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

The Effect of Stellar Contamination on Space-based Transmission Spectroscopy

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

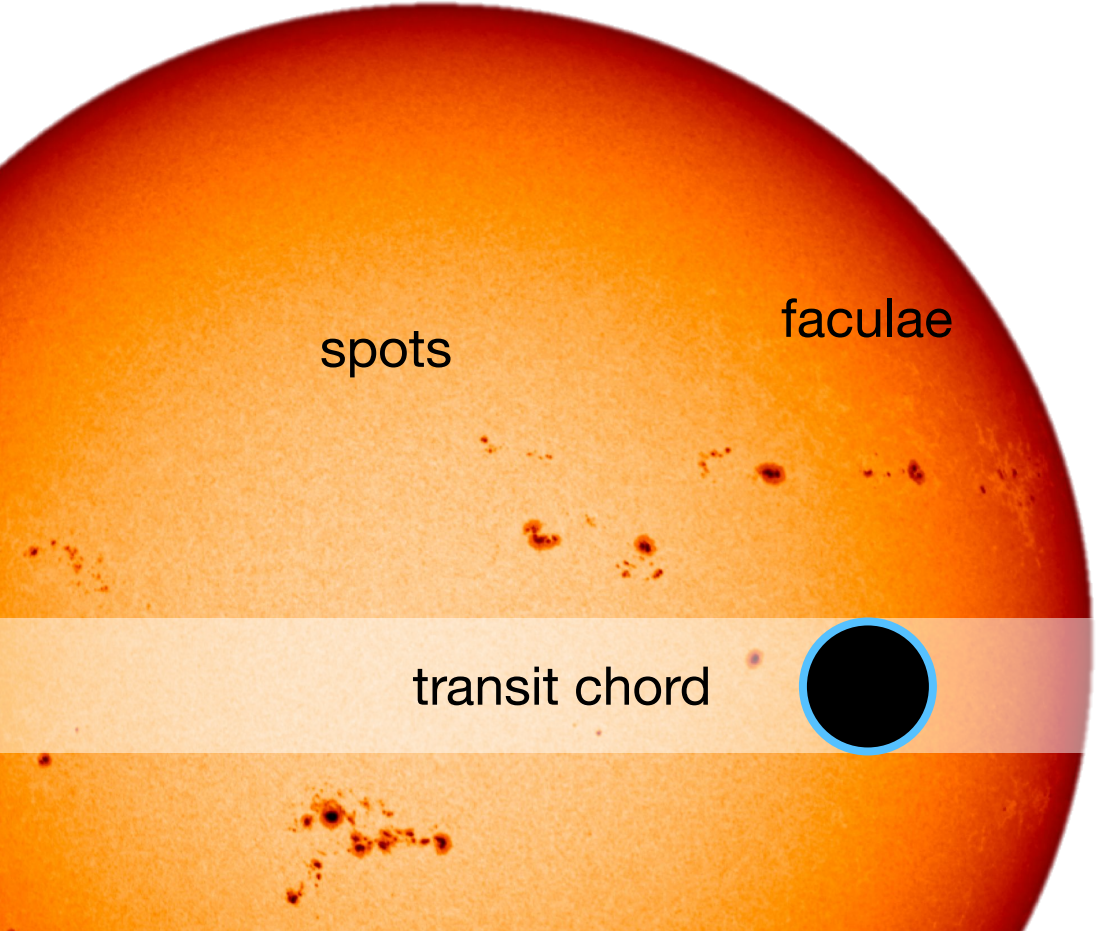
ExoPAG 25 Update | 10 Jan 2022

Outline

1. **SAG21 Overview**
2. **Summary of Main Findings**
3. **Conclusions**

1. SAG21 Overview

The Challenge: “Stellar Contamination”



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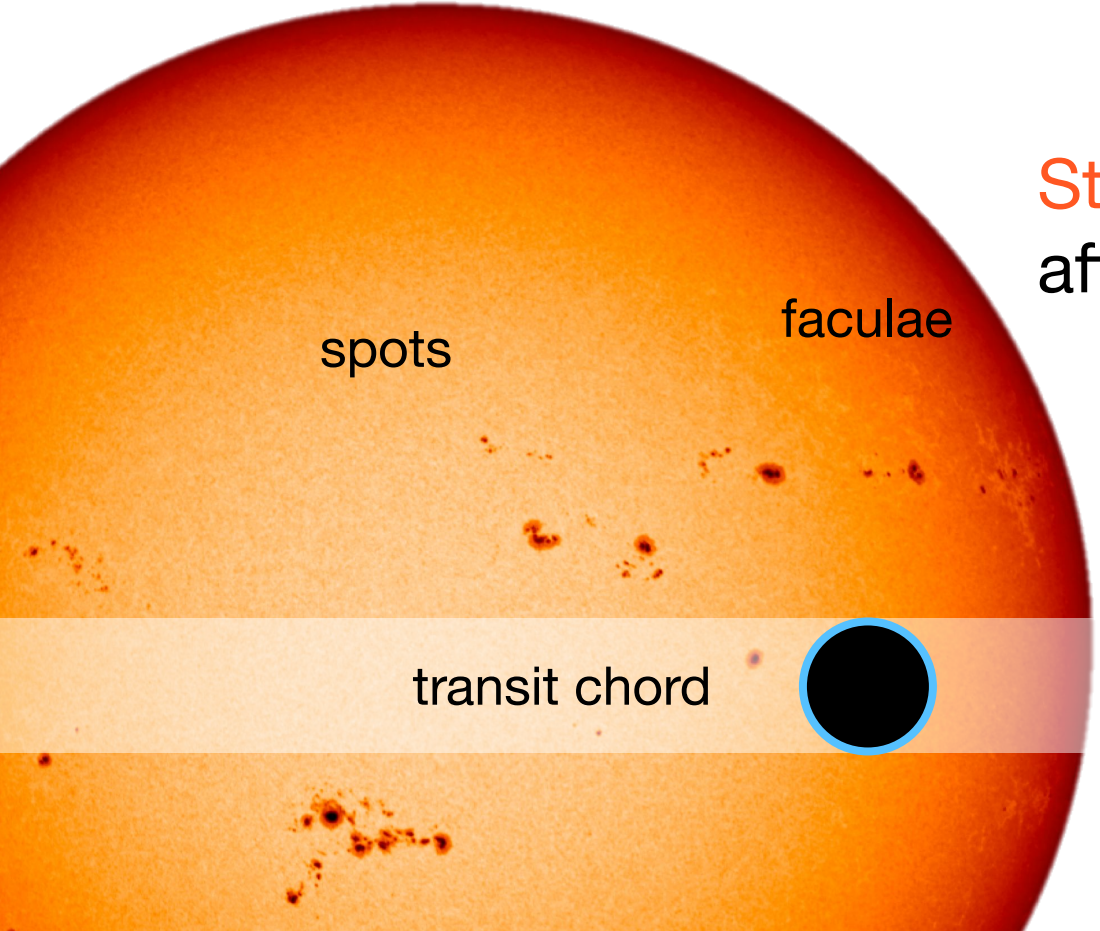
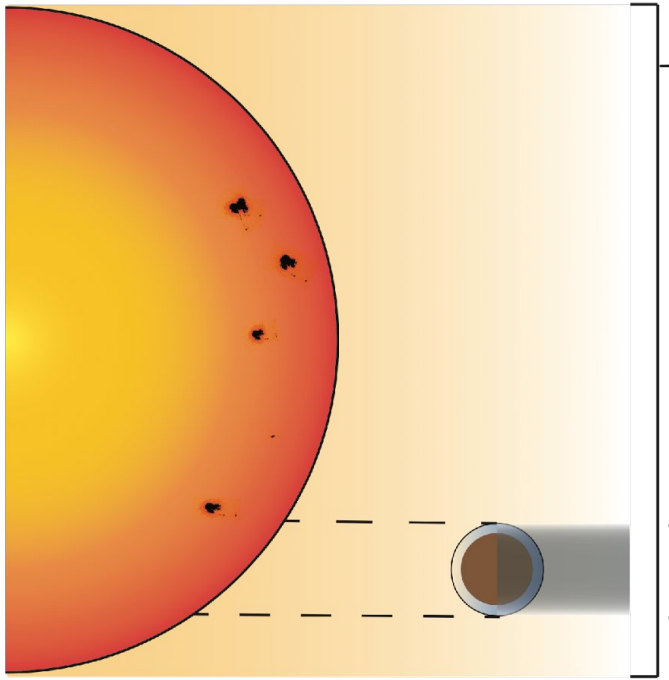
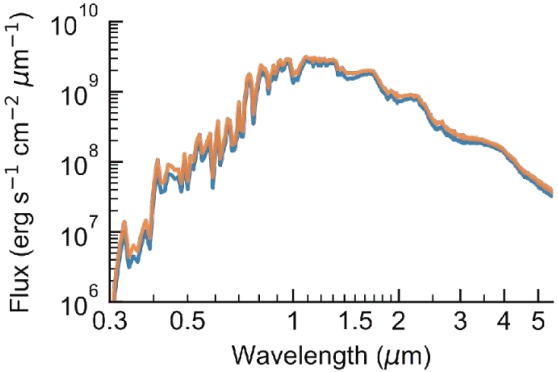


Stellar heterogeneity
affects transits depths too!

The Transit Light Source Effect

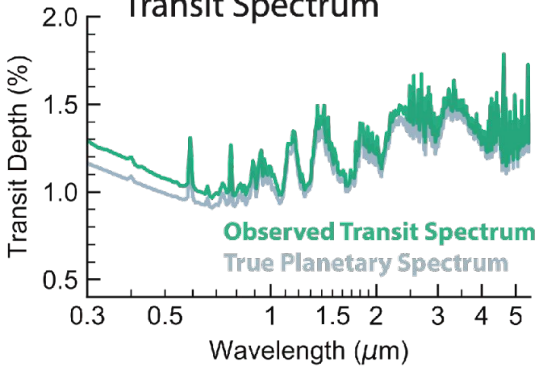


Pre-transit Stellar Disk is the **Assumed Light Source**



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

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



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?

Main deliverable:
SAG21 report to NASA

SG1: Stellar Photospheric & Chromospheric Heterogeneity
Leads: S. Berdyugina, H. Korhonen & A. Shapiro

SG2: Stellar & Planetary Retrievals
Leads: R. MacDonald, B. Rackham

SG3: Occulted Active Regions
Leads: B. Morris & M. Oshagh

SAG21

Chairs: N. Espinoza & B. Rackham

SG4: Unocculted Active Regions
Leads: B. Montet & Y. Unruh

SG5: Future Complementary Observations
Leads: E. Quintana & R. Zellem

SAG21 (original) Timeline

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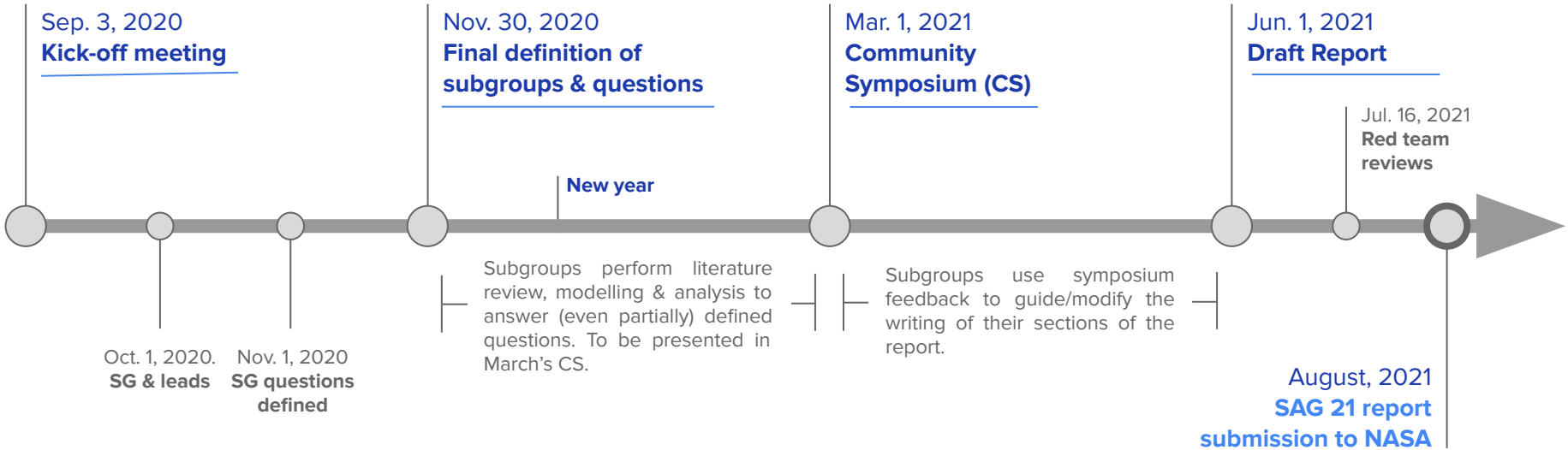
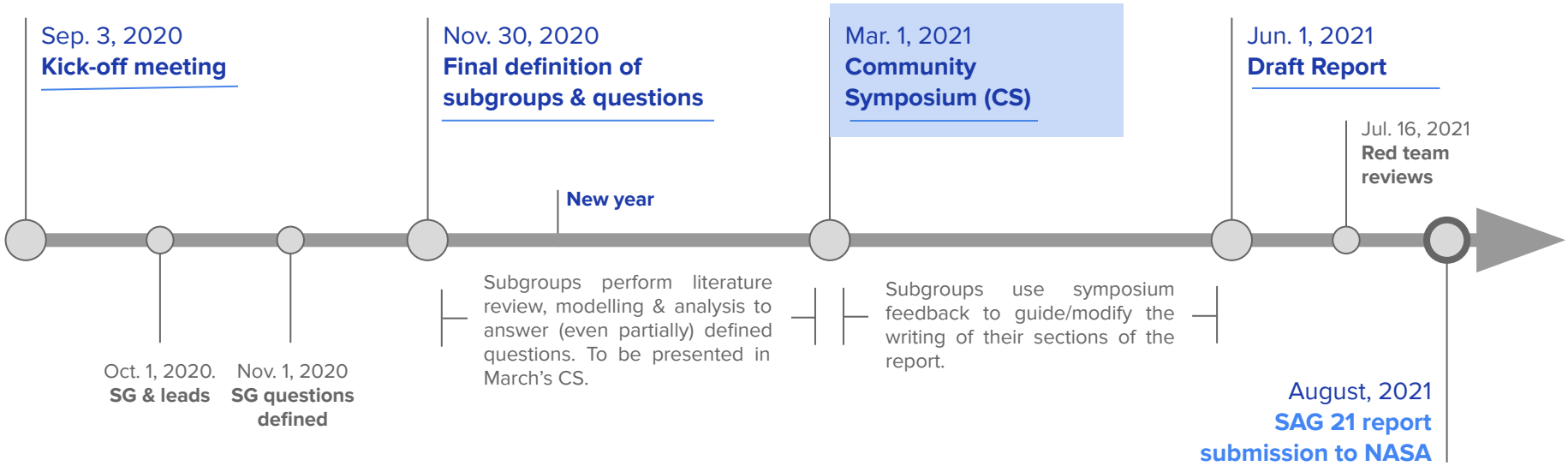
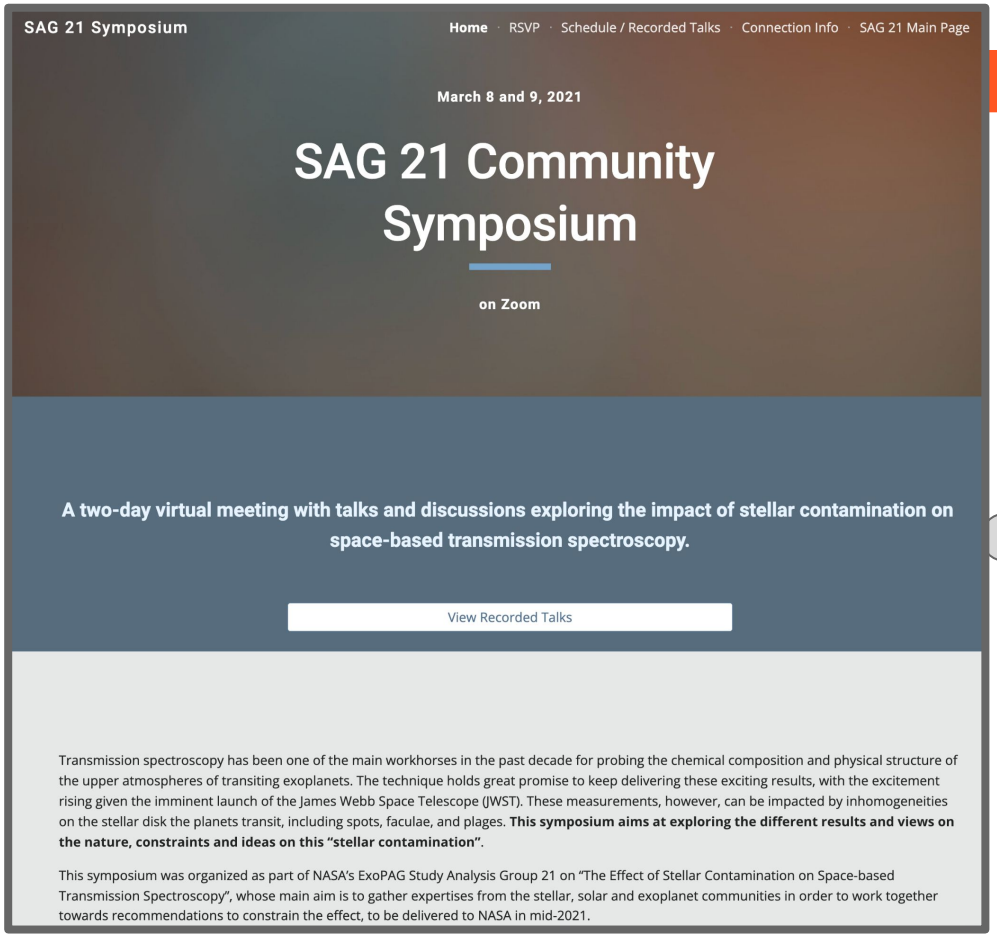


SAG21 (original) Timeline



https://sites.google.com/view/sag21symposium/home



line

Mar. 1, 2021
Community Symposium (CS)

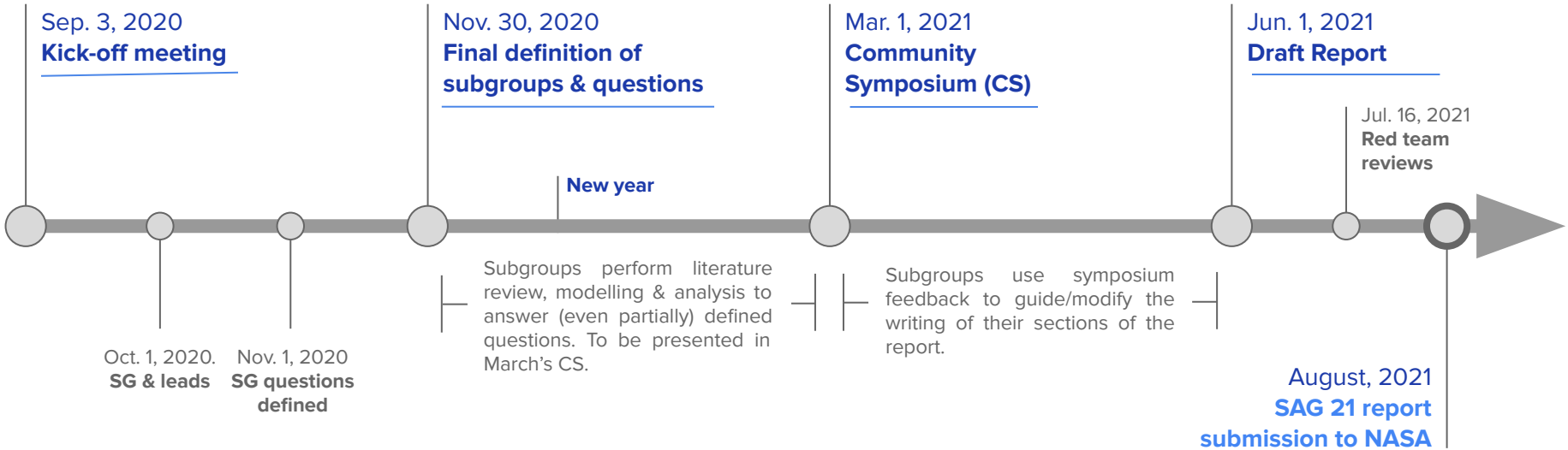
Jun. 1, 2021
Draft Report

Jul. 16, 2021
Red team reviews

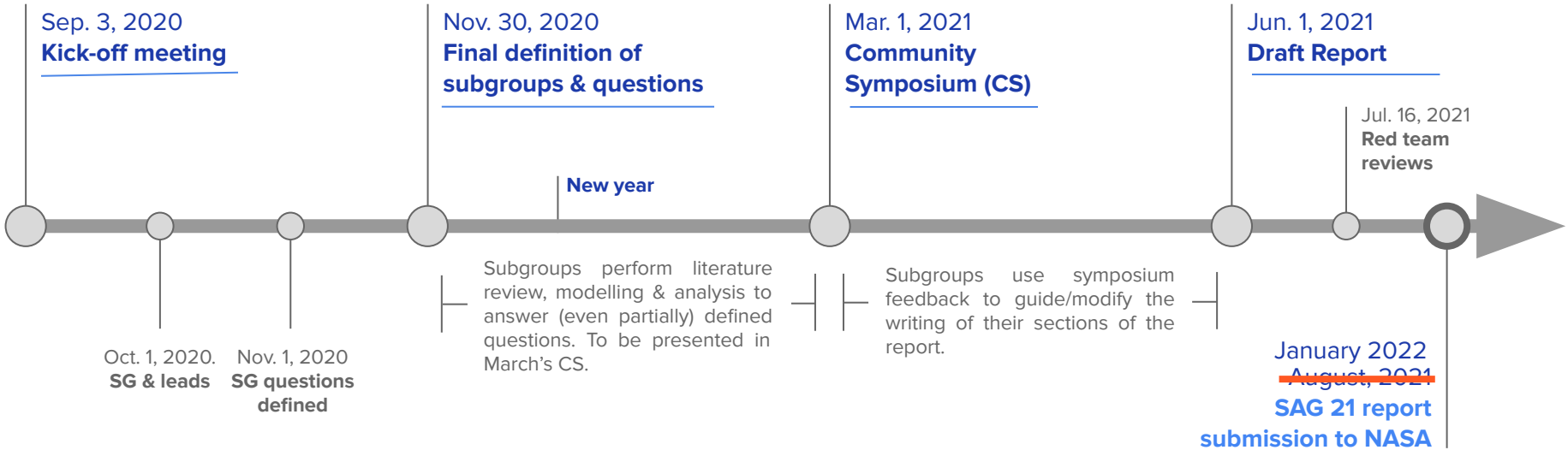
Subgroups use symposium feedback to guide/modify the writing of their sections of the report.

August, 2021
SAG 21 report submission to NASA

SAG21 (original) Timeline



SAG21 (original) Timeline



SAG21: the report

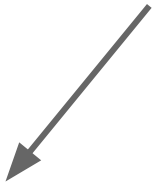
SAG21: the report

- **90+ pages**,
  lots of figures (and fun).
- **5 main chapters**
  (one per subgroup).
- **40+ major contributors**,
  total of 100+ scientists from helio & exo/planetary communities.

2. Summary of Main Findings

Science Themes

14 Findings } 7 Overarching Questions } 3 Science Themes



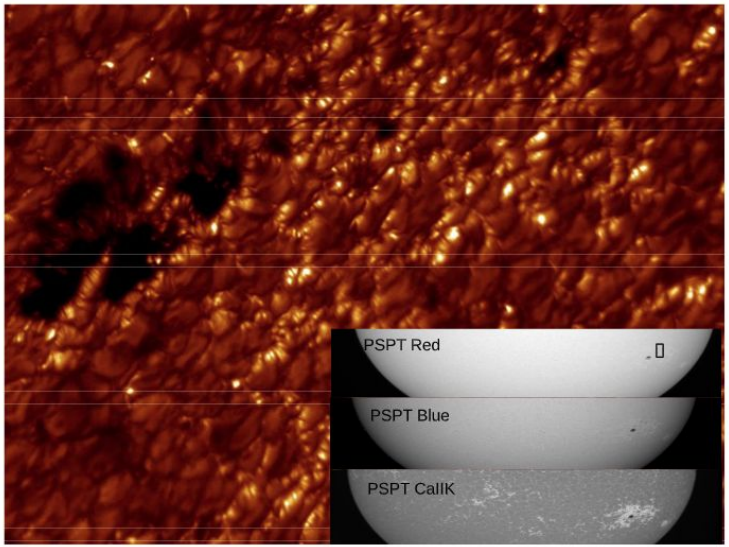
The Sun as the Stellar Benchmark

Surface Heterogeneities of Other Stars

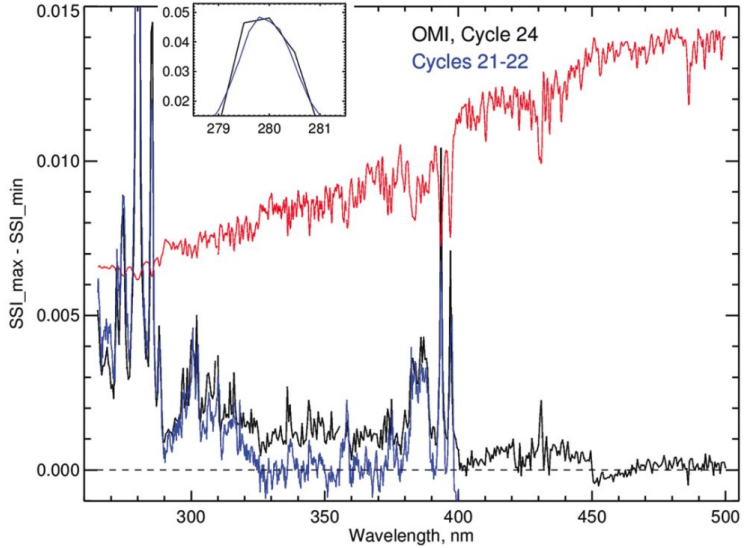
Mapping Stellar Knowledge to Transits and Vice Versa

The Sun as the Stellar Benchmark

What are the spectral properties of solar photospheric and chromospheric heterogeneities as a function of time and location?

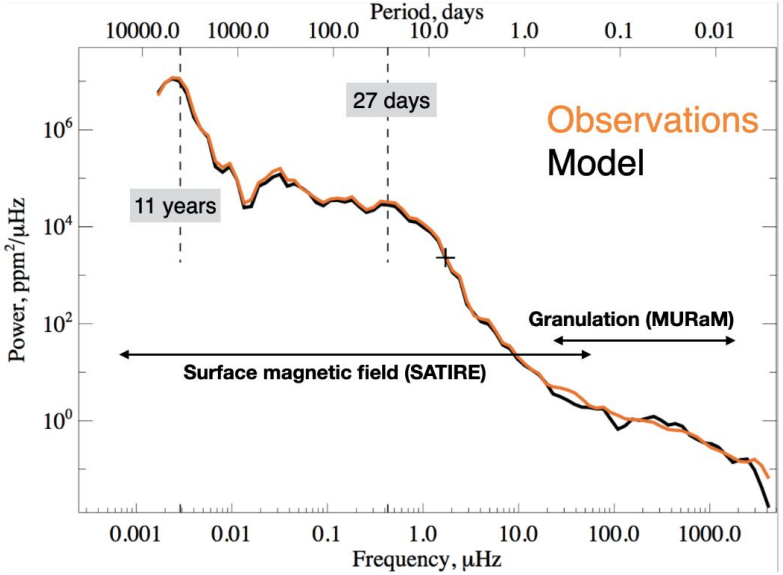


Credit: Institute for Solar Physics

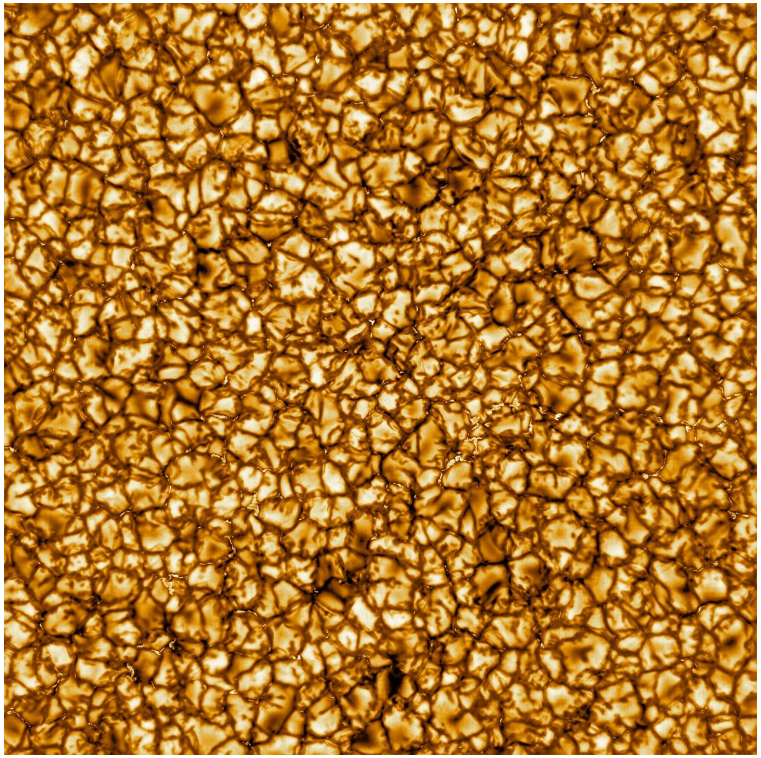


Marchenko et al. (2019)

What are the spectral properties of solar granules?



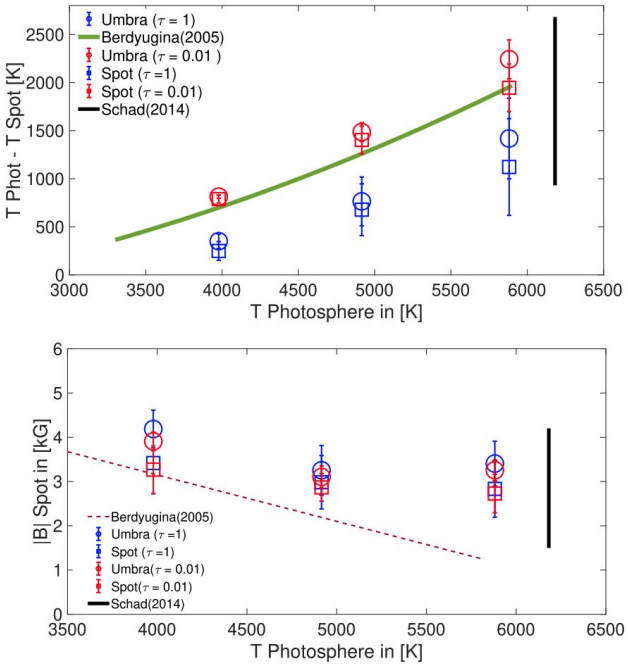
Shapiro et al. (2017)



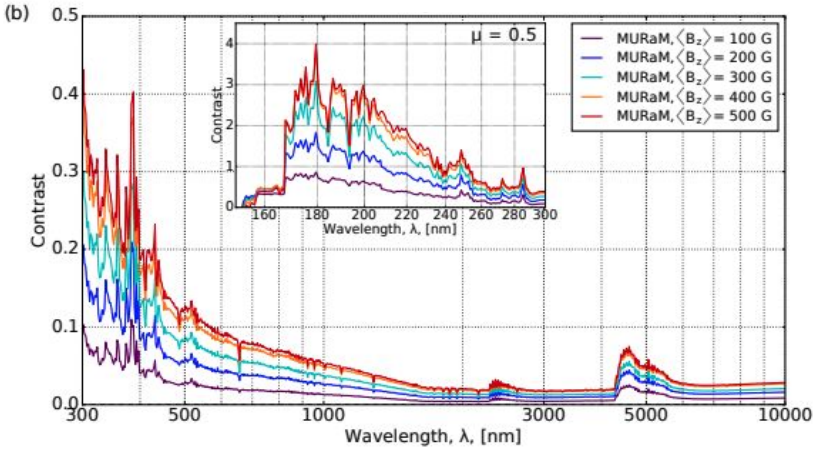
Credit: NSO/NSF/AURA

Surface Heterogeneities of Other Stars

How are the spectral properties of spots and faculae governed by the fundamental parameters of stars?

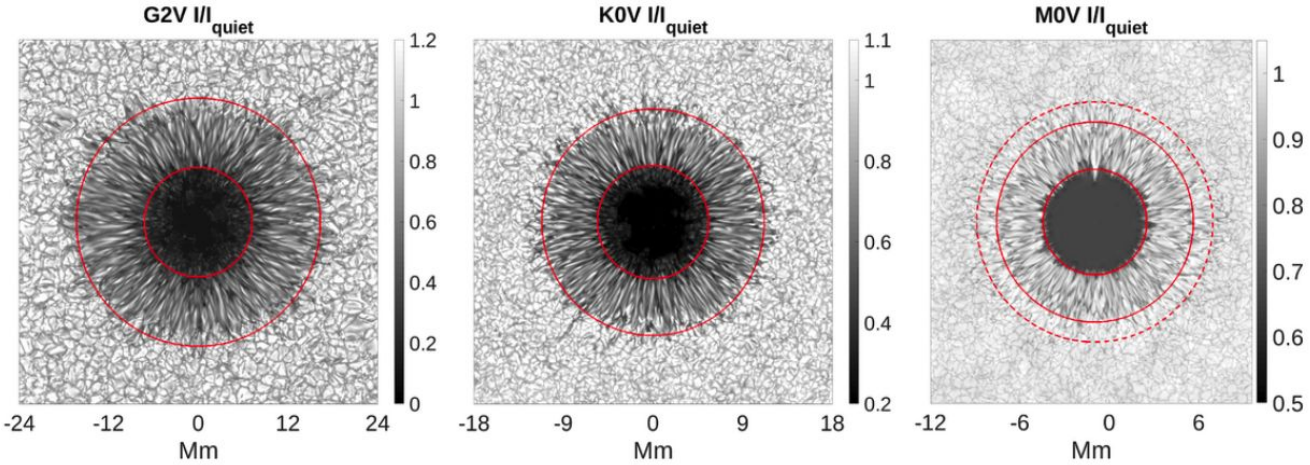


Panja et al. (2020)



Norris et al. (2017)

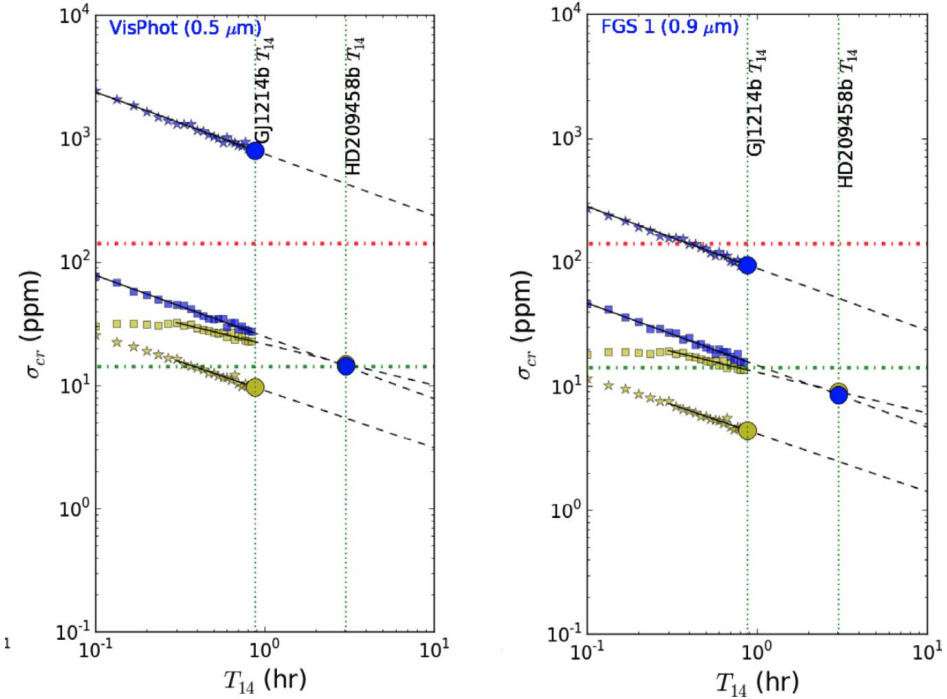
What are the spectral properties of spots and faculae on high-priority exoplanet host stars?



Panja et al. (in prep.)

What is the impact of granulation on precise transit studies?

noise floor:

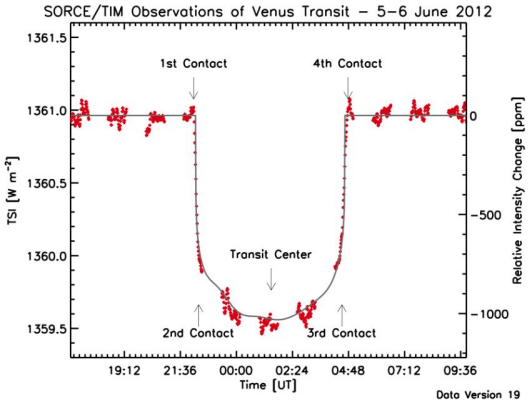


Sarkar et al. (2018)

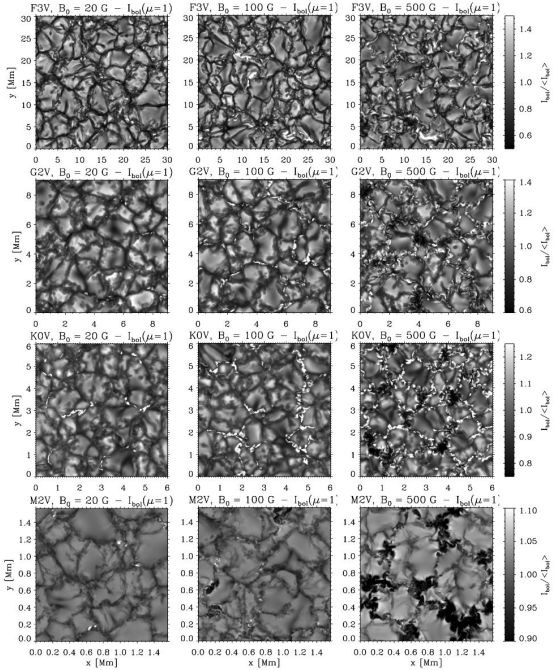
Spectral bias: 1–2 ppm?
(e.g., Chiavassa et al. 2017)

Mapping Stellar Knowledge to Transits and Vice Versa

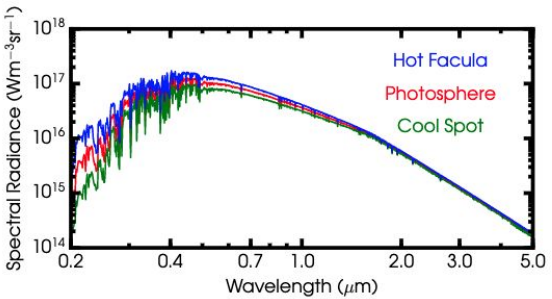
How do we translate knowledge of surface heterogeneities on other stars to transit observations?



Kopp (2021)

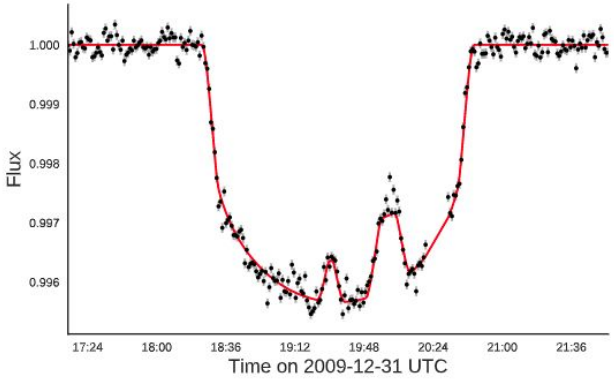


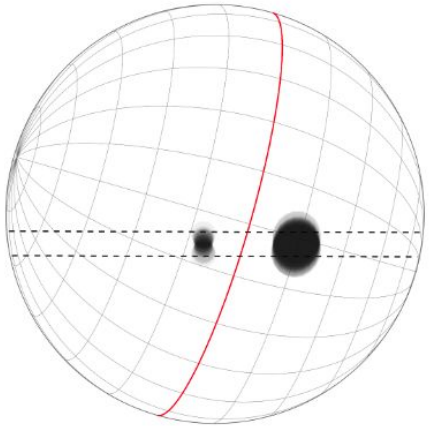
Beeck et al. (2015)



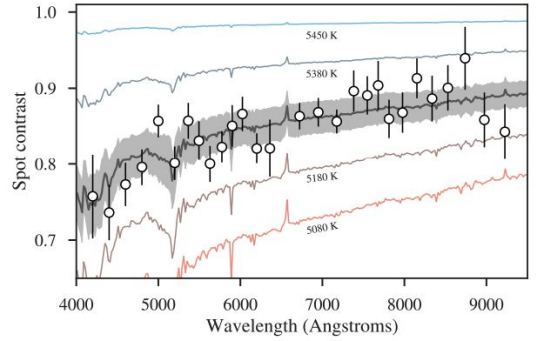
Pinhas et al. (2018)

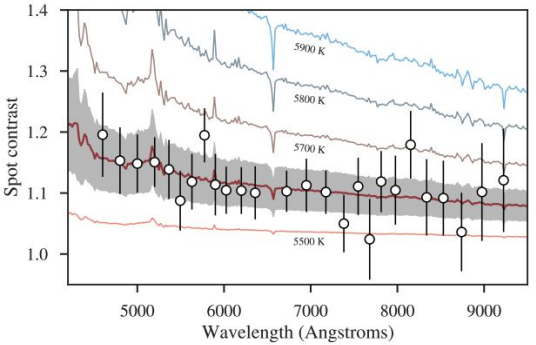
What unique constraints on stellar heterogeneity are enabled by transit observations?





Morris et al. (2017)





Espinoza et al. (2019)

Conclusions

1. **SAG21's goal of delivering report to NASA is about to be completed:** currently receiving feedback from ExoPAG EC. Happy to share report — just contact Ben or Néstor!

2. **SAG21's many by-products provided valuable assets to the community:** including the Community Symposium (21 contributed talks + 5 overview talks — over 100 attendees) and simply getting helio/exo/planetary communities to talk to each other.

3. **SAG21 report will be publicly available in the arXiv during this month.**

Communication & sharing channels

(Link has been shared via e-mail)

SAG 21

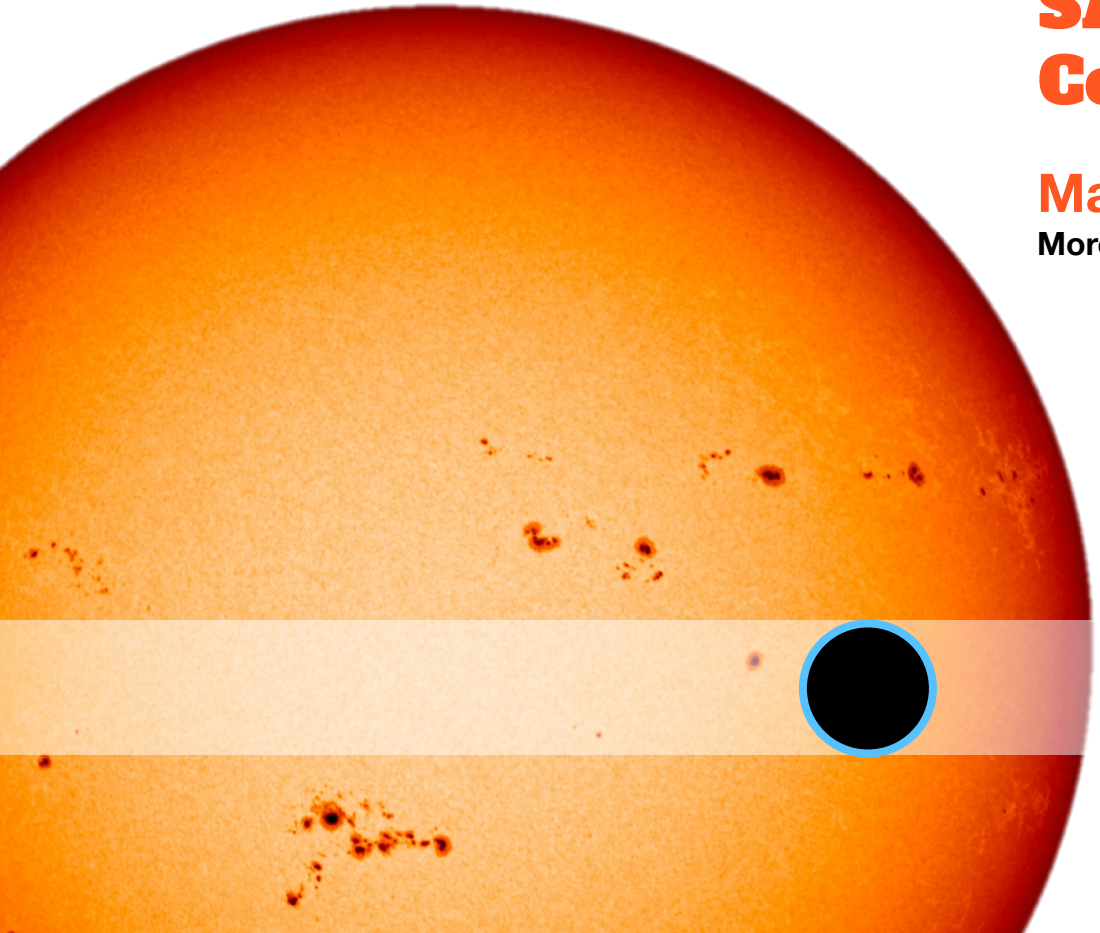
Google Drive

(Link has been shared via e-mail)

NASA's ExoPAG SAG21 webpage

(Link has been shared via e-mail)

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**.

The road to submission

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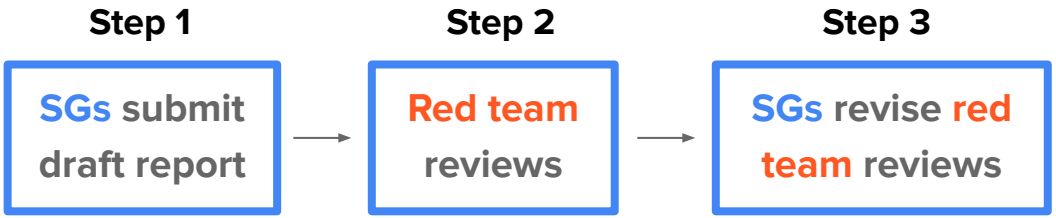

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- **3** week **turnaround**.

Step 4

Co-chairs review & revise

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

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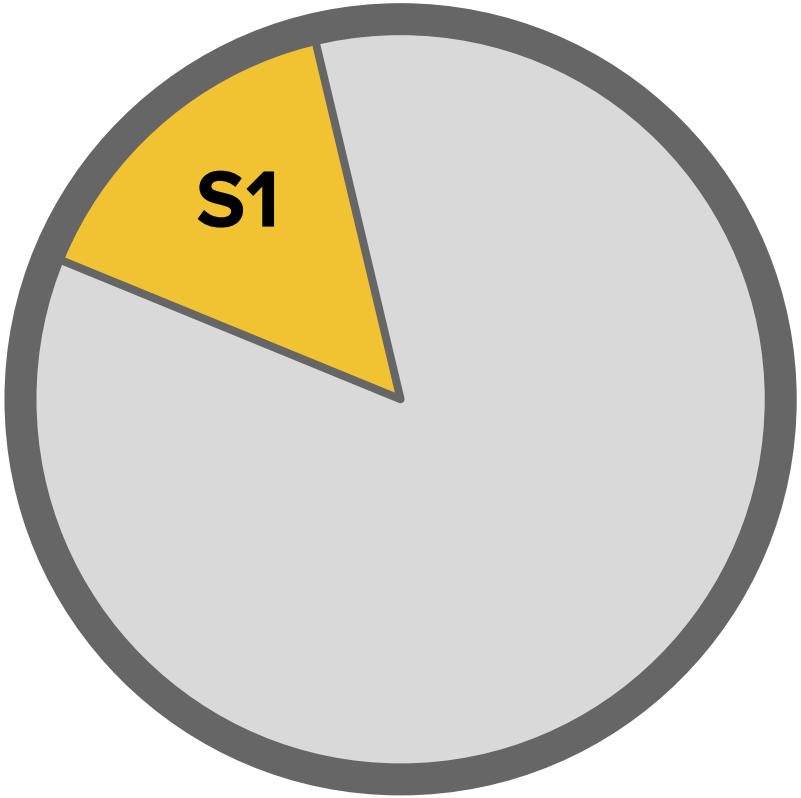
Submit To NASA

S1: Stellar Photospheric Heterogeneity

Leads: Svetlana Berdyugina, Heidi Korhonen & Alexander Shapiro



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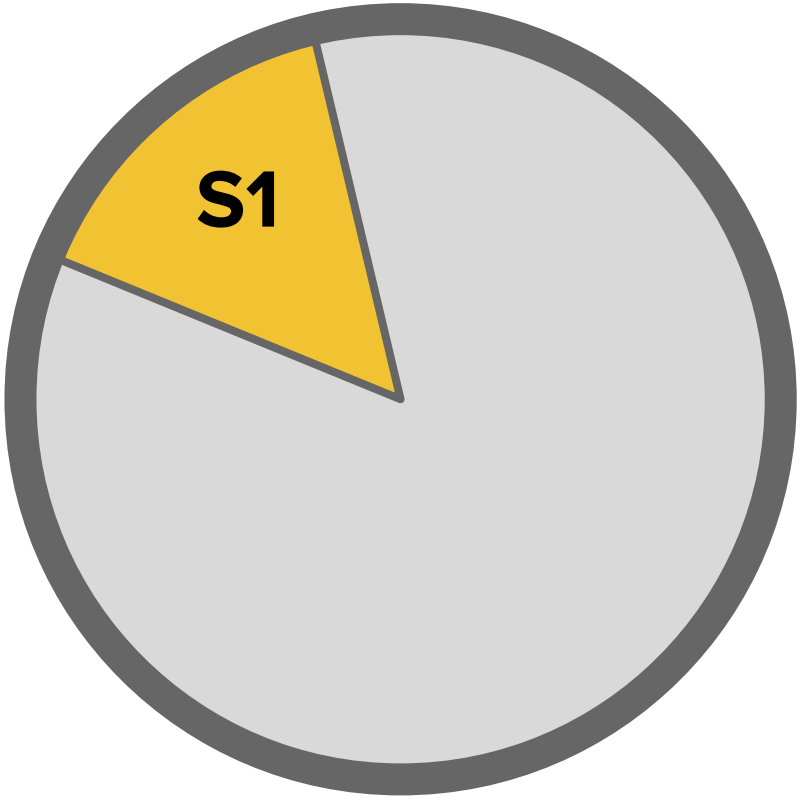
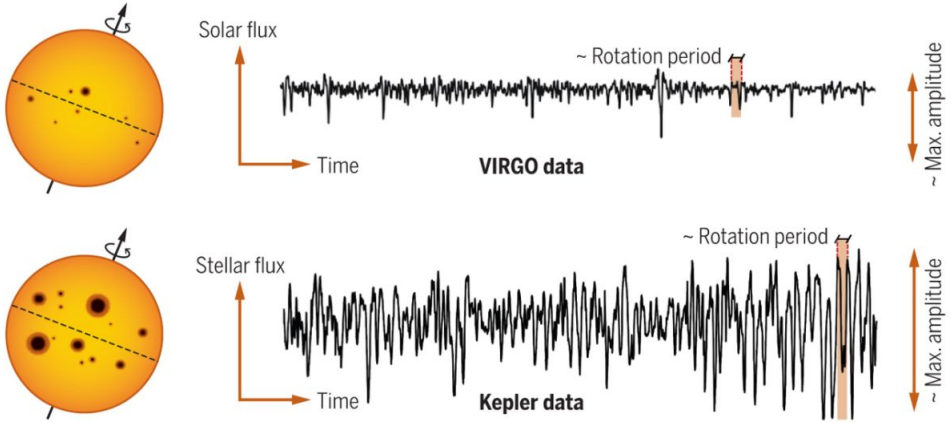


Photometric monitoring

Figure source: [Santos & Mathur (2020)]



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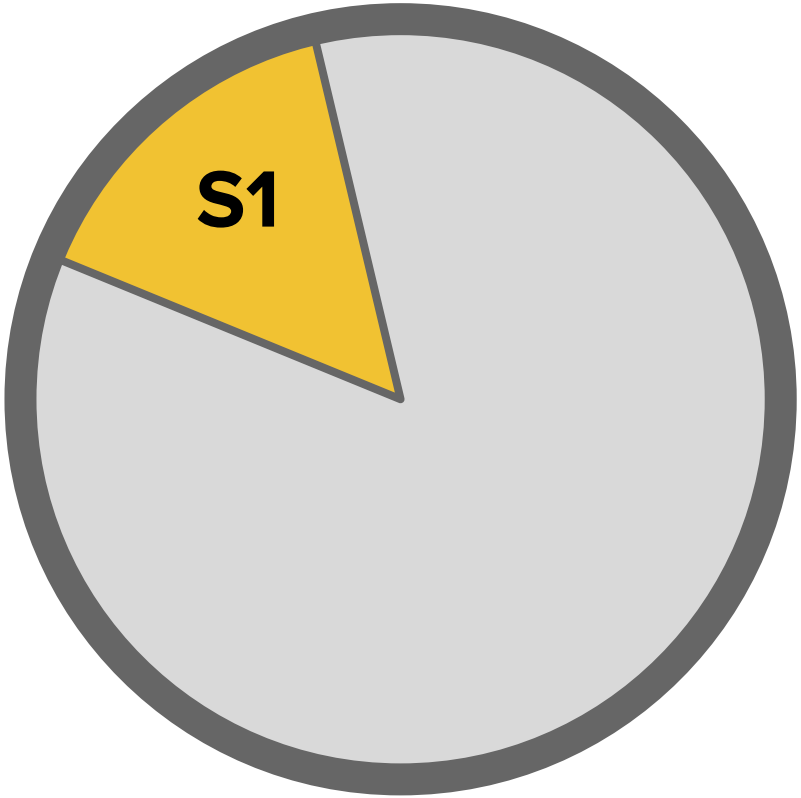
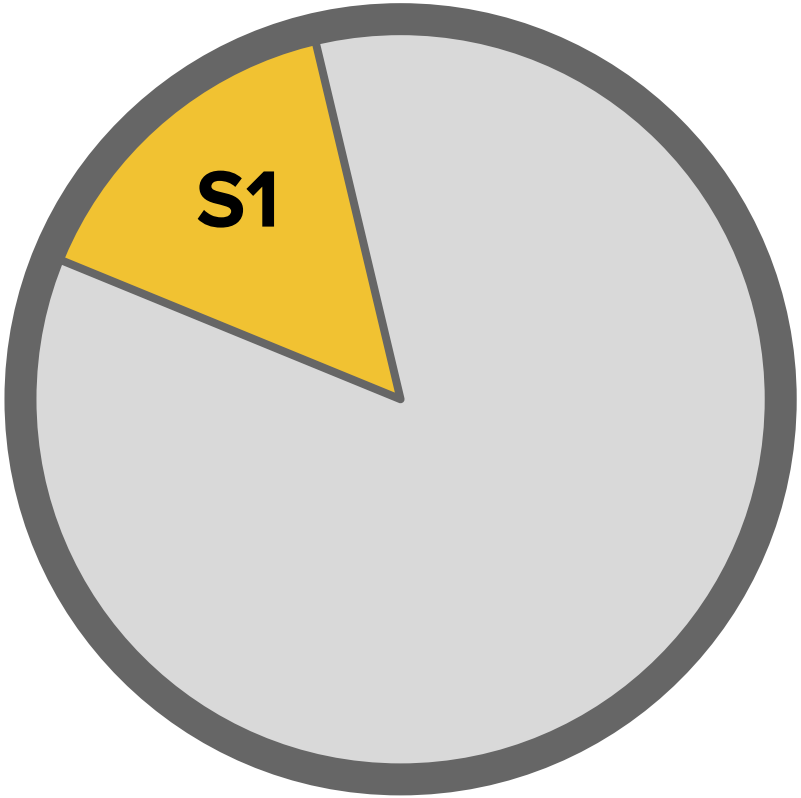


Finding 1.1:

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

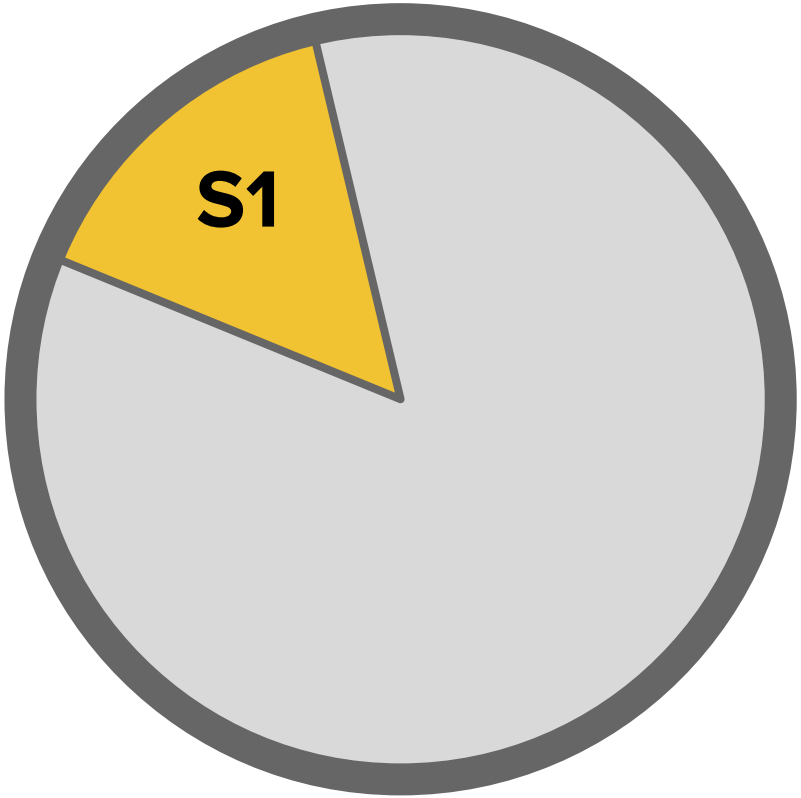


Finding 1.2:

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?

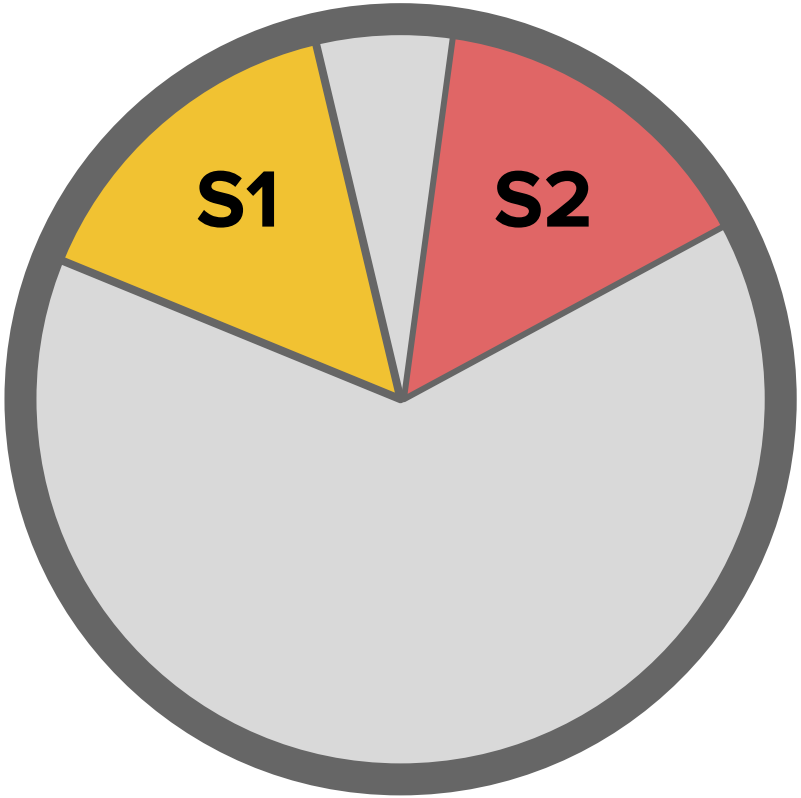
Q1.2 What spectral indicators are most useful for constraining photospheres?

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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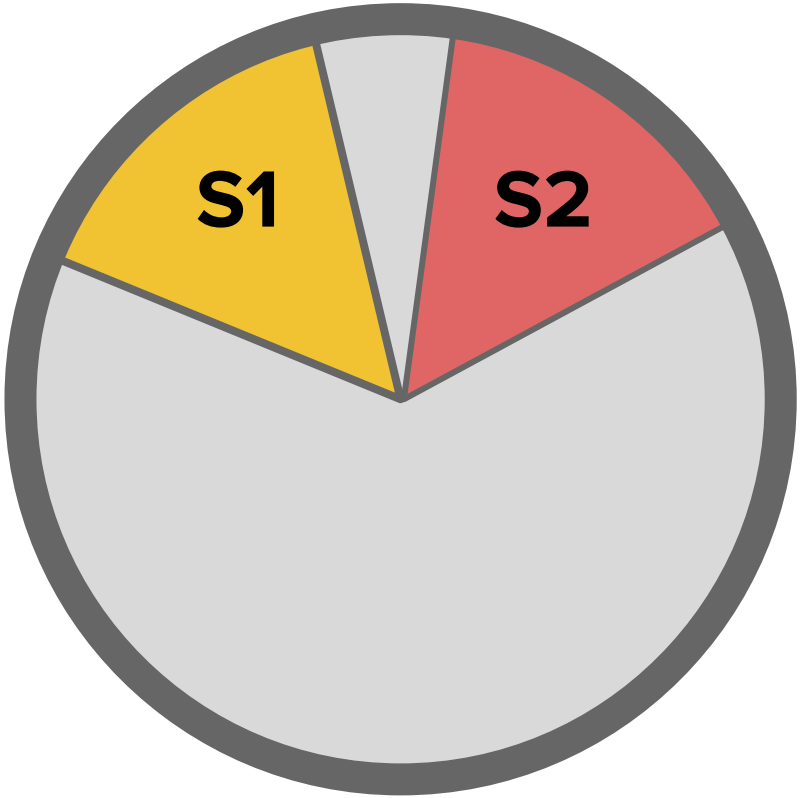
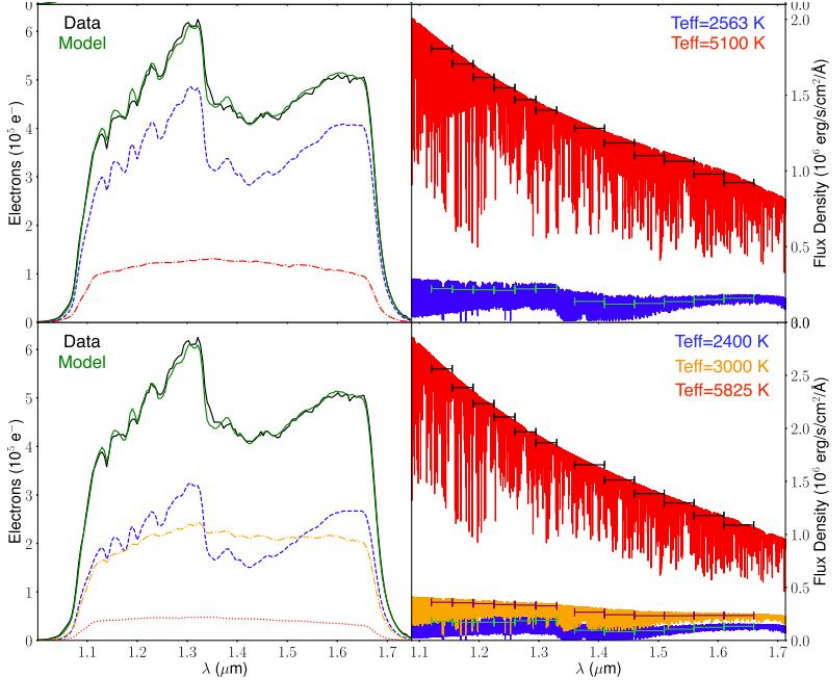


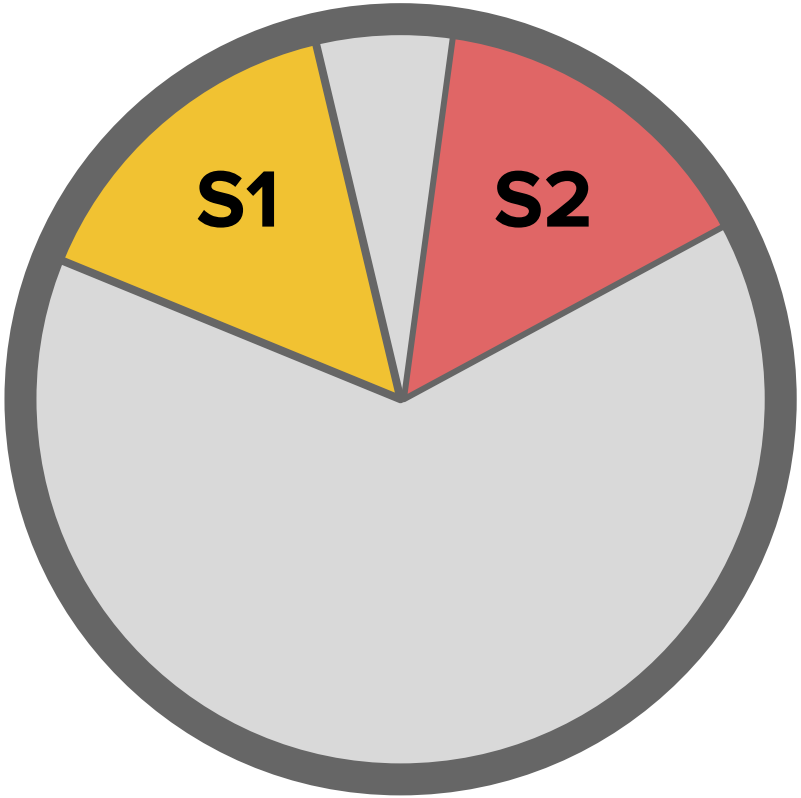
The case of TRAPPIST-1

Wakeford et al. (2019)



S2: Stellar Spectral Decomposition

Leads: Joanna Barstow, Benjamin Rackham, & Ryan McDonald

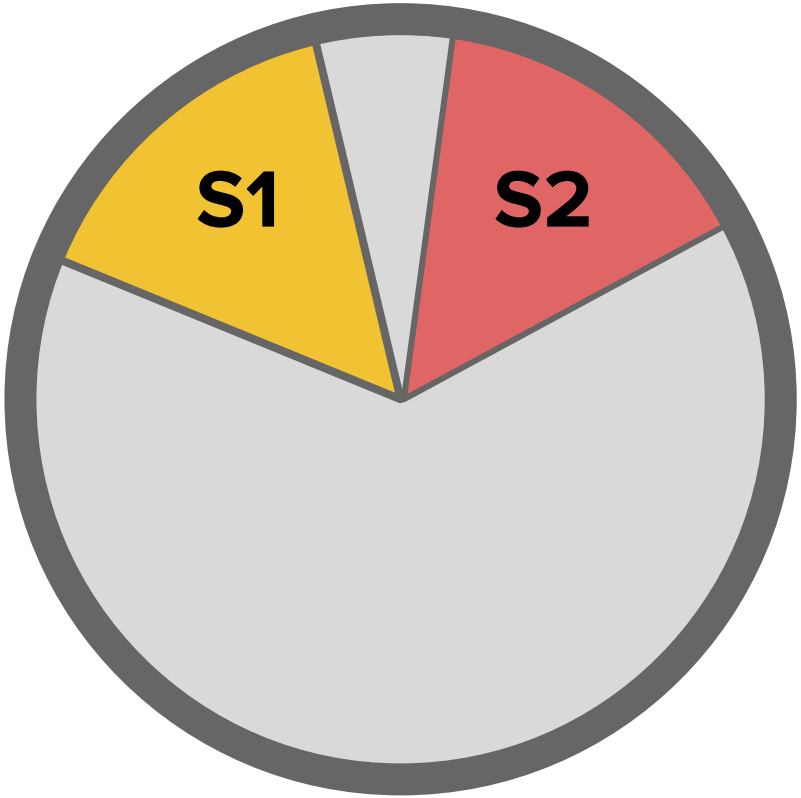


Finding 2.1:

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

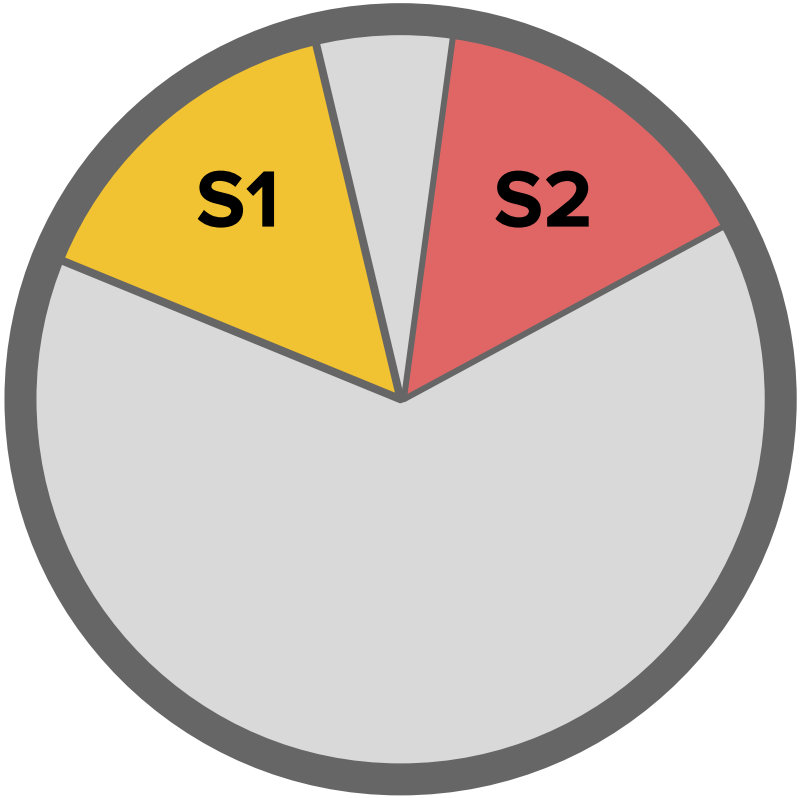


Finding 2.2:

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

Leads: Joanna Barstow, Benjamin Rackham, & Ryan McDonald



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?

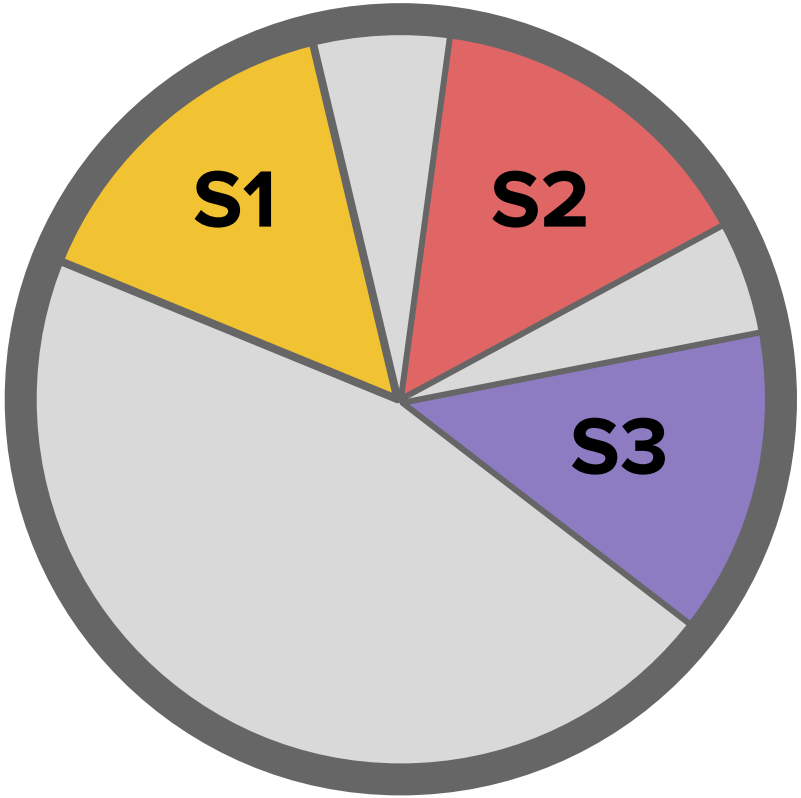
Q2.2 How useful is low-resolution spectral decomposition of exoplanet host stars? How far can, e.g., JWST spectra be pushed to resolve the photospheric components?

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



S3: Occulted Active Regions

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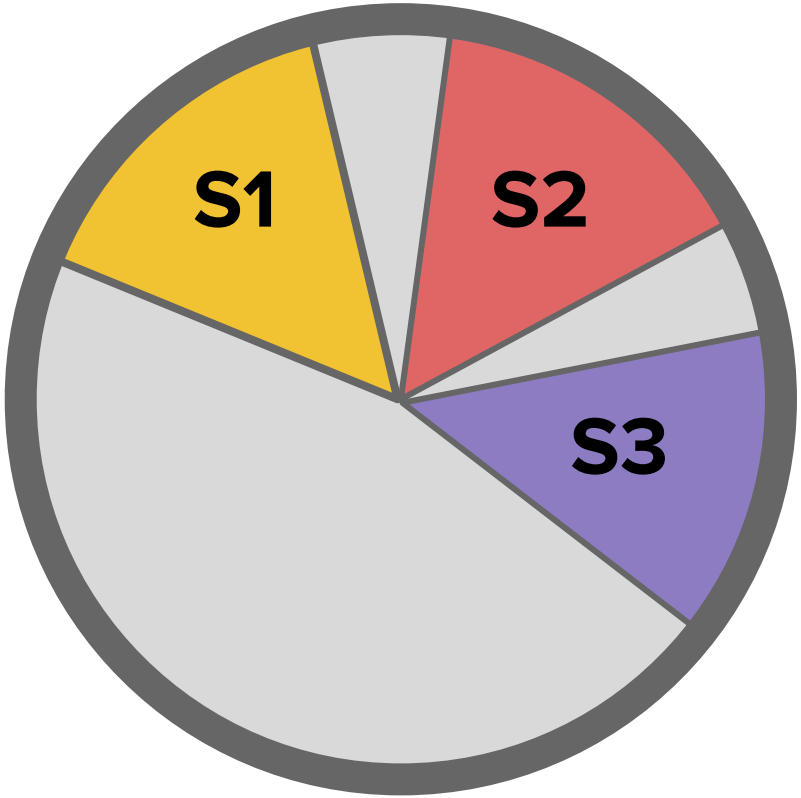
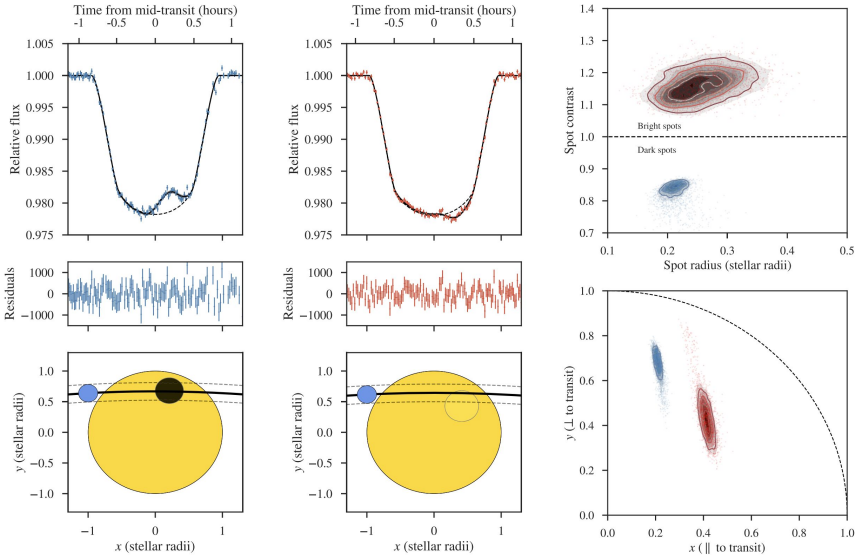


The case of WASP-19b

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



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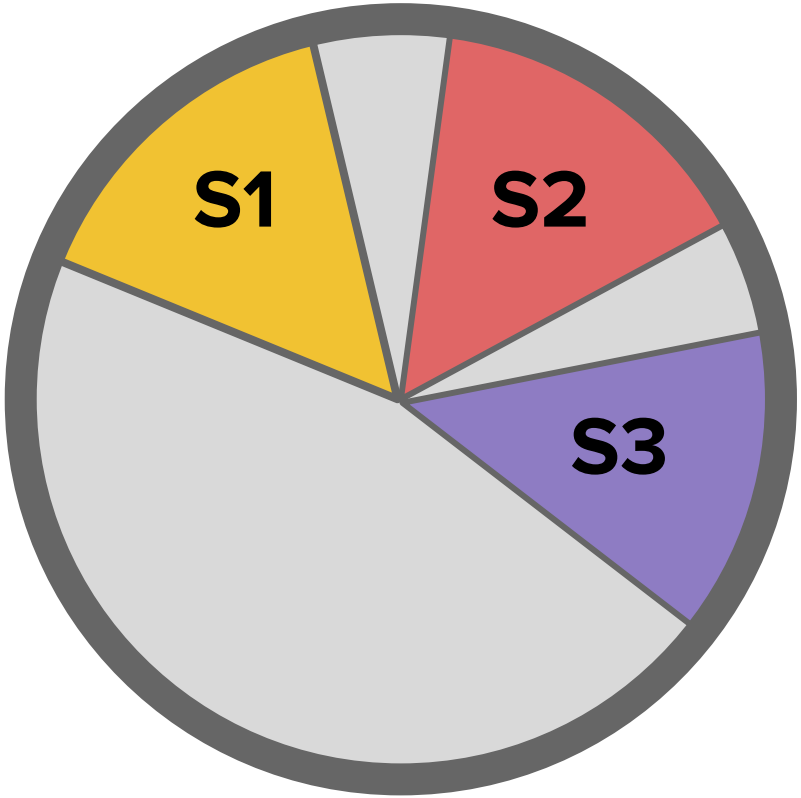

The case of WASP-19b

Figure source: Espinoza et al. (2019)

S3: Occulted Active Regions

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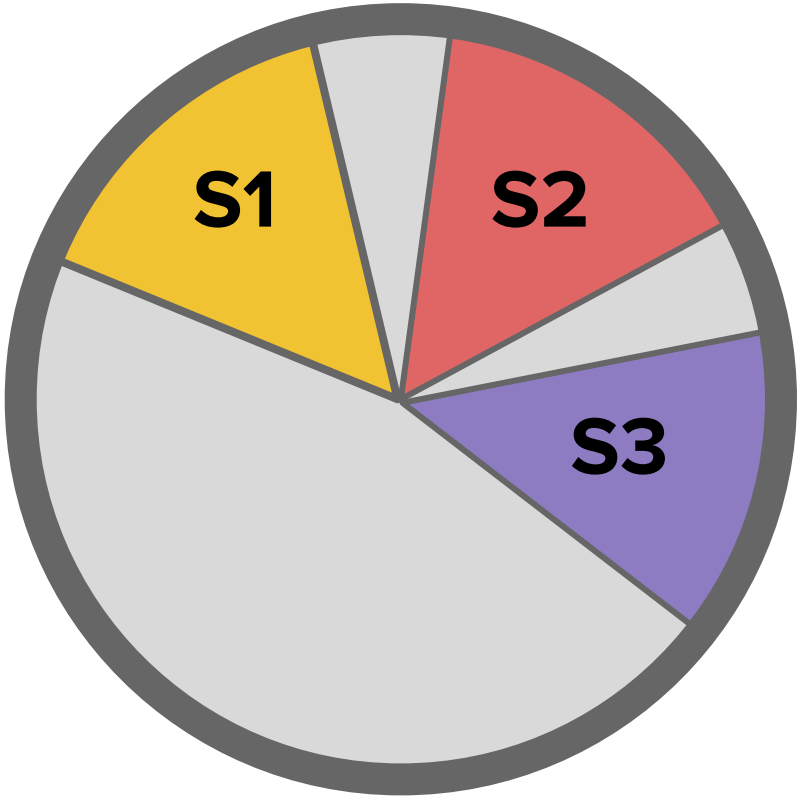

Finding 3.1:

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

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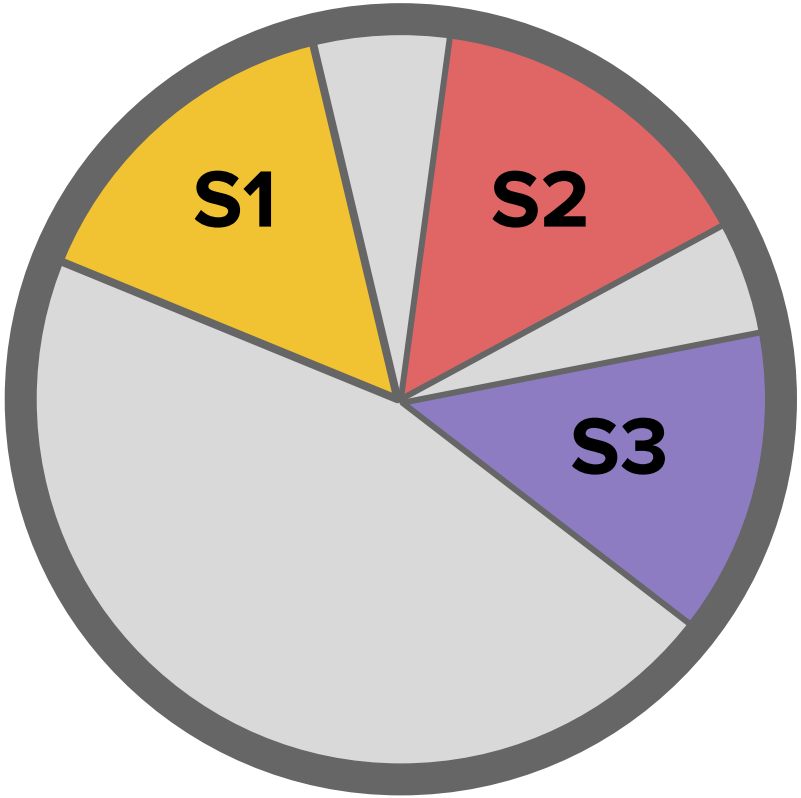
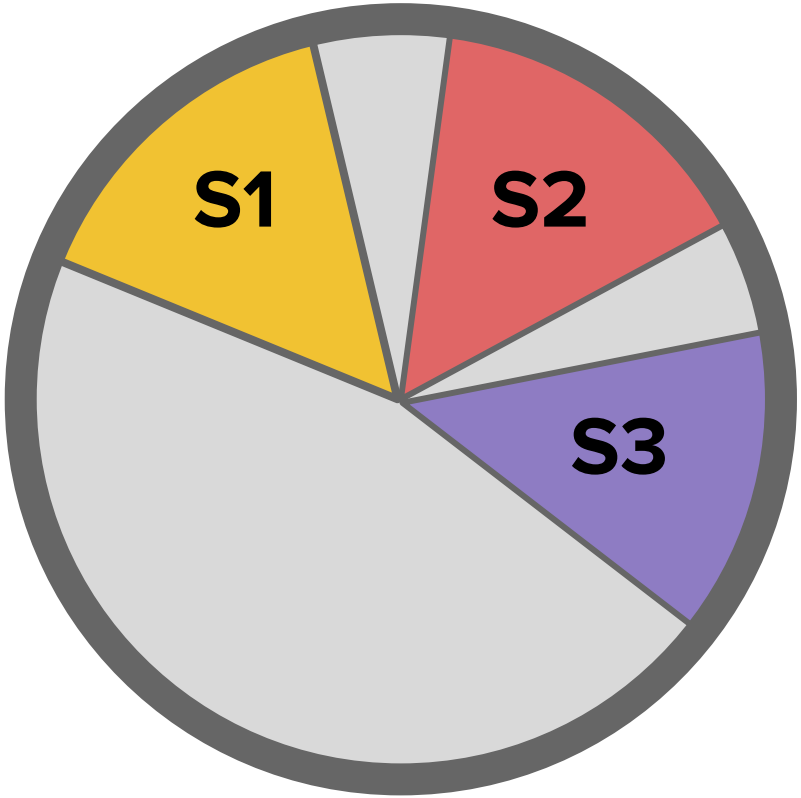


Finding 3.2:

There are **several publicly available forward modeling tools** for starspot occultations in broad photometric bandpasses. **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; **further studies are needed to understand the effects of spectroscopic resolution on biases in transit spectrophotometry**.

S3: Occulted Active Regions

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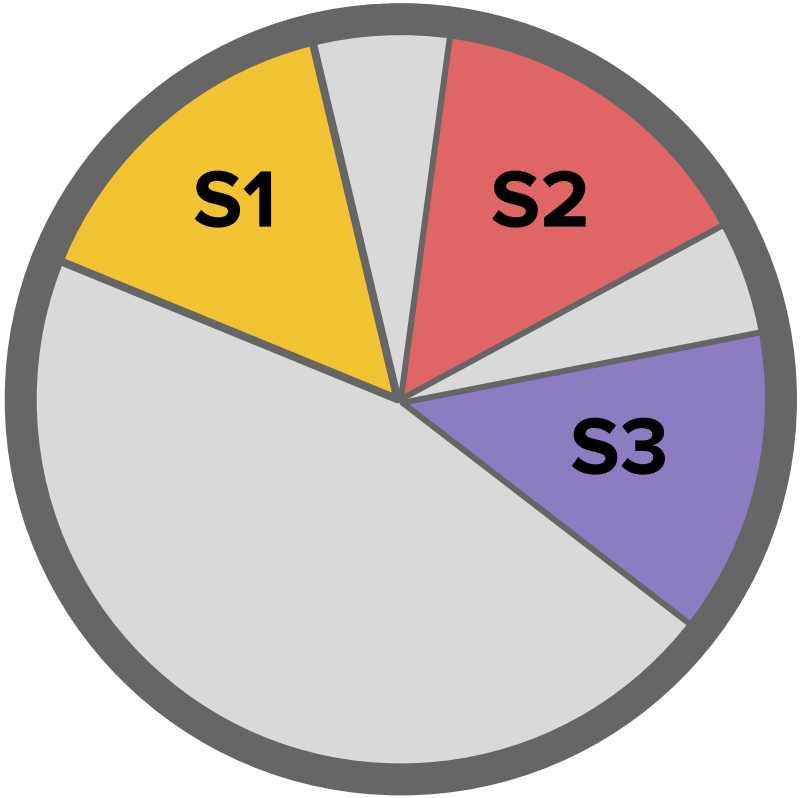

Finding 3.4:

***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

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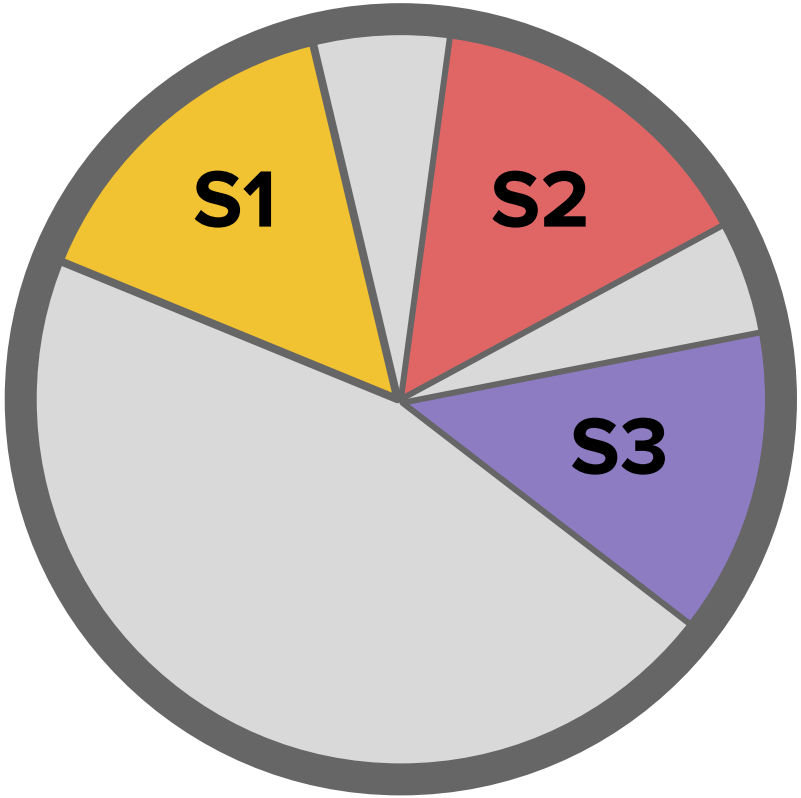


Finding 3.5:

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

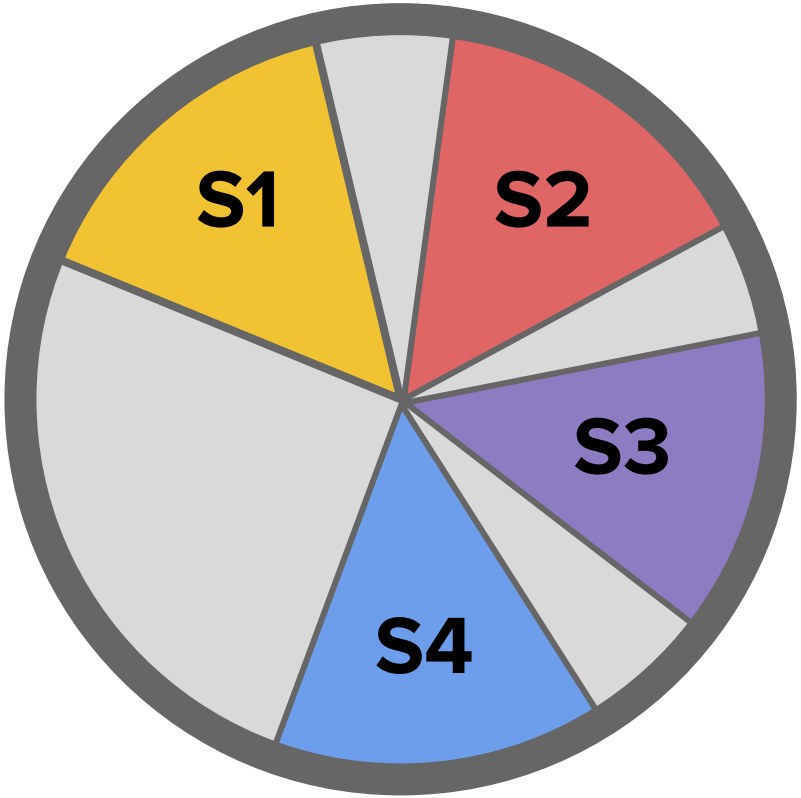
Q3.1 What is the state-of-the-art of this technique?

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?

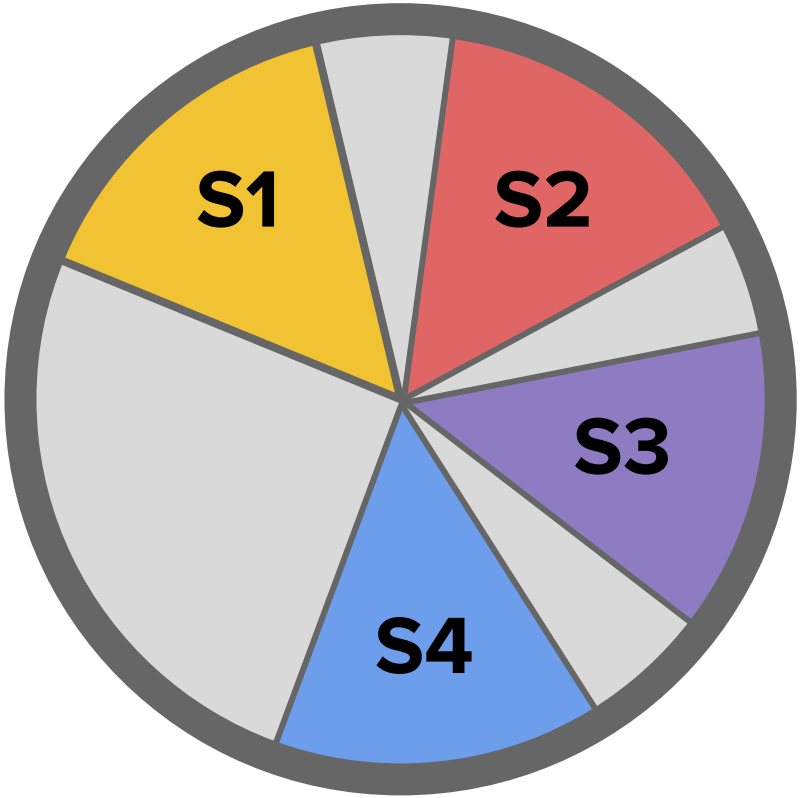
S4: Unocculted Active Regions

Leads: Yvonne Unruh & Ben Montet



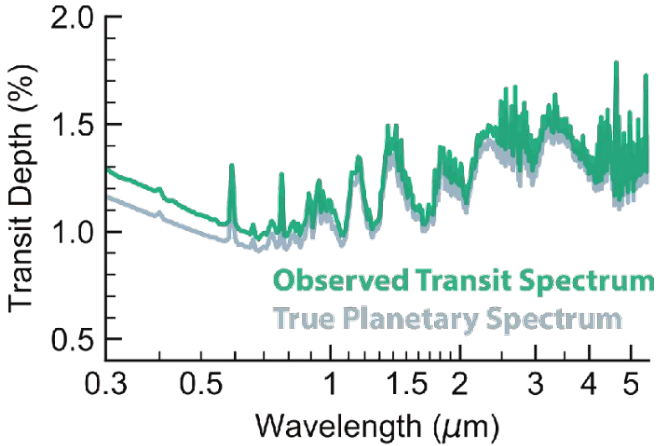
S4: Unocculted Active Regions

Leads: Yvonne Unruh & Ben Montet



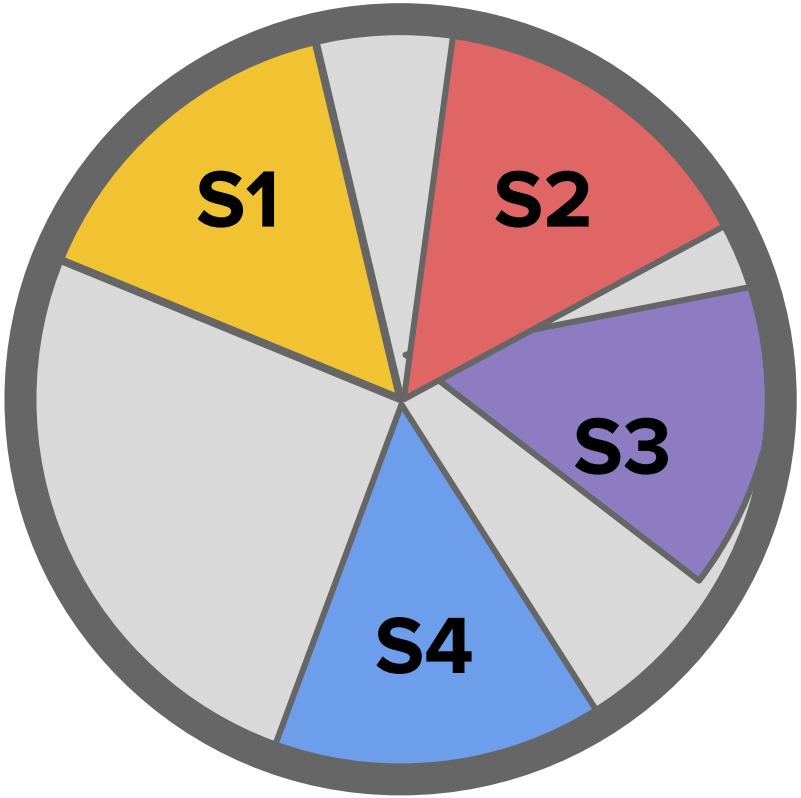
The Transit Light Source Effect

Figure source: Rackham et al. (2018)



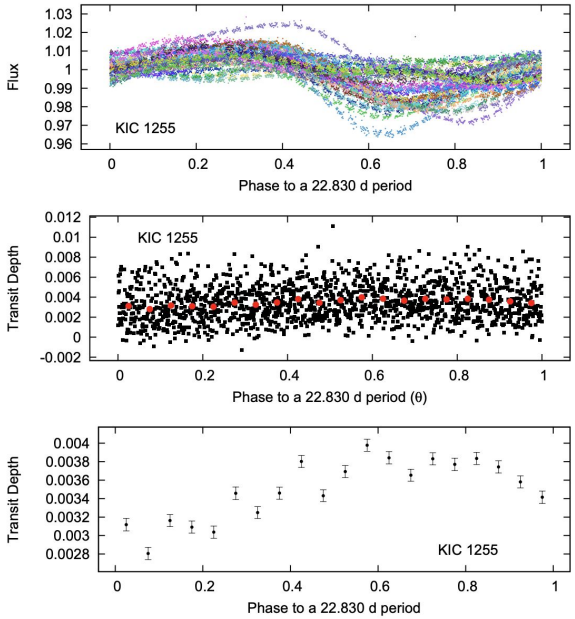
S4: Unocculted Active Regions

Leads: Yvonne Unruh & Ben Montet



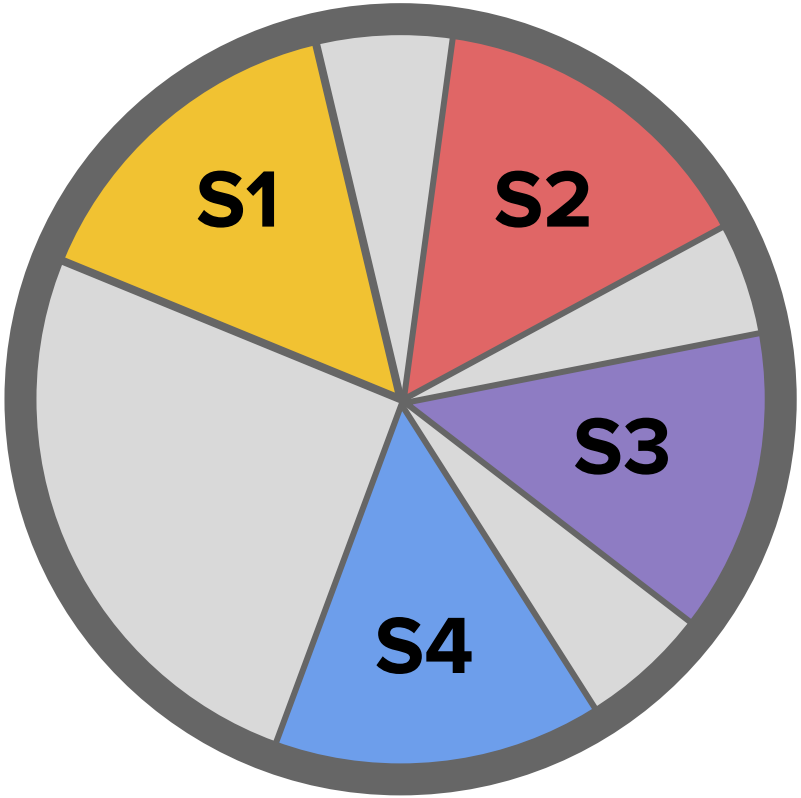
Transit depth variations in time

Figure source: Croll et al. (2015)



S4: Unocculted Active Regions

Leads: Yvonne Unruh & Ben Montet

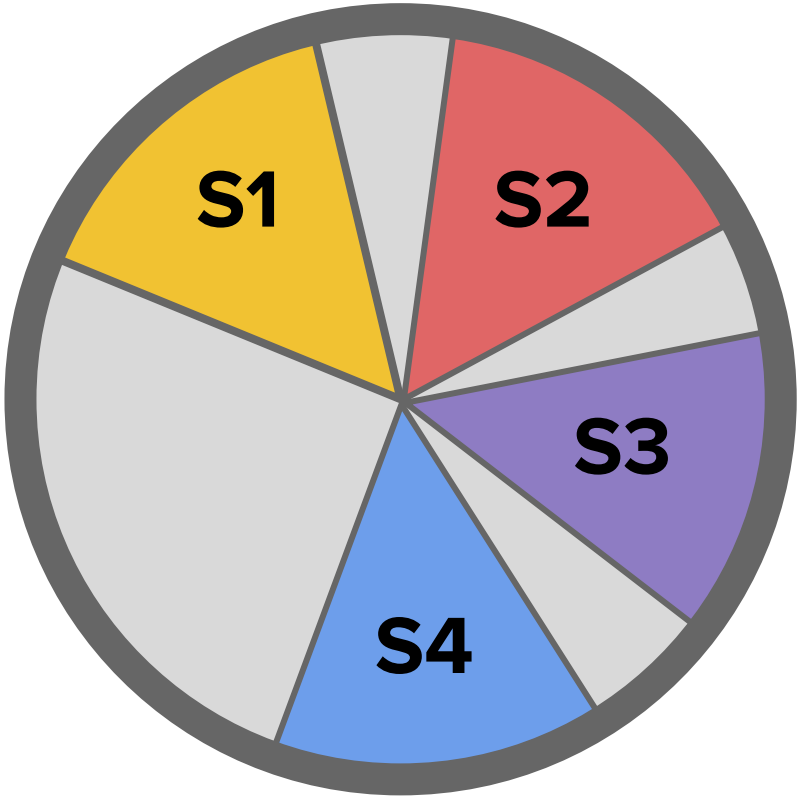


Finding 4.1:

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

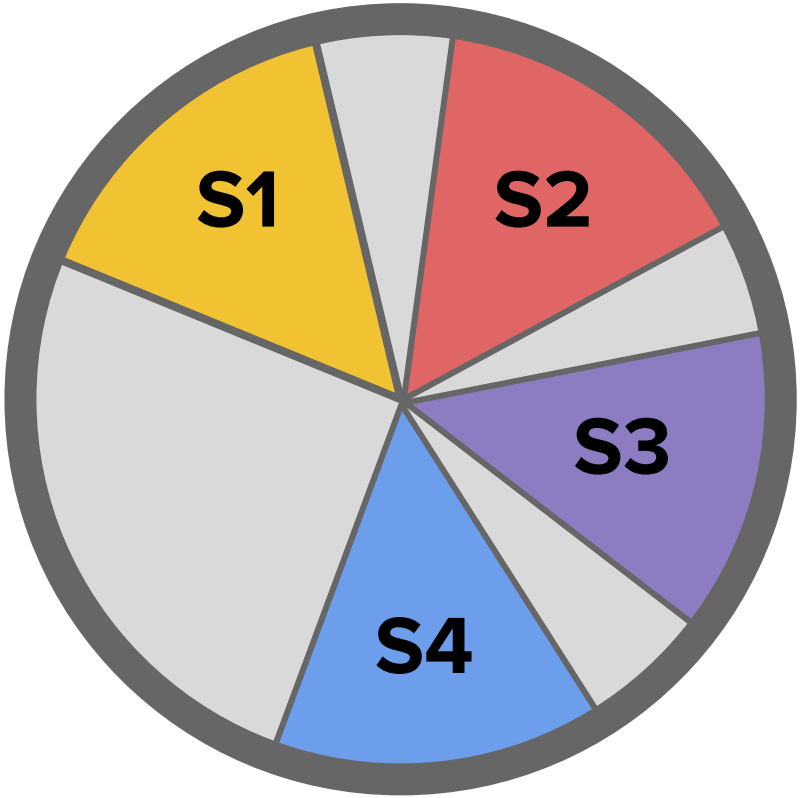


Finding 4.2:

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

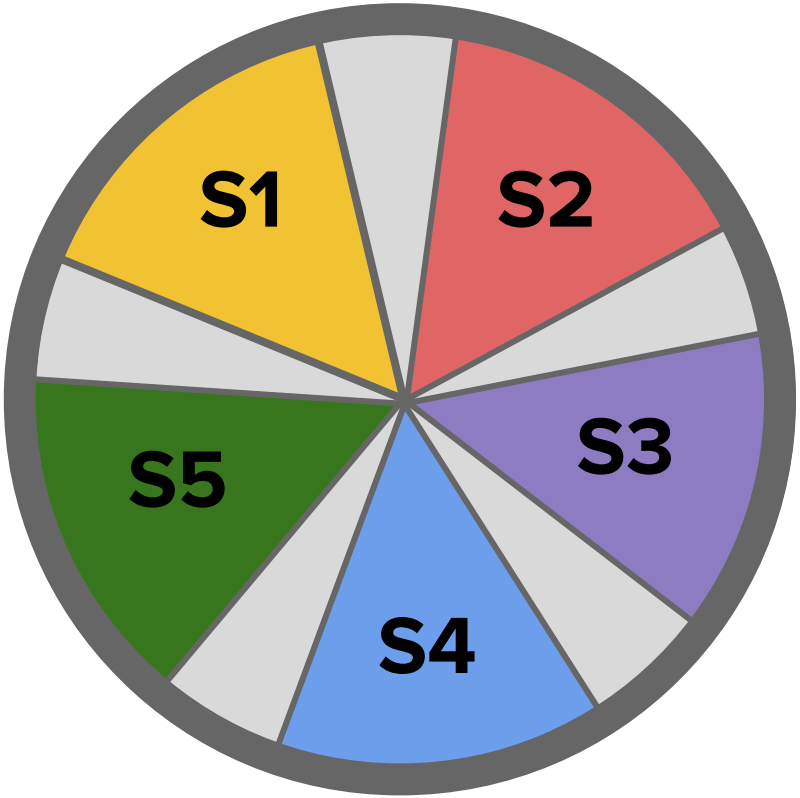


Finding 4.4:

Stellar "granulation flicker" constitutes a fundamental "noise floor" that increases with decreasing stellar surface gravity and a**t 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.

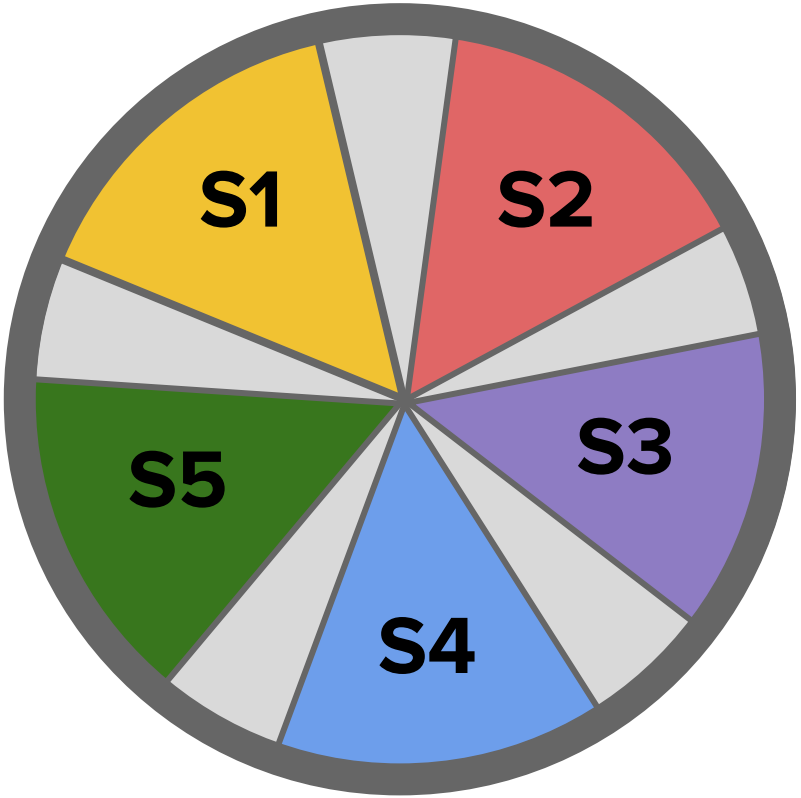
S5: Future Complementary Observations

Leads: Elisa Quintana & Rob Zellem



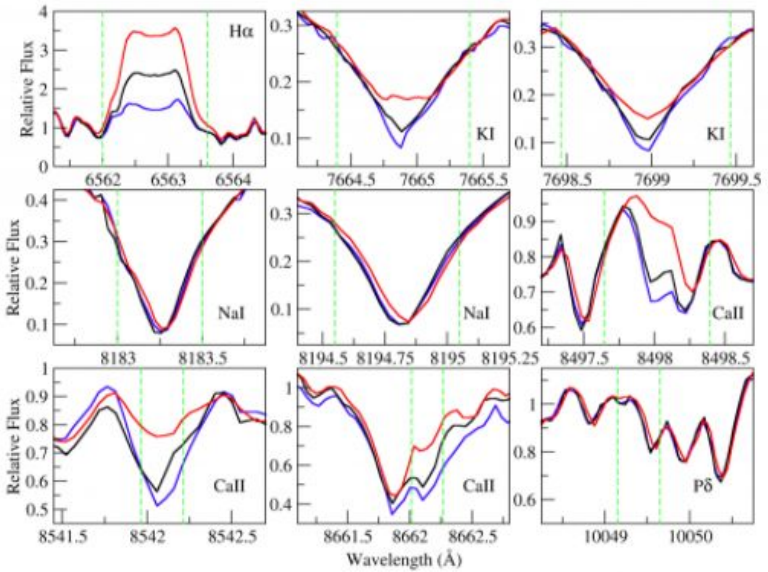
S5: Future Complementary Observations

Leads: Elisa Quintana & Rob Zellem



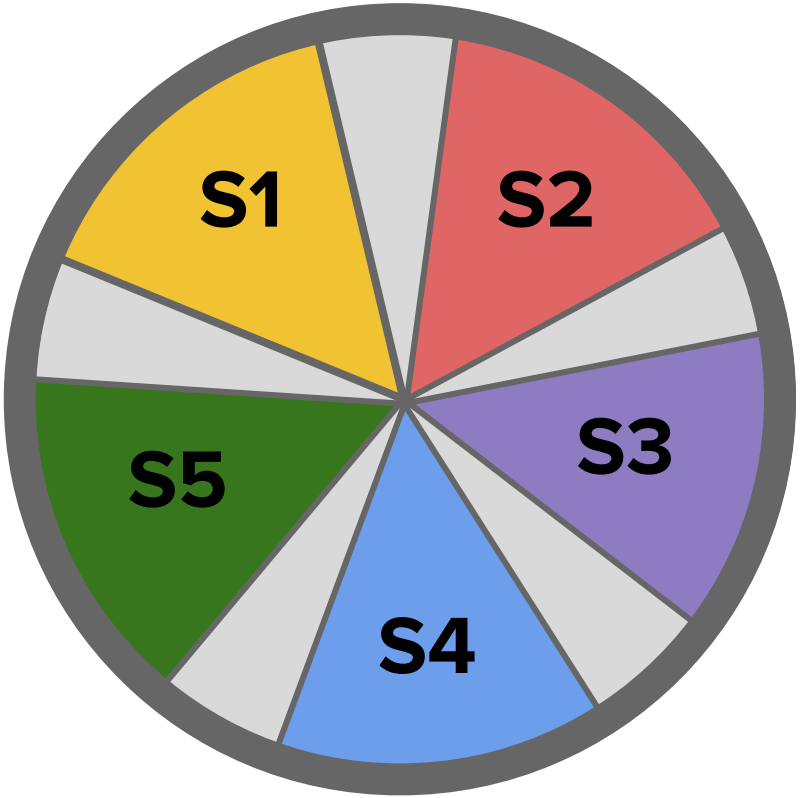
Spectroscopic monitoring

Figure source: Robertson (2016)



S5: Future Complementary Observations

Leads: Elisa Quintana & Rob Zellem



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

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