# From Wobbles to Worlds:

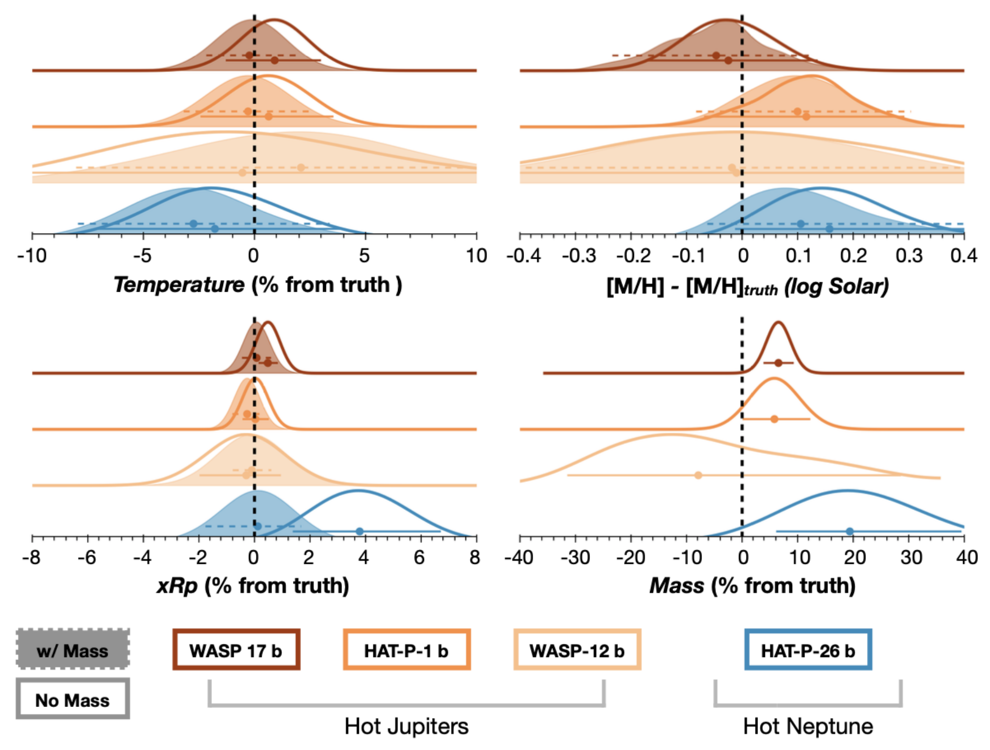
# The role of precision radial velocities in exoplanet discovery and characterization

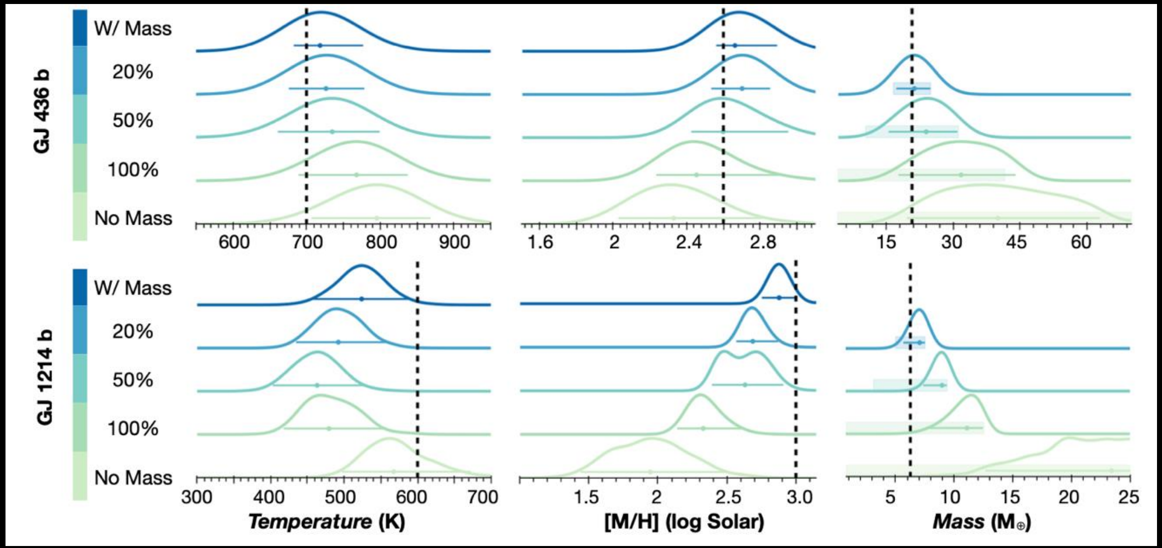
Dr. Jennifer Burt
Exoplanet Exploration Program Office

“Mass is the most fundamental property of a planet, and knowledge of a planet’s mass (along with a knowledge of its radius) is essential to understand its bulk composition and to interpret spectroscopic features in its atmosphere”

--2018 National Academy of Sciences Exoplanet Science Strategy report

# Mass is crucial to accurate interpretations of a planet's atmospheric transmission spectrum



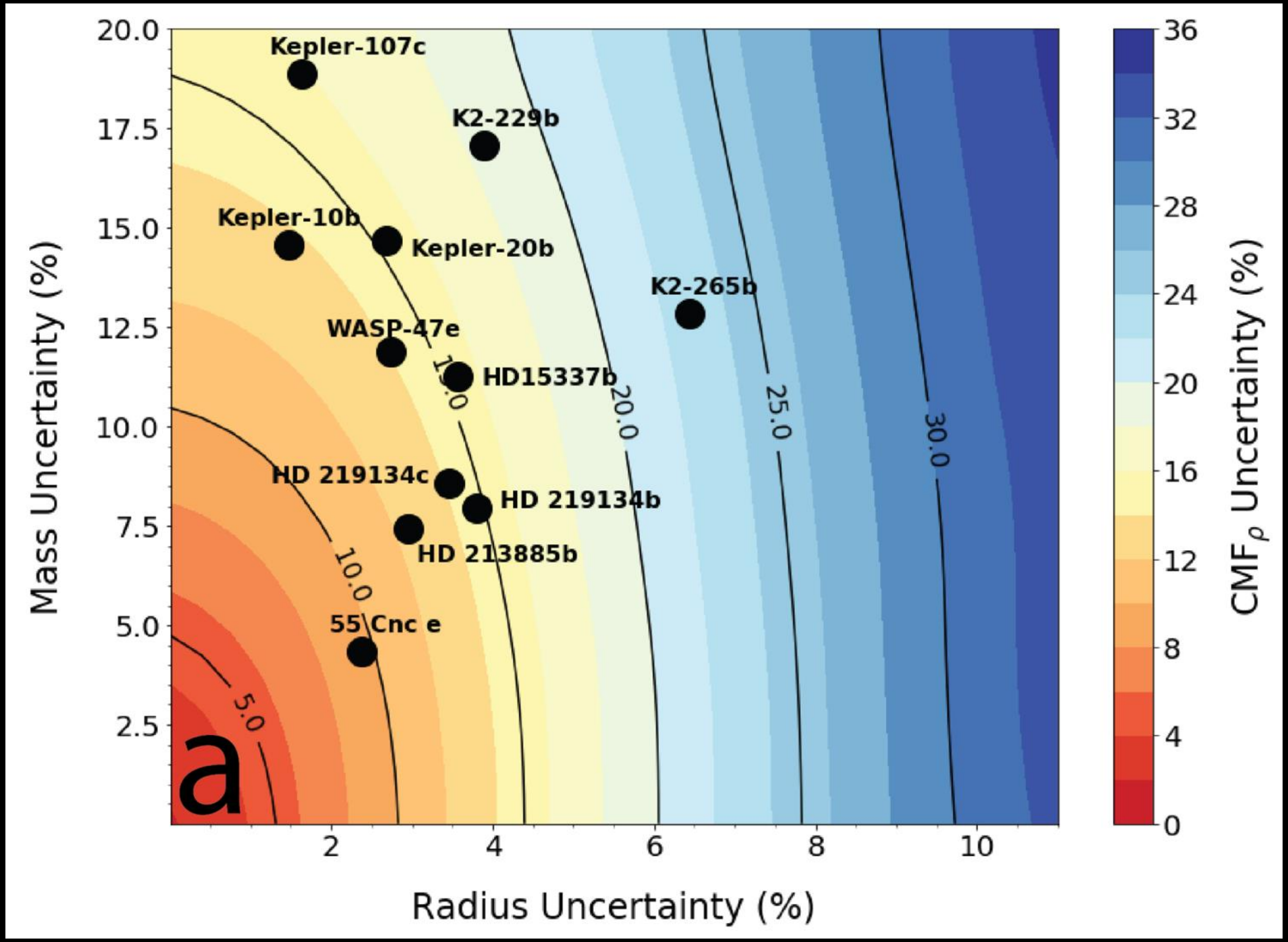




Hot Jupiters and Neptunes require 2σ mass measurements

Temperate planets smaller than Neptune require 5σ mass measurements

Batalha et al. 2019

# As well as to interpretations of its interior composition

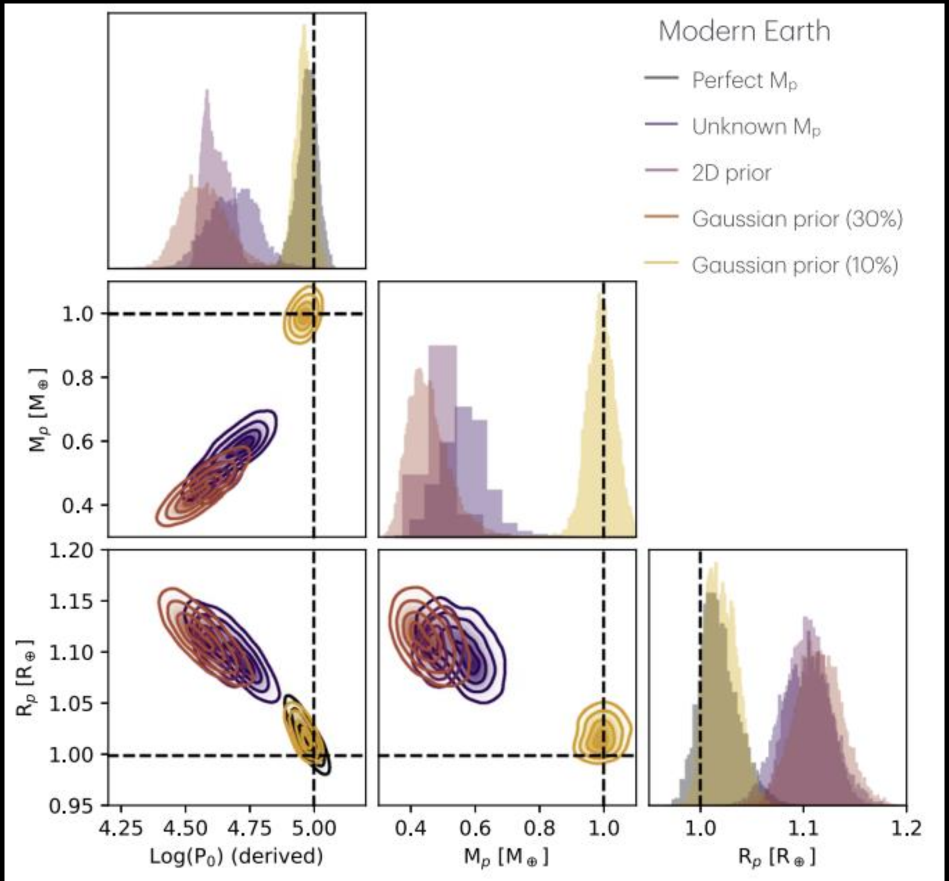


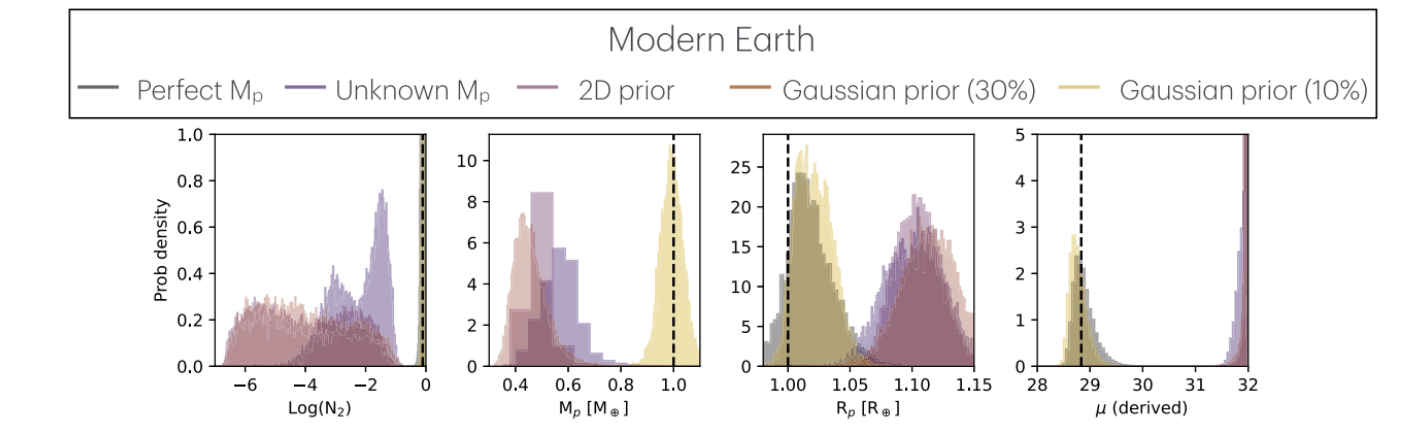

Mass uncertainties better than 5$\sigma$ are also sufficient to characterize the interiors of small, transiting, planets

(Assuming you also know the Fe, Mg, and Si abundances of the star to better than 0.01 dex)

Schulze et al. 2021

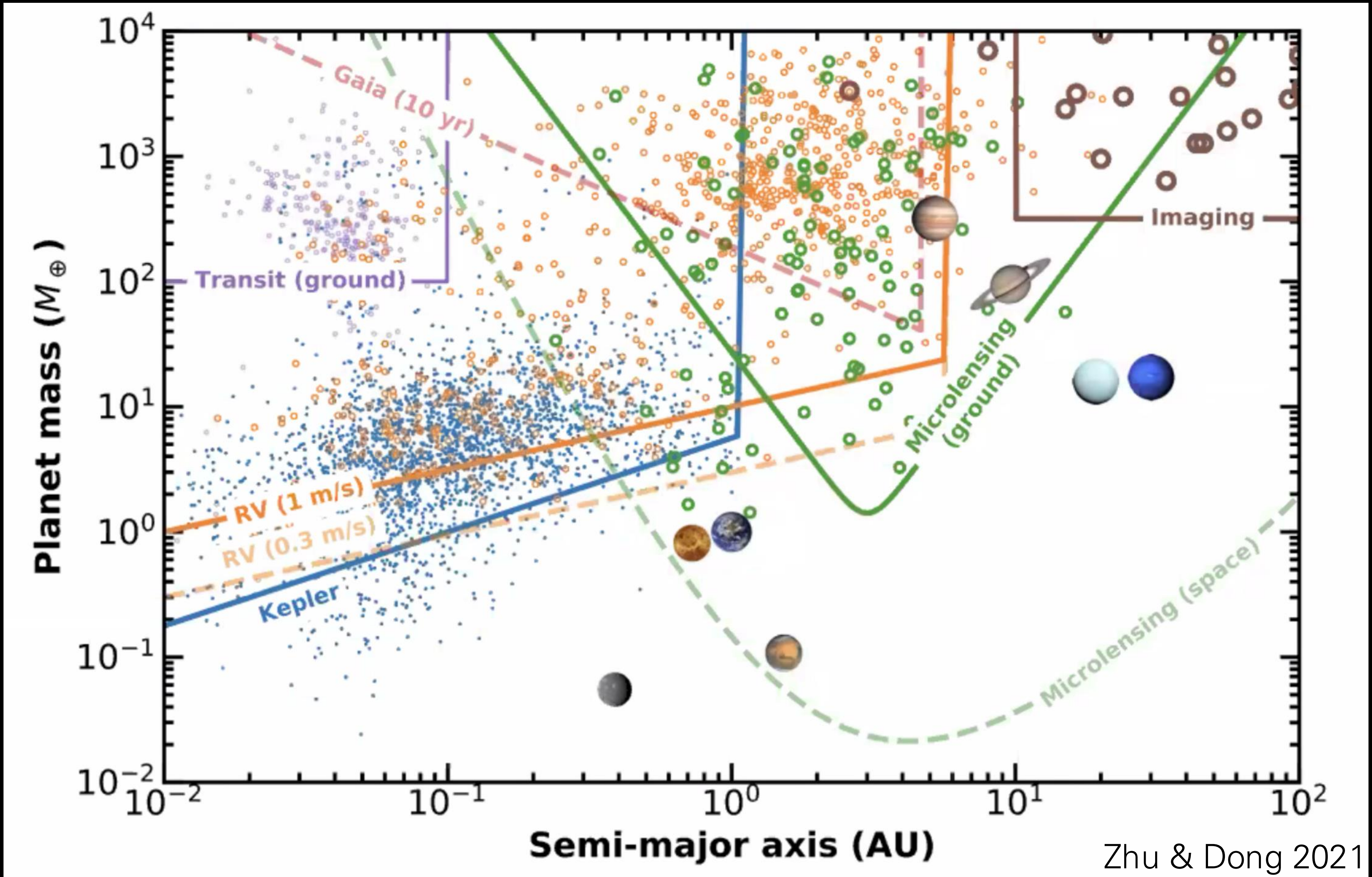
# This is likely also true for reflected light spectra (HWO)




**Mass uncertainties better than 10$\sigma$ are necessary to accurately identify secondary gasses in the atmospheres of Earth-like planets**

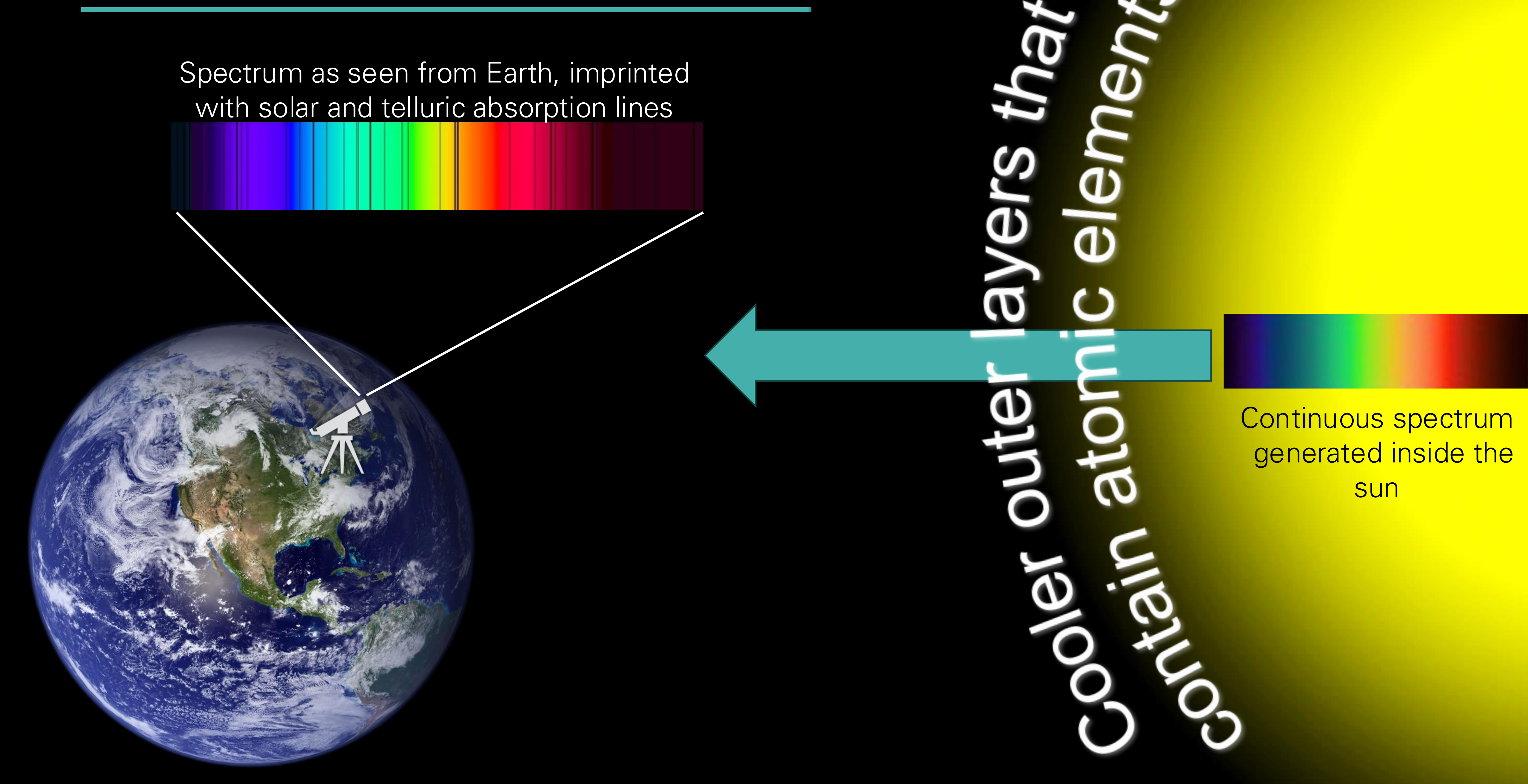
Damiano et al. 2025



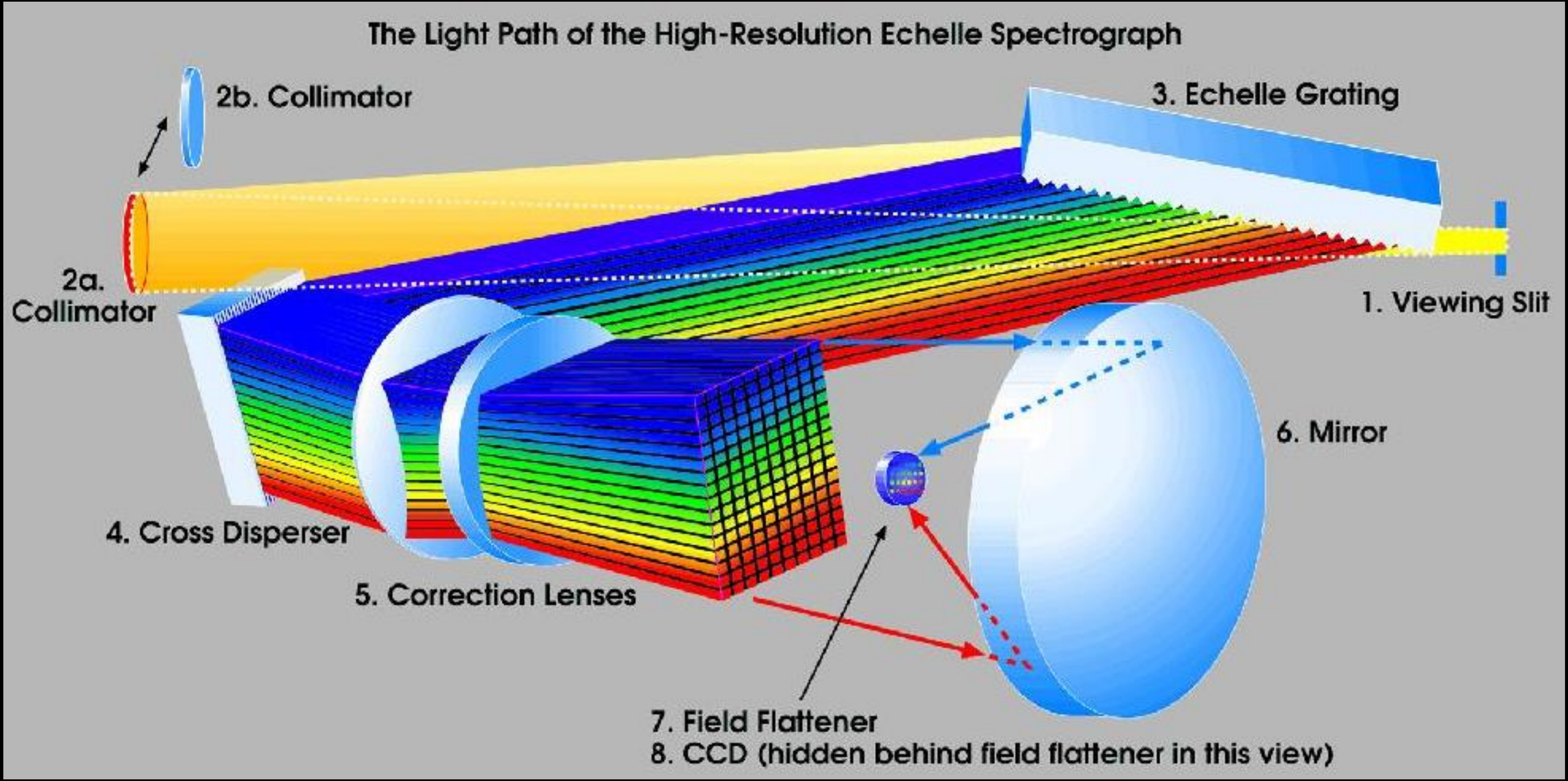

Zhu & Dong 2021


National Aeronautics and Space Administration
Exoplanet Missions
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
4 ESA/Swiss Space Office
5 NSF Partnership (NN-EXPLORE)
Roman
Habitable Worlds Observatory
JWST2
TESS
NASA Missions
Kepler/K2 [retired]
ARIEL (CASE1)
PLATO
Spitzer [retired]
CHEOPS4
ESA Partner Missions
Hubble1
Pandora
NASA Cube/Small Satellites
Ground Telescopes with NASA Participation
W. M. Keck Observatory
Large Binocular Telescope
WIYN5
SMARTS 1.5m5
MINERVA-Australis5
www.nasa.gov
All of these have / will soon have radial velocity instruments on them

# Radial Velocities are an indirect detection technique

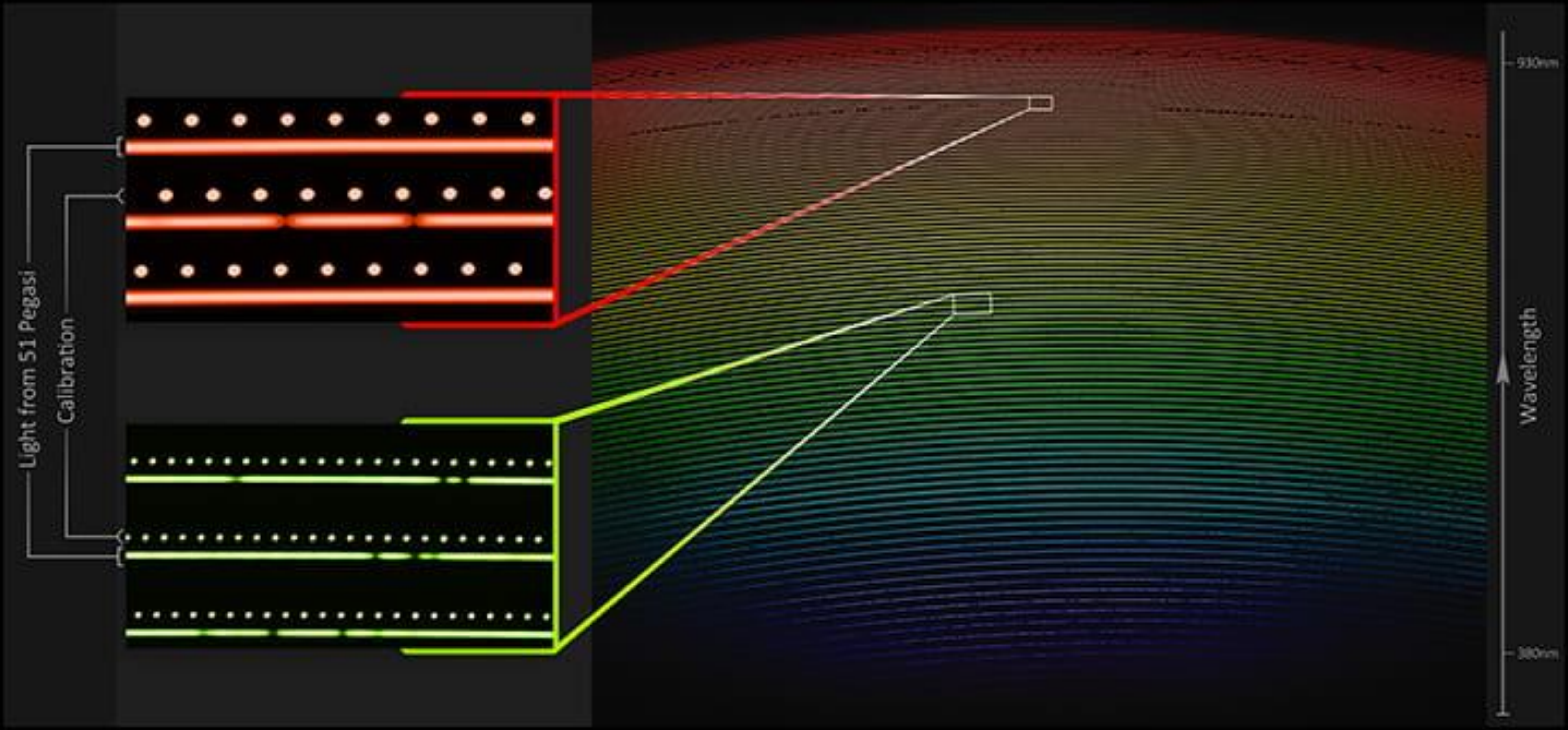

Spectrum as seen from Earth, imprinted with solar and telluric absorption lines
Cooler outer layers that contain atomic elements
Continuous spectrum generated inside the sun

# Échelle spectrographs

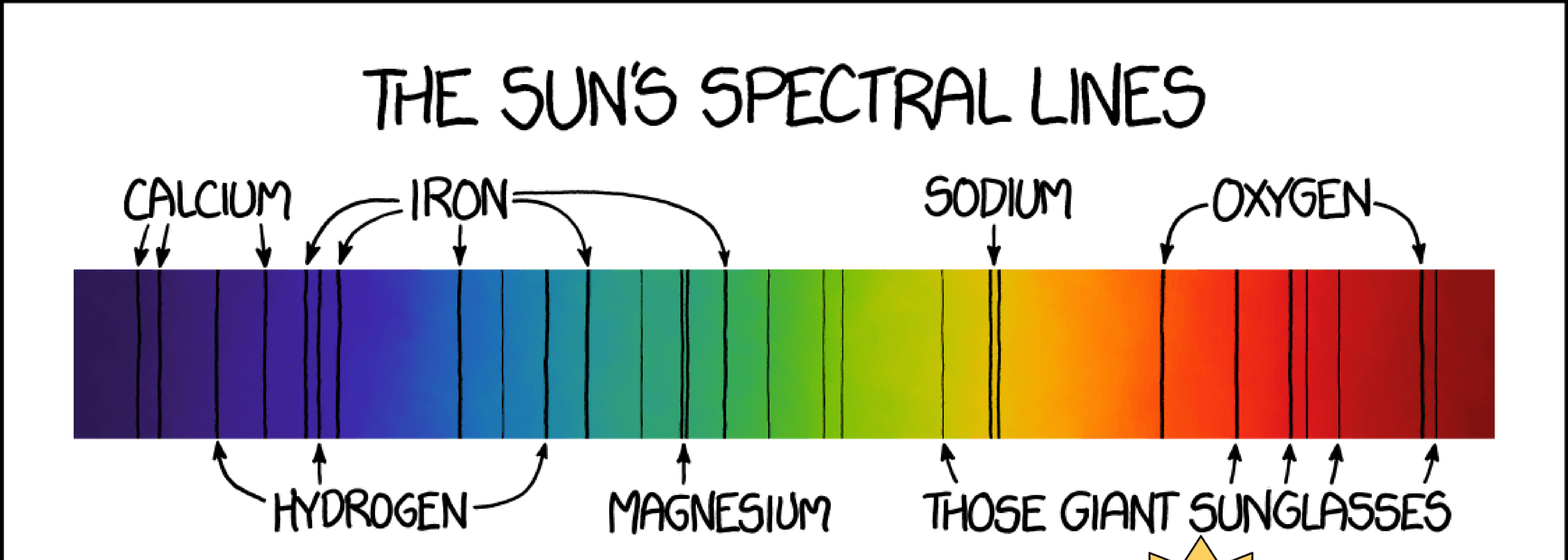



HIRES, courtesy Keck Observatory

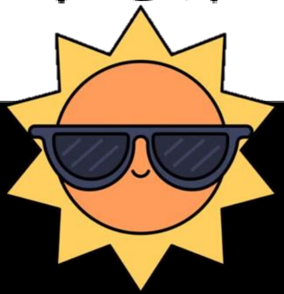
# Échelle spectrographs

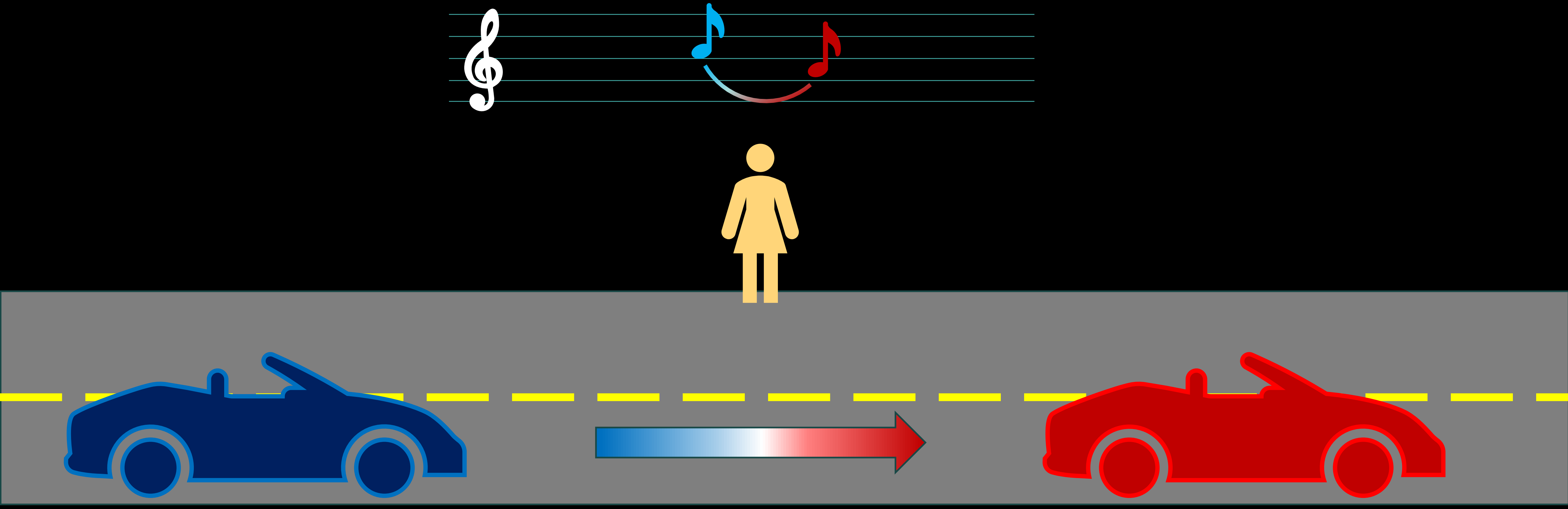



NEID First light announcement

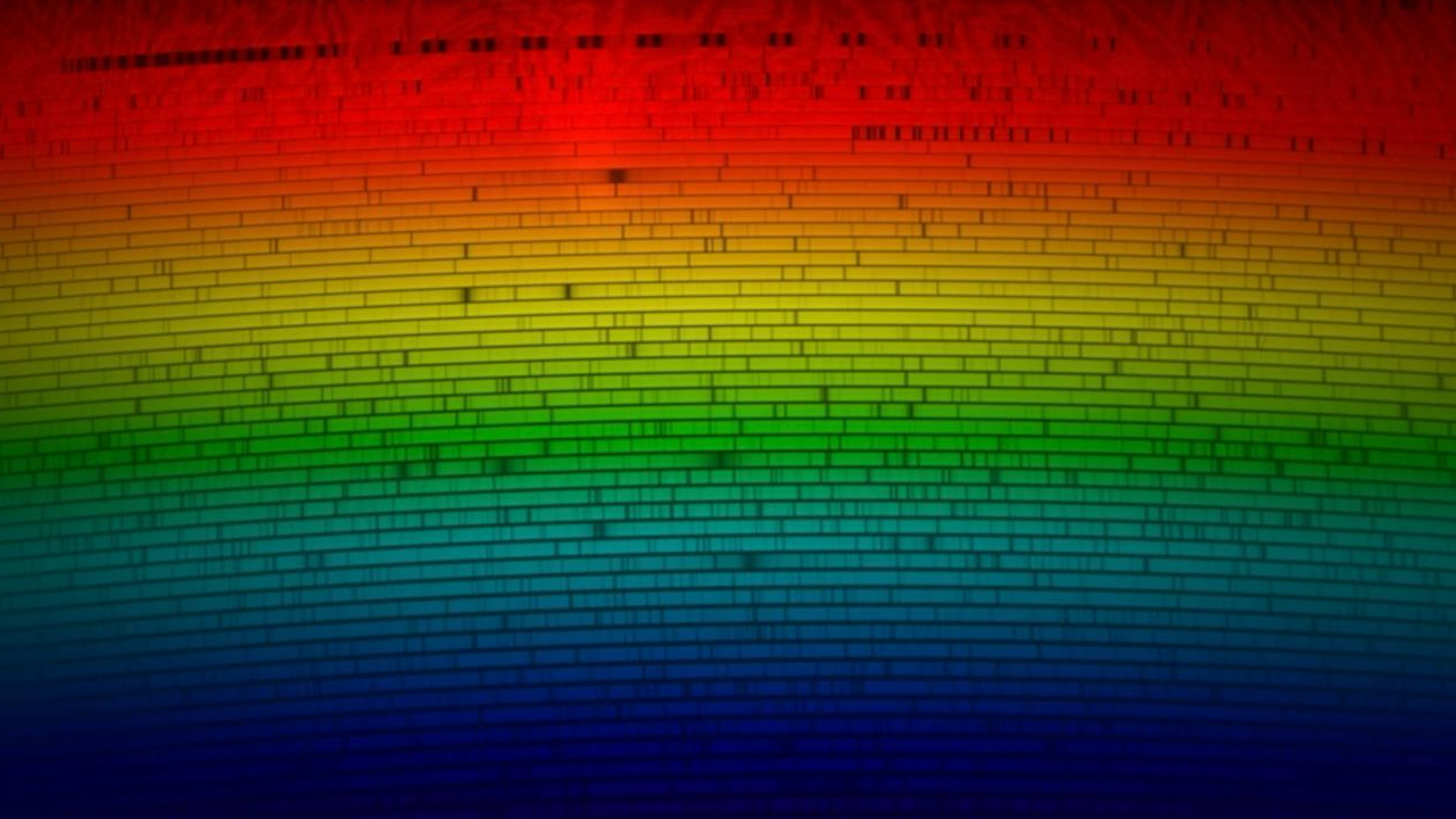



https://xkcd.com/1733/



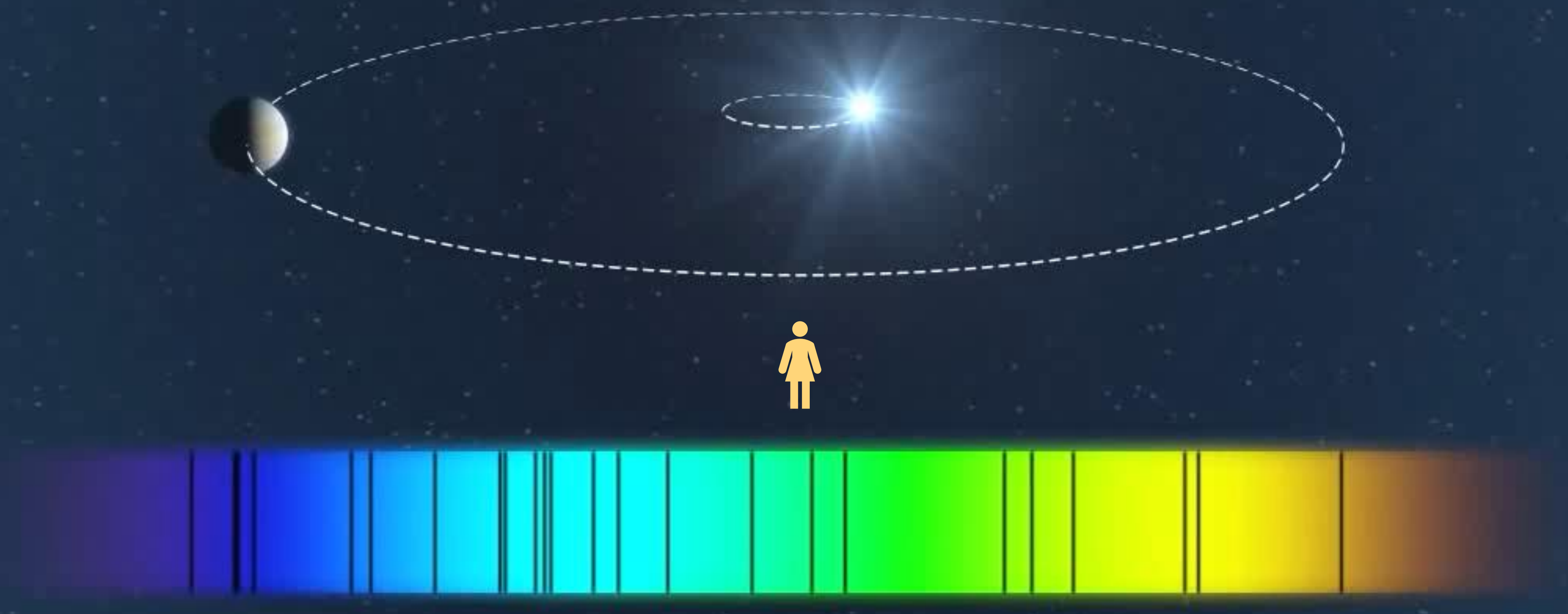


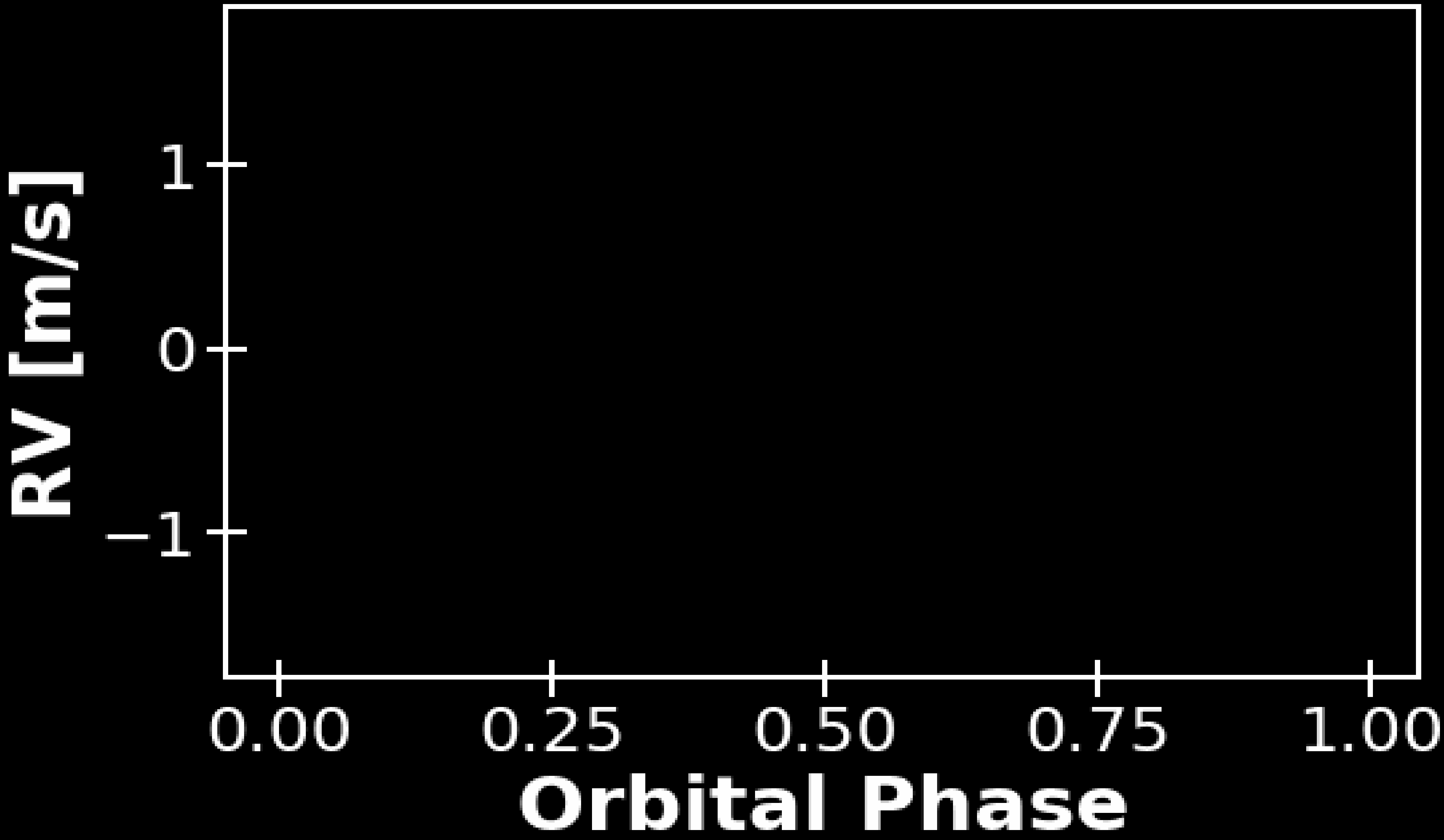
$$f_{obs} = \frac{(v + v_o)}{(v - v_s)} f$$



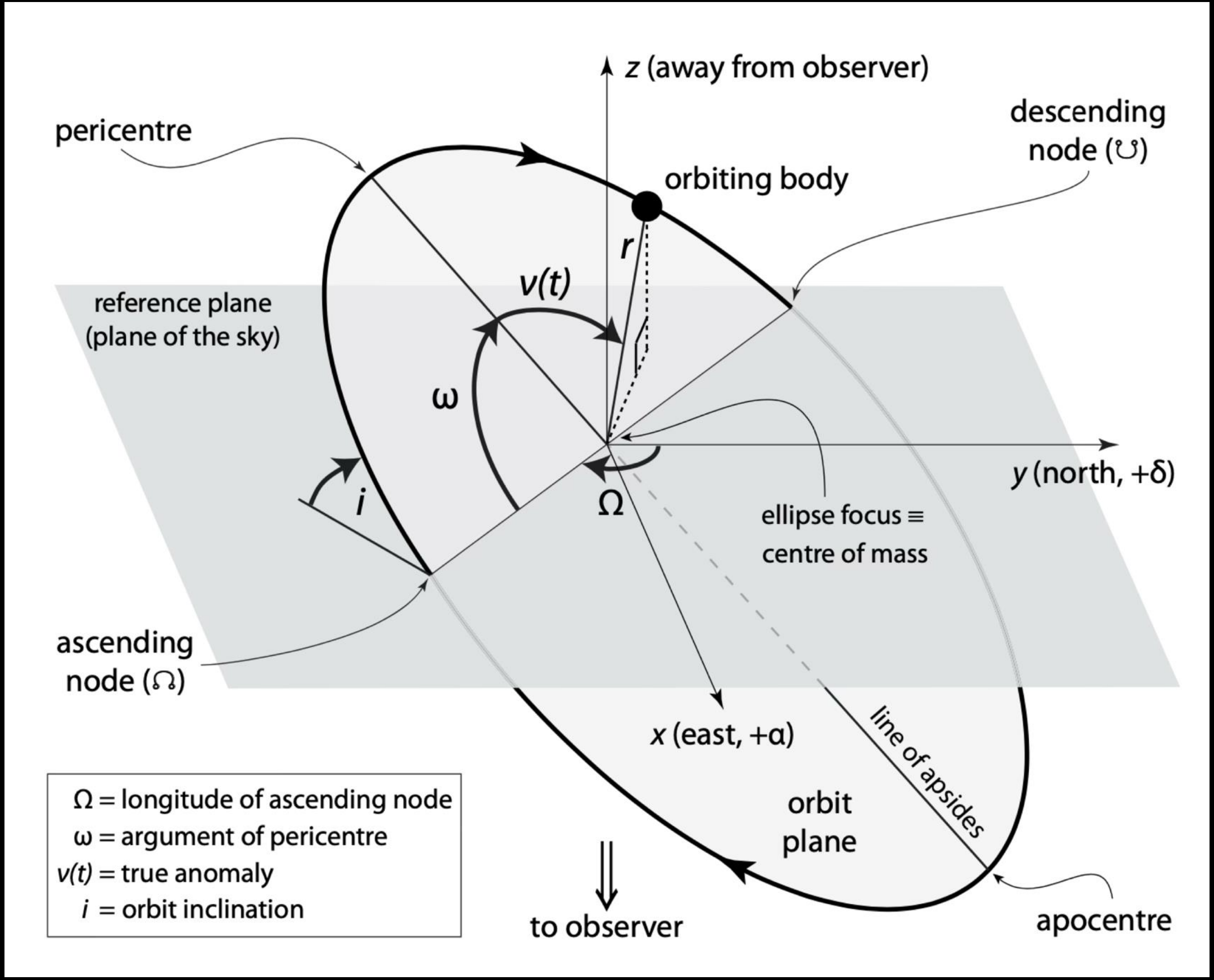
$$f_{obs} = \frac{(v + v_o)}{(v - v_s)} f$$

$$\frac{\Delta\lambda}{\lambda_o} = \frac{v}{c}$$




RV [m/s]
1
0
−1
0.00
0.25
0.50
0.75
1.00
Orbital Phase

# Planetary Orbits




## Need 7 elements to define a Keplerian orbit in 3D

$a$ : semi-major axis of the orbit
$e$ : eccentricity of the orbit
$P$ : orbital period
$t_p$ : position of the planet at pericenter

$i$ : orbital inclination w.r.t. the reference plane. Zero inclination is face on orbit (can't do RV), 90° inclination is edge on orbit (best for RV)
$\Omega$ : longitude of the ascending node, where the object moves away from the observer through the plane of reference
$\omega$ : angular coordinate of the object's pericenter relative to its ascending node, measured in the orbital plane and in the direction of motion.

# Planetary Orbits

## The parameters we generally derive when fitting RV data are a little different

Period [days] : Time the planet takes to complete one orbit around its host star

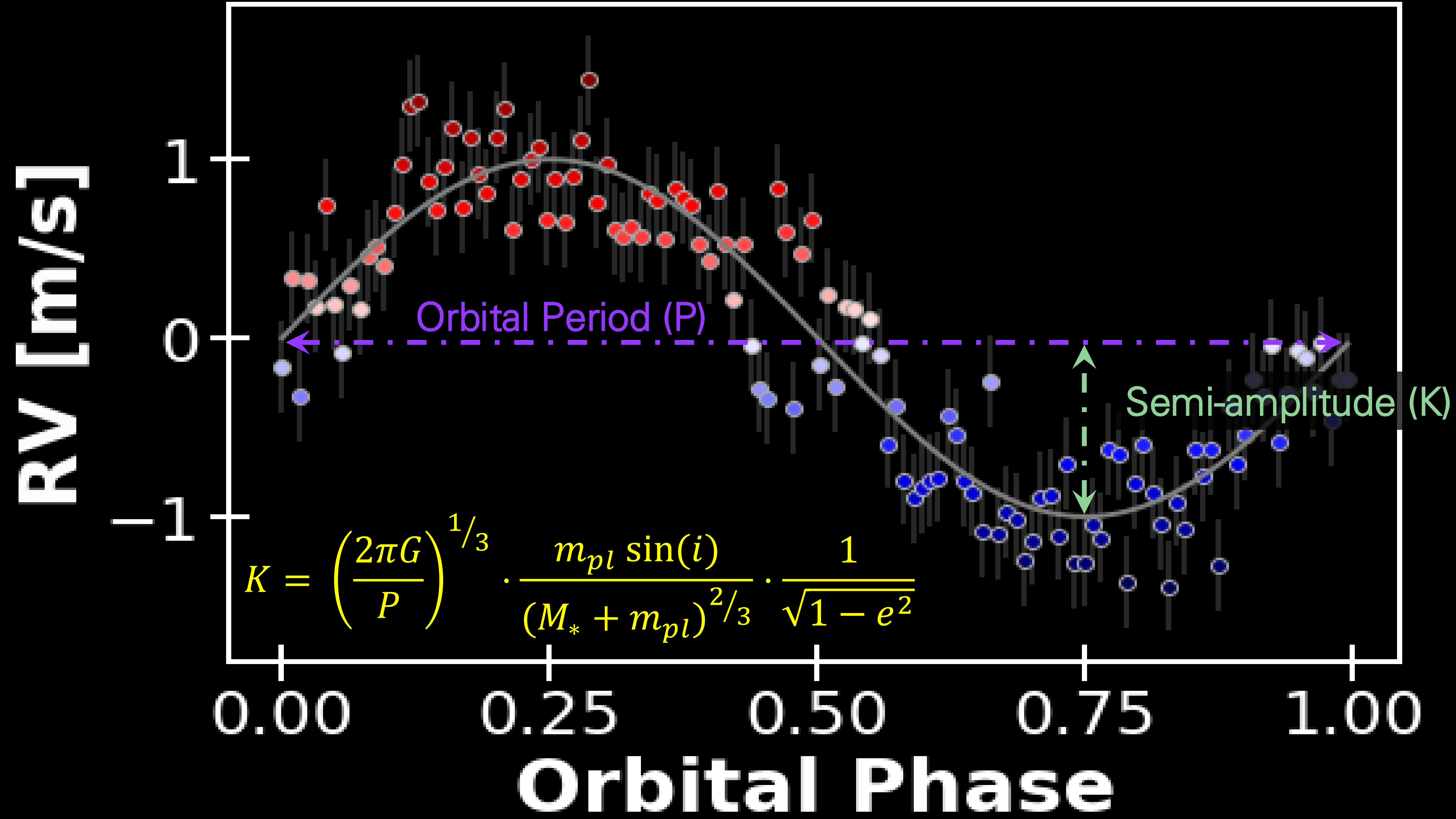
Semi-amplitude [m/s] : Peak velocity of the reflex motion a planet imparts on its host star

Eccentricity : Ellipticity of the planet's orbit

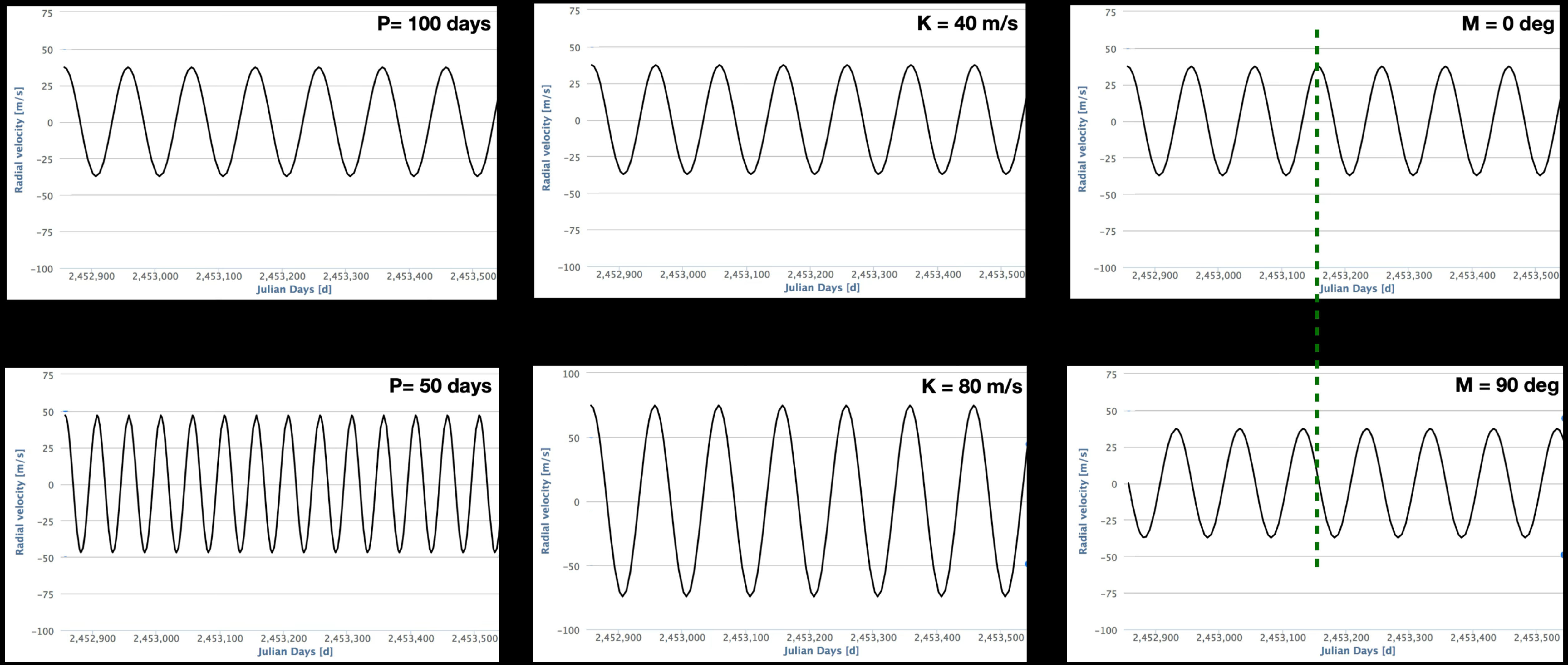
Longitude of periastron [deg] : Orbital angle at which the planet goes through periastron

Time of periastron [JD] : Date when the planet passes through its periastron point

Mean anomaly [deg] : Angular distance from pericenter the planet would have if e=0


RV [m/s]
1
0
−1
Orbital Period (P)
Semi-amplitude (K)
$K = \left(\frac{2\pi G}{P}\right)^{1/3} \cdot \frac{m_{pl}\sin(i)}{(M_* + m_{pl})^{2/3}} \cdot \frac{1}{\sqrt{1-e^2}}$
0.00
0.25
0.50
0.75
1.00
Orbital Phase

# What do these parameters do to the shape of an RV orbit?



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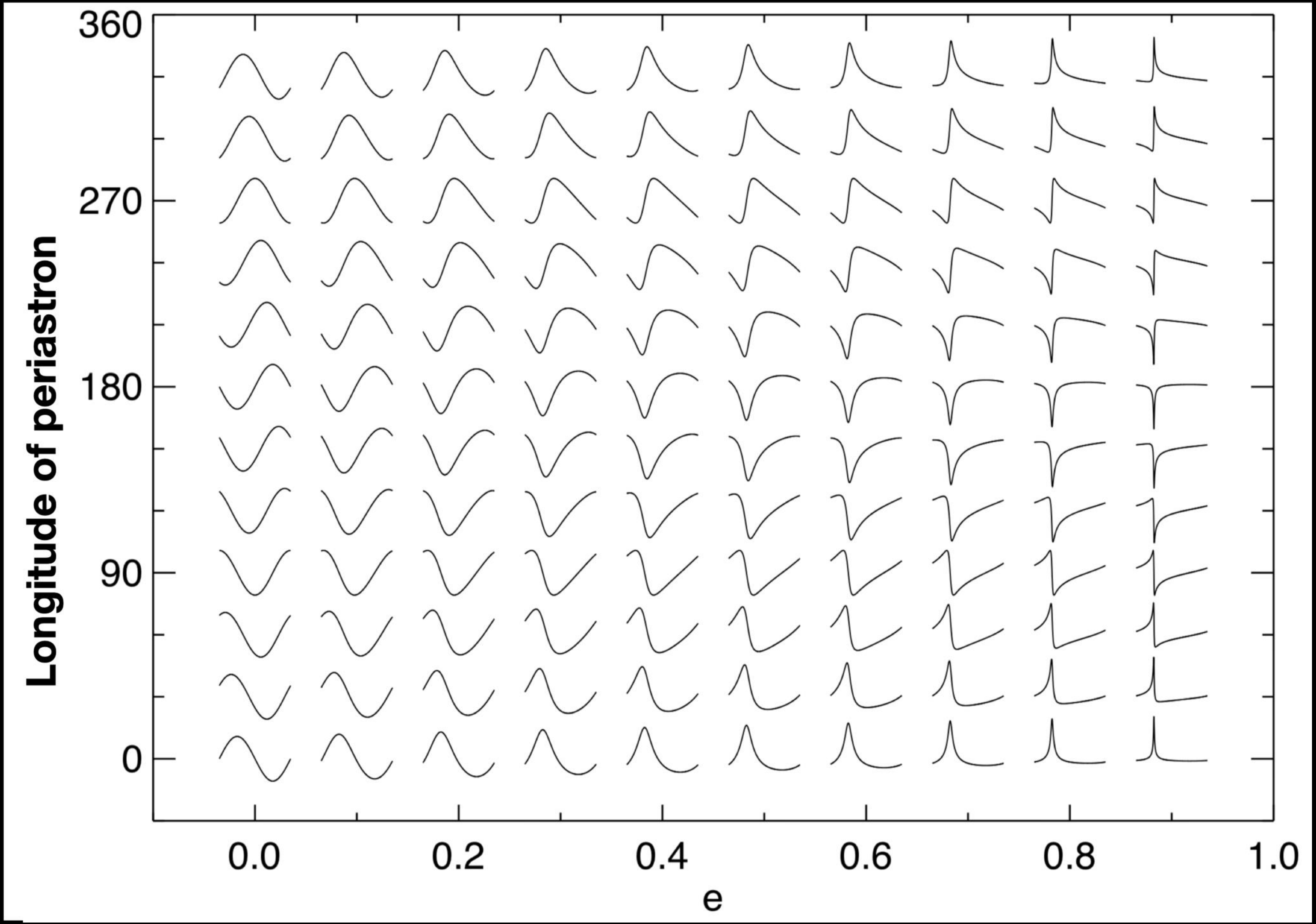
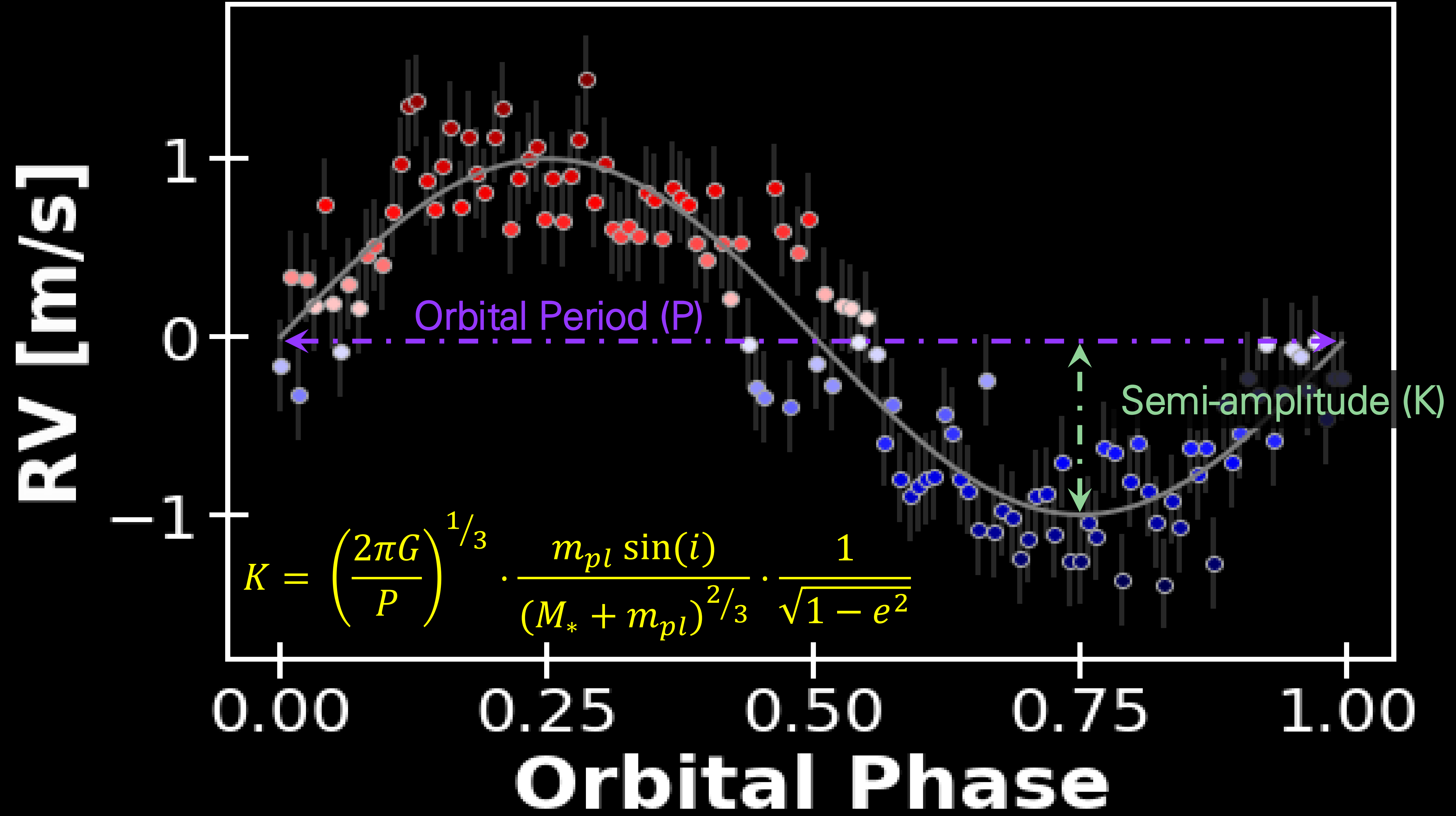


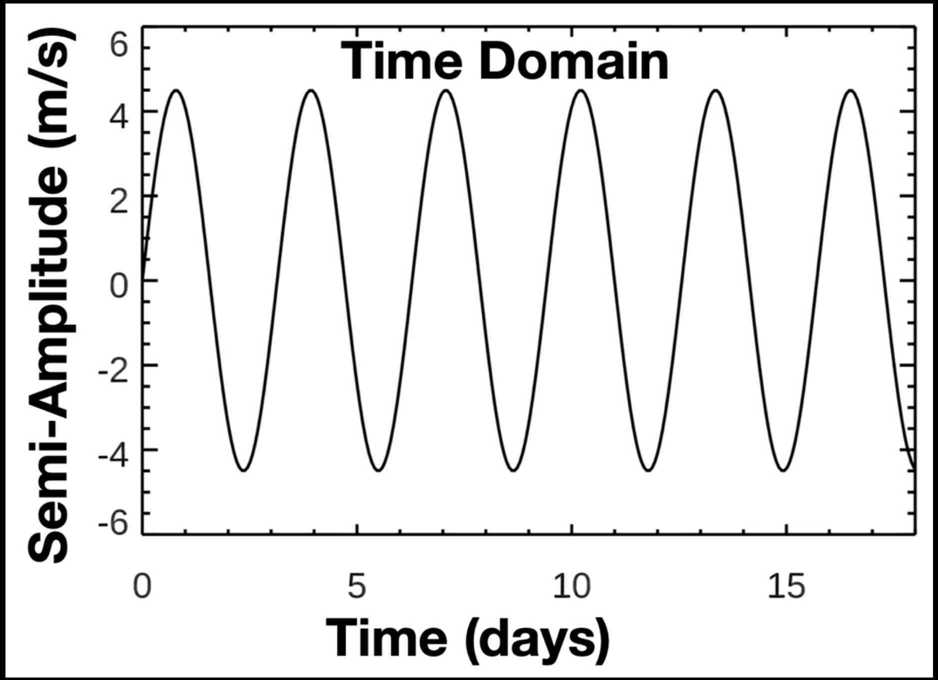

Rubenzahl 2024



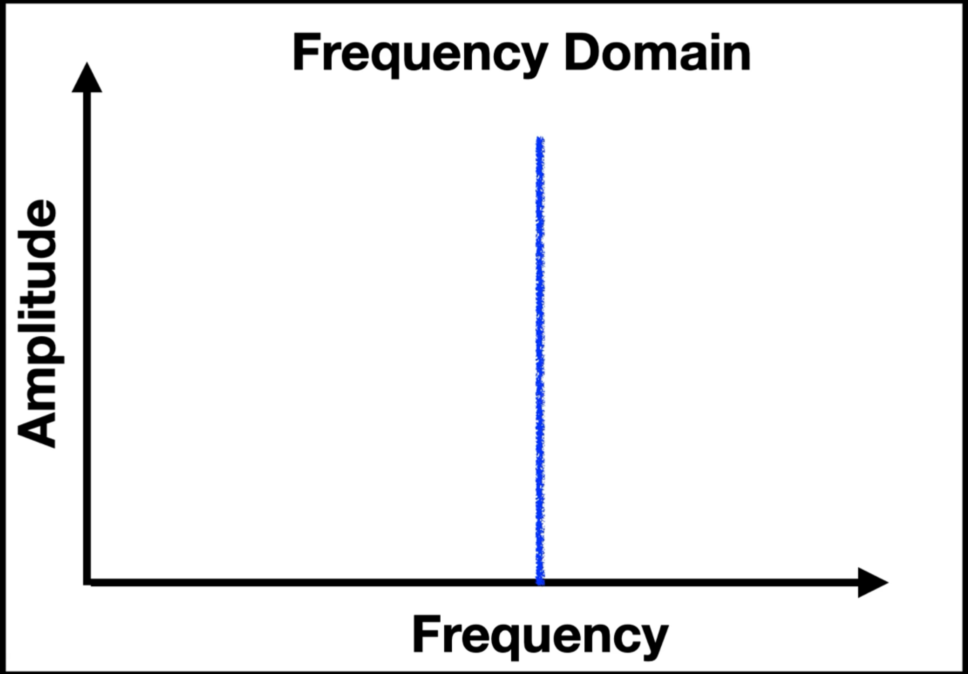
RV [m/s]
1
0
−1
Orbital Period (P)
Semi-amplitude (K)
$K = \left(\frac{2\pi G}{P}\right)^{1/3} \cdot \frac{m_{pl}\sin(i)}{(M_* + m_{pl})^{2/3}} \cdot \frac{1}{\sqrt{1-e^2}}$
0.00
0.25
0.50
0.75
1.00
Orbital Phase

# RV points to planets

Idealized case: Use a discrete fourier transform (DFT) to identify perfectly sinusoidal signals in time series data

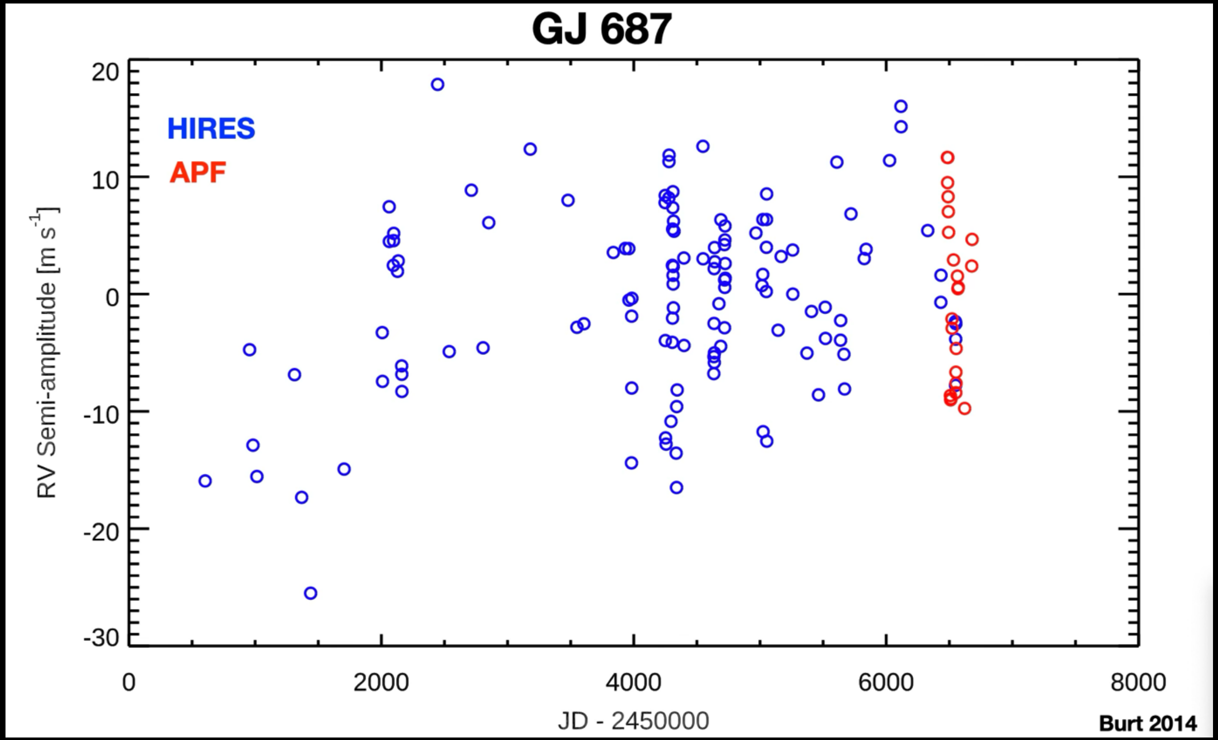


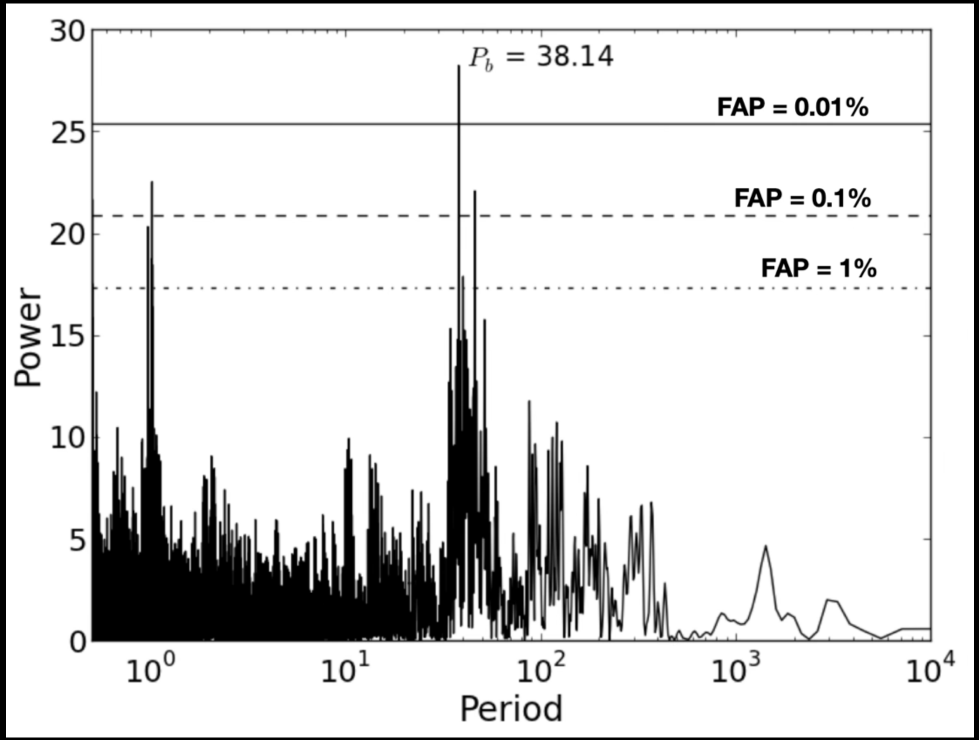

$$\mathrm{DFT}_X(\omega) = \sum_{i=1}^{N} X(t_j)e^{-i\omega t_j}$$



# RV points to planets

Realistic case: Use a Lomb-Scargle periodogram to identify sinusoidal signals in unevenly sampled time series data

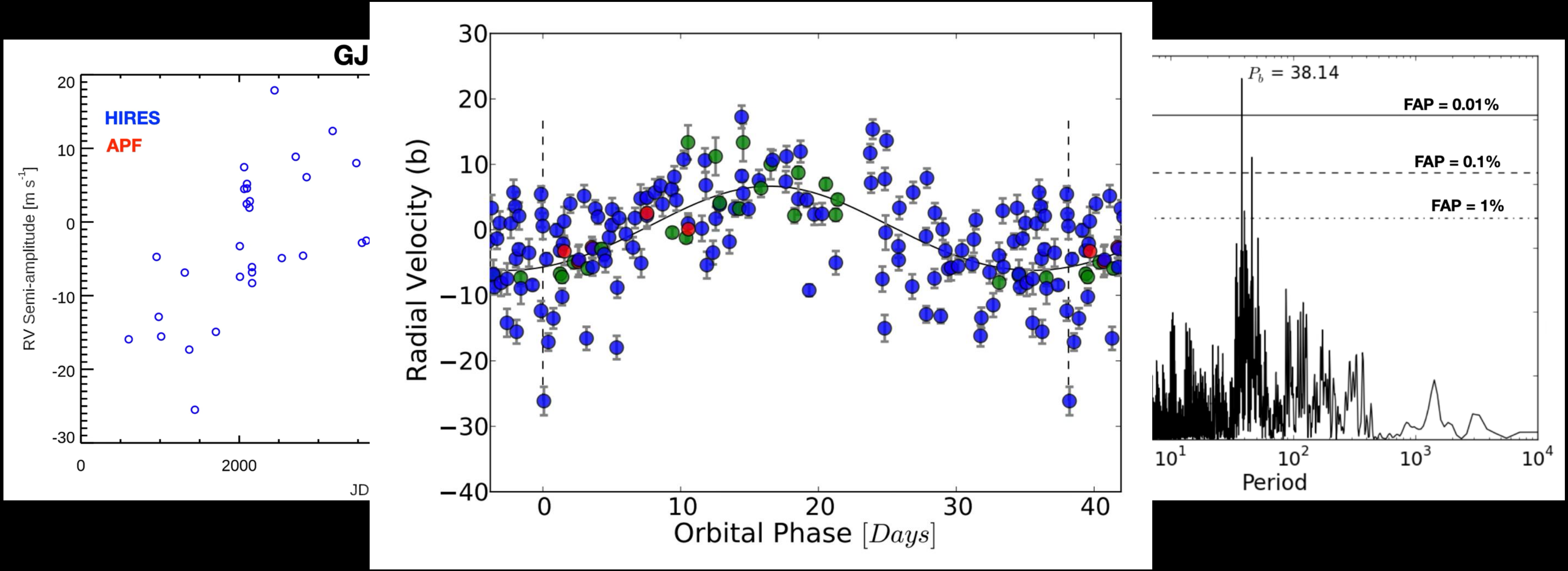



Burt et al. 2014

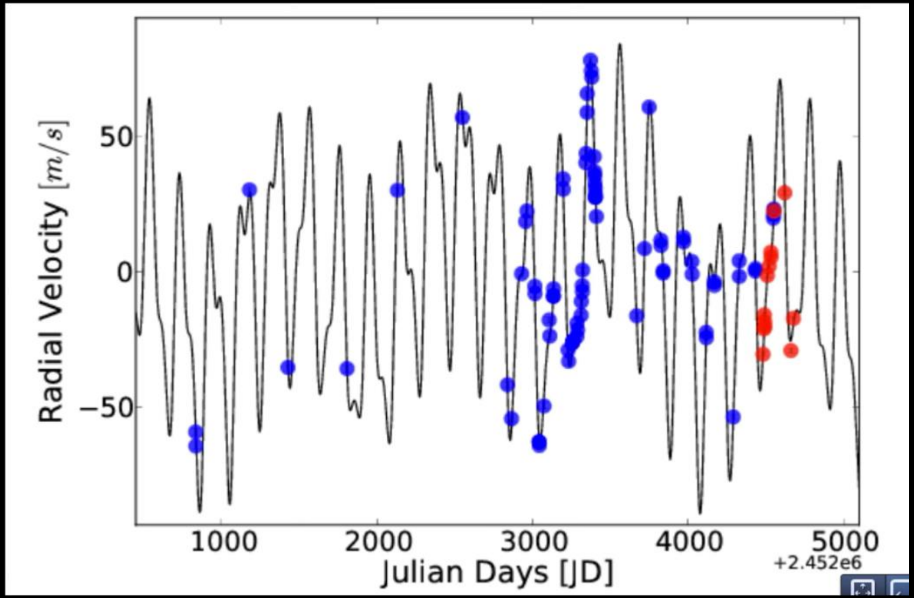
# RV points to planets

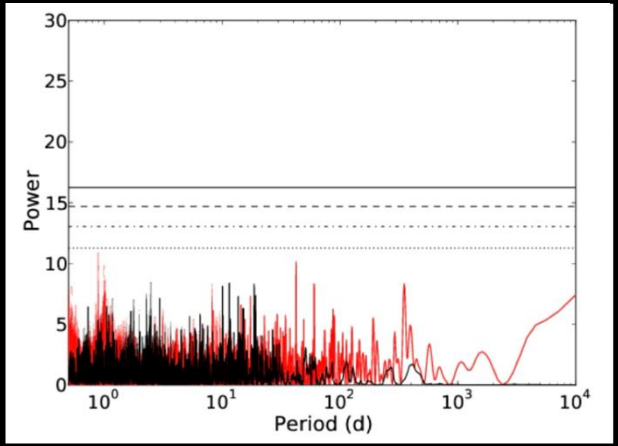
Realistic case: Use a Lomb-Scargle periodogram to identify sinusoidal signals in unevenly sampled time series data

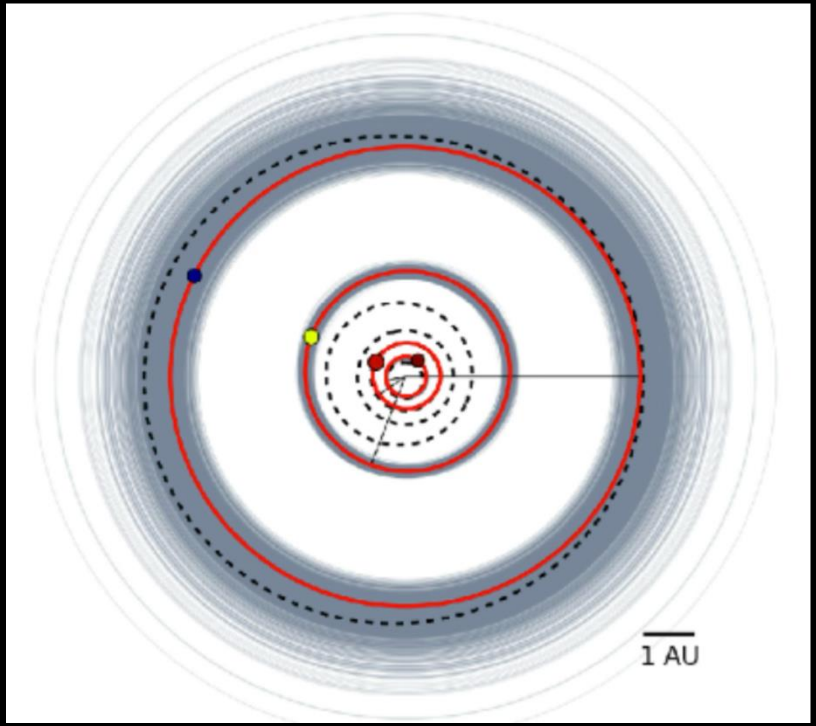



Burt et al. 2014

# RV points to planets

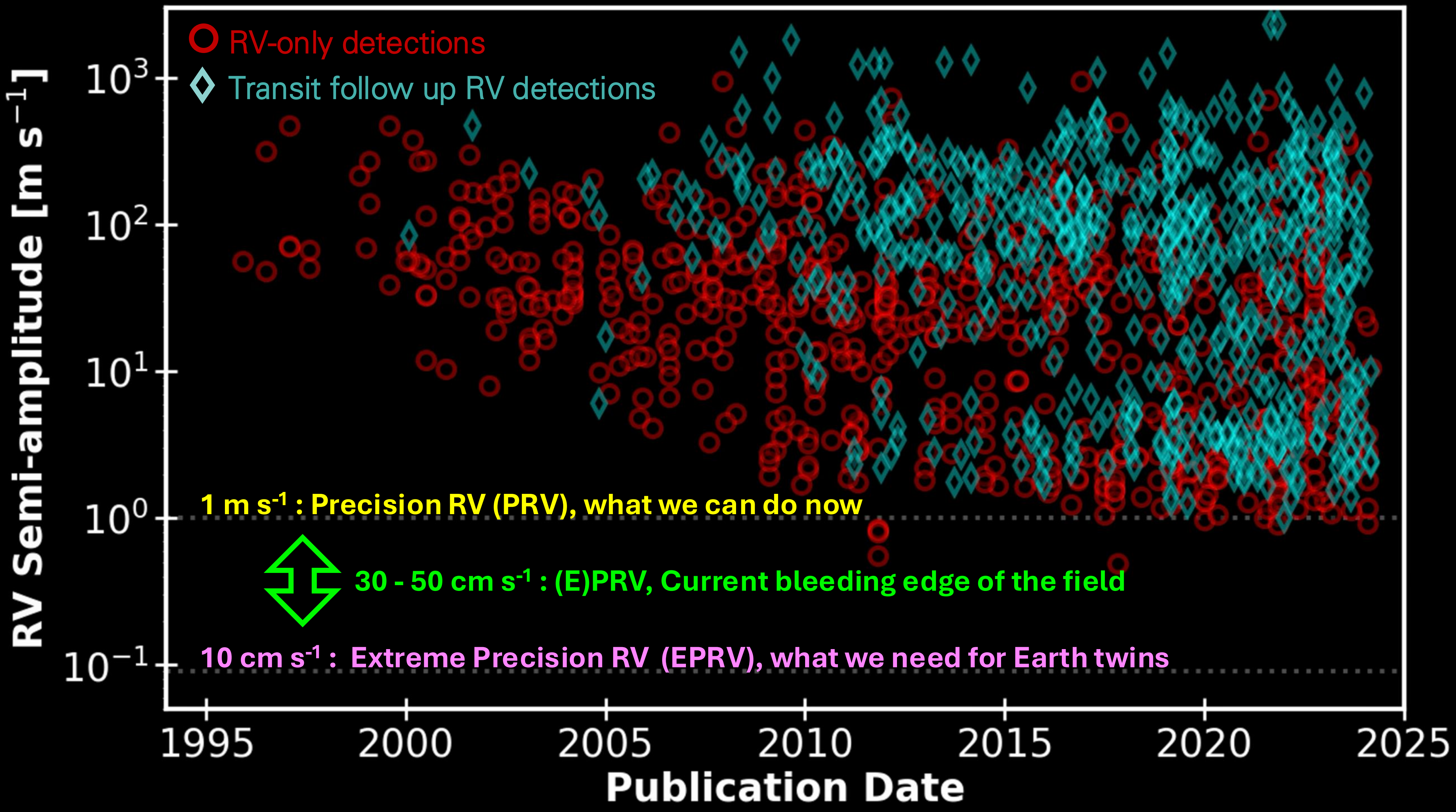


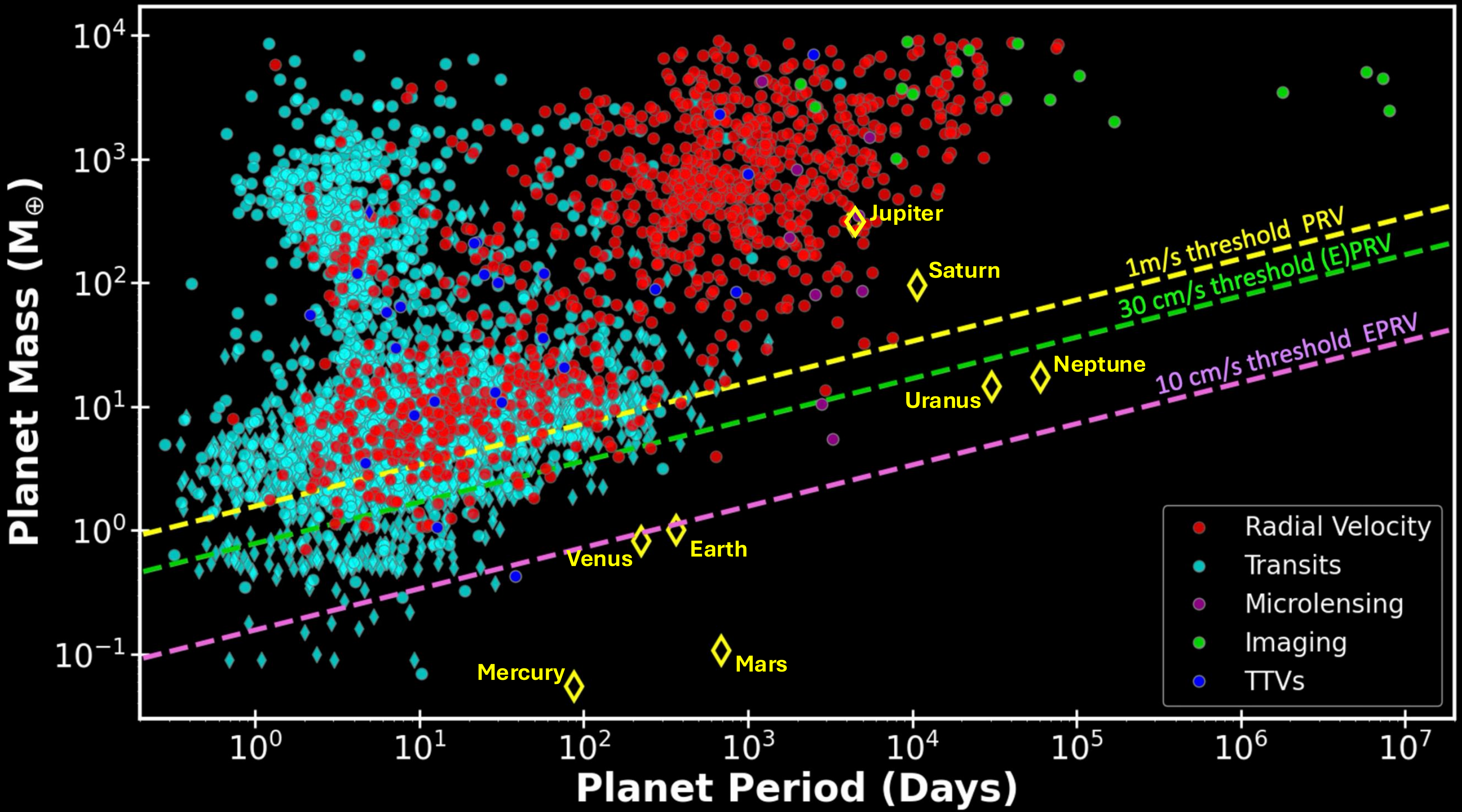




Vogt et al. 2014

# What can we currently detect?

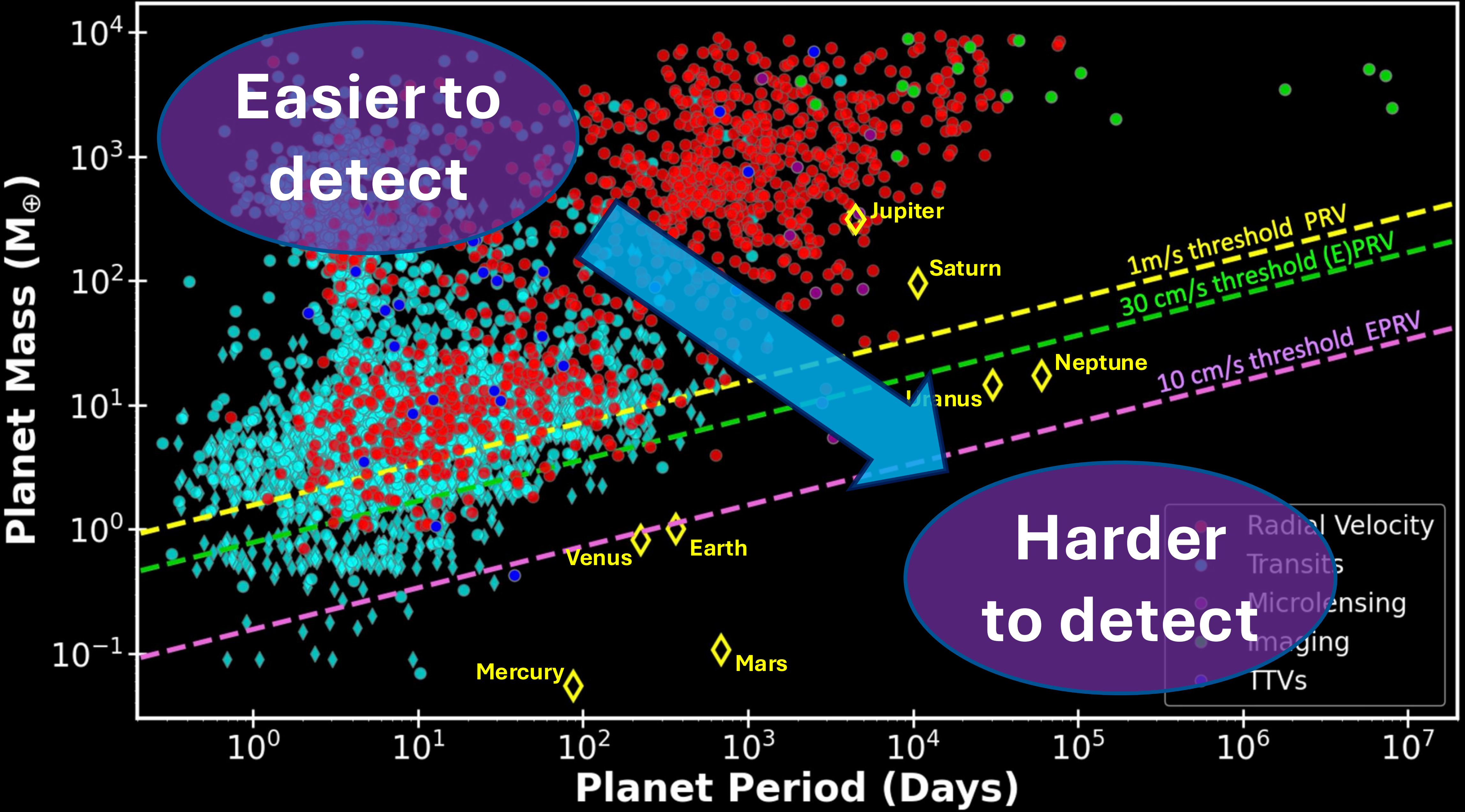


# What can we currently detect?

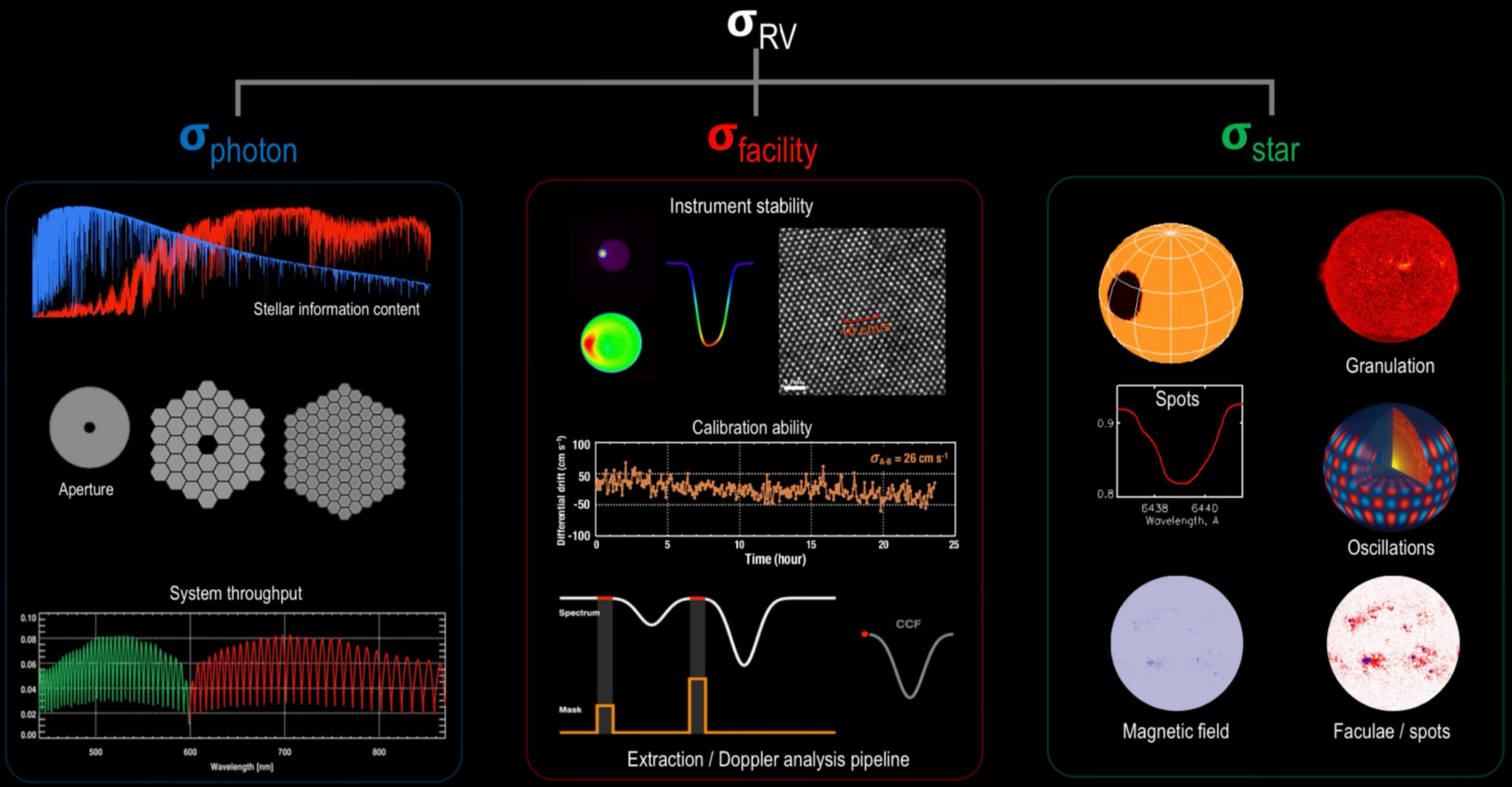


# What can we currently detect?

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \cdot \frac{m_{pl}\sin(i)}{(M_* + m_{pl})^{2/3}} \cdot \frac{1}{\sqrt{1-e^2}}$$

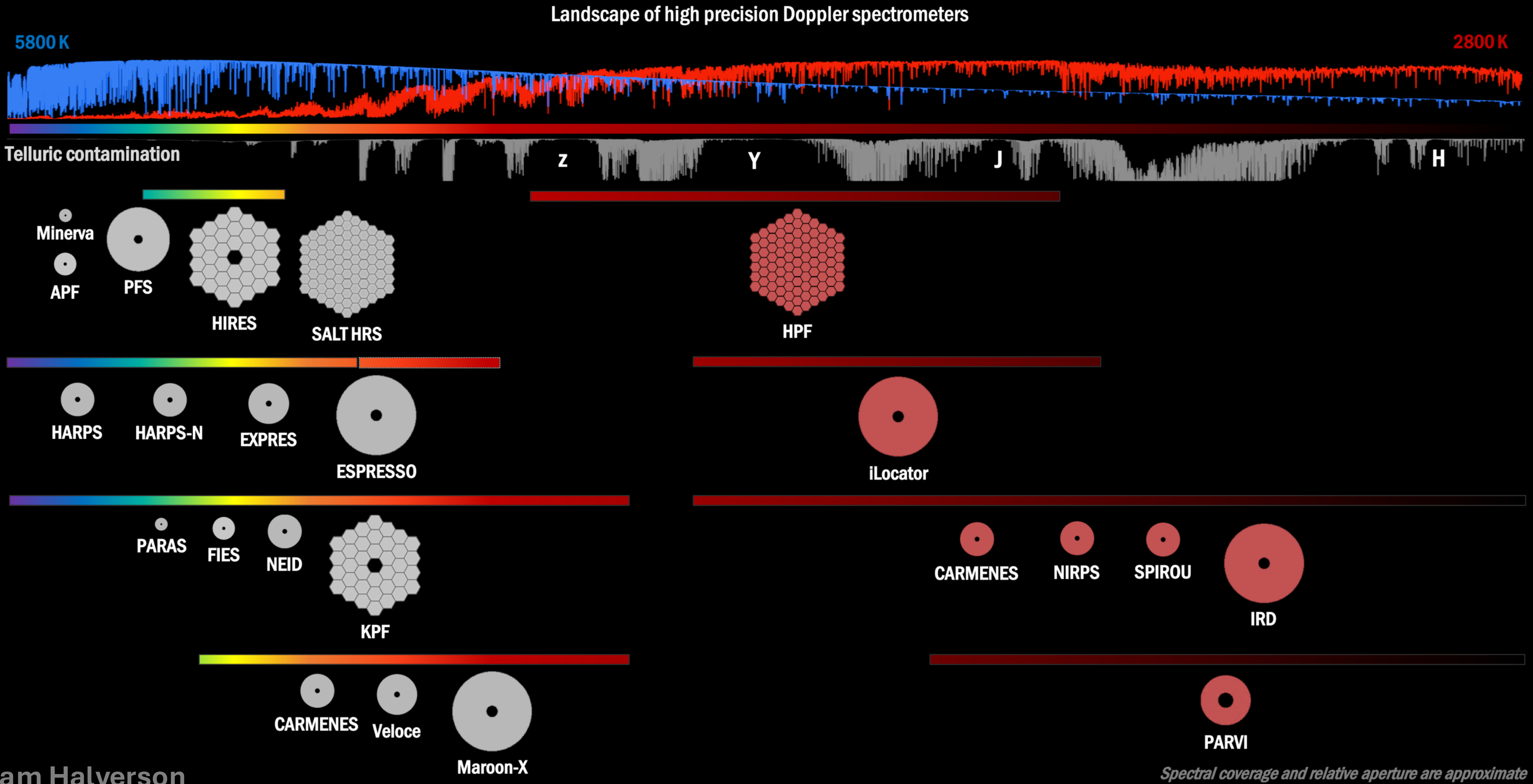


# RV Uncertainty Contributions




Sam Halverson

# RV Uncertainty Contributions – photon noise



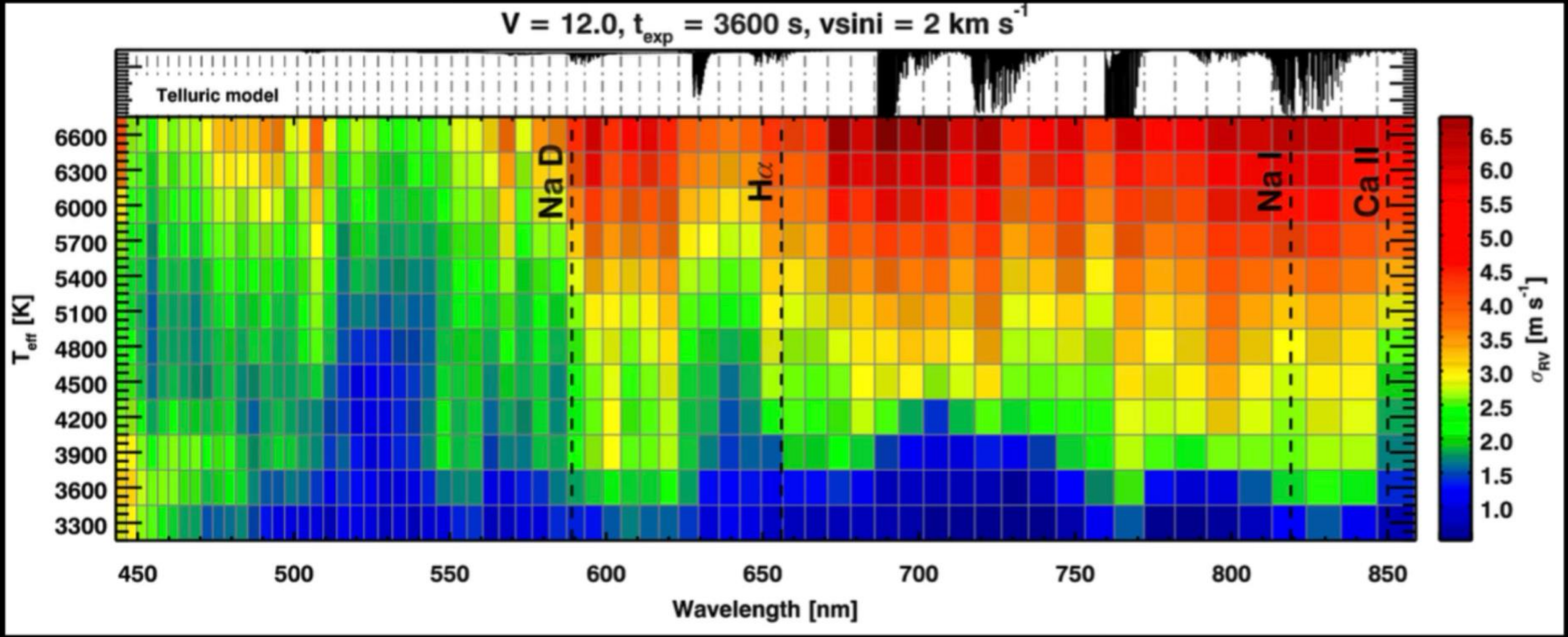

Sam Halverson

# RV Uncertainty Contributions – stellar information content

Beatty & Gaudi 2015

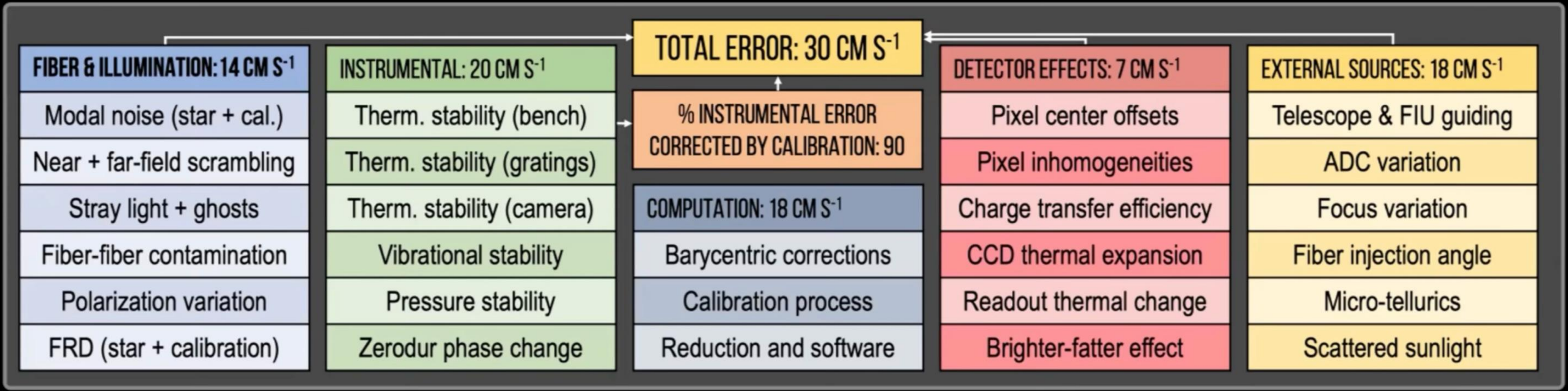
$$\sigma_V = \frac{1}{\sqrt{\sum \frac{I_{0,i}}{\sigma^2_{V,i}}}} \left( \frac{0.5346\Theta_0(T_{eff})}{\Theta_0(T_{eff})} + \frac{\sqrt{0.2166\Theta_0^2 + \Theta_R^2 + 0.518\,\Theta_{rot}^2 + \Theta_{mac}^2}}{\Theta_0(T_{eff})} \right)^{3/2} \times f(T_{eff})\ f(\log g)\ f([\mathrm{Fe/H}]).$$

- Effective Temperature
- Rotational Velocity
- Surface Gravity
- Metallicity
- Macroturbulent Velocity



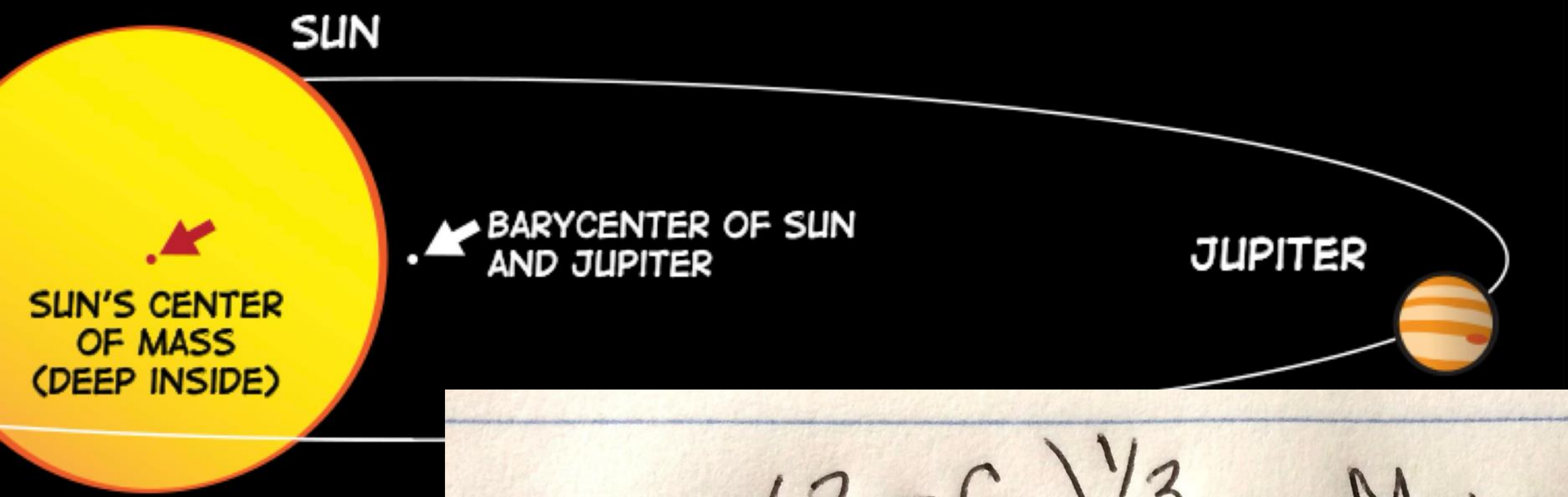

Sam Halverson

# RV Uncertainty Contributions -- facility




Gibson et al. 2024

# Setting the Scale




$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \cdot \frac{M_{pl} \cdot \sin(i)}{(M_{star} + M_{pl})^{2/3}}$$

$M_{Sun} = 1.98 \times 10^{30}$ kg

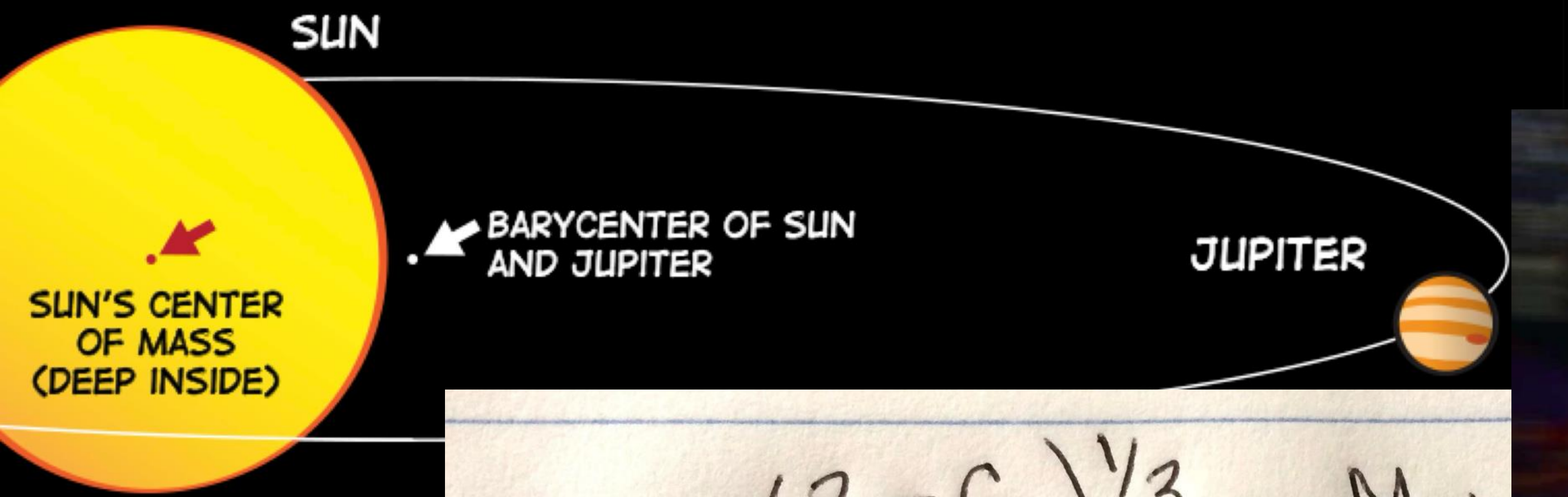
$M_{Jupiter} = 1.89 \times 10^{27}$ kg

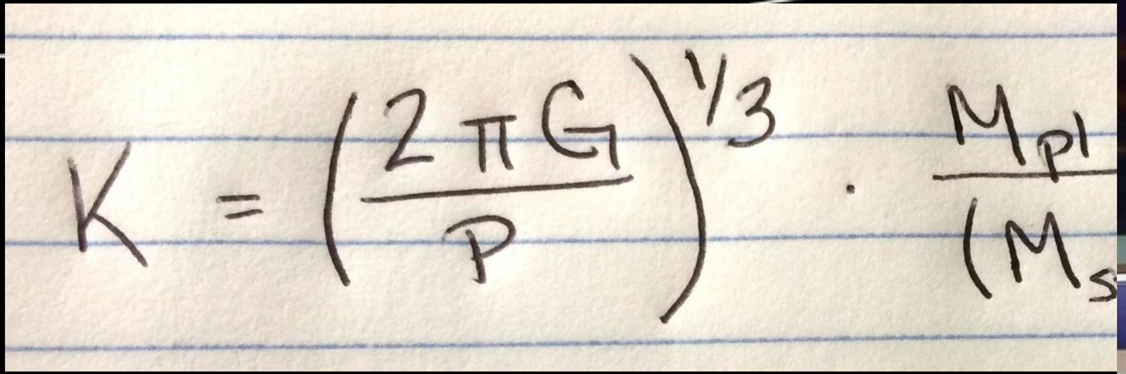
$P_{Jup} = 11.86$ years

G = 6.67 x 10-11 m3 kg$^{-1}$ s$^{-2}$

$$K = 12.46 \text{ m s}^{-1}$$

# Setting the Scale




Usain Bolt

12.07 m/s
(aka 27 mph)

$M_{Sun}$ = 1.98 x $10^{30}$ kg
$M_{Jupiter}$ = 1.89 x $10^{27}$ kg

$P_{Jup}$ = 11.86 years
G = 6.67 x 10-11 m3 $kg^{-1}$ $s^{-2}$

$$K = 12.46 \text{ m s}^{-1}$$

# Setting the Scale

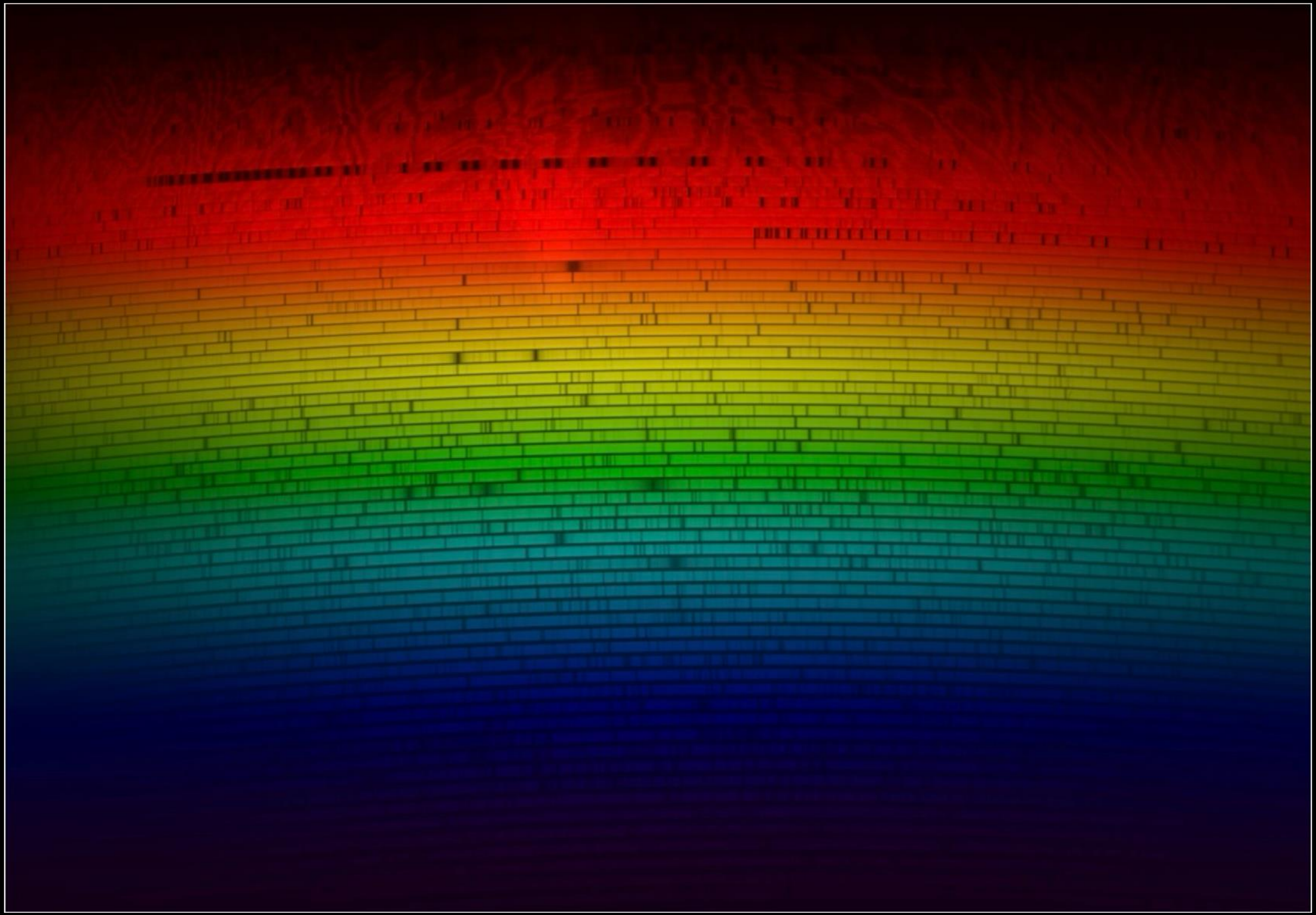
## Doppler Shift Equation

$$\frac{\Delta\lambda}{\lambda_o} = \frac{v}{c}$$

$K_{Jup} = 12.46 \text{ m s}^{-1}$

$\lambda_o = 510 \text{ nm}$

$\Delta\lambda = 2.11 \times 10^{-5} \text{ nm}$

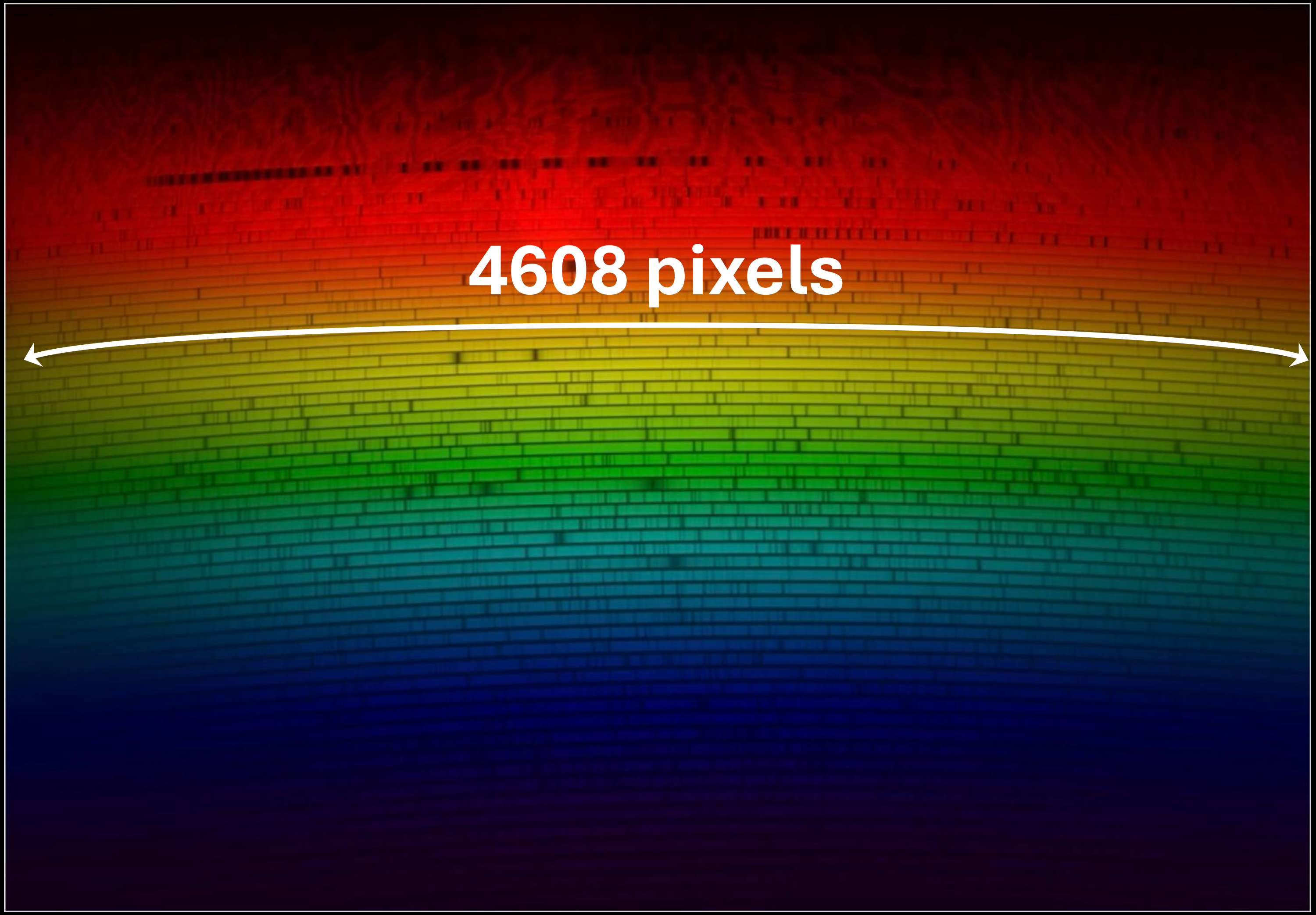


# Setting the Scale

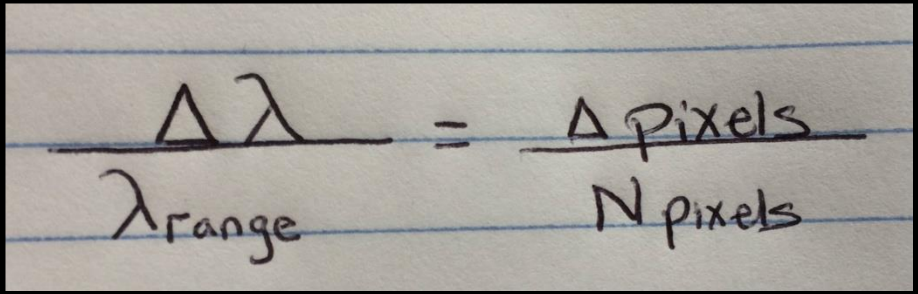
One order ~ 6nm

So what is our ***Δλ*** in pixels?

$$\frac{\Delta\lambda}{\lambda_{range}} = \frac{\Delta \text{pixels}}{N \text{ pixels}}$$



# Setting the Scale

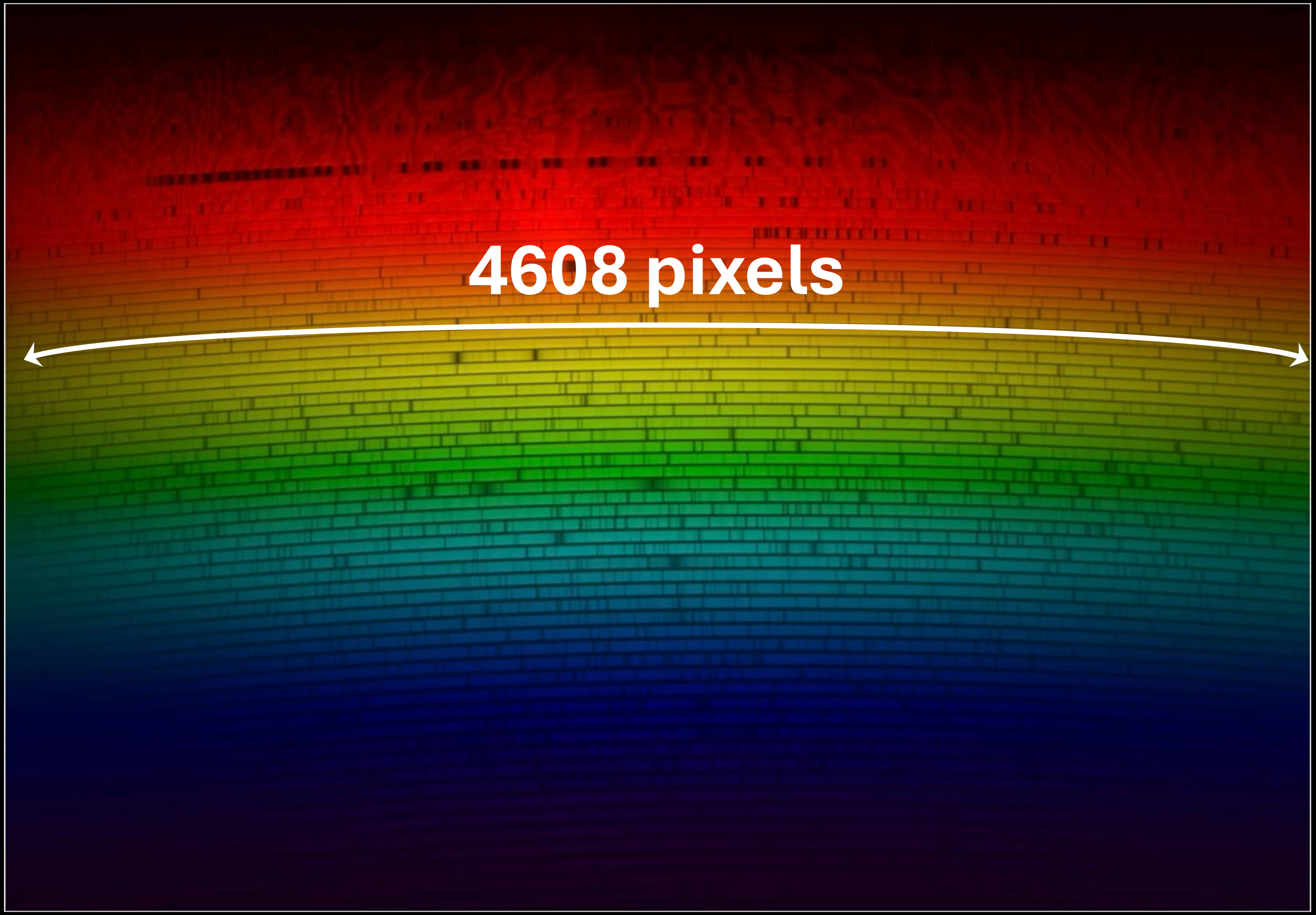



$\Delta\lambda = 2.11 \times 10^{-5}$ nm

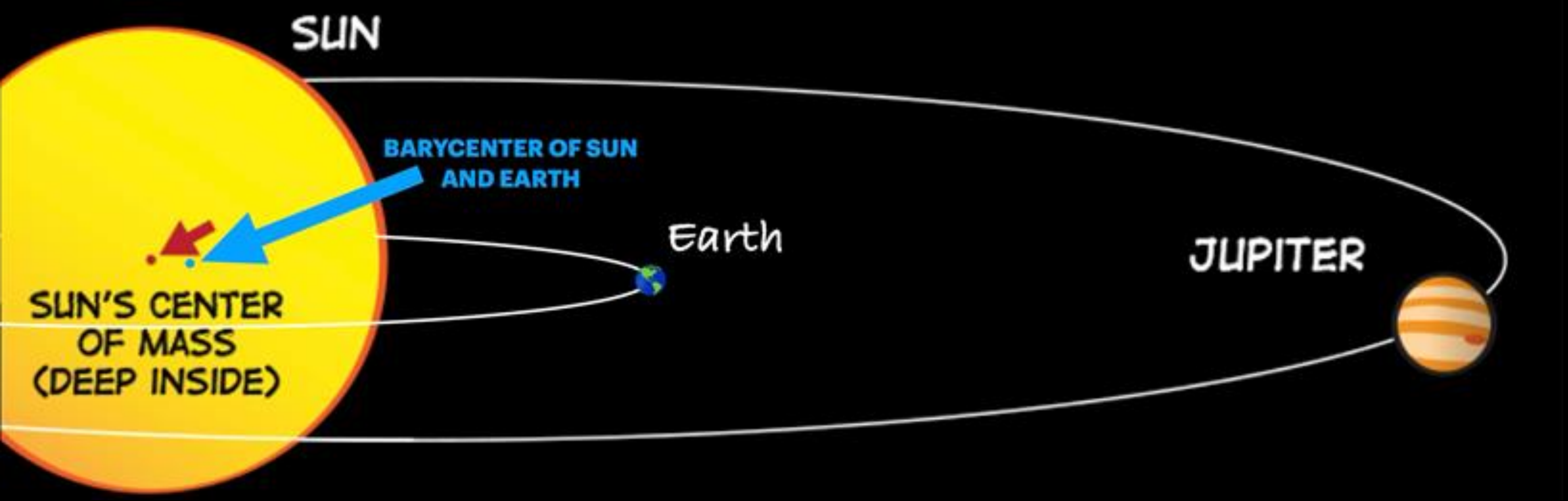
$\lambda_{range} = 6$ nm

$N_{pixels} = 4608$

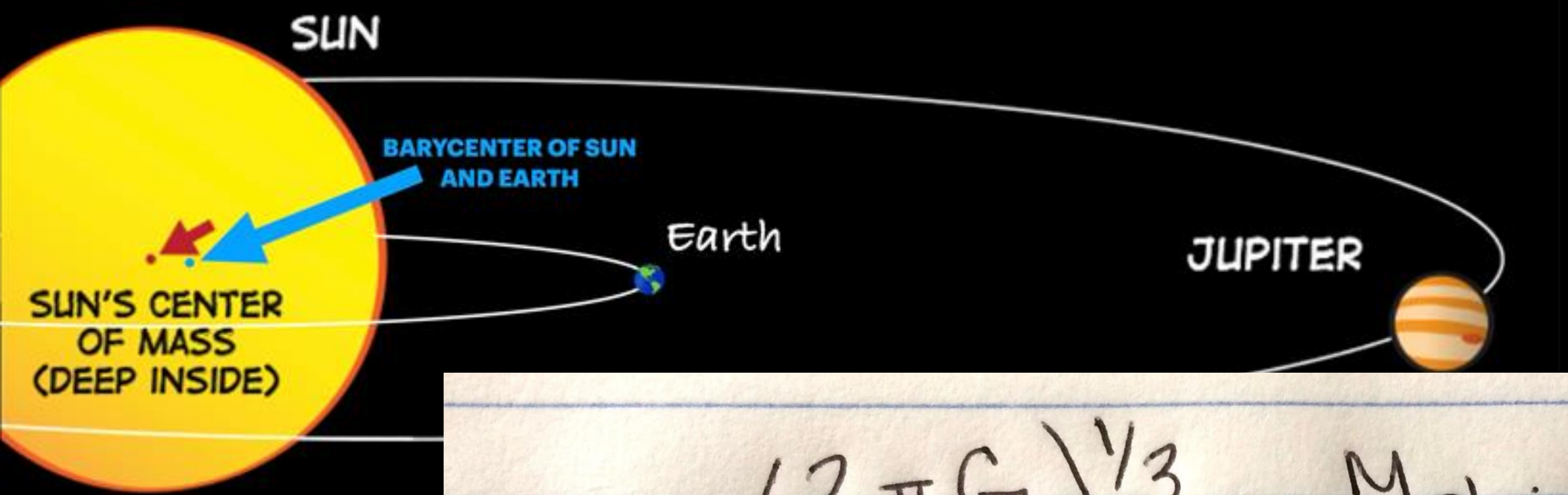
**$\Delta$pixels = 0.016 pix**



# Setting the Scale



# Setting the Scale



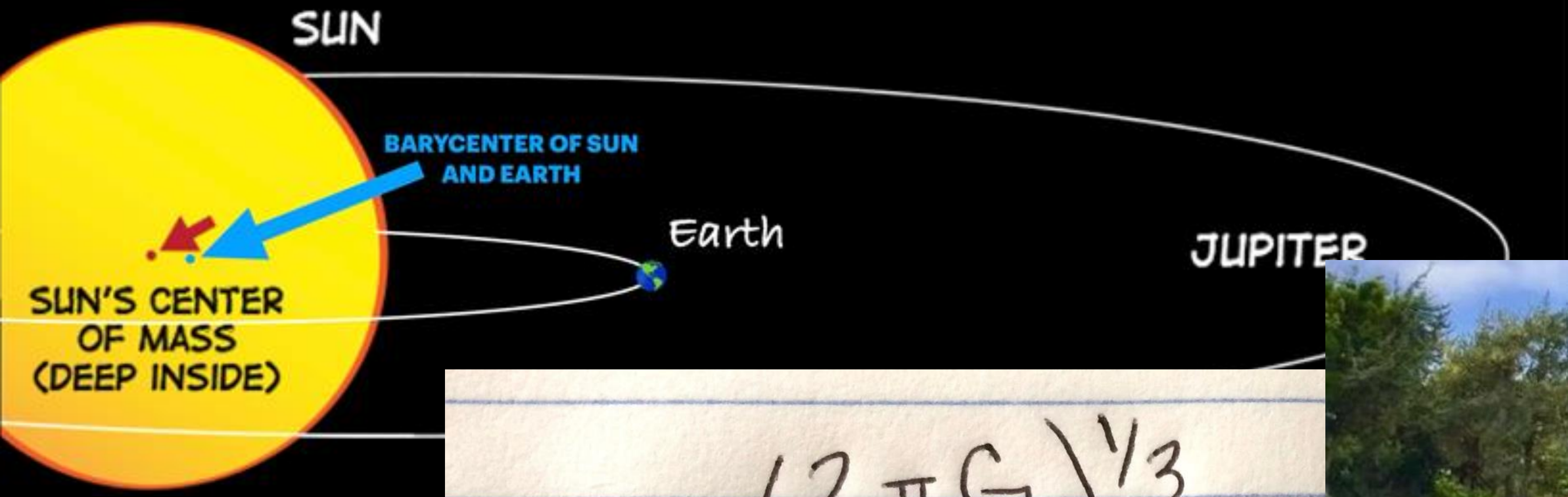

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \cdot \frac{M_{pl} \cdot \sin(i)}{(M_{star} + M_{pl})^{2/3}}$$

$M_{Sun} = 1.98 \times 10^{30}$ kg
$M_{Earth} = 5.97 \times 10^{24}$ kg

$P_{Earth} = 1.0$ years
$G = 6.67$ x 10-11 m3 kg$^{-1}$ s$^{-2}$

**$K = 0.09$ m s$^{-1}$**

# Setting the Scale

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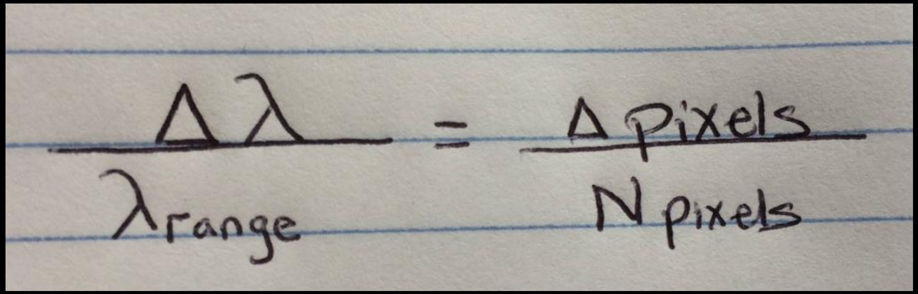
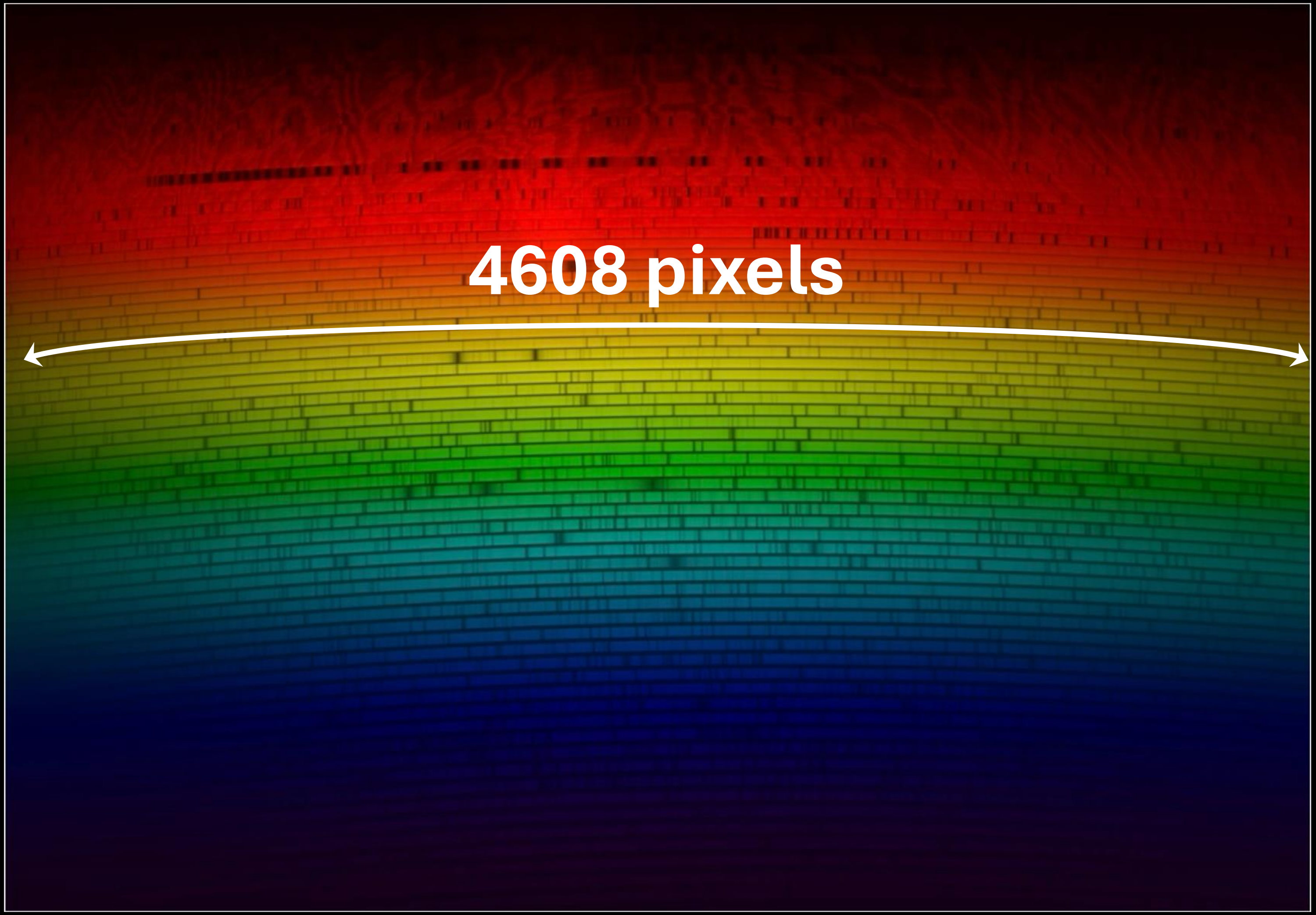



$K = 9\ cm\ s^{-1}$

$\Delta\lambda = 0.0000153$ nm
$\lambda_{range} = 6$ nm
$N_{pixels} = 4608$

$\Delta$pixels =
0.00012 pixels



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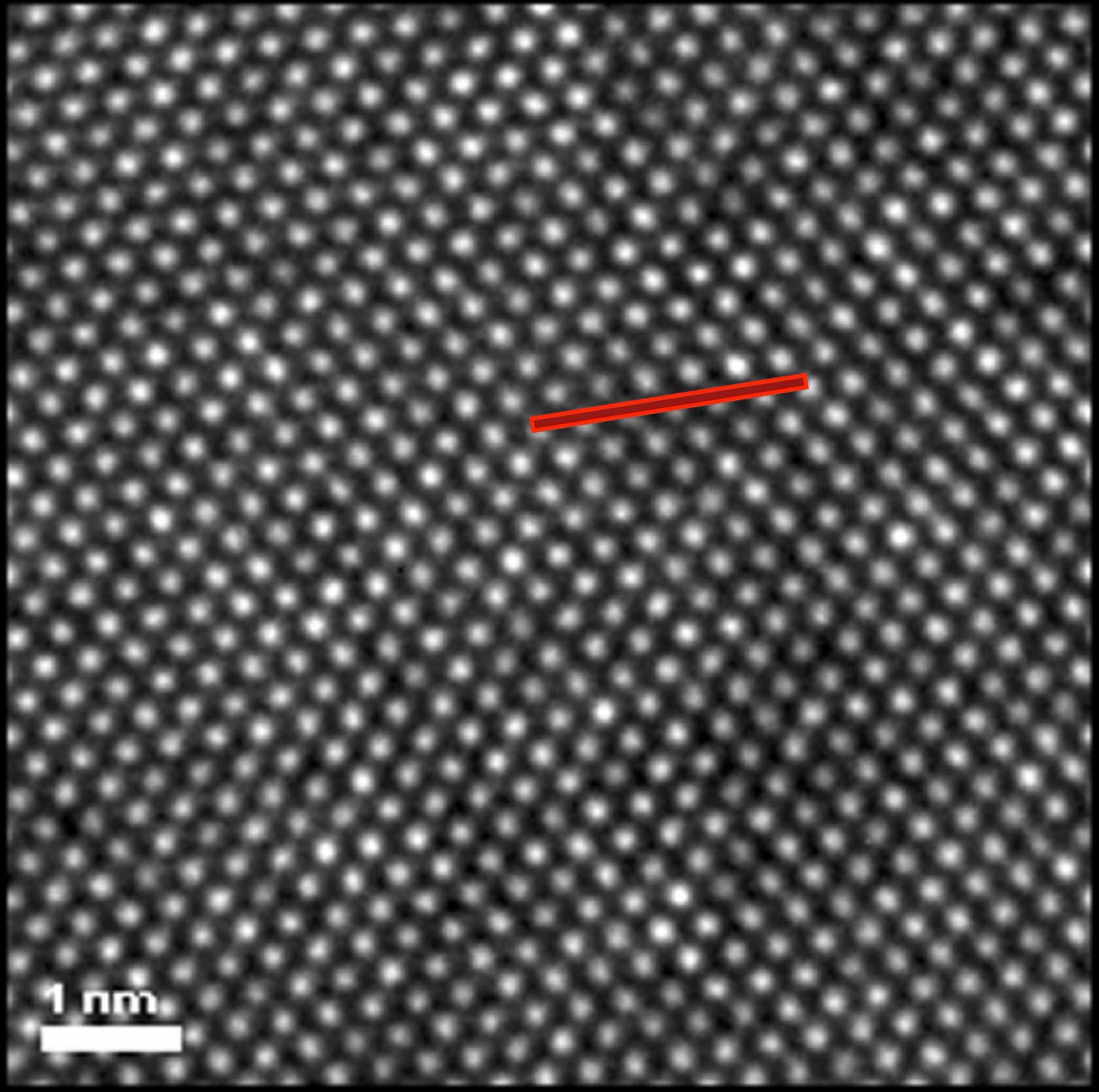
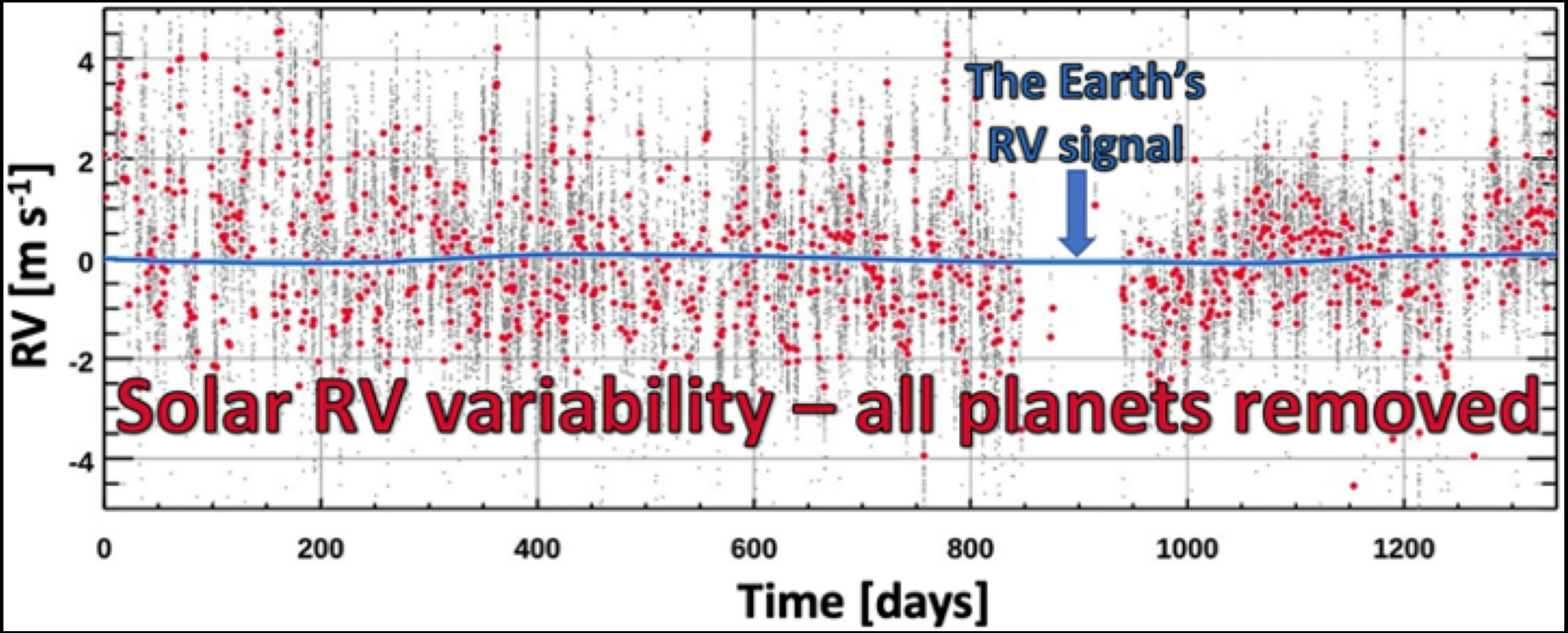
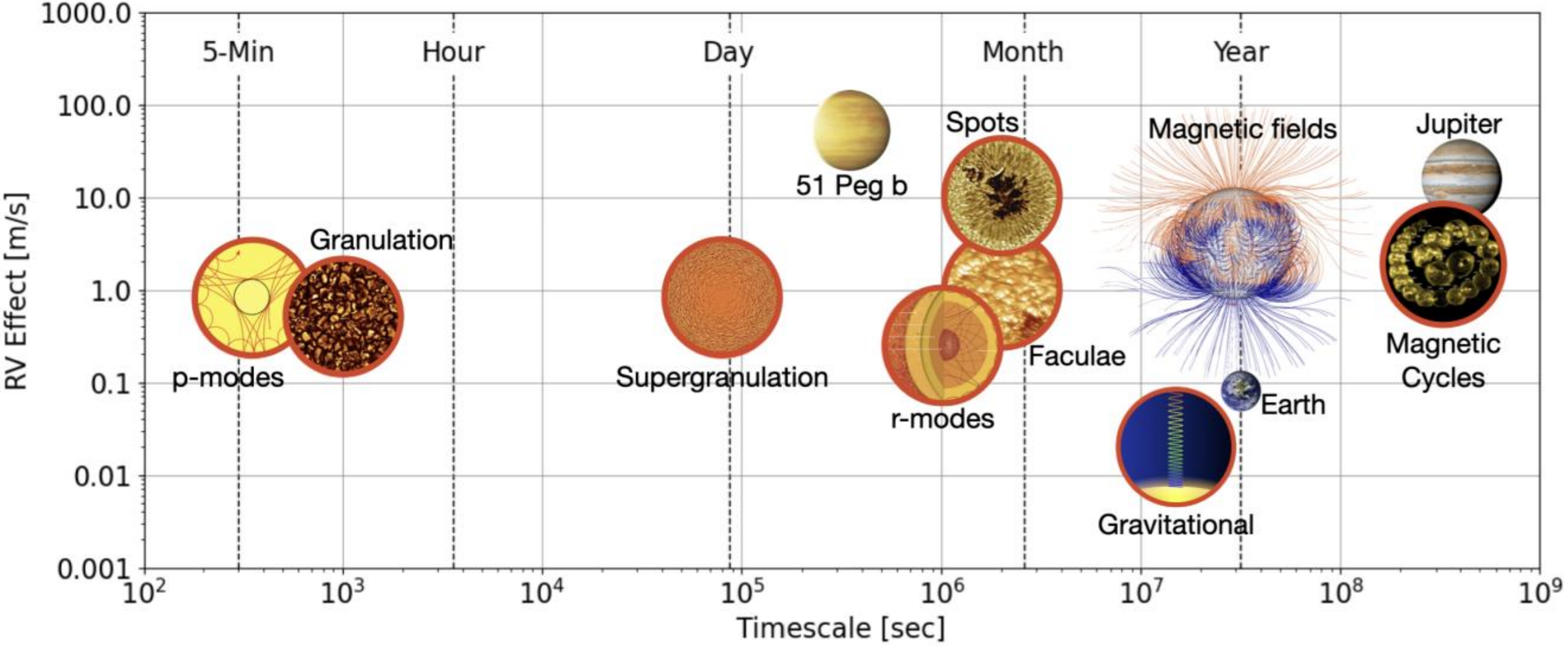



**The RV signal of Earth around the sun is equivalent to an absorption line moving by SIX silicon atoms**

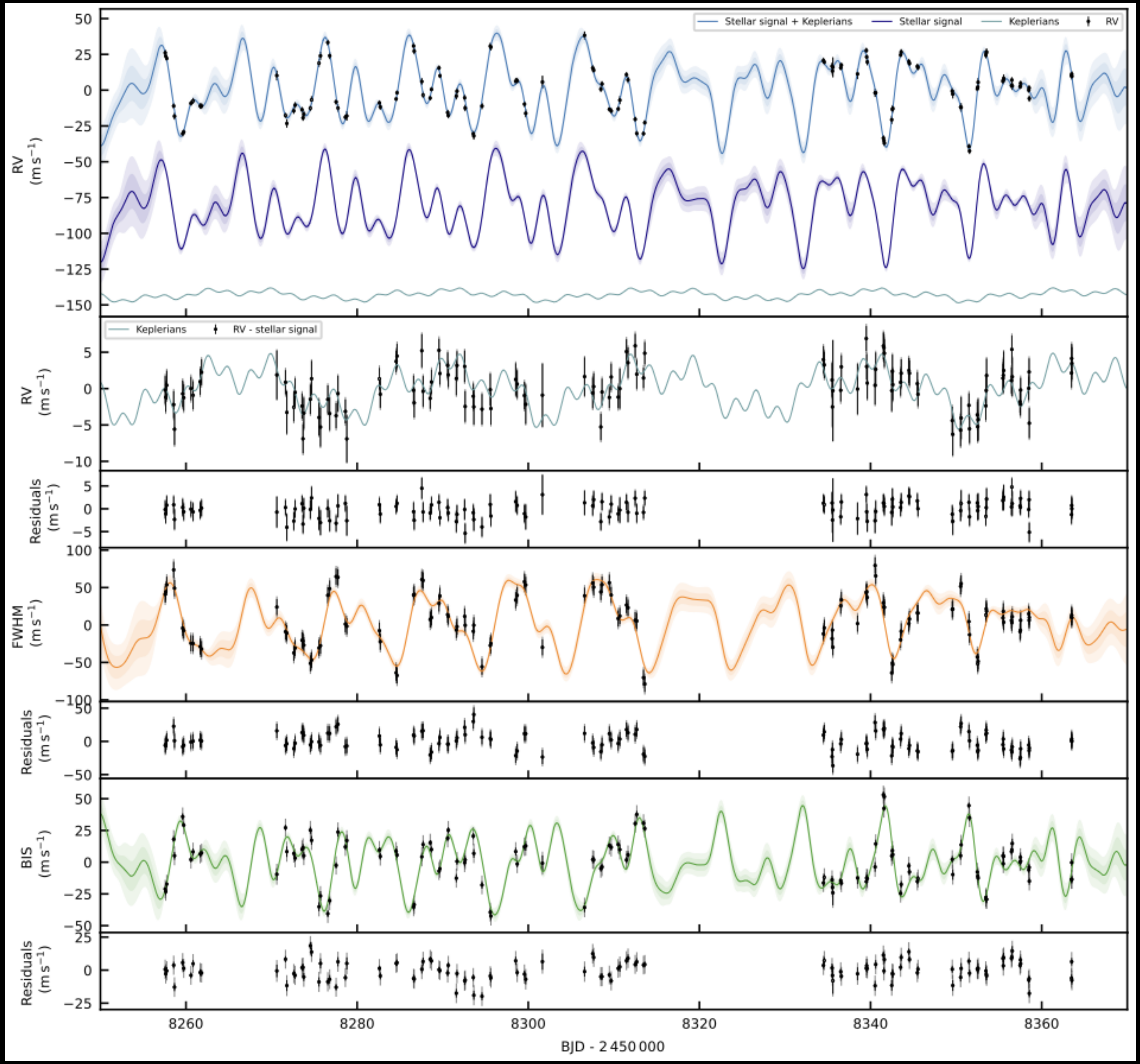
# Setting the Scale



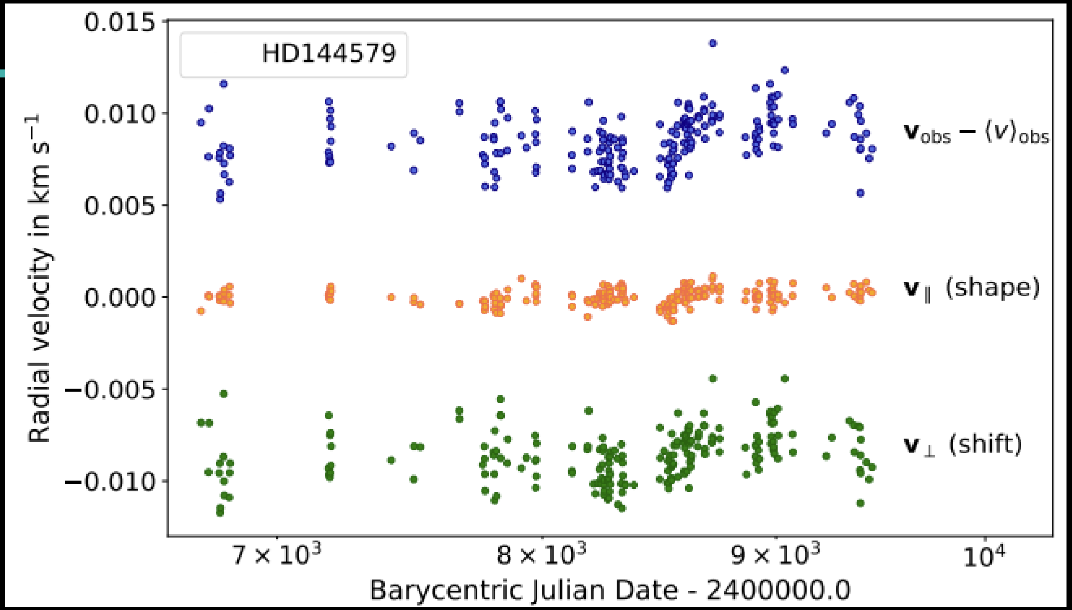
# RV Uncertainty Contributions – stellar variability

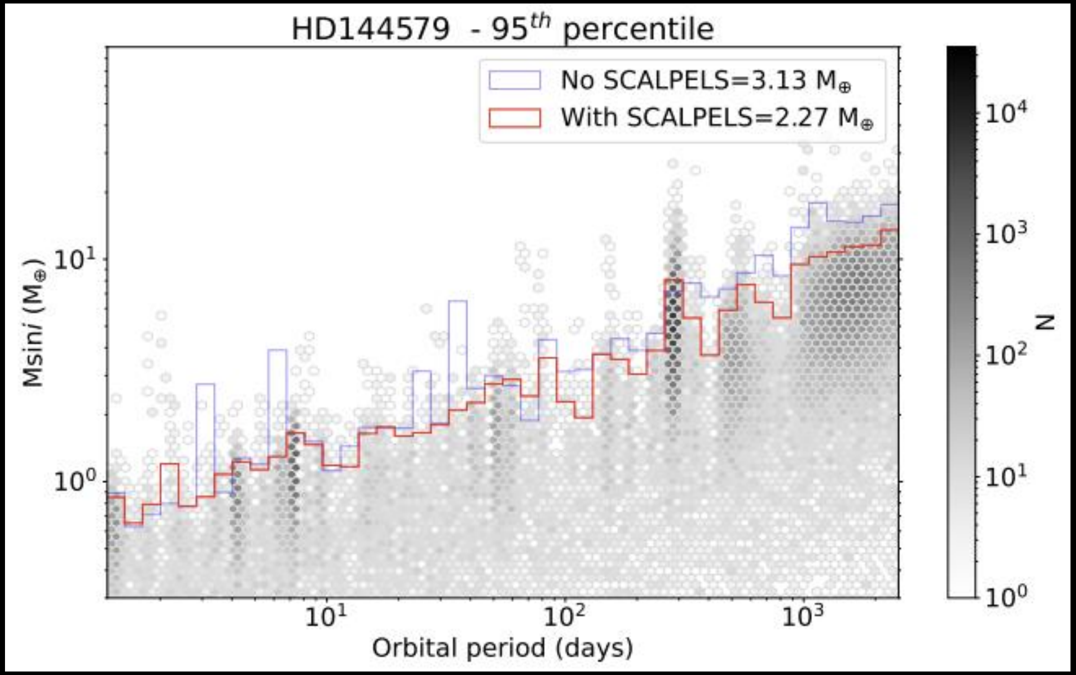


# Stellar Variability



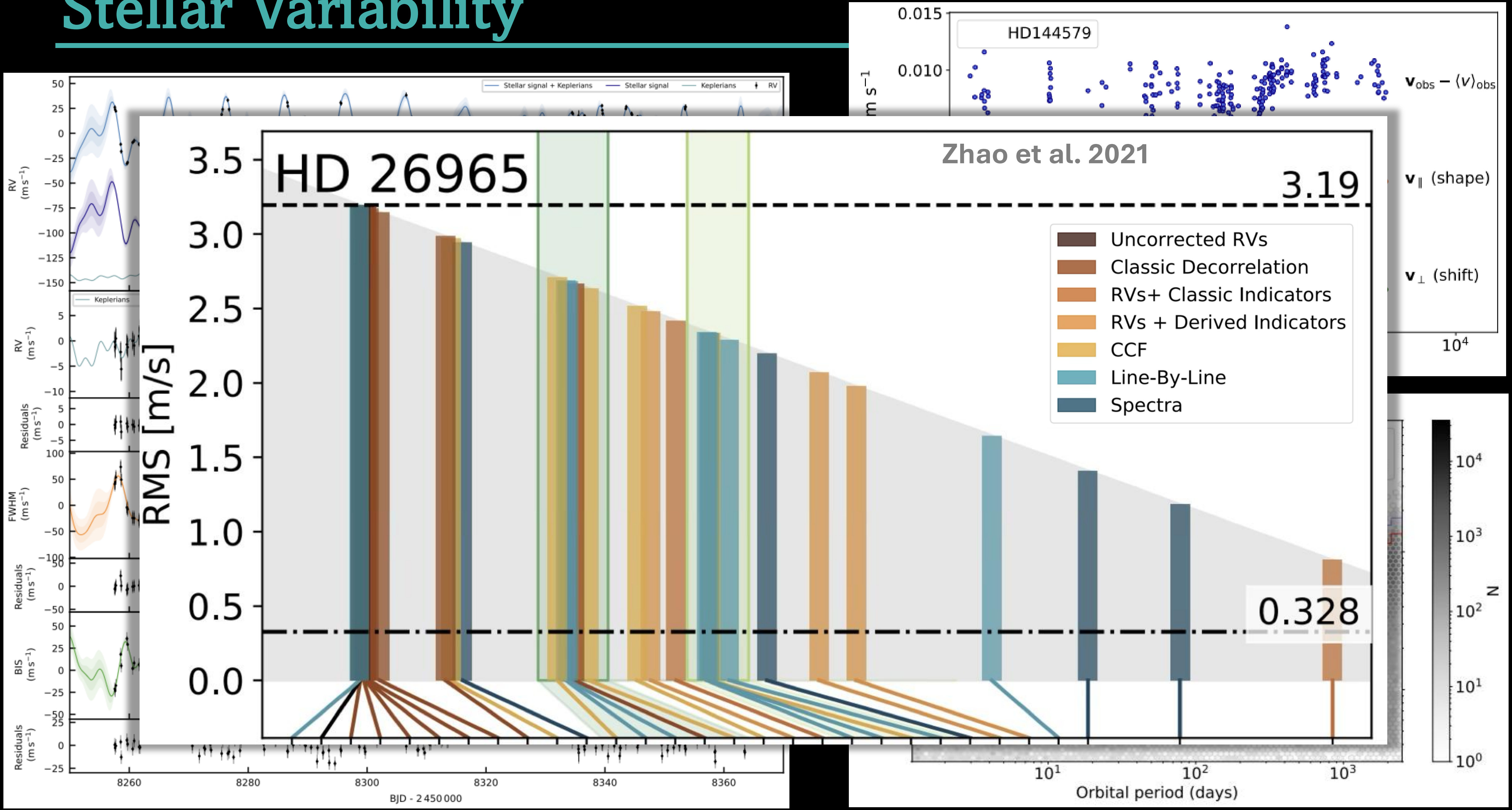

Barragan et al. 2023




John et al. 2024

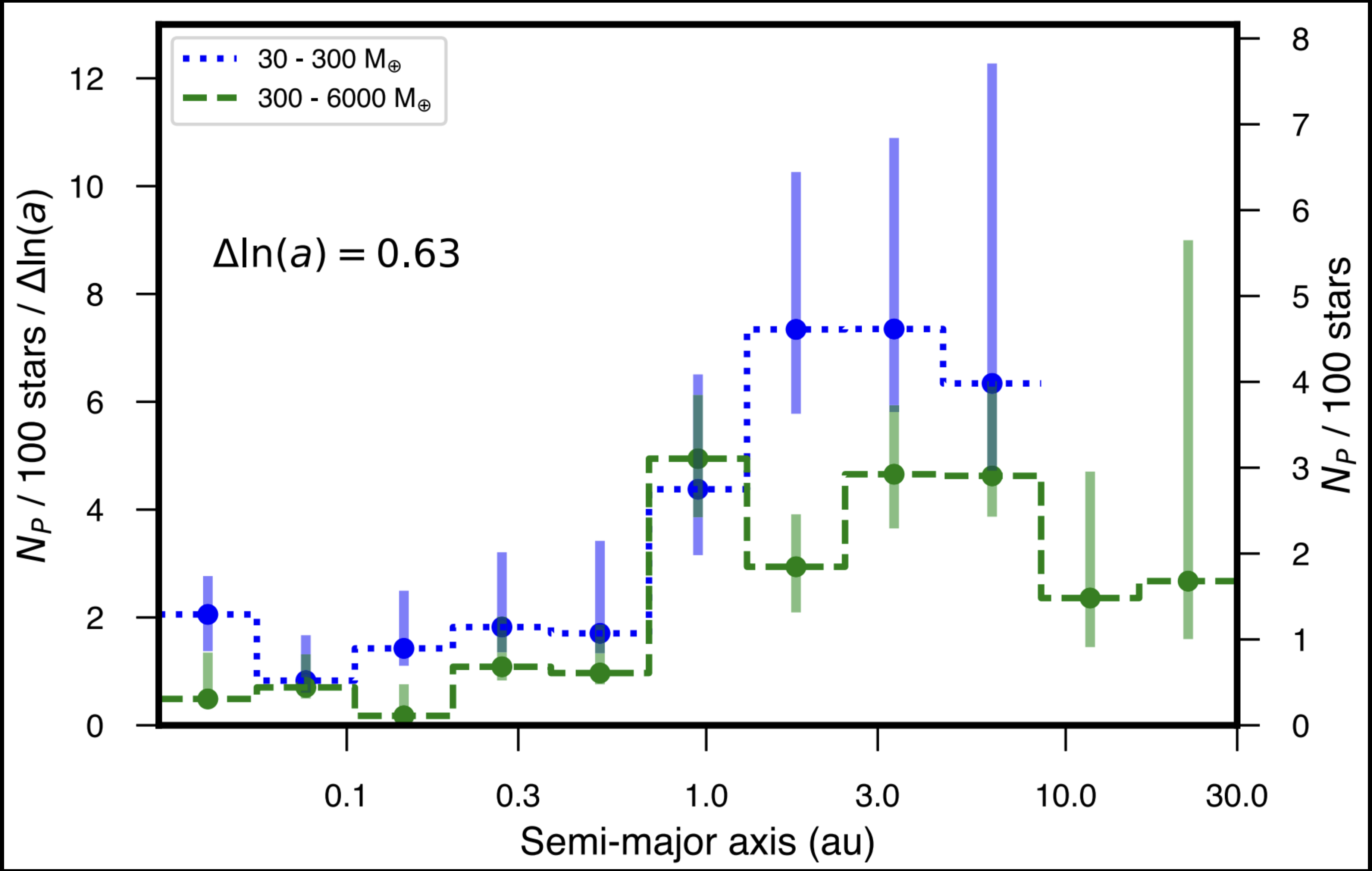
# Stellar Variability




Barragan et al. 2023

John et al. 2024

# State of the Field




Fulton et al. 2021

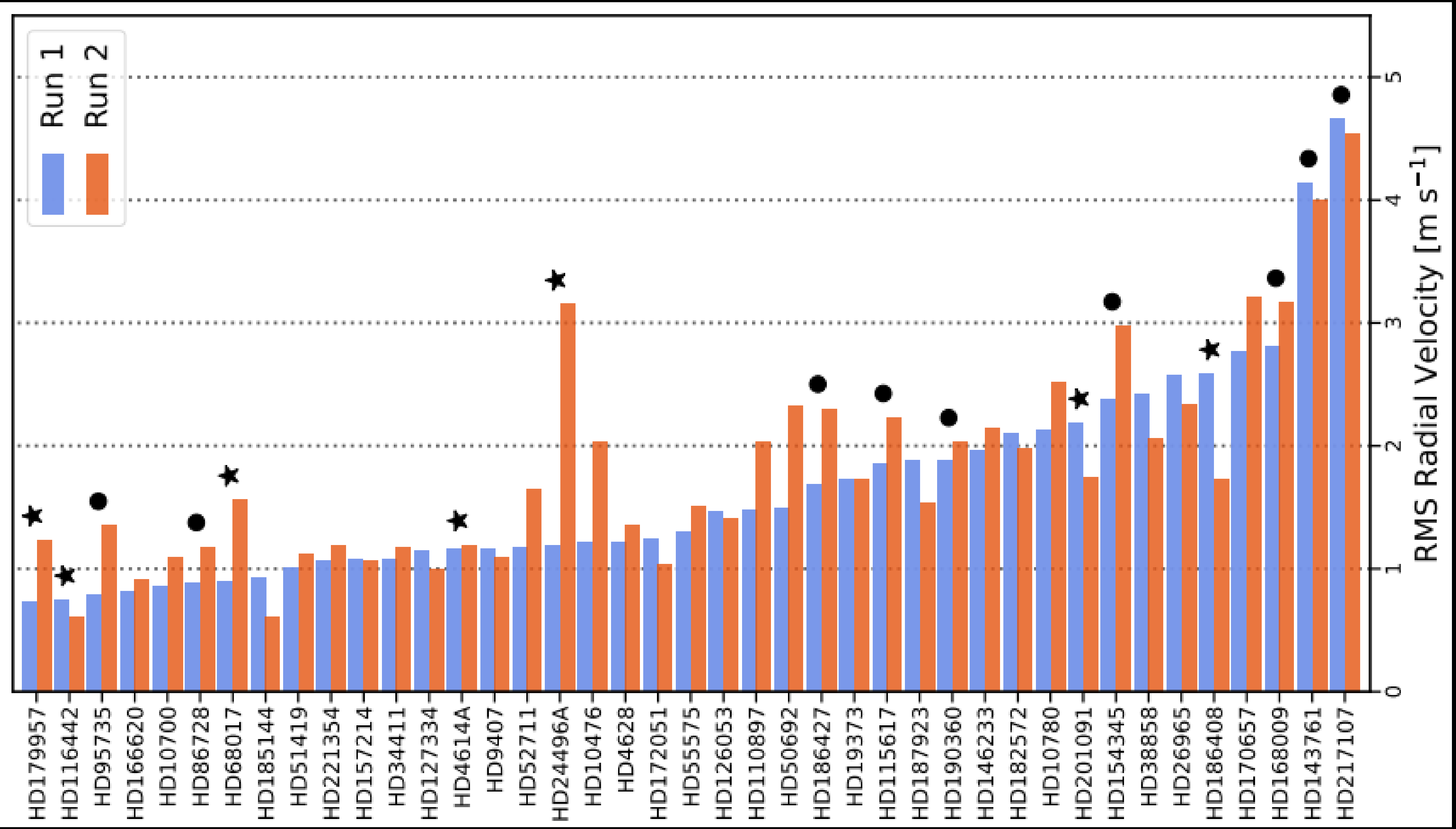
# State of the Field

- EXPRES 100 Earths Survey
- NEID Earth Twins Survey
- HARPS-N Rocky Planet Search
- ESPRESSO GTO
- Terra Hunting Experiment (HARPS3)
- HUnting for M Dwarf Rocky planets Using MAROON-X (HUMDRUM)
- … many additional, PI-level efforts

# State of the Field – Time series RMS

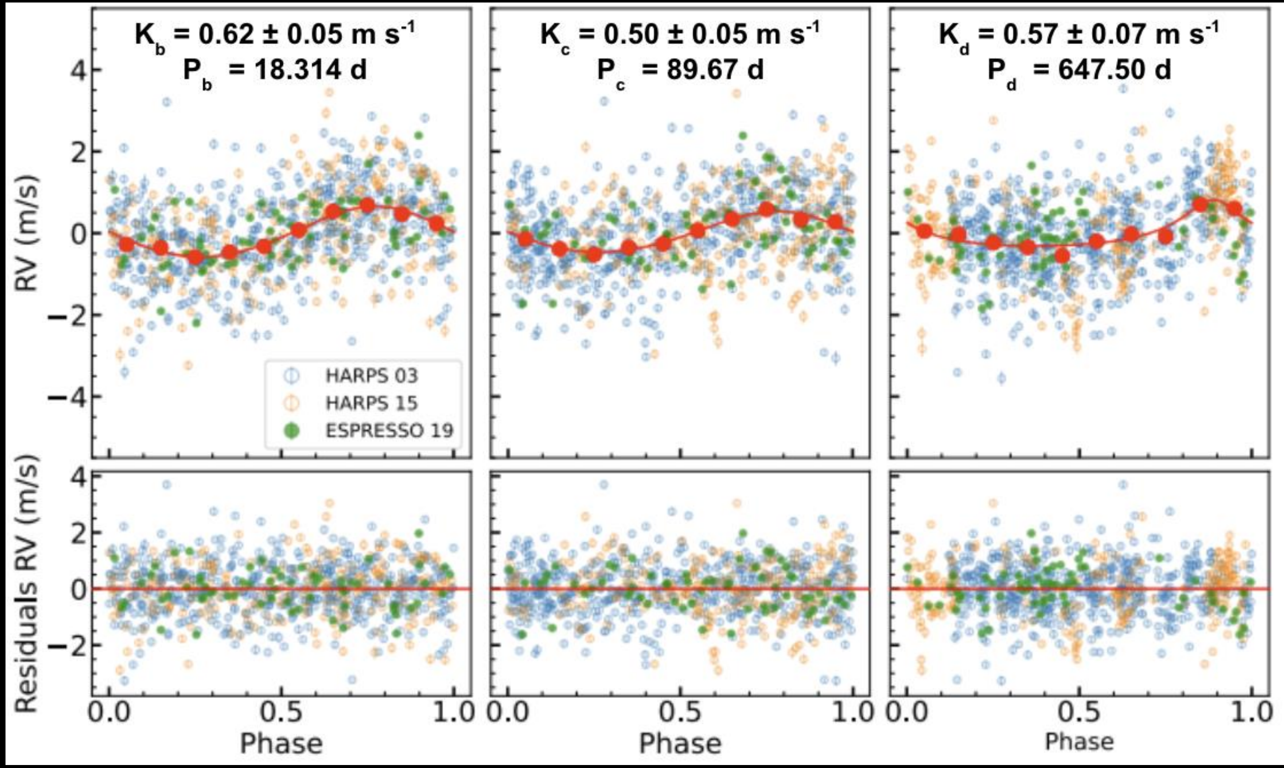
Run 1:
October 2020
– June 2022

Run 2:
October 2022
– August 2024

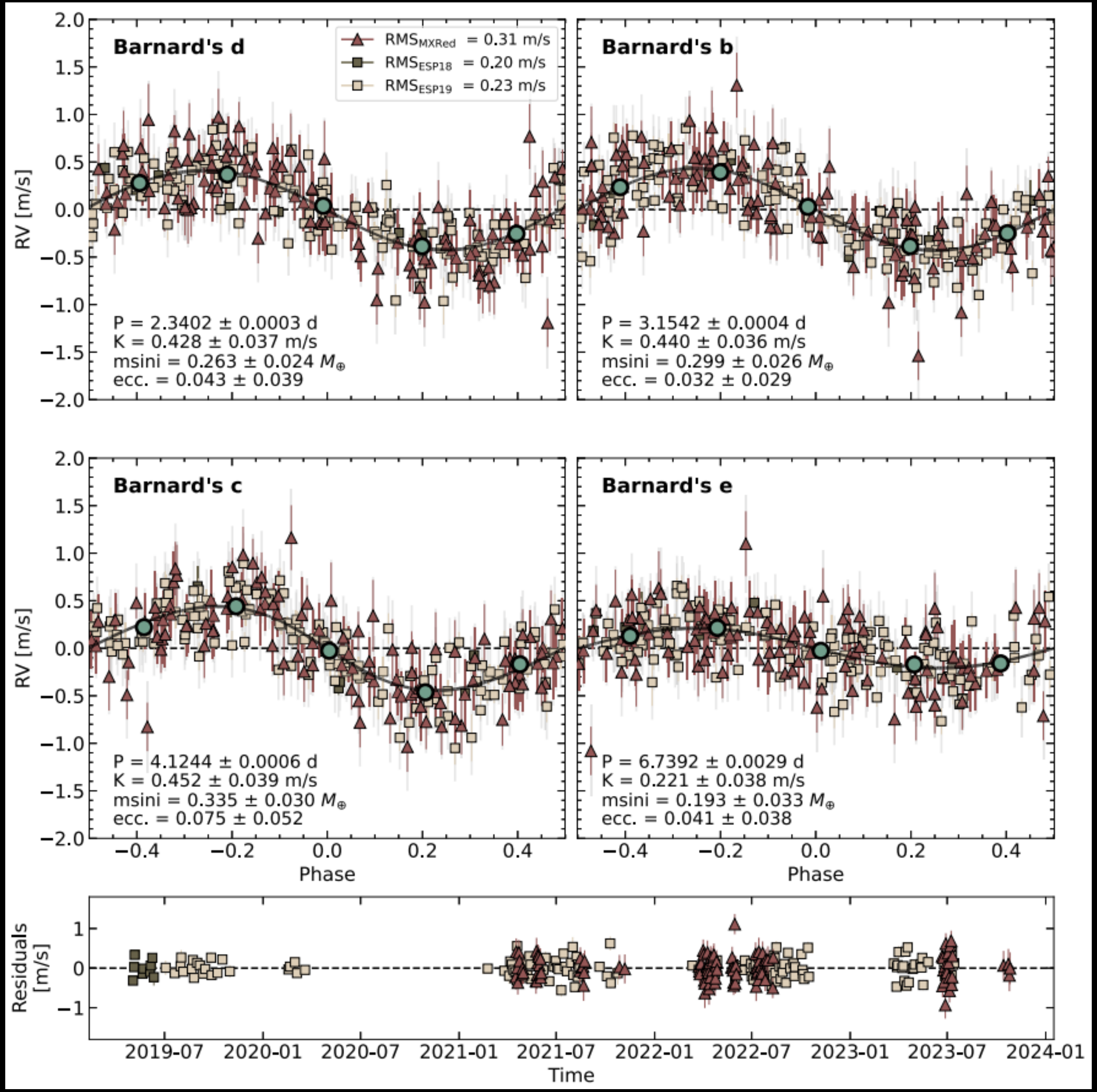



Gupta et al. in review

# State of the Field – Pure RV Detections

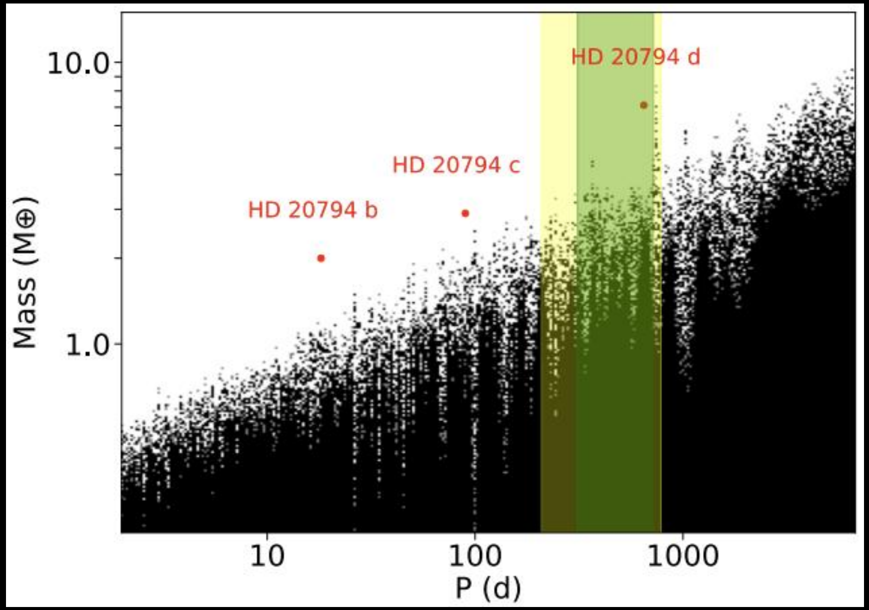



Nari et al. 2025

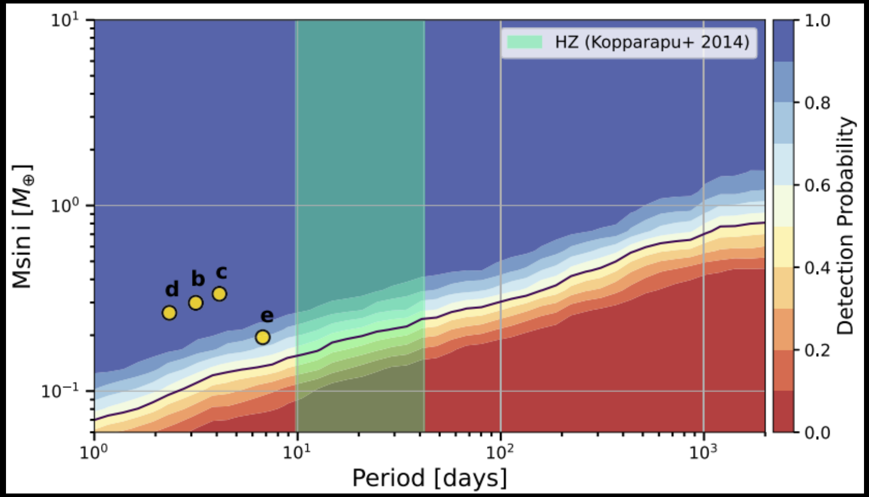



Basant et al. 2025

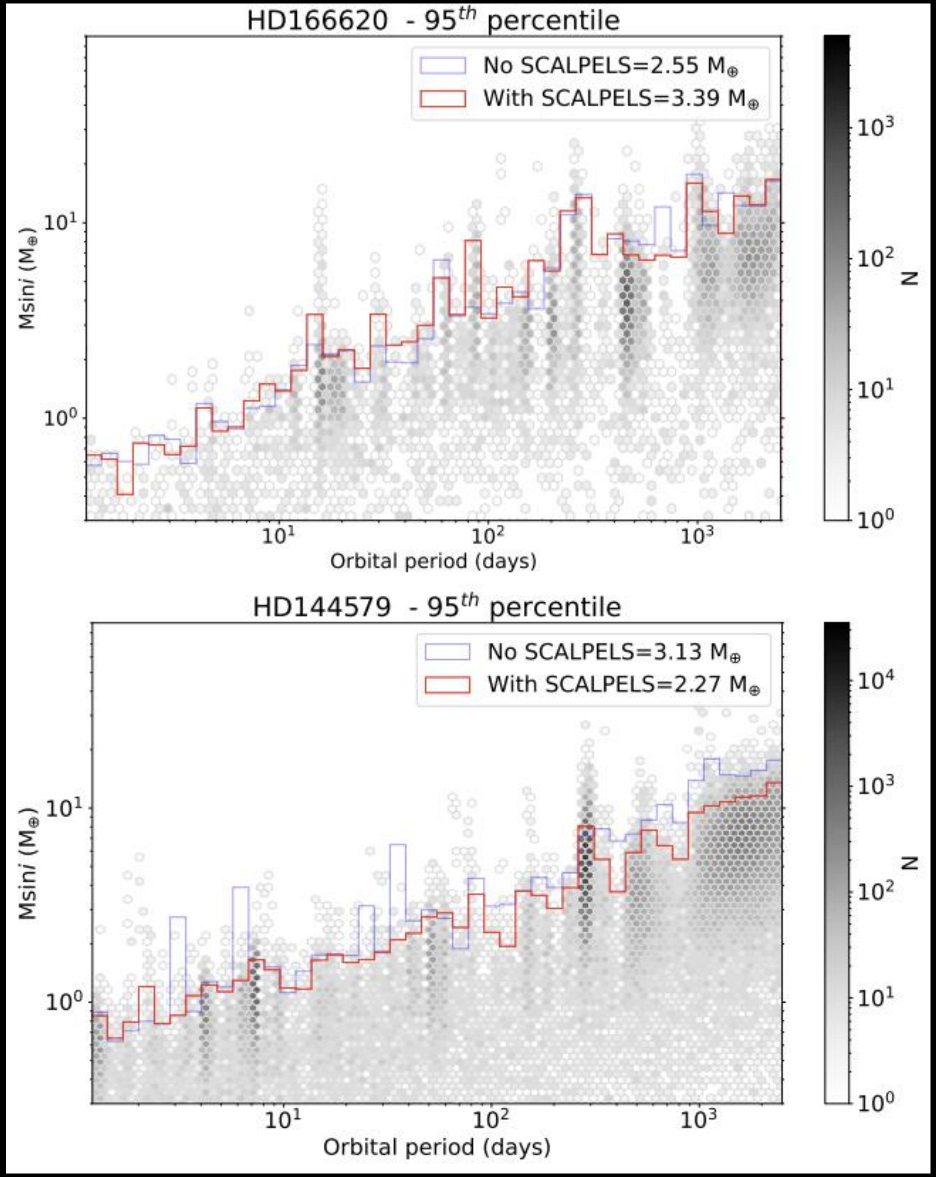
# State of the Field – RV Sensitivity




Nari et al. 2025

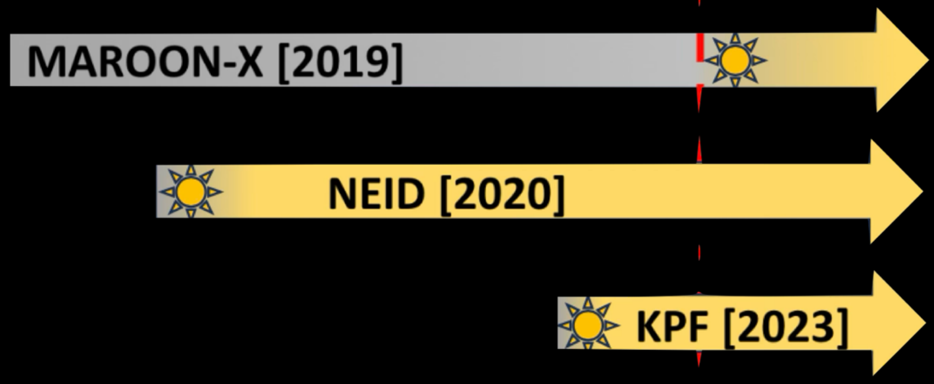



Basant et al. 2025




John et al. 2024

# State of the Field – Solar RV

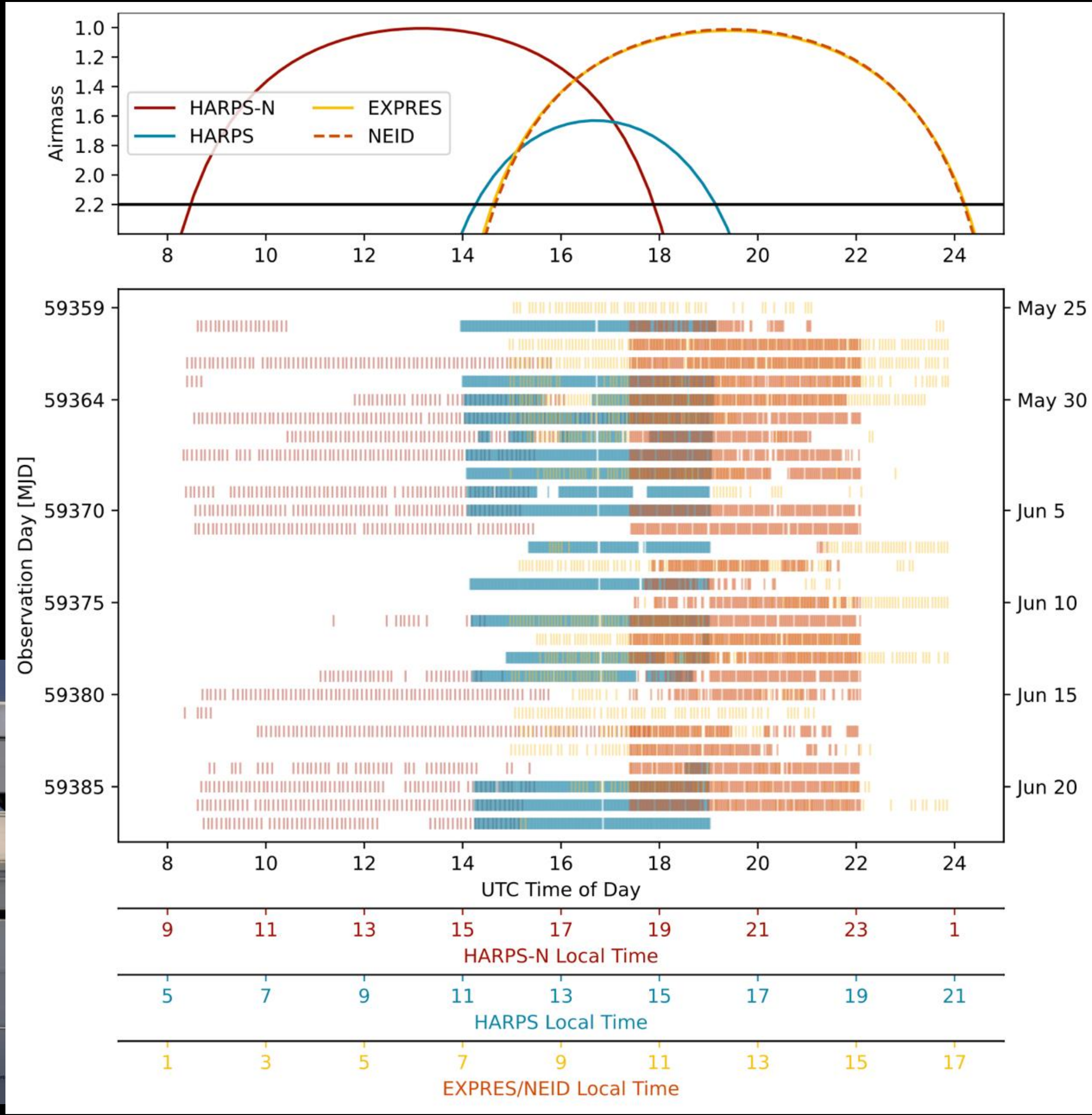



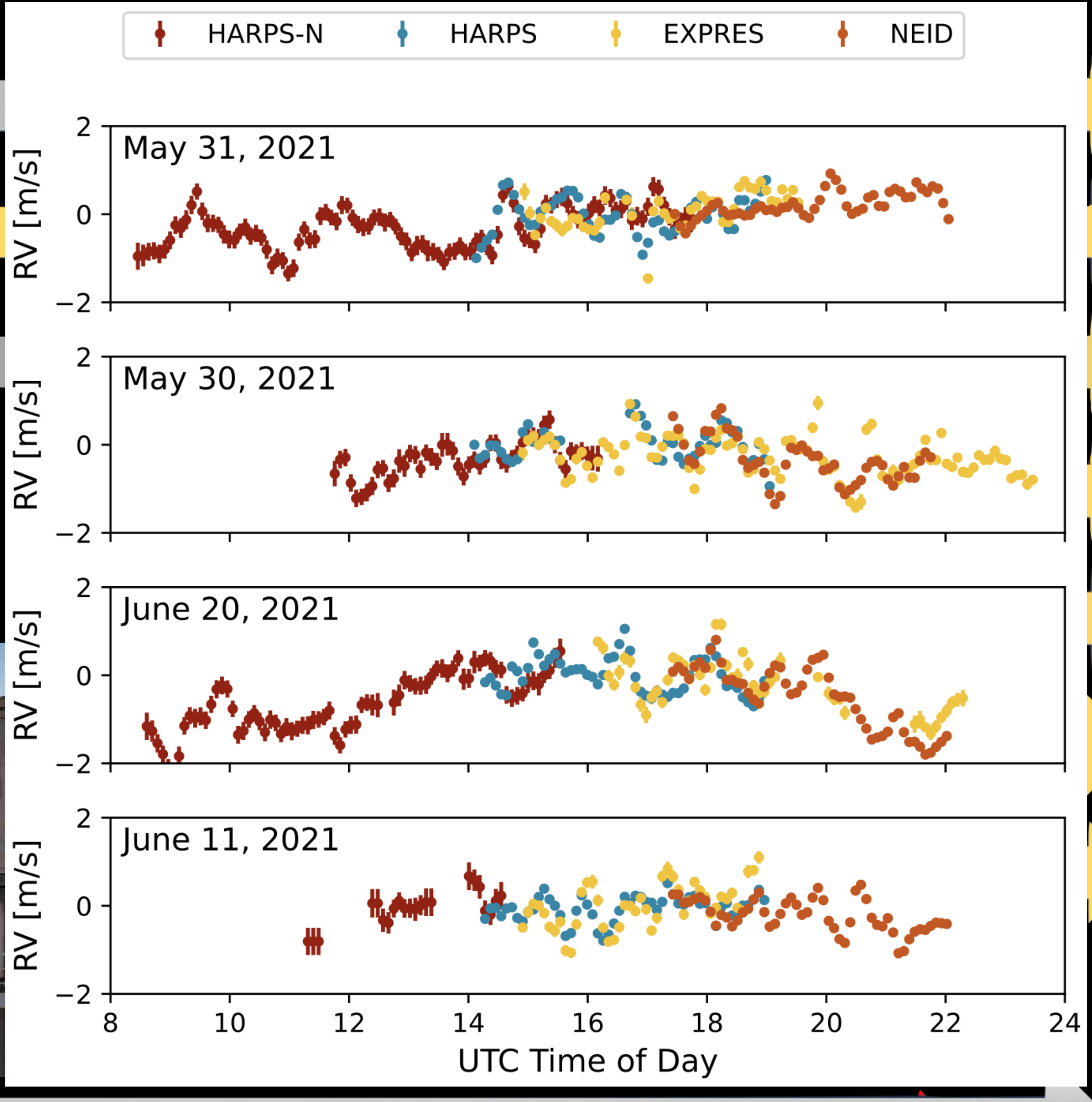

NEID

HARPS-N

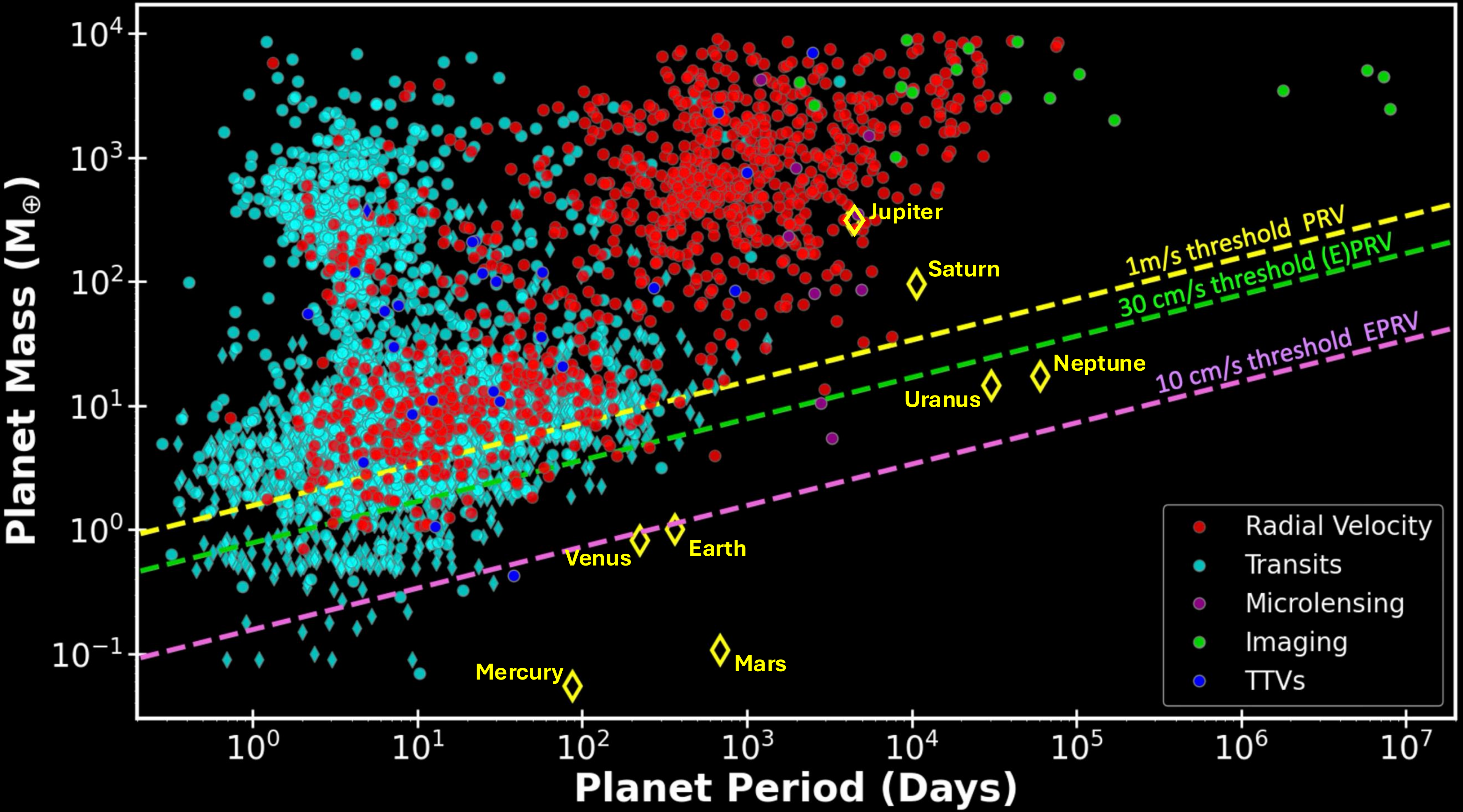
# State of the Field – Solar RV

Zhao et al. 2023

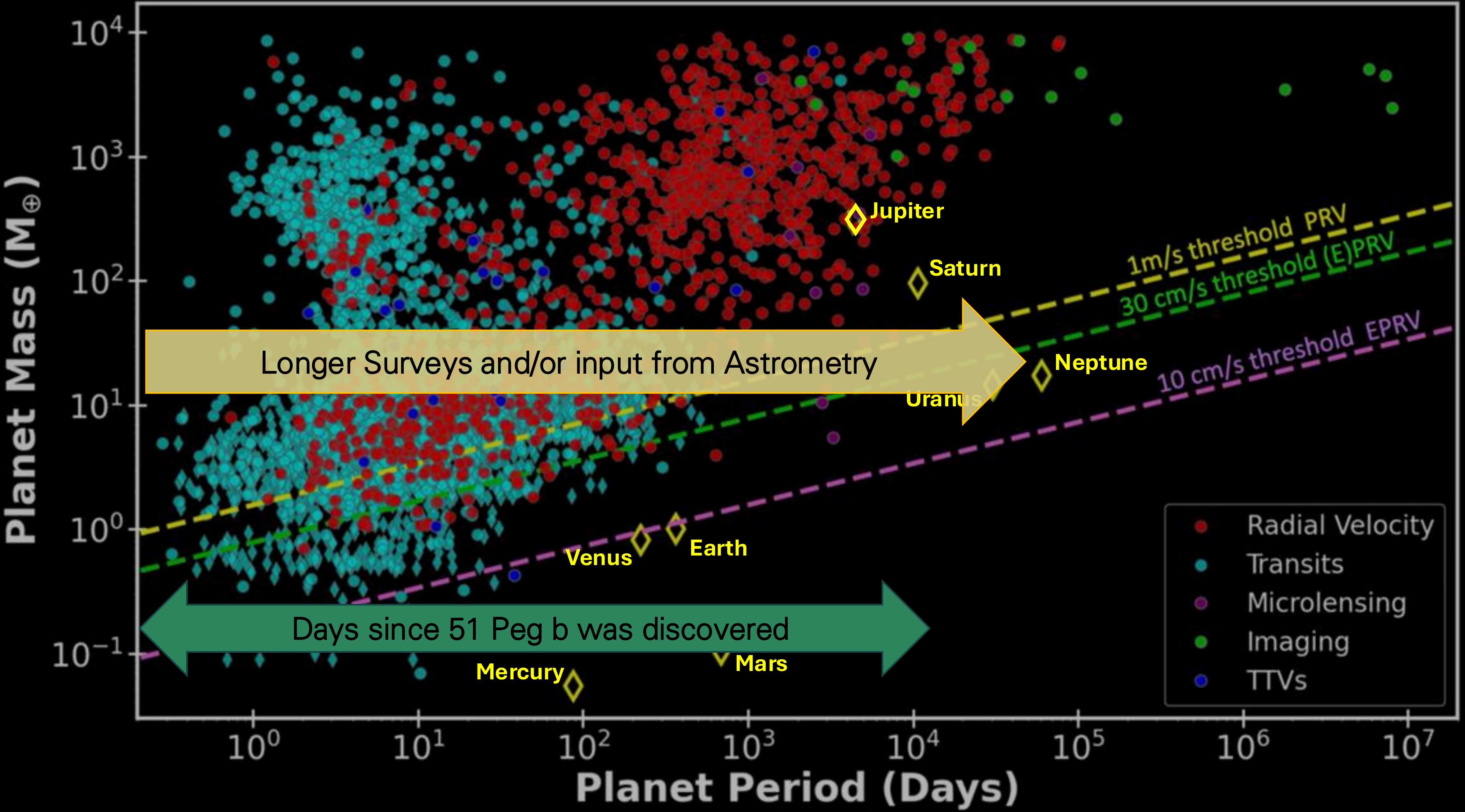


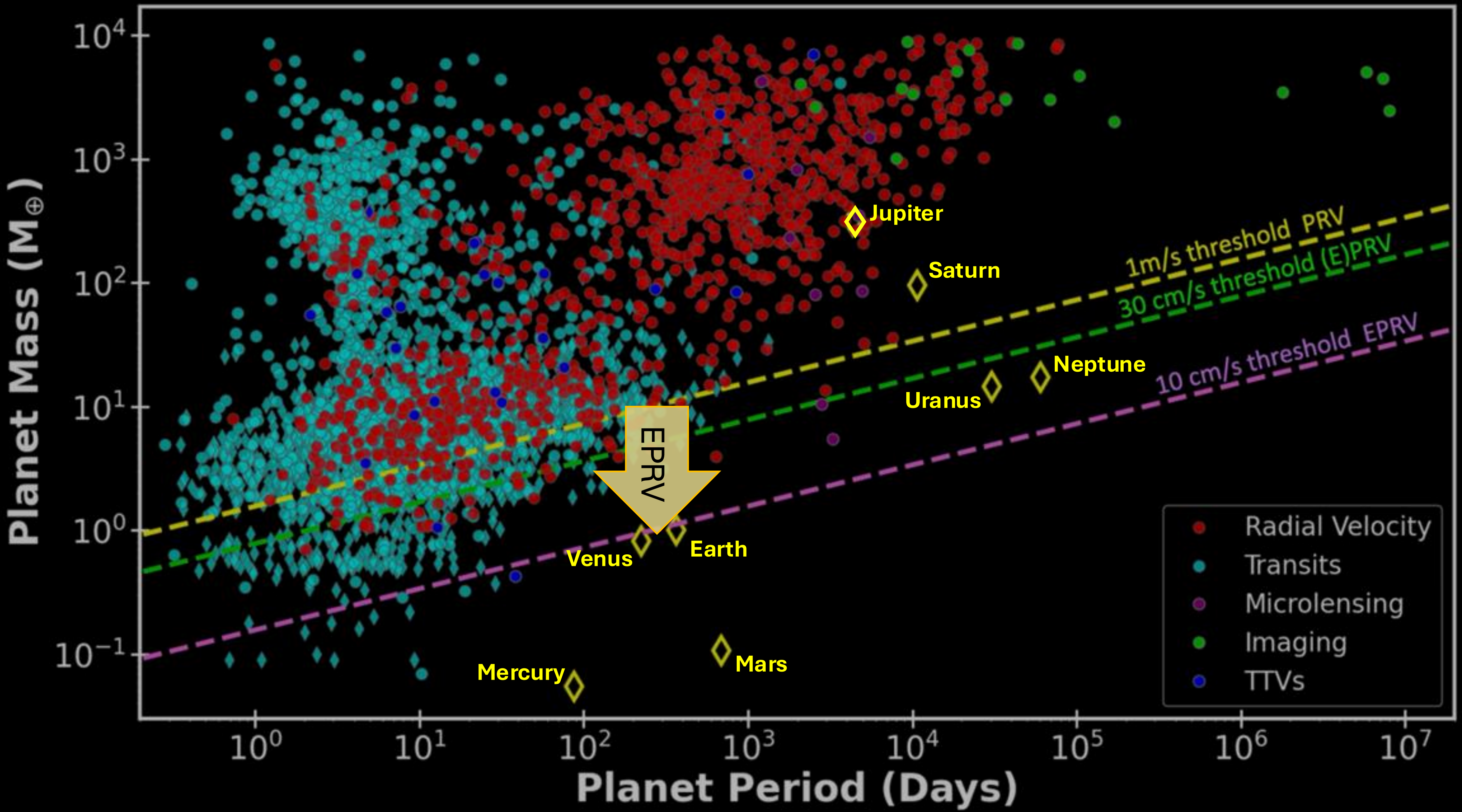

# Major Challenges



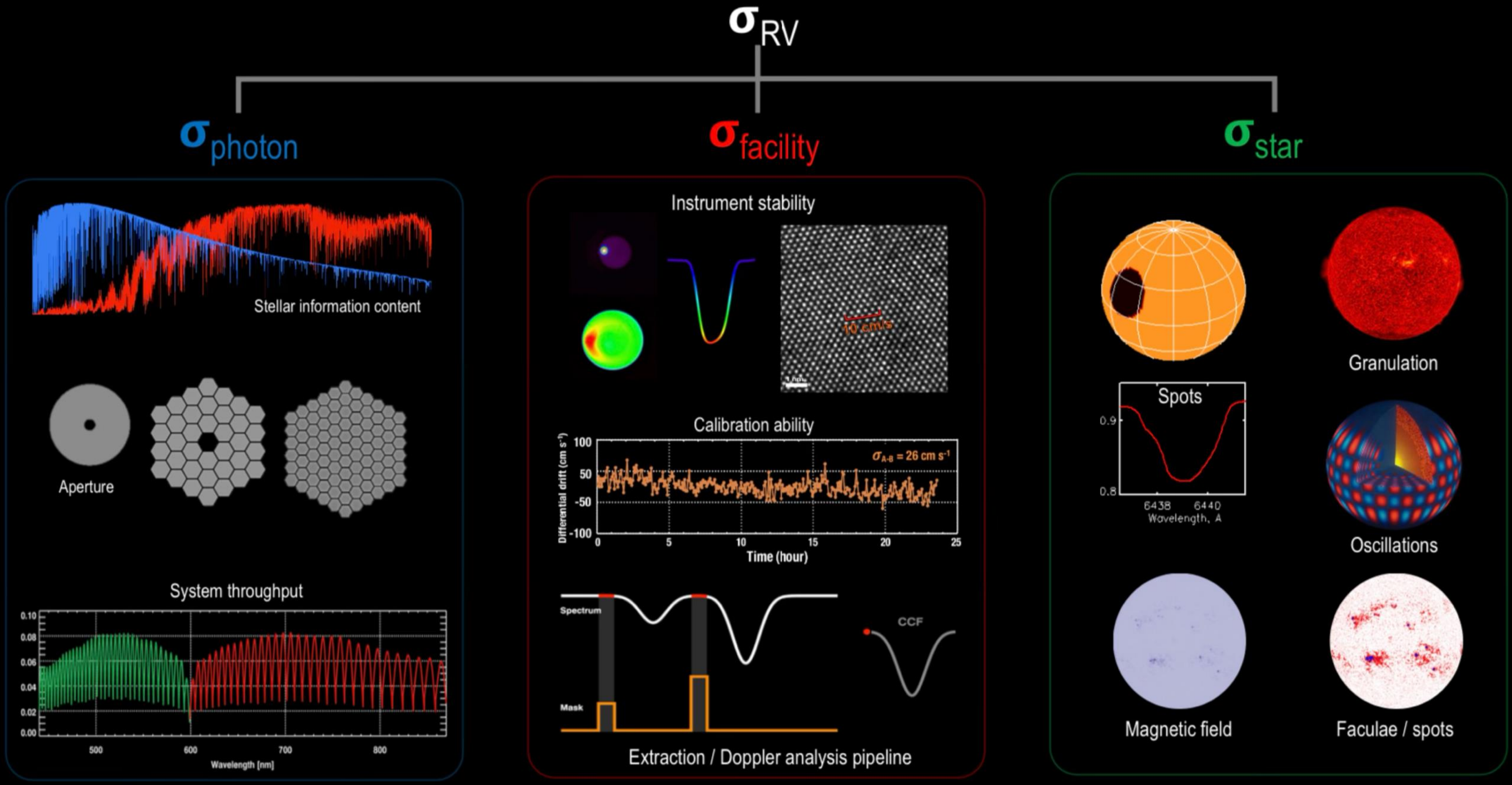
# Major Challenges



# Major Challenges



# Major Challenges




Sam Halverson

# Major Challenges

**Useful overview on what's needed to move the field forward to Earth-detecting capabilities presented in the EPRV Working Group's Final Report**

**(Crass et al. 2021)**

**TABLE 6-1.** Near-term Roadmap (1–5 years) to determine the feasibility and likelihood of a successful EPRV survey.

| **Stellar Variability:** |
|---|
| Support the adoption of solar feeds for spectrographs that demonstrate >100k spectral resolution, SNR > 300 and <50 cm/s stability over a day. |
| Determine how well variability mitigation strategies built from Sun-as-a-star knowledge translate to other spectral types present in the proposed list of target stars. |
| Determine the level of RV precision and accuracy enabled by stellar variability mitigation strategies and modeling and the corresponding implications for the planet mass determinations. |
| **Instrumentation:** |
| Maximize knowledge gained from current instruments still under development, construction, commissioning, and that have recently begun operations. |
| Establish or use existing testbeds for full instrument system development and component testing and characterization, and verification of software-based instrument simulators and select pipeline modules. |
| Determine whether it will be possible to secure a sufficient number of CCDs for a full EPRV survey in a timely manner. |
| Determine whether CMOS (complementary metal-oxide semiconductor) detectors are an acceptable replacement for CCD detectors. |
| Investigate the continued availability of gratings required for high-resolution spectrographs. |
| Determine if there are alternative, cheaper, and more robust methods of fabricating gratings. |
| Investigate the feasibility of securing robust, long-lived, high-stability calibration sources. |
| **Architecture:** |
| Determine whether extreme AO in the visible combined with fiber injection of single-mode fiber-fed diffraction limited spectrographs presents a viable and more desirable option than traditional seeing-limited RV instruments. |
| Determine whether it would be practical to retrofit existing telescopes for dedicated, robotic operation for EPRV observations, or whether new telescopes are required. Determine which of these options presents the least risk and requires the fewest resources. |
| Identify suppliers for multiple, large-aperture telescope systems and conduct site selection surveys, should the building of new telescopes be required for the full EPRV survey. |
| **Telluric Line Contamination:** |
| Determine whether telluric contamination lines in spectra can be adequately mitigated, over a sufficiently broad wavelength range. |
| **Extensive and Detailed Theoretical Analysis:** |
| Determine what combination of spectral bandwidth, resolution, SNR and cadence is sufficient for the detection of Earth-analog systems. |
| Explore the advantages of spectropolarimetry in EPRV observations (e.g., as implemented in SPIRou). |
| Specify, based on lessons learned from observational data, the required quality of the spectra (including resolution and SNR) to detect Earth analogs, which then constrains the required effective apertures, observing time, and cadence. |
| **Software:** |
| Support the development of a well-designed, well-engineered, and actively maintained open-source pipeline with demonstrated ability to retrieve state of the art results on EPRV data from multiple instruments. |
| **Programmatics:** |
| Ensure the needed staffing of personnel with expertise in PRV, heliophysics, and stellar variability to conduct the necessary analysis as well as conduct an EPRV survey. This necessarily involves establishing formal collaborations with non-U.S. entities, and creating attractive employment paths for early career (graduate students, postdoctoral fellows, and non-tenure track researchers) experts in PRV science and technology. |
| Establish a Research Coordination Network and Standing Advisory Committee. |

# Major Challenges

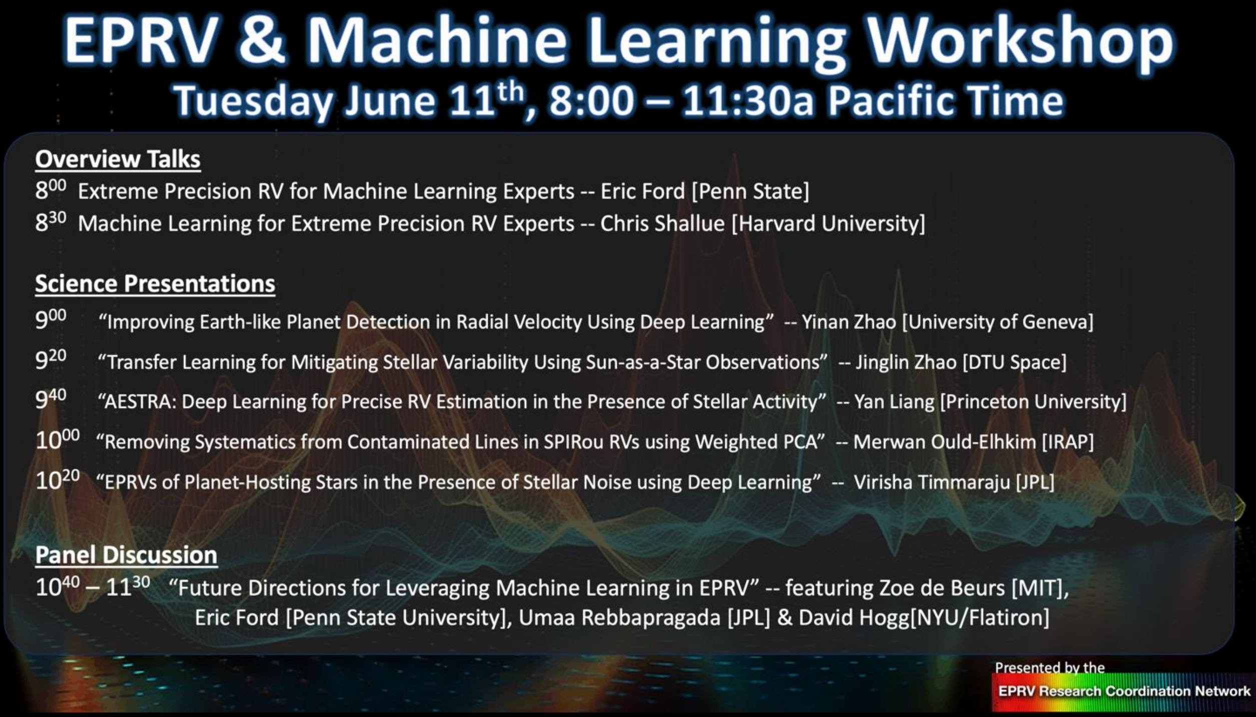
Make sure to also check out recordings from the 2020 Sagan Summer Workshop which was entirely focused on EPRV!

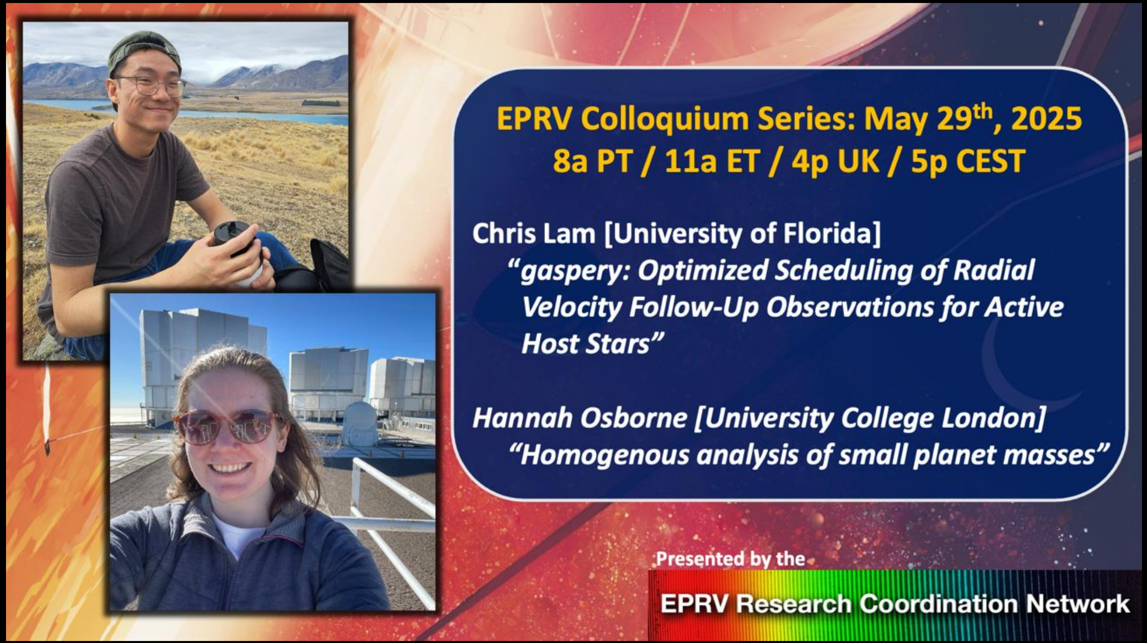
Themes included:

- Fundamentals of PRV, Error Budgets, Instrumentation
- Fundamentals of Data Analysis and Statistical Significance
- Stellar Signals and Tellurics
- Beyond EPRVs: Characterizing Planets

https://nexsci.caltech.edu/workshop/2020/agenda_virtual.shtml

# EPRV Research Coordination Network

# From Wobbles to Worlds:

# The role of precision radial velocities in exoplanet discovery and characterization

Dr. Jennifer Burt
Exoplanet Exploration Program Office