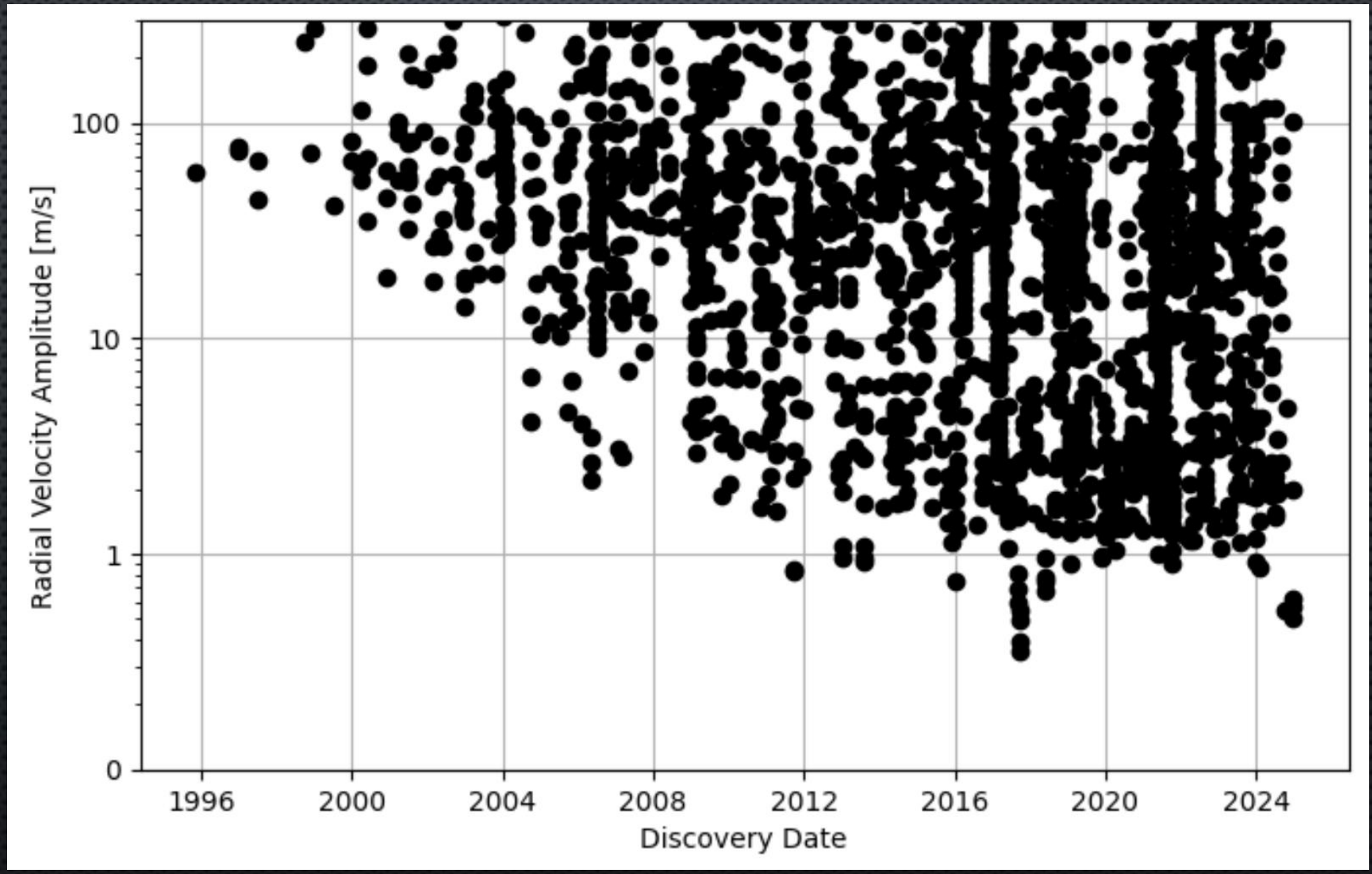
Planetary Masses in Motion: Navigating the Impact of Stellar Variability on Exoplanet Mass and Orbit Determinations

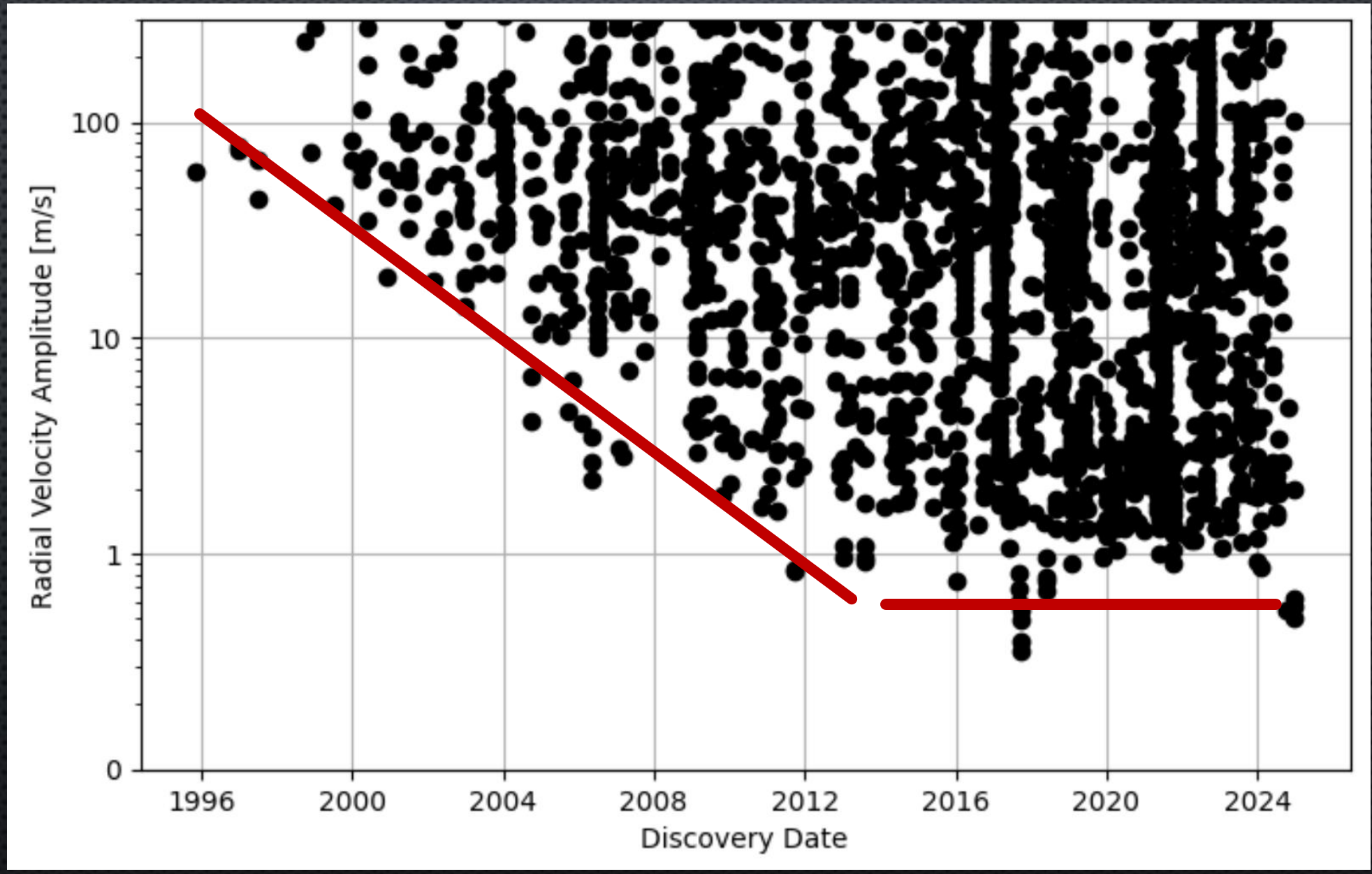
BJ Fulton

THE PROBLEM

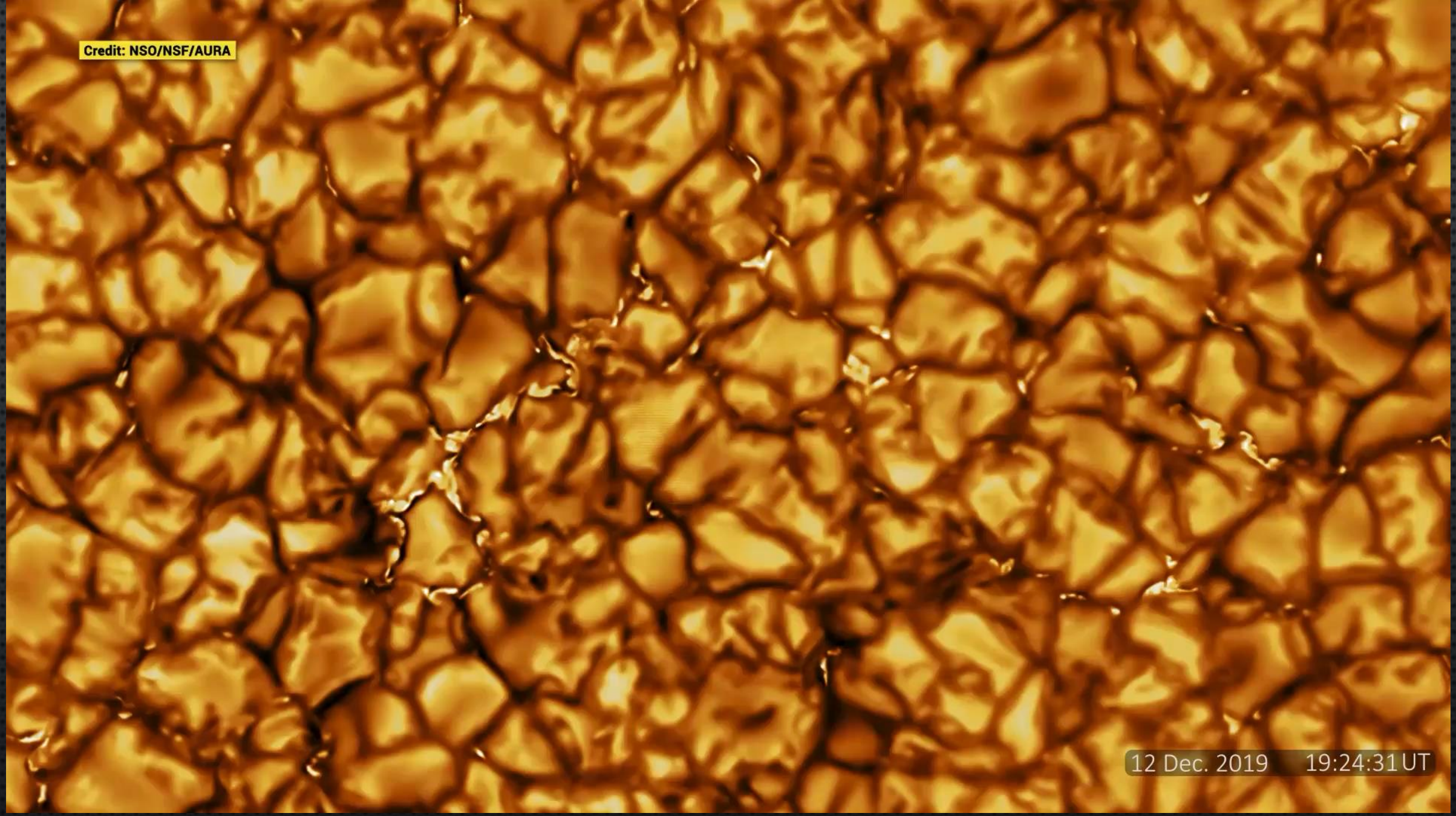
- EPRV spectrographs are now reaching incredible precisions
- Cm/s on stars hundreds of parsecs away
- Several atoms in the silicon lattice structure in the CCD



NASA Exoplanet Archive

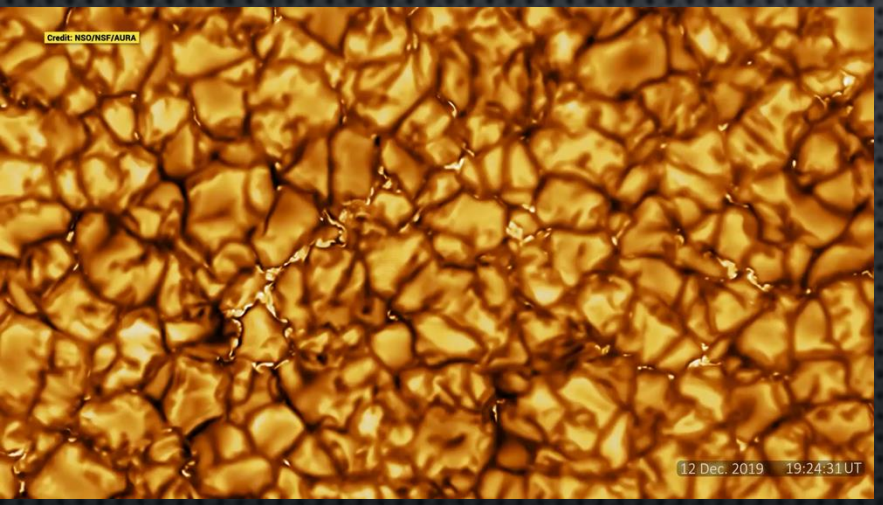


NASA Exoplanet Archive

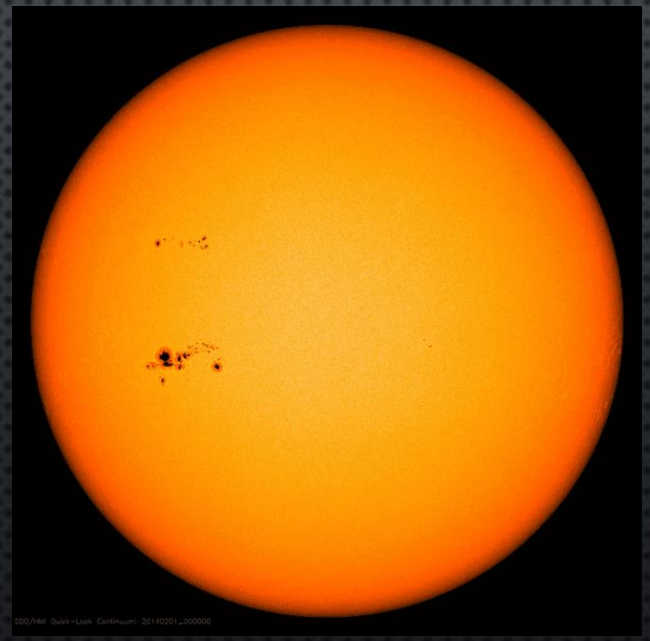

Credit: NSO/NSF/AURA
12 Dec. 2019 19:24:31 UT

THREE CLASSES OF ACTIVITY

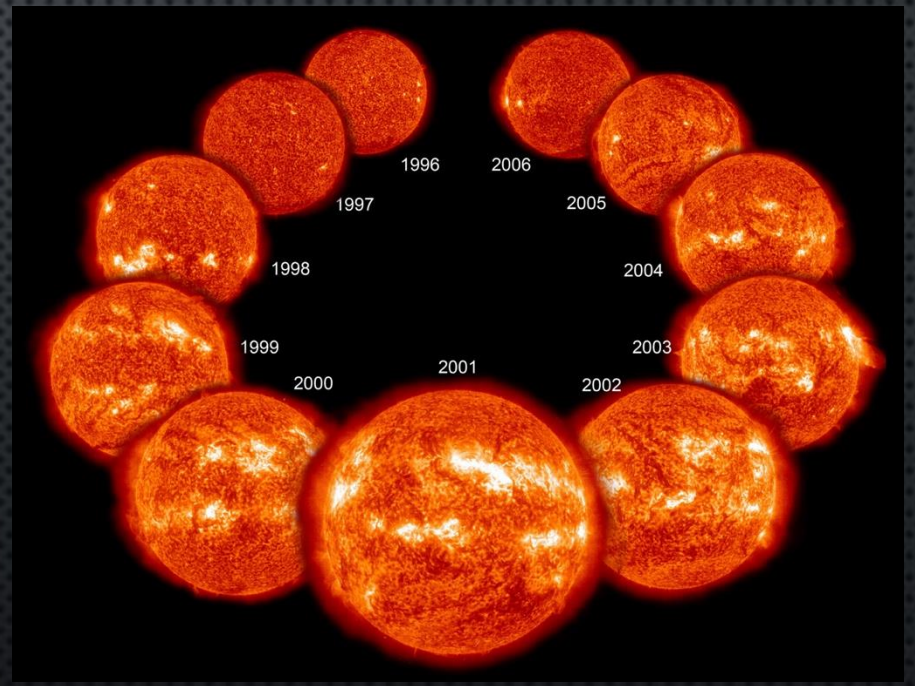
granulation



rotation

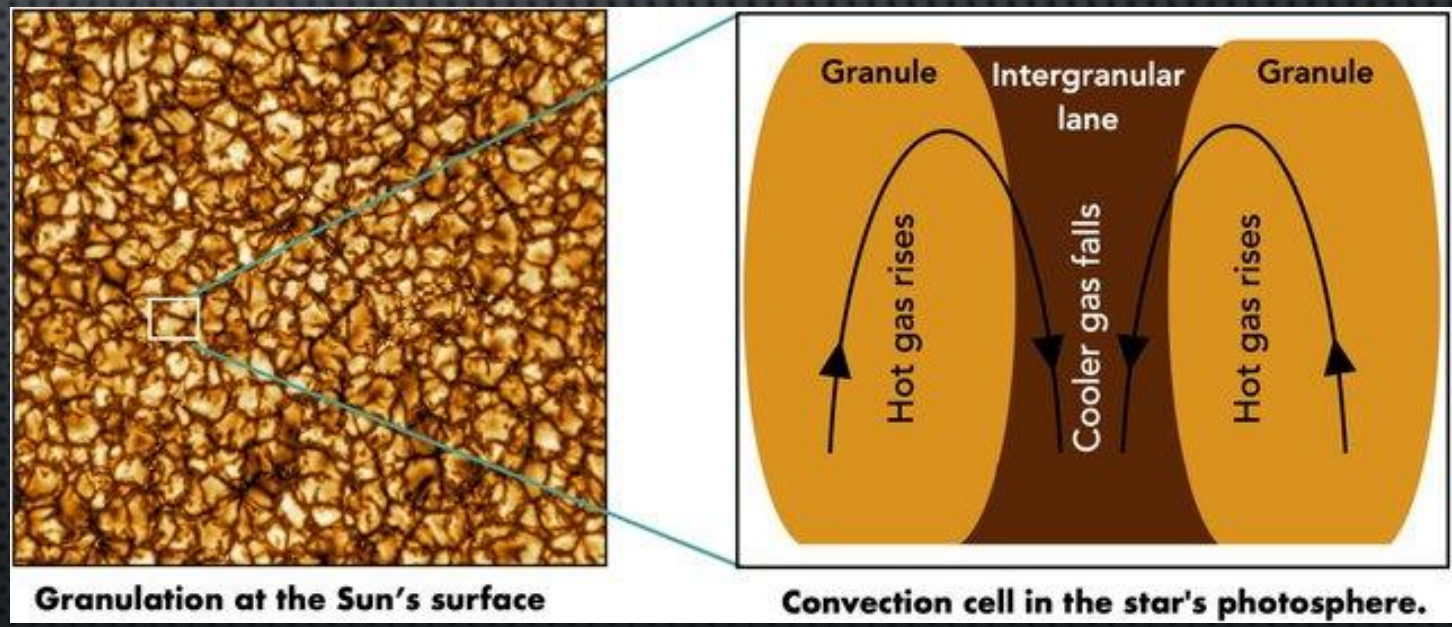


magnetic cycles



GRANULATION

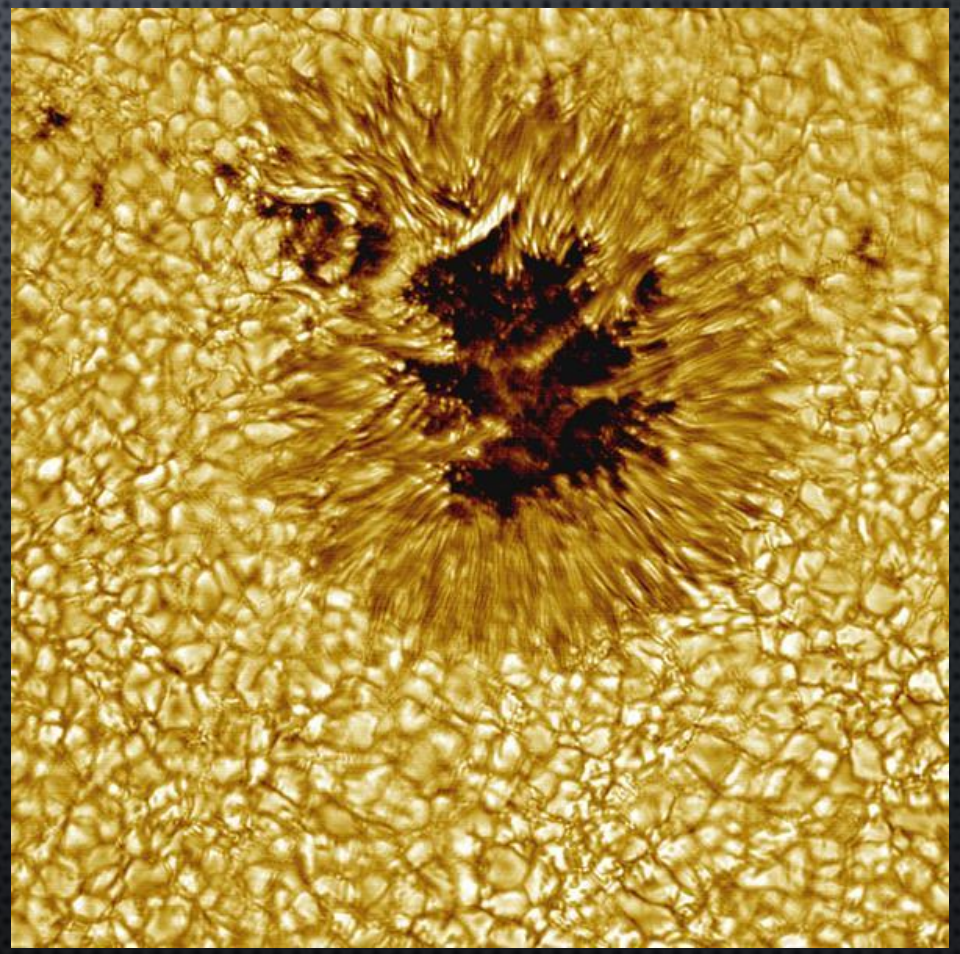
- Convective cells
- Bright "granules" are hotter material moving toward the surface
  - ~1 km/s vertical velocity
- Dark intergranular lanes are where cooler gas sinks away from the surface
  - Smaller area but sink faster than granules rise
- Hours timescale for Sun-like stars
- More upwelling area than downwelling leads to convective blueshift



Dalal et al. (2023)

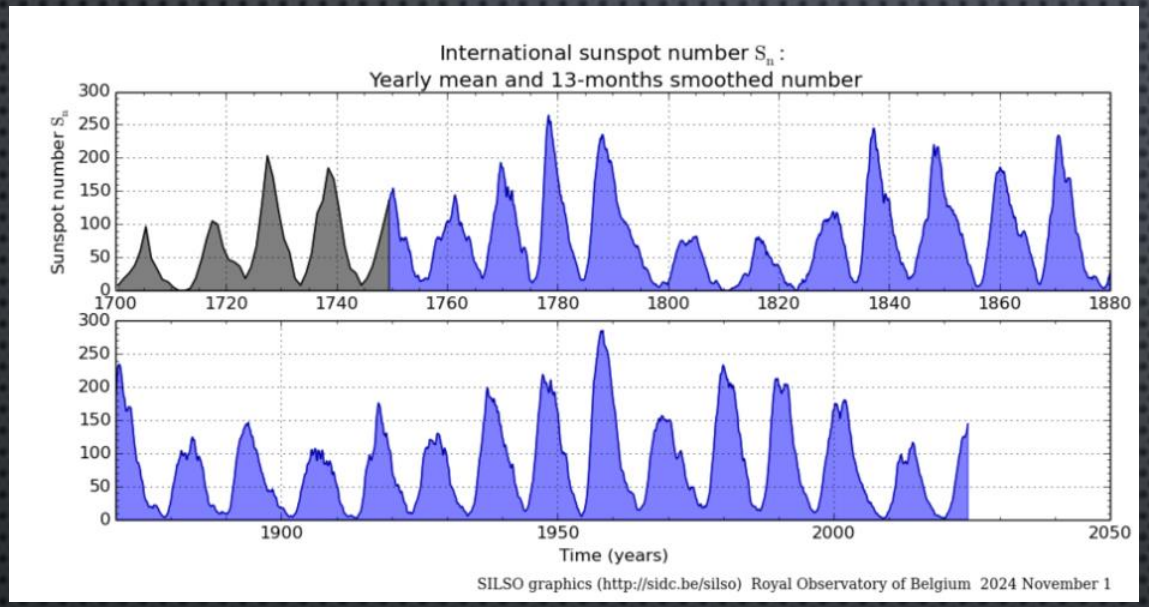
ROTATION

- Star spots and faculae interfere with granulation
- Blocks a portion of the convective blueshift
- As the star rotates the radial component of the overall convective blueshift changes
- Huge variability in amplitude for different stellar types
- Significantly worse for young stars

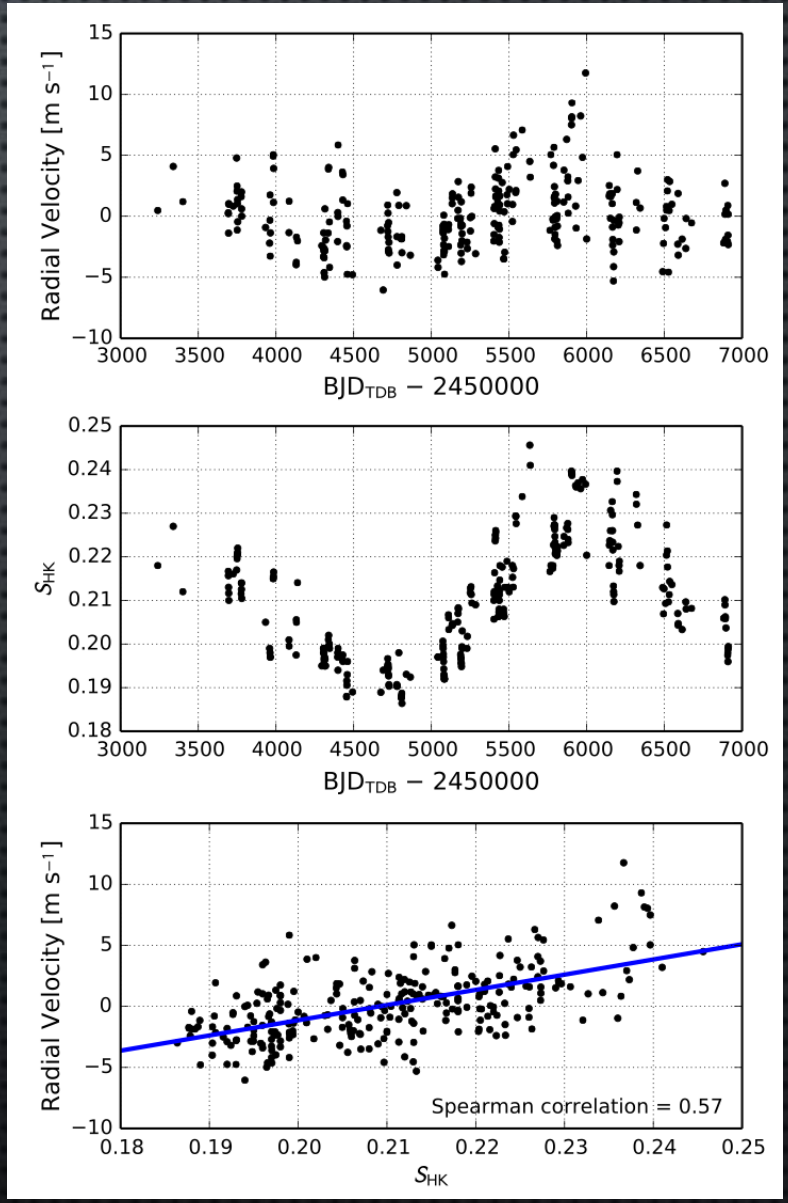


NSO, NOAO

MAGNETIC ACTIVITY CYCLES

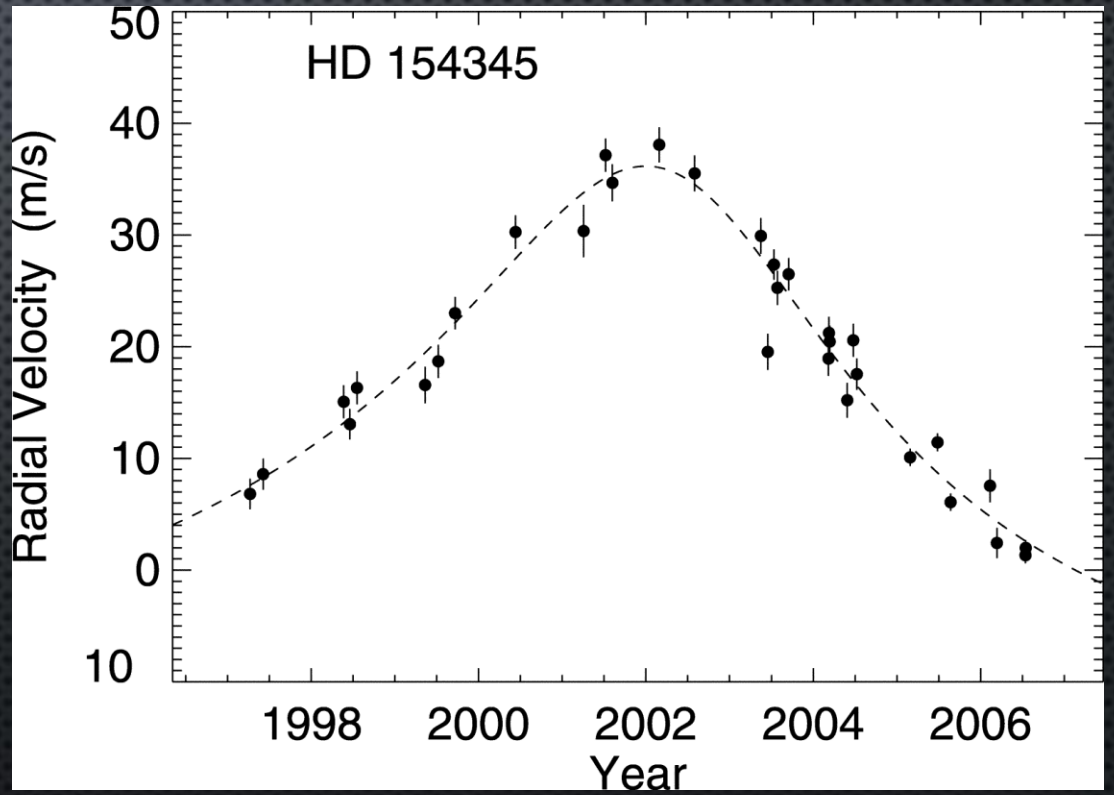


- MEAN NUMBER OF SPOTS CHANGES SIGNIFICANTLY
- MORE SPOTS = LESS CONVECTIVE BLUESHIFT
- MORE SPOTS = MORE ROTATIONAL MODULATION
- TRACKED NICELY BY CAHK



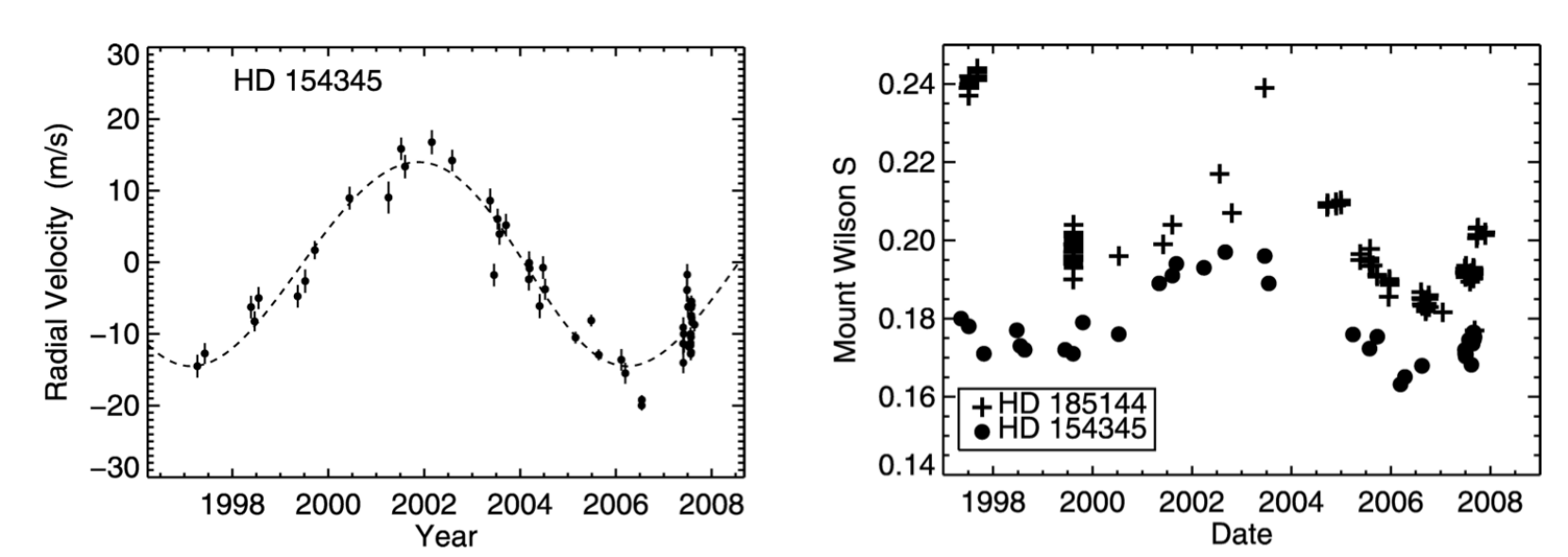
THE STORY OF HD 154345

- PUBLISHED AS A PLANET CANDIDATE IN 2007 WITH A PARTIAL ORBIT



Wright et al. (2007)

THE STORY OF HD 154345

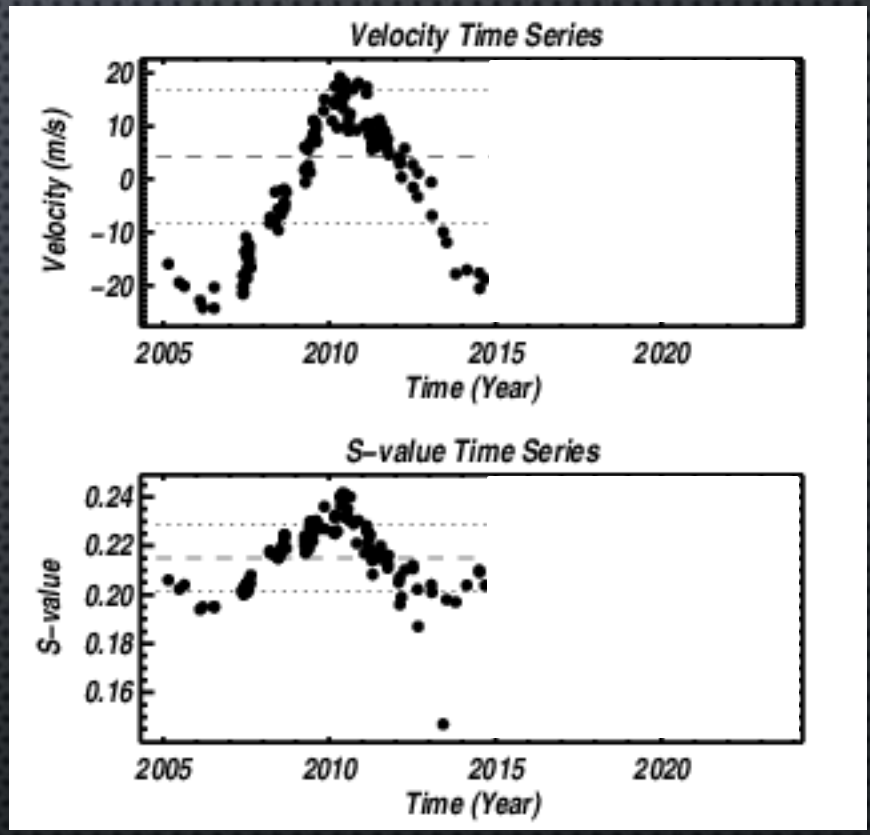


Wright et al. (2009)

- PUBLISHED AS A CONFIRMED "JUPITER-TWIN" IN 2009 WITH ONE FULL ORBIT
- S-VALUES DERIVED FROM CAHK SHOWED SAME PATTERN AS VELOCITIES BUT INTERPRETED AS SIMPLY A COINCIDENCE BECAUSE THE RV SIGNAL WAS TOO LARGE TO BE CAUSED BY ACTIVITY

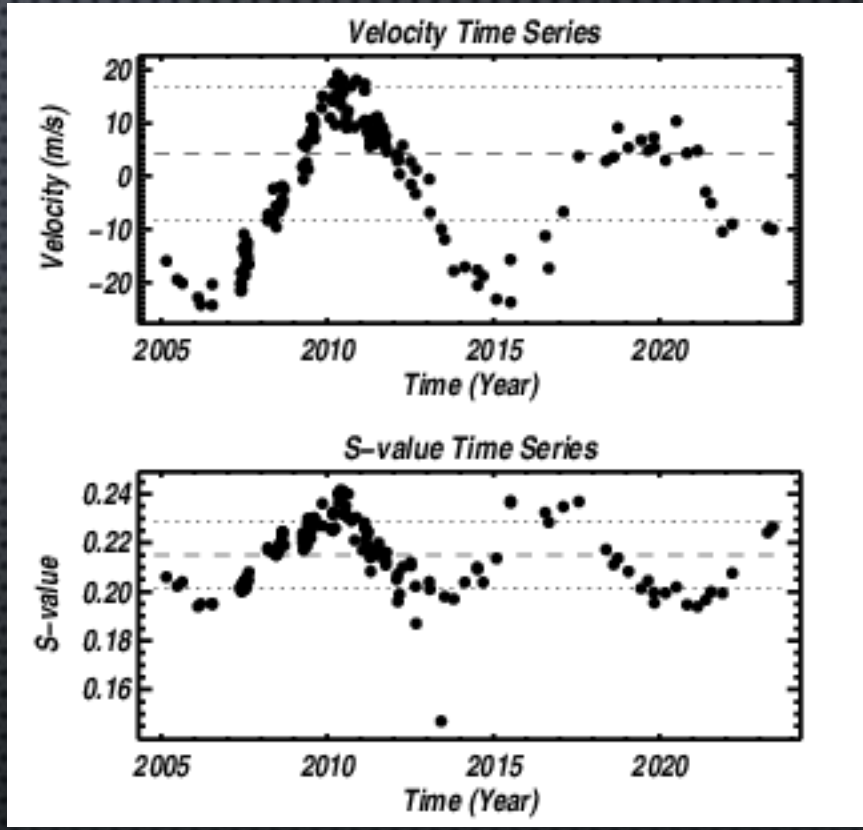
THE STORY OF HD 154345

- In the next decade we started to see other stars with similar high amplitude correlations between S-value and RV
- "Continued monitoring of HD 154345 since 2008 has shown that the activity cycle continues to be well correlated with the RVs, amplifying the coincidence. Similar correlations among a small number of other stars of similar spectral type have begun to cast doubt on the planetary hypothesis for HD 154345"



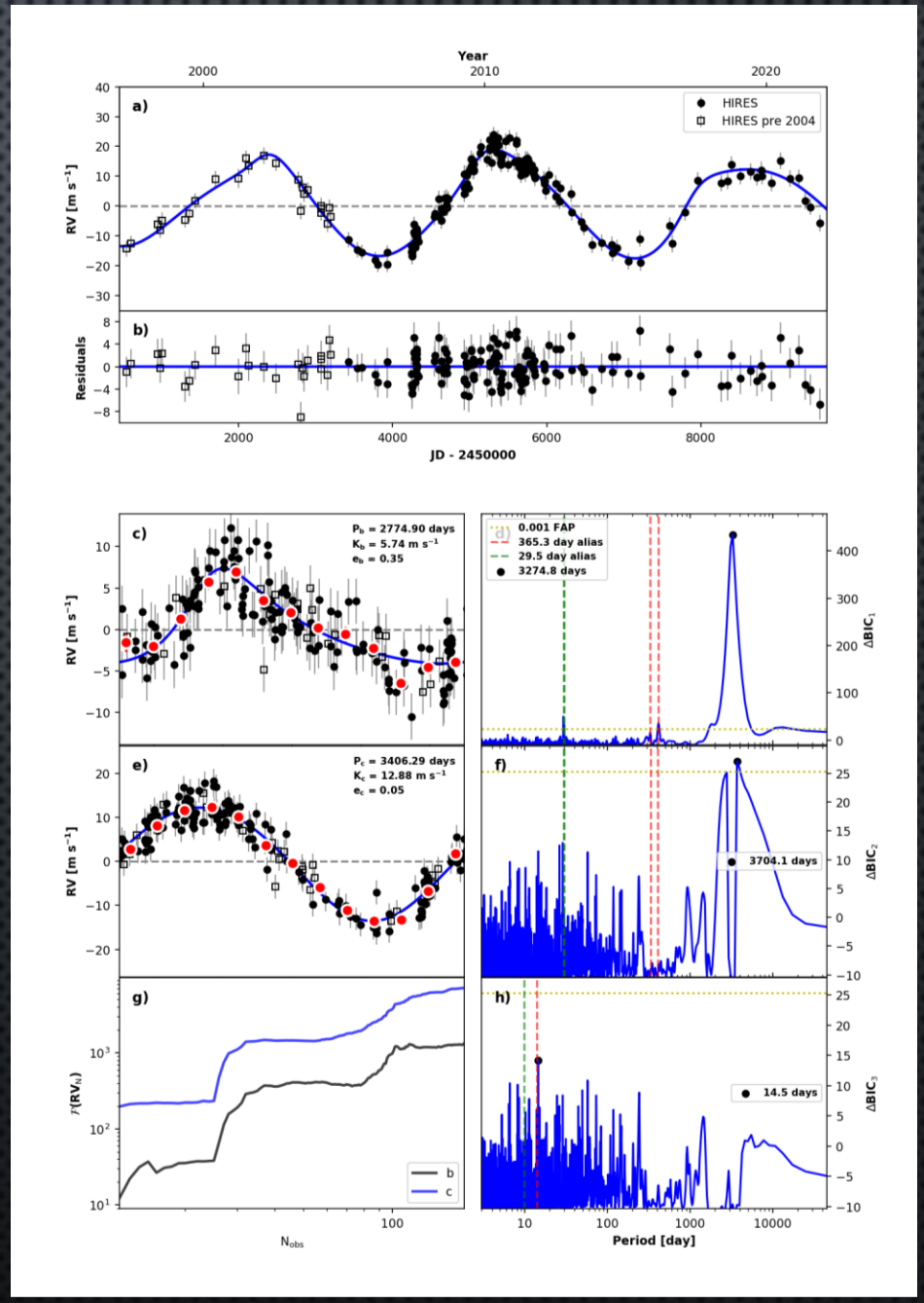
THE STORY OF HD 154345

- After 2015 we started to notice that the S-values were completely out of phase with the RV signal



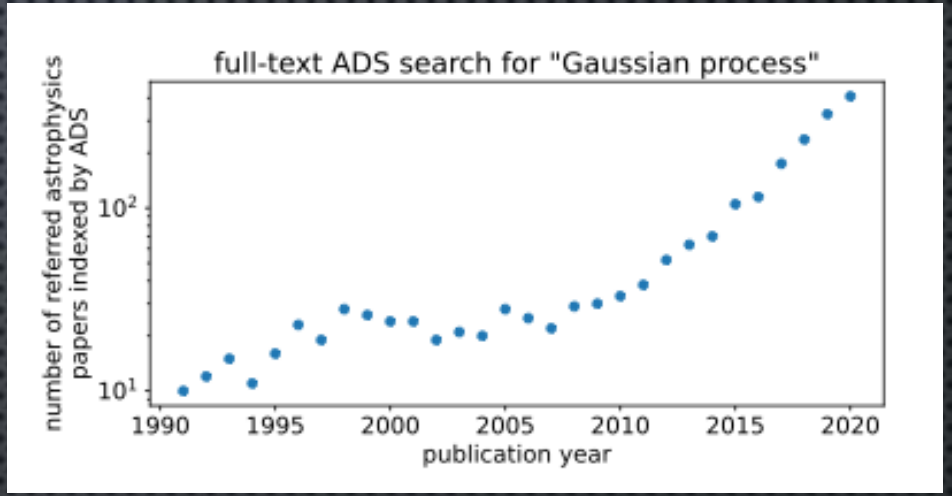
THE STORY OF HD 154345

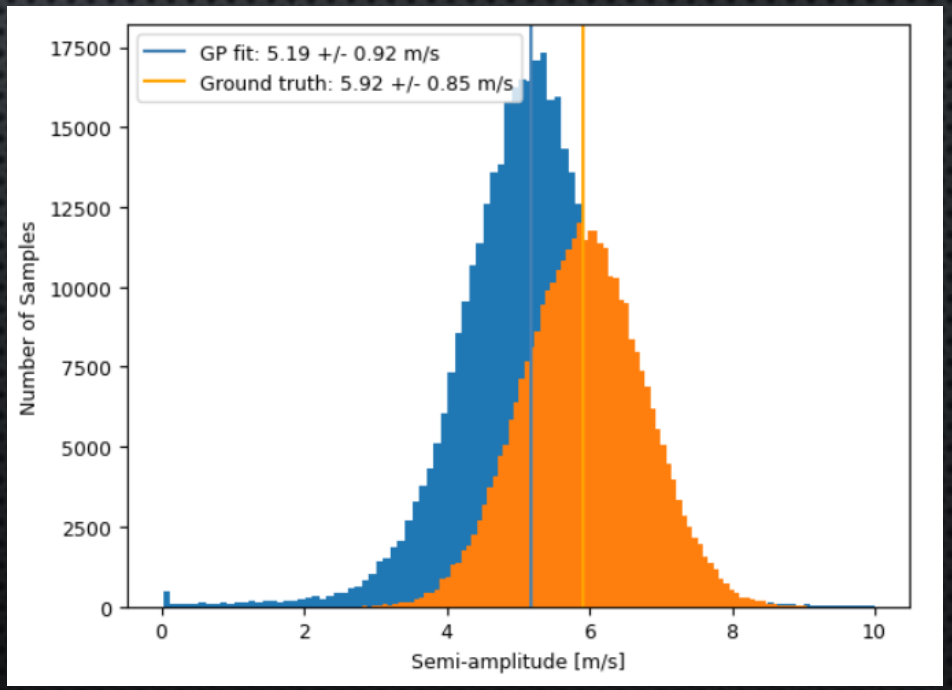
- By 2021 we were able to separate the two signals using the RVs alone
- Quasi-periodic activity signal with a period of 7.6 years
- Planet on circular orbit with period of 9.3 years

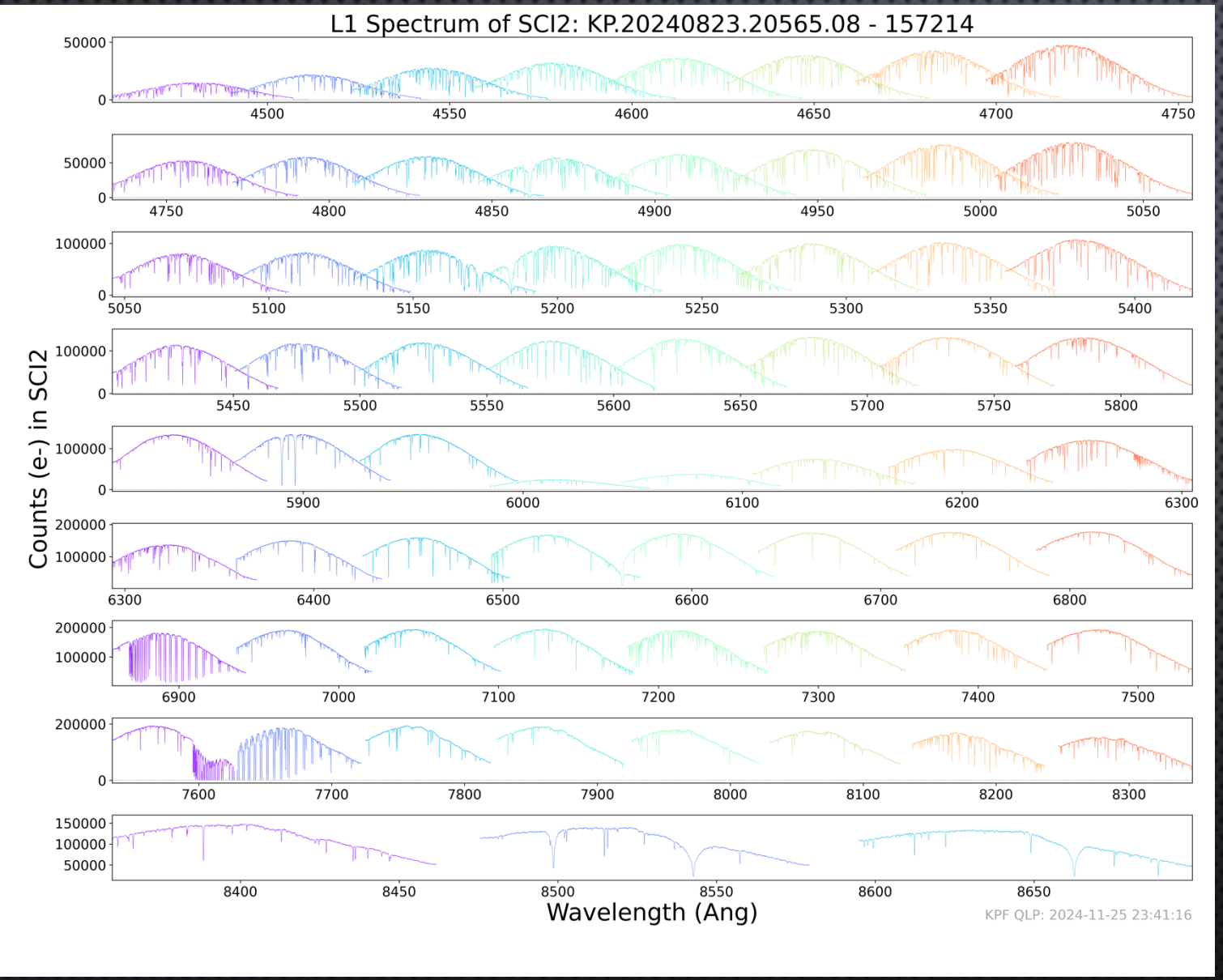


COMPENSATING FOR STELLAR ACTIVITY

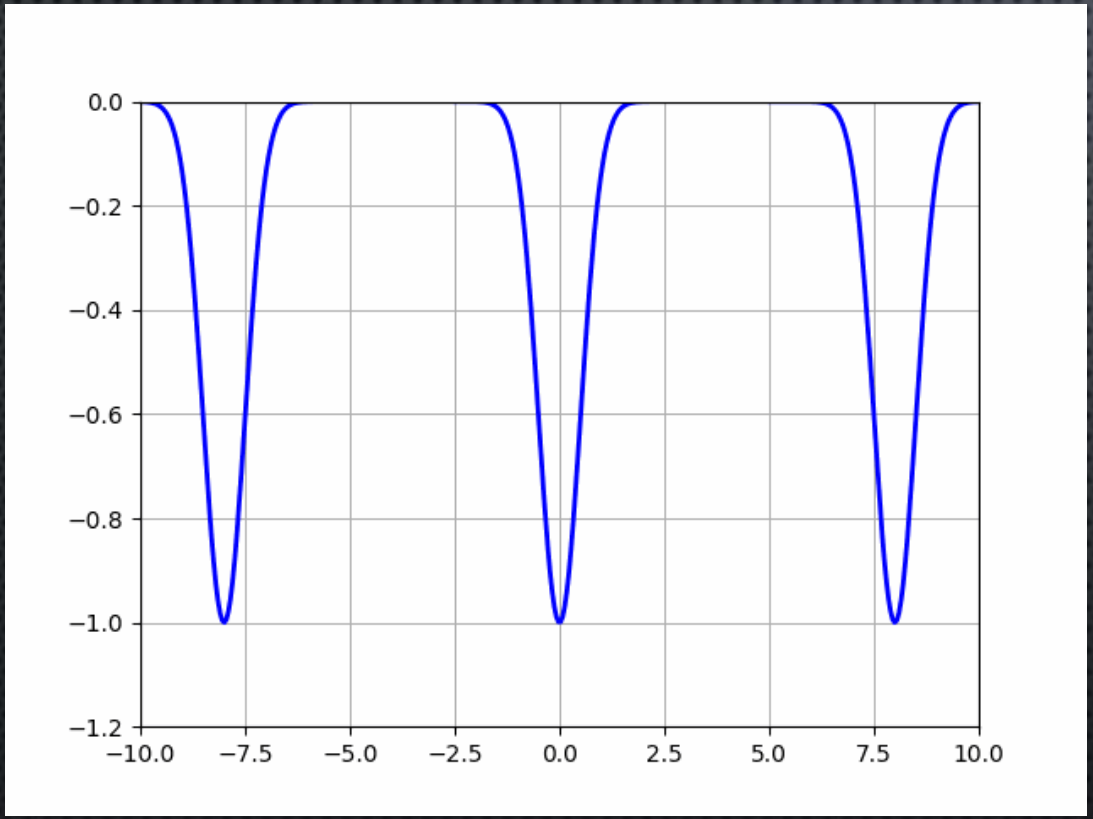
- GAUSSIAN PROCESS REGRESSION
- QUICKLY GAINED POPULARITY IN THE LATE 2010'S AS A WAY TO SIMULTANEOUSLY FIT FOR STELLAR ACTIVITY IN THE TIMESERIES DATASETS THEMSELVES
- ESPECIALLY USEFUL IN CASES WHERE WE KNOW BOTH THE PLANET'S PERIOD AND THE ROTATION PERIOD OF THE STAR
- CAN CONSTRAIN THE GP HYPERPARAMETERS FROM MANY DIFFERENT DATASETS AT ONCE (E.G. CAHK, PHOTOMETRY, CCF CHARACTERISTICS, ETC.)
- QUASI-PERIODIC KERNEL MOST COMMON
- PROBLEMS FOR RVS:
  - DIFFICULT TO DISENTANGLE QUASI-PERIODIC AND PERIODIC SIGNALS FROM RV DATA ALONE, ESPECIALLY FOR LOW-AMPLITUDE SIGNALS
  - THE GP CAN INTERFERE WITH THE KEPLERIAN FIT AND BIAS THE AMPLITUDE



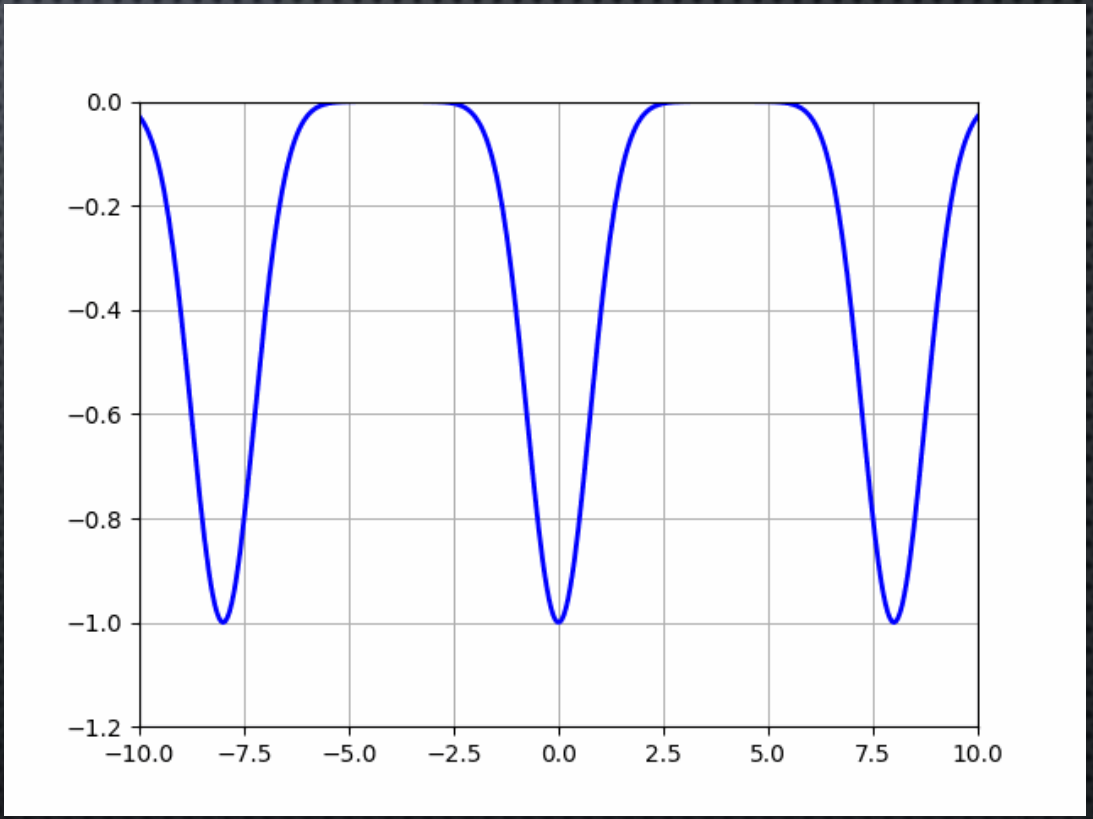


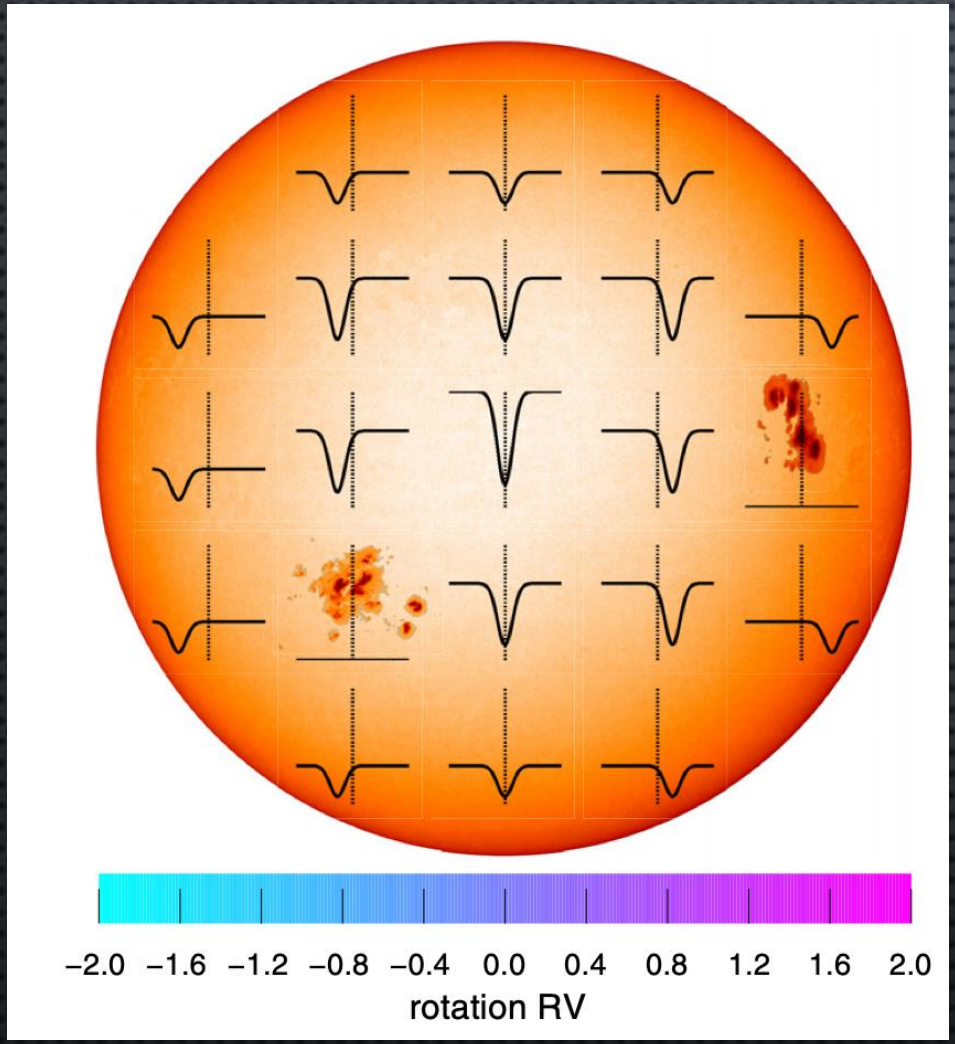

L1 Spectrum of SCI2: KP.20240823.20565.08 - 157214
Counts (e-) in SCI2
Wavelength (Ang)
KPF QLP: 2024-11-25 23:41:16

DOPPLER SHIFT

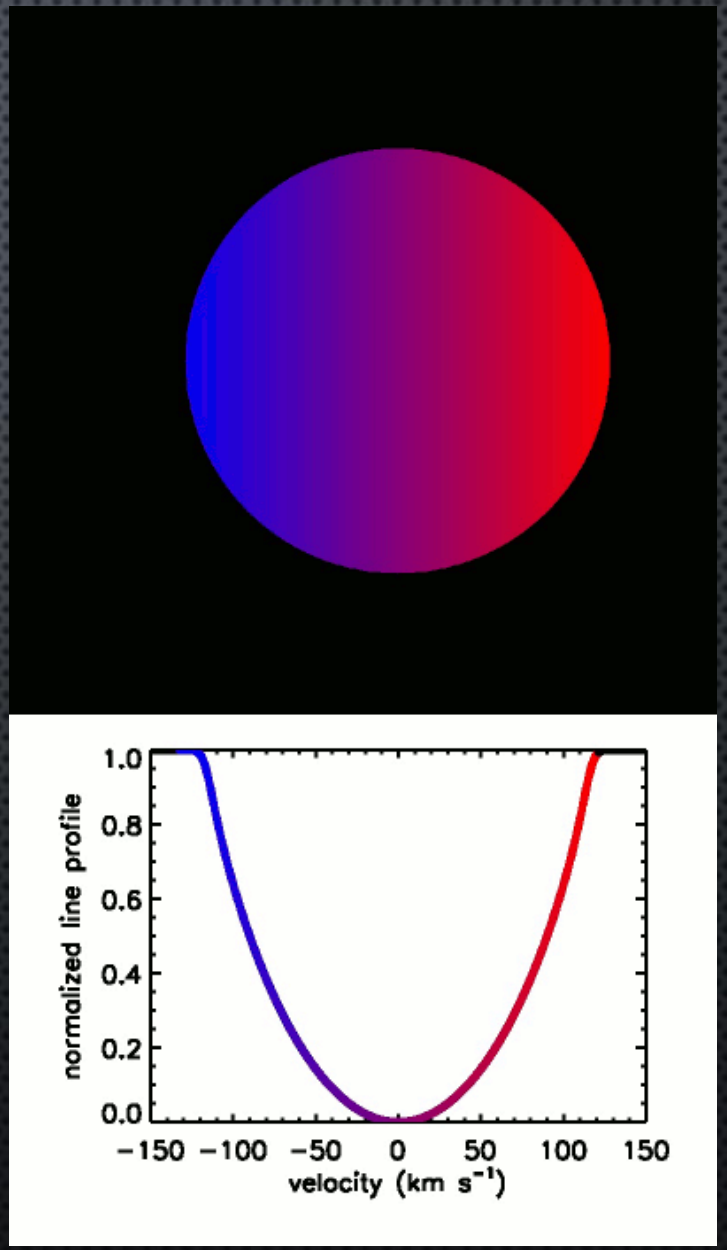


LINE DISTORTIONS

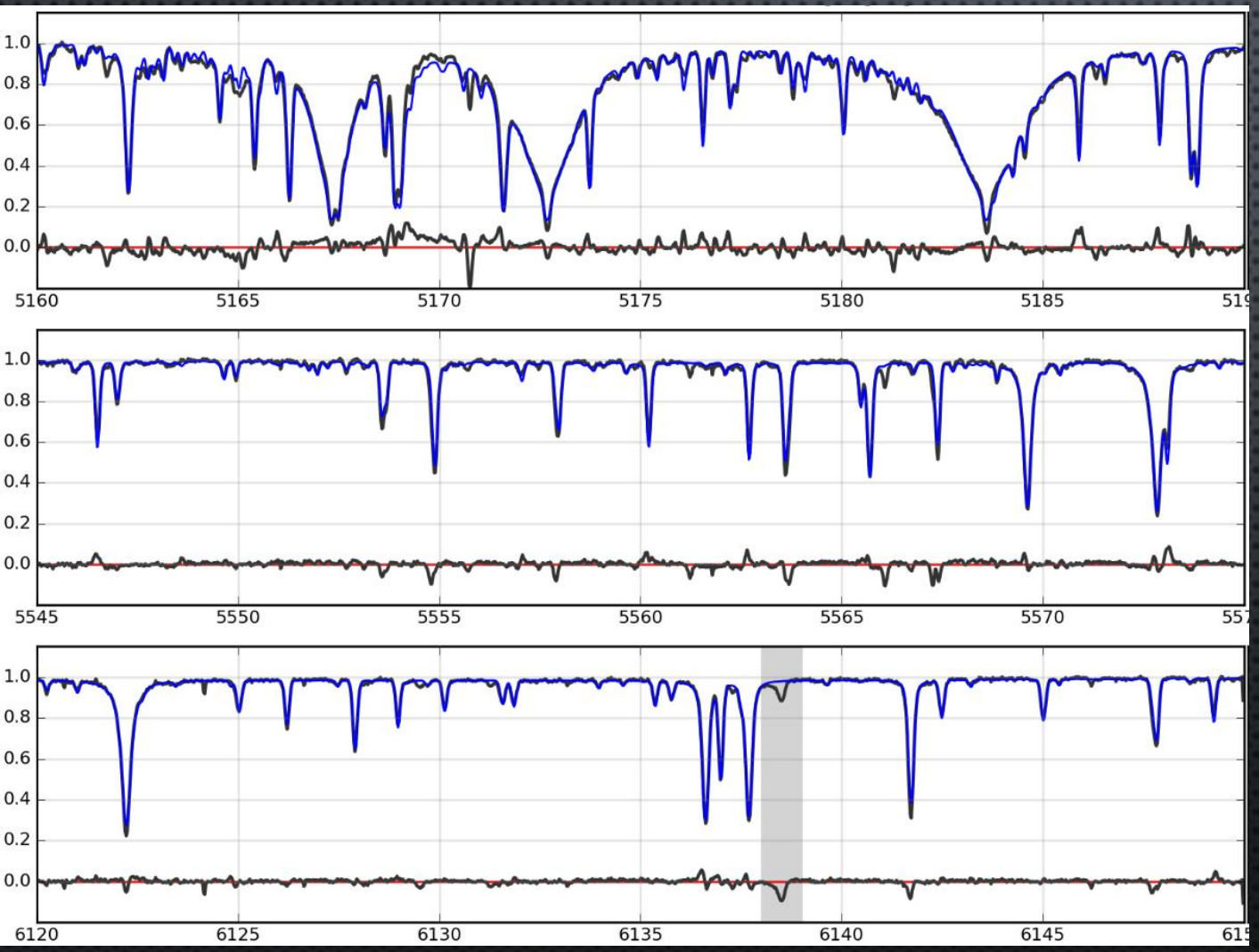


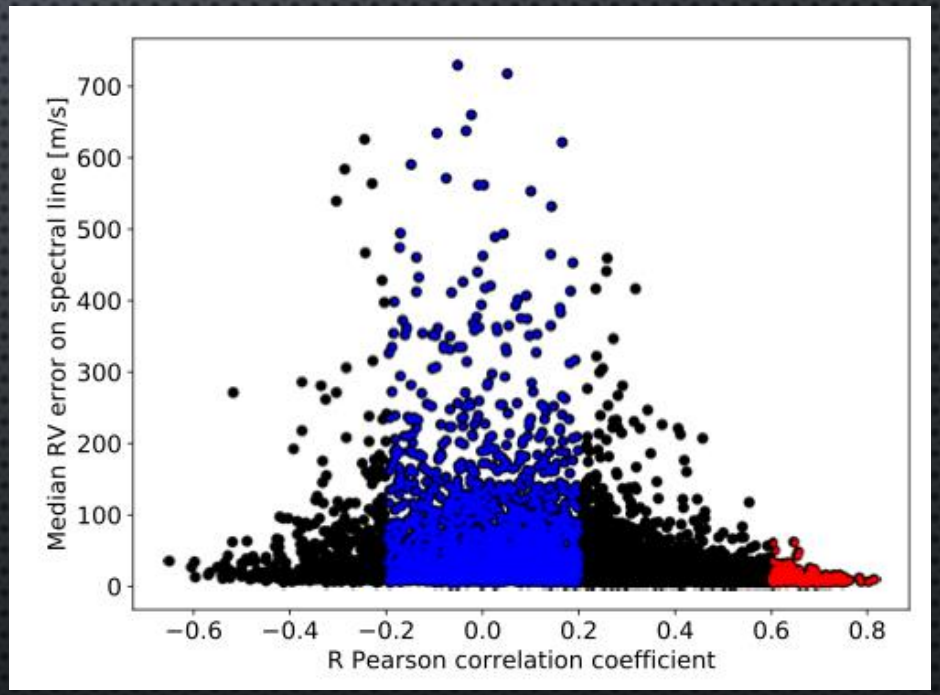


Dumusque et al. (2014)

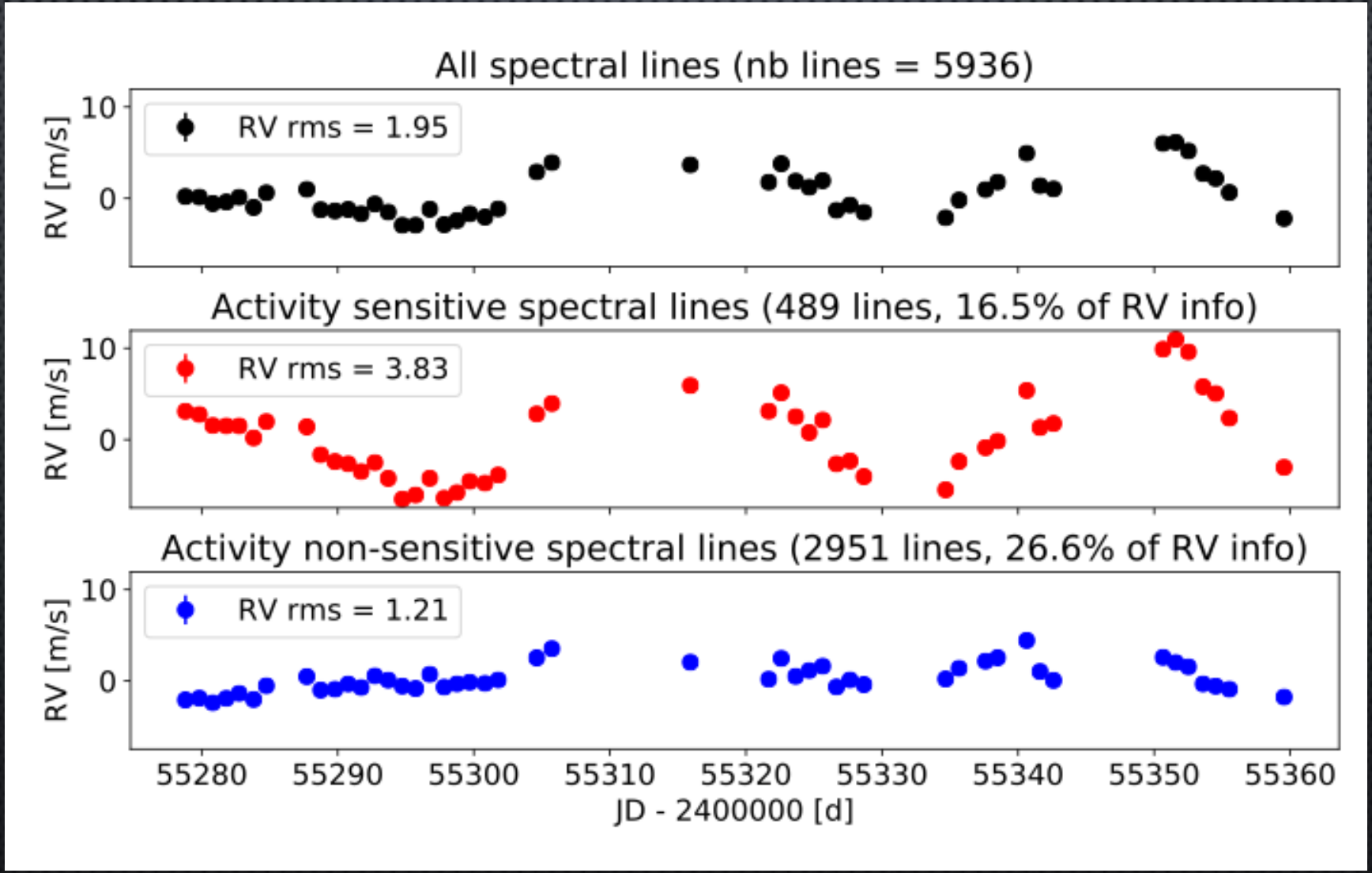


Marshall Johnson

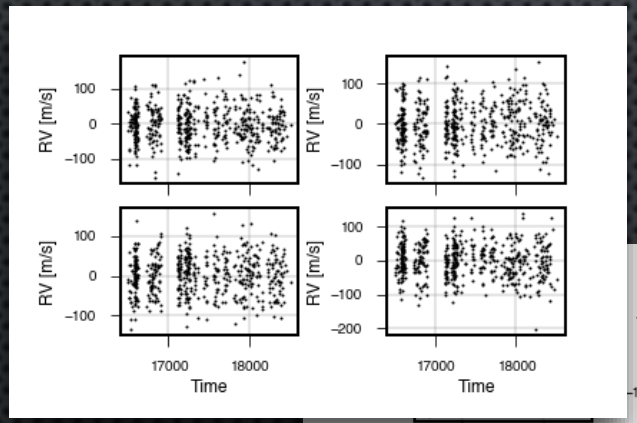




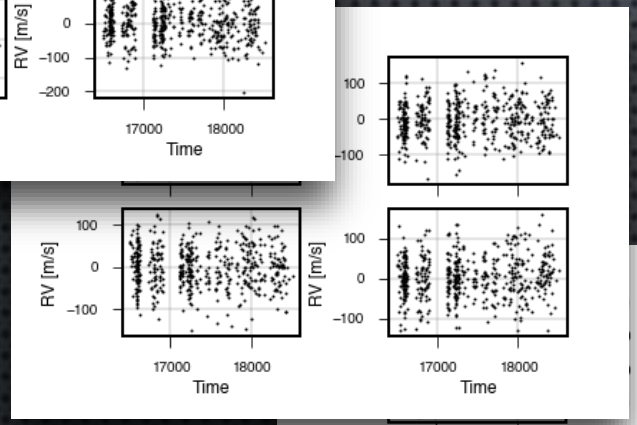
Dumusque et al. (2018)

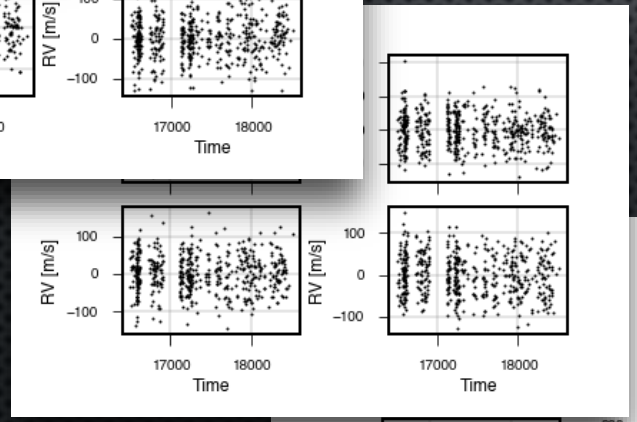


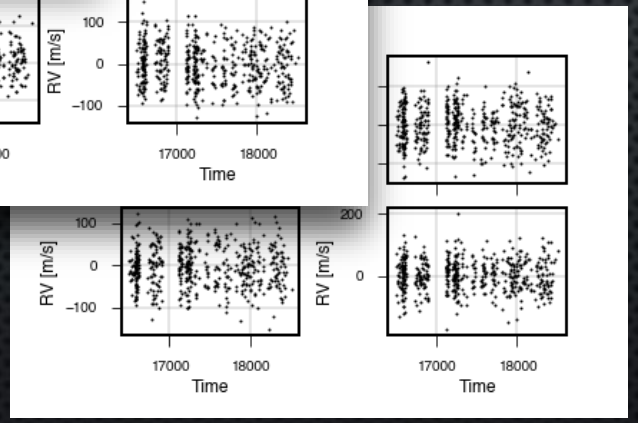
Dumusque et al. (2018)

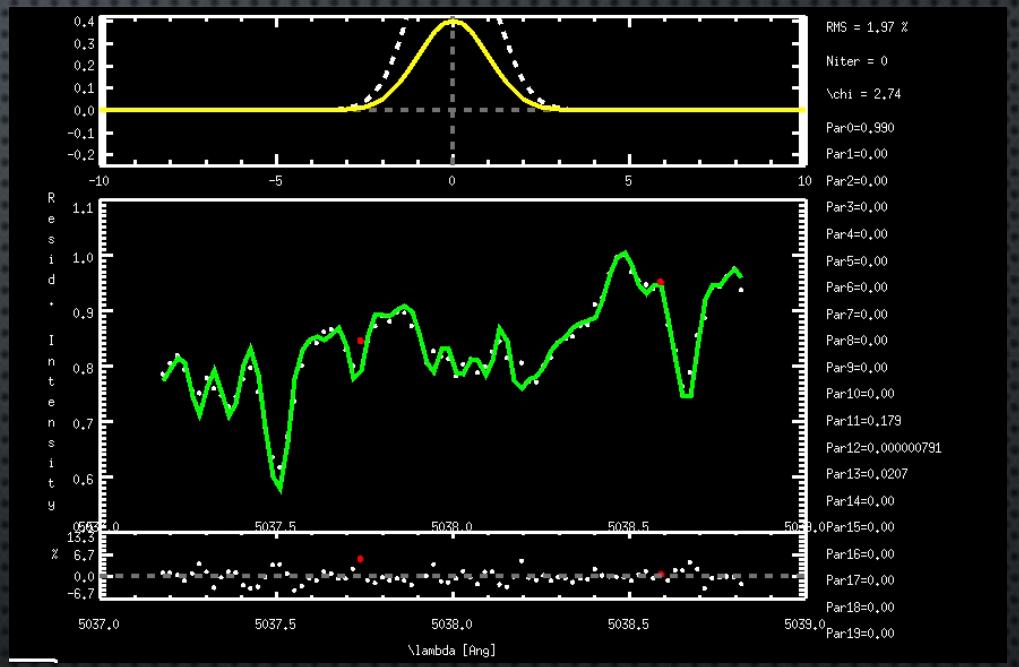

RV [m/s]
Time
17000
18000

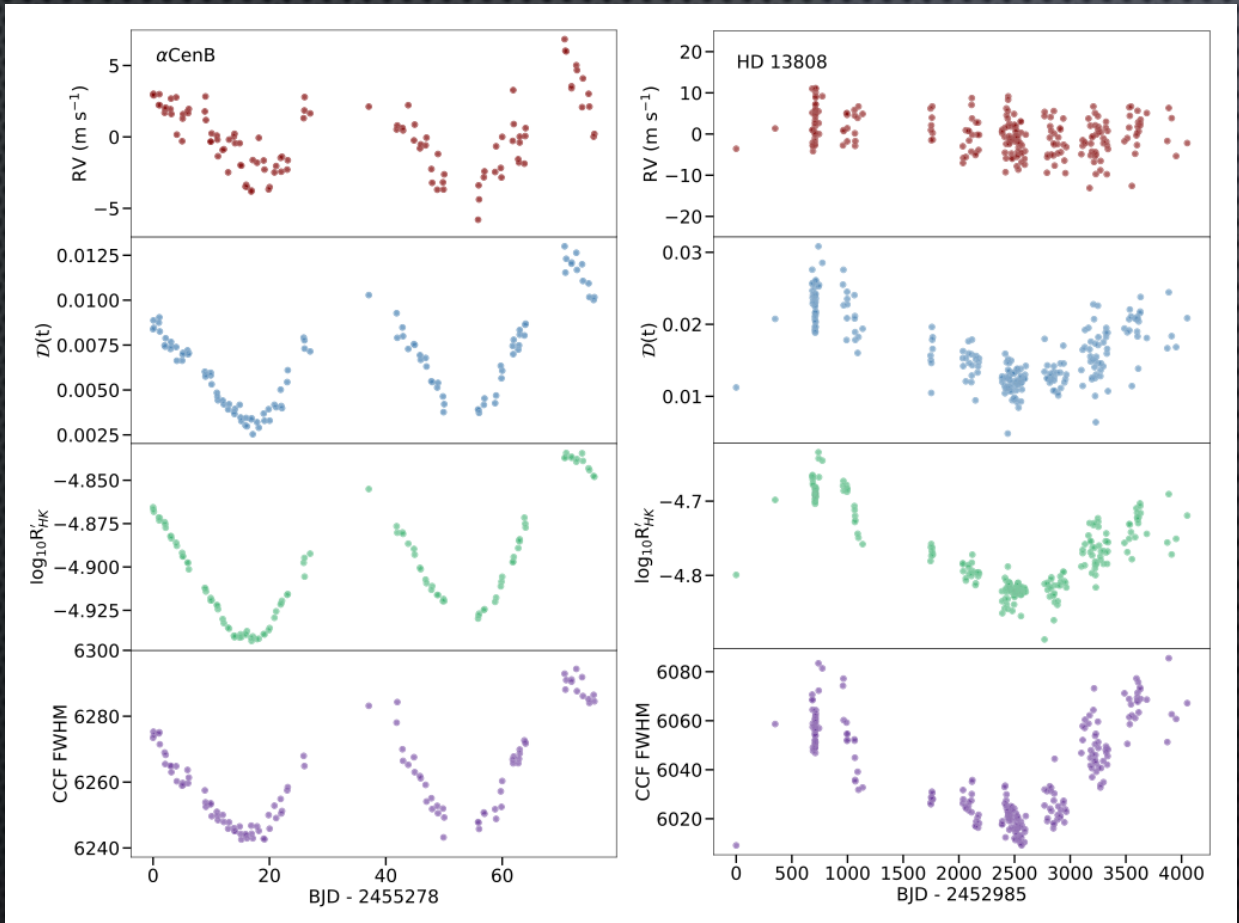
Chunk


RV [m/s]
Time
17000
18000

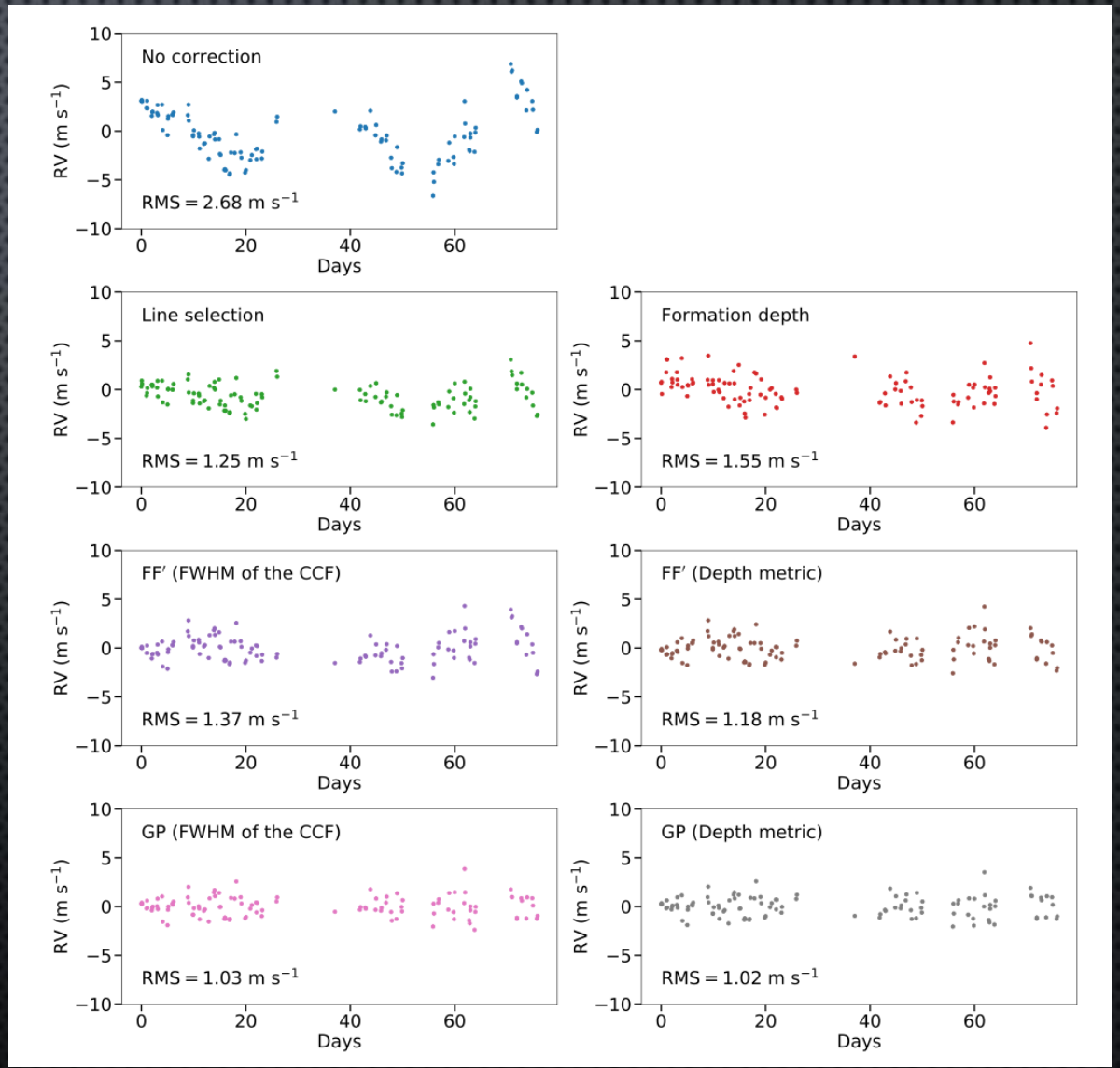

RV [m/s]
Time
17000
18000


RV [m/s]
Time
17000
18000


RMS = 1.97 %
Niter = 0
\chi = 2.74
Par0=0.990
Par1=0.00
Par2=0.00
Par3=0.00
Par4=0.00
Par5=0.00
Par6=0.00
Par7=0.00
Par8=0.00
Par9=0.00
Par10=0.00
Par11=0.179
Par12=0.000000791
Par13=0.0207
Par14=0.00
Par15=0.00
Par16=0.00
Par17=0.00
Par18=0.00
Par19=0.00
Resid. Intensity
%
\lambda [Ang]

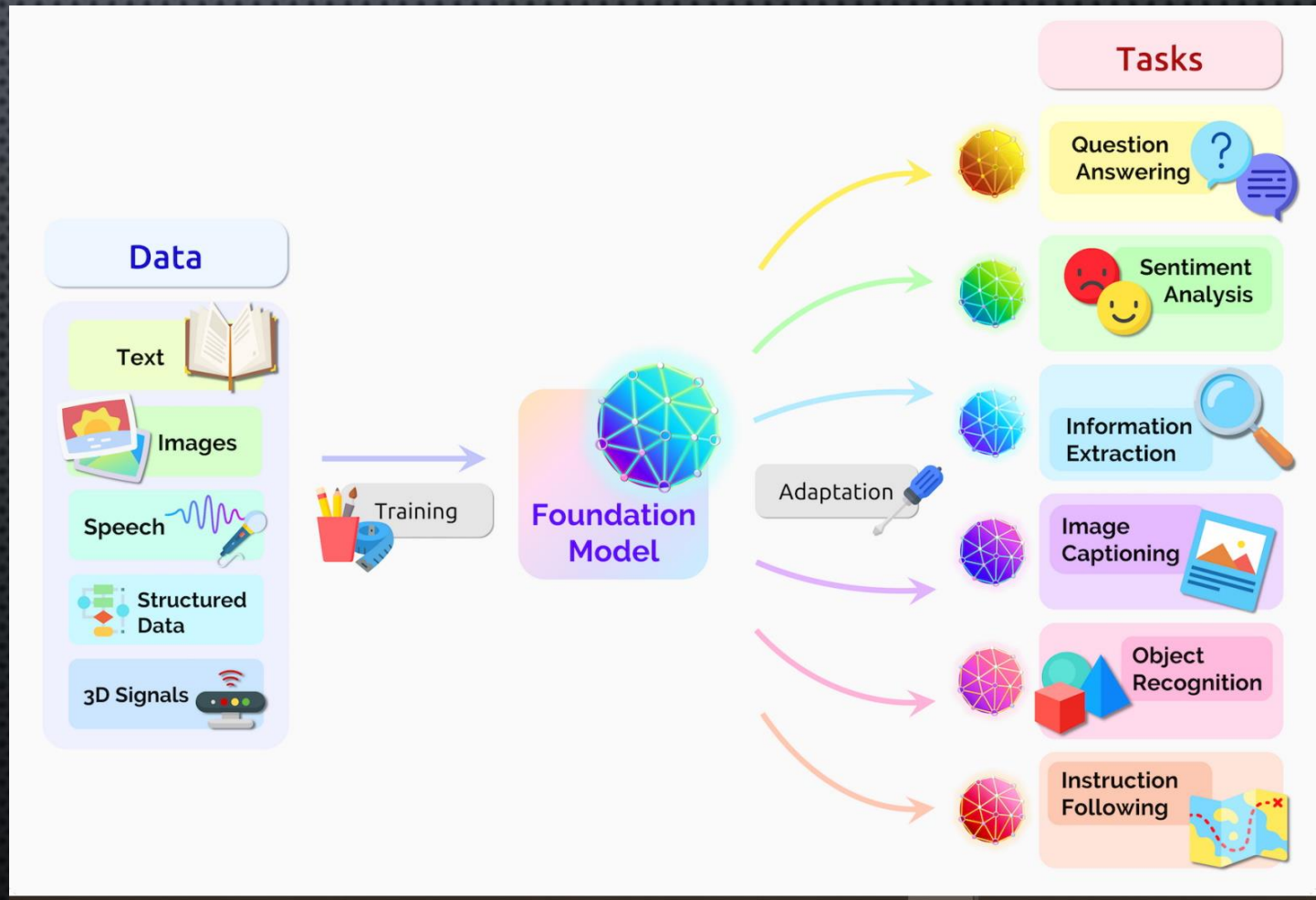


Siegel et al. (2024)



ARE TRANSFORMERS IN OUR FUTURE?

- TRANSFORMERS HAVE REVOLUTIONIZED THE CAPABILITIES OF AI/ML
- PREVIOUS GENERATIONS OF NEURAL NETWORKS RELIED ON MASSIVE PRE-LABELED DATASETS
- TRANSFORMERS CAN DISCOVER RELATIONSHIPS WITHIN THE DATA ON THEIR OWN
- ASTRONOMY DATASETS AND BUDGETS ARE GENERALLY TOO SMALL TO TRAIN FOUNDATIONAL MODELS
- FINE-TUNING EXISTING MODELS MAY SUFFICE



NVIDIA

Summary

- We're good at building spectrographs
- Stellar photospheres are moving targets
- Stars are always trying to trick us
- RV datasets are now large enough to explore new computing techniques