Recent developments in RV technics and new instruments

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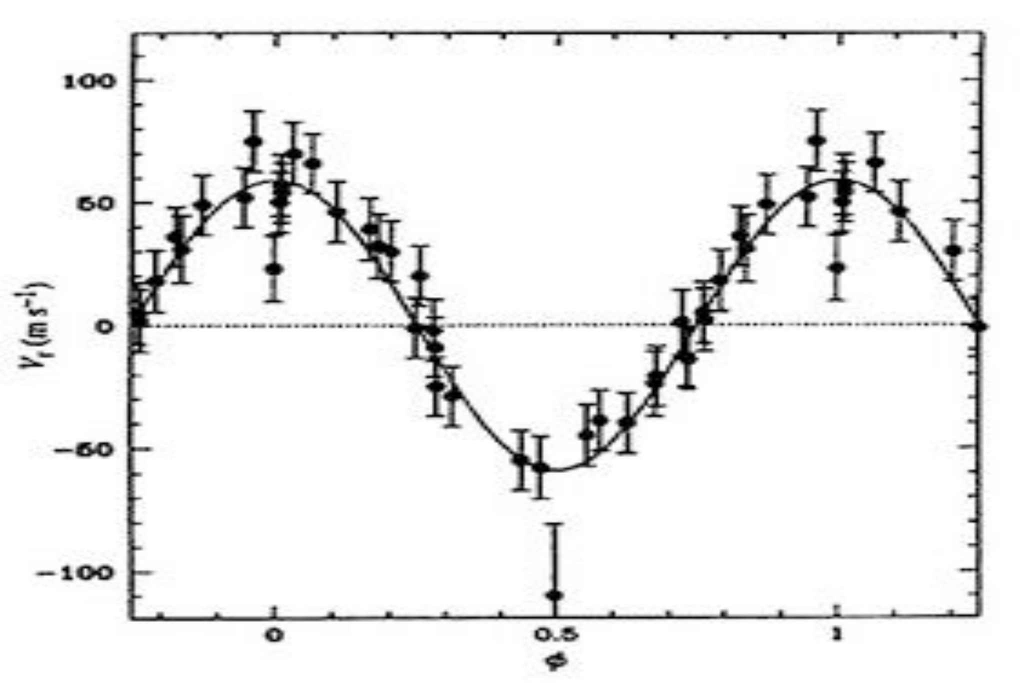
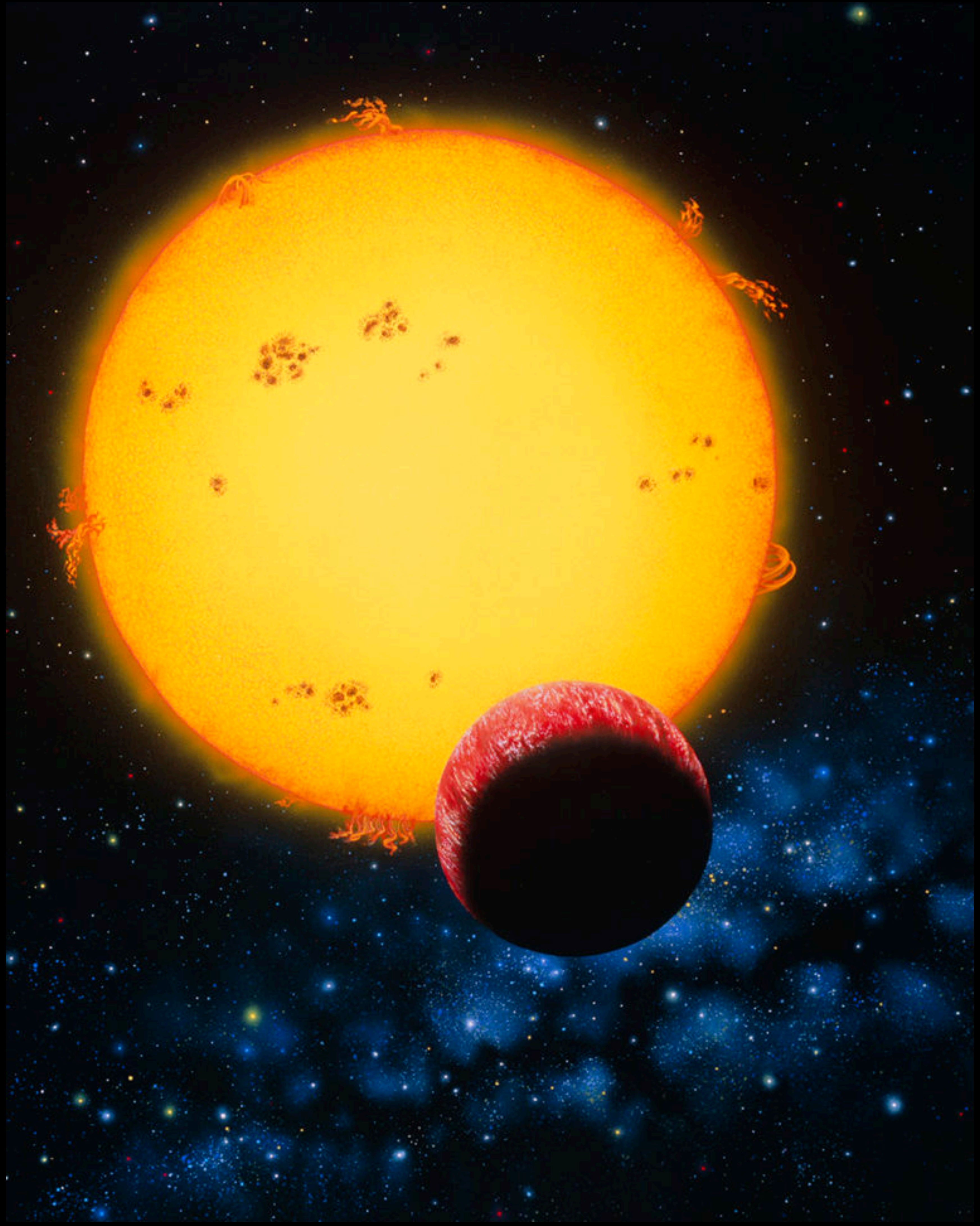
PLATO GOP Workshop 2022 - 17-19 October 2022

51 Peg b and the start of historical RV surveys

- Improve precision (<= 10 m/s), telescope time and strategy for better yield
- Sample of many suitable targets, e.g. defined by volume, magnitude or spectral type
- Search for giant planets on any kind of orbit
- Understand the variety, in the limit of achievable precision



Mayor & Queloz, *Nature* 1995

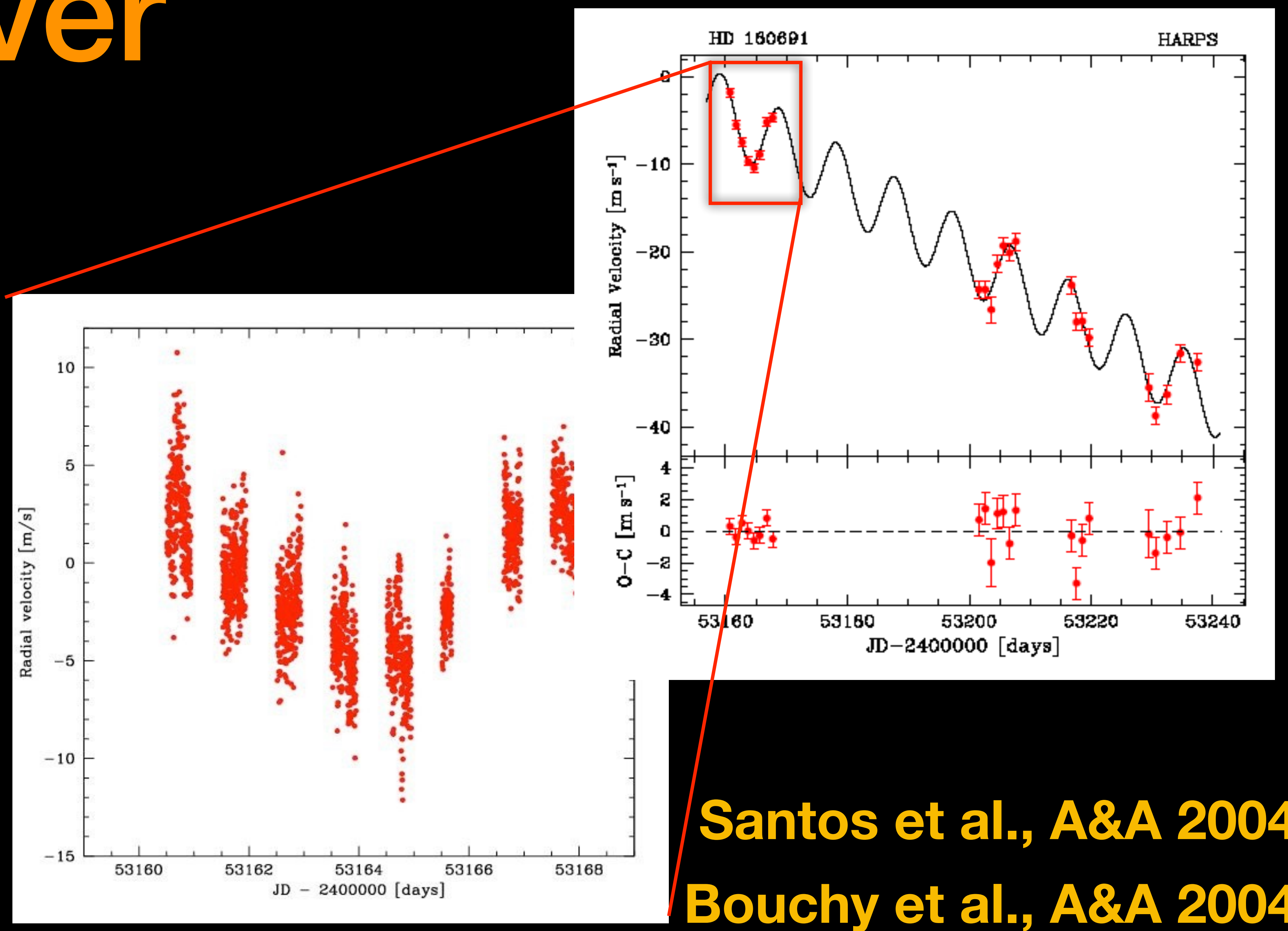


Lynette Cook

The HARPS Survey - A turnover

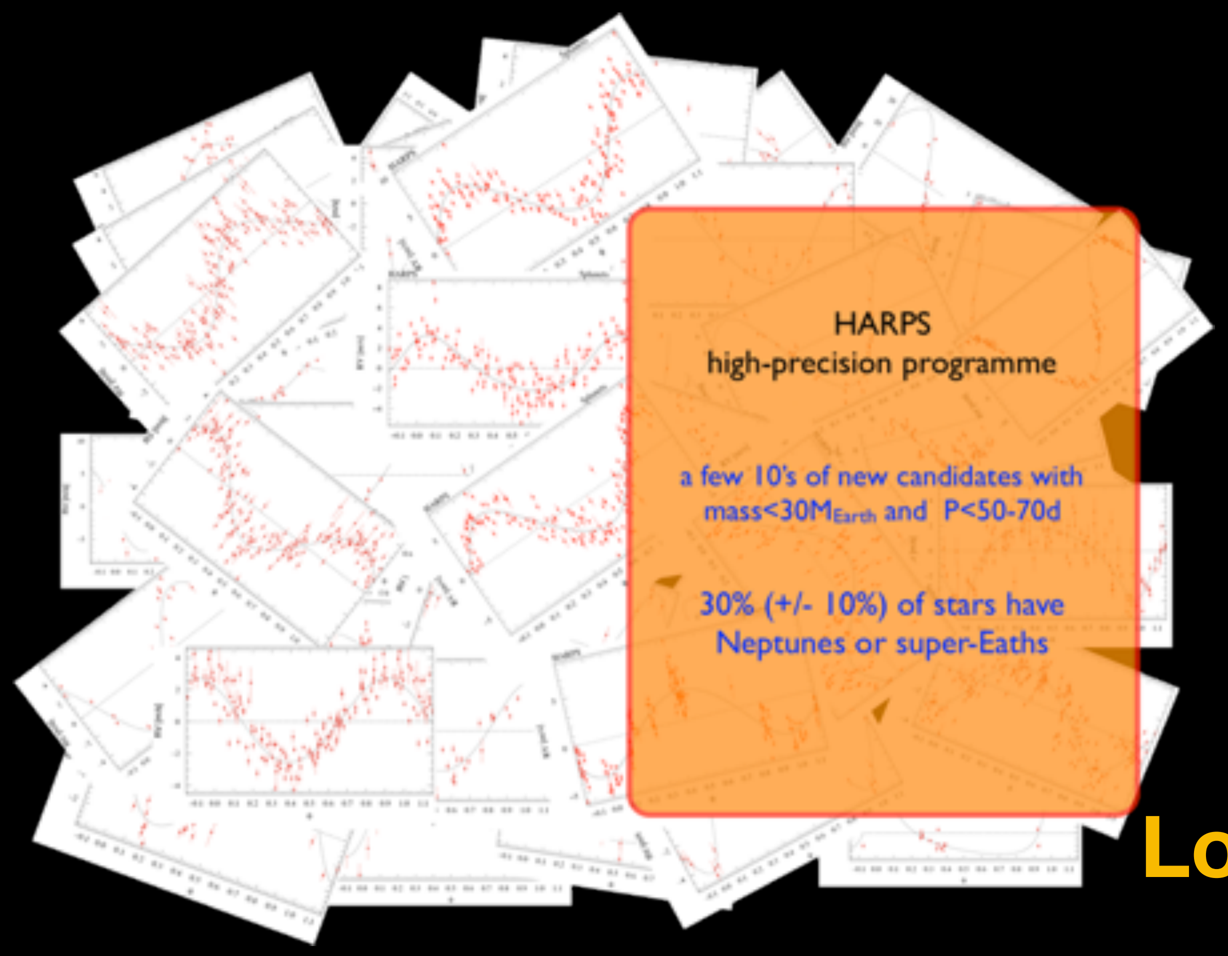
- Demonstration that 1 m/s precision is achievable
- Comprehensive sample of the most suitable targets (best achievable precision)
- Search for exoplanets with particular emphasis on precision and low-mass
- Discovery of µAra c, that opens the era of mini-Neptunes and super-Earths. Low-mass planets are VERY frequent! Characterize ‘all’ kinds of planets and measure their frequency

µAra



Santos et al., A&A 2004

Bouchy et al., A&A 2004



HARPS
high-precision programme

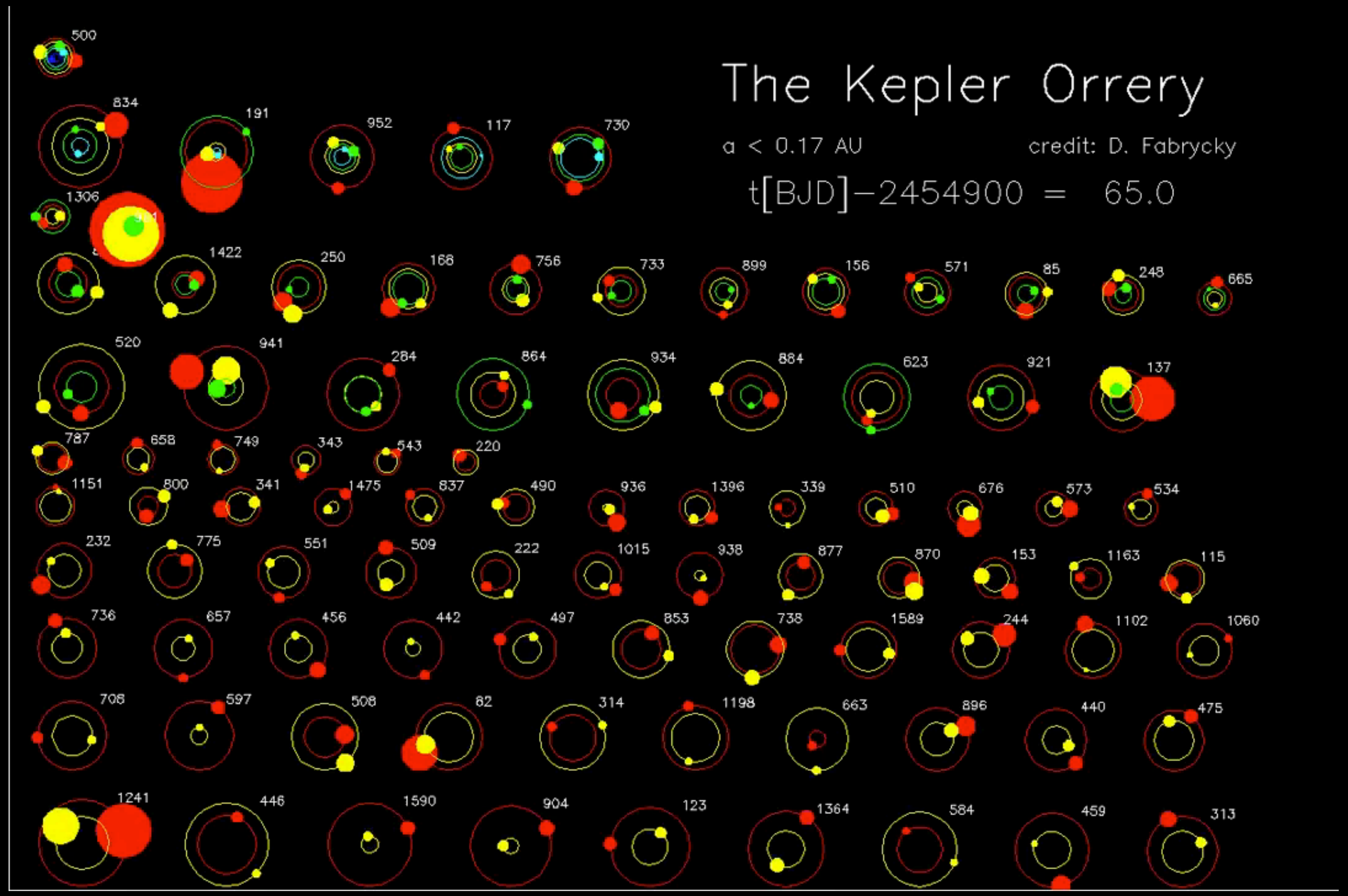
a few 10’s of new candidates with mass<$30M_{Earth}$ and P<50-70d

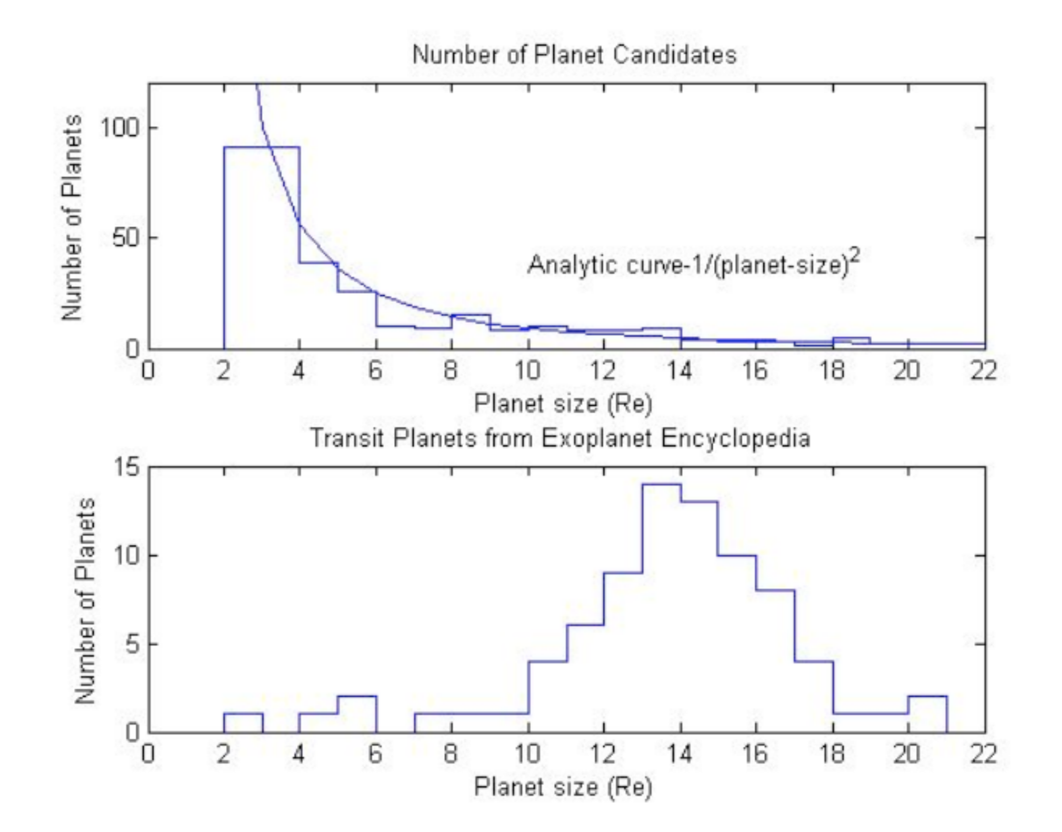
30% (+/- 10%) of stars have Neptunes or super-Eaths

Lovis 2007 p.c.

The era of transit surveys

- RV samples are ‘designed’ for the RV follow-up of transiting candidates
- Measure the mass (and thus the density) of planets on a statistically relevant sample
- End of the ‘just search for planets’ era and start of the ‘characterization era. Awareness of complementarity of (all) techniques rather than ‘competition’, but also that target brightness is relevant for follow-up -> new space- and ground-based project are designed -> TESS/PLATO



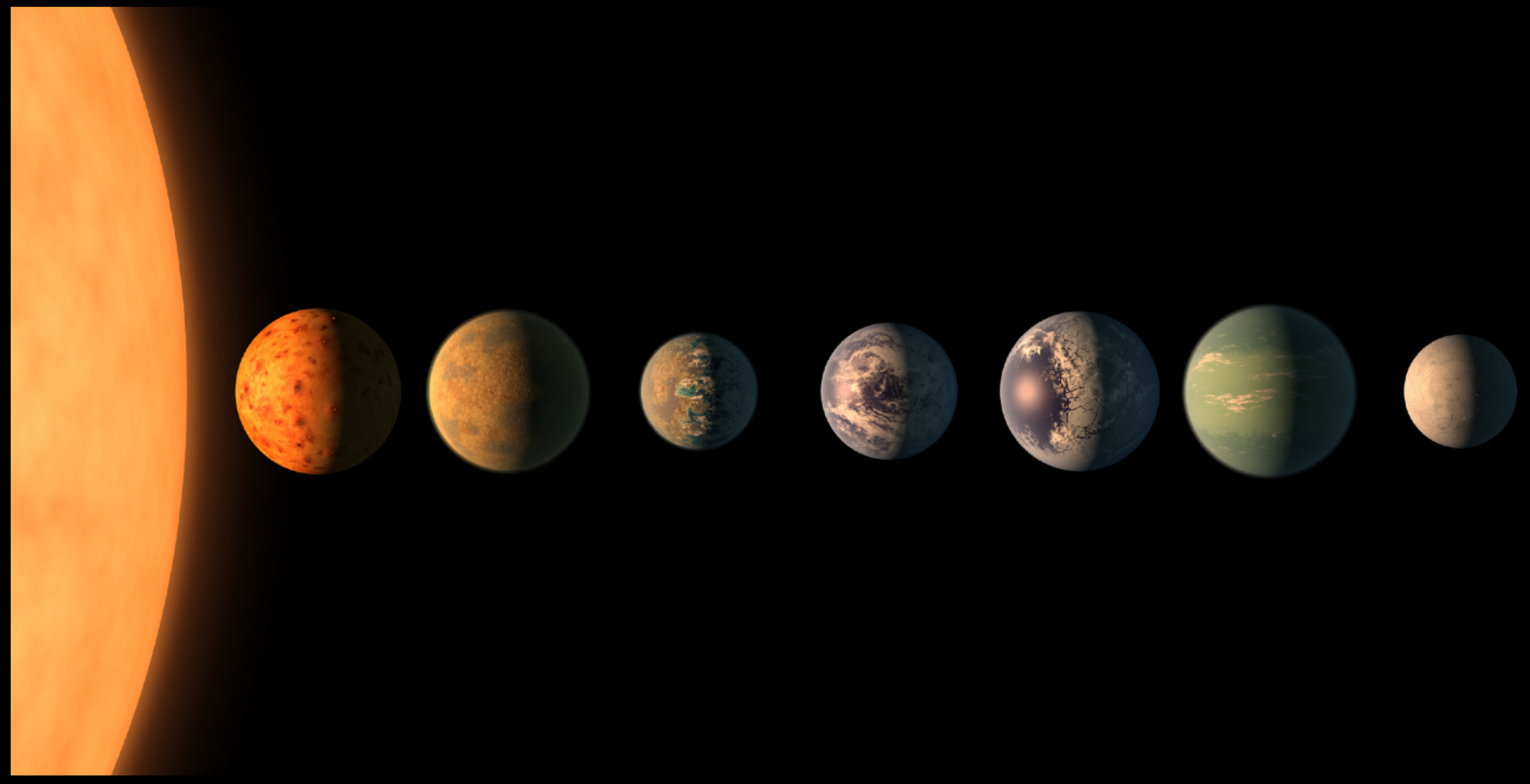


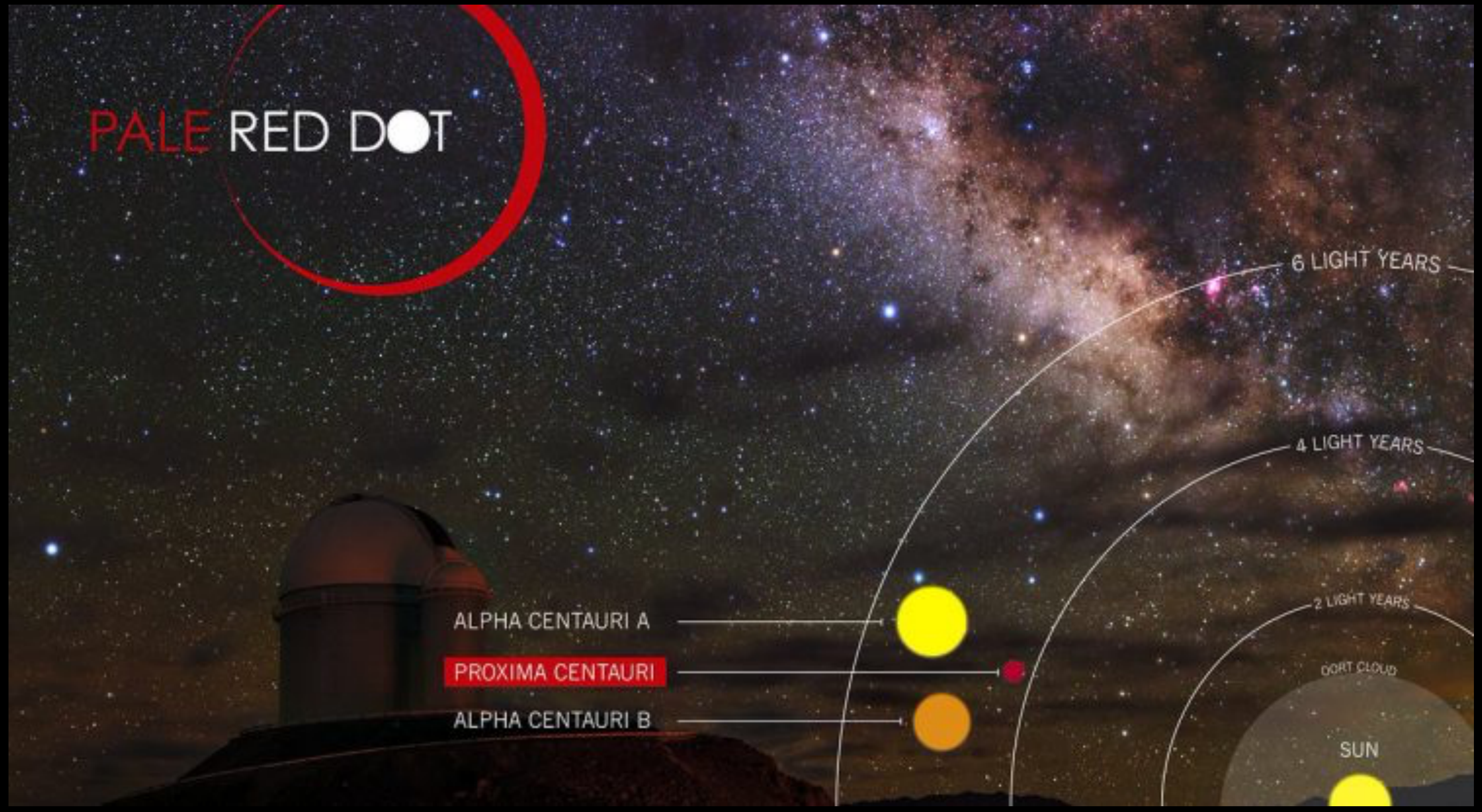
Borucki et al. 2010

Shooting for “habitable” planets

- < 1 m/s precision and/or infrared wavelengths
- Focusing on individual particularly suitable targets (near-by, quite, non-rotating targets, especially M-stars; high-cadence RV campaigns) in the awareness that they are very frequent!
- Looking for Earth-mass planets in the HZ of parent stars, possibly close-by for better follow-up with other techniques or instruments
- Stellar jitter becomes the (additional) limiting factor because of amplitude and typical periods

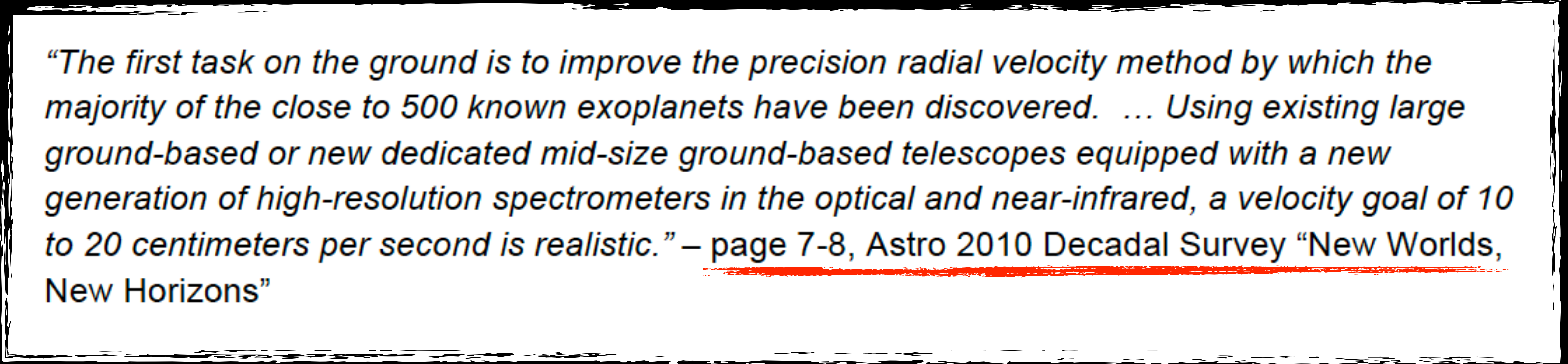
Gillon et al., *Nature*, 2018

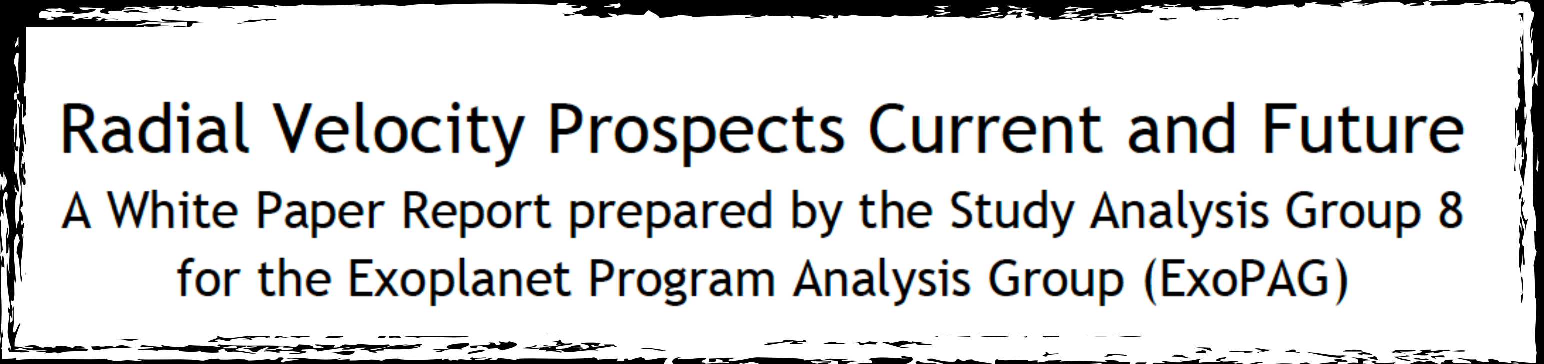




Anglada-Escudé et al., *Nature*, 2016

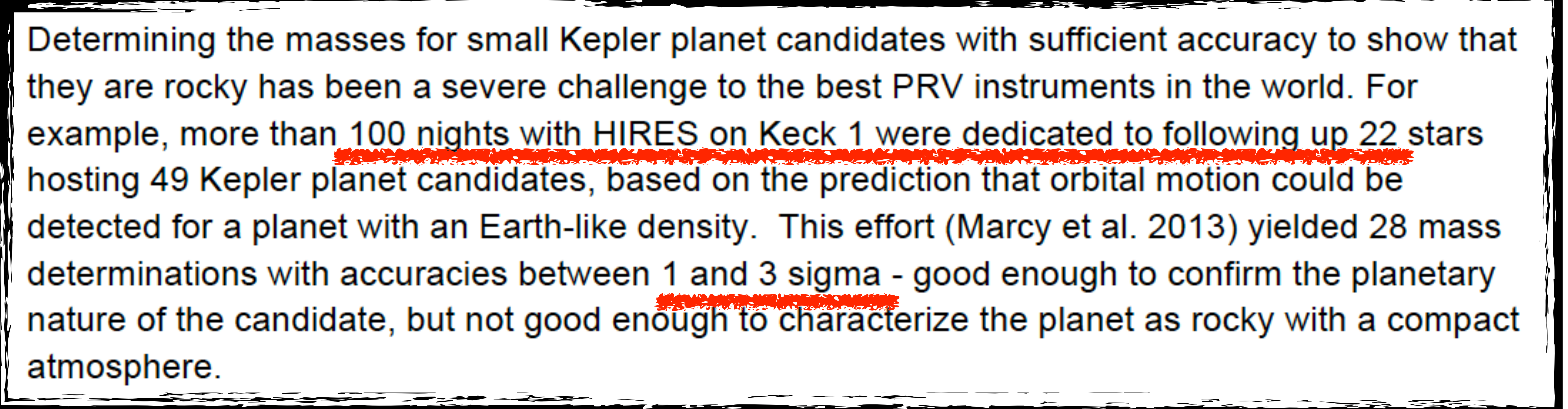
Why (EP)RVs?

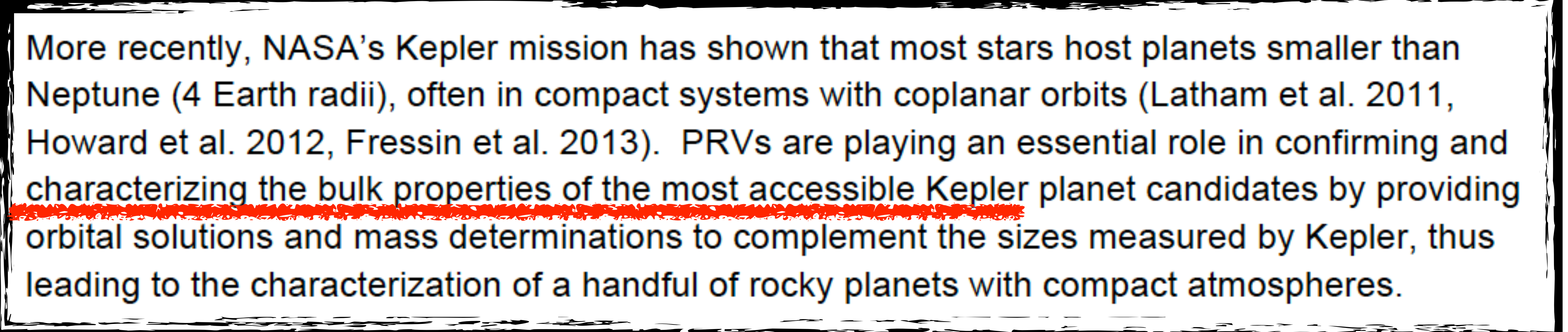

“The first task on the ground is to improve the precision radial velocity method by which the majority of the close to 500 known exoplanets have been discovered. … Using existing large ground-based or new dedicated mid-size ground-based telescopes equipped with a new generation of high-resolution spectrometers in the optical and near-infrared, a velocity goal of 10 to 20 centimeters per second is realistic.” – page 7-8, Astro 2010 Decadal Survey “New Worlds, New Horizons”

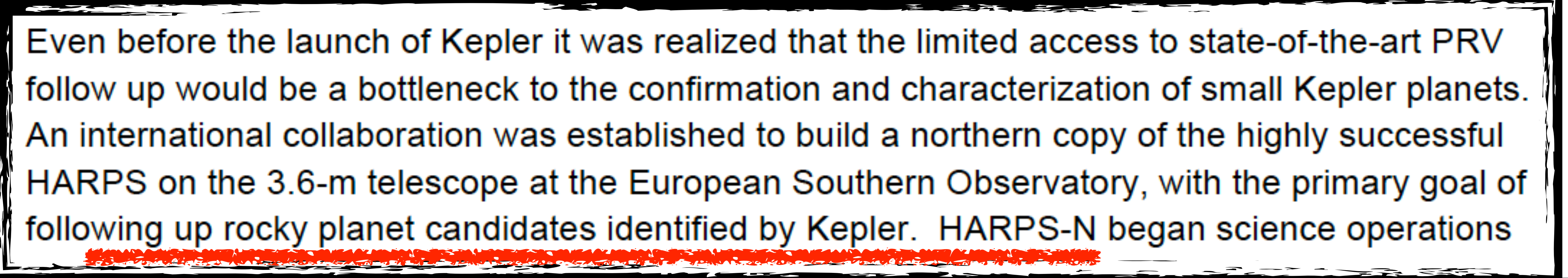

Radial Velocity Prospects Current and Future

A White Paper Report prepared by the Study Analysis Group 8
for the Exoplanet Program Analysis Group (ExoPAG)

ExoPAG: Plavchan et al., arXiv:1503.01770v2 (2015)


Determining the masses for small Kepler planet candidates with sufficient accuracy to show that they are rocky has been a severe challenge to the best PRV instruments in the world. For example, more than 100 nights with HIRES on Keck 1 were dedicated to following up 22 stars hosting 49 Kepler planet candidates, based on the prediction that orbital motion could be detected for a planet with an Earth-like density. This effort (Marcy et al. 2013) yielded 28 mass determinations with accuracies between 1 and 3 sigma - good enough to confirm the planetary nature of the candidate, but not good enough to characterize the planet as rocky with a compact atmosphere.


More recently, NASA’s Kepler mission has shown that most stars host planets smaller than Neptune (4 Earth radii), often in compact systems with coplanar orbits (Latham et al. 2011, Howard et al. 2012, Fressin et al. 2013). PRVs are playing an essential role in confirming and characterizing the bulk properties of the most accessible Kepler planet candidates by providing orbital solutions and mass determinations to complement the sizes measured by Kepler, thus leading to the characterization of a handful of rocky planets with compact atmospheres.


Even before the launch of Kepler it was realized that the limited access to state-of-the-art PRV follow up would be a bottleneck to the confirmation and characterization of small Kepler planets. An international collaboration was established to build a northern copy of the highly successful HARPS on the 3.6-m telescope at the European Southern Observatory, with the primary goal of following up rocky planet candidates identified by Kepler. HARPS-N began science operations

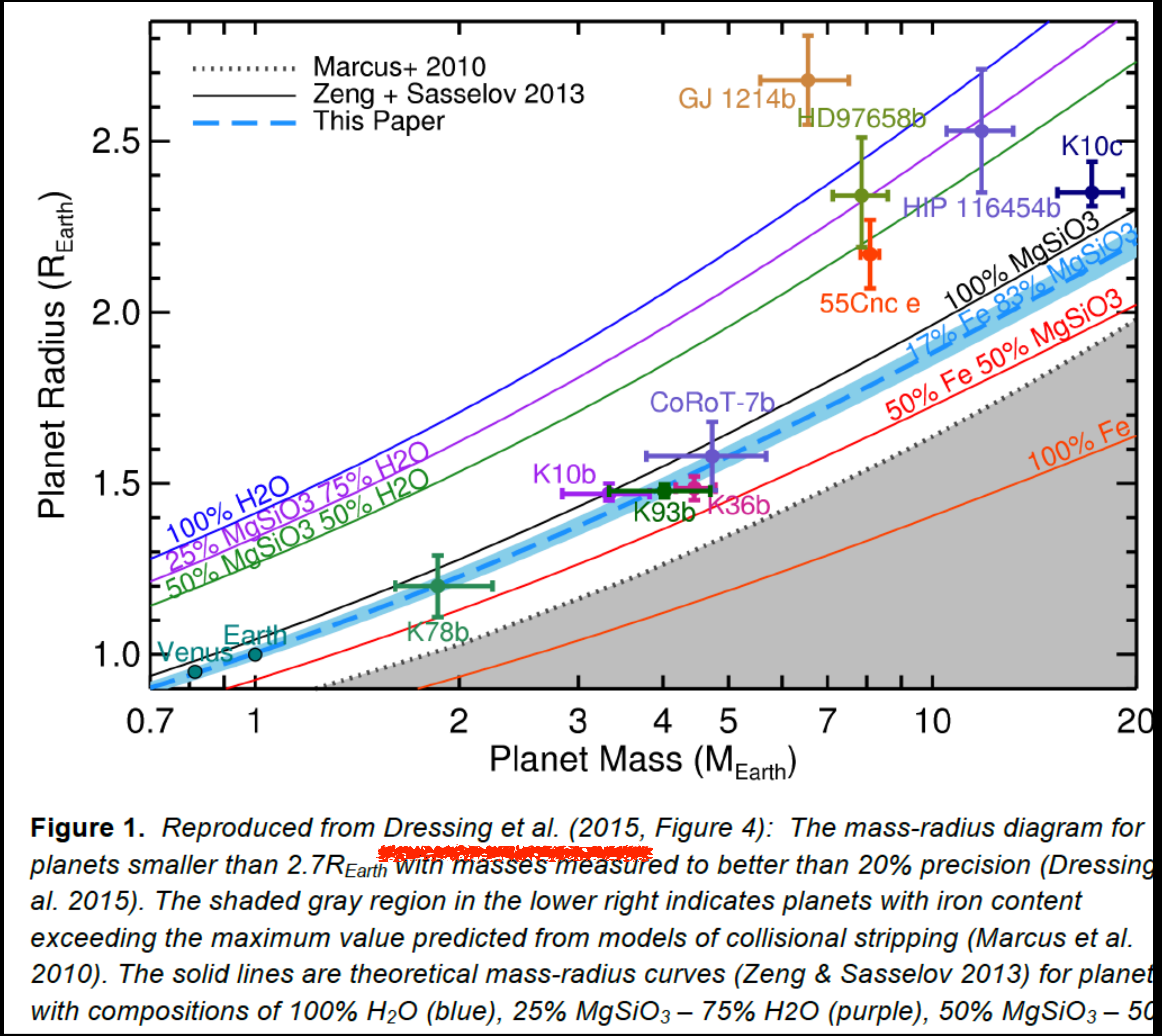


Figure 1. *Reproduced from Dressing et al. (2015, Figure 4): The mass-radius diagram for planets smaller than 2.7R_{Earth} with masses measured to better than 20% precision (Dressing al. 2015). The shaded gray region in the lower right indicates planets with iron content exceeding the maximum value predicted from models of collisional stripping (Marcus et al. 2010). The solid lines are theoretical mass-radius curves (Zeng & Sasselov 2013) for planet with compositions of 100% H_2O (blue), 25% $MgSiO_3$ – 75% H2O (purple), 50% $MgSiO_3$ – 50*

RV Instruments…

… and many more

Pepe et al., Nature (2014)

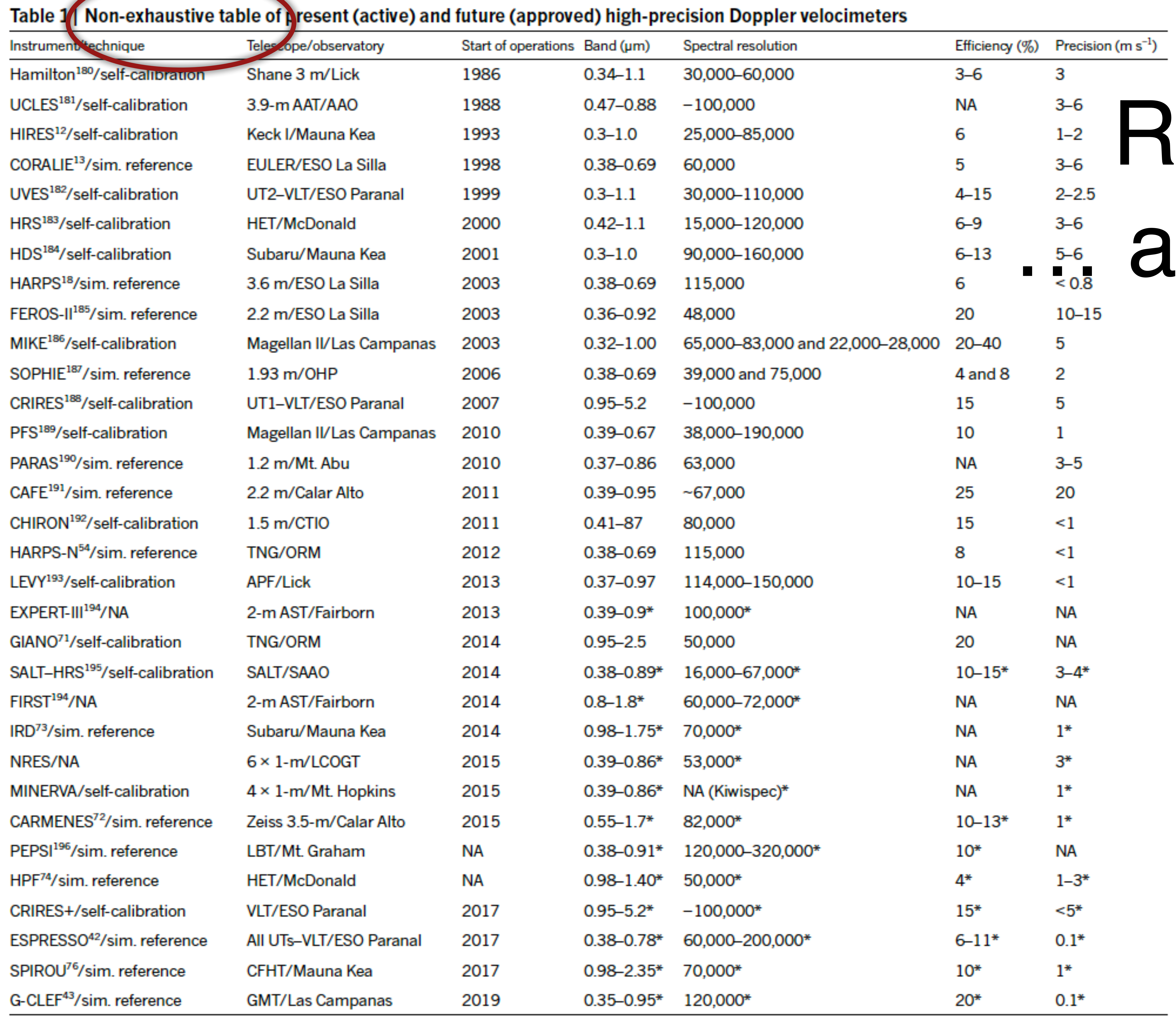


Table 1 | Non-exhaustive table of present (active) and future (approved) high-precision Doppler velocimeters

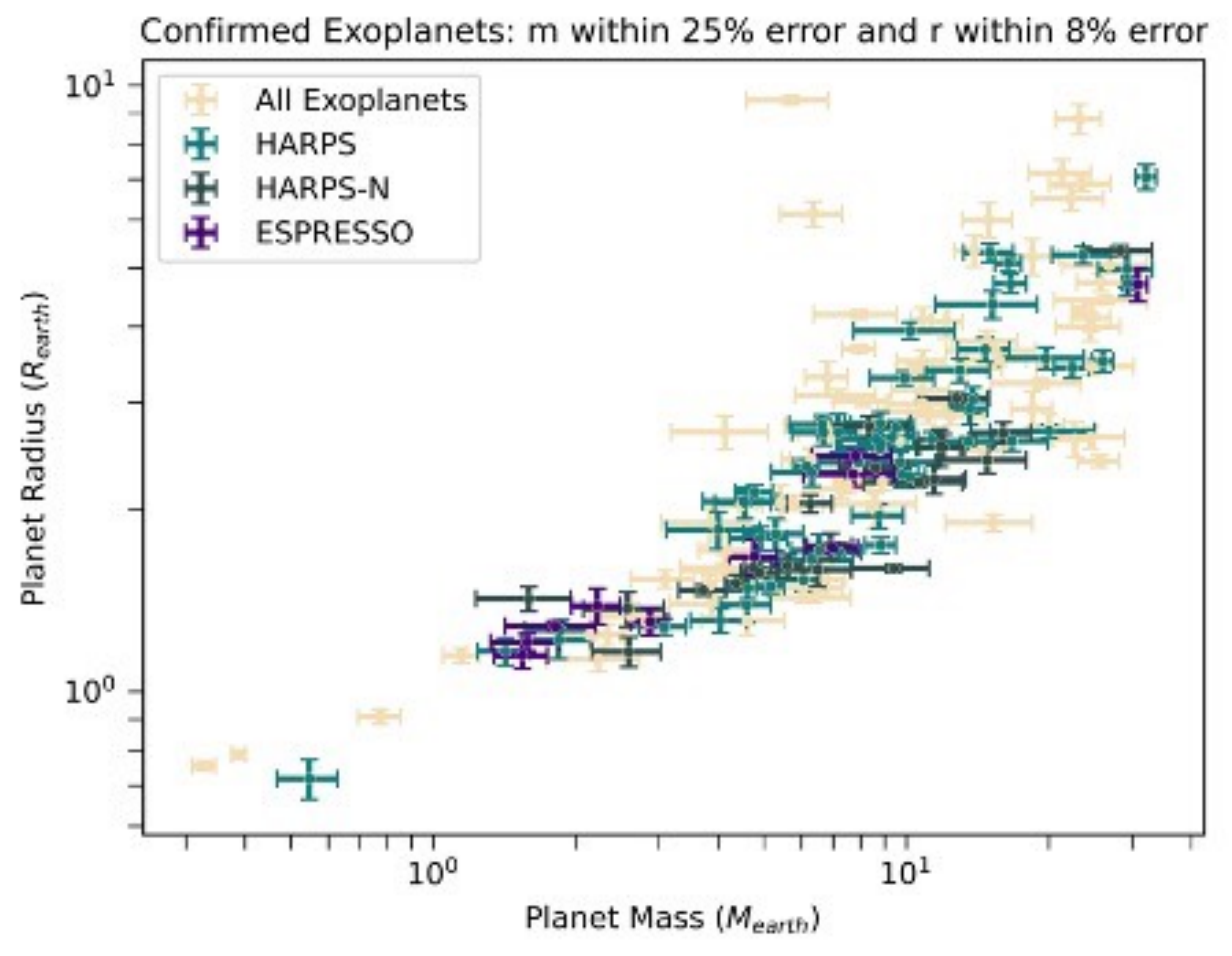
Instrument/technique	Telescope/observatory	Start of operations	Band (μm)	Spectral resolution	Efficiency (%)	Precision ($\mathrm{m\,s^{-1}}$)
Hamilton[180]/self-calibration	Shane 3 m/Lick	1986	0.34–1.1	30,000–60,000	3–6	3
UCLES[181]/self-calibration	3.9-m AAT/AAO	1988	0.47–0.88	−100,000	NA	3–6
HIRES[12]/self-calibration	Keck I/Mauna Kea	1993	0.3–1.0	25,000–85,000	6	1–2
CORALIE[13]/sim. reference	EULER/ESO La Silla	1998	0.38–0.69	60,000	5	3–6
UVES[182]/self-calibration	UT2–VLT/ESO Paranal	1999	0.3–1.1	30,000–110,000	4–15	2–2.5
HRS[183]/self-calibration	HET/McDonald	2000	0.42–1.1	15,000–120,000	6–9	3–6
HDS[184]/self-calibration	Subaru/Mauna Kea	2001	0.3–1.0	90,000–160,000	6–13	5–6
HARPS[18]/sim. reference	3.6 m/ESO La Silla	2003	0.38–0.69	115,000	6	< 0.8
FEROS-II[185]/sim. reference	2.2 m/ESO La Silla	2003	0.36–0.92	48,000	20	10–15
MIKE[186]/self-calibration	Magellan II/Las Campanas	2003	0.32–1.00	65,000–83,000 and 22,000–28,000	20–40	5
SOPHIE[187]/sim. reference	1.93 m/OHP	2006	0.38–0.69	39,000 and 75,000	4 and 8	2
CRIRES[188]/self-calibration	UT1–VLT/ESO Paranal	2007	0.95–5.2	−100,000	15	5
PFS[189]/self-calibration	Magellan II/Las Campanas	2010	0.39–0.67	38,000–190,000	10	1
PARAS[190]/sim. reference	1.2 m/Mt. Abu	2010	0.37–0.86	63,000	NA	3–5
CAFE[191]/sim. reference	2.2 m/Calar Alto	2011	0.39–0.95	~67,000	25	20
CHIRON[192]/self-calibration	1.5 m/CTIO	2011	0.41–87	80,000	15	<1
HARPS-N[54]/sim. reference	TNG/ORM	2012	0.38–0.69	115,000	8	<1
LEVY[193]/self-calibration	APF/Lick	2013	0.37–0.97	114,000–150,000	10–15	<1
EXPERT-III[194]/NA	2-m AST/Fairborn	2013	0.39–0.9*	100,000*	NA	NA
GIANO[71]/self-calibration	TNG/ORM	2014	0.95–2.5	50,000	20	NA
SALT–HRS[195]/self-calibration	SALT/SAAO	2014	0.38–0.89*	16,000–67,000*	10–15*	3–4*
FIRST[194]/NA	2-m AST/Fairborn	2014	0.8–1.8*	60,000–72,000*	NA	NA
IRD[73]/sim. reference	Subaru/Mauna Kea	2014	0.98–1.75*	70,000*	NA	1*
NRES/NA	6 × 1-m/LCOGT	2015	0.39–0.86*	53,000*	NA	3*
MINERVA/self-calibration	4 × 1-m/Mt. Hopkins	2015	0.39–0.86*	NA (Kiwispec)*	NA	1*
CARMENES[72]/sim. reference	Zeiss 3.5-m/Calar Alto	2015	0.55–1.7*	82,000*	10–13*	1*
PEPSI[196]/sim. reference	LBT/Mt. Graham	NA	0.38–0.91*	120,000–320,000*	10*	NA
HPF[74]/sim. reference	HET/McDonald	NA	0.98–1.40*	50,000*	4*	1–3*
CRIRES+/self-calibration	VLT/ESO Paranal	2017	0.95–5.2*	−100,000*	15*	<5*
ESPRESSO[42]/sim. reference	All UTs–VLT/ESO Paranal	2017	0.38–0.78*	60,000–200,000*	6–11*	0.1*
SPIROU[76]/sim. reference	CFHT/Mauna Kea	2017	0.98–2.35*	70,000*	10*	1*
G-CLEF[43]/sim. reference	GMT/Las Campanas	2019	0.35–0.95*	120,000*	20*	0.1*

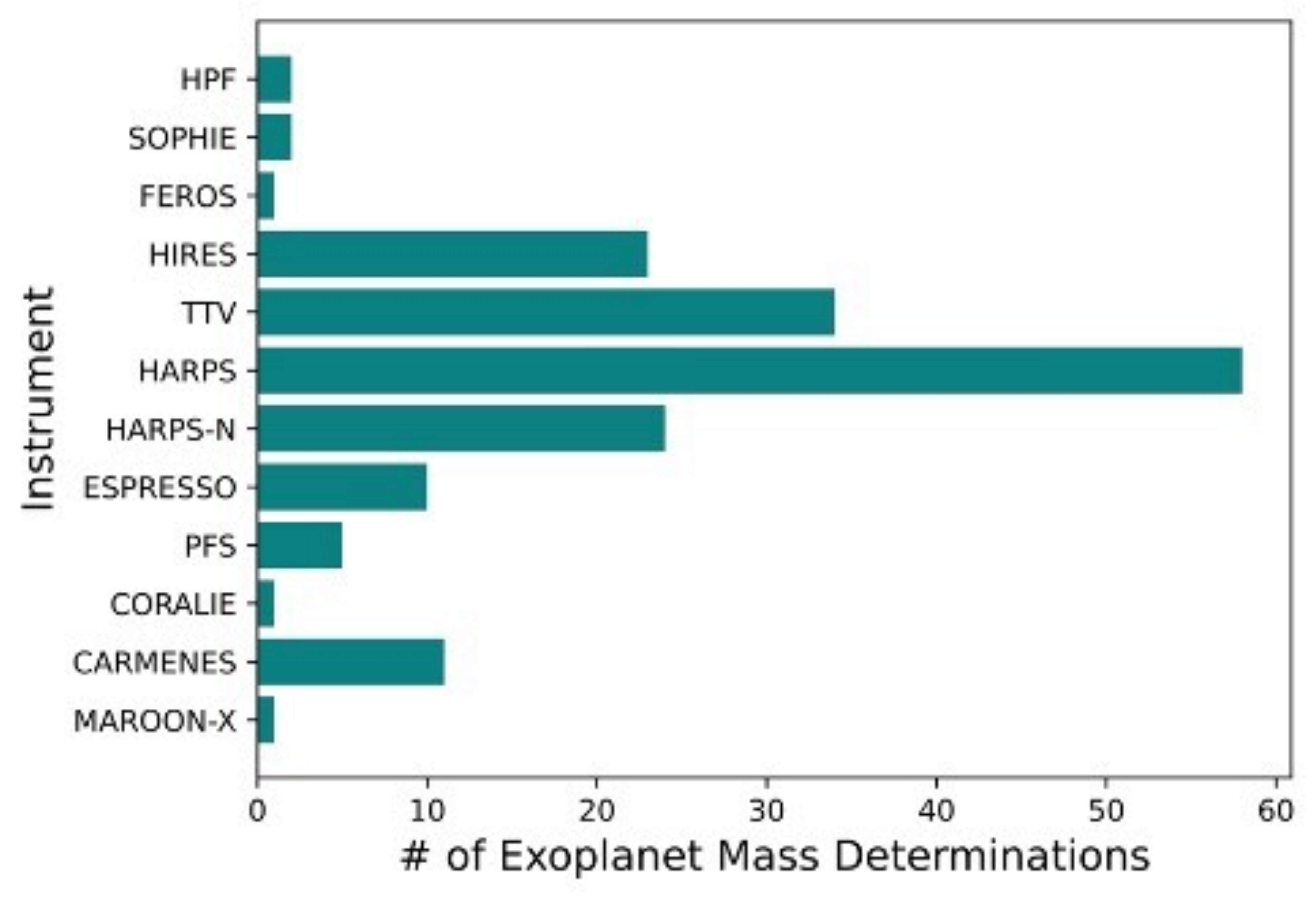
NEID, 2021 (Schwab et al. 2016)
MAROON-X, 2020 (Seifahrt et al. 2018)
EXPRES, 2019 (Jurgenson et al. 2016)
KPF, 2022 (Gibson et al. 2016)
NIRPS, 2023 (Wildi et al. 2022)

HARPS-3, 2024 (Thompson et al. 2016)
G-CLEF@GMT (Szengyorgyi et al. 20
ANDES@ELT (Marconi et al. 2022)
….

Mass-Radius diagramme

- Mass-radius diagram of small exoplanets as of August 2022. Only planets published in a refereed journal with a mass precision better than 25% and a radius precision better than 8% are shown

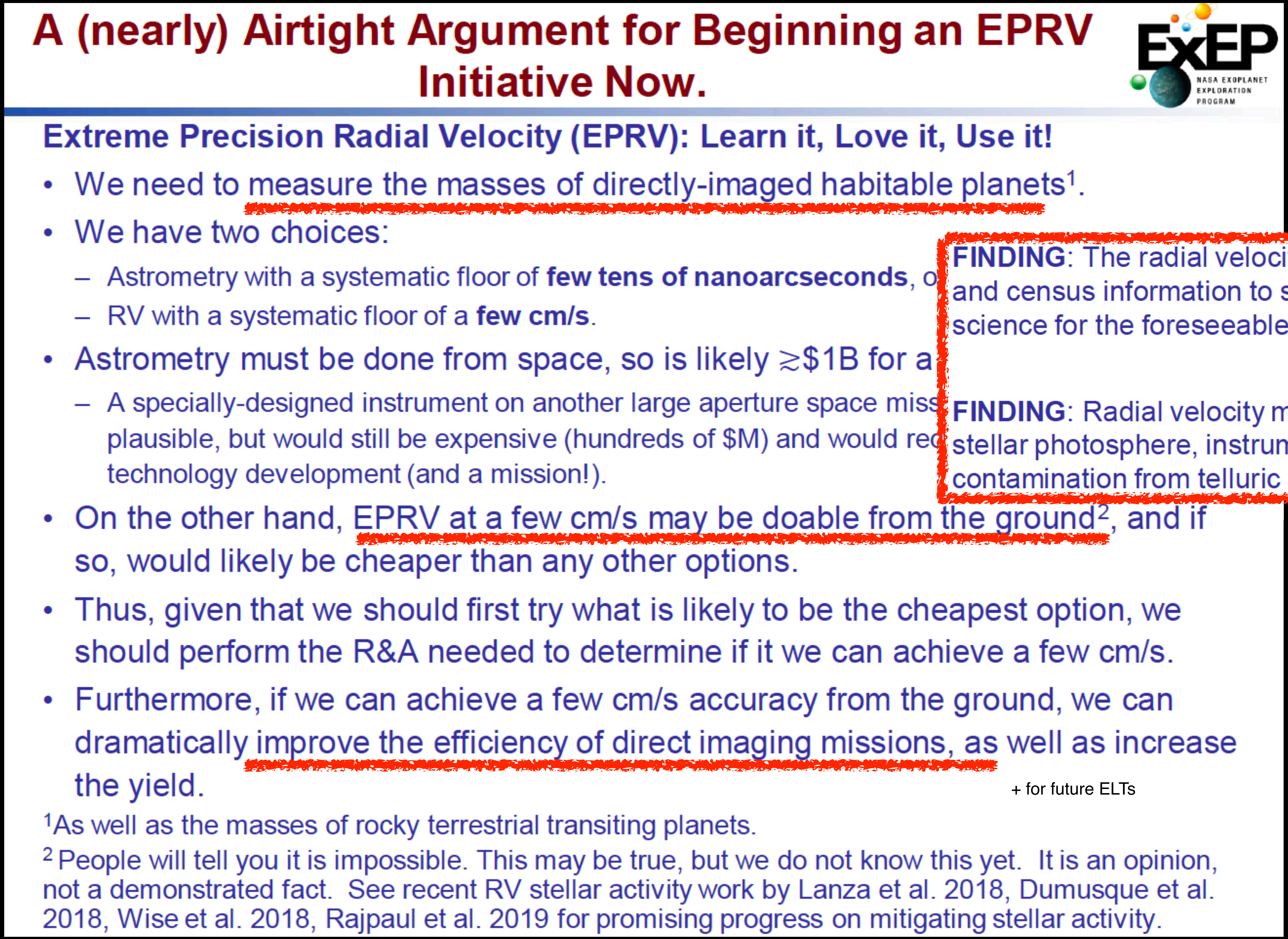




Naidar, private communication

Why EPRVs?

Gaudi, Blackwood, et al. (March 2020): Extreme Precision Radial Velocity Initiative (CL#20-1588, https://exoplanets.nasa.gov/internal_resources/1556/)



A (nearly) Airtight Argument for Beginning an EPRV Initiative Now.

Extreme Precision Radial Velocity (EPRV): Learn it, Love it, Use it!

- We need to measure the masses of directly-imaged habitable planets[1].
- We have two choices:
  - Astrometry with a systematic floor of **few tens of nanoarcseconds**, o
  - RV with a systematic floor of a **few cm/s**.
- Astrometry must be done from space, so is likely ≳$1B for a
  - A specially-designed instrument on another large aperture space miss plausible, but would still be expensive (hundreds of $M) and would rec technology development (and a mission!).
- On the other hand, EPRV at a few cm/s may be doable from the ground[2], and if so, would likely be cheaper than any other options.
- Thus, given that we should first try what is likely to be the cheapest option, we should perform the R&A needed to determine if it we can achieve a few cm/s.
- Furthermore, if we can achieve a few cm/s accuracy from the ground, we can dramatically improve the efficiency of direct imaging missions, as well as increase the yield.

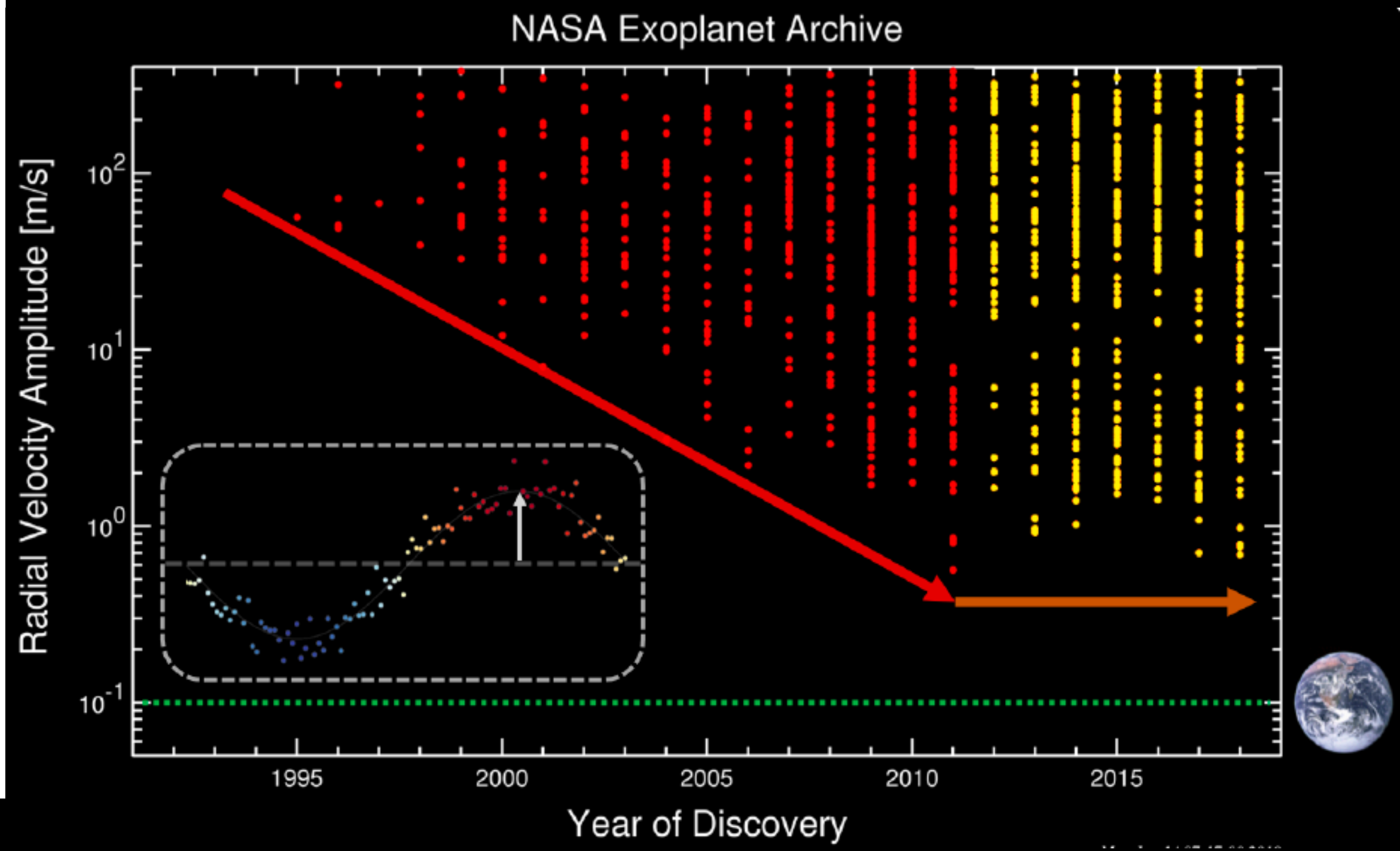
+ for future ELTs

[1] As well as the masses of rocky terrestrial transiting planets.

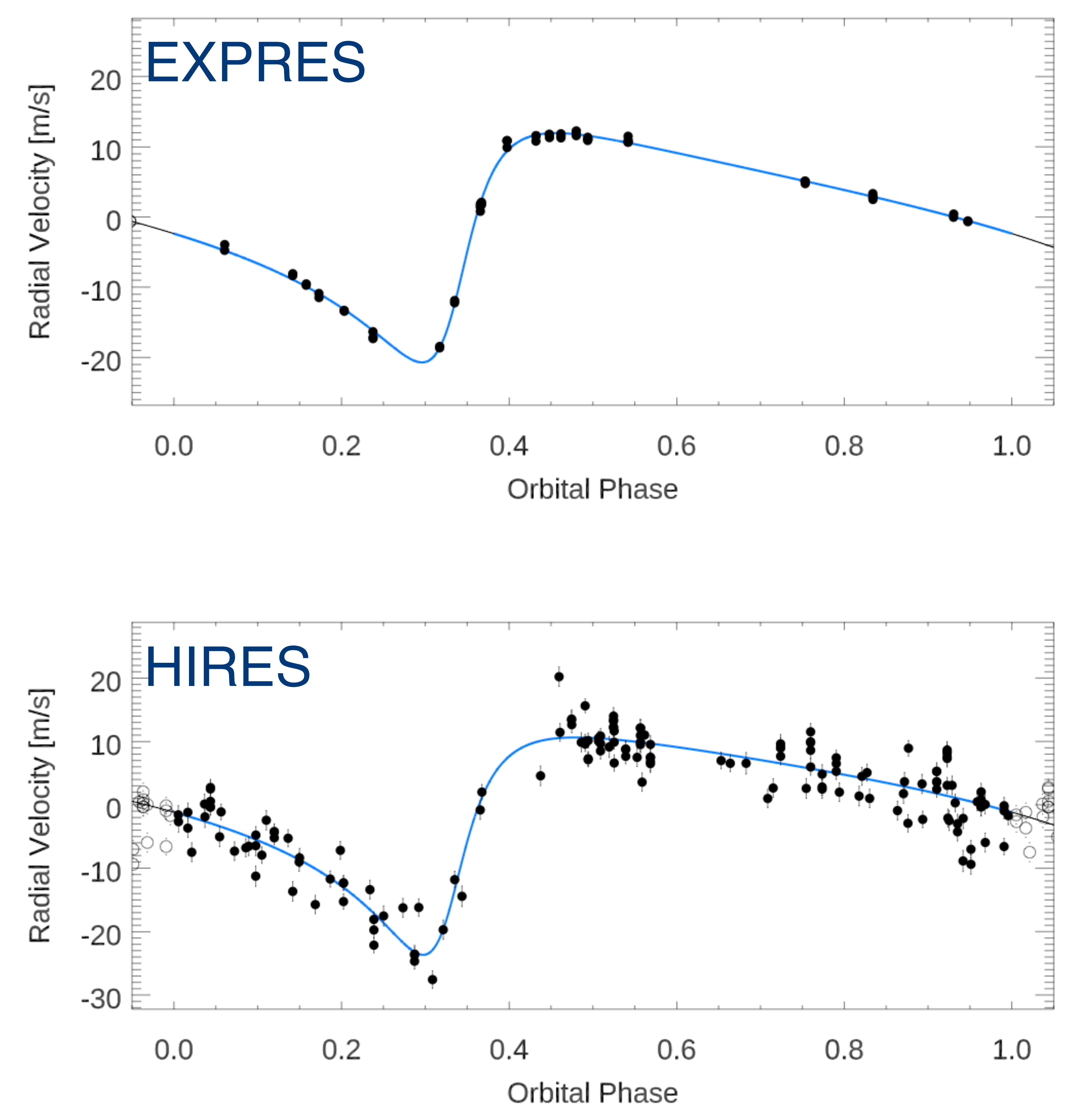
[2] People will tell you it is impossible. This may be true, but we do not know this yet. It is an opinion, not a demonstrated fact. See recent RV stellar activity work by Lanza et al. 2018, Dumusque et al. 2018, Wise et al. 2018, Rajpaul et al. 2019 for promising progress on mitigating stellar activity.

FINDING: The radial velocity method will continue to provide essential mass, orbit, and census information to support both transiting and directly imaged exoplanet science for the foreseeable future.

FINDING: Radial velocity measurements are currently limited by variations in the stellar photosphere, instrumental stability and calibration, and spectral contamination from telluric lines. *Progress will require new instruments installed on*



HD3651b with EXPRES



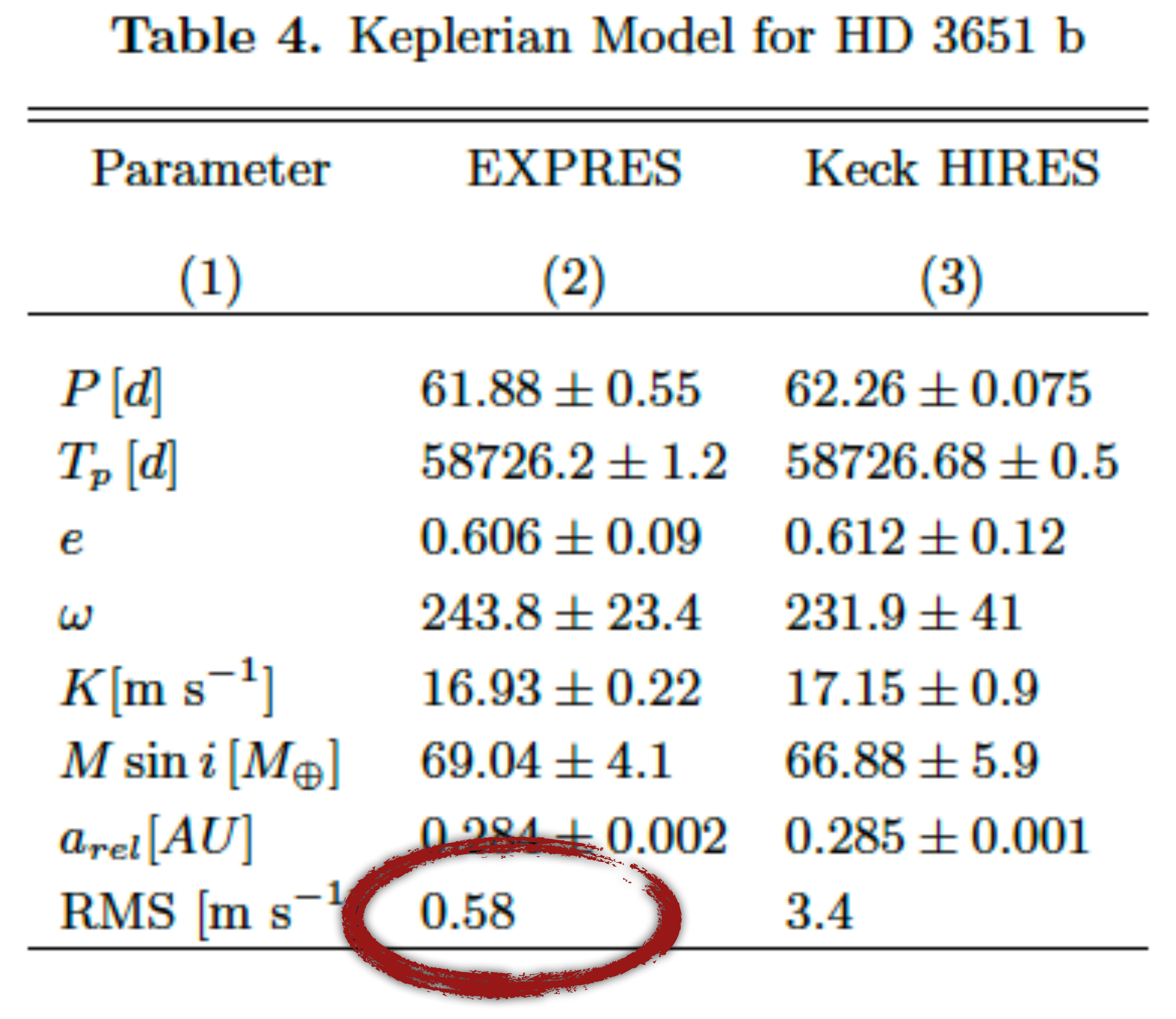


Table 4. Keplerian Model for HD 3651 b

Parameter (1)	EXPRES (2)	Keck HIRES (3)
P [d]	61.88 ± 0.55	62.26 ± 0.075
T_p [d]	58726.2 ± 1.2	58726.68 ± 0.5
e	0.606 ± 0.09	0.612 ± 0.12
ω	243.8 ± 23.4	231.9 ± 41
K[m s^{-1}]	16.93 ± 0.22	17.15 ± 0.9
$M \sin i$ [$M_\oplus$]	69.04 ± 4.1	66.88 ± 5.9
a_{rel}[AU]	0.284 ± 0.002	0.285 ± 0.001
RMS [m s^{-1}]	0.58	3.4

Brewer et al., Astron. J. (2020)

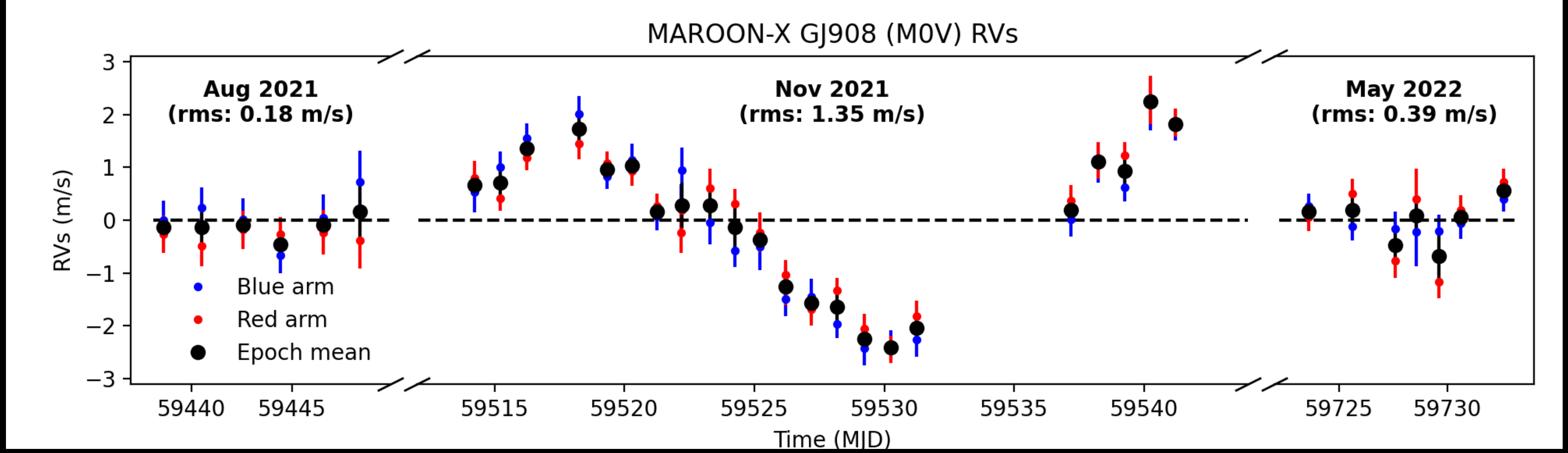
Maroon X (Courtesy of J. Bean)

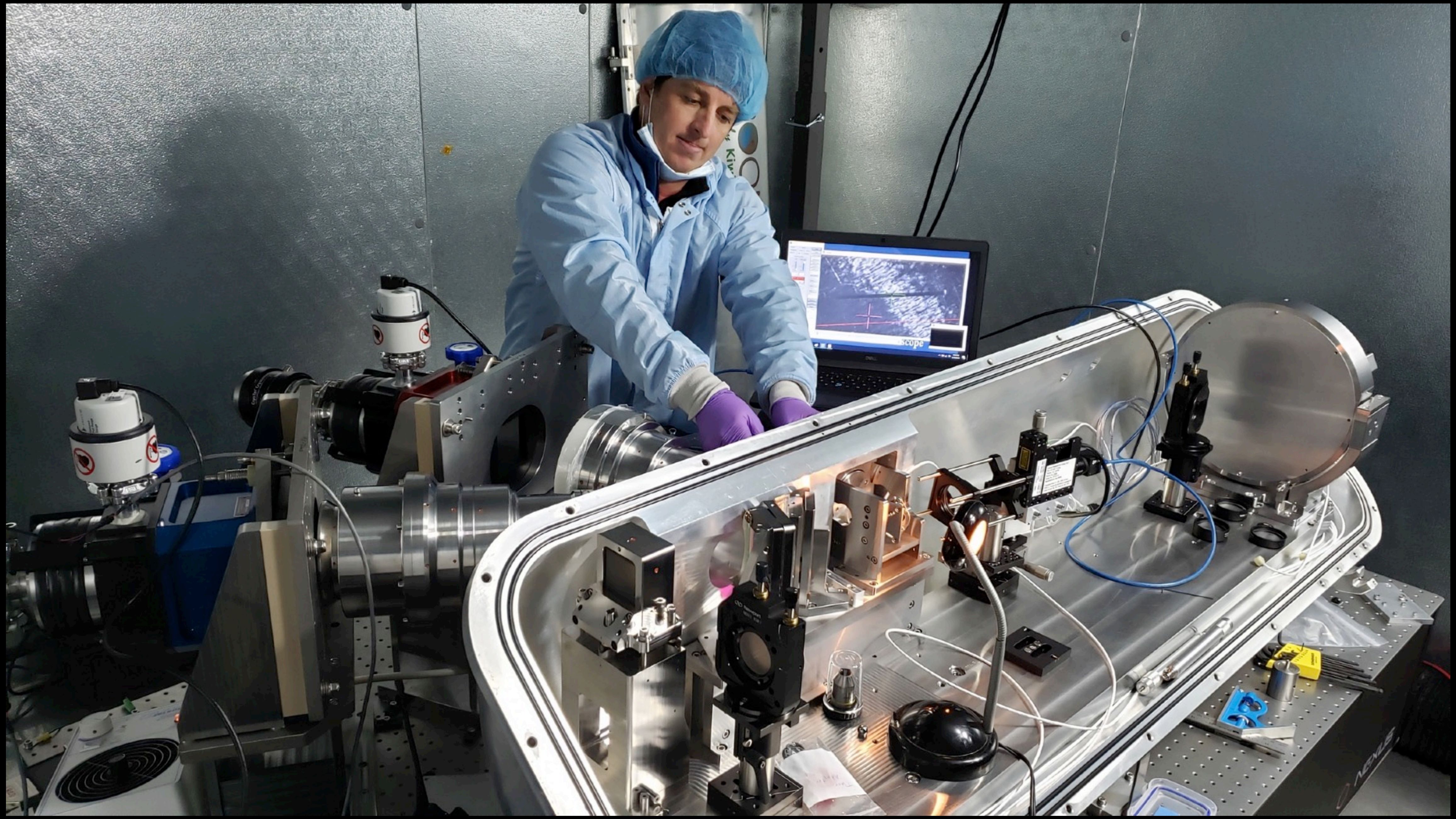
Seifahrt et al. 2022

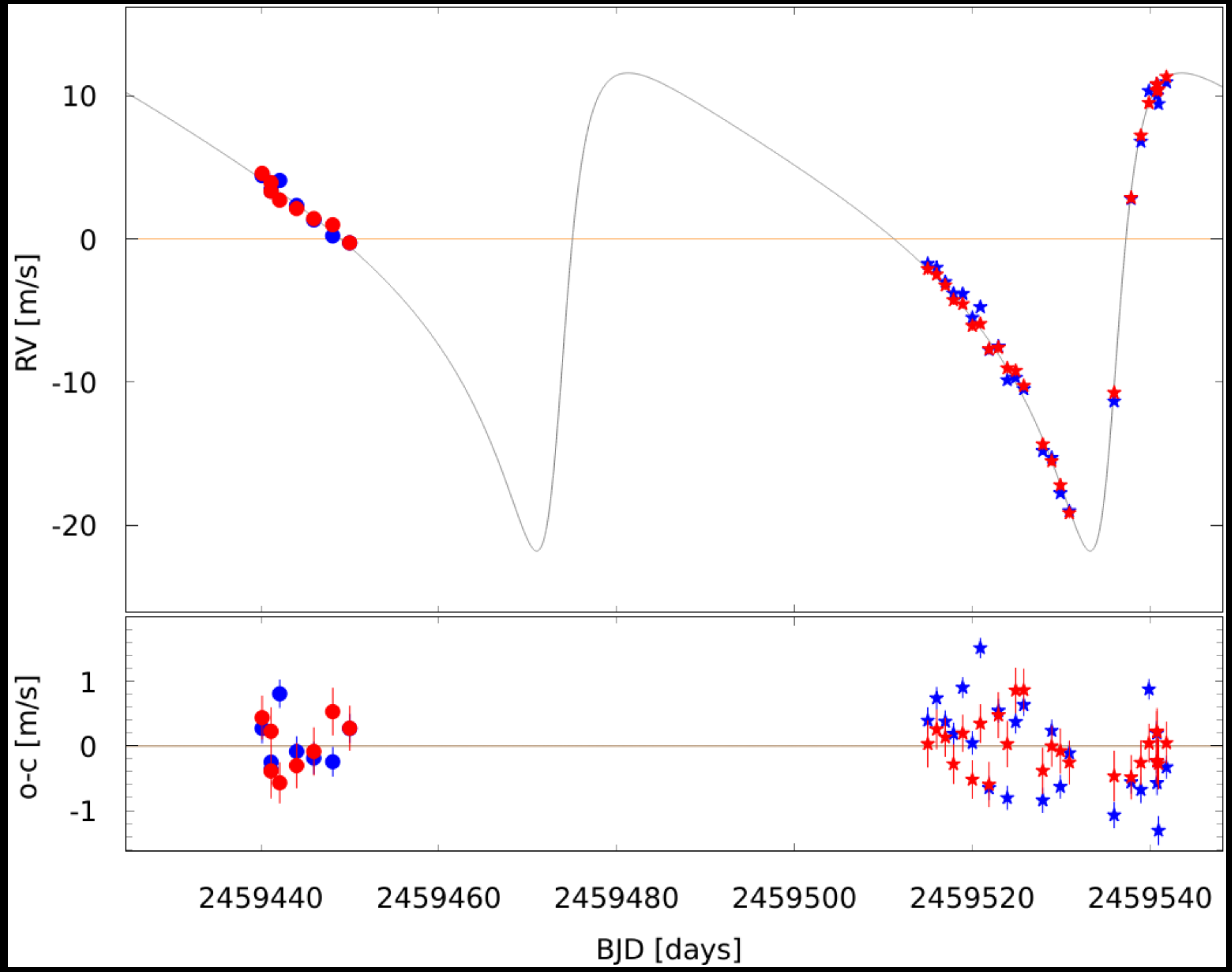
Primary science driver: Confirmation and mass measurement of transiting, temperate, and terrestrial planets that are feasible targets for atmospheric spectroscopy. I.e., *TESS* follow up.

Goal: $\sigma = 1$ m s^{-1} in <30 min for late M dwarfs out to 20 pc (V=16.5).

Approach: A highly-stabilized, fiber-fed spectrograph covering 500 – 900 nm at R=85k with simultaneous calibration feed and pupil slicing.



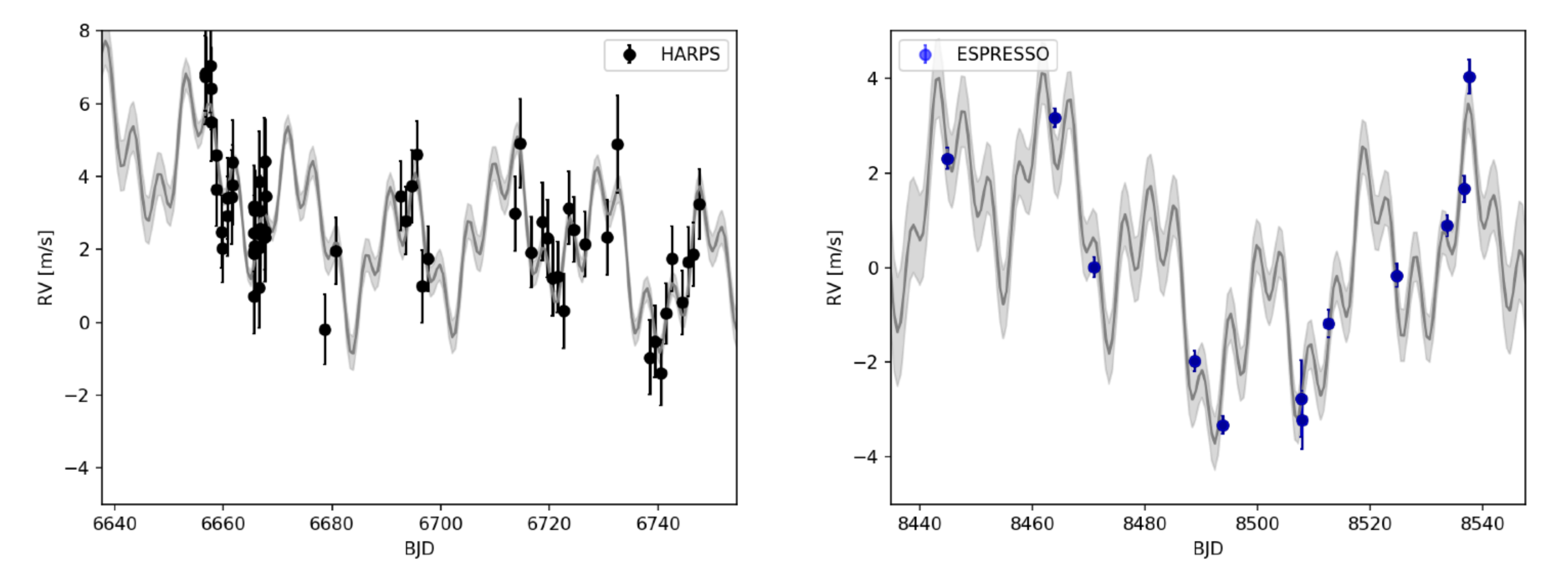




HD3651

rms to the orbit fit of 38 cm/s for the red arm and 63 cm/s for the blue arm

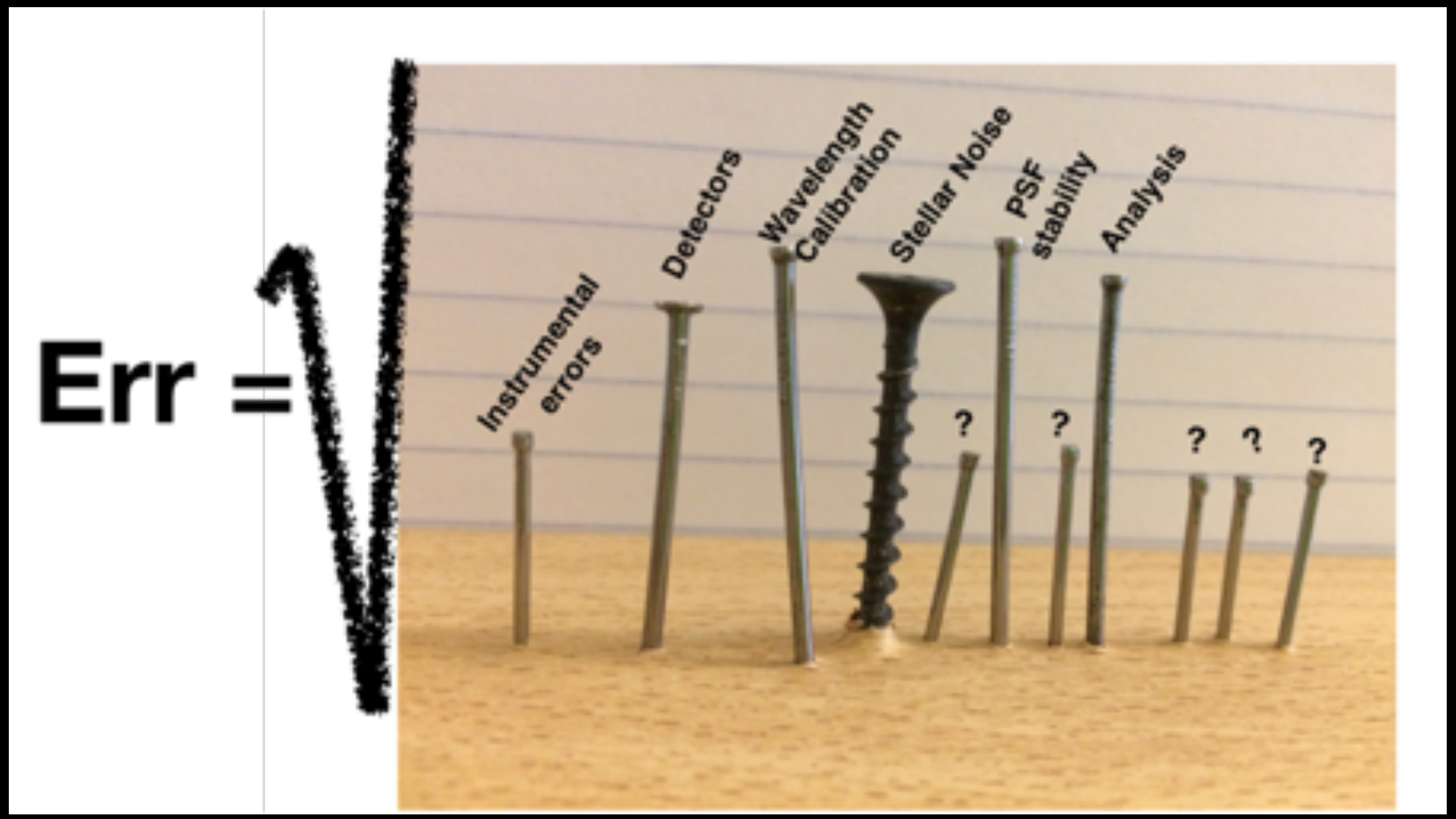
Today’s challenges



- Stellar activity and RV-jitter. It does not only degrade the measurement precision, but can actually prevent detection of HZ-planets or bias mass measurements.

- Instrumental limits. Even 1 m/s is not (yet) a simple standard! There is an underestimation of the difficulty in the air …

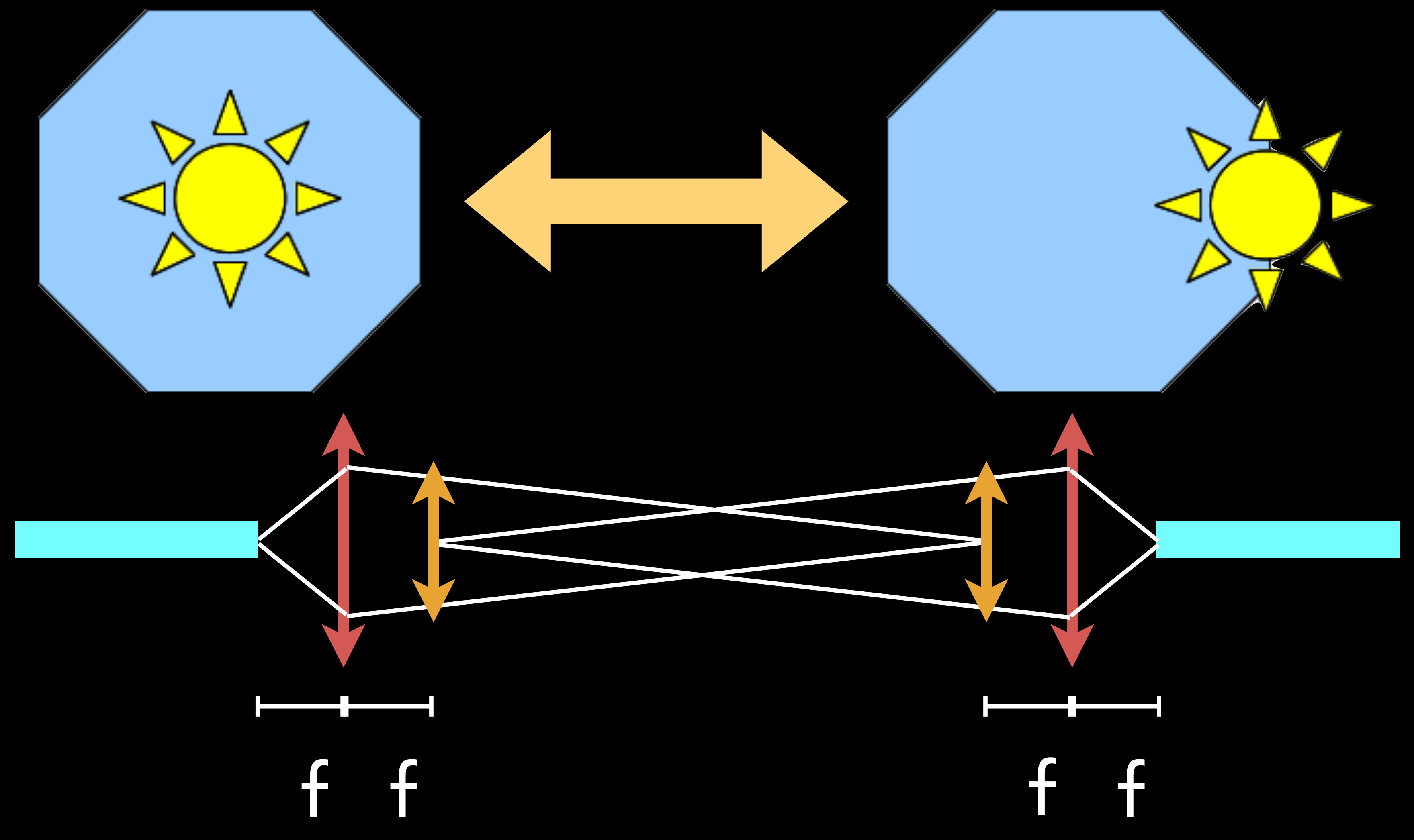
- High-resolution spectroscopy is a Photon-starving technique! Implications for space-based instruments are dramatic and on ground-based facilities sometimes forgotten!



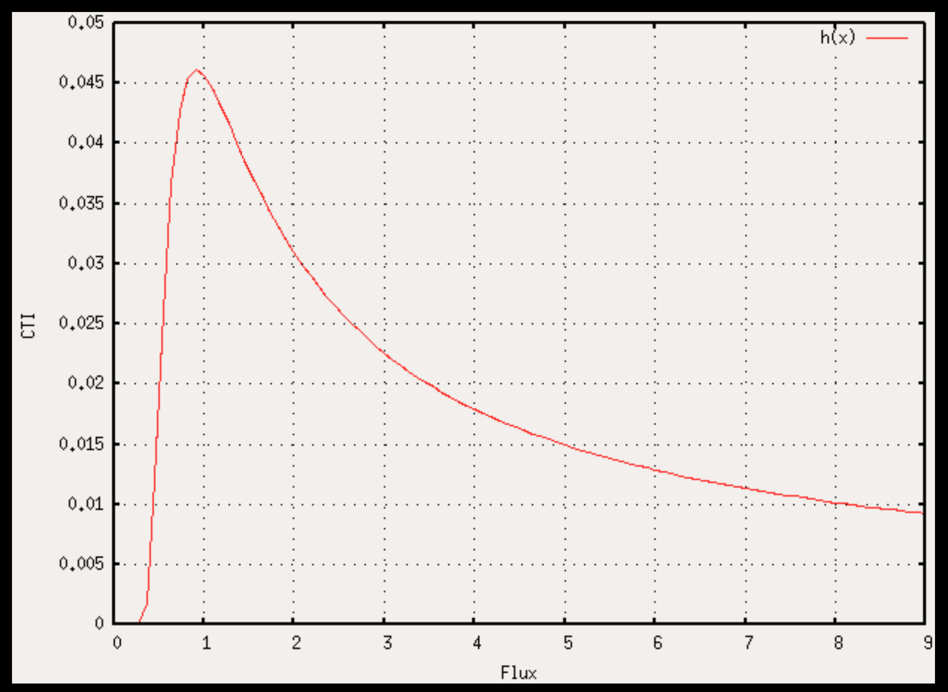
Courtesy of Debra Fisher

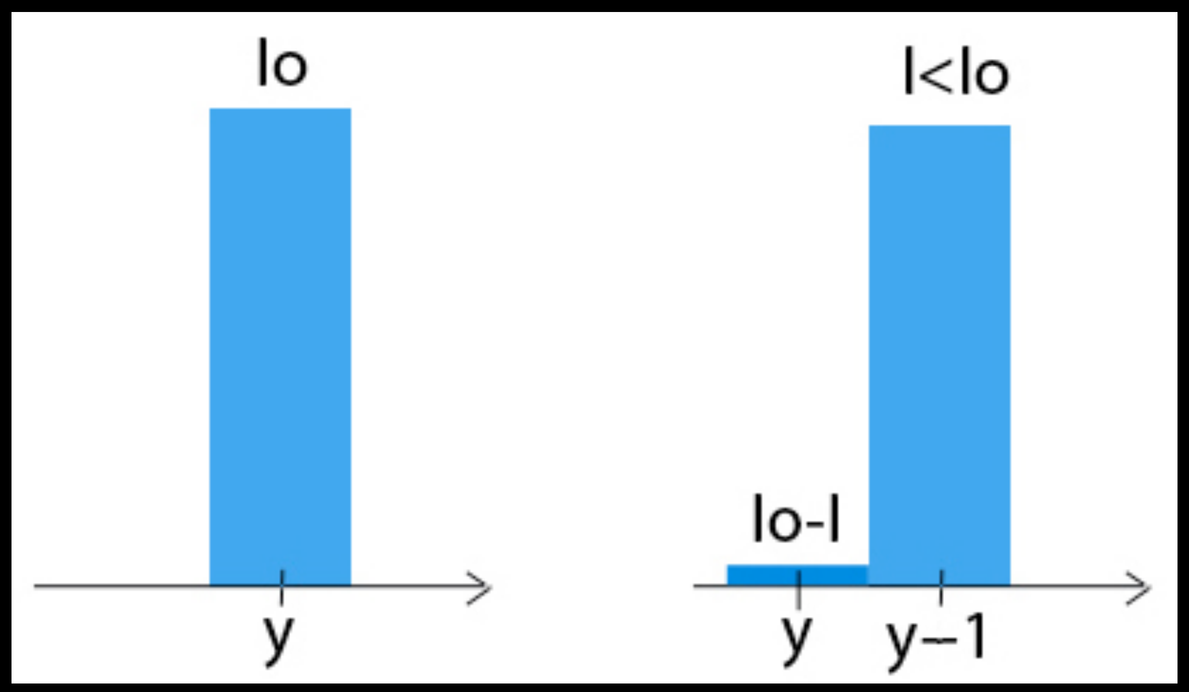
1. Solving the instrumental error problem at the root

1. Stable illumination
2. Stable IP (opto-thermo-mechanical stability of the spectrograph, vacuum)
3. ‘Perfect’ detectors (thermo-mechanical stability, CTE(l), flat-field, gain, pixel geometry) etc.



Double Scrambler

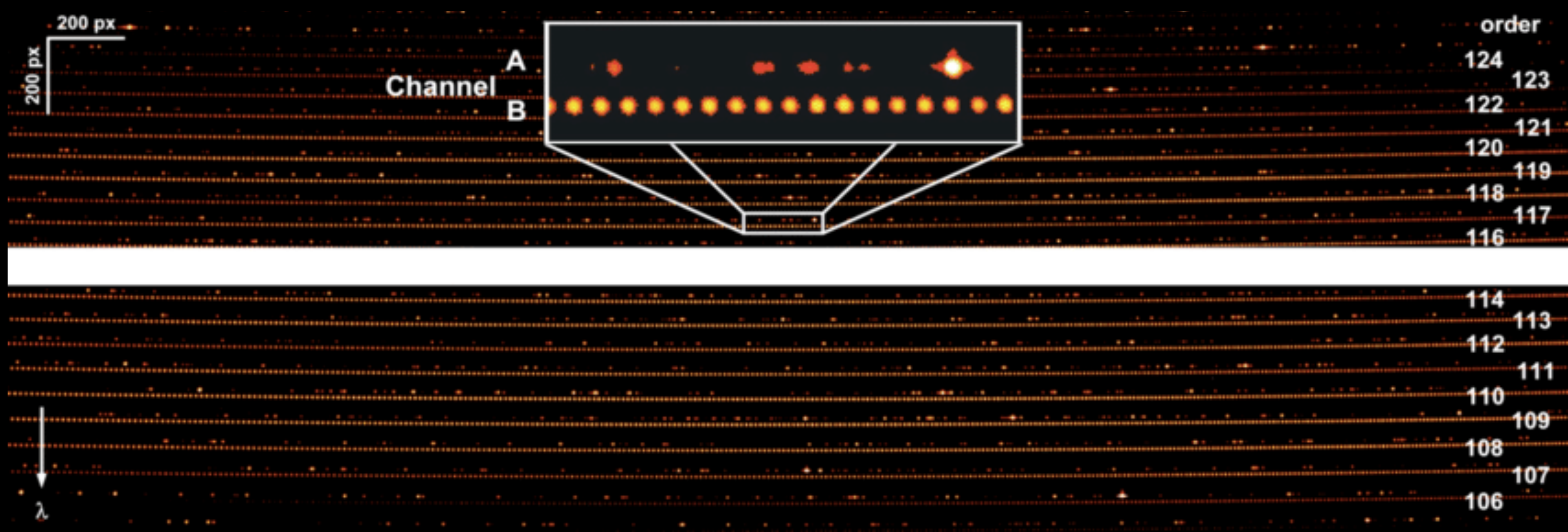




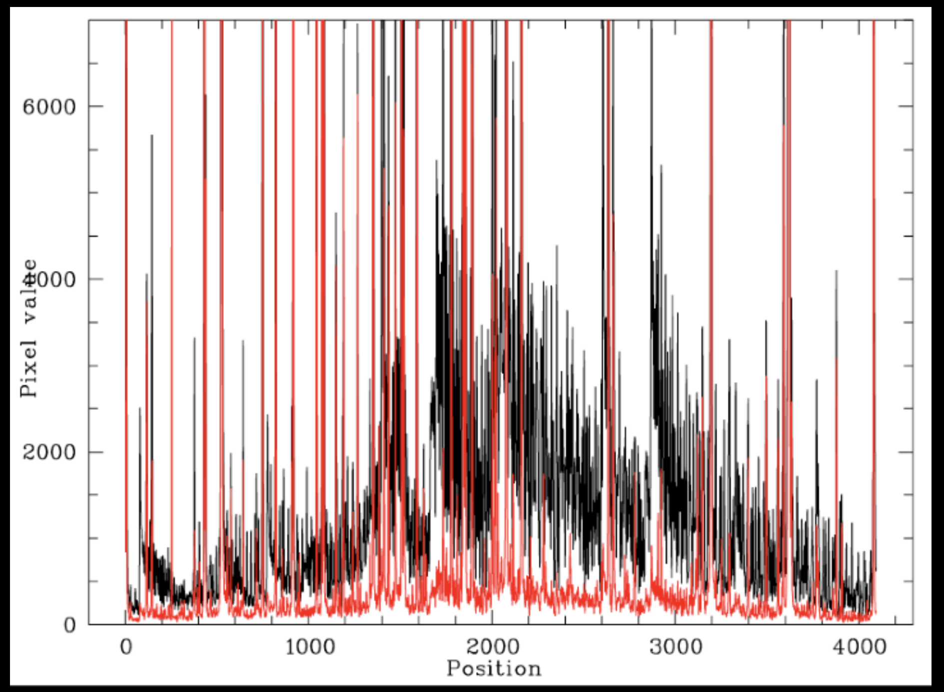
2. Repeatable and accurate calibration

1. ‘Perfect’ flat-fielding sources
2. Perfect wavelength references (Flux and many, unresolved lines covering the full spectrum, known (absolute) frequencies or wavelength
3. Ability of tracking (all kind of) changes: self-calibration, simultaneous reference, ‘sandwich’ observations

LFC



Fabry-Pérot



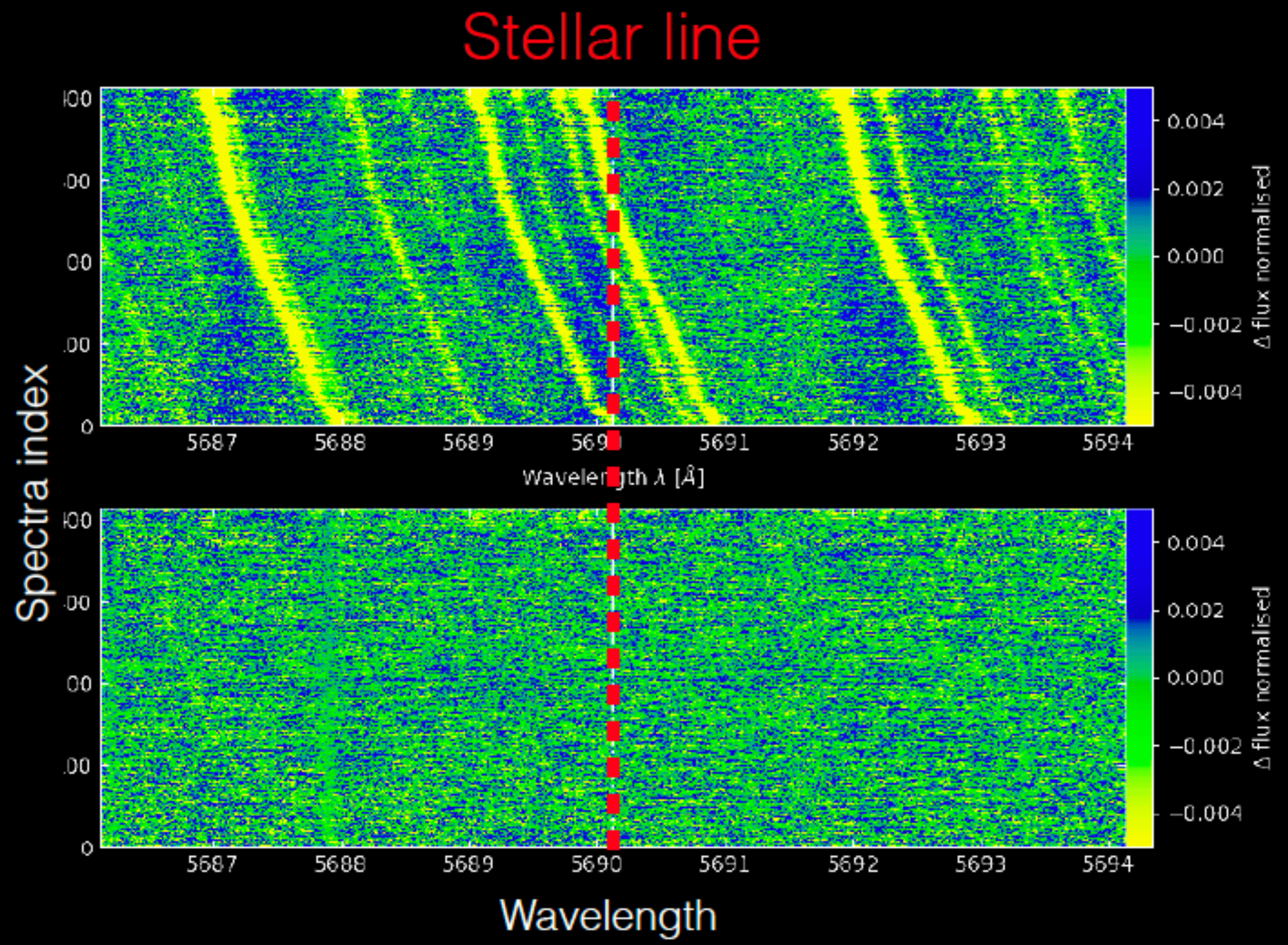
ThAr

3. Remove (internal) instrumental signatures and mesure optimally the observable(s)

1. Data reduction or forward modelling?
2. Remove or model instrumental response. Transfer the ‘accurate’ wavelength reference to the stellar measurement
3. Optimised signal extraction, many methods, depend on spectral type, resolving power, etc.
4. Line-by-line analysis for spotting non-common effects (Dumusque et al. 2018, Cretignier et al. 2020) or ‘common line-shape characteristics (talk by Zucker)
5. Remove or model any (known) instrumental error or (uncalibrated) systematics by ‘post-processing’. But!

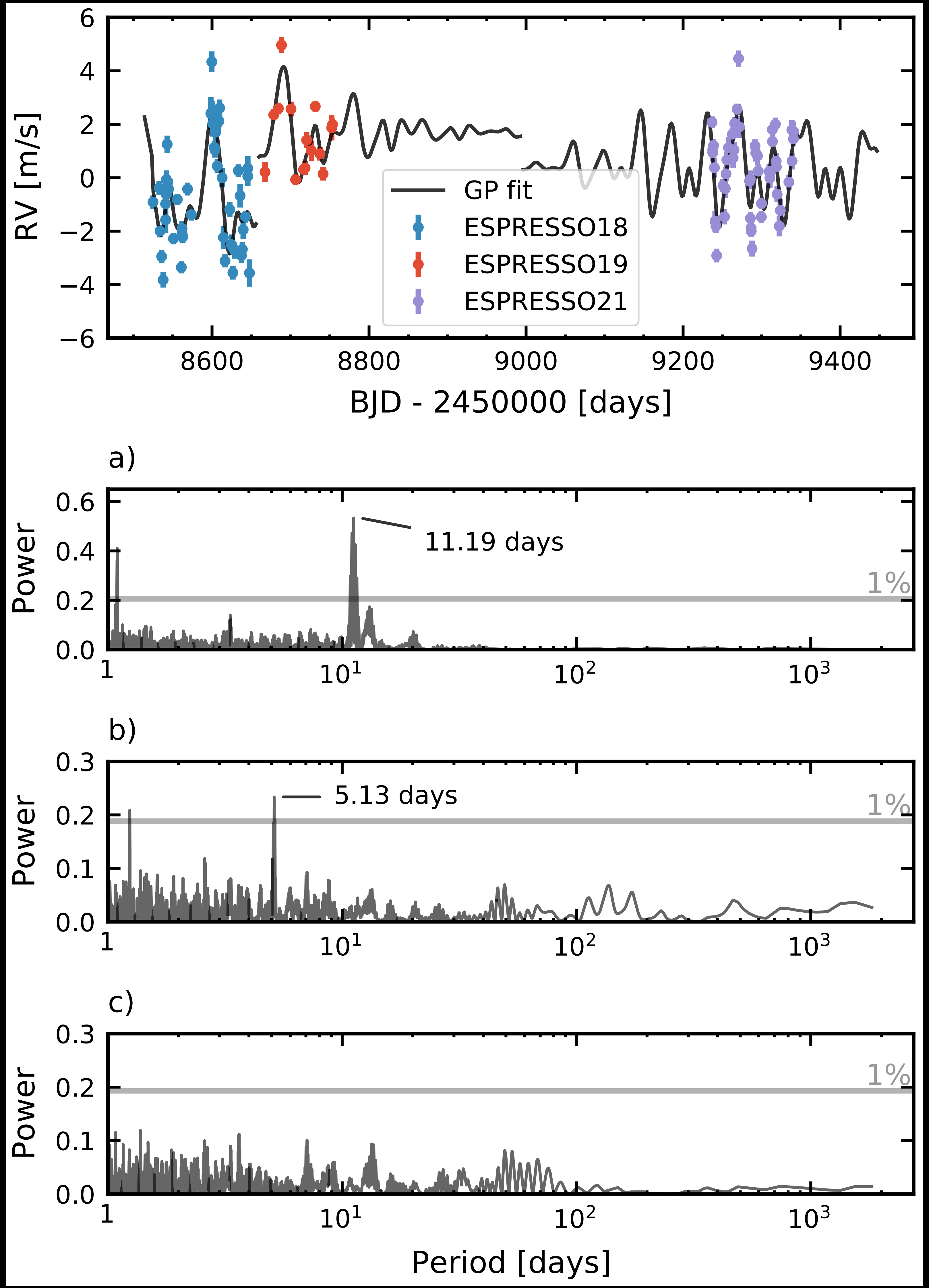
4. Data analysis: Timeseries and ‘external’ error removal and stellar-effect indicators

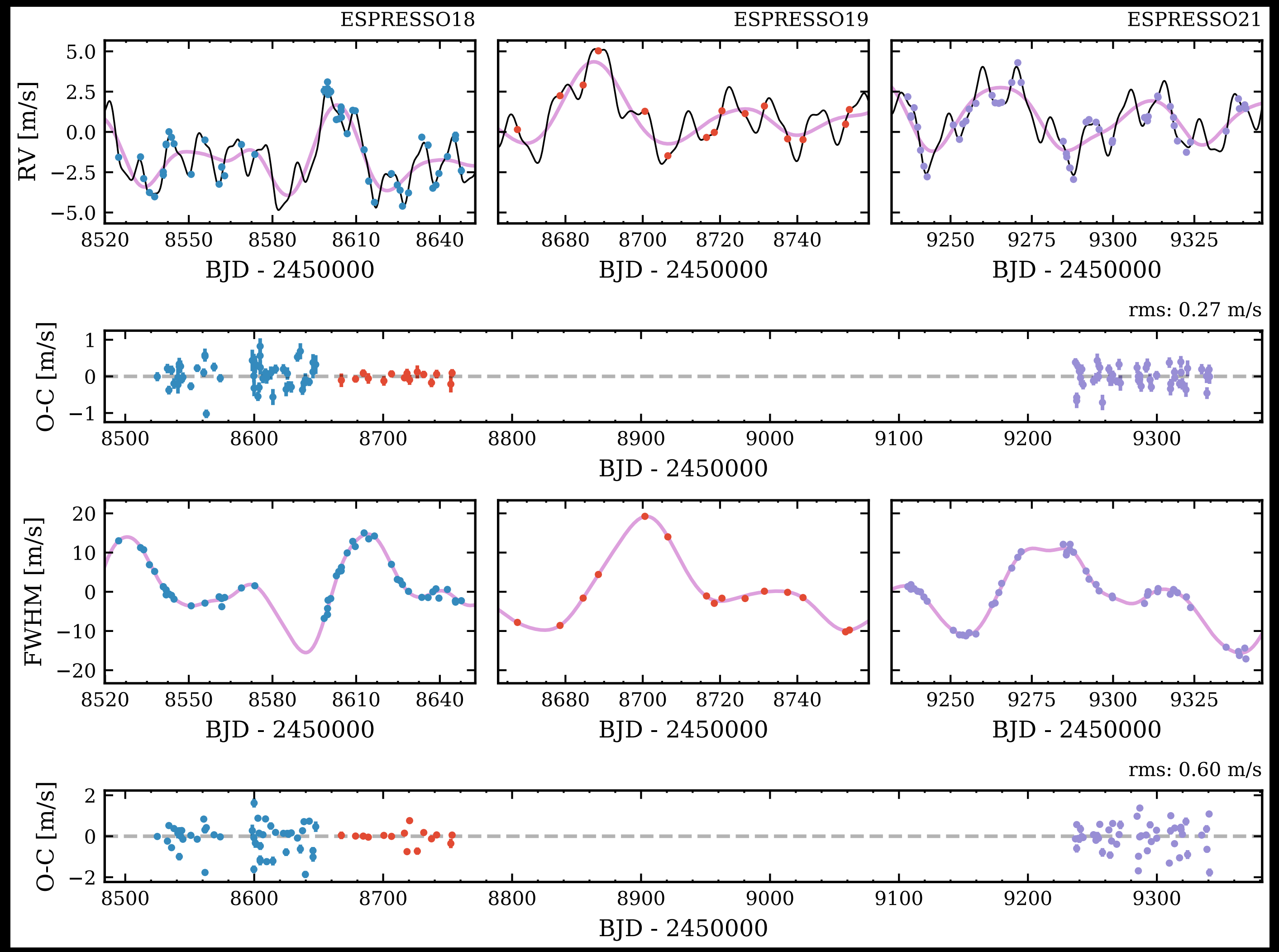
1. Convert stellar stellar ‘jitter’ into signal
2. Use time series to discriminate RV signal from stellar and other signals (Fourier, GLS, GP, etc.
3. Use ‘internal’ indicators (line shape, depths, contrast) to correct to find correlations, de-trend and/or correct RV series
4. Use ‘external’ measurements to find correlations, de-trend and/or correct RV series (e.g. H-alpha, logR’(HK), line species

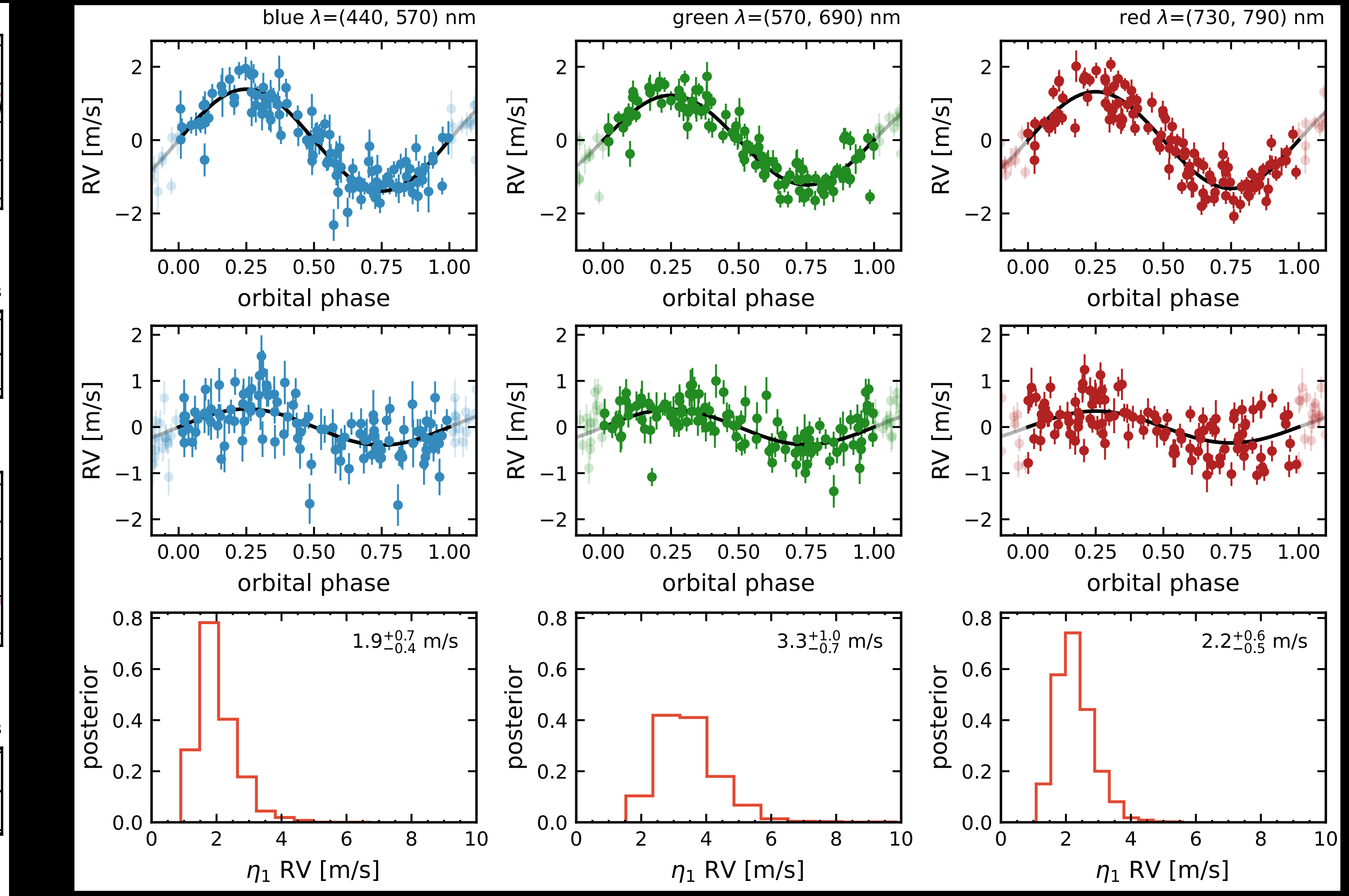


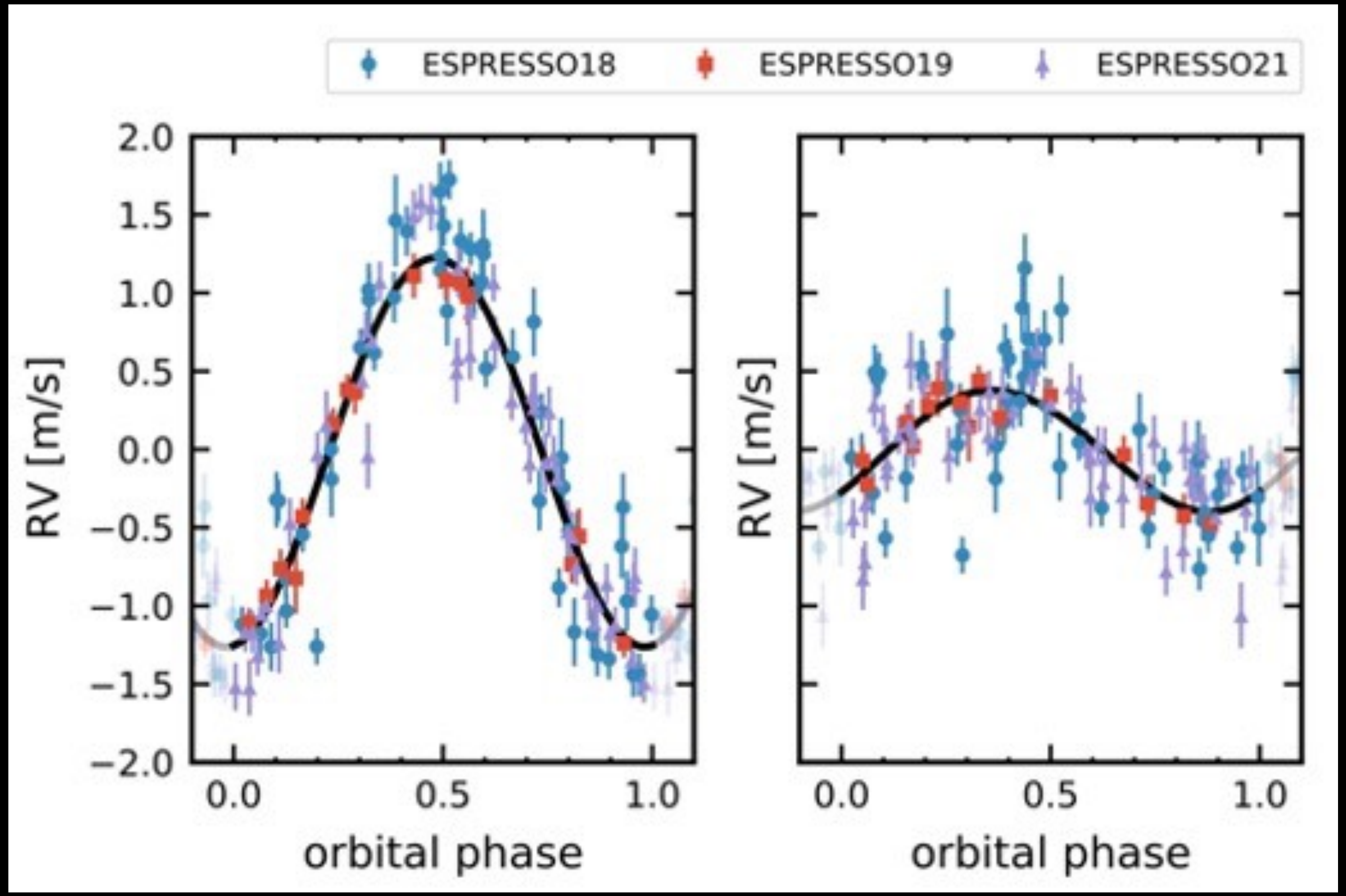
Cretignier et al. 2021, 2022

The example of Proxima Cen (ESPRESSO)









Proxima Cen

rms to the orbit fit of 29 cm/s. Planet d of 0.26 M_E on a 5-day orbit!

Faria et al., A&A 2022

Take-away messages

- (EP)RVs are and remain important: Finding ‘Earth-like’ planets, feeding future space and ground-base missions with suitable targets, follow-up to measure mass and density precisely, transit spectroscopy, etc.
- RV measurements are ‘photon-starving: Need for large telescopes, high resolution, many dedicated telescopes and instrument, high-cadence and long-term coverage, intensive and optimised programs. Only having enough ‘signal’ will allow us to understand (and correct for) other effects.
- Understanding the limits and convert stellar jitter (noise) into stellar ‘signal’ becomes fundamental -> Understand the star, enough photons, improve data analysis techniques to mitigate or possibly solve for the stellar signal!
- Make sure that the instrument does NOT introduce systematics. We are NOT YET at the cm/s *precision*, and far from being at the cm/s *accuracy* or long-term repeatability. Still a lot of effort going on.
- RVs are (still) derived from high-resolution spectroscopy. There is much more information in a spectrum than ‘only’ RVs! (Stellar physics, planetary atmosphere, etc.)