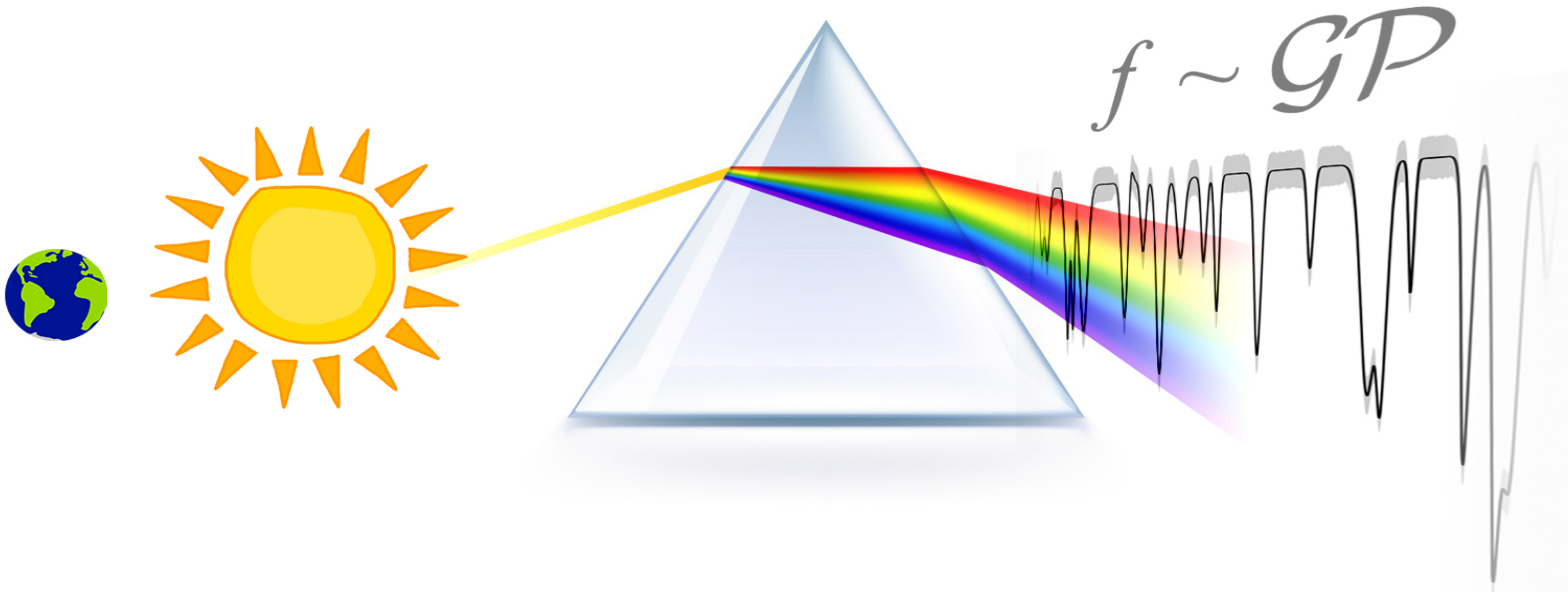
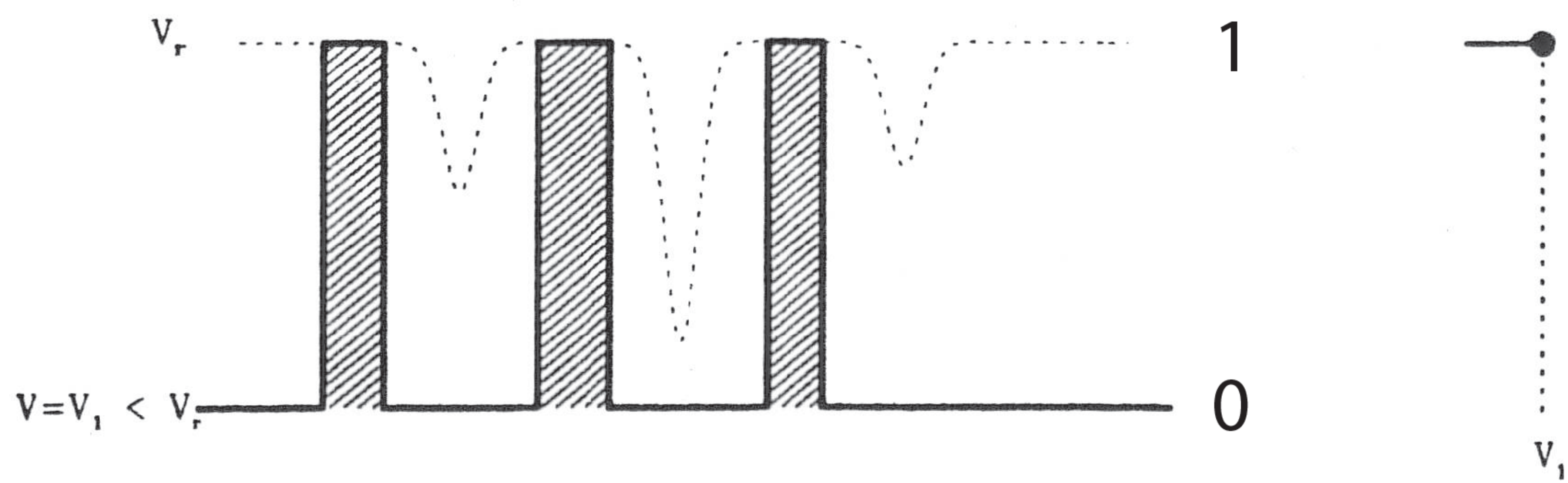
A simple approach to robust & ultra-precise RVs

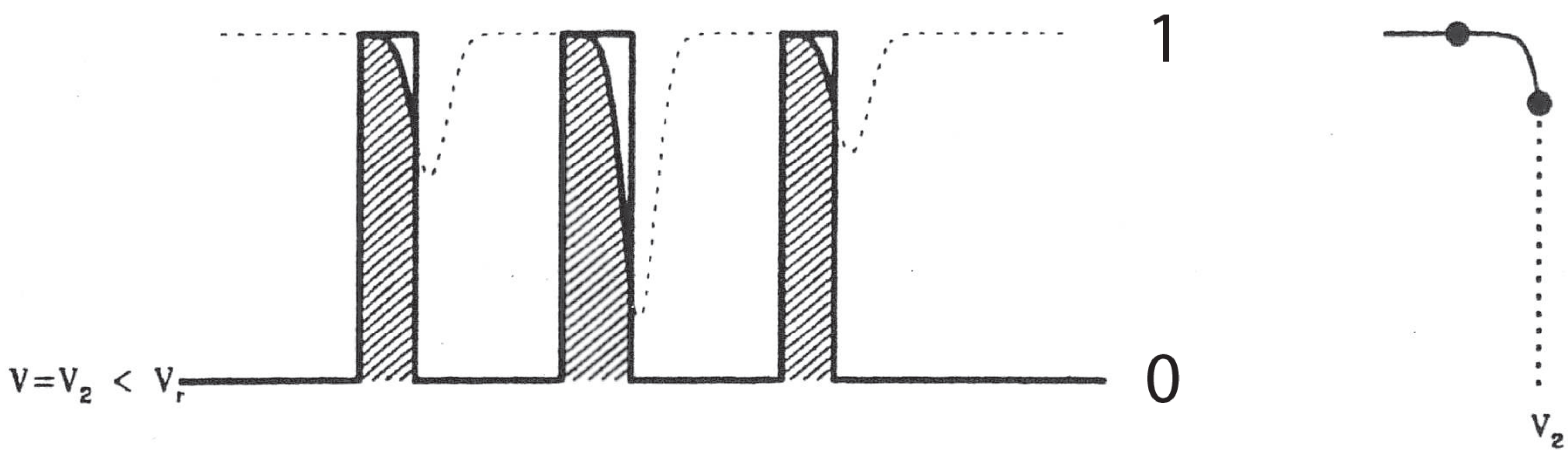
Vinesh Maguire-Rajpaul,
Suzanne Aigrain, Lars A. Buchhave



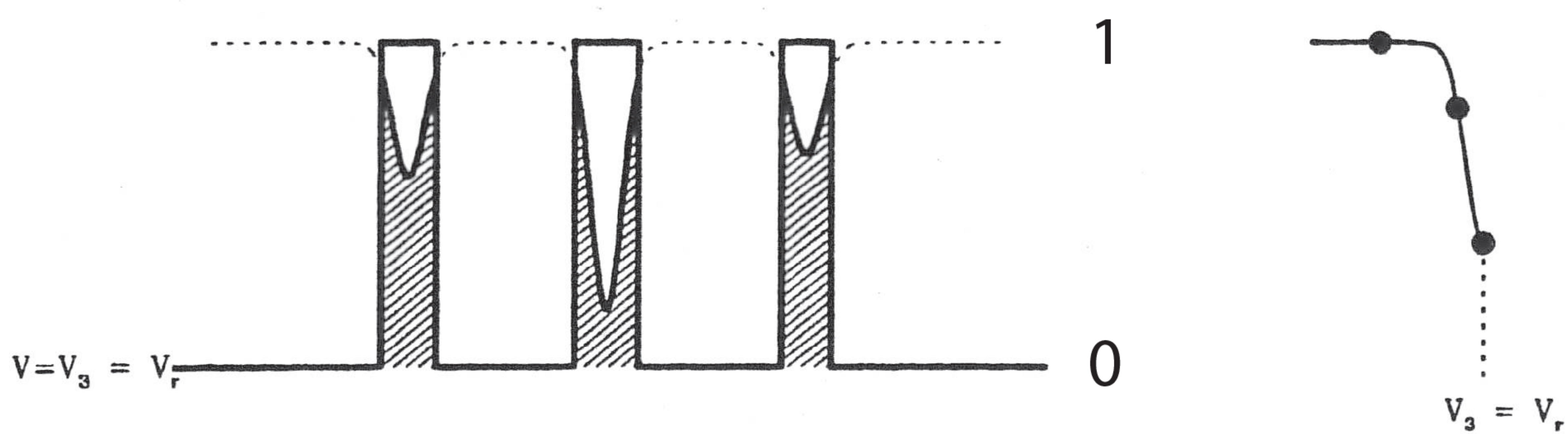
UNIVERSITY OF CAMBRIDGE
Cavendish Laboratory



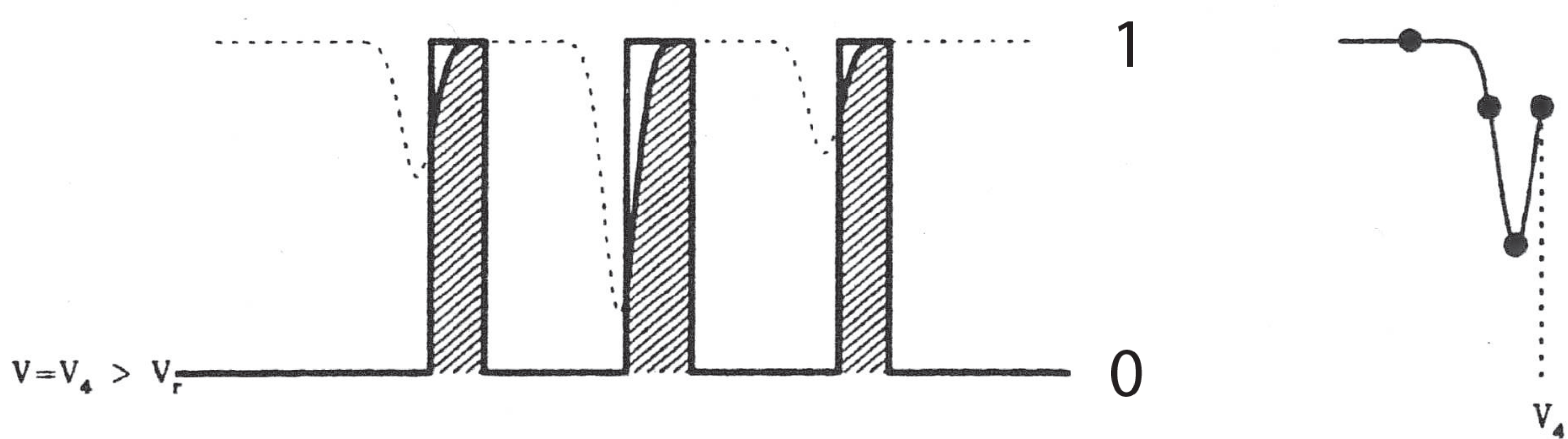
(from Melo 2001, PhD thesis)



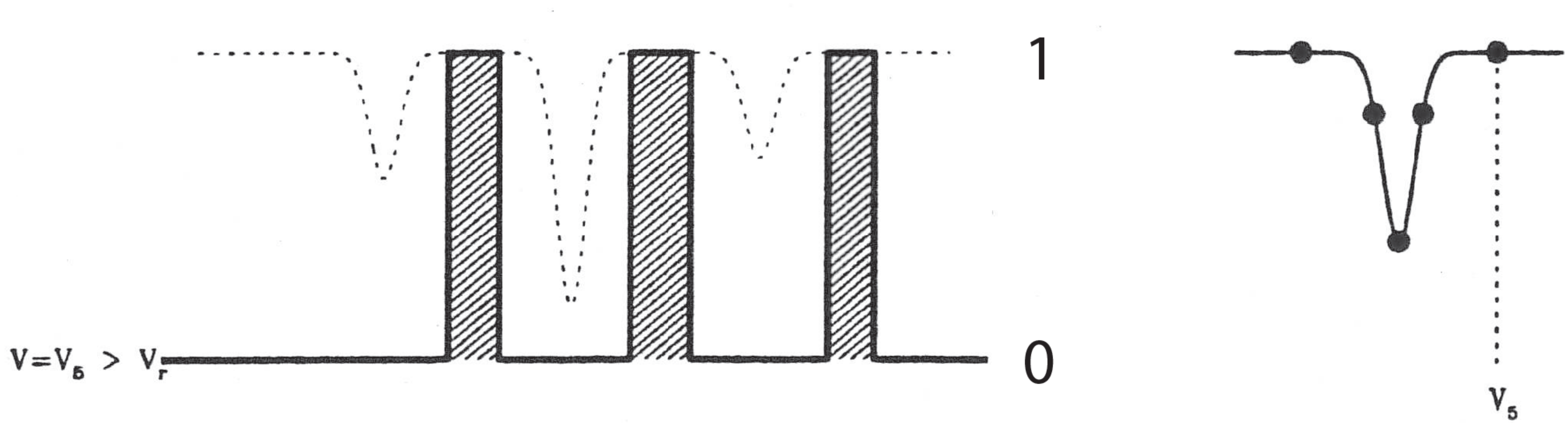
(from Melo 2001, PhD thesis)



(from Melo 2001, PhD thesis)



(from Melo 2001, PhD thesis)



(from Melo 2001, PhD thesis)

Traditional RV extraction

Traditional RV extraction

1. Imperfect templates

Traditional RV extraction

1. Imperfect templates
2. RV information lost (masking)

Traditional RV extraction

1. Imperfect templates
2. RV information lost (masking)
3. Tellurics? Activity?

Traditional RV extraction

1. Imperfect templates
2. RV information lost (masking)
3. Tellurics? Activity?
4. Wavelength covariance structure ignored

Traditional RV extraction

1. Imperfect templates
2. RV information lost (masking)
3. Tellurics? Activity?
4. Wavelength covariance structure ignored
5. Acquiring more spectra does not help

Traditional RV extraction

1. Imperfect templates
2. RV information lost (masking)
3. Tellurics? Activity?
4. Wavelength covariance structure ignored
5. Acquiring more spectra does not help
6. Complicated and/or opaque pipelines

A simple solution

A simple solution

A simple solution

Given N spectra…

A simple solution

Given *N* spectra…

1. Model every spectrum with a GP

A simple solution

Given N spectra…

1. Model every spectrum with a GP

2. Align all ~ N^2 pairs of GP spectra

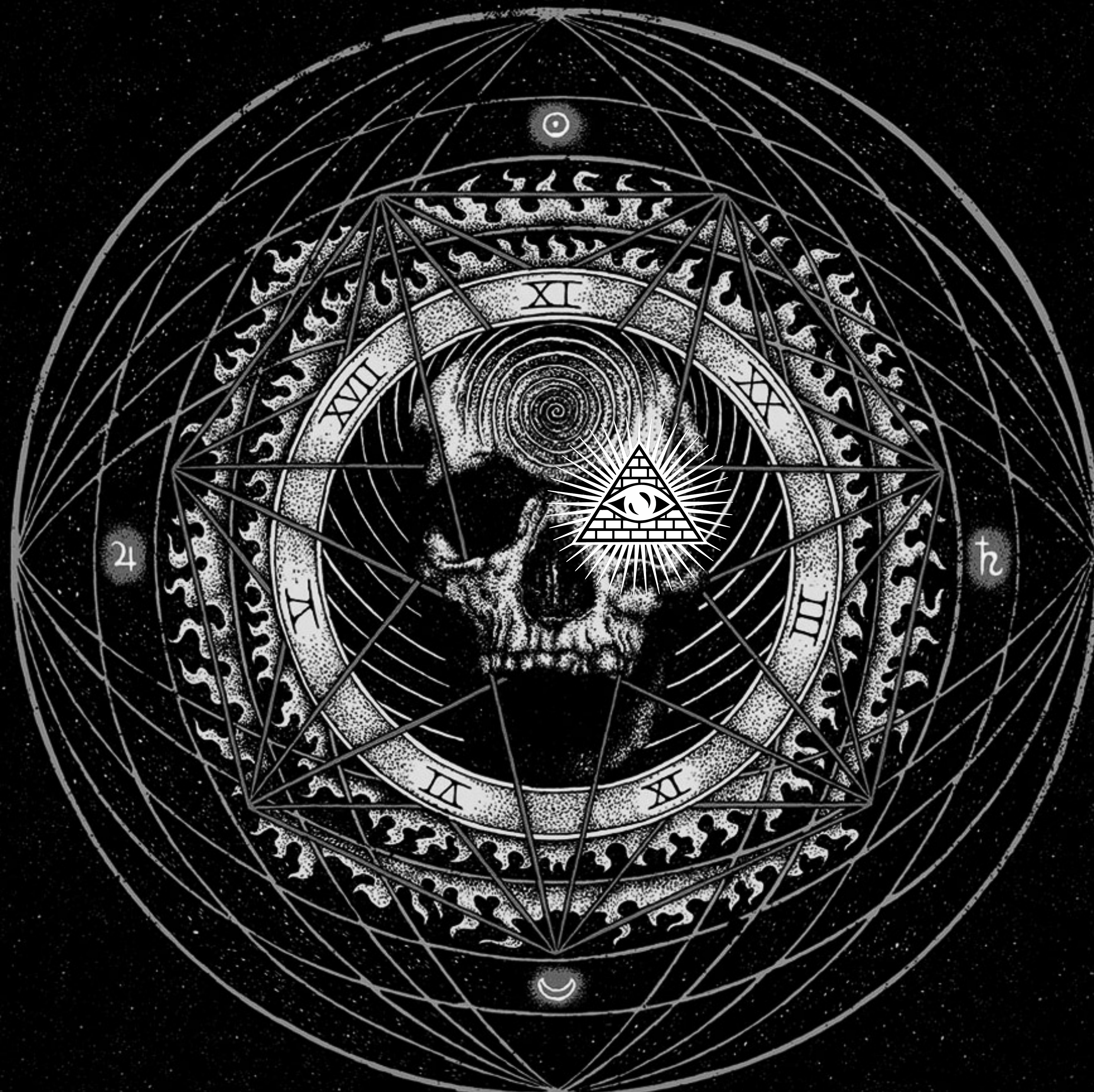
A simple solution

Given *N* spectra…

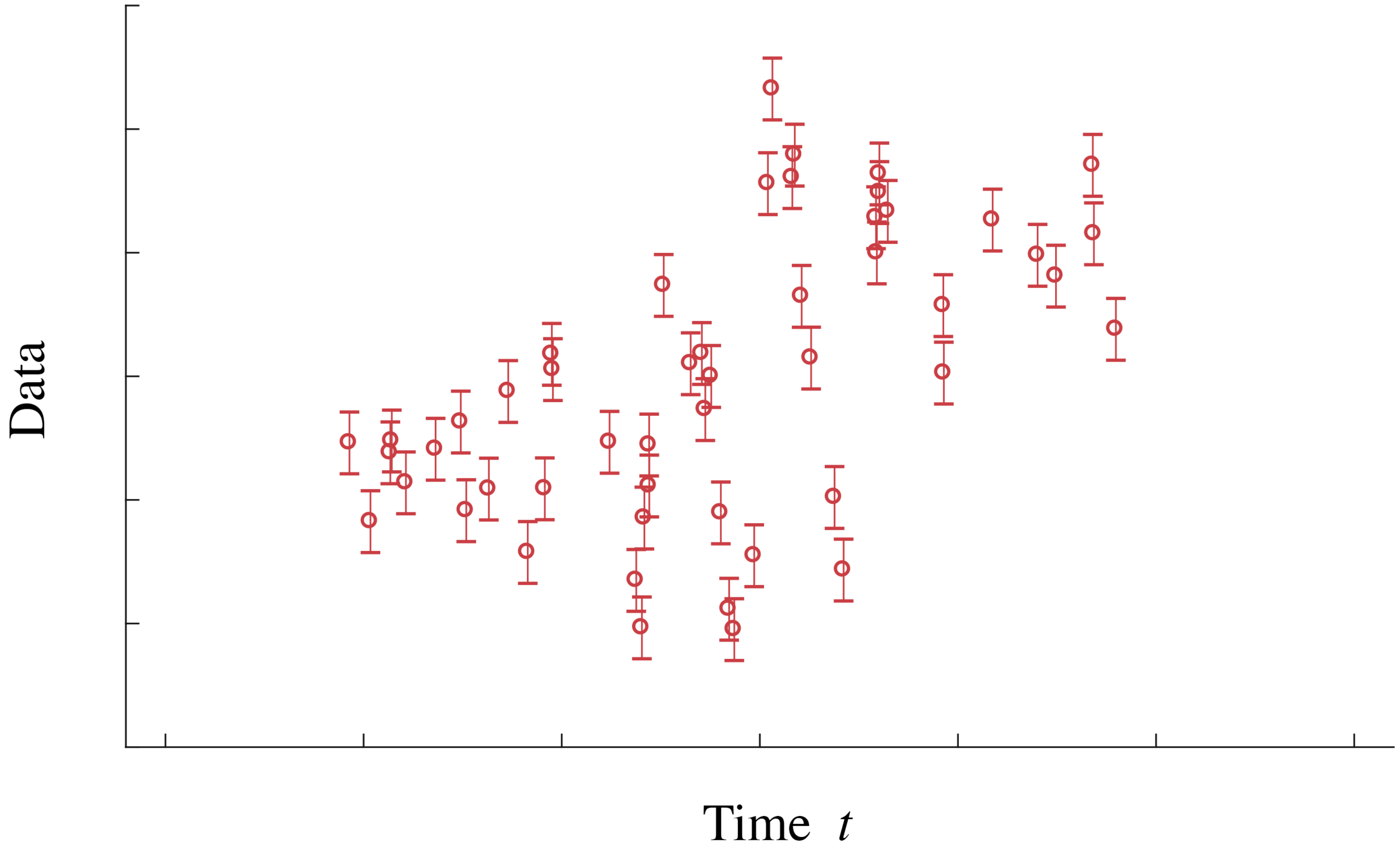
1. Model every spectrum with a GP
2. Align all ~ N^2 pairs of GP spectra
3. Put it all together → *N* differential RVs

Why GPs?

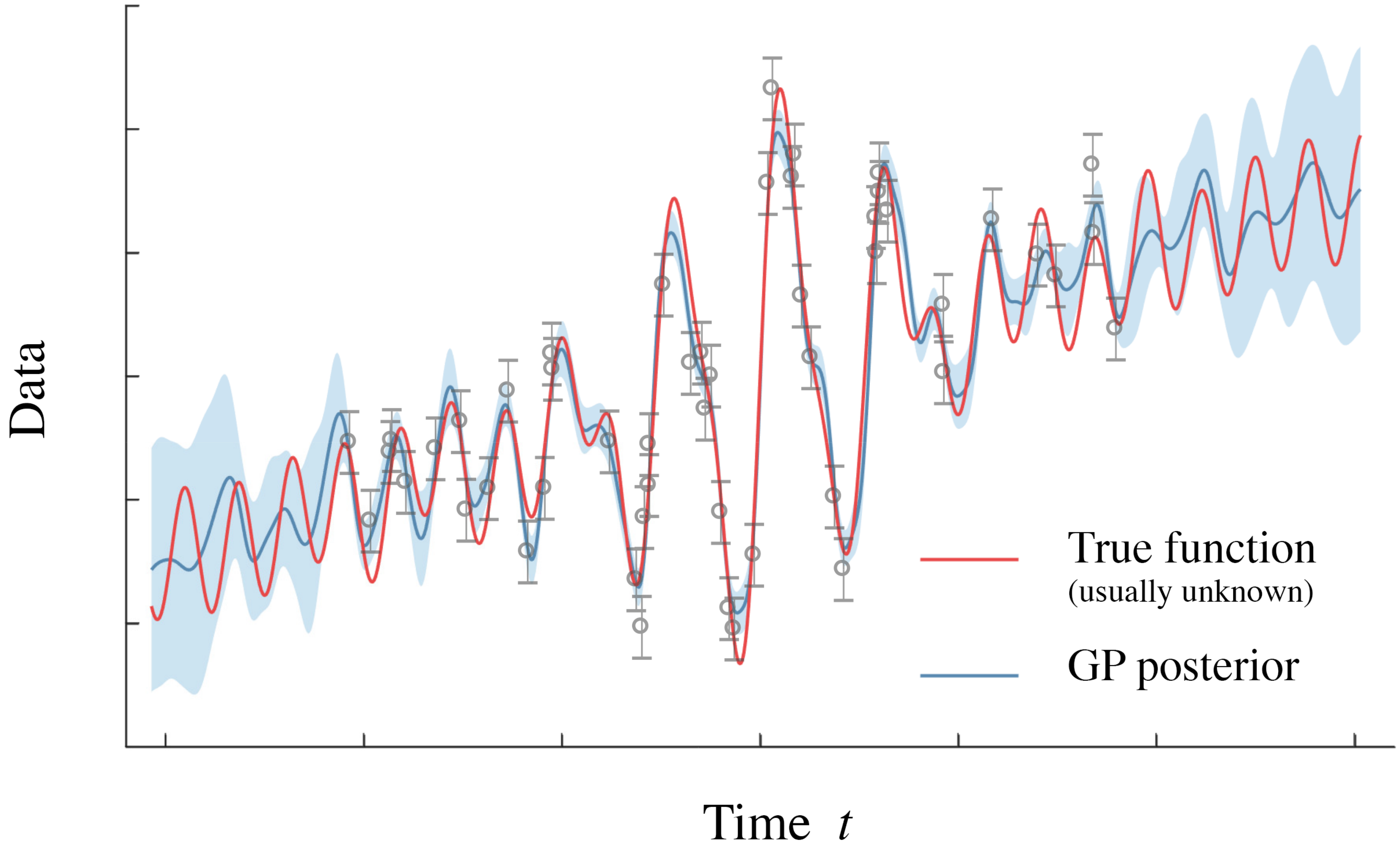

XI
XVII
XX


XI
XVII
XX

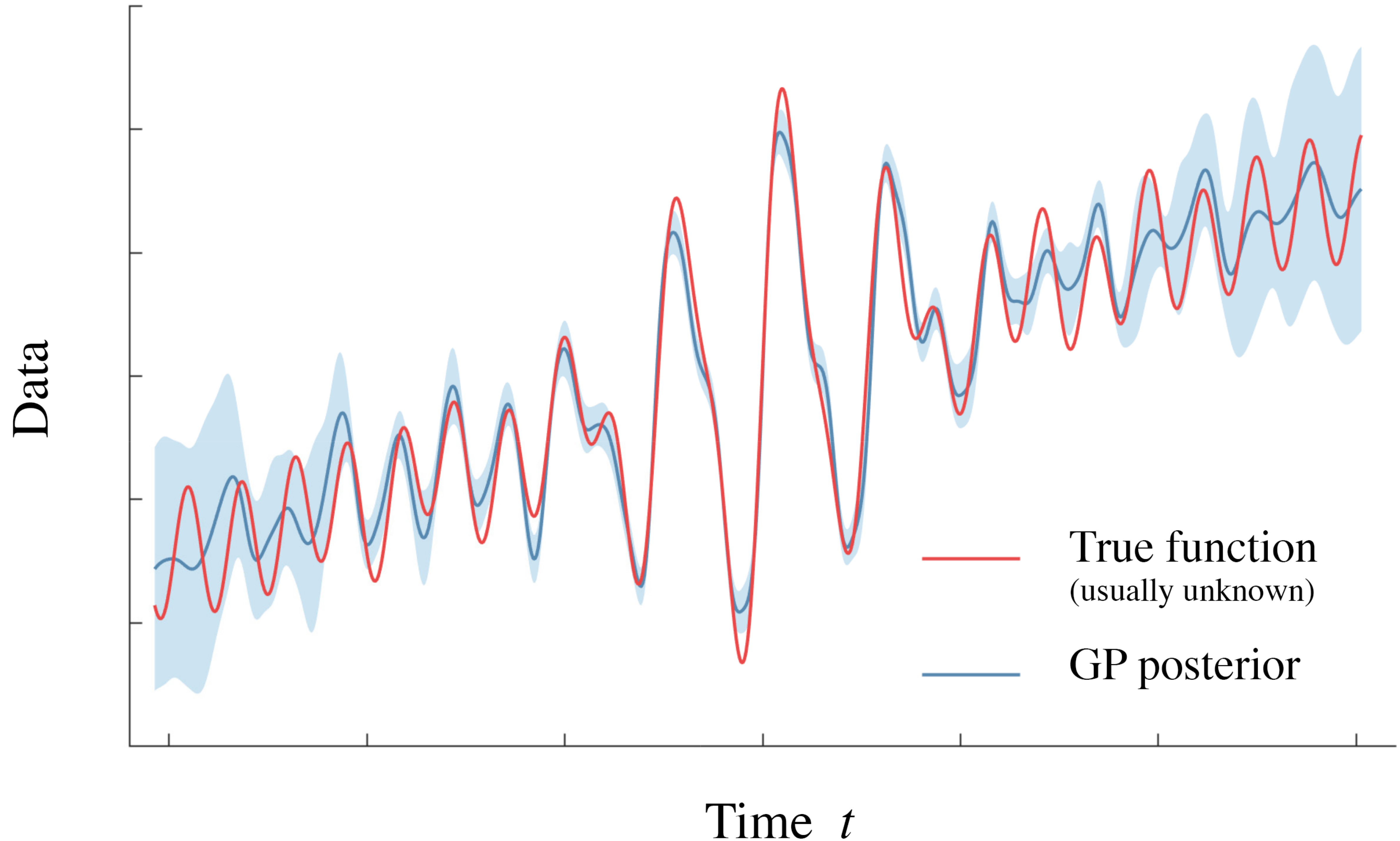
Why GPs?



Why GPs?



Why GPs?



Why GPs?

Why GPs?

- **Non-parametric**; no atomic/stellar astrophysics needed

Why GPs?

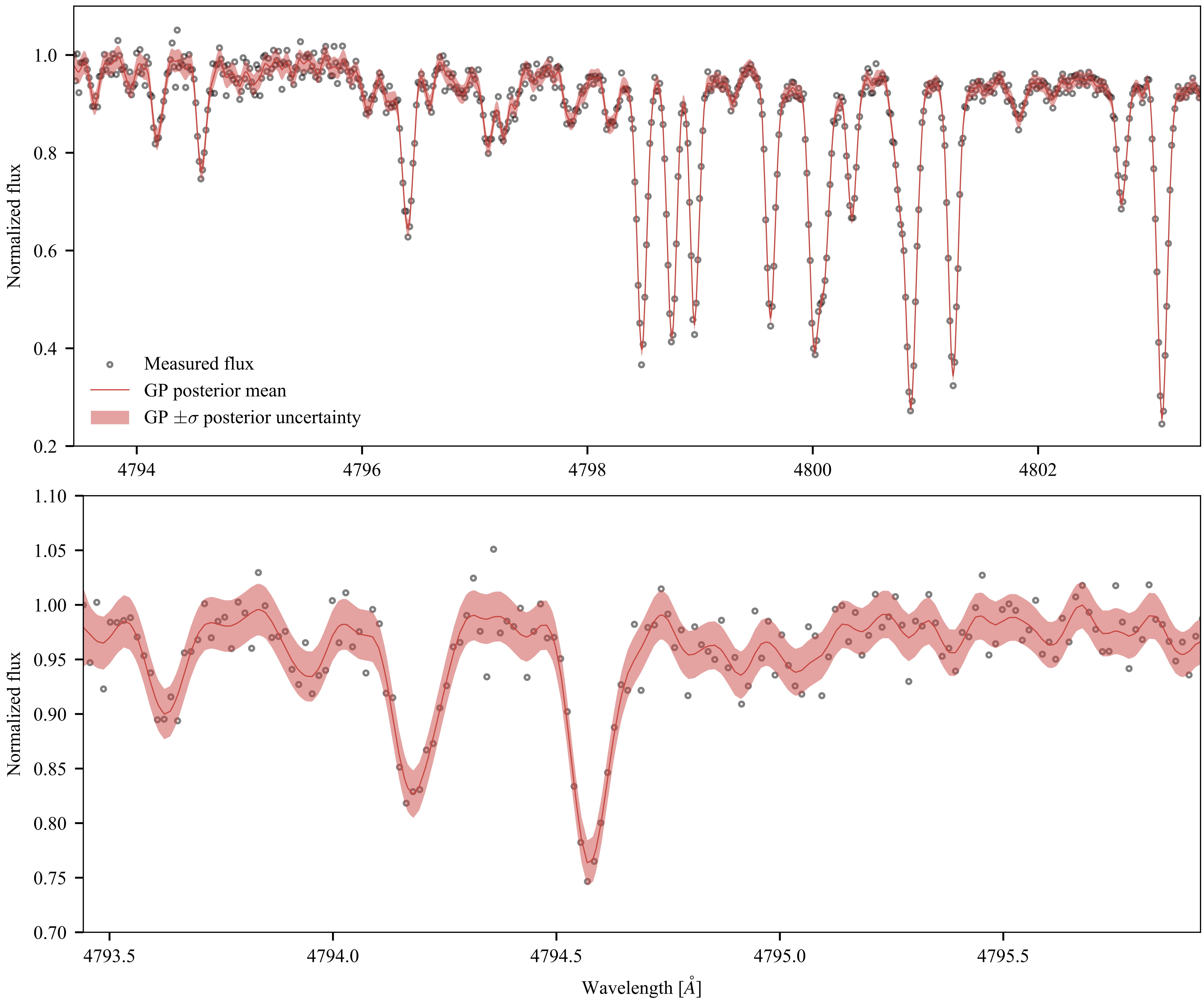
- **Non-parametric**; no atomic/stellar astrophysics needed
- **Analytic** resampling, interpolation, cross-correlation, error propagation, etc.

Why GPs?

- **Non-parametric**; no atomic/stellar astrophysics needed
- **Analytic** resampling, interpolation, cross-correlation, error propagation, etc.
- Model **wavelength covariance**

Why GPs?

- **Non-parametric**; no atomic/stellar astrophysics needed
- **Analytic** resampling, interpolation, cross-correlation, error propagation, etc.
- Model **wavelength covariance**
- Model **temporal covariance**: see later



Normalized flux
Measured flux
GP posterior mean
GP ±σ posterior uncertainty
4794
4796
4798
4800
4802
0.2
0.4
0.6
0.8
1.0
Normalized flux
4793.5
4794.0
4794.5
4795.0
4795.5
0.70
0.75
0.80
0.85
0.90
0.95
1.00
1.05
1.10
Wavelength [Å]

Why pairwise RVs?

Why pairwise RVs?

- Simple mathematical proof of equivalence

Why pairwise RVs?

- Simple mathematical proof of equivalence
- Absolute RVs not needed

Why pairwise RVs?

- Simple mathematical proof of equivalence
- Absolute RVs not needed
- **Computationally efficient** vs. aligning everything at once

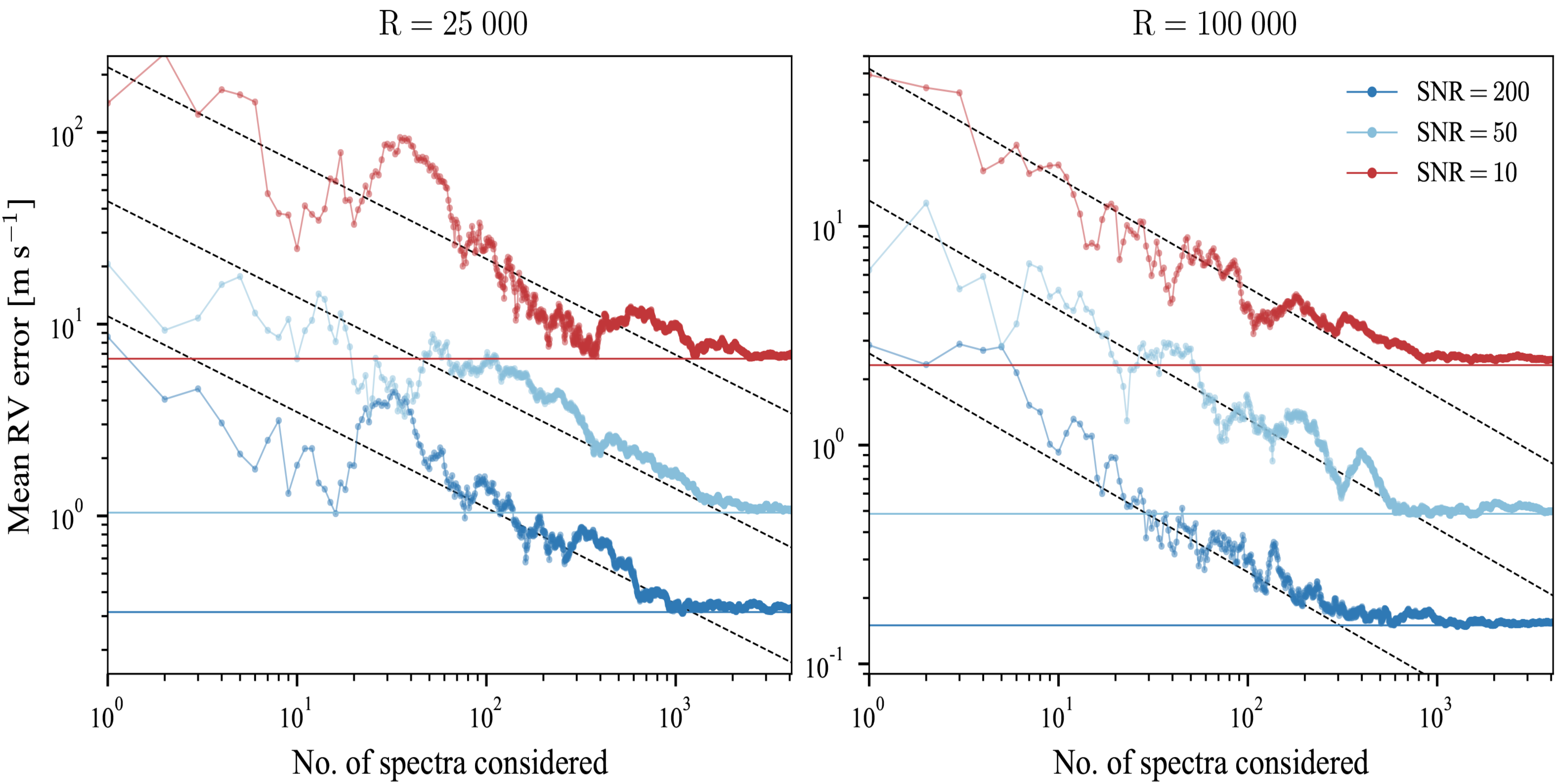
Why pairwise RVs?

- Simple mathematical proof of equivalence
- Absolute RVs not needed
- **Computationally efficient** vs. aligning everything at once
- RV errors decrease as $1/\sqrt{N}$

Why pairwise RVs?

- Simple mathematical proof of equivalence
- Absolute RVs not needed
- **Computationally efficient** vs. aligning everything at once
- RV errors decrease as $1/\sqrt{N}$
- End up building a **super-resolved** (implicit) **template**

Synthetic data



R = 25 000
R = 100 000
Mean RV error [m s^{-1}]
No. of spectra considered
No. of spectra considered
SNR = 200
SNR = 50
SNR = 10
10^0
10^1
10^2
10^3
10^{-1}

A HARPS-N standard star

HD 127334

HD 127334

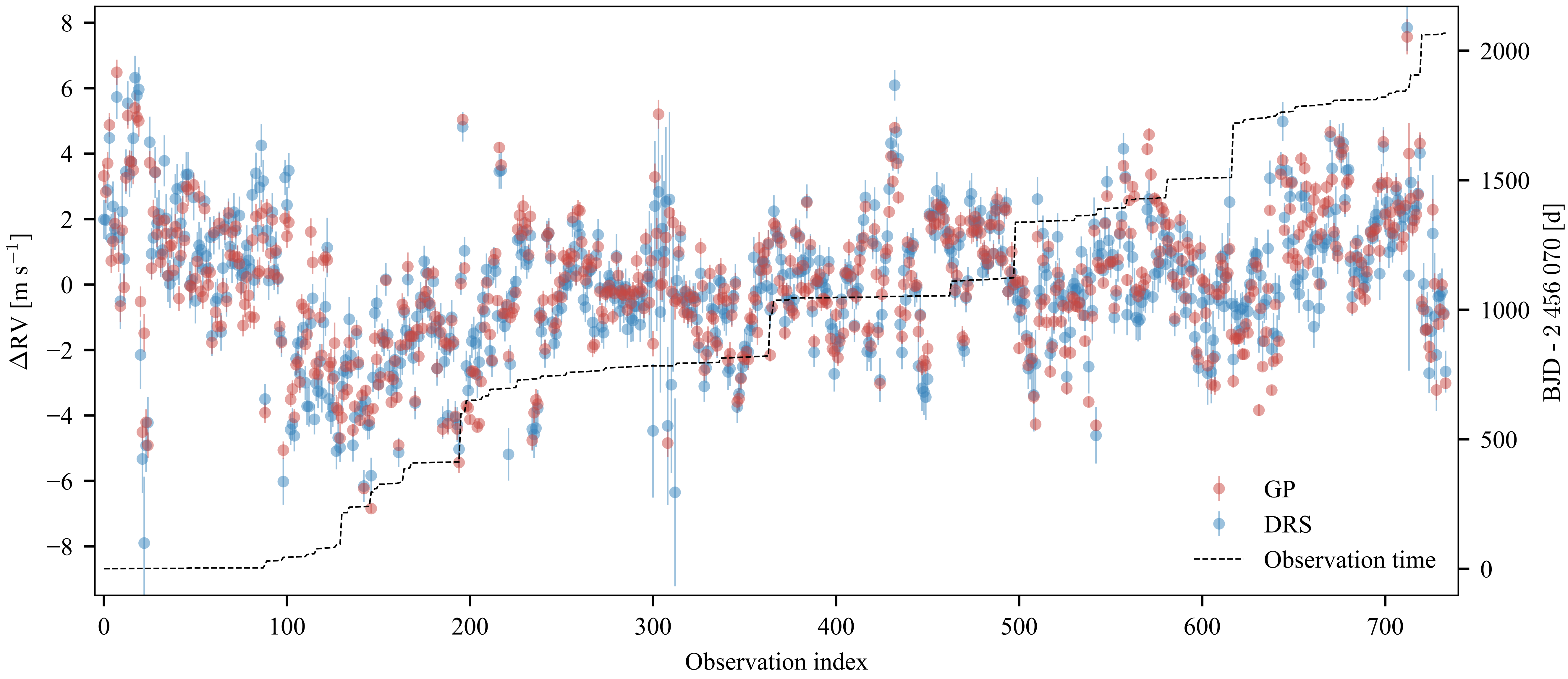
- m_V = 6.36, G5 V star; log R’HK ≲ -5.05 [**very inactive**]

HD 127334

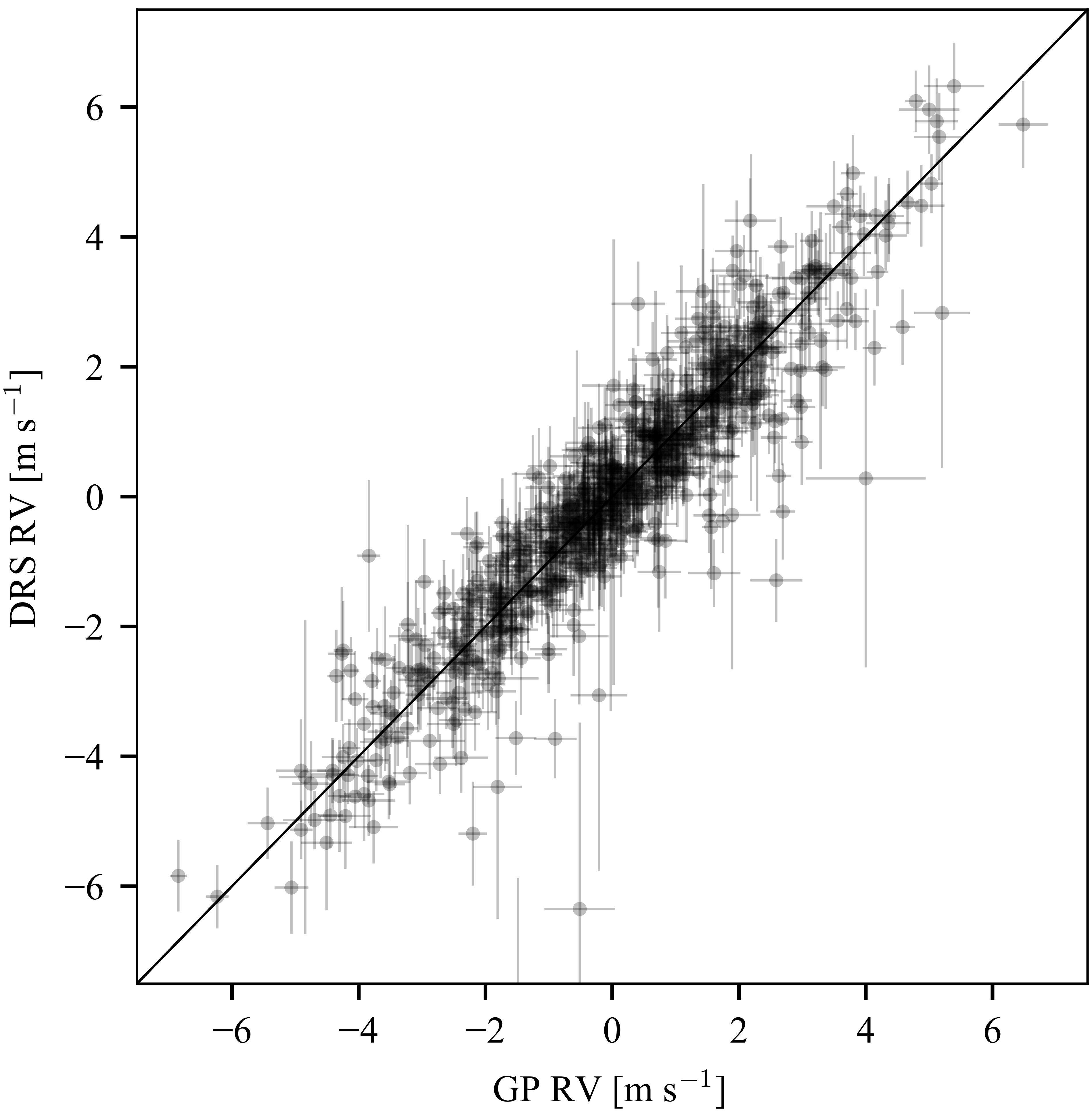
- m_V = 6.36, G5 V star; log $R'_{HK} \lesssim -5.05$ [**very inactive**]
- Stable with RV rms scatter of ~ 2 m/s

HD 127334

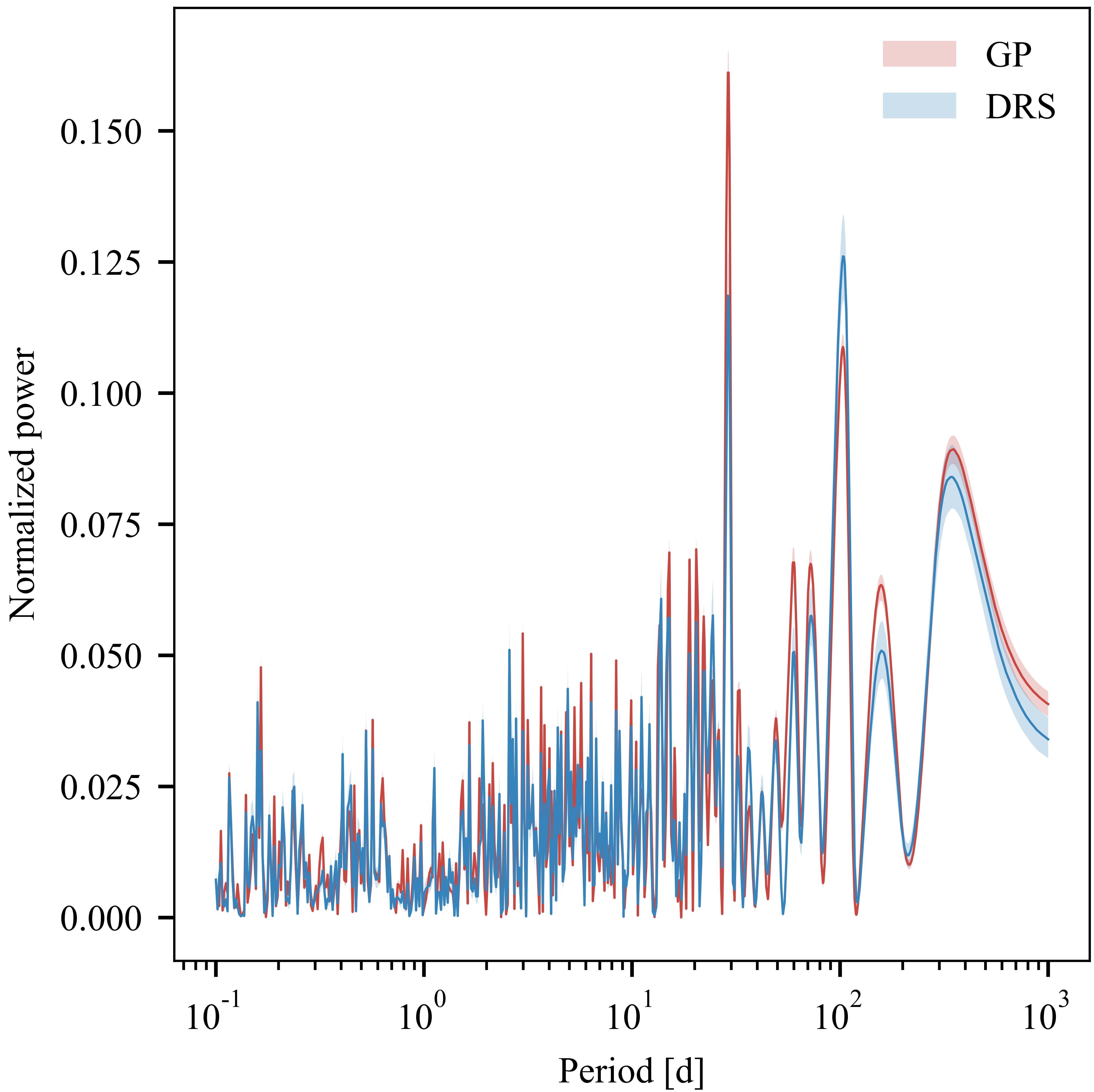
- mv = 6.36, G5 V star; log R'HK ≲ -5.05 [**very inactive**]
- Stable with RV rms scatter of ~ 2 m/s
- Model ~ 735 HARPS-N spectra taken between May 2012 and January 2018
- Integration times: mostly in range 120 s to 450 s

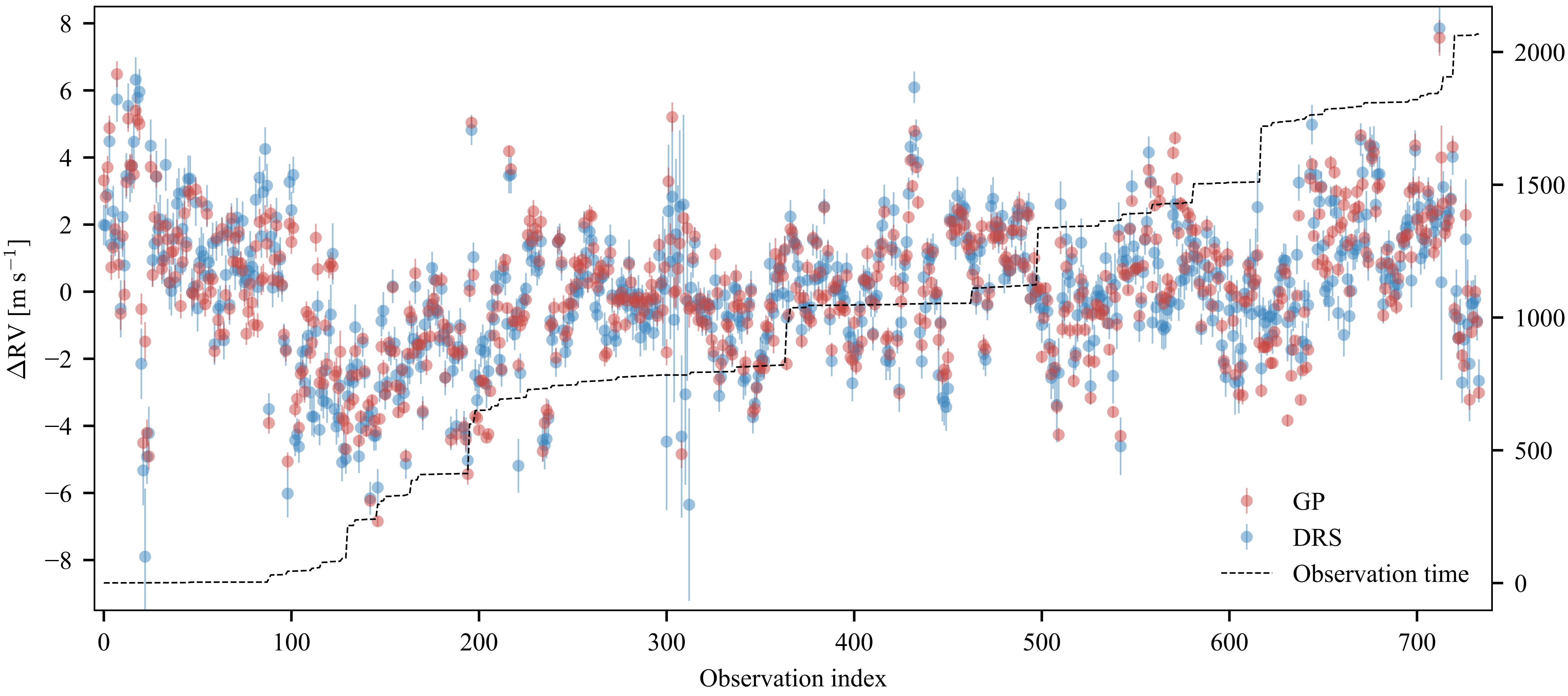


ΔRV [m s^{-1}]
BJD - 2 456 070 [d]
Observation index
GP
DRS
Observation time



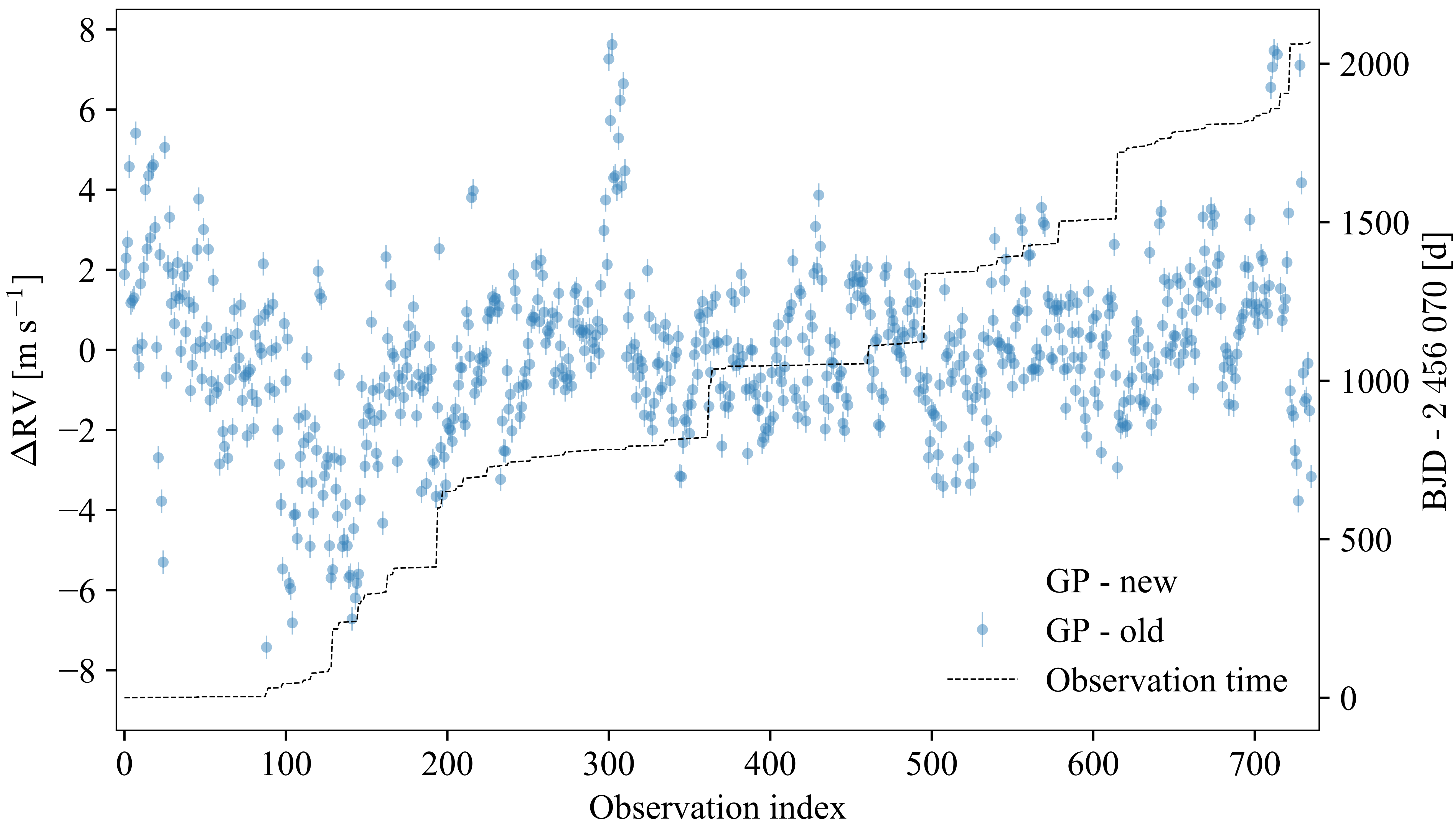
DRS RV [m s^{-1}]
GP RV [m s^{-1}]
−6
−4
−2
0
2
4
6


GP
DRS
Normalized power
0.150
0.125
0.100
0.075
0.050
0.025
0.000
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Period [d]

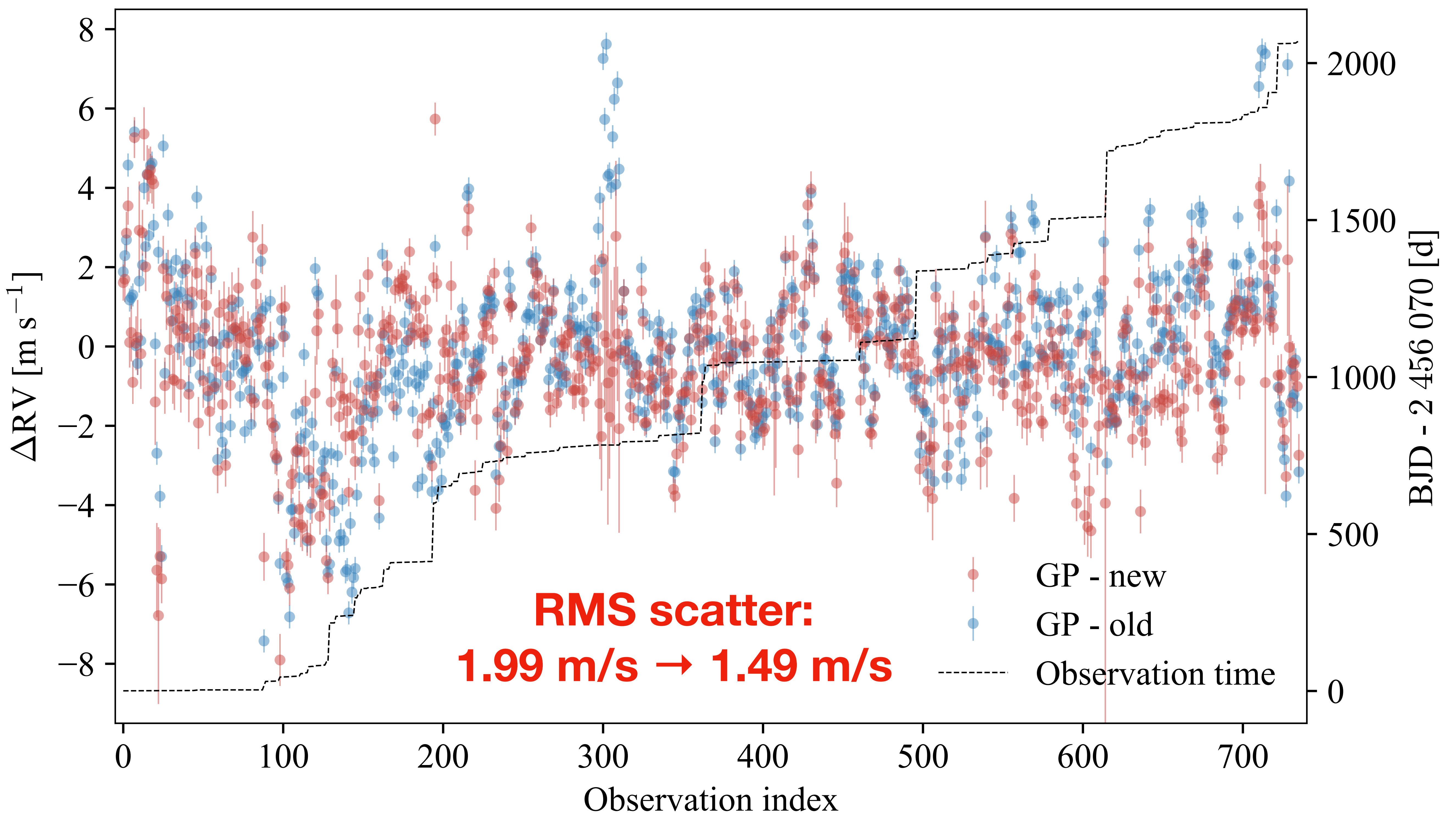


2 m/s RMS scatter in both GP and DRS RVs

Reducing the RV scatter



ΔRV [m s−1]
BJD - 2 456 070 [d]
Observation index
GP - new
GP - old
Observation time



ΔRV [m s⁻¹]
BJD - 2 456 070 [d]
Observation index
GP - new
GP - old
Observation time
RMS scatter:
1.99 m/s → 1.49 m/s

Reducing RV scatter

Reducing RV scatter

- DRS: 1.99 m/s scatter, 60 cm/s error bars

Reducing RV scatter

- DRS: 1.99 m/s scatter, 60 cm/s error bars
- GP: 1.49 m/s scatter, 40 cm/s error bars

Reducing RV scatter

- DRS: 1.99 m/s scatter, 60 cm/s error bars
- GP: 1.49 m/s scatter, 40 cm/s error bars
- FWHM correlation disappears in GP RVs

Reducing RV scatter

- DRS: 1.99 m/s scatter, 60 cm/s error bars
- GP: 1.49 m/s scatter, 40 cm/s error bars
- FWHM correlation disappears in GP RVs
- Correlations remain with some instrumental parameters

Next steps

Next steps

Next steps

- Paper to be submitted ASAP (!)

Next steps

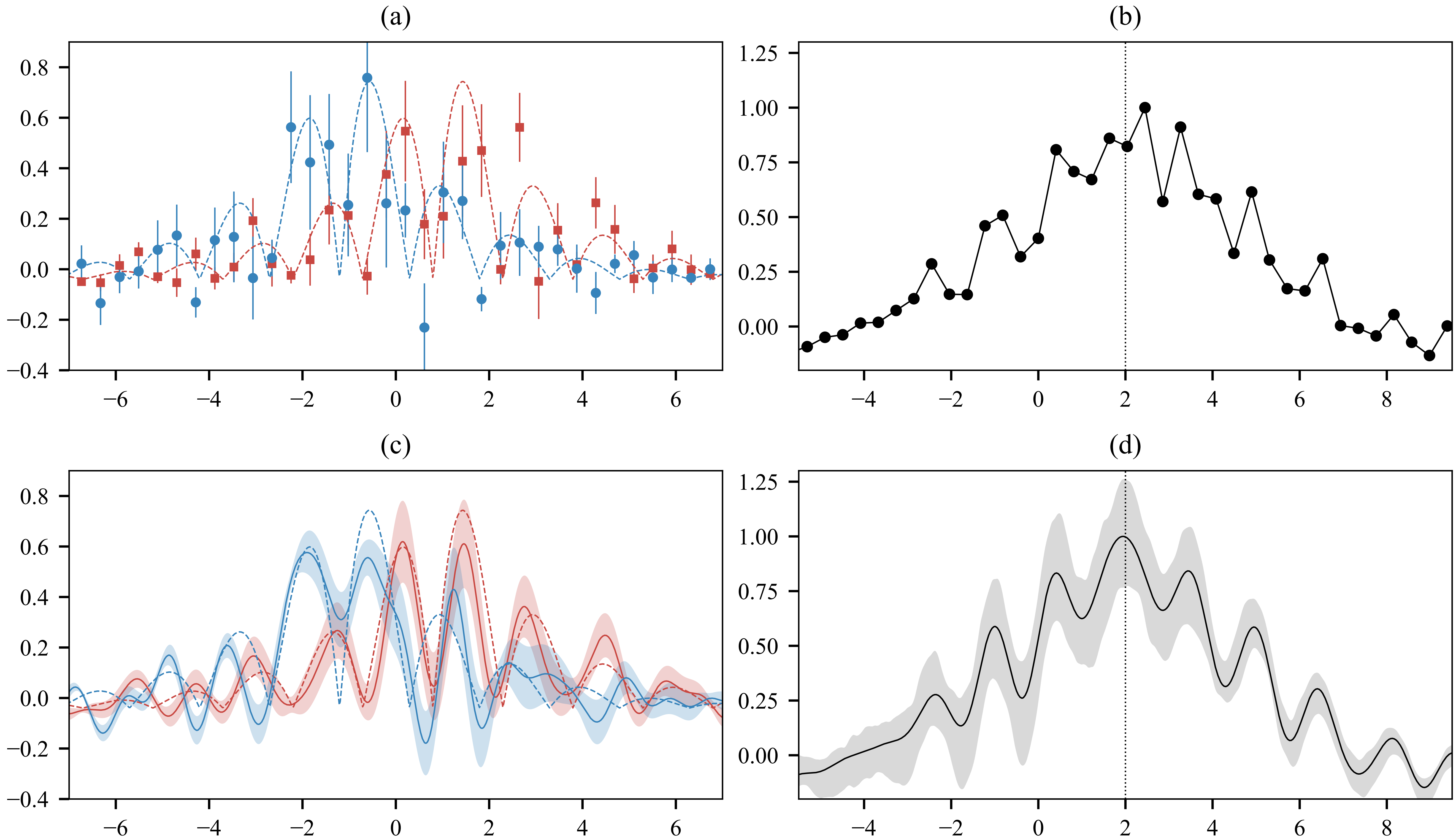
- Paper to be submitted ASAP (!)

- Apply to interesting systems, other stellar types

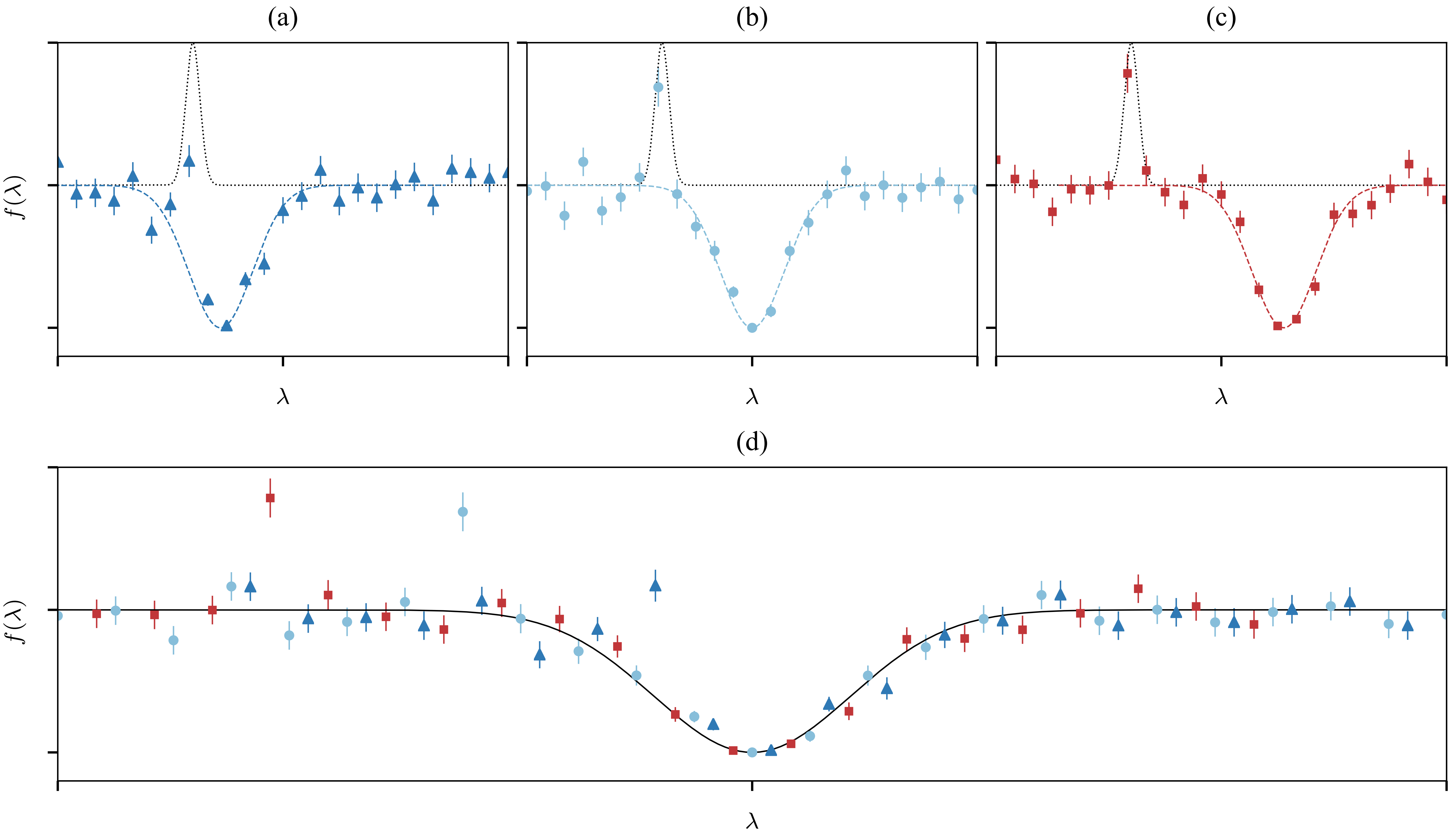
Next steps

- Paper to be submitted ASAP (!)
- Apply to interesting systems, other stellar types
- Extensions to the basic method - led by Suzanne

End

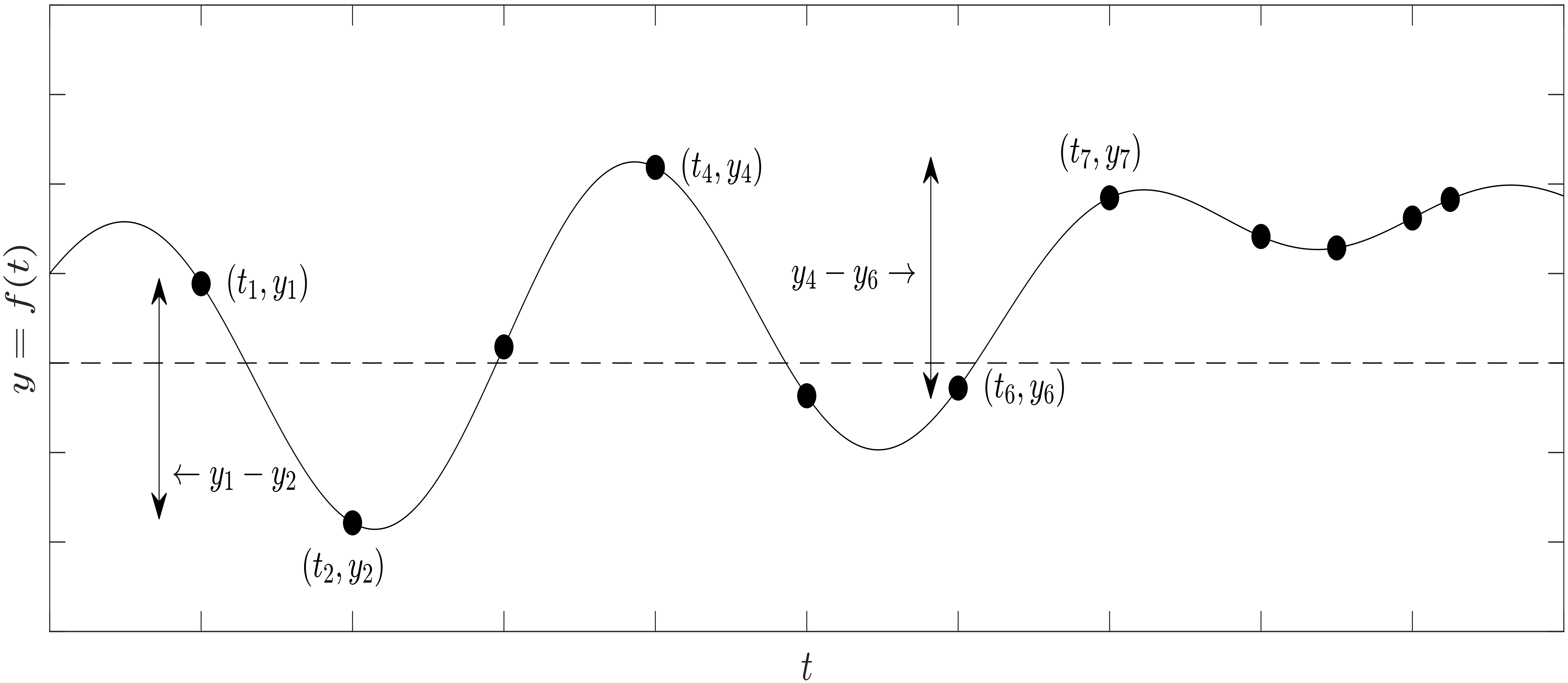


(a)
(b)
(c)
(d)



(a)
(b)
(c)
(d)
$f(\lambda)$
λ

Why pairwise RVs?



Why pairwise RVs?

Why pairwise RVs?

y_i

Why pairwise RVs?

$$y_i = \frac{1}{N}\sum_{j=1}^{N} y_i$$

Why pairwise RVs?

$$
\begin{aligned}
y_i &= \frac{1}{N}\sum_{j=1}^{N} y_i \\
&= \frac{1}{N}\sum_{j=1}^{N}\left(y_i - y_j\right) + \frac{1}{N}\sum_{j=1}^{N} y_j
\end{aligned}
$$

Why pairwise RVs?

$$y_i = \frac{1}{N}\sum_{j=1}^{N} y_i$$

$$= \frac{1}{N}\sum_{j=1}^{N}\left(y_i - y_j\right) + \cancel{\frac{1}{N}\sum_{j=1}^{N} y_j}^{\;\gamma}$$

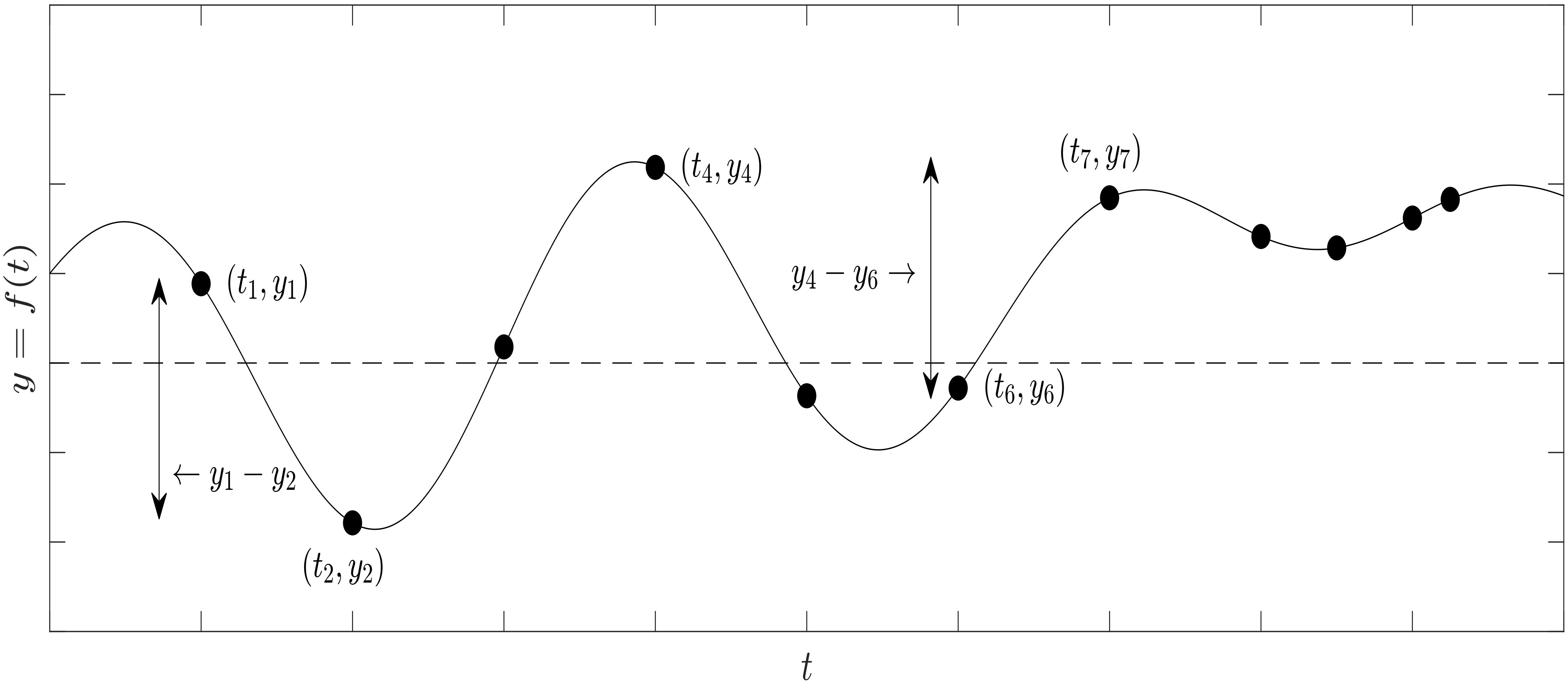
Why pairwise RVs?

$$y_i = \frac{1}{N}\sum_{j=1}^{N} y_i$$

$$= \frac{1}{N}\sum_{j=1}^{N}\left(y_i - y_j\right) + \frac{1}{N}\sum_{j=1}^{N} y_j$$

γ

Why pairwise RVs?



HD 127334: DRS vs GP RVs

HD 127334: DRS vs GP RVs

- Error bars: **60 ± 31 cm/s (DRS)** vs **27 ± 8 cm/s (GP)**

HD 127334: DRS vs GP RVs

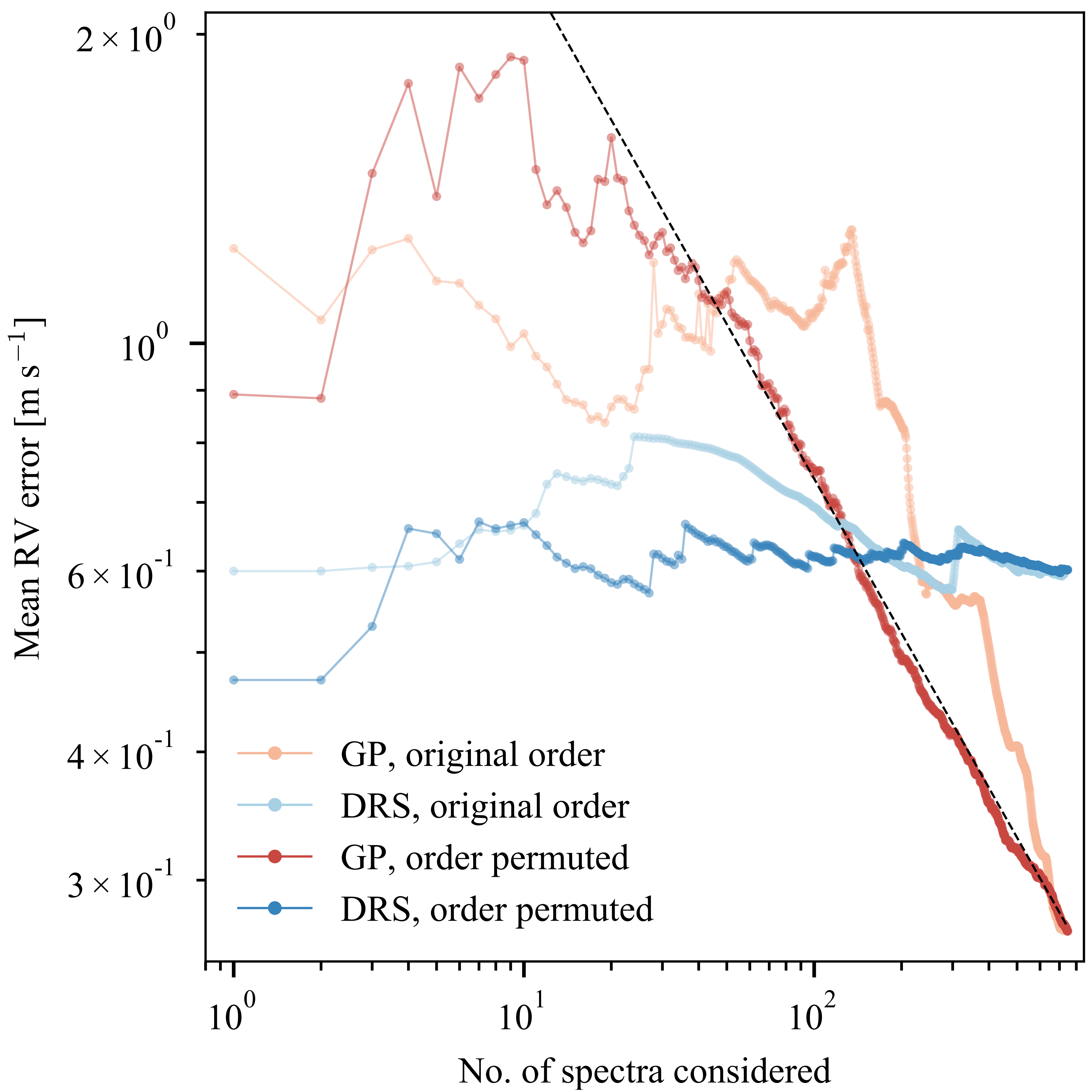
- Error bars: **60 ± 31 cm/s (DRS)** vs **27 ± 8 cm/s (GP)**
- **96.5 % of RVs consistent** within 2σ error estimates

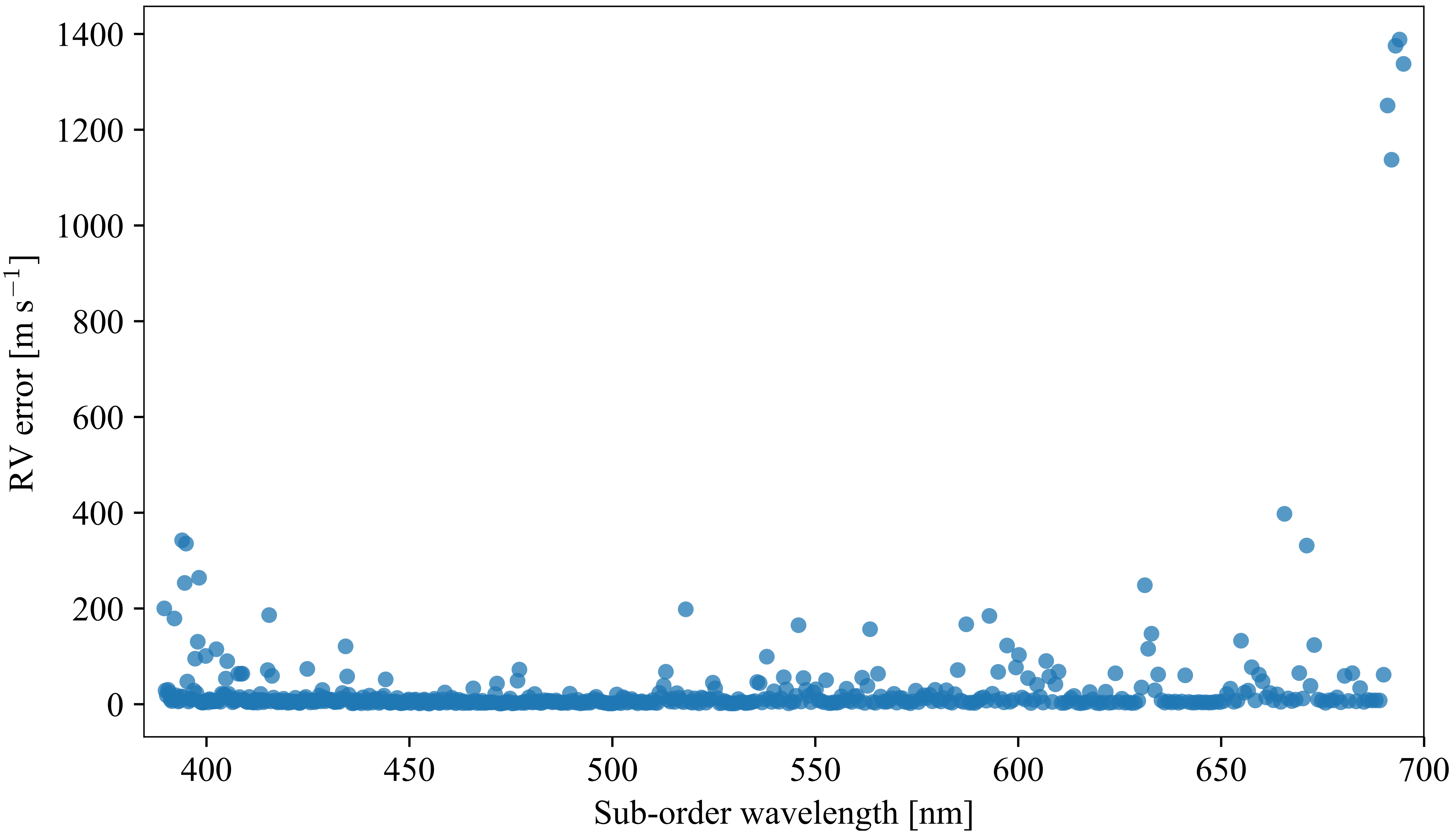
HD 127334: DRS vs GP RVs

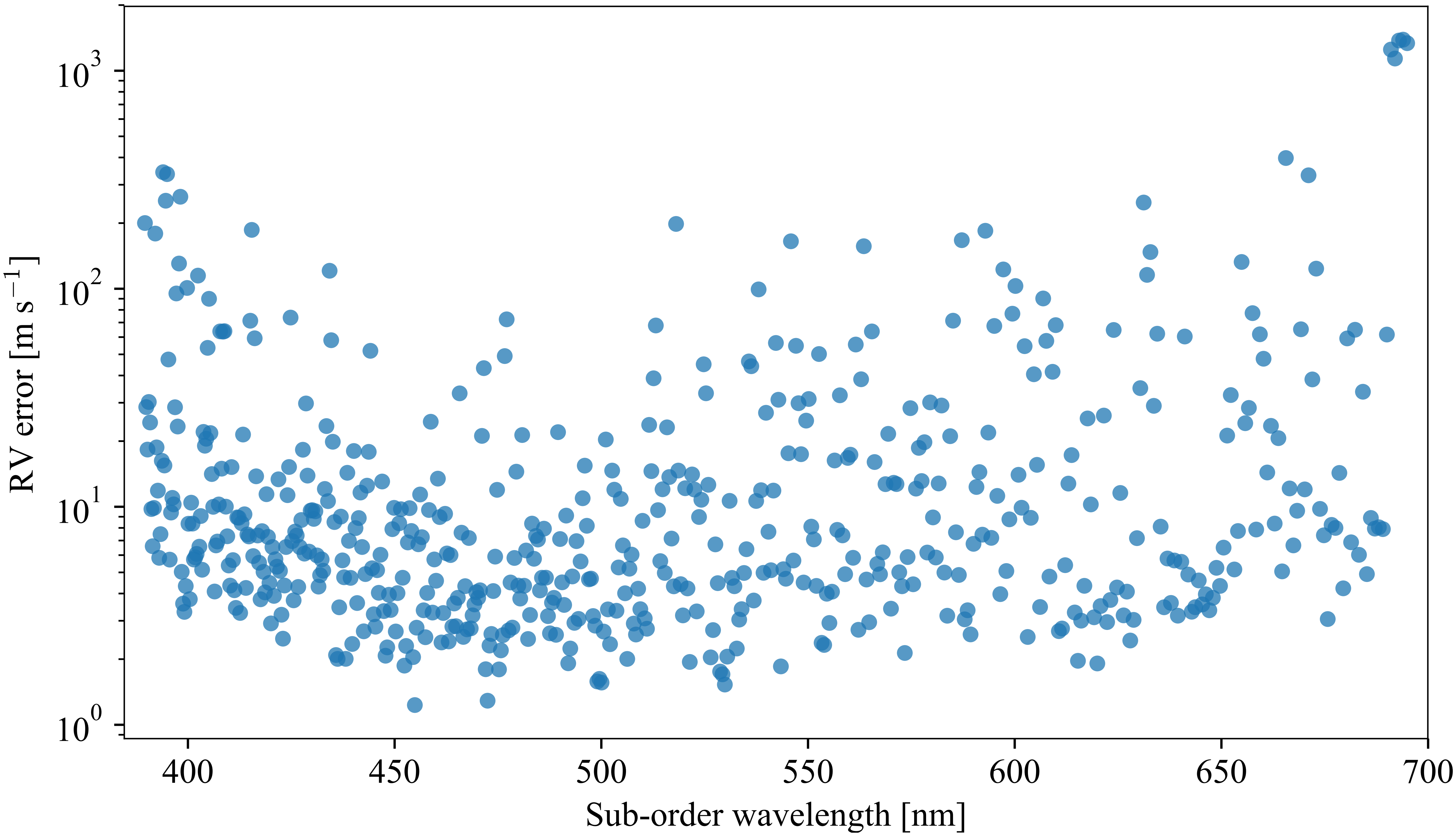
- Error bars: **60 ± 31 cm/s (DRS)** vs **27 ± 8 cm/s (GP)**
- **96.5 % of RVs consistent** within 2σ error estimates
- GP error bars derived from many independent RV estimators

HD 127334: DRS vs GP RVs

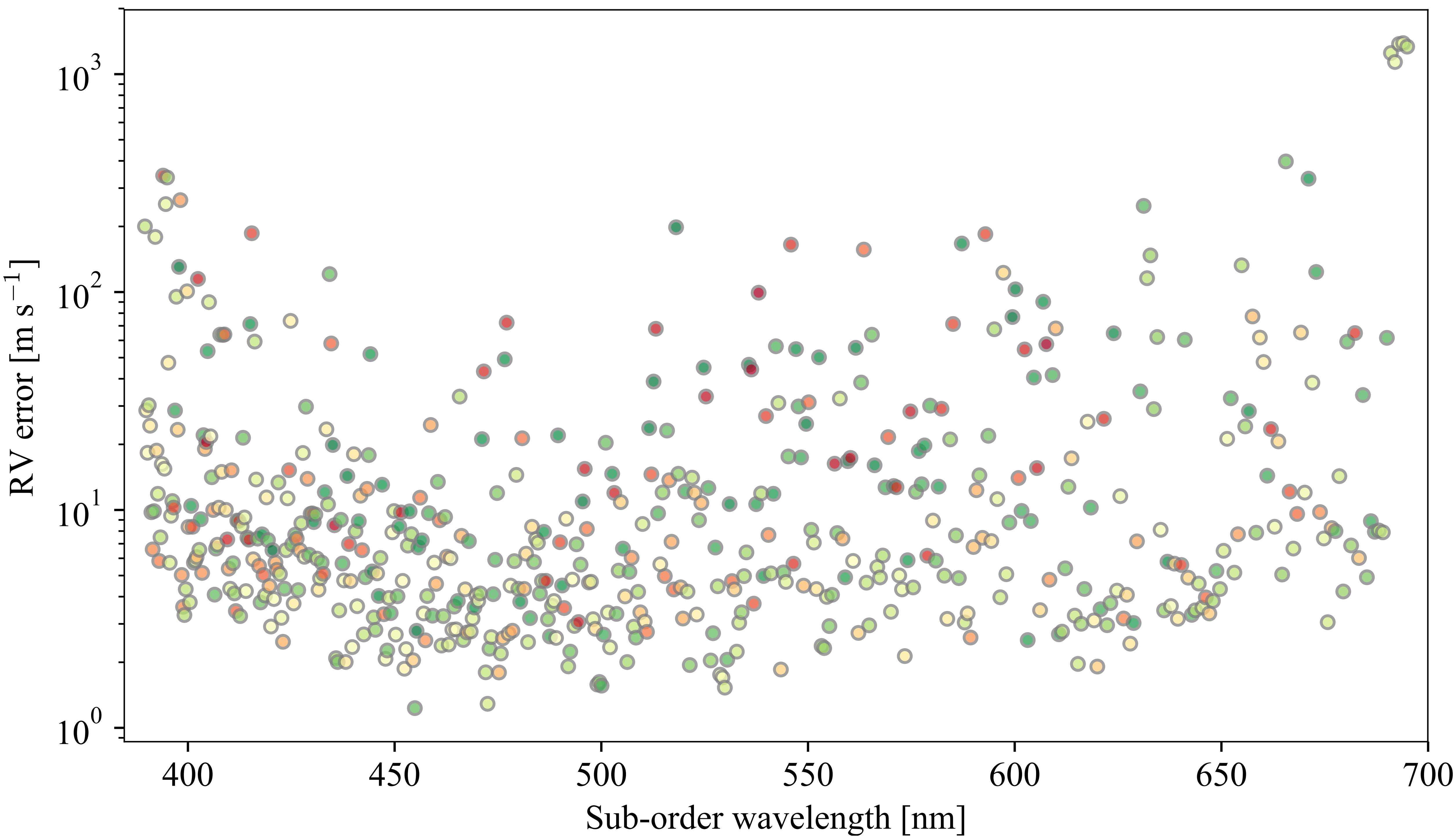
- Error bars: **60 ± 31 cm/s (DRS)** vs **27 ± 8 cm/s (GP)**
- **96.5 % of RVs consistent** within 2σ error estimates
- GP error bars derived from many independent RV estimators
- Errors > fundamental photon noise limit (Bouchy+ 2001)


2×10^0
10^0
6×10^{-1}
4×10^{-1}
3×10^{-1}
Mean RV error [m s^{-1}]
10^0
10^1
10^2
No. of spectra considered
GP, original order
DRS, original order
GP, order permuted
DRS, order permuted


RV error [m s^{-1}]
0
200
400
600
800
1000
1200
1400
400
450
500
550
600
650
700
Sub-order wavelength [nm]



10^3
10^2
10^1
10^0
RV error [m s^{-1}]
400
450
500
550
600
650
700
Sub-order wavelength [nm]



RV error [m s^{-1}]
10^3
10^2
10^1
10^0
400
450
500
550
600
650
700
Sub-order wavelength [nm]