NASA's ExoPAG Study Analysis Group (SAG) 21:

The Effect of Stellar Contamination on Space-based Transmission Spectroscopy

Nestor Espinoza (STScI) & Benjamin Rackham (MIT) on behalf of SAG21

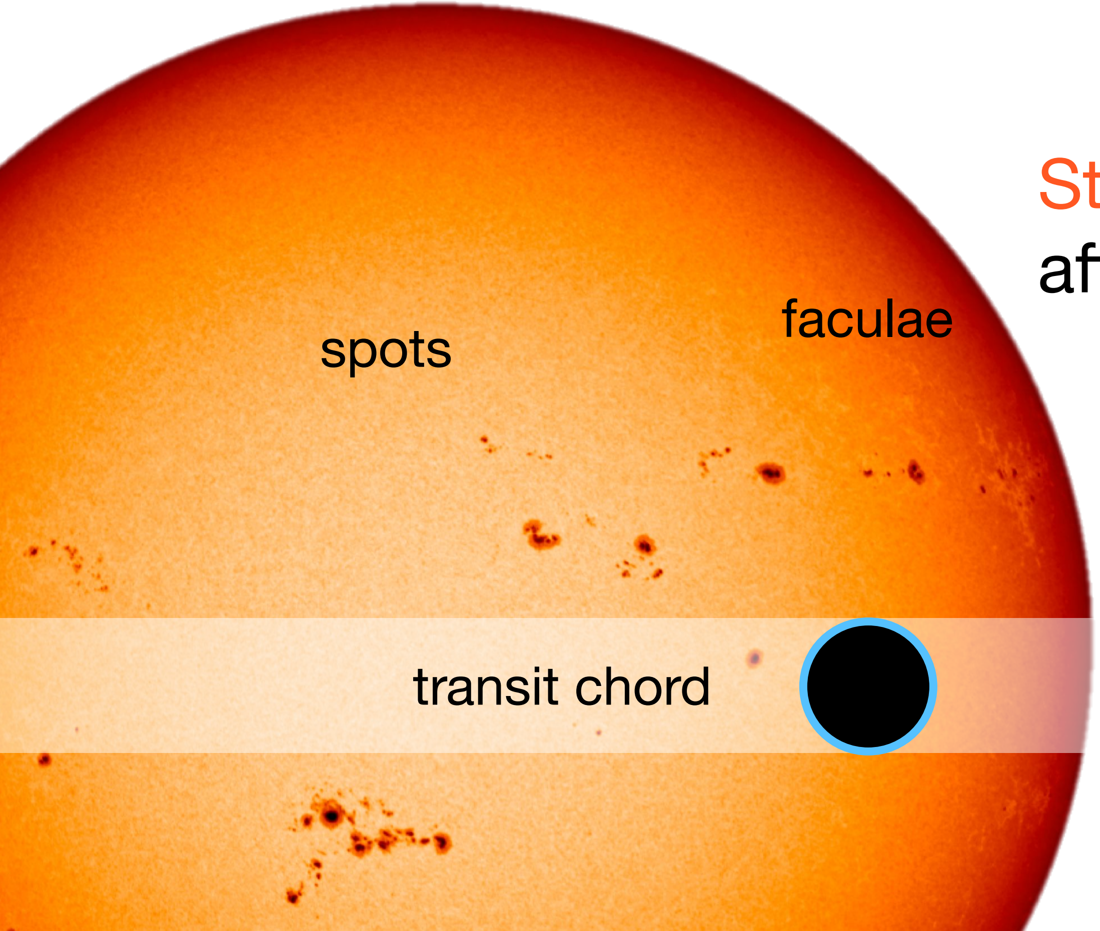
ExoPAG 24 Update | 24 Jun 2021

Outline

1. SAG21's Goals & Timeline
2. Community Symposium
3. Status of the Report

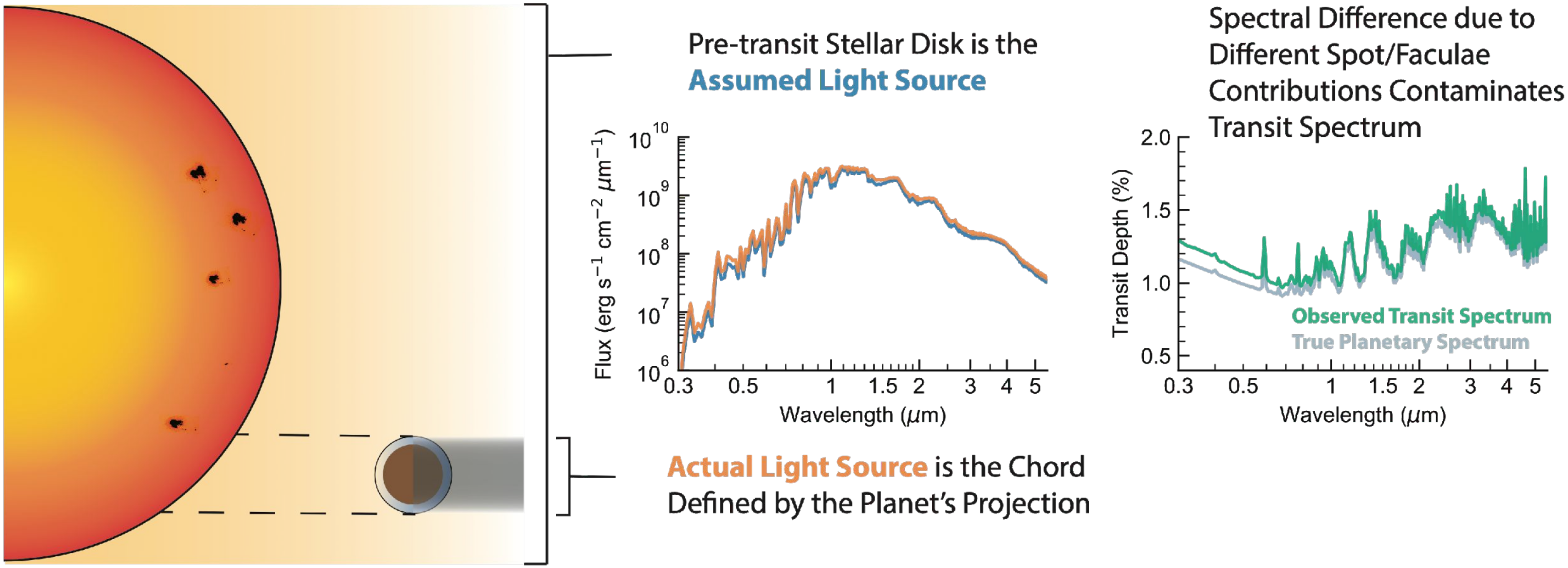
1. SAG's Goals & Timeline

The Challenge: “Stellar Contamination”



Stellar heterogeneity
affects transits depths too!

The Transit Light Source Effect

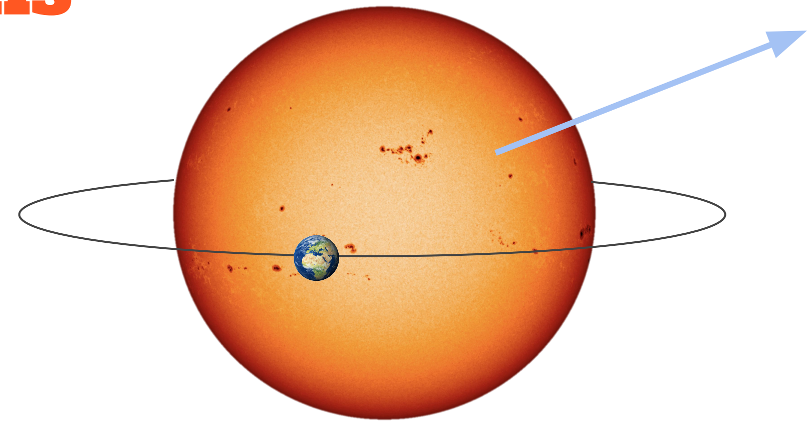


Rackham et al. (2018)

See also: Pont+08, Bean+10, Berta+11, Sing+11, Aigrain+12, Huitson+13, Jordán+13, Kreidberg+14, McCullough+14, Nikolov+15, Herrero+16, Zellem+17

To what extent will this impact space-based transmission spectra?

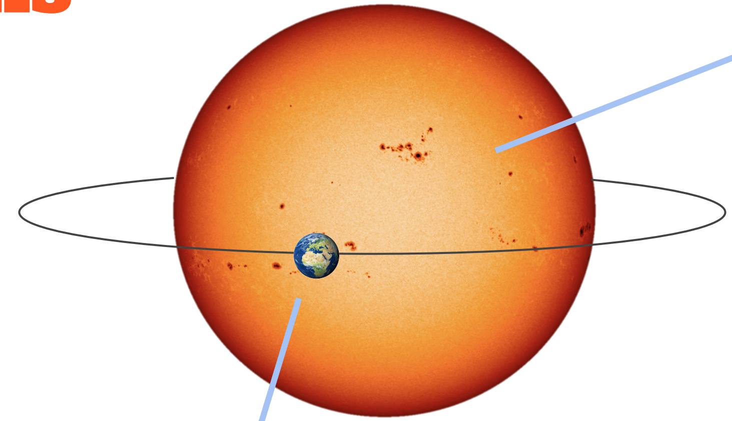
Goals



What do we know & what can we learn from the star?

e.g., chromospheric activity, photometric monitoring, polarization

Goals



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What can we learn from transits?

Planet

e.g., transit spectroscopy

Star

e.g., unocculted surface, occulted active regions, flares.

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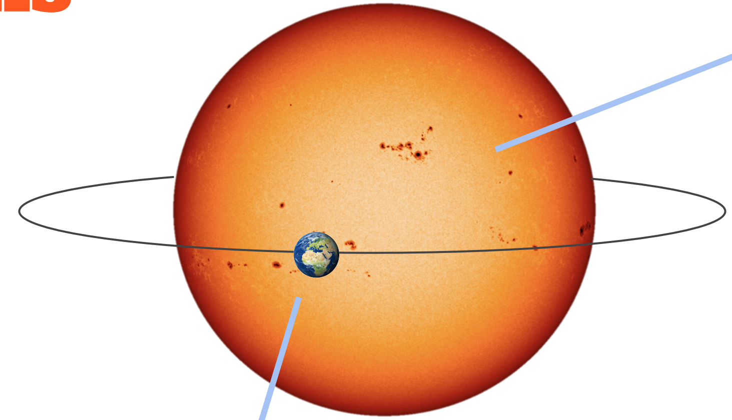

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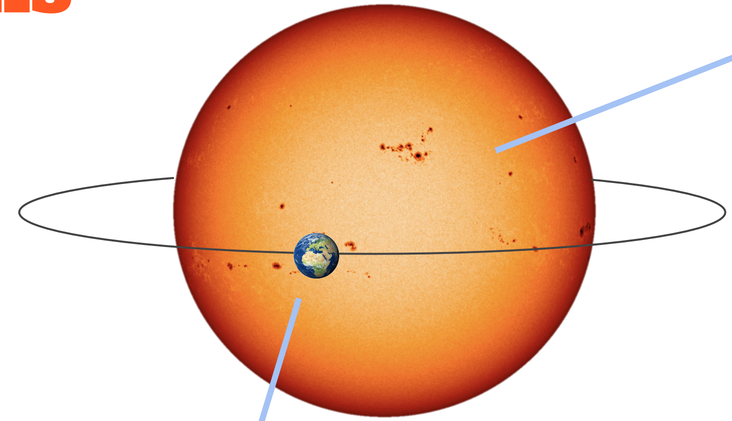
What will the impact be on future studies?

Goals



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Star

e.g., unocculted surface, occulted active regions, flares.

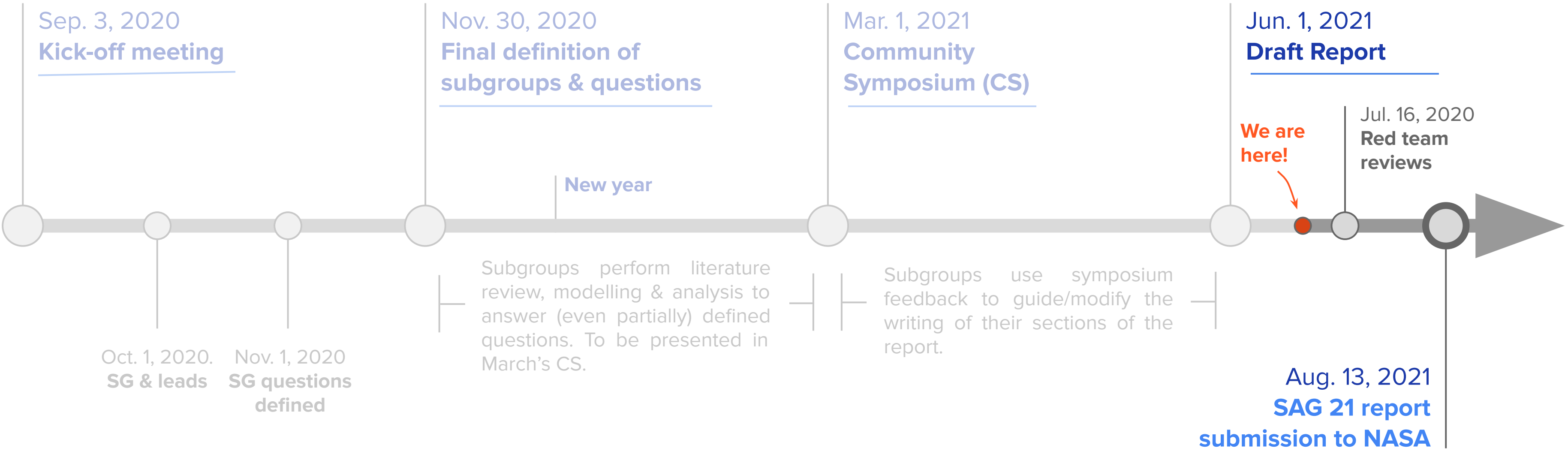
What will the impact be on future studies?

What complementary observations will be useful?

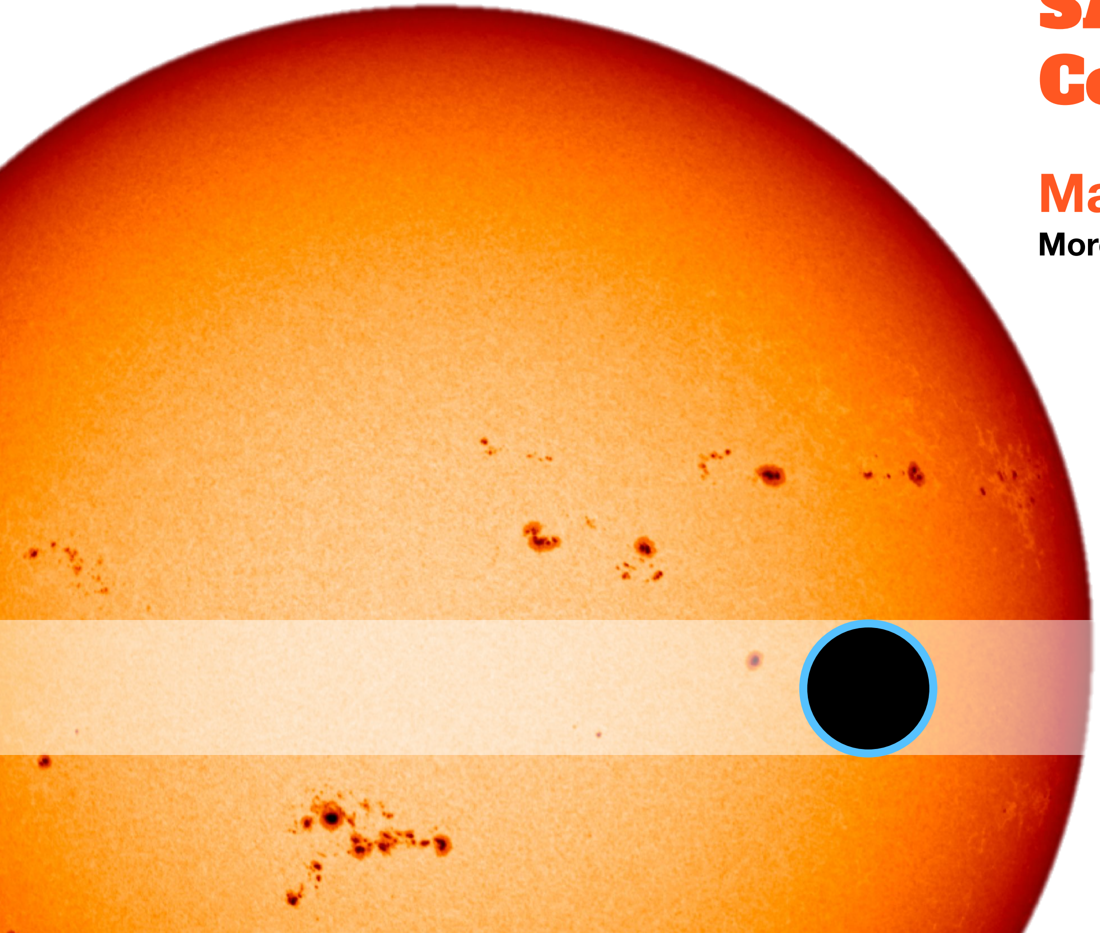
Main deliverable:

SAG21 report to NASA by mid-2021

SAG21 Timeline



2. Community Symposium



SAG21's (virtual) Community Symposium

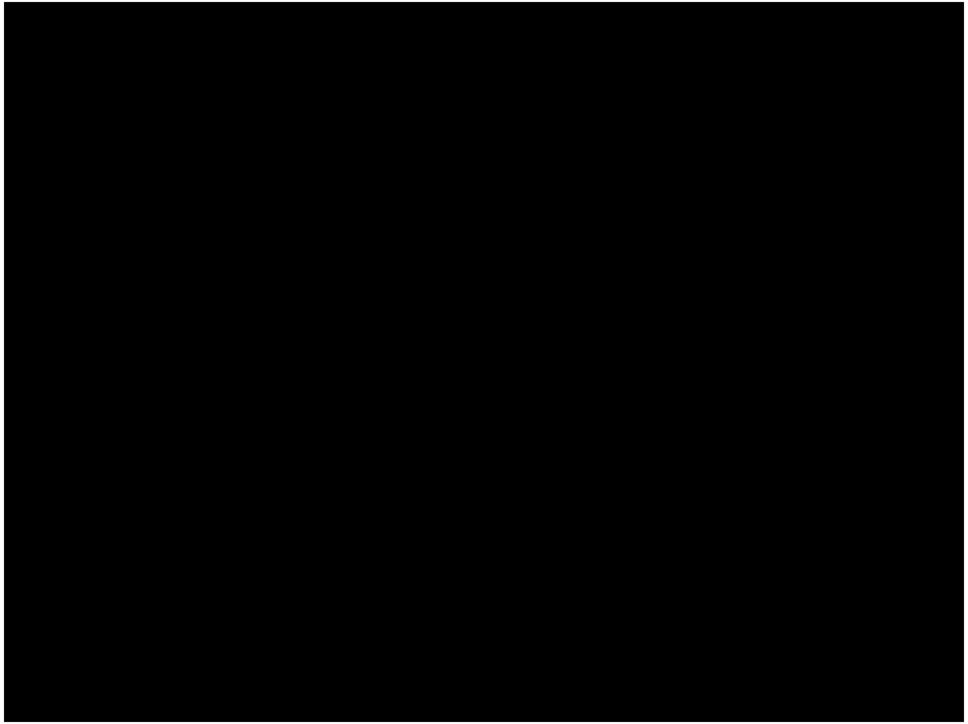
March 8 and 9, 2021

More info: sites.google.com/view/sag21symposium

5 overview presentations from subgroup leads

21 contributed talks from the community

~110 attendees, 46 active participants on Slido



SAG21's (virtual) Community Symposium

Recorded talks available on the symposium website:

sites.google.com/view/sag21symposium

3. Status of the report

The road to submission

The road to submission

Step 1

SGs submit draft report

- **11** SG leads.
- **40** contributors
- **Monthly** SG Leads meetings.

The road to submission

We're here

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Red team reviews

- **19** red reviewers.
- Different career stages/expertises.
- **3** week **turnaround**.

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- **Polish** executive summary.
- General **text editing**.
- **Fill gaps** between SG Chapters via Introduction.

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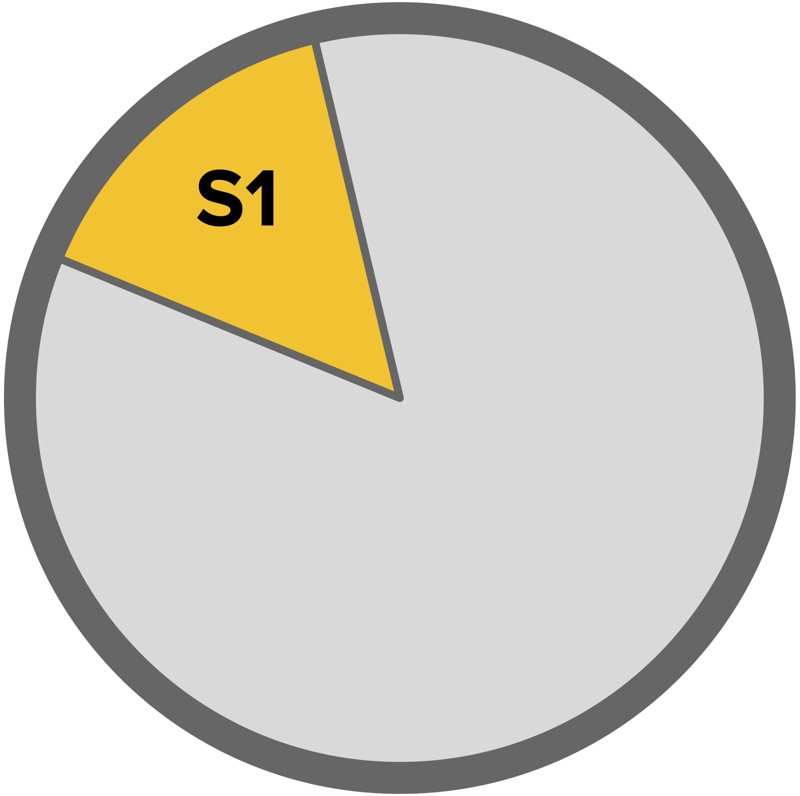
Submit To NASA

S1: Stellar Photospheric Heterogeneity

Leads: Svetlana Berdyugina, Heidi Korhonen & Alexander Shapiro



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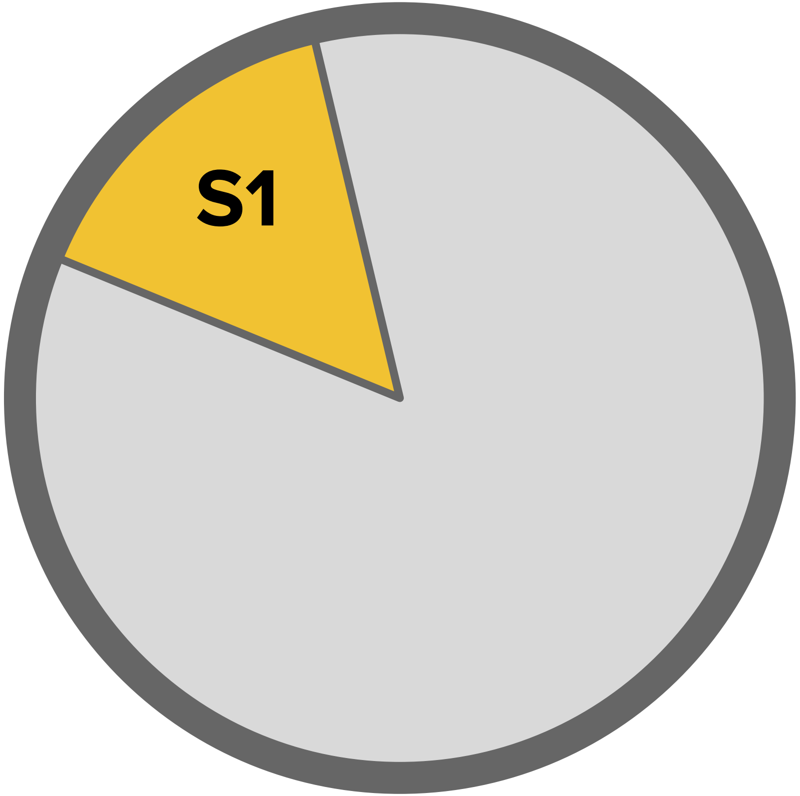
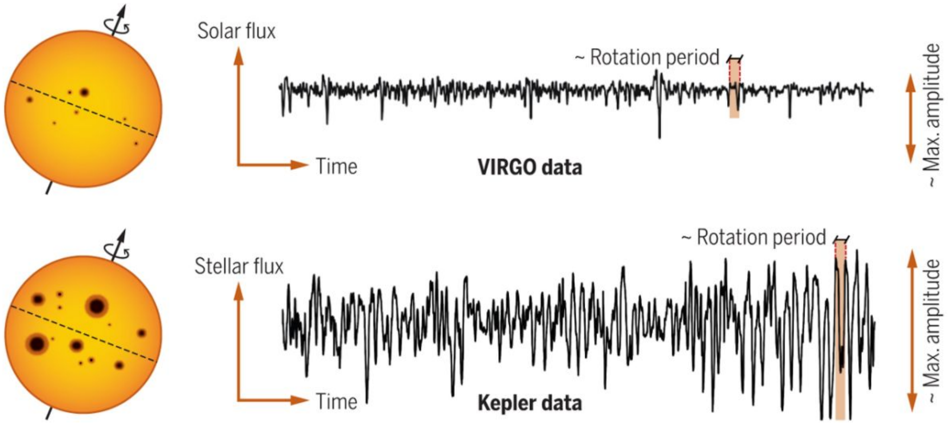
Leads: Svetlana Berdyugina, Heidi Korhonen & Alexander Shapiro



Photometric monitoring

Figure source: Santos & Mathur (2020)



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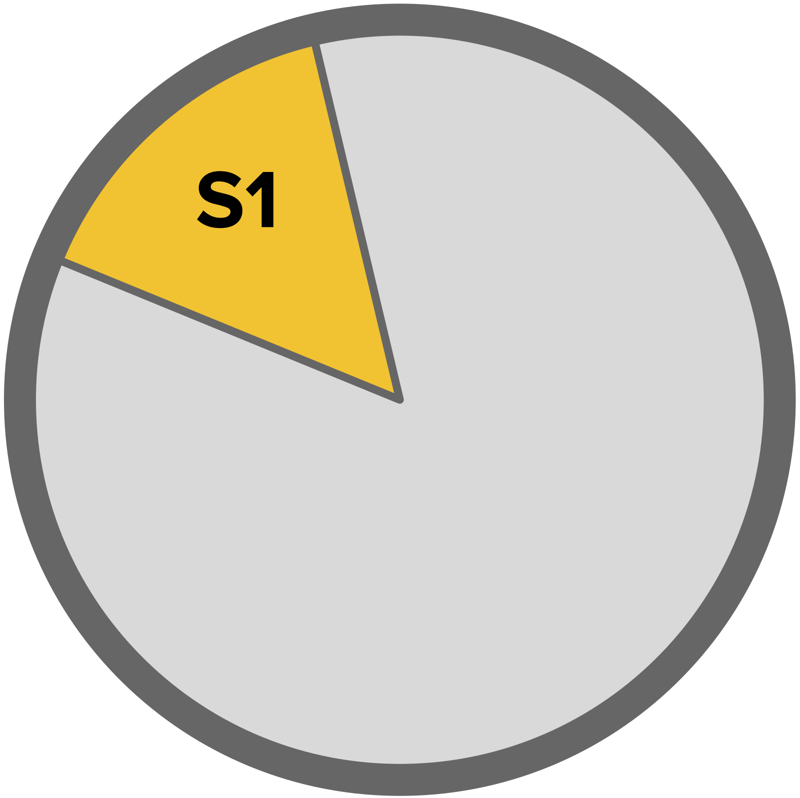
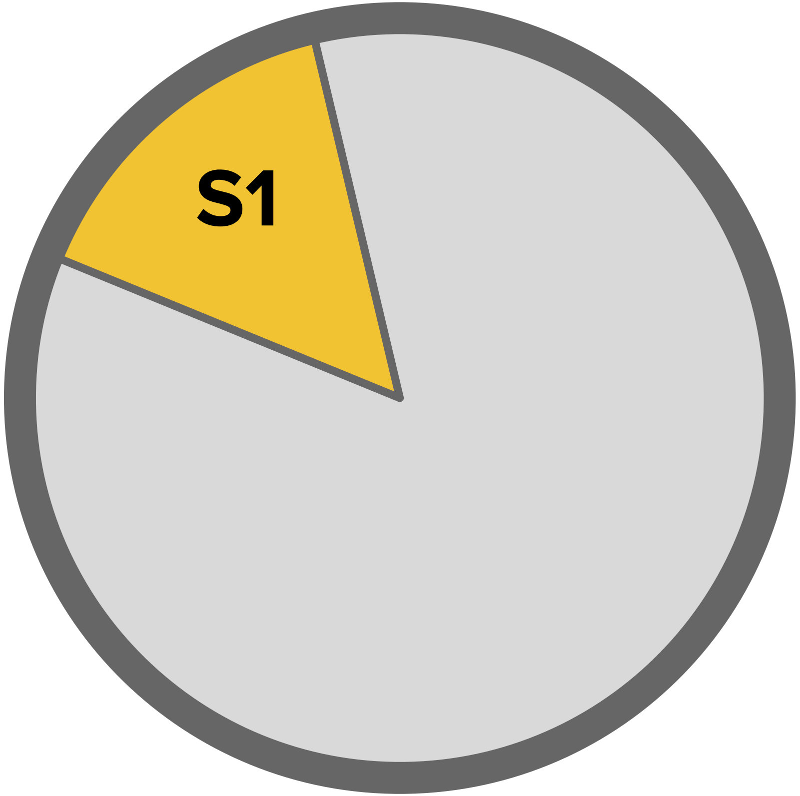


Finding 1.1:

Studying the optical and infrared spectral variations of solar surface structures on time-scales from minutes to years will provide a benchmark for analogous stellar studies and is therefore necessary for transmission spectroscopy of exoplanets.

S1: Stellar Photospheric Heterogeneity

Leads: Svetlana Berdyugina, Heidi Korhonen & Alexander Shapiro

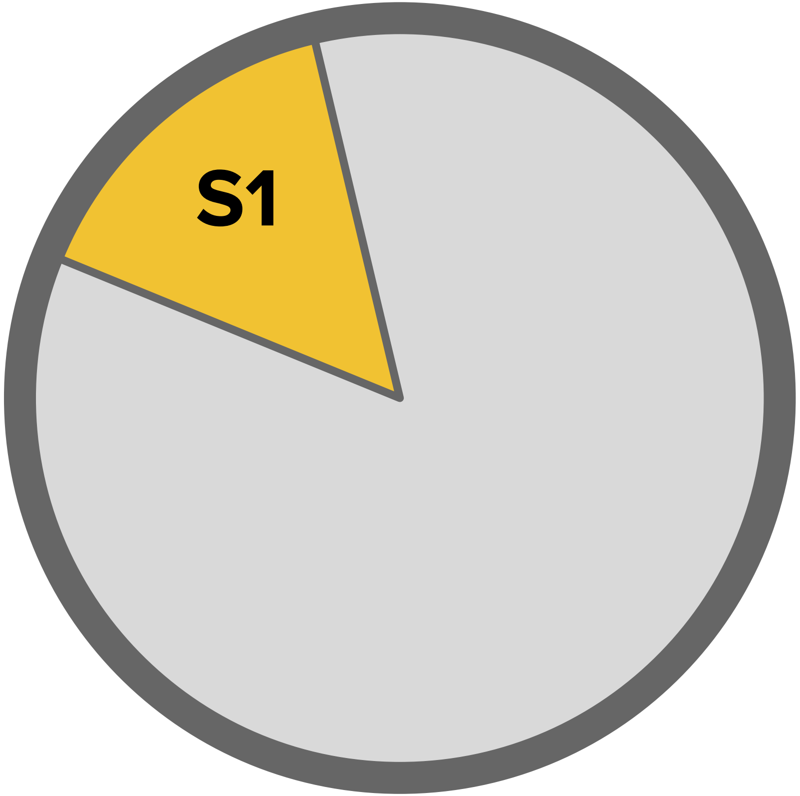


Finding 1.2:

Many lower activity stars, i.e., exoplanet hosts that are interesting for transmission spectroscopy, are faculae-dominated. Currently, there are very few detailed spectral studies of stellar faculae. Therefore, a study of spectral variability of stellar faculae is urgently needed.

S1: Stellar Photospheric Heterogeneity

Leads: Svetlana Berdyugina, Heidi Korhonen & Alexander Shapiro



Finding 1.3:

The effect of magnetic fields strongly depends on the fundamental parameters of stars. Thus, simulations of magnetic features and spectral synthesis for a larger range of stellar parameters (e.g., metallicity, temperatures, ages) are crucial for distinguishing spectral contributions from stellar magnetic features and exoplanetary atmospheres.

S1: Stellar Photospheric Heterogeneity

Leads: Svetlana Berdyugina, Heidi Korhonen & Alexander Shapiro

Q1.1 What photometric indicators are most useful for constraining photospheres?

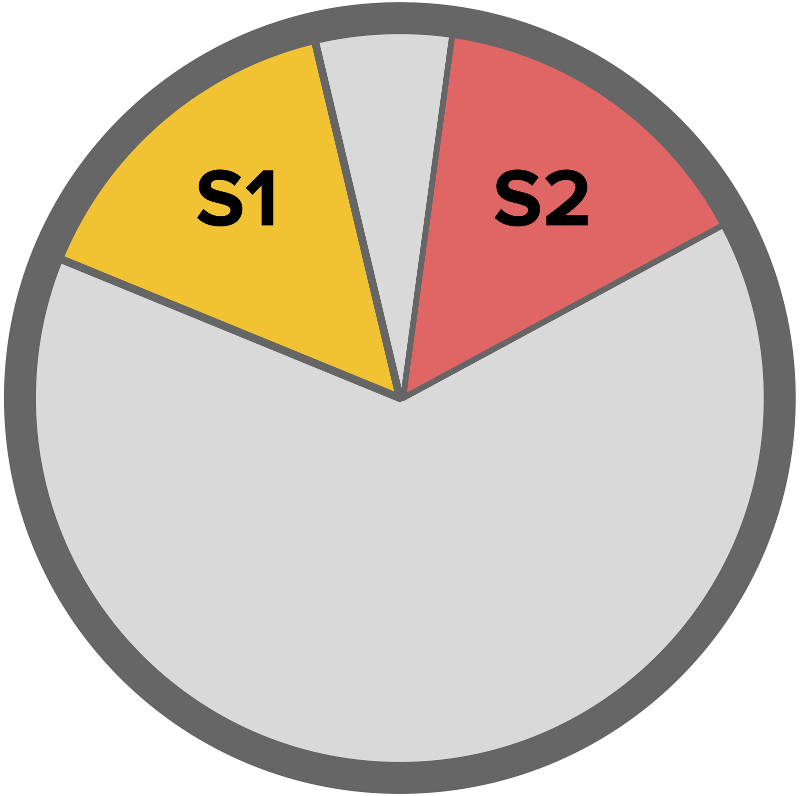
Q1.2 What spectral indicators are most useful for constraining photospheres?

Q1.3 What other datasets and/or techniques can help to unveil stellar photospheres? (e.g., polarimetry, doppler imaging).

Q1.4 What is known about the activity of high-priority exoplanet host stars?

S2: Stellar Spectral Decomposition

Leads: Joanna Barstow, Benjamin Rackham, & Ryan McDonald



S2: Stellar Spectral Decomposition

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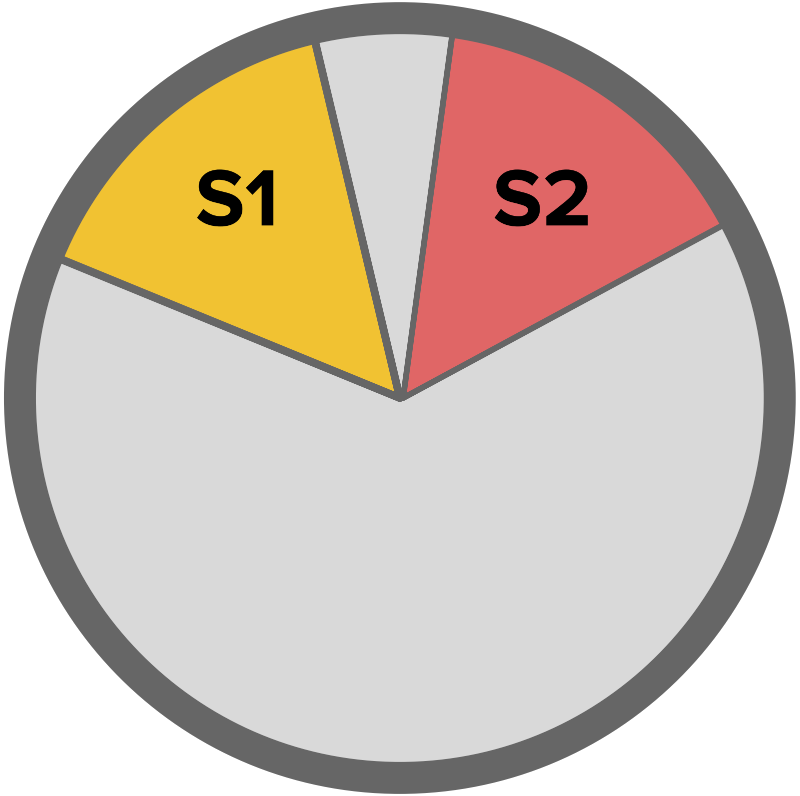
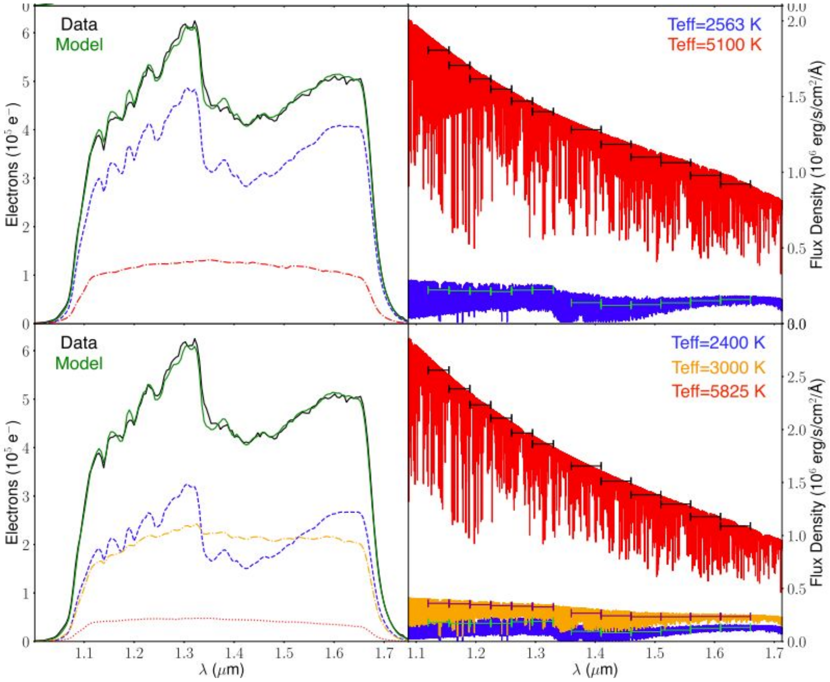


The case of TRAPPIST-1

[Wakeford et al. (2019)]



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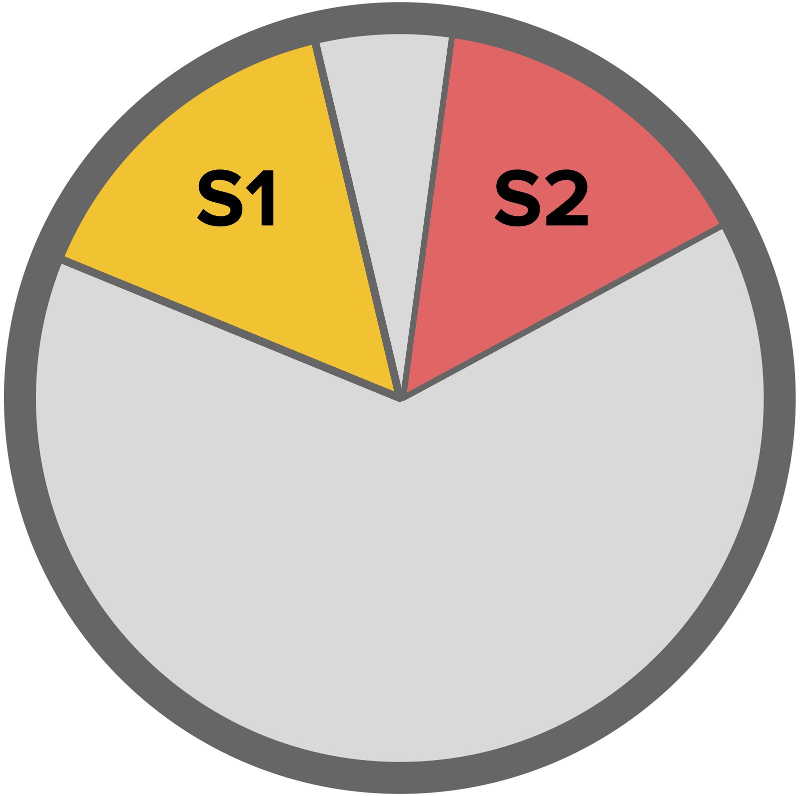
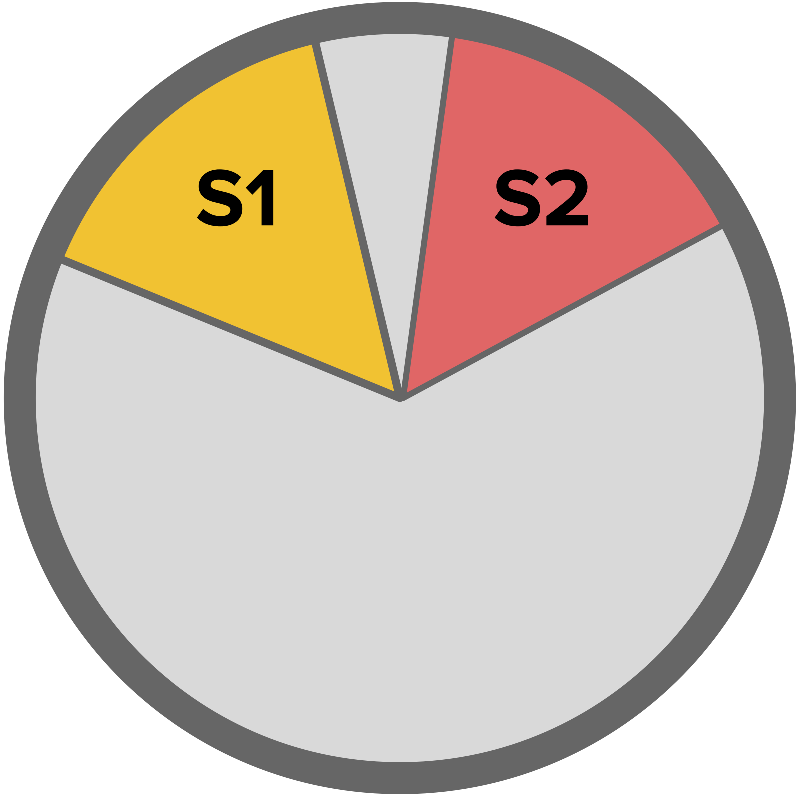


Finding 2.1:

Retrievals of transmission spectra that include the effects of unocculted active regions can guard against biases. More work is needed to understand when these retrievals are necessary and what are the limitations and best practices of this approach.

S2: Stellar Spectral Decomposition

Leads: Joanna Barstow, Benjamin Rackham, & Ryan McDonald



Finding 2.2:

Retrieval approaches rely on stellar models, and thus their accuracy is limited by model fidelity. More work is needed to (1) further test and develop models for cool stars, (2) assess the impact of using stellar spectra to approximate active regions, and (3) develop model spectra for active regions, particularly faculae, for different spectral types.

S2: Stellar Spectral Decomposition

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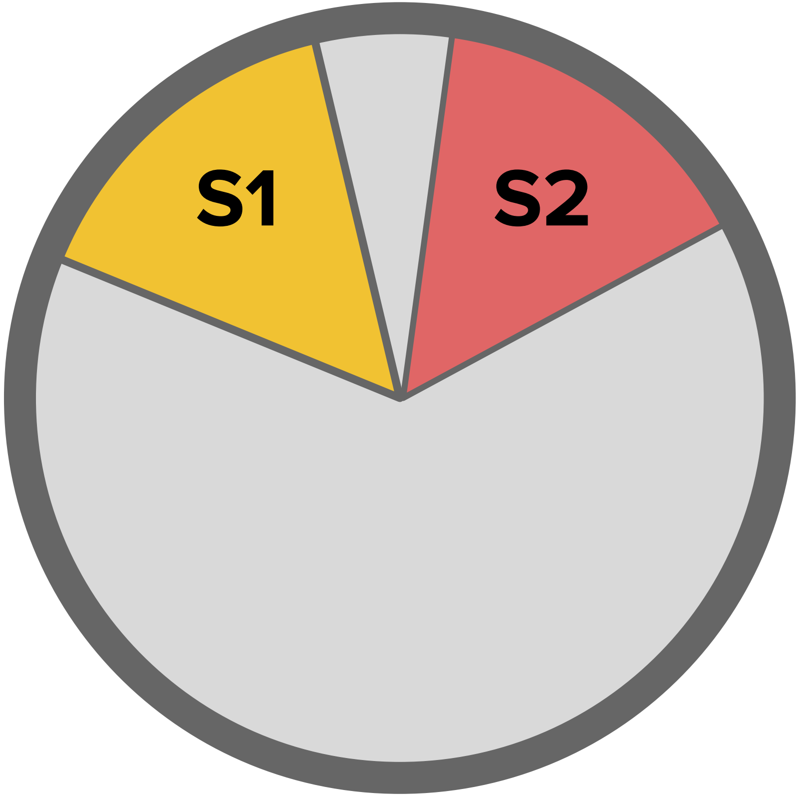


Finding 2.3:

For low-resolution transmission spectra, the impact of unocculted active regions is larger at shorter wavelengths. More work is needed to quantify the complementary nature of such spectra for JWST observations.

S2: Stellar Spectral Decomposition

Leads: Joanna Barstow, Benjamin Rackham, & Nestor Espinoza

Q2.1 What is the state-of-the-art on spectral decomposition of observed stellar spectra?

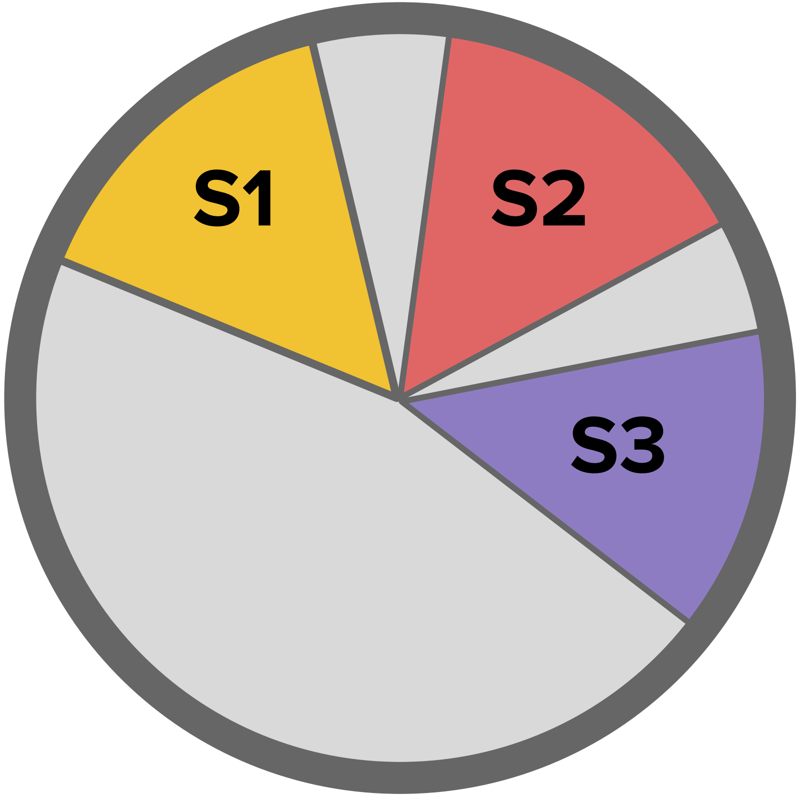
Q2.2 How useful is low-resolution spectral decomposition of exoplanet host stars? How far can, e.g., JWST spectra be pushed to resolve the photospheric components?

Q2.3 How useful is high-resolution spectral decomposition of exoplanet host stars? Is higher resolution better? Can ground-based observations complement space-based ones? Is it critical to get them at the same time as JWST observations?

Q2.4 How can this information be propagated to retrieval analyses? How constraining is it for them?

S3: Occulted Active Regions

Leads: Mahmoud Oshagh & Brett Morris



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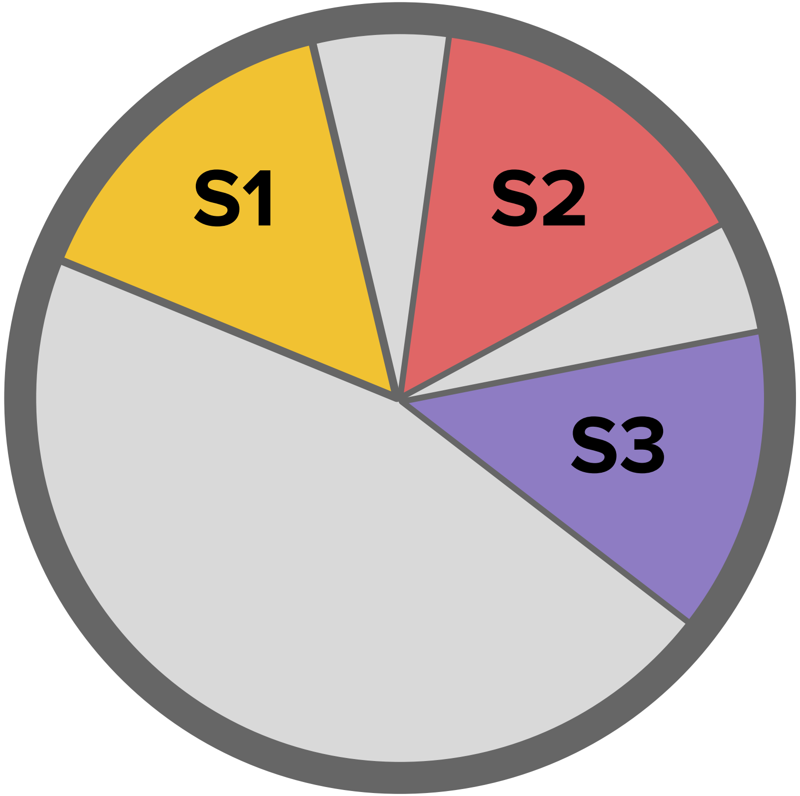
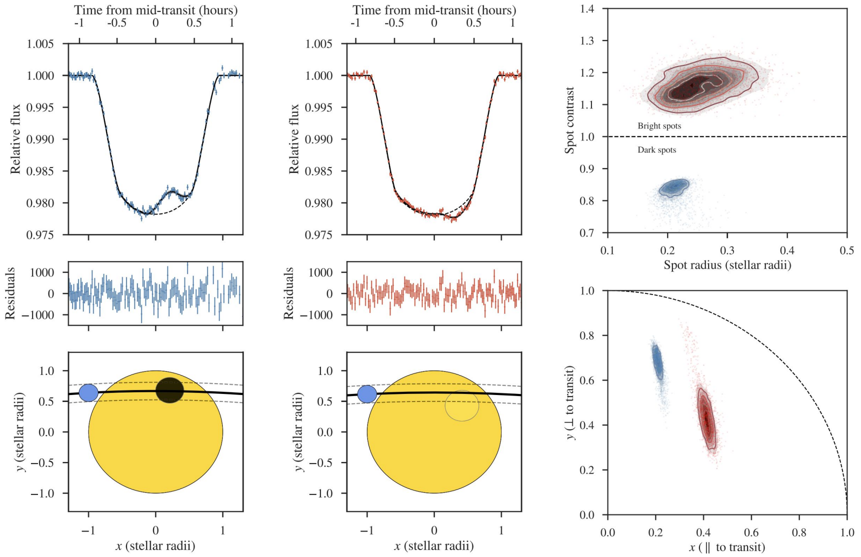


The case of WASP-19b

Figure source: [Espinoza et al. (2019)]()



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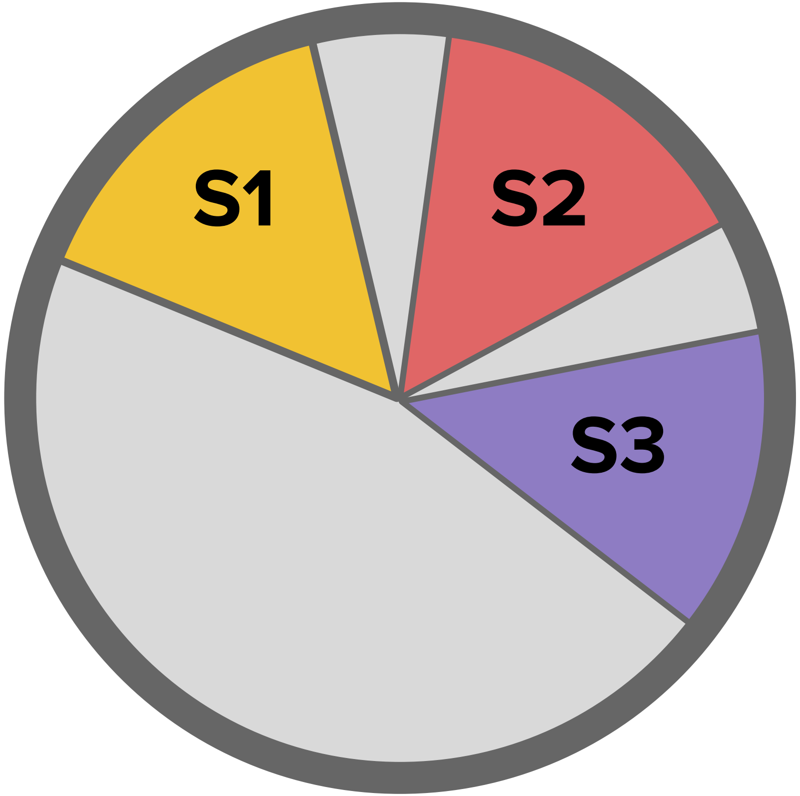

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Figure source: Espinoza et al. (2019)

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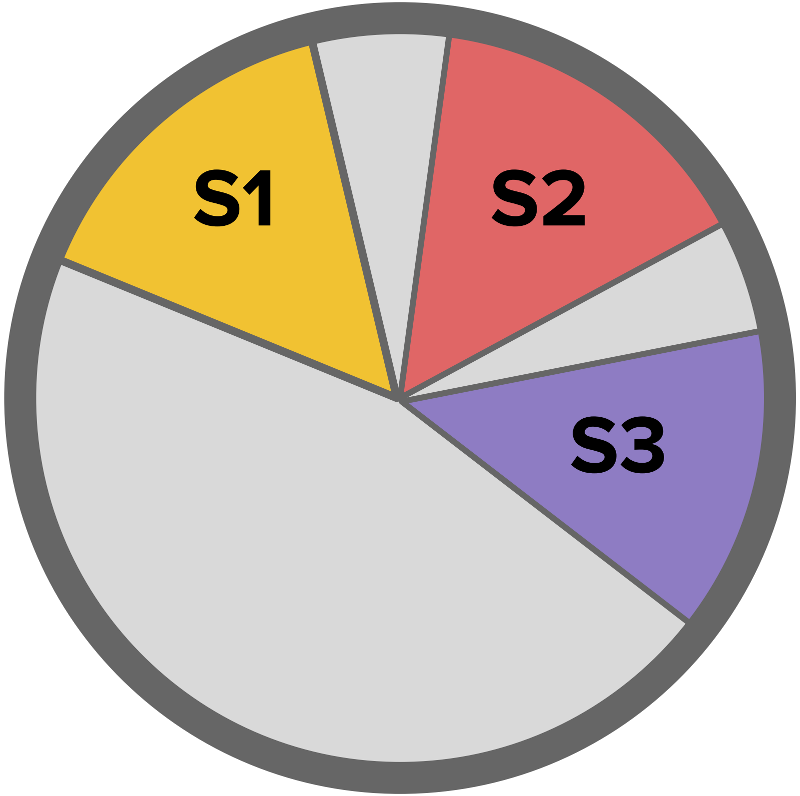
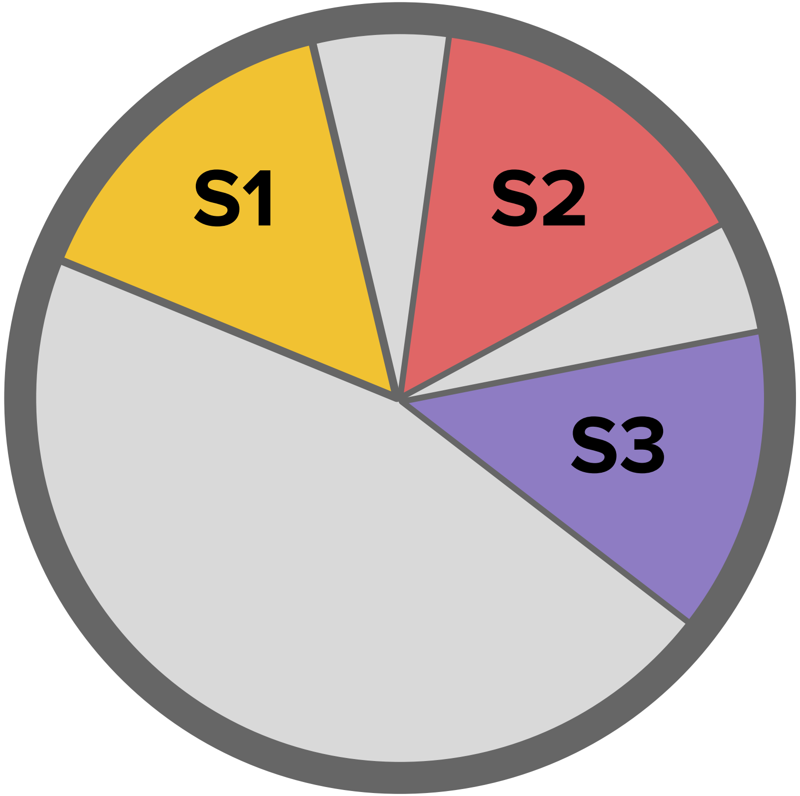


Finding 3.1:

Precise space-based photometry enables detections of active region occultations. As precision improves, we expect to be sensitive to smaller spots, which are more numerous. More work is necessary to understand how undetected active region occultations bias transit depths.

S3: Occulted Active Regions

Leads: Mahmoud Oshagh & Brett Morris

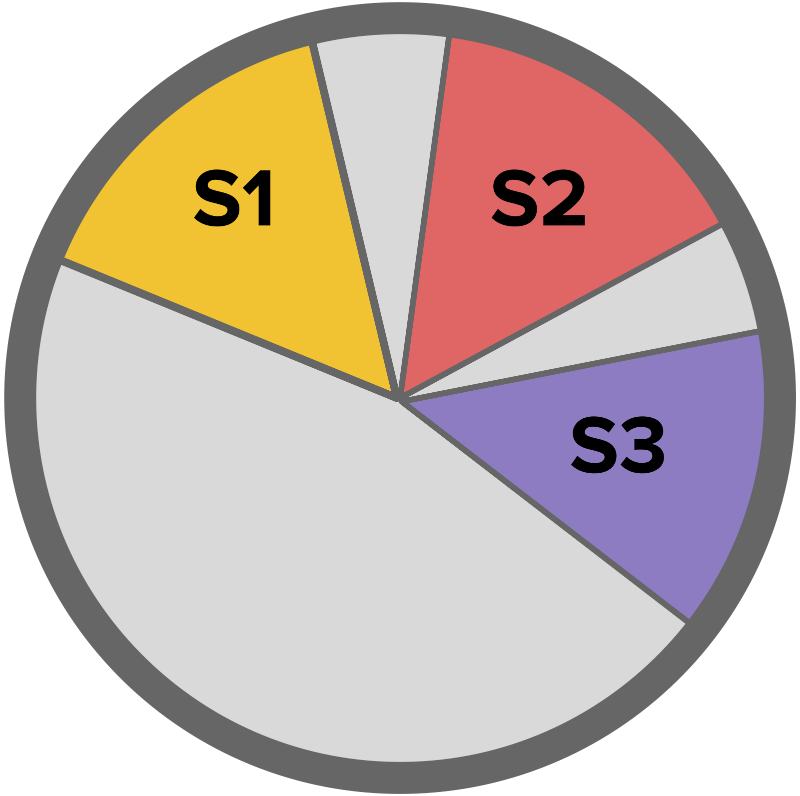


Finding 3.2:

There are several publicly available forward modeling tools for starspot occultations in broad photometric bandpasses. More work is necessary to fully leverage space-based datasets (e.g., Kepler, TESS, CHEOPS, HST) with these tools.

S3: Occulted Active Regions

Leads: Mahmoud Oshagh & Brett Morris

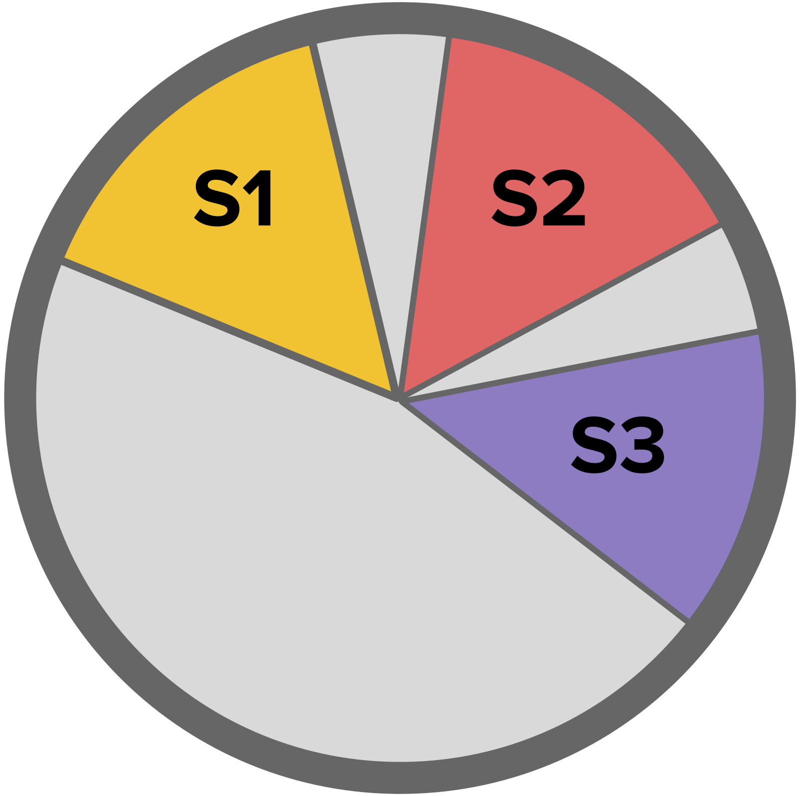


Finding 3.3:

Both narrow- and broad-band spectroscopic signatures of spot occultations affect transmission spectroscopy, and further studies are needed to understand the effects of spectroscopic resolution on biases in transit spectrophotometry.

S3: Occulted Active Regions

Leads: Mahmoud Oshagh & Brett Morris

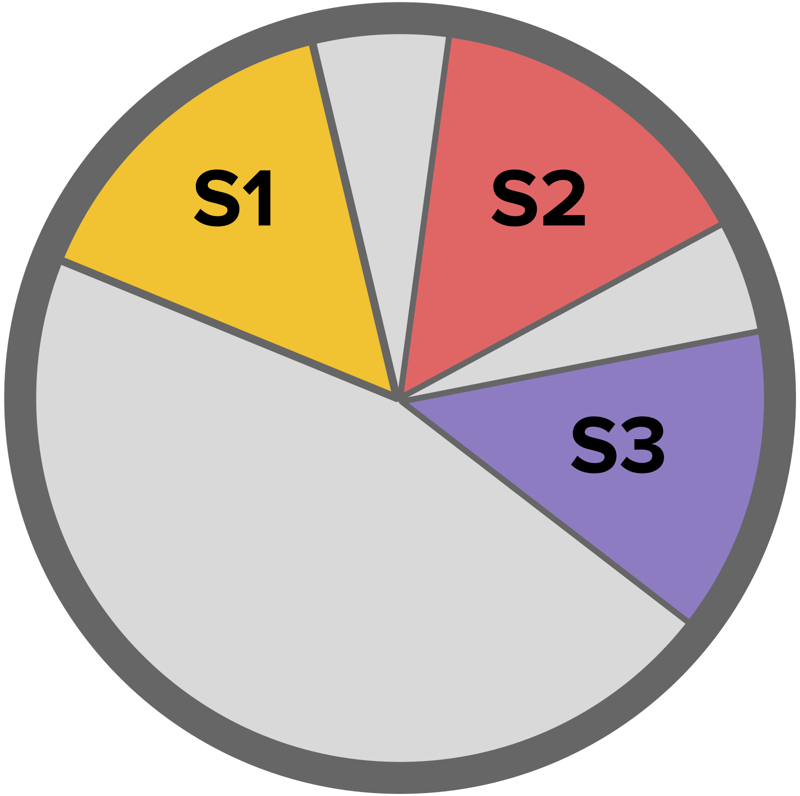


Finding 3.4:

Ab initio models of stellar magnetic activity should be used to inform priors on spot occultation parameters, such as spot contrasts and temperatures, for both Sun-like stars and other spectral types. More work on developing these models is needed.

S3: Occulted Active Regions

Leads: Mahmoud Oshagh & Brett Morris



Finding 3.5:

Long-term and/or multiwavelength monitoring of exoplanet host stars can constrain otherwise degenerate properties of occulted active regions such as the spot coverage and temperature. More multiwavelength monitoring observations are needed.

S3: Occulted Active Regions

Leads: Mahmoud Oshagh & Brett Morris

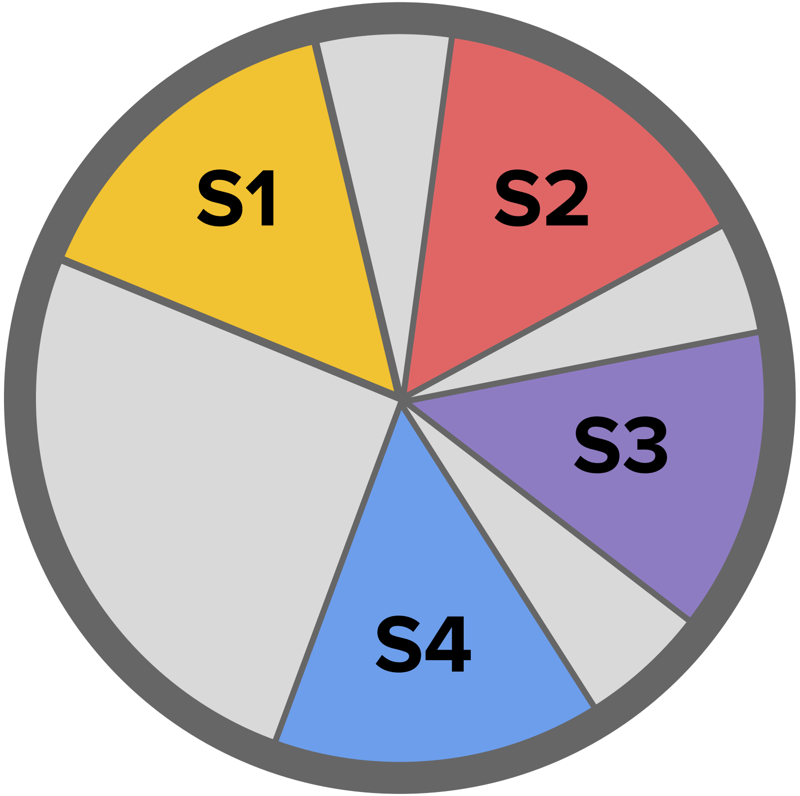
Q3.1 What is the state-of-the-art of this technique?

Q3.2 Are current modelling techniques of spot crossing events good enough for the precision of current and future observatories? (e.g., spot shape/geometry modelling, assumptions such as limb-darkening, etc).

Q3.3 Are “spot” spectra that are currently used sufficient or are more sophisticated models necessary?

S4: Unocculted Active Regions

Leads: Yvonne Unruh & Ben Montet



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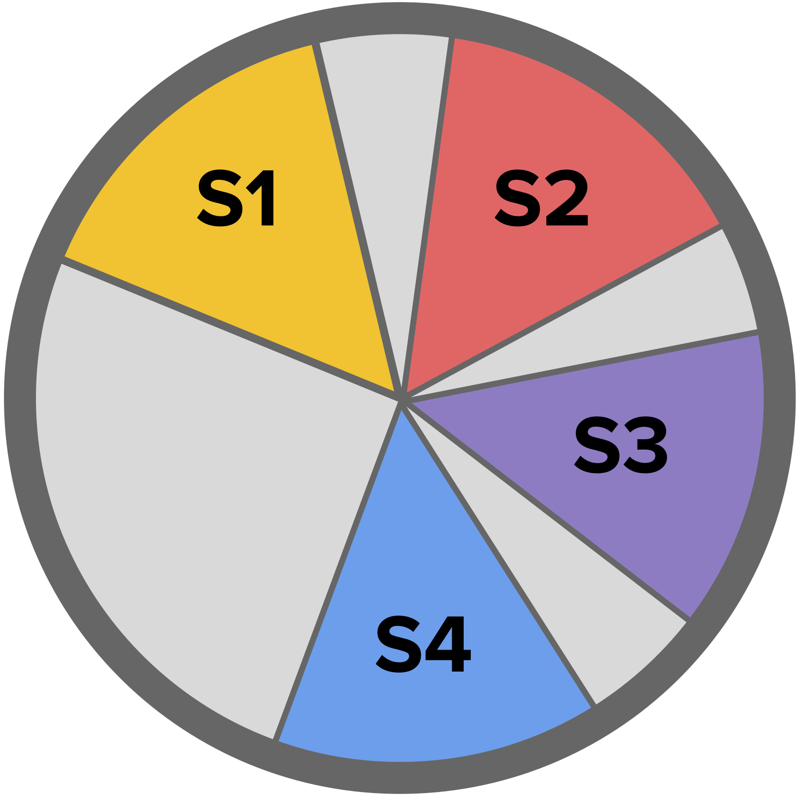
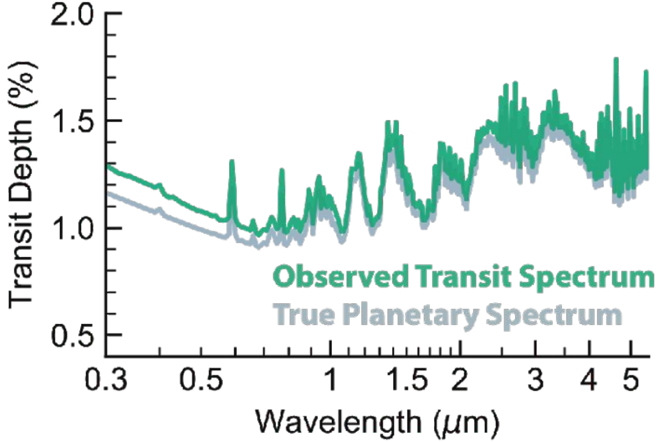


The Transit Light Source Effect

Figure source: [Rackham et al. (2018)]



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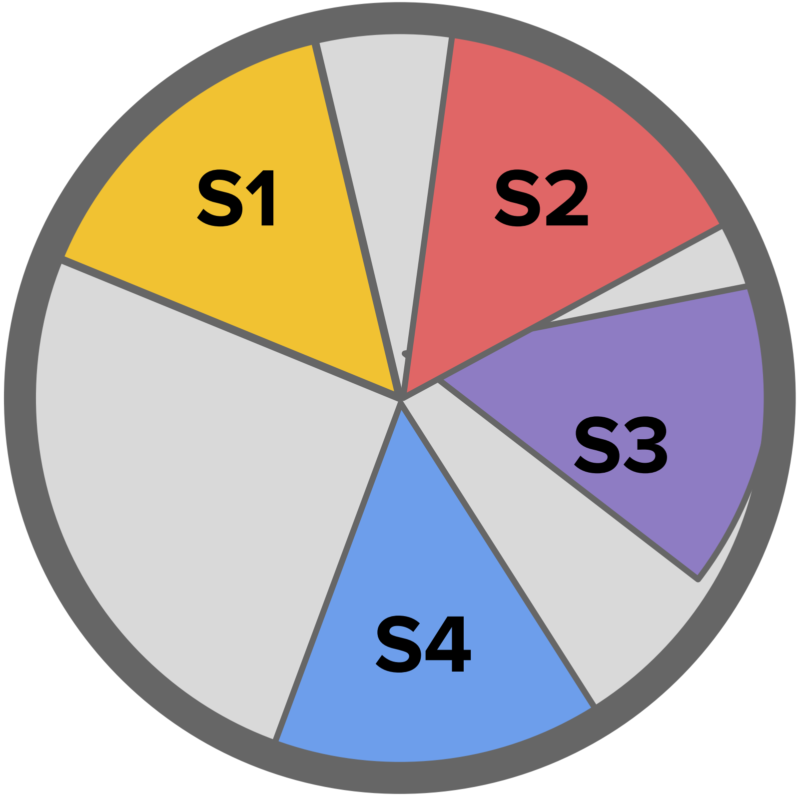
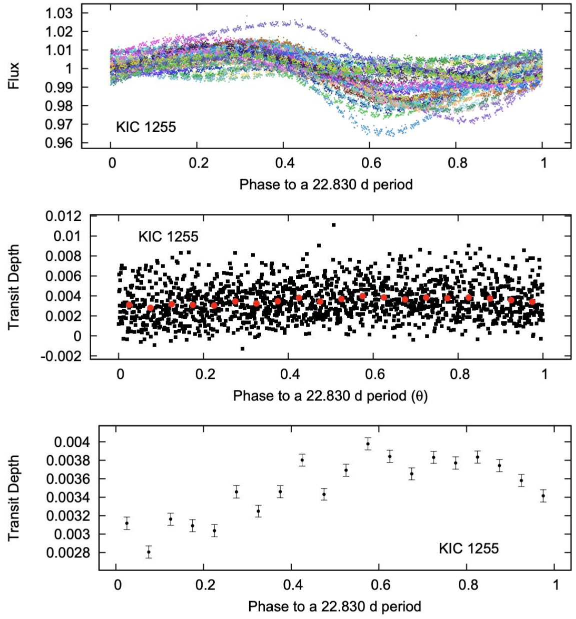


Transit depth variations in time

Figure source: [Croll et al. (2015)]



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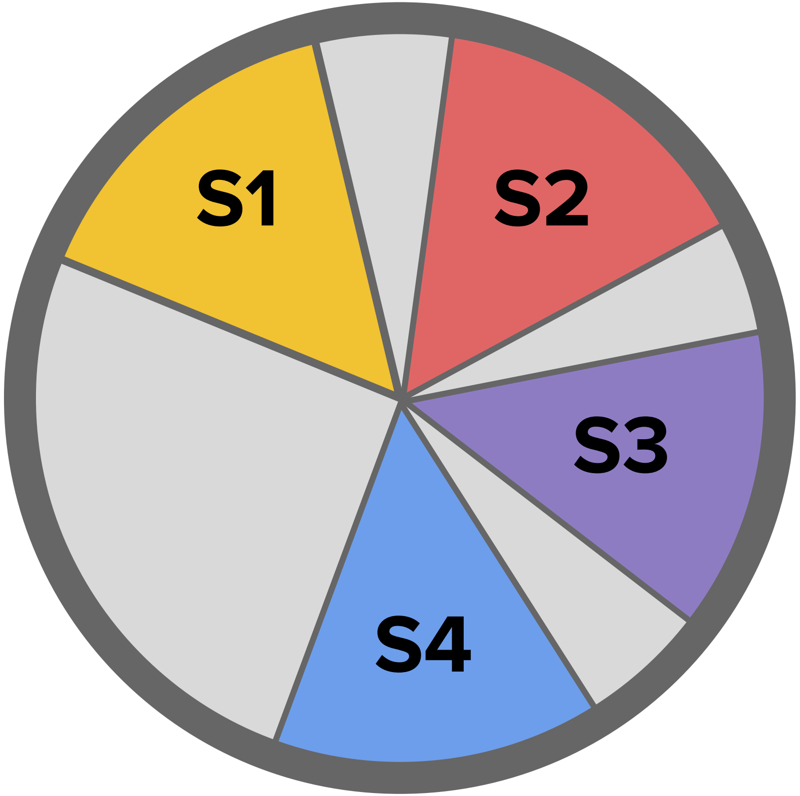
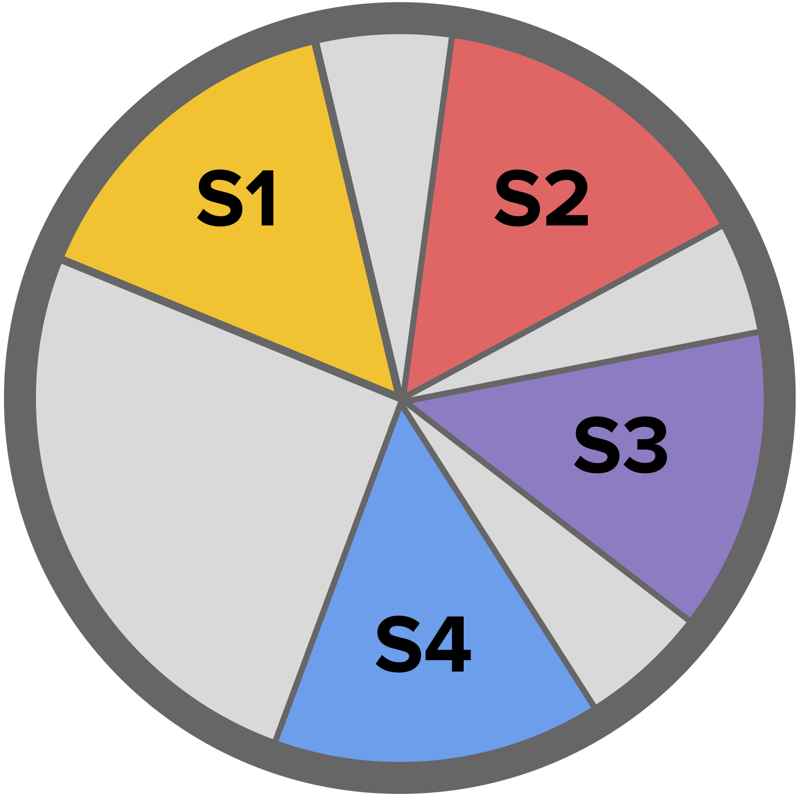


Finding 4.1:

High-cadence light curves provide the potential to understand unocculted active regions, but unambiguous measurements are elusive at present. Major theoretical work is needed to understand the relations between observational signatures of stellar activity in light curves.

S4: Unocculted Active Regions

Leads: Yvonne Unruh & Ben Montet

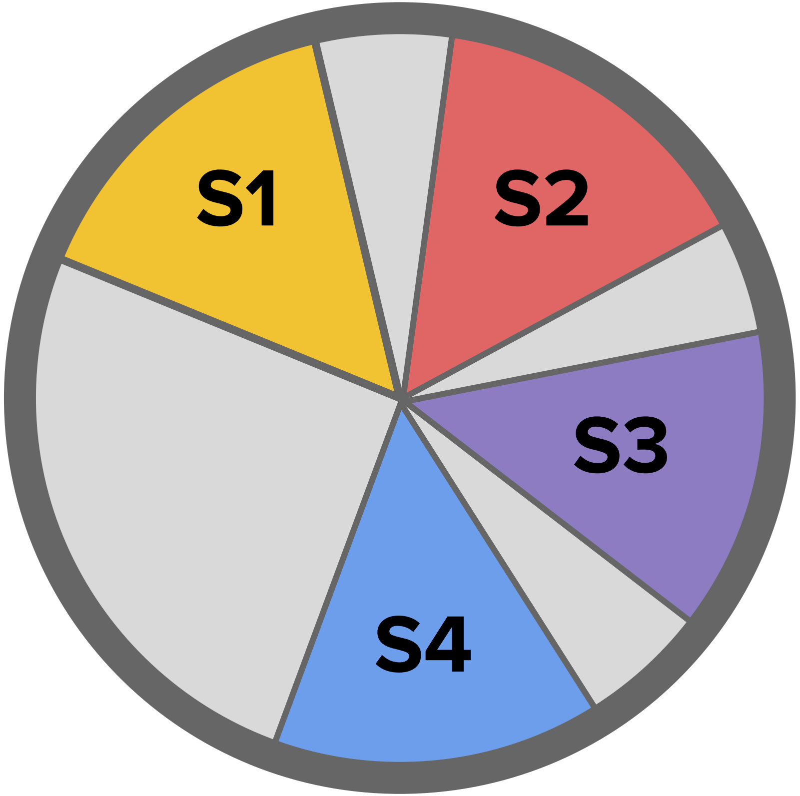


Finding 4.2:

Simultaneous photometry and spectroscopy provide critical information for understanding the potential effects of active regions on transmission spectra. While other data sets can provide information on filling factors, theoretical work is needed to maximise the utility of these data for transmission spectroscopy purposes.

S4: Unocculted Active Regions

Leads: Yvonne Unruh & Ben Montet

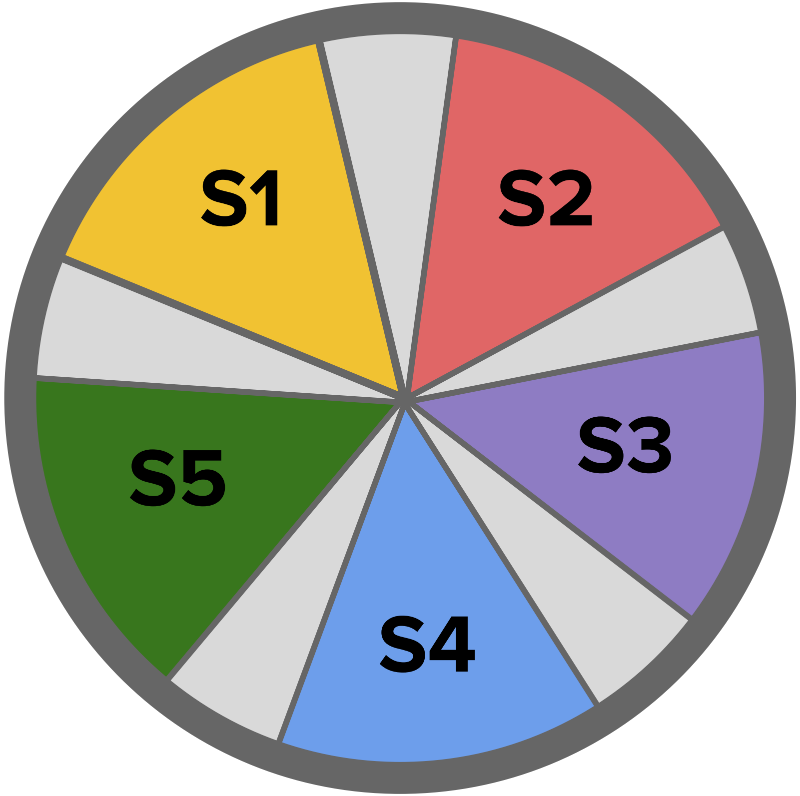


Finding 4.4:

Stellar "granulation flicker" constitutes a fundamental "noise floor" that increases with decreasing stellar surface gravity and at shorter wavelengths, dominating the atmosphere retrieval error budget in some cases. More work on understanding this noise source for long-duration, visible transits of solar-type stars is needed.

S5: Future Complementary Observations

Leads: Elisa Quintana & Rob Zellem



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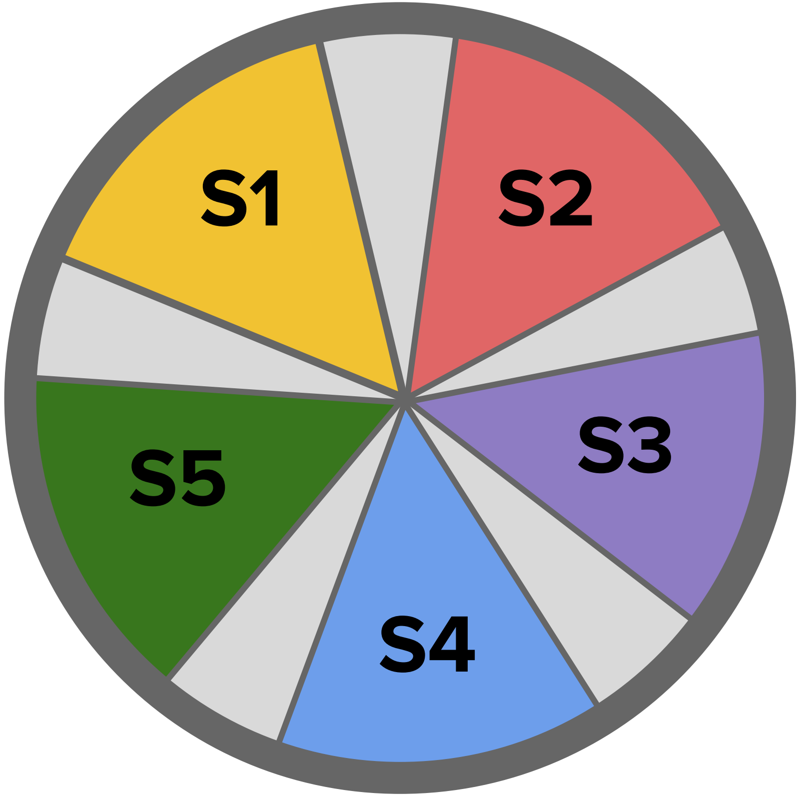
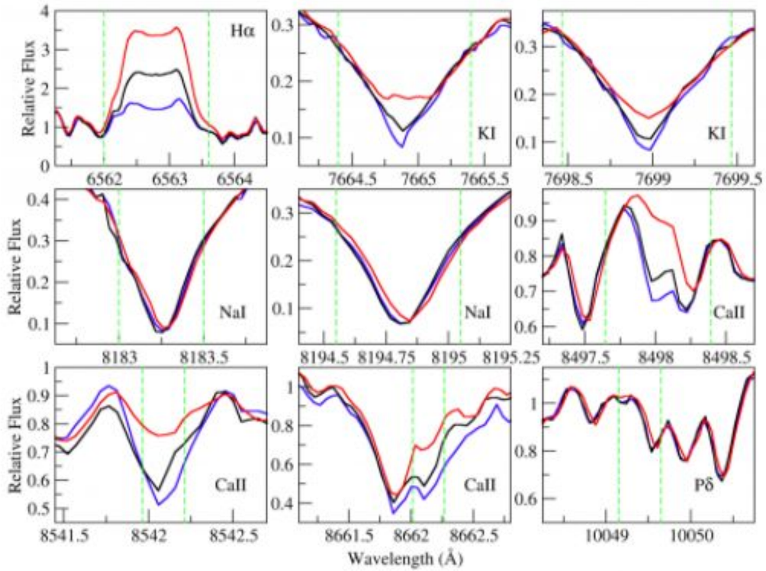


Spectroscopic monitoring

Figure source: Robertson (2016)



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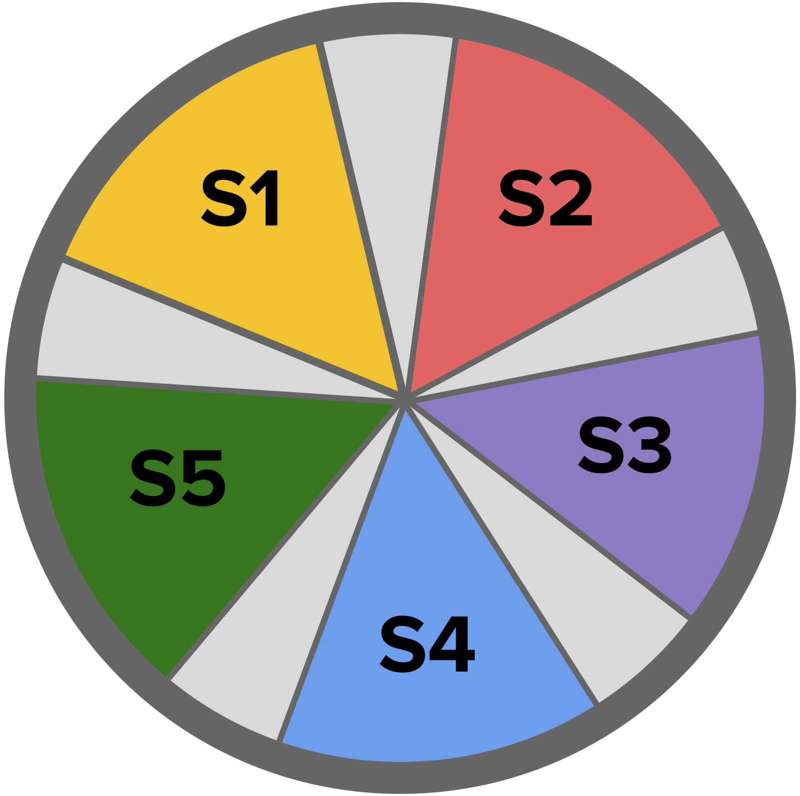

Findings, which build on earlier analyses, are in prep.

All this information (+more):
sites.google.com/view/sag21

Summary

1. **SAG21's goal is to deliver a report to NASA by mid-2021:** focus is on stellar contamination and its impact on transit spectroscopy from space-based observatories.

2. **SAG21's Community Symposium was a success**: 21 contributed talks + 5 overview talks from SAG21. Over 100 attendees.

3. **SAG21's report is on-track to be submitted by mid-August**.

Communication & sharing channels

SAG 21

slack

(Link has been shared via e-mail)

Google Drive

(Link has been shared via e-mail)

NASA's ExoPAG [SAG21 webpage]

Overleaf

(Link has been shared via e-mail)