FourIEr *phase* SpecTrum Analysis (ΦESTA / FIESTA)

Parametrising Stellar Variability in Fourier Space

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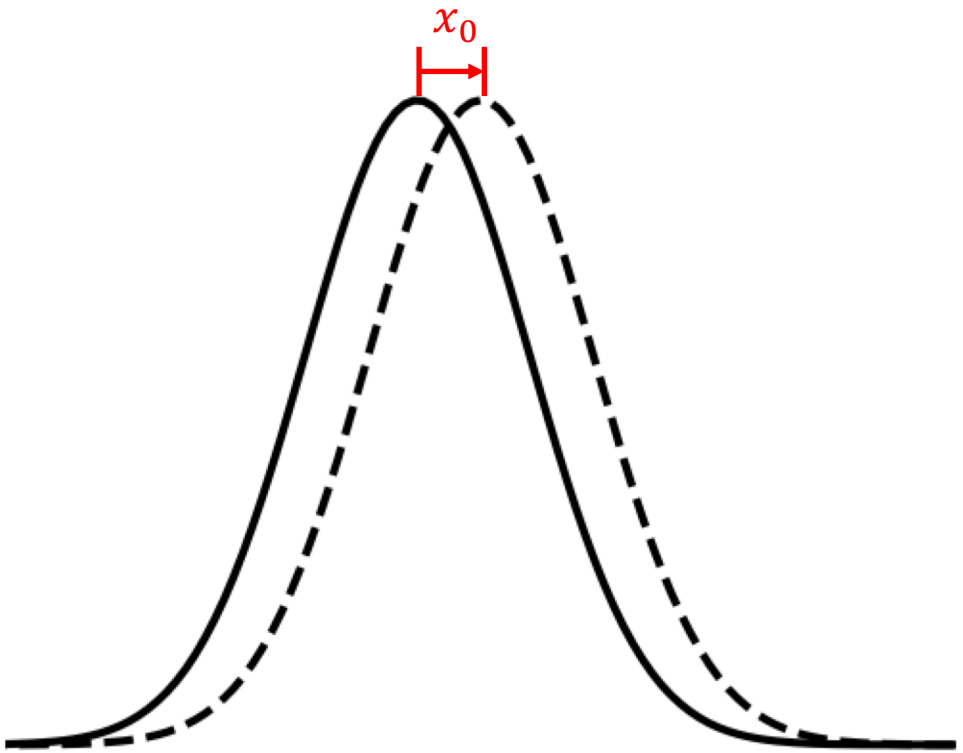
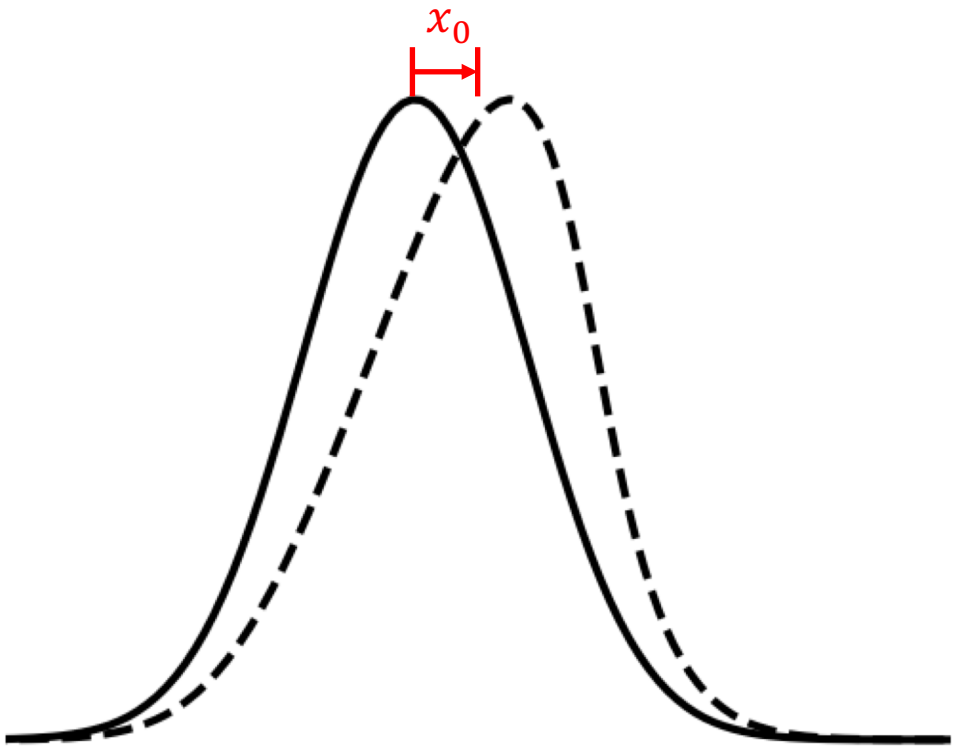
2. Australian Centre for Astrobiology, UNSW Sydney

Challenge

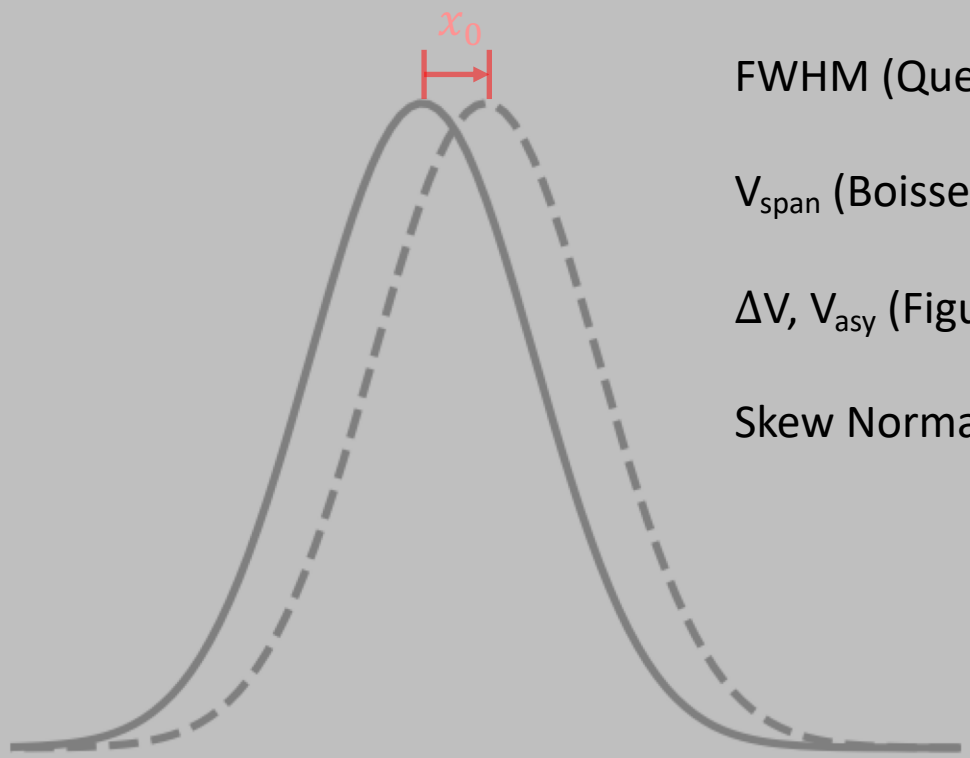


Intrinsic shift (orbiting companions)



Apparent shift (stellar variability)

Challenge



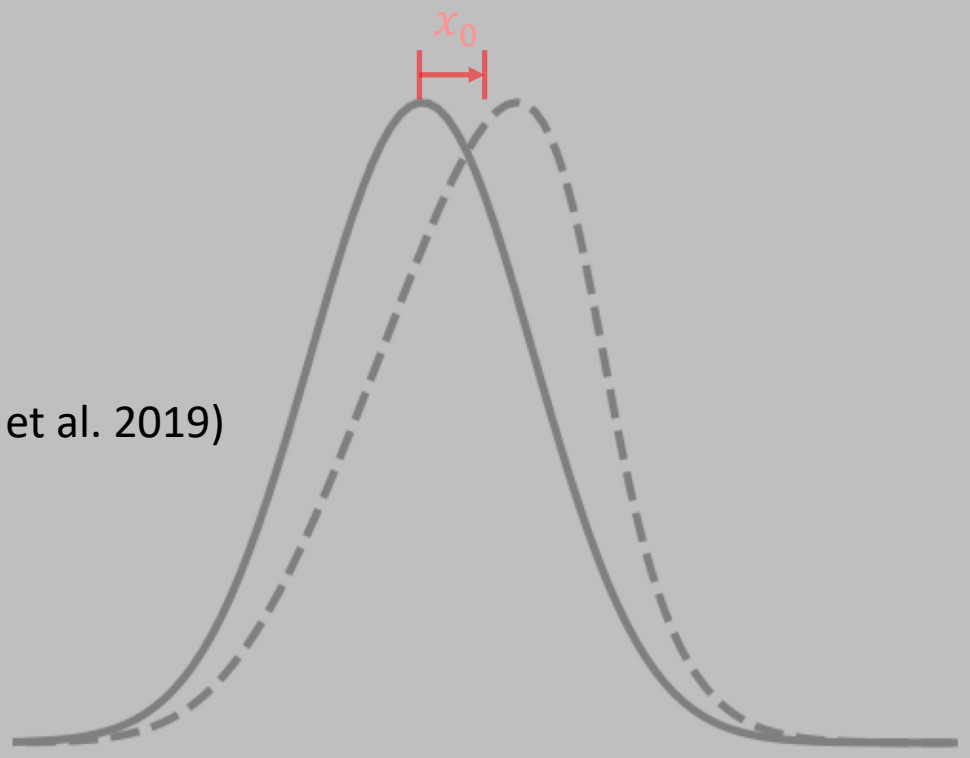
Bisector (Queloz et al. 2001)

FWHM (Queloz et al. 2009)

V_{span} (Boisse et al. 2011)

ΔV, V_{asy} (Figueira et al. 2013)

Skew Normal density (Simola et al. 2019)



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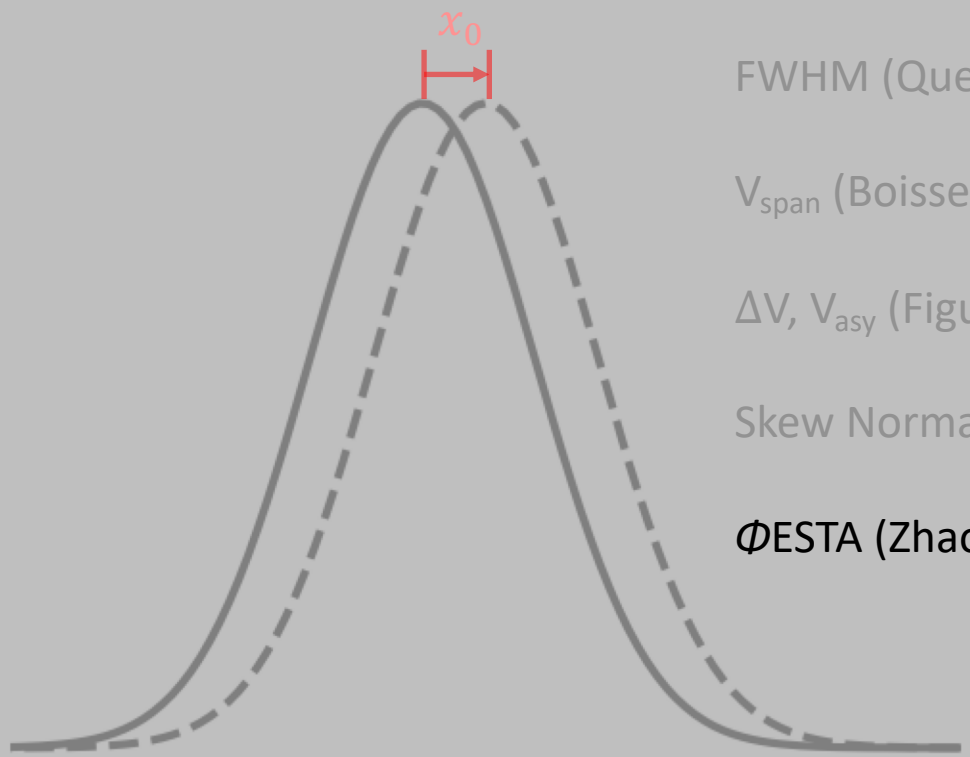

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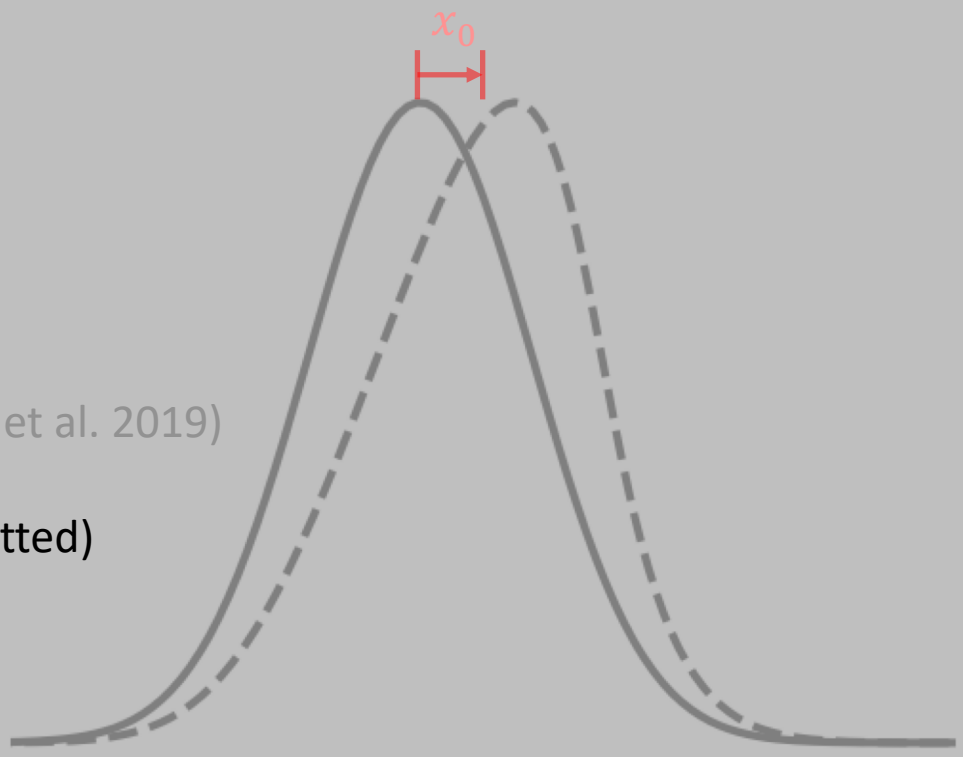
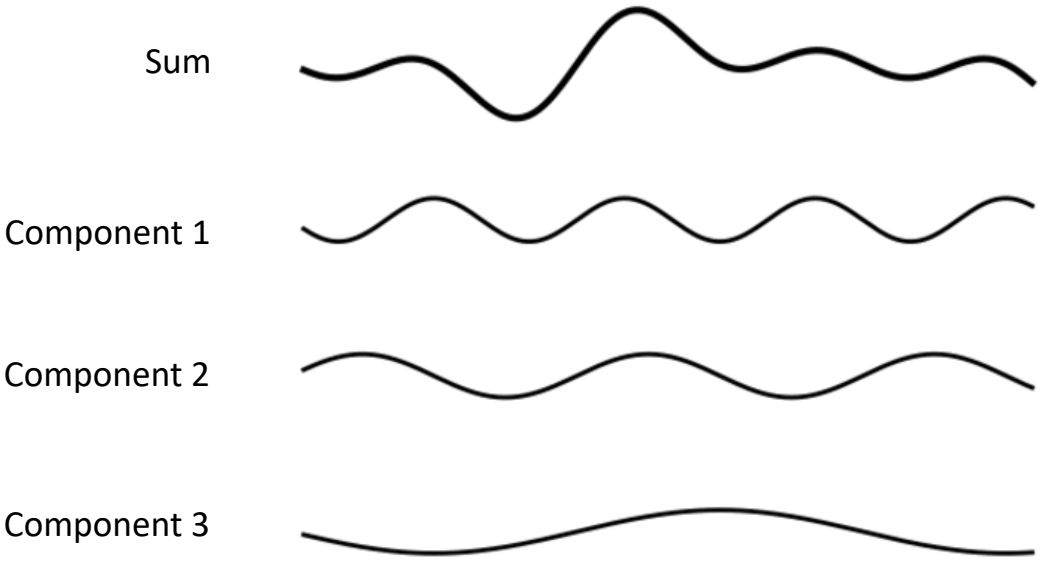
*Φ*ESTA (Zhao & Tinney, submitted)

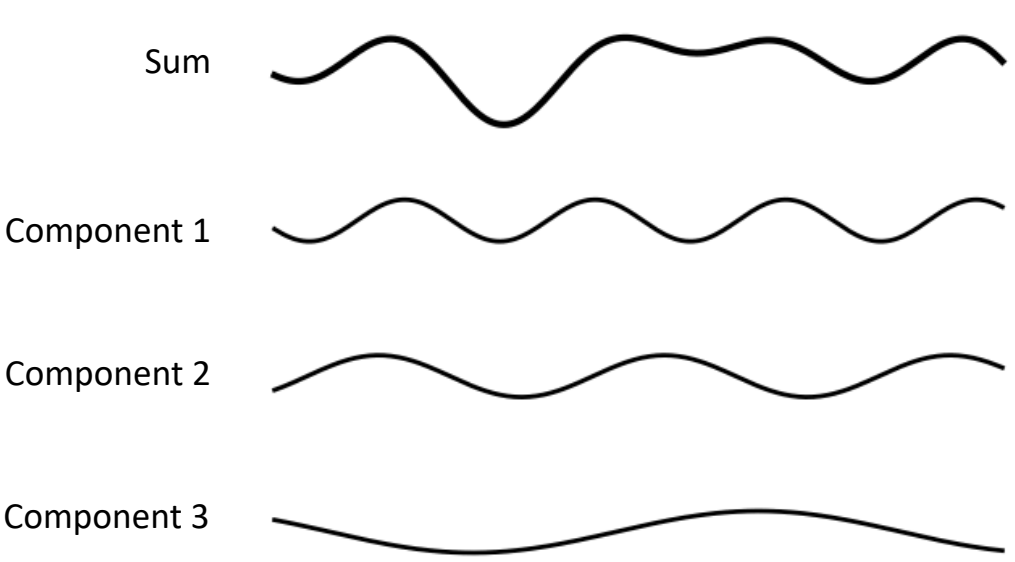


Entrée

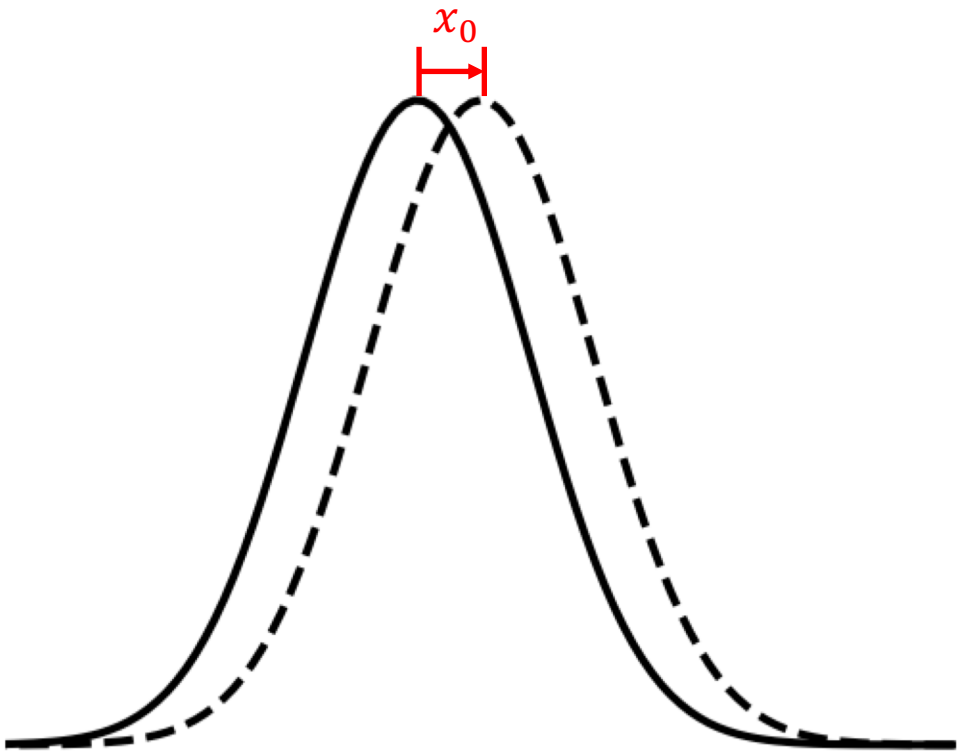
Signal shifted

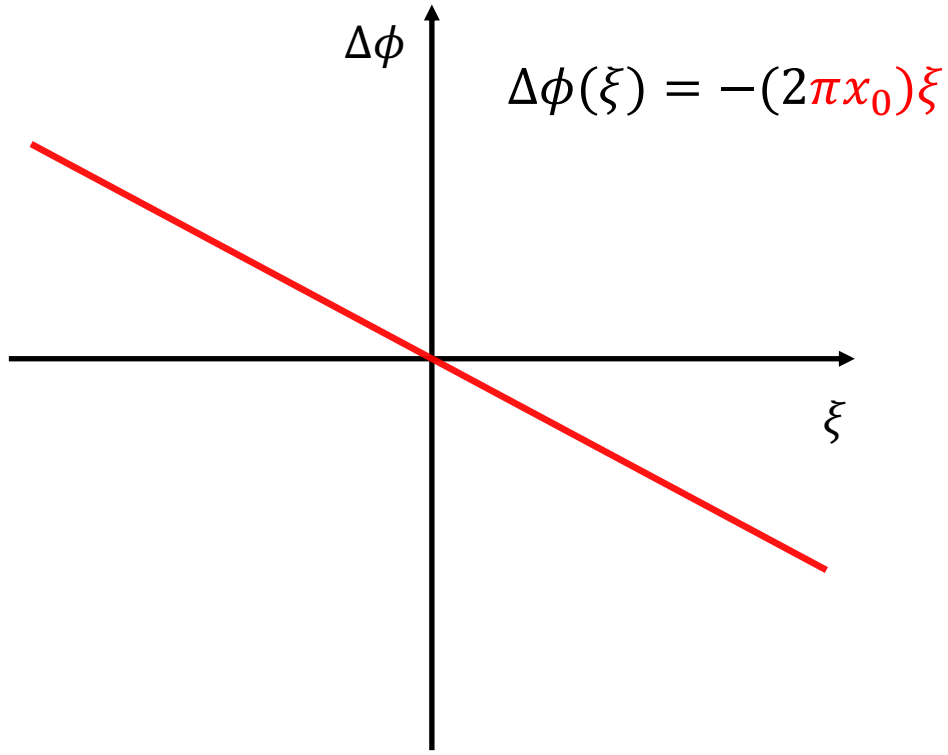


Signal deformed



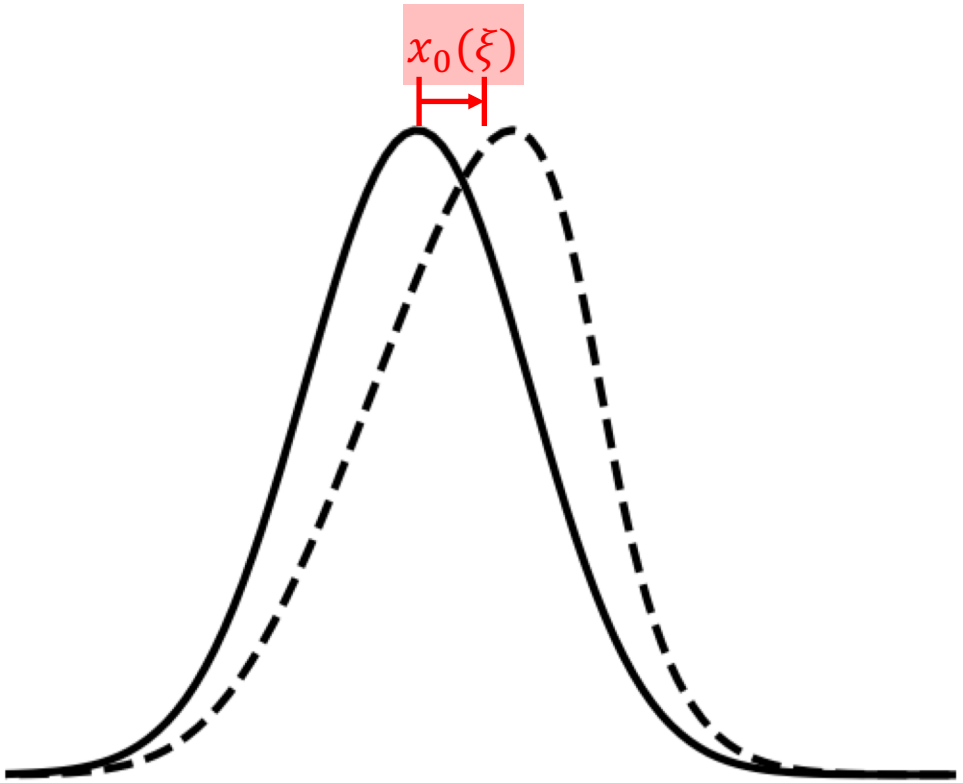
Translation Property – Line Shift

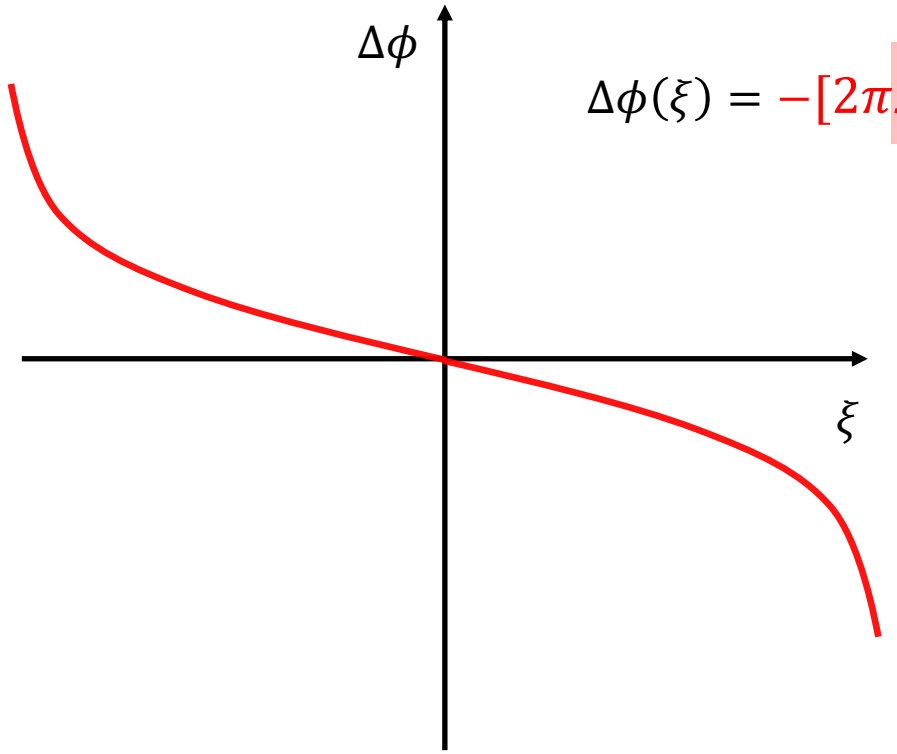




- If $h(x) = f(x - x_0)$, then $\hat{h}(\xi) = e^{-2\pi i x_0 \xi}\hat{f}(\xi)$
- Phase shift $\Delta\phi(\xi) = -(2\pi x_0)\xi$

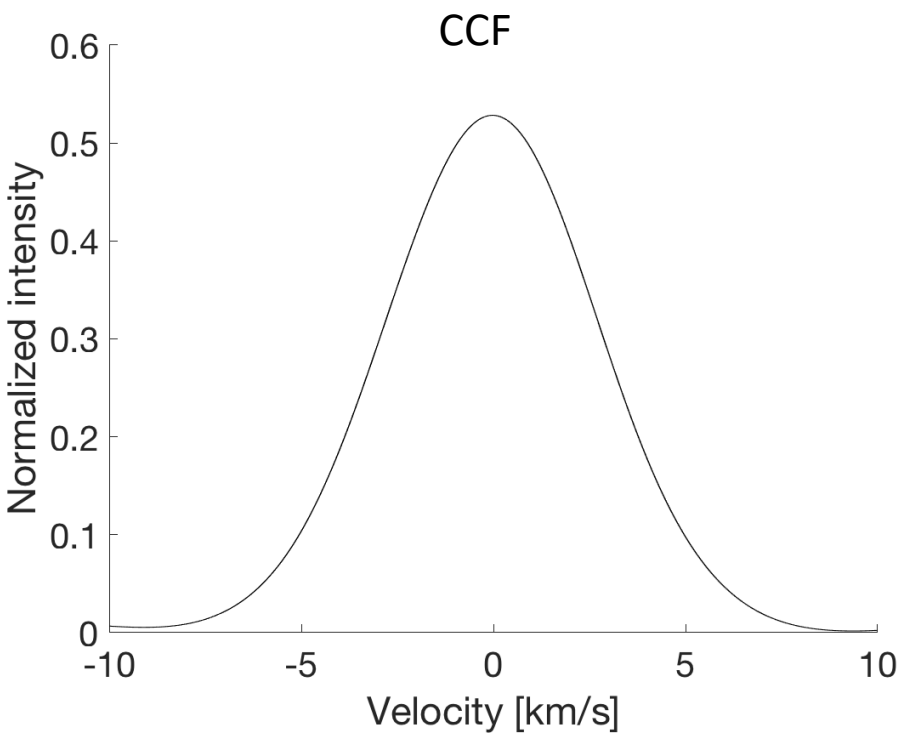
Translation Property – Line Deformation

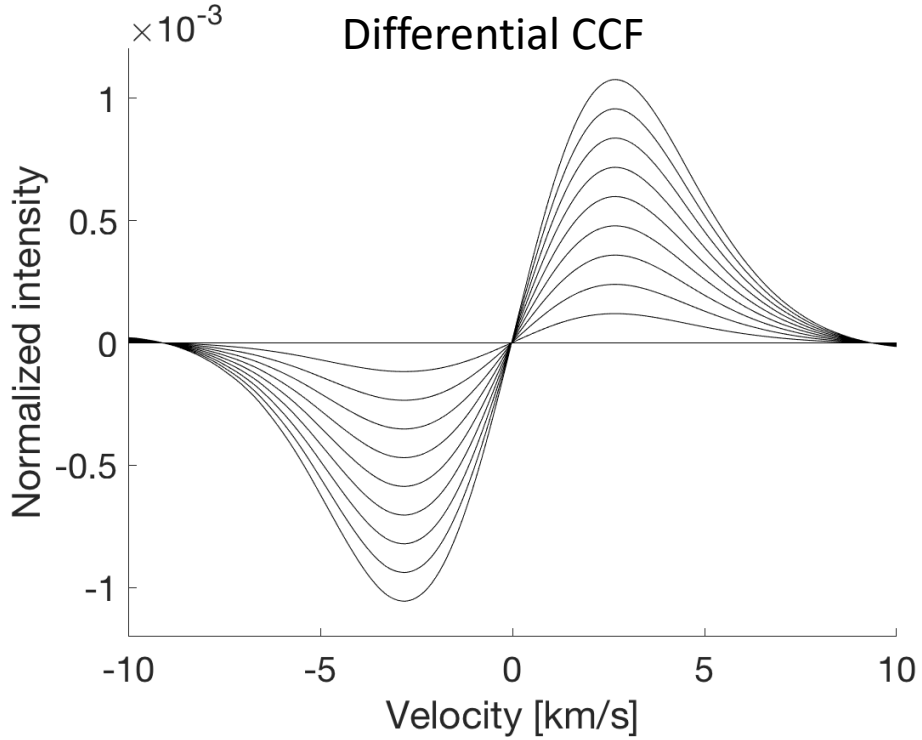




$\Delta\phi(\xi) = -[2\pi x_0(\xi)]\xi$

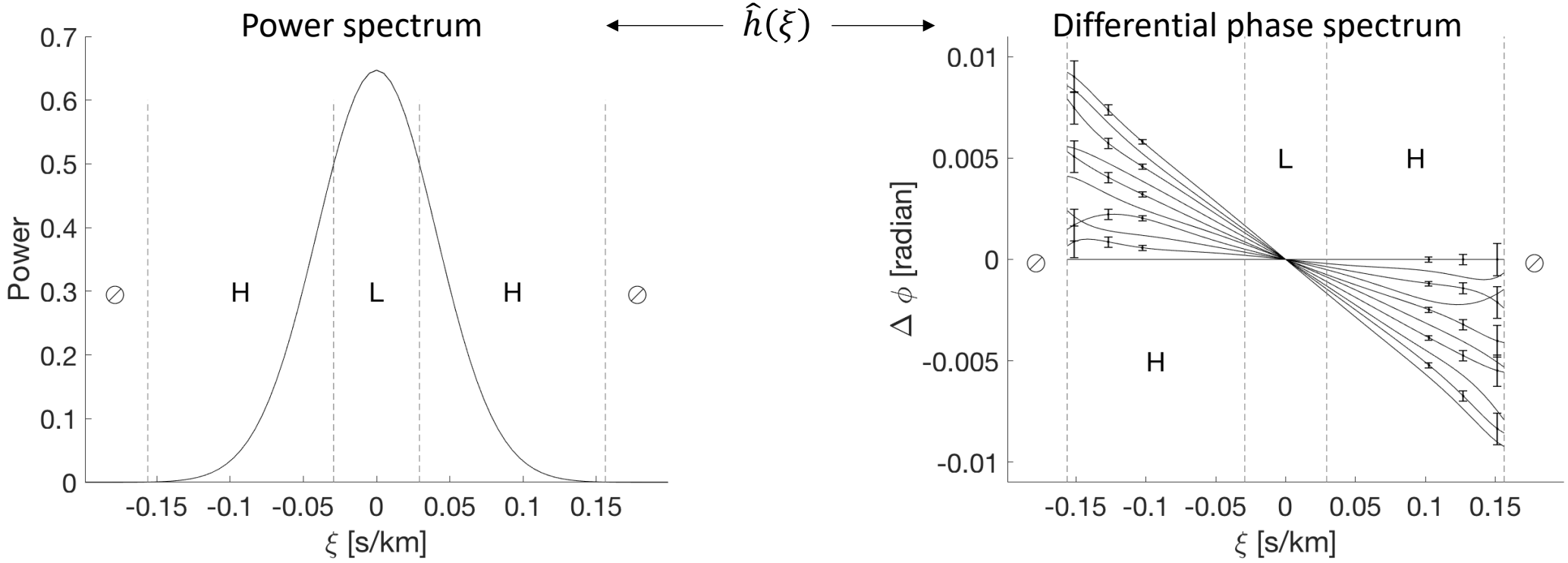
- Phase shift $\Delta\phi(\xi) = -[2\pi x_0(\xi)]\xi$





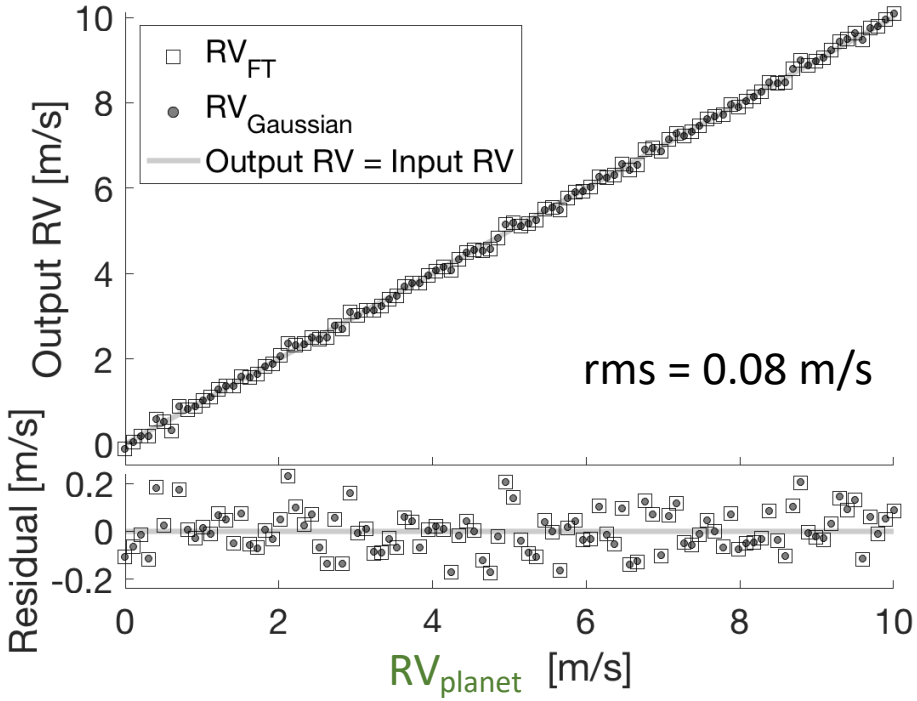
Line Shift – Velocity Domain

SOAP simulator (Boisse et al. 2012; Dumusque et al. 2014)

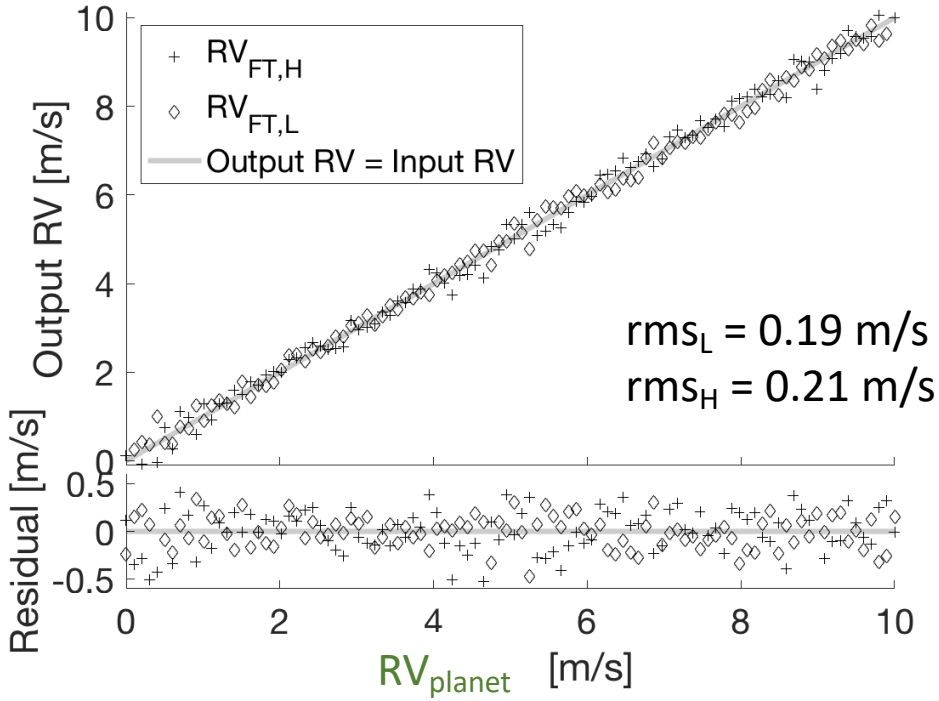


Line Shift – Inverse Velocity Domain

Full range

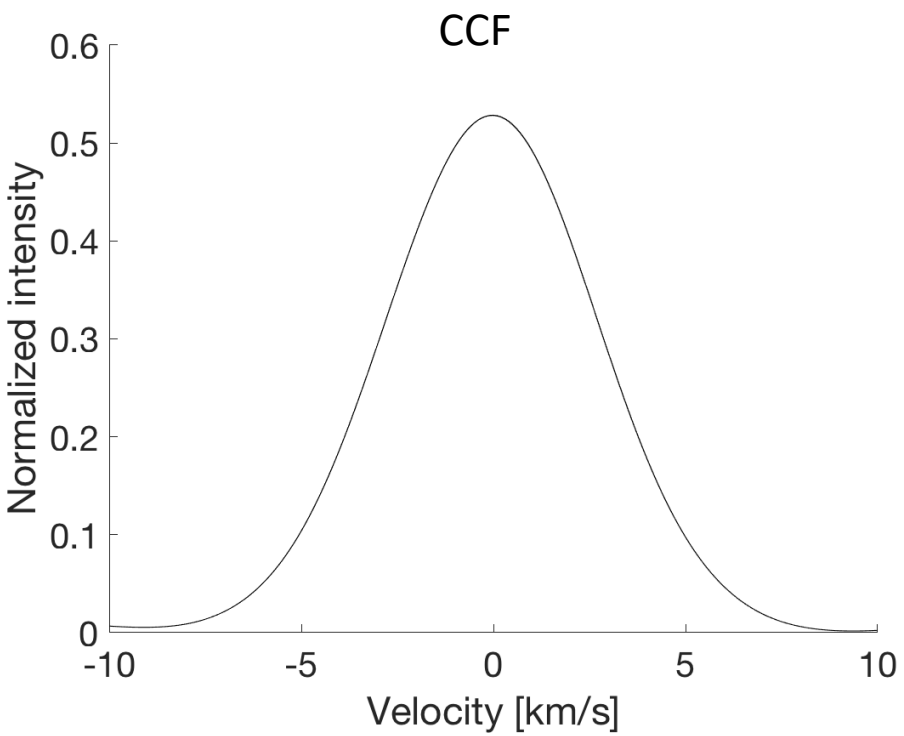


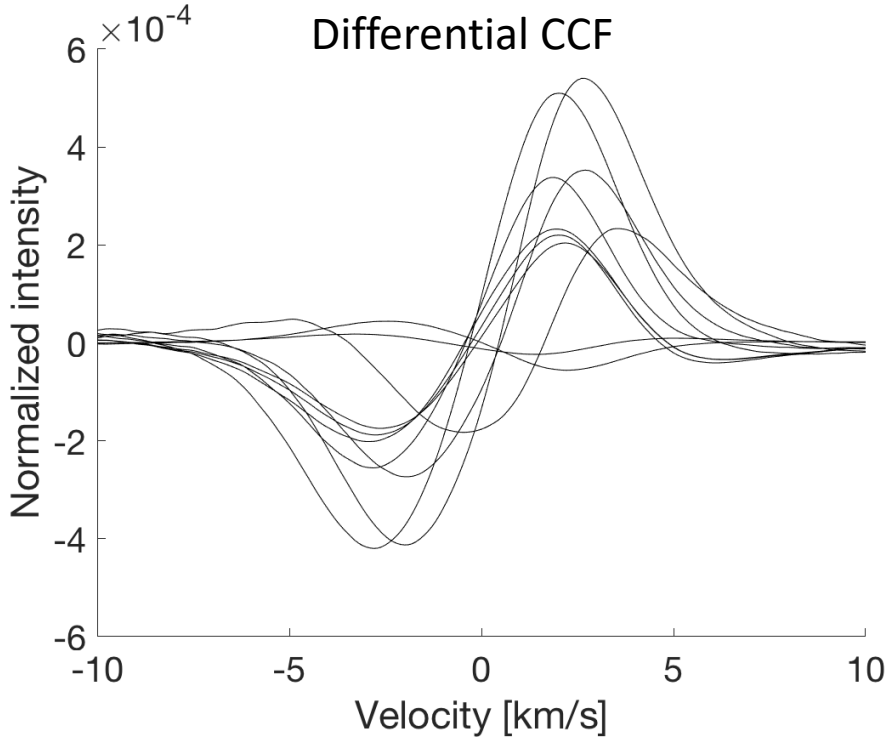
Half range



Line Shift – ØESTA Measurements

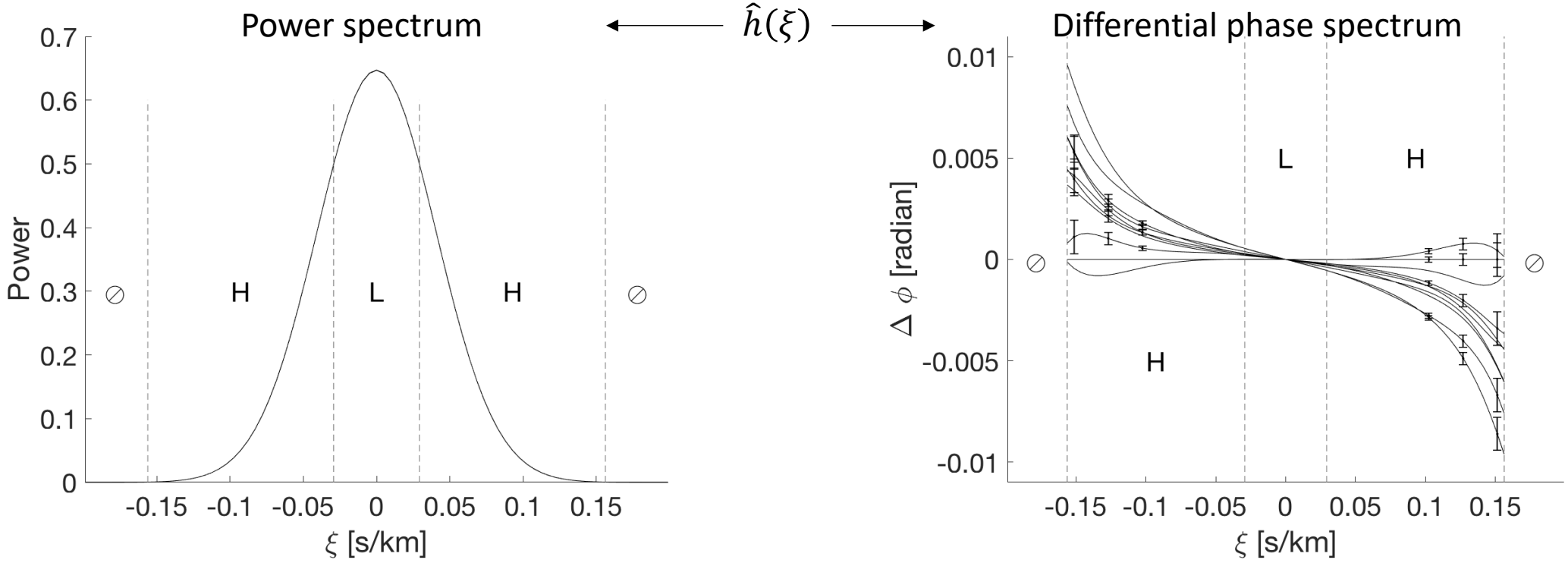
$RV_{Gaussian} = RV_{FT} = RV_{FT,L} = RV_{FT,H} = RV_{planet}$





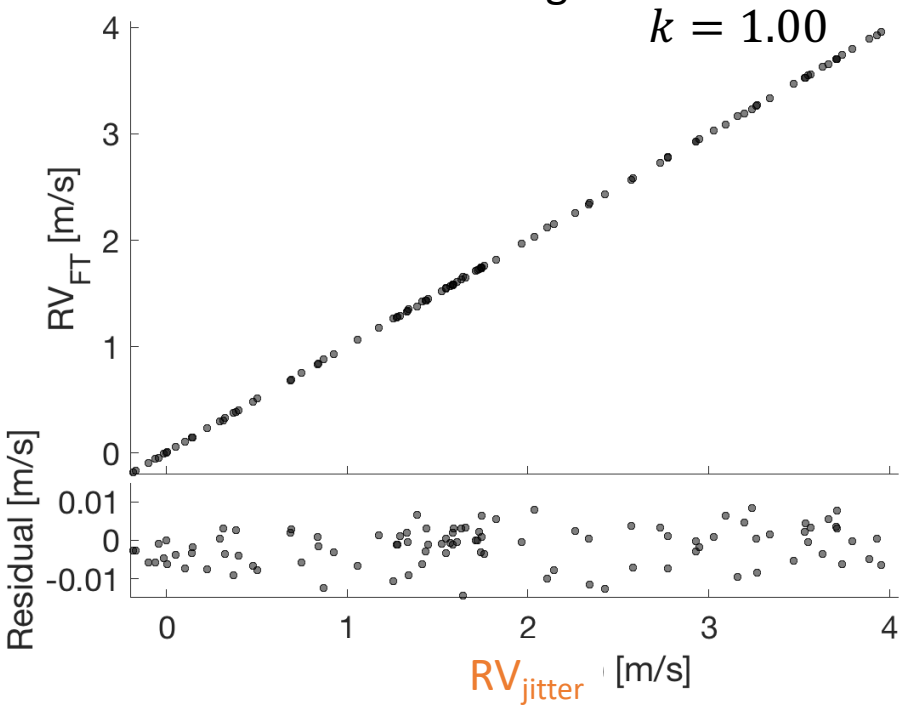
Line Deformation – Velocity Domain

SOAP simulation (3 starspots)

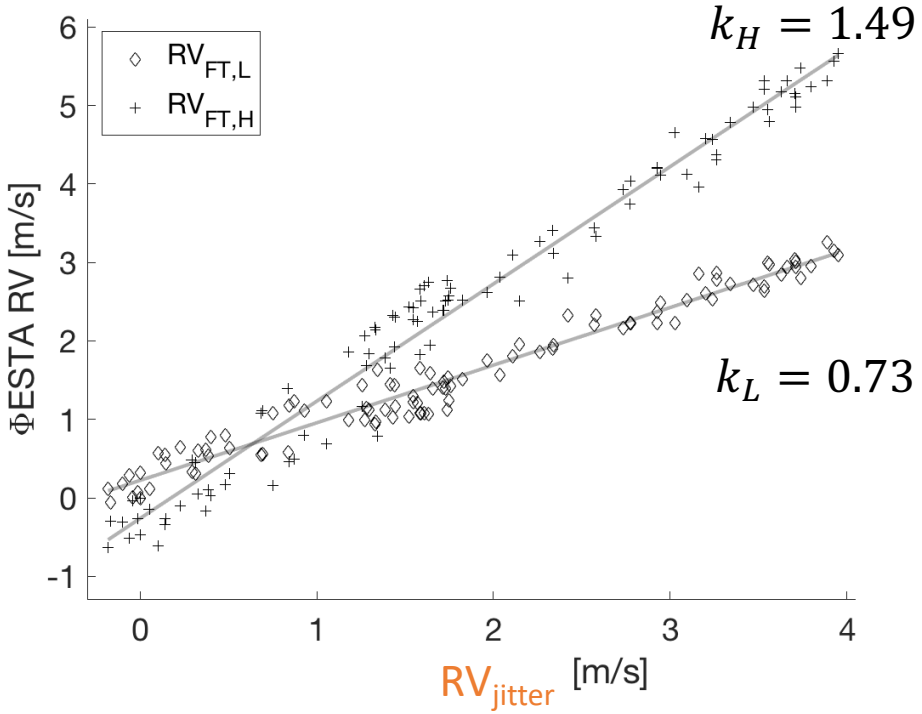


Line Deformation – Inverse Velocity Domain

Full range



Half range



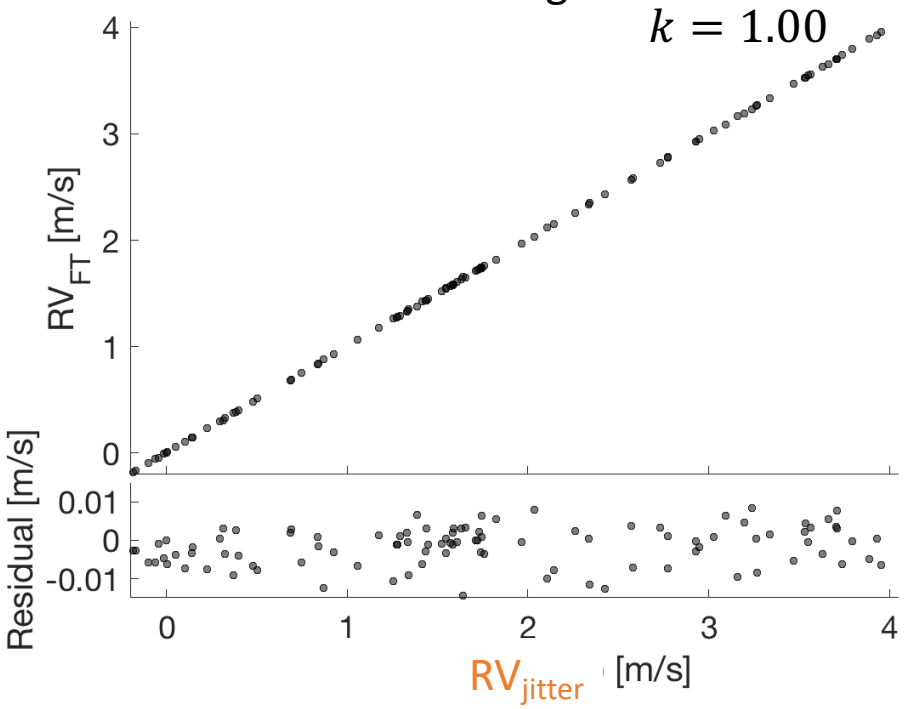
Line Deformation – ΦESTA Measurements

RV_{FT} = $RV_{Gaussian}$ = RV_{jitter}

$RV_{FT,L}$ = k_L RV_{jitter} $(k_L < 1)$

$RV_{FT,H}$ = k_H RV_{jitter} $(k_H > 1)$

Full range



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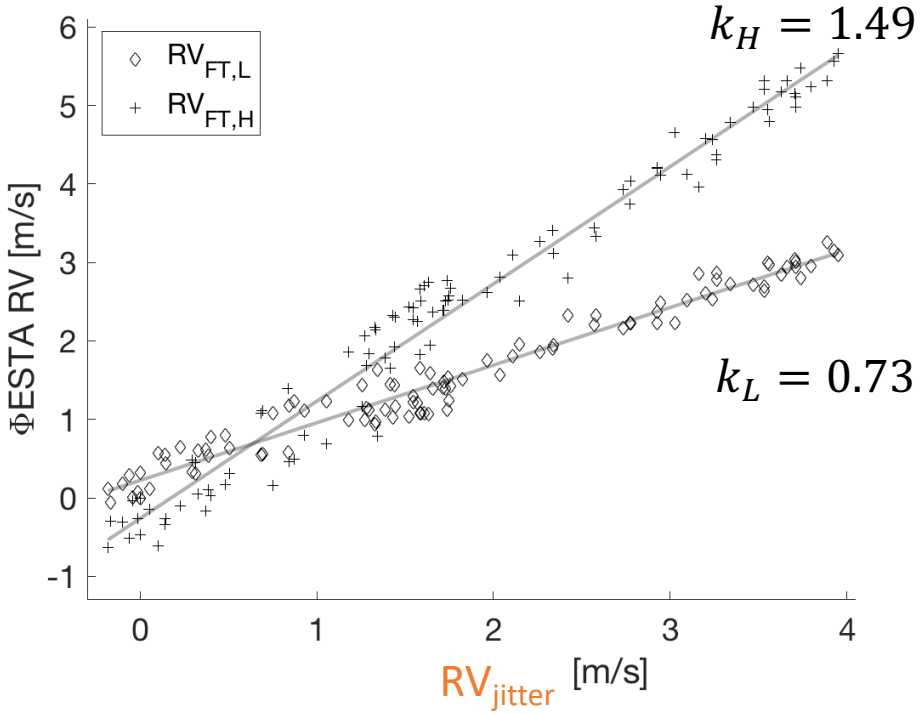


Line Deformation – ΦESTA Measurements

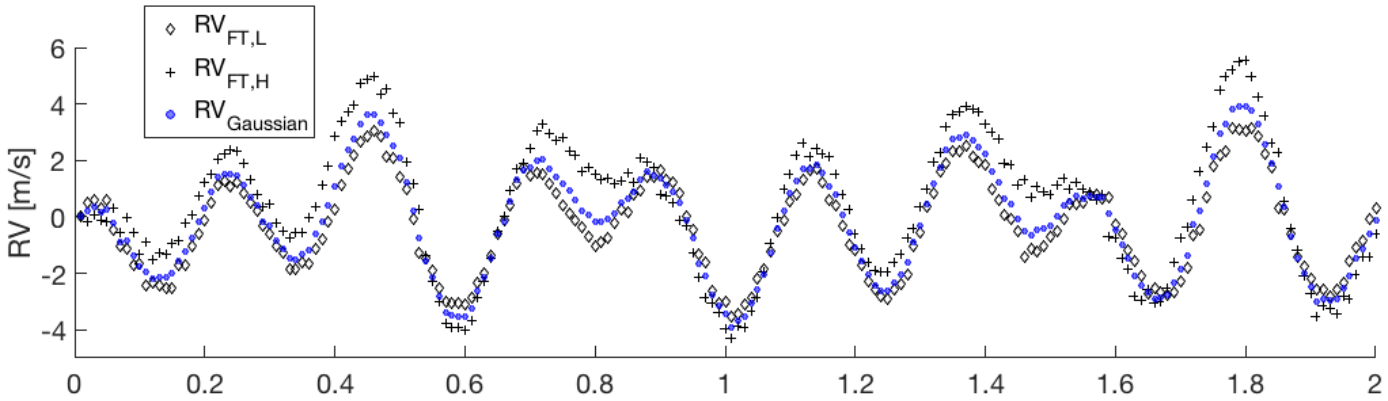
RV_{FT} = $RV_{Gaussian}$ = RV_{jitter}

$RV_{FT,\,L}$ = k_L RV_{jitter} $(k_L < 1)$ less sensitive to jitter

$RV_{FT,\,H}$ = k_H RV_{jitter} $(k_H > 1)$ more sensitive to jitter

$RV_{Gaussian} - RV_{FT,\,L} \propto RV_{jitter}$

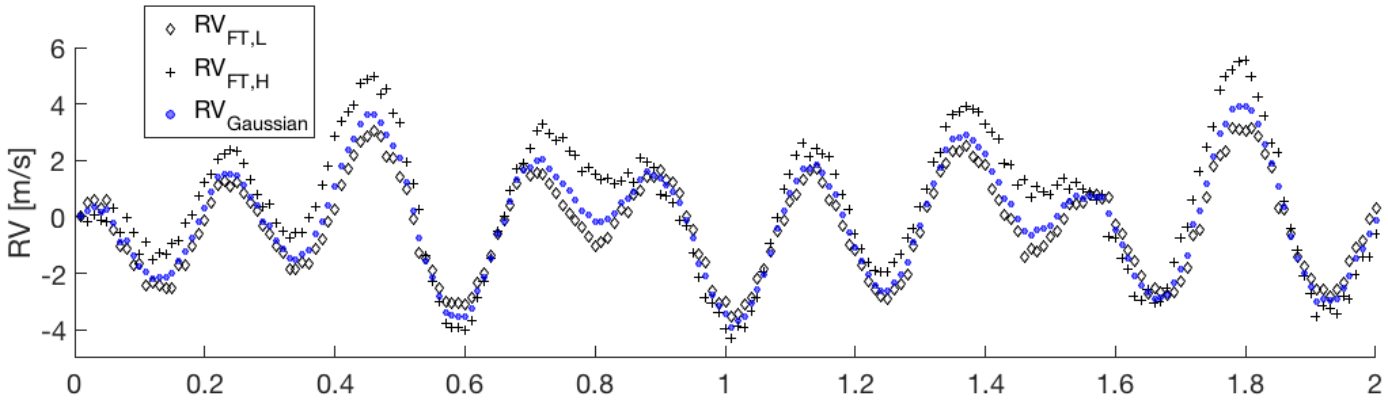
$RV_{FT,\,H} - RV_{Gaussian} \propto RV_{jitter}$



Stellar rotation phase

ΦESTA Jitter Metrics

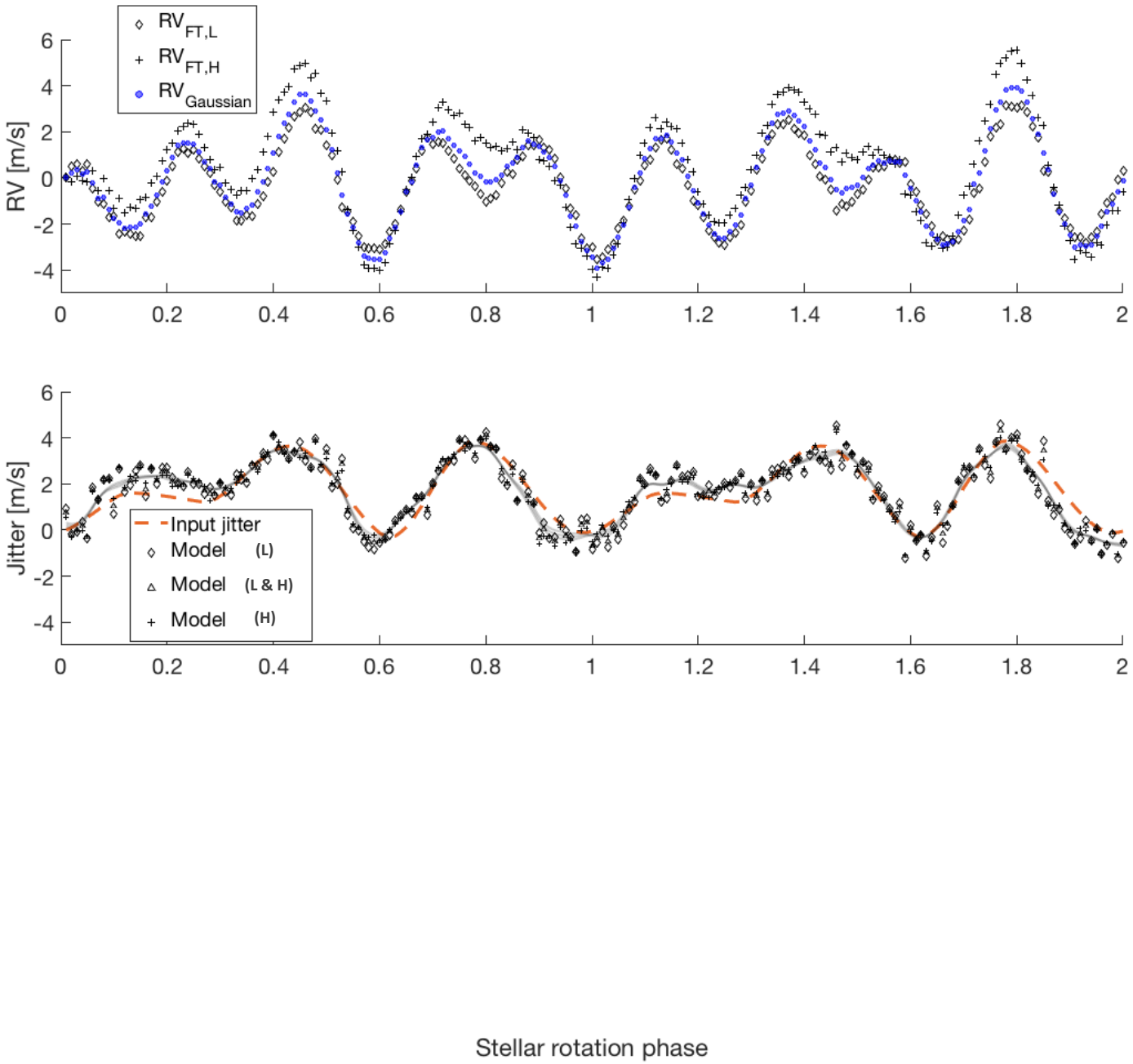
- $\Delta RV_L = RV_{Gaussian} - RV_{FT,\,L} \propto RV_{jitter}$
- $\Delta RV_H = RV_{FT,\,H} - RV_{Gaussian} \propto RV_{jitter}$



Stellar rotation phase

ΦESTA Jitter Model

- $\Delta RV_L = RV_{Gaussian} - RV_{FT,\,L} \propto RV_{jitter}$
- $\Delta RV_H = RV_{FT,\,H} - RV_{Gaussian} \propto RV_{jitter}$
- Linear combination of ΔRV_L and $\Delta RV_H \propto RV_{jitter}$



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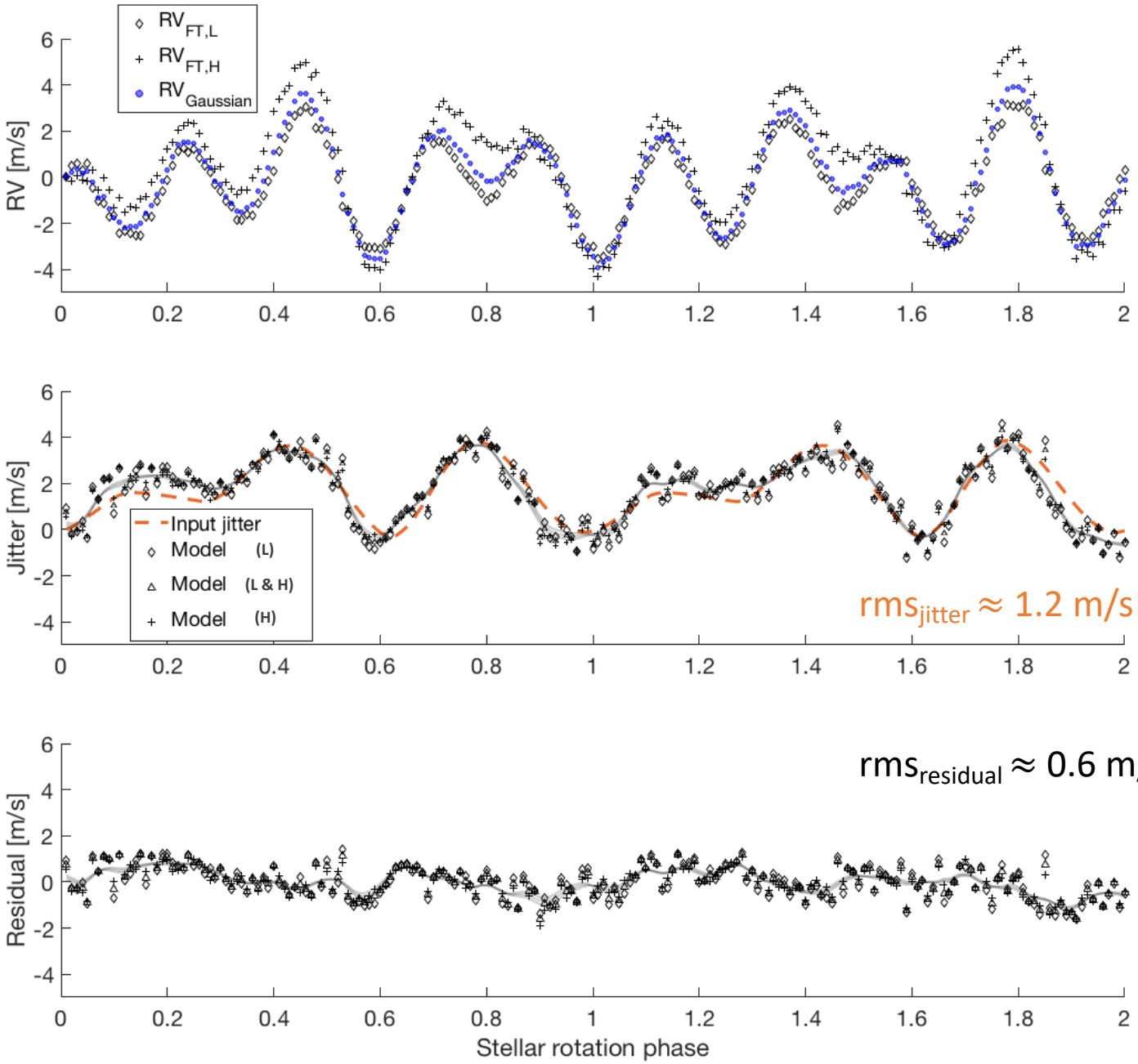
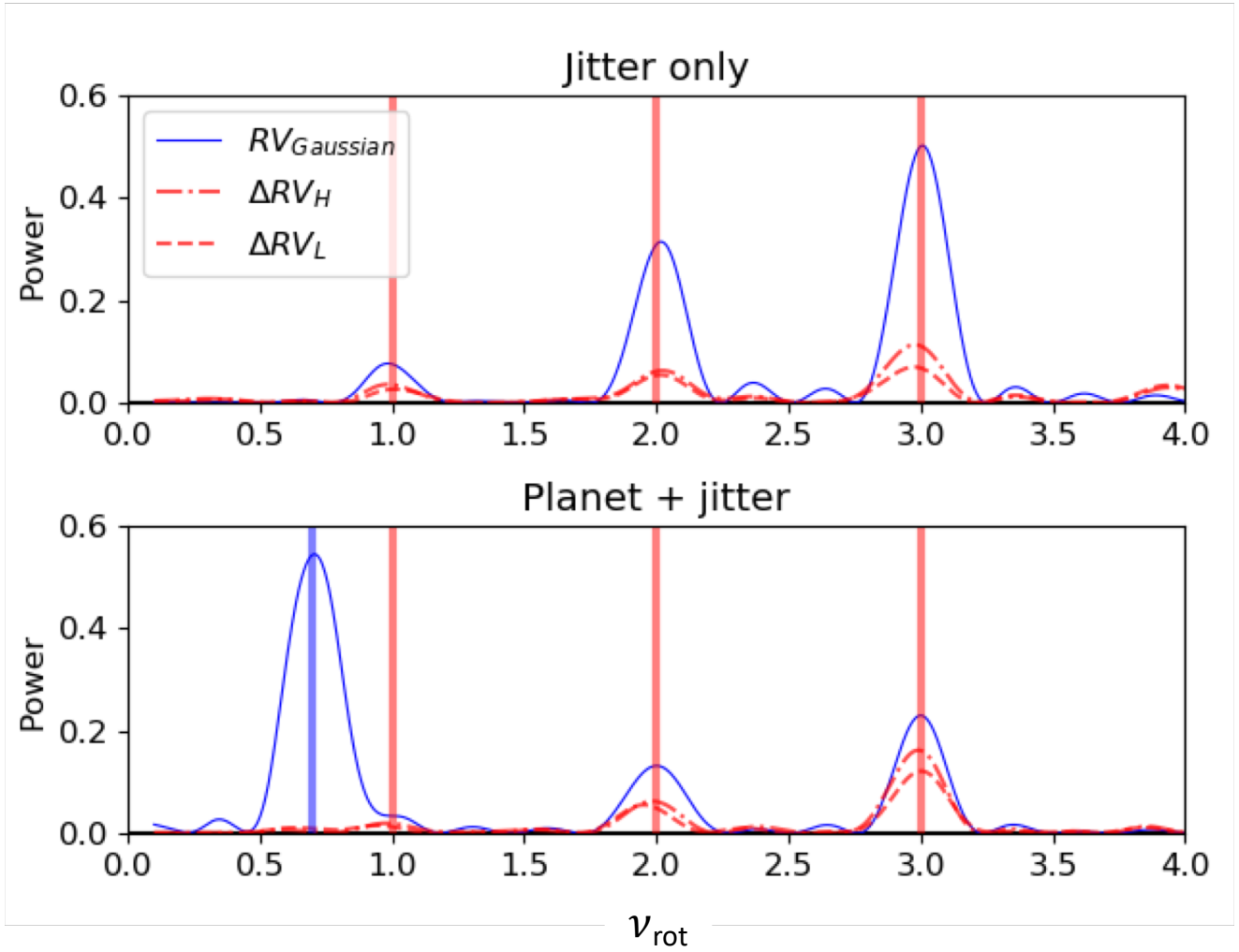


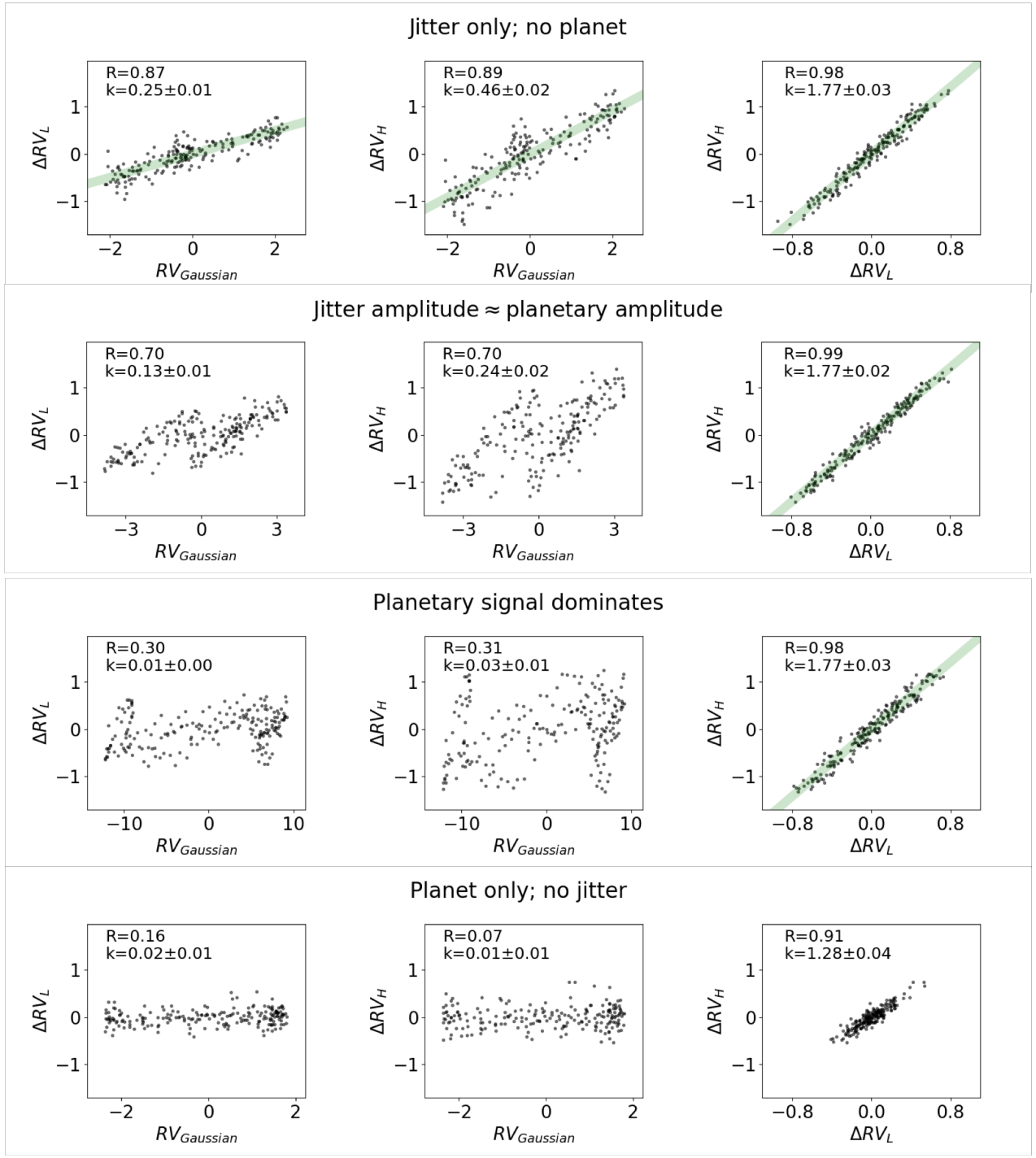
Application
Periodogram Analysis

- Stellar jitter: 3 spots
- Input ν_{orb} = 0.7 ν_{rot}
- CCF S/N = 2,000 (SNR ~ 50/pixel)



Application Classifications

- Jitter amplitude ≈ 2 m/s
- RV_{Planet} amplitude = 0, 2, 10 m/s
- CCF S/N = 10,000

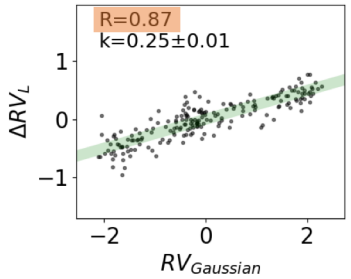


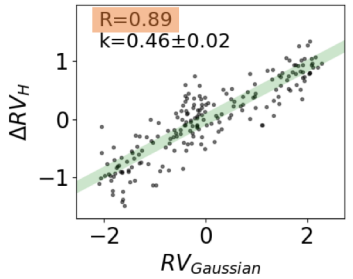
Application Classifications

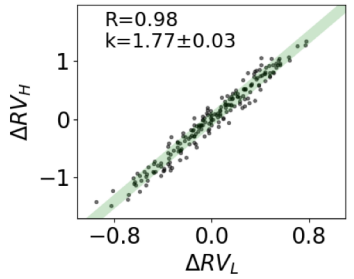
- Jitter amplitude ≈ 2 m/s
- RV_{Planet} amplitude = 0, 2, 10 m/s
- CCF S/N = 10,000

Strong correlation

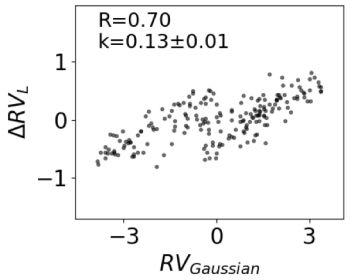
Jitter only; no planet

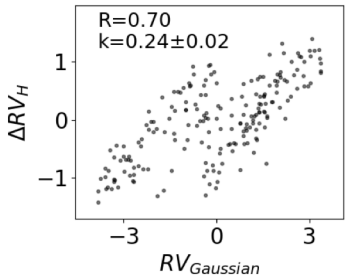


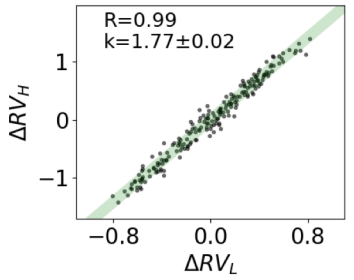




Jitter amplitude ≈ planetary amplitude

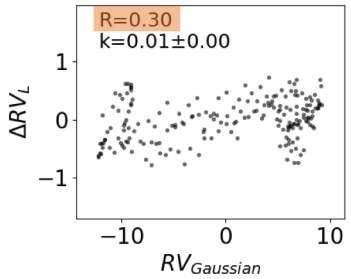


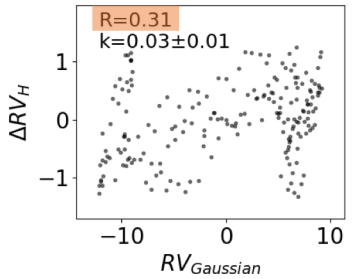


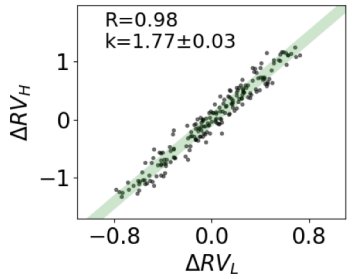


Weak correlation

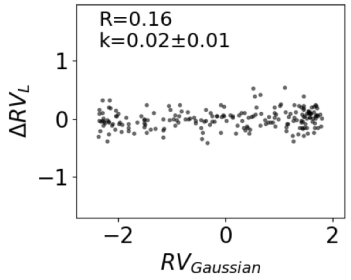
Planetary signal dominates

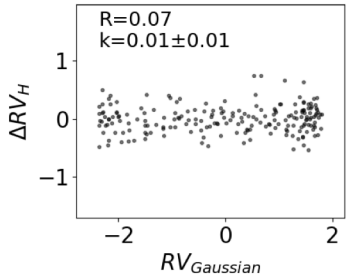


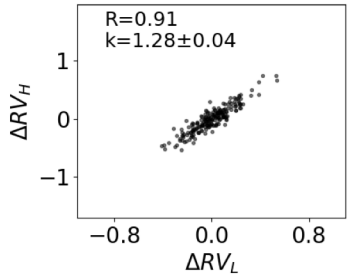




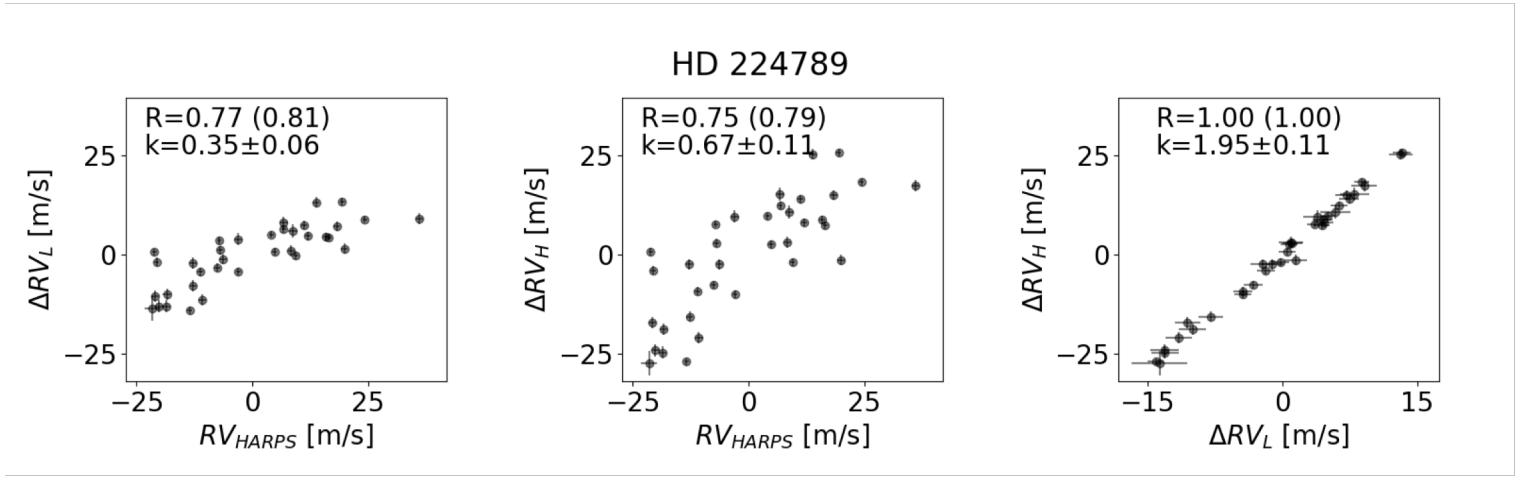
Planet only; no jitter







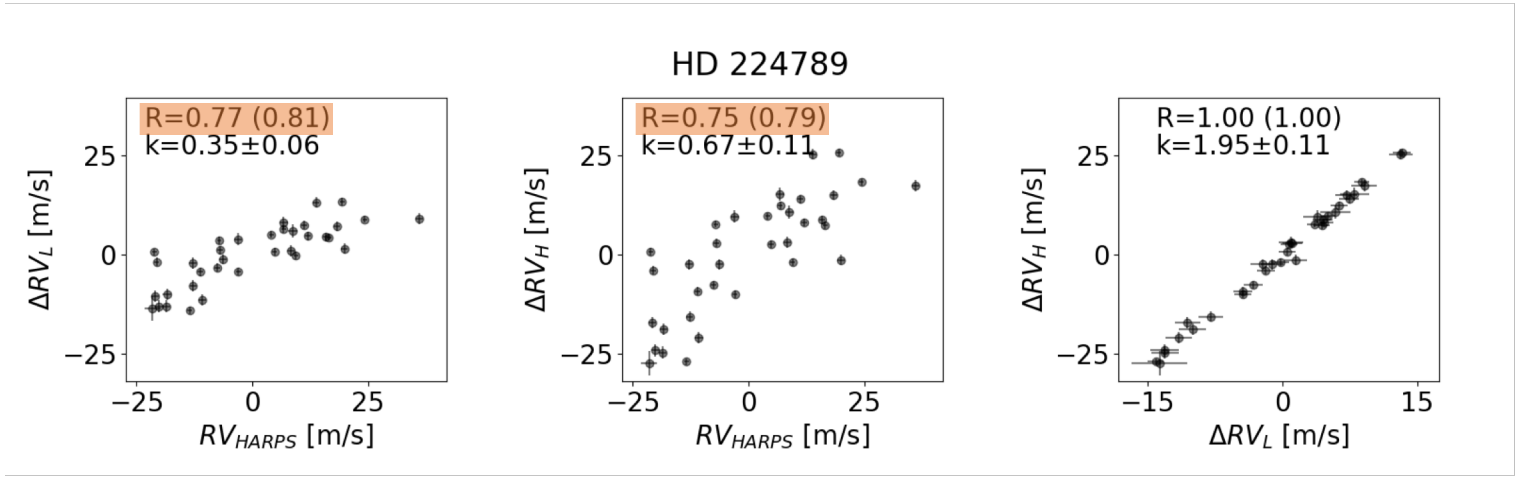
ΦESTA on HARPS *An Active Star*



- Log R'_{HK} = -4.46 (Figueira et al. 2013)
- Jitter amplitude ~ 30 m/s
- CCF S/N ~ 4000; HARPS SNR = 106/pixel
- Median RV_{noise} = 0.63 m/s

ΦESTA on HARPS *An Active Star*

Strong correlation due to stellar jitter



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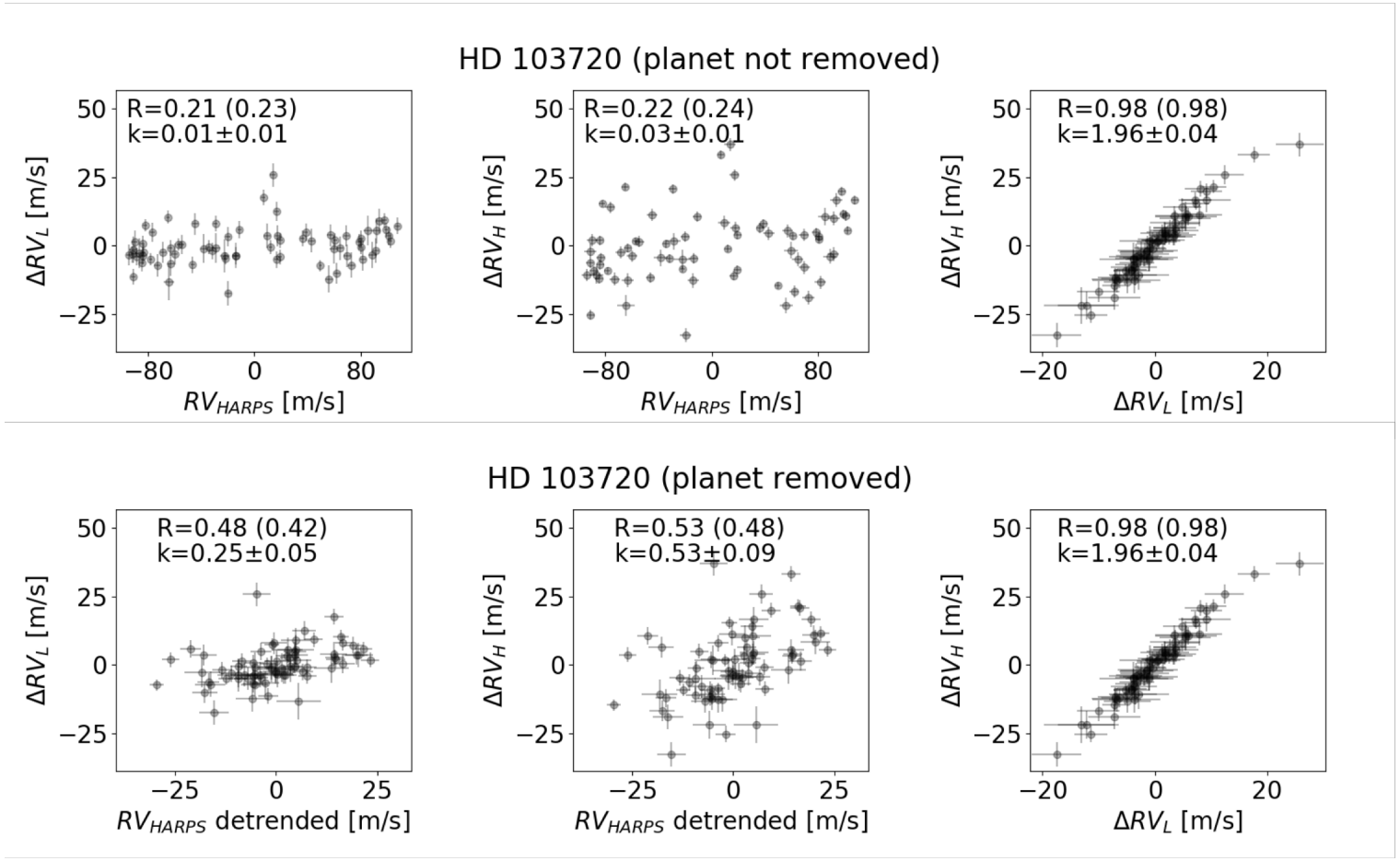
ΦESTA on HARPS *An Active Planet-host Star*

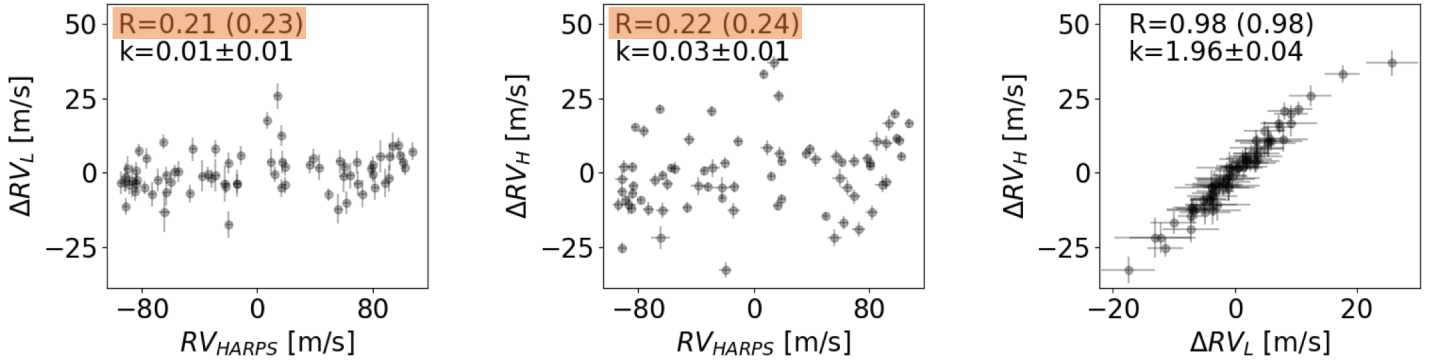


- Log R'$_{HK}$ = -4.46 (Figueira et al. 2013)
- Planetary orbital amplitude ~ 80 m/s; jitter amplitude ~ 9 m/s (Moutou et al. 2015)
- CCF S/N ~ 1400; HARPS SNR = 35/pixel
- Median RV$_{noise}$ = 2 m/s

ΦESTA on HARPS *An Active Planet-host Star*

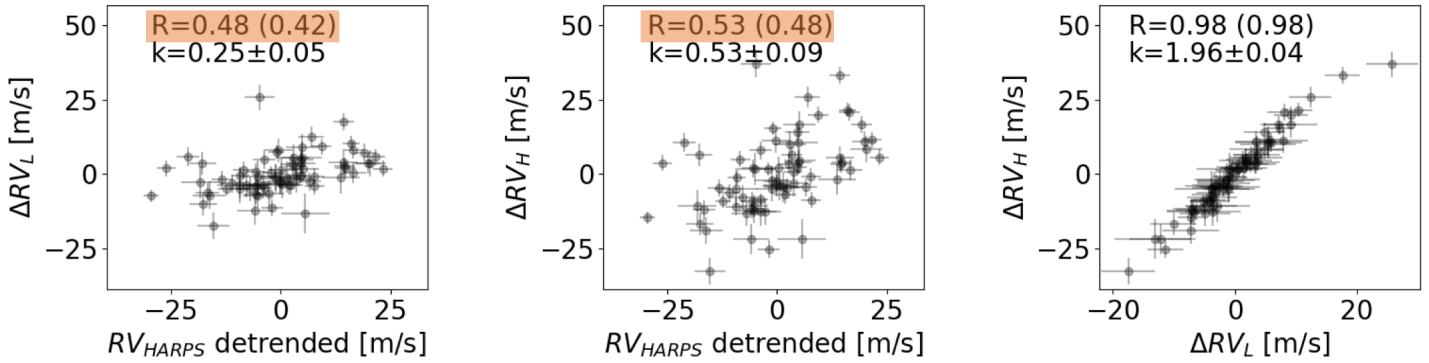
Weak correlation

HD 103720 (planet not removed)



Moderate correlation

HD 103720 (planet removed)



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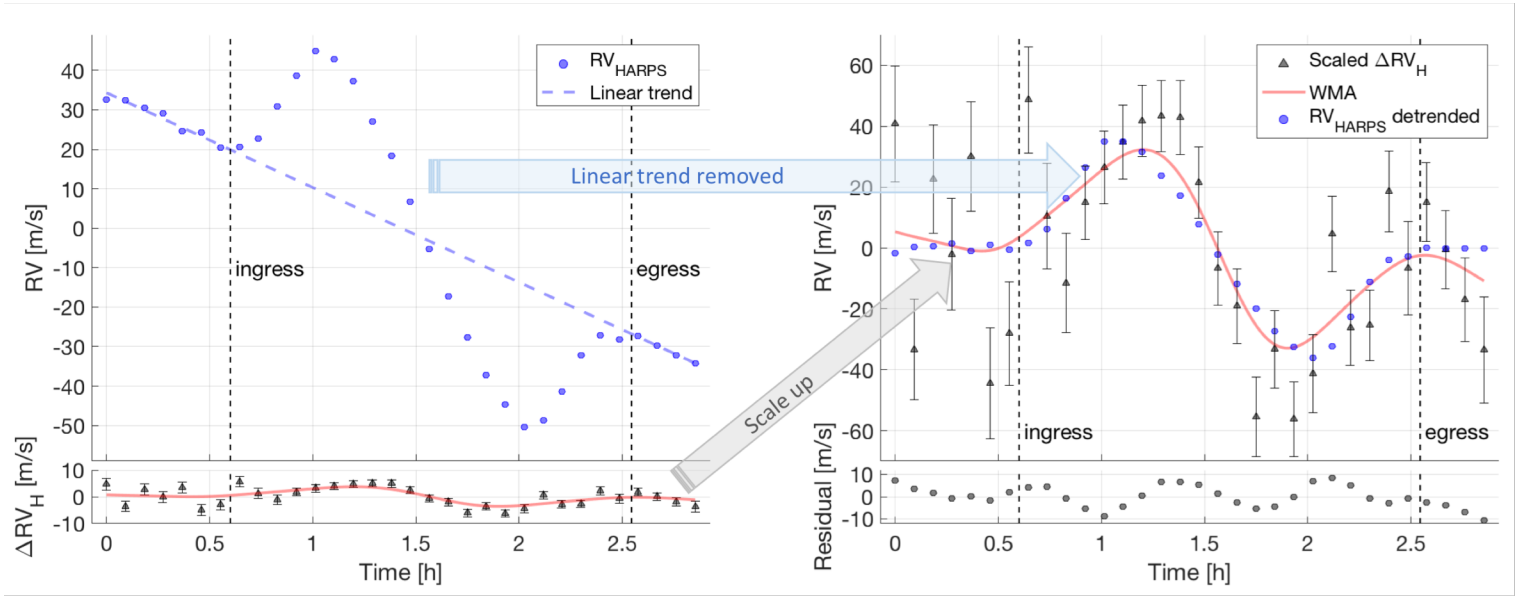
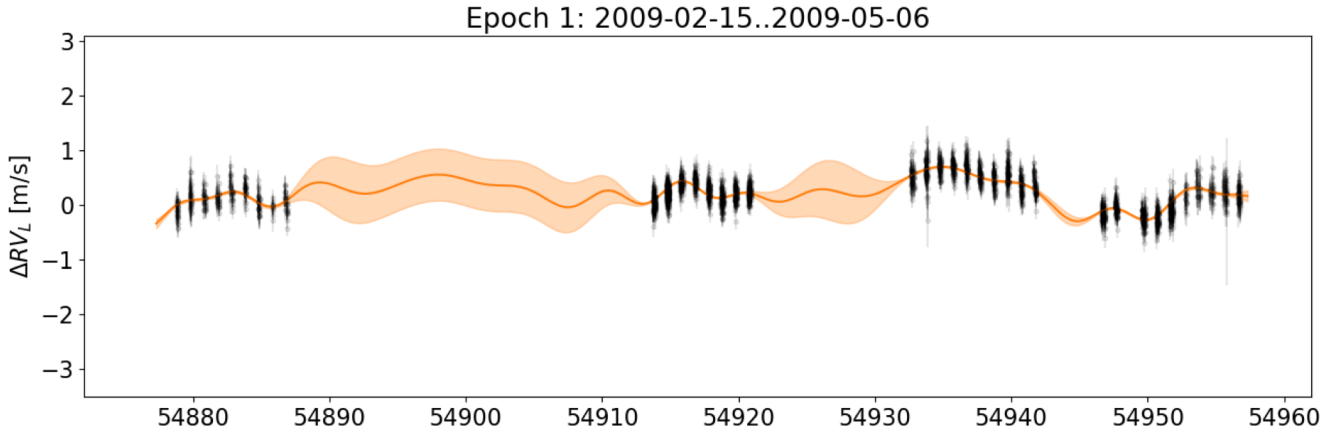
- Median RV_{noise} = 2 m/s

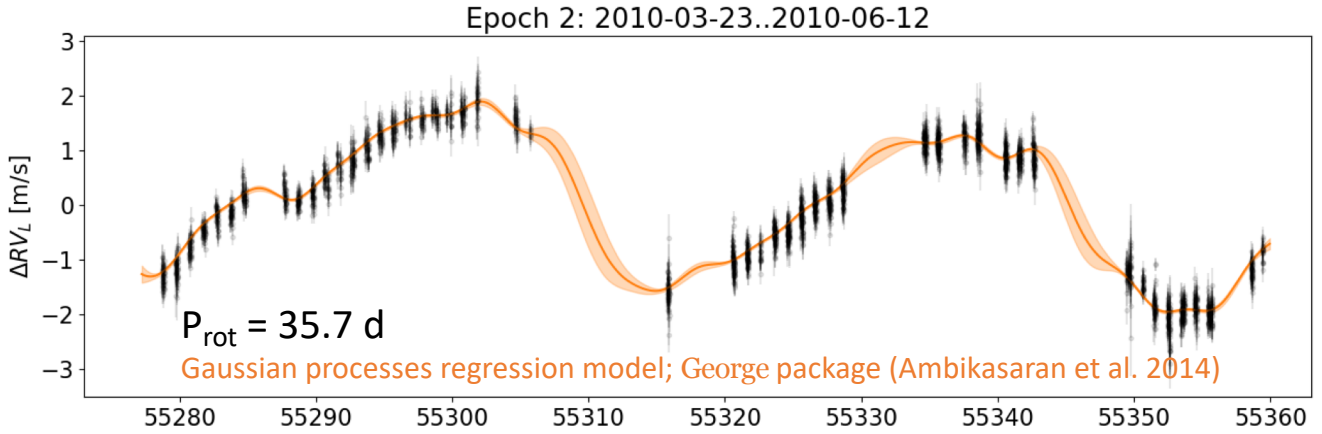
ΦESTA on HARPS *Rossiter-McLaughlin effect*

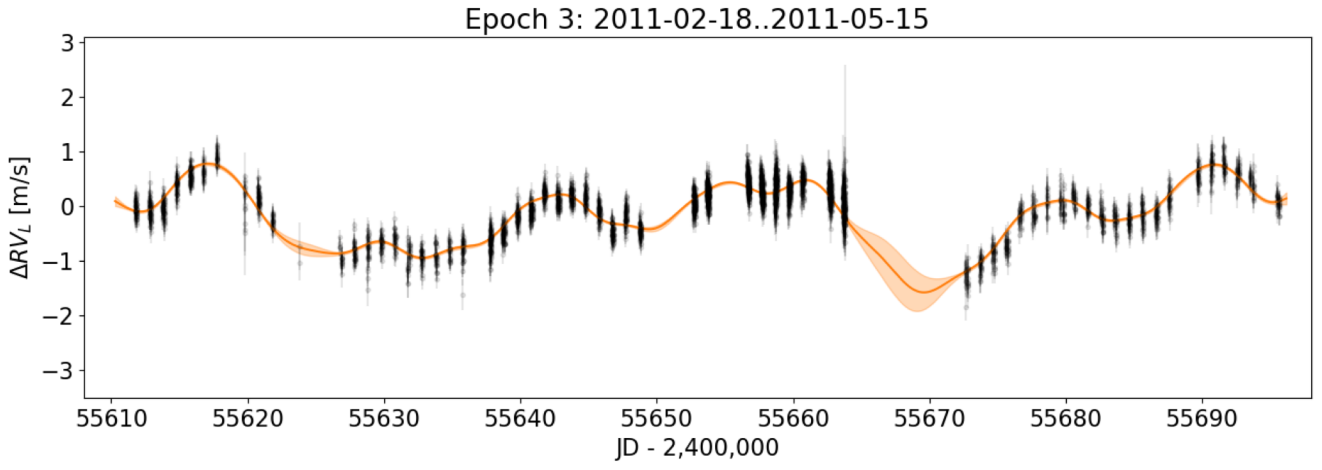


- Linear trend: binary (HD 189733 B) + exoplanet (HD 189733 b)
- Rossiter-McLaughlin velocity anomaly amplitude ~ 40 m/s
- ΦESTA jitter model constructed with ΔRV_H
- Residual amplitude ~ 10 m/s

ΦESTA on HARPS
α Centauri B

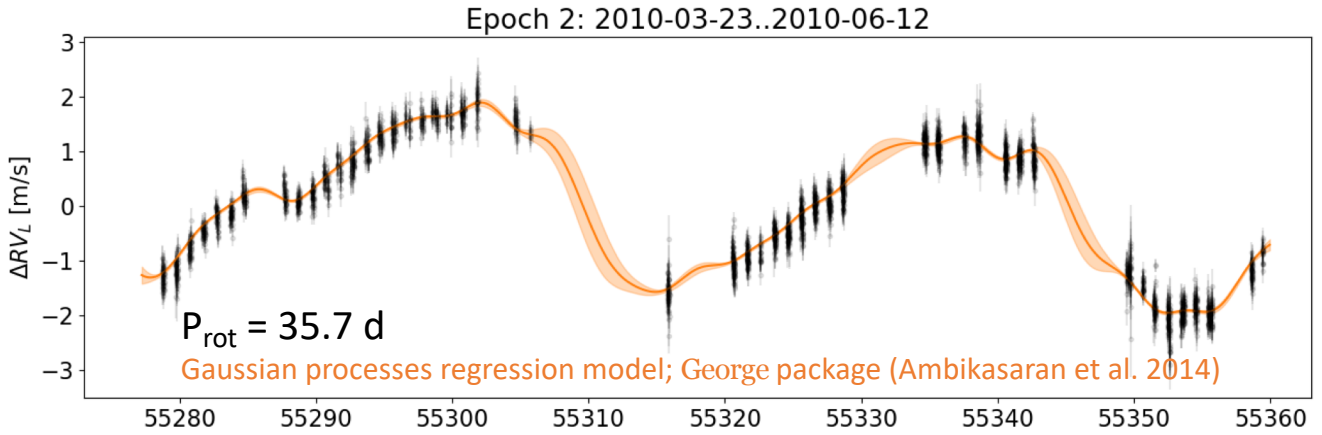






The ΔRV_L in this slide was computed using an older version of ΦESTA; the scale can be slightly different but the trends of jitter metrics remain consistent with the latest version.

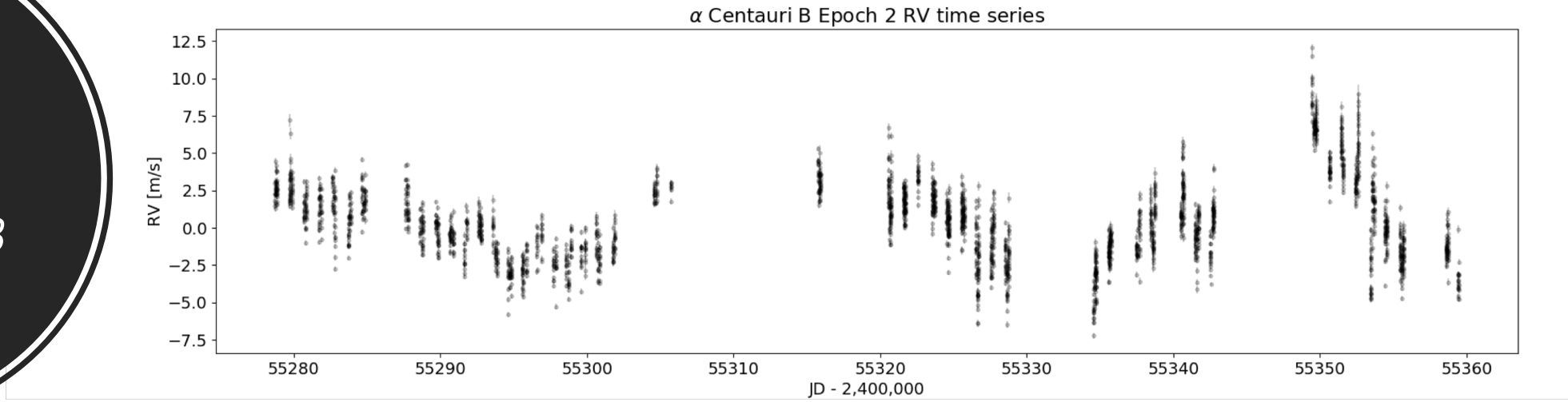
ΦESTA on HARPS
α Centauri B



- > 2400 observations
- CCF S/N ~ 10,000; HARPS SNR = 250/pixel
- Median RV_{noise} = 0.2 m/s

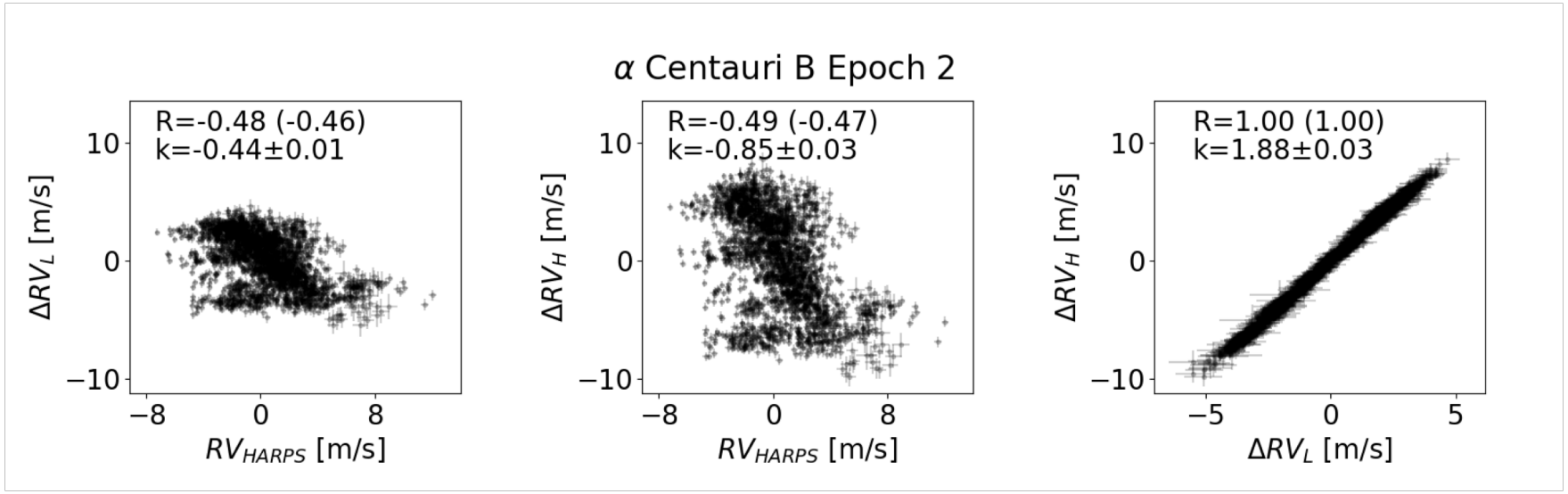
The ΔRV_L in this slide was computed using an older version of ΦESTA; the scale can be slightly different but the trends of jitter metrics remain consistent with the latest version.

ΦESTA on HARPS
α Centauri B



- Binary removed (2nd order polynomial, Dumusque et al. 2012)
- Linear trend corrected

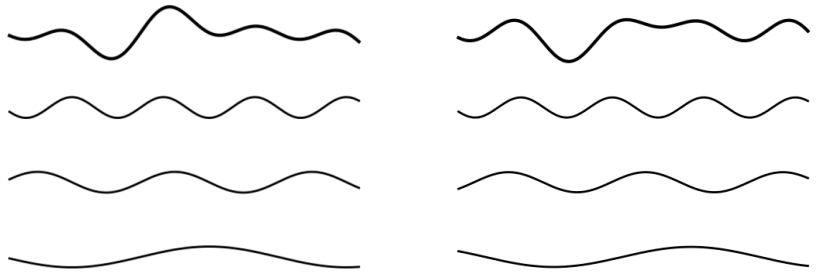
ΦESTA on HARPS
α Centauri B



- Planet candidate orbiting α Centauri B?
- Binary not corrected removed / systematics?
- Correlation between ΦESTA jitter metrics and stellar jitter can be non-linear?

Summary

- ΦESTA measurement of line deformation $x_0(\xi)$
  - $RV_{FT,\,L} = k_L\, RV_{jitter}$ $(k_L < 1)$
  - $RV_{FT,\,H} = k_H RV_{jitter}$ $(k_H > 1)$

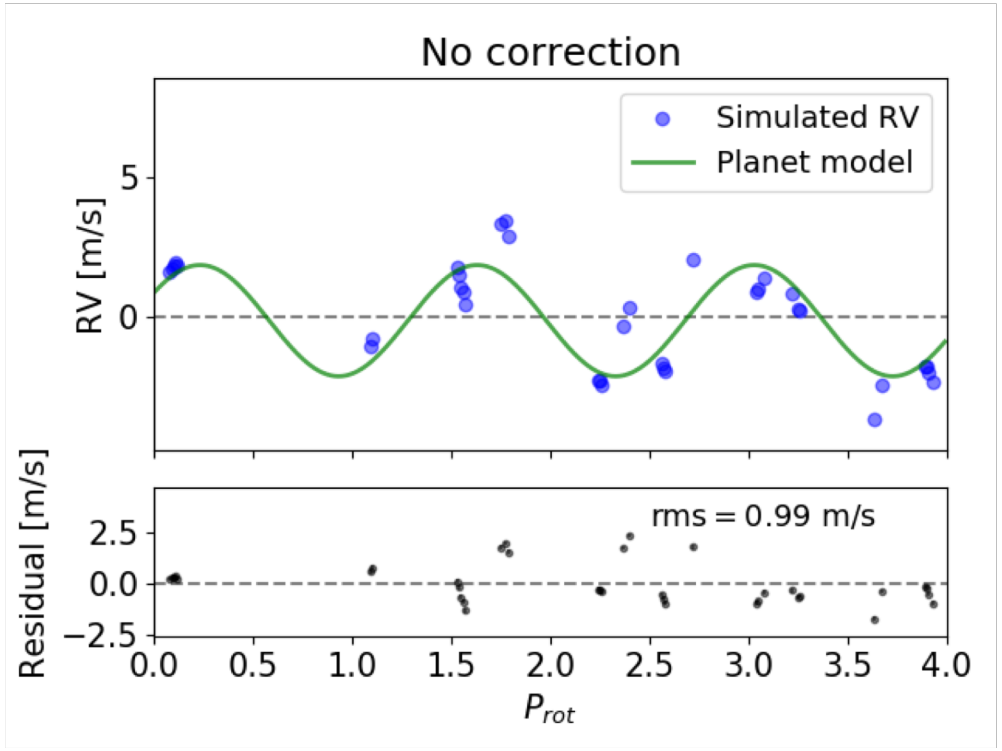


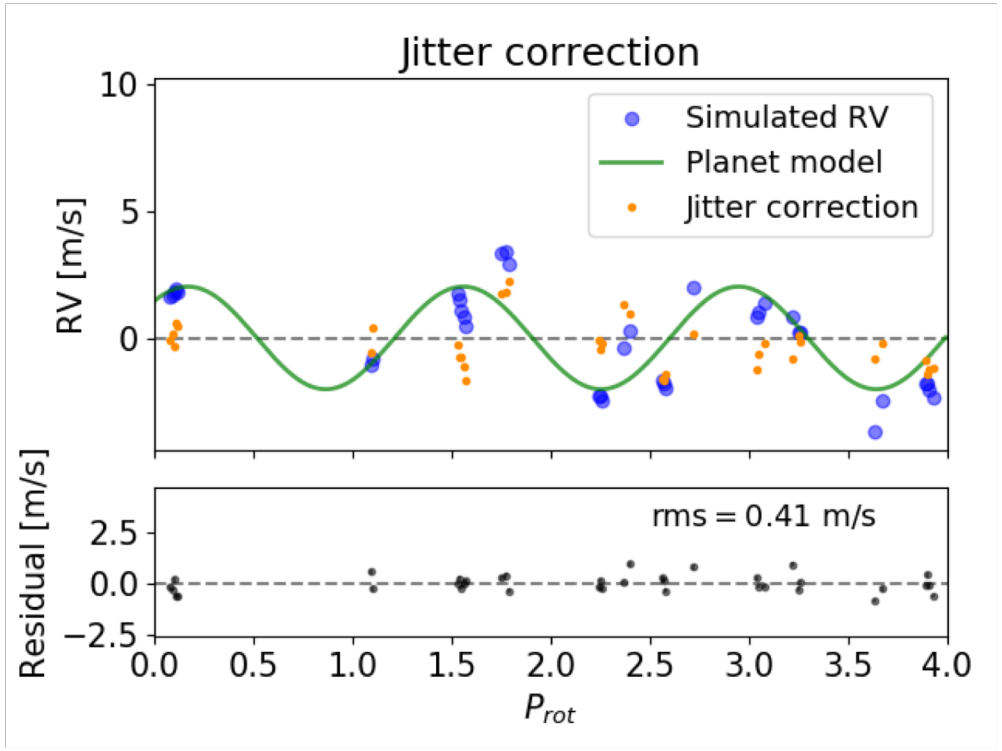
- ΦESTA jitter metrics
  - $\Delta RV_L = RV_{Gaussian} - RV_{FT,\,L} \propto (1/4)\, RV_{jitter}$
  - $\Delta RV_H = RV_{FT,\,H} - RV_{Gaussian} \propto (1/2)\, RV_{jitter}$

- Application
  - Periodogram analysis (activity indicator)
  - Classifications (linearity)
    - Active star (HD 224789)
    - Active planet-host star (HD 103720)
    - Rossiter-McLaughlin effect (HD 189733)
    - α Centauri B – remain unsolved

- Collaborations?
- Postdoc positions?
- jinglin.zhao1@unsw.edu.au

Supplementary Material



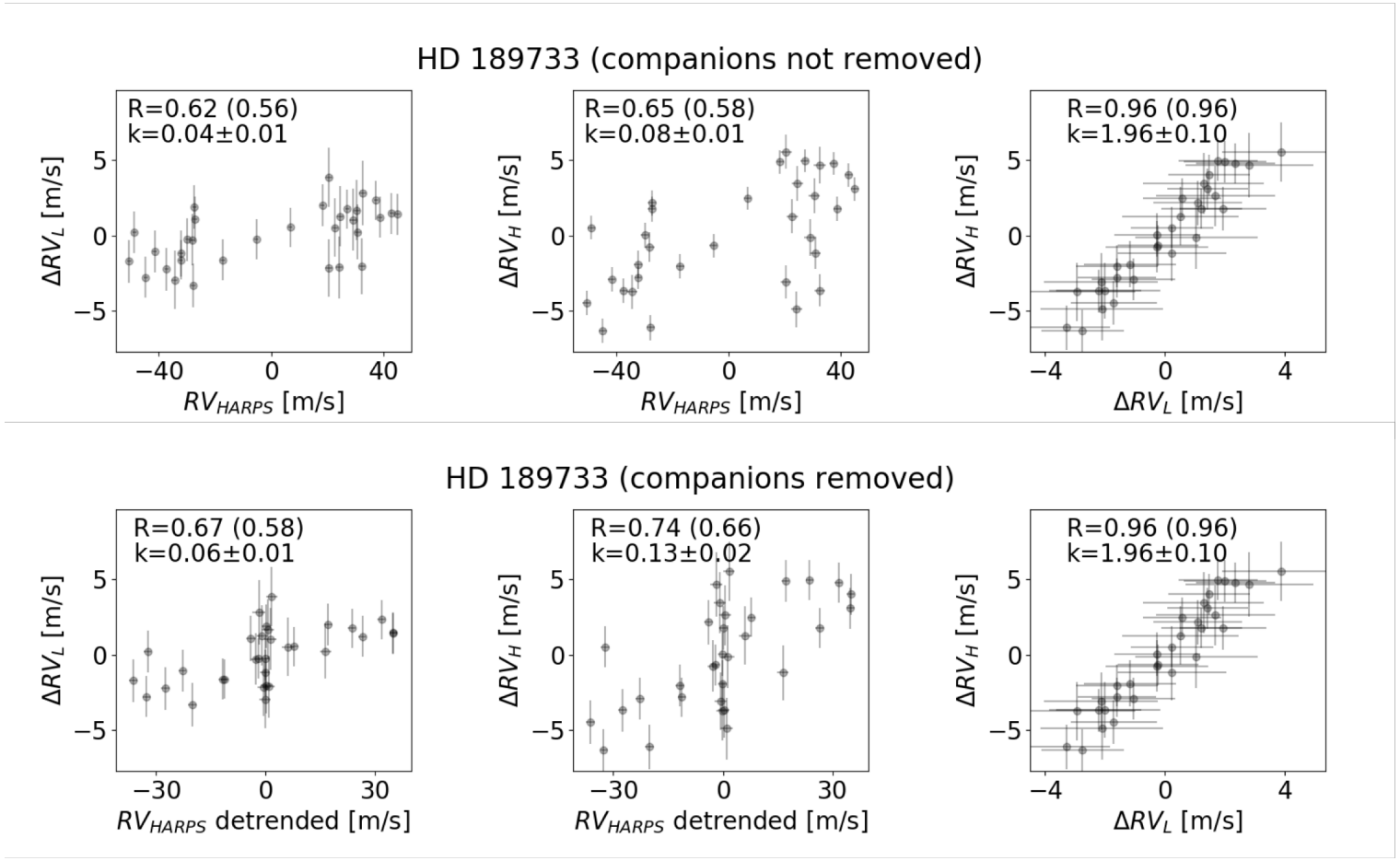


Jitter Correction

RV = ØESTA jitter Model + Keplerian Orbits

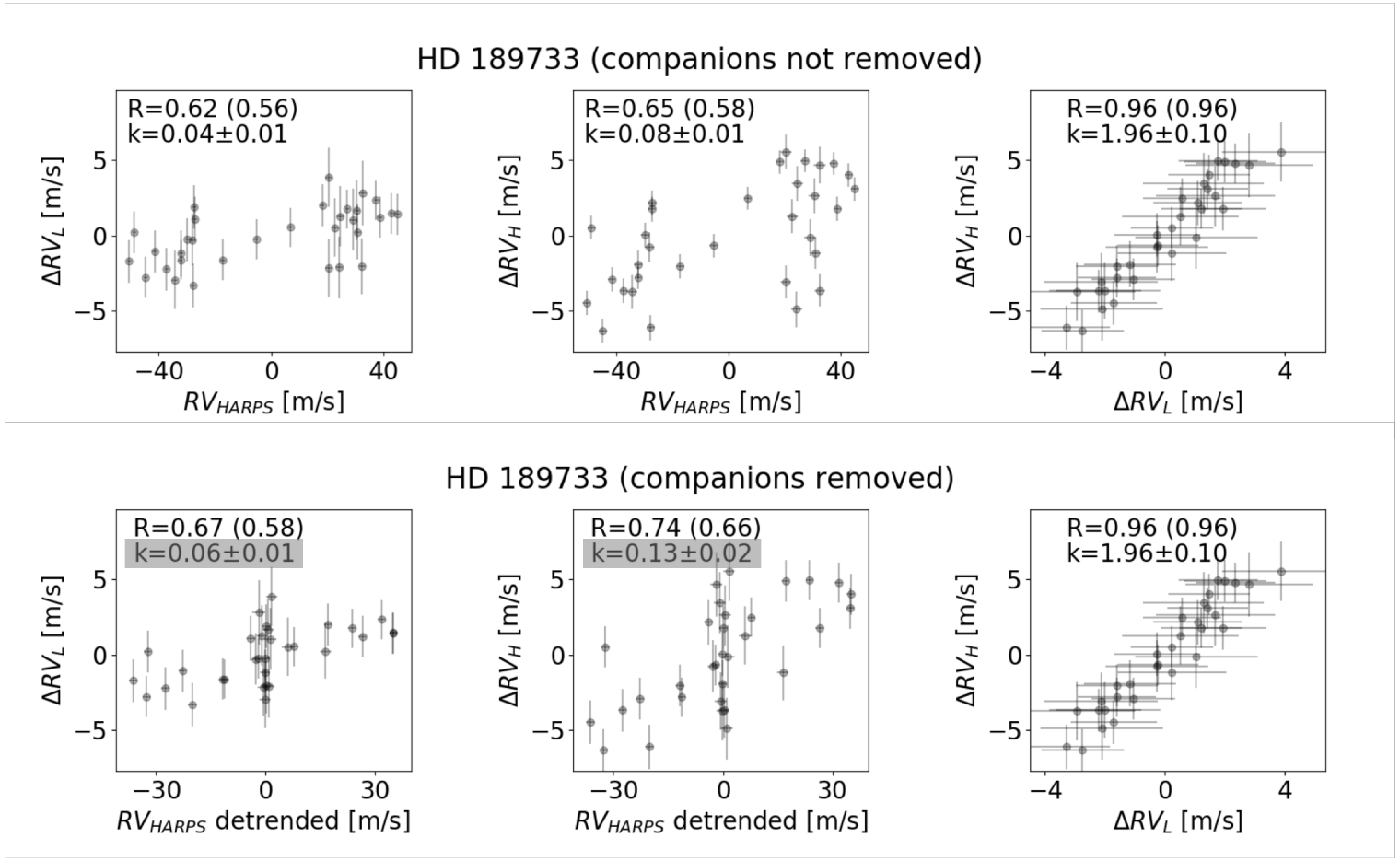
Triples the percentage of planets recovered to within 10% of input orbital parameters (Zhao & Tinney, submitted).

ΦESTA on HARPS *Rossiter-McLaughlin effect*



- CCF S/N ~ 2600; HARPS SNR = 85/pixel
- Median RV_{noise} = 0.83 m/s

ΦESTA on HARPS *Rossiter-McLaughlin effect*



- k underrepresented
- k dependency on spot temperature (Zhao & Tinney, submitted)