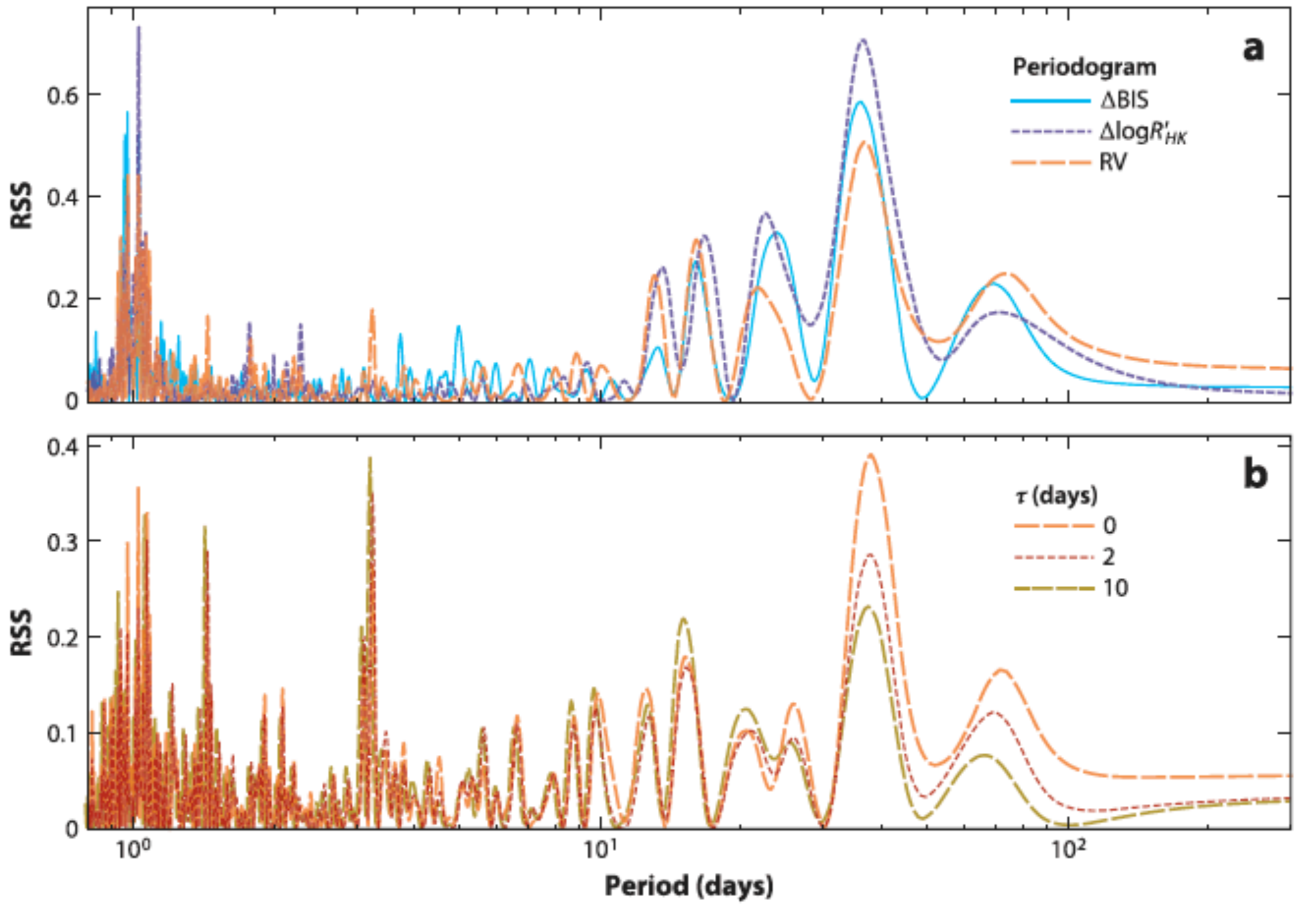




Modelling: which noise properties, priors?



Are planets detected? Which ones?



Hara & Ford, Annual Reviews of statistisics and Its Application: what are the problems to solve?

An optimal exoplanet detection criterion

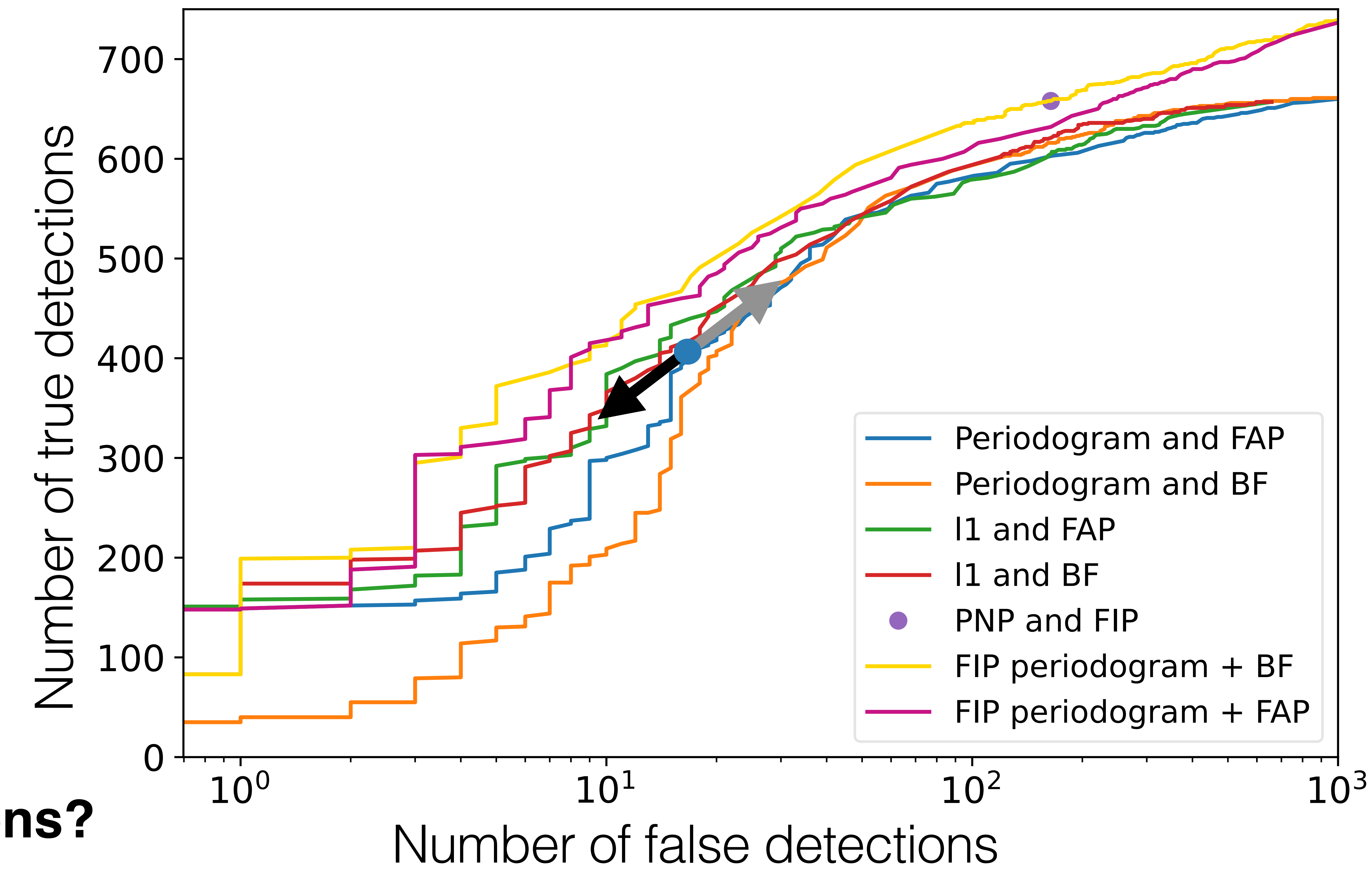
1000 radial velocity datasets with 0,1 or 2 planets

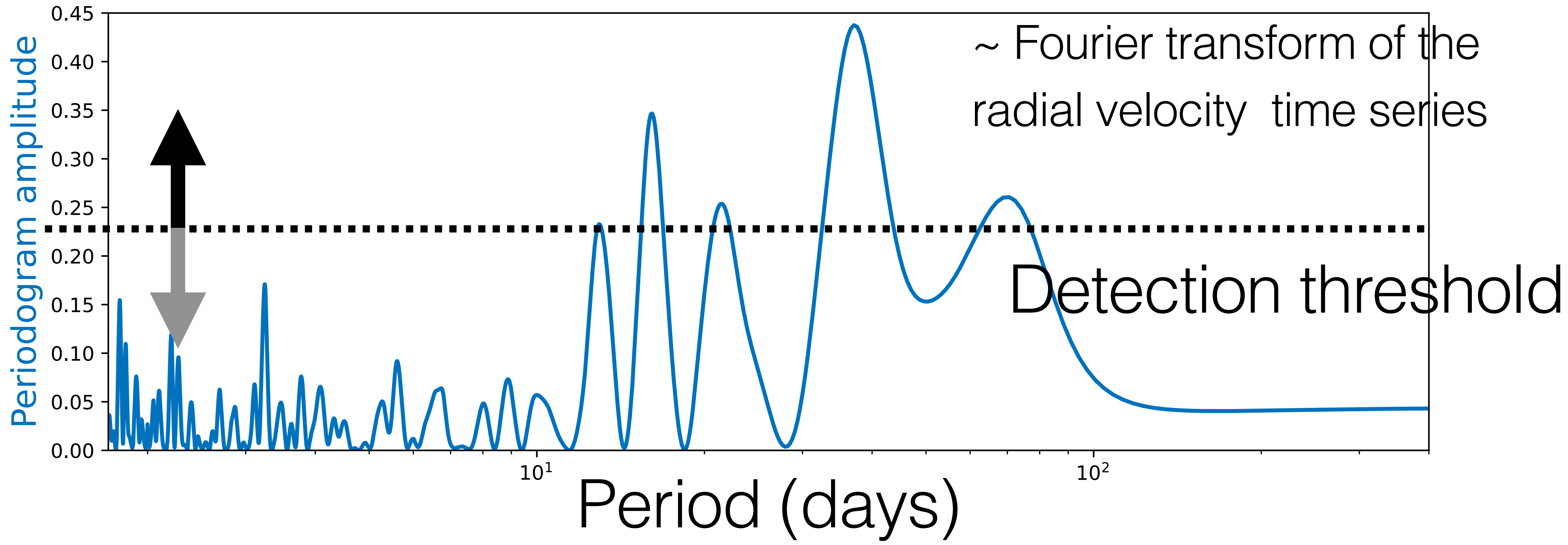
- Analysed with the same model
- With different detection criteria

Bayes factors and FAPs

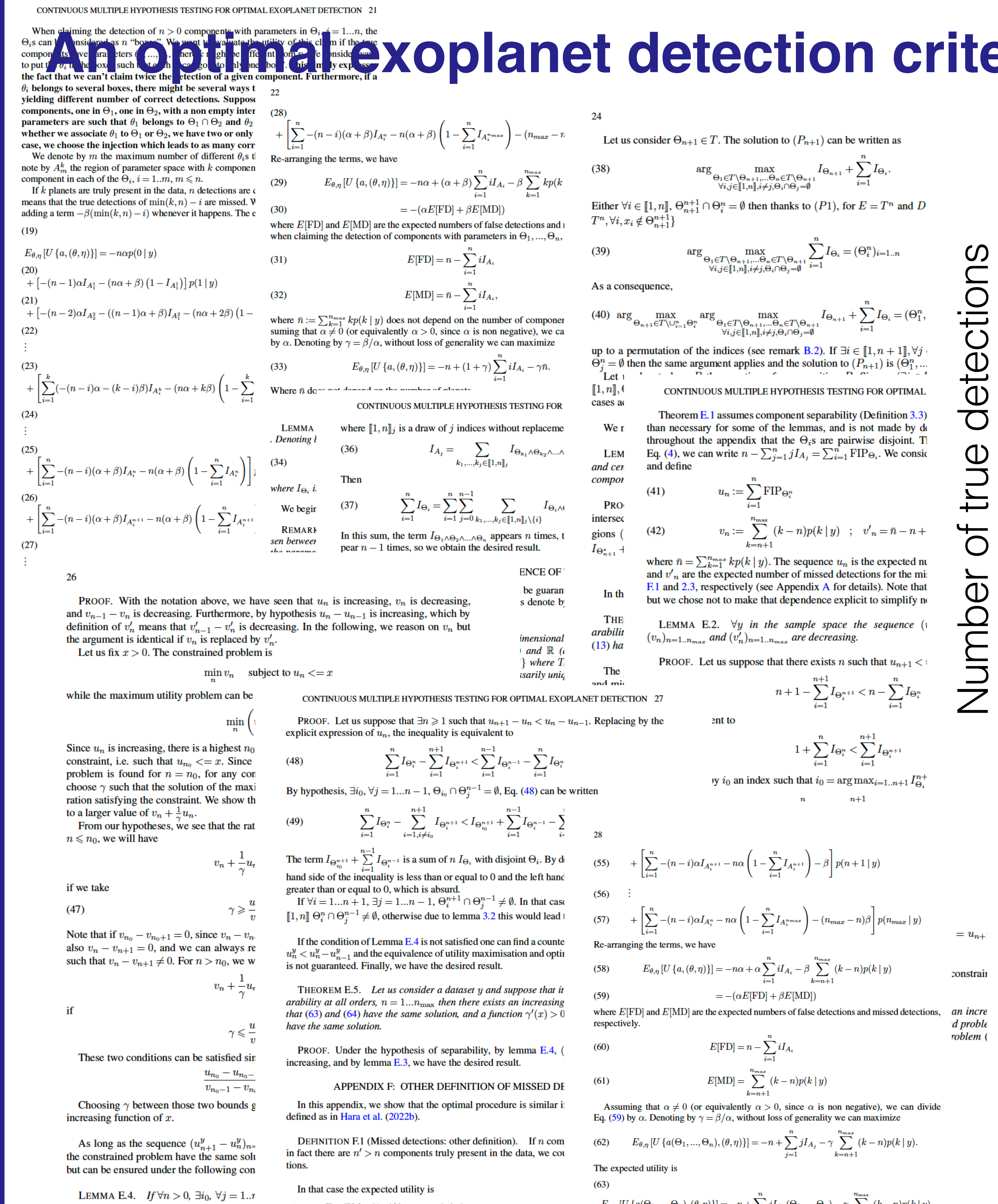
- **Optimal?**
  Which criterion maximises true detections?
- Do not encode where the planet is

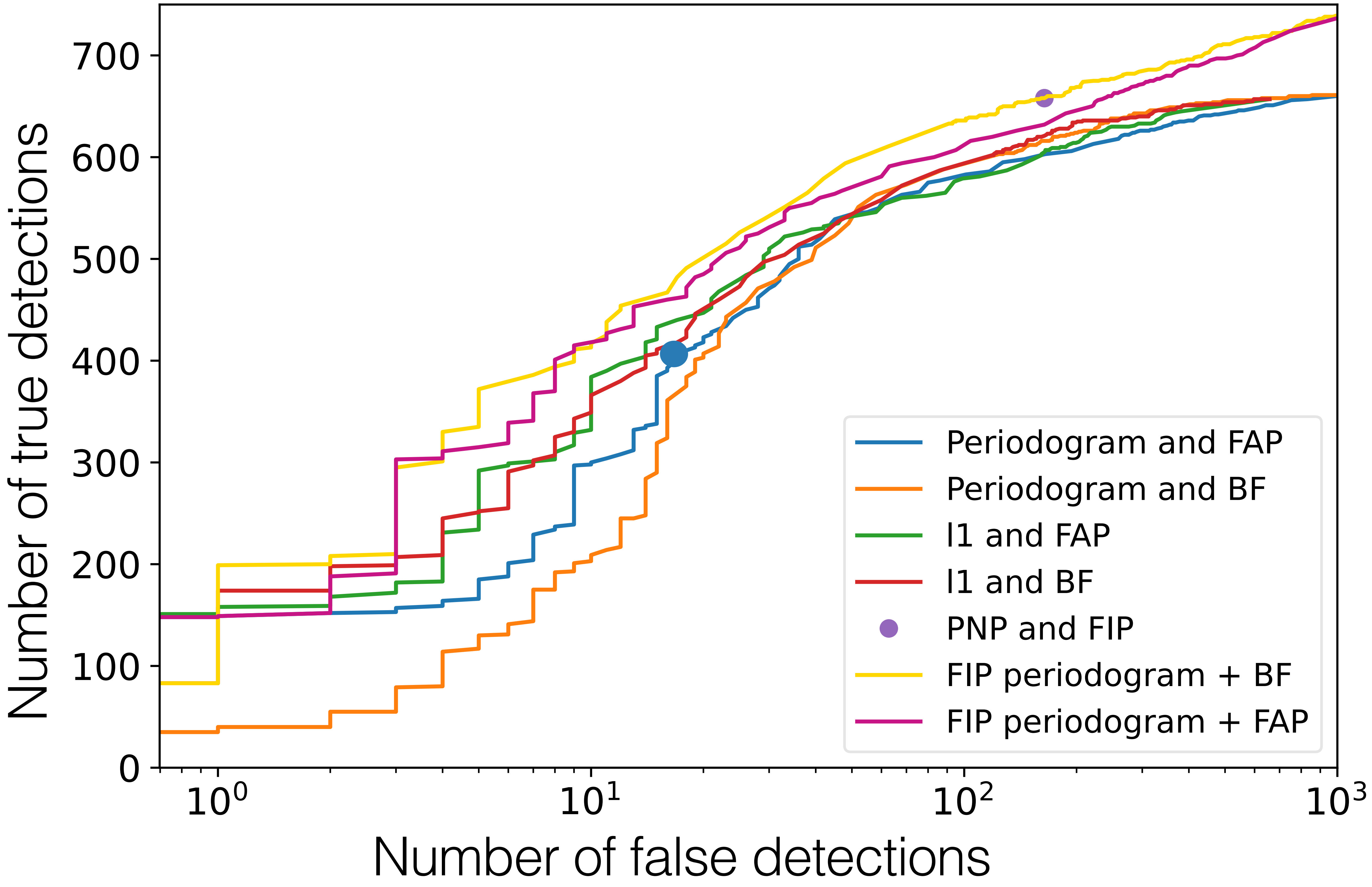
- Are not defined on a very intuitive scale

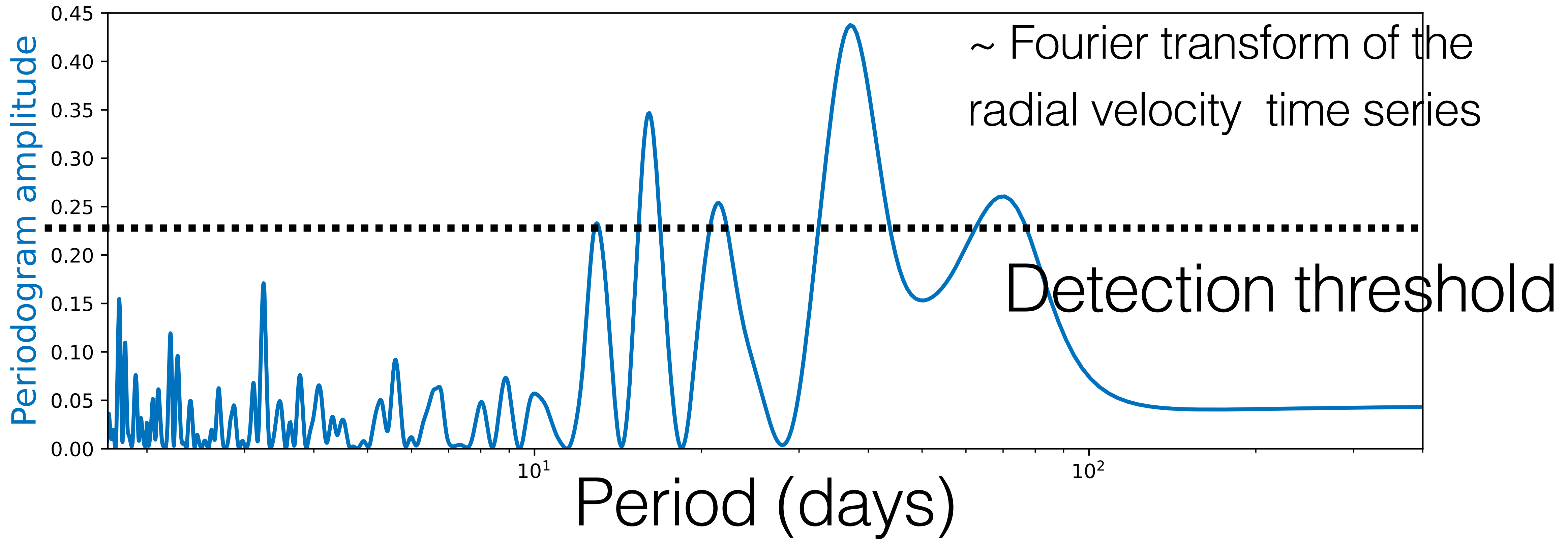




An optimal exoplanet detection criterion







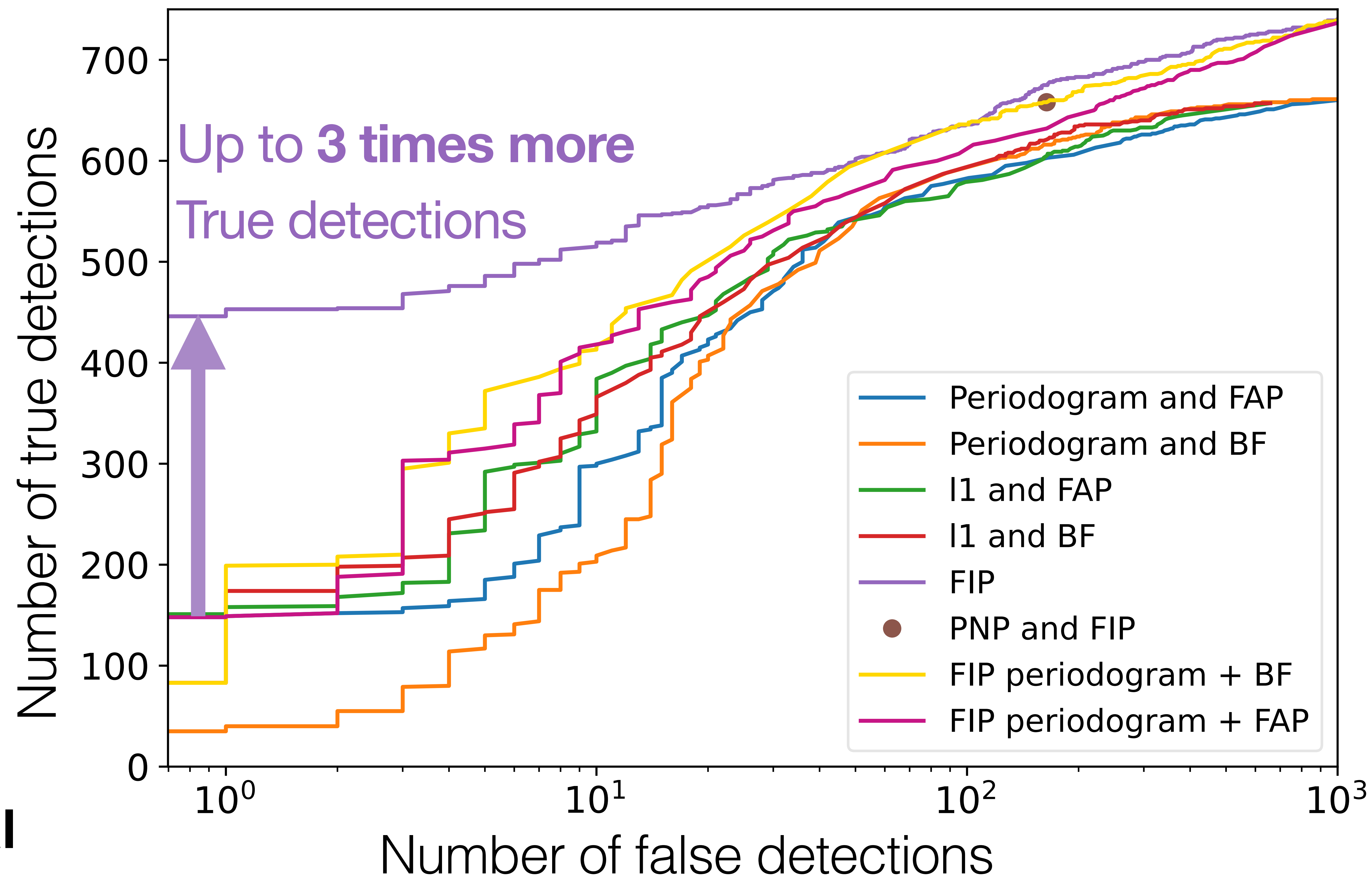
An optimal exoplanet detection criterion

- **Mathematical proof of optimality** of a new detection criterion called « True inclusion probability » (TIP)
- Optimal in a general case

Hara et al. 2023, Annals of Applied Statistics (in revision)
Hara, Unger, Delisle, Díaz, Ségransan 2022

Bayes factors and FAPs

- Optimal?
  ⟶ **New criterion demonstrably optimal**
- Do not encode where the planet is
  ⟶ **Encoded in new criterion**
- Are not defined on a very intuitive scale
  ⟶ **New criterion is an actual probability**



In a collection of independent detections made with TIP 99%, on average 99% are correct

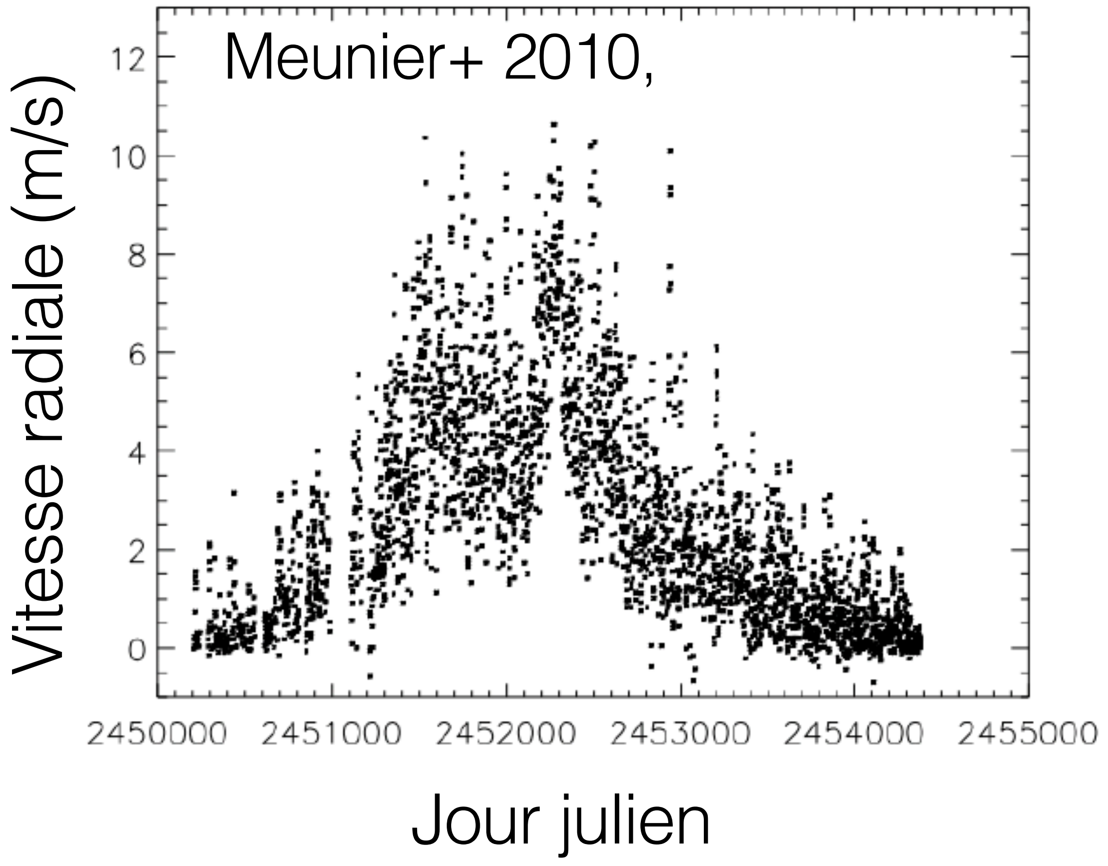
90%	90%
50%	50%

Understanding stellar variability to correct it

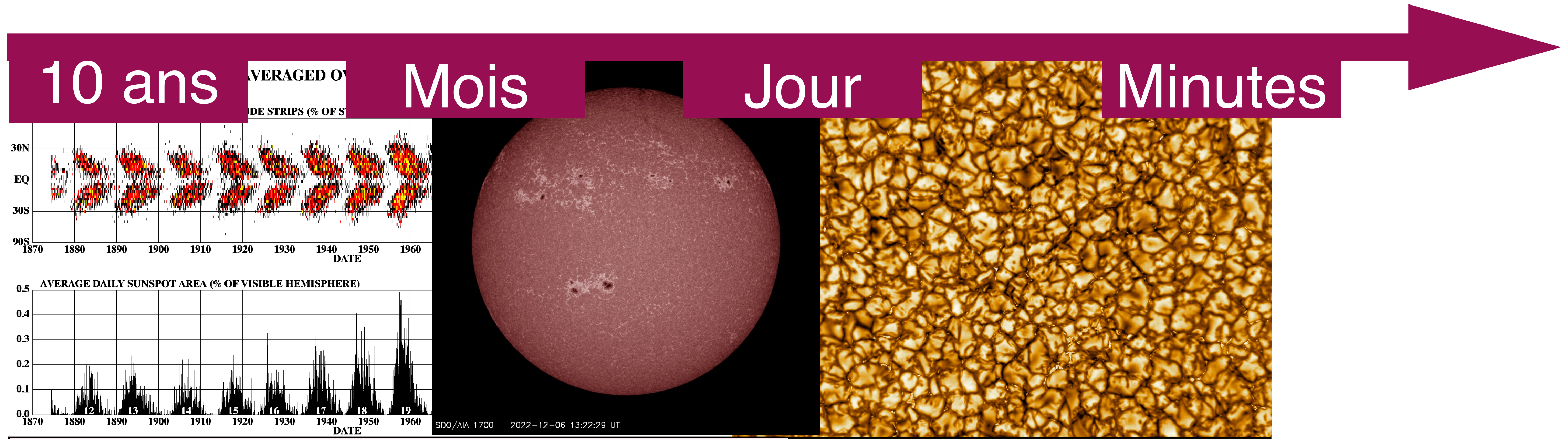
Detailed physical models
Analysis of solar data

?

Data analysed with a statistical model supposed Gaussian and stationary with qualitative parameters



Numerous processes at
Different timescales

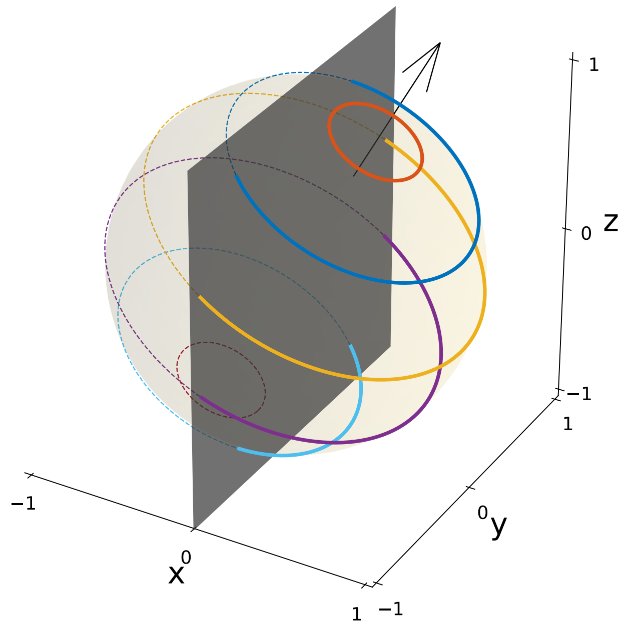


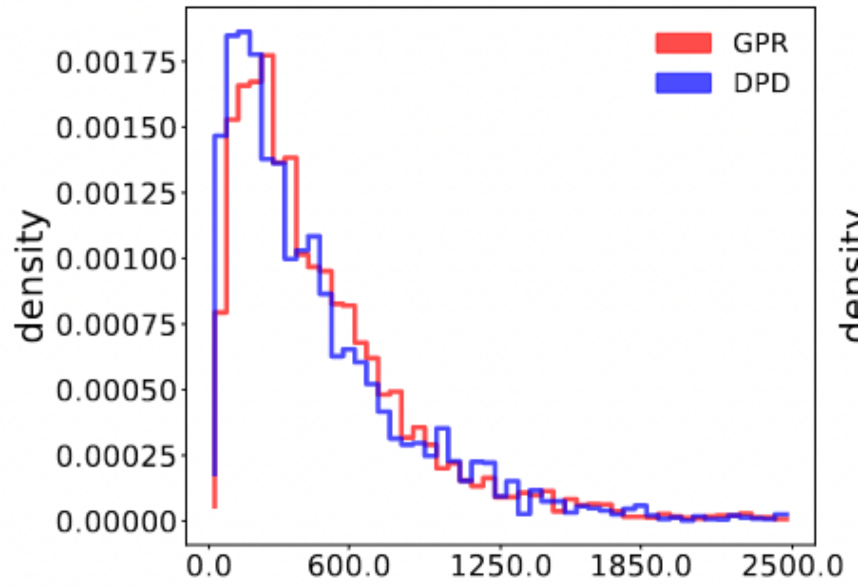
Magnetic activity	Granulation and super granulation
p.ex. Meunier+ 2010, 2012, 2019 Boisse+ 2012, Dumusque+ 2014, Haywood+ 2016, Al Moulla 2023	Cegla+2013, 2019 Dravins+ 2021,

+ oscillations, winds, gravitational redshift…

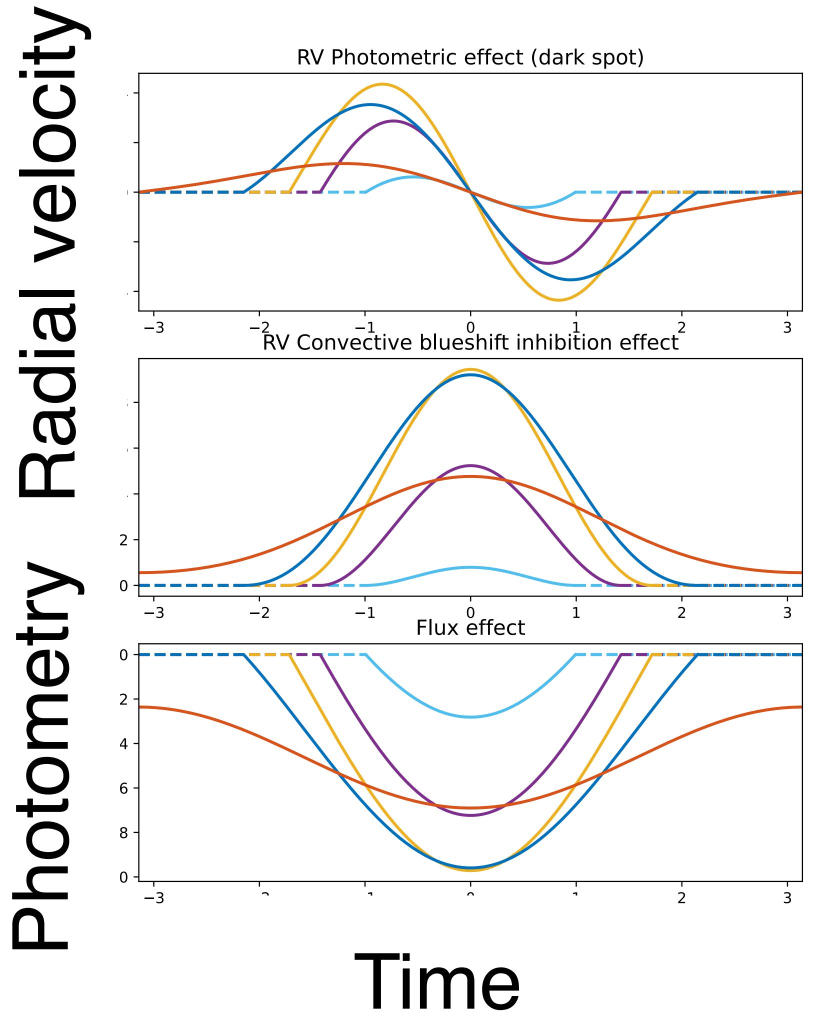
Build the statistical model from a physical one

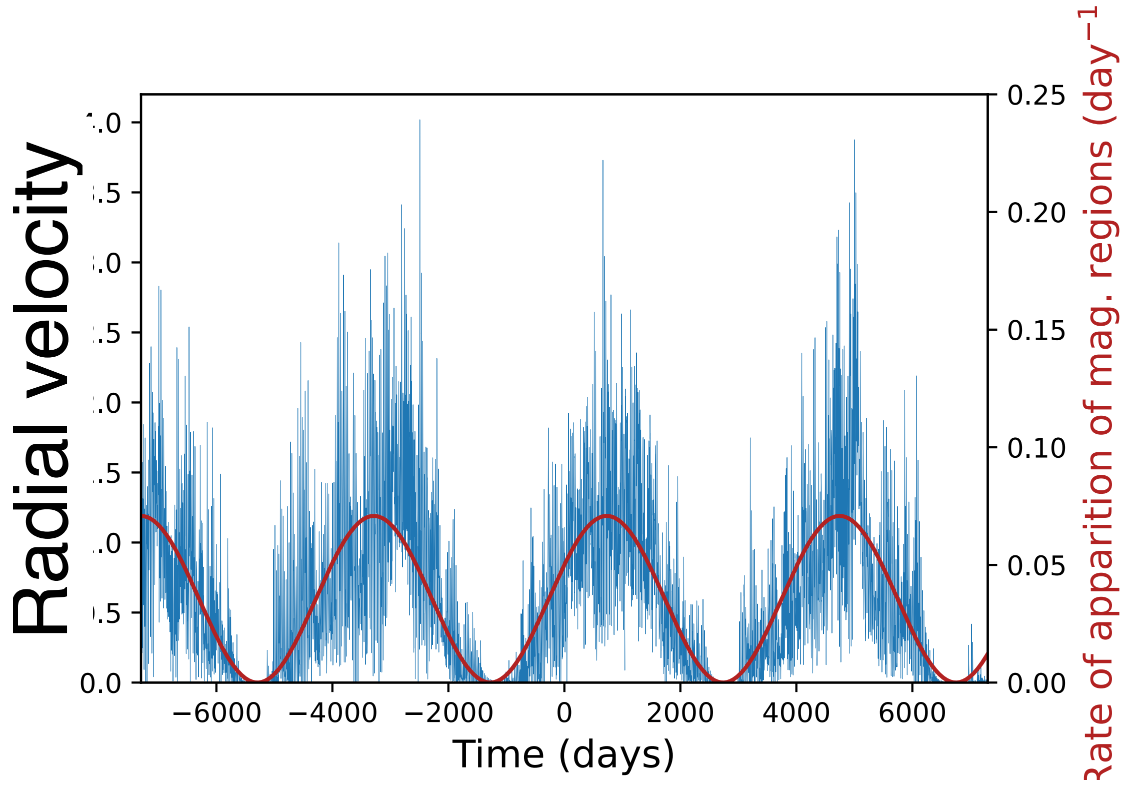
Hara & Delisle 2023





Area of spots
(μHemisphere)





Understanding stellar variability to correct it

Detailed physical models
Analysis of solar data

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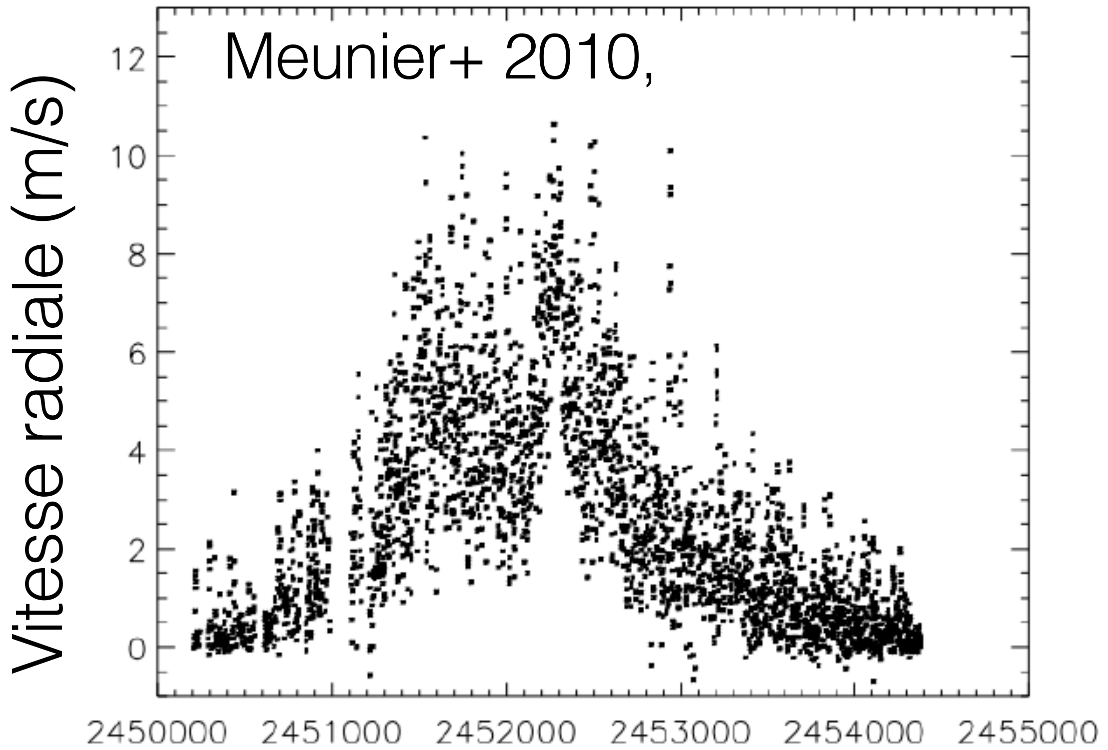
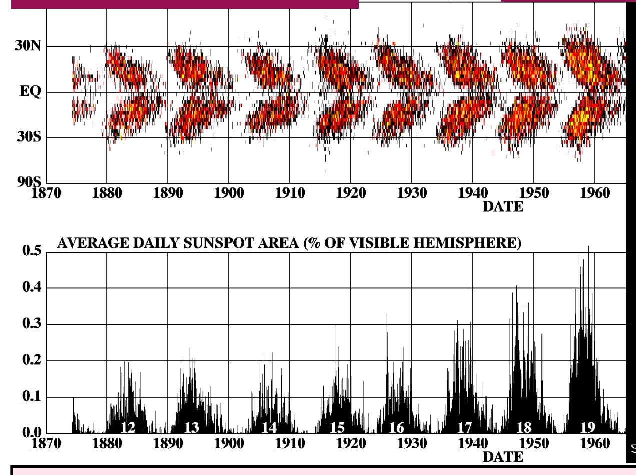
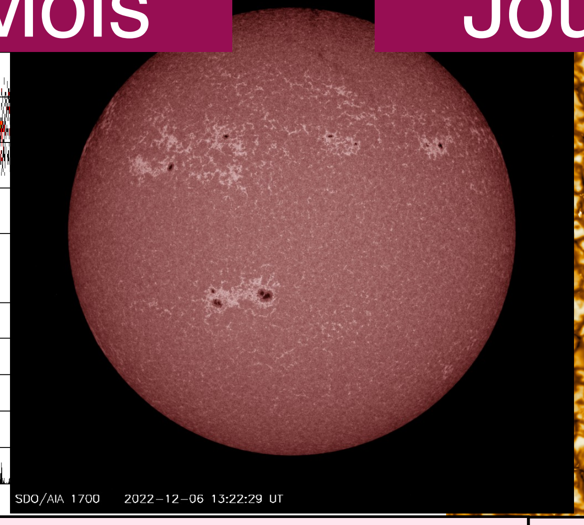
Building the statistical model

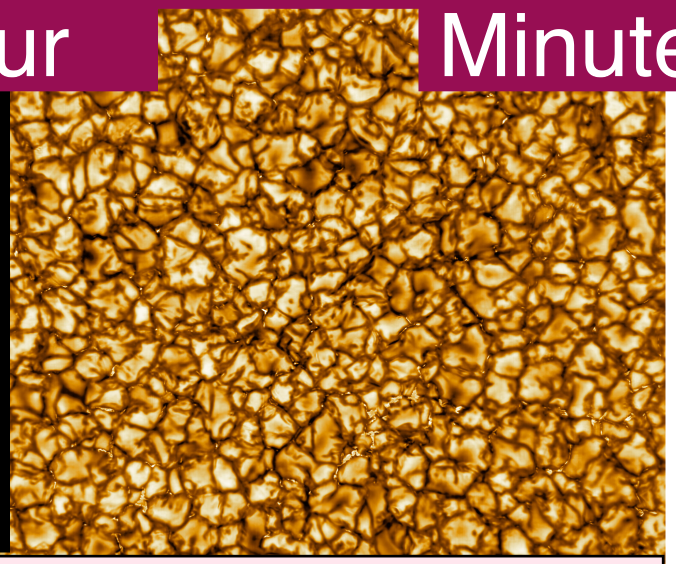


Numerous processes at
Different timescales

10 ans
Mois
Jour
Minutes



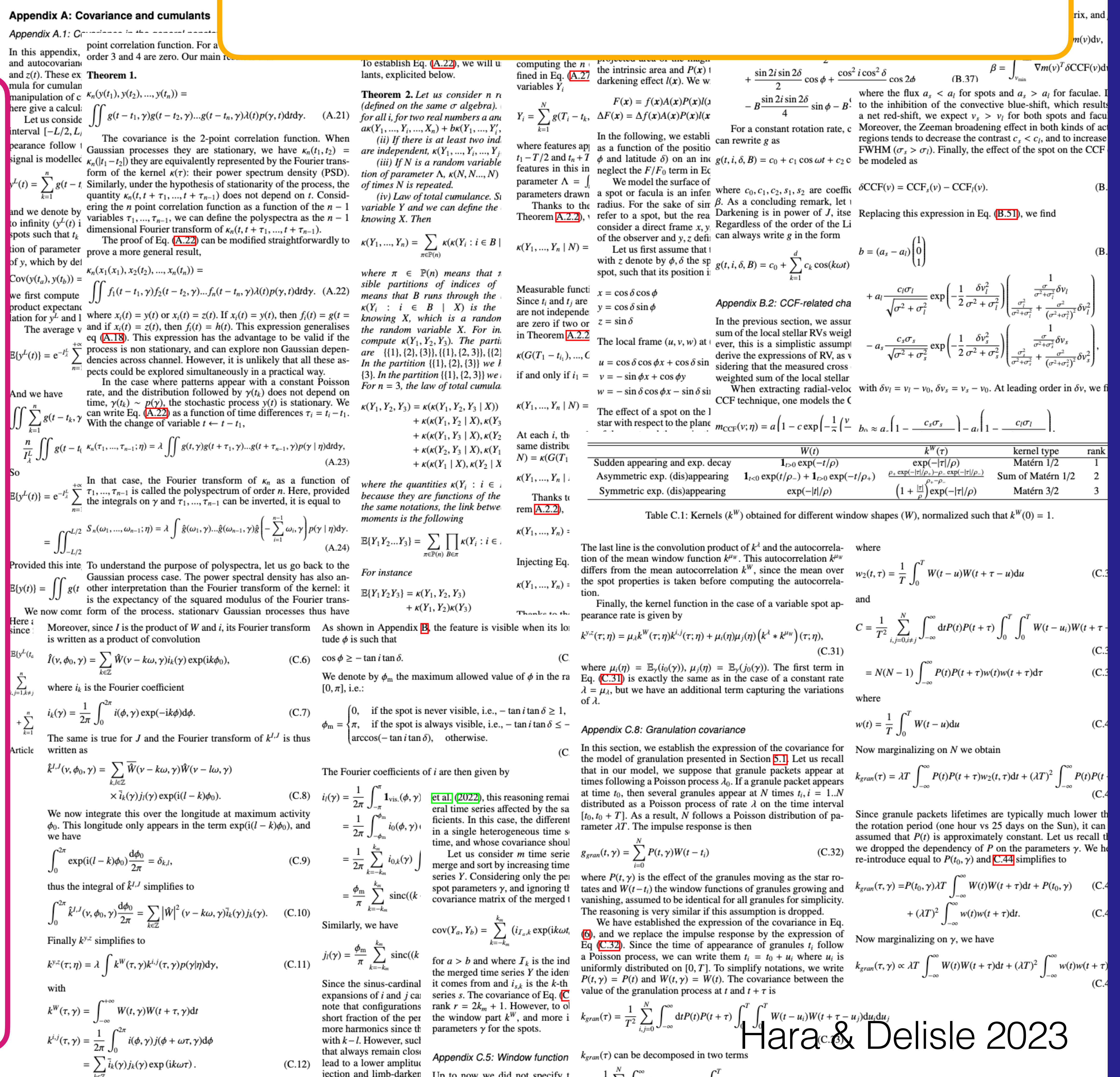




Magnetic activity
p.ex. Meunier+ 2010, 2012, 2019
Boisse+ 2012, Dumusque+ 2014,
Haywood+ 2016, Al Moulla 2023

Granulation and
super granulation
Cegla+2013, 2019
Dravins+ 2021,

+ oscillations,
winds,
gravitational
redshift…



Hara & Delisle 2023

Phase shifts and faculae/spot ratios

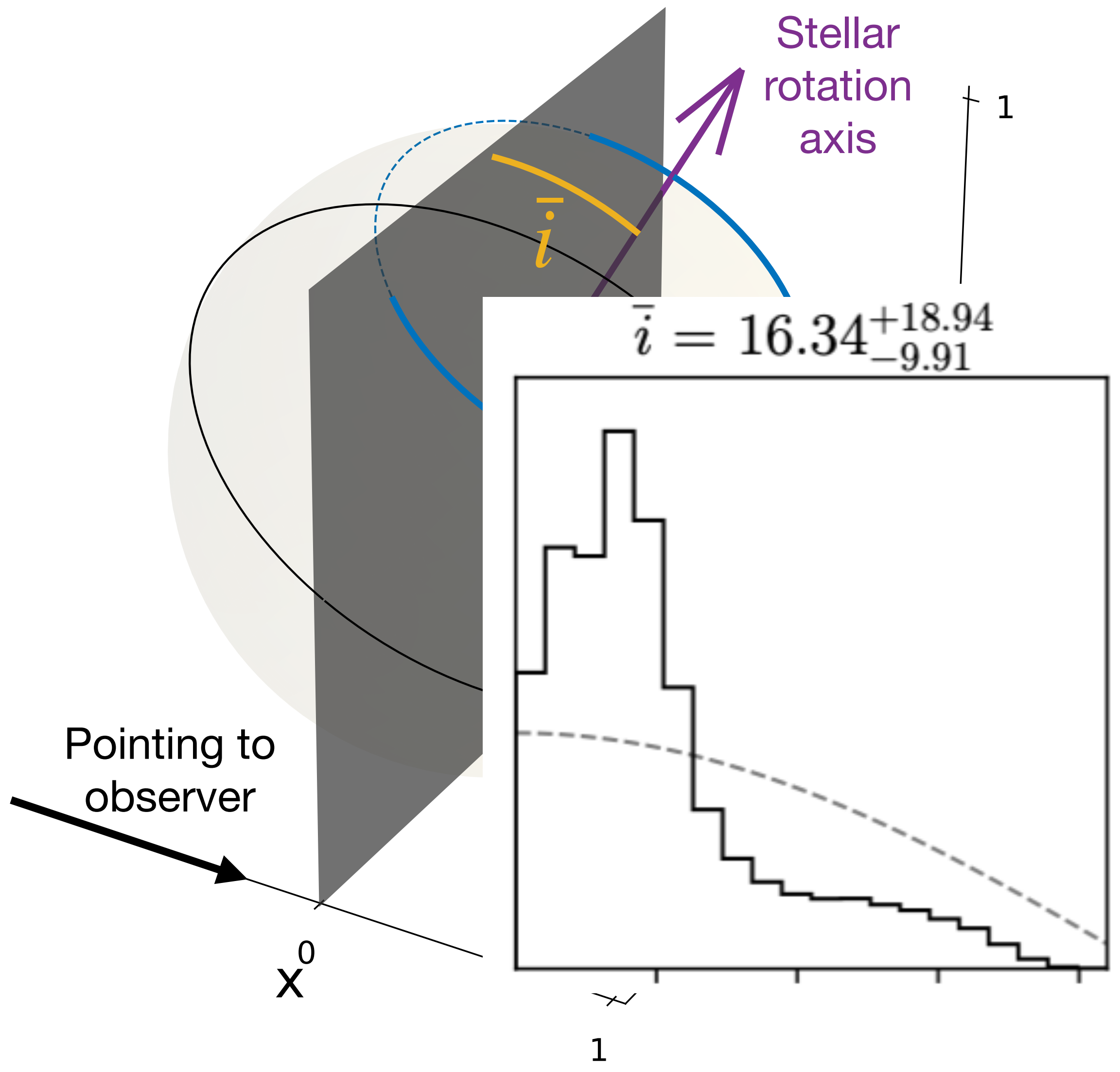
Detailed physical models
Analysis of solar data

Hara & Delisle 2023 →

← (In review)

Statistical model with
physical parameters

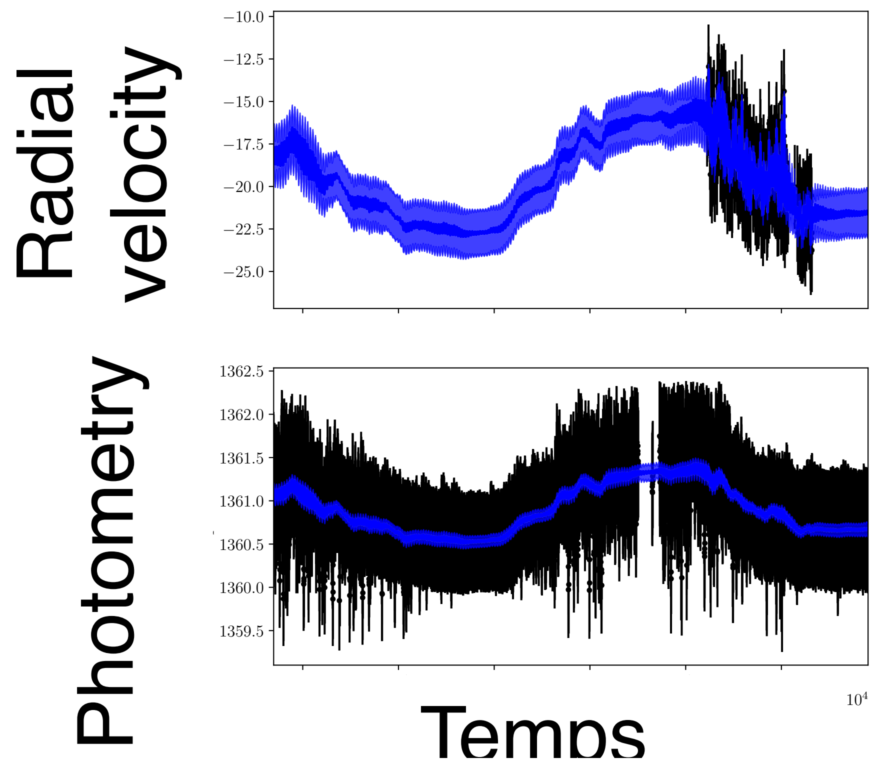
Statistical Doppler imaging

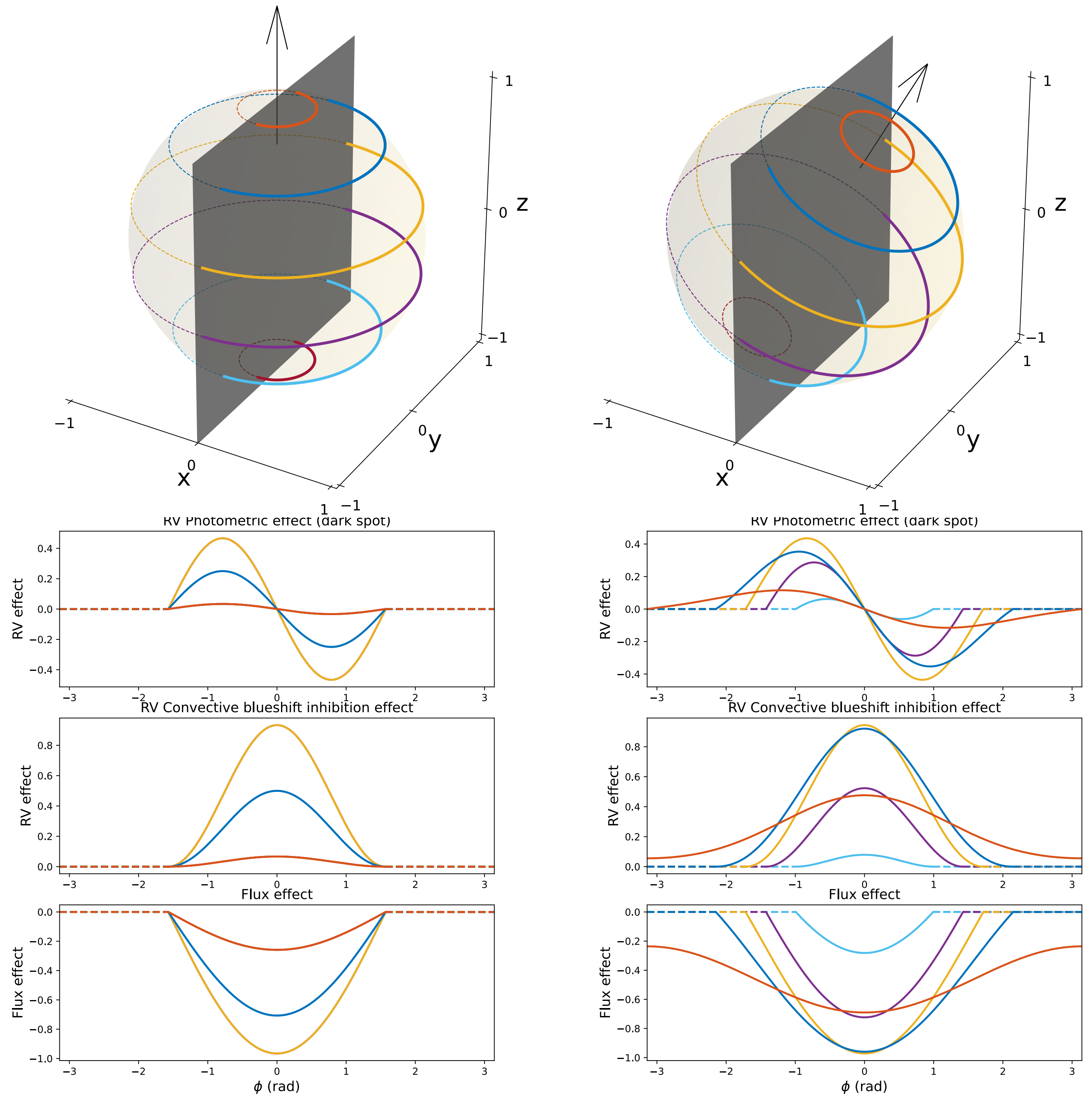


Finding the solar inclination from RVs (HARPS-N) and photometry (SORCE)

To be refined

Solar observations

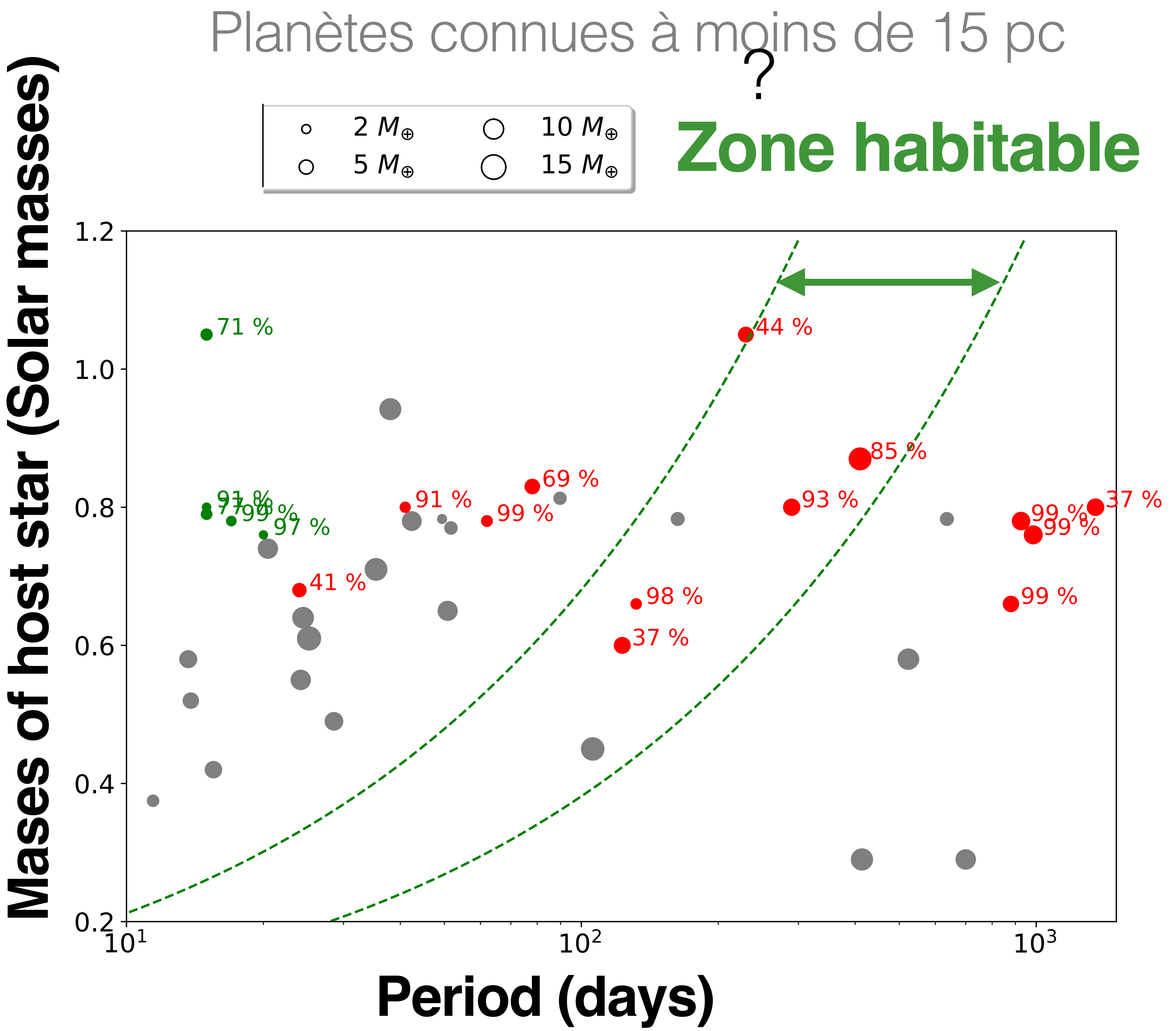


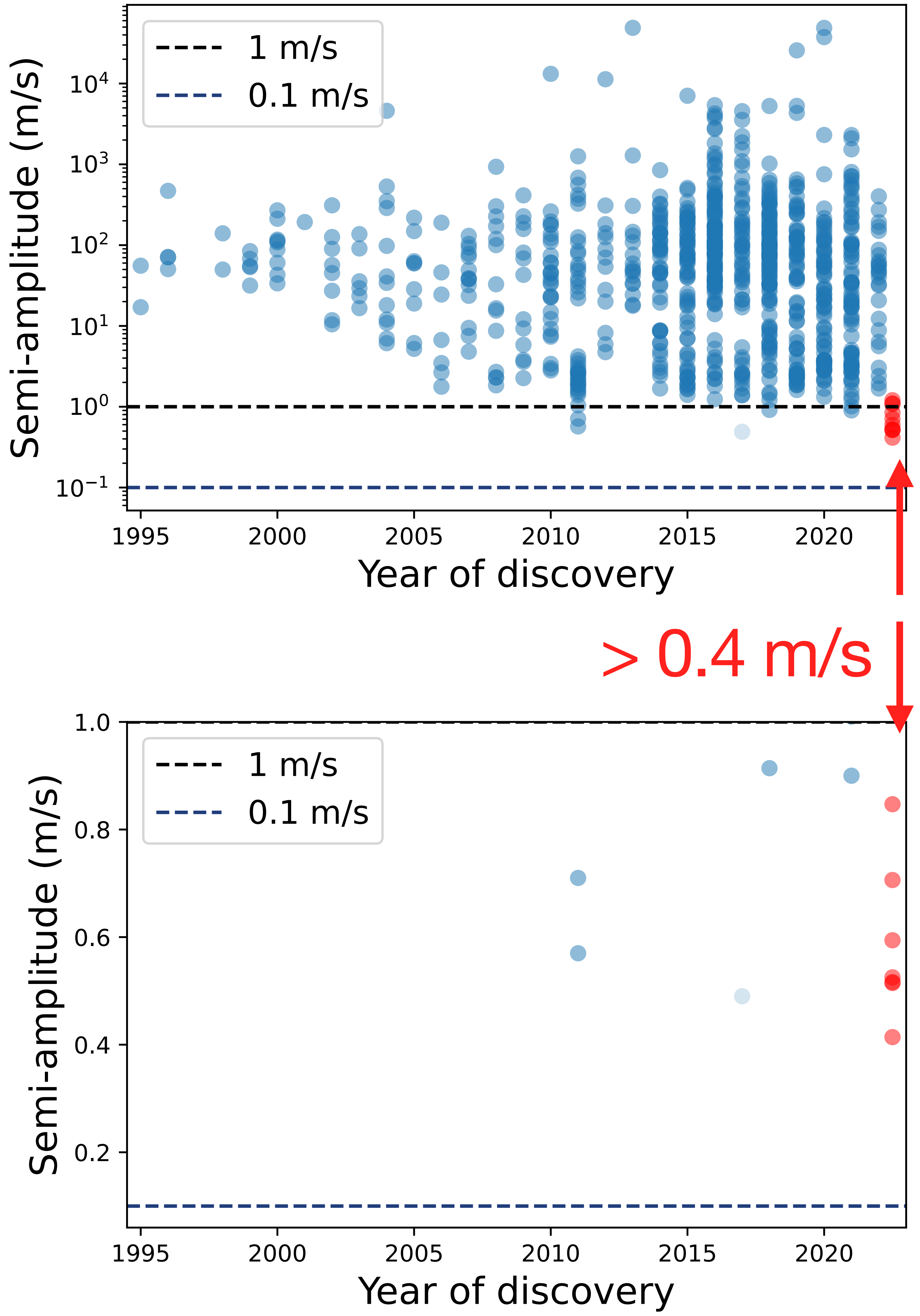


Fast,
Applicable to transit
Spectroscopy

Application: super-Terres dans la zone habitable

From 2 to 7 candidates in the habitable zone of nearby stars

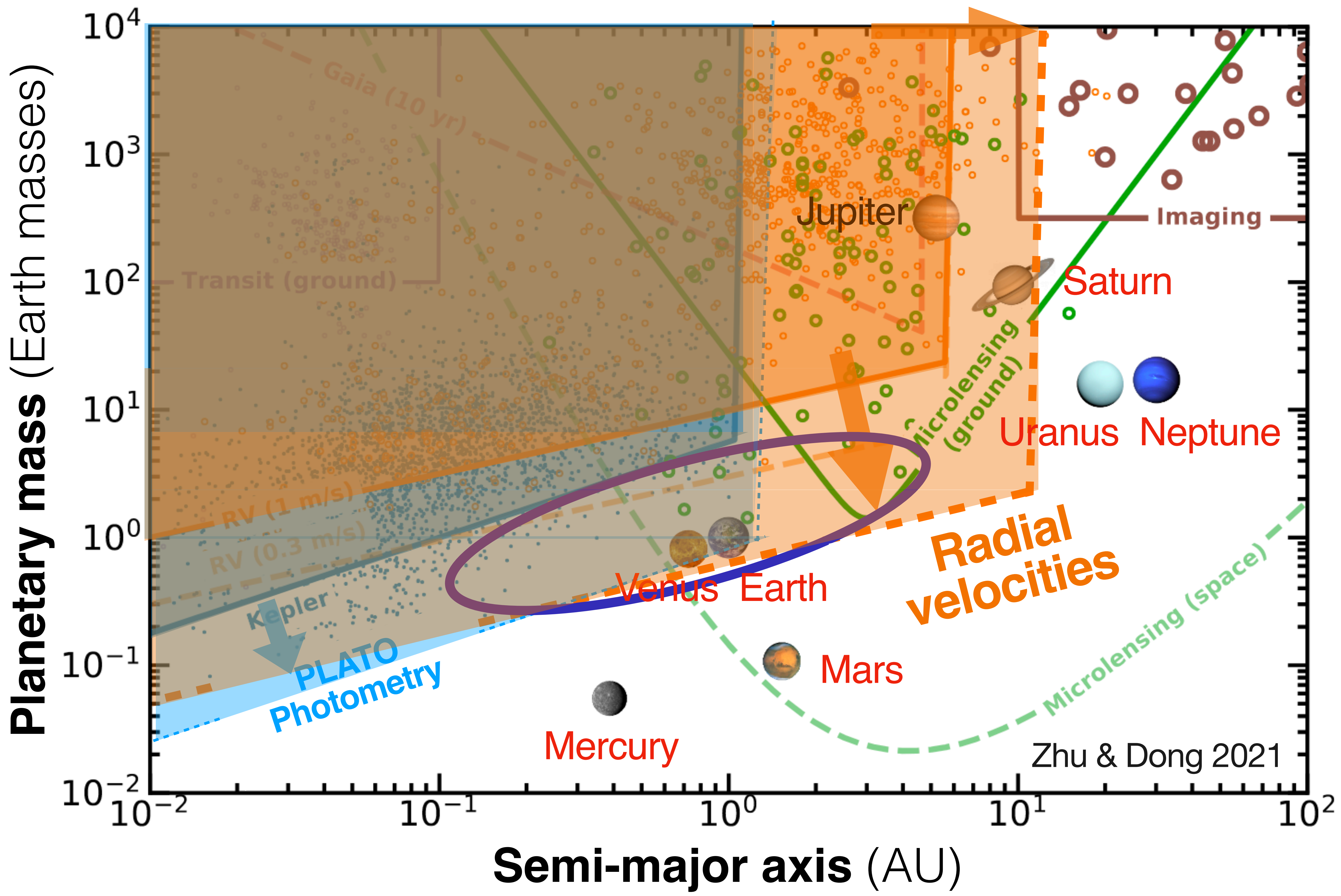




Large program HARPS (PI) 340h to confirm these detections

(with X. Dumusque, M. Crétignier, N. Unger) Oct. 2022- Oct. 2023

Conclusion

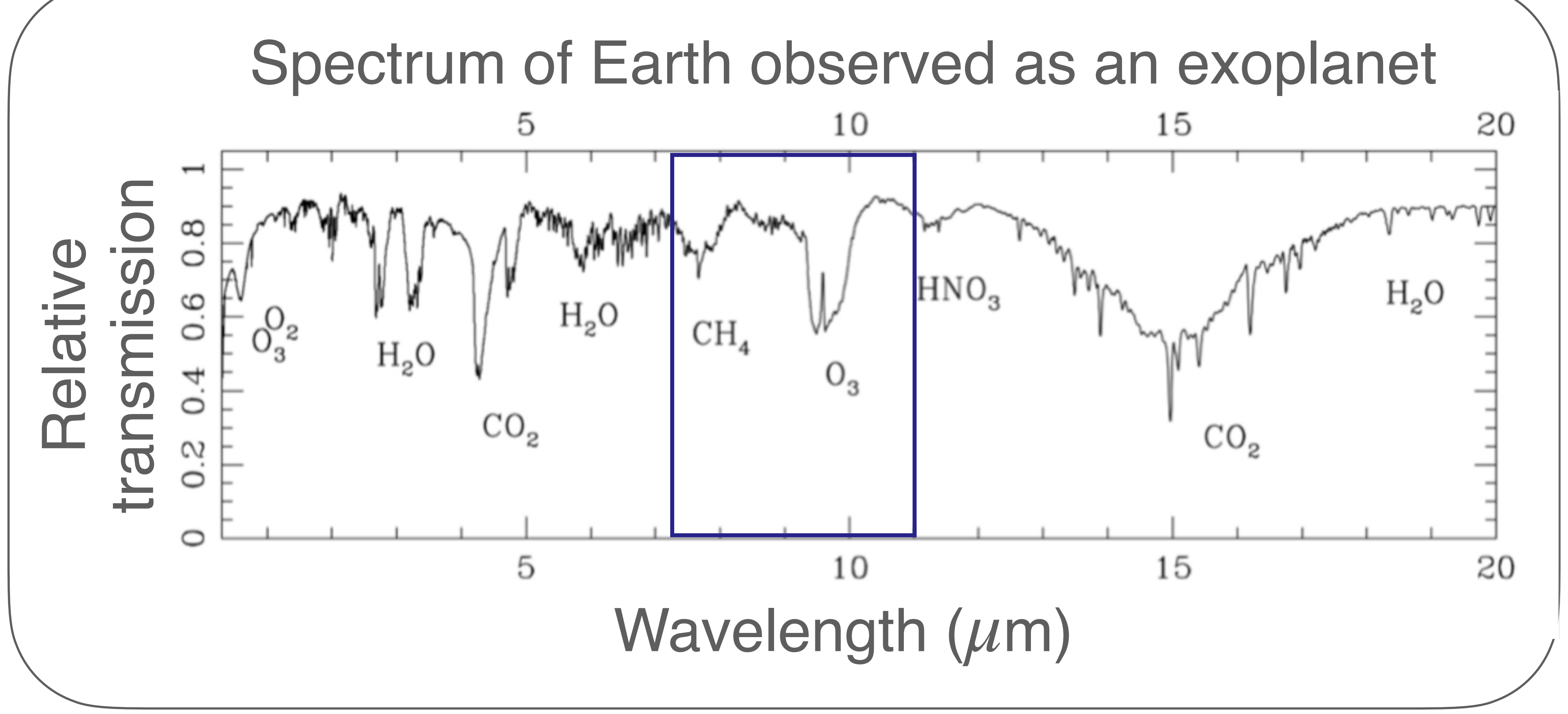


Radial velocity measurements would greatly improve the scientific yield of 2050 flagship missions

Detecting Earth like planets with radial velocities is a very difficult problem but progress is made

Results of the large program end of next year

Instruments for the identification of life



Exoplanets

Transit Spectroscopy

Spectro-imaging

Interferometry

Radial velocities 2022

PLATO 2026

ARIEL 2029

ANDES@ELT 2030

PCS@ELT* +2035

LUVEX NASA +2040

LIFE ESA +2040

Lab experiments

Identification of biosignatures

Europa Clipper 2030

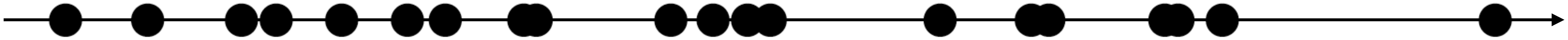
JUICE 2031

Dragonfly 2034

Solar system

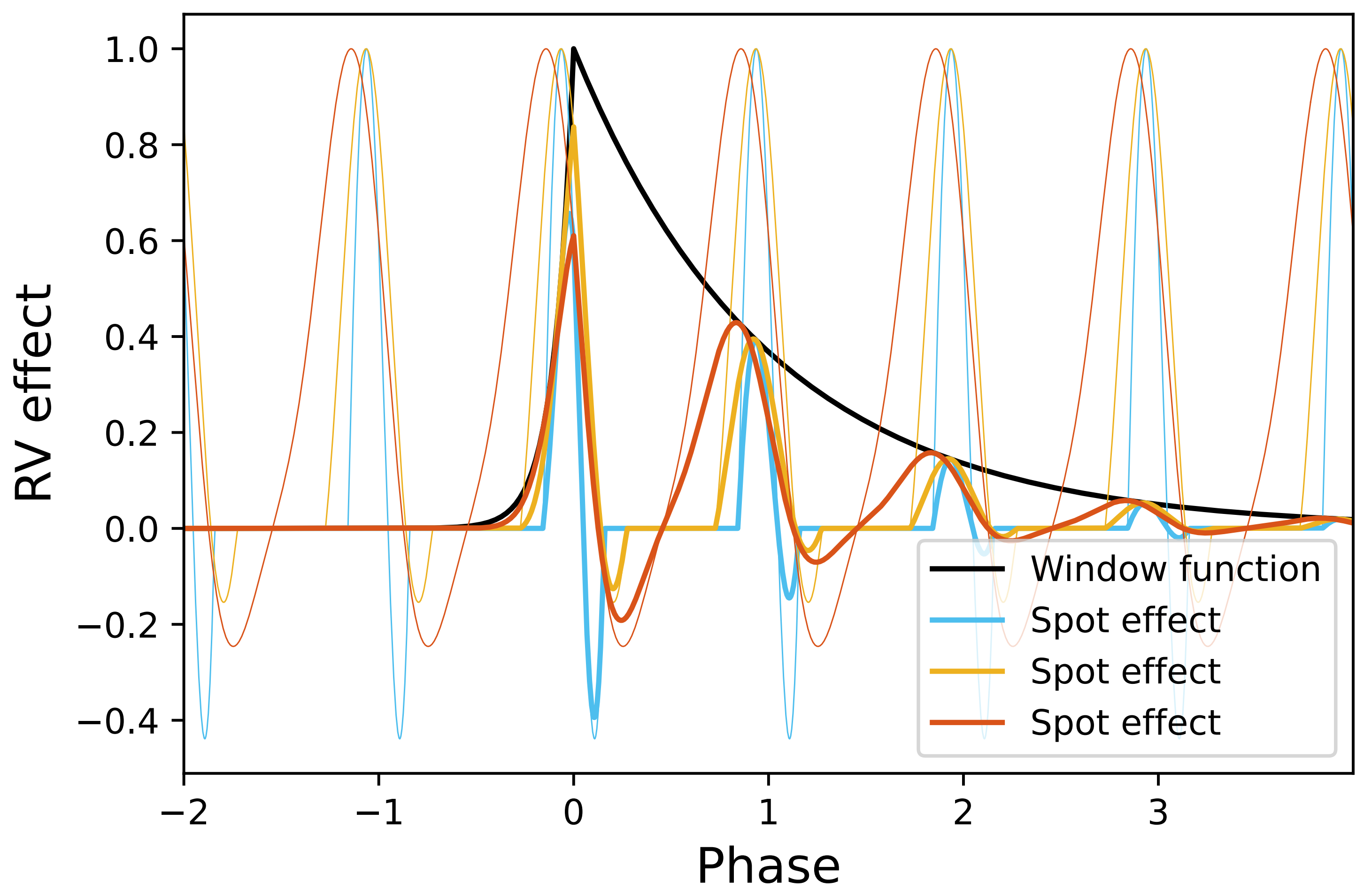
Generate realisations of the FENRIR model

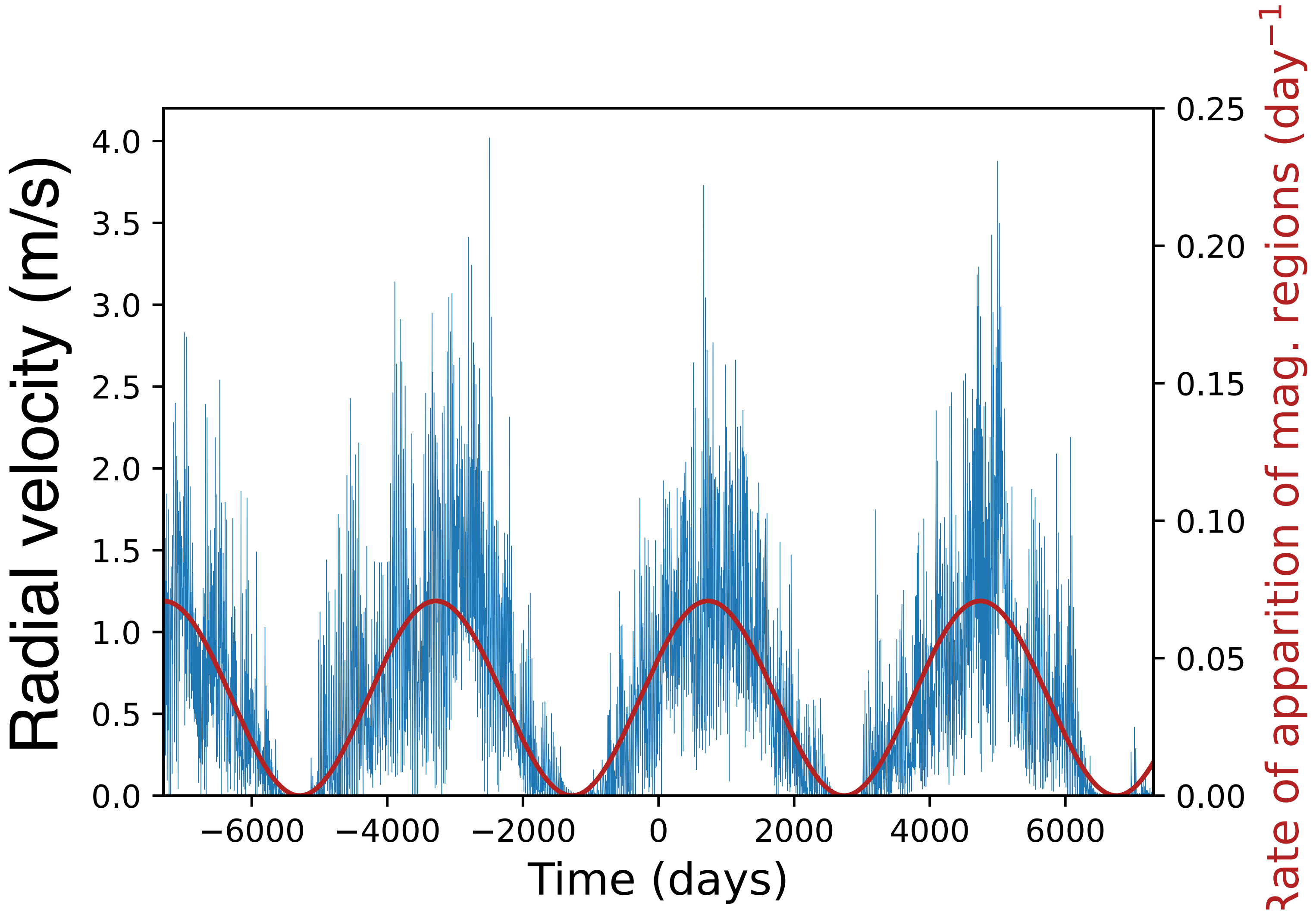
(1) Draw times at which features appear according to a **variable rate** $\lambda(t)$



(2) If a feature appears at time t draw its parameters γ from distribution $p(\gamma \mid \eta, t)$
Where η are the stellar parameters

γ → (3) Add $g(t - t_1, \gamma)$ to your photometry time series and $h(t - t_1, \gamma)$ to your RV time series





From the physical model, compute the covariance of the likelihood function

$$\iint g(t - t_1, \gamma) h(t - t_1', \gamma) \lambda(t) p(\gamma \mid t, \eta) \mathrm{d}t \mathrm{d}\gamma = \kappa_\eta(P(\mathbf{t}), RV(\mathbf{t}'))$$

$$\iint g(t - t_1, \gamma) g(t - t_2, \gamma) \lambda(t) p(\gamma \mid t, \eta) \mathrm{d}t \mathrm{d}\gamma = \kappa_\eta(P(\mathbf{t}), P(\mathbf{t}))$$

$$\iint h(t - t_1', \gamma) h(t - t_2', \gamma) \lambda(t) p(\gamma \mid t, \eta) \mathrm{d}t \mathrm{d}\gamma = \kappa_\eta(RV(\mathbf{t}'), RV(\mathbf{t}'))$$

$$\iint l(t - t_1', \gamma) h(t - t_2', \gamma) \lambda(t) p(\gamma \mid t, \eta) \mathrm{d}t \mathrm{d}\gamma = \kappa_\eta(I(\mathbf{t}''), RV(\mathbf{t}'))$$

	photometry	RV	indicator
photometry	$\kappa_\eta(P(\mathbf{t}), P(\mathbf{t}))$	$\kappa_\eta(P(\mathbf{t}), RV(\mathbf{t}'))$	
RV		$\kappa_\eta(RV(\mathbf{t}'), RV(\mathbf{t}'))$	
indicator		$\kappa_\eta(I(\mathbf{t}''), RV(\mathbf{t}'))$	

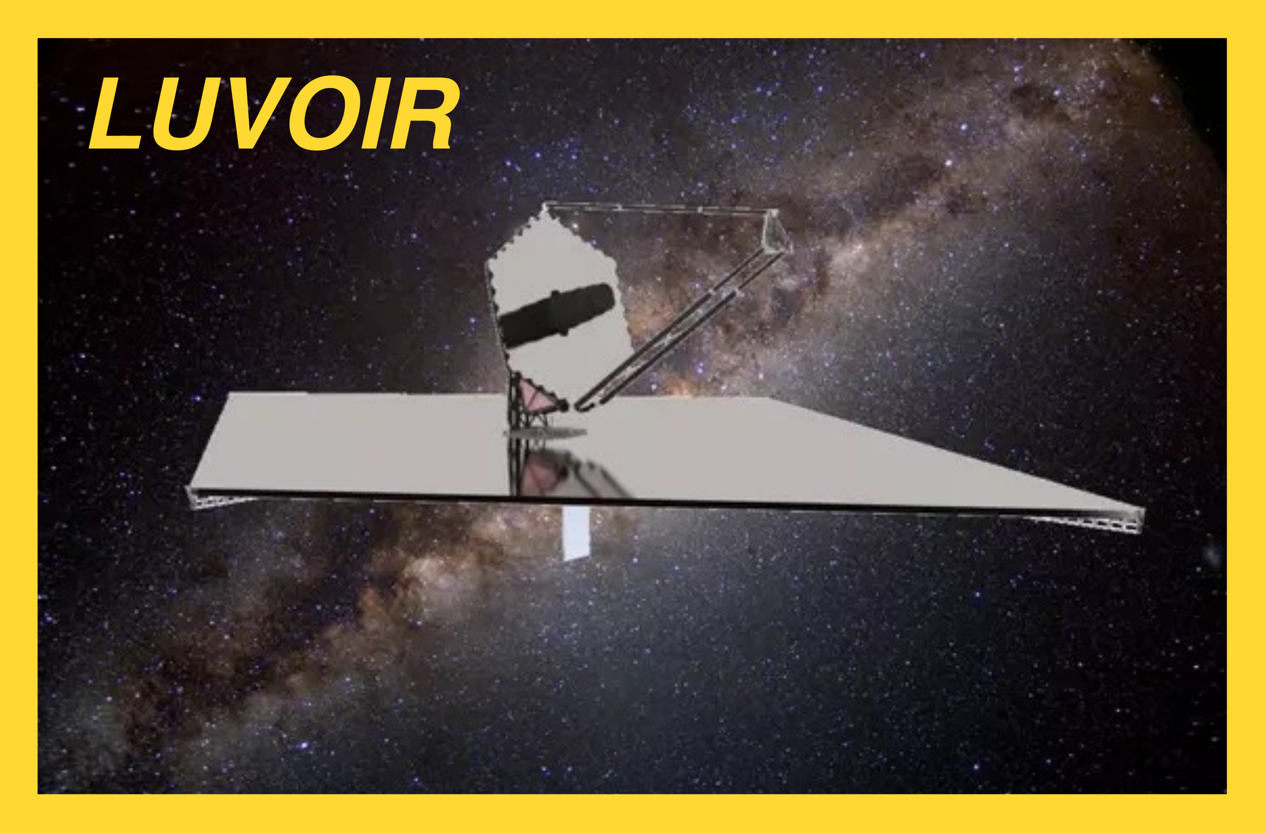
Objectives

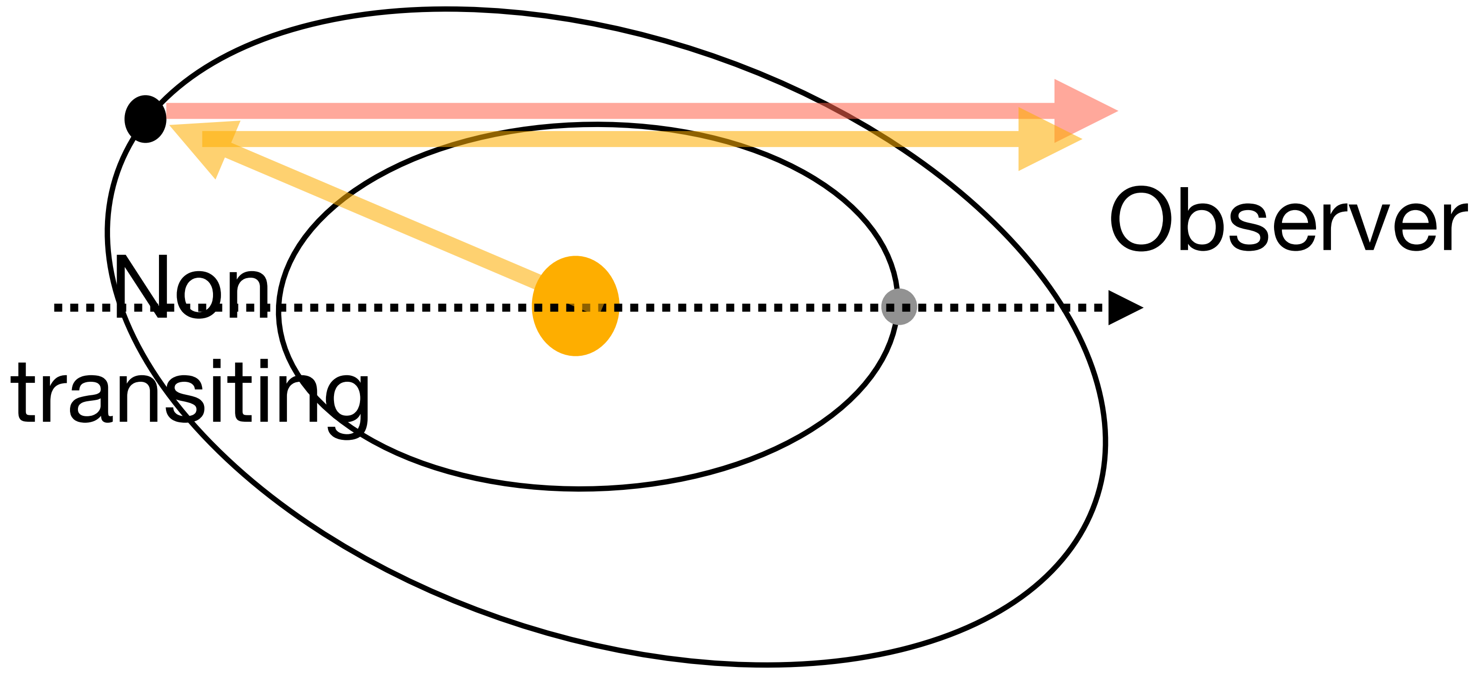
Exploplanet observations

Characterizing Earth-analogs
Detecting life outside of Earth

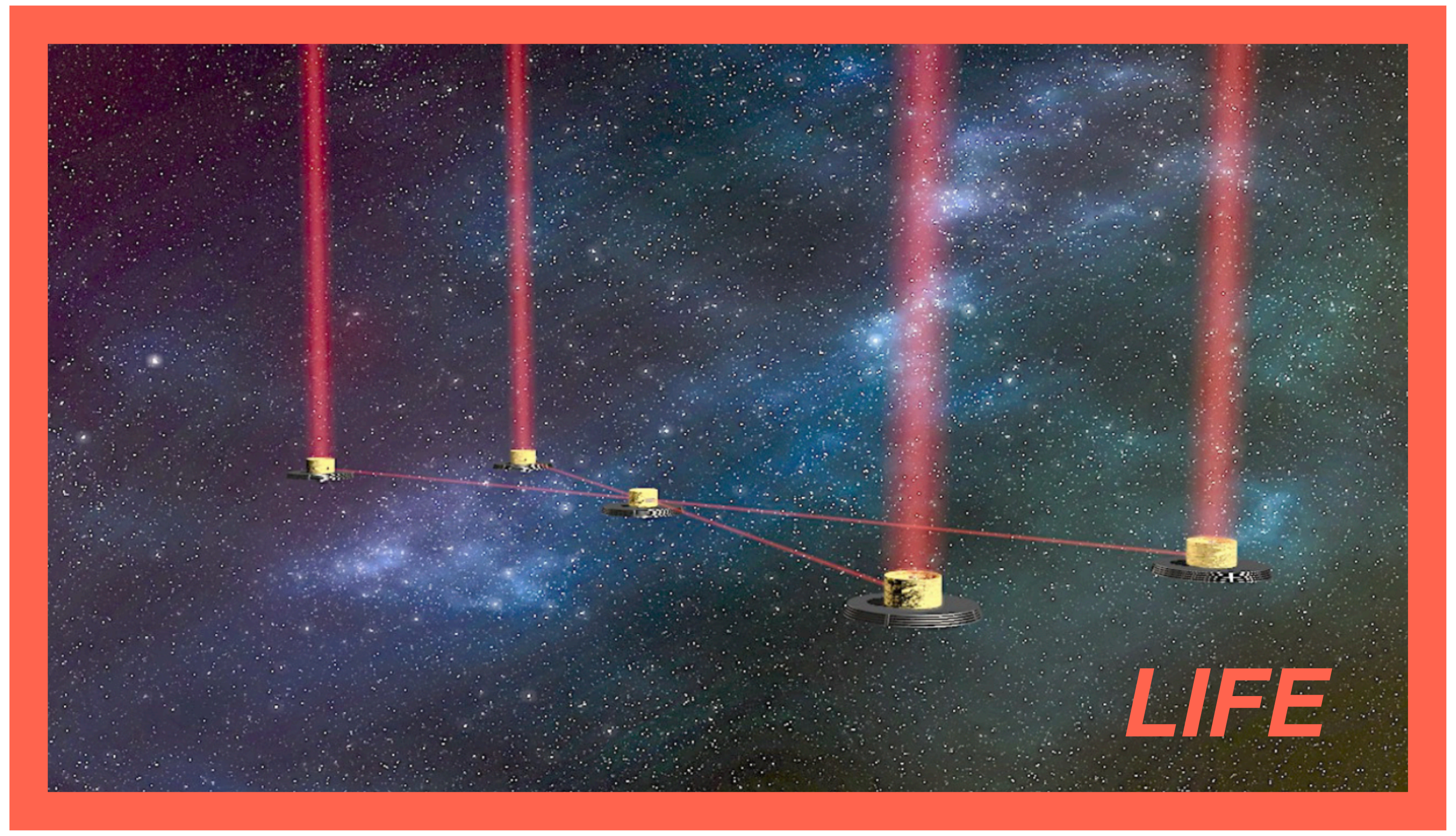
Characterization of exoplanetary atmospheres

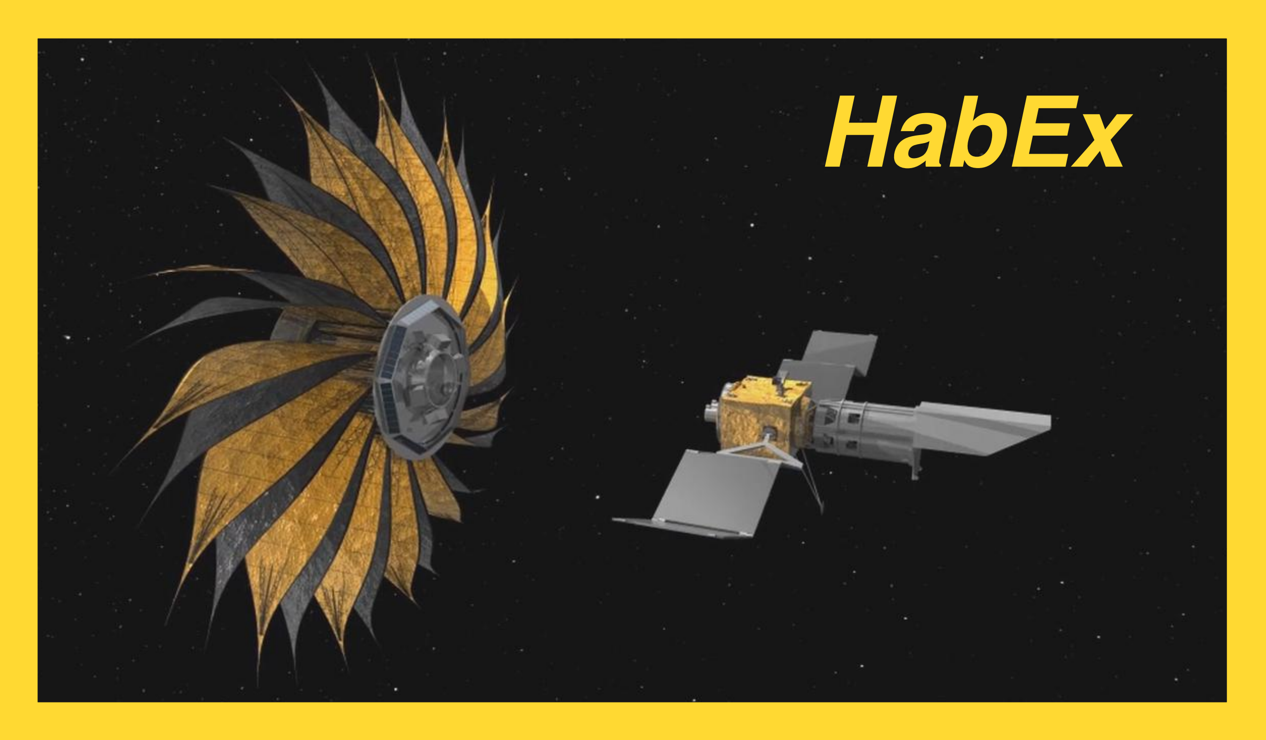
Spectro-imaging: LIFE (ESA), LUVEX (NASA), JWST), PCS@ELT





Detecting life outside of Earth





Thermal emission:
LIFE, ESA

Reflected light:
HWO, NASA

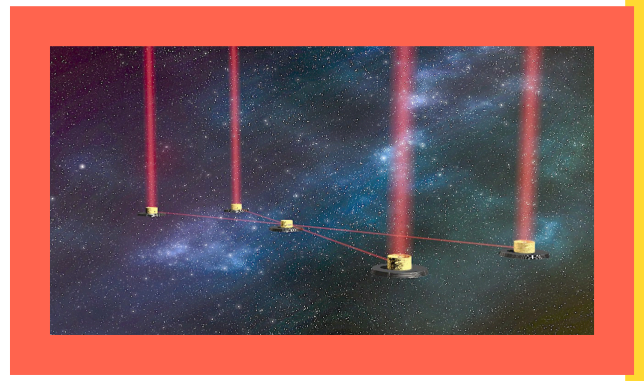
Objectives

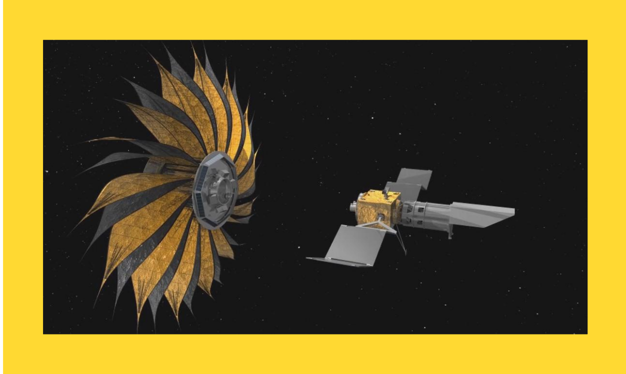
Exoplanet observations

Characterizing Earth-analogs
Detecting life outside of Earth

Characterization of exoplanetary atmospheres (chemical composition, reflectance, variability)

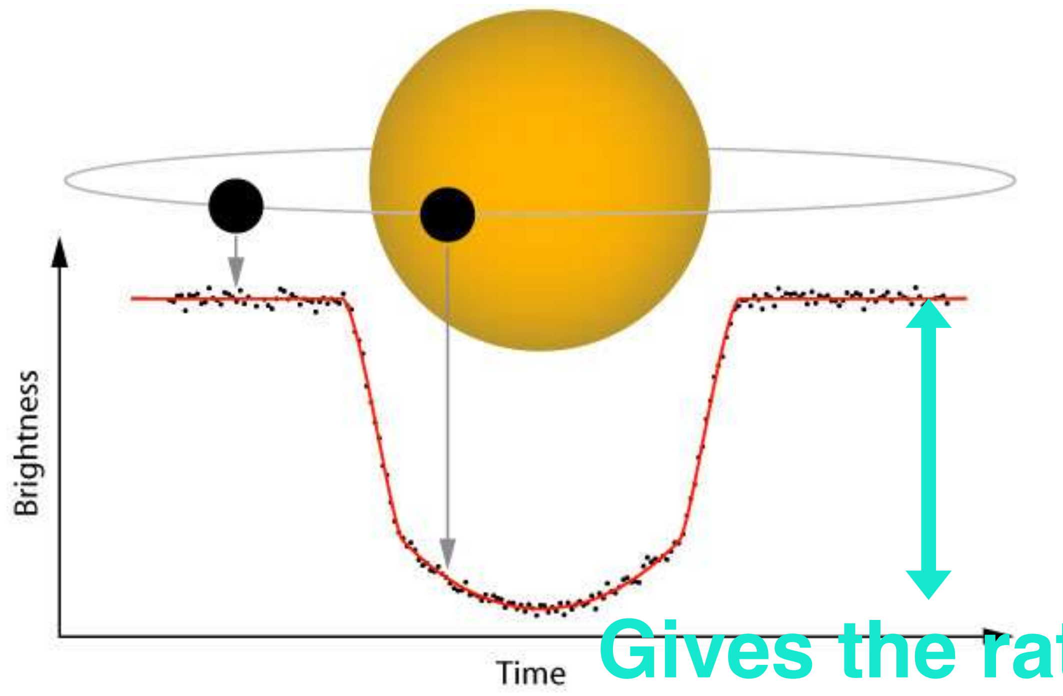
Detecting Earth-like planets, mass, radius, and orbits





Require targets $\lesssim$ 20 parsec

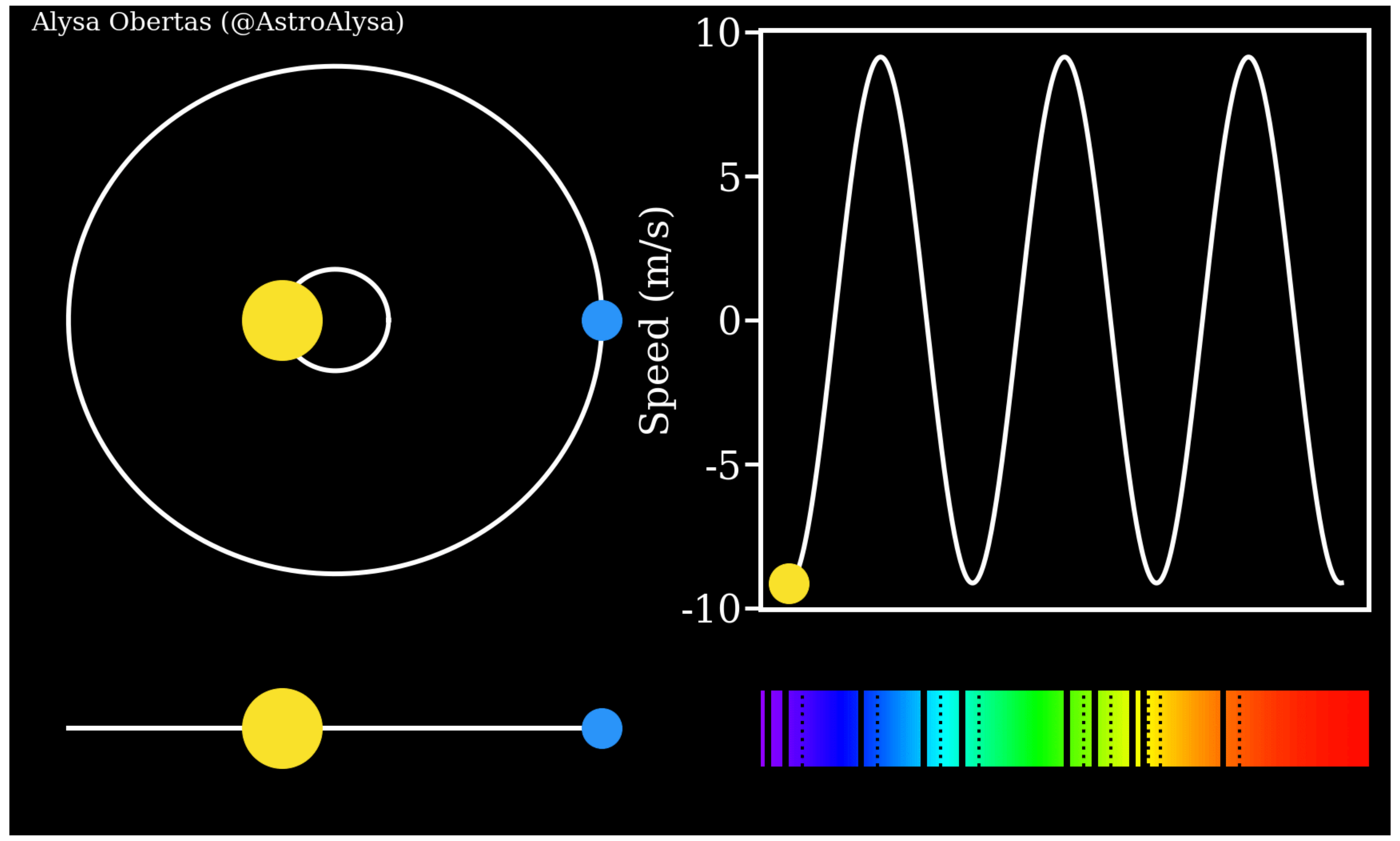
Transits

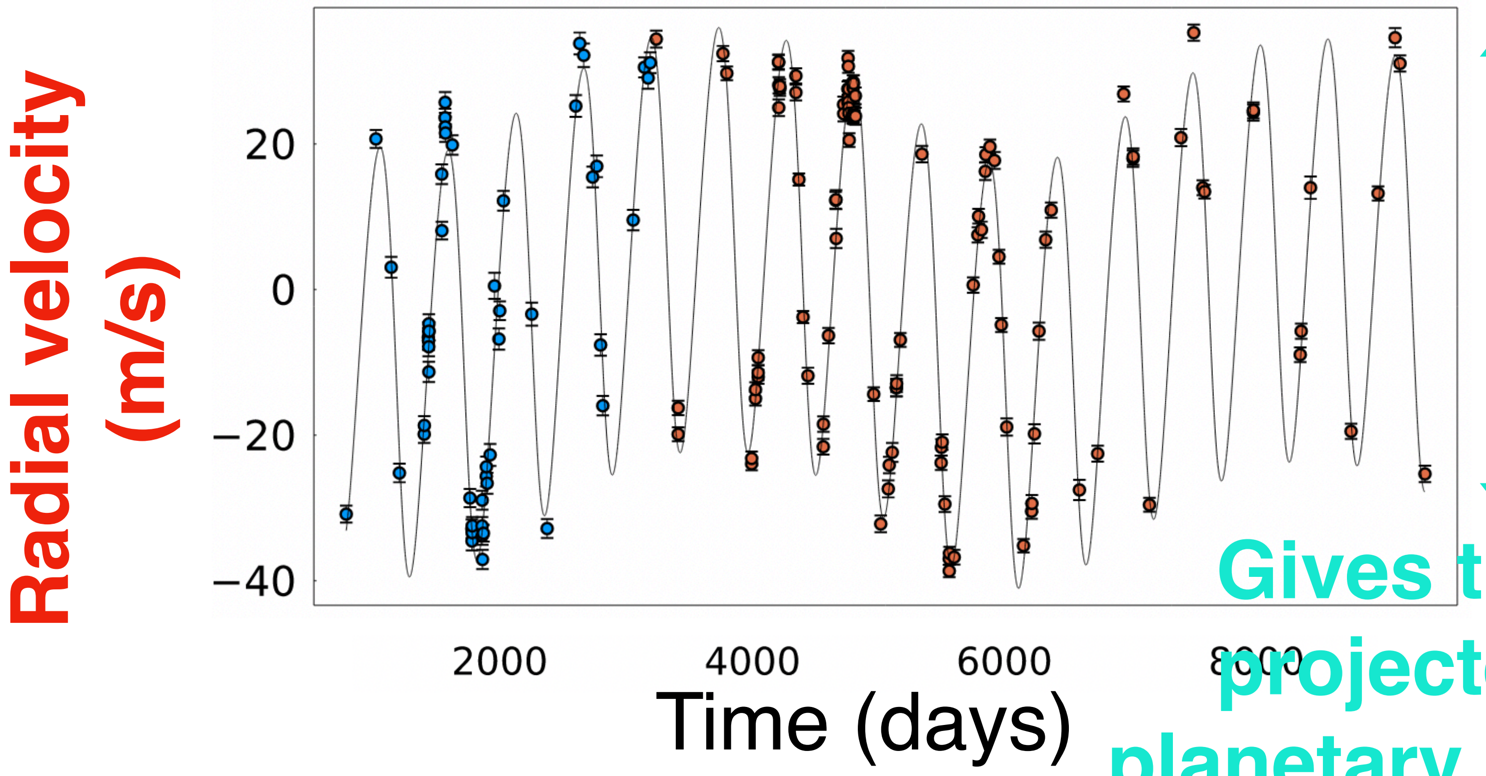


Gives the ratio
Of planetary and
Stellar radii

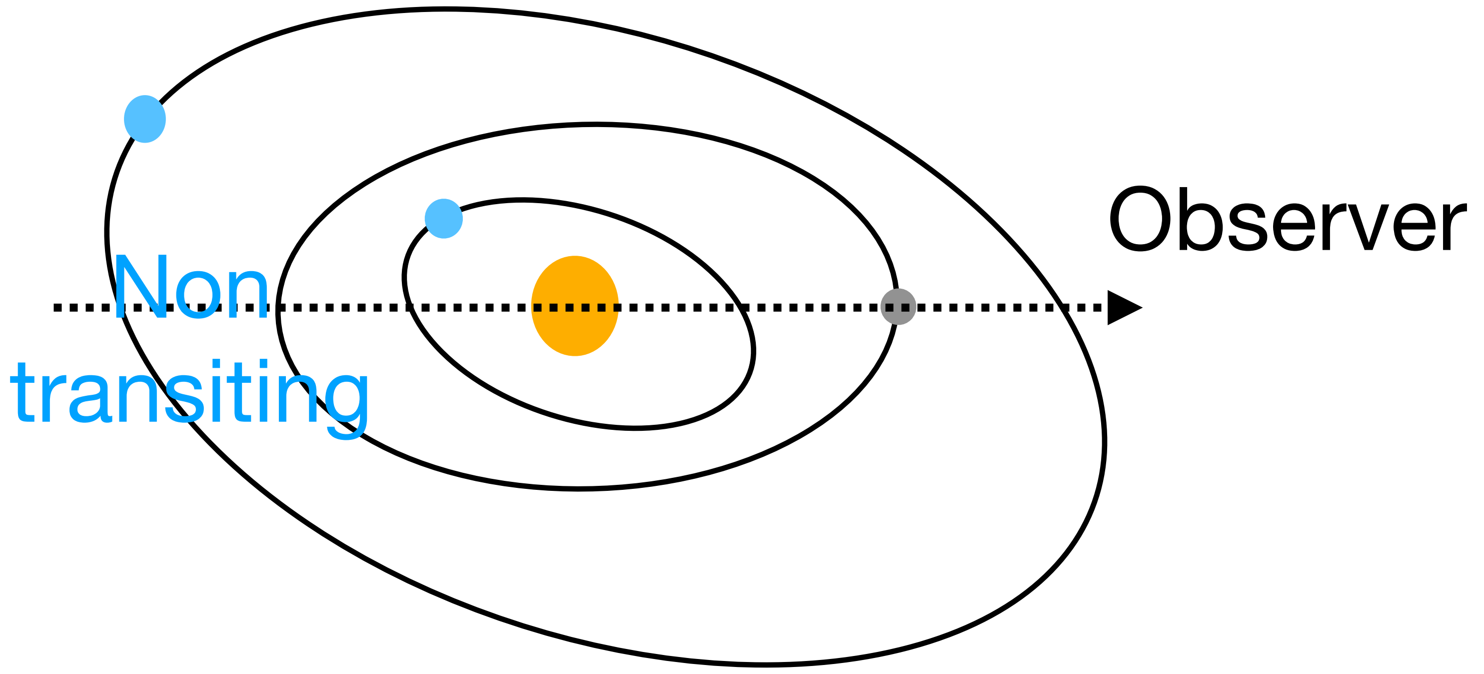
Requires very
Specific system
geometry

Radial velocity (RV)

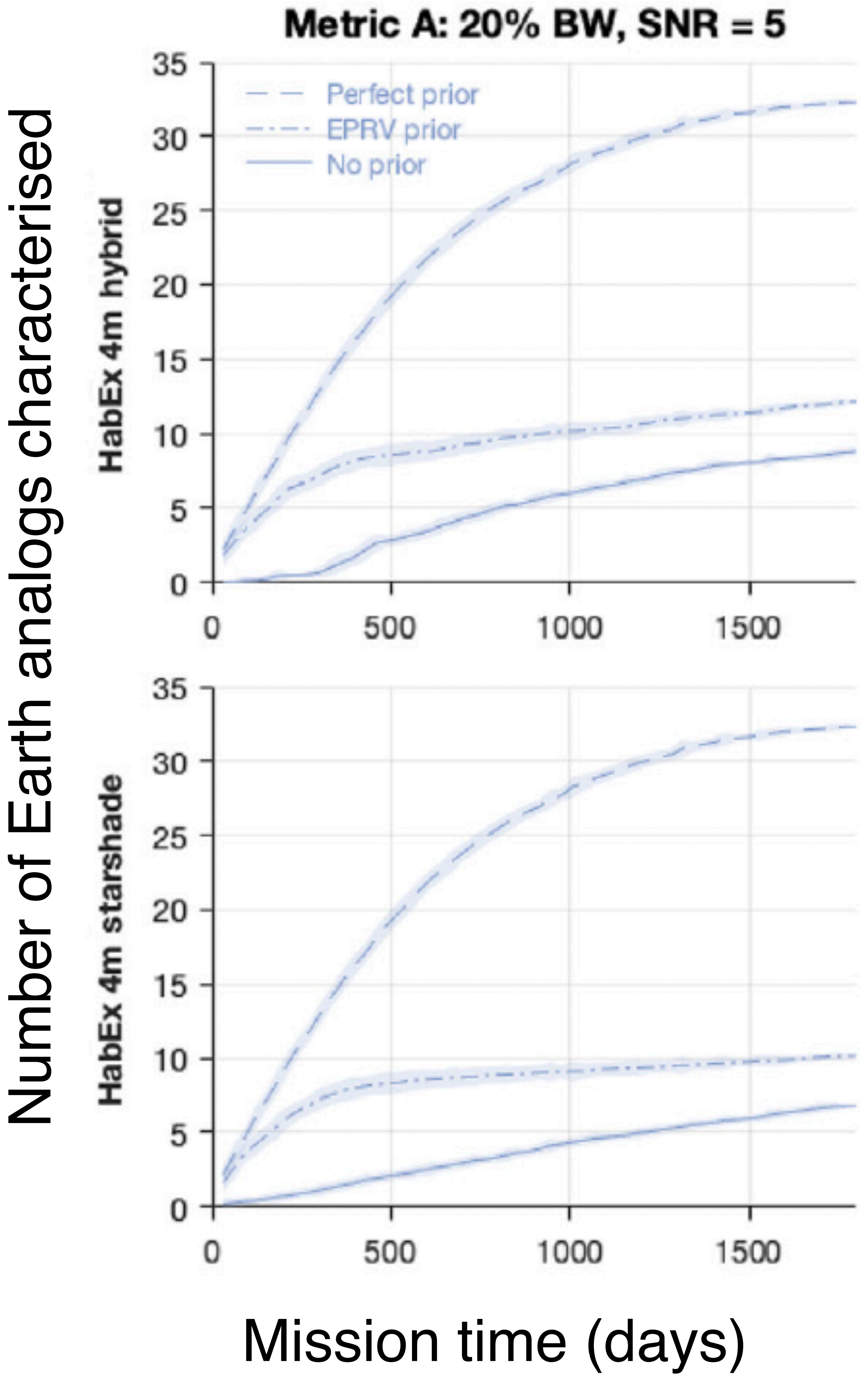




Gives the
projected
planetary Mass



Radial velocites are key



Morgan et al. 2021

Mass is essential to interpret spectroscopic observations of atmospheres (Batalha et al. 2017, 2019)

The yield of atmospheric characterization is greatly improved if Earth like planets are detected in advance, **require targets $\lesssim$ 20 parsec**

+ Results obtained faster, more time for characterisation
+ Mitigates the risk of the missions
+ True for other kinds of planets

Radial velocity (RV)