Extreme Precision Radial Velocities

A critical tool in the hunt for habitable planets

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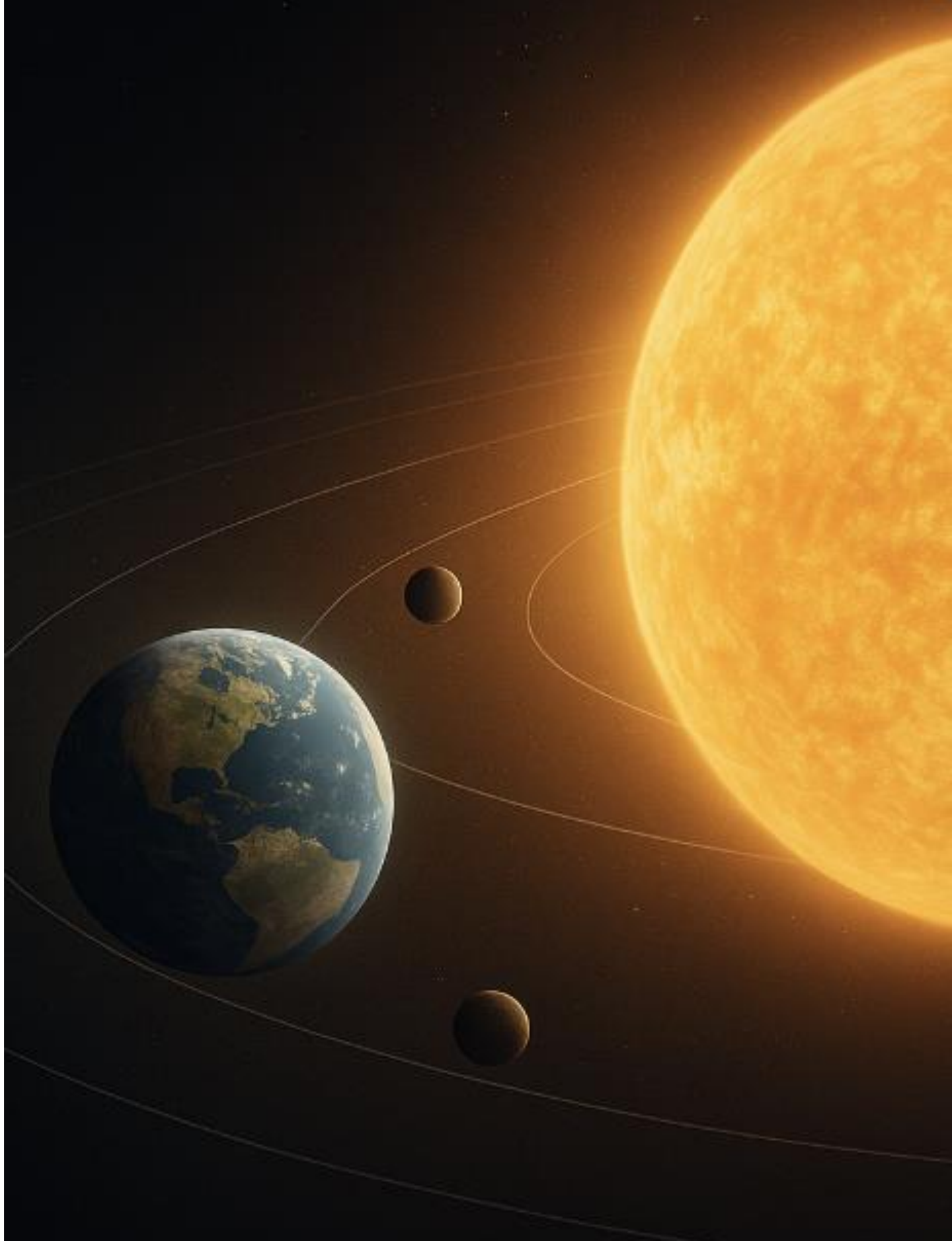
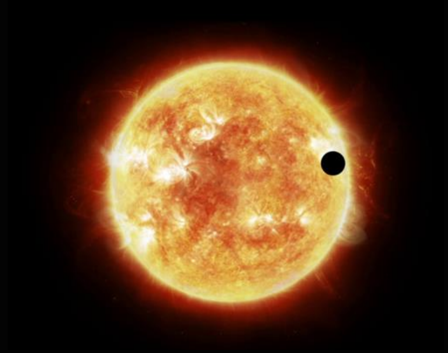
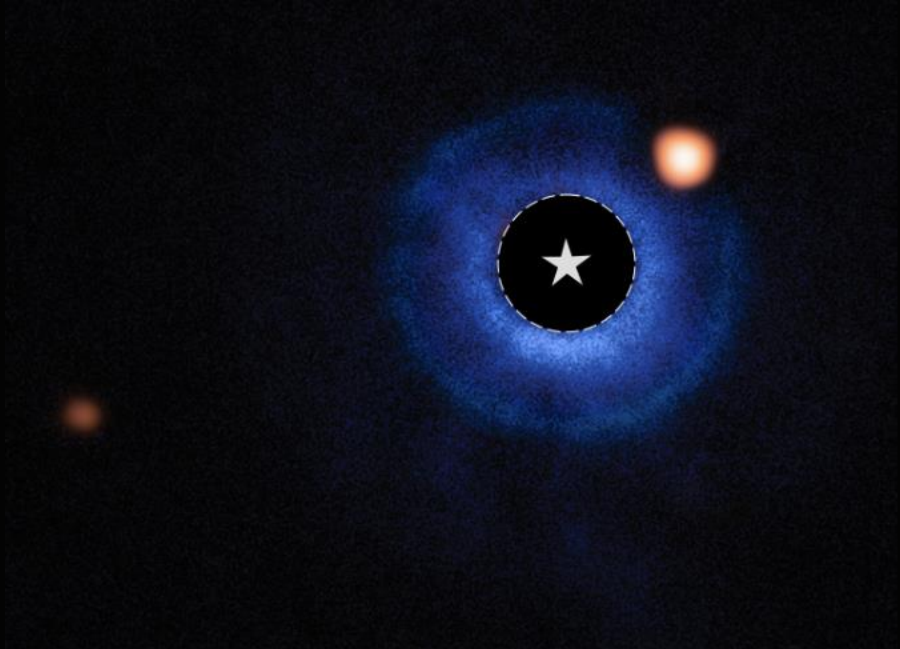


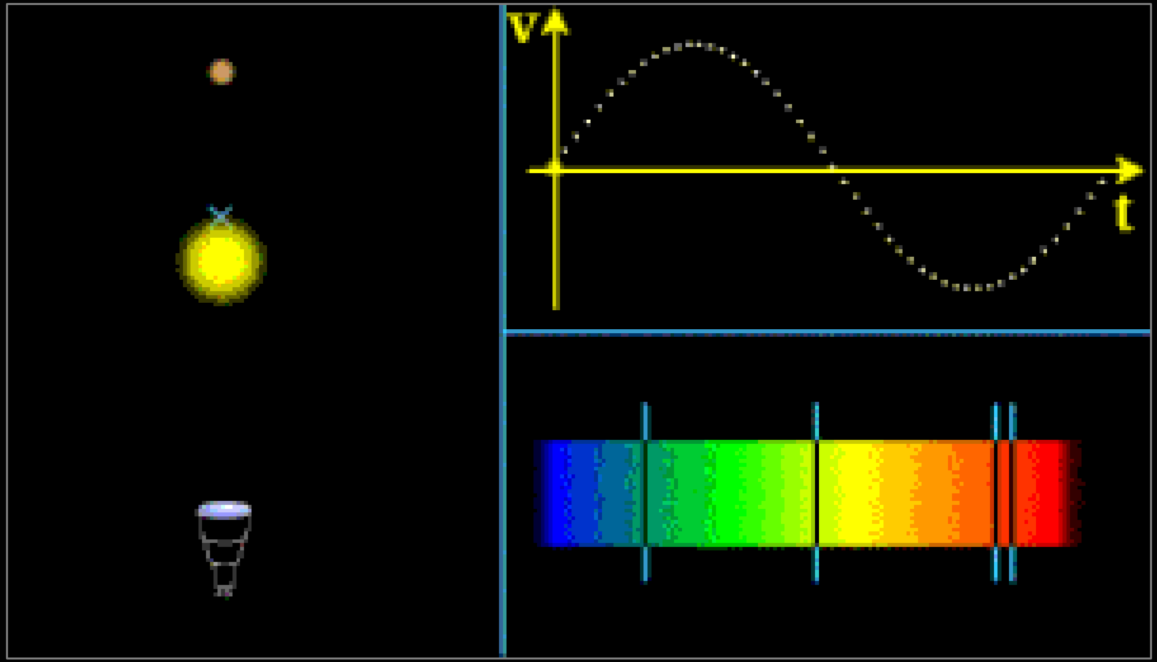
After this presentation, you should understand:

1. What kind of exoplanets can be detected with the Doppler method
2. How RV precision has evolved over the past 3 decades
3. Breakthrough EPRV results – Barnard’s star
4. Key challenges and my future predictions for EPRV

What kind of exoplanets can be detected with the Doppler method?







Spectroscopic time-series RV of star

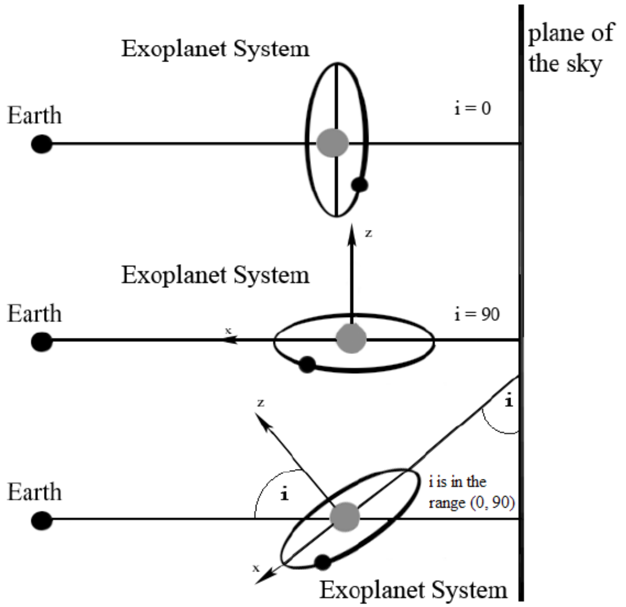
- Amplitude of 1 m/s → shifts < 0.002 pix
- K depends on mass (of star and planet), period, and inclination
- Need to observe for 1 full orbit

RVs provide planet masses.

The Extreme value of EPRV

- EPRV enables detection of non-transiting Earth analogs.
- Currently best method for detecting Earthlike planets orbiting nearby (< 20 pc) stars.
- Limited to GKM type stars (earlier type stars have fewer spectral lines, broadened by rotation).

EPRV detection and orbital inclination



The Doppler method measures line-of-sight velocity.

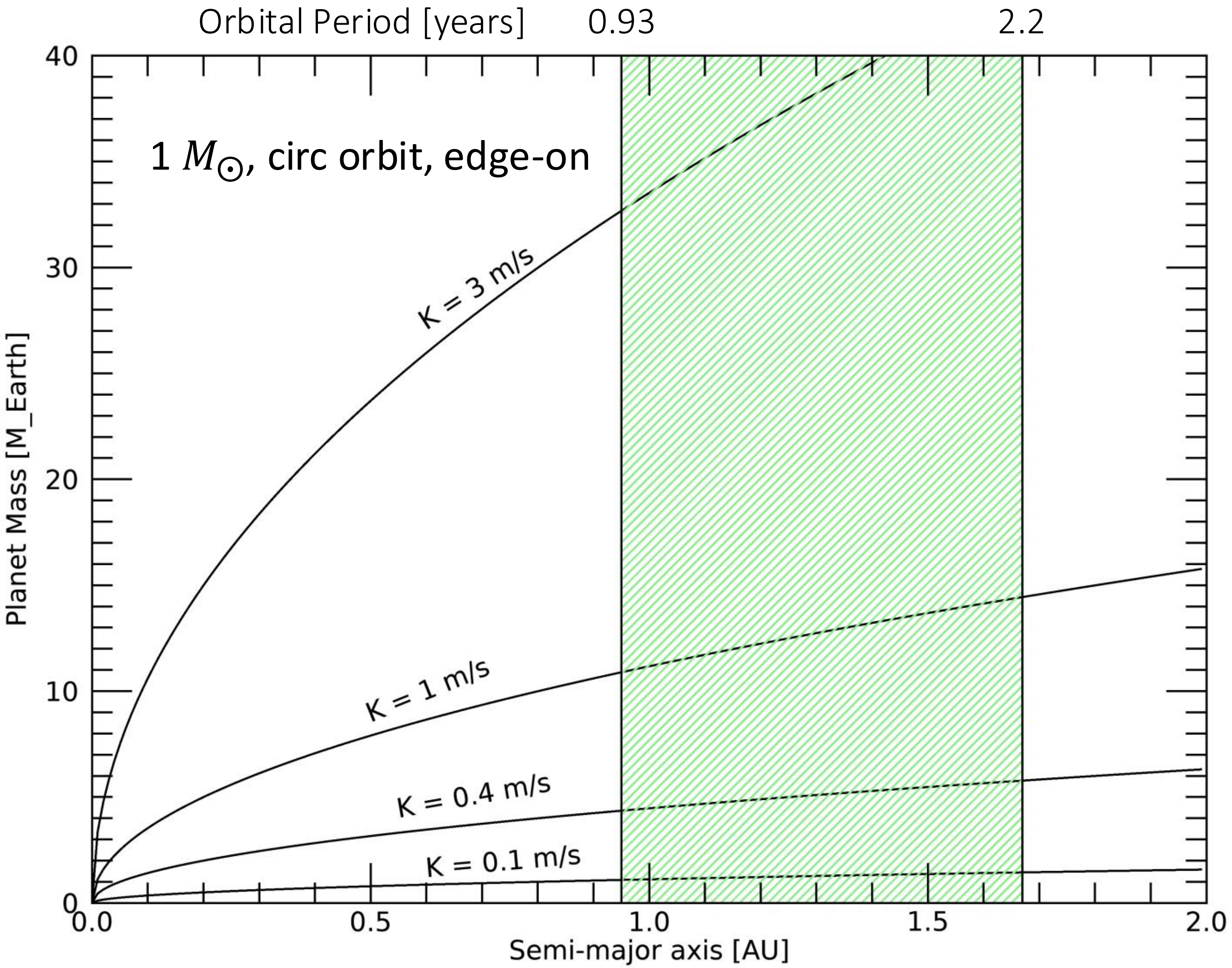
The EPRV “masses” are really $m_{pl}sini$.

$$P(i_1 \leq i \leq i_2) = \int_{i_2}^{i_2} sin(i)di = cos(i_1) - cos(i_2)$$

i	$P(i)$	M_{pl}	
60 - 90	0.5	< 1.15 $m_{pl}\sin(i)$	Half of RV exoplanets have true $m_{pl} < 1.15\ m_{pl}\sin(i)$
30 - 90	0.87	< 2 $m_{pl}\sin(i)$	87% of exoplanets have true $m_{pl} < 2\ m_{pl}sin(i)$

A **small fraction of detectable amplitudes** will be missed because of orbital inclination.
But much lower sensitivity to inclination relative to transits.
Statistically, true m_{pl} are within a factor of 2 of measured $m_{pl}sin(i)$ for almost 90% of cases.

Precision matters. I. Solar-type stars

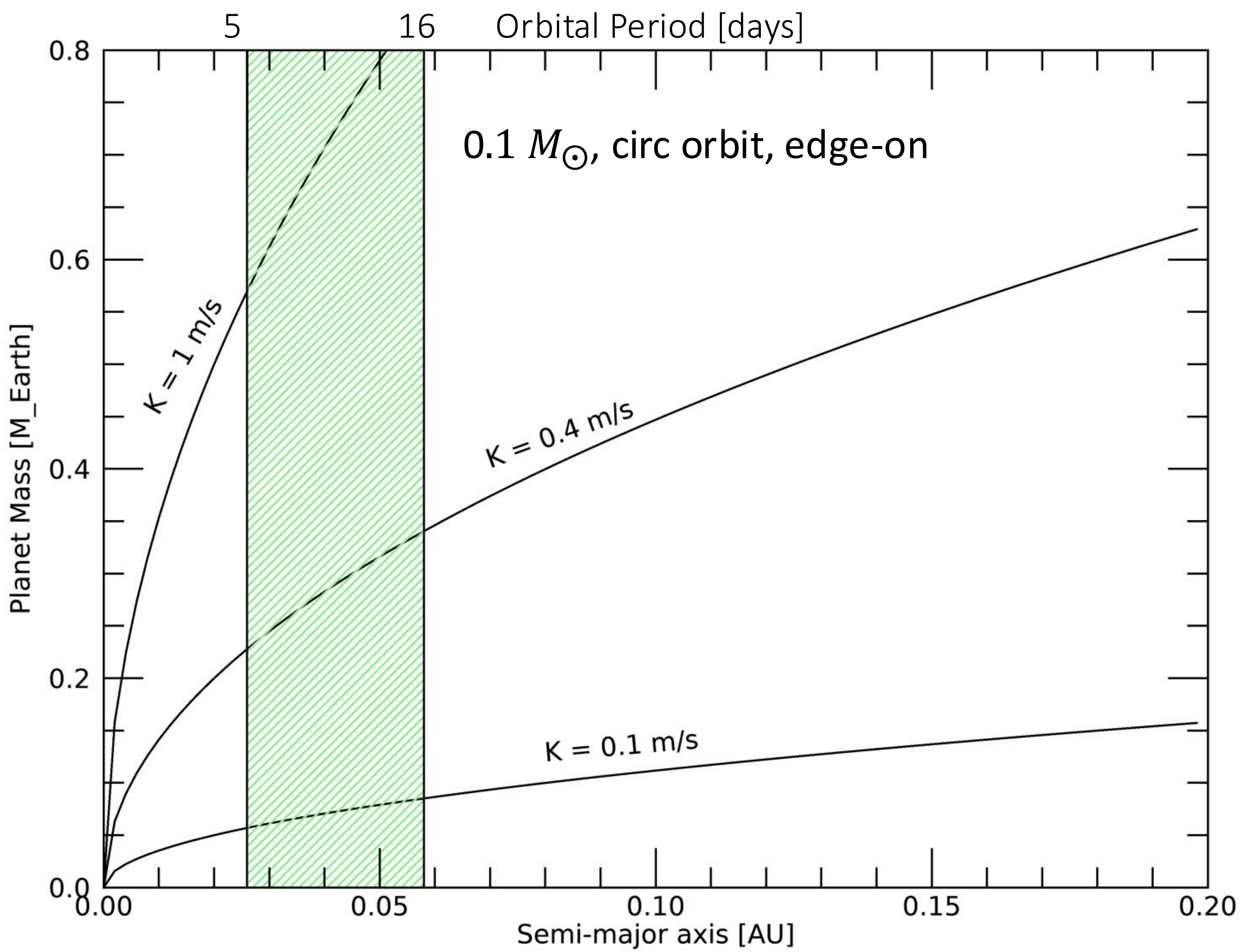


(V~5 at 10 pc) and bright stars can be observed at high SNR with small (3-m) telescopes.

Earths at HZ distances around any type star requires extreme precision.

With current state of the art, an exoplanet that is a few times $m_\oplus$ can be detected around solar type stars.

Precision matters. II. M dwarf stars



(V~17 at 10 pc) so a larger aperture telescope is required for adequate SNR on Mdwarfs.

Reflex RV is larger with lower mass stars and the orbital periods are much shorter in HZ orbits. Habitable worlds are much easier to detect around lower mass stars!

With current state of the art RV precision, sub-Earth mass planets can be detected at HZ distances.

How has RV precision evolved over the past 3 decades?

What matters for the Doppler method:

- Stellar mass
- Planet mass
- Orbital period
- Orbital inclination
- Measurement precision

We can only control the last factor.
So, how are we doing? Has there been significant improvement in precision with the Doppler method over the past 30 years?

The Extreme challenges of EPRV

Reaching sub-m/s precision requires exquisite stability.
Earth induces a 9 cm/s signal on the Sun (a 0.0002-pixel shift amplitude)
Stellar activity and granulation introduce 'jitter' or noise in the RVs.

Instrumental systematics must be tightly controlled.

- High-stability spectrographs (EXPRES, ESPRESSO, NEID, MAROON-X, KPF).
- Laser frequency combs and Fabry-Pérot calibration.
- Vacuum chambers, fiber scrambling, thermal control.

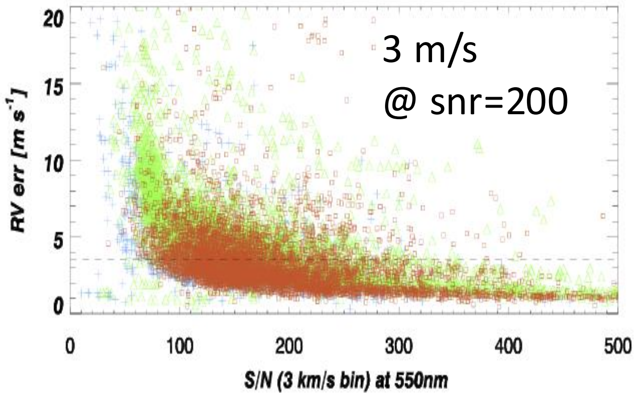
Data systematics must be controlled

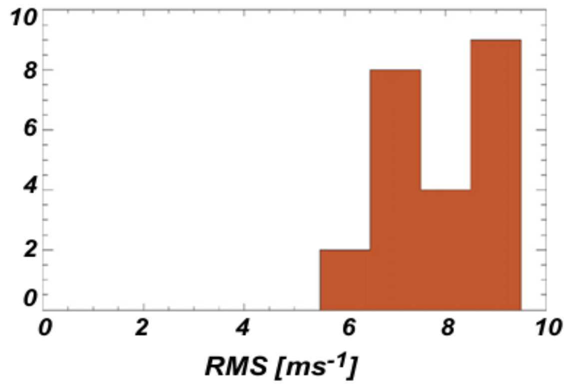
- Stellar activity must be modeled (e.g. with Gaussian process regression).
- Robust telluric modeling is essential.

1990's

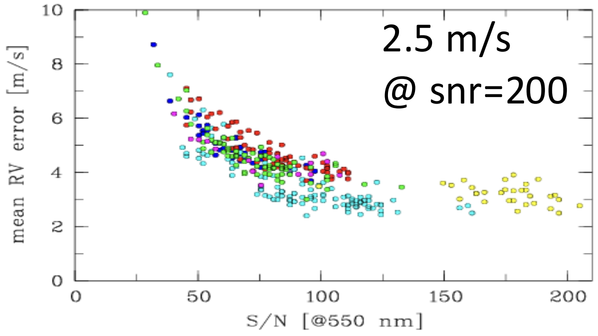
Lick / Hamilton Iodine cell, R=50,000, RMS > 5 m/s

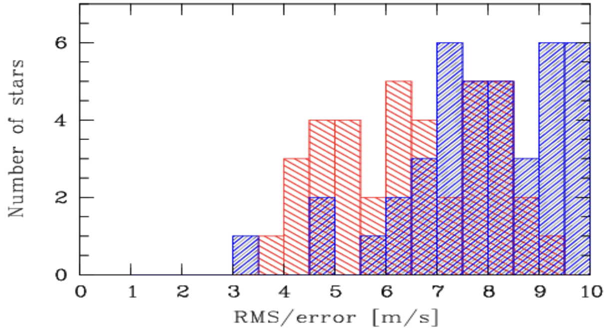
Fischer et al. 2016, "State of the Field: EPRV"



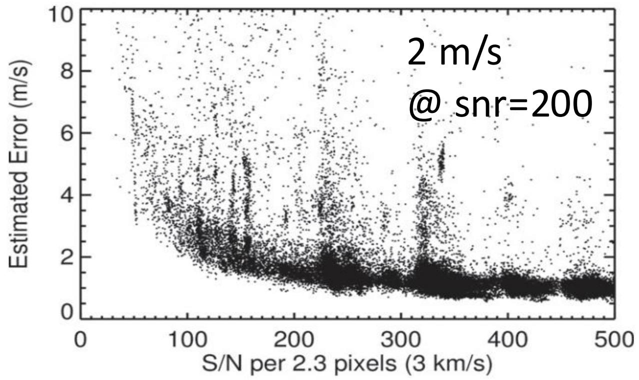


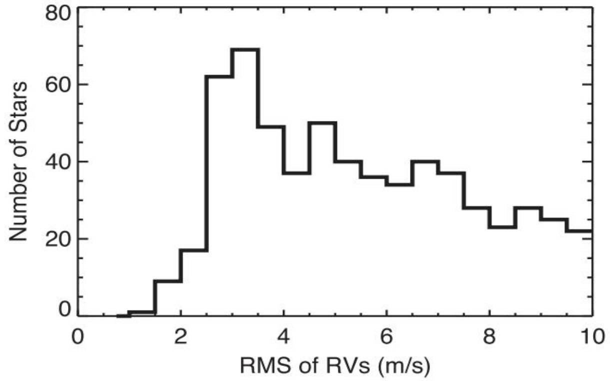
McDonald / HRS Iodine cell, R=60,000, thermal control, RMS > 4 m/s





Keck / Hires Iodine cell, R=55,000, RMS ~ 3m/s





La Silla / HARPS 2003, ThAr and CCF, R=115,000, Vacuum chamber

2000's

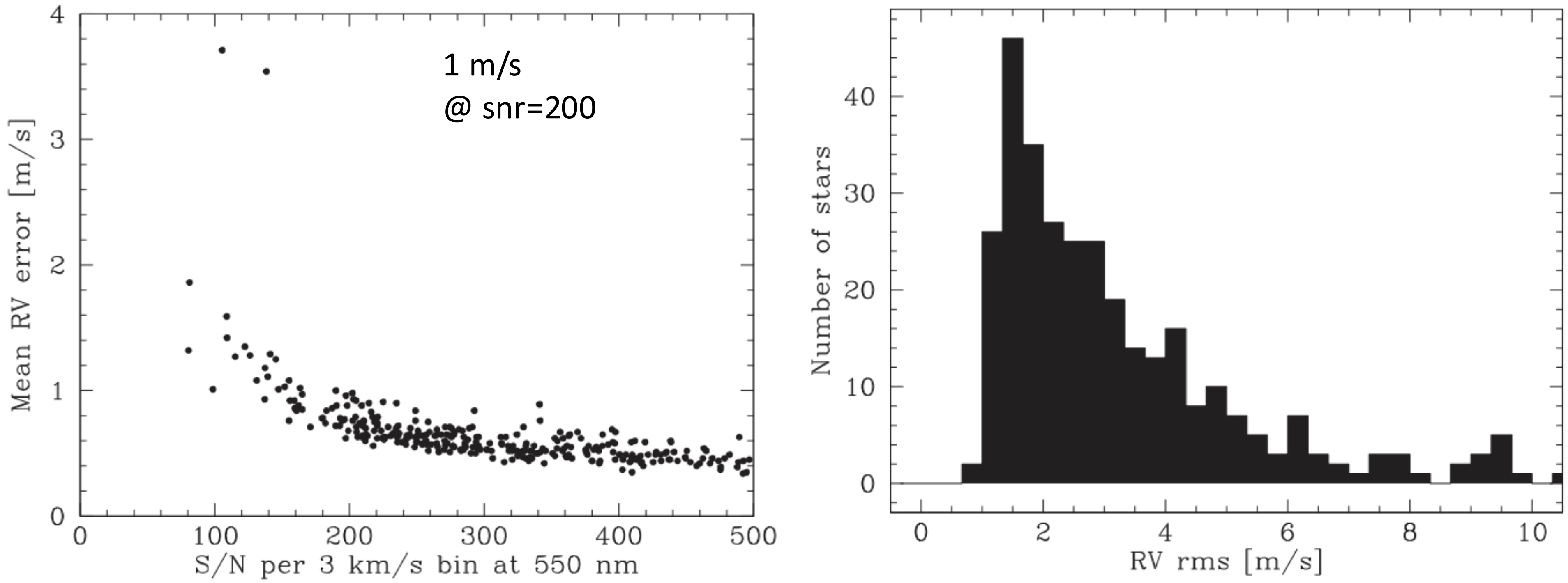


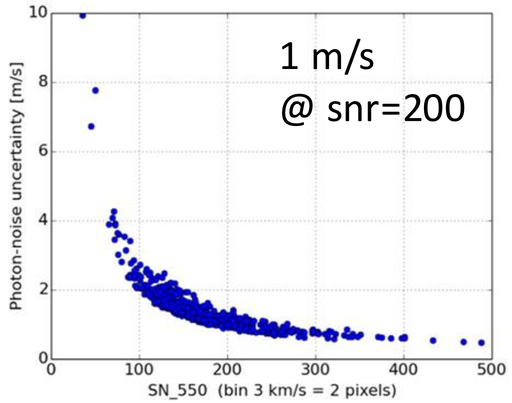
Figure 6. Single measurement precision as a function of S/N (left) and radial velocity scatter (right) at HARPS for the target sample of FGK dwarfs to search for super Earth and Neptune mass exoplanets with HARPS. (Courtesy of Christophe Lovis.)

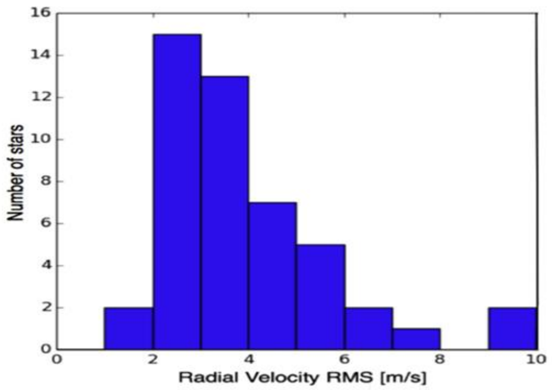
Figure in Fischer et al. 2016, "State of the Field: EPRV"

Based on the empirical measurements of uncertainty and RMS, a rule of thumb is that the minimum RMS is about $2 \times \sigma$….. Stellar Activity? Instrumental errors? Undetected planets?

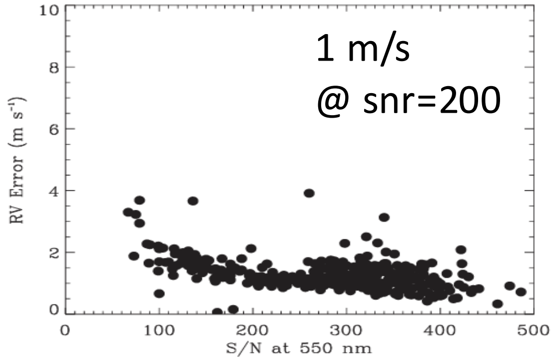
2010’s

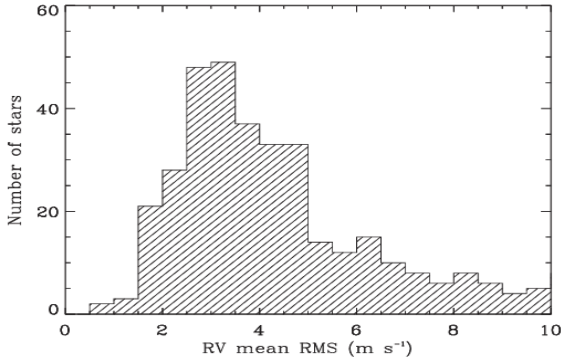
Haute Provence / Sophie ThAr, R=75,000, thermal control



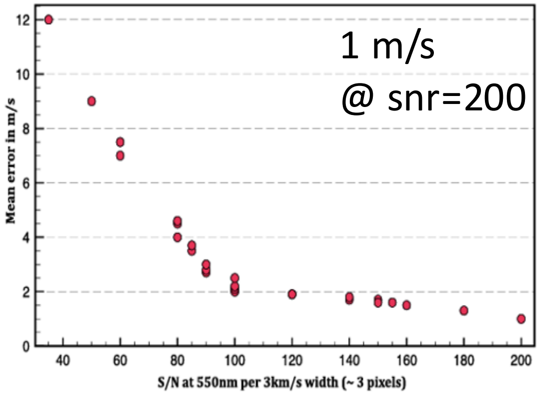


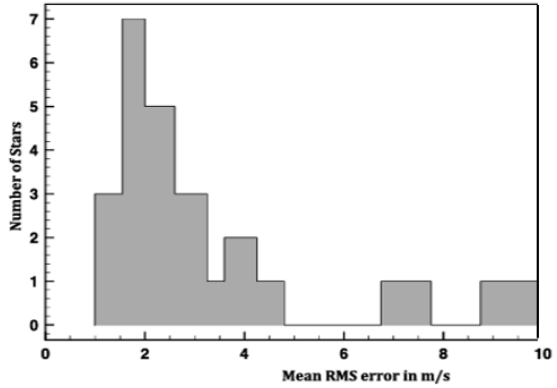
Las Campanas / PFS Iodine cell, R=76,000, thermal control





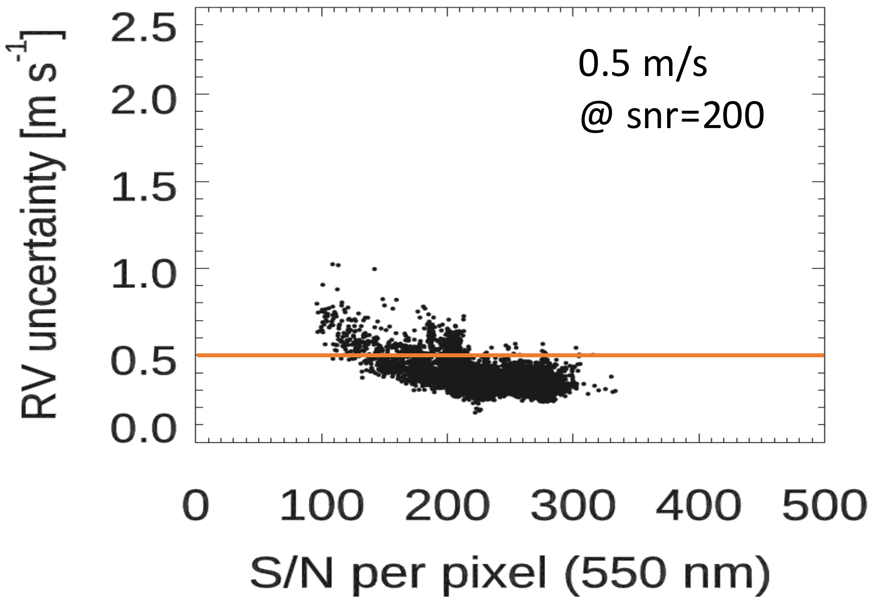
Mt Abu / PARAS ThAr, R=75,000, vacuum chamber (ala HARPS)

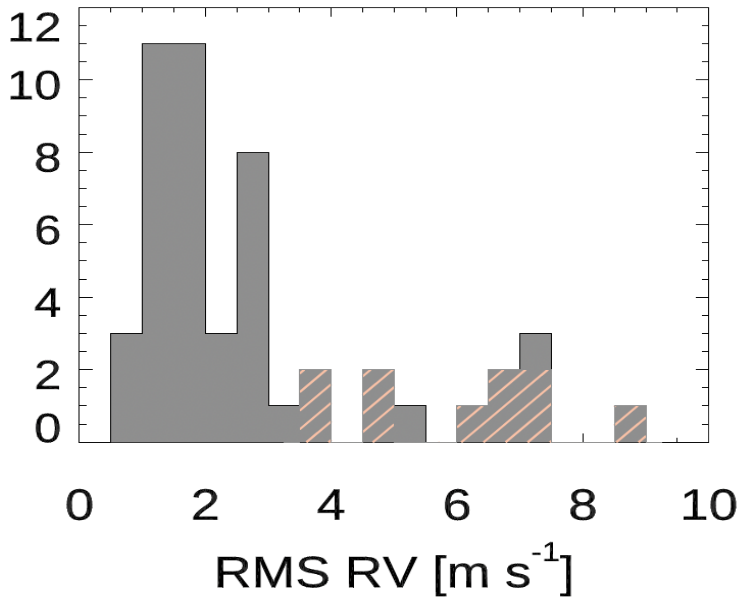




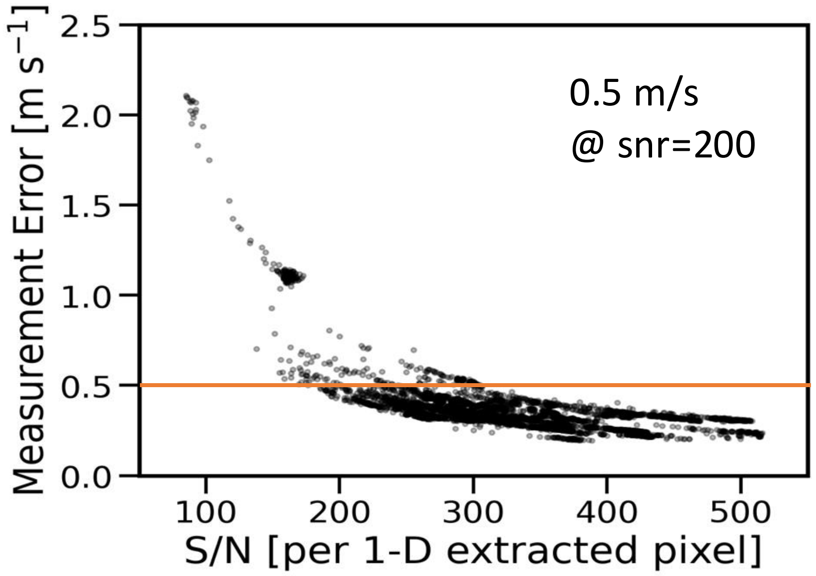
2020’s

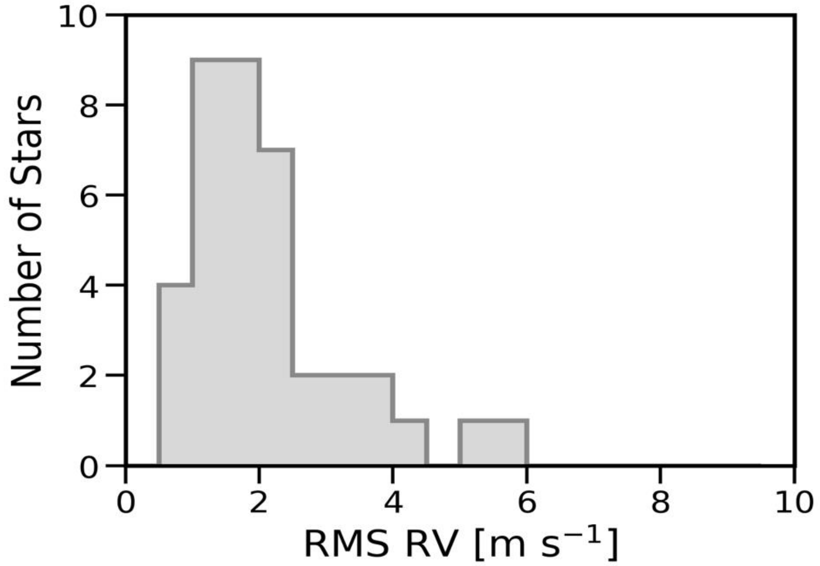
Lowell / EXPRES LFC, R=138,000, vacuum control



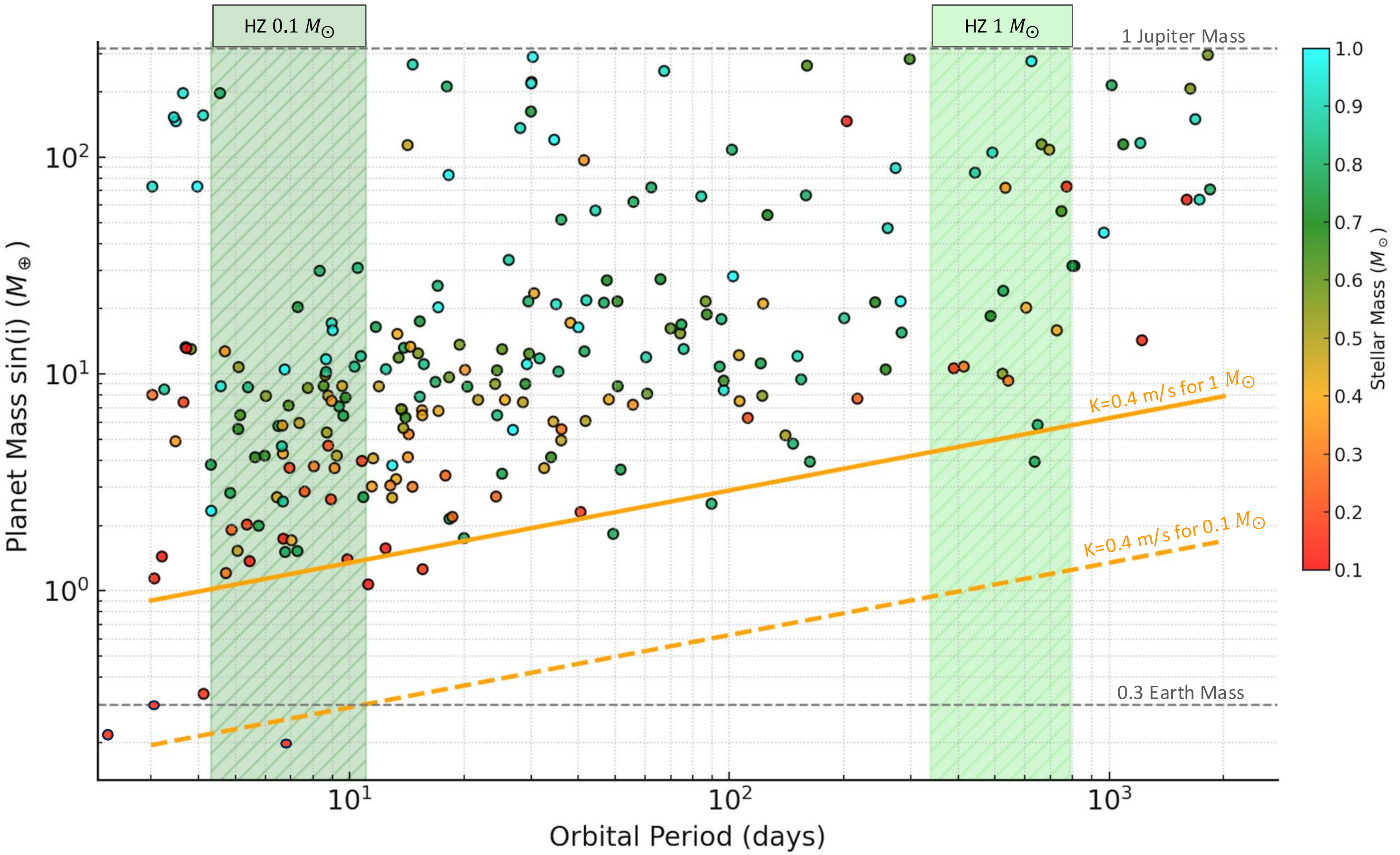


Kitt Peak/ NEID LFC, R=110,000, vacuum control



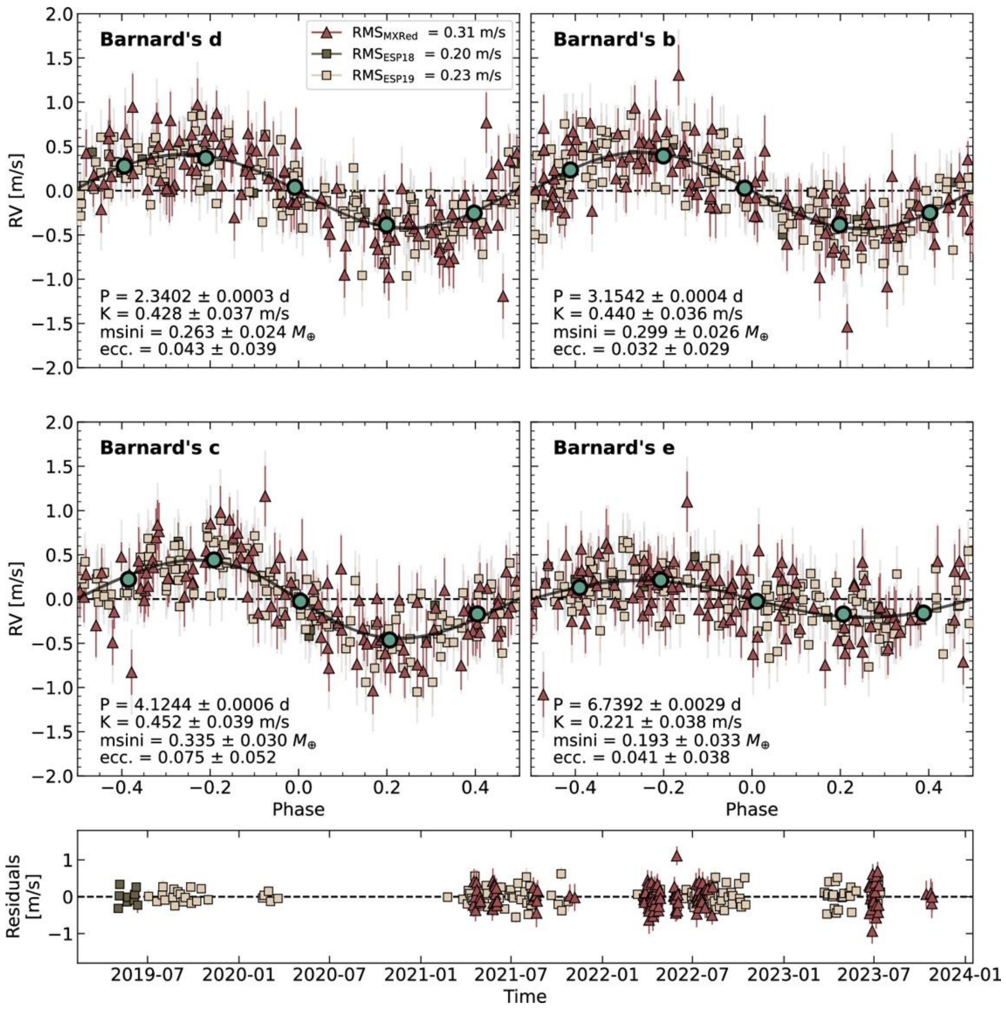


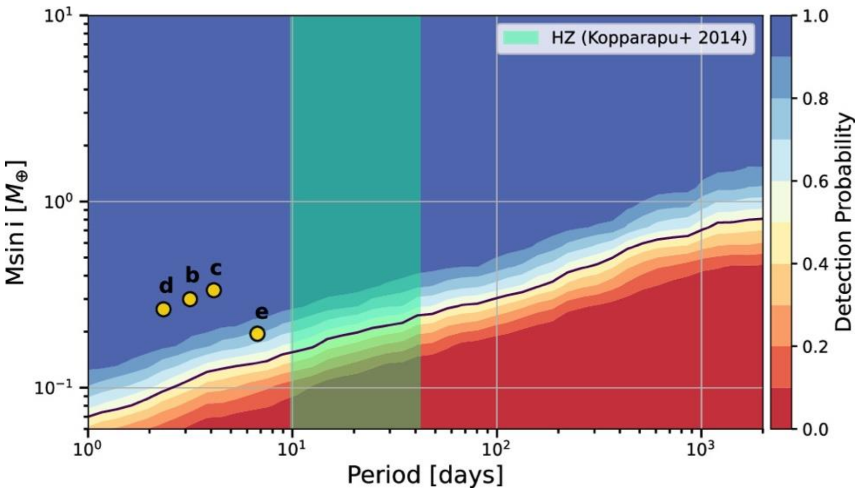
As of 2025: RV-detected exoplanets - Msini vs Orbital Period



Data source: /exoplanet.eu

A breakthrough era for EPRV – Barnard's star





Figures from Basant et al. 2025

Data from:

González Hernández et al. 2024, "A sub-Earth mass planet orbiting Barnard's Star" A&A

Basant et al. 2025, "Four Sub-Earth Planets Orbiting Barnard's Star from MAROON-X and ESPRESSO" ApJL

Detection confidence: $\text{“}SNR\text{”} \approx \frac{K}{\sigma}\sqrt{N}$

SNR	Interpretation
5-7	Robust (FAP < 1%)
3-5	Suggestive – need more data
< 3	Indistinguishable from noise

So for a given K, the confidence / detectability can be improved by increasing the number of observations or improving the measurement precision.

This statistical estimate assumes that there is also good phase coverage.
It also assumes that systematic noise sources have been modeled out.

Case of Barnard's star: Many orbital periods were observed, with excellent phase coverage

ESPRESSO: 4.5 years, $\sigma = 0.1\, ms^{-1}, N = 157, \frac{K}{\sigma}\sqrt{N} = 50$

MAROON-X: 2.5 years, $\sigma = 0.3\, ms^{-1}, N = 112, \frac{K}{\sigma}\sqrt{N} = 14$

High confidence result!

Key EPRV challenges and my predictions for the future of EPRV

The progress has been impressive. The single measurement precision for GKM stars is now about 20 cm/s.

The challenges from the last decade have been reduced and are better understood:

- Stellar activity
- Instrumental stability

Extensive work has been done on each of these challenges!
Several lectures possible on each – just a cursory glance here.

Stellar activity

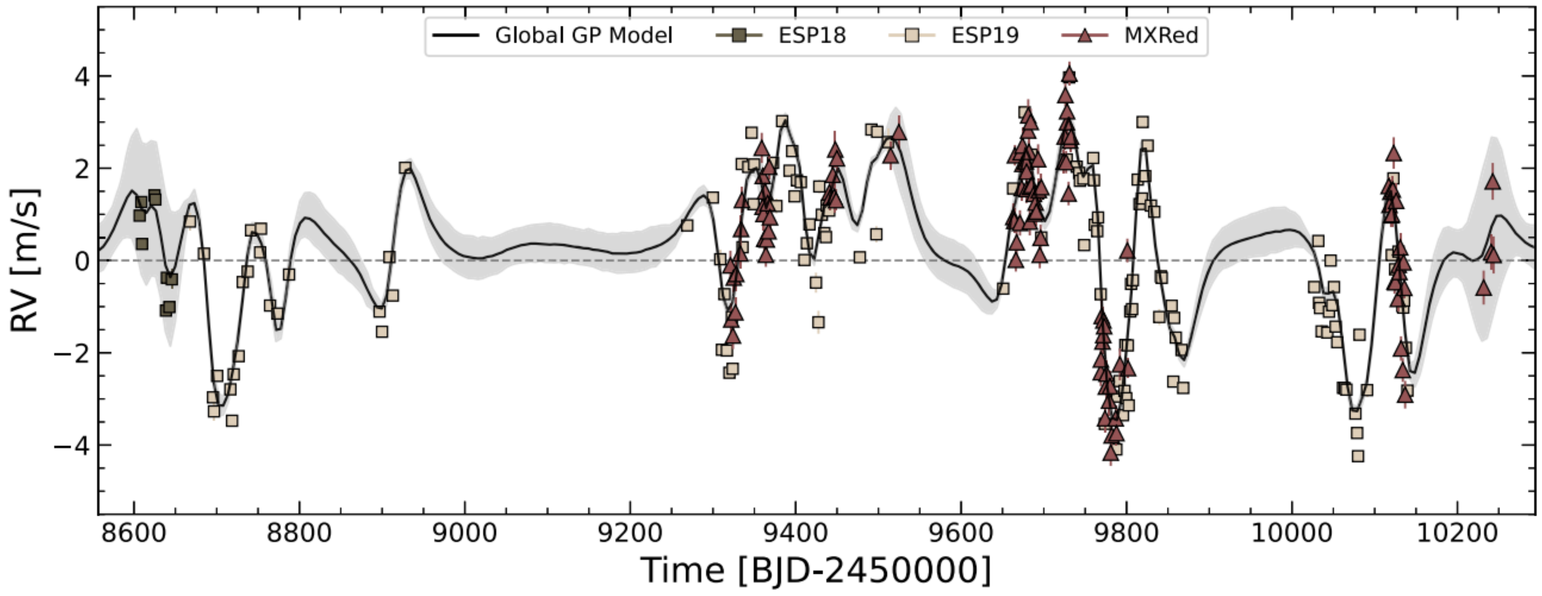


Figure 7. This plot shows the global GP model for the 4-Keplerian model joint fit between the MAROON-X Red channel and ESPRESSO data sets.

From Basant et al. 2025

The actual RVs for Barnard's star are $\pm$ 4 m/s!

Yet, four exoplanet signals with amplitudes of 0.4 m/s were extracted by modeling stellar activity with Gaussian Process regression.

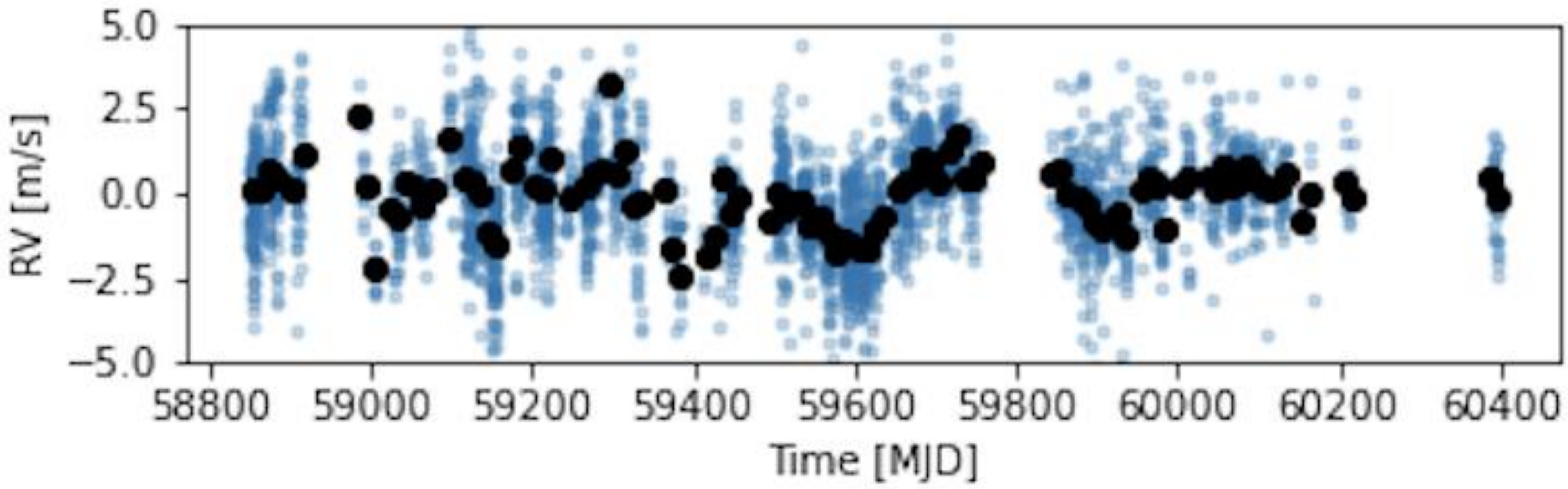
In GP modeling, the **kernel** (**covariance function**) defines how data points are correlated with each other. This encodes assumptions about the function's **smoothness**, **periodicity**, or **noise structure**.

Activity signals (and aliases) from long-lived spots create spectral line profile variations that mimic Doppler signals from planets. Good correlation b/t FWHM of CCF and activity-induced RVs (see Suárez Mascareño et al. 2020). This offers a compelling approach for separating spot signals from planetary signals in M-dwarfs.

Instrumental stability

Looking for systematic “instrumental” RV errors (work by Lily Zhao)

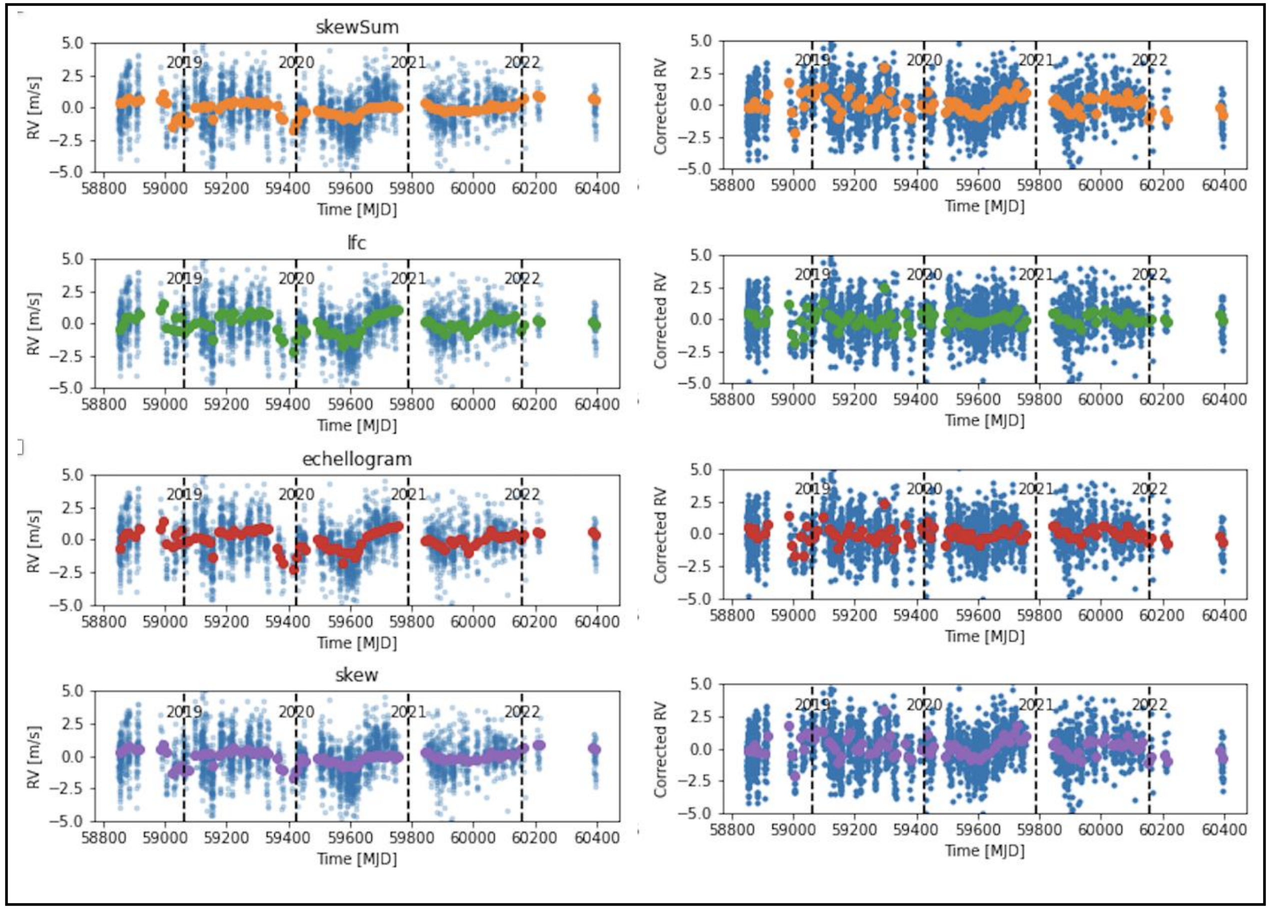
Time-series RVs for several quiet stars observed with EXPRES are overplotted – show common structural (instrumental errors) – here, from knonwn uncontrolled temperature variations.



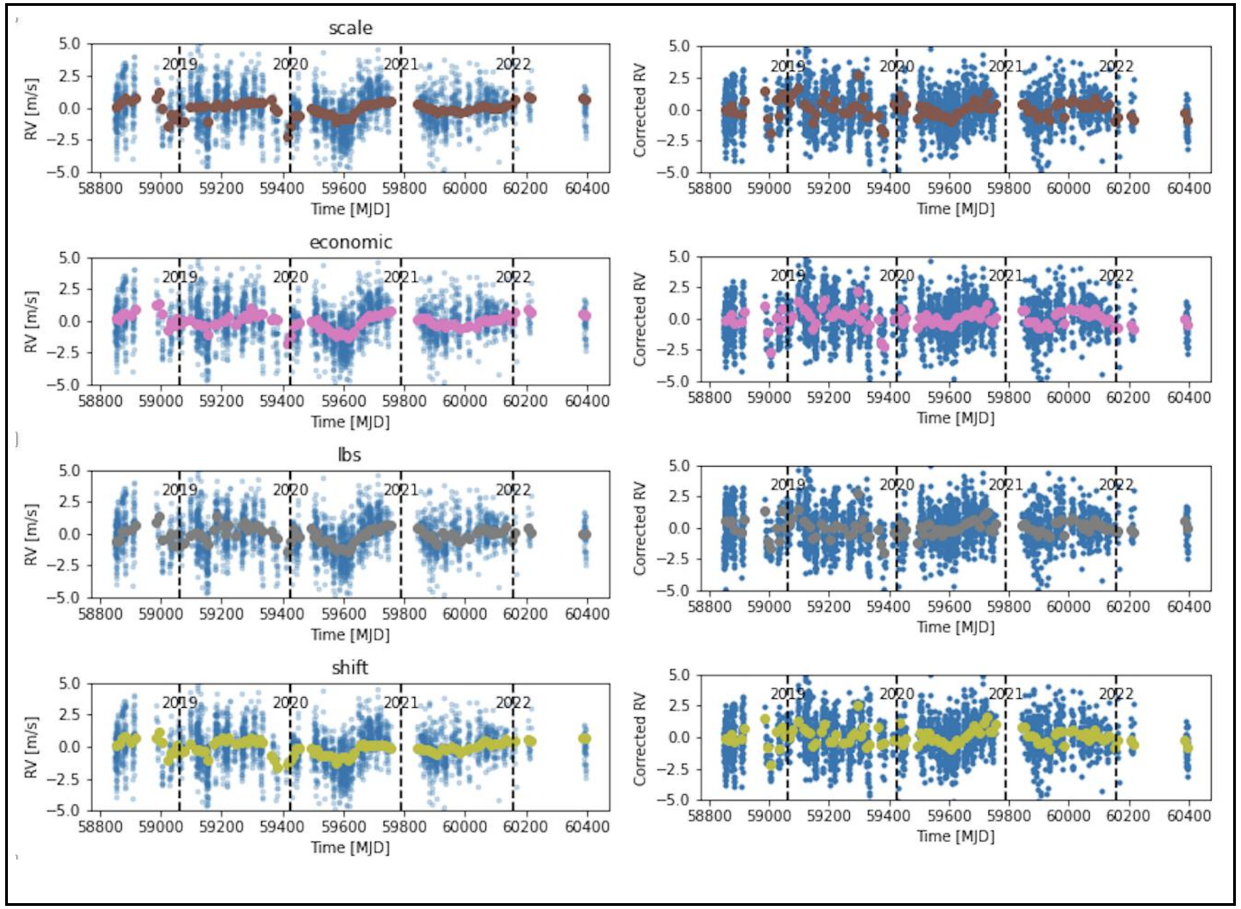
These systematic instrumental errors would have been undetectable in 1 m/s precision spectrographs.

Instrumental stability

Before After



Before After



Looking for systematic “instrumental” RV errors in EXPRES data (work by Lily Zhao)

CONCLUSIONS AND MY PREDICTIONS

1. We will continue to be limited by stellar activity but models will improve. With EPRV spectrographs, excellent progress has been made in modeling underlying stellar activity. But more work still needs to be done:
   - There is still a concerning lack of agreement between the RVs returned by different activity models (Zhao et al. 2022).
   - Solar telescopes provide an ideal training ground – instrumental errors can be isolated and measured velocity variations trace flows on the solar surface (Zhao et al. 2023).

2. More work needs to be done improving and monitoring environmental stability. Lesson for EPRV: monitor and record environmental parameters everywhere in the spectrograph.

3. The current generation of EPRV instruments (ESPRESSO, EXPRES, NEID, MAROON-X) have different designs, but all are reaching a single measurement precision on stars of 10 – 30 cm/s. This is already reaching potentially habitable Earth-mass planets around M and late K dwarfs and planets that are a few Earth-masses around solar type stars.

4. To reach an Earth mass planet around a solar type star with the Doppler method, we need to improve stellar activity models and the environmental stability of current EPRV instruments. With focused work and investments, this is within reach in the next decade.