



Strategies for Mitigating Stellar Variability

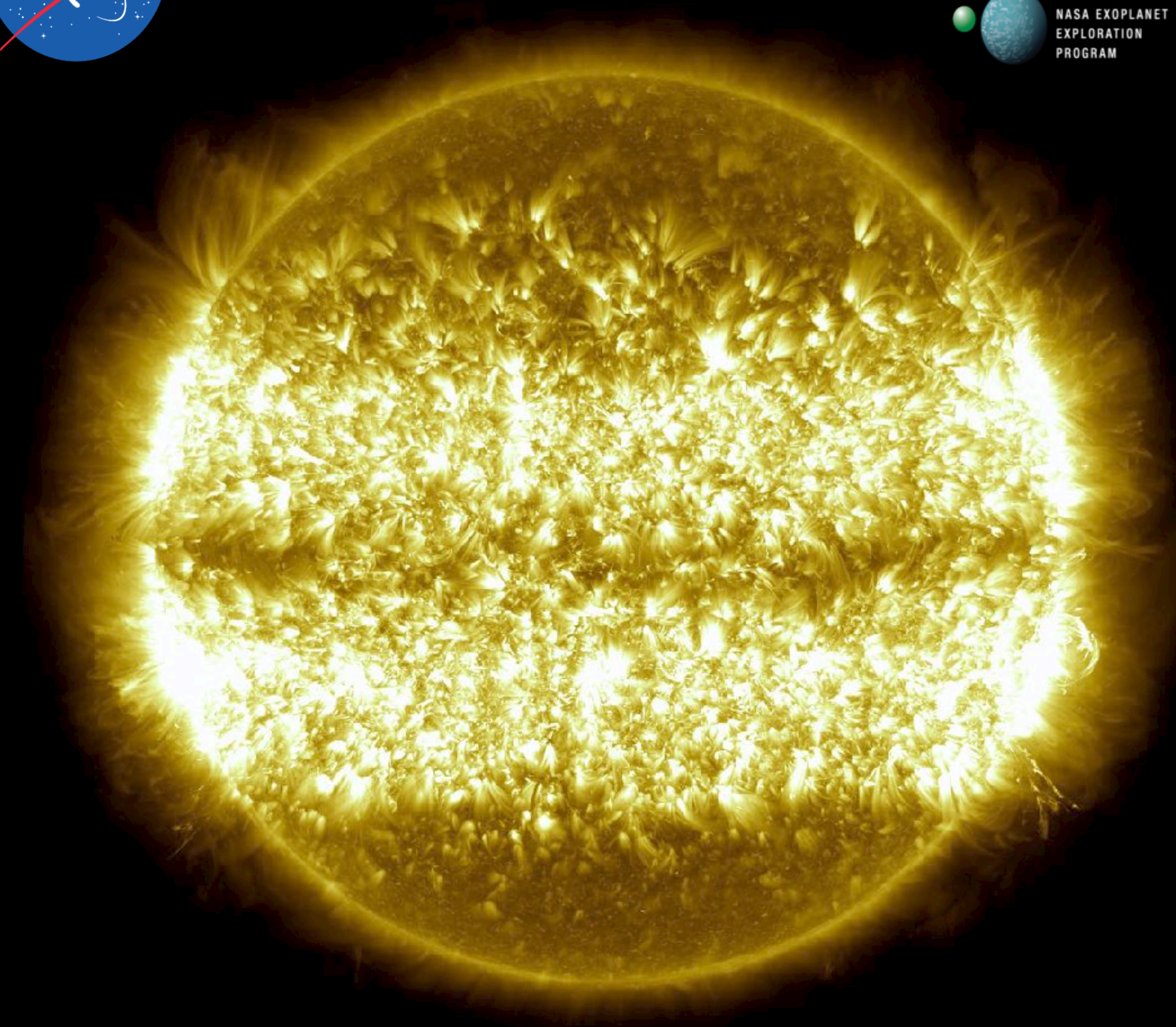
Jennifer Burt¹

2020 Sagan Summer Workshop

CL#20-3396

¹ Jet Propulsion Laboratory, California Institute of Technology

Image credit: NASA Goddard Space Flight Center



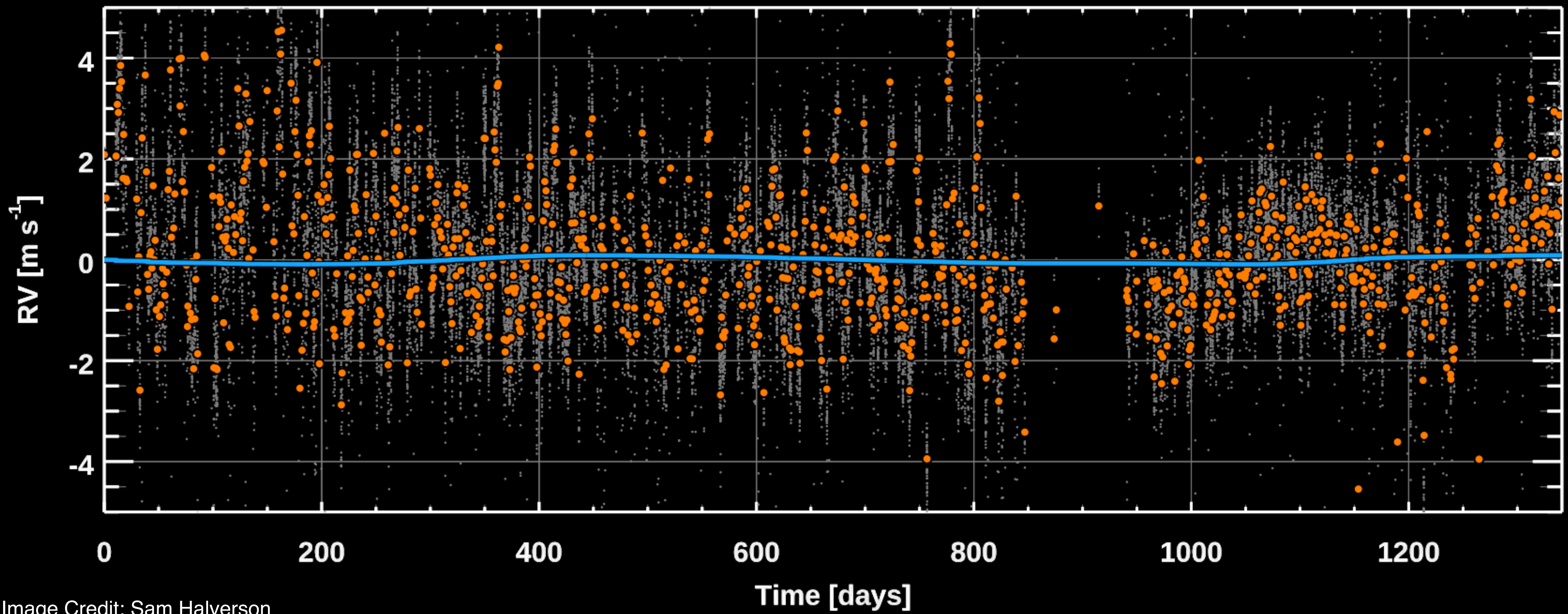


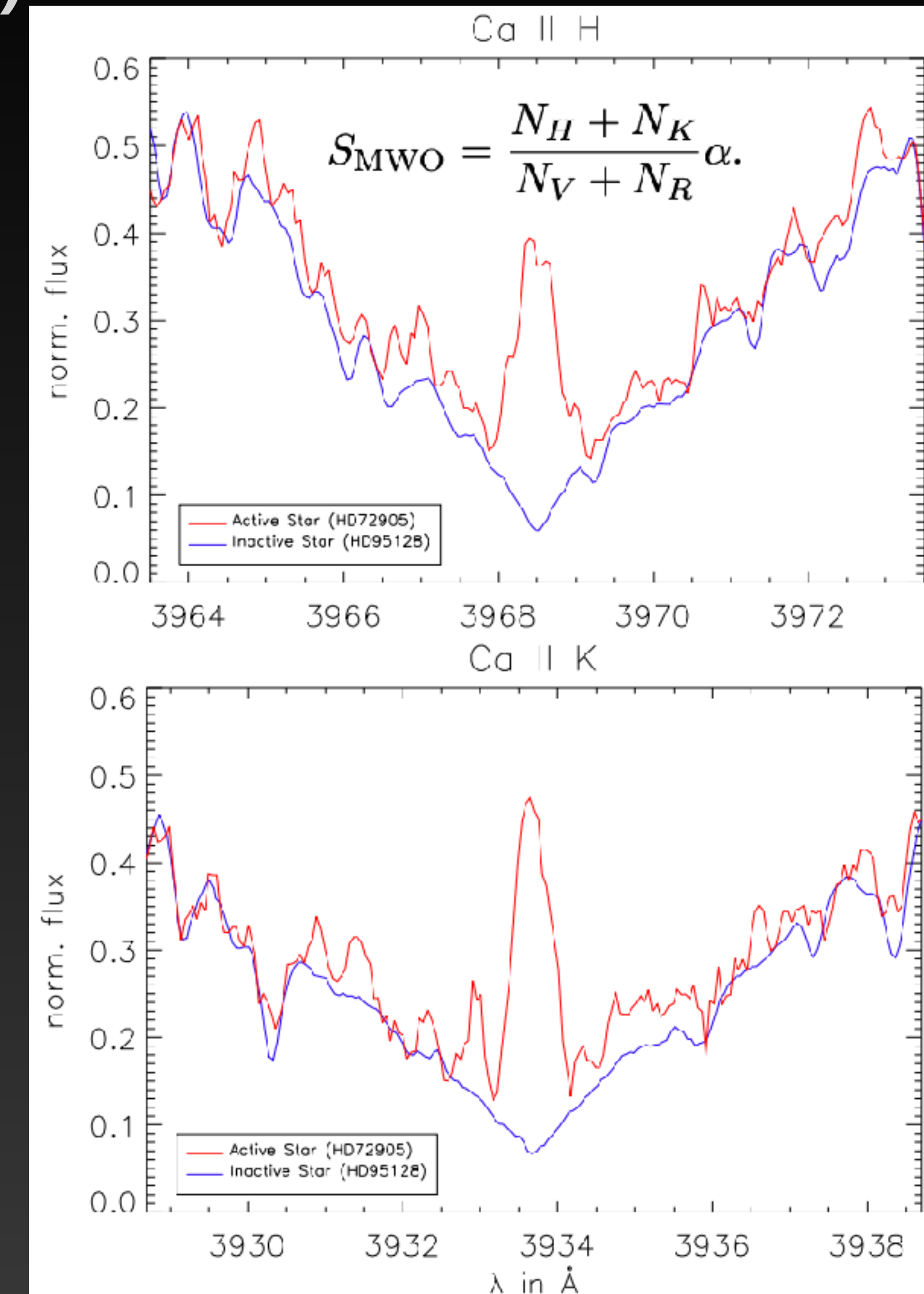
Image Credit: Sam Halverson

**How do you detect and
measure stellar variability?**

Spectroscopic Variability

I. Ca II H&K lines (S-index)

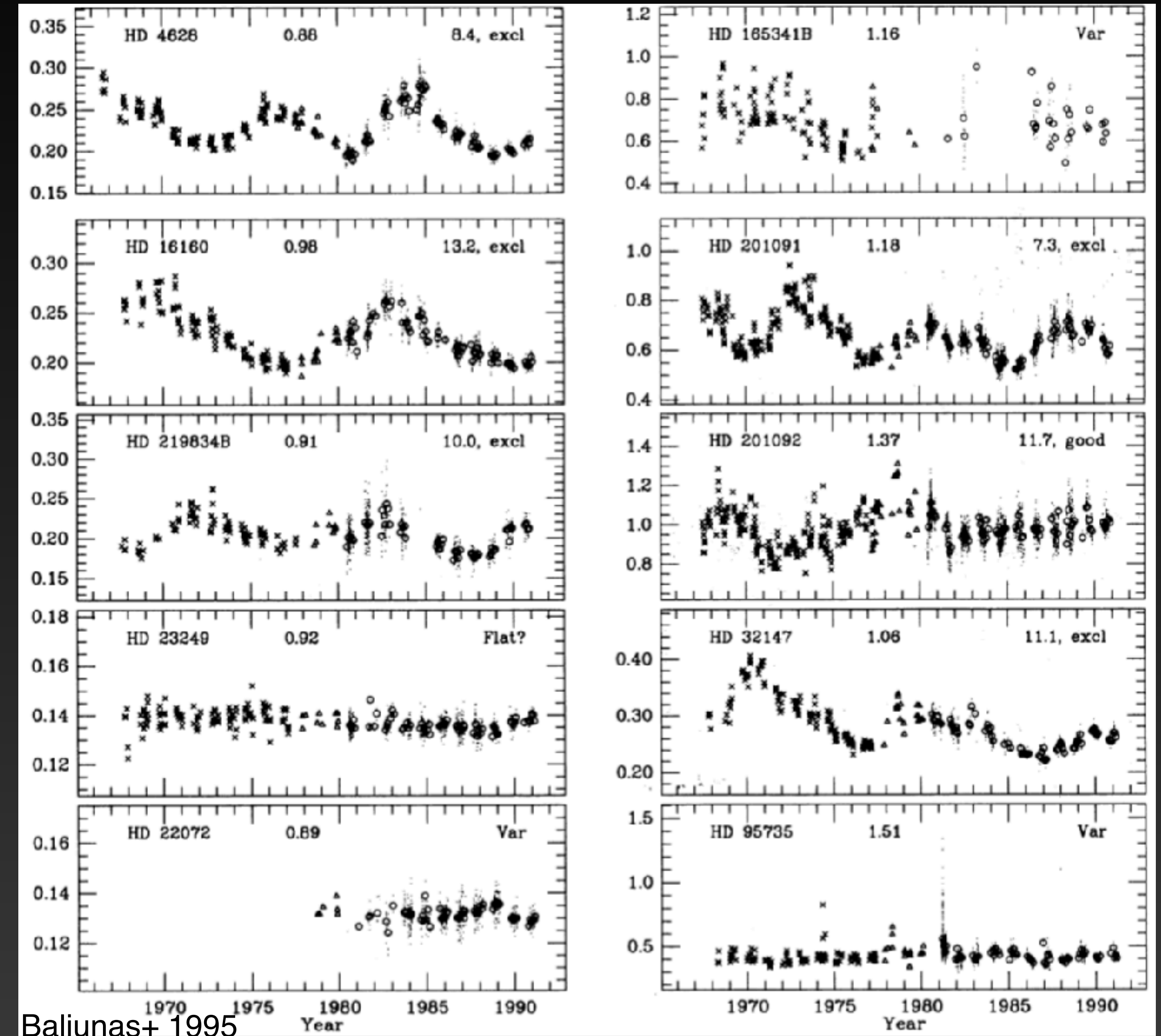
- Source: Singly-ionized Calcium H & K lines (3968.5Å and 3933.7Å)
- Method: measure flux ratio of the two Ca lines and two nearby continuum regions.
- Tells you about: chromospheric and photospheric activity. Since the line core emission is concentrated in plage regions, S-index often shows variations with the rotation period of the star. Proxy for the number of spots on the sun.



Spectroscopic Variability

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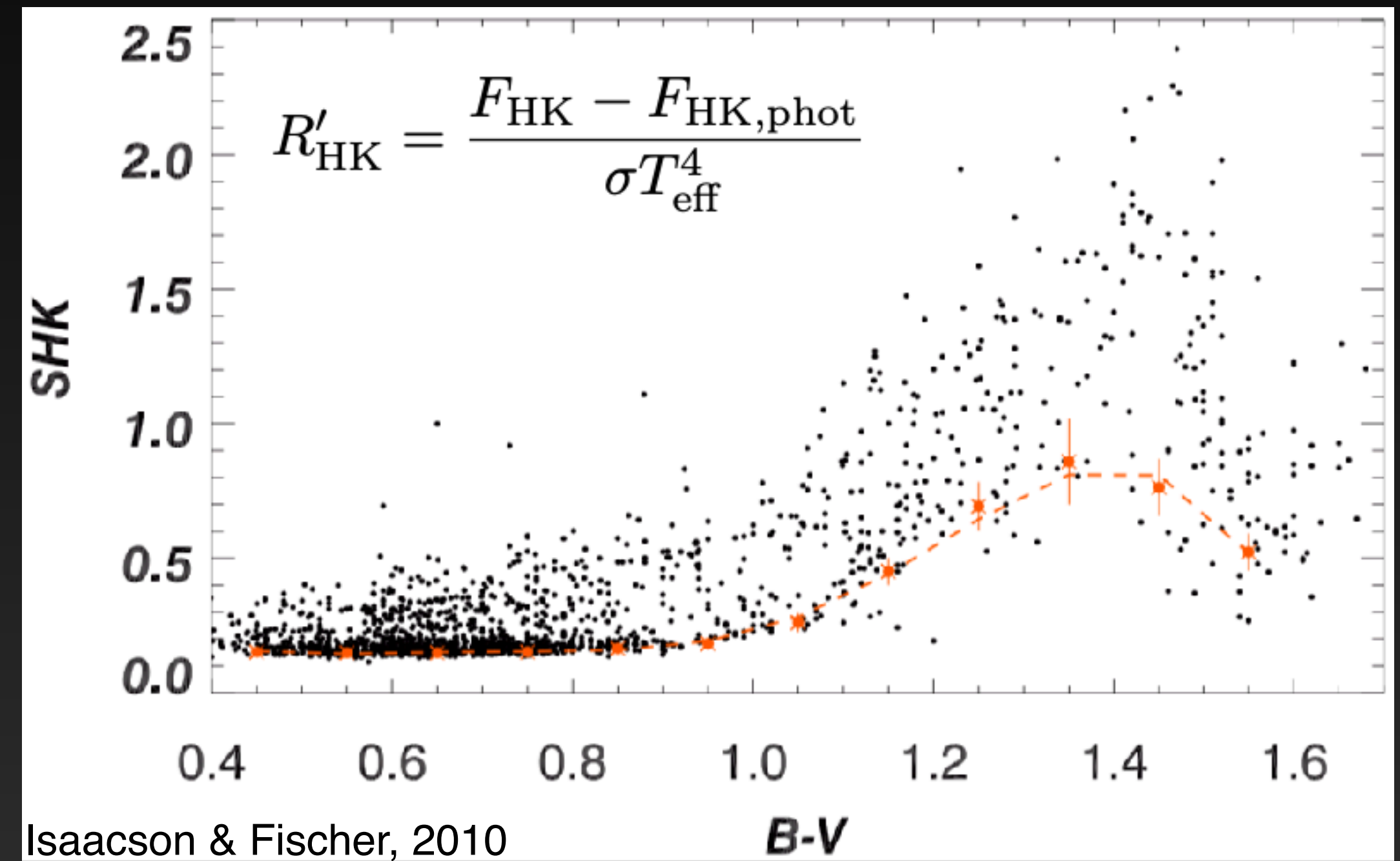
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Spectroscopic Variability

Ib. R'_{HK}

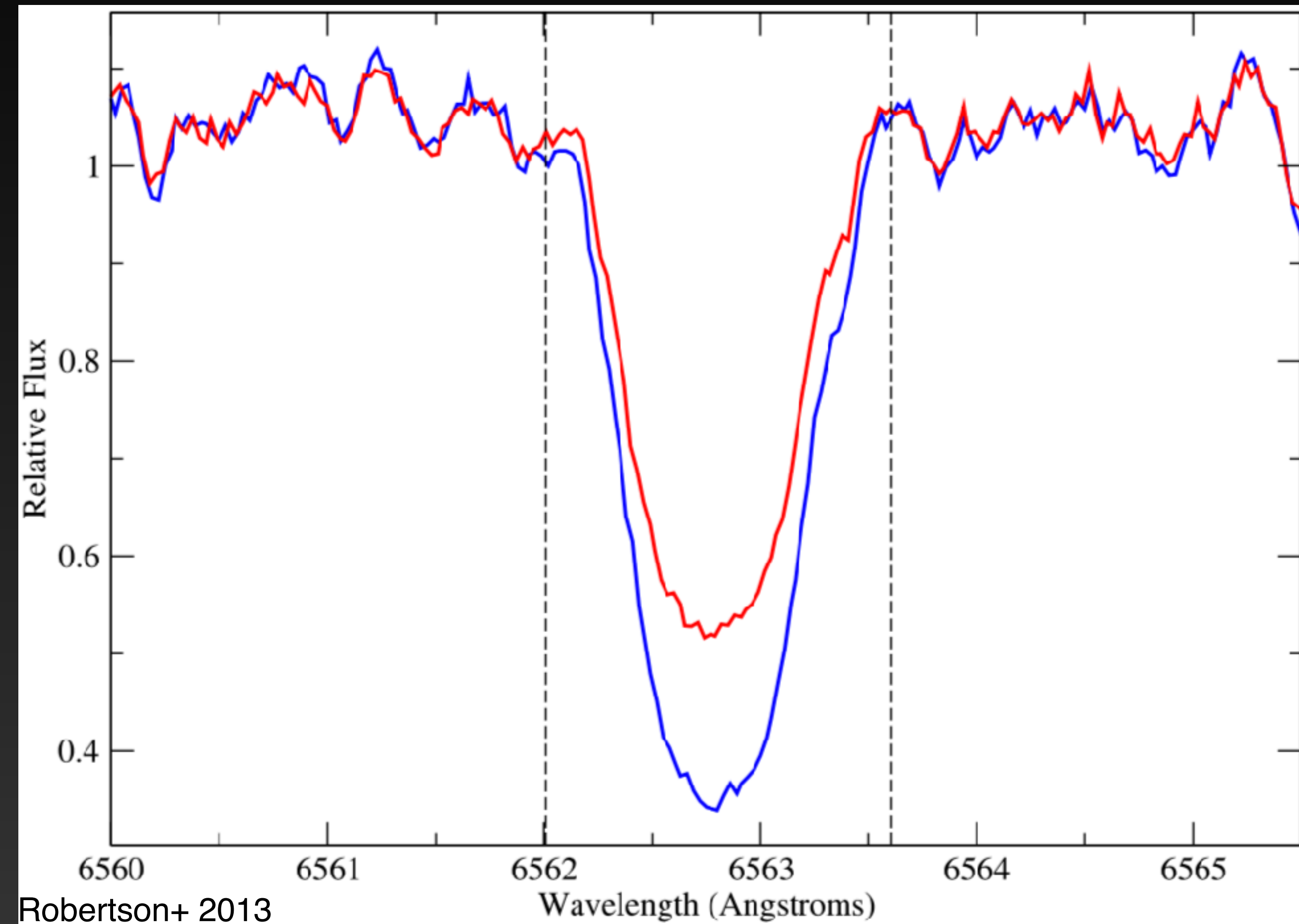
- Related to the S-index, but takes out the basal (rotation independent) photospheric flux.
- The photospheric flux that falls into the S-index filters introduces a dependency on T_{eff} . By removing it, you produce a measure of activity that can be compared across spectral types



Spectroscopic Variability

II. H-alpha

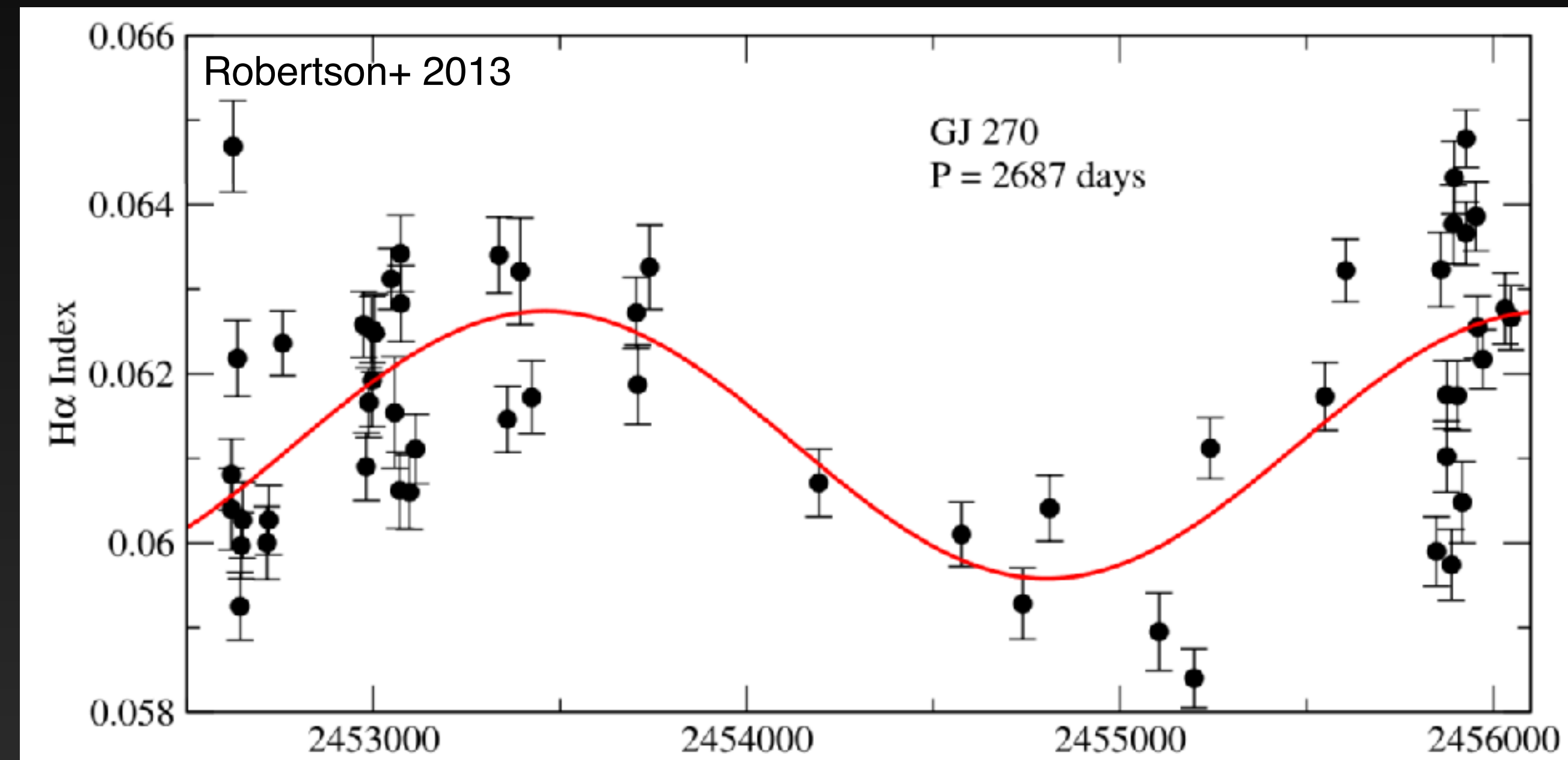
- Source: Hydrogen Balmer line (6562.828Å)
- Method: measure flux ratio of the H-alpha line and two nearby continuum regions.
- Tells you about: chromospheric activity. In areas where magnetic field lines influence plages, H α photons are emitted which produces an activity-dependent depth of the H α absorption line



Spectroscopic Variability

II. H-alpha

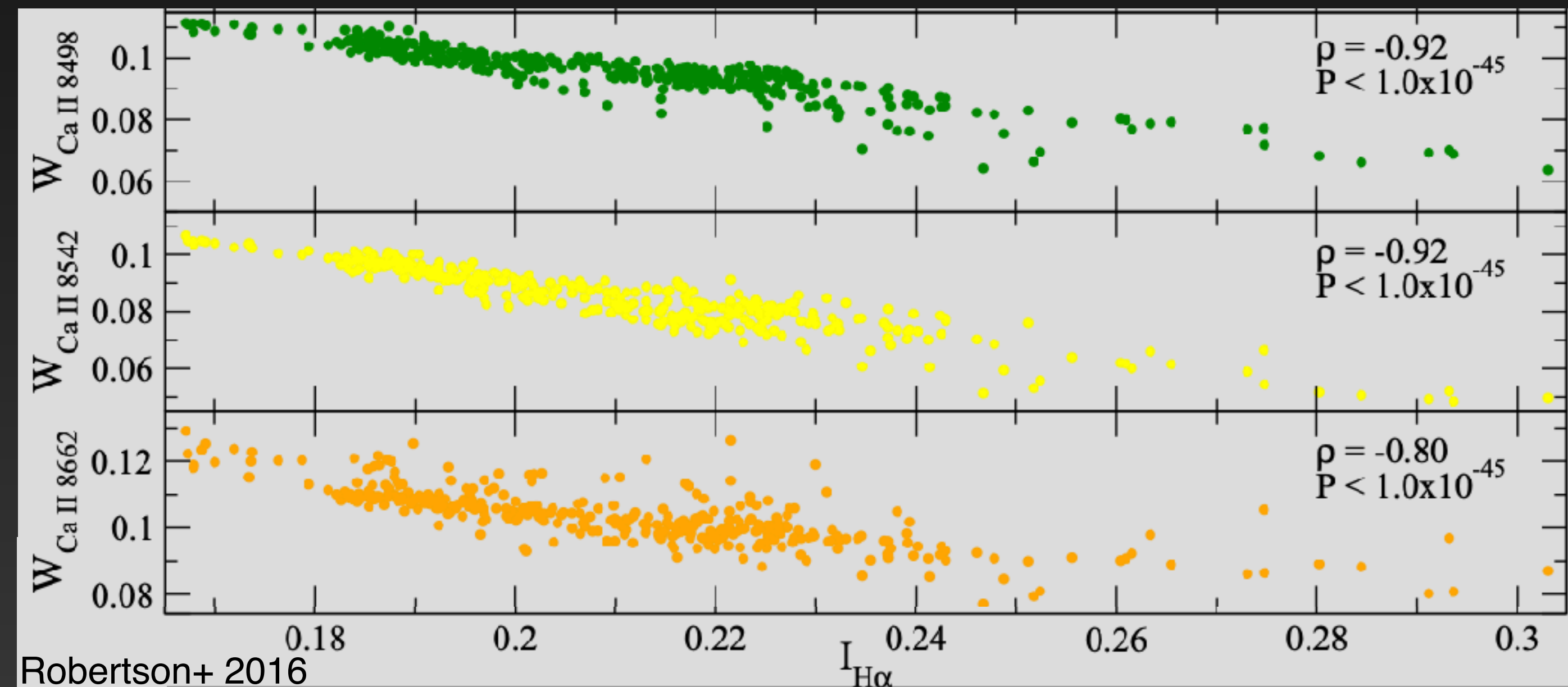
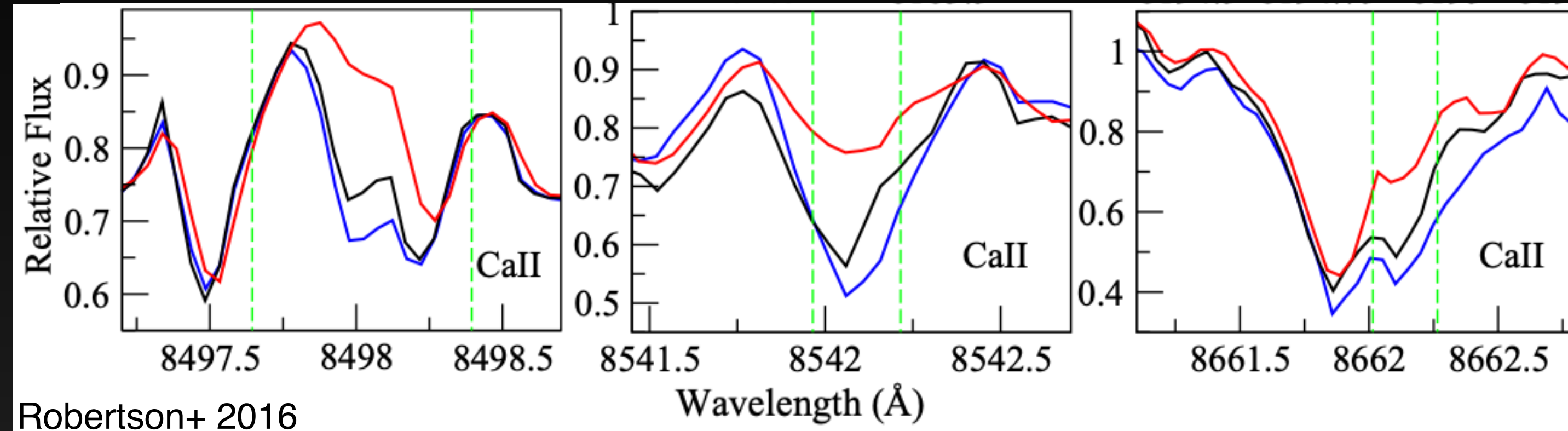
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Spectroscopic Variability

III. Ca IR Triplet

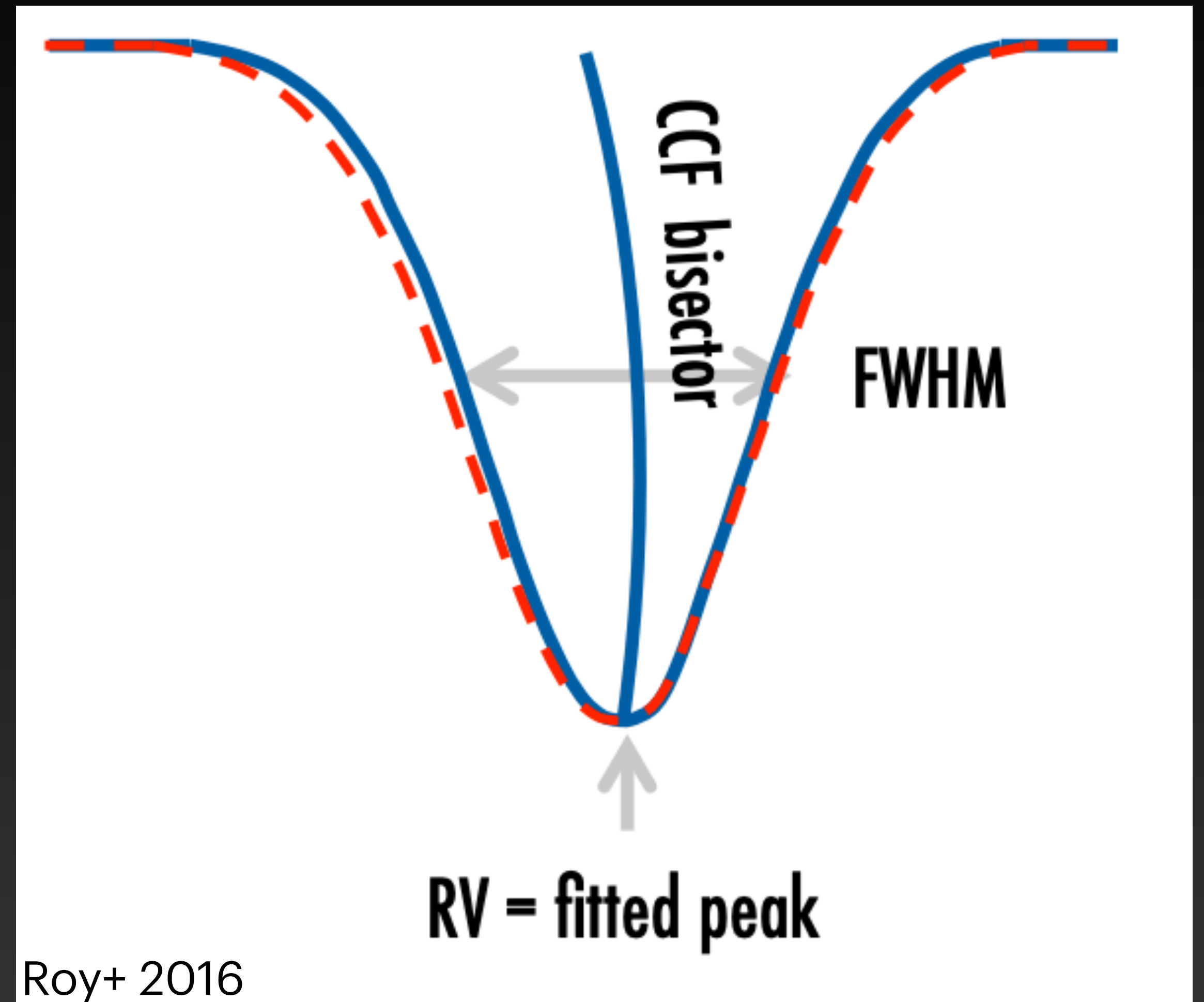
- Source: Three ionized Ca lines at 8498.02, 8542.09, and 8662.14Å
- Method: take the average flux within a band centered on the line, weighted by the average of nearby reference bands chosen to be relatively free of tellurics and molecular bands
- Tells you about: chromospheric activity, correlates with H-alpha.



Spectroscopic Variability

IV. CCF Line Bisectors/ Bisector Spans (BIS) / FWHM

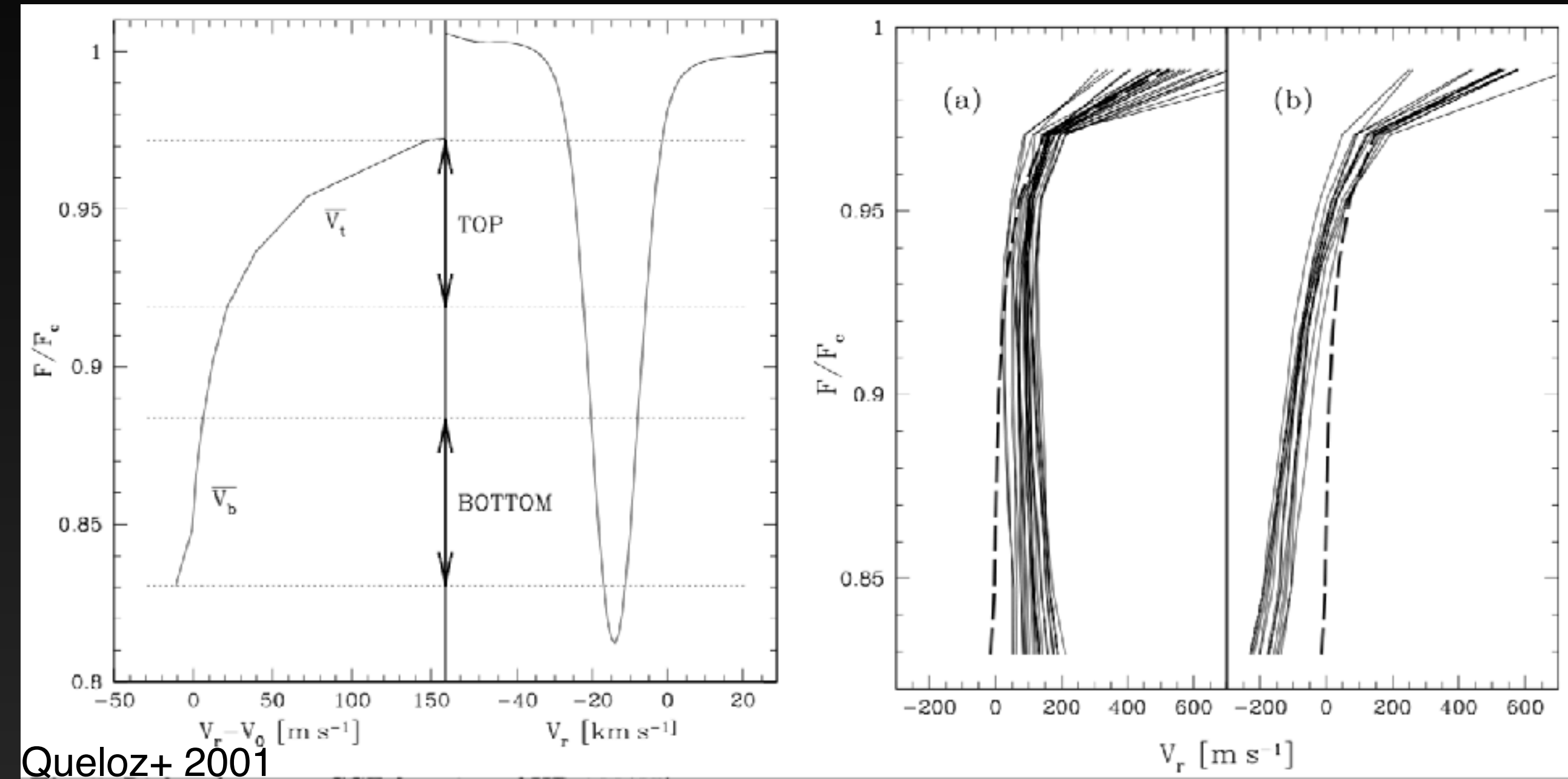
- Source: The CCF from each RV observation
- Method: Measure the mid line as a function of depth below the continuum and look for curvature in the resulting “bisector”. Measure the line’s FWHM.
- Tells you about: Whether the stellar spectra show line shape asymmetries. Keplerian motion should only induce lateral shifts, but activity-based movement will change the line shape as well.



Spectroscopic Variability

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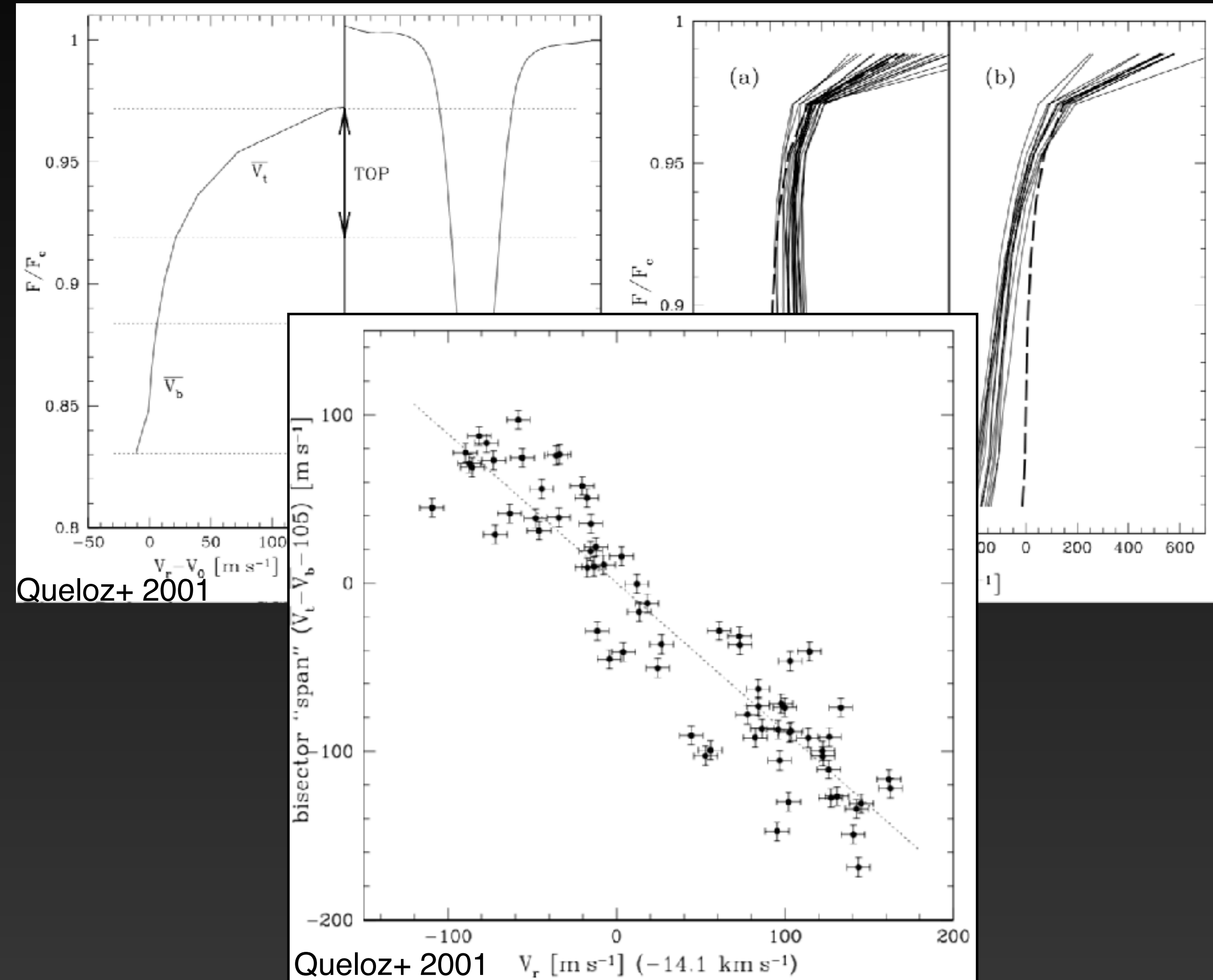
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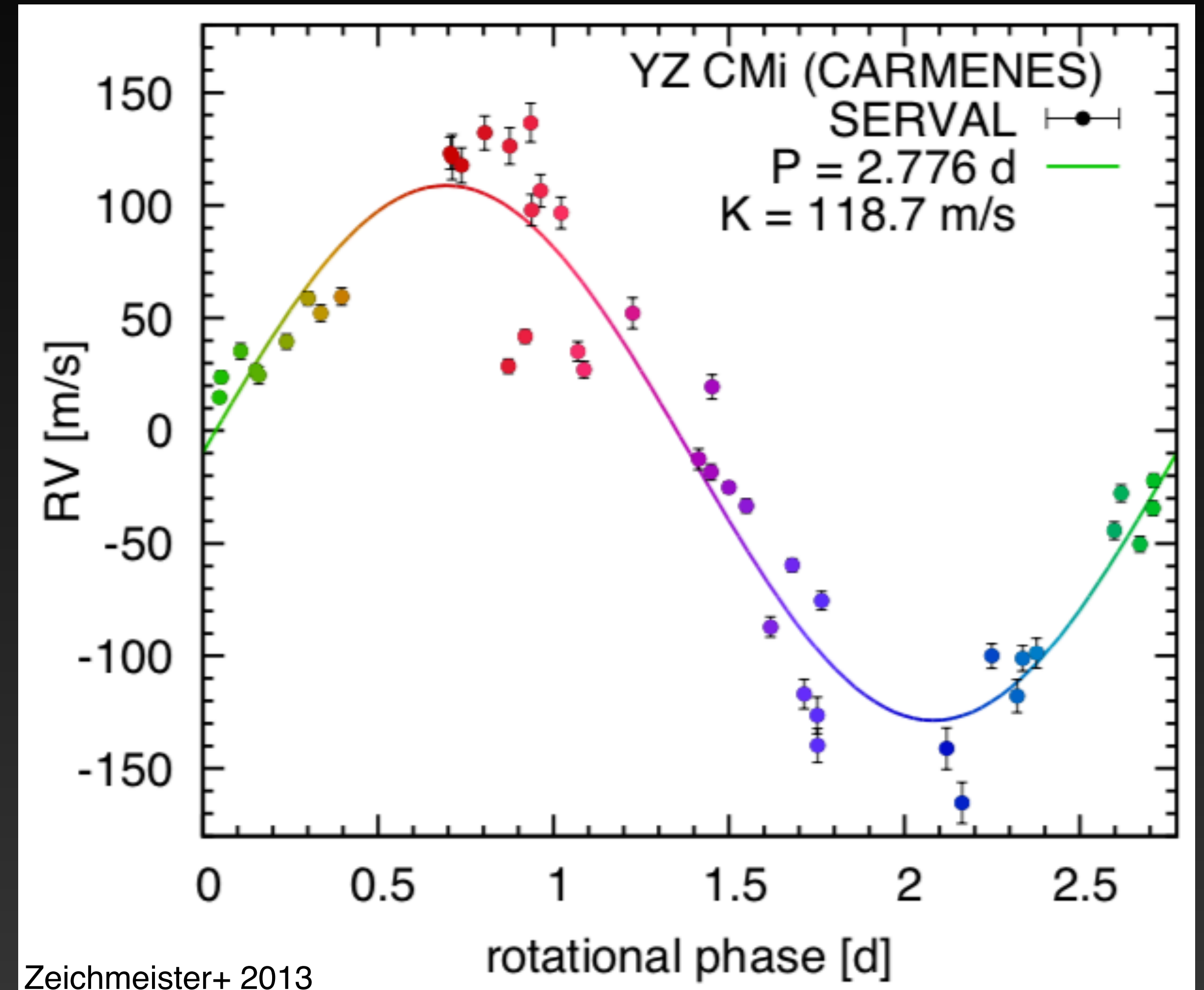
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RV Chromaticity

I. Compare K at different orders of the same instrument

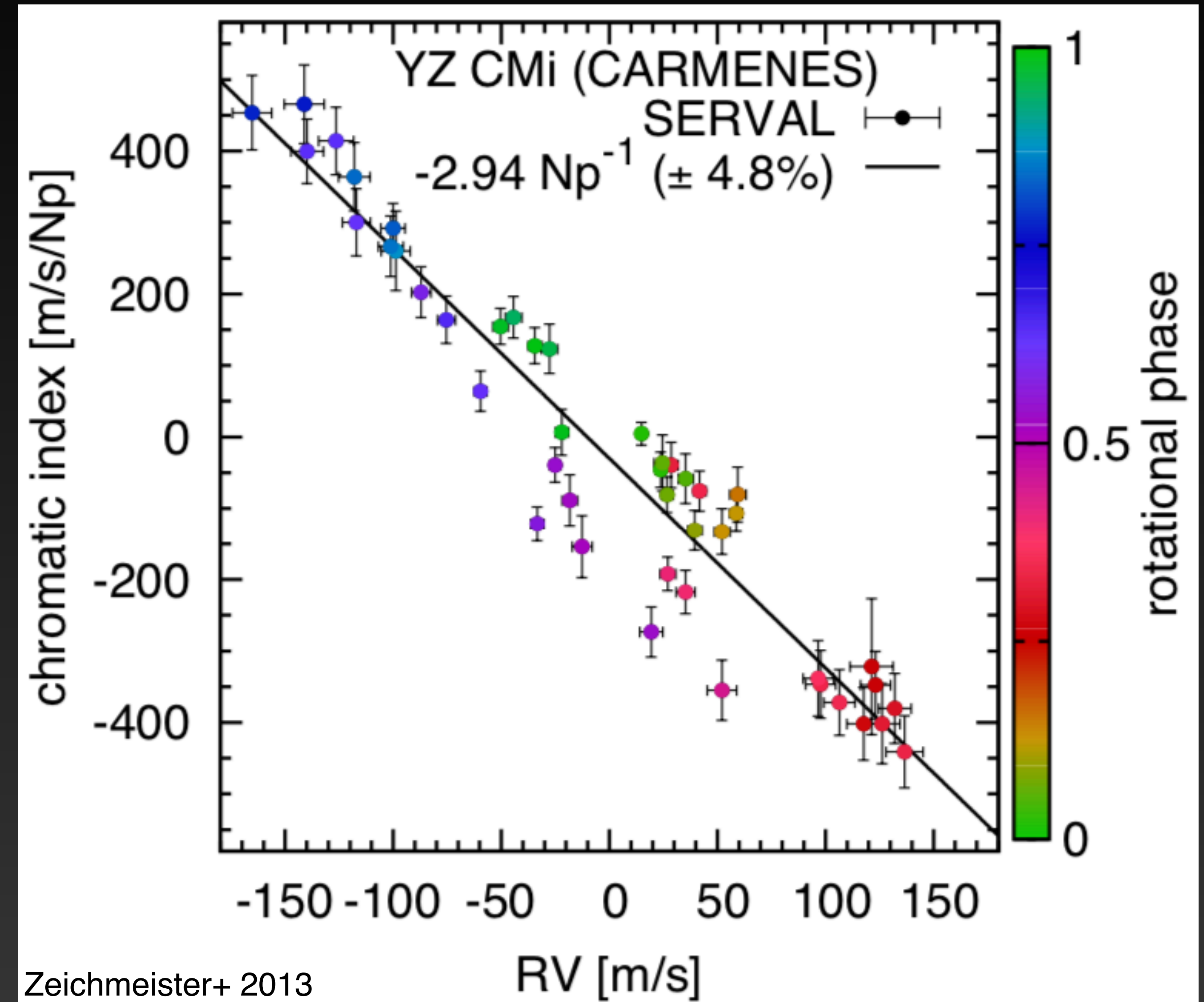
- Chromatic Index (CrX): Determine the RV shift in each echelle order and fit for linear trend
- Tells you about: Whether the RV amplitude is achromatic (as expected for Keplerian signals) or wavelength dependent (as expected for activity-induced signals)



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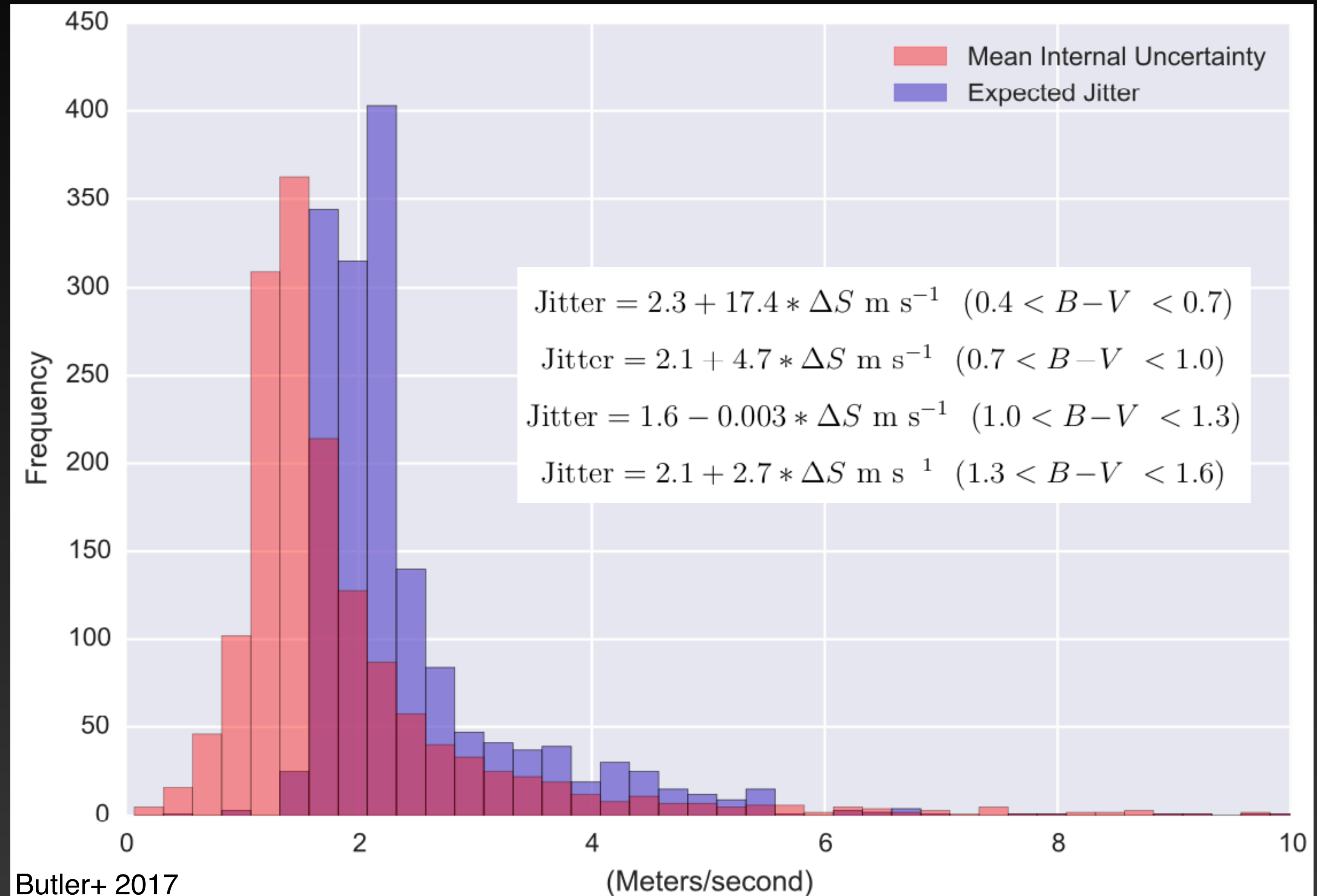
**How do you mitigate
stellar variability?**

Target Selection

Target Selection

I. Avoid active stars

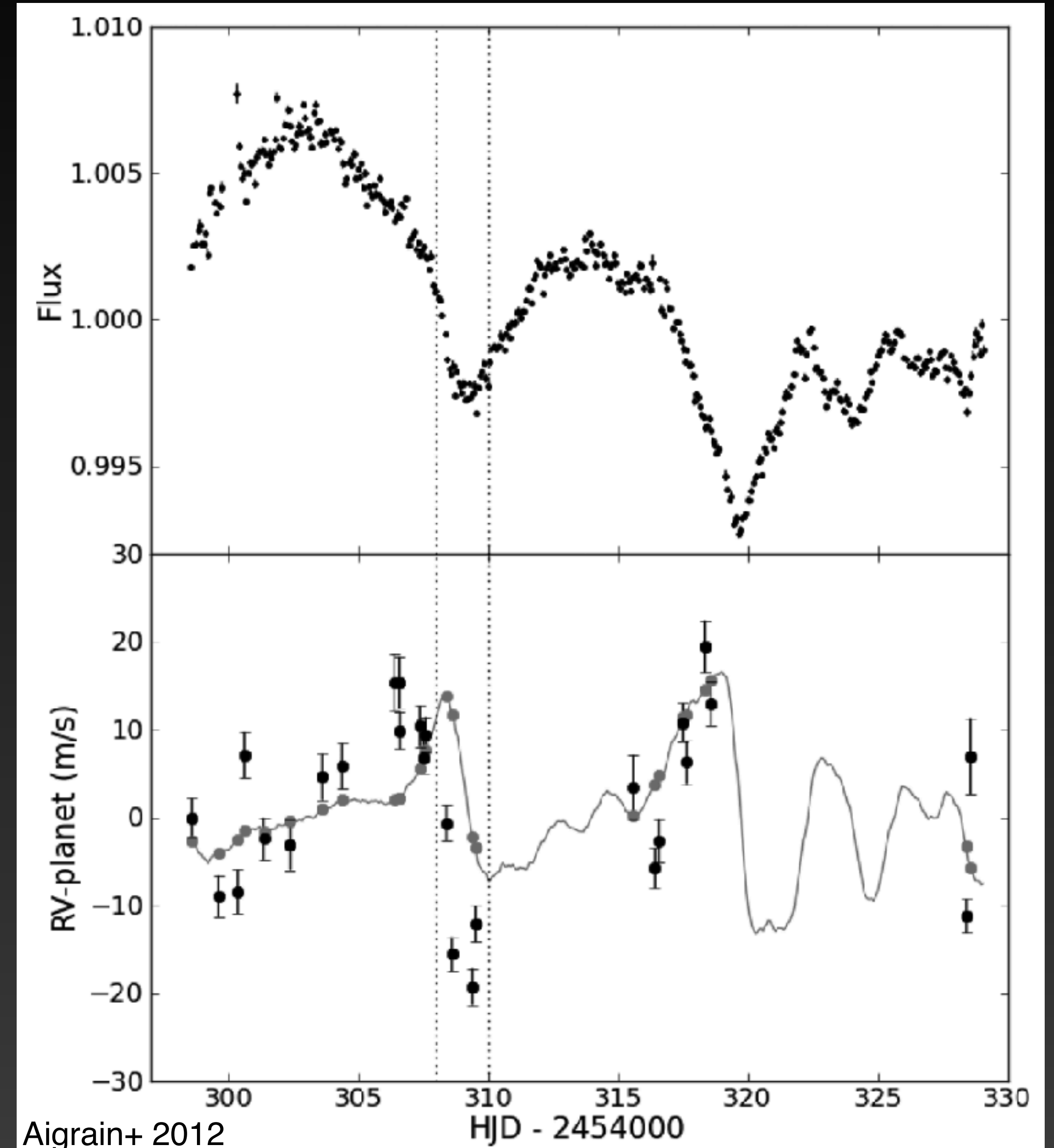
- Can combine a star's median S-value and its B-V color to calculate an expected jitter (see, e.g., Isaacson & Fischer 2010)
- Can then apply cuts that eliminate stars likely to exhibit RV jitter past some threshold you set



Target Selection

I. Avoid active stars

- With a well sampled light curve, you can use the FF' method to simulate the star's RV curve and determine the variability
- Can then apply cuts that eliminate stars likely to exhibit RV jitter past some threshold you set



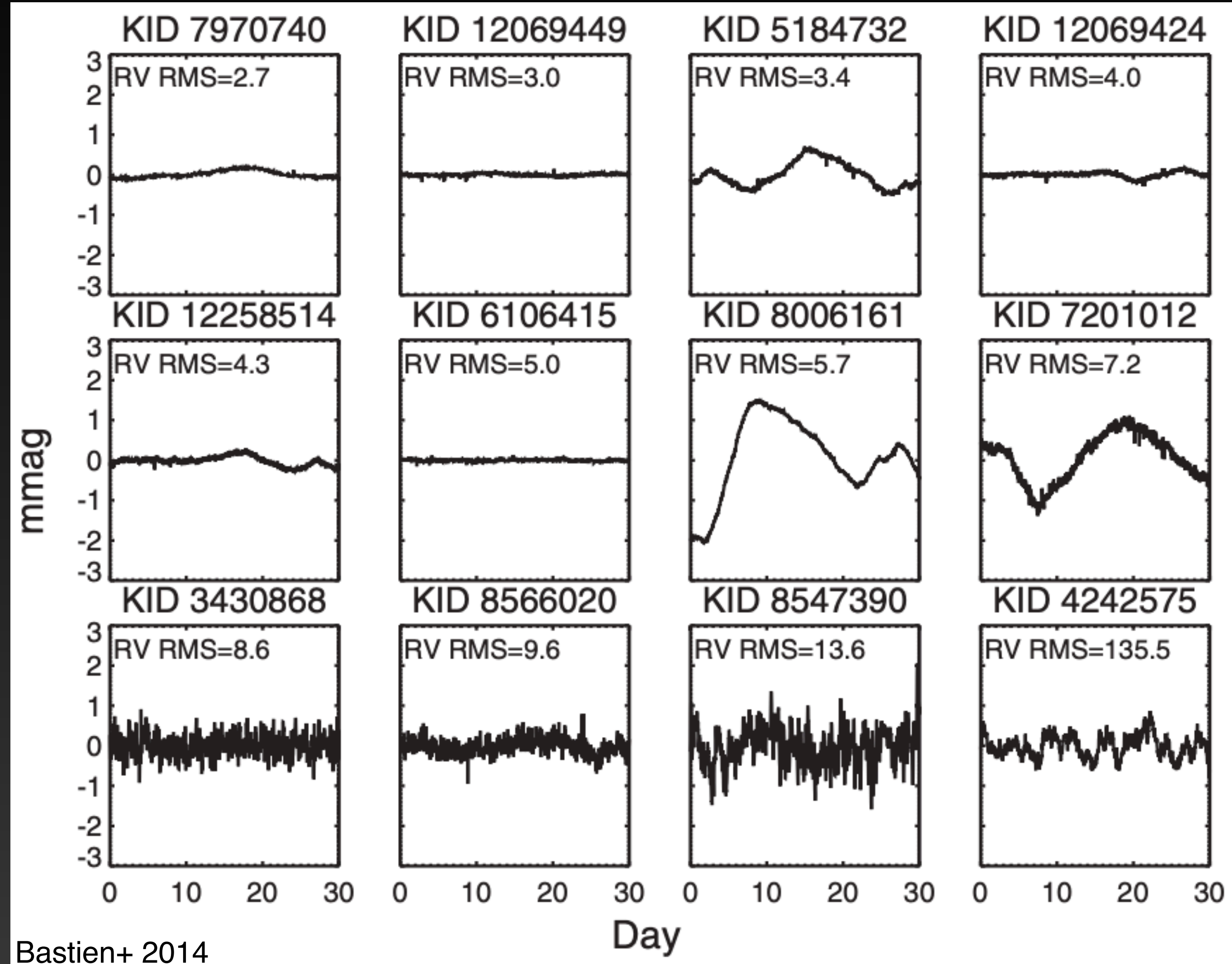
Target Selection

I. Avoid active stars

- Using a star's Flicker analysis, as described earlier, you can get an estimate of the expected RV RMS from the light curve's periodogram

$$\text{RV rms} = (3.8 \pm 1.7 \text{ ms}^{-1}) \times (N_{\text{peaks}})^{0.3 \pm 0.1}$$

- RV jitter is most sensitive to high frequency photometric variability - can select against these stars for follow up efforts



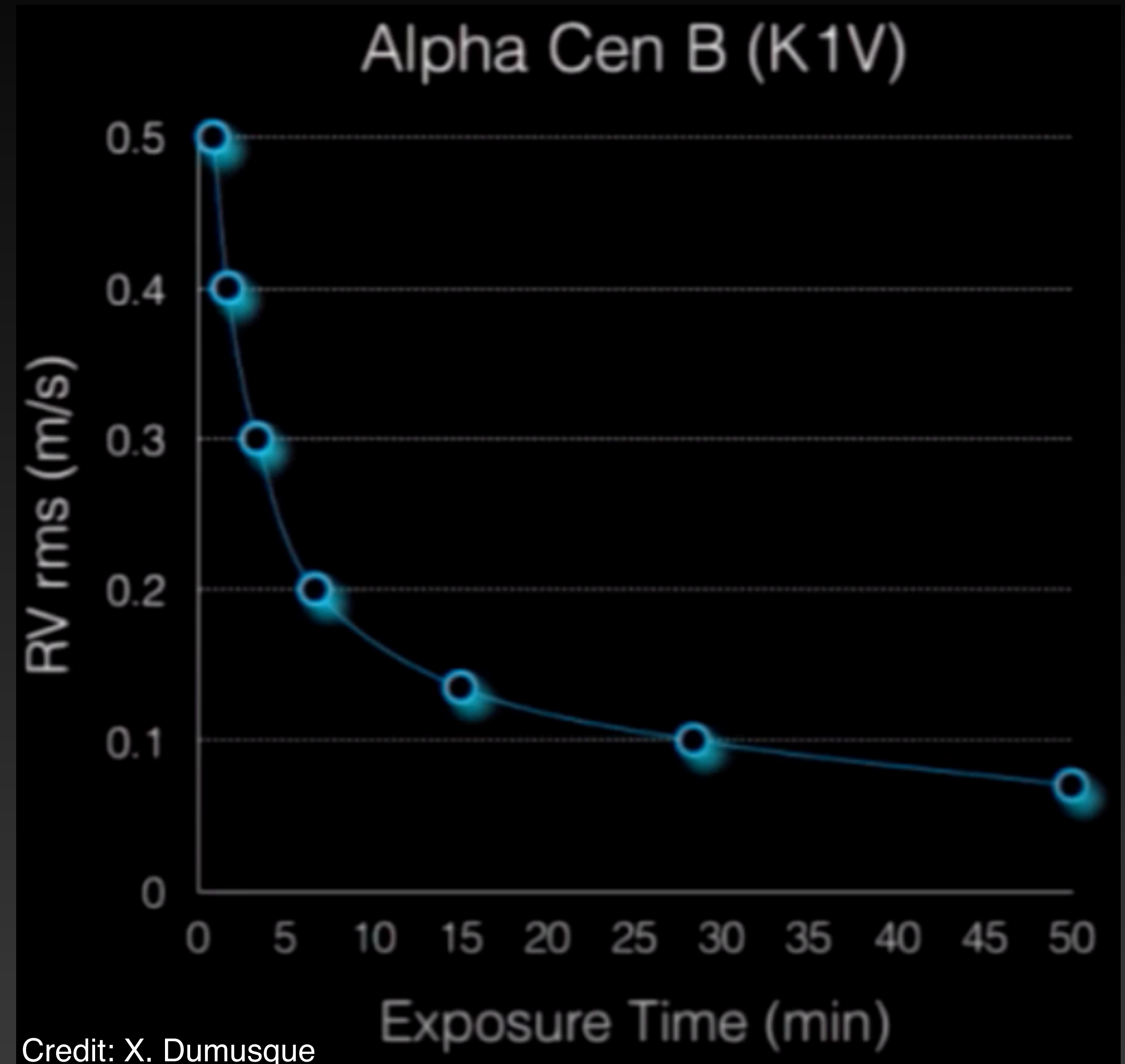
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Observing Strategy

Observing Strategy

I. Average over shortest period signals (pulsations)

- Need on-target clock time to extend longer than the acoustic oscillation period of the star so the pulsations get averaged out
- Generally not hard, as P_{osc} is \sim 5-15min for RV amenable stars
- Recent work by Chaplin et al. 2019 has provided ways to calculate this value for a given target based on luminosity, surface gravity and effective temperature



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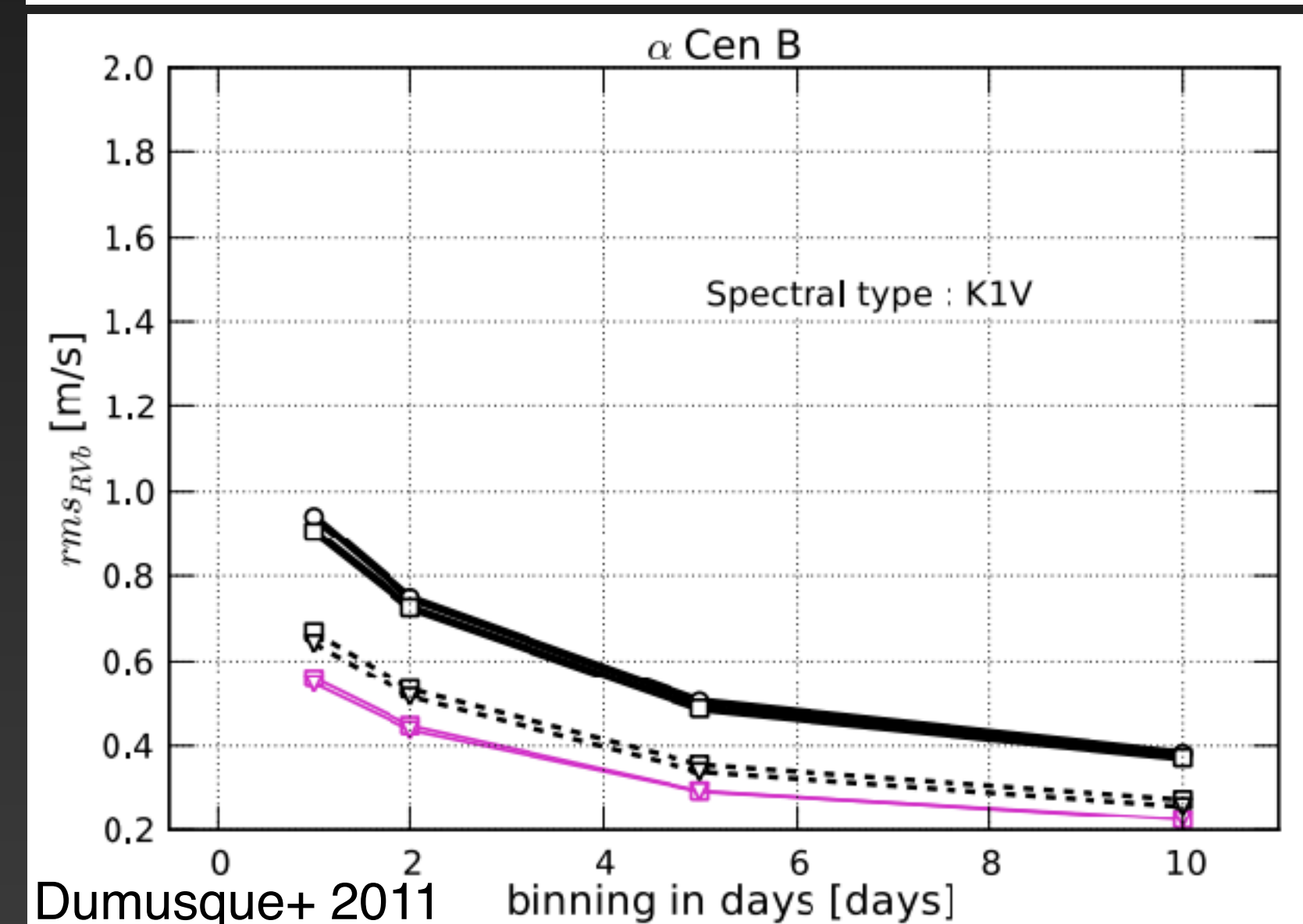
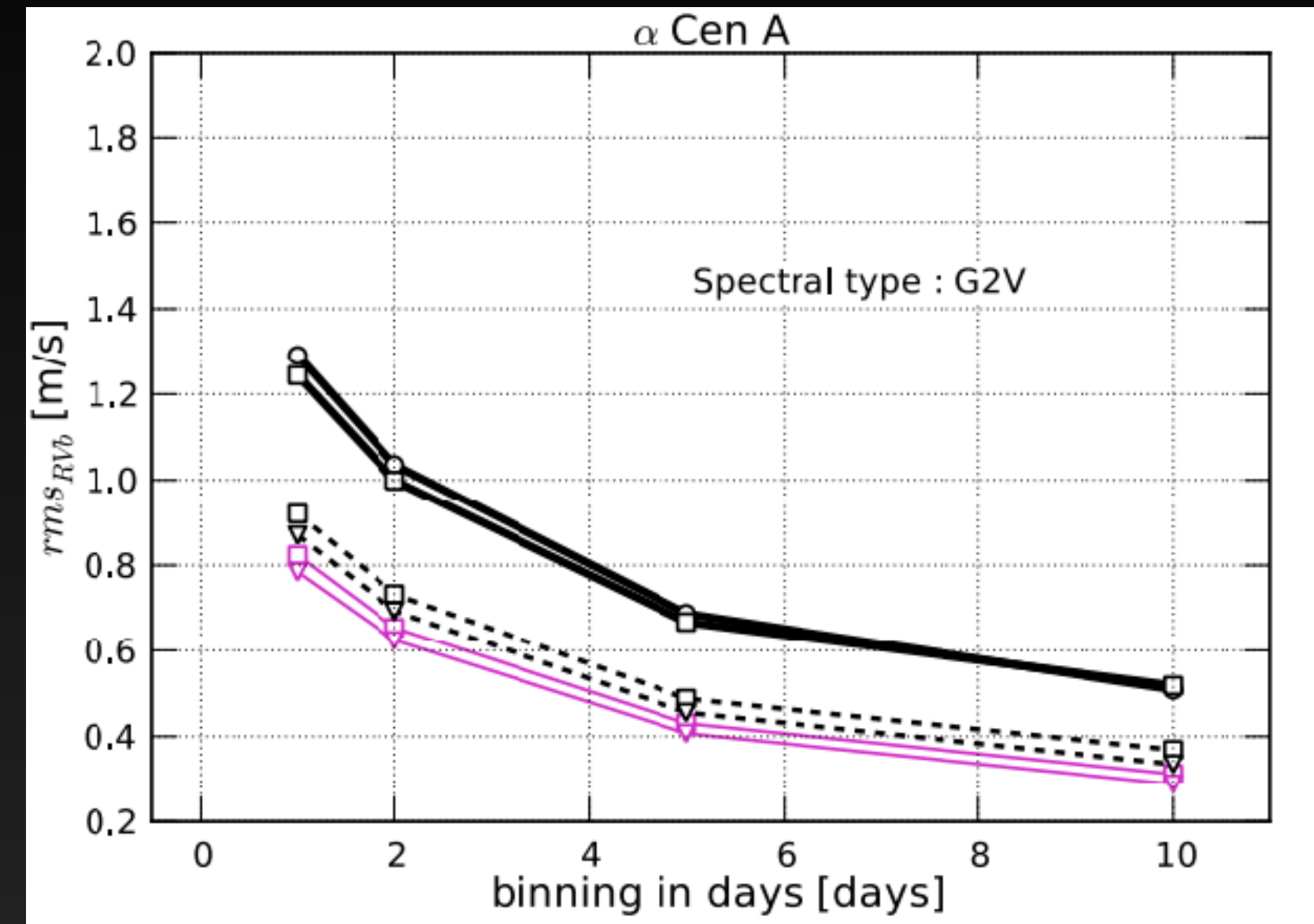
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Star	M (M_{\odot})	R (R_{\odot})	T_{eff} (K)	$\log g$ (dex)	L (L_{\odot})	Spectral type	K (cm s^{-1})	$\Delta t_c^{0.1}$ (min)	Δt_c^K (min)
τ Ceti	0.79	0.85	5290	4.48	0.51	G8V	12.0	$3.9^{+4.9}_{-1.0}$	$3.7^{+0.7}_{-1.3}$
α Cen B	0.93	0.91	5145	4.49	0.52	K1V	11.0	$3.6^{+0.7}_{-1.1}$	$3.5^{+0.7}_{-1.2}$
70 Oph A	0.89	0.91	5300	4.47	0.59	K0V	10.9	$4.0^{+5.1}_{-1.1}$	$3.9^{+0.8}_{-1.1}$
Sun	1.00	1.00	5777	4.44	1.00	G2V	9.0	$9.7^{+5.9}_{-5.6}$	$10.1^{+7.4}_{-5.8}$
δ Pav	1.07	1.20	5550	4.31	1.23	G8IV	8.3	$13^{+10}_{-7.8}$	16^{+12}_{-10}
α Cen A	1.11	1.24	5745	4.30	1.50	G2V	7.7	$14^{+13}_{-8.4}$	22^{+13}_{-10}
ι Hor	1.23	1.16	6080	4.40	1.65	F8V	7.2	$13^{+10}_{-8.6}$	21^{+11}_{-10}
μ Ara	1.21	1.39	5665	4.23	1.79	G3IV-V	7.1	21^{+14}_{-14}	30^{+18}_{-15}
β Vir	1.42	1.69	6050	4.13	3.44	F9V	5.5	43^{+23}_{-21}	80^{+42}_{-34}
β Hyi	1.08	1.89	5790	3.92	3.60	G2IV-G0V	6.3	88^{+54}_{-40}	141^{+119}_{-58}
α CMi	1.46	2.13	6485	3.95	7.20	F5IV-V	4.5	102^{+64}_{-45}	203^{+247}_{-62}

Observing Strategy

II. Revisit stars throughout the night to average out granulation

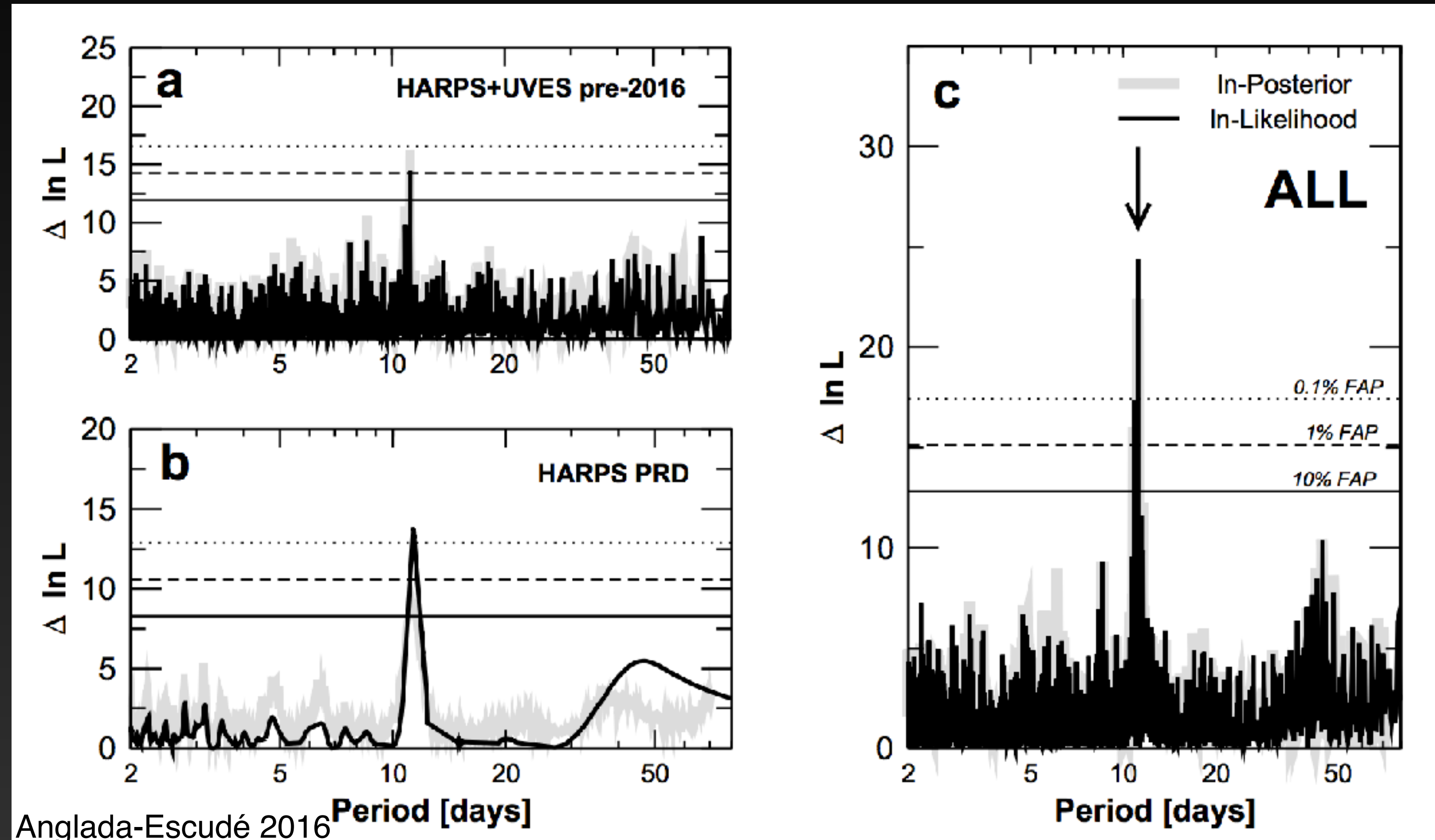
- Since granulation occurs on minutes - day timescales, can observe the star 2-3x per night to sample different sections of RV phase



Observing Strategy

III. Observing baseline - short and intensive approach

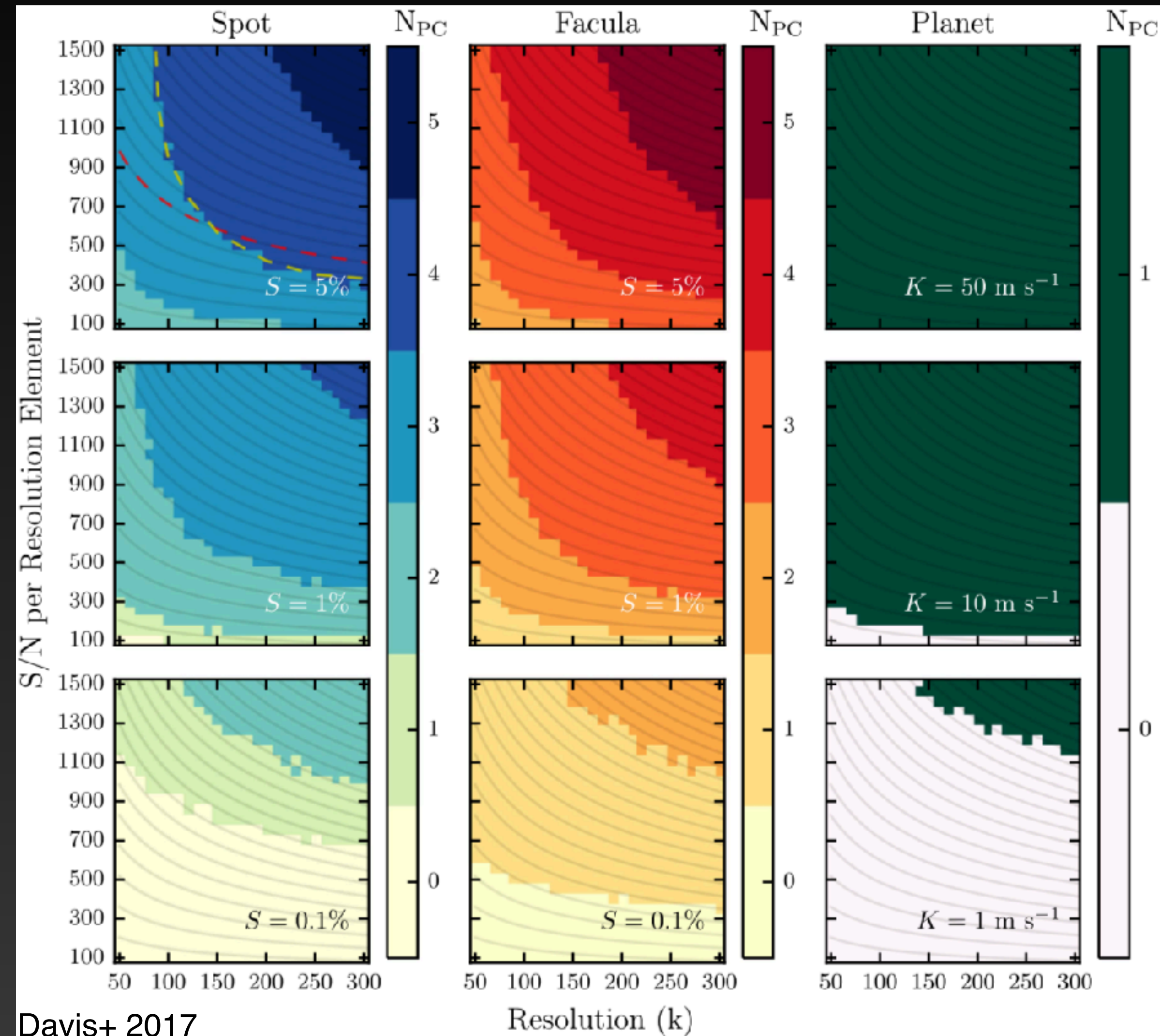
- Intensive observations over a short timescale mean that the stellar activity is more cohesive, easier to model



Observing Strategy

III. Emphasize high SNR and high cadence observing

- Need to treat variability as an additional signal that you want to model / mitigate
- Requires high resolution spectra taken at high SNR and preferably at nightly cadence

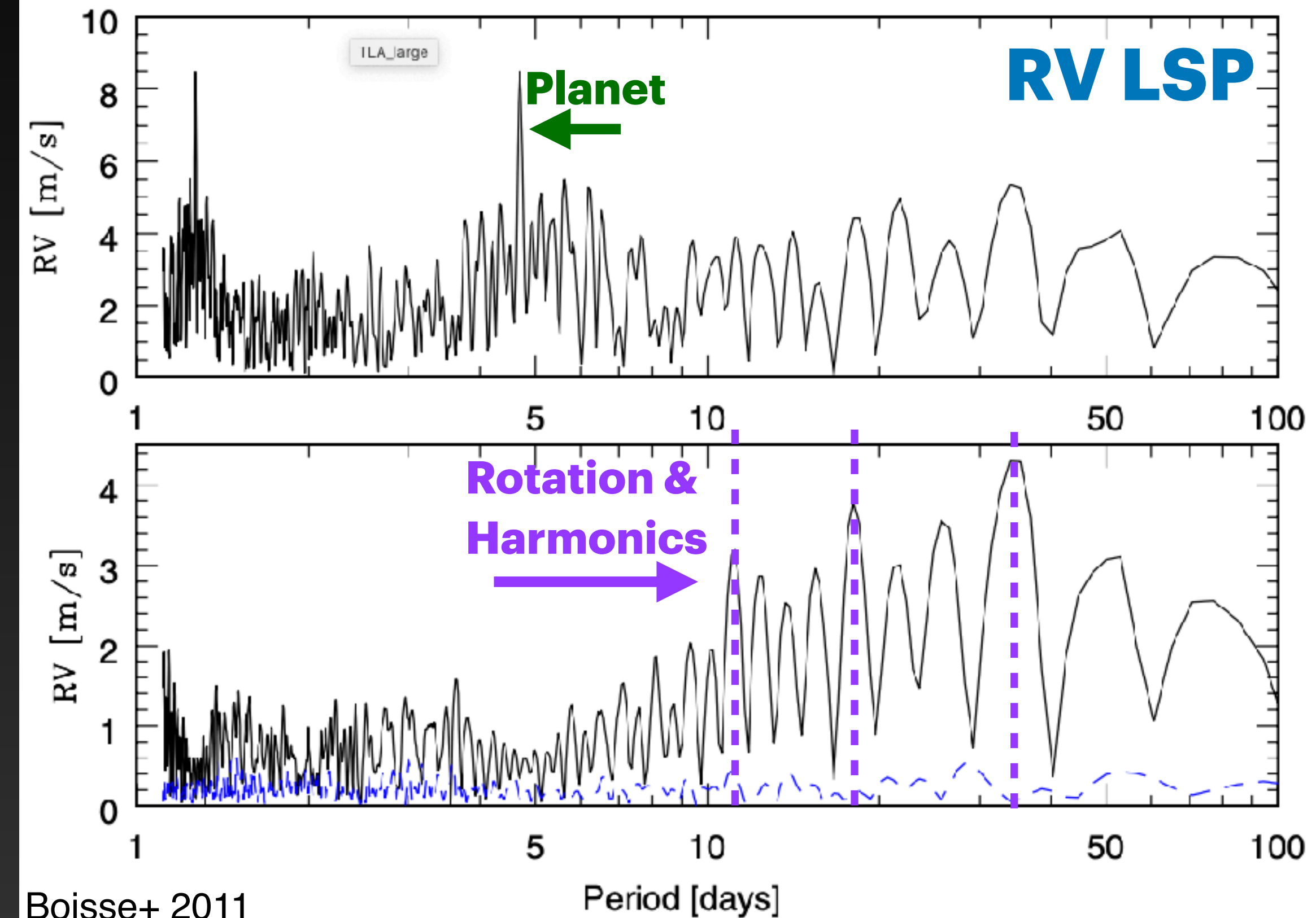
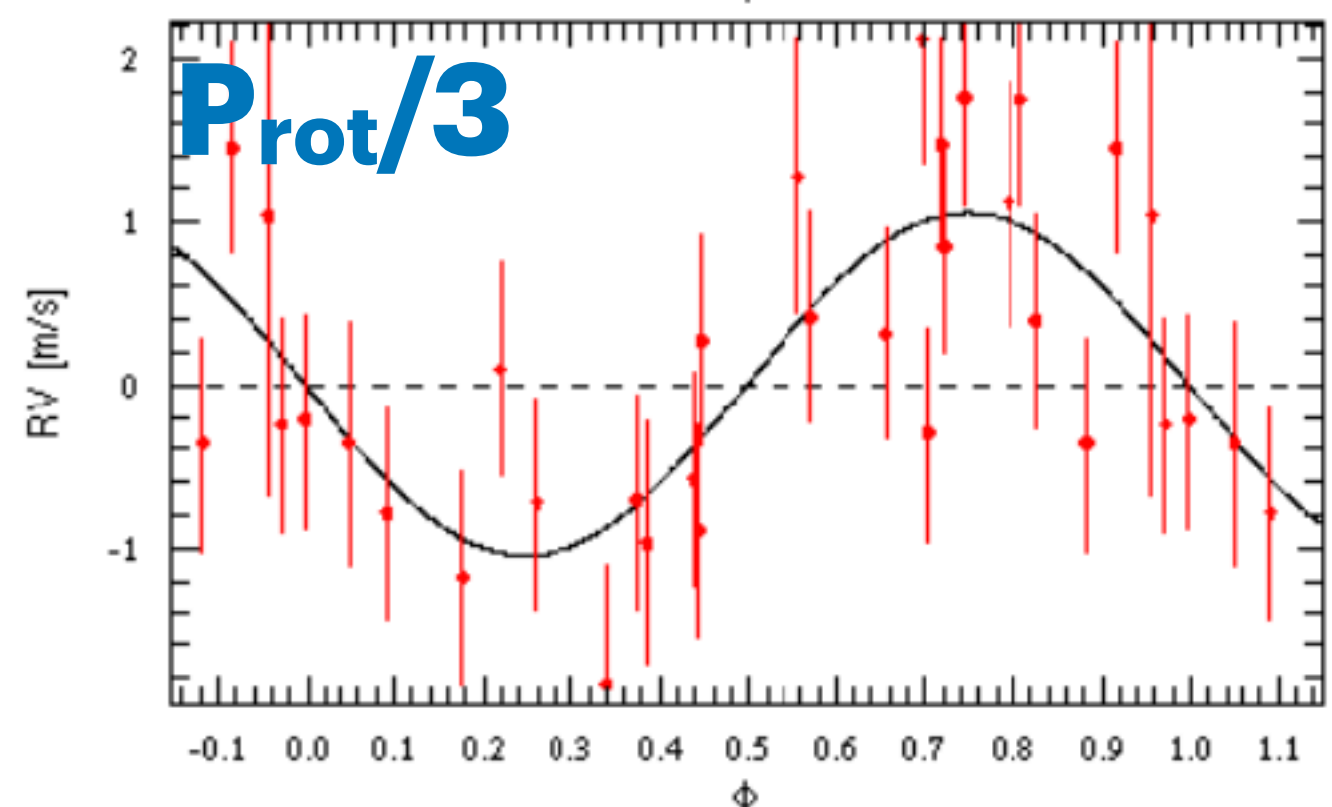
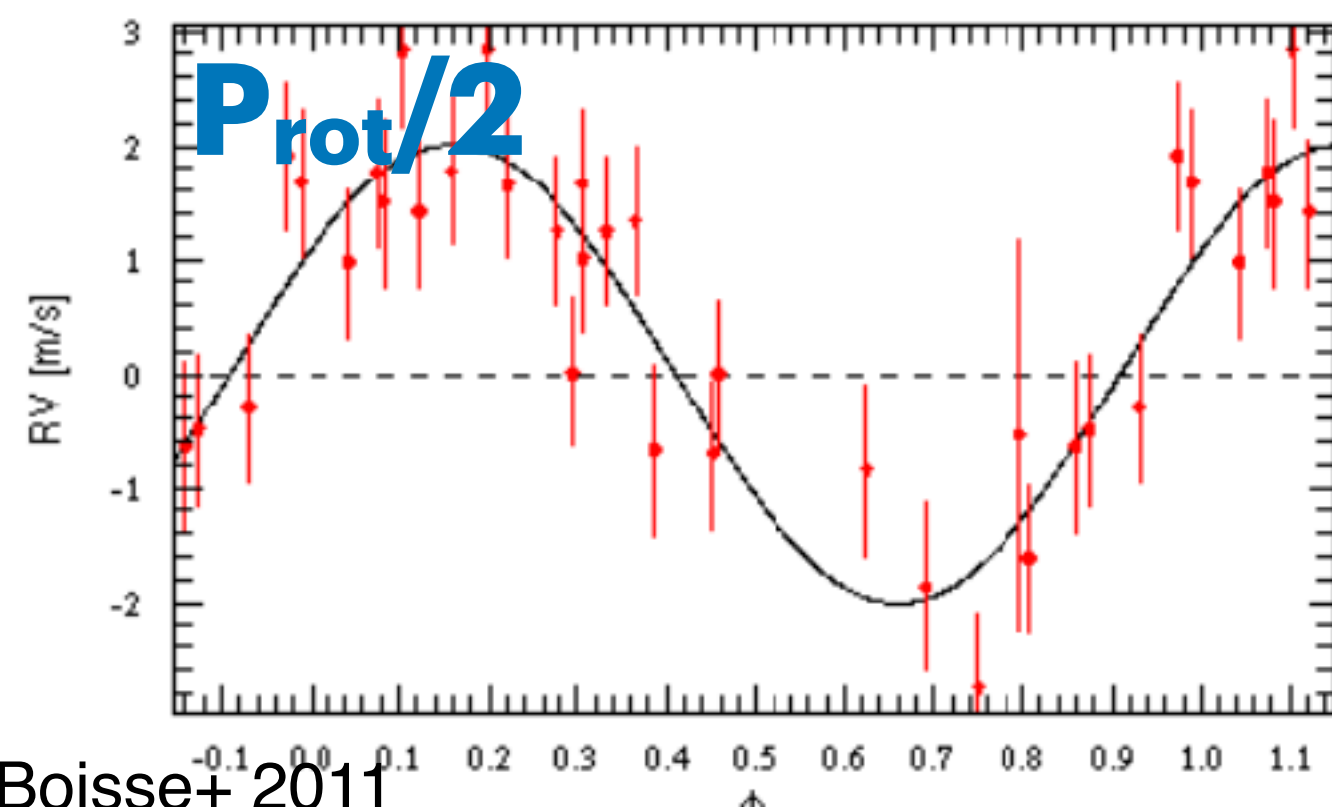
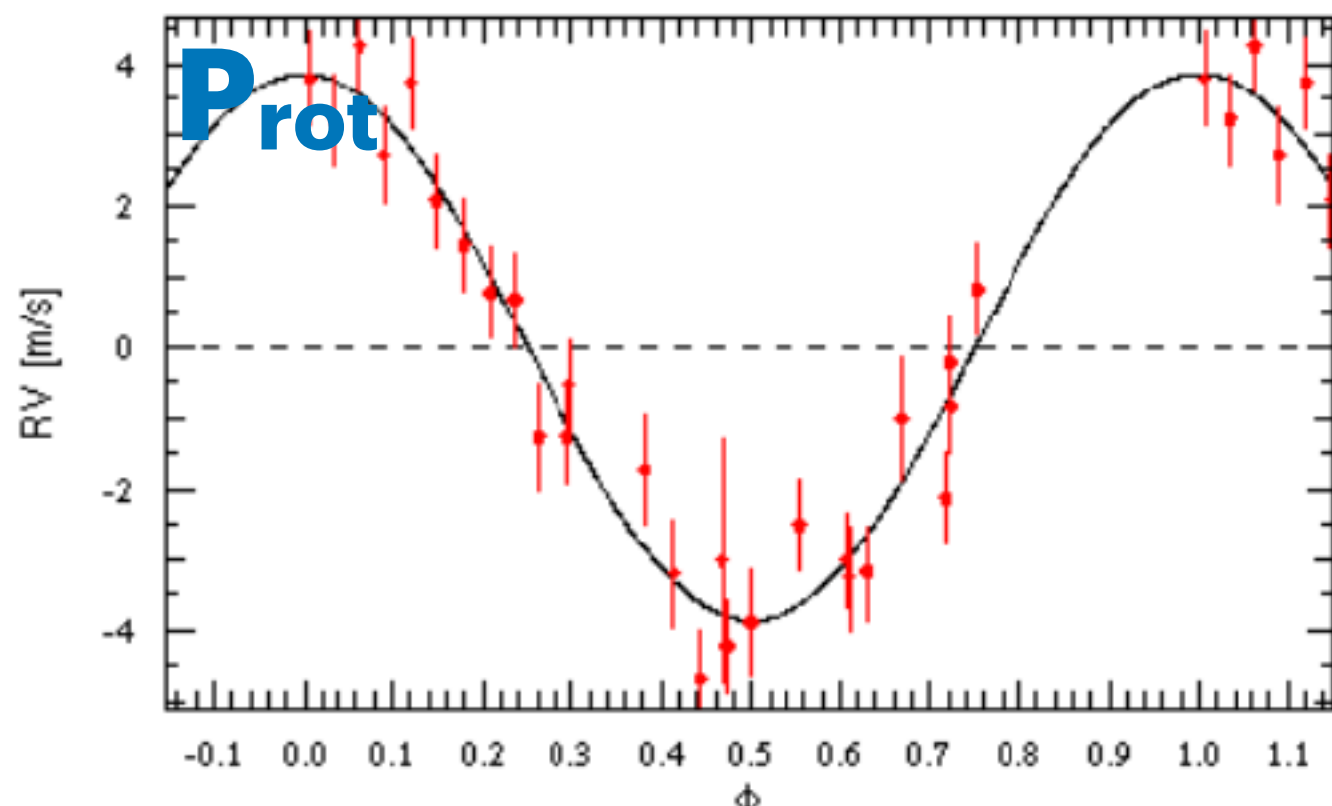
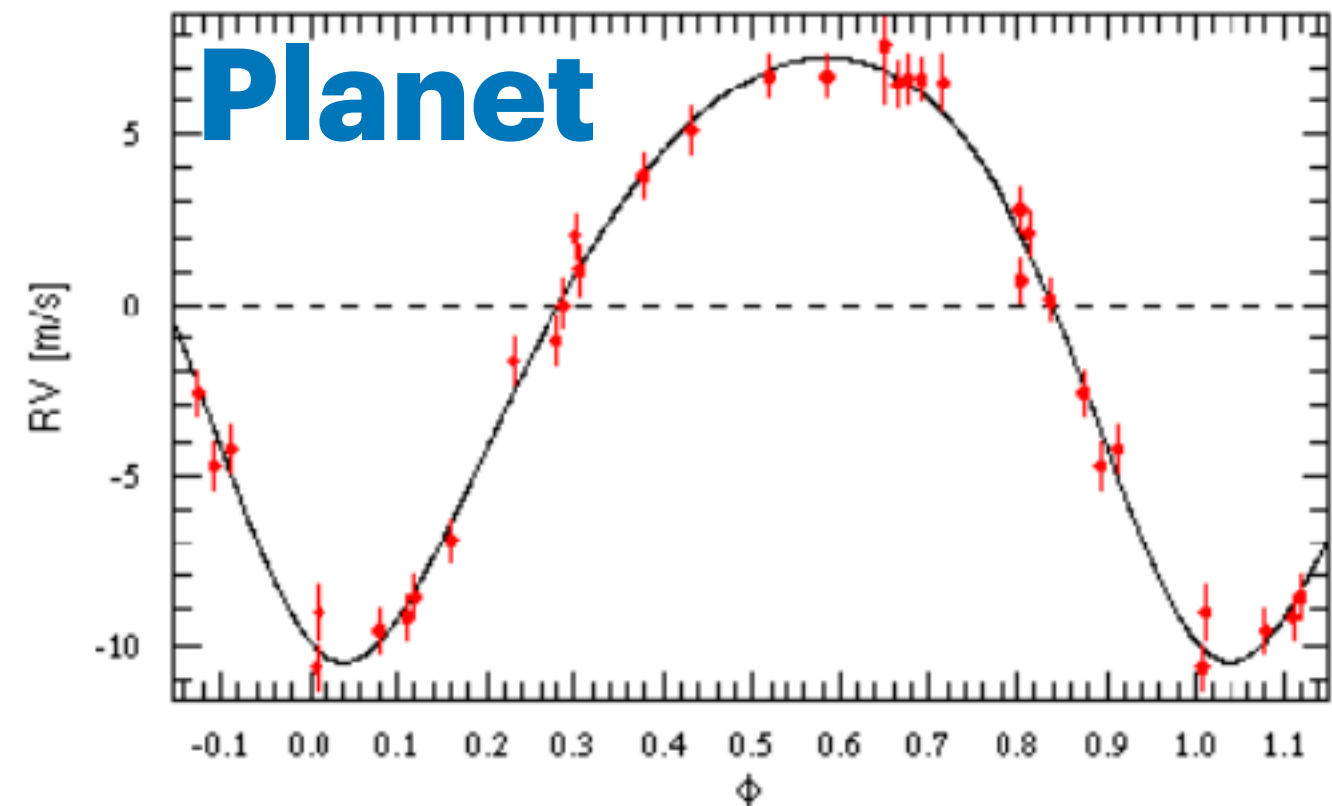


**How do you mitigate
stellar variability?**

Data Analysis

Data analysis

I. Model rotation periods & harmonics as additional Keplerian signals

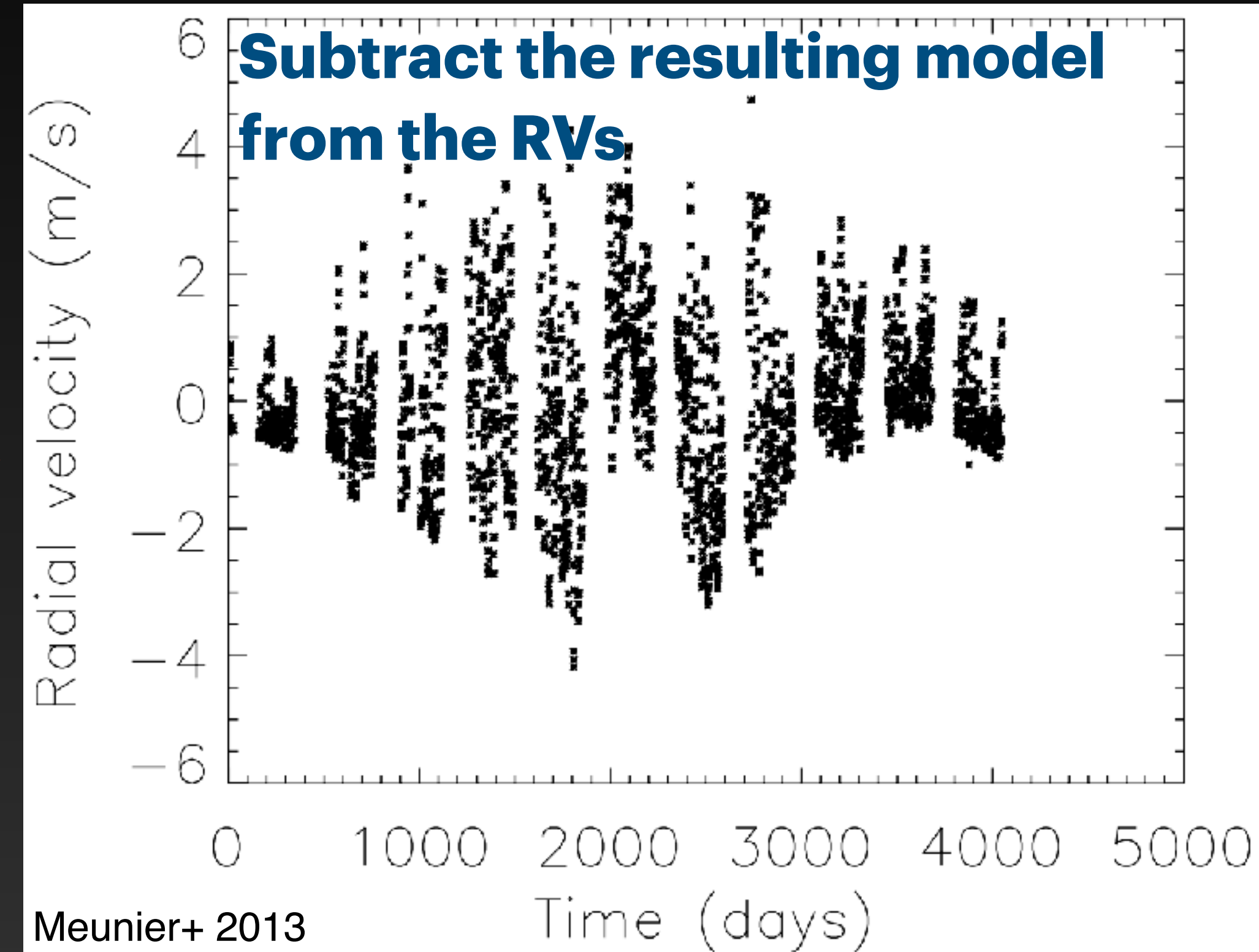
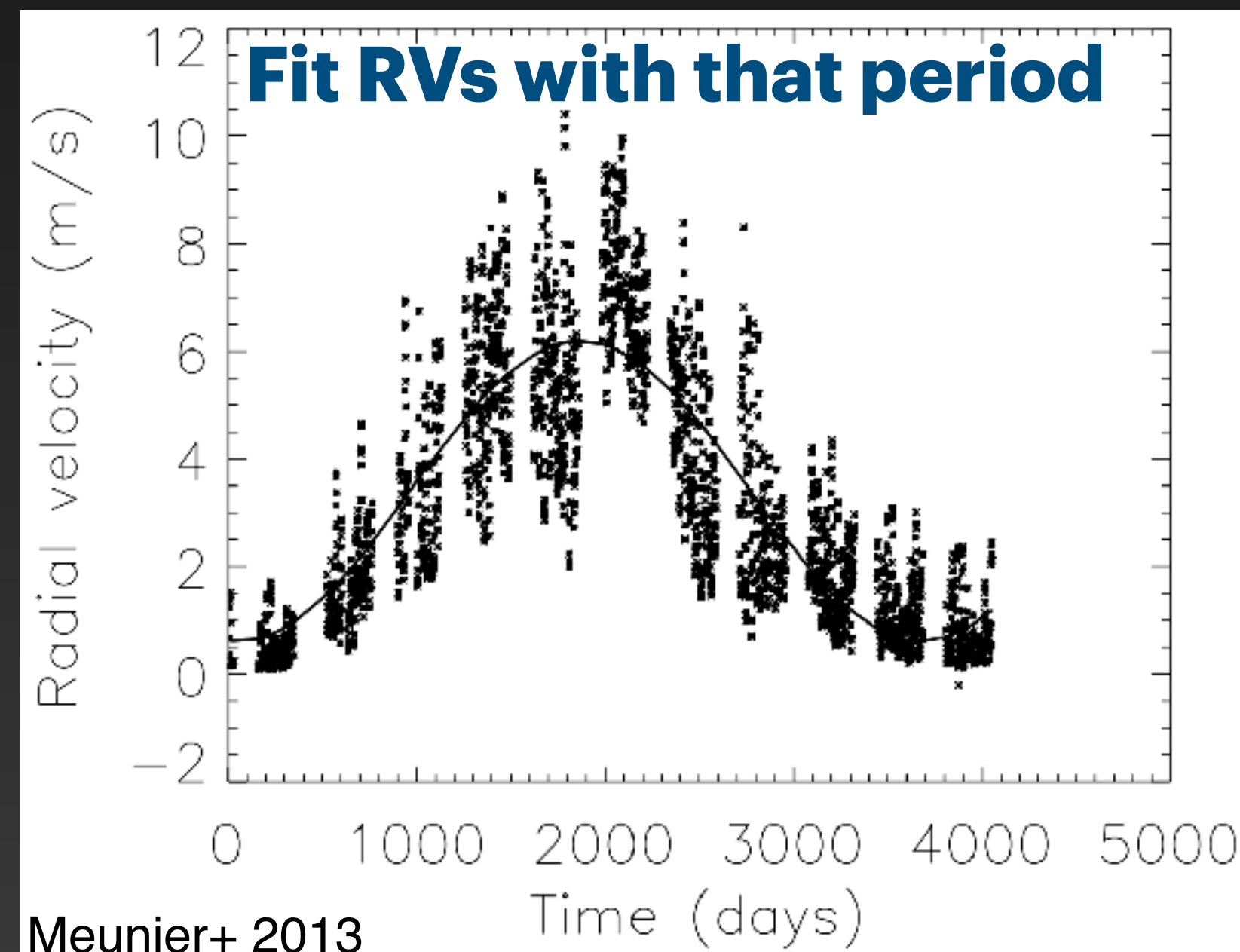
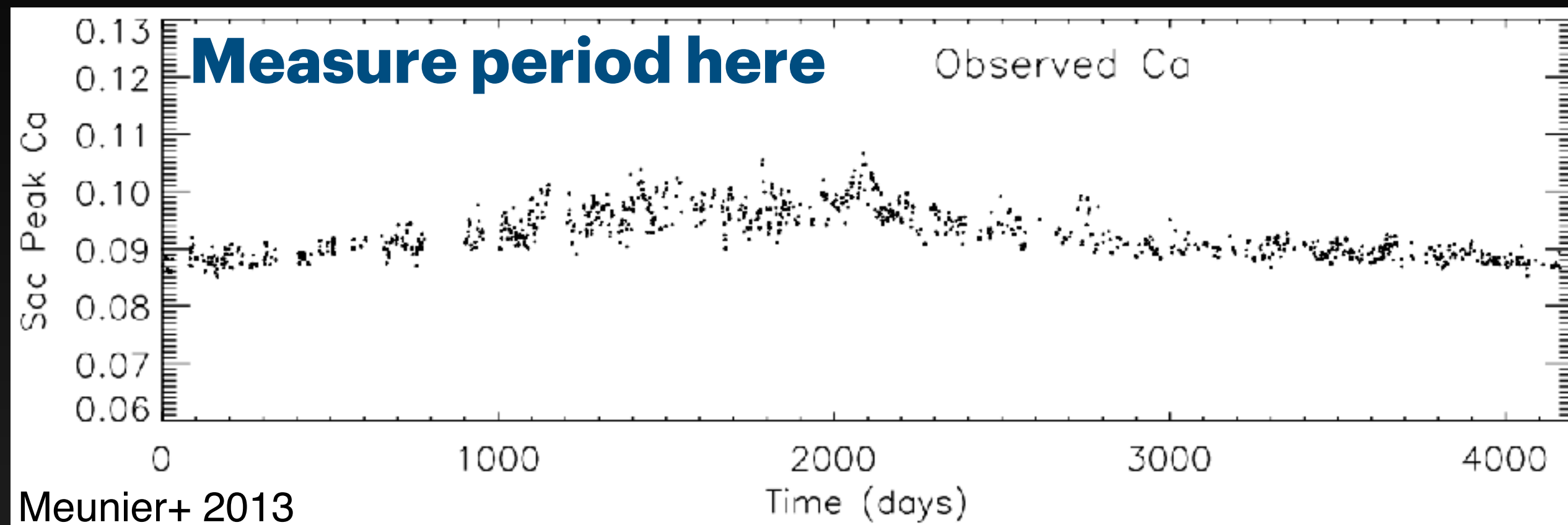


Boisse+ 2011

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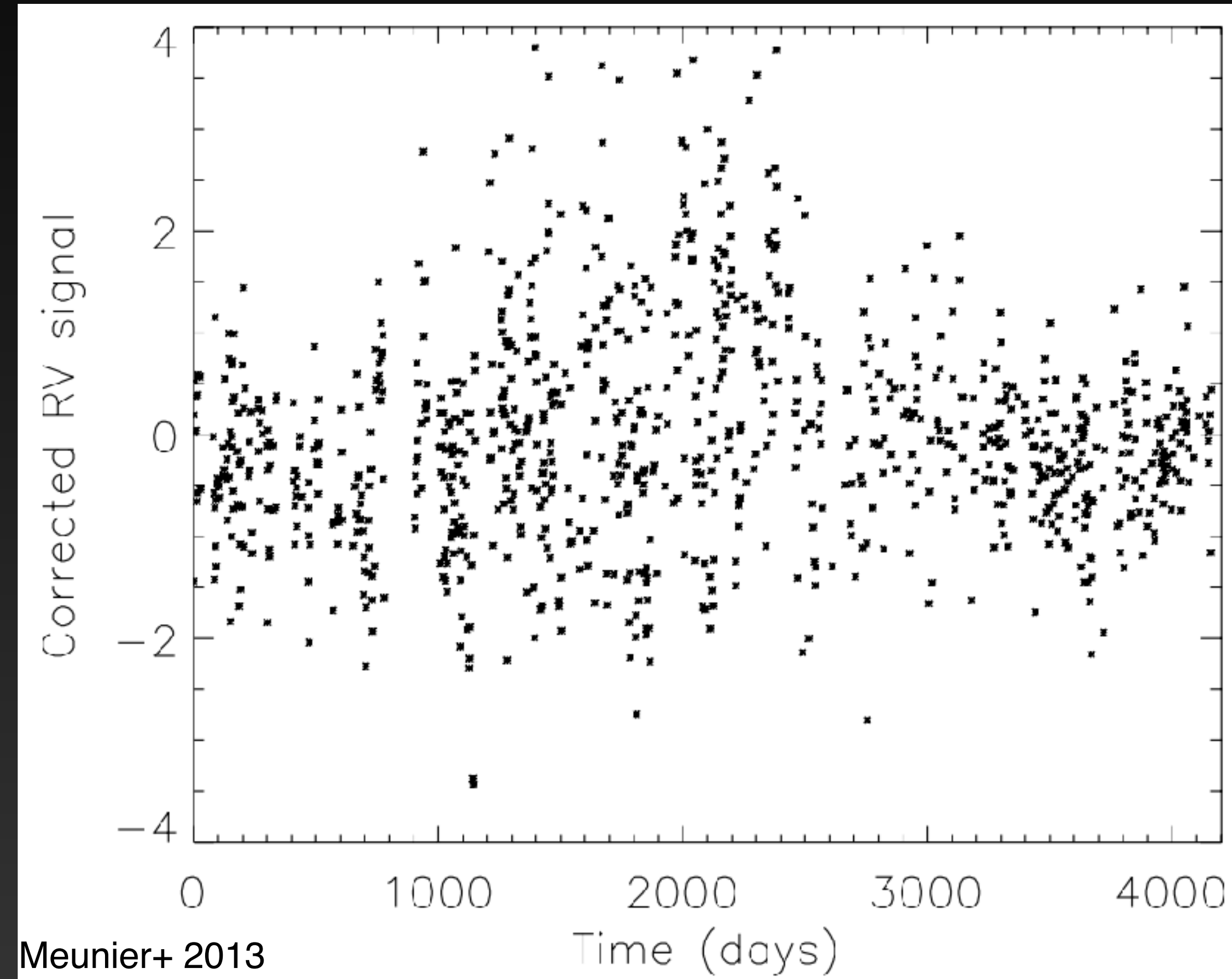
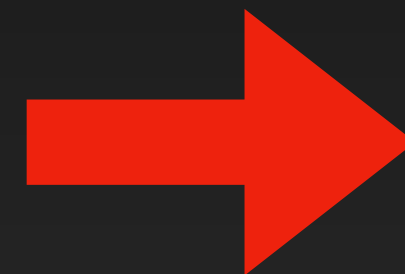
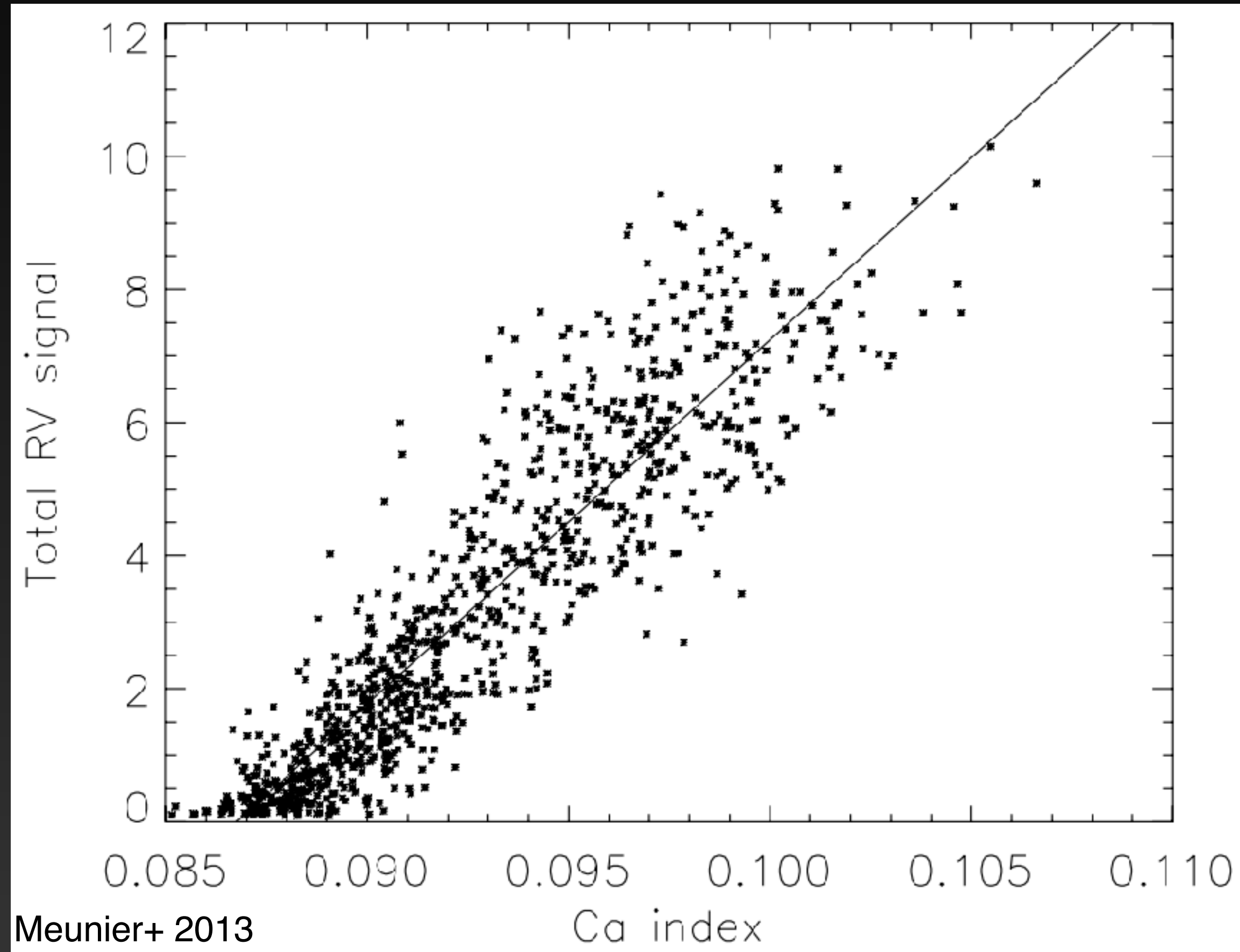
Data analysis

II. Fit spectral activity indicators & apply correction to RVs



Data analysis

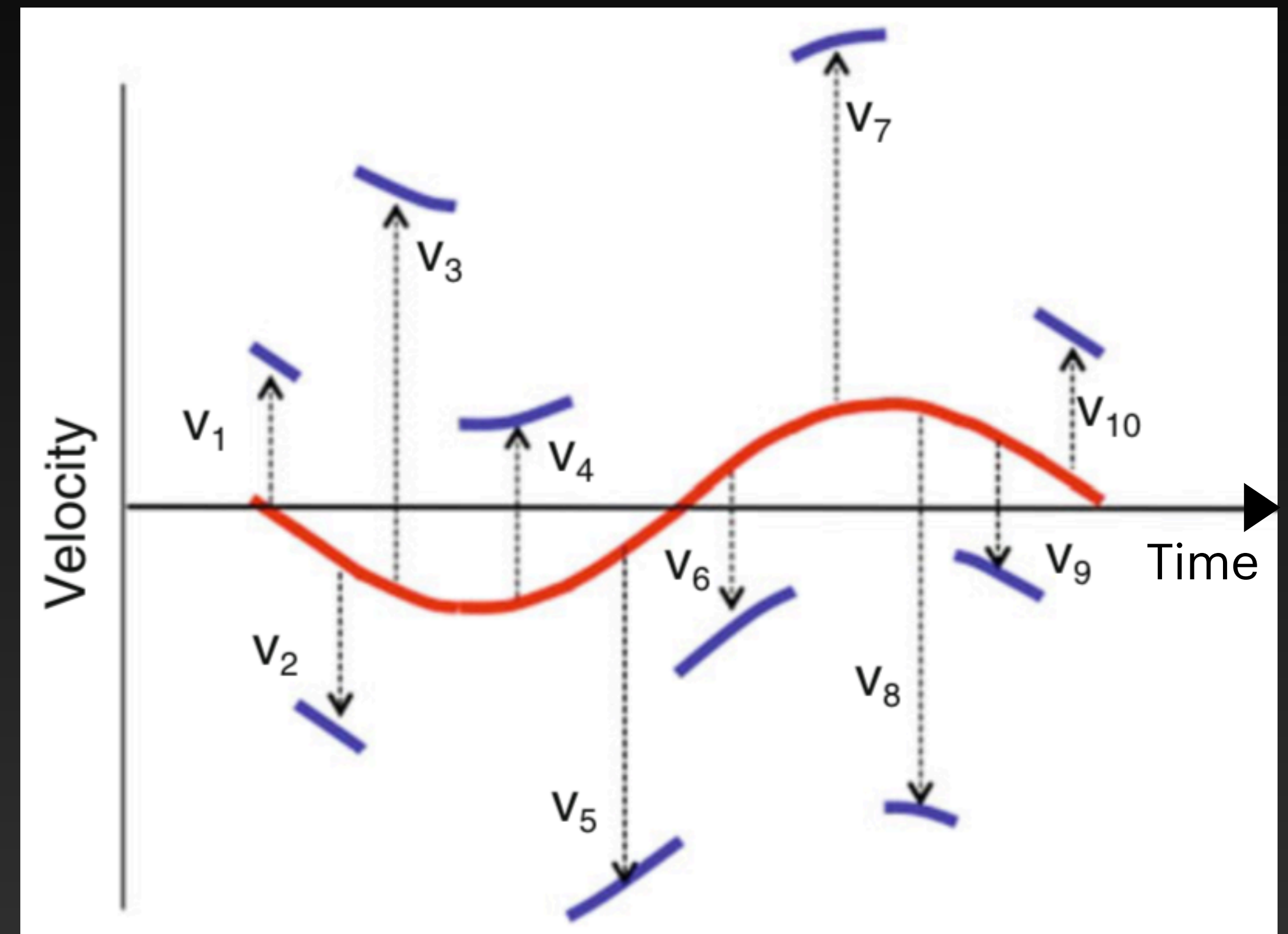
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Data analysis

III. Floating chunk method

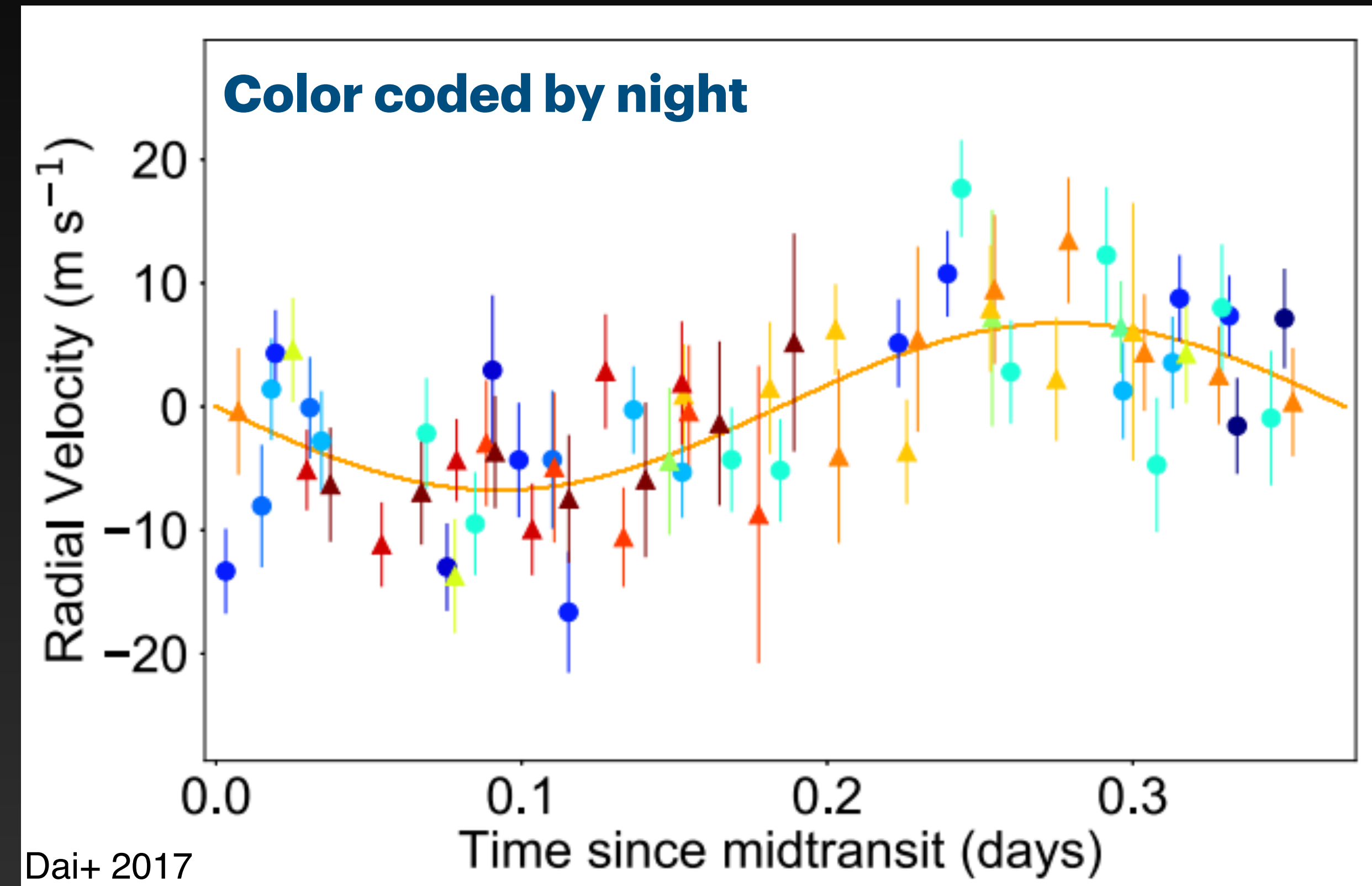
- Especially useful for short period planets where you can observe a non-trivial portion of the phase curve in one night
- Allow for an additional term “offset” term between each night’s RVs because they’re undergoing additional motion from activity and/or longer period planets



Data analysis

III. Floating chunk method

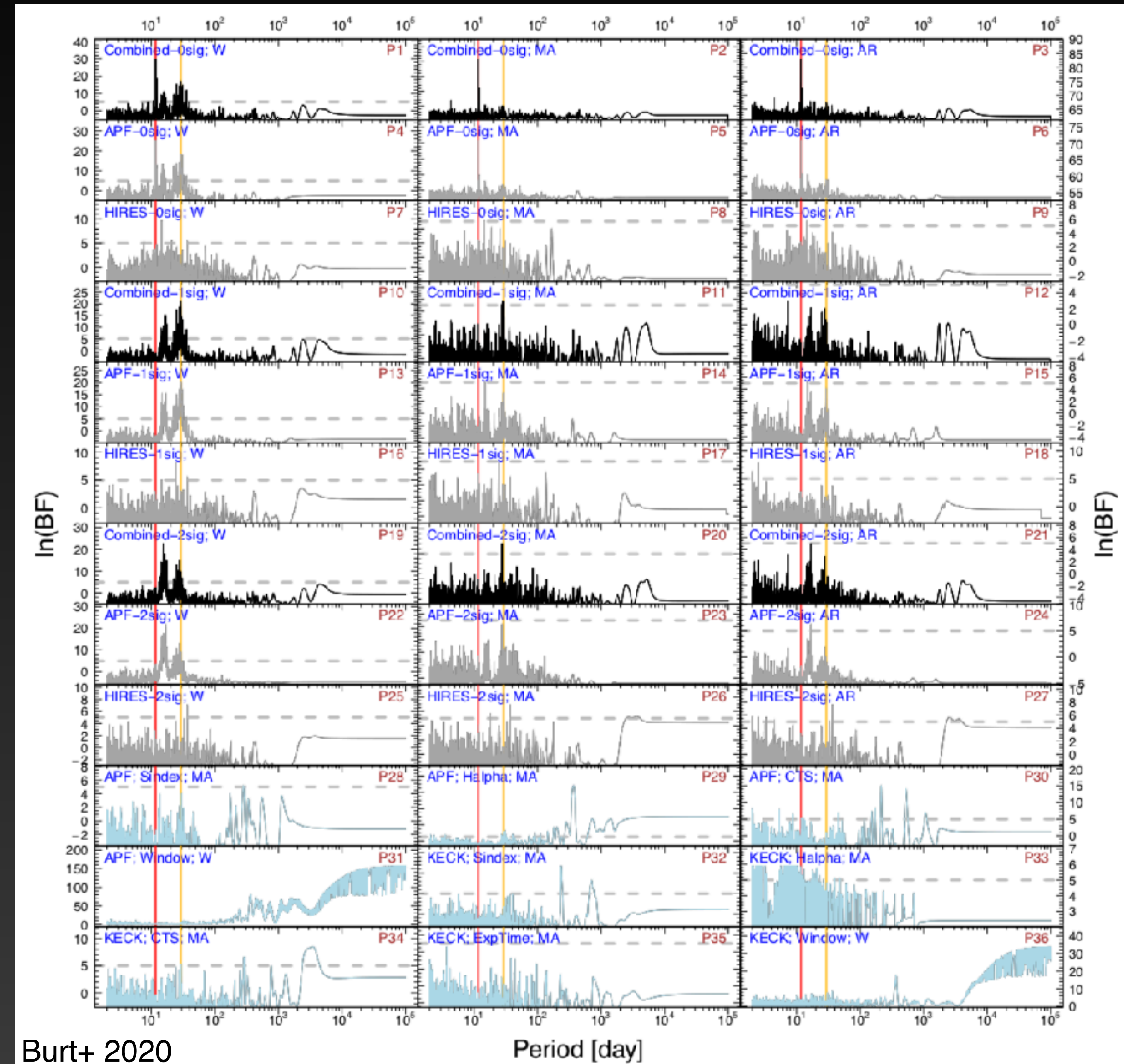
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Data analysis

IV. Moving Average

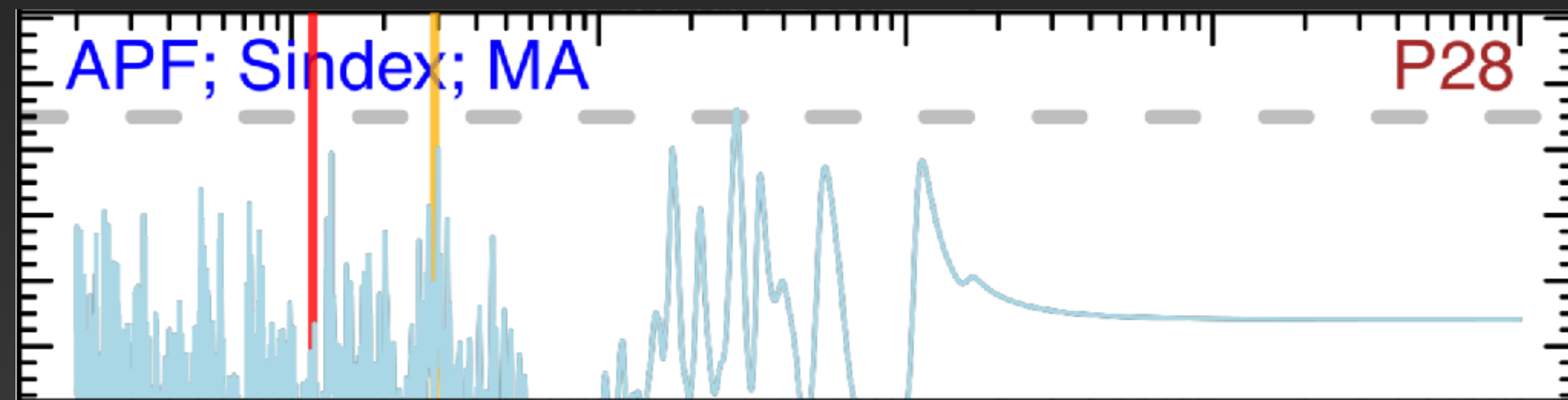
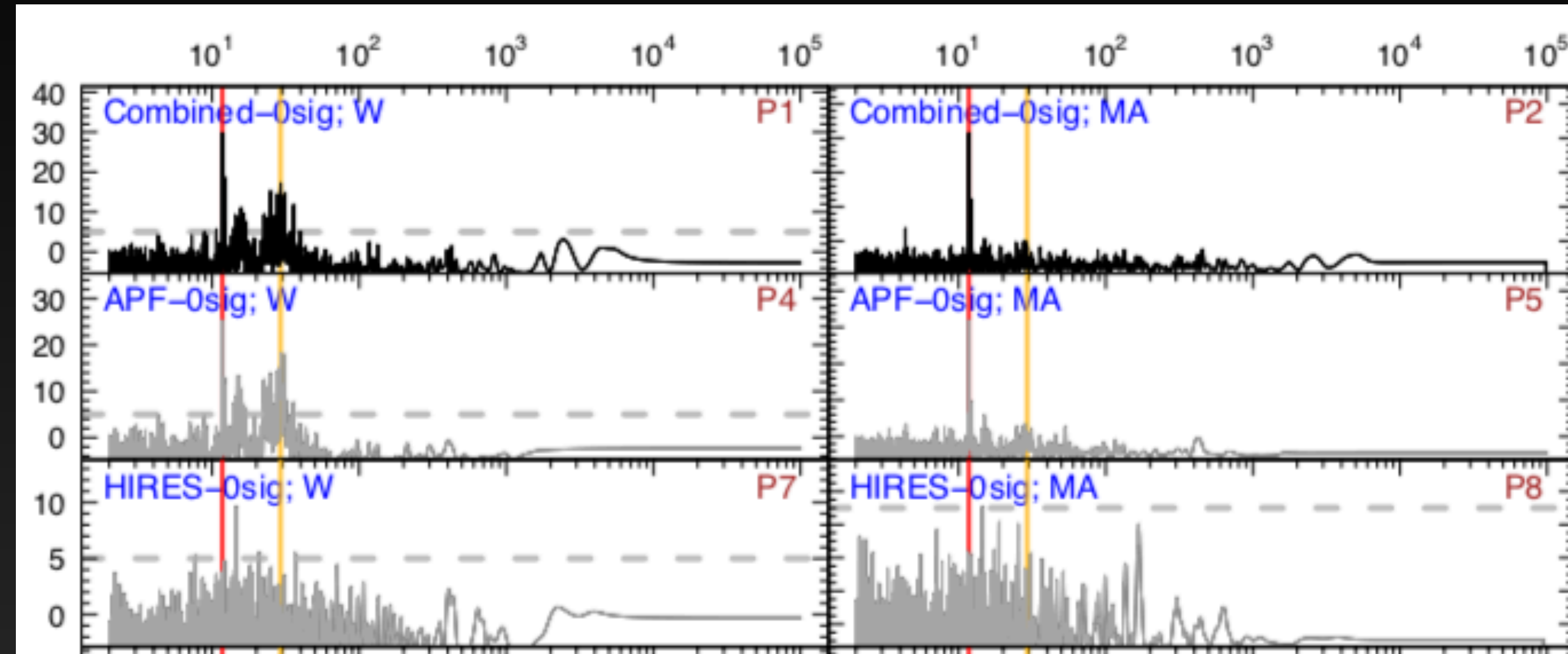
- Applies a model that accounts for the most important sources of variability in a radial velocity time-series: Keplerian signals, an unknown amount of white noise, different unknown levels of red noise, and potential linear correlations between RVs and available spectroscopic activity proxies. Also searches for wavelength dependent noise when order-by-order RVs are available



Data analysis

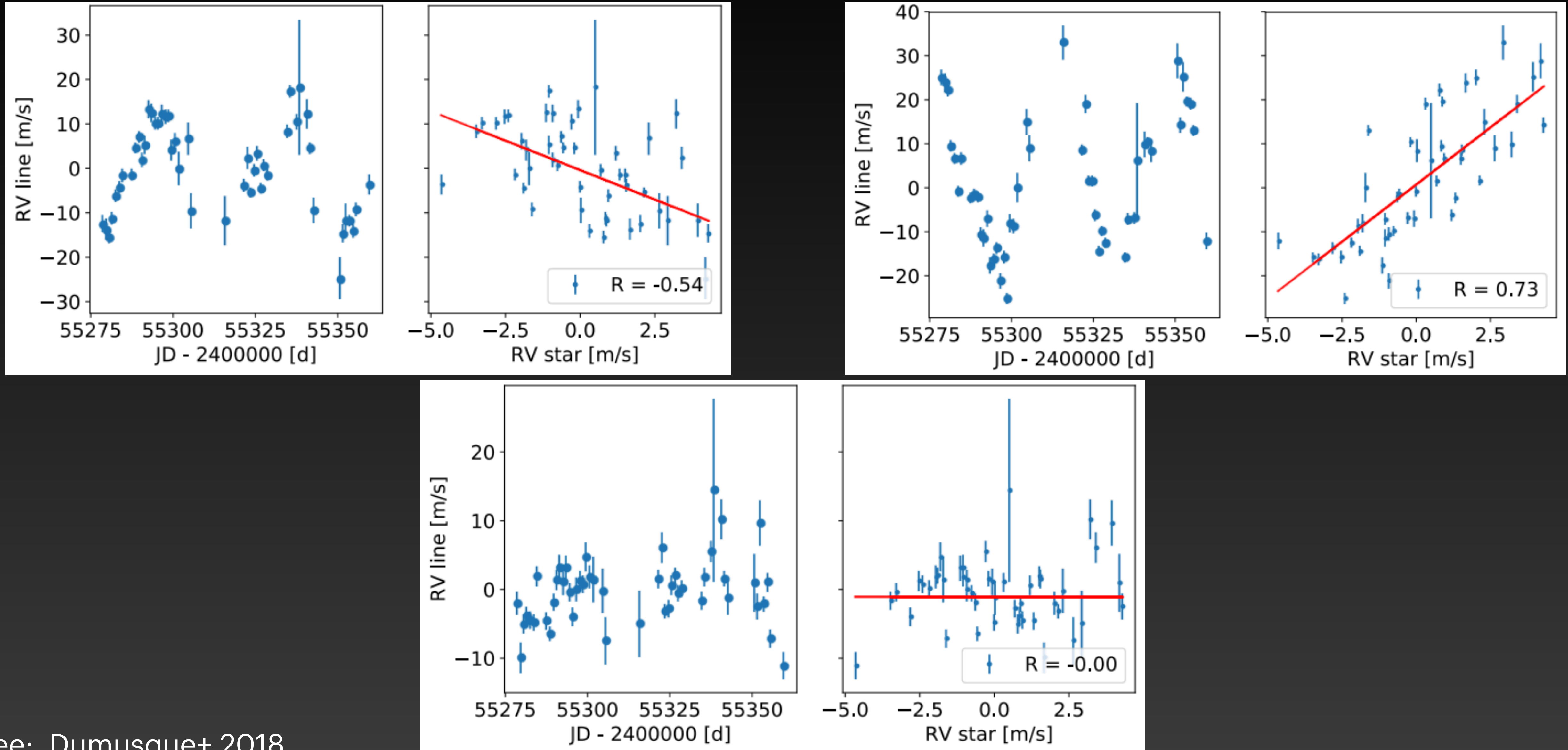
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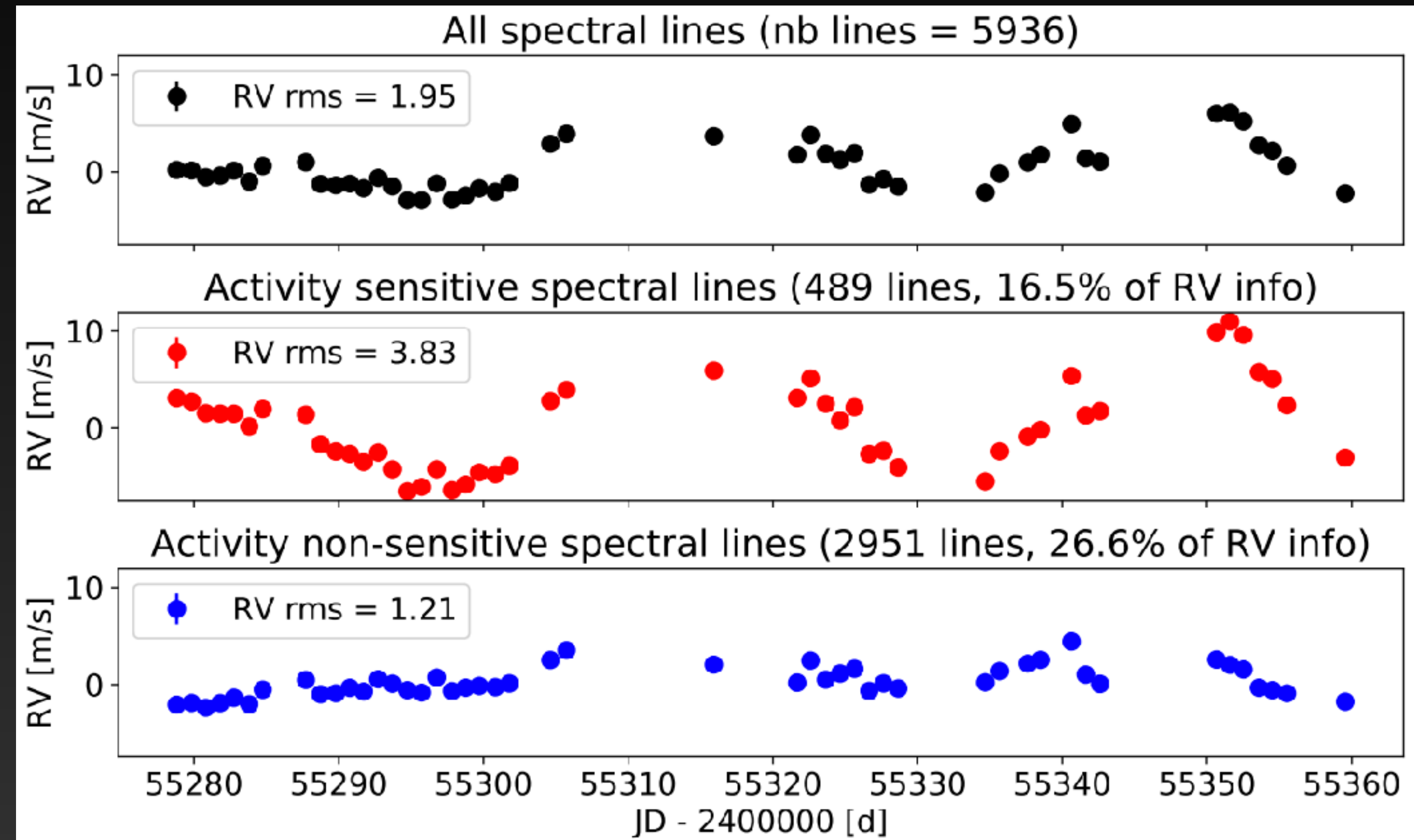
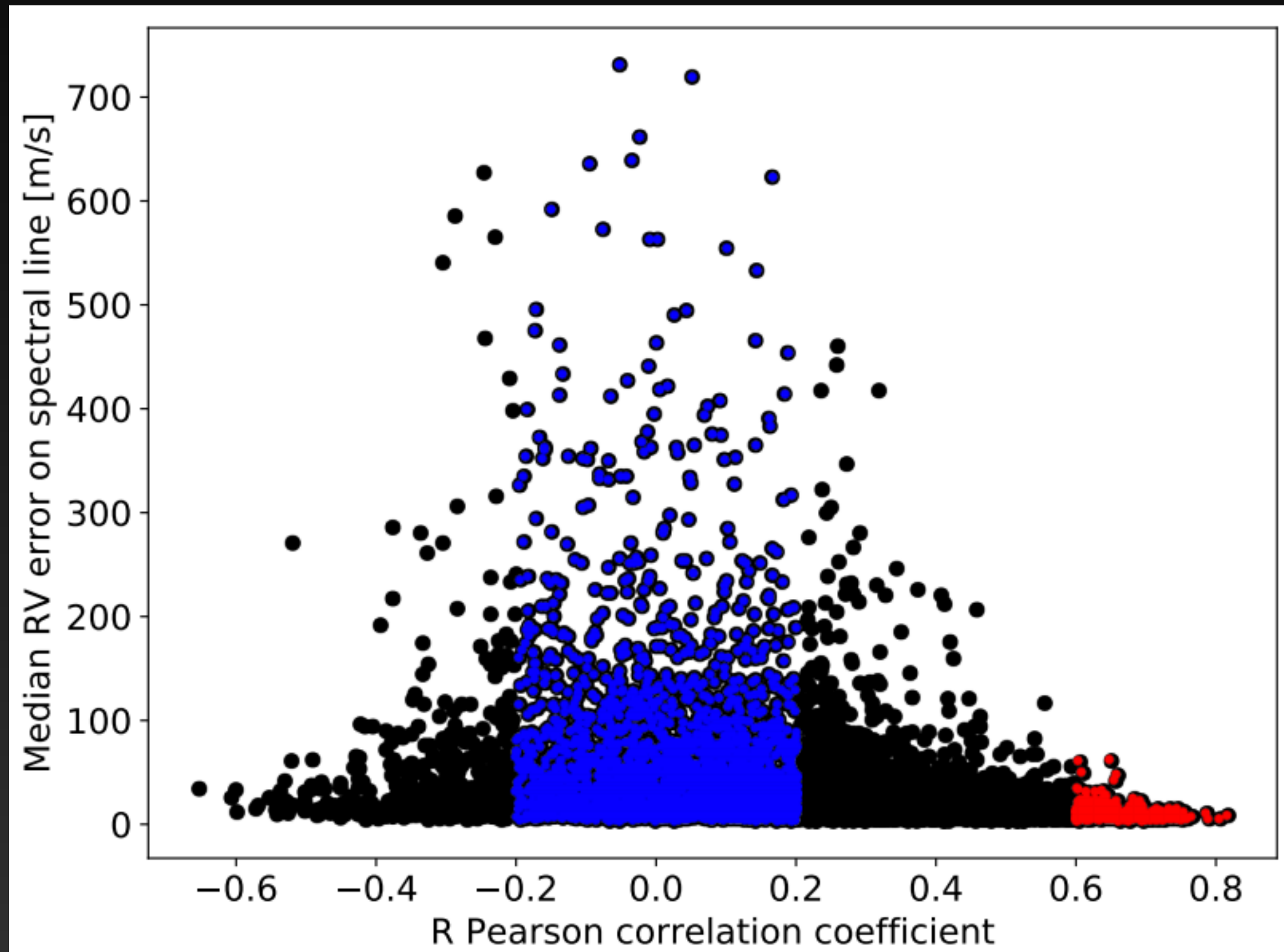
Data analysis

V. Individual Line Measurements



Data analysis

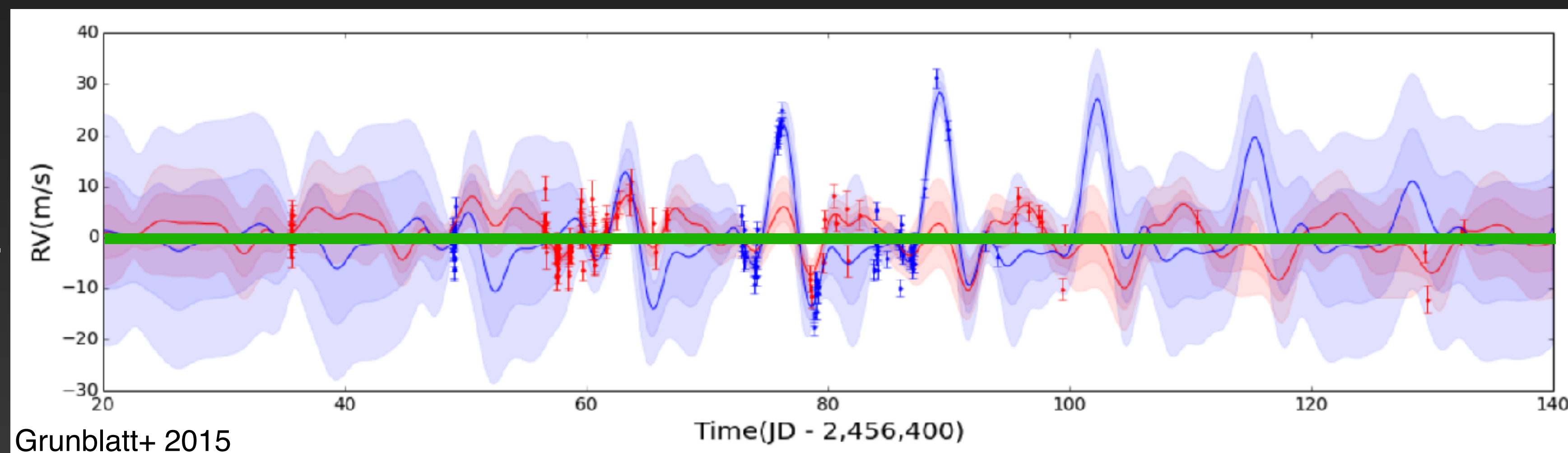
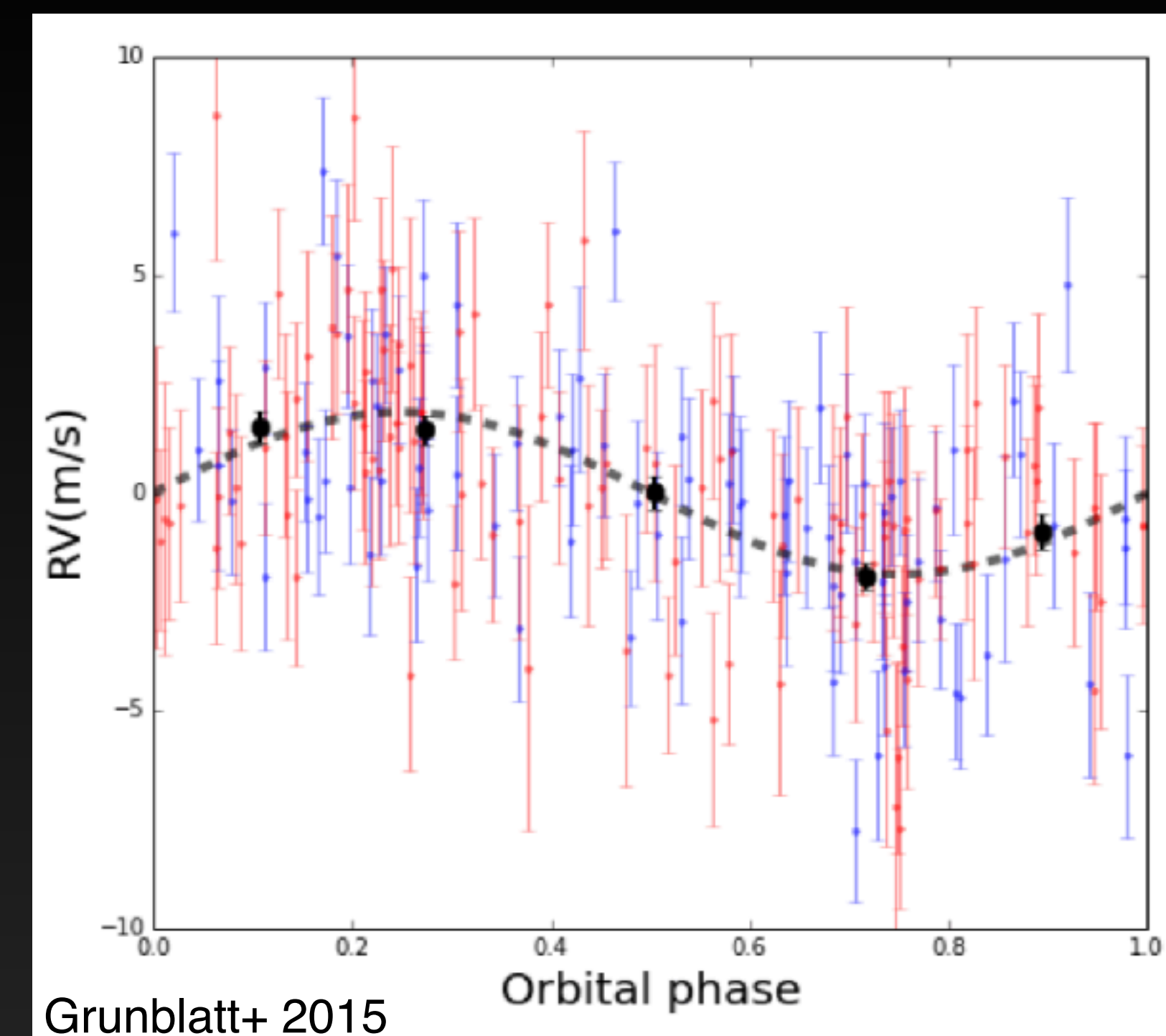
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Data analysis

VI. Gaussian Processes

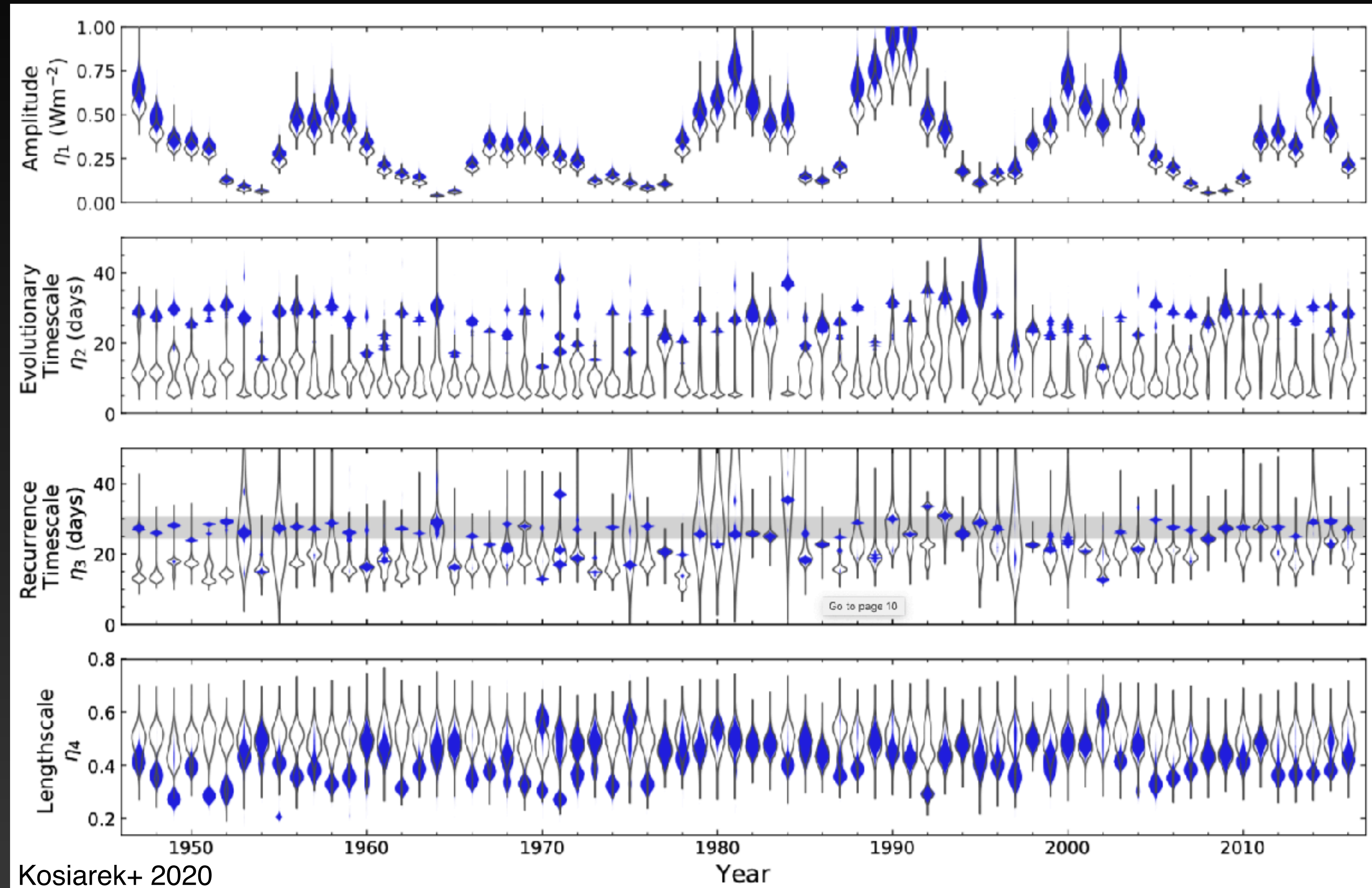
- For stellar signals, GP is generally a quasi-periodic function:
- Specify priors that tell the GP about the star's rotation period ('recurrence timescale') and spot lifetime ('evolutionary timescale'), among others
- GP is trained on a data set that contains information about stellar activity (photometry, S-index, etc)



Data analysis

VI. Gaussian Processes

- But even in cases of copious, high SNR data to train the GP on you still need to be careful!
- Decades worth of solar data gets P_{rot} wrong the majority of the time if you don't enforce an additional prior that $P_{\text{rot}} < P_{\text{spot_evol}}$



Conclusions

- Stellar variability that appears in RV data comes from a variety of physical phenomena within the star that occur on a variety of time scales
- The affects of some of these phenomena (pulsations & granulation) can often be mitigated via good observing practices, but others (active regions & magnetic cycles) generally need to be handled in the data analysis phase
- Obtaining auxiliary measurements (spectroscopic activity indicators, photometry, etc) is crucial for determining what the star's activity looks like
- There are a large variety of ways to address stellar variability in RV data, but the approaches that treat variability like correlated signals (Moving Average) and/or quasi-periodic signals (Gaussian Processes) tend to perform the best



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Image credit: NASA Goddard Space Flight Center

