



# Unveiling spot coverages of exoplanetary host stars across the main sequence with HST

\*Part of HST Stellar Treasure Trove  
Legacy Archival Program (HST AR  
17551)

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Post Doctoral Associate

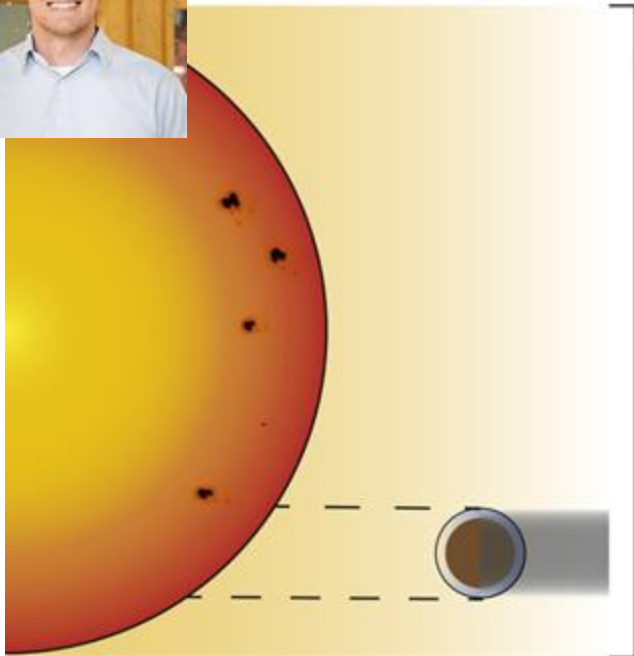
Disruptive Planets Group

EAPS, MIT

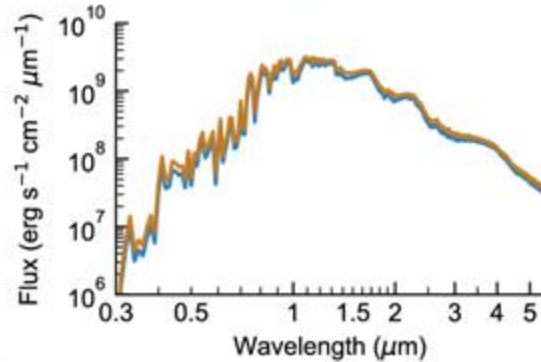
Know Thy Star, Feb 4th,  
2025

In collaboration with: Benjamin Rackham, Julien de Wit, Daniel Apai, David Berardo, Rachael Amaro, Mark Giampapa, Lionel Garcia, Hannah Wakeford, Megan Weiner Mansfield, Zoë de Beurs

# The Transit Light Source Effect

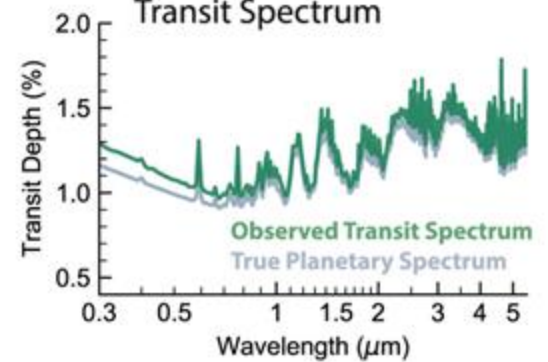


Pre-transit Stellar Disk is the **Assumed Light Source**

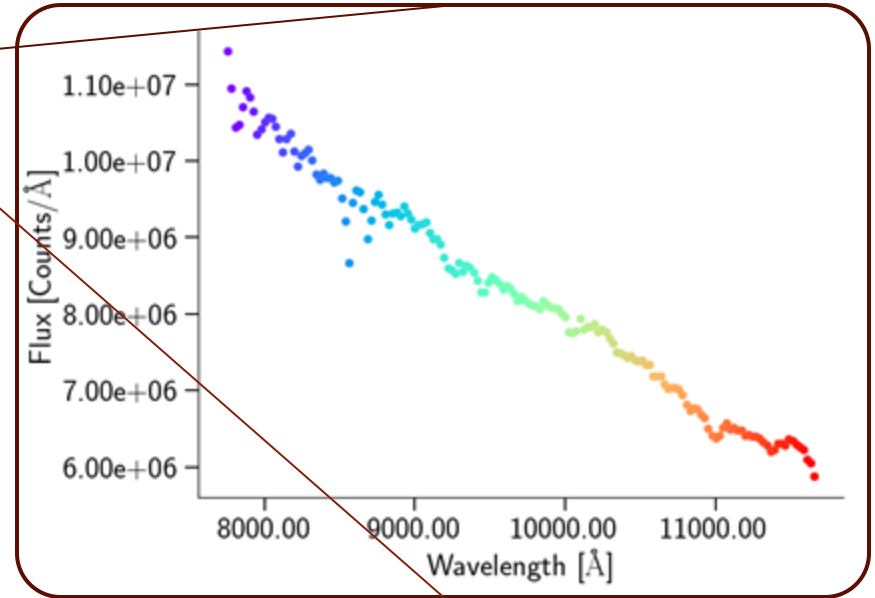
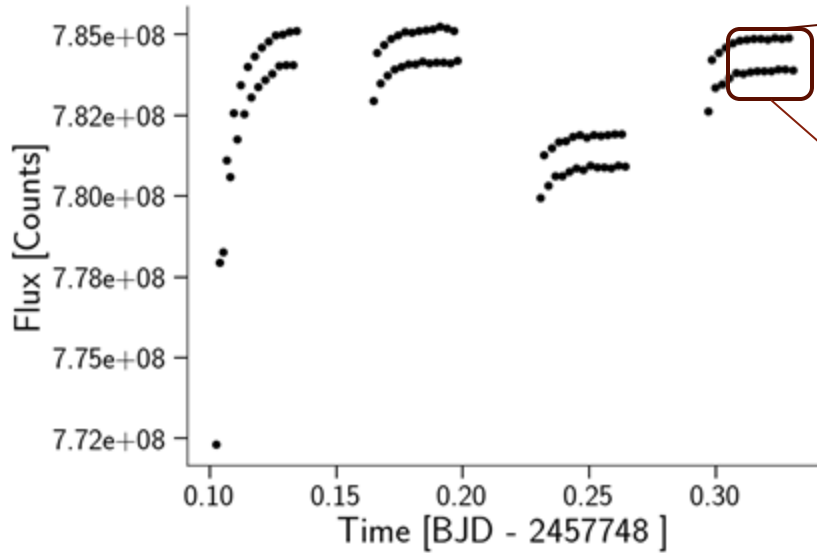


**Actual Light Source** is the Chord Defined by the Planet's Projection

Spectral Difference due to Different Spot/Faculae Contributions Contaminates Transit Spectrum

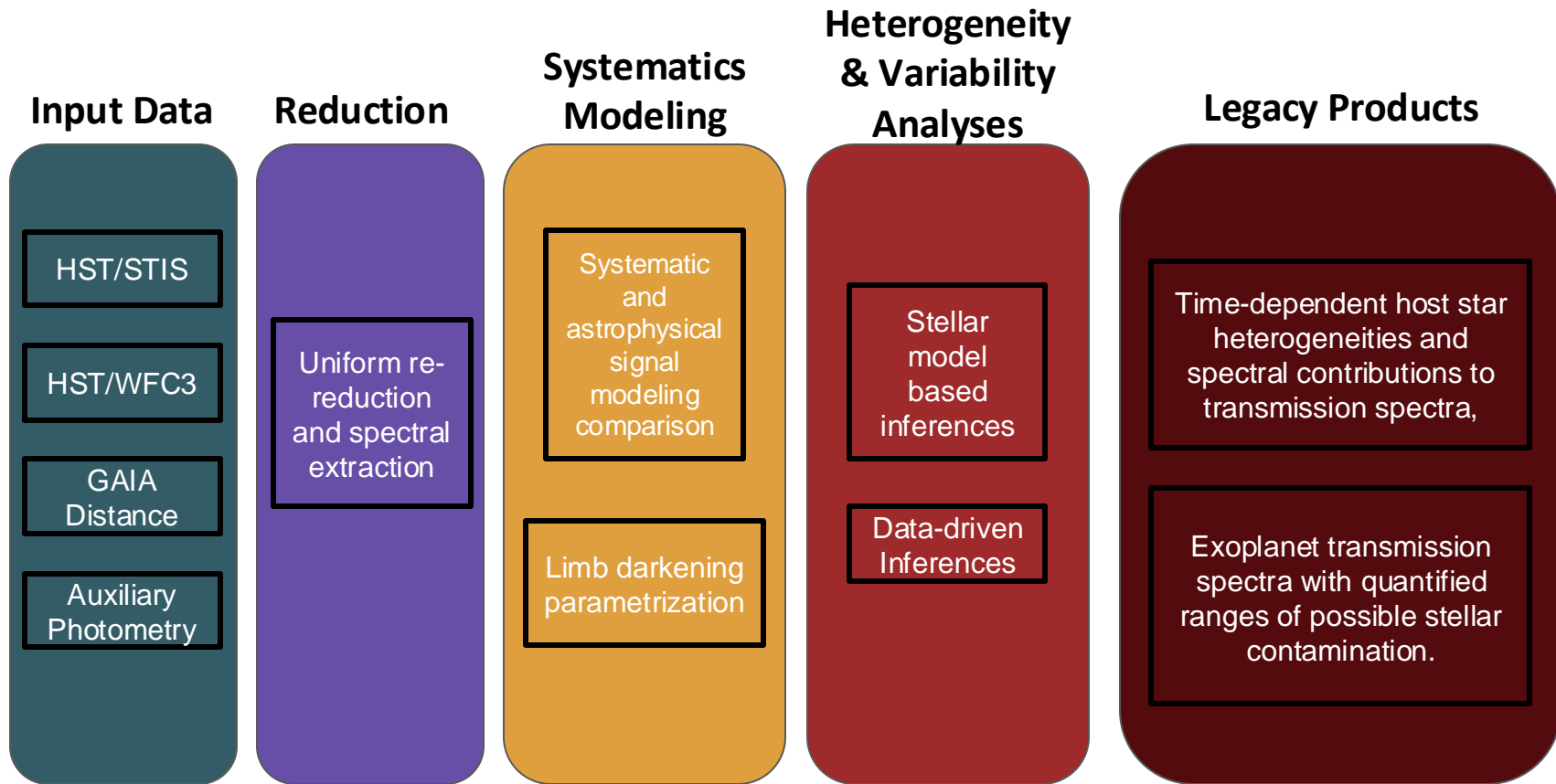


# Leveraging Out-of-Transit Spectra



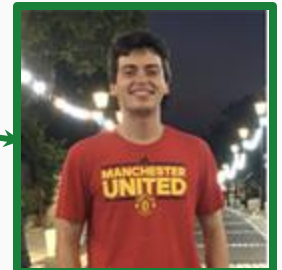
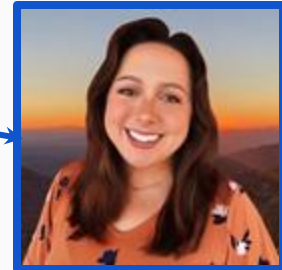
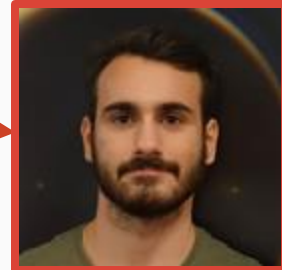
HAT-P-11 G102

# HST Stellar Treasure Trove Program Goals - AR 17551



# Our Targets

| Star       | Teff (K) | STIS/CCD |       |       | WFC3/UVIS | WFC3/IR |      |
|------------|----------|----------|-------|-------|-----------|---------|------|
|            |          | G430L    | G750M | G750L | G280      | G102    | G141 |
| TRAPPIST-1 | 2,566    | 1        | 0     | 0     | 0         | 0       | 657  |
| GJ 1214    | 3,074    | 2        | 0     | 4     | 0         | 2       | 1165 |
| GJ 436     | 3,456    | 30       | 0     | 10    | 0         | 2       | 830  |
| K2-18      | 3,464    | 1        | 0     | 0     | 0         | 0       | 808  |
| AU Mic     | 3,665    | 8        | 0     | 10    | 0         | 320     | 324  |
| K2-3       | 3,920    | 0        | 0     | 0     | 0         | 0       | 779  |
| HAT-P-12   | 4653     | 17       | 0     | 9     | 12        | 0       | 159  |
| HAT-P-11   | 4778     | 20       | 0     | 11    | 0         | 594     | 212  |
| HD 189733  | 5023     | 55       | 28    | 1     | 0         | 0       | 865  |
| HAT-P-26   | 5062     | 21       | 0     | 11    | 16        | 89      | 148  |
| HD 3167    | 5284     | 1        | 0     | 0     | 0         | 0       | 1012 |
| WASP-39    | 5327     | 20       | 0     | 11    | 24        | 84      | 138  |
| WASP-19    | 5503     | 16       | 0     | 9     | 0         | 0       | 992  |
| WASP-12    | 6154     | 30       | 0     | 11    | 0         | 280     | 1882 |
| WASP-17    | 6548     | 21       | 0     | 11    | 5         | 140     | 201  |
| WASP-121   | 6776     | 21       | 0     | 11    | 0         | 156     | 993  |



# Three Guiding Questions

1. **How spotted** are exoplanet host stars?

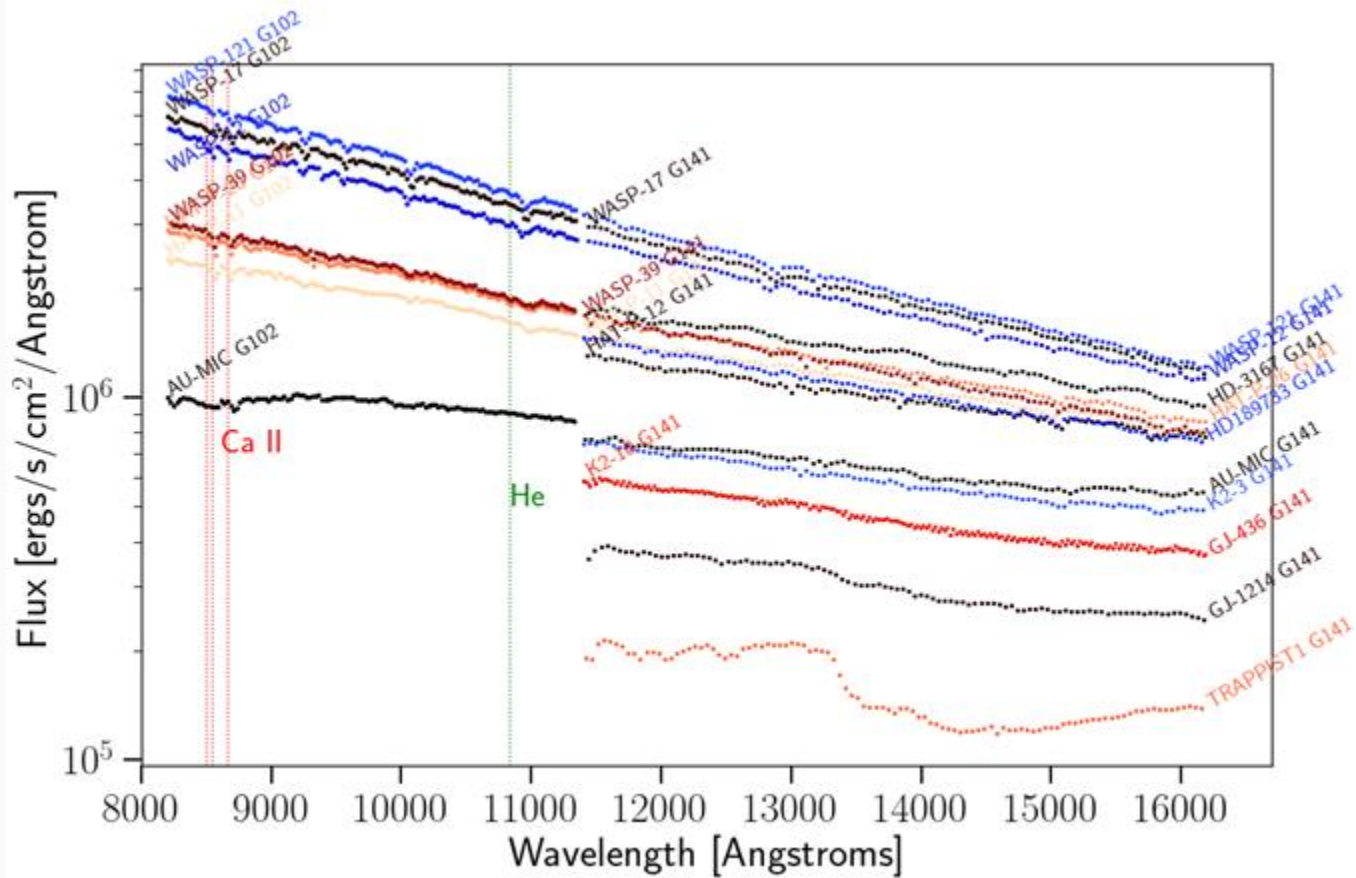
2. How do **spot temperatures** and **covering fractions** vary over time?

3. How does stellar photospheric heterogeneity **affect exoplanetary atmospheric retrievals**?



# Spectral Analysis

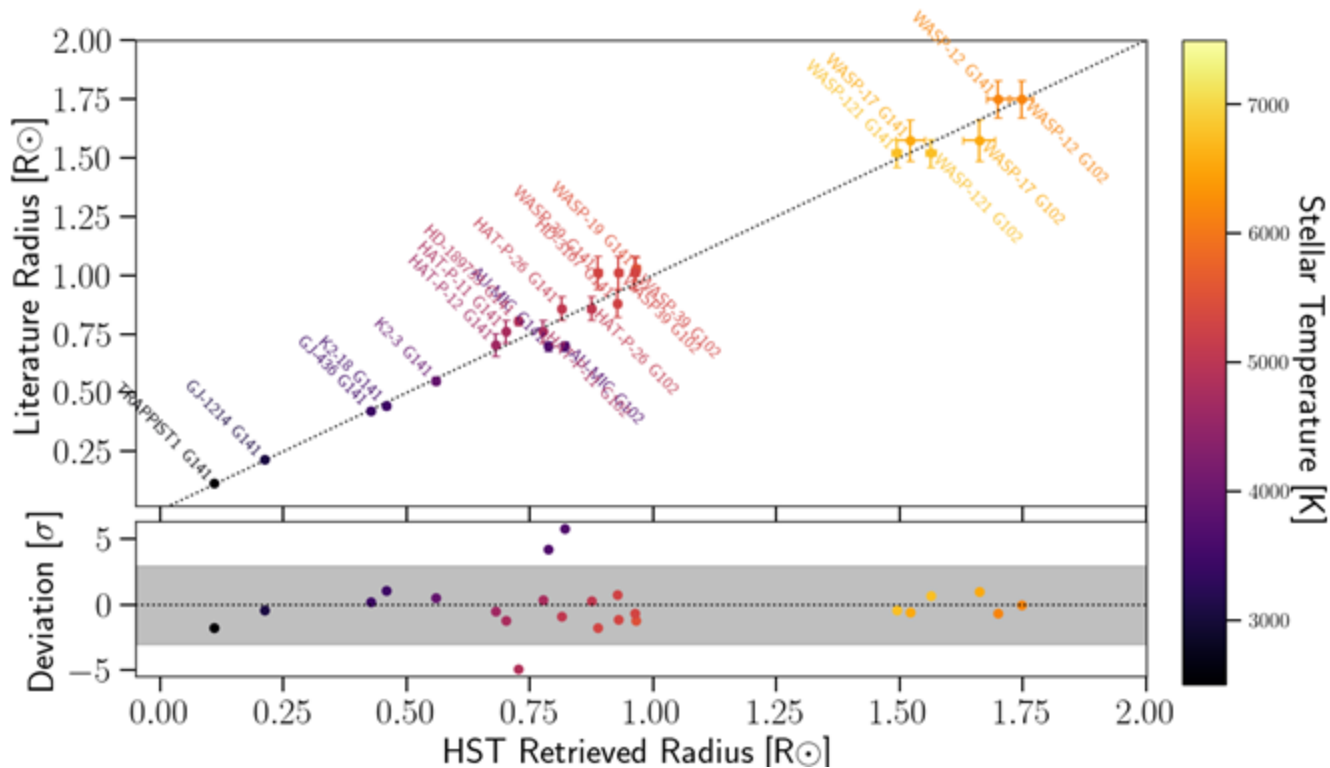
# Calibrated Flux







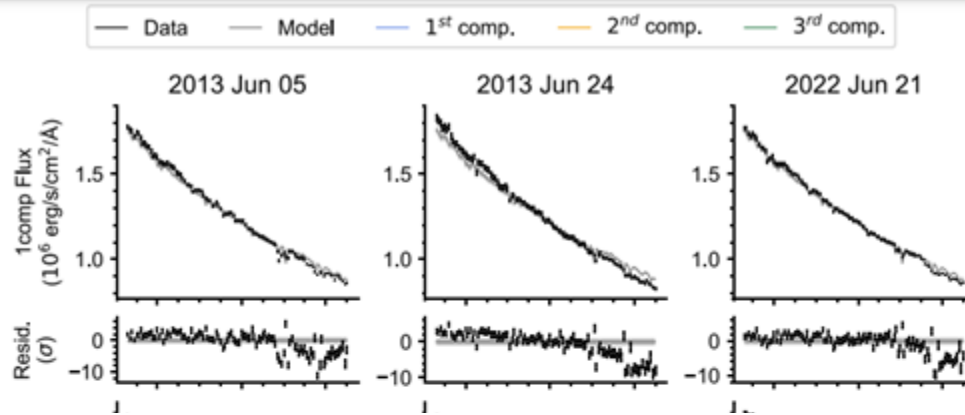
# Radius Comparison





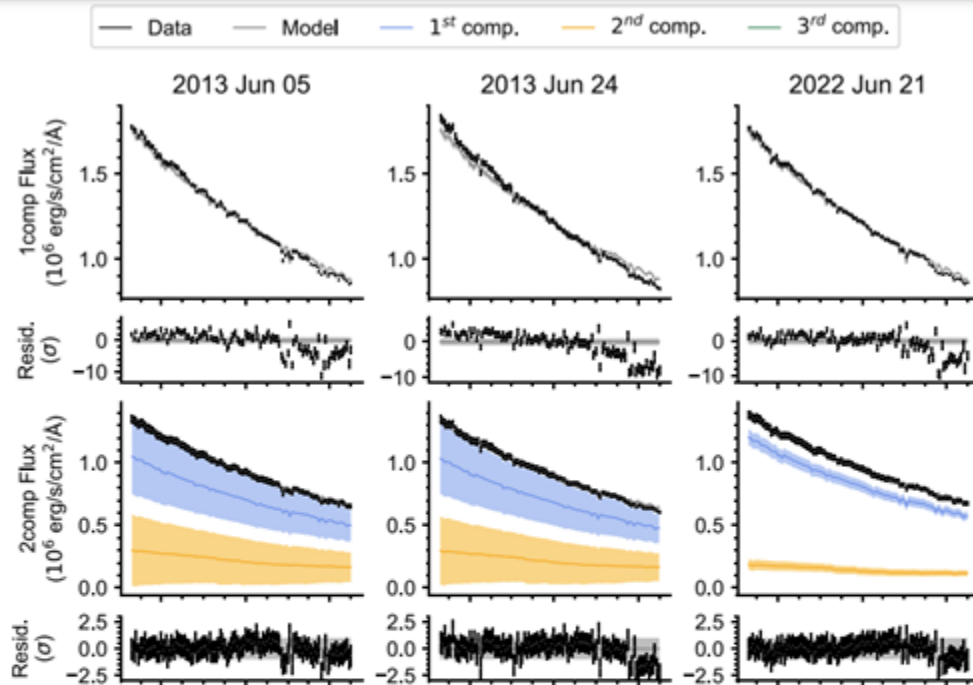
# HD 189733 - The Pilot Study

# Absolutely Calibrated Flux



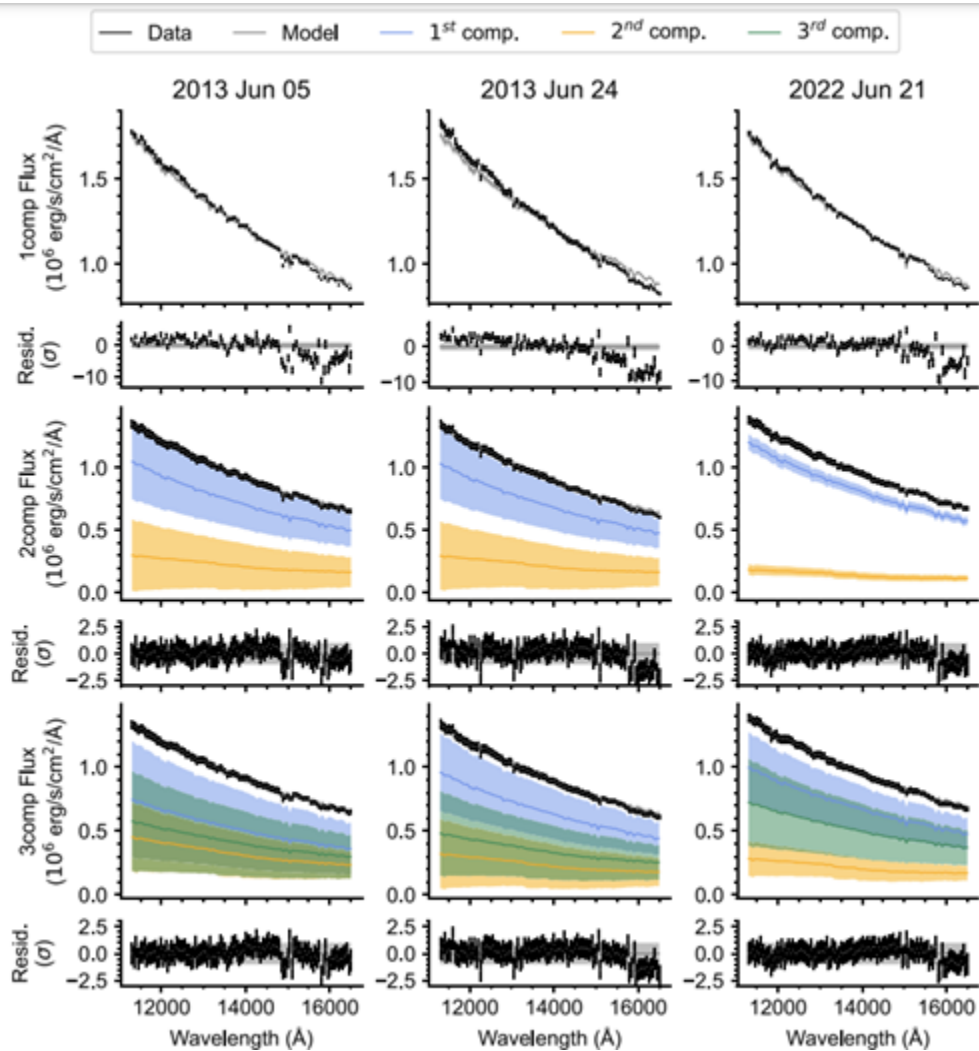
# HD 189733

# Absolutely Calibrated Flux



## HD 189733

# Absolutely Calibrated Flux



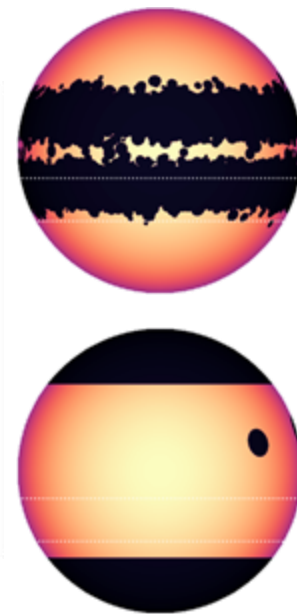
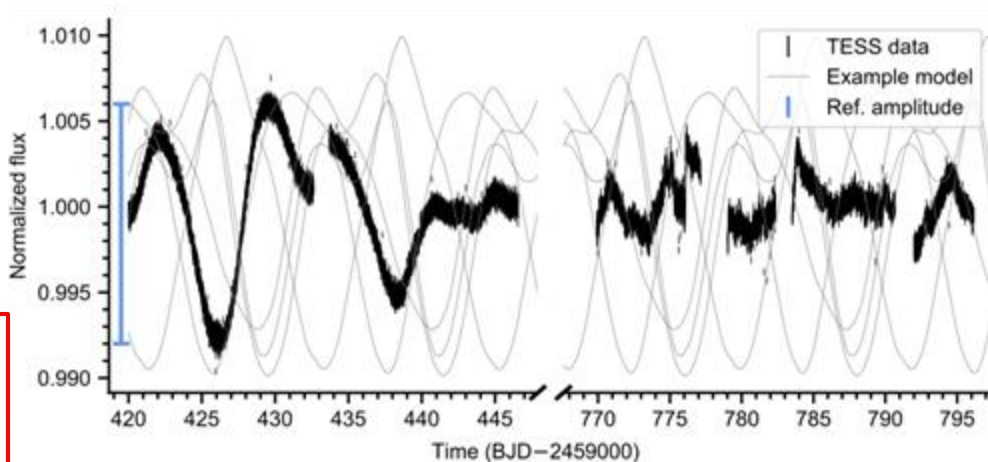
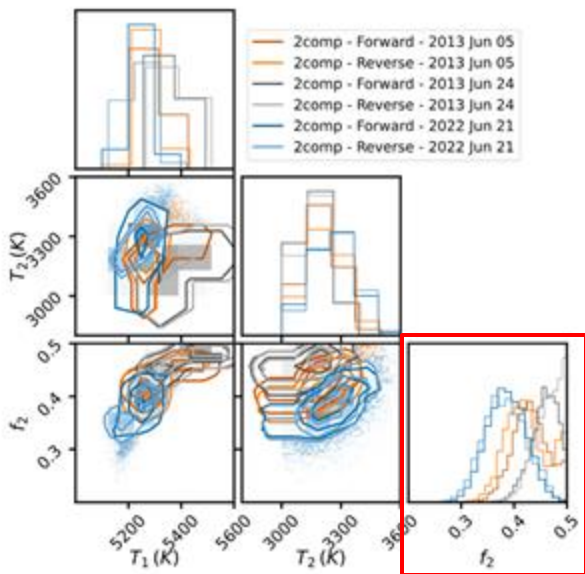
## HD 189733

# Axisymmetrically spotted K dwarf- HD 189733 b

High Spot Coverage

Low Photometric Modulation

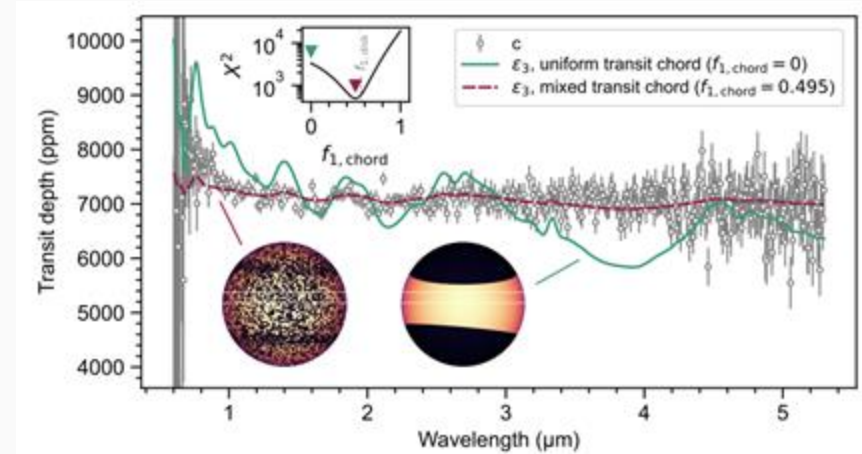
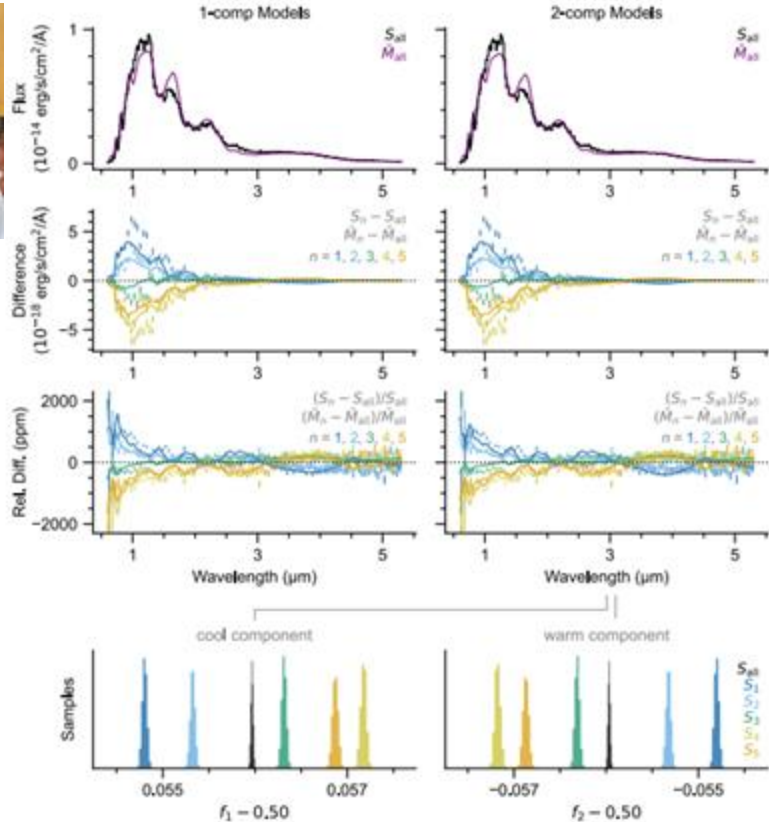
High Axisymmetric Spot Coverage



# High Fraction and Well Mixed Spots in TRAPPIST-1



Thursday: 9AM





HAT-P-11



# HAT-P-11

## Data:

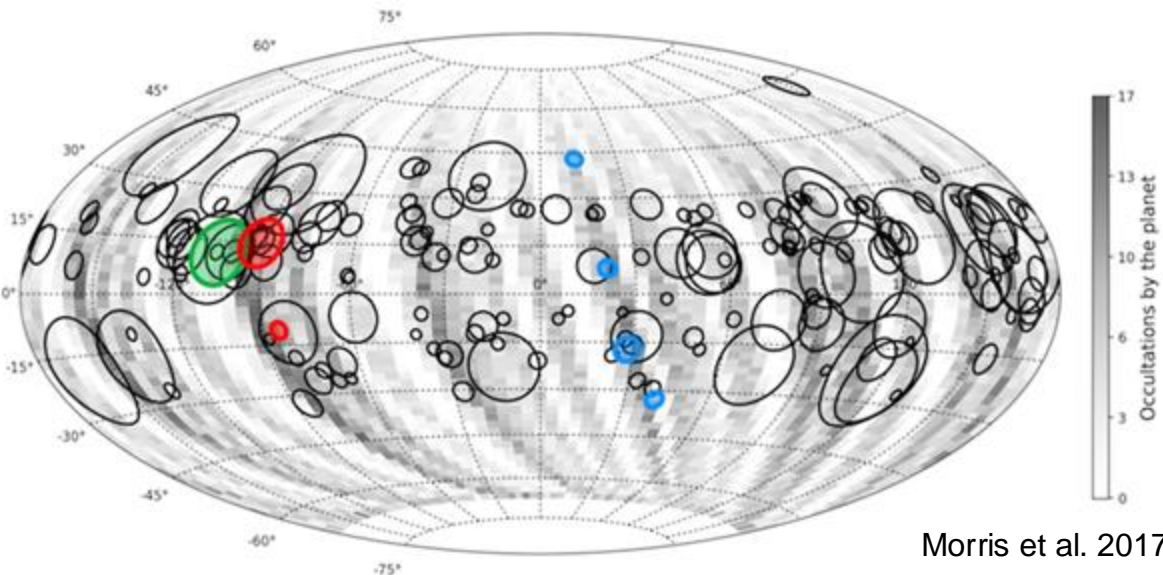
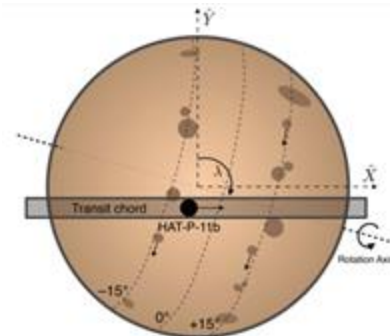
STIS/G430L, STIS/G750M, WFC3/IR/G102,  
WFC3/IR/G141

## Science questions:

1. **How spotted** is HAT-P-11?
1. How do **spot temperatures** and **covering fractions** vary over time?
1. How might stellar inhomogeneities **affect the exoplanetary atmospheric retrievals**?

Table 1. System properties of HAT-P-11.

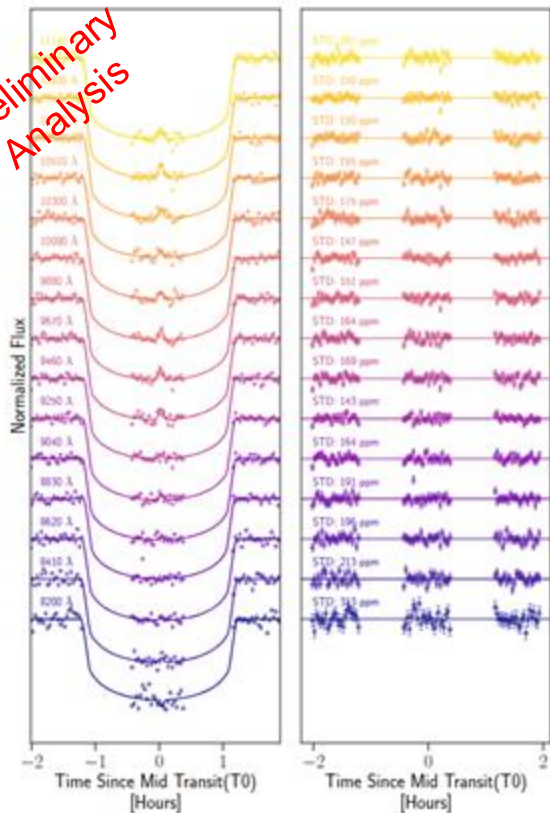
| Property         | Units            | Value                        |
|------------------|------------------|------------------------------|
| TIC Identifier   | -                | 28230919                     |
| $T_{\text{eff}}$ | K                | $4778^{+118}_{-107}$         |
| Fe/H             | dex              | $0.300 \pm 0.053$            |
| M                | $M_{\odot}$      | $0.770^{+0.100}_{-0.076}$    |
| R                | $R_{\odot}$      | $0.760^{+0.045}_{-0.051}$    |
| $\rho$           | $\text{gm/cm}^3$ | $2.474^{+0.641}_{-0.59}$     |
| log g            | $\text{gm/cm}^3$ | $4.5631^{+0.0925}_{-0.0883}$ |
| Parallax         | arcsec           | $7.044 \pm 0.010$            |
| Distance         | pc               | $141.965 \pm 0.201$          |
| Rotation Period  | days             | $29.2^c$                     |



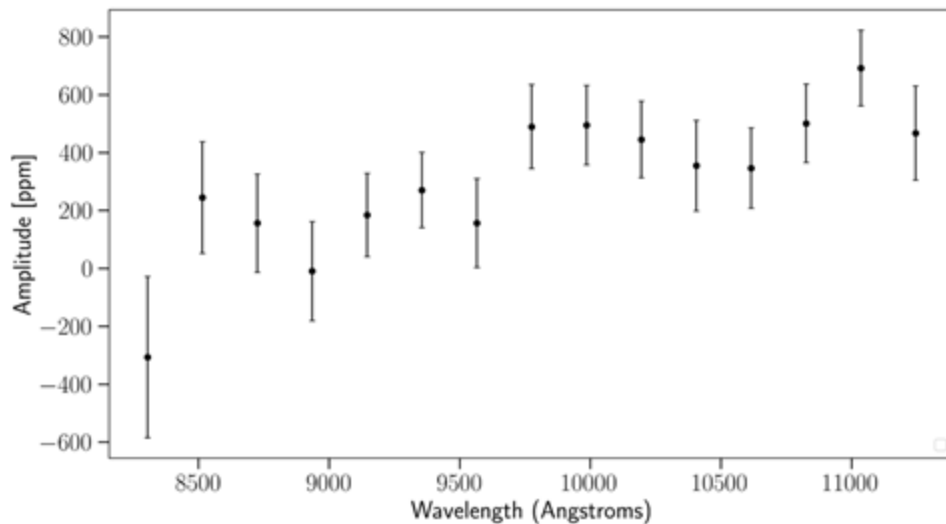
Morris et al. 2017

# Spot Temperature Contrast

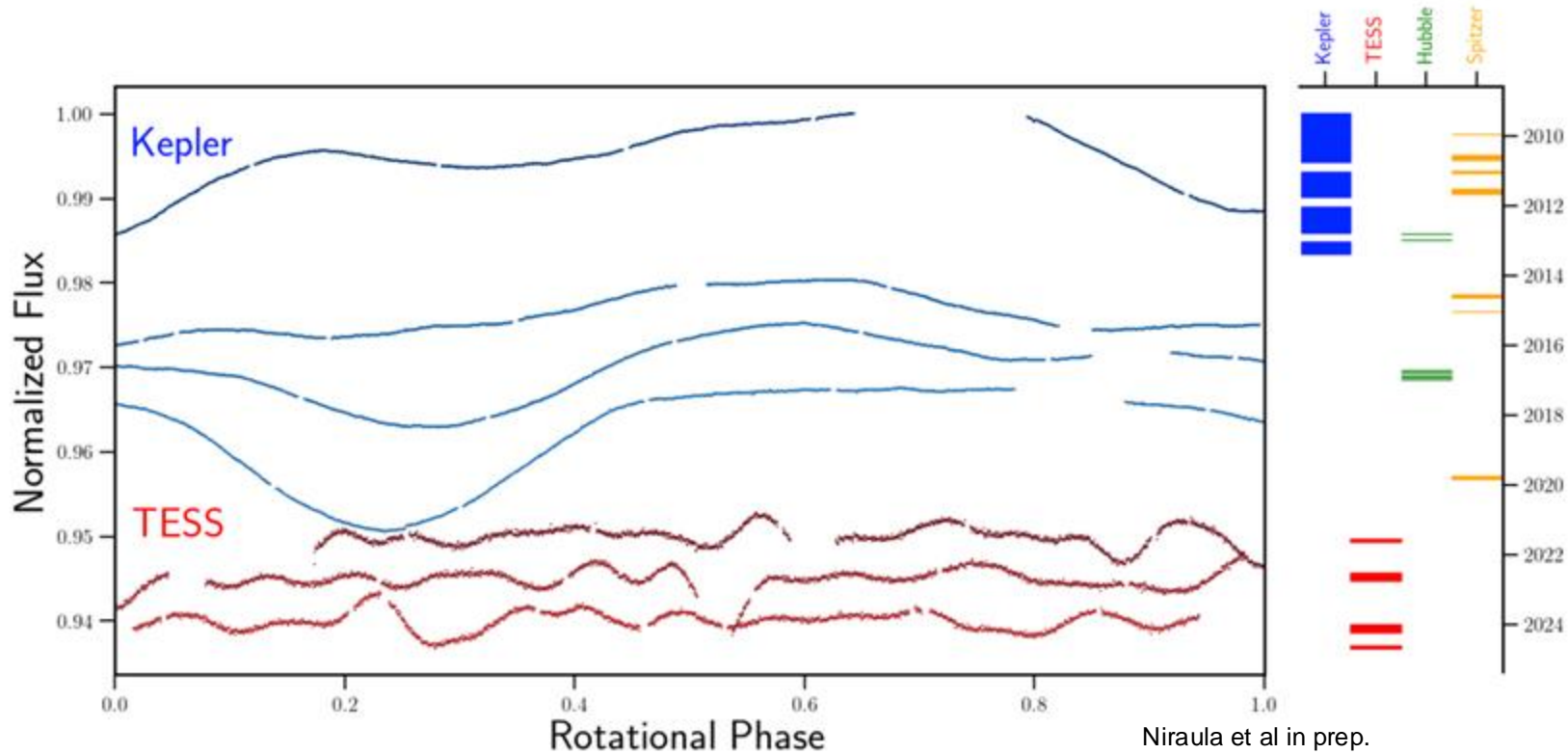
Preliminary  
Analysis



|                  | Morris et al. 2018 | G-102              | G-141                |
|------------------|--------------------|--------------------|----------------------|
| Spot Fraction    | $3_{-1}^{+6}$      | $30_{-9}^{+14}$    | $30 \pm 6$           |
| Spot Temperature | 4500               | $3515_{-60}^{+83}$ | $3258_{-102}^{+105}$ |

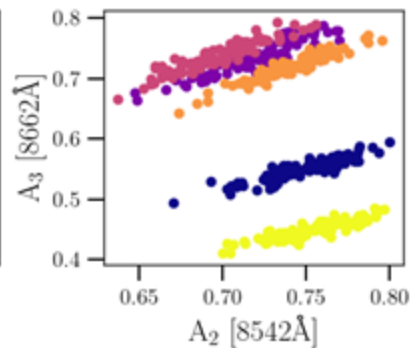
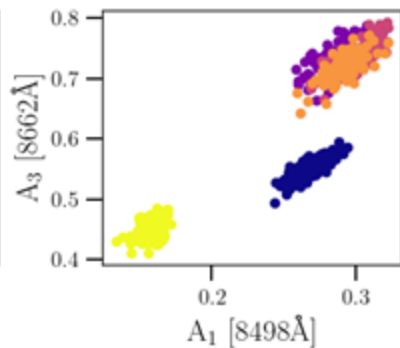
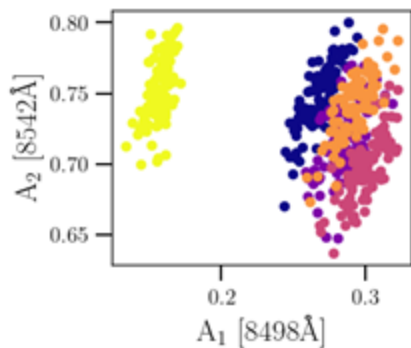
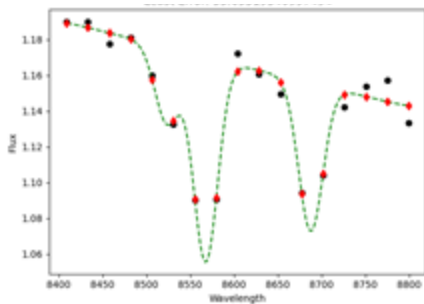


# An Evolving Stellar Cycle?



# Changing Calcium Infrared Feature

2016-09-14



2016-09-14

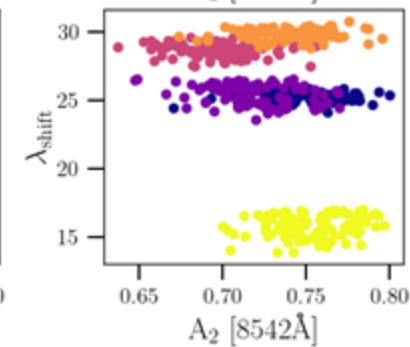
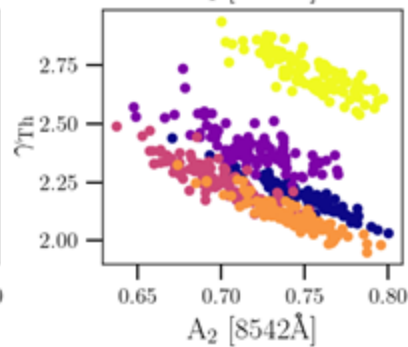
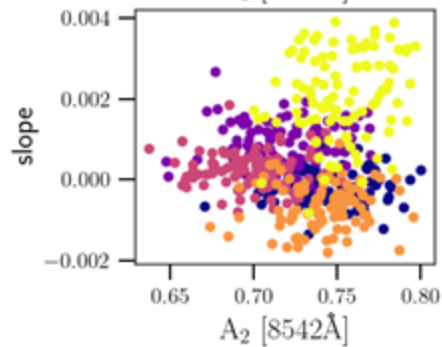
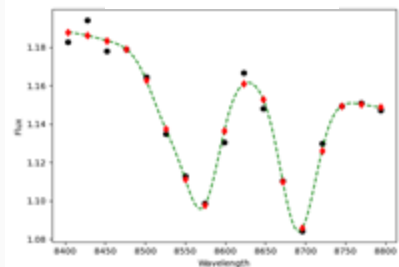
2016-10-13

2016-11-07

2016-11-26

2016-12-26

2016-10-13



Niraula et al in prep.

# Conclusions



## 1. Persistent Stellar Spottedness

Many active stars likely have persistent fraction of their photosphere covered in spots. K dwarfs such as HD 189733 b and HAT-P-11 have a persistent spot coverage of 35% and 30% respectively.

## 1. Constraining Spot Temperature

The temperature constrained from the mean out of transit spectrum suggest different temperature obtained from spot crossing for K dwarfs.

## 1. Impact on Atmospheric Retrievals

Combining different epochs data without properly accounting for the evolving stellar activity will introduce offset and, thereby affecting the exoplanetary atmospheric retrievals.

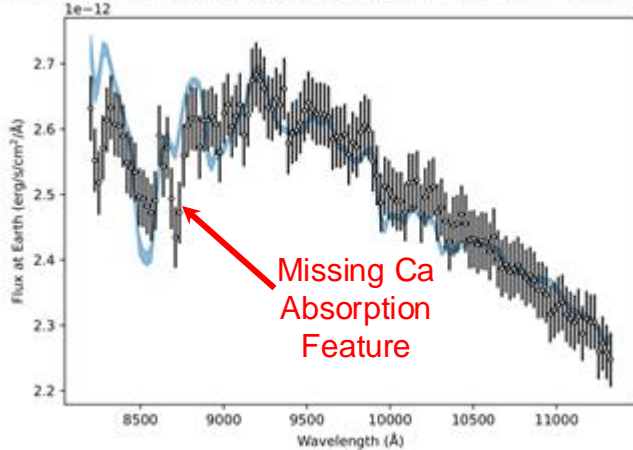
A horizontal banner image featuring a large, bright orange sun on the left, a smaller dark planet with a white ring in the center, and a starry space background on the right. The text "Backup slides" is overlaid in white on the sun.

# Backup slides

# Problems in our stellar models

## Inconsistent Stellar Parameters

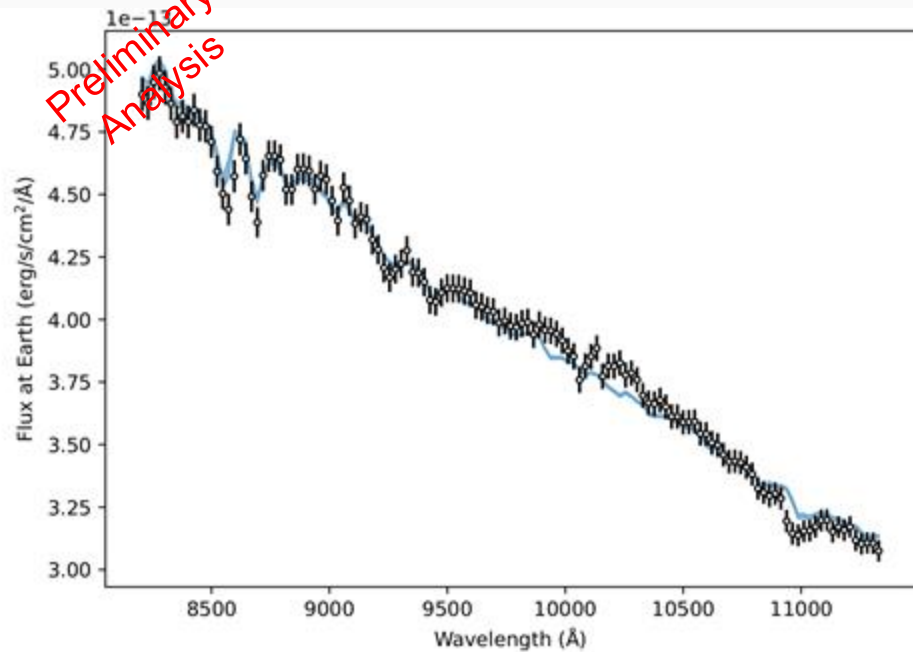
results\_AU-MIC\_2022-04-14\_Orbit\_1\_Forward/phoenix/ncomp1/ |  $\chi^2 = 719.47$  |  $\log Z = 3912.45 \pm 0.44$



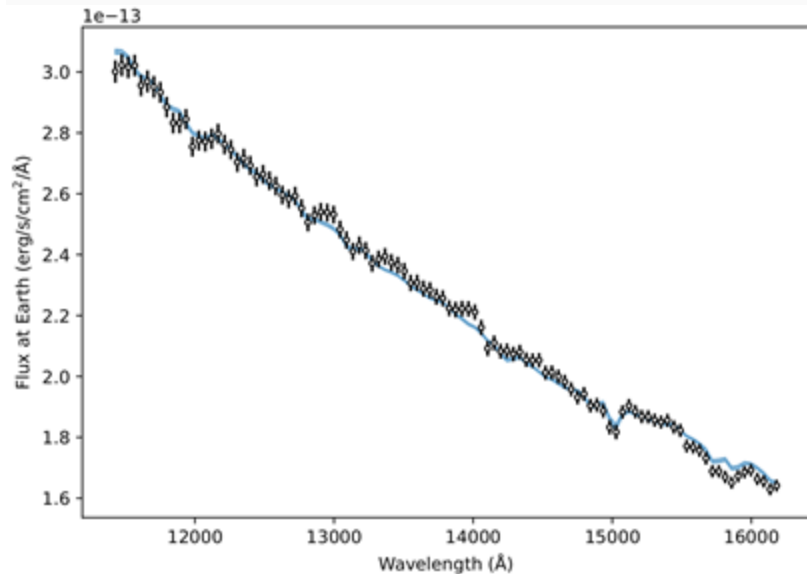
| Source                                  | Wittrock et al. 2023                          | Donati et al. 2023 | Zicher et al. 2022                   | Gilbert et al. 2022                       |
|---|---|--------------------|--------------------------------------|---|
| $T_{\text{eff}}$ (K)                    | 3678 <sup>+90</sup> <sub>-58</sub>            | 3665±31            | 3700±100                             | ---                                       |
| $L_*$ ( $\log_{10}(L_{\odot})$ )        | -1.038 <sup>+0.049</sup> <sub>-0.049</sub>    | -0.99±0.01         | -1.0 <sup>+0.1</sup> <sub>-0.1</sub> | ---                                       |
| $M_*$ ( $M_{\odot}$ )                   | 0.510 <sup>+0.028</sup> <sub>-0.027</sub>     | 0.60±0.04          | 0.50±0.03                            | ---                                       |
| $R_*$ ( $R_{\odot}$ )                   | 0.744 <sup>+0.023</sup> <sub>-0.021</sub>     | 0.82±0.02          | 0.75±0.03                            | 0.750 <sup>+0.029</sup> <sub>-0.030</sub> |
| Sp. T                                   | ---   | ---                | ---                                  | ---                                       |
| $v \sin i$ (km/s)                       | ---   | 8.5±0.2            | 7.8±0.3                              | ---                                       |
| Age (Gyr)                               | 0.0201 <sup>+0.0025</sup> <sub>-0.0024</sub>  | 0.0185±0.0024      | 0.022±0.003                          | ---                                       |
| $P_{\text{rot}}$ (days)                 | ---   | 4.856±0.003        | 4.86±0.01                            | 4.85±0.03                                 |
| $\gamma$ (km/s)                         | ---   | ---                | ---                                  | ---                                       |
| $\rho_*$ (g/cm <sup>3</sup> )           | 1.75 <sup>+0.14</sup> <sub>-0.16</sub>        | ---                | ---                                  | 1.67 <sup>+0.38</sup> <sub>-0.34</sub>    |
| $\log g$ ( $\log_{10}(\text{cm/s}^2)$ ) | 4.404 <sup>+0.026</sup> <sub>-0.031</sub>     | 4.52±0.05          | 4.39±0.03                            | ---                                       |
| Metallicity (dex)                       | 0.23 <sup>+0.24</sup> <sub>-0.30</sub> [Fe/H] | 0.12±0.10 [M/H]    | ---                                  | ---                                       |

# HAT-P-11 Fits

G-102



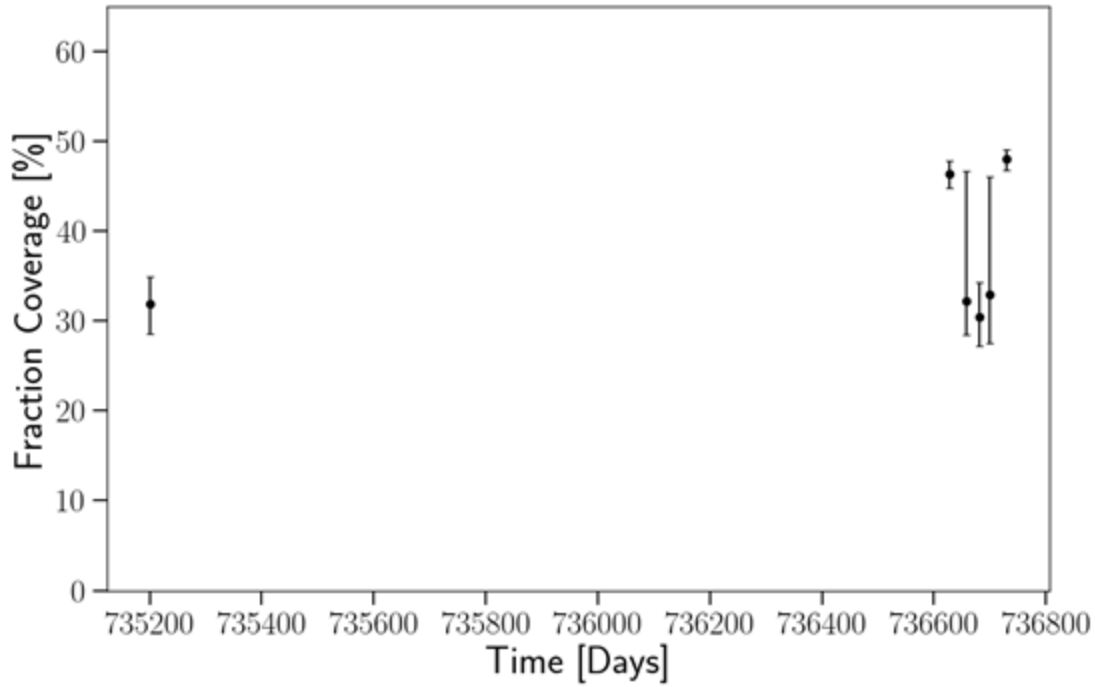
G-141



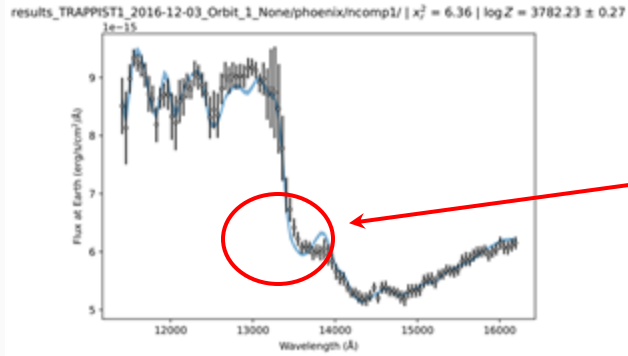


# HAT-P-11 Temporal Evolution

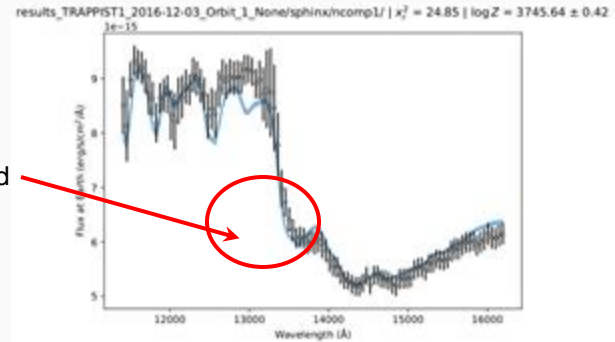
Preliminary  
Analysis



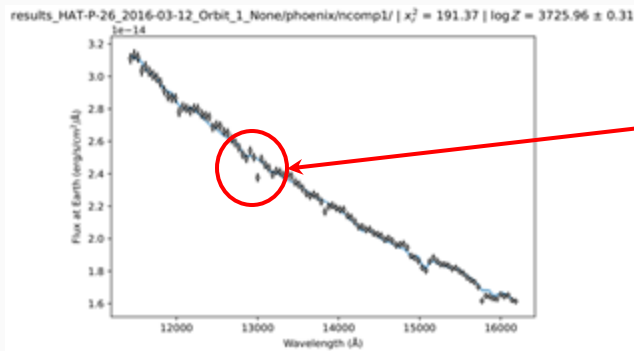
# Inter-Model Comparison



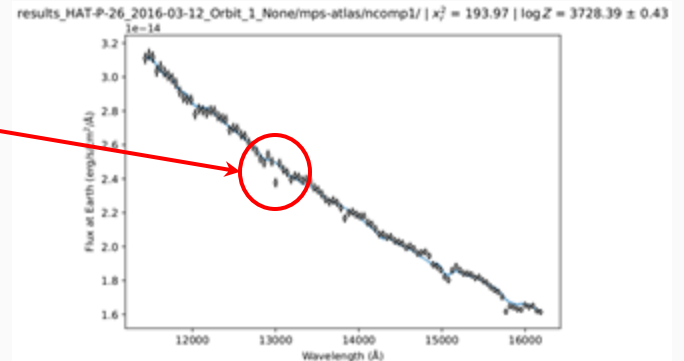
Phoenix



Sphinx



Phoenix

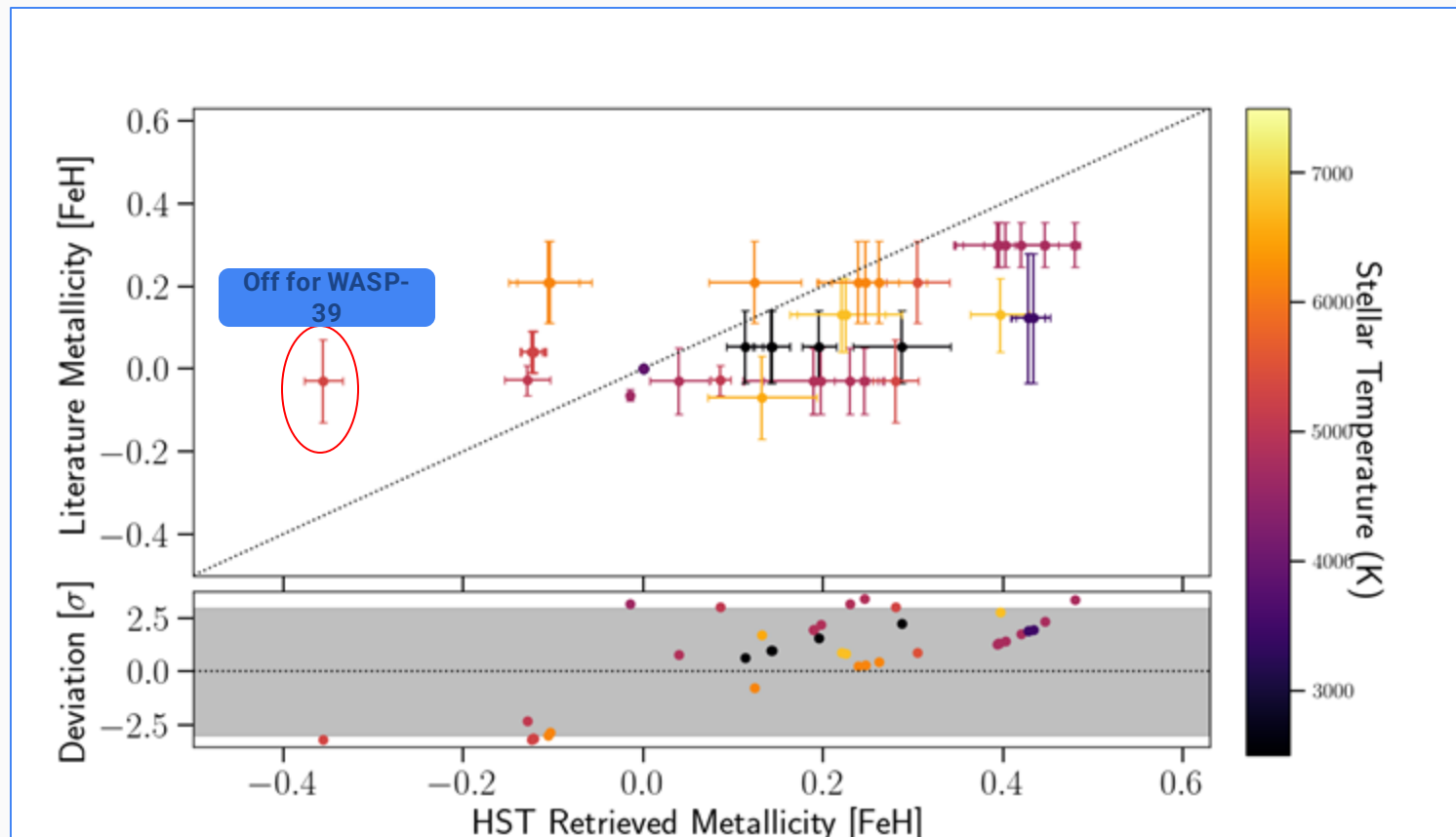


MPS-Atlas

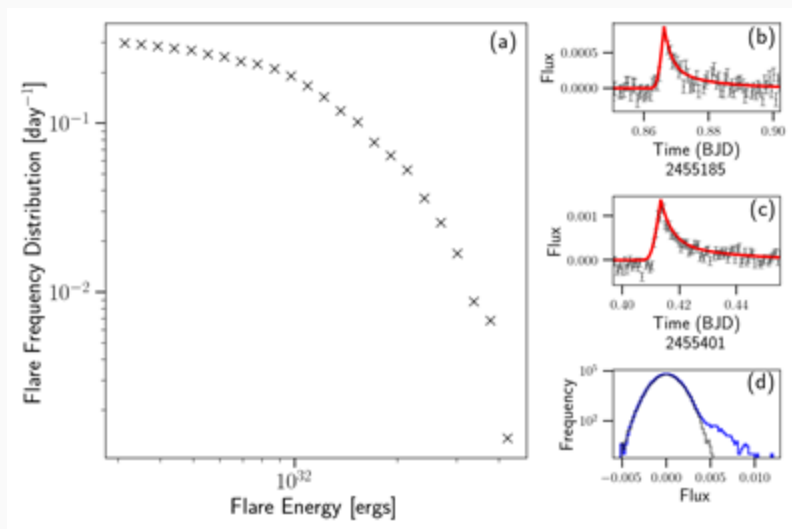
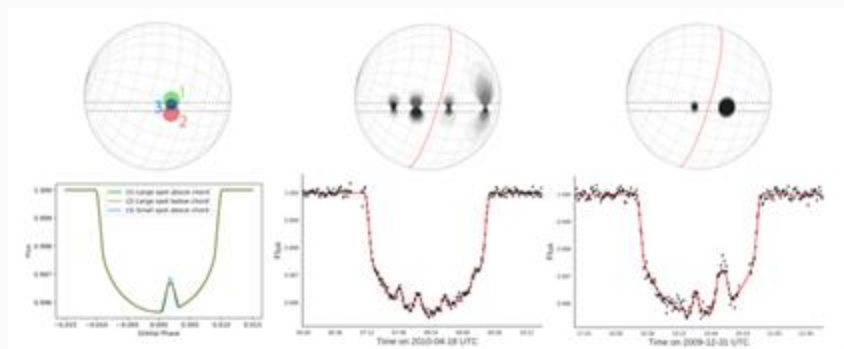
Water band

Missing  
Absorption  
Feature

# Retrieving Metallicity

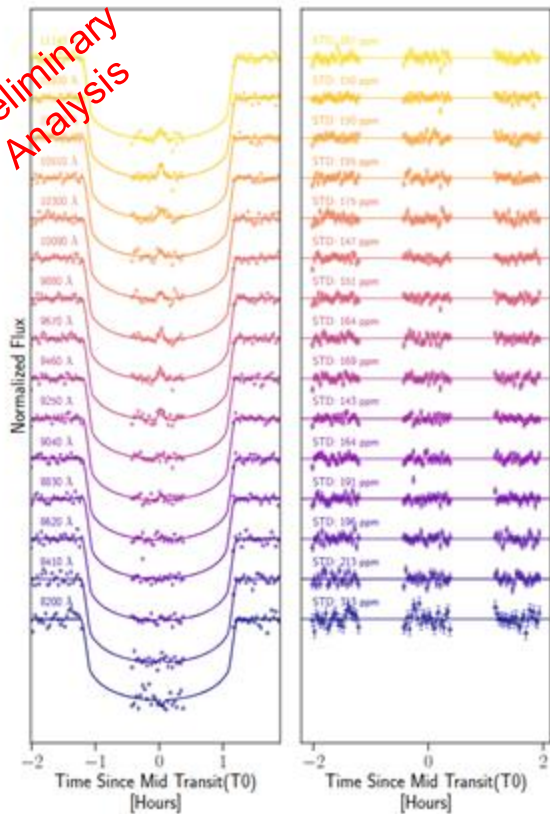


# Connection between Flares and Spots lacking



# Spot Temperature Contrast

Preliminary  
Analysis



|                  | Morris et al. 2018 | G-102              | G-141                |
|------------------|--------------------|--------------------|----------------------|
| Spot Fraction    | $3_{-1}^{+6}$      | $30_{-9}^{+14}$    | $30 \pm 6$           |
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