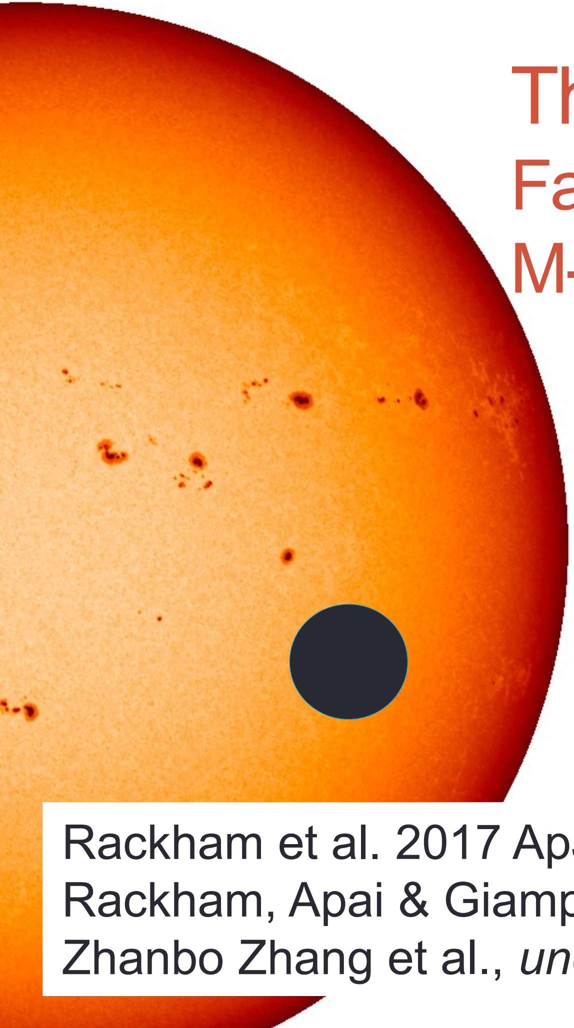


The Transit Light Source Effect:
False Spectral Features and Biased Densities for M-dwarf Transiting Planets

Benjamin Rackham
University of Arizona

with: **Dániel Apai, Mark Giampapa,**
Zhanbo Zhang, and Yifan Zhou

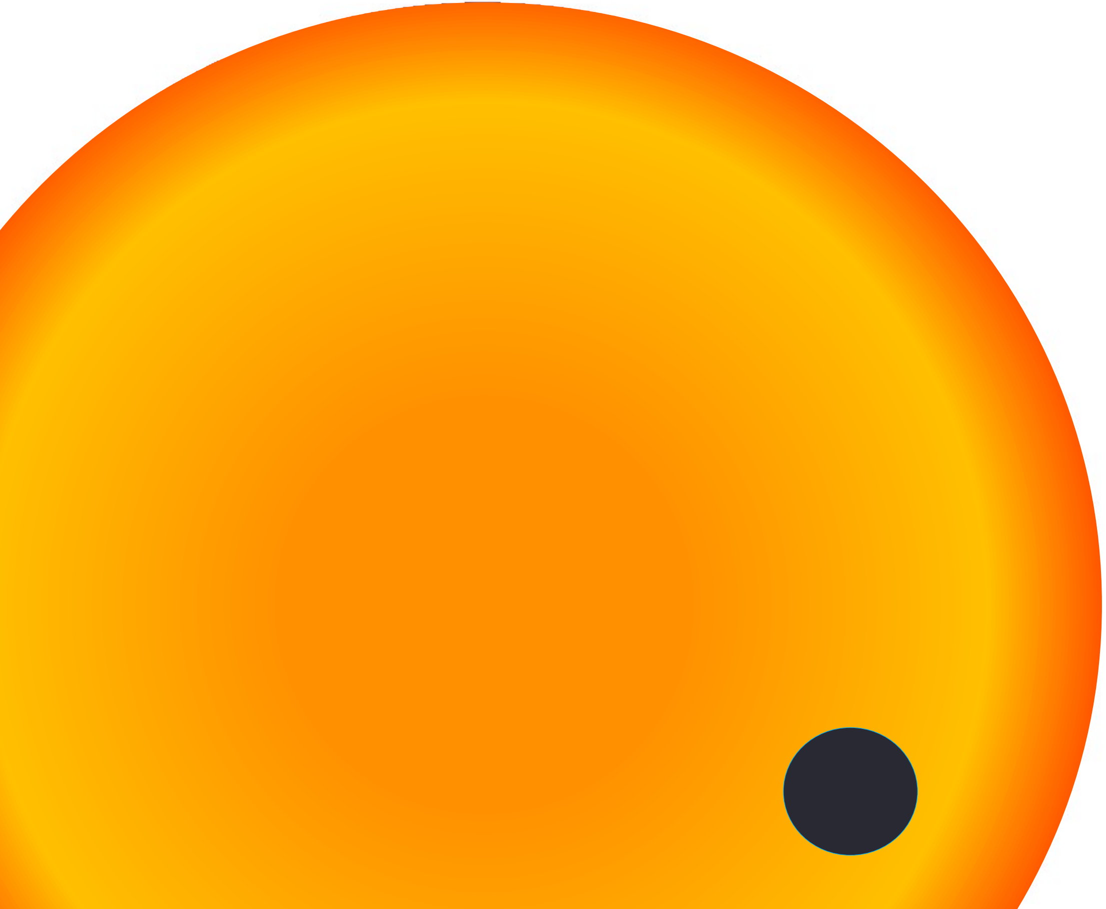
Rackham et al. 2017 ApJ 834, 151
Rackham, Apai & Giampapa 2018 ApJ 853, 122
Zhanbo Zhang et al., *under review*

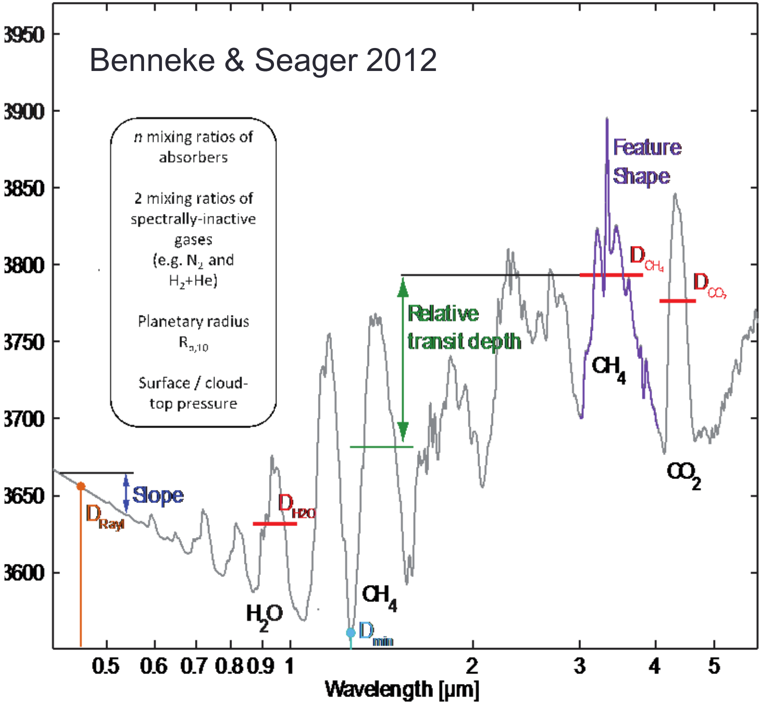
Earths in Other Solar Systems - The Delivery of Organics and Volatiles to Habitable Planets - University of Chile - Pontific University of Chile - NOAO - University of Chicago - University of Arizona -

NSF

ARIZONA

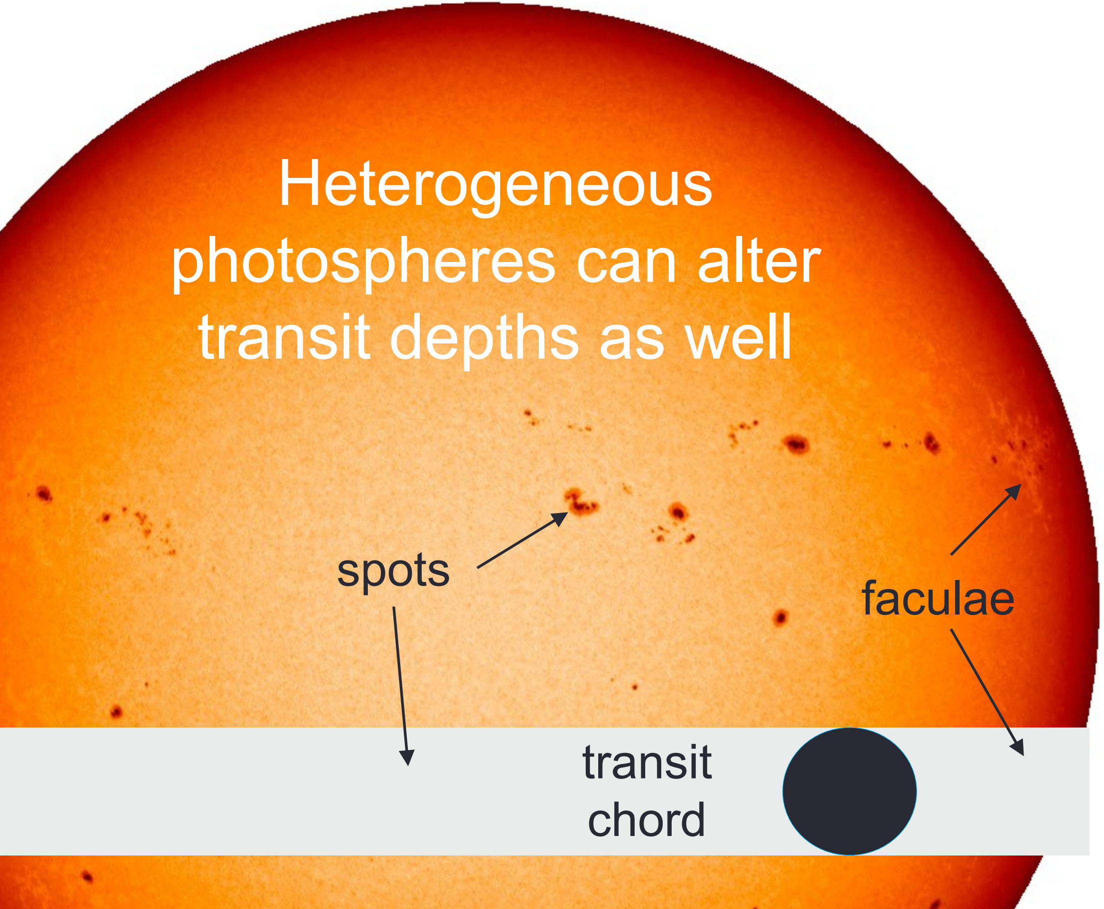
Transmission spectroscopy involves two atmospheres (at least)

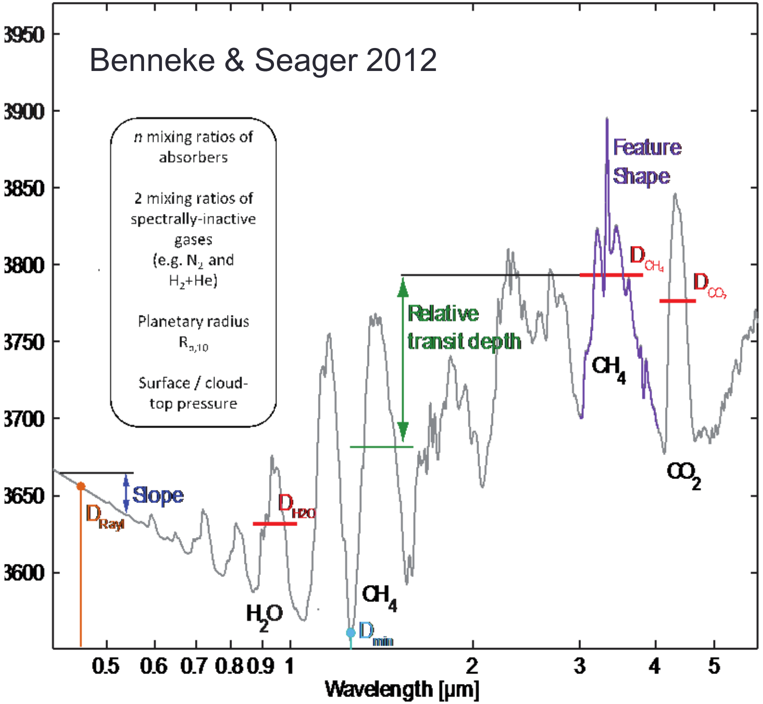




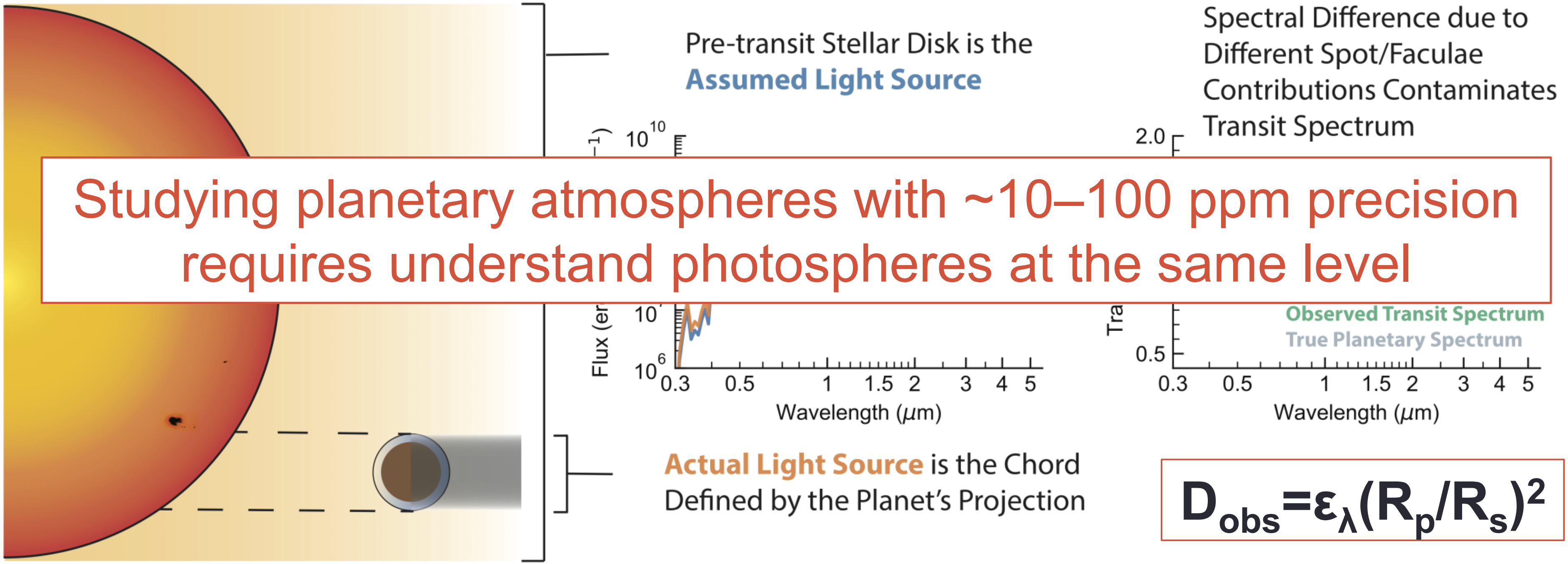
Transmission spectroscopy involves two atmospheres (at least)

Heterogeneous photospheres can alter transit depths as well





The Transit Light Source Effect



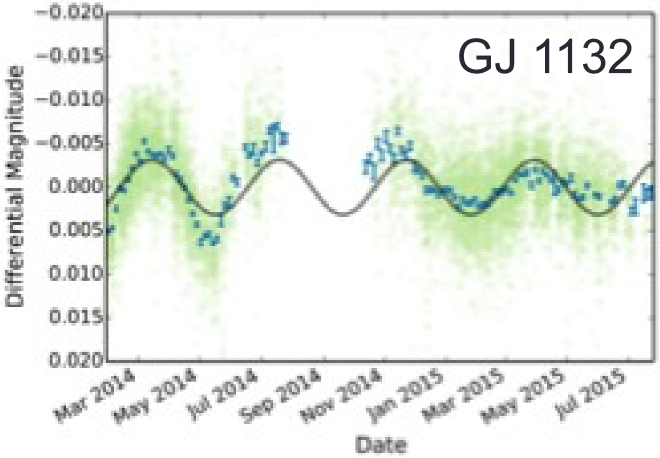
Studying planetary atmospheres with ~10–100 ppm precision requires understand photospheres at the same level

$$D_{obs}=\varepsilon_\lambda(R_p/R_s)^2$$

Pont+2008, Bean+2010, Sing+2011, Aigrain+2012, Huitson+2013, Jordán+2013, Kreidberg+2014, McCullough+2014, Nikolov+2015, Herrero+2016, Zellem+2017

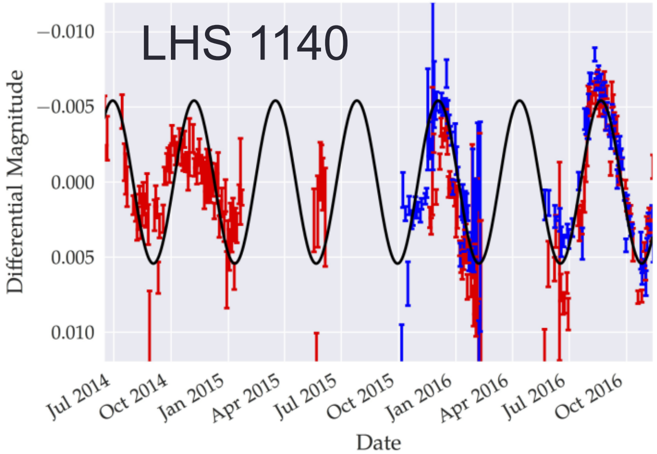
Rackham, Apai & Giampapa 2018

Exoplanet host stars have heterogeneous photospheres

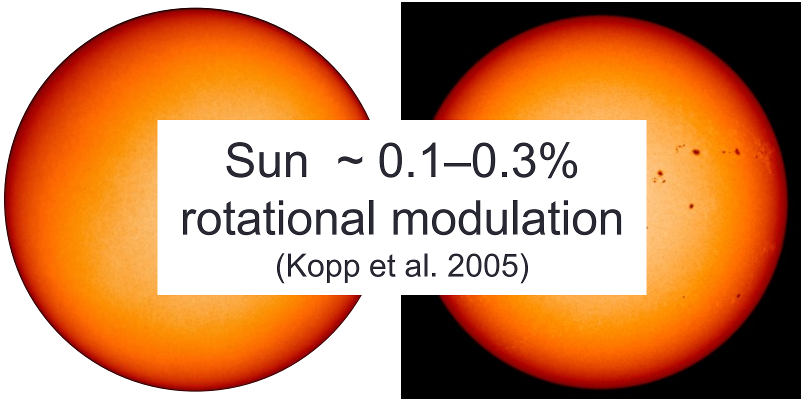


Berta-Thompson et al. 2015

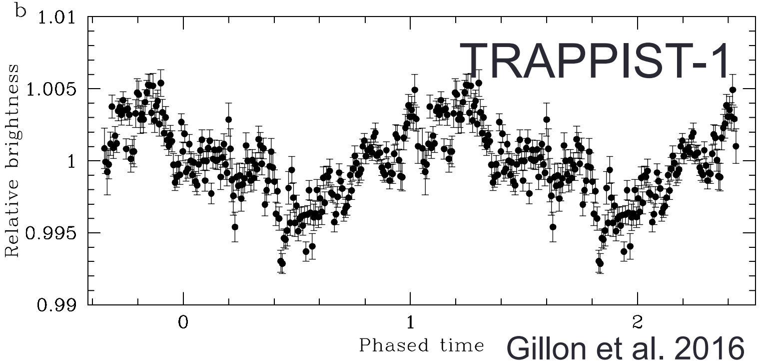
M dwarf exoplanet hosts:
~1% (10 mmag)
rotational modulation



Dittmann et al. 2017

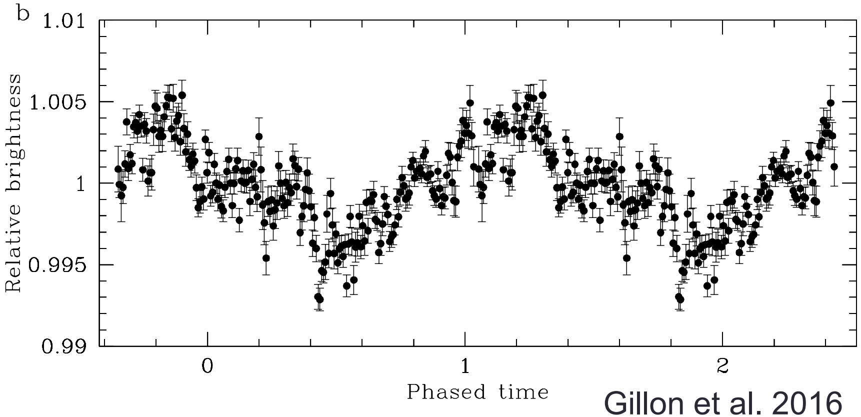


Sun ~ 0.1–0.3%
rotational modulation
(Kopp et al. 2005)



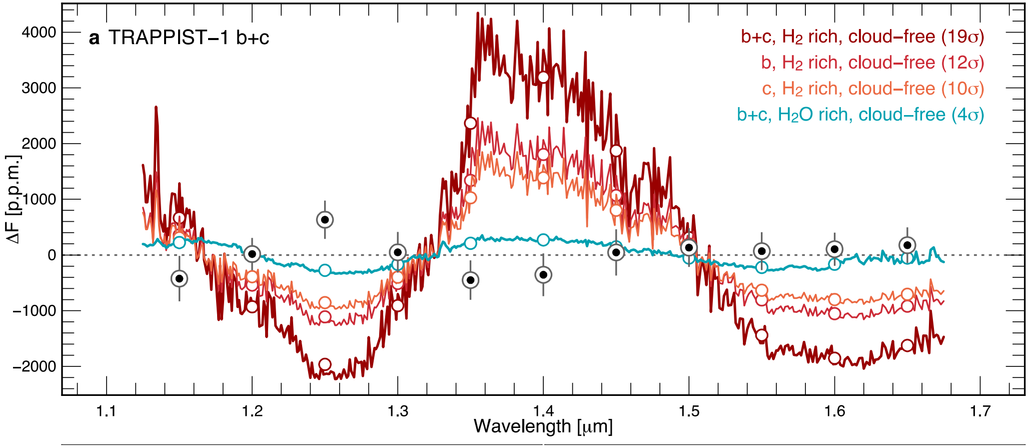
Gillon et al. 2016

What active region covering fractions can produce reported variabilities?



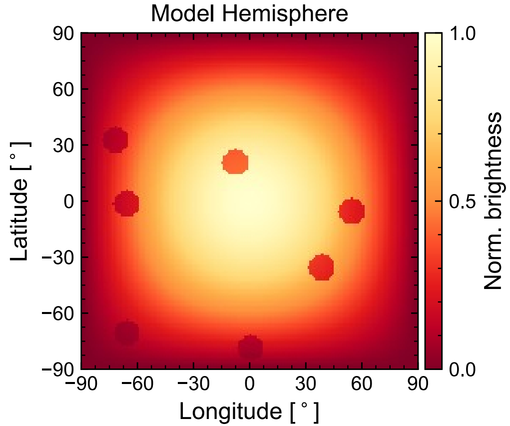
Gillon et al. 2016

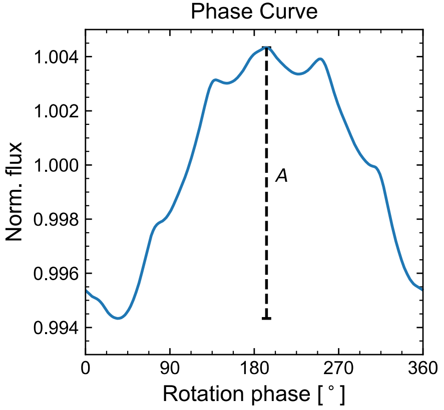
How will they affect high-precision transmission spectra of M-dwarf exoplanets?

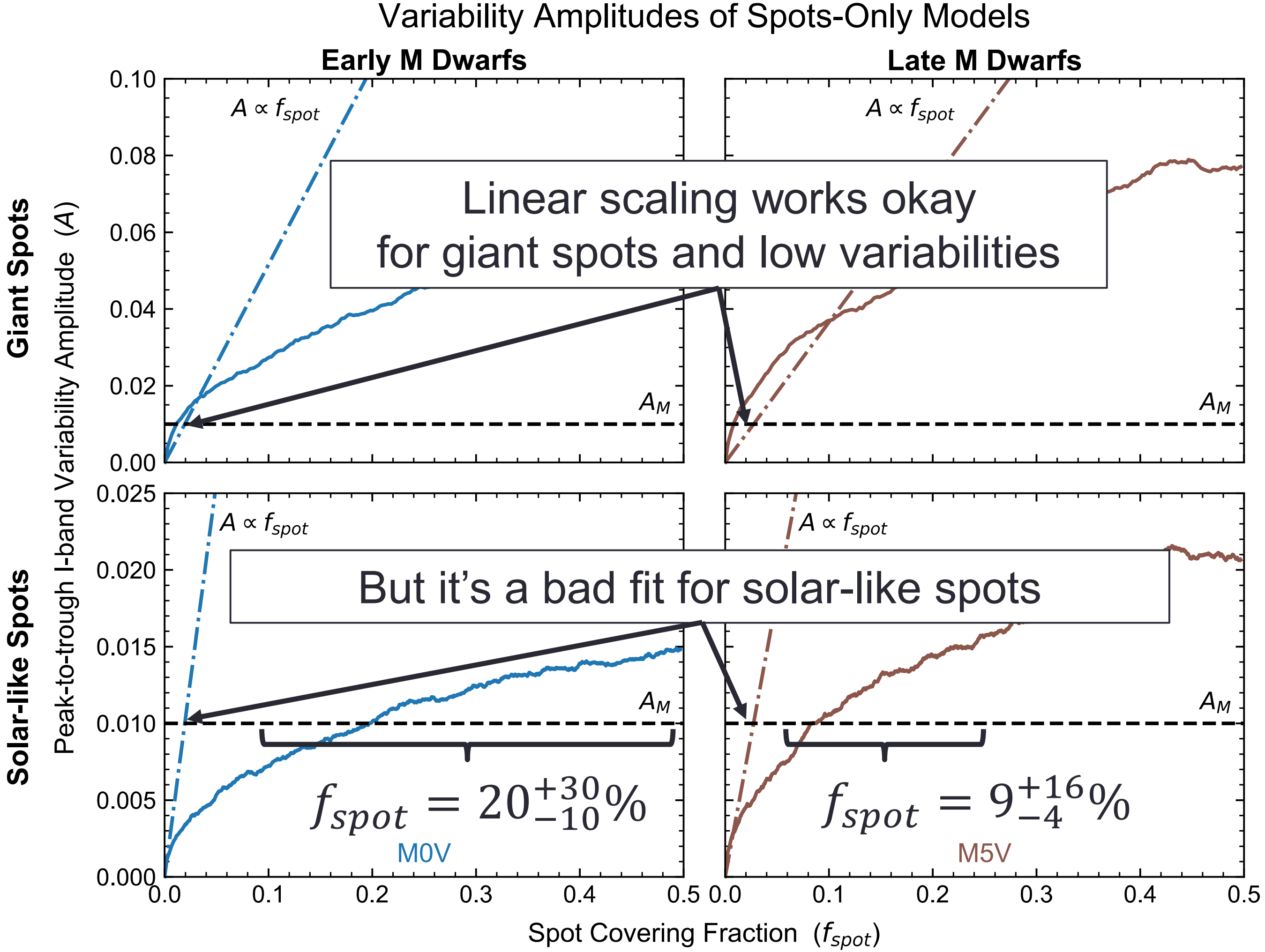


de Wit et al. 2016

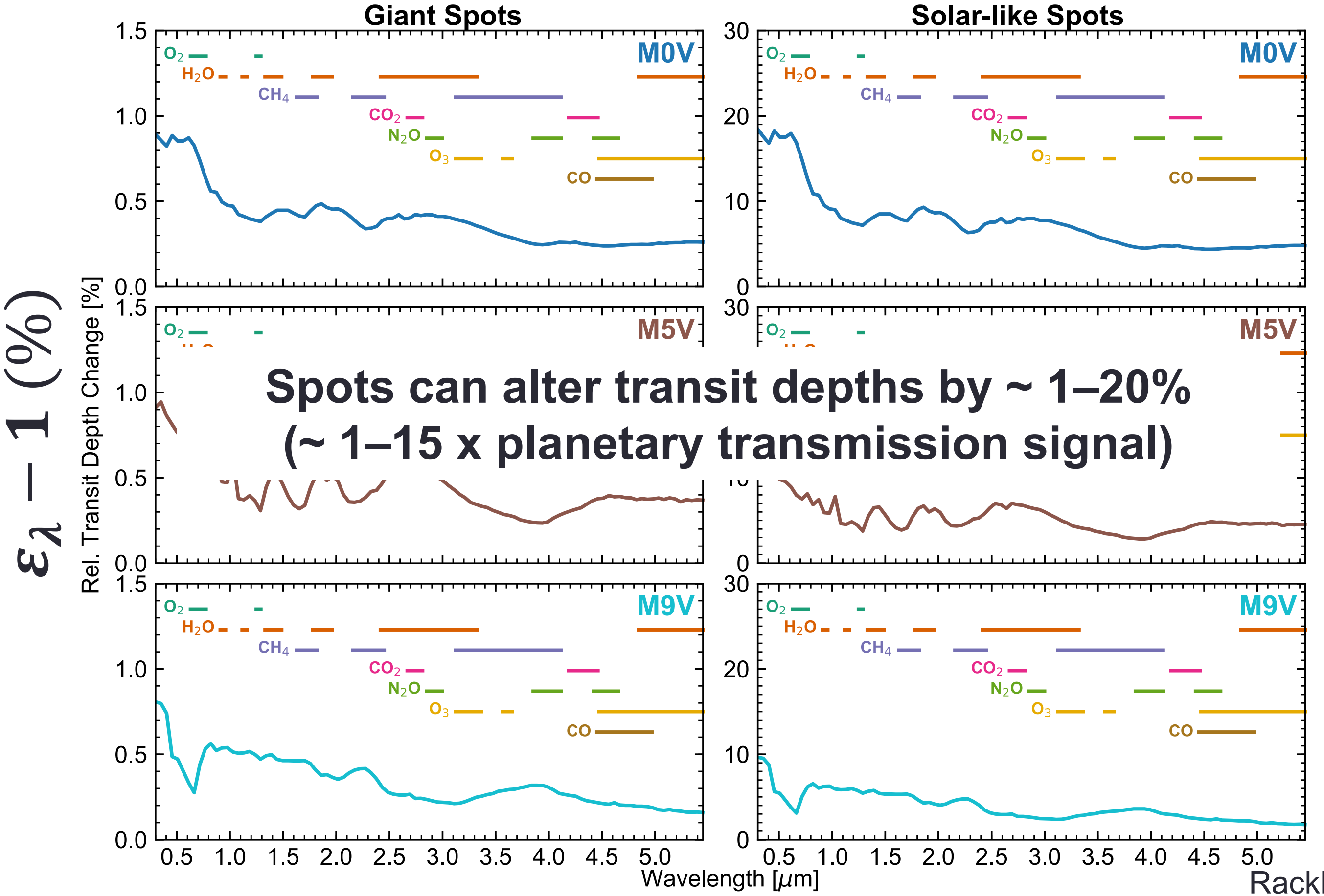
Covering fractions







Stellar contamination is a concern for all M dwarfs.



Spots can alter transit depths by ~ 1–20%
(~ 1–15 x planetary transmission signal)

Planetary signal:

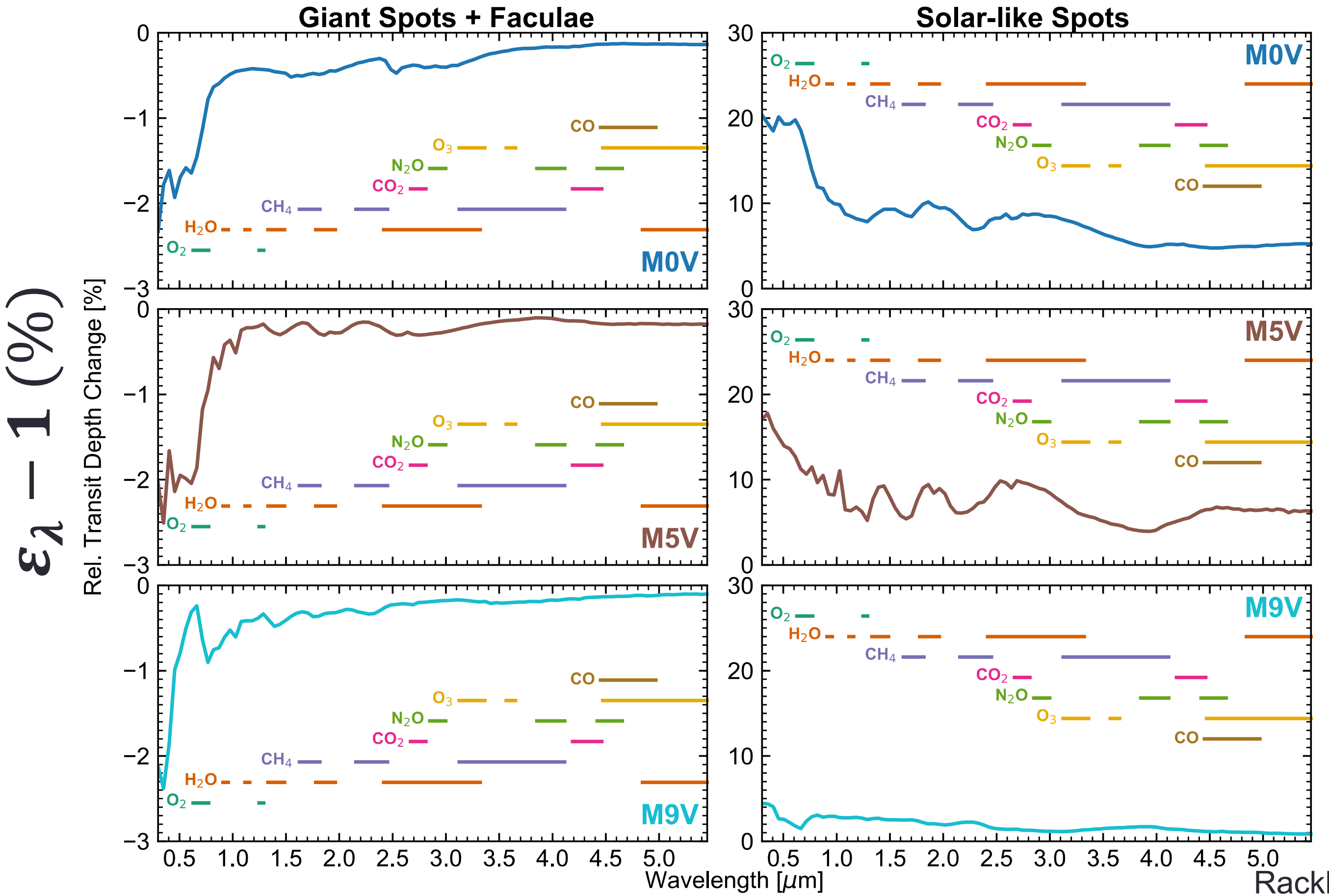
ε =1.4%

ε =1.4%

ε =1.4%

Rackham, Apai & Giampapa 2018

Effect of faculae is poorly constrained



Planetary signal:

ε =1.4%

ε =1.4%

ε =1.4%

Rackham, Apai & Giampapa 2018

Are these features observable?

Table 6. Transit depths and absolute transit depth changes for a transiting Earth-twin by spectral type

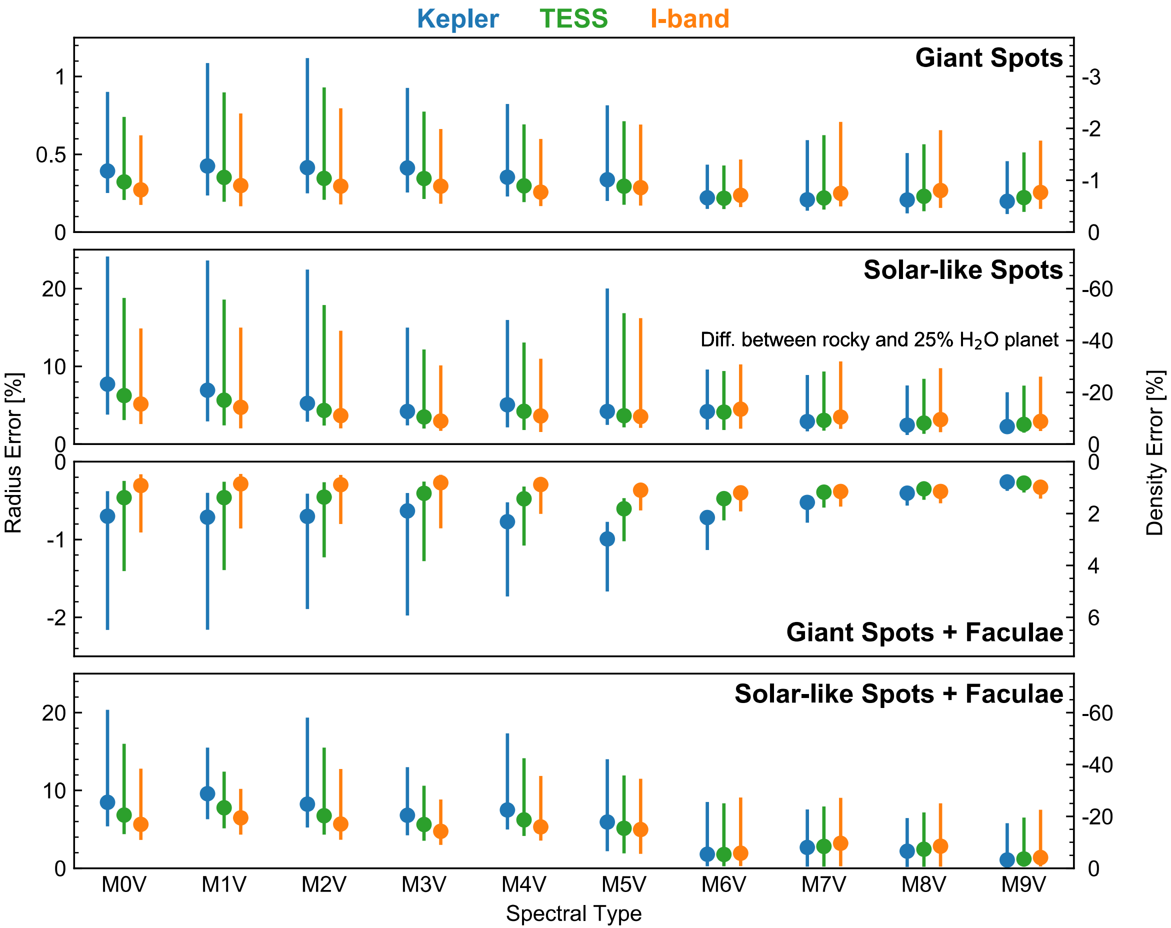
Sp. Type	D (ppm)	ΔD_p (ppm)	ΔD_s by Heterogeneity Case: Giant Spots (ppm)	Solar-like Spots (ppm)	Giant Spots + Faculae (ppm)	Solar-like Spots + Faculae (ppm)
M0V	220	[illegible]	[illegible]	[illegible]	[illegible]	16
M1V	350	[illegible]	[illegible]	[illegible]	[illegible]	29
M2V	430	[illegible]	[illegible]	[illegible]	[illegible]	29
M3V	550	[illegible]	[illegible]	19	-1.4	31
M4V	1200	16	4.0	56	-2.8	82
M5V	2100	27	6.5	73	-5.4	120
M6V	3700	48	9.4	180	-10	76
M7V	5800	76	15	210	-15	190
M8V	6900	90	20	230	-17	210
M9V	13000	170	35	400	-29	190

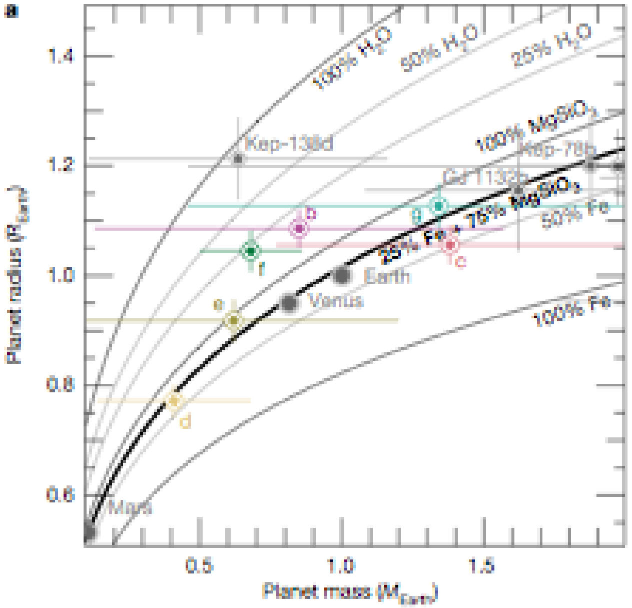
Planetary features M6V +

Giant spots M9V

Solar-like spots M3V +

Effect on Density Calculations





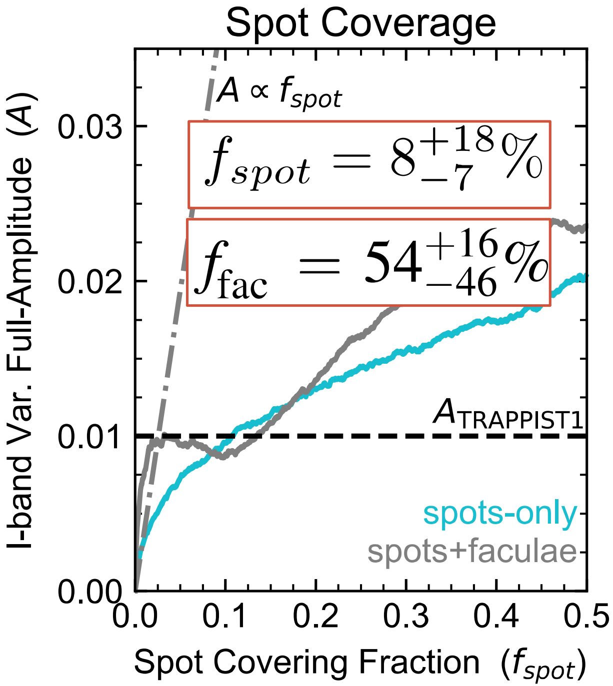
TRAPPIST-1 densities may be underestimated by:

$$\Delta(\rho) = -8^{+7}_{-20}\%$$

Predictions for TRAPPIST-1

Rackham, Apai & Giampapa 2018

Stellar Contamination in the TRAPPIST-1 System



Prediction:

ΔD_{het}~3% (1–15) %

combined transit depth:
D = 0.03474

ΔD_{het} = 1000 ppm (350–5200) ppm

Prediction: stellar contamination overwhelms planetary features

Prediction:

ΔD_{het}~3% (1–15) %

combined transit depth:
D = 0.03474

ΔD_{het} = 1000 ppm (350–5200) ppm

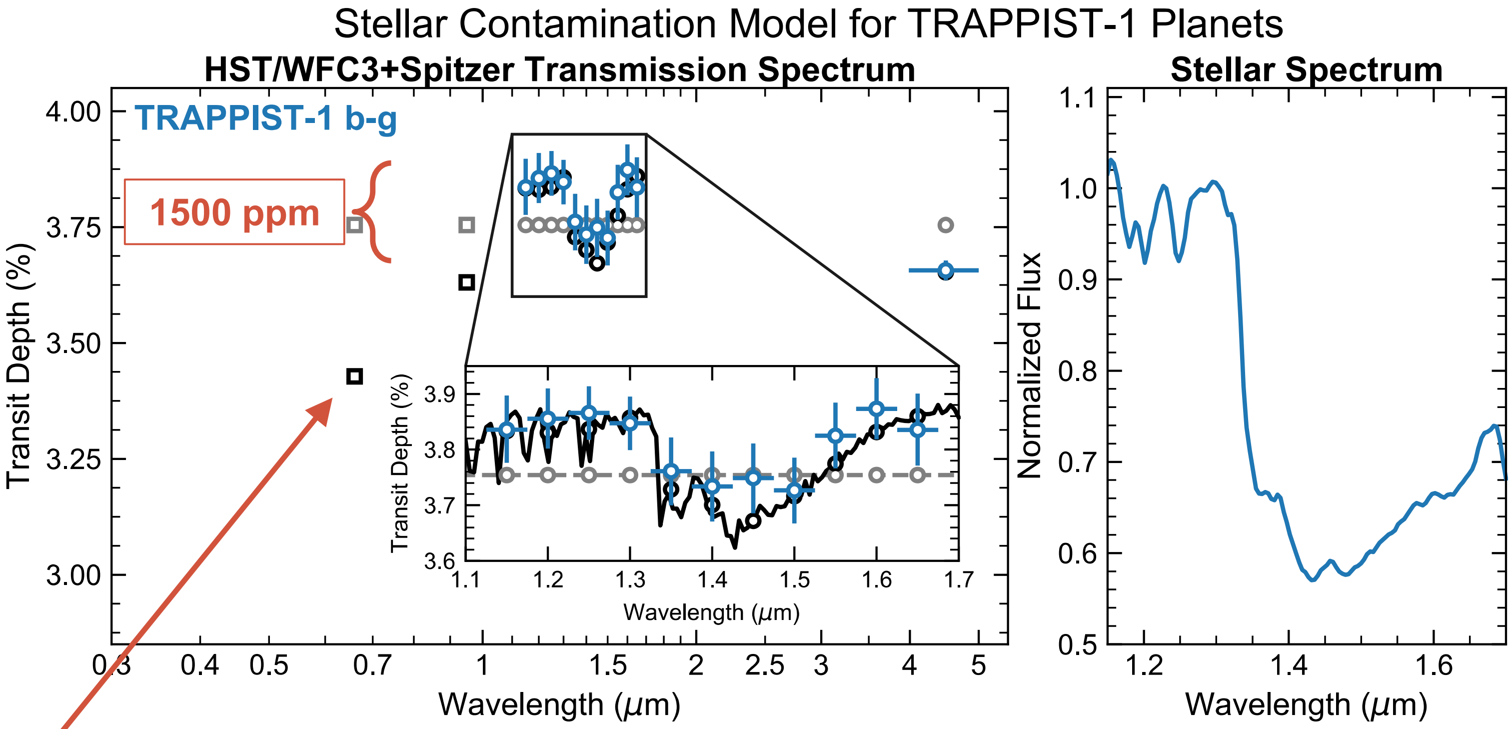
TRAPPIST-1 Data

Prediction:

ΔD_{het}~3% (1–15) %

combined transit depth:
D = 0.03474

ΔD_{het} = 1000 ppm (350–5200) ppm

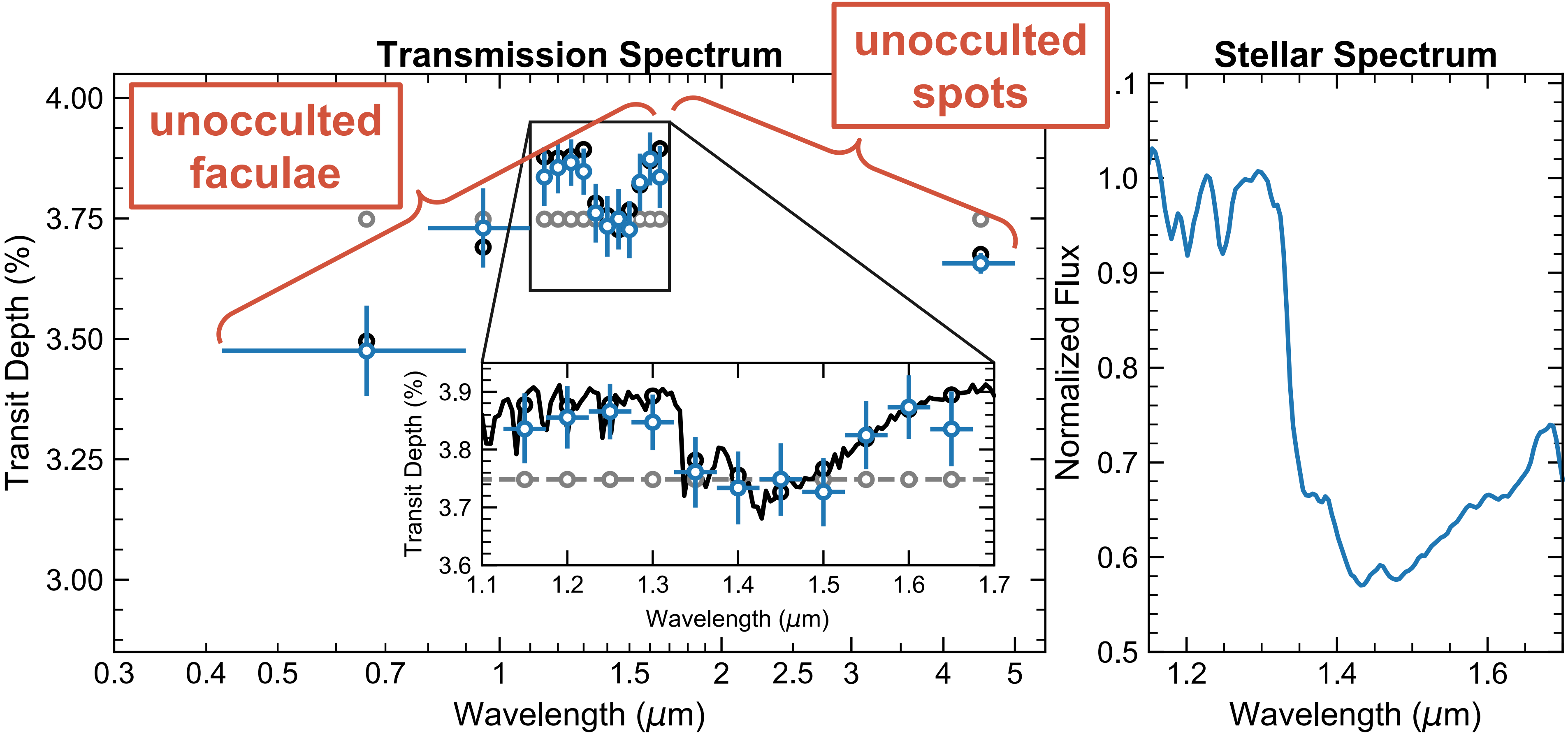


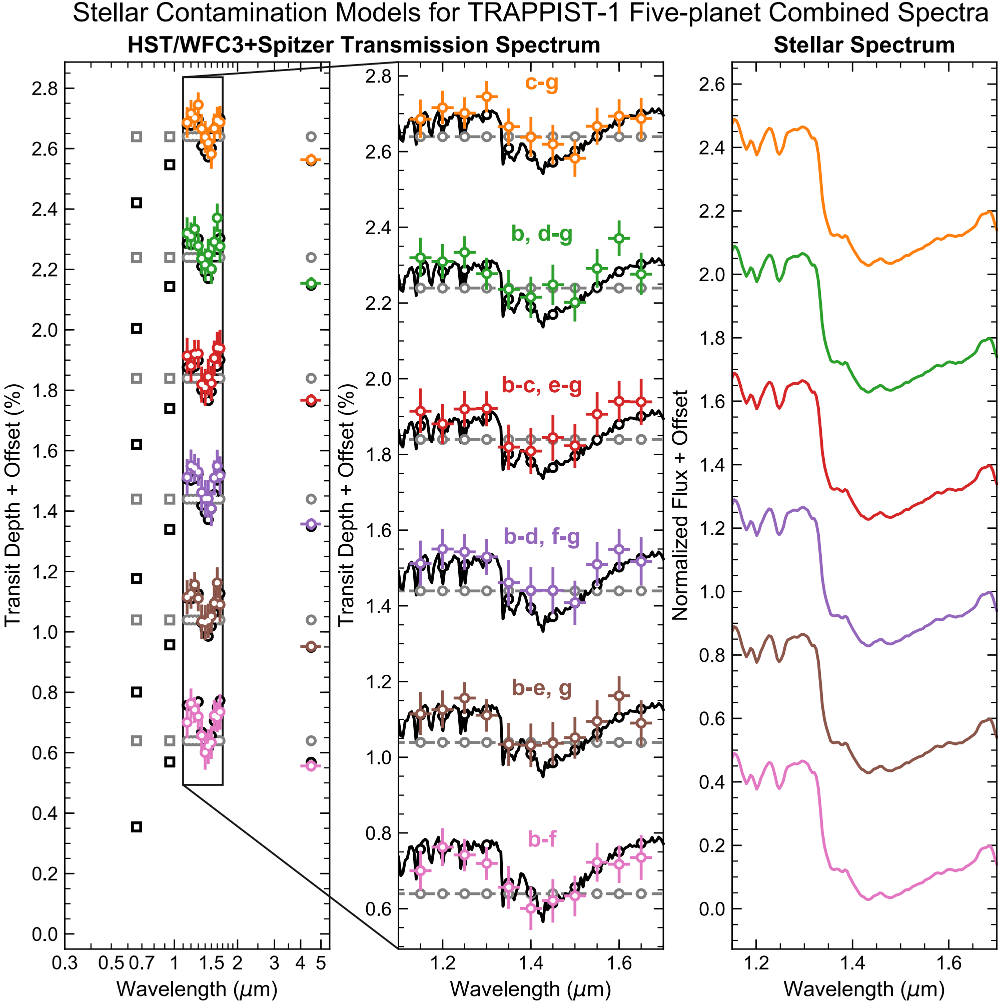
Model accurately predicts K2 and I+z transit depths from Ducrot et al. (2018)

Zhang, Zhou, Rackham, and Apai, *under review*

(Independent analysis of data from de Wit et al. 2016, 2018)

TRAPPIST-1 b–g spectrum affected by multiple heterogeneities





Excluding single planets doesn't change the interpretation

Stellar contamination model preferred for all five-planet combined spectra

Three components:

$T_{\rm phot}$ (K)	$T_{\rm spot}$ (K)	$T_{\rm fac}$ (K)
2425^{+168}_{-178}	2006^{+127}_{-93}	2957^{+43}_{-25}

Whole-disk covering fractions:

$F_{\rm spot}$	$F_{\rm fac}$
38^{+8}_{-8}	48^{+6}_{-8}

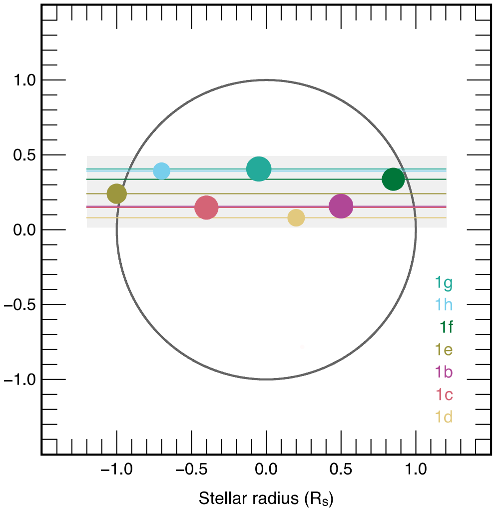
Transit chord covering fractions:

$f_{\rm spot}$	$f_{\rm fac}$
10^{+4}_{-10}	45^{+6}_{-6}

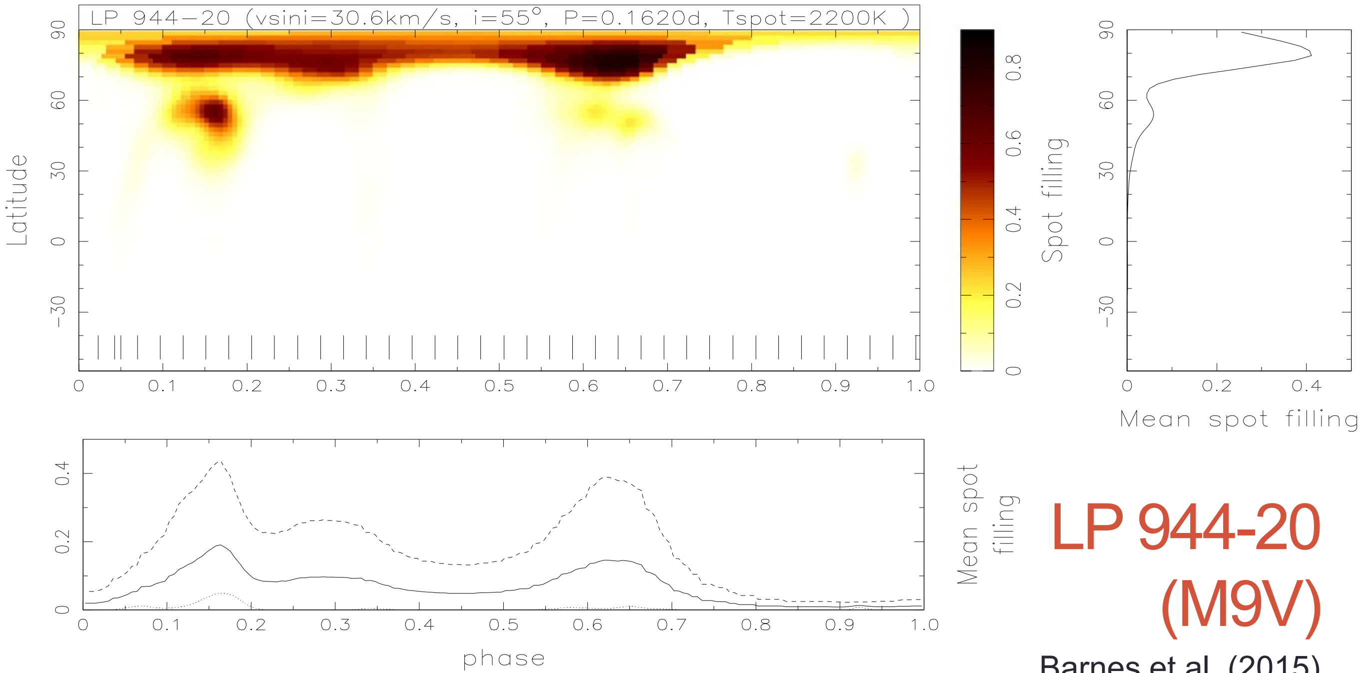
Morris et al. (2018) bright spots?

Zhang, Zhou, Rackham, and Apai, *under review*

High-latitude / polar spots on TRAPPIST-1?

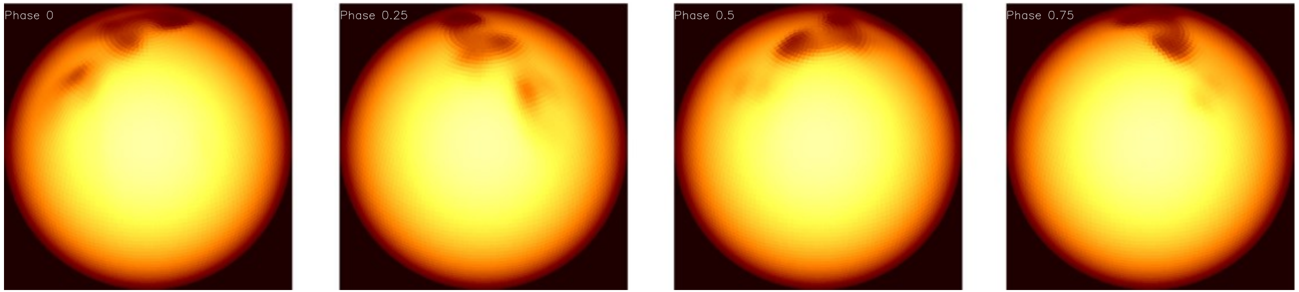


Delrez et al. (2018)

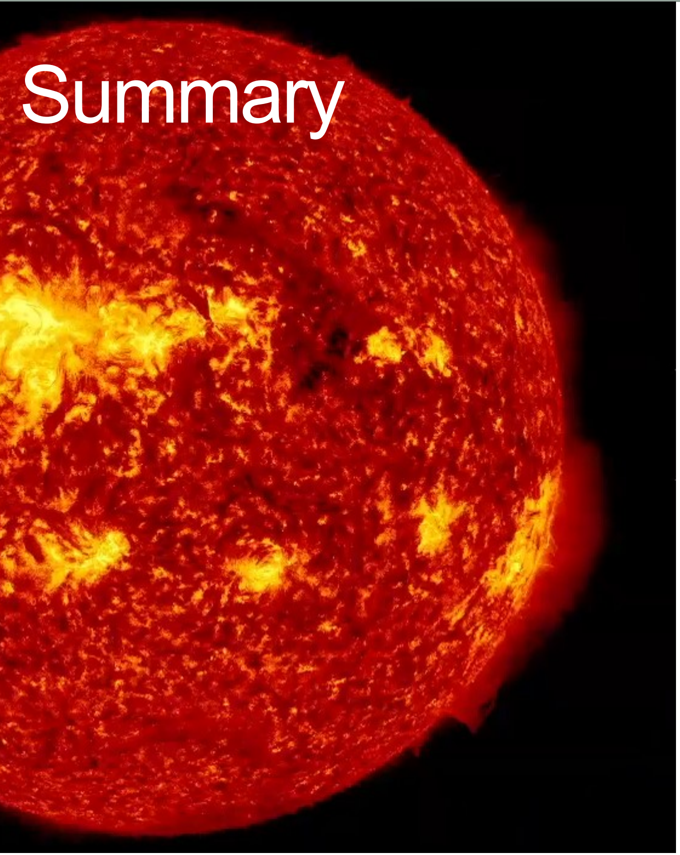


LP 944-20 (M9V)

Barnes et al. (2015)



Summary



Rackham et al., 2017
Rackham, Apai & Giampapa 2018
Zhanbo Zhang et al., *under review*

- Transmission spectroscopy involves **two atmospheres** (at least)
- **Spot and faculae coverages for M dwarfs** are **likely higher** than previously appreciated
- **Stellar contamination** is a concern for **all M dwarfs**
- TRAPPIST-1 combined transmission spectrum shows evidence for **unocculted active regions** affecting even **HST and Spitzer depths**
- **Active region crossings** provide valuable constraints and **retrieval models** can constrain both stellar and planetary parameters

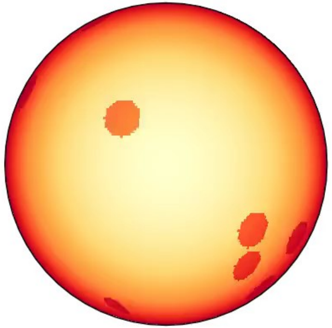
Extra slides

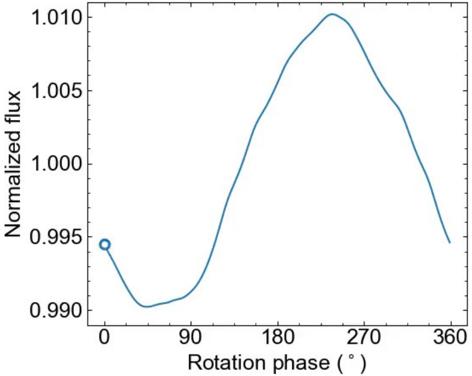
Spot and faculae coverages are likely higher than previously thought

Important parameters:

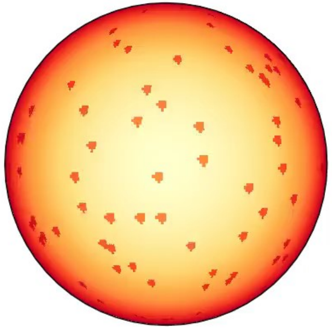
Spot size

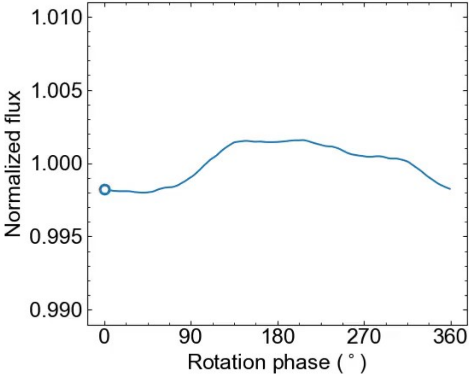
Giant spots (R=7º)





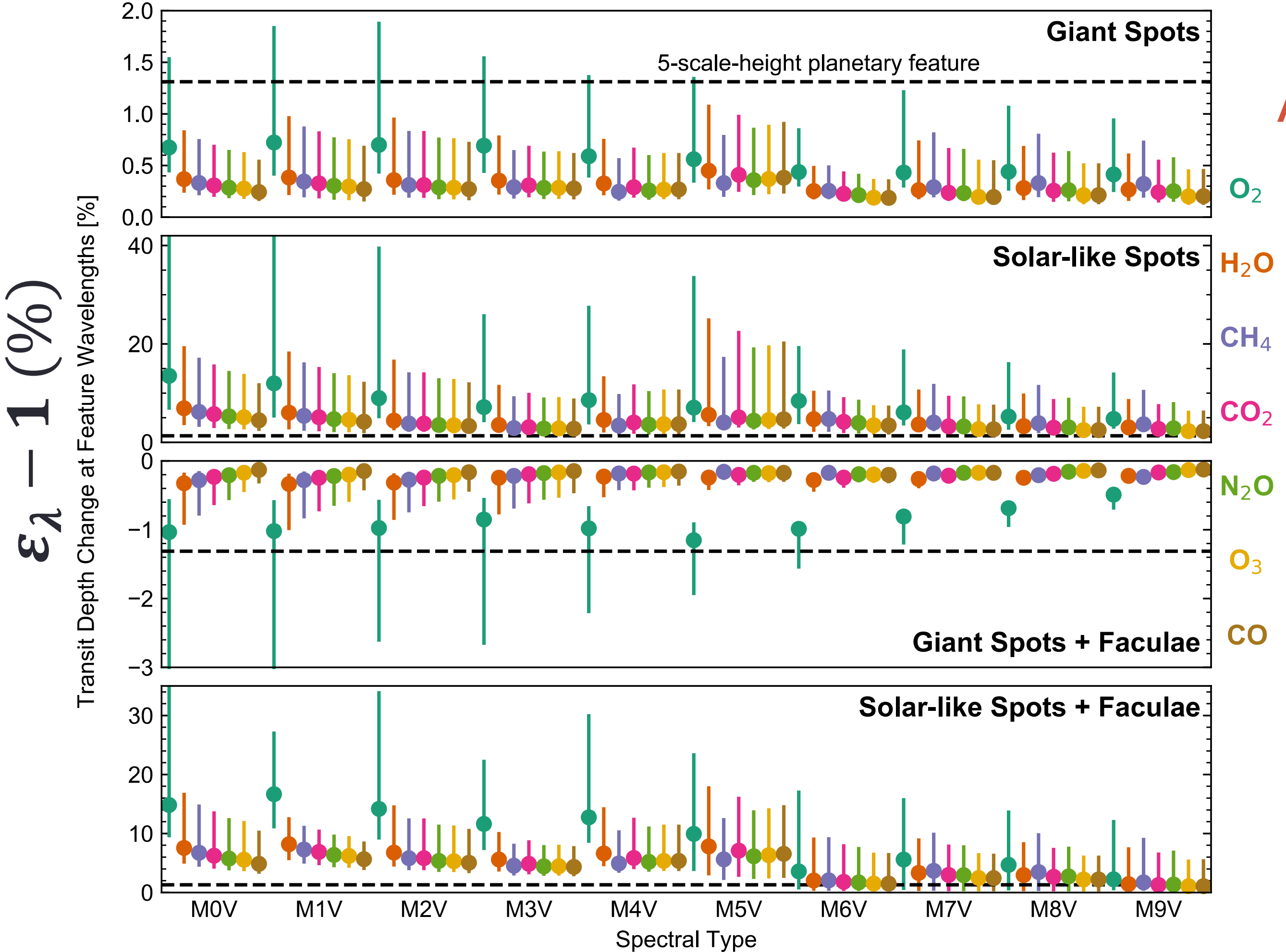
Solar-like spots (R=2º)





Rackham, Apai & Giampapa 2018

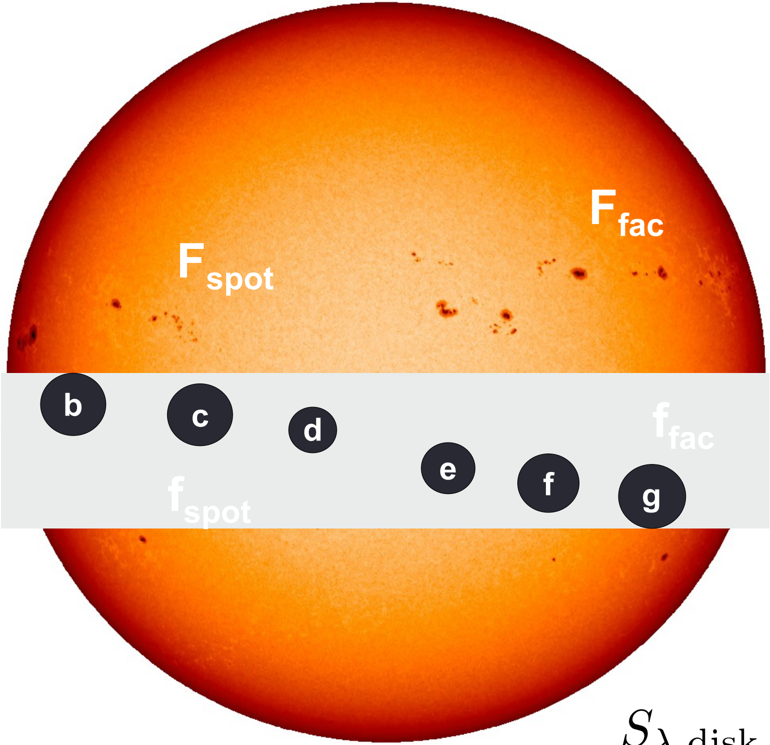
Effect on Planetary Absorption Features



Stellar contamination strongest for:

- Smaller spots
- Earlier M dwarfs
- Shorter wavelengths

Stellar contamination model for very heterogeneous stars



Observed transmission spectrum:

$$D_{\lambda,\mathrm{obs}} = \epsilon_\lambda D$$

Stellar contamination:

Transit chord

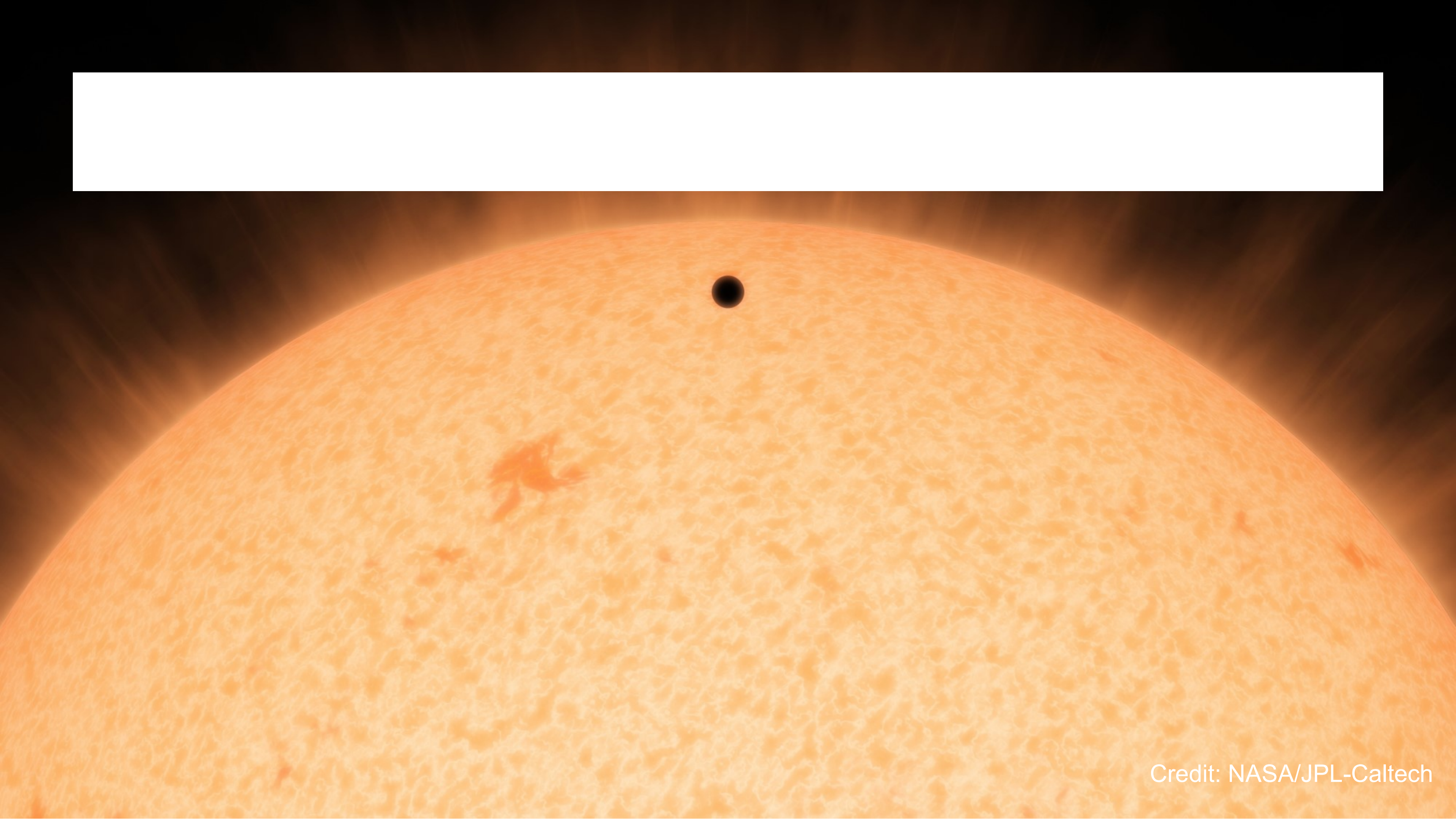
$$\epsilon_\lambda = \frac{(1 - f_{\mathrm{spot}} - f_{\mathrm{fac}}) S_{\lambda,\mathrm{phot}} + f_{\mathrm{spot}} S_{\lambda,\mathrm{spot}} + f_{\mathrm{fac}} S_{\lambda,\mathrm{fac}}}{(1 - F_{\mathrm{spot}} - F_{\mathrm{fac}}) S_{\lambda,\mathrm{phot}} + F_{\mathrm{spot}} S_{\lambda,\mathrm{spot}} + F_{\mathrm{fac}} S_{\lambda,\mathrm{fac}}}$$

Whole disk

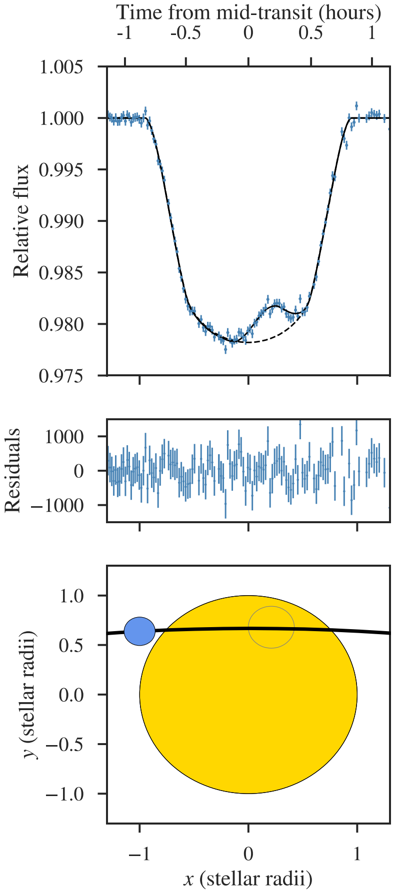
Stellar spectrum:

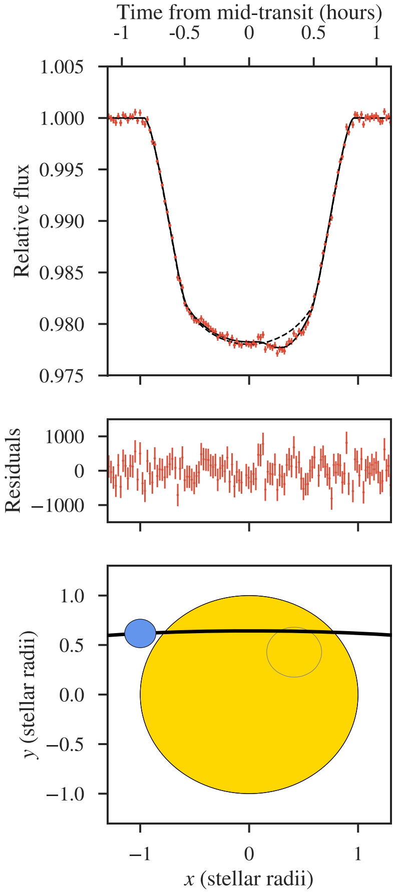
$$S_{\lambda,\mathrm{disk}} = (1 - F_{\mathrm{spot}} - F_{\mathrm{fac}}) S_{\lambda,\mathrm{phot}} + F_{\mathrm{spot}} S_{\mathrm{spot}} + F_{\mathrm{fac}} S_{\lambda,\mathrm{fac}}$$

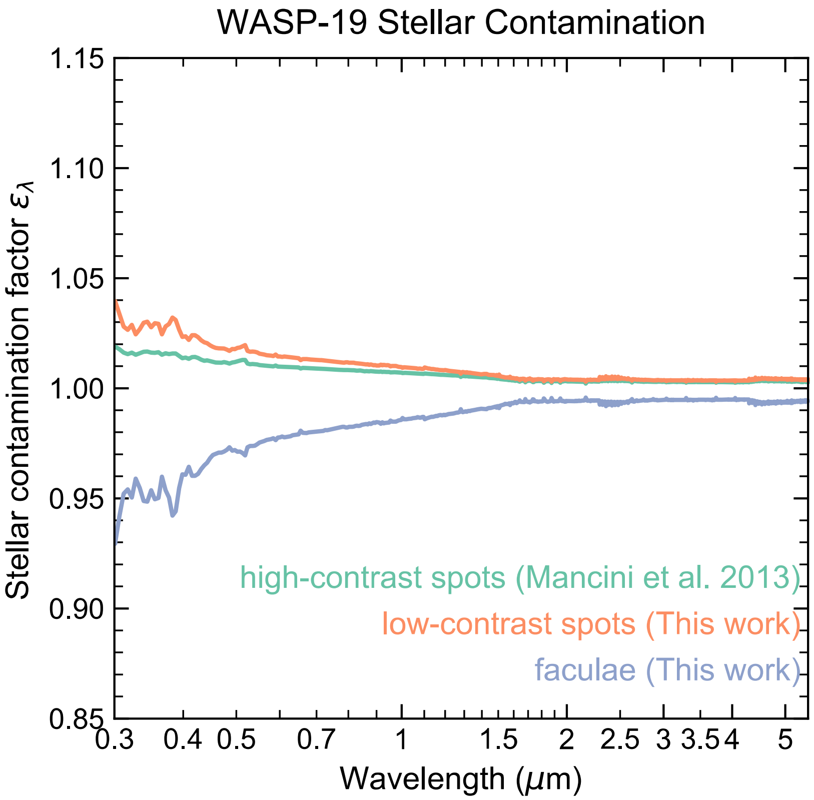
Zhang, Zhou, Rackham, and Apai, *under review*


Credit: NASA/JPL-Caltech

Active region crossings provide valuable constraints on filling factors







Work led by Néstor Espinoza

Espinoza, Rackham et al., *under review*

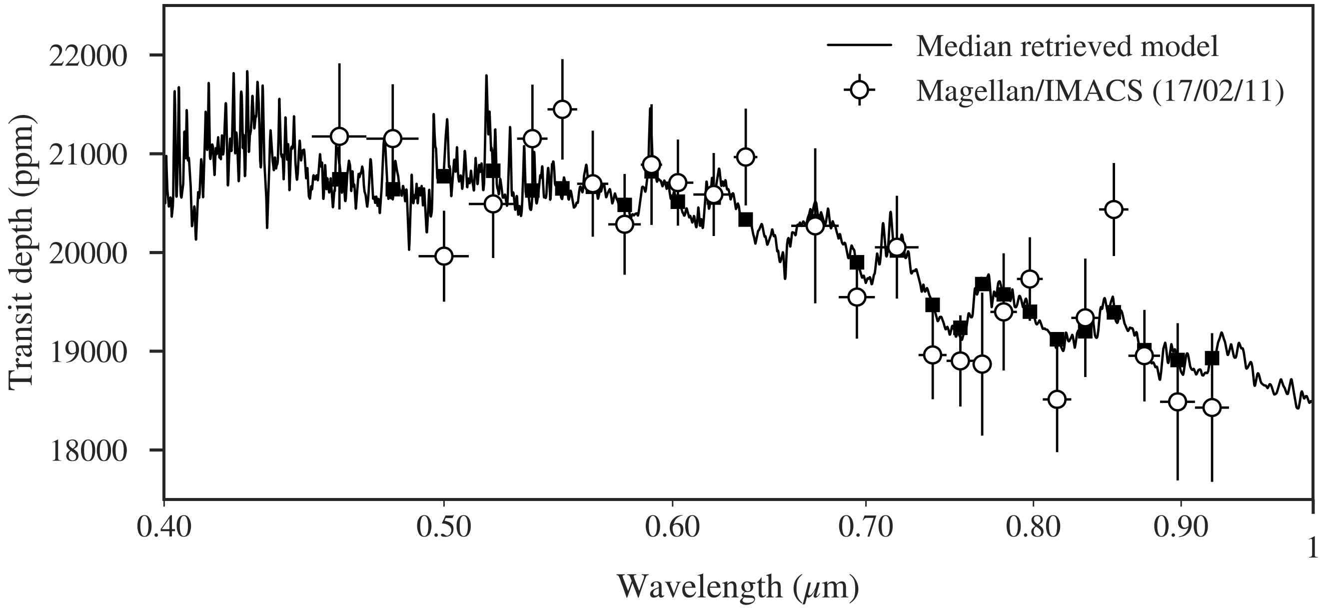
Atmospheric retrievals can probe for stellar contamination features

WASP-19b

6 transits from Magellan/IMACS

2 show active region crossings

1 shows stellar features in retrieval

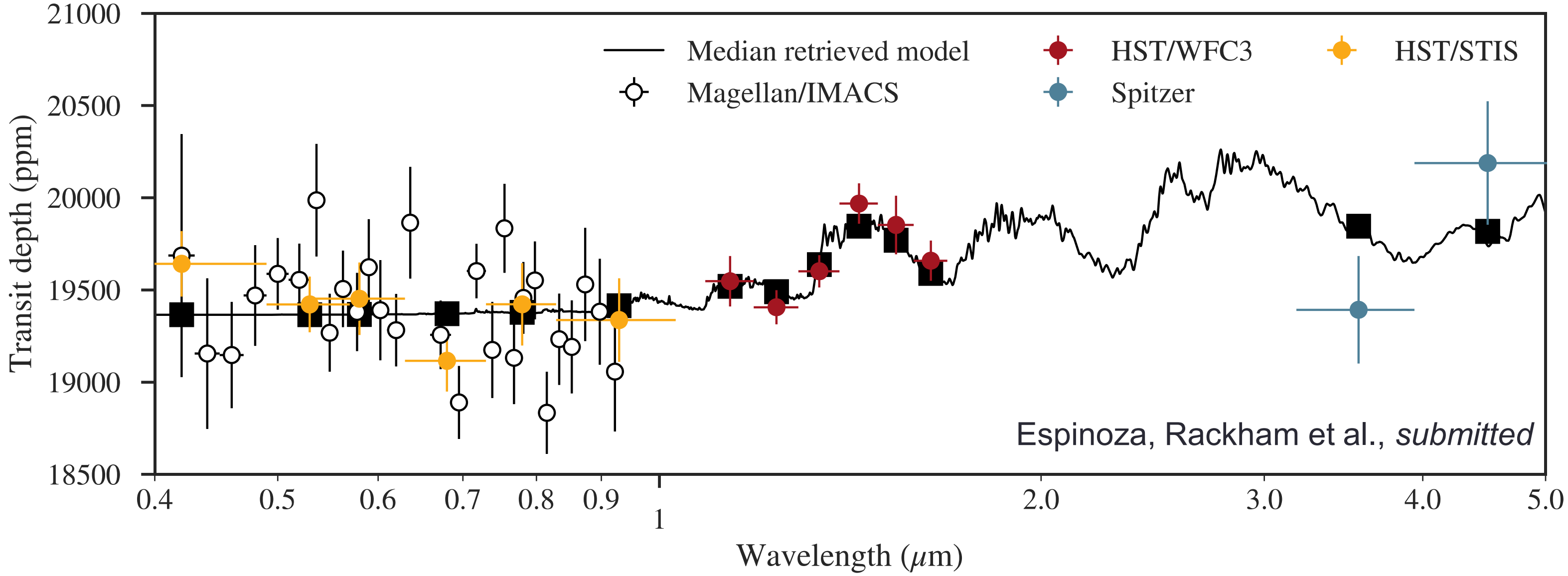


ACCESS

Co-PIs: Mercedes López-Morales, Dániel Apai, Andrés Jordán, Dave Osip

Espinoza, Rackham et al., *under review*

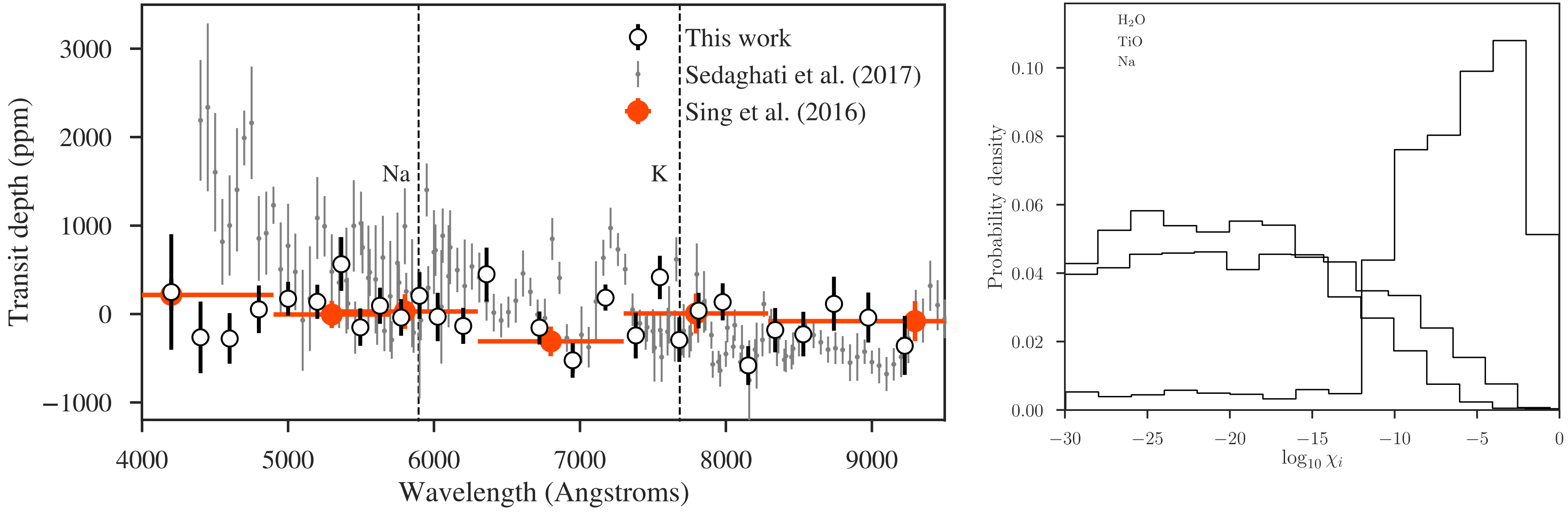
A featureless optical transmission spectrum for WASP-19b



ACCESS

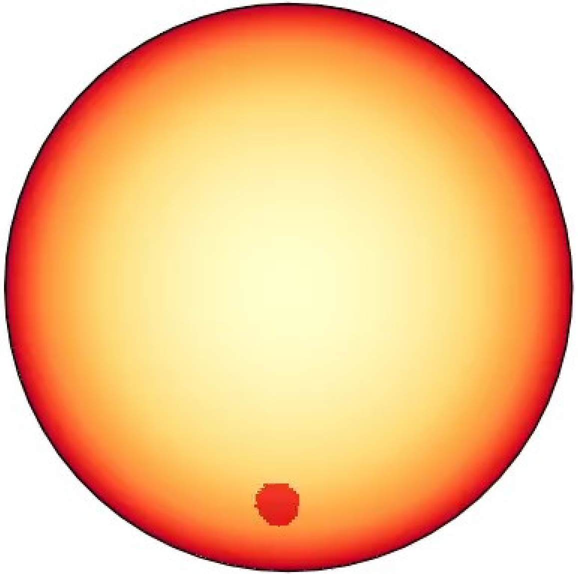
Ground-based optical data constrains stellar contamination and informs interpretations of HST and Spitzer data at longer wavelengths

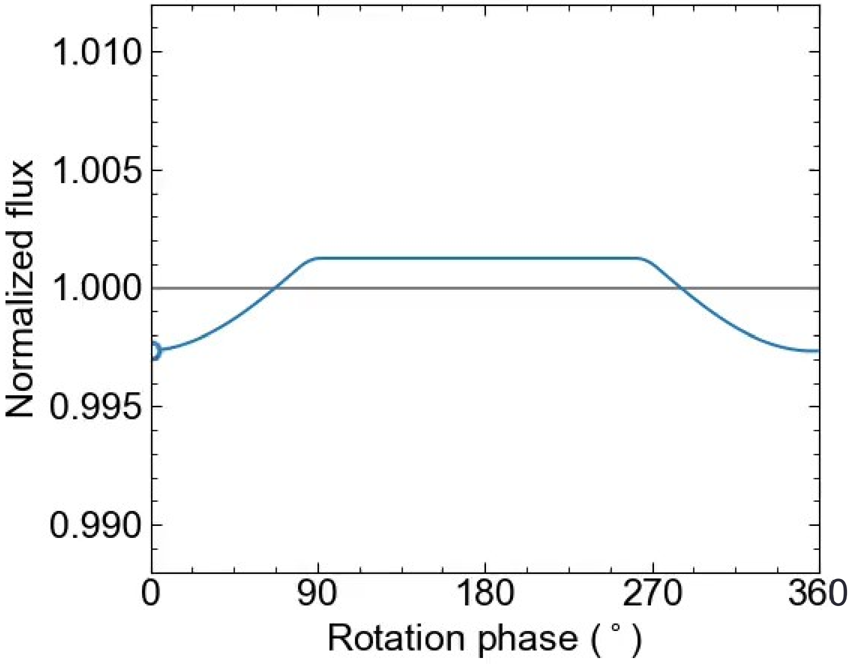
Magellan/IMACS spectrum from 6 transits is consistent with HST/STIS spectrum and doesn't show evidence for TiO



Espinoza, Rackham, et al., *under review*

What active region covering fractions can produce reported variabilities?





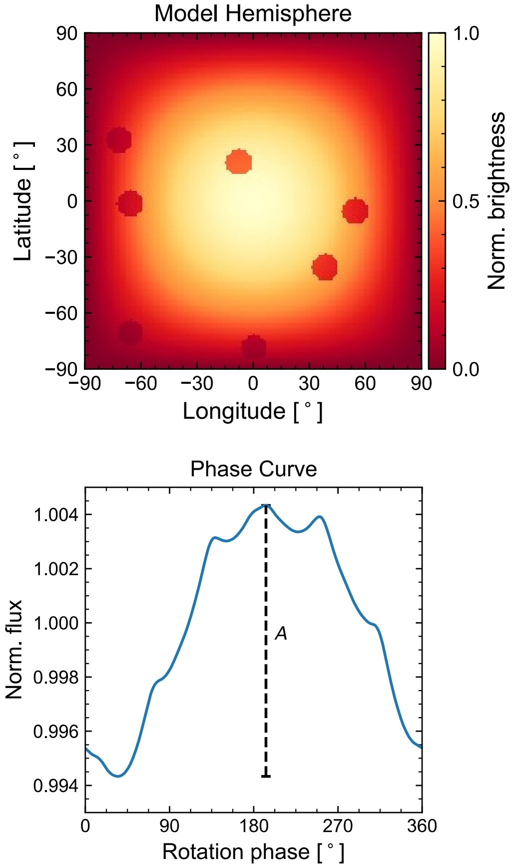
Amplitudes grow non-linearly

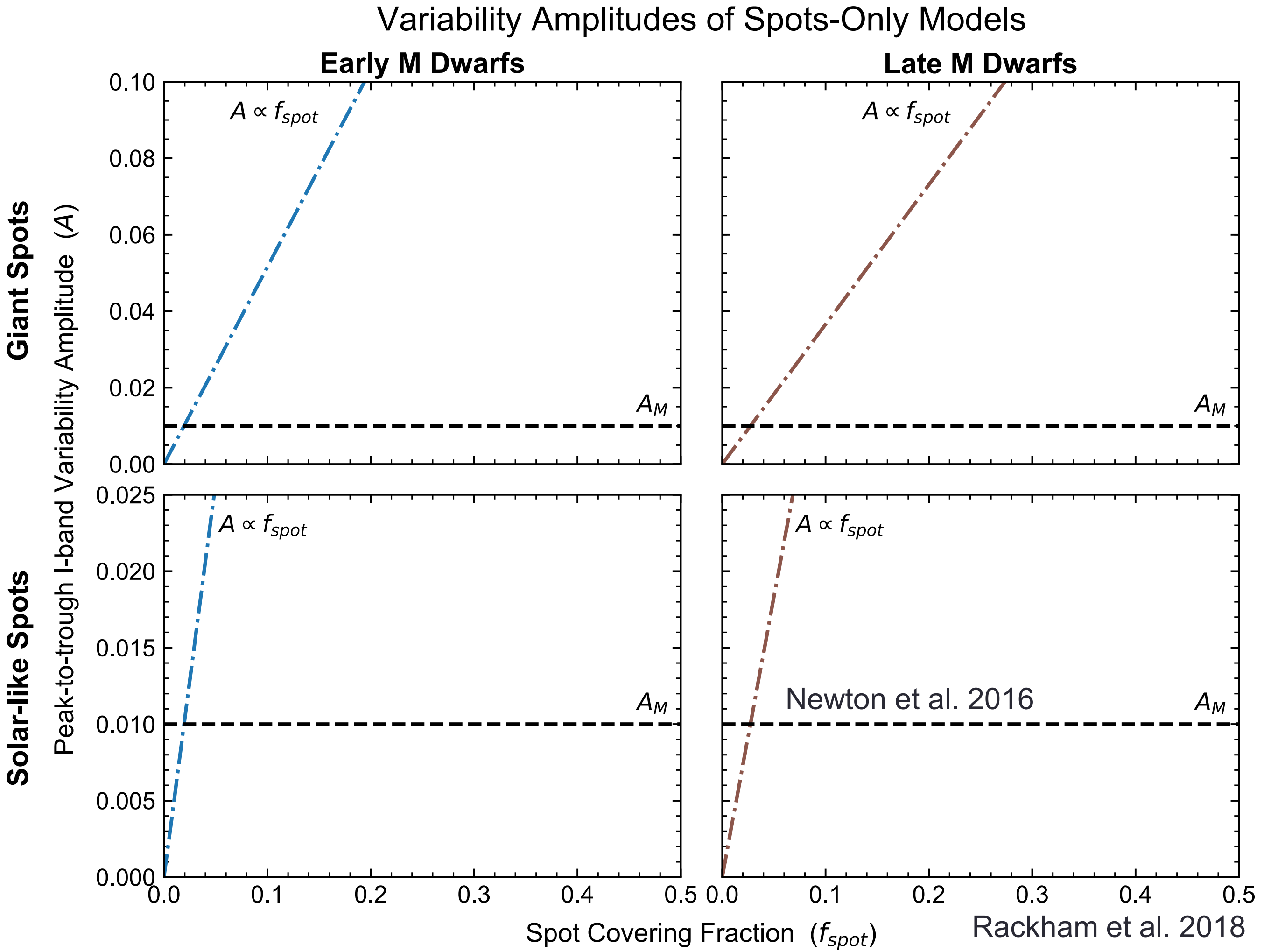
Active regions can be hidden from variability monitoring

- Rotate model photospheres with active regions, record variabilities
- Repeat 100 x

Rackham, Apai & Giampapa 2018

Covering fractions





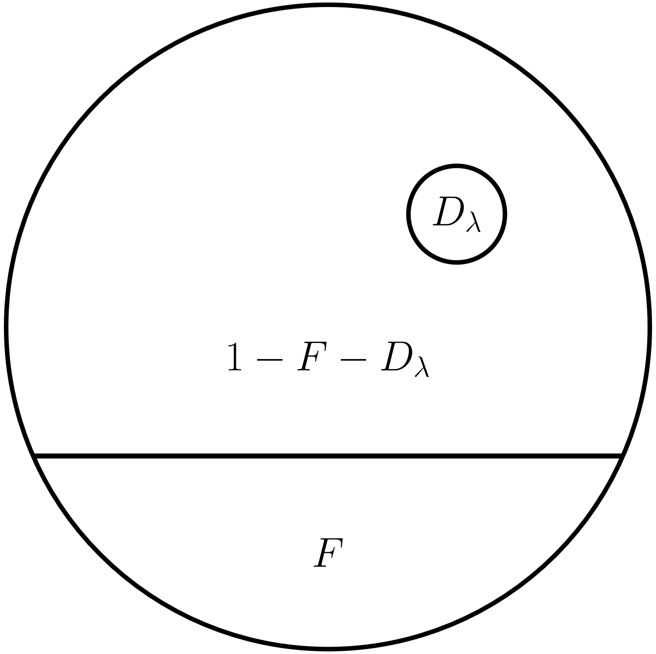
Rackham et al. 2018

How will active regions affect high-precision transmission spectra of M-dwarf planets?

Composite Photosphere and Atmospheric Transmission Model

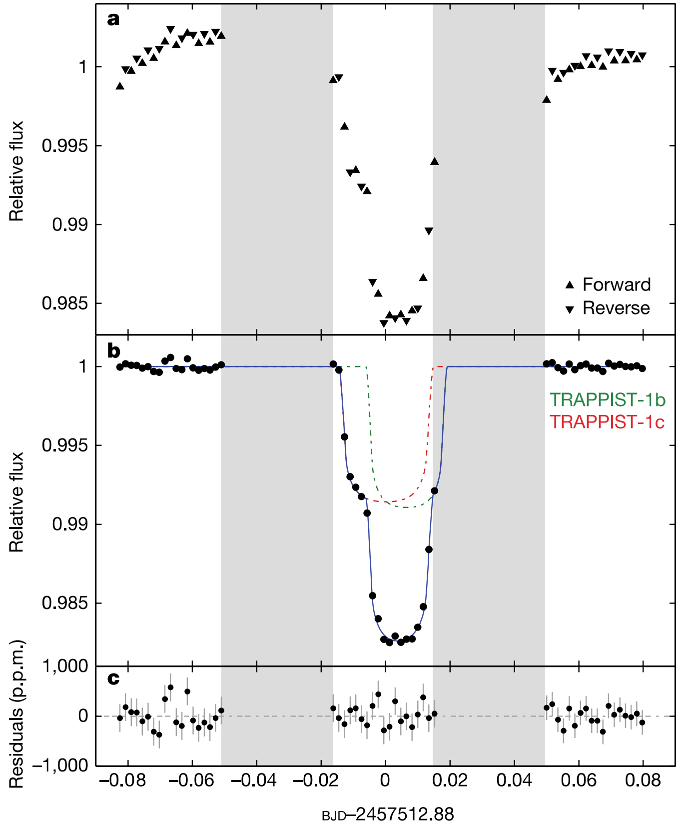
$$D_{obs,\lambda} = \varepsilon_\lambda D_\lambda = \varepsilon_\lambda (R_p/R_s)^2$$

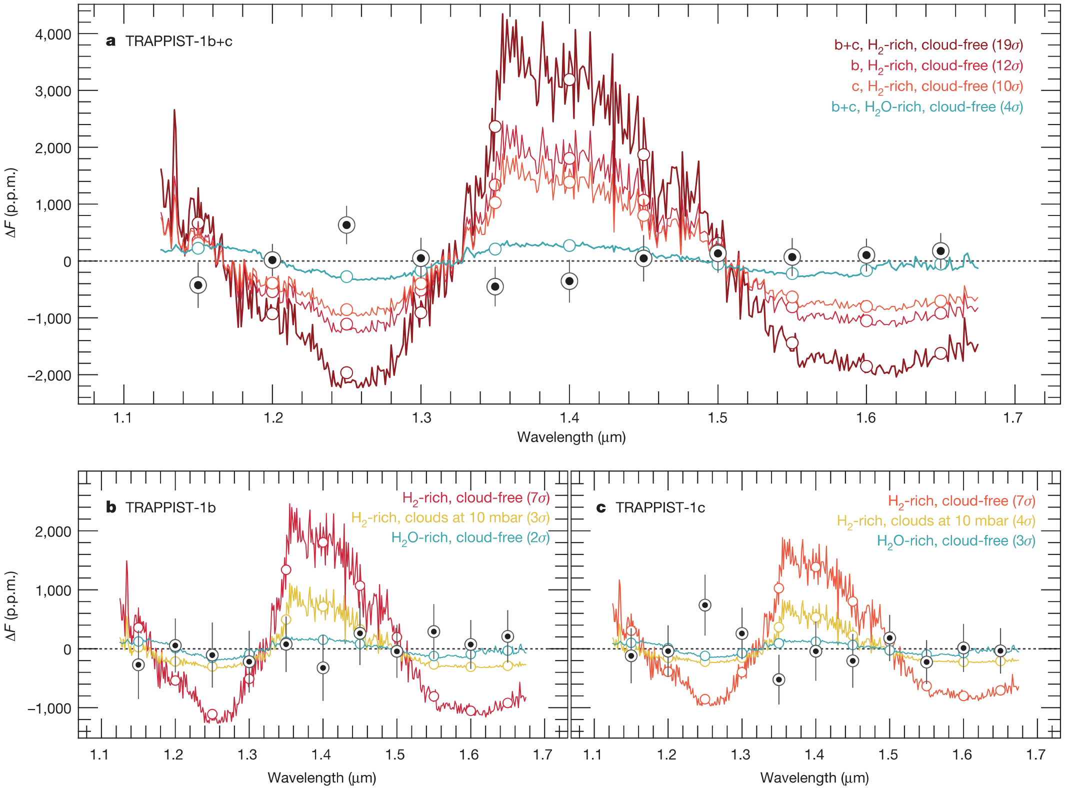
$$\varepsilon_\lambda = \frac{1}{1 - F_{het}\left(1 - \frac{S_{het}}{S_{phot}}\right)}$$



Rackham et al. 2017, 2018

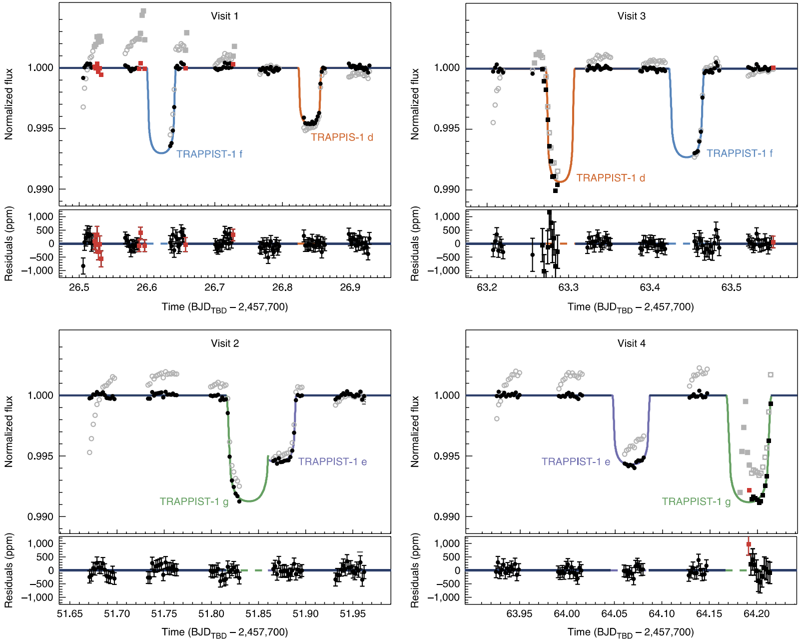
A combined transmission spectrum of TRAPPIST-1b and c from HST

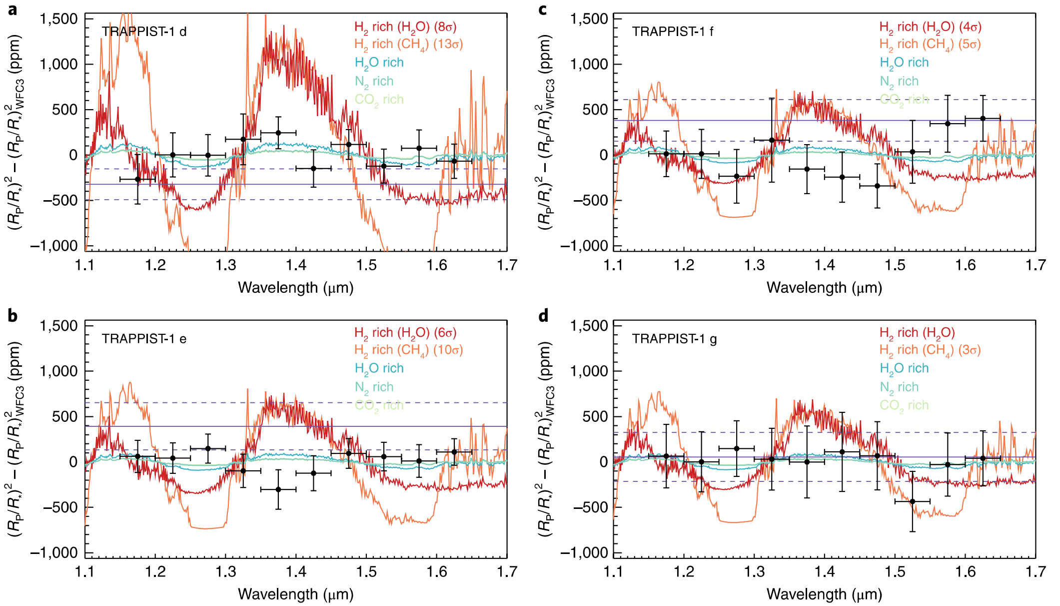




de Wit et al. 2016

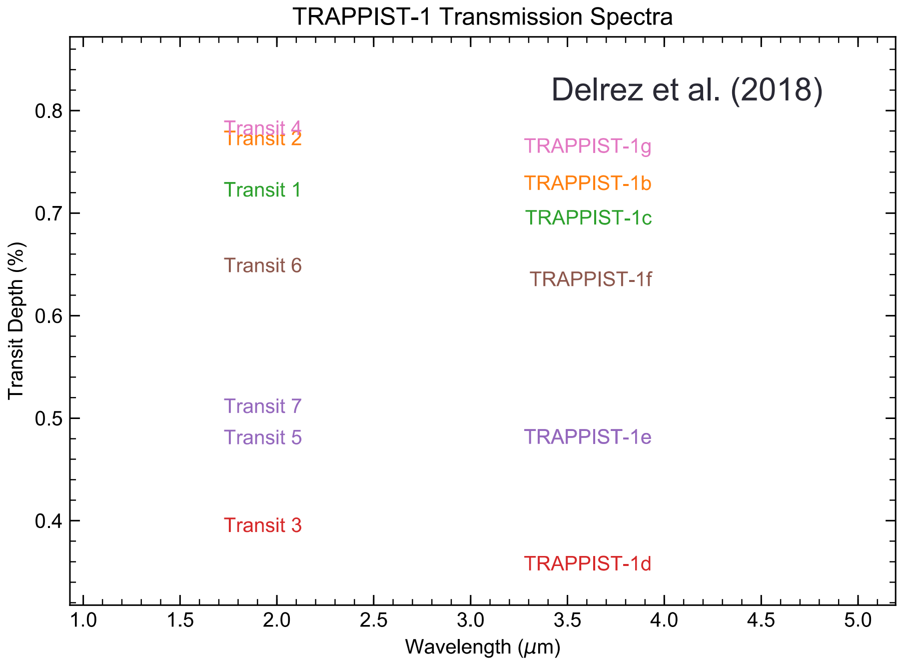
HST transmission spectra of TRAPPIST-1d–g

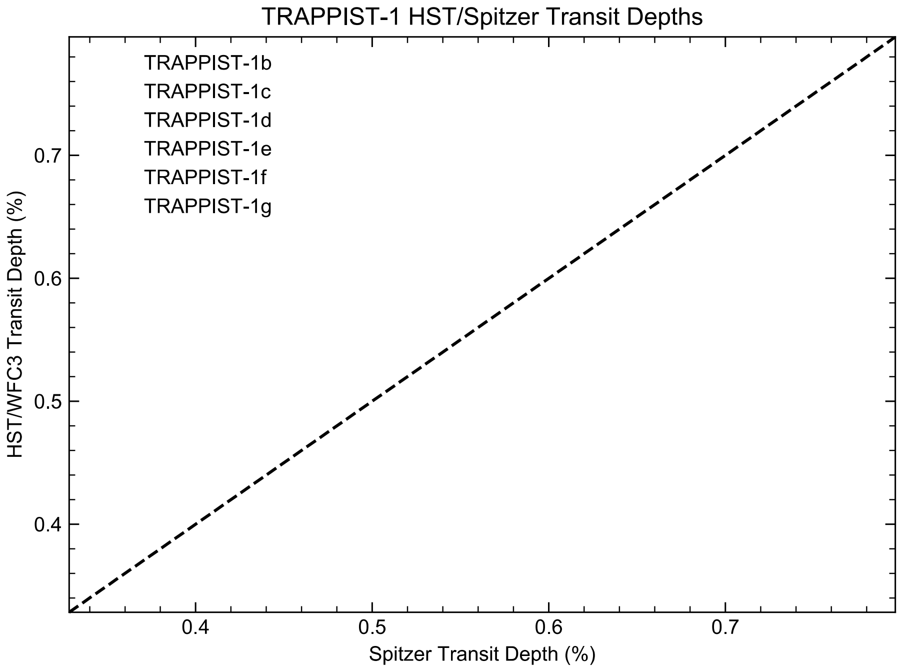




de Wit et al. 2018

Independent analysis of TRAPPIST-1 transmission spectra





Hints of features?

HST depths are larger

Zhang, Zhou, **Rackham**, and Apai, *under review*