Resolving Oscillations and Granulation Within a Night with EPRV Spectrographs

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Cool Stars 23 — Splinter Session 4 — June 16, 2026

EPRV

“the only method potentially capable of detecting and measuring the masses of Earth analogs orbiting solar-type stars from the ground”

Crass et al. 2021

Amplitudes and Timescales of Stellar Variability

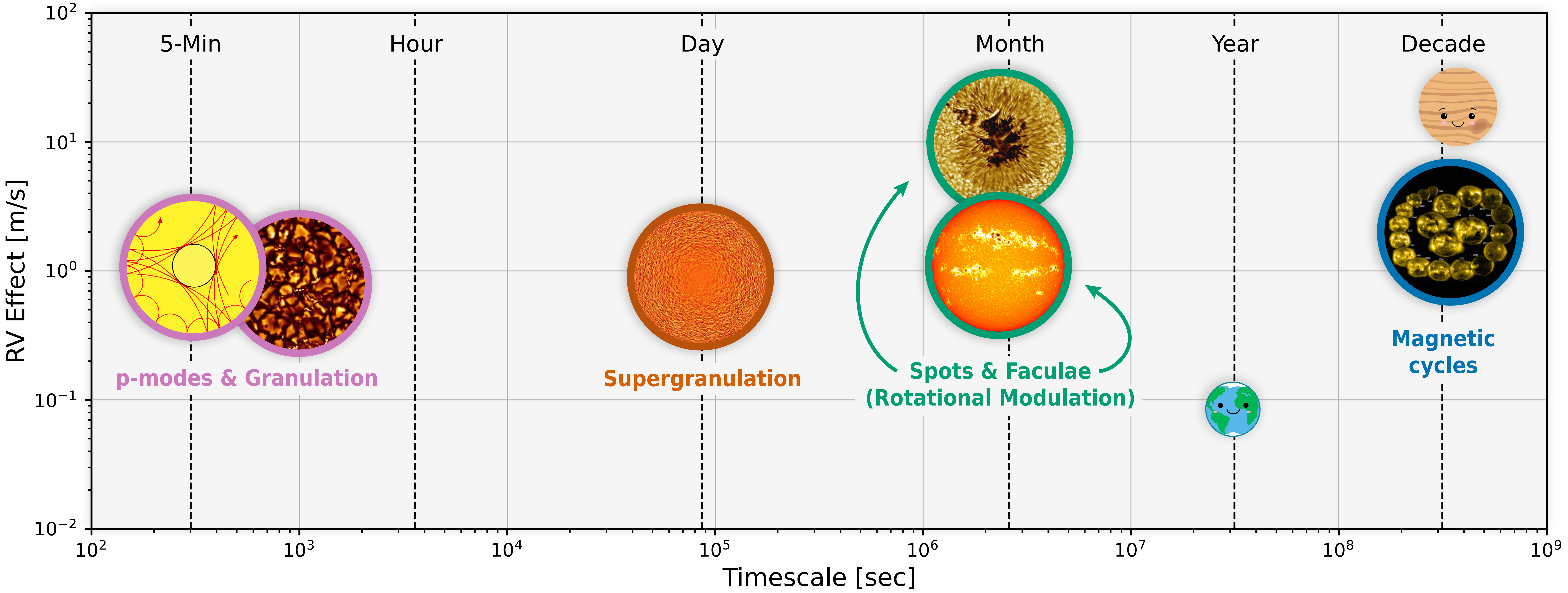
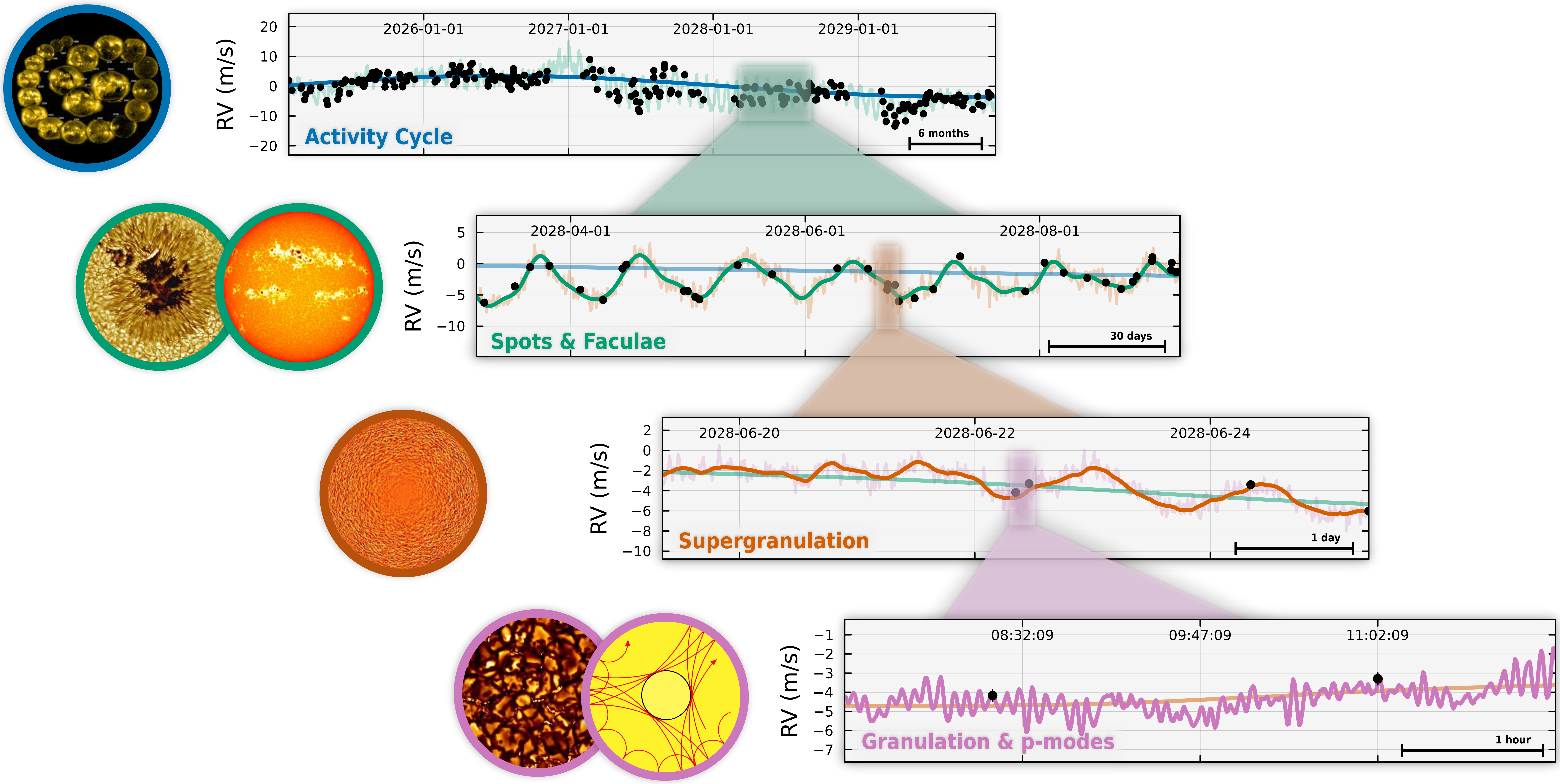


Figure adapted from R. Rubenzahl PhD thesis (2024)

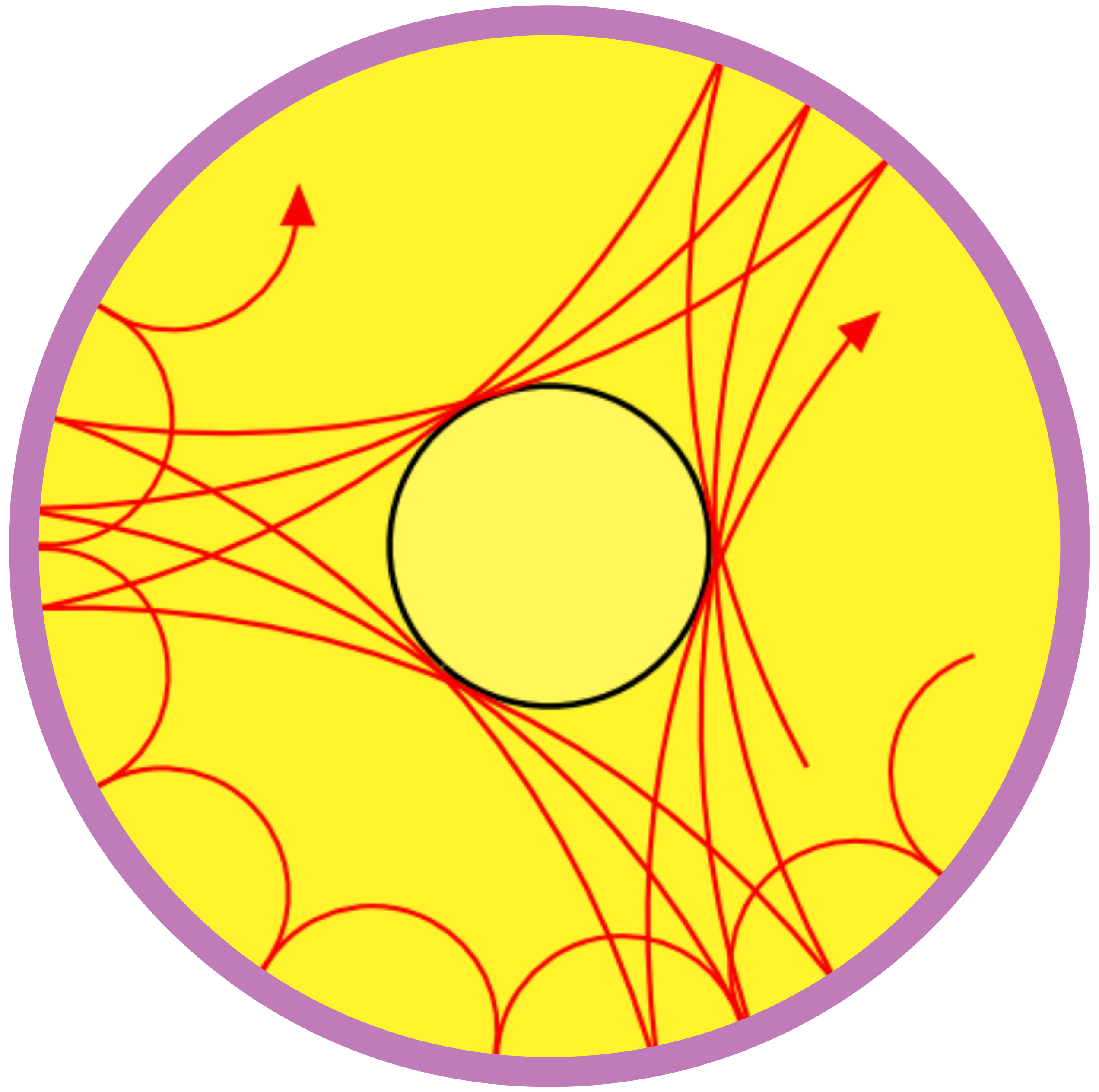


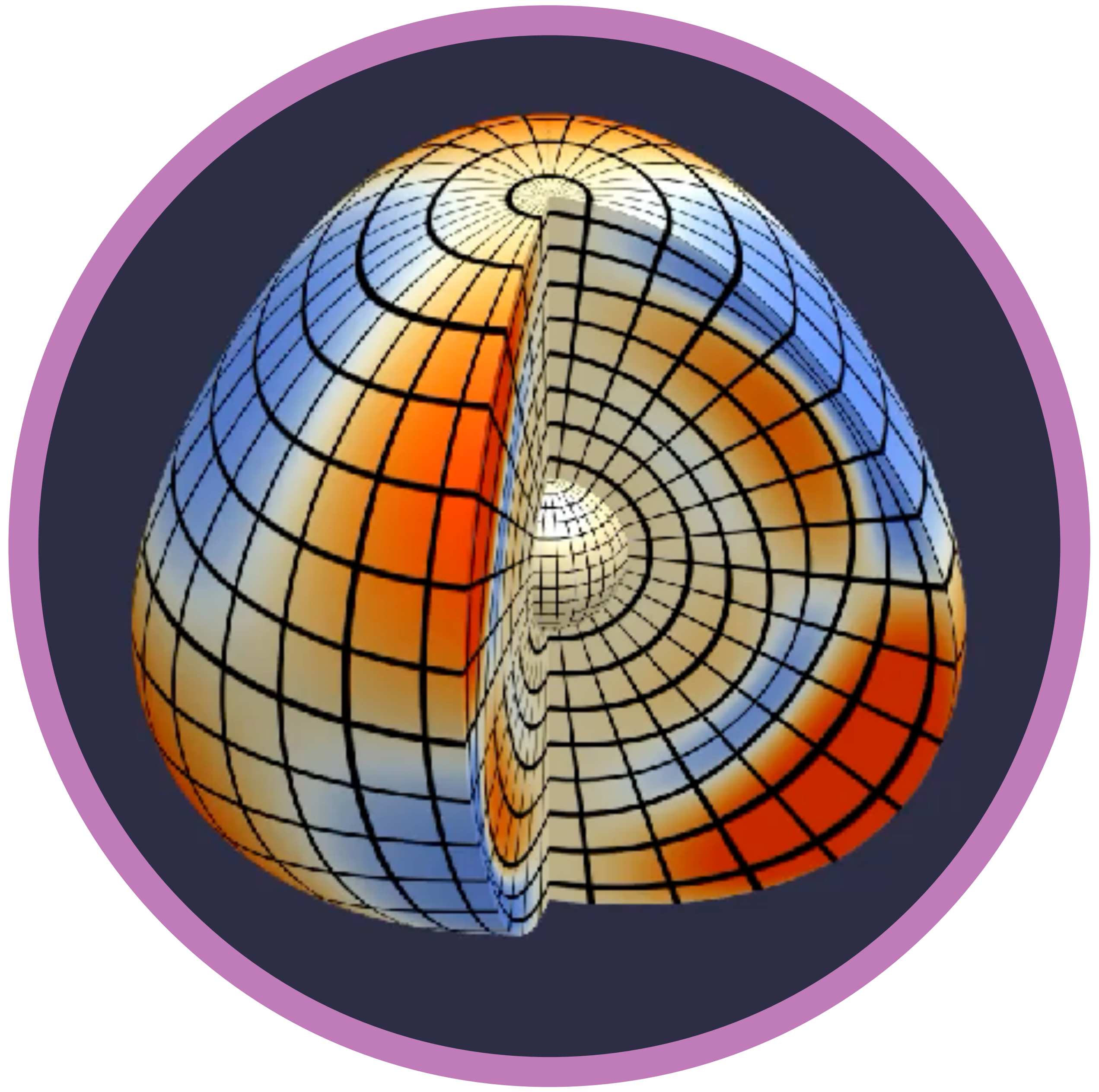
Activity Cycle
RV (m/s)
2026-01-01
2027-01-01
2028-01-01
2029-01-01
6 months
Spots & Faculae
2028-04-01
2028-06-01
2028-08-01
30 days
Supergranulation
2028-06-20
2028-06-22
2028-06-24
1 day
Granulation & p-modes
08:32:09
09:47:09
11:02:09
1 hour

P-mode Oscillations

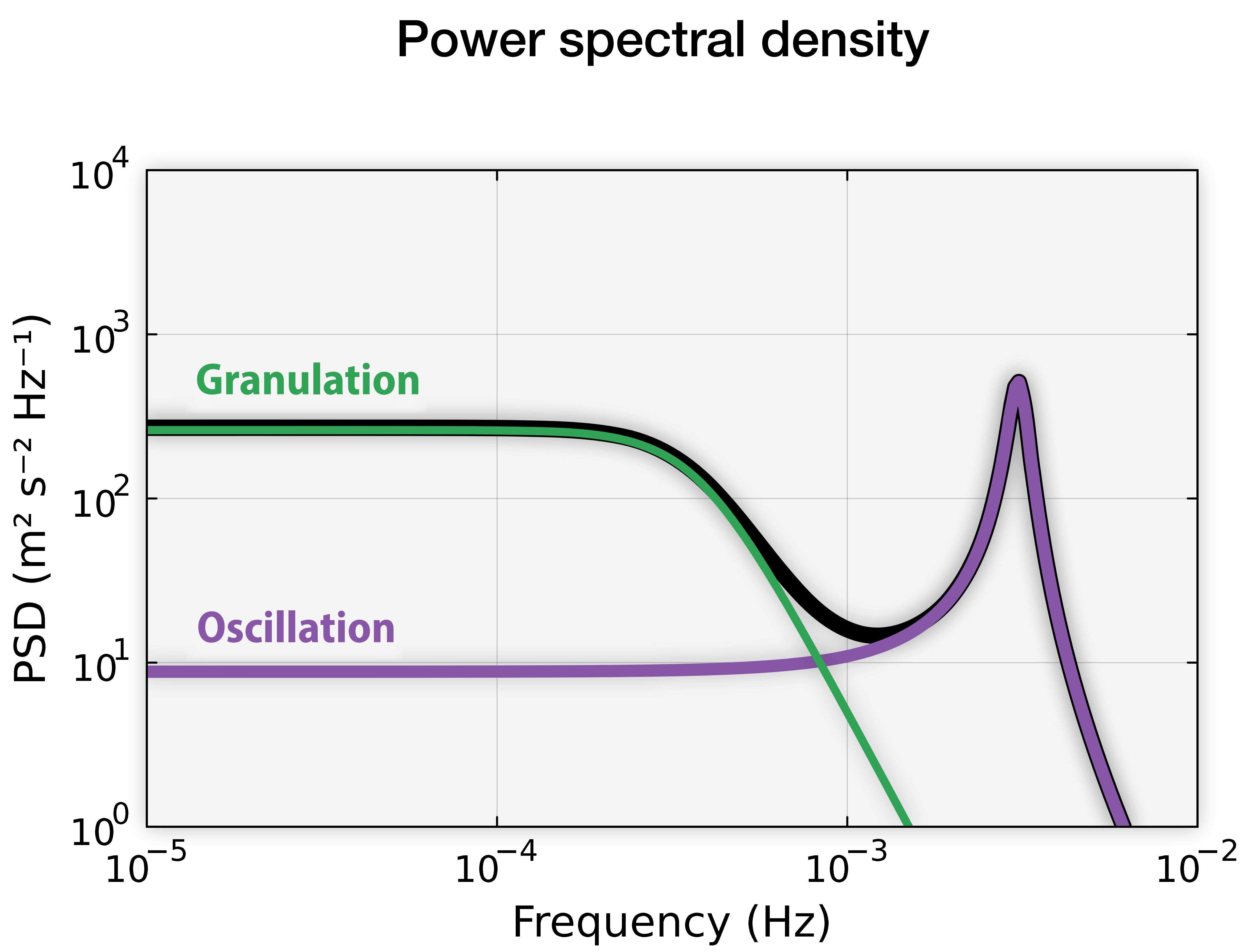
Pressure-driven waves excited by convection

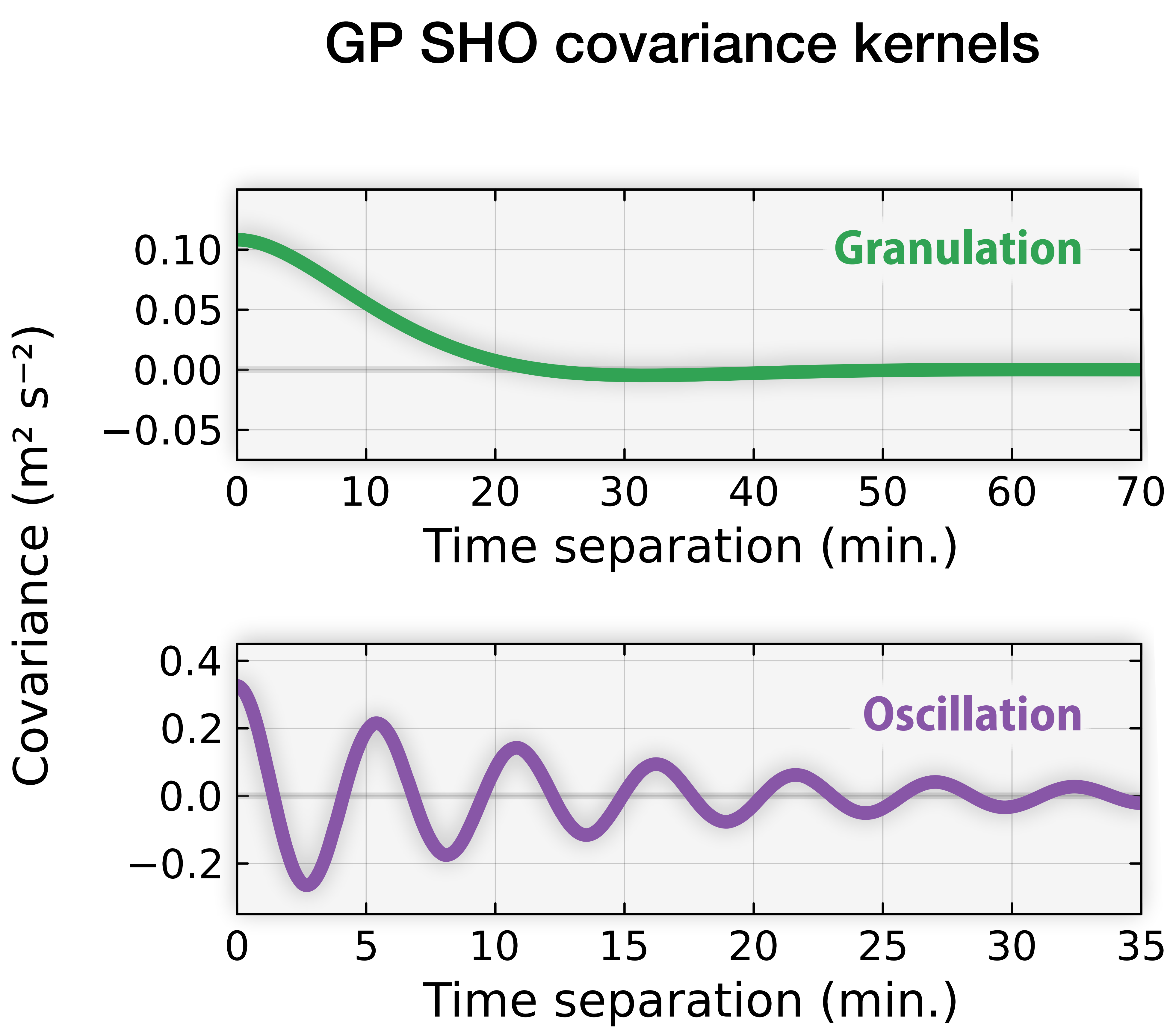
Characteristic solar timescale ~5.5 minutes





Physically motivated Gaussian Processes





Luhn et al. (2023) (See also Foreman-Mackey+ 2017, Pereira+ 2019, Guo+ 2022)

Diagnosing spectral effects

Are p-mode oscillations distinguishable as a shape change?

Planet

(pure Doppler shift)

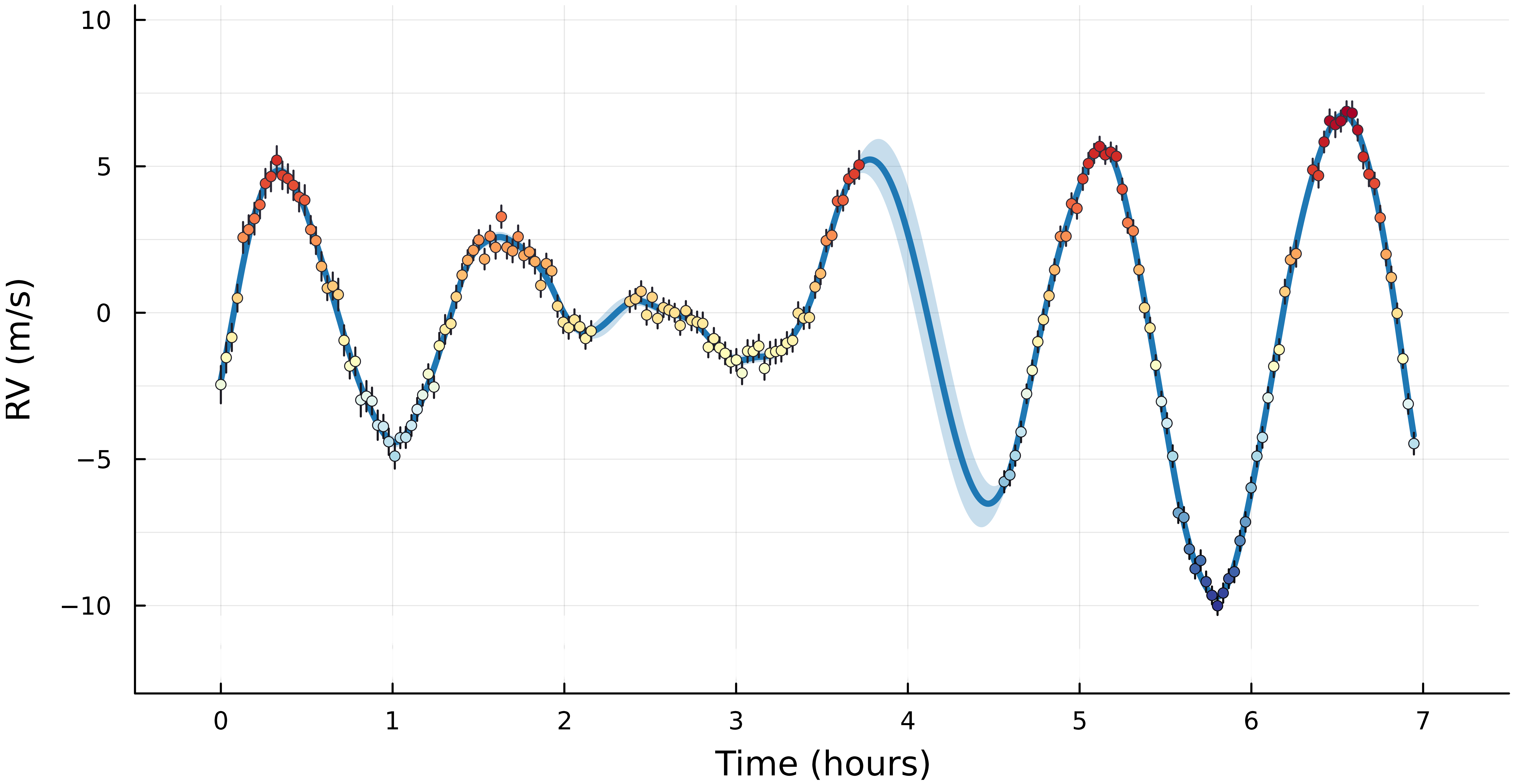
Stellar Variability

(shape distortion)

(e.g., Collier Cameron+ 2021, Zhao, J.+ 2022, de Beurs+ 2024, Colwell+ 2025)

Starting with the extremes

A subgiant case study with NEID



Luhn et al. 2025

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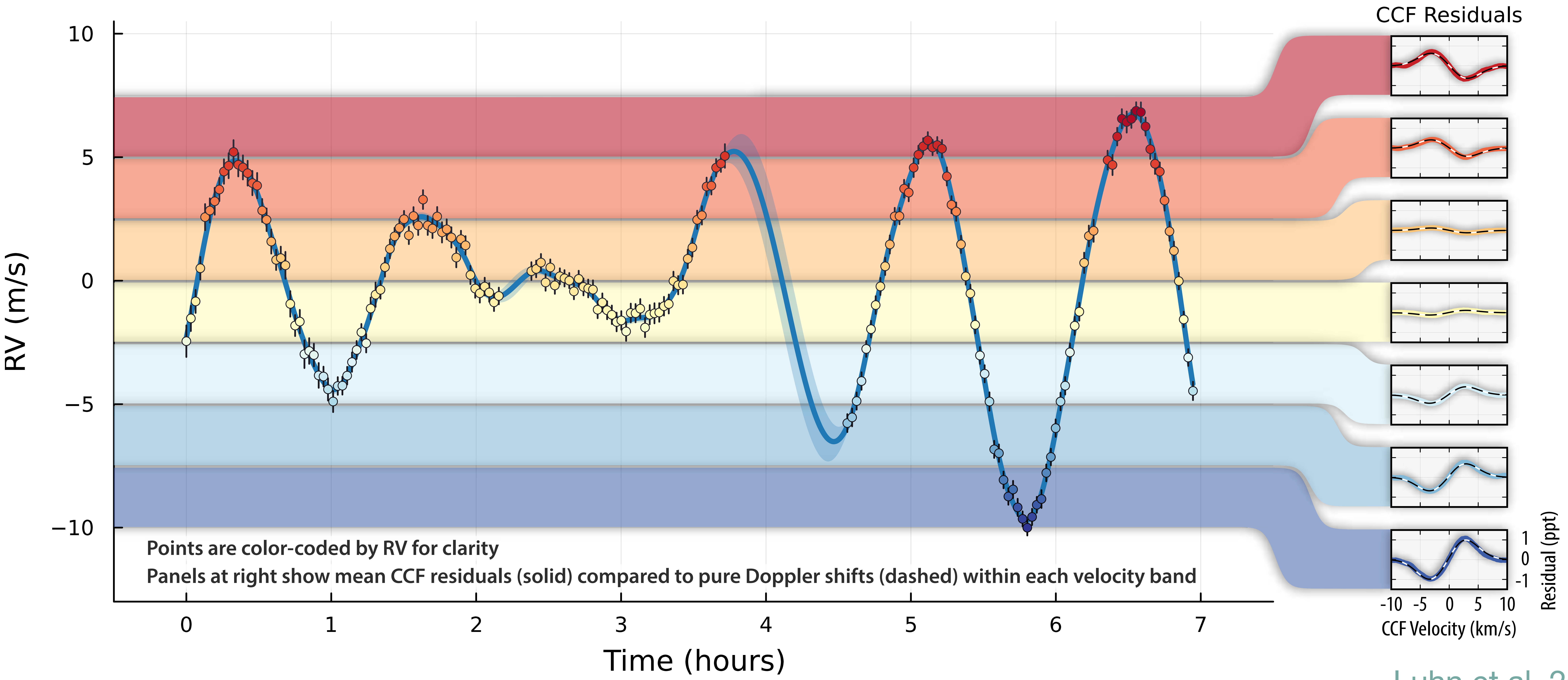
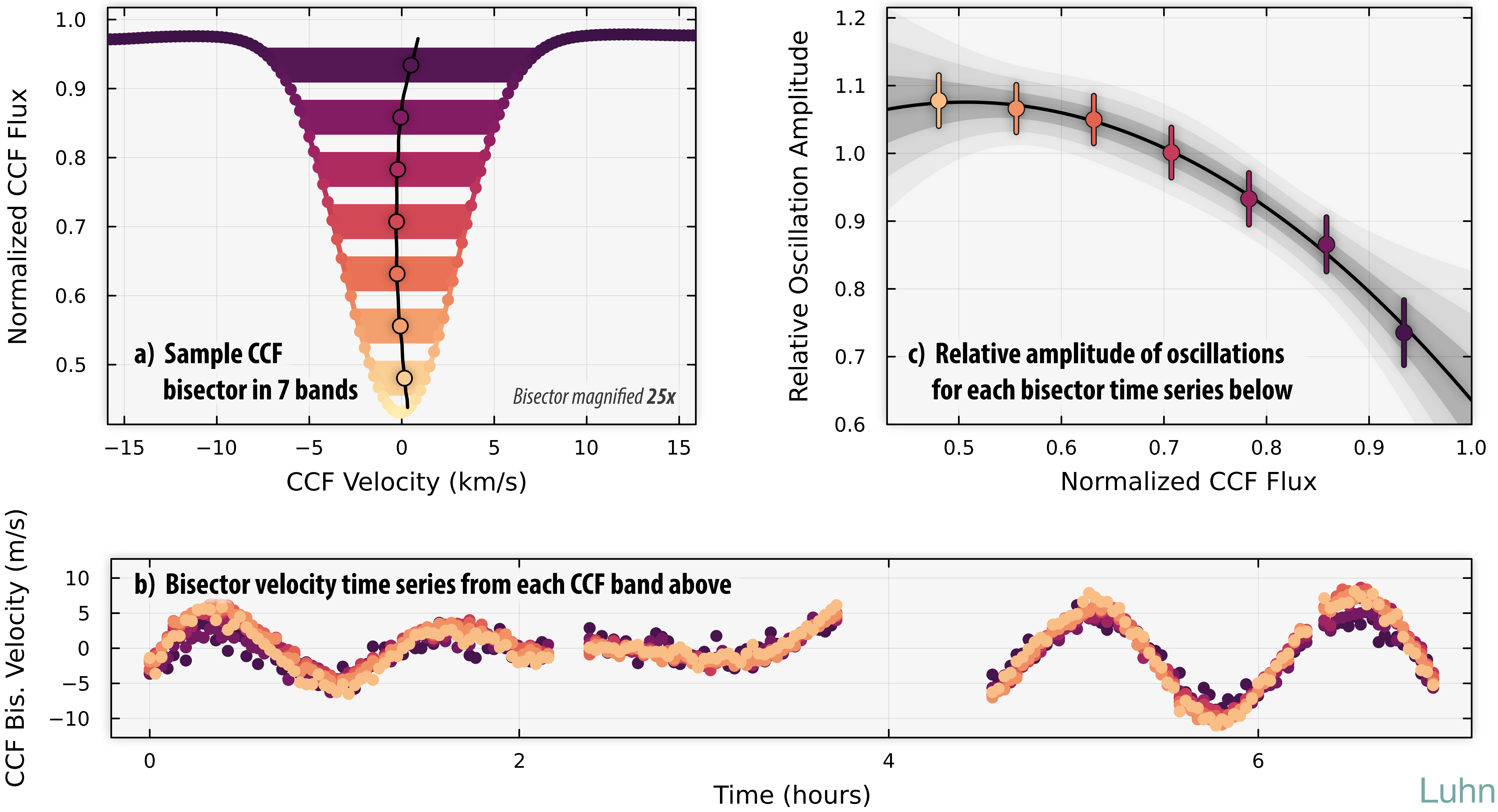


Luhn et al. 2025

CCF diagnostics of subgiant oscillations



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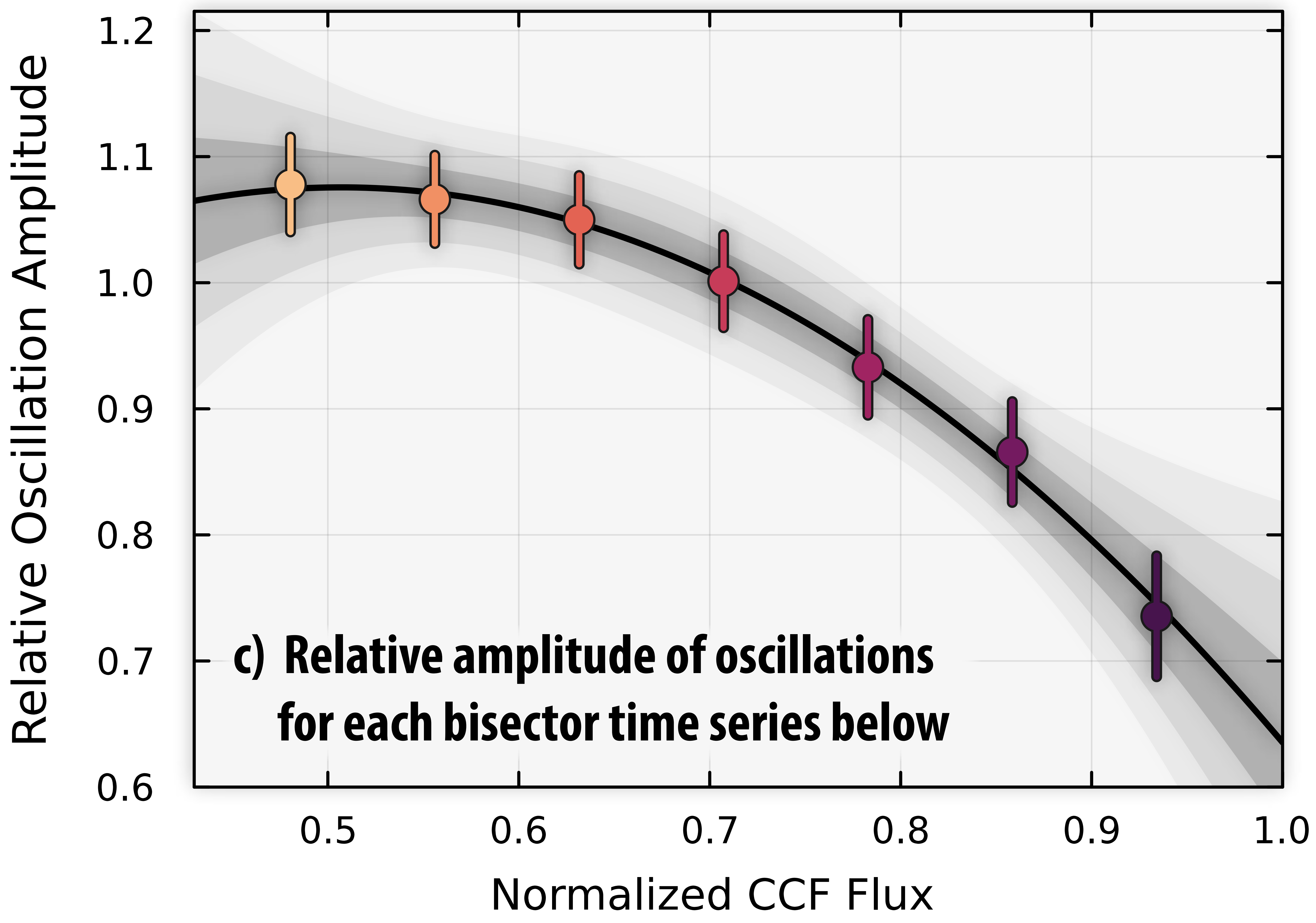
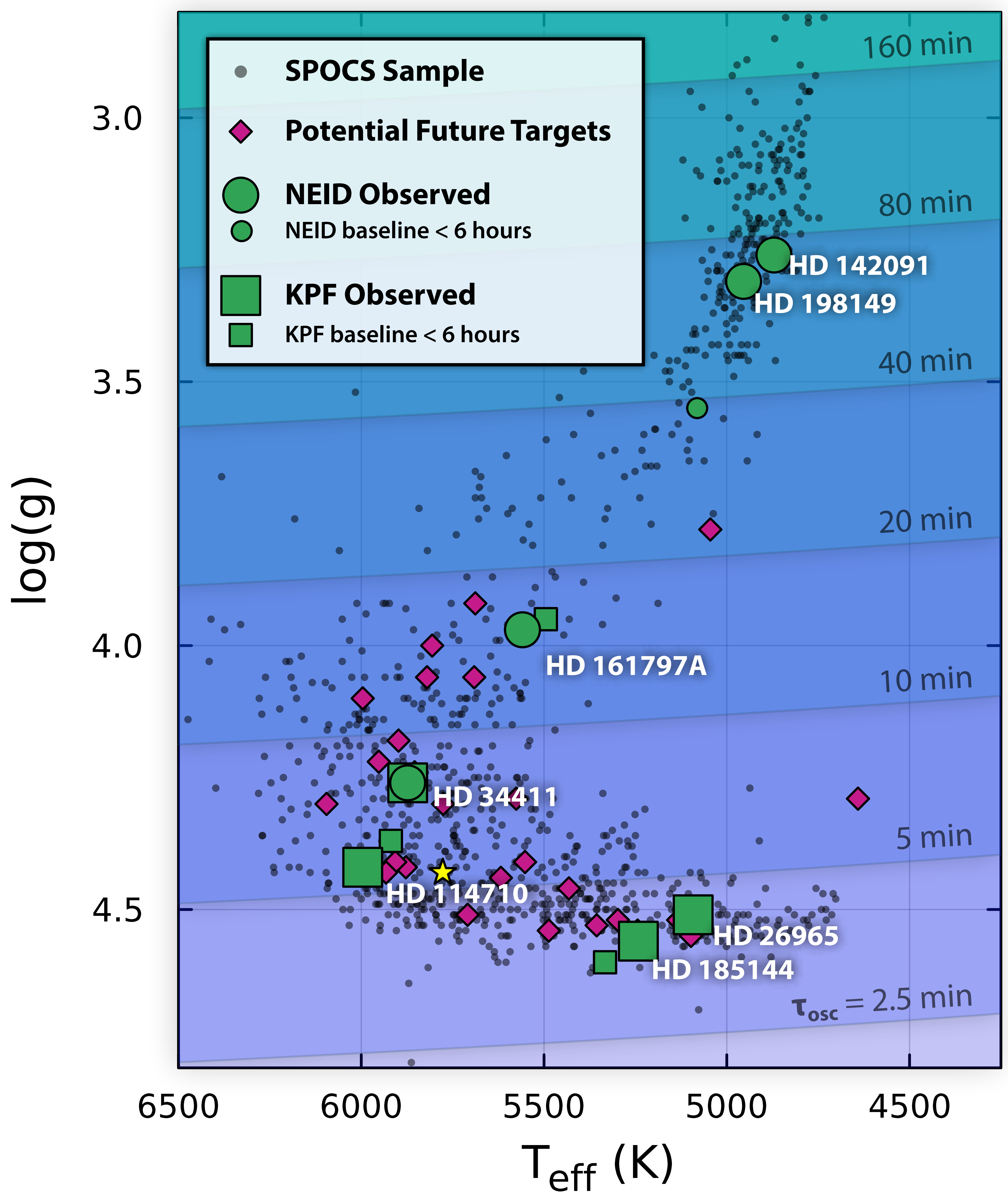


Tracing velocity (density) profile of the stellar atmosphere

Isaak+ 1989, Baudin+ 2005, Houdek+ 2006

Luhn et al. 2025

NEID & KPF: From giants to dwarfs



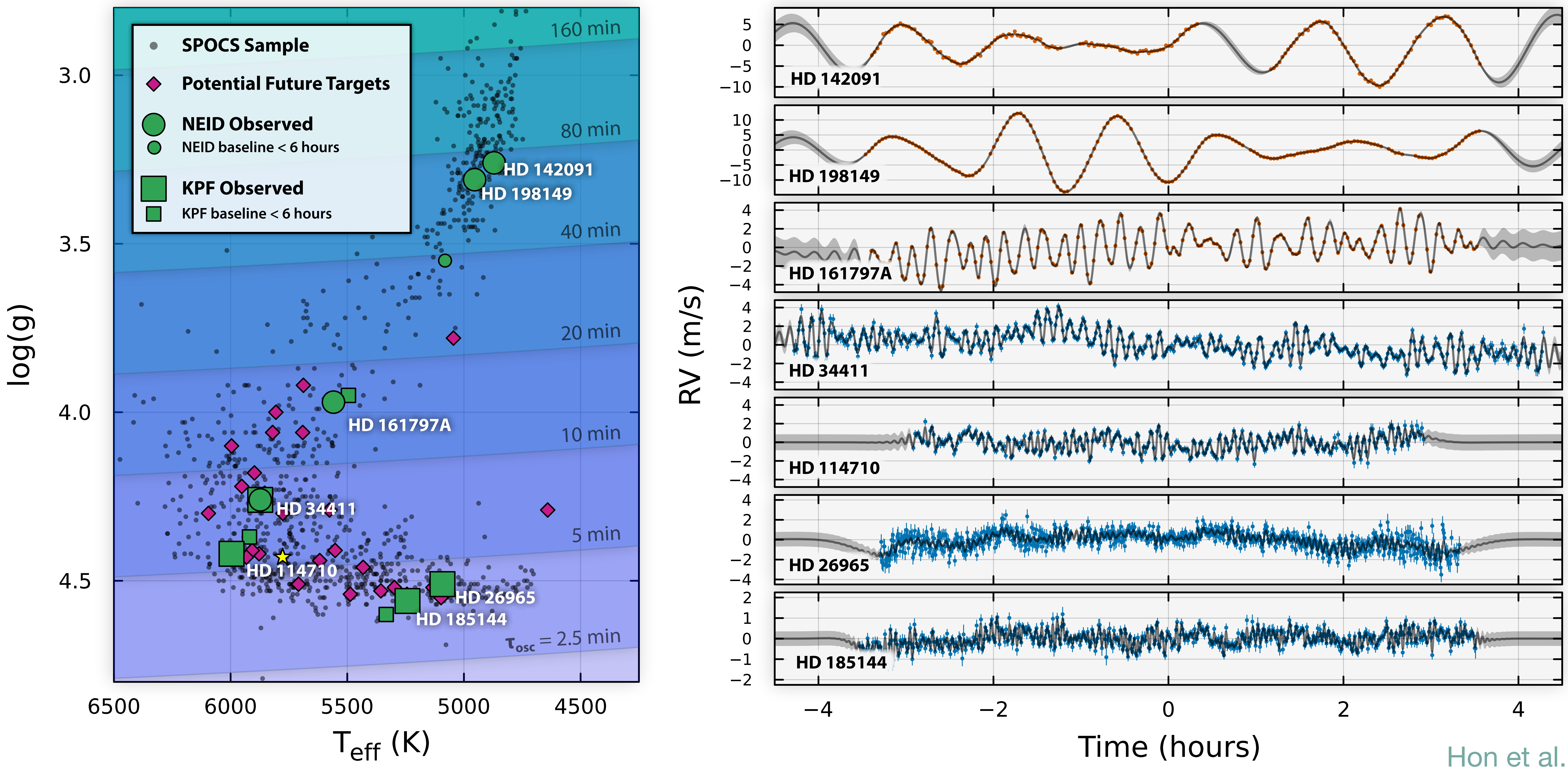
NEID: evolved stars

KPF: dwarf stars with fast readout mode

12 high-cadence sequences

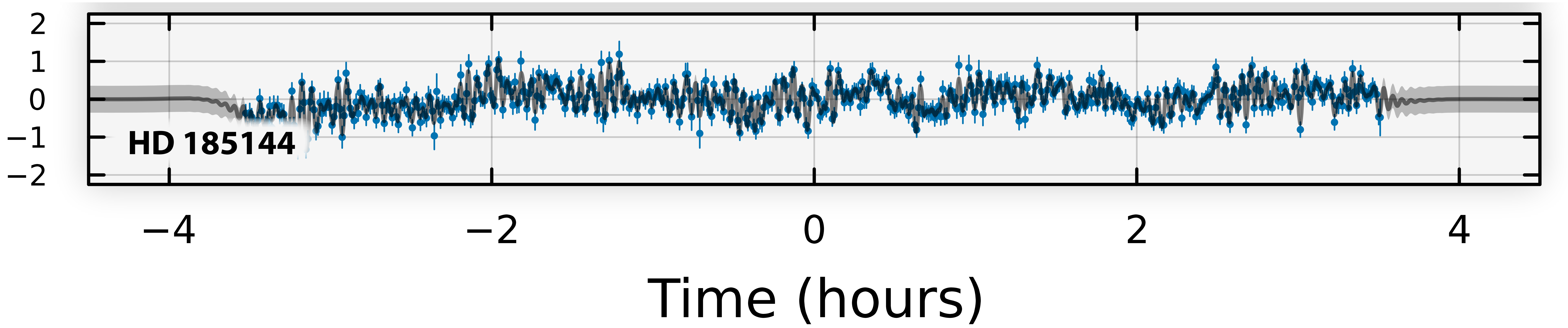
7 with more than 6 hour baseline

NEID & KPF: From giants to dwarfs



Hon et al. 2024

A quick aside: GP kernels when $\tau_{exp} \sim \tau_{gp}$



Problem

Exposures average over the “latent” oscillation signal

Traditional SHO GP kernels only account for instantaneous covariance

Solution

Use *integrated* SHO kernels (Luhn et al. 2026)

Simple

Harmonic

Oscillators

Harnessing

Exposure

Integration

Simple

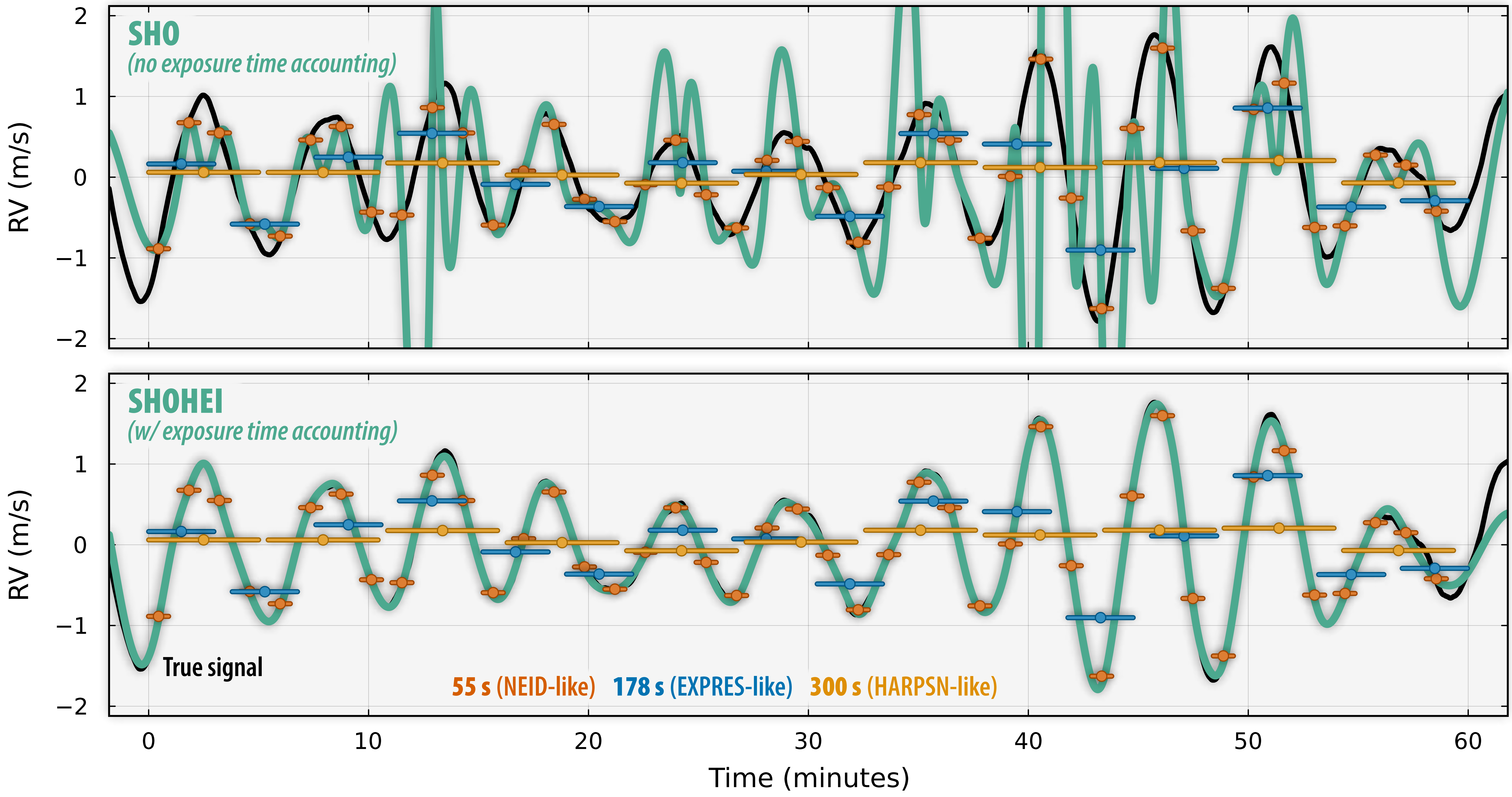
Harmonic

Oscillators

Harnessing

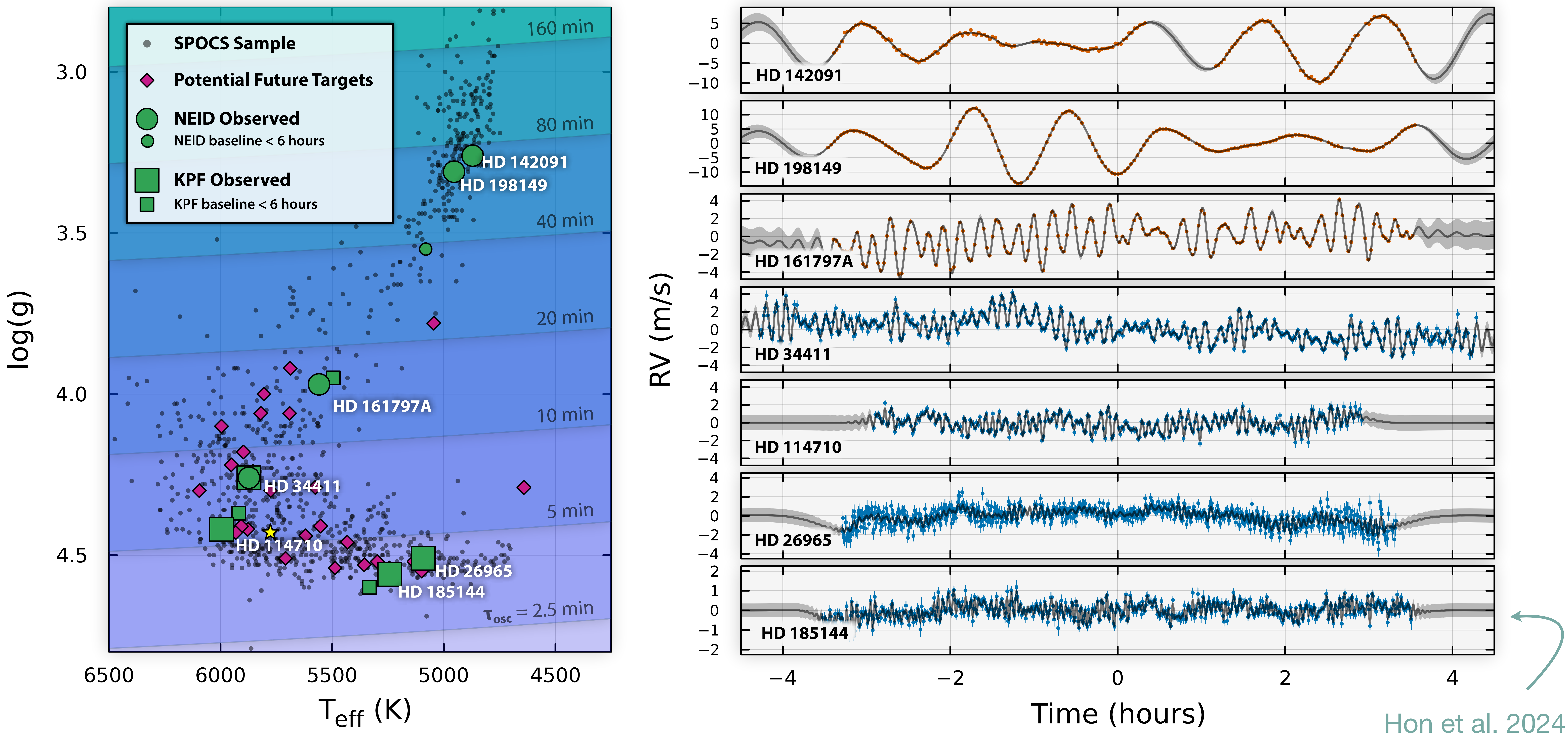
Exposure

Integration



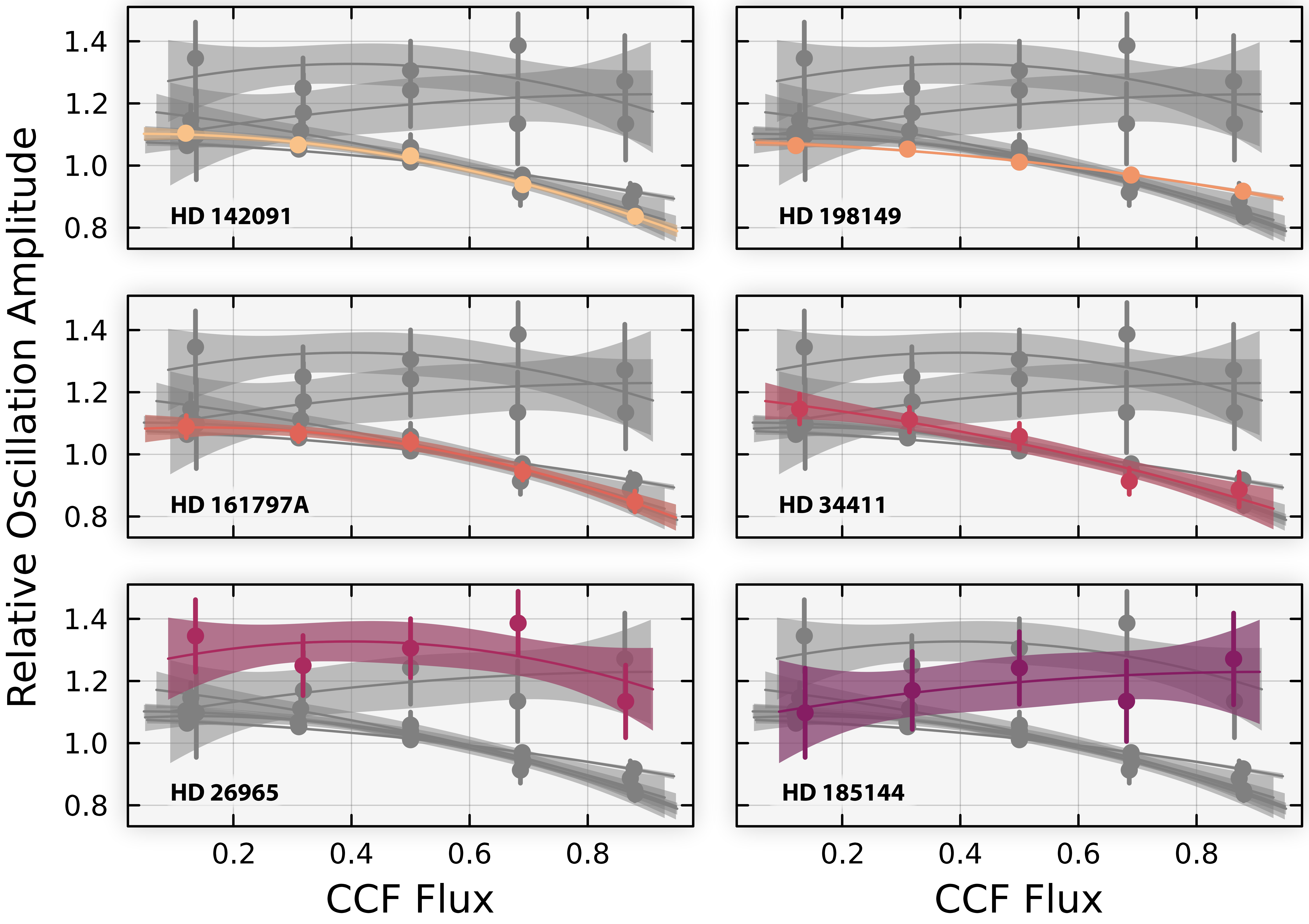
SHO
(no exposure time accounting)
SHOHEI
(w/ exposure time accounting)
True signal
55 s (NEID-like)
178 s (EXPRES-like)
300 s (HARPSN-like)
RV (m/s)
Time (minutes)

NEID & KPF: From giants to dwarfs



Hon et al. 2024

Oscillations across the HR diagram

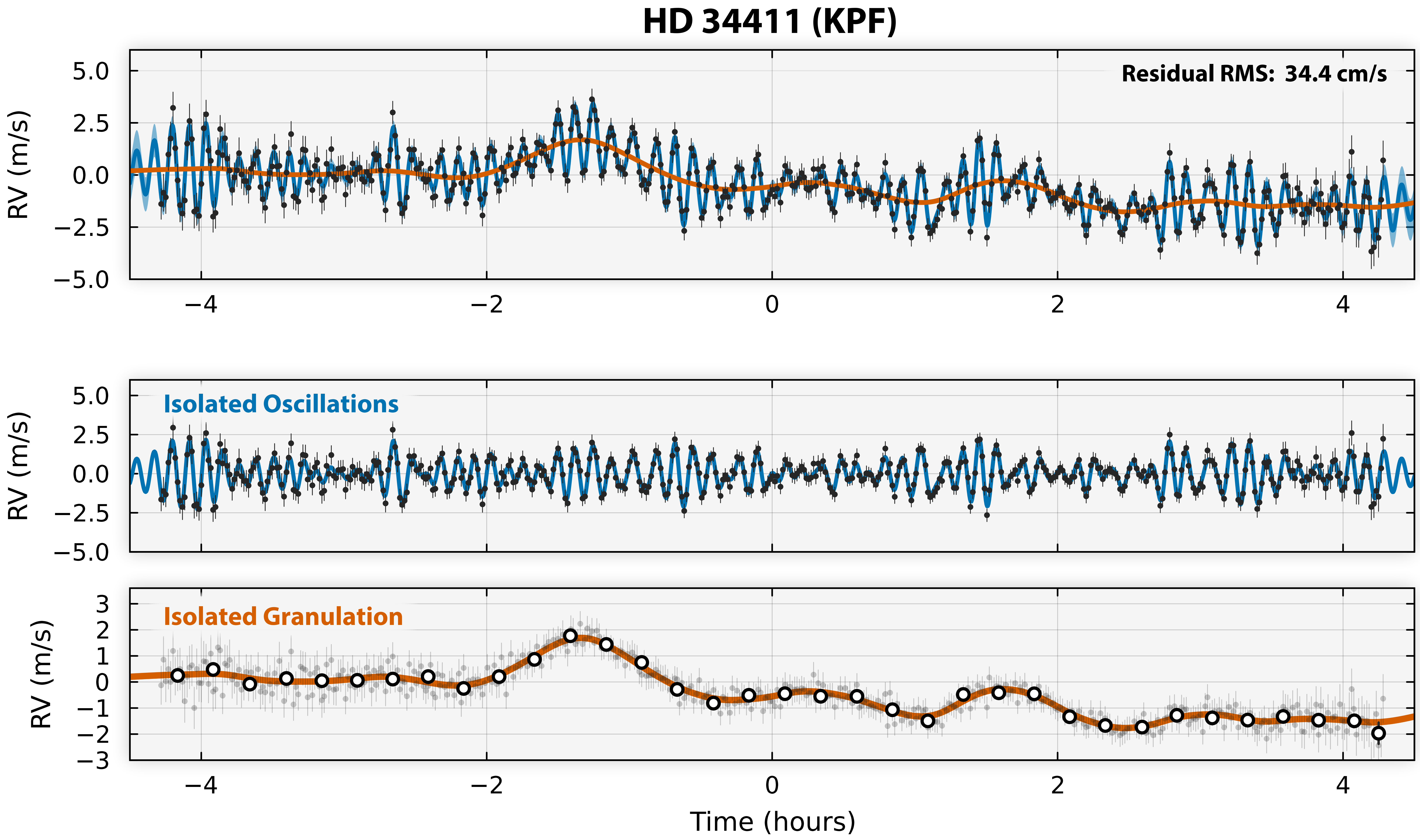


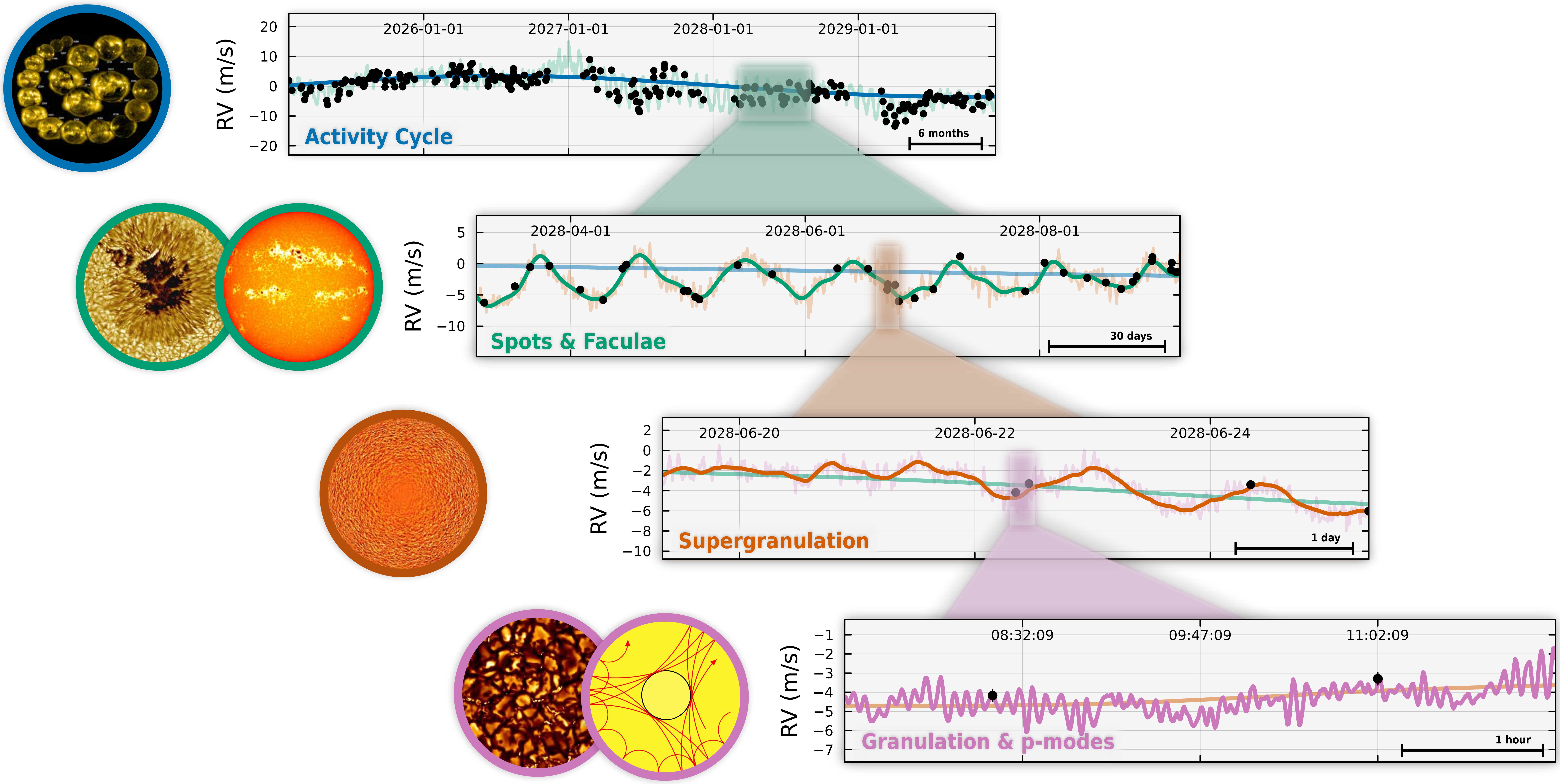
Consistent trend for most targets

Flattening (reversal?) for K dwarfs?

Isolated granulation signals

Multicomponent GP decomposition in Luhn+ 2026





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Takeaways

Oscillation amplitudes are stronger at the core of the CCF, higher in the star

Trend holds for less evolved stars, hint of a flattening/reversal for K dwarfs

Next steps

CCF diagnostics of granulation

RVs tied to physical properties (height, density, formation temperature)

Perform community data challenge to assess ability to mitigate variability