Towards Doppler Eclipse Mapping of Hot Jupiters

An observational perspective on WASP-33 b with SPIRou

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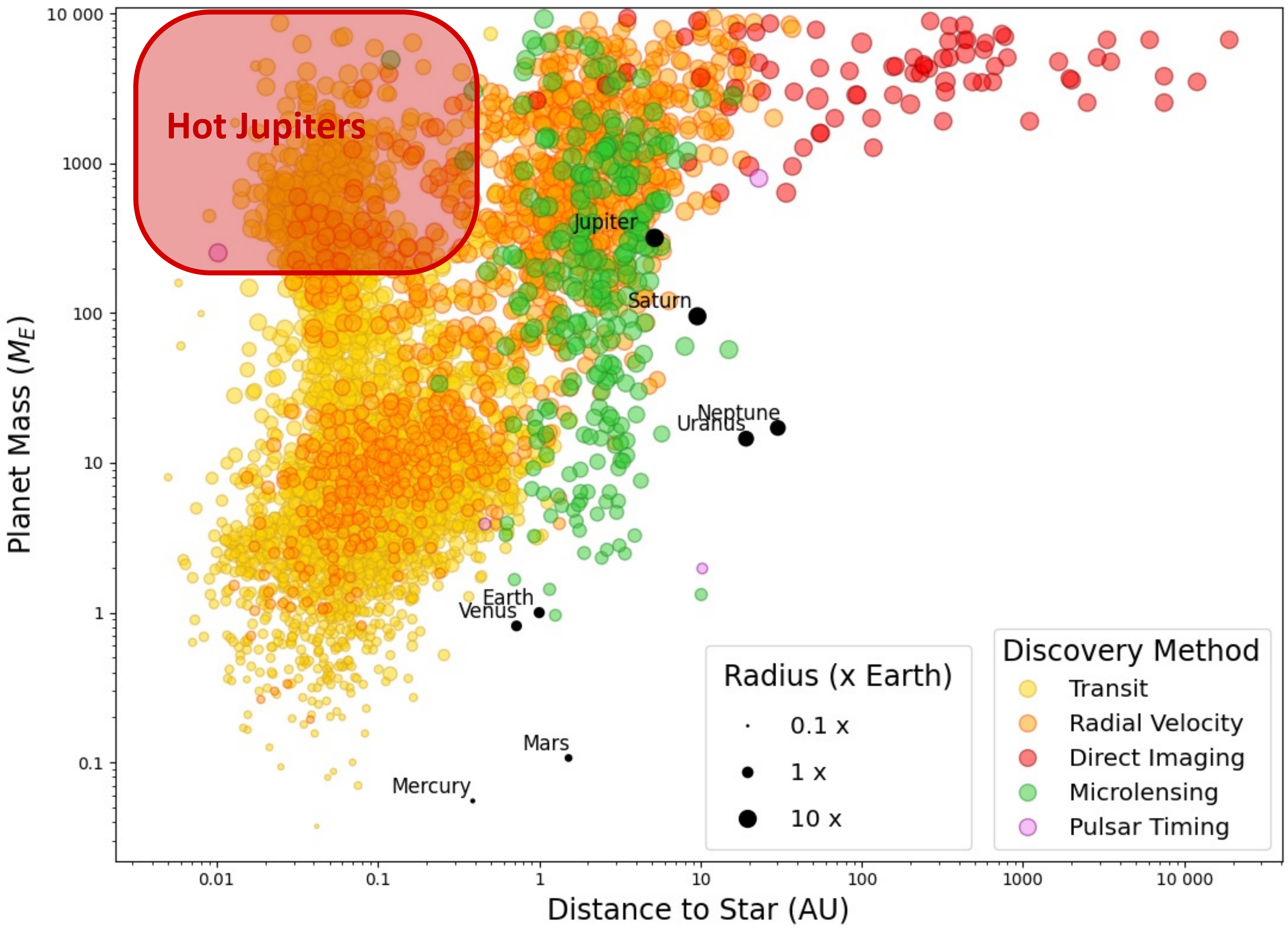
Ateliers SF2A 2026

SPiRou

ATMOSPHERIX

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

Hot Jupiters: A quick introduction



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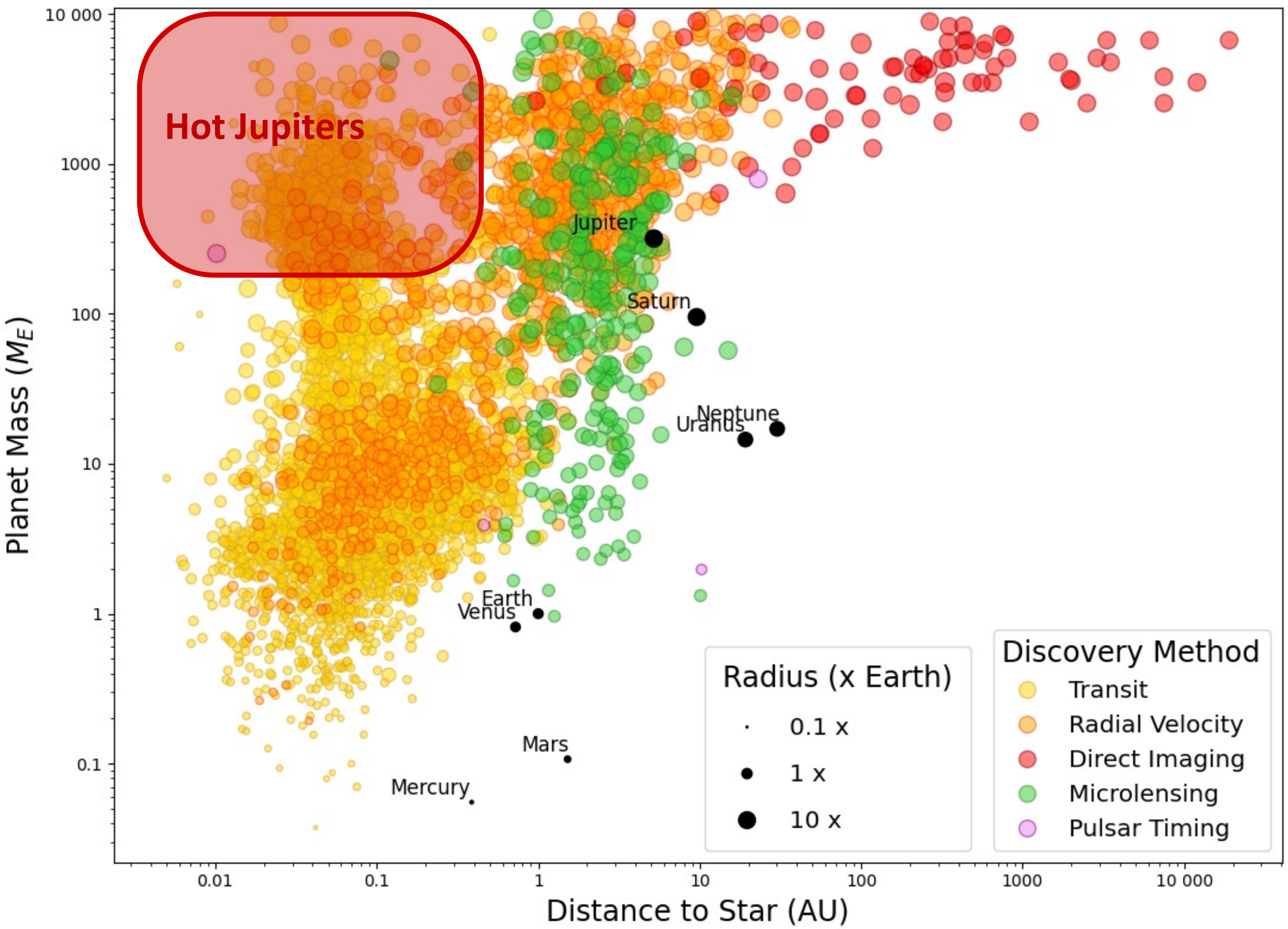


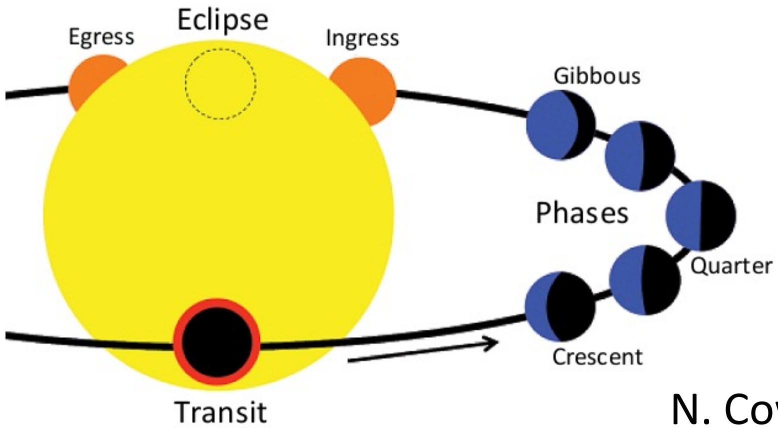
➔ Large Radii

➔ High Temperatures

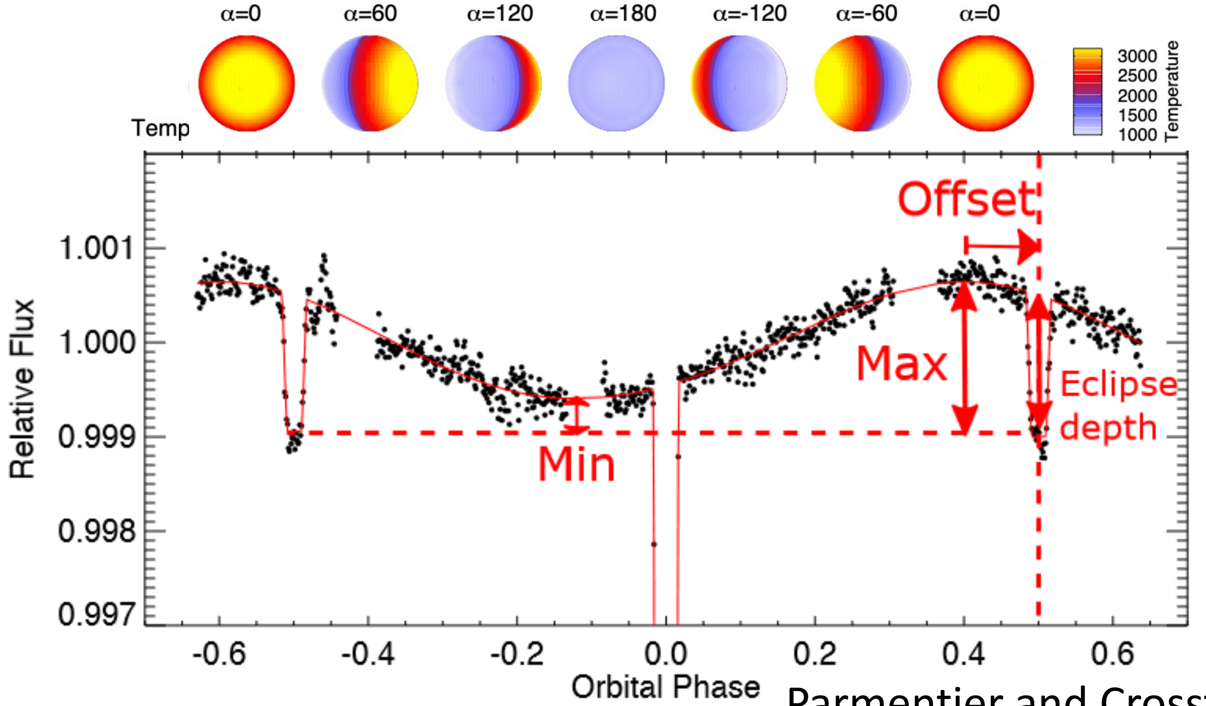
➔ Short Period

➔ Easiest targets for in-depth characterisation and comparison with 3D models

Hot Jupiters: What we know from observations



N. Cowan (2014)

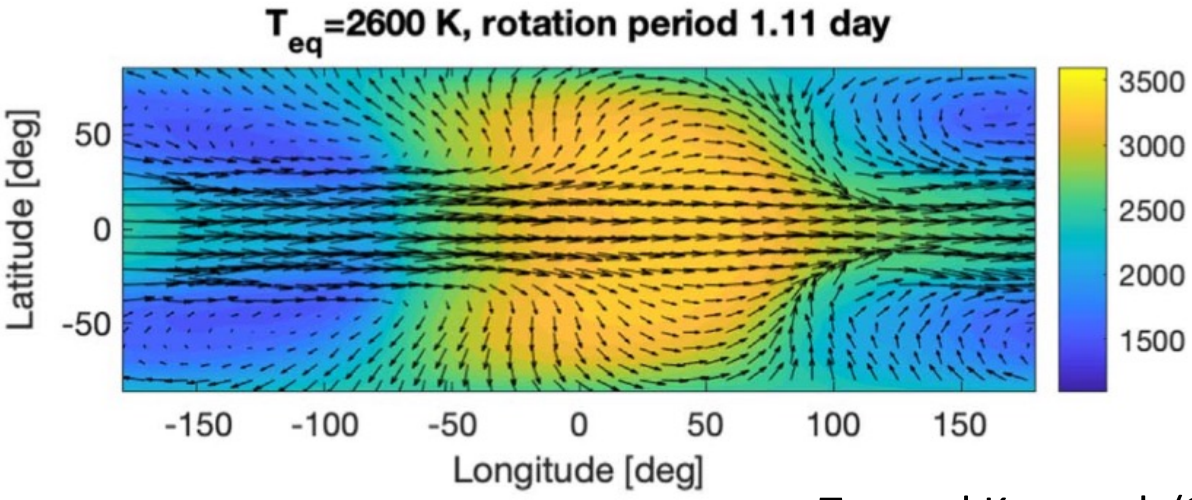


Parmentier and Crossfield (2018)

➔ Easiest targets for **in-depth characterisation** and comparison with 3D models

- Extreme day/night **temperature contrasts** due to tidal locking

Hot Jupiters: What we know from observations

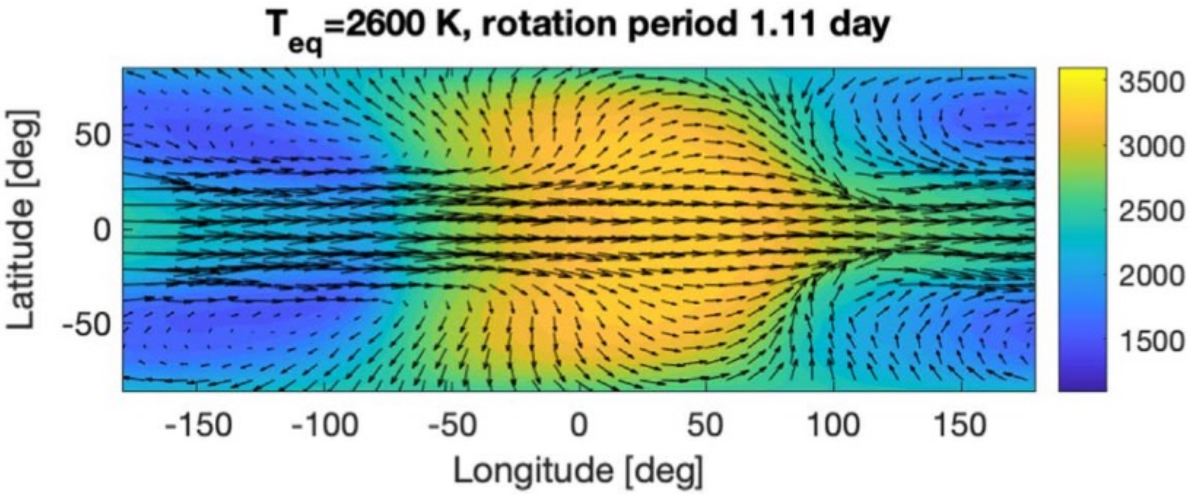


Tan and Komacek (2019)

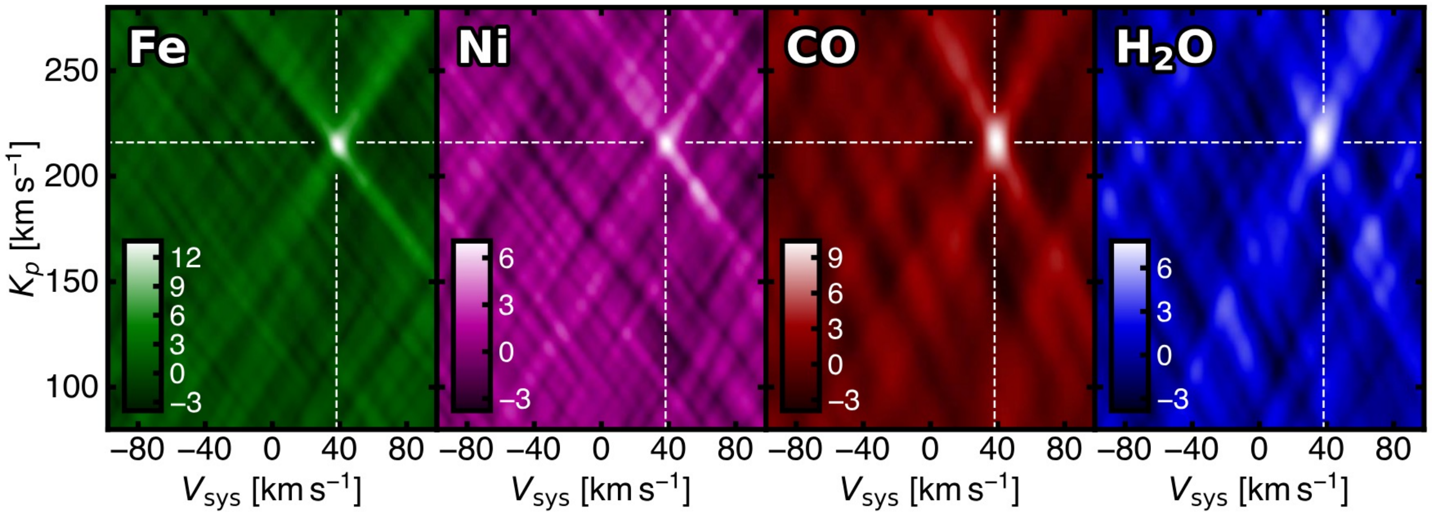
➔ Easiest targets for **in-depth characterisation** and comparison with 3D models

- Extreme day/night **temperature contrasts** due to tidal locking
- Thermally driven **supersonic winds**

Hot Jupiters: What we know from observations



Tan and Komacek (2019)



Pelletier et al. (2025)

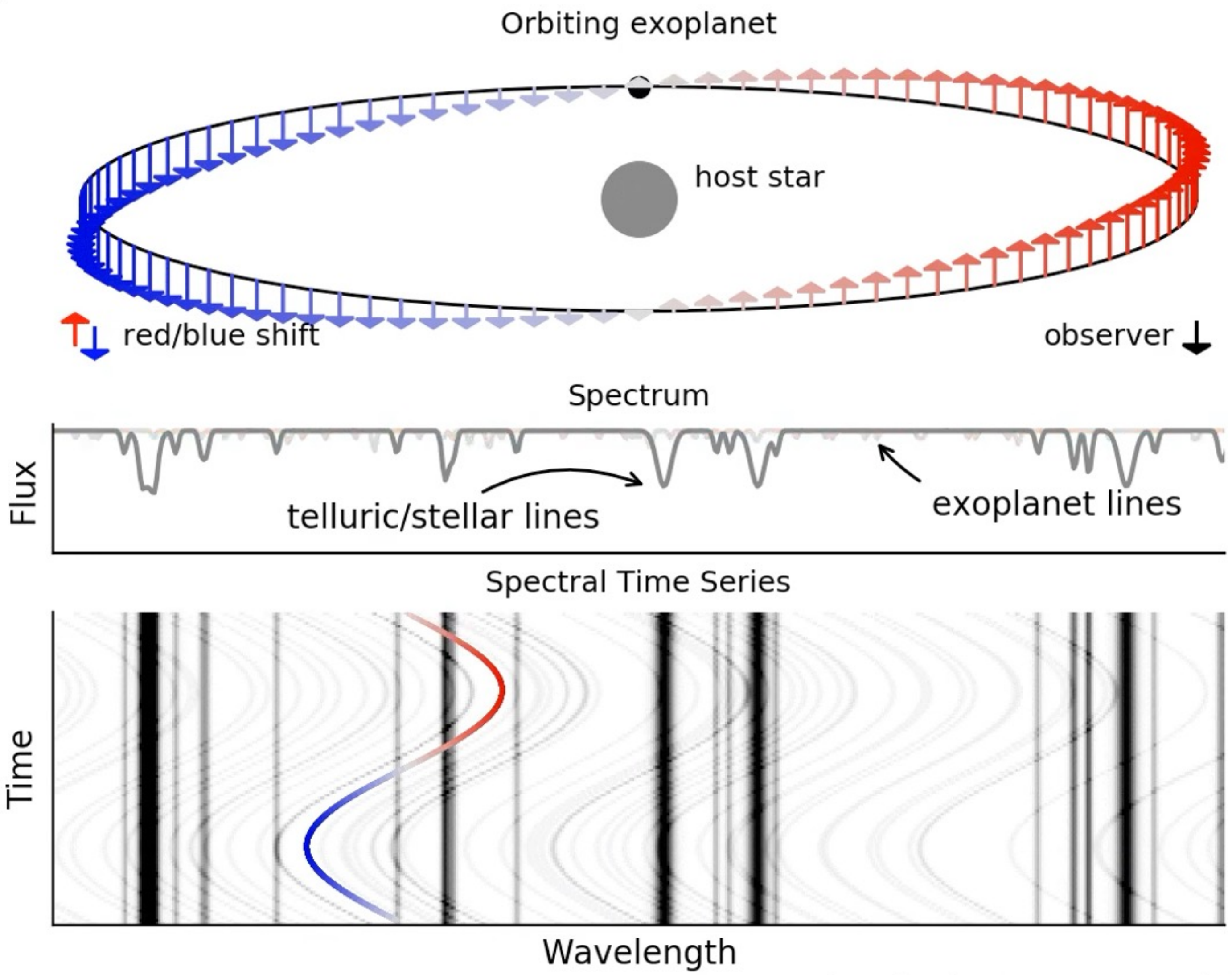
➔ Easiest targets for **in-depth characterisation** and comparison with 3D models

- Extreme day/night **temperature contrasts** due to tidal locking
- Thermally driven **supersonic winds**
- Most molecules **thermally dissociated**
- **Silicates & Metals vapourised** on the dayside / "cold trapped" on the nightside

High Resolution Spectroscopy crash-course

- Stellar/Telluric lines:
  Mostly static over time-series

- Planetary lines:
  Doppler shift through the orbit (>10s km/s over a few hours)



Animation by Lennart van Sluijs

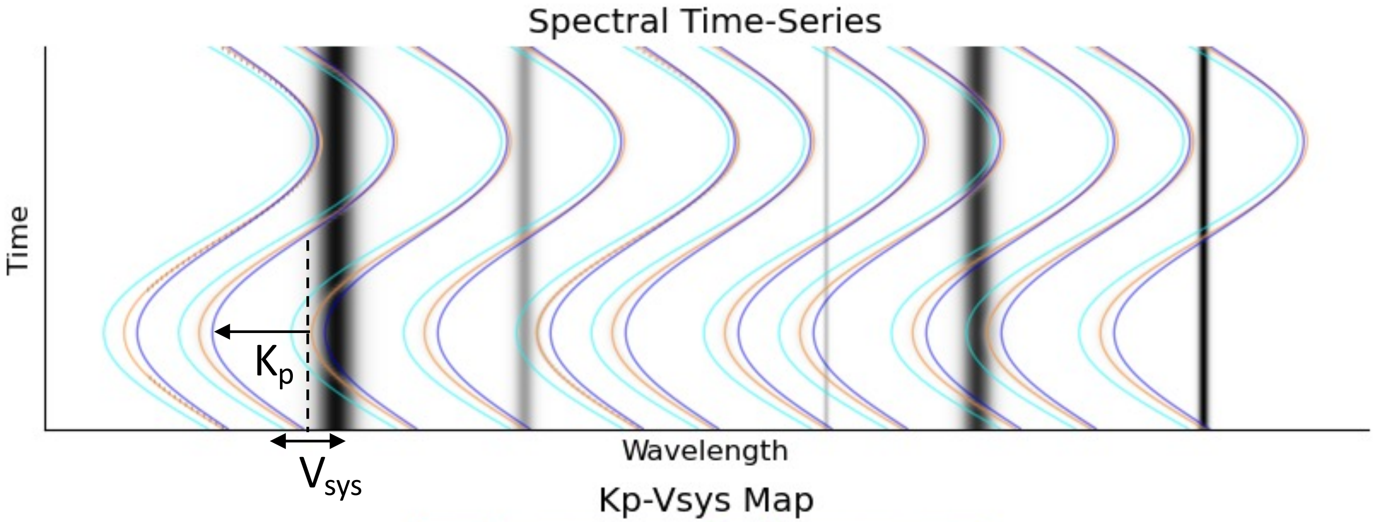
High Resolution Spectroscopy crash-course

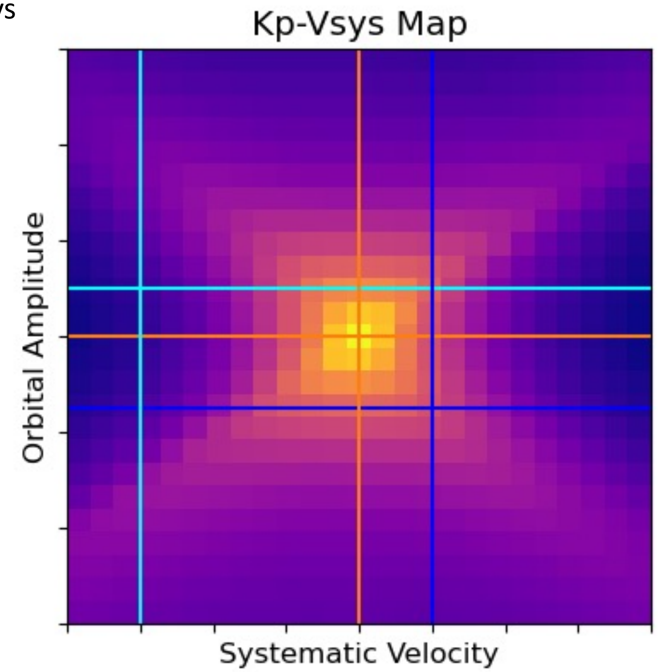
- Stellar/Telluric lines:
  Mostly static over time-series

- Planetary lines:
  Doppler shift through the orbit (>10s km/s over a few hours)

- Cross-Correlation:
  Sum signal from 1000s of planetary lines to **overcome residual noise**

- Detection Maps:
  Sum CCFs over time-series to quantify detection SNR

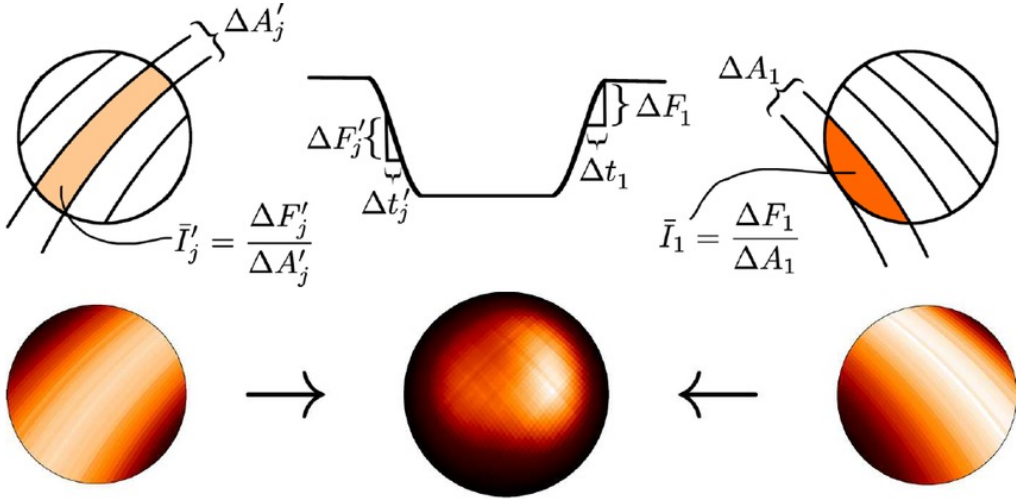




Eclipse Mapping

- **Flux variations** in eclipse are linked to **temperature** of the occulted planet surface

➔ Time-resolved Flux = Temperature Map



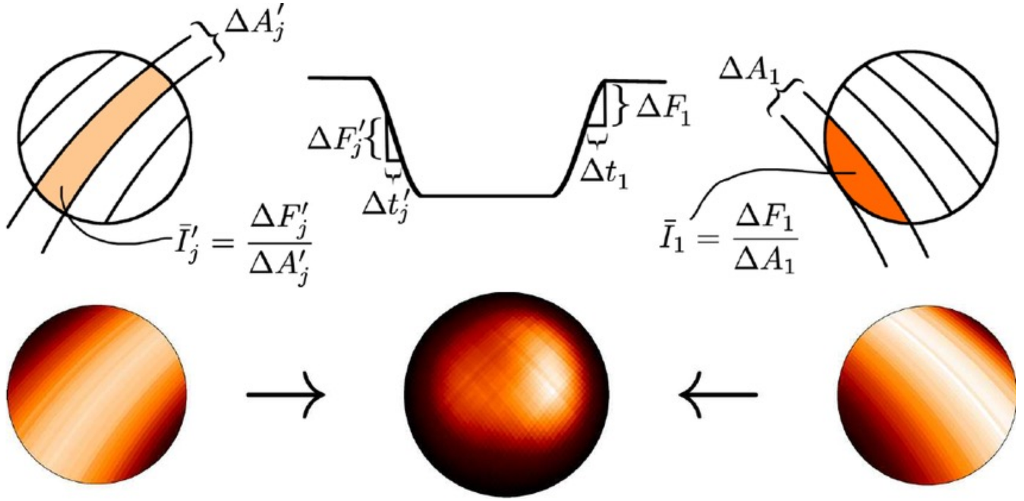
Cowan & Fuji (2012)

Eclipse Mapping

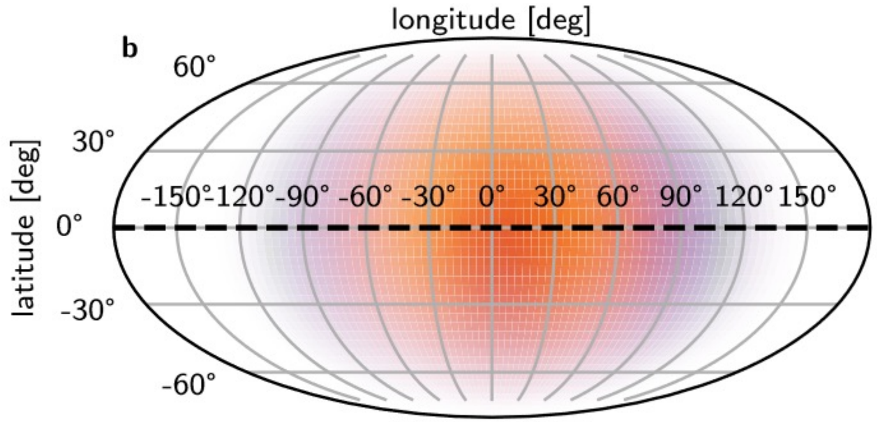
- **Flux variations** in eclipse are linked to **temperature** of the occulted planet surface

➔ Time-resolved Flux = Temperature Map

- Successfully performed on a few targets with JWST



Cowan & Fuji (2012)



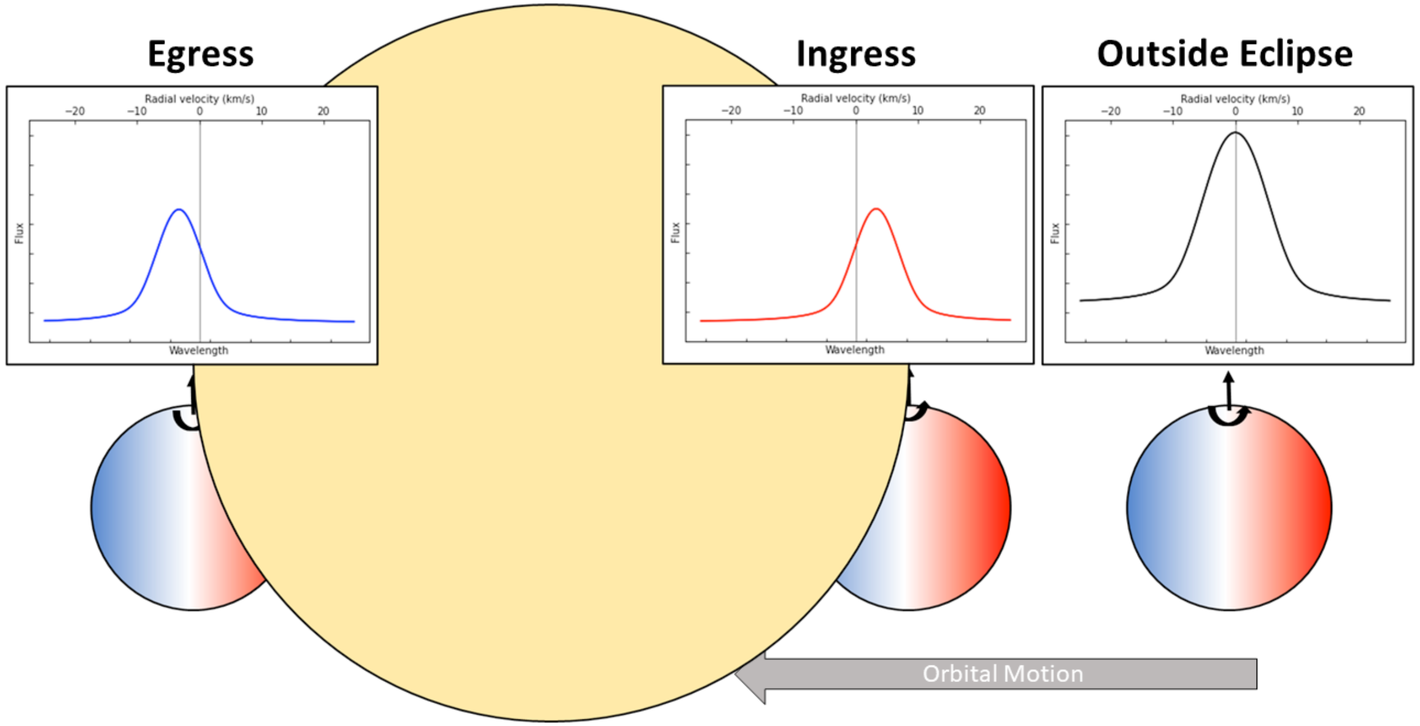
Coulombe et al. (2023)

Eclipse Mapping

➔ Time-resolved Flux = Temperature Map

Eclipses at High Resolution:

- Line shifting effect
- Change in line shape

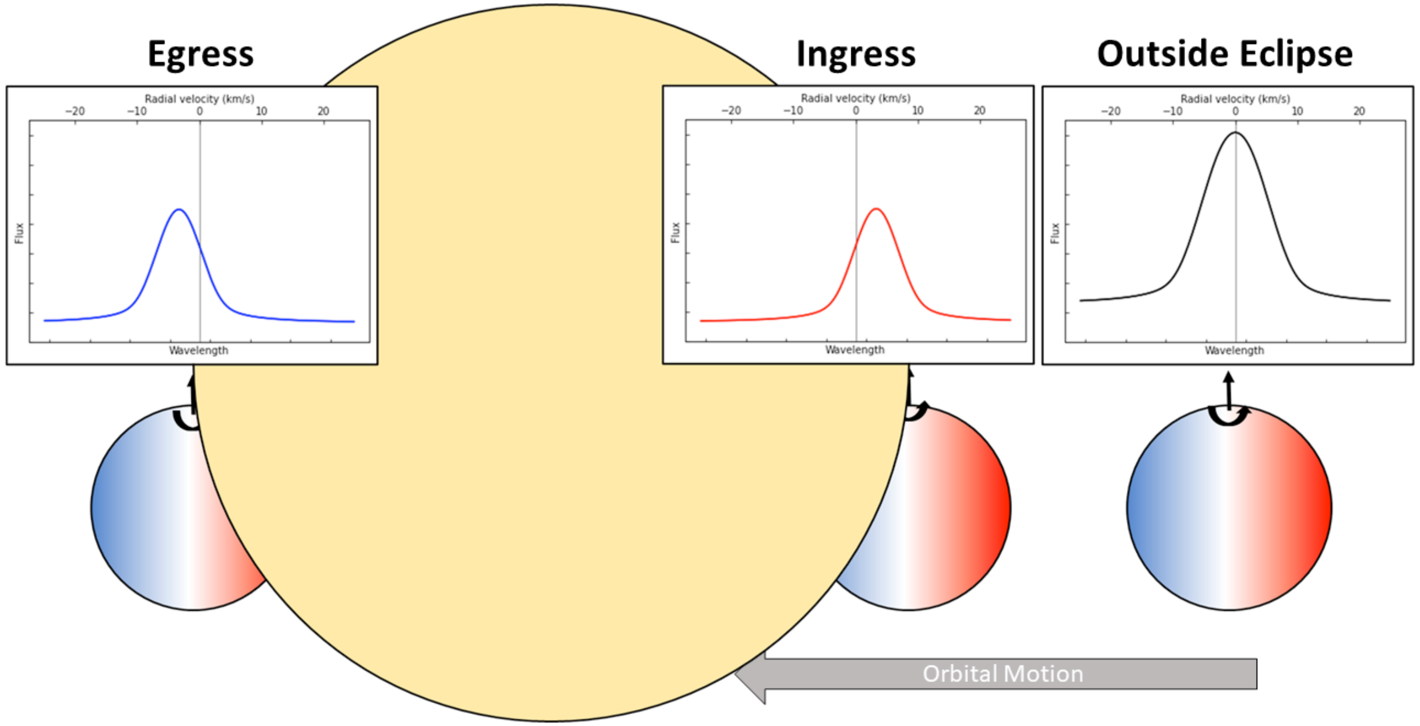


Eclipse Mapping

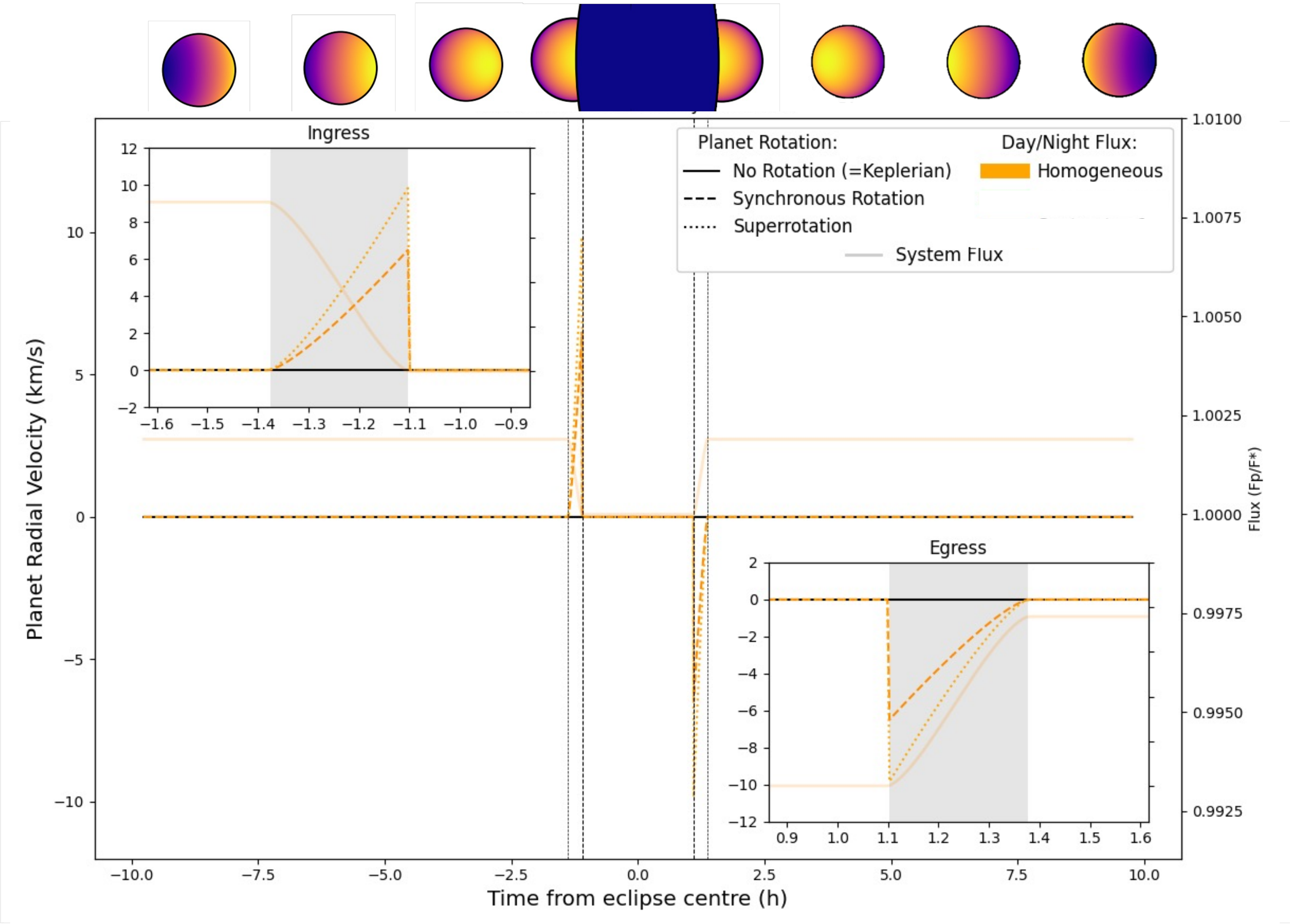
➔ Time-resolved Flux = Temperature Map

Eclipses at High Resolution:
- Line shifting effect
- Change in line shape

In contrast to Low-Resolution:
- Sensitive to vertical temperature gradient
- Sensitive to spatial repartition of individual species
- Sensitive to planet rotation and wind profiles



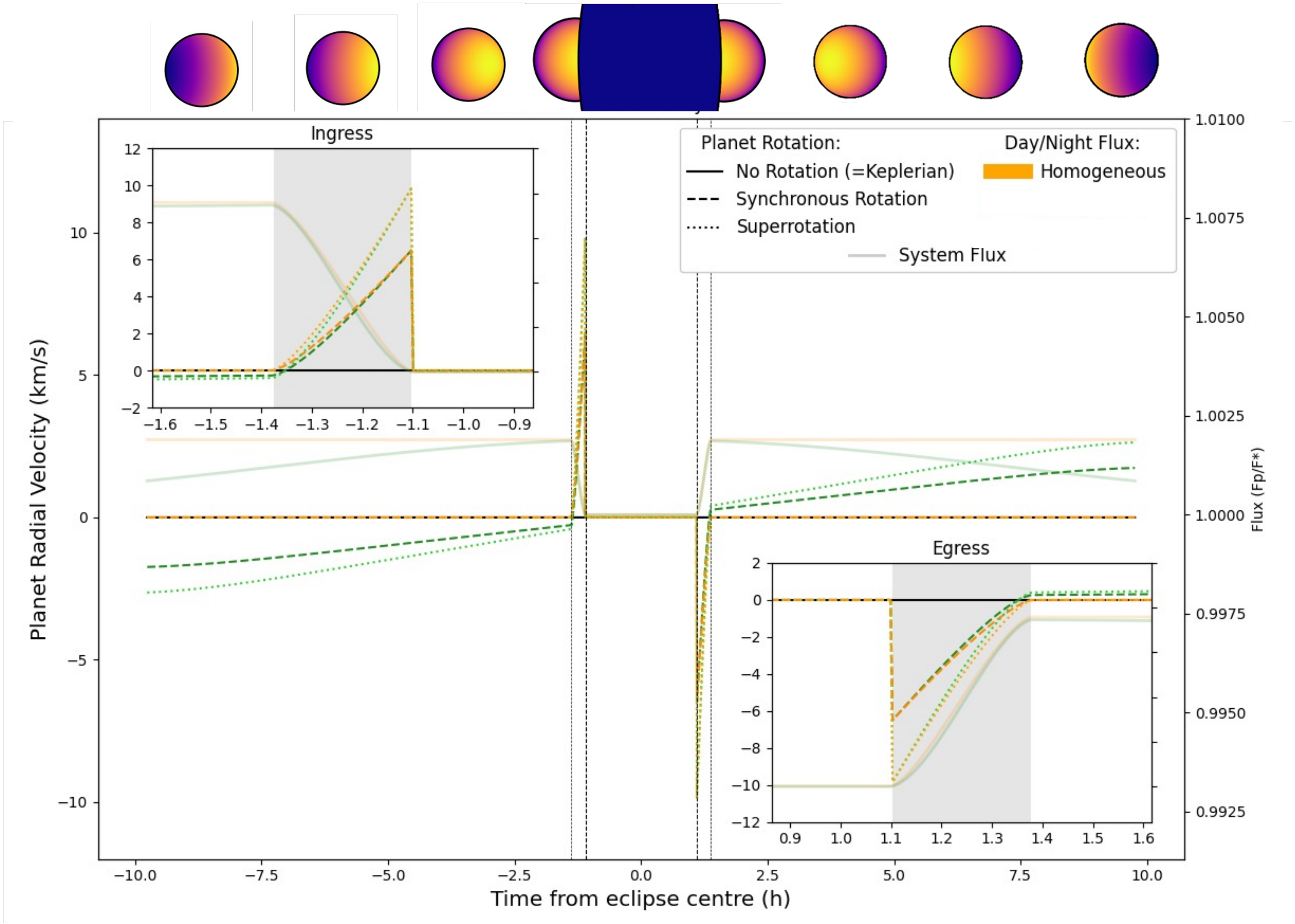
Velocity Offsets: In and out of eclipse



The rotation effect in eclipse:

- Redshifted during ingress
- Blueshifted during egress

Velocity Offsets: In and out of eclipse



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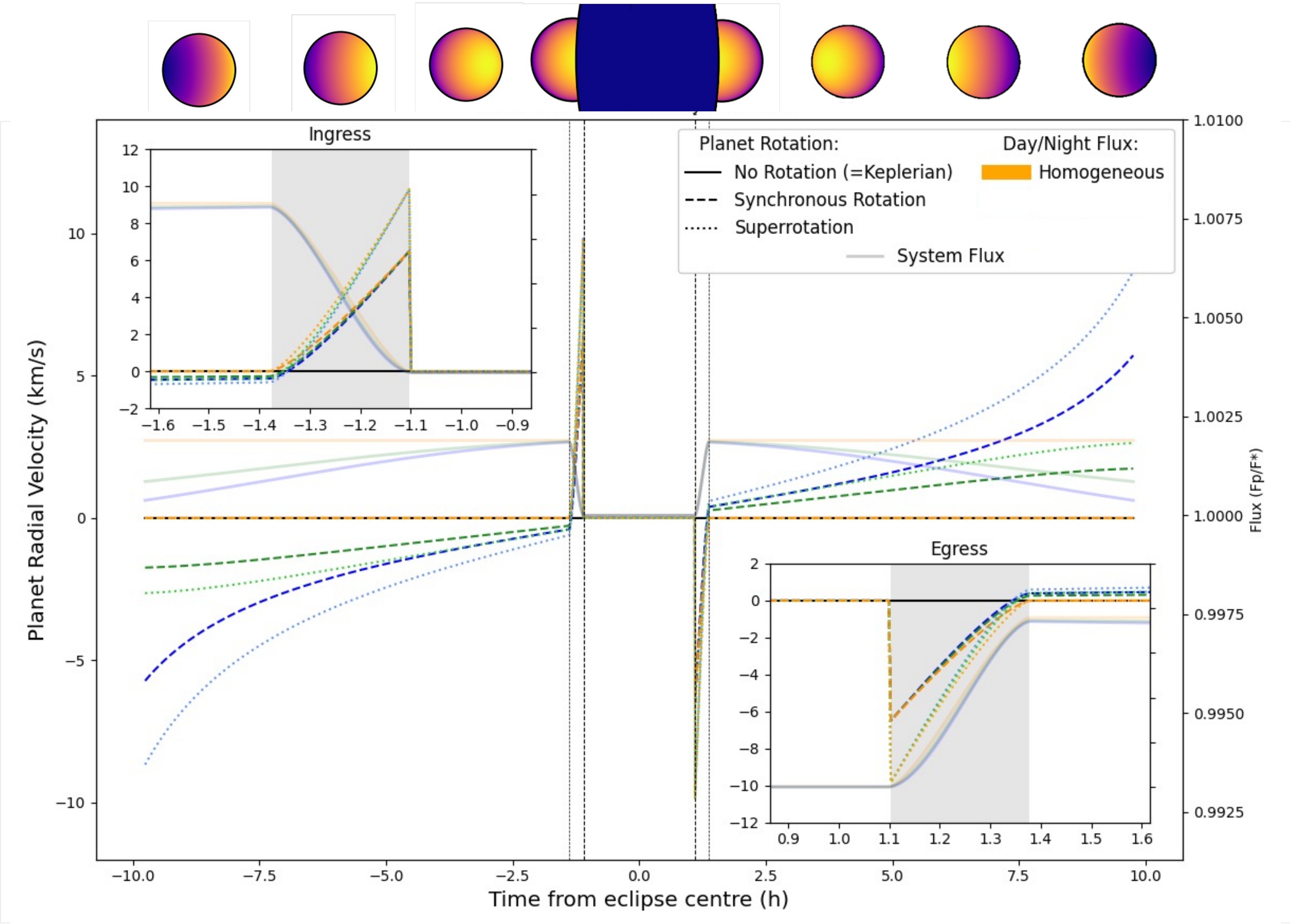
- Day/Night contrast results in **Kp offsets outside eclipse**

Velocity Offsets: In and out of eclipse



The rotation effect in eclipse:

- Redshifted during ingress
- Blueshifted during egress

- Day/Night contrast results in **Kp offsets outside eclipse**

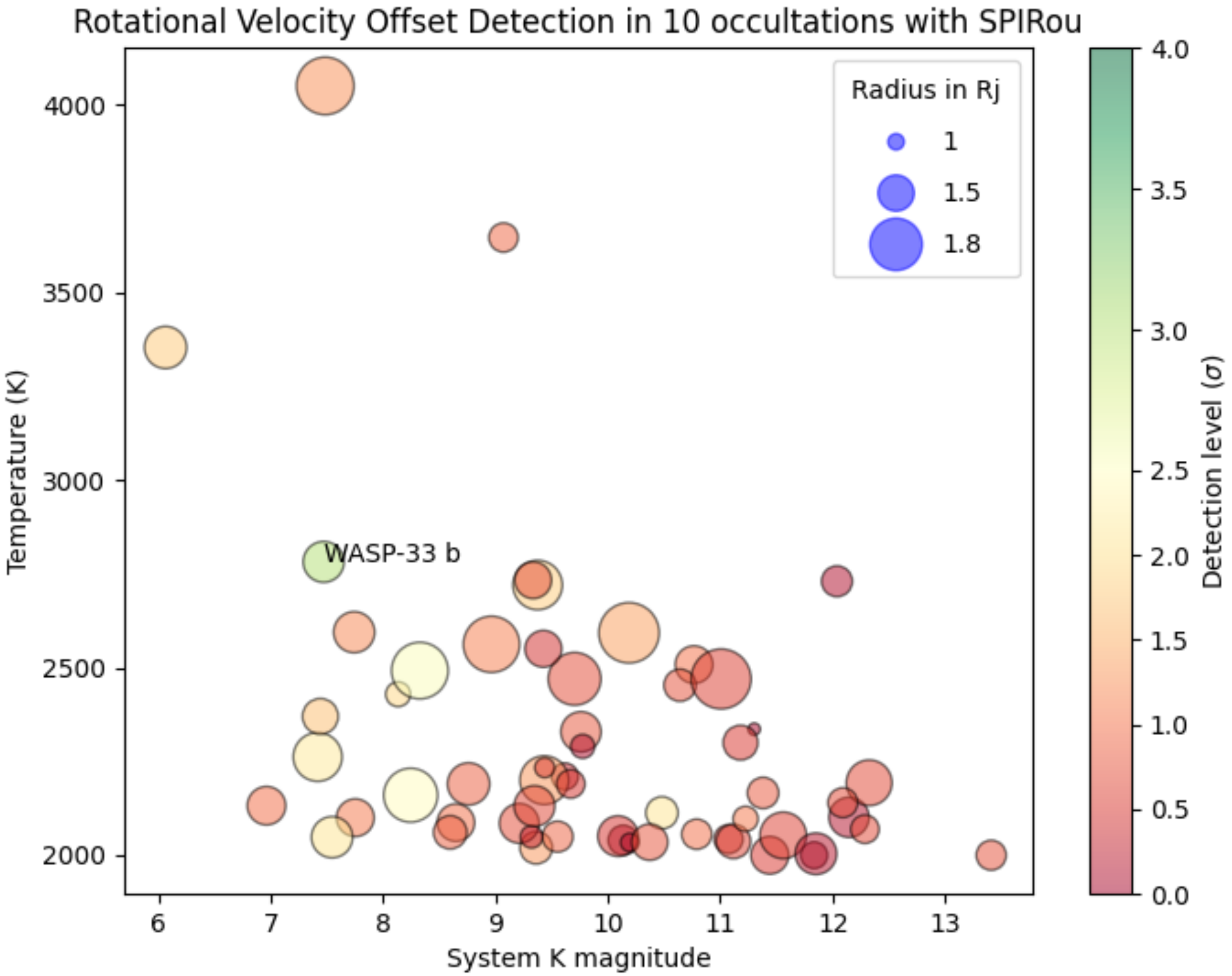
- In-eclipse effect **less impacted** by contrast ratio

A promising target for SPIRou?

- WASP-33b is currently the **only feasible target** within the known population of ultra Hot-Jupiters (T_{eq}>=2000K)
- Rotation effect could be **detectable within 10 eclipses** (photon noise limit)

<u>SPIRou</u>

D – 3.6m
R ~ 70 000
λ – 0.95-2.35µm
η ~ 12%



WASP-33b: A quick introduction

Star Parameters

R_* – 1.5 $R_\odot$

T_{eff} – 7400 K

m_K – 7.5

v_{sini} – 90km/s

Sp.T. – Am (δ scuti)

Planet Parameters

P – 1.2 days

R_P – 1.6 Rj

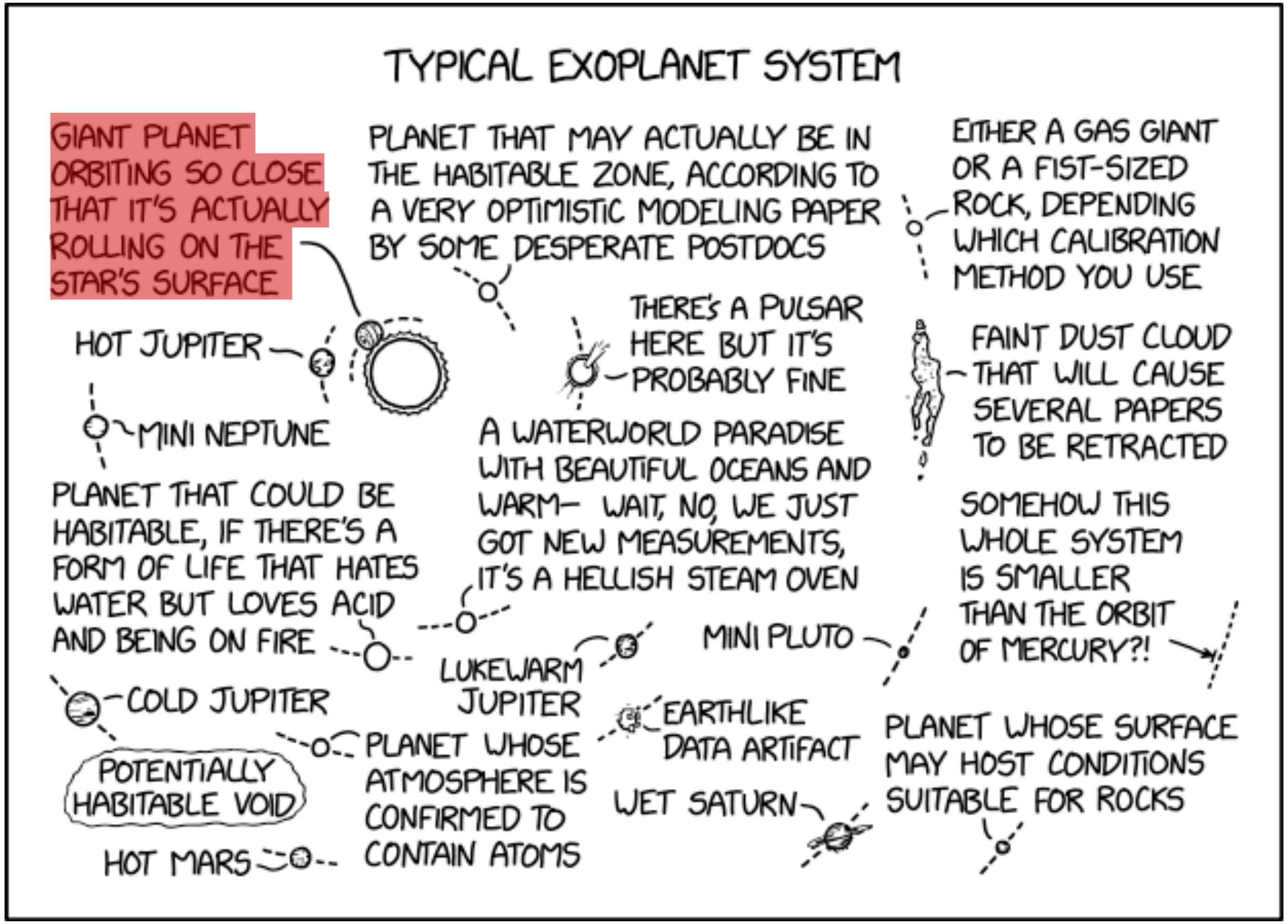
M_p – 2.1 Rj

T_{eq} – 2800 K

v_{syn} – 6.7 km/s

K_p – 231 km/s

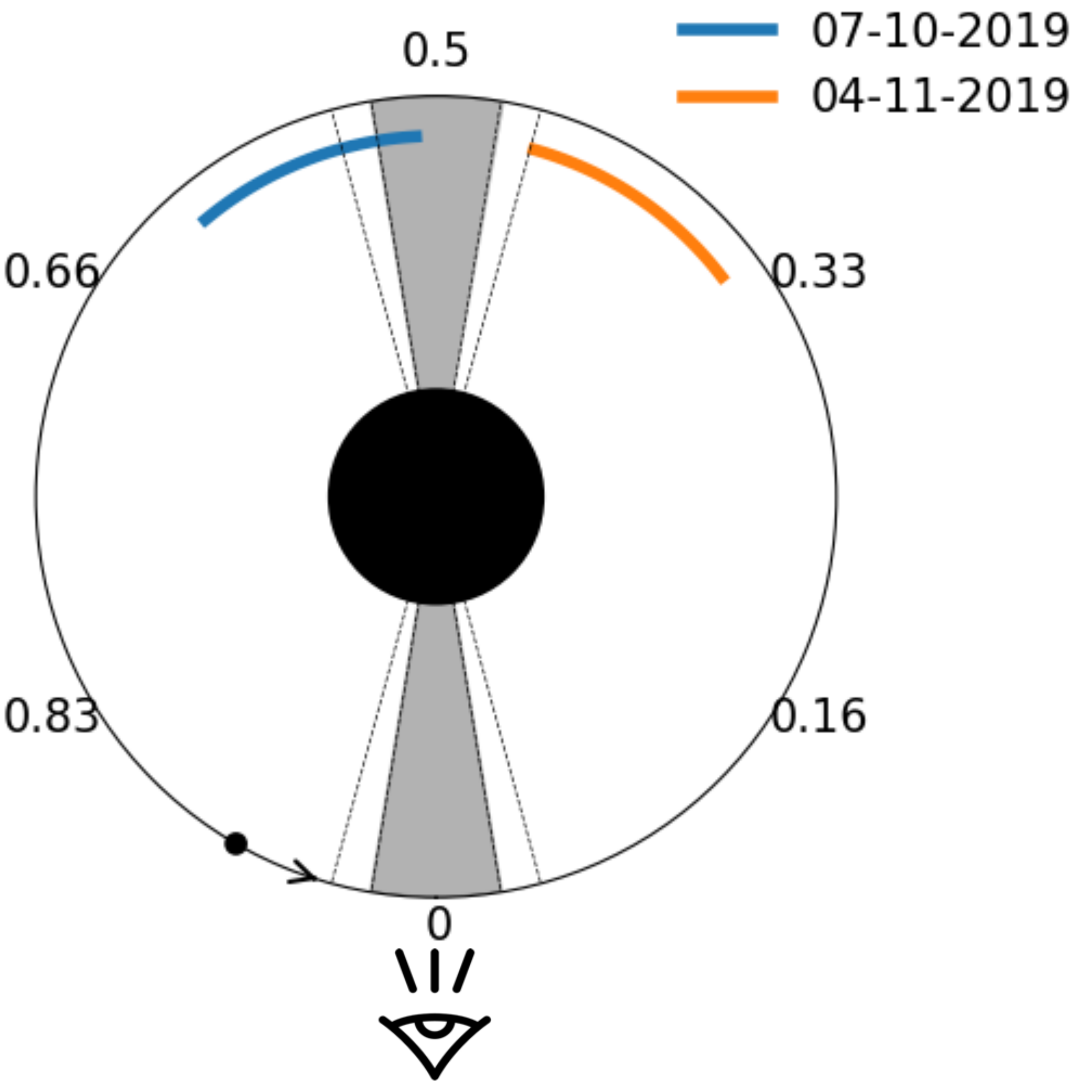
- Canonical **Ultra-Hot Jupiter**
- Temperature-Pressure **inversion**
- **Many species** detected on its dayside with HRS (Fe, CO, OH…)



xkcd.com

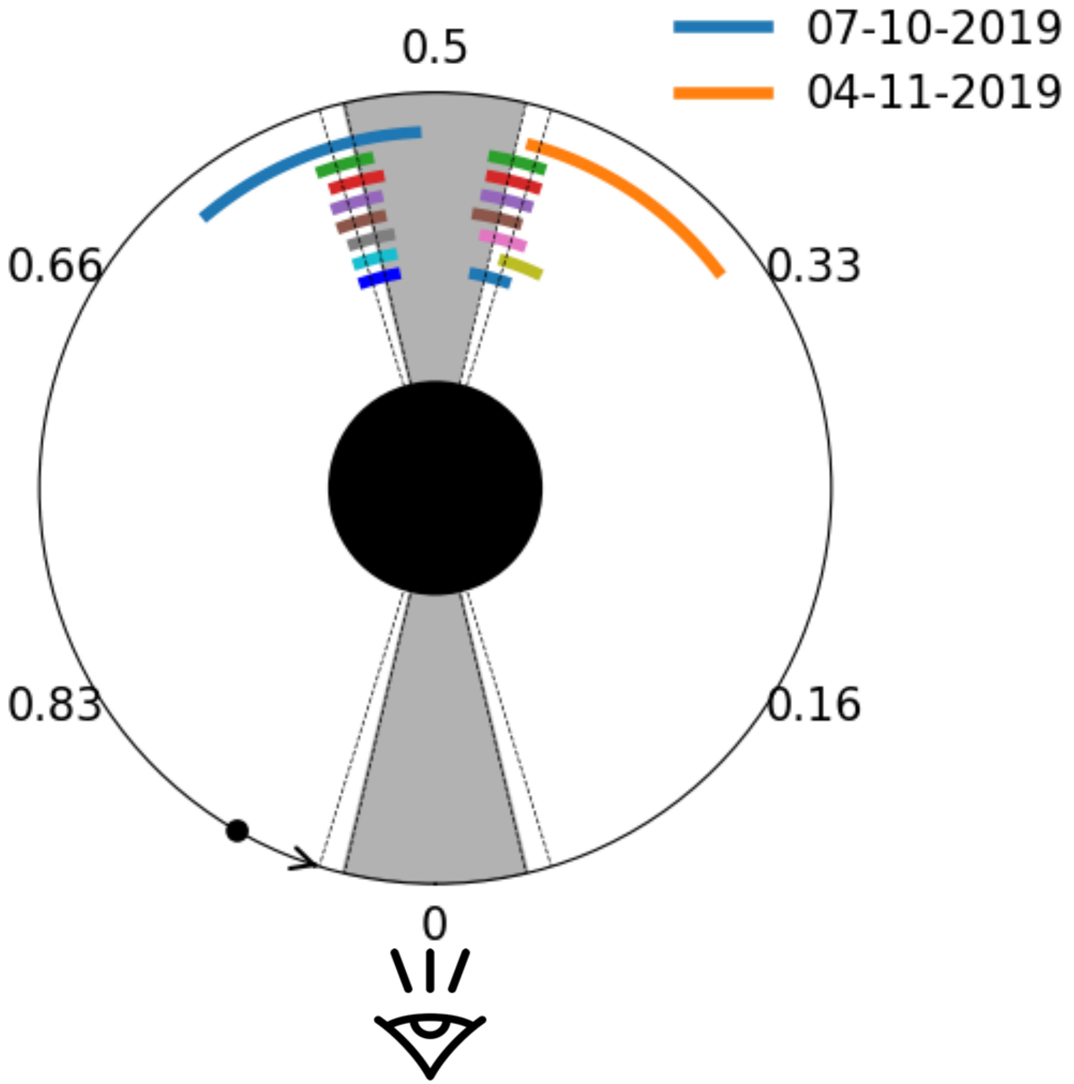
Observations

- Archival dayside observations (PI: Darveau-Bernier)



Observations

- Archival dayside observations (PI: Darveau-Bernier)
- 8 Ingresses and Egresses from 2023B and 2024B (Atmospherix LP and PI program)



Data Reduction

Telluric-Corrected 2D spectra (APERO)

↓

Mask outliers & Deep Telluric lines (<30% transmission)

↓

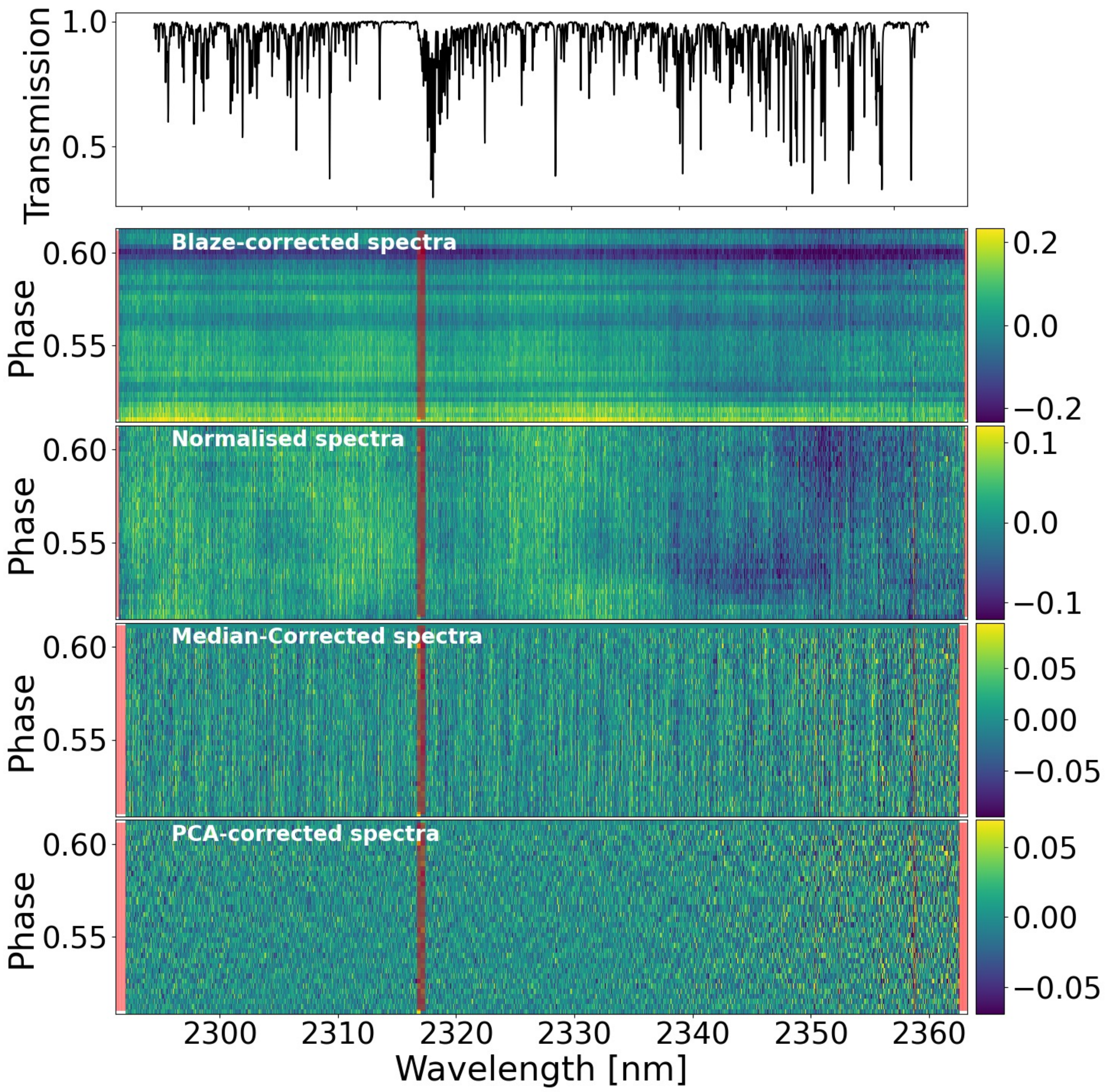
Remove median star spectrum

↓

Fit residual time variance with PCA (1-3 PCs removed)

↓

Residual "white noise-like" spectra



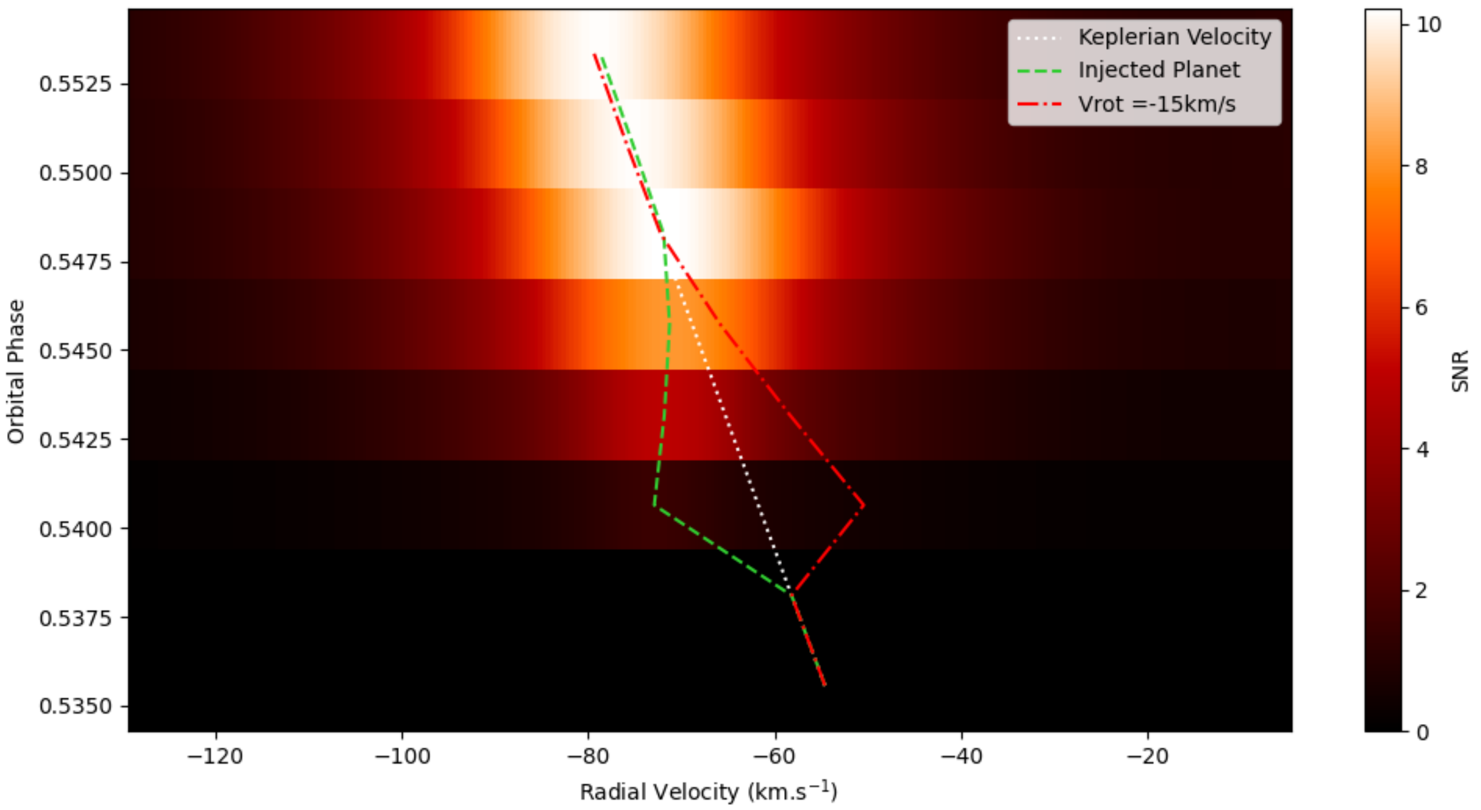
Data Reduction - Challenges

- Velocity shifts in ingress/egress shift the trail **closer to fixed velocities** in short time-series
- With rotational broadening, planet signal is **overlapping in velocity space** across frames

➔ Median spectrum **removing** some planetary contribution

➔ PCA **degrades planet signal** with fewer PCs

Signal Injection – Egress time-series

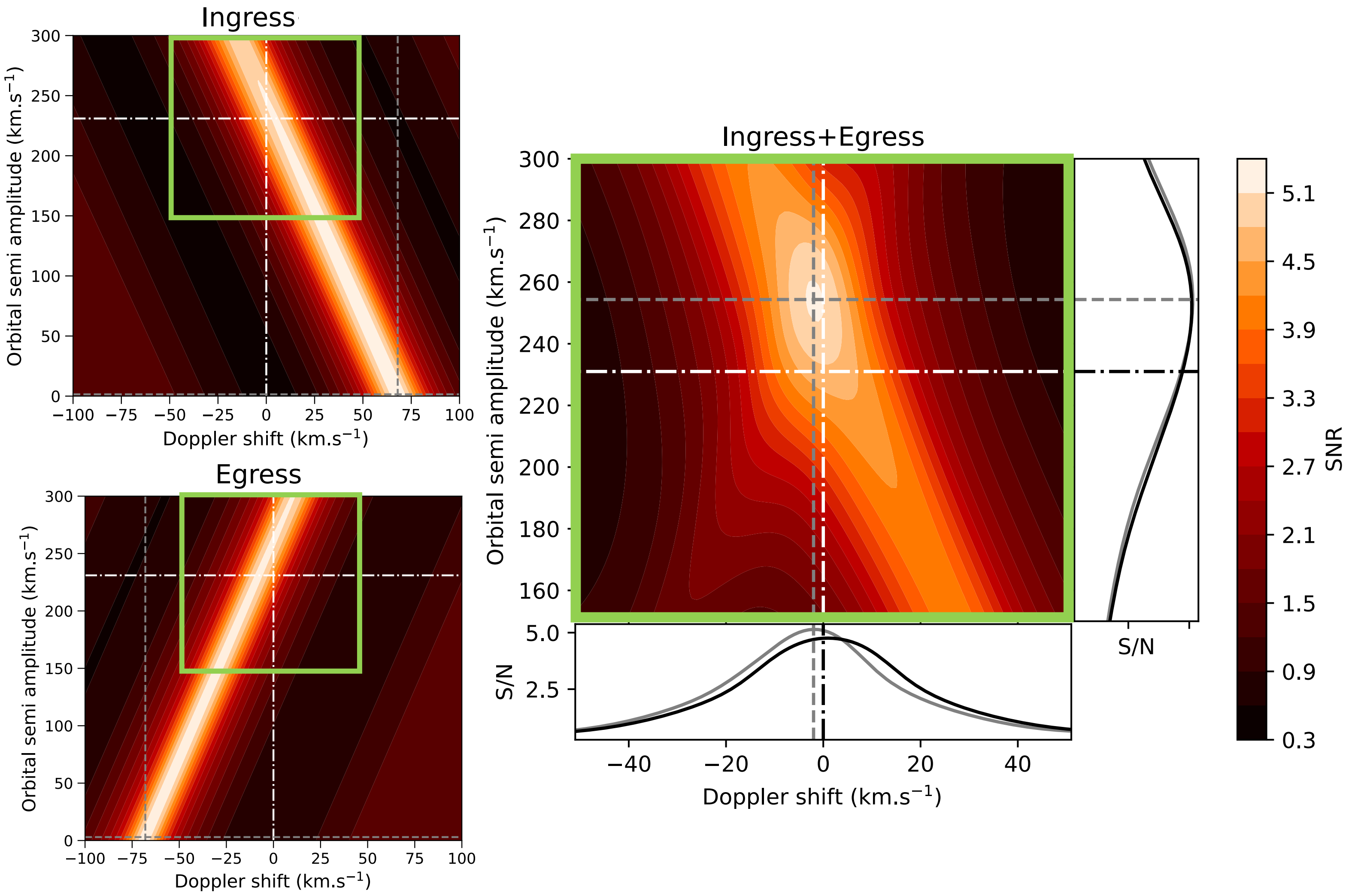


What should we expect to see in Kp-Vsys?

- Ingress and Egress trail **shifted away** from each other

➢ In/egress only: maxima shifted to **lower Kp**

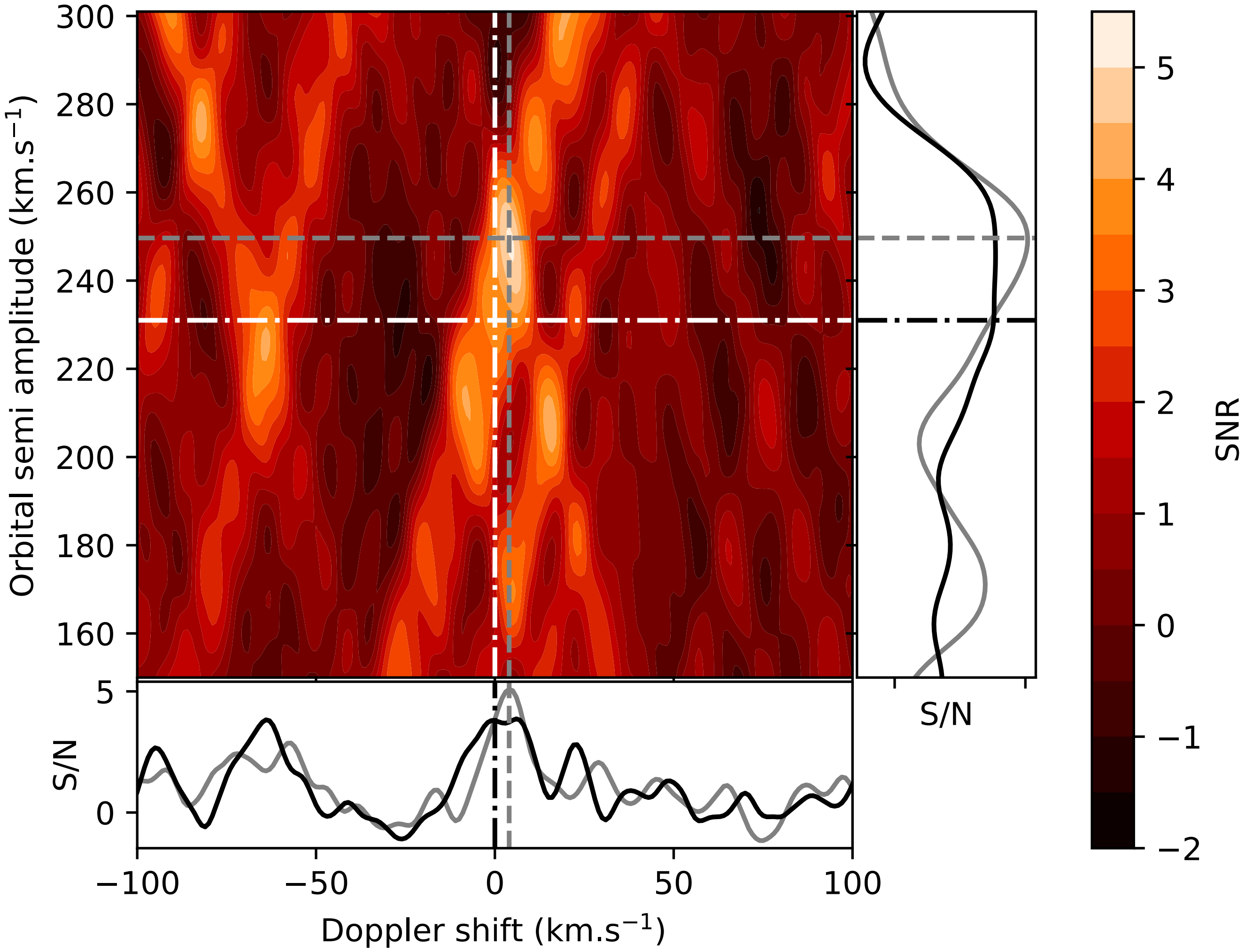
➢ Full eclipse: maxima shifted to **higher Kp**



What does the data say?

Over 8 eclipses so far...

- **Tentative** CO detection with wide velocity uncertainty
- **Higher than expected Kp** could hint we are seeing the velocity offset

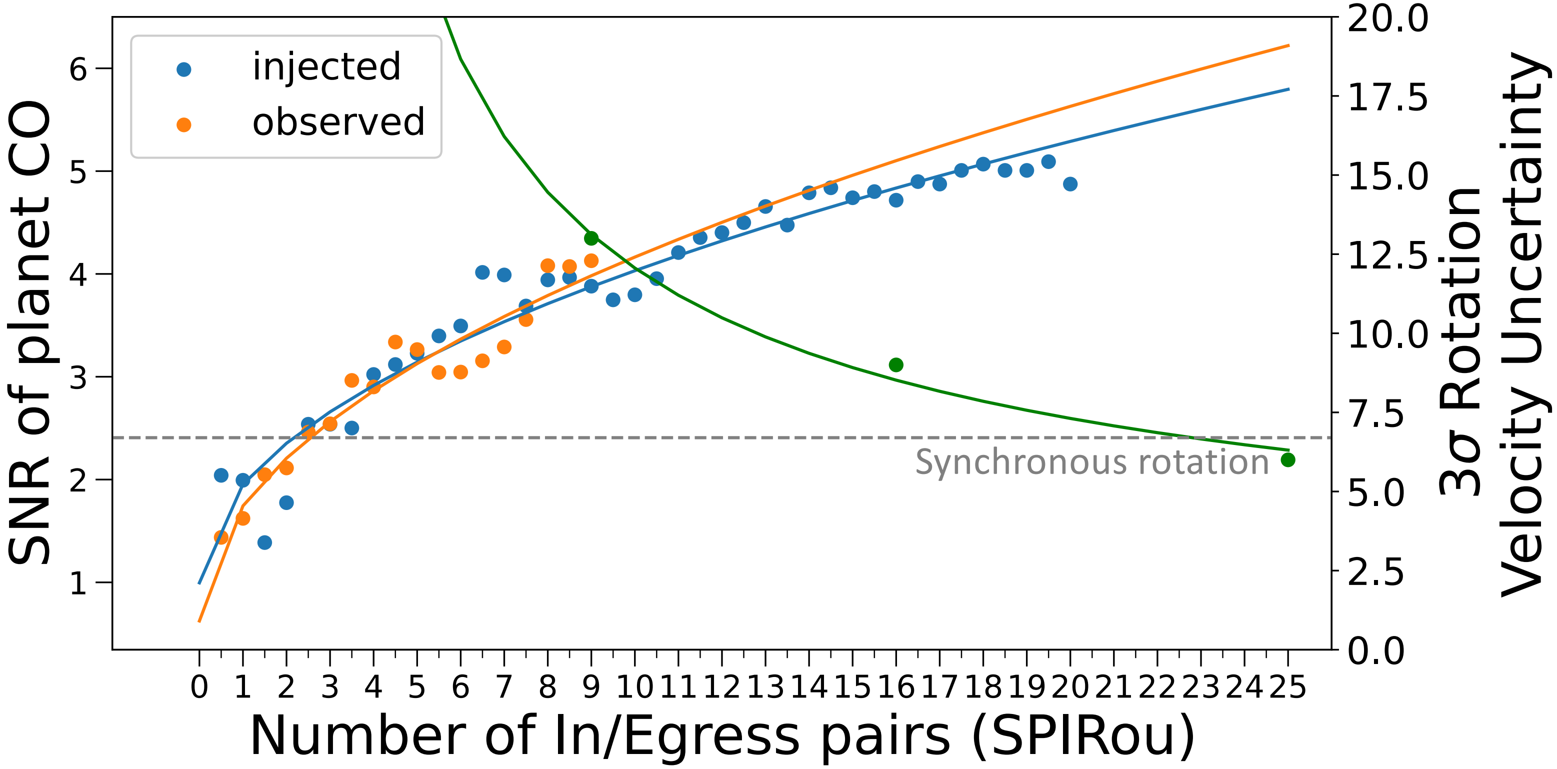


What does the data say?

Over 8 eclipses so far...

- **Tentative** CO detection with wide velocity uncertainty
- **Higher than expected Kp** could hint we are seeing the velocity offset
- Observed **SNR scaling as expected** from injection-recovery tests

➢ 10-15 more eclipses required for robust velocity constraints

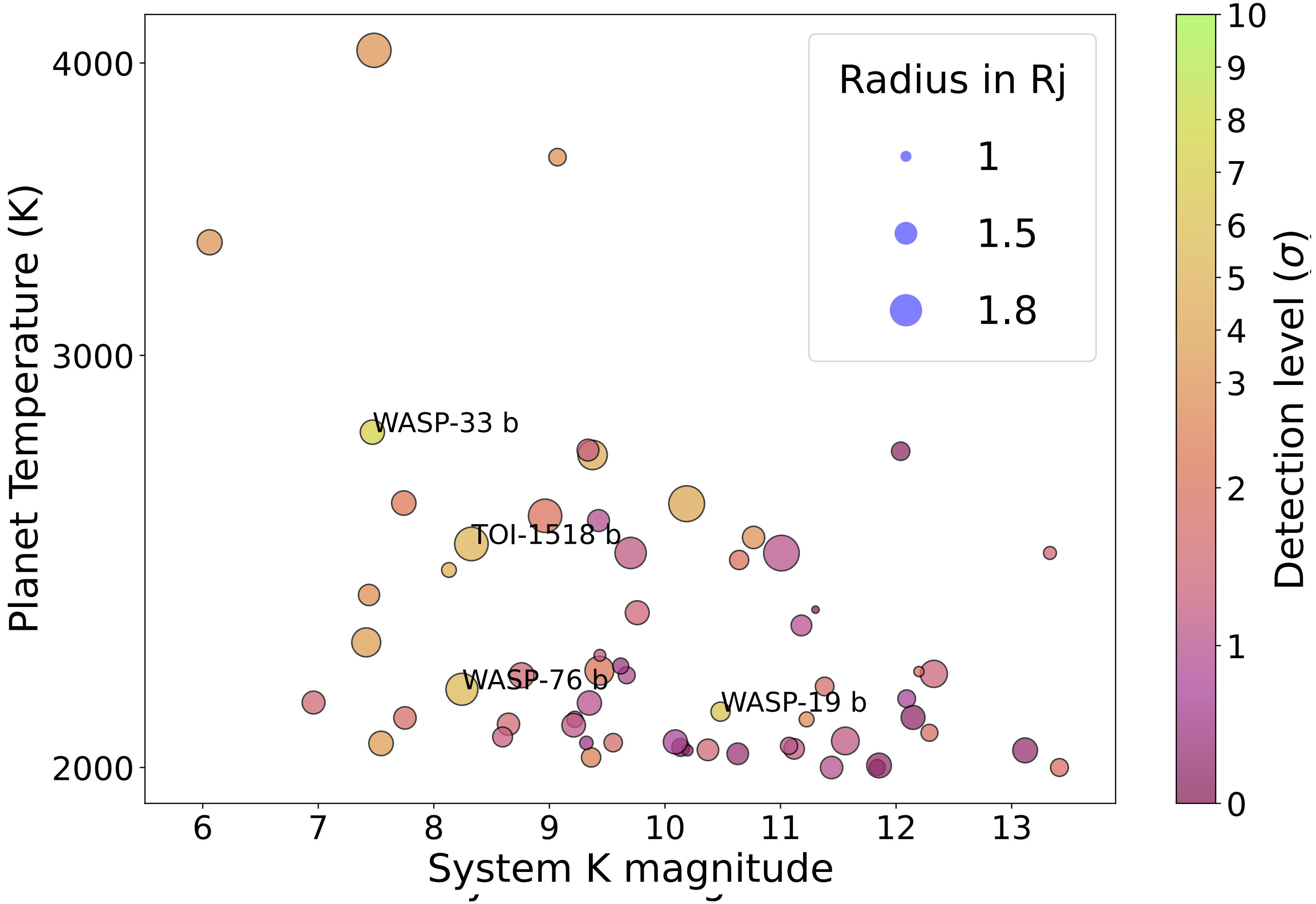


Prospects with ELT

- ✓ MICADO (R=20K) provides 10x improvement over SPIRou

→ Doppler mapping possible in **a few eclipses** for hottest targets

MICADO: 1 Eclipse



Prospects with ELT

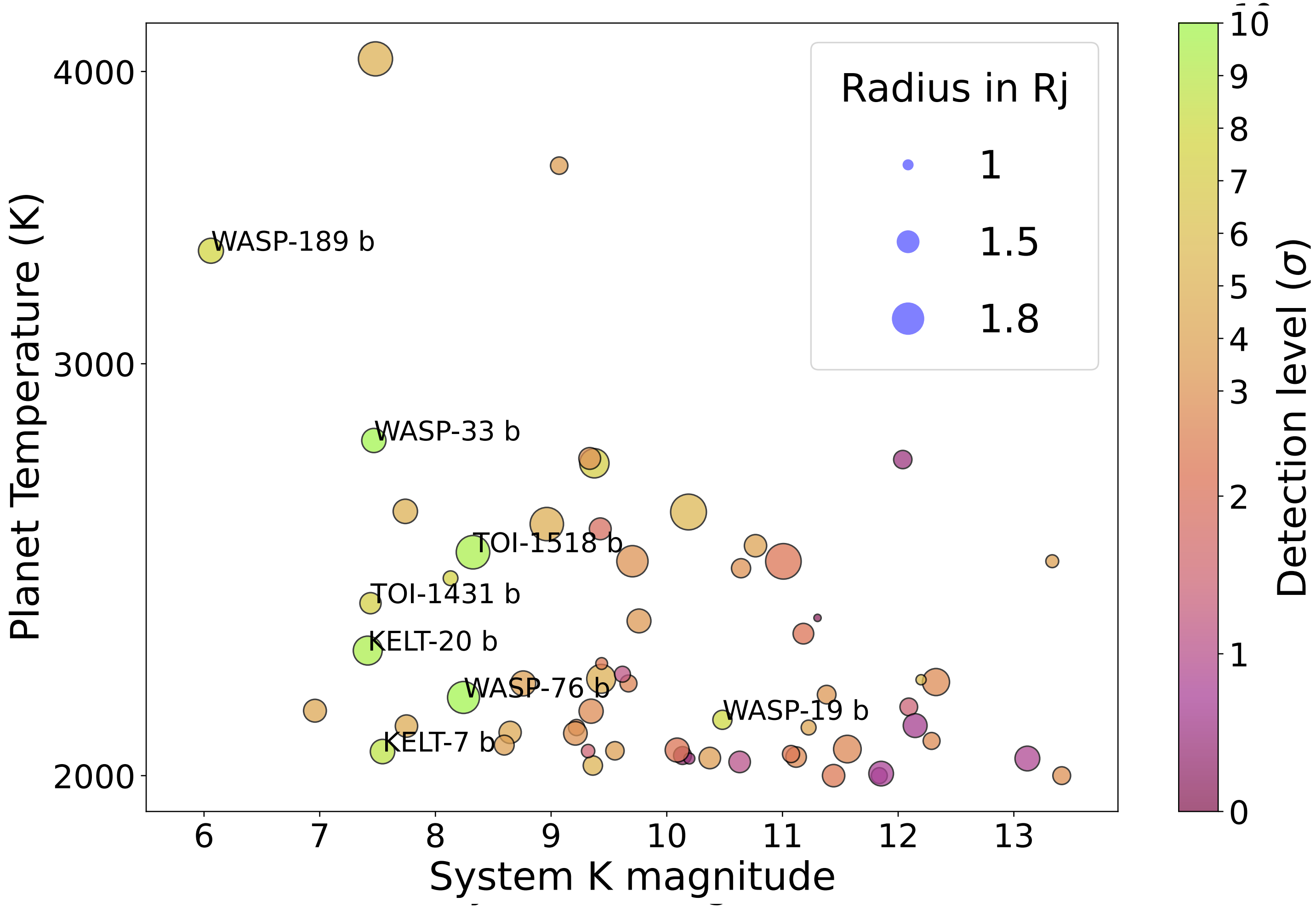
✓ MICADO (R=20K) provides 10x improvement over SPIRou

→ Doppler mapping possible in **a few eclipses** for hottest targets

✓ ANDES in K band would provide 30x improvement

→ Doppler mapping possible in a **single eclipse** for multiple targets

ANDES: 1 Eclipse

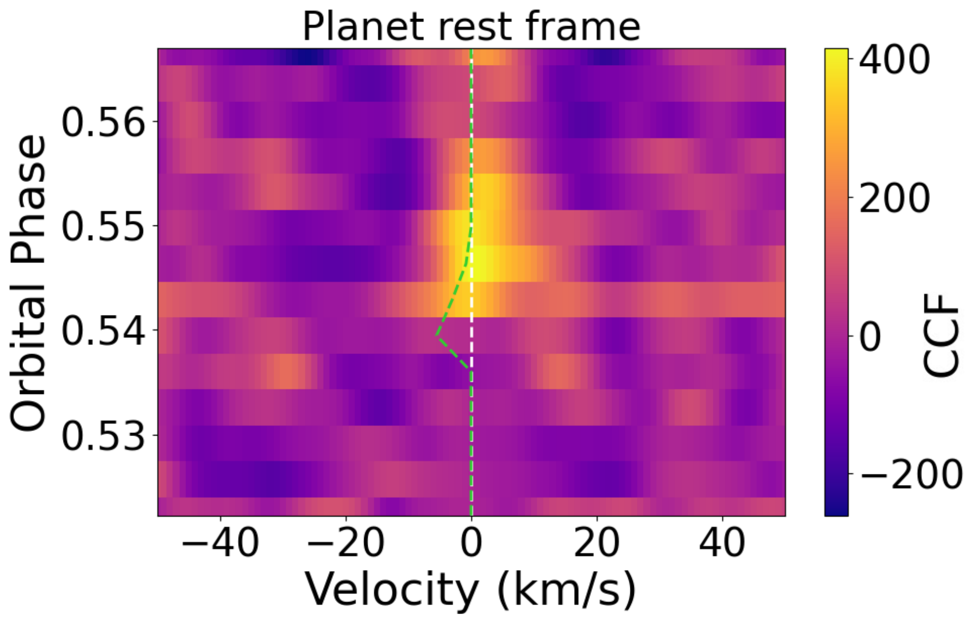


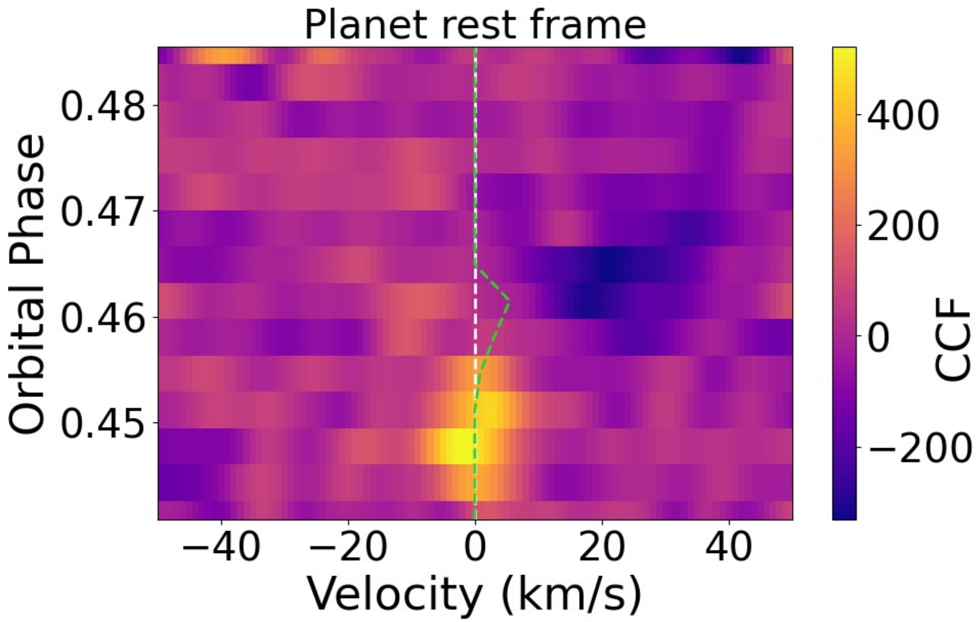
IGRINS-2 Program

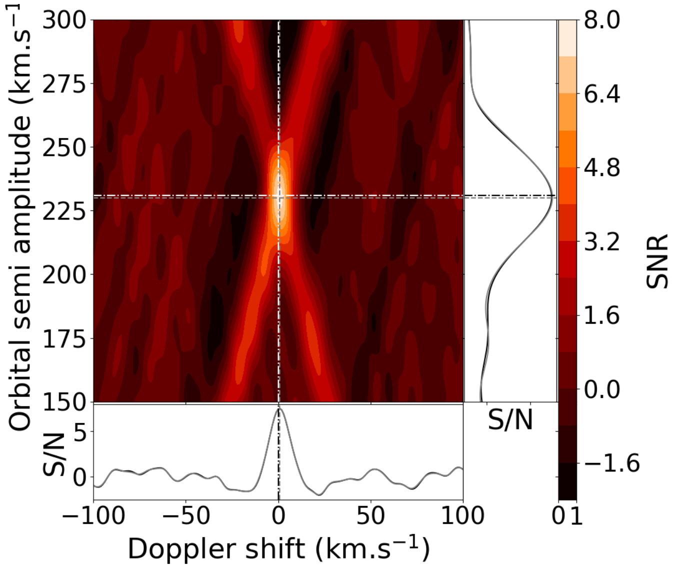
5 Observed eclipses…

- **Strong CO** detection at 8σ (from just 2 eclipses)
- Planet **trail clearly visible**
- No obvious hints of an offset…

More to come…!







Take-home messages

- Doppler mapping can be a powerful approach to get spatially resolved signatures of close-in exoplanets, but is currently **limited by photon collecting power**
- Pilot program with SPIRou has provided **encouraging initial results**
- Unique **science case for ANDES** which could accomplish this in a **single observation**, opening up a wider population and other parameters (e.g. axial tilt)
- **Follow-up study with IGRINS-2** under way, stay tuned!

Read the paper here!

Computing Photon-Limited Velocity Uncertainties

RV contributions at each pixel i summed according to optimal weight W

A_0 - Intensity (photons), σ – Detector noise

Quality Factor – measure of the quality and the spectral line richness of the spectrum

→Uncertainty on Cross-Correlation velocity

Calculated for a given photon noise ($\sqrt{Ne}$)

→Additional weight Z as noise coming from star while RV from planet

$$\frac{\delta V}{c} = \frac{\sum \frac{\delta V(i)}{c} W(i)}{\sum W(i)}.$$

$$W(i) = \frac{\lambda^2(i)\left(\partial A_0(i)/\partial\lambda(i)\right)^2}{A_0(i) + \sigma_{\mathrm{D}}^2}.$$

$$Q = \frac{\sqrt{\sum W(i)}}{\sqrt{\sum A_0(i)}}.$$

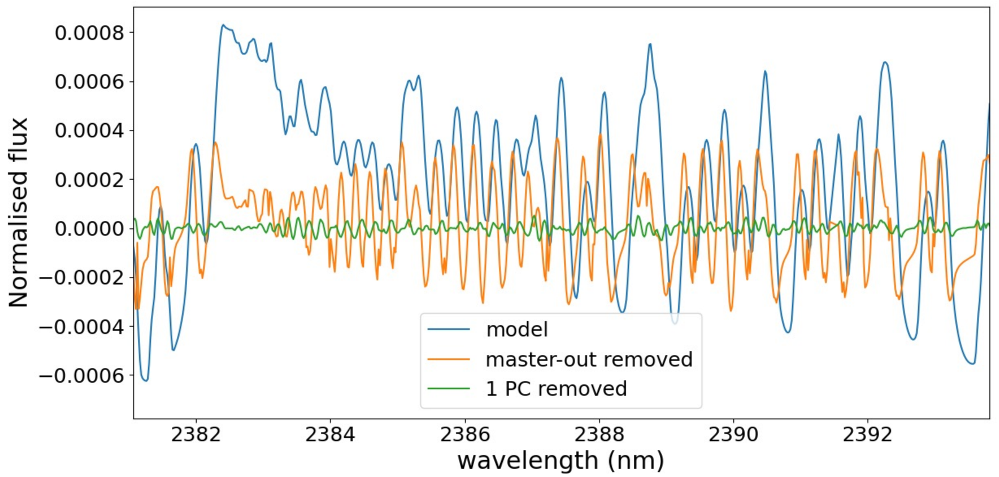
$$\delta V_{\mathrm{RMS}} = \frac{c}{Q\sqrt{N_{\mathrm{e^-}}}}.$$

Bouchy et al, 2001

$$Z(i) = \frac{A_{0p}(i)}{A_{0*}(i)}.$$

$$\delta V_{RMS} = \frac{c\sqrt{\Sigma A_{0*}(i)}}{Q\Sigma A_{0p}(i)}$$

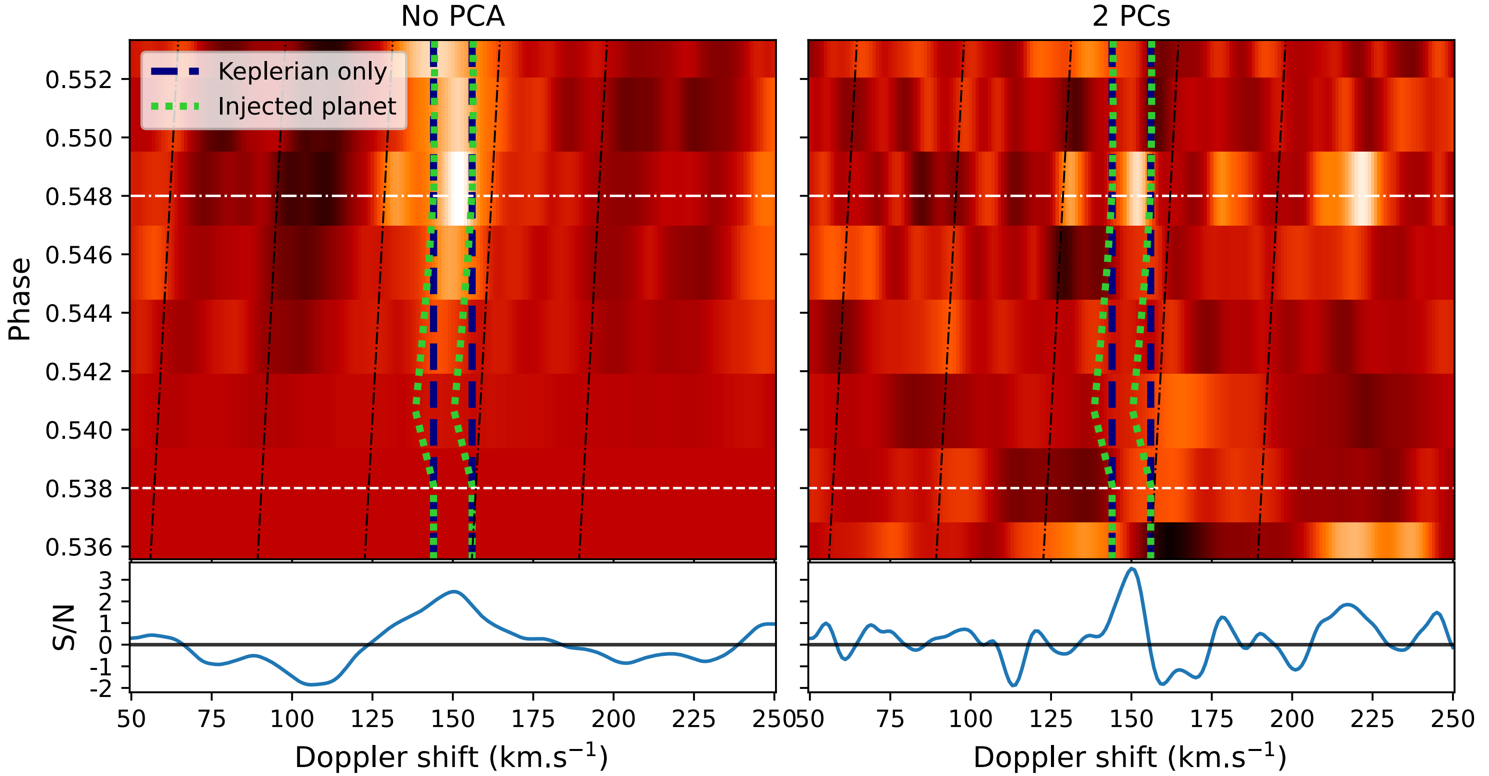
Dealing with short Integrations



- Master-out & PCA removing most of the planetary contribution

➢ Tests perform better without master out and PCA

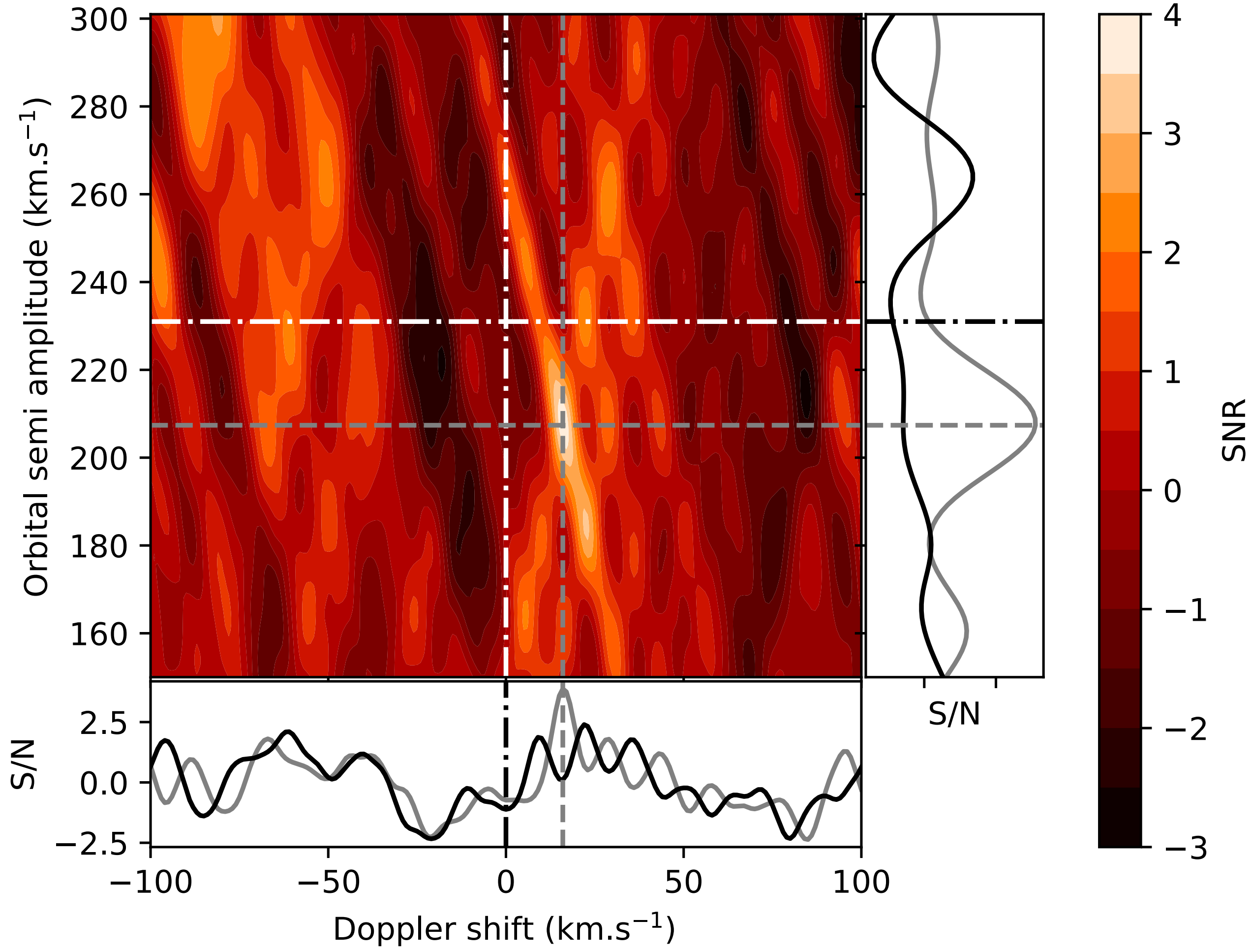
➢ PCA improves observed SNR, but biases signal to higher Kp



In eclipse signal only?

Limiting to in-eclipse data doesn't seem to bring out the shifted signal...

- Could be a slightly offset ephemeris
- Could be one side (ingress) is contributing more



Injection-Recovery

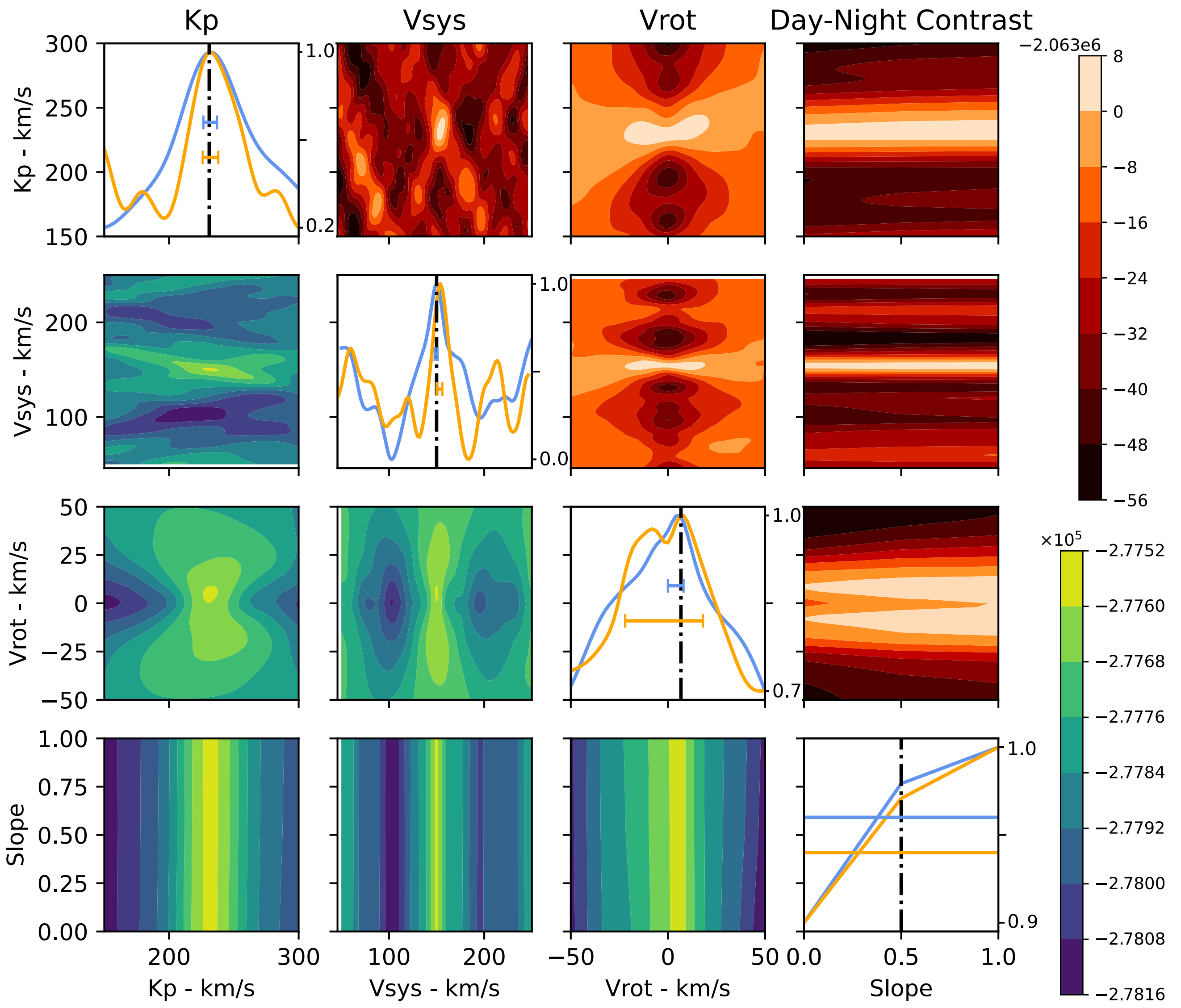
- Synchronous rotation can be reliably detected with **25 eclipses**

- Dayside Phases: rotation constraint comes from **broadening only** (double peak)

- Eclipses alone have a harder time constraining the **orbital amplitude**
  - ➢ Longer daysides help to solve this

- Day/Night contrast is not constrained in our SPIRou data (longer baseline needed)

Comparison: Eclipses (blue) – Daysides (orange)



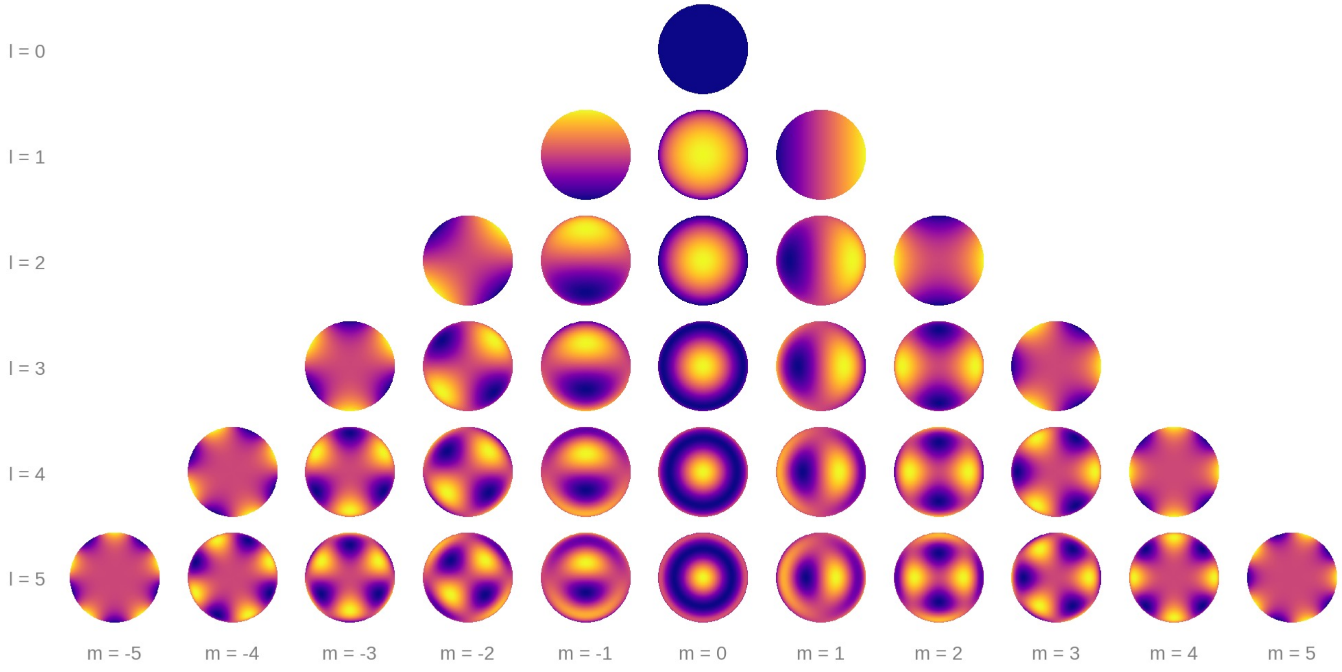
Modelling Velocity offsets

(Luger et al., 2019)

Planetary Maps with Starry:

- Surface intensity parametrised with spherical harmonics
- Solid Rotation over planet surface

➢ Intensity-weighted velocity phase curve



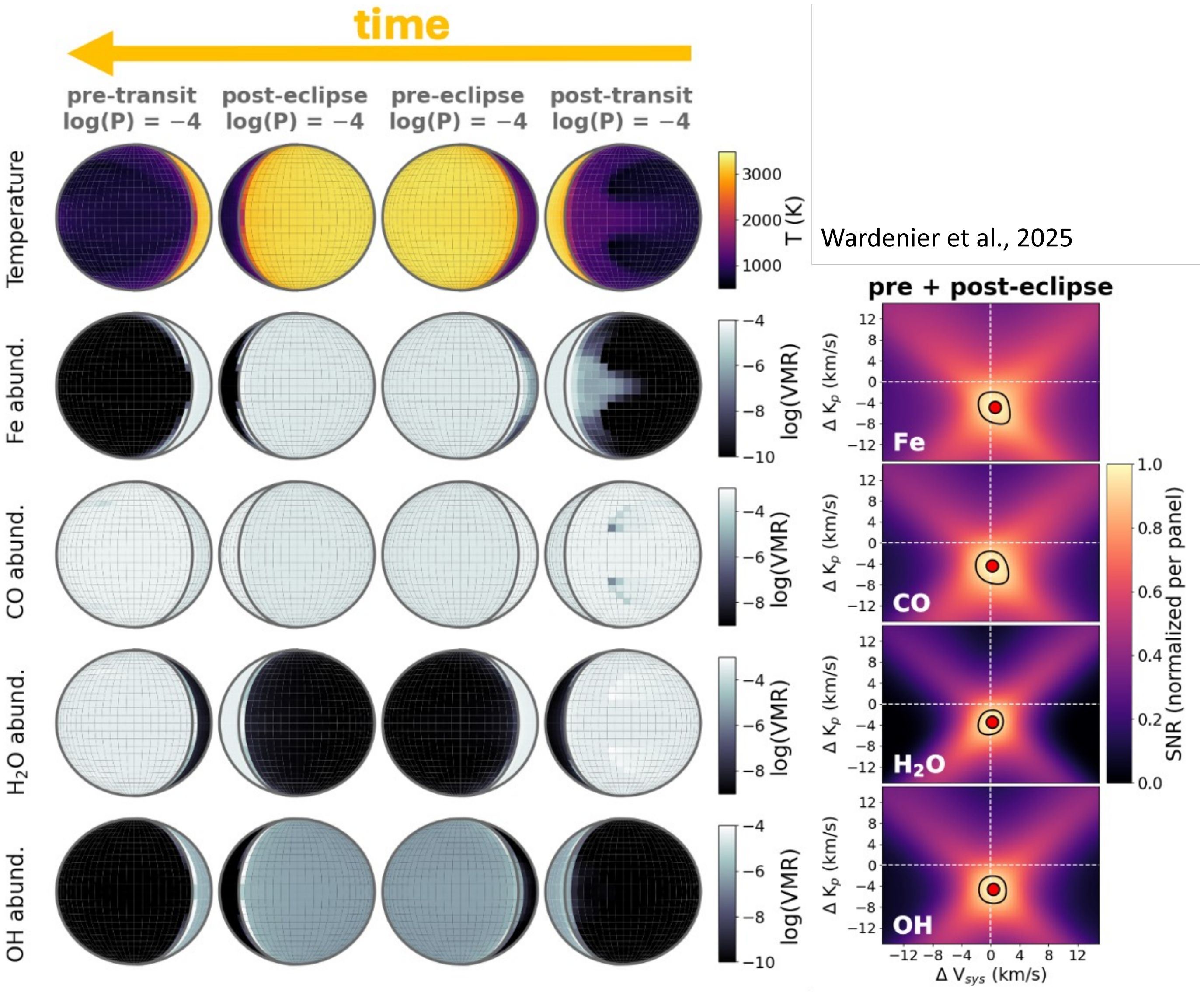
Predictions from 3D models

Predictions from GCMs for composition of a similar ultra-Hot Jupiter to WASP-33b (WASP-76b), and associated predicted KP-Vsys (offset) detections for pre and post eclipse emission

→ Different molecules will have different signatures (based on their spatial repartition)

→ CO is the only probe present over the whole planet

→ Eclipses can provide independent evidence for different repartitions



Wardenier et al., 2025