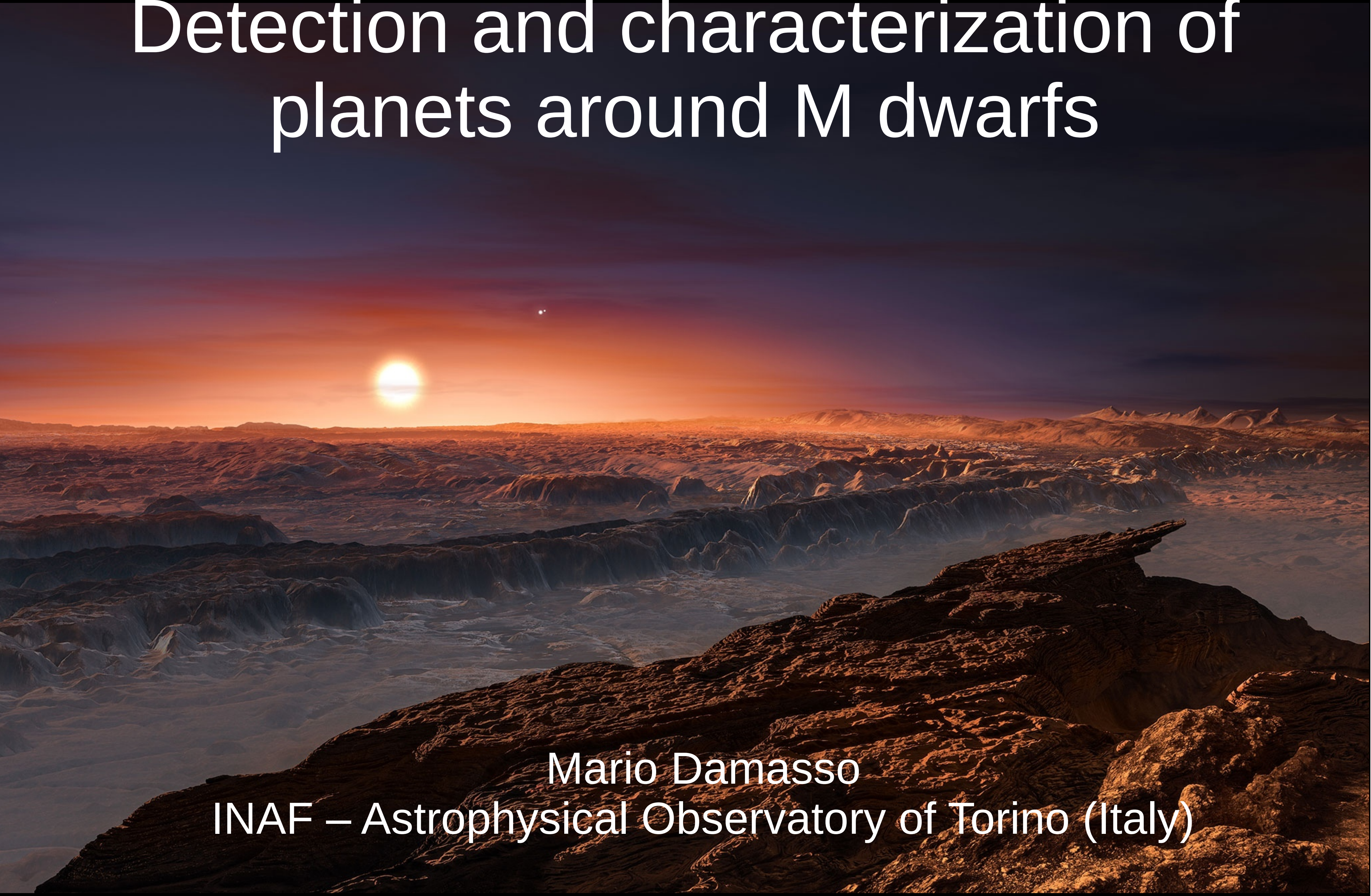
Detection and characterization of planets around M dwarfs



Mario Damasso
INAF – Astrophysical Observatory of Torino (Italy)

Outline

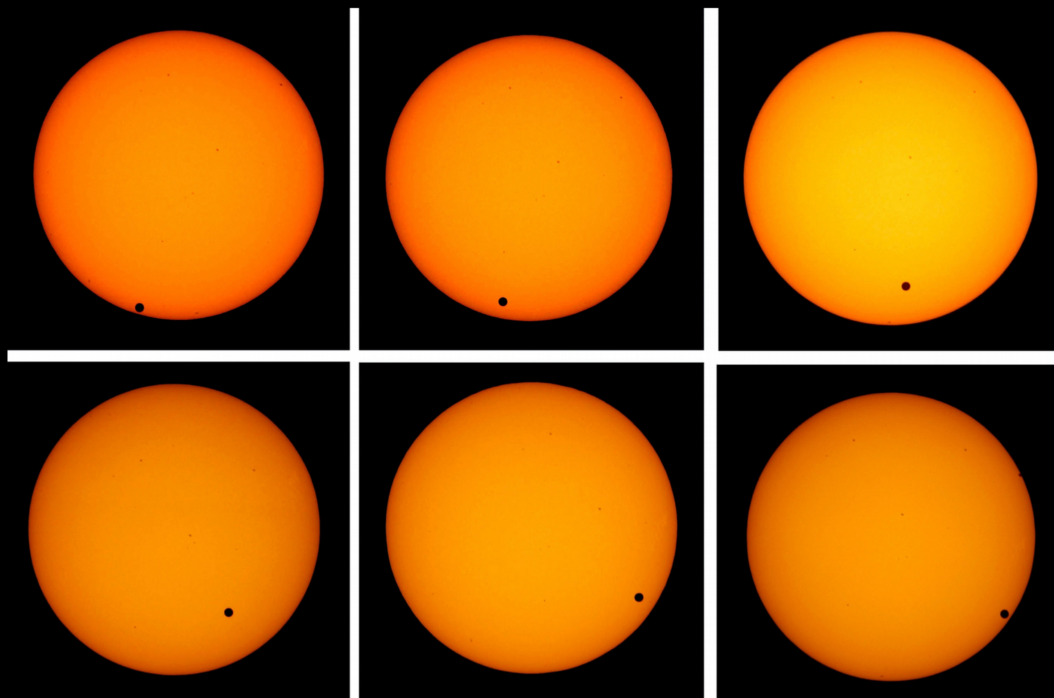
* Detecting and characterizing planets:
  how and why M dwarfs are a treasure trove

* Overview of ground-based photometric and spectroscopic surveys

* Limits to detection and characterization of low-mass planets
  due to stellar activity: causes and methods for (partially) suppressing it

* Discussion on some real targets

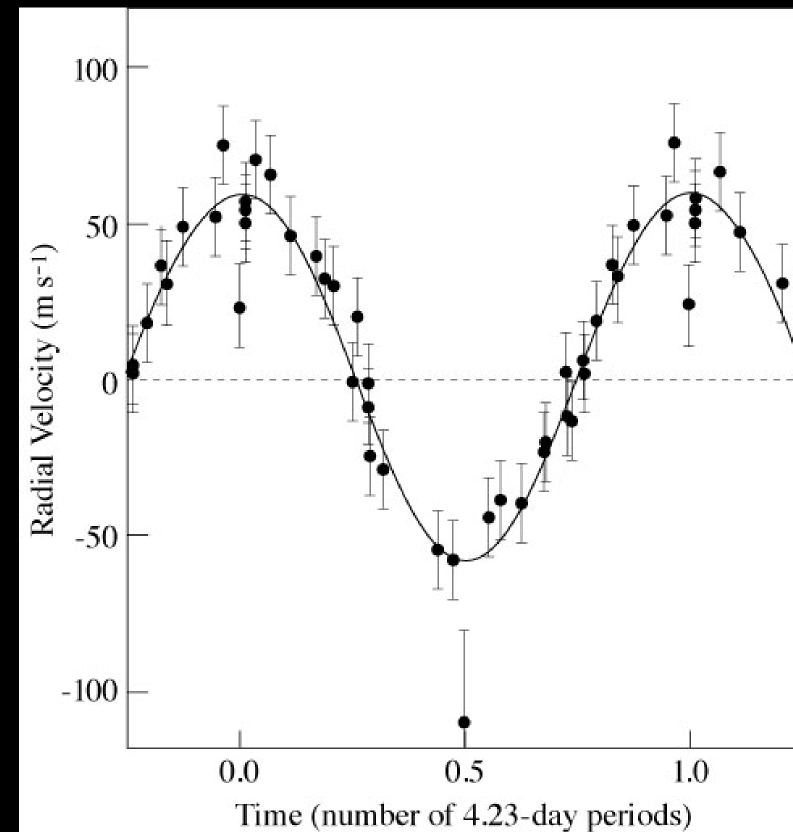
Photometric transit method



$$\frac{\Delta f}{f} \approx 1\% \left(\frac{r_p}{r_{Jup}}\right)^2 \left(\frac{R_*}{R_{Sun}}\right)^{-2}$$

$$P_{tran} \sim \frac{R_s + R_p}{a_p}$$

Radial velocity method



Signal semi-amplitude $\propto 1/(P_{orb})^{1/3}$

Signal semi-amplitude $\propto 1/(M_{star})^{2/3}$

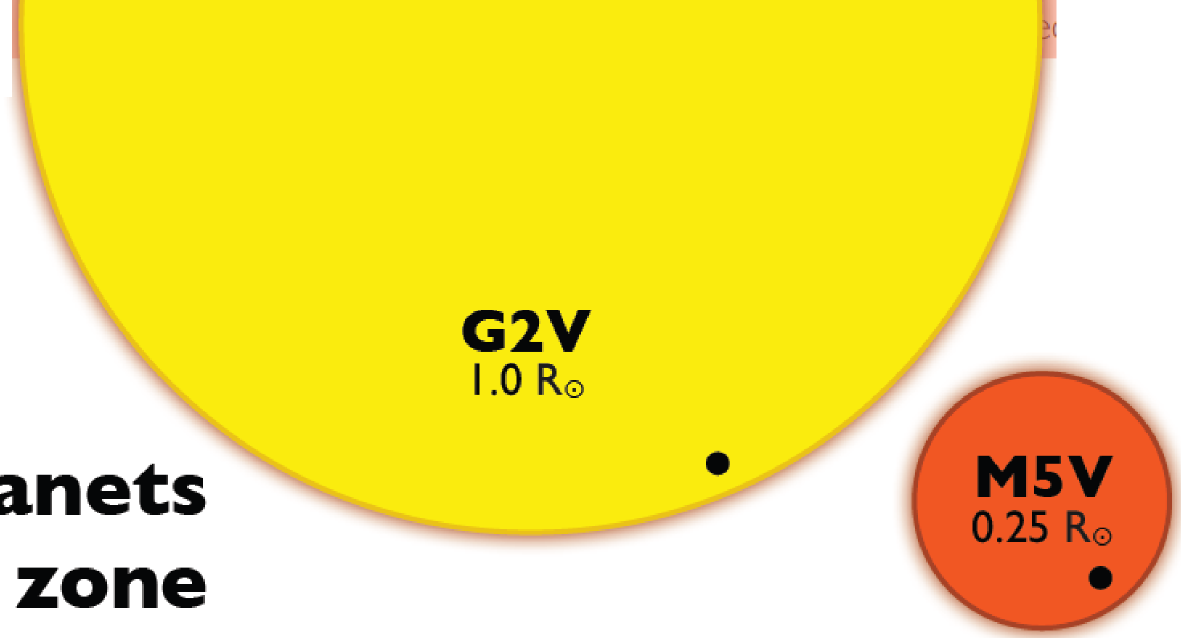
Signal semi-amplitude $\propto M_{planet}$

First good reasons to target M dwarfs
(mostly to search for potentially hab planets)

They are/have:

- small ($0.08\ R_{sole} < R < 0.6\ R_{sole}$)
- low-mass ($0.08\ M_{sole} < M < 0.6\ M_{sole}$)
- the ~75% of all the star sample in our Galaxy
- a ‘lifetime’ in the ZAMS which measures in **trilion** of years

Statistical results show that potentially hab planets around M dwarfs could be widespread



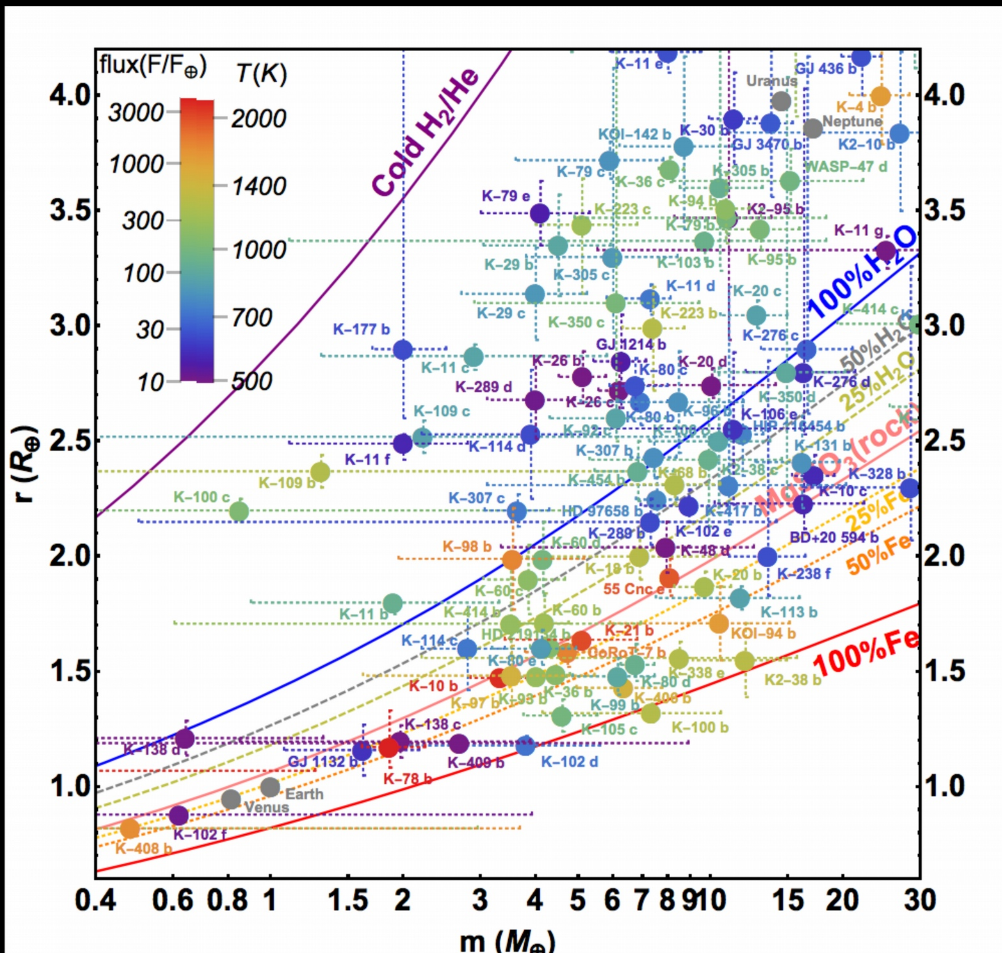
super-Earth planets
in the **habitable zone**

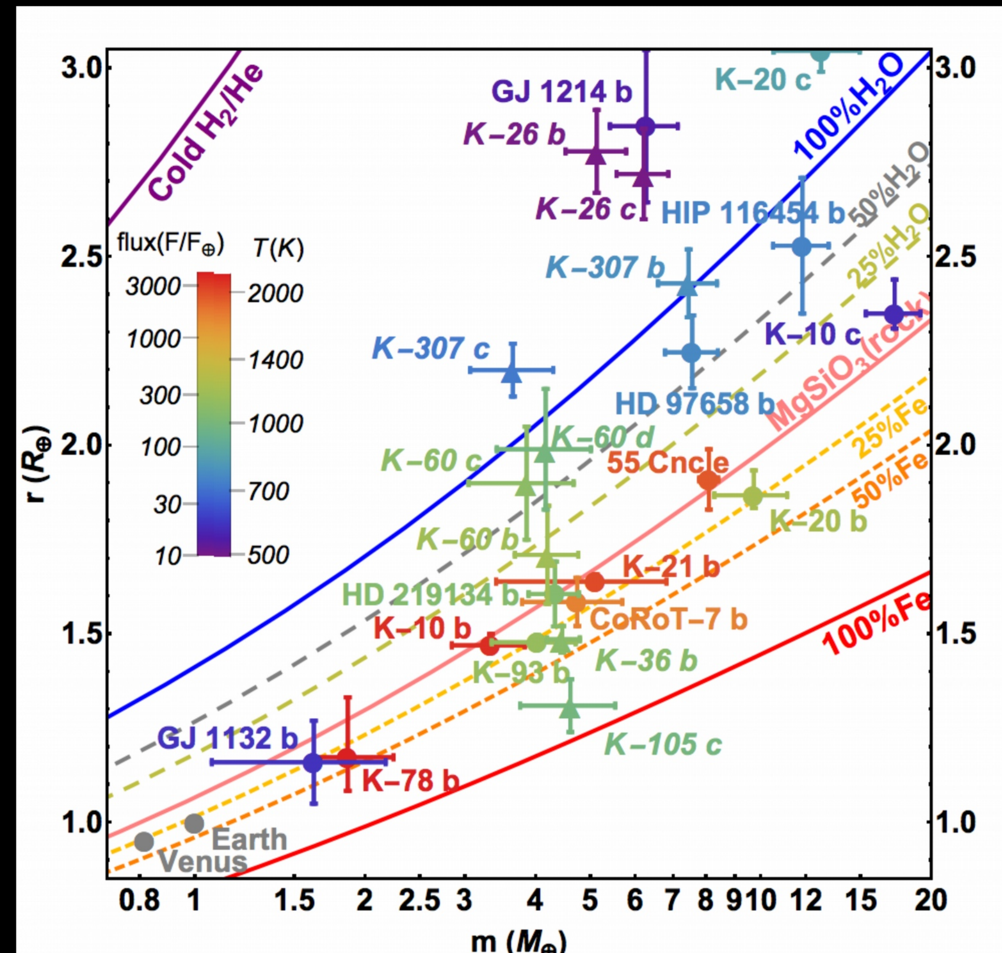
2 $R_\oplus$, 7 $M_\oplus$, Earth-like insolation

transit depth =	**0.03%**	**0.5%**
Doppler wobble =	**60 cm/s**	**5 m/s**
transit probability =	**0.5%**	**1.5%**
orbital period =	**1 year**	**2 weeks**

Nutzman & Charbonneau (2008)

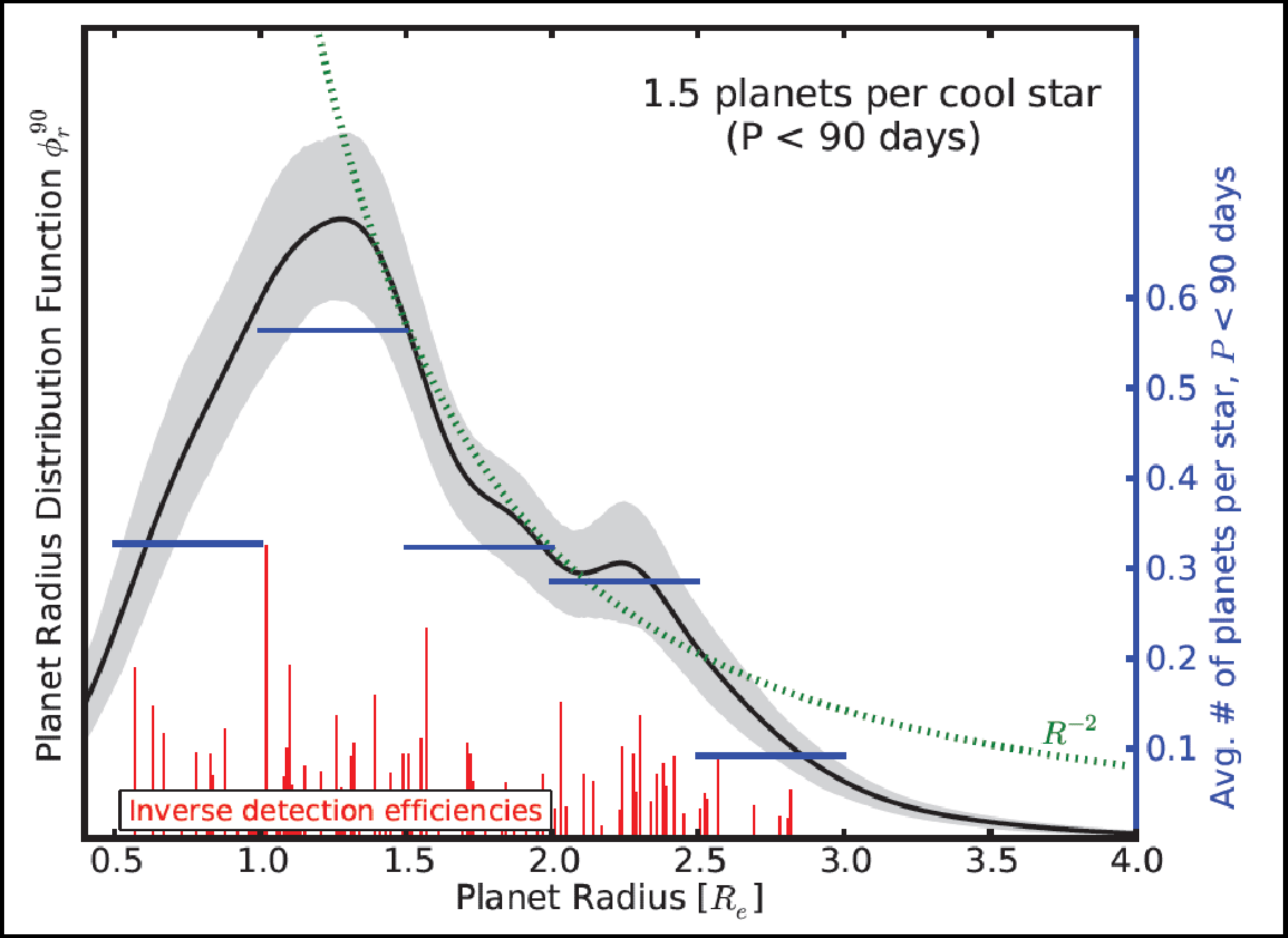
Mass-radius diagram





After Li Zeng
https://www.cfa.harvard.edu/~lzeng/planetmodels.html

Some Kepler-based statistical results



Morton & Swift 2014

"Earths" in the Habitable Zone of M dwarfs

Paper	Eta Earth	HZ Inner Edge	HZ Outer Edge	Planet Properties
Bonfils+ 2013	**0.41** (+0.54/-0.13)	Recent Venus (Selsis +2007)	Early Mars (Selsis+ 2007)	$1 < m \sin I < 10\ M_{Earth}$
Gaidos 2013	**0.46** (+0.18/-0.15)	50% Clouds (Selsis+ 2007)	50% Clouds (Selsis+ 2007)	$R_P > 0.8\ R_{Earth}$
Kopparapu 2013 (Conservative)	**0.48** (+0.12/-0.24)	Moist Greenhouse (Kopparapu+ 2013)	Max Greenhouse (Kopparapu+ 2013)	$0.5 < R_P < 1.4\ R_{Earth}$
Kopparapu 2013 (Optimistic)	**0.61** (+0.07/-0.15)	Recent Venus (Kopparapu+ 2013)	Early Mars (Kopparapu+ 2013)	$0.5 < R_P < 2\ R_{Earth}$
Dressing & Charbonneau 2013	**0.15** (+0.13/-0.06)	Water Loss (Kasting+ 1993)	CO_2 Condensation (Kasting+ 1993)	$0.5 < R_P < 1.4\ R_{Earth}$
Dressing & Charbonneau (2015)	**0.56** (+0.32/-0.13)	Moist Greenhouse (Kopparapu+ 2013)	Max Greenhouse (Kopparapu+ 2013)	$0.5 < R_P < 1.4\ R_{Earth}$

ηE (eta Earth) = frequency of Earth-like planets per star

D&C (2015) estimate a cumulative occurrence rate of 2.5±0.2 planets per M dwarf with radii 1-4 R_{Earth} and P<200 days

The APACHE project

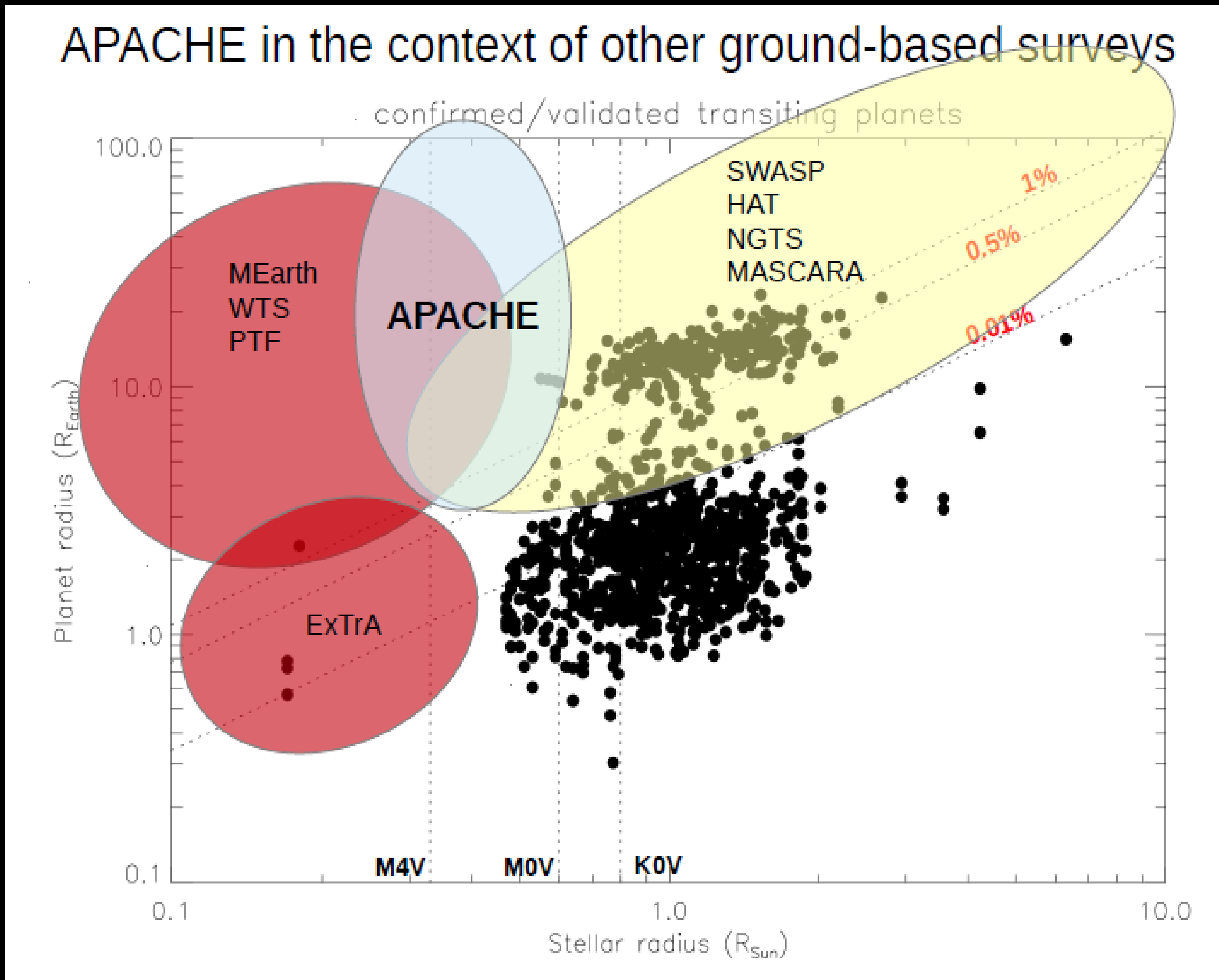
- **APACHE stands for**
  A PAthway toward the Characterization of Habitable Earths

- **It is a 5 years long targeted, small field photometric survey aimed at discovering transiting, small-size exoplanets (super-Earths) around a well-defined sample of hundreds of nearby dM0-dM5 stars, using an array of five 40-cm telescopes**

- **APACHE is the only survey of this kind based in Europe**

- **The APACHE photometric database will greatly contribute to the astrophysics of the M dwarfs, in particular by characterizing their variability (rotation, activity,...) → very helpful for radial velocity surveys!**

Photometry

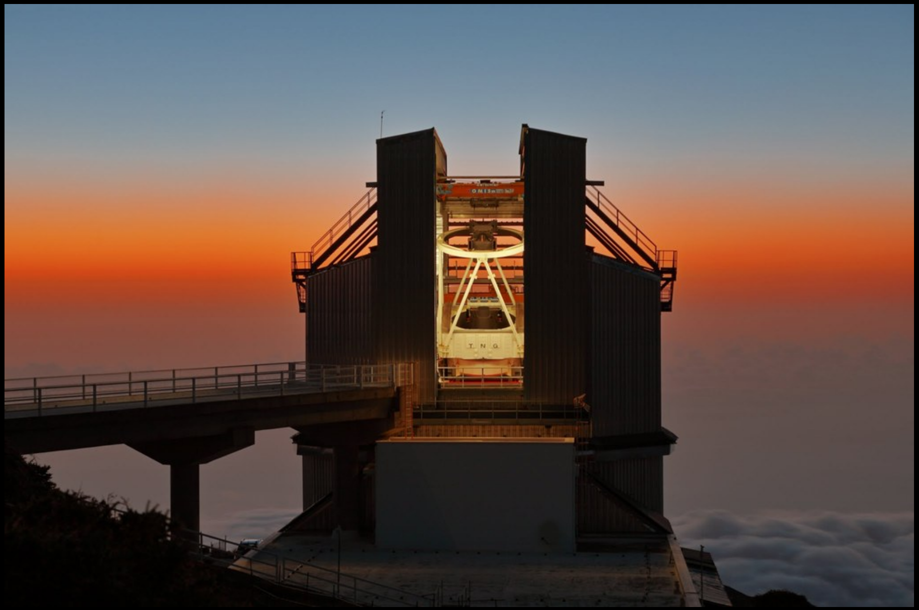

APACHE in the context of other ground-based surveys
confirmed/validated transiting planets
MEarth
WTS
PTF
APACHE
SWASP
HAT
NGTS
MASCARA
ExTrA
1%
0.5%
0.01%
M4V
M0V
K0V
Planet radius (R_{Earth})
Stellar radius (R_{Sun})
100.0
10.0
1.0
0.1
0.1
1.0
10.0

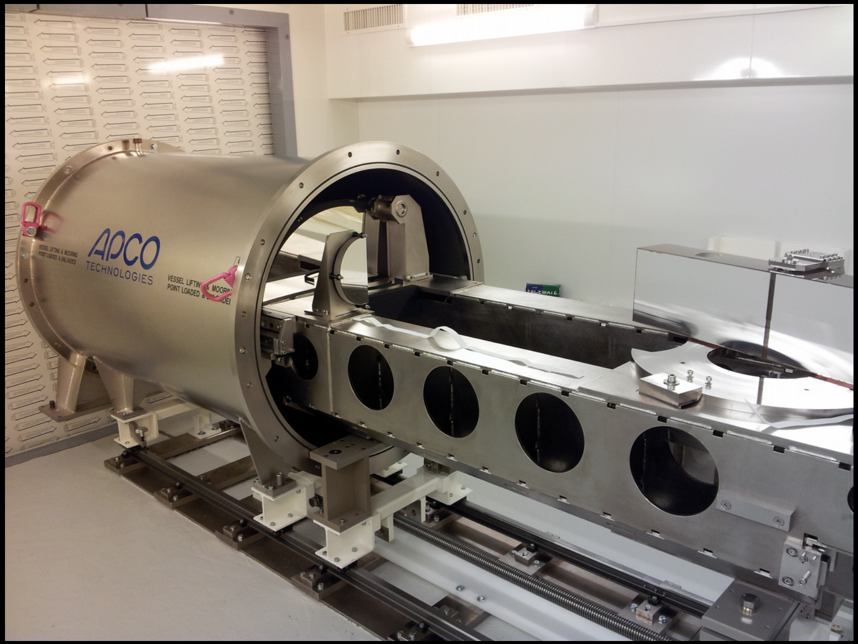
- ~1800 days of operations (4.9 yrs)
- ~40% of good weather
- > 800,000 useful images
- ~400 targets observed

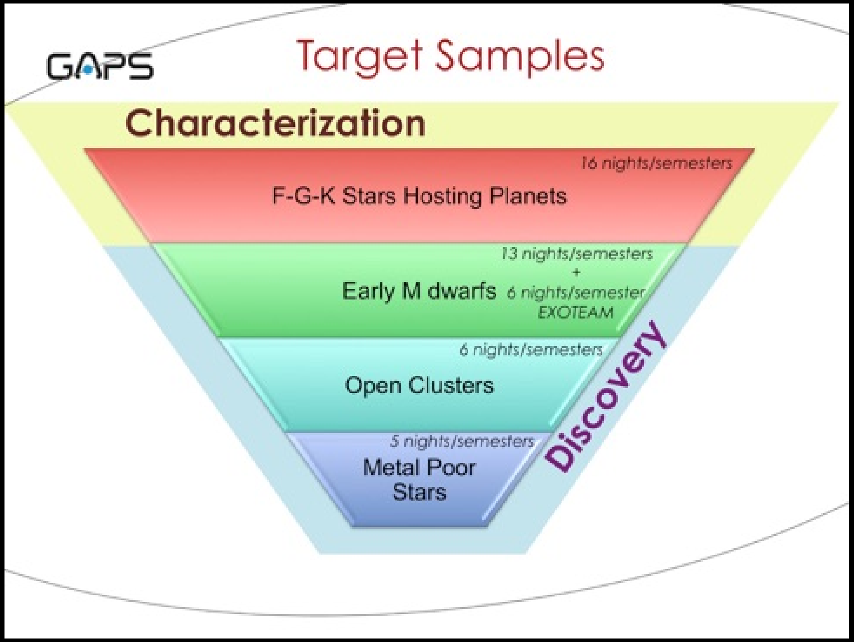
  a dozen of which are test targets, with known transiting planets we have well recovered
- 0.005 mag of mean photometric precision

GAPS and GAPS 2.0

https://www.oact.inaf.it/exoit/EXO-IT/Projects/Entries/2011/12/27_GAPS.html







HADES: THE Harps-n red Dwarf Exoplanet Survey

A collaboration between GAPS – EXOTEAM:

Italian Global Architecture of Planetary Systems Consortium (GAPS)
Institut de Ciencies de l'Espai de Catalunya (IEEC-CSIC)
Instituto de Astrofisica de Canarias (IAC)

Original sample: 106 stars (M0-M4) - Timespan: 4.7 yrs
[Lepine & Gaidos 2013; PMSU, Reid et al. 1995; **APACHE catalog**, Sozzetti et al. 2013; Gaia scans]
27 rejected (wrong spectral types, binaries, rotators, strong activity)
7 stars still unobserved

23 ≥ 80 obs
15 ≥ 100 obs
Tot: 3830

Jitter ≈ 1.0 – 3.0 m/s
Mean internal error = 2.2 m/s
Mean RMS = 68.8 m/s (several long term trends)
Median RMS = 4.4 m/s

HADES Discoveries:

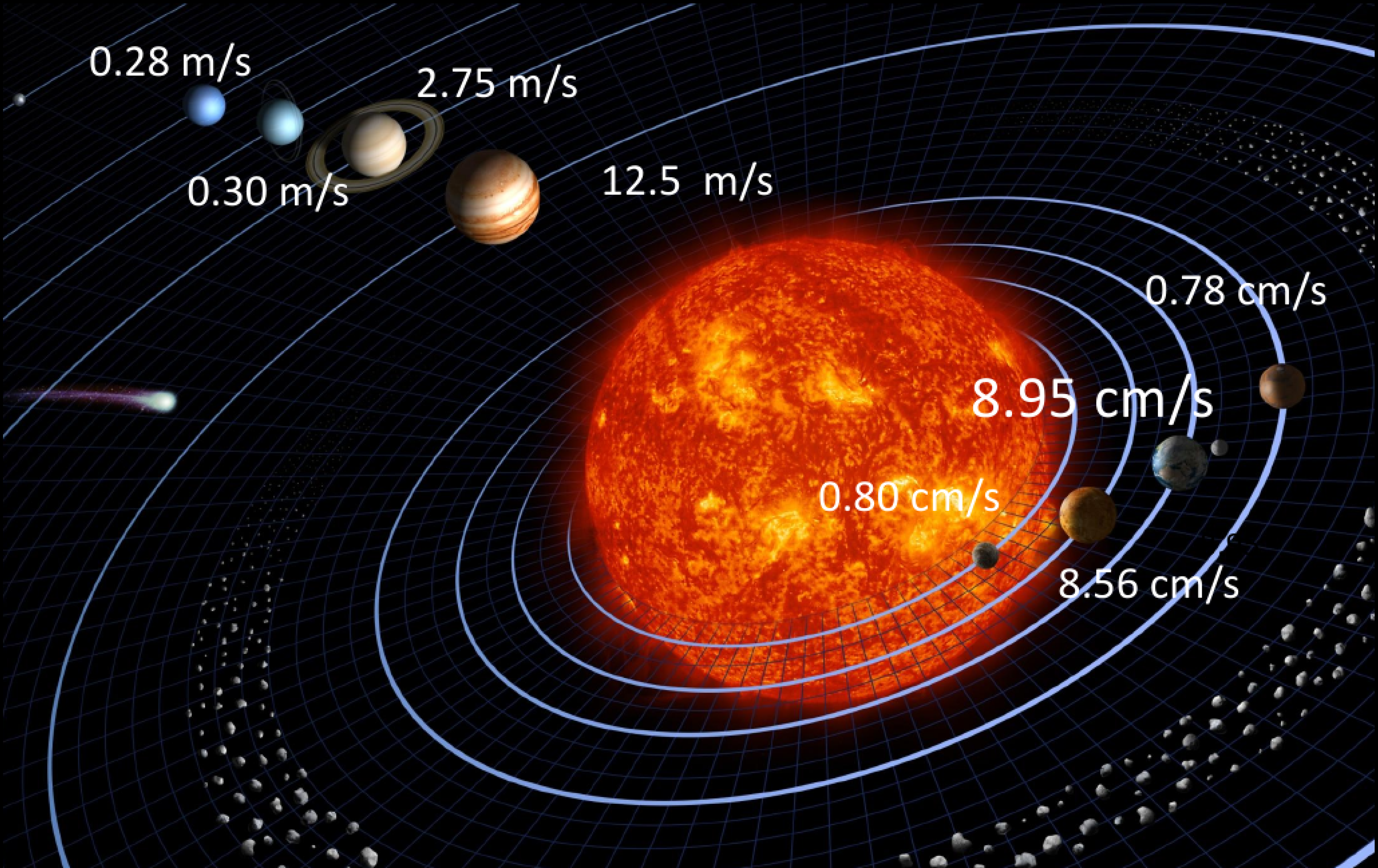
Affer et al. 2016	GJ 3998 b:	P = 2.6 d	$m_p \sin i = 2.5\ M_E$
	GJ 3998 c:	P = 13.7 d	$m_p \sin i = 6.3\ M_E$
Suárez Mascareño et al. 2017	GJ 625 b:	P = 14.6 d	$m_p \sin i = 2.8\ M_E$
Perger et al. submitted	GJ 3942 b:	P = 6.9 d	$m_p \sin i = 7.9\ M_E$
Pinamonti et al. submitted	GJ 15A b:	P = 7648 d	$m_p \sin i = 45\ M_E$

TESS
Transiting Exoplanet Survey Satellite

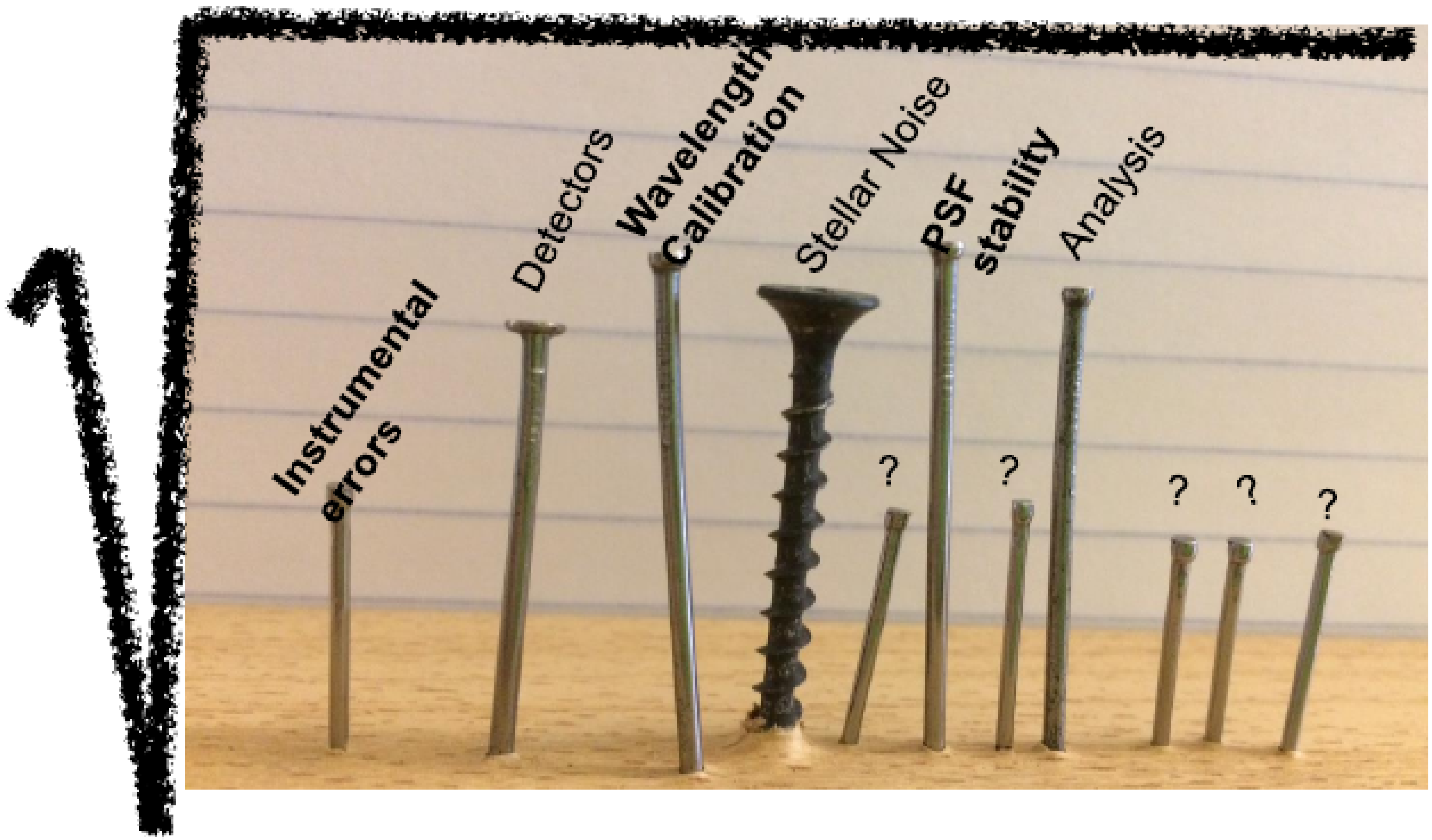
To be launched on March 2018.

It is expected to discover ~980 transiting planets around M dwarfs, Including ~50 bright M dwarfs.

Spectroscopic observations will be necessary to determine the mass of the planet and search for possible non-transiting systems.


0.28 m/s
2.75 m/s
0.30 m/s
12.5 m/s
0.78 cm/s
8.95 cm/s
0.80 cm/s
8.56 cm/s

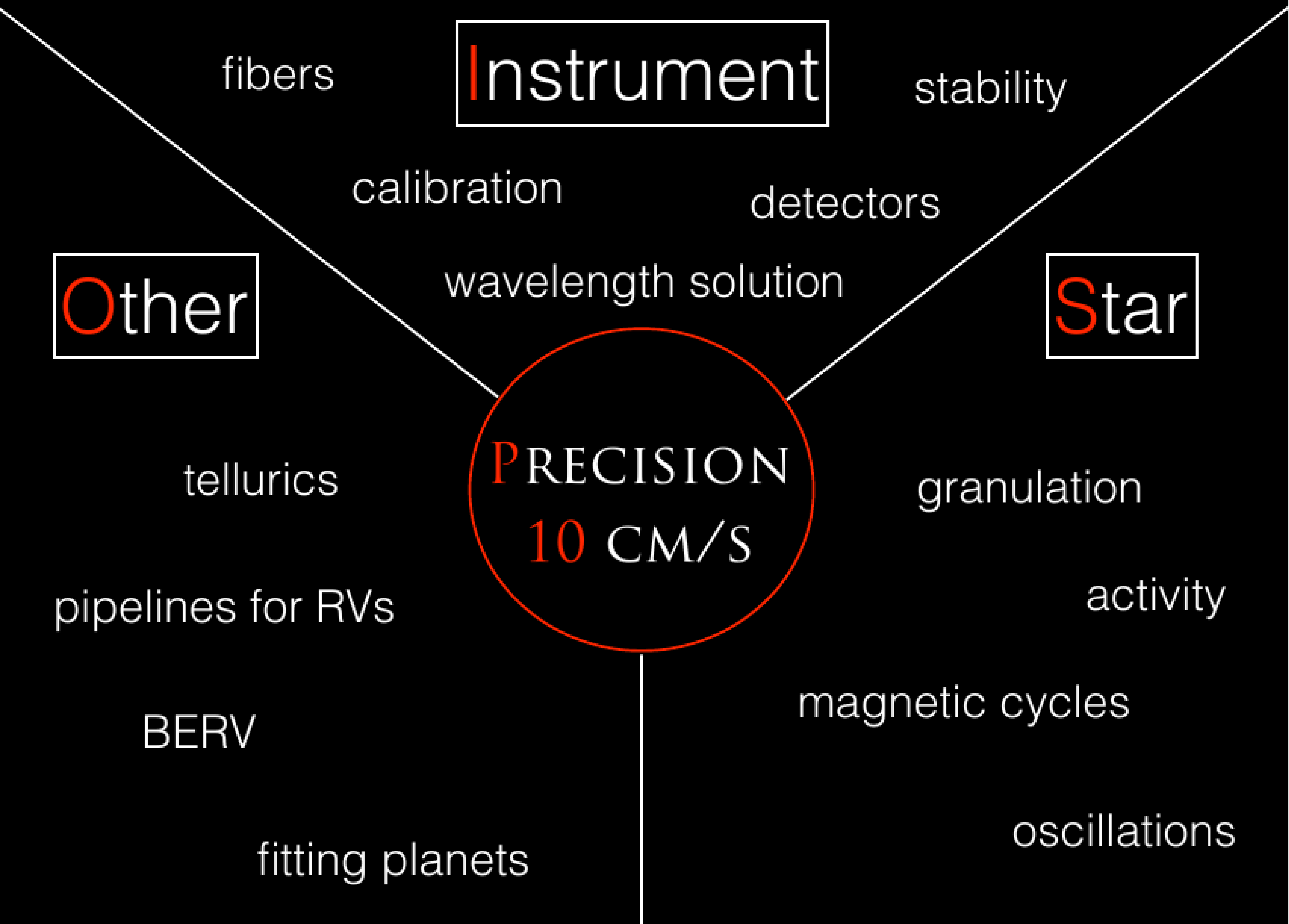
This is how Debra Fischer portrayed the problem at the recent "Extreme Precision Radial Velocity" meeting at Yale (2015)



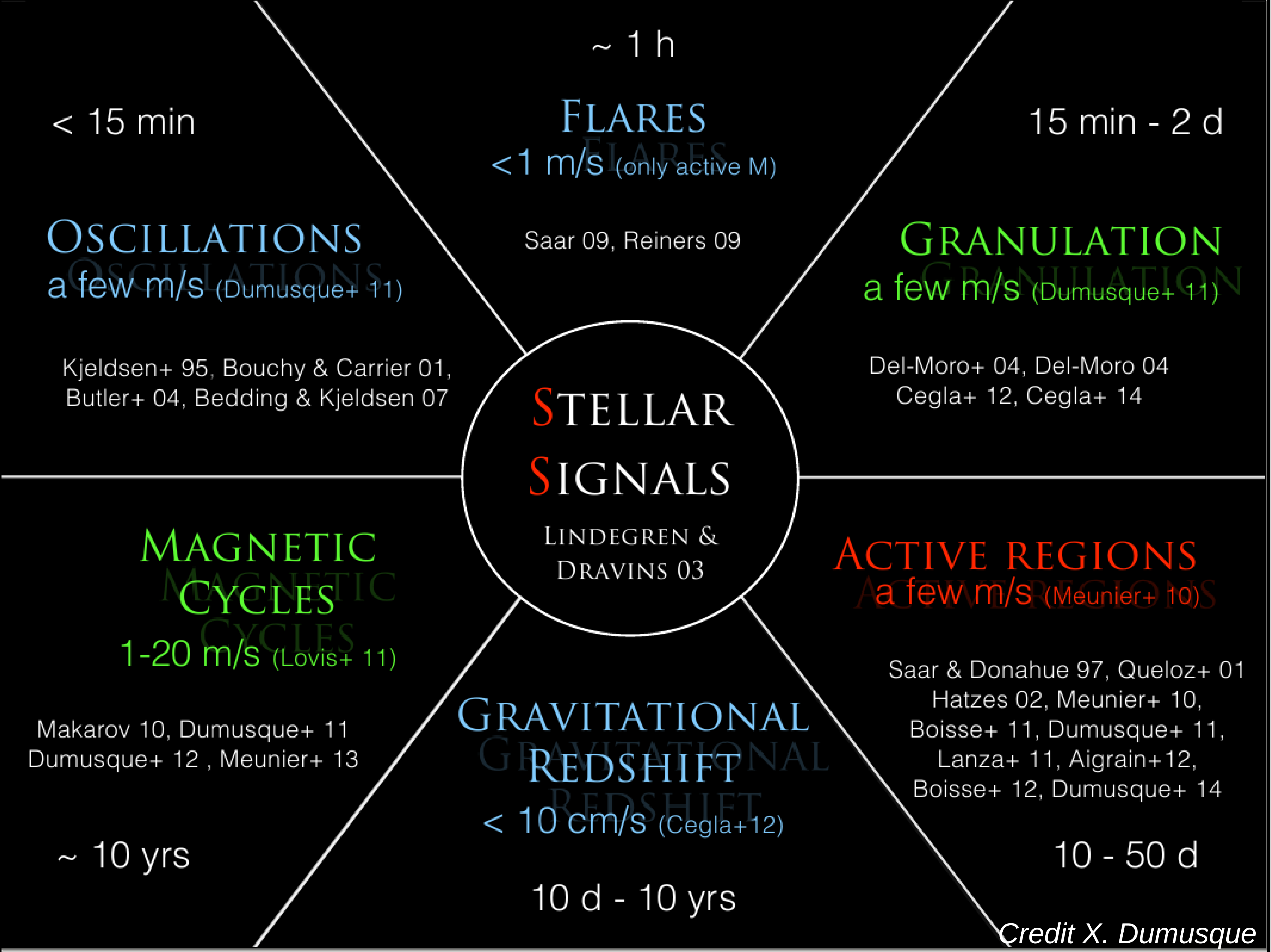
Radial velocity measurements

If we eliminate all other error sources except stellar noise, we won’t see significant precision gains.

A key challenge for **detecting** and reliably **characterizing** low-mass planets is to separate planetary signals from stellar activity induced signals.
In other words, it must be found a way **to mitigate** the stellar noise

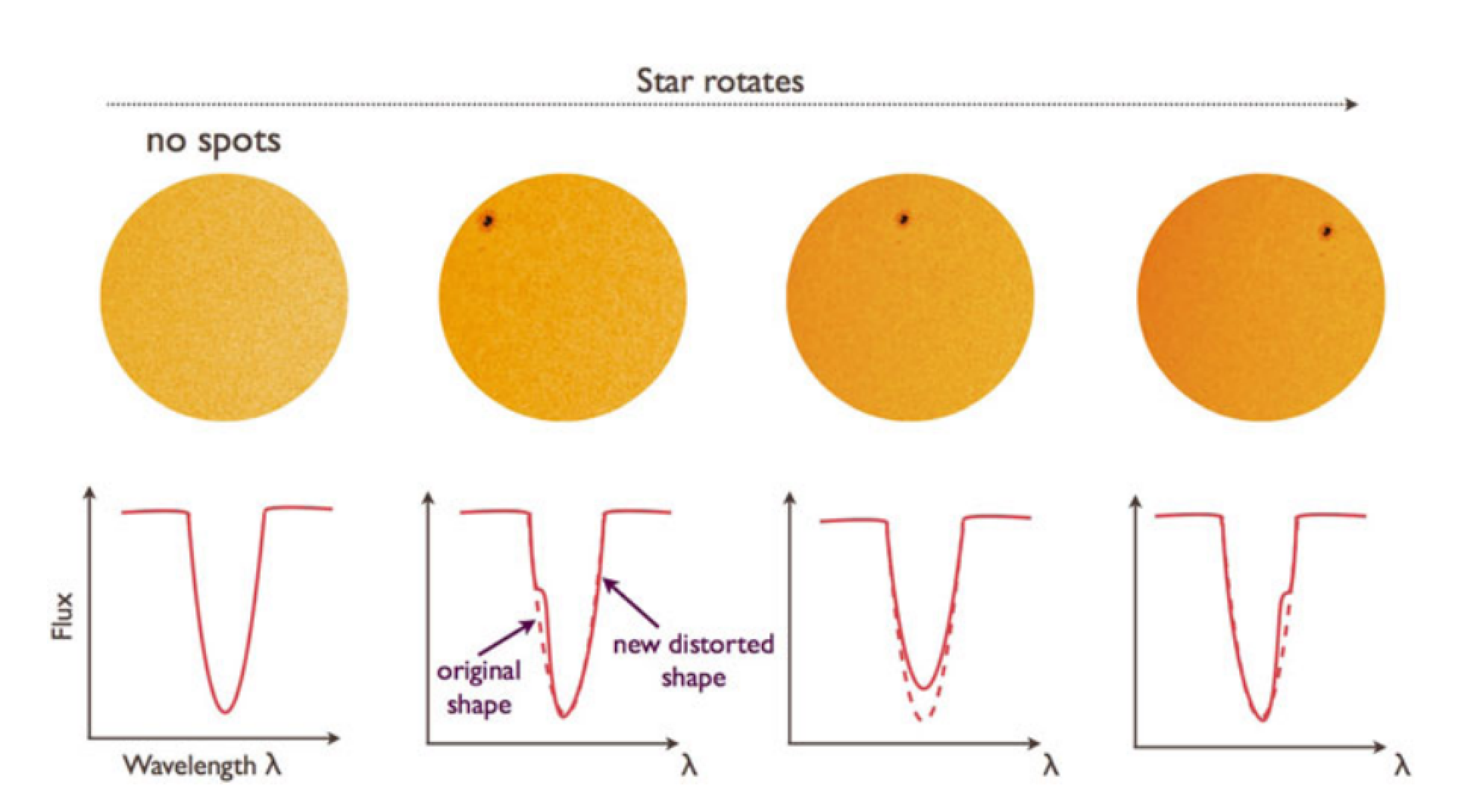


Credit X. Dumusque



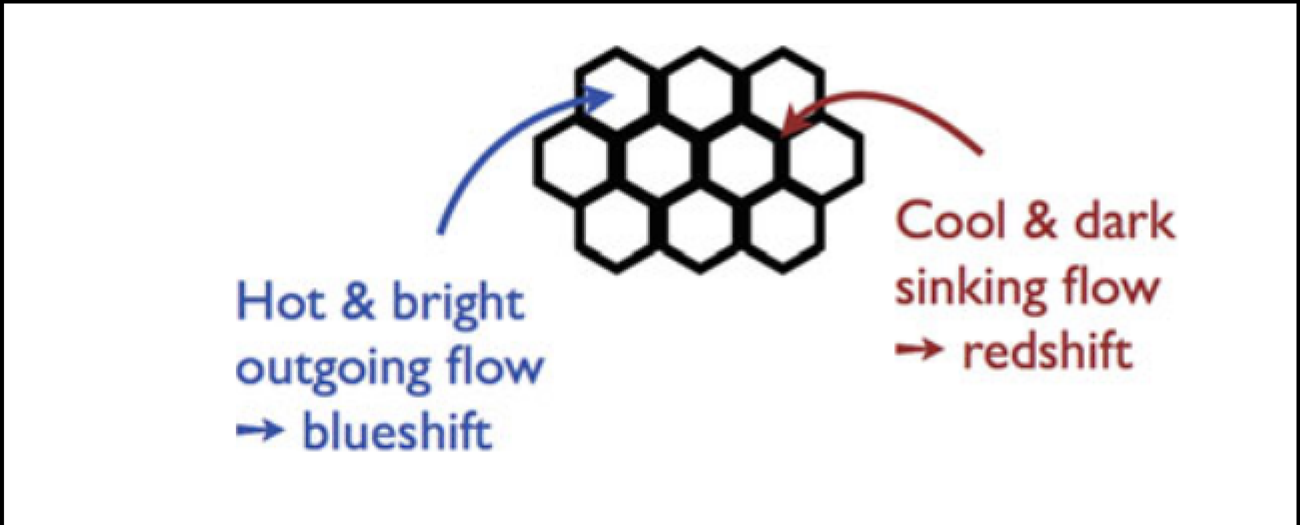
~ 1 h
FLARES
<1 m/s (only active M)
Saar 09, Reiners 09
< 15 min
OSCILLATIONS
a few m/s (Dumusque+ 11)
Kjeldsen+ 95, Bouchy & Carrier 01,
Butler+ 04, Bedding & Kjeldsen 07
15 min - 2 d
GRANULATION
a few m/s (Dumusque+ 11)
Del-Moro+ 04, Del-Moro 04
Cegla+ 12, Cegla+ 14
STELLAR
SIGNALS
LINDEGREN &
DRAVINS 03
MAGNETIC
CYCLES
1-20 m/s (Lovis+ 11)
Makarov 10, Dumusque+ 11
Dumusque+ 12 , Meunier+ 13
~ 10 yrs
ACTIVE REGIONS
a few m/s (Meunier+ 10)
Saar & Donahue 97, Queloz+ 01
Hatzes 02, Meunier+ 10,
Boisse+ 11, Dumusque+ 11,
Lanza+ 11, Aigrain+12,
Boisse+ 12, Dumusque+ 14
10 - 50 d
GRAVITATIONAL
REDSHIFT
< 10 cm/s (Cegla+12)
10 d - 10 yrs
Credit X. Dumusque

Flux blocked by starspots on the rotating stellar disc induces asymmetries in the spectral lines, leading to variations in RV



Courtesy of R. Haywood

Convective blueshift



The photometric effect of faculae is negligible as they are not significantly brighter than the quiet photosphere and they are evenly spread on the stellar disc; they do, however, induce a strong signature in spectroscopic observations.

Suppression of convective blueshift is thought to play a dominant role in activity-induced RV variations on Sun-like stars, particularly in the case of faculae/plage, which are thought to cover a much larger fraction of the stellar surface than spots

Gaussian Processes

Instead of assuming that the noise is white, the likelihood function is generalized to include covariances between data points.

$$\ln p(\{y_n\} \,|\, \{t_n\},\, \{\sigma_n^2\},\, \theta) = -\frac{1}{2}\, \boldsymbol{r}^{\mathrm{T}}\, K^{-1}\, \boldsymbol{r} - \frac{1}{2} \ln \det K - \frac{N}{2} \ln 2\pi$$

$$\boldsymbol{r} = \begin{pmatrix} y_1 - f_\theta(t_1) \\ y_2 - f_\theta(t_2) \\ \vdots \\ y_N - f_\theta(t_N) \end{pmatrix}$$

$$K = \begin{pmatrix} \sigma_1^2 & 0 & & 0 \\ 0 & \sigma_2^2 & & 0 \\ & & \ddots & \\ 0 & 0 & & \sigma_N^2 \end{pmatrix}$$

$$\xrightarrow{\text{Including covariance}}$$

$$K_{ij} = \sigma_i^2\, \delta_{ij} + k(t_i,\, t_j)$$

Once a covariance function is chosen, a MCMC fitting is used to derive hyper-parameters (i.e. parameters of the covariance function)

See R. Haywood PhD thesis for a nice description of GPs

Application to the Kepler Fitting Challenge

Dumusque et al. 2017
https://rv-challenge.wikispaces.com

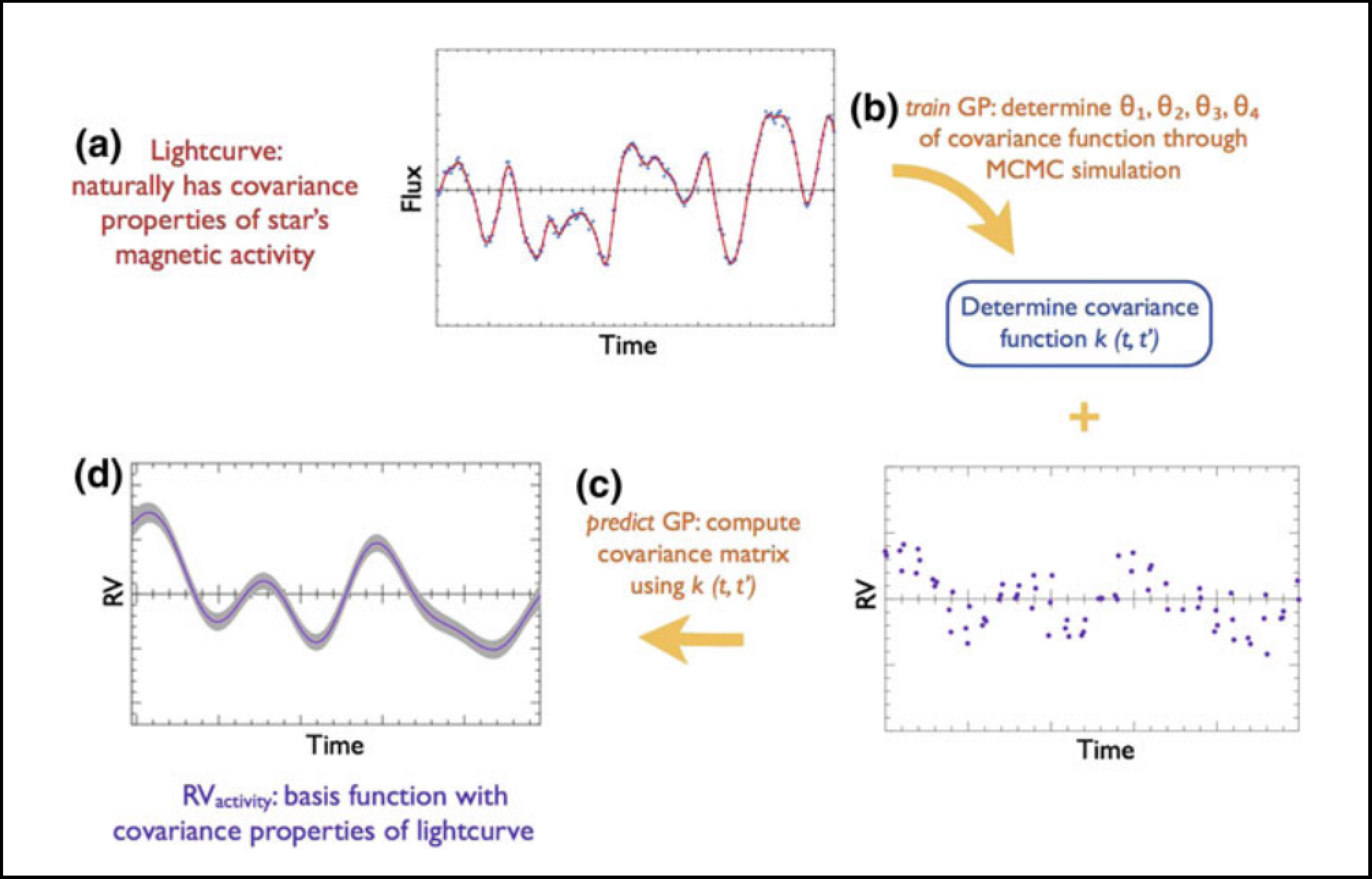
15 simulated RV datasets using one of the best noise model on the market

OBSERVABLES: RV, BIS, FWHM, log(R'hk)

Some useful covariance functions

Gaussian Process Kernel Options

Name	Mathematical expression	Hyperparameters[a]	Comments
Squared exponential	$h^2 \exp\left[-\left(\frac{t_i - t_j}{\lambda}\right)^2\right]$	h, λ	h amplitude of covariance function, λ average time it takes to cover that range
Periodic	$h^2 \exp\left[-\frac{\sin^2[\pi(t_i - t_j)/\theta]}{2w^2}\right]$	h, θ, w	θ equivalent to P_{rot}, Roughness w equivalent to λ expressed as a fraction of θ
quasi-periodic	$h^2 \exp\left[-\frac{\sin^2[\pi(t_i - t_j)/\theta]}{2w^2} - \left(\frac{t_i - t_j}{\lambda}\right)^2\right]$	h, θ, w, λ	w represents timescale of periodic variation while λ represents timescale of aperiodic variation.



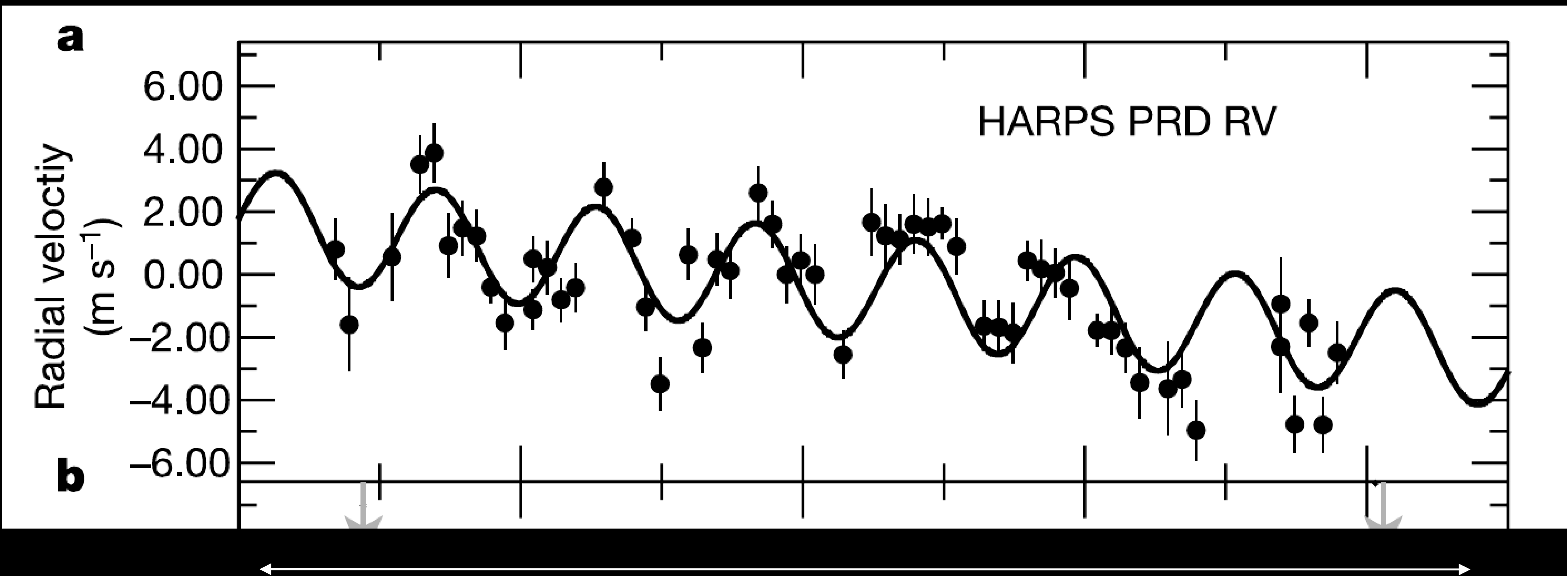
Credits: R. Haywood

Discussion on real targets

Proxima Centauri b

(Anglada-Escudé et al. 2016; Damasso & Del Sordo, 2017)

Pale Red Dot campaign



Anglada-Escudé et al., Nature, 2016

Proxima Centauri reloaded: Unravelling the stellar noise in radial velocities

M. Damasso[1] and F. Del Sordo[2,3]

[1] INAF–Osservatorio Astrofisico di Torino, via Osservatorio 20, 10025 Pino Torinese, Italy
e-mail: damasso@oato.inaf.it
[2] Department of Geology & Geophysics, and Department of Astronomy, Yale University, 06520 New Haven, CT, USA
e-mail: fabio.delsordo@yale.edu
[3] Nordita, Royal Institute of Technology and Stockholm University, 10691 Stockholm, Sweden

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ABSTRACT

Context. The detection and characterisation of Earth-like planets with Doppler signals of the order of 1 $\mathrm{m\,s^{-1}}$ currently represent one of the greatest challenge for extrasolar-planet hunters. As results for such findings are often controversial, it is desirable to provide independent confirmations of the discoveries. Testing different models for the suppression of non-Keplerian stellar signals usually plaguing radial velocity data is essential to ensuring findings are robust and reproducible.
Aims. Using an alternative treatment of the stellar noise to that discussed in the discovery paper, we re-analyse the radial velocity dataset that led to the detection of a candidate terrestrial planet orbiting the star Proxima Centauri. We aim to confirm the existence of this outstanding planet, and test the existence of a second planetary signal.
Methods. Our technique jointly modelled Keplerian signals and residual correlated signals in radial velocities using Gaussian processes. We analysed only radial velocity measurements without including other ancillary data in the fitting procedure. In a second step, we have compared our outputs with results coming from photometry, to provide a consistent physical interpretation. Our analysis was performed in a Bayesian framework to quantify the robustness of our findings.
Results. We show that the correlated noise can be successfully modelled as a Gaussian process regression, and contains a periodic term modulated on the stellar rotation period and characterised by an evolutionary timescale of the order of one year. Both findings appear to be robust when compared with results obtained from archival photometry, thus providing a reliable description of the noise properties. We confirm the existence of a coherent signal described by a Keplerian orbit equation that can be attributed to the planet Proxima b, and provide an independent estimate of the planetary parameters. Our Bayesian analysis dismisses the existence of a second planetary signal in the present dataset.

A&A, in press

Method used in the discovery paper

$$
\begin{aligned}
\Delta RV_{tot}(t_i) &= \Delta RV_{Kep}(t_i) + \epsilon_i + Cte + \alpha\, t_i + \beta\, t_i^2 + \\
&+ c_{01}\,\text{BIS SPAN} + c_{02}\,\text{FWHM} + c_{03}\,\log(R'_{HK}) \\
&+ \phi\left[\Delta RV_{tot}(t_{i-1}) - \Delta RV_{Kep}(t_{i-1})\right] exp^{\frac{t_{i-1}-t_i}{\tau}}
\end{aligned}
$$

Method used by D&D (Gauss. Proc.)

$$
\begin{aligned}
k(t,t') &= h^2 \cdot \exp\left[-\frac{(t-t')^2}{2\lambda^2} - \frac{\sin^2(\pi(t-t')/\theta)}{2w^2}\right] \\
&\quad + (\sigma^2_{\mathrm{RV}}(t) + \sigma^2_j) \cdot \delta_{t,t'},
\end{aligned}
$$

Proxima photometry

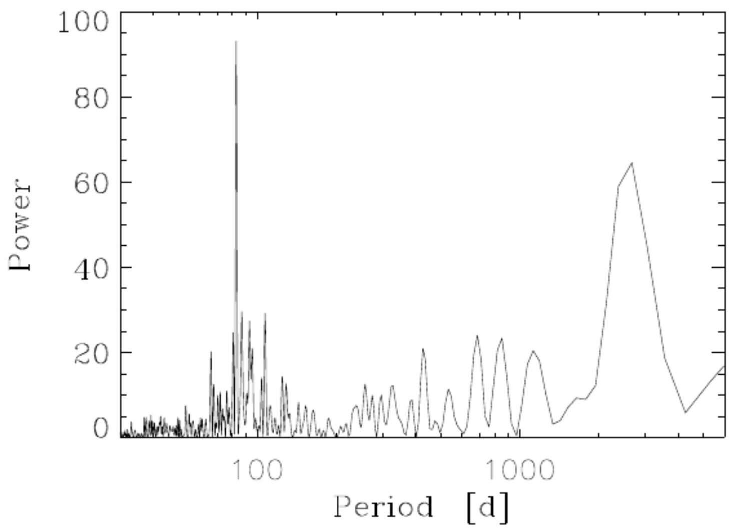
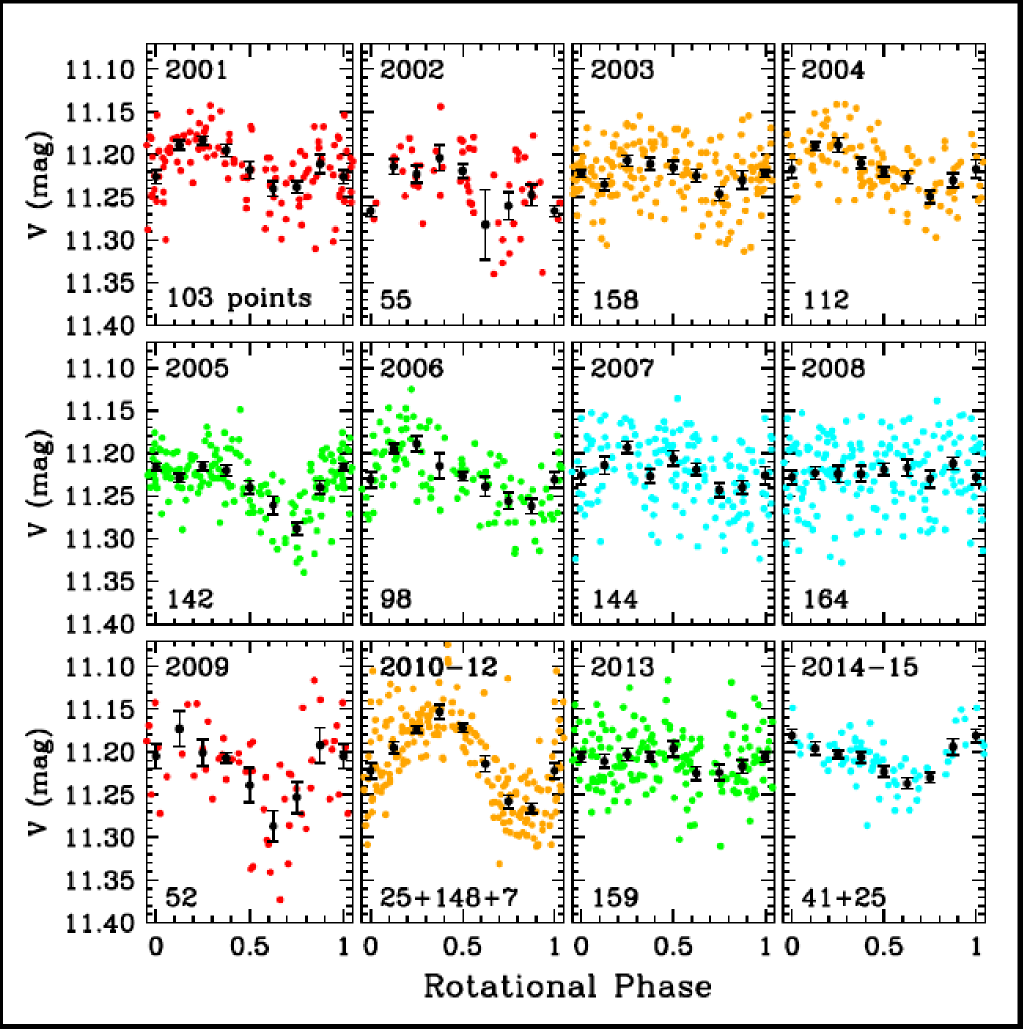
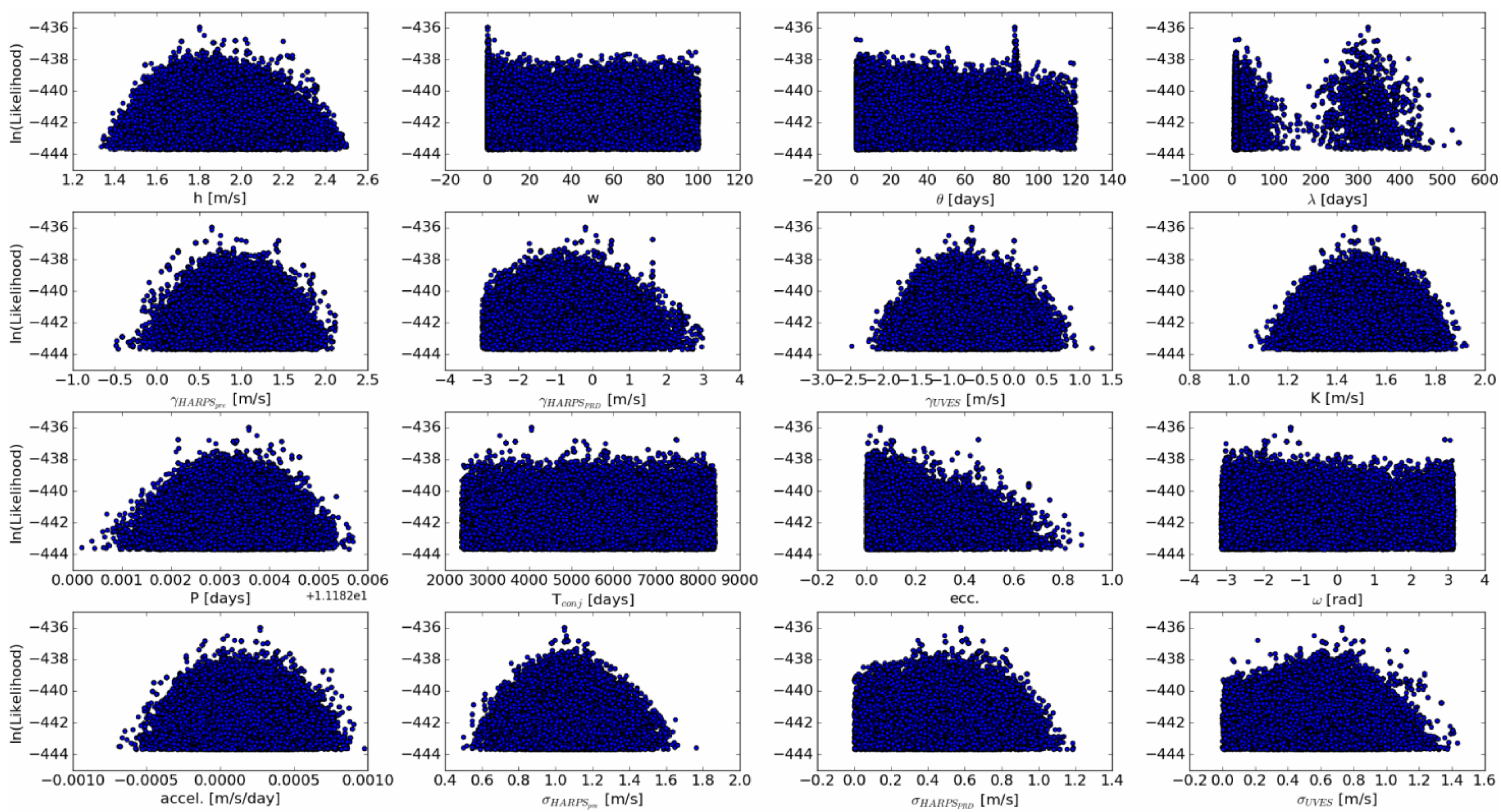


Figure 1. Lomb-Scargle periodogram of V-band ASAS data. Rotation peak is at 83.1 d and the broad peak around 2600 d (∼7 yr) is from the stellar cycle.



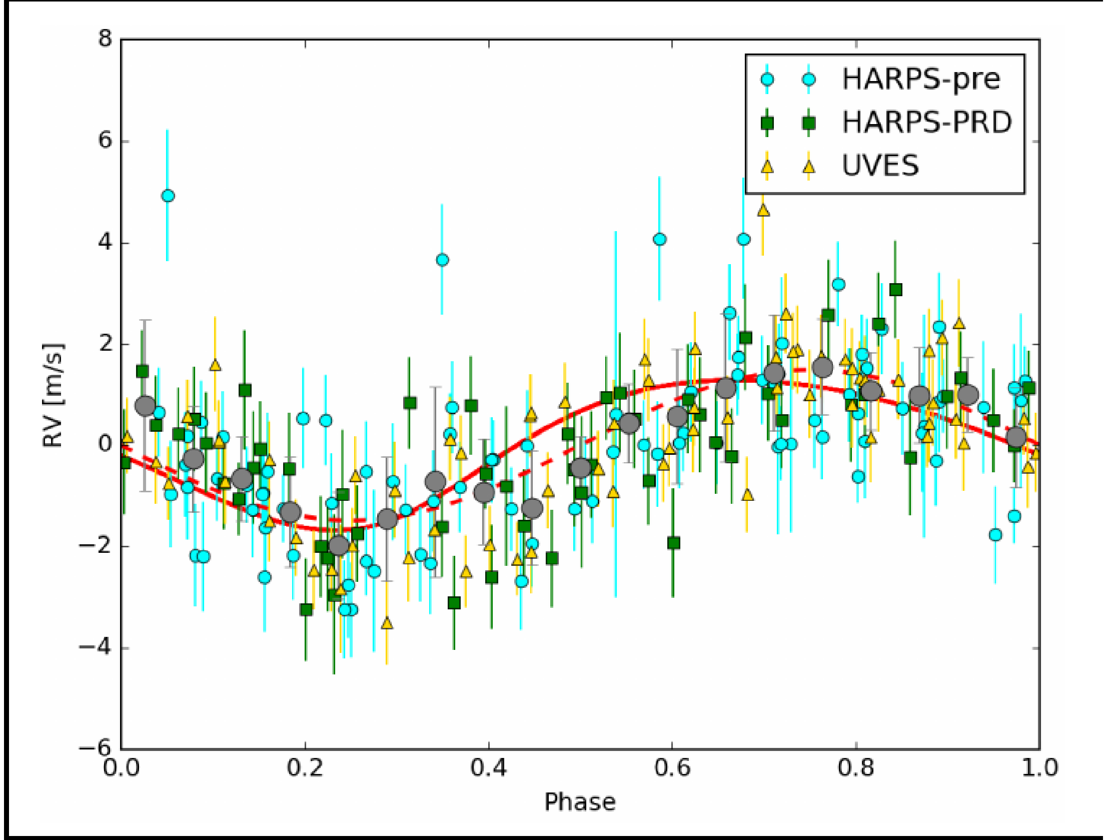
Wargelin et al. 2017

Gaussian process + Keplerian global model



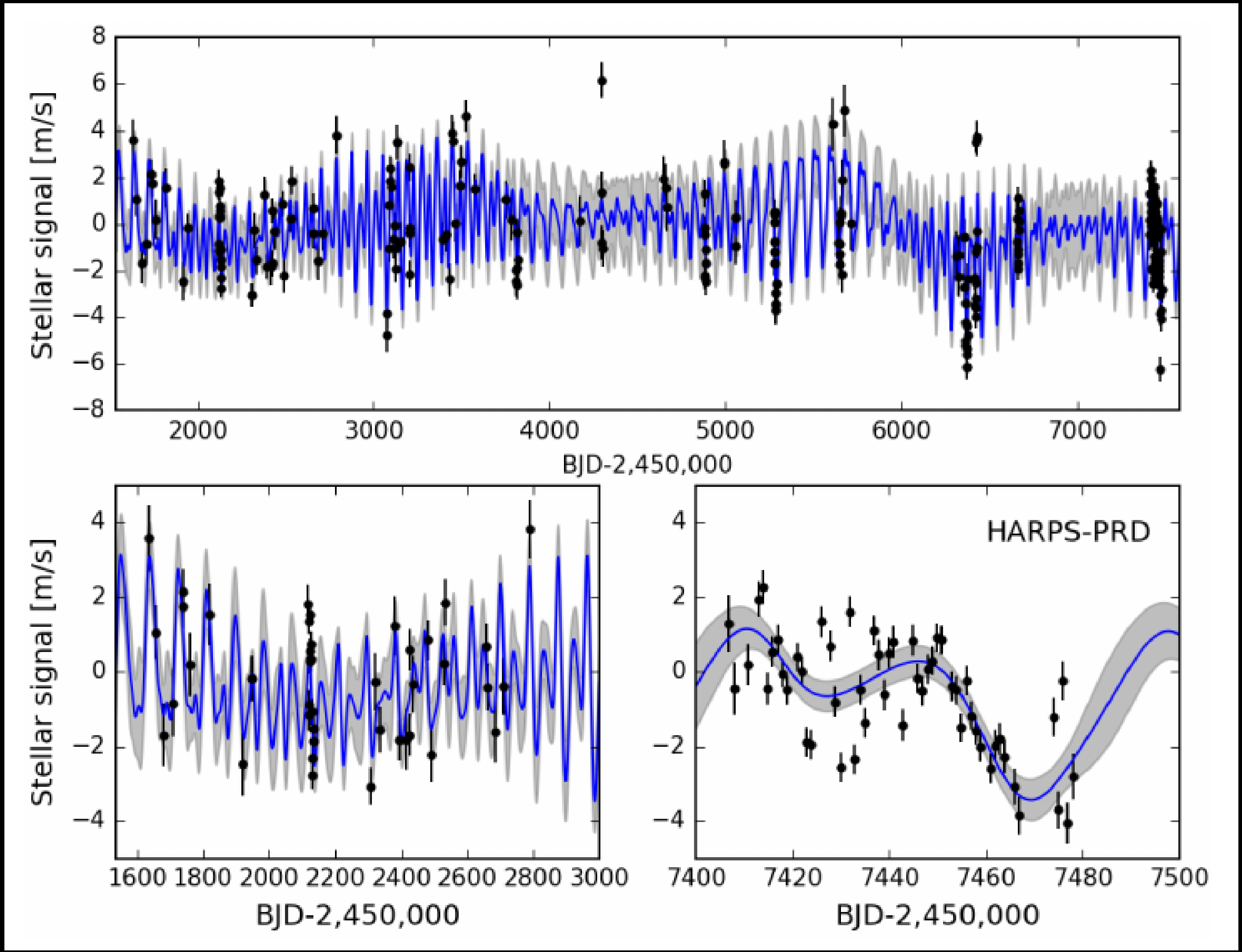
D&D results for planet b

Jump parameter	Value (This work)	Value (Anglada-Escudé et al. 2016)
h [m s^{-1}]	$1.91^{+0.30}_{-0.23}$	
λ [days]	311^{+71}_{-54}	
w	$0.34^{+0.07}_{-0.06}$	
θ [days]	$87.1^{+0.9}_{-0.7}$	
$\gamma_{\mathrm{HARPS}_{\mathrm{pre-2016}}}$ [m s^{-1}]	0.92 ± 0.56	
$\gamma_{\mathrm{HARPS}_{\mathrm{PRD}}}$ [m s^{-1}]	$-0.58^{+0.94}_{-0.85}$	
γ_{UVES} [m s^{-1}]	$-0.48^{+0.39}_{-0.52}$	
K_1 [m s^{-1}]	$1.48^{+0.13}_{-0.12}$	1.38 ± 0.21
P_1 [days]	$11.1855^{+0.0007}_{-0.0006}$	$11.186^{+0.001}_{-0.002}$
$T_{c,1}$ [JD-2 400 000]	$60\,728.17 \pm 0.38$	
e_1	$0.17^{+0.21}_{-0.12}$	<0.35
ω_1 [rad]	$-2.49^{+1.49}_{-0.35}$	5.41 (unconstrained)
$\mathrm{d}V_r/\mathrm{d}t$ $(\cdot 10^{-4})$ [m s^{-1} day^{-1}]	$3.2^{+2.1}_{-3.0}$	2.3 ± 8.4
$\sigma_{\mathrm{jit,HARPS}_{\mathrm{pre-2016}}}$ [m s^{-1}]	1.11 ± 0.10	$1.76^{+0.60}_{-0.54}$
$\sigma_{\mathrm{jit,HARPS}_{\mathrm{PRD}}}$ [m s^{-1}]	$0.63^{+0.17}_{-0.19}$	$1.14^{+0.70}_{-0.57}$
$\sigma_{\mathrm{jit,UVES}}$ [m s^{-1}]	$0.71^{+0.20}_{-0.18}$	$1.69^{+0.64}_{-0.47}$
Minimum mass, $m_p \sin i$ $(M_\oplus)^a$	1.21 ± 0.16	$1.27^{+0.19}_{-0.17}$
Orbital semi-major axis, a (AU)^a	0.048 ± 0.002	$0.0485^{+0.0041}_{-0.0051}$

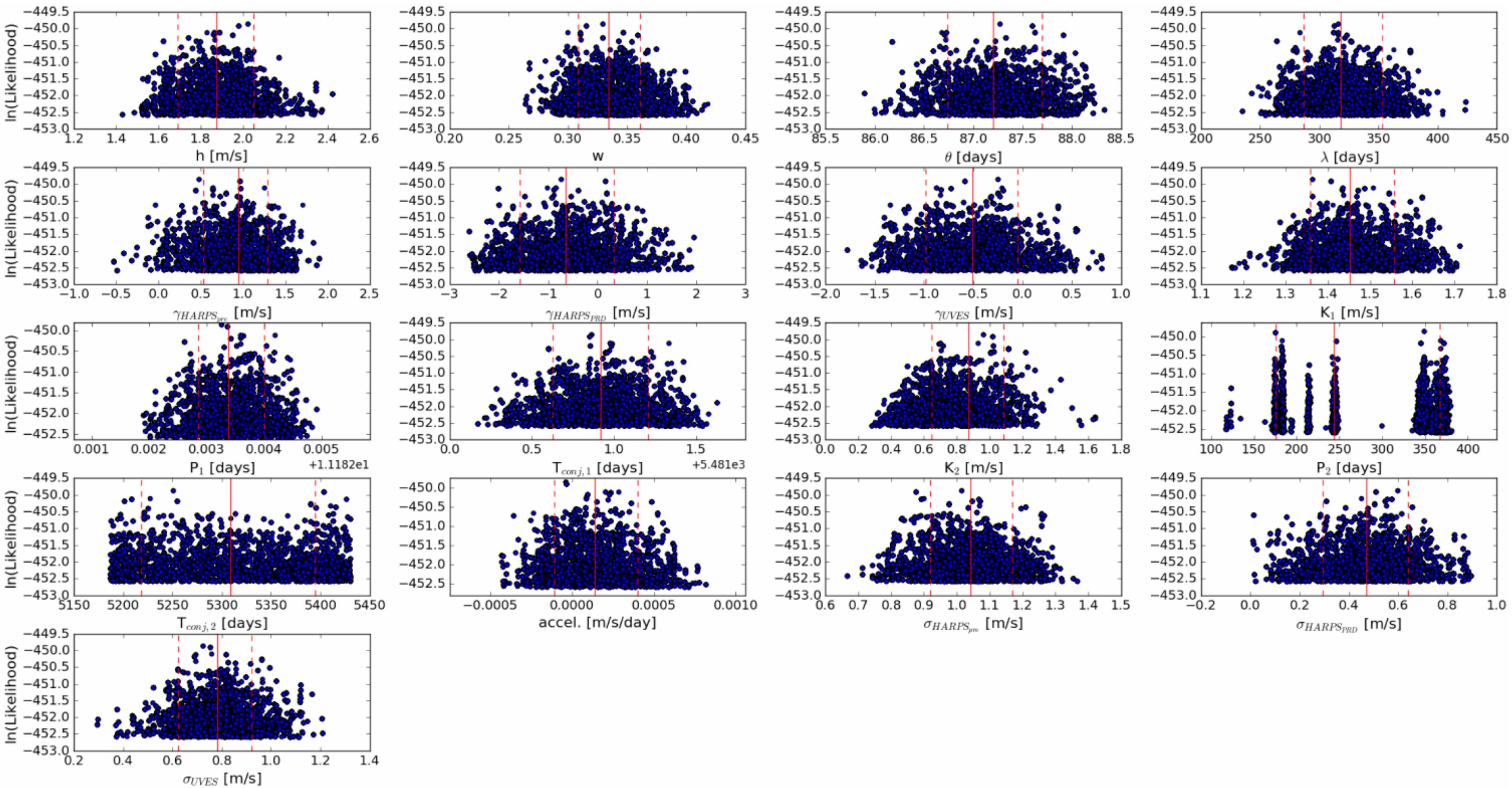


Proxima b orbit is likely circular

Structure of the correlated (stellar) signal



Nothing else?



The model with 2 planets is statistically unlikely.

The Project

GIARPS is the new common feeding for HARPS-N and GIANO

Aim: high resolution VIS-NIR spectra + high precision radial velocities

Method: simultaneous use of:

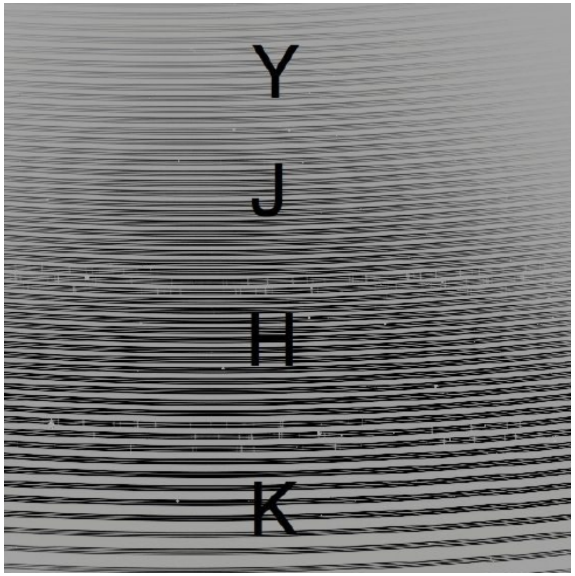
- ❑ HARPS-N (0.38 μm < λ< 0.69 μm)
- ❑ GIANO (0.95 μm < λ < 2.45 μm)

already on duty at TNG

Courtesy of R. Claudi

GIANO_B

- NIR high resolution echelle spectrograph of TNG, offered in 2015
- Spectral range from Y to K band (0.95 – 2.45 μm) in a single exposure
- Resolution of 50,000
- RV accuracy ≈ 10m/s (Carleo et al. 2016)
- Science case: Exoplanets, stellar populations, galactic stars, star clusters, …



Courtesy of R. Claudi

Scientific Drivers

- **Mainly Exoplanets**: hot atmospheres; hot planets around cool stars; Giant planets in OC and around young nearby stars

- **Other science**: Young Stellar Object; X Ray Binaries and Magnetostars; CVs and Novae; Intermediate Luminosity Optical Transients; SN I;
GRB and SN

Courtesy of R. Claudi

Science with GIARPS: RVs

- Crucial to distinguish planetary signal from stellar "noise"
  - Activity
  - Pulsation
  - *Any colored signal*

Courtesy of R. Claudi

GIANO_B

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