

Transmission Spectroscopy of the Atmosphere of TRAPPIST-1g using Subaru / MOIRCS and Gemini / GMOS-N

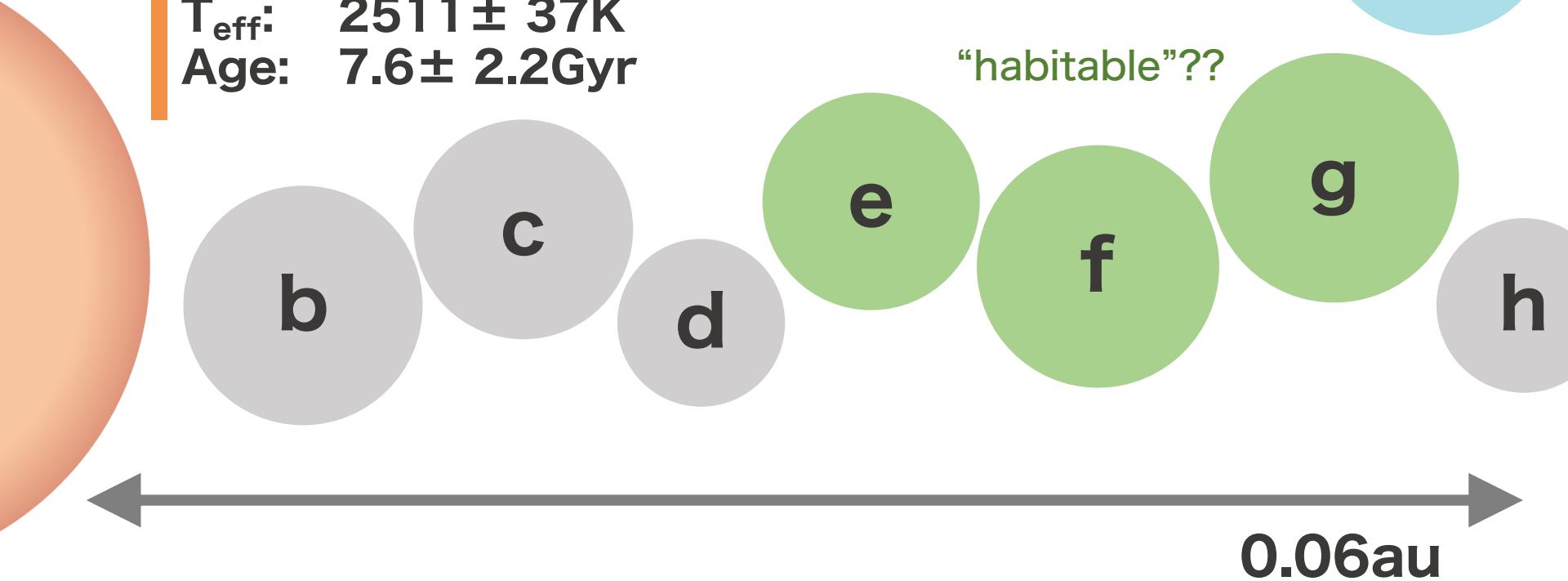
Mayuko Mori University of Tokyo

In collaboration with

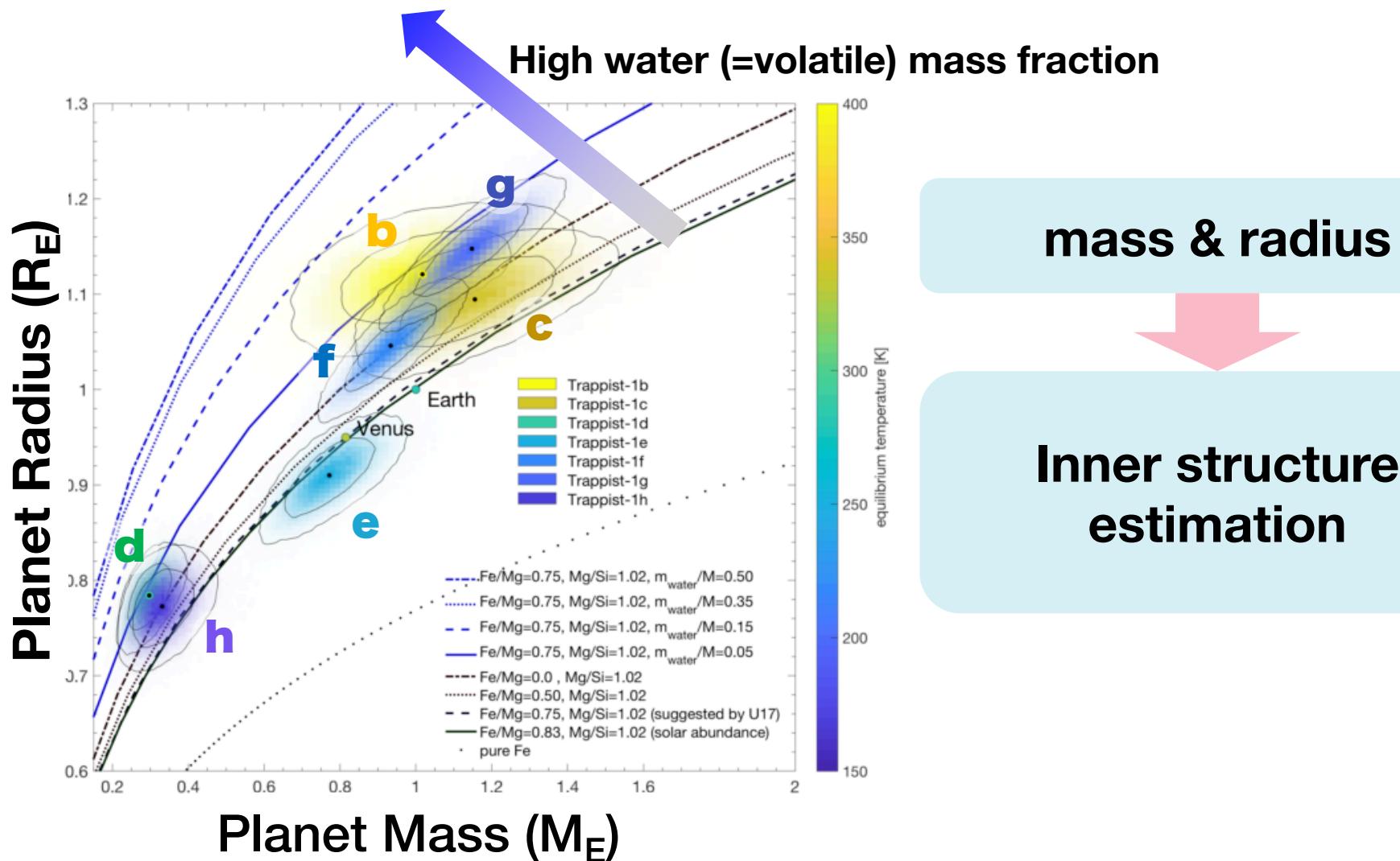
**Akihiko Fukui, Norio Narita, John Livingston, Hannu Parviainen,
Yui Kawashima, Kiyoie Kawauchi, Motohide Tamura**

TRAPPIST-1 system

Dist: 12.14 ± 0.12 pc
Mass: $0.089 \pm 0.006 M_{\text{sun}}$
Type: M8V
 T_{eff} : 2511 ± 37 K
Age: 7.6 ± 2.2 Gyr



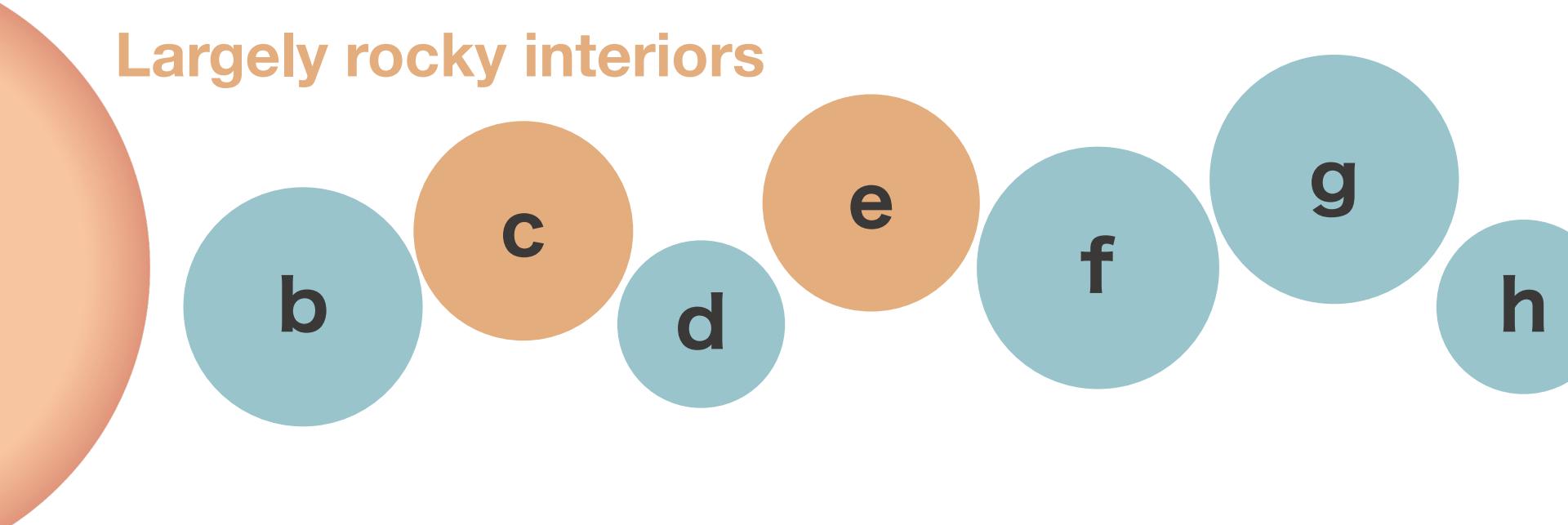
The nature of the TRAPPIST-1 exoplanets (Grimm et al. 2018)



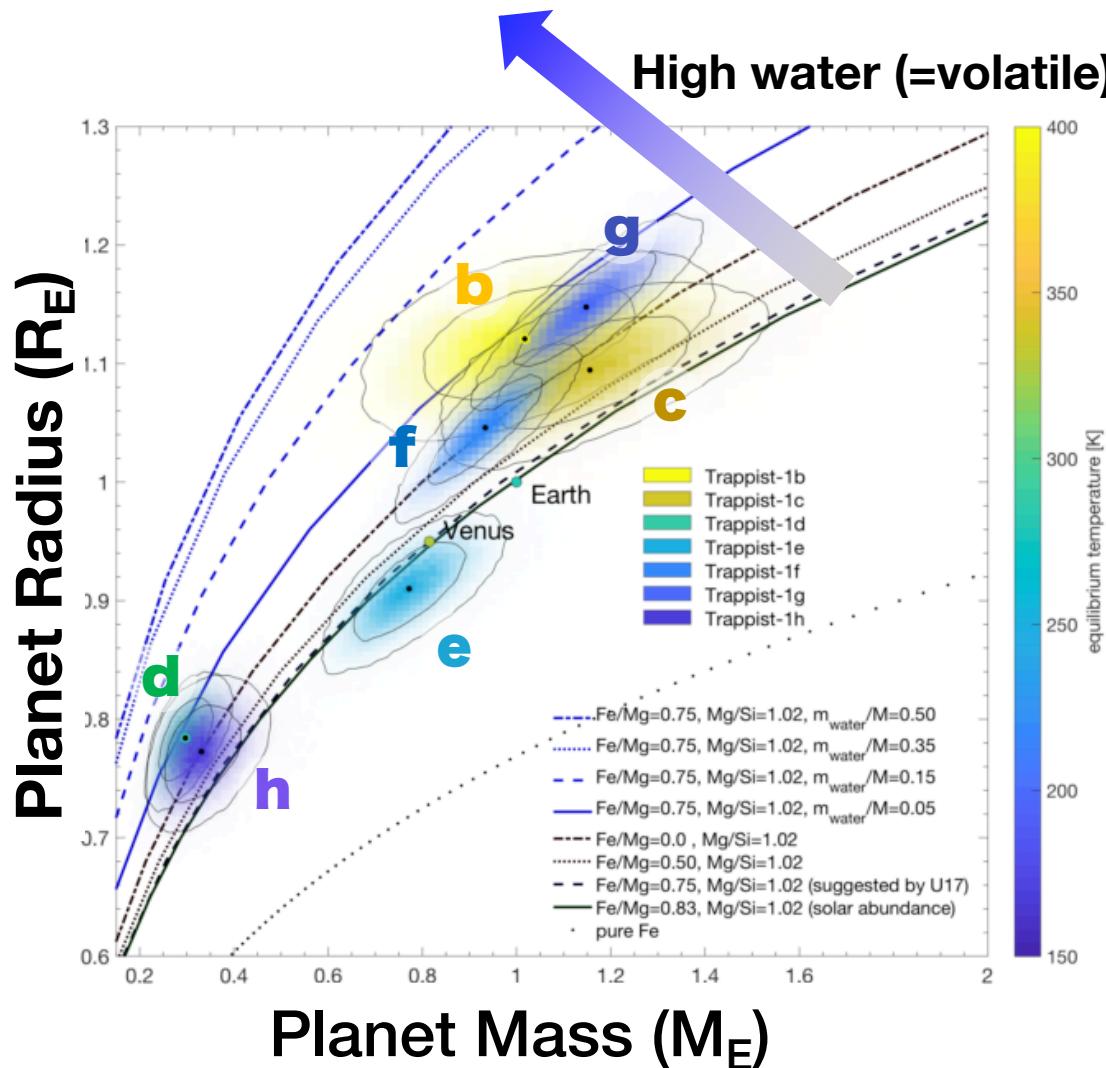
The nature of the TRAPPIST-1 exoplanets (Grimm et al. 2018)

Rock + Envelopes of volatiles
(water mass fractions <5%)

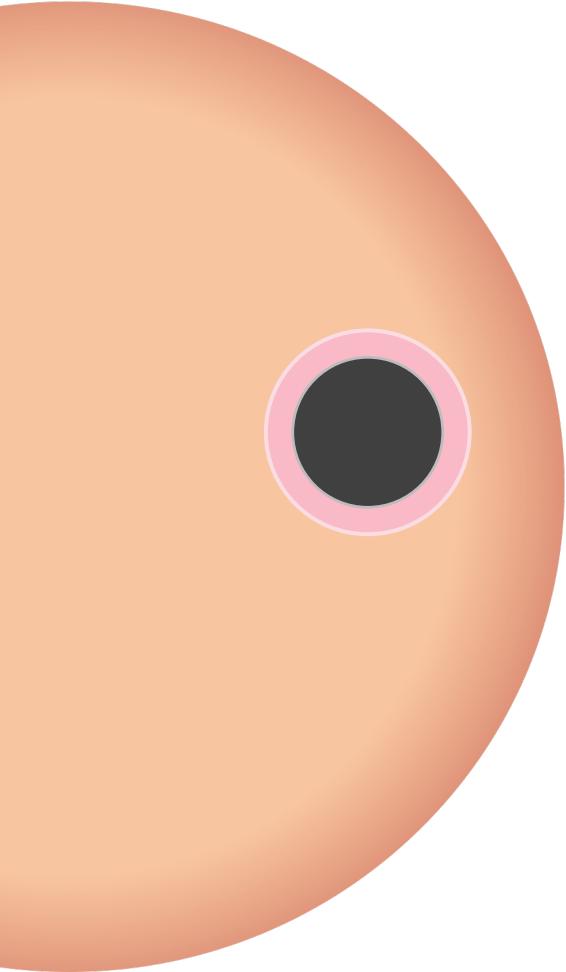
Largely rocky interiors



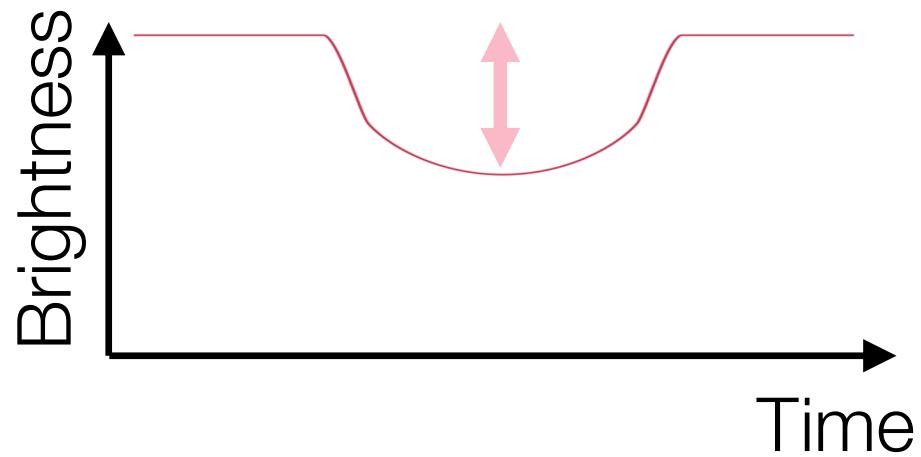
The nature of the TRAPPIST-1 exoplanets (Grimm et al. 2018)



Transmission Spectroscopy

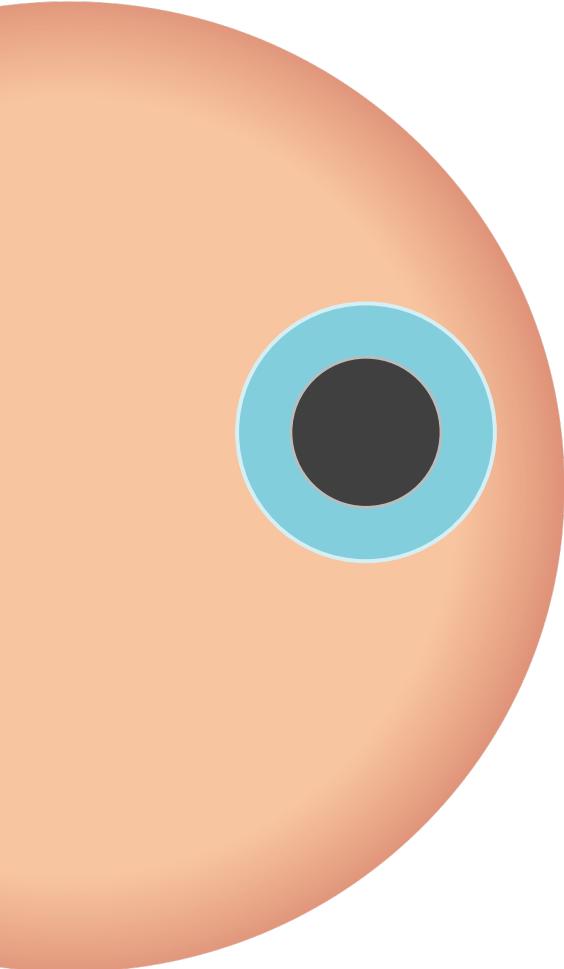


Transit Light Curve

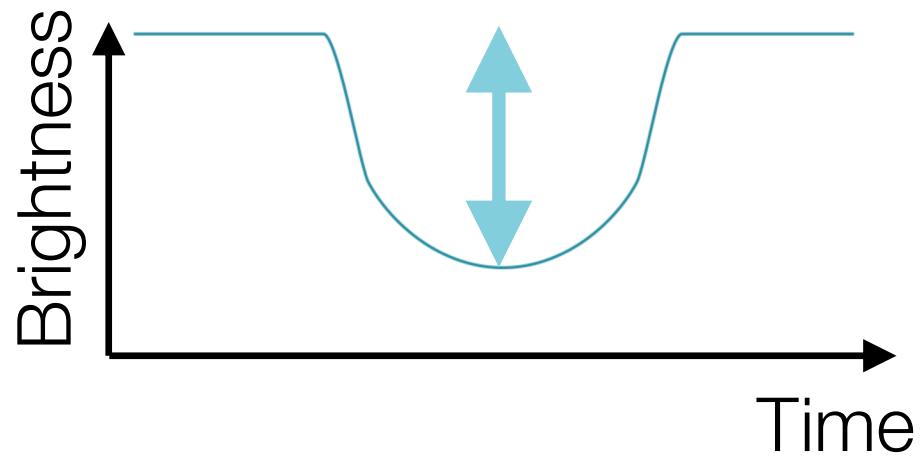


$$\text{Transit Depth} \approx (R_p/R_s)^2$$

Transmission Spectroscopy

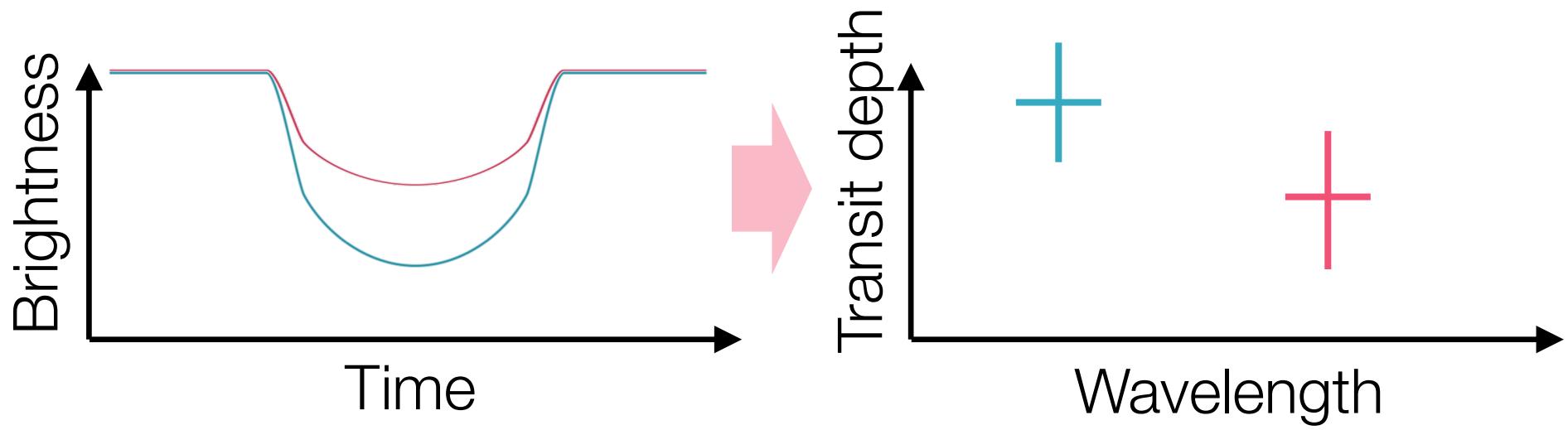


Transit Light Curve

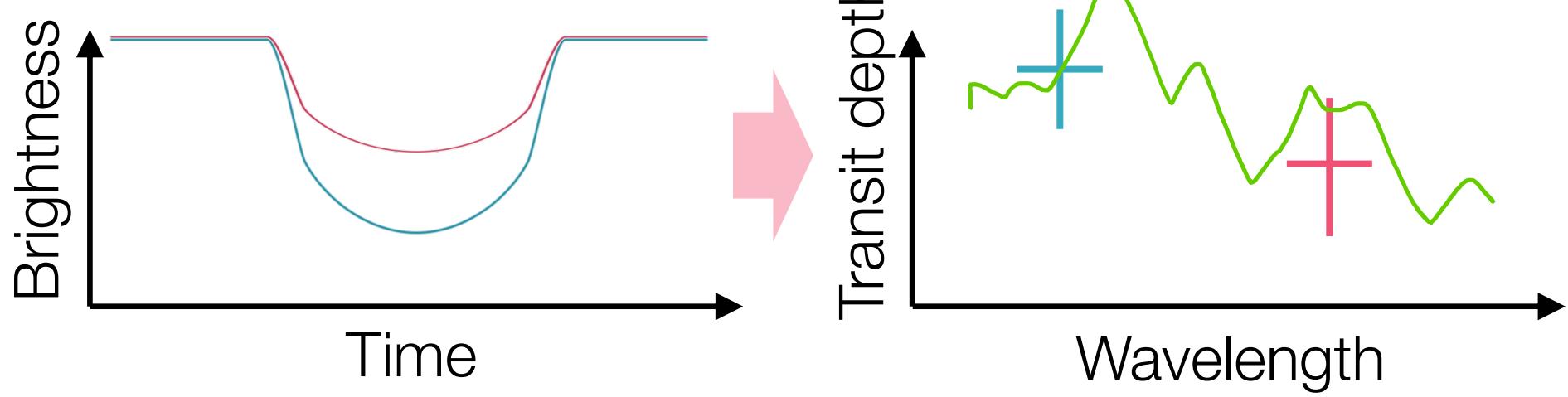


$$\text{Transit Depth} \approx (R_p/R_s)^2$$

Transmission Spectroscopy

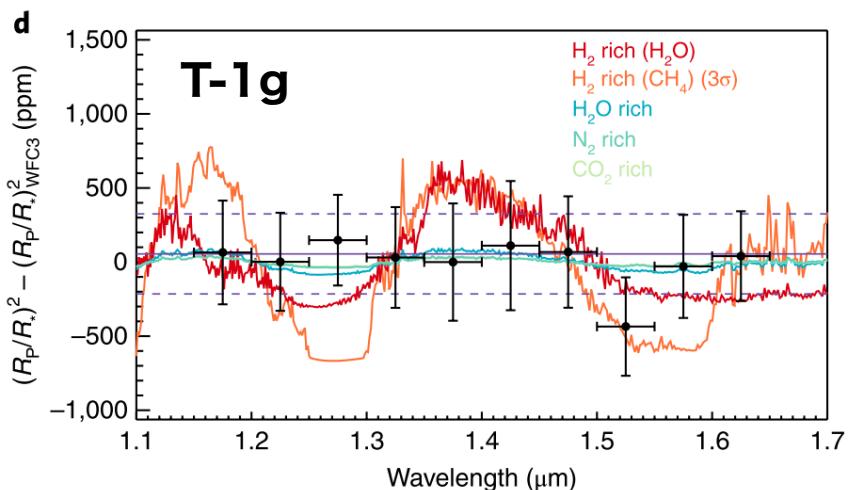
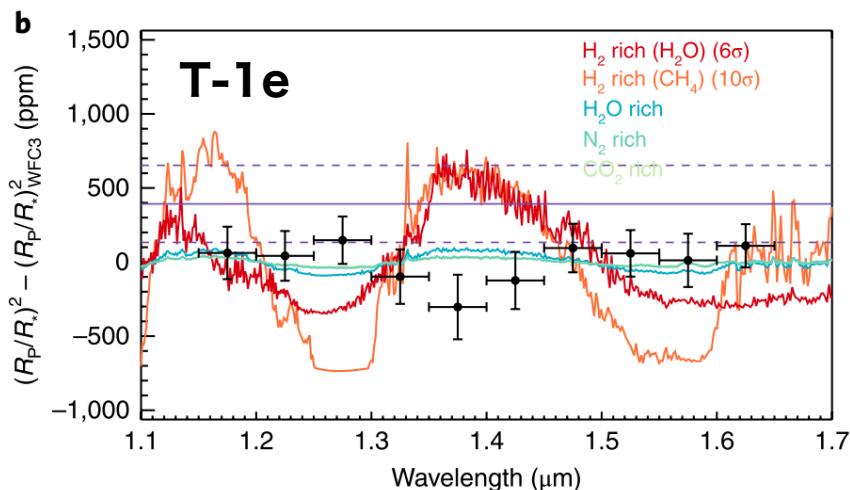
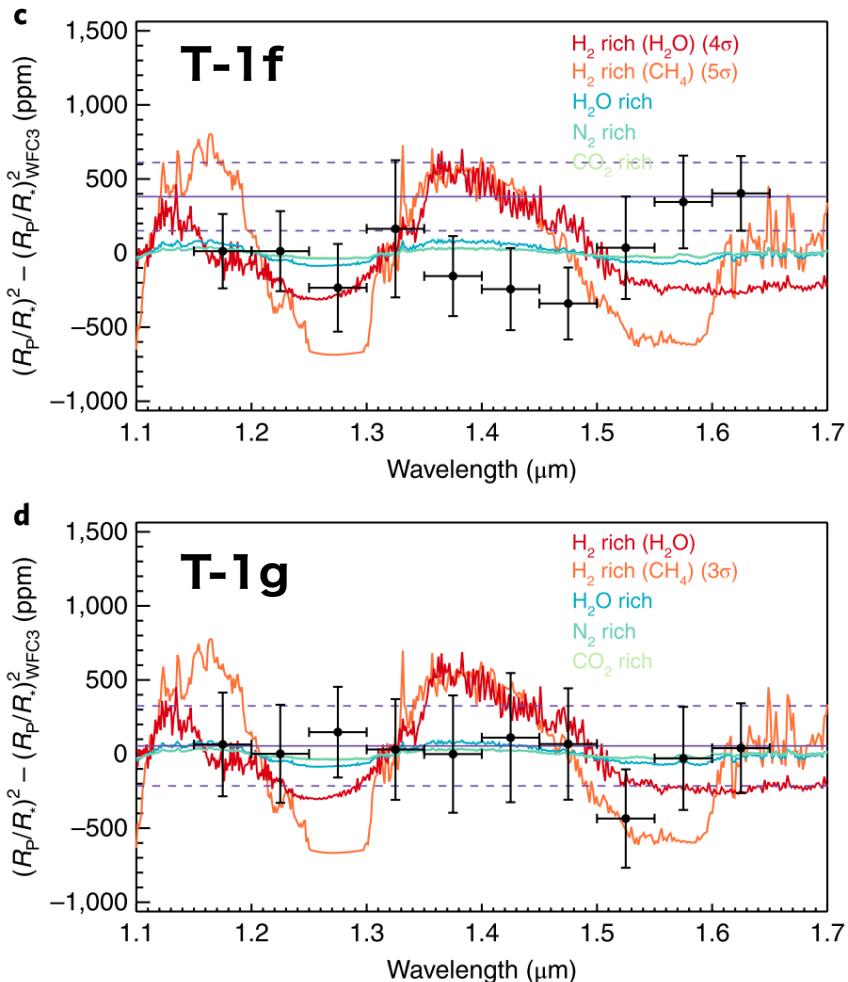
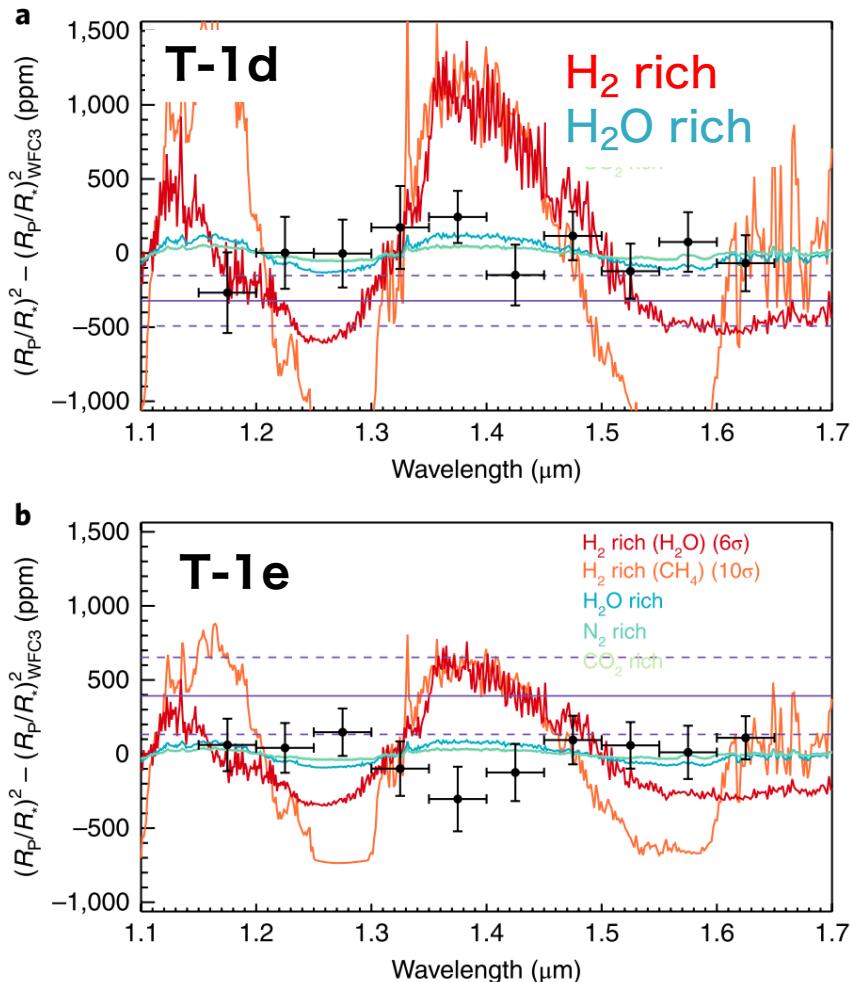


Transmission Spectroscopy



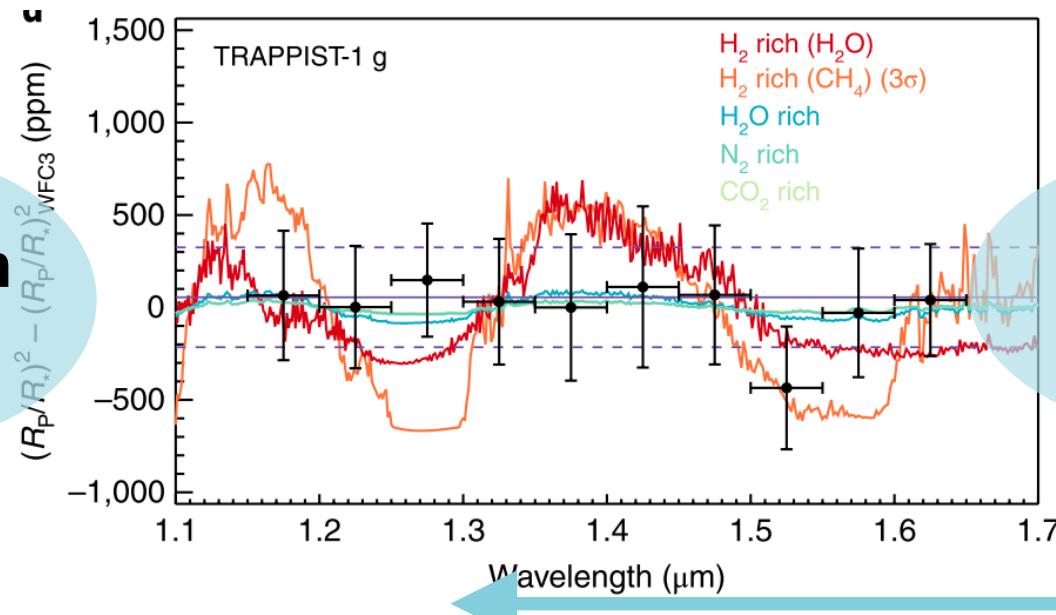
Atmospheric reconnaissance of the habitable-zone Earth-sized planets orbiting TRAPPIST-1 (de Wit et al. 2018)

Spectroscopy with HST / WFC3 • G141 grism



Purpose of the study

To derive transmission spectrum in wider wavelength range to restrict the major component of the **TRAPPIST-1g's** atmosphere



Photometry @ optical

Spectroscopy @ 2 μm (IR)

Observation

Observed by Dr. Akihiko Fukui et al. on Sep 1st, 2017



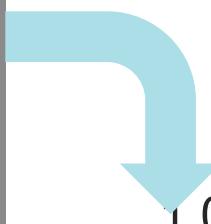
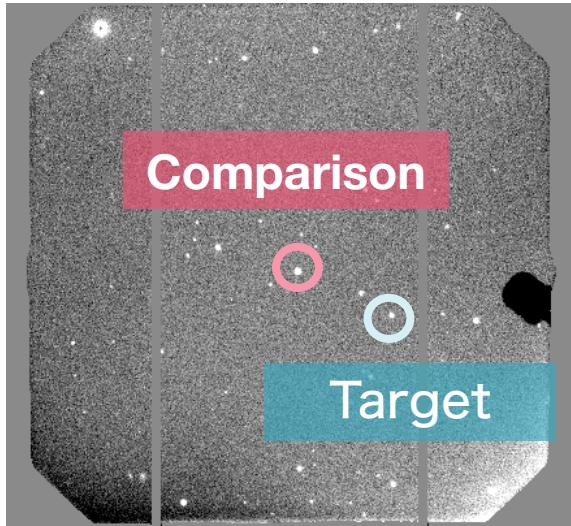
Gemini North / GMOS
8.1m Telescope
Photometry
@ r-band (562-698 nm)

Subaru / MOIRCS
8.2m Telescope
Spectroscopy
@ 1300-2300 nm

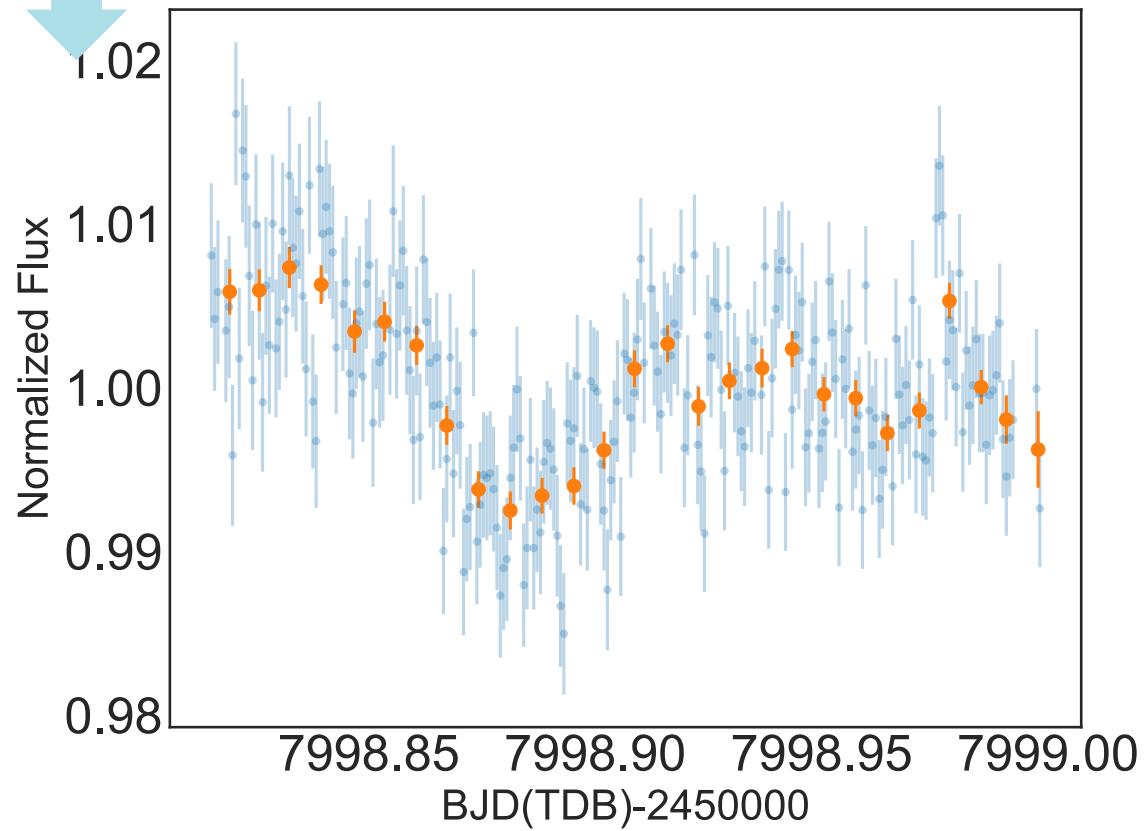
©University of Hawaii

Data Analysis (GMOS-N) - Photometry

Field of View



reduction,
photometry



Data Analysis (MOIRCS) - Spectroscopy

Field of View

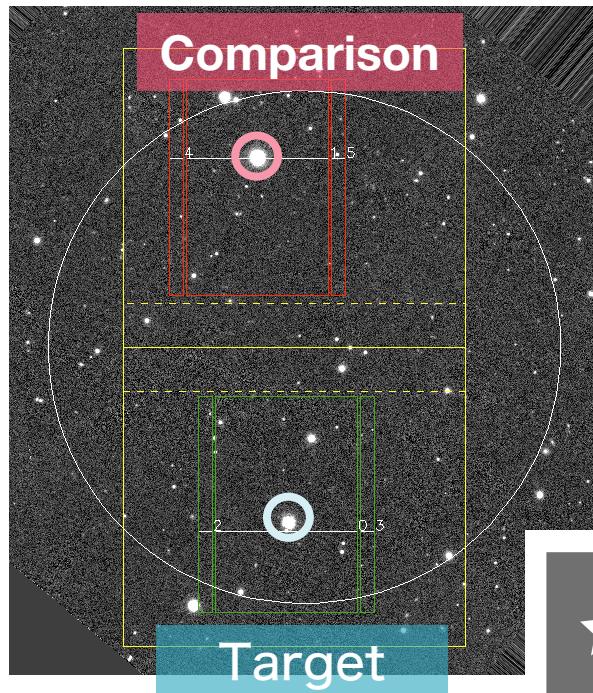
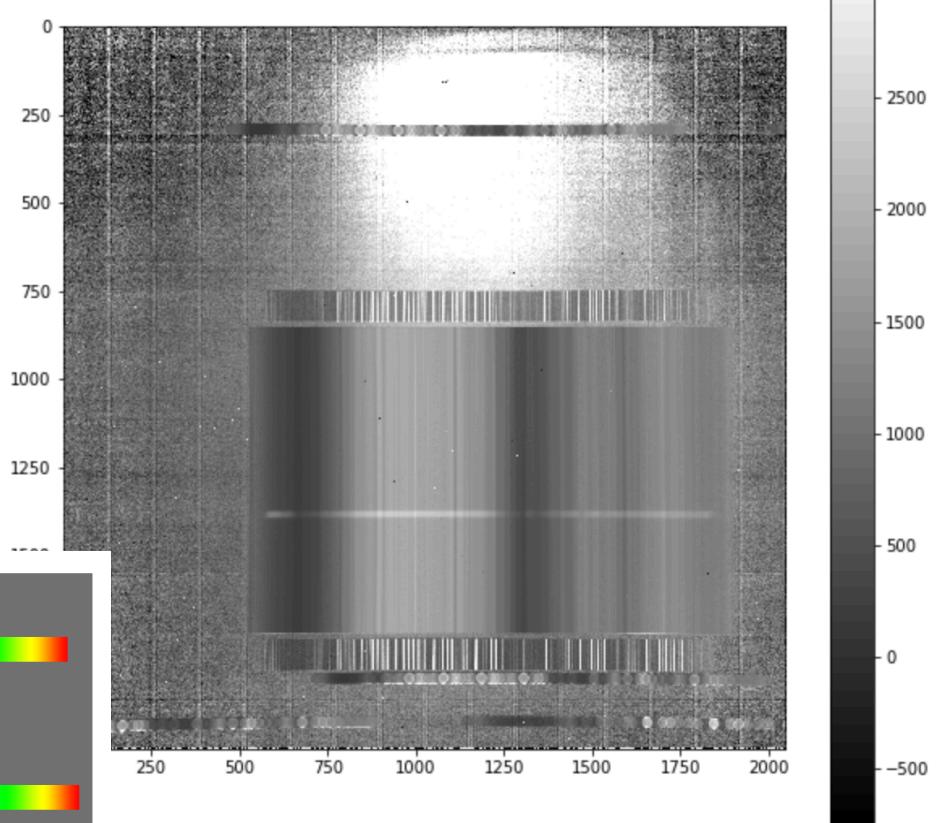
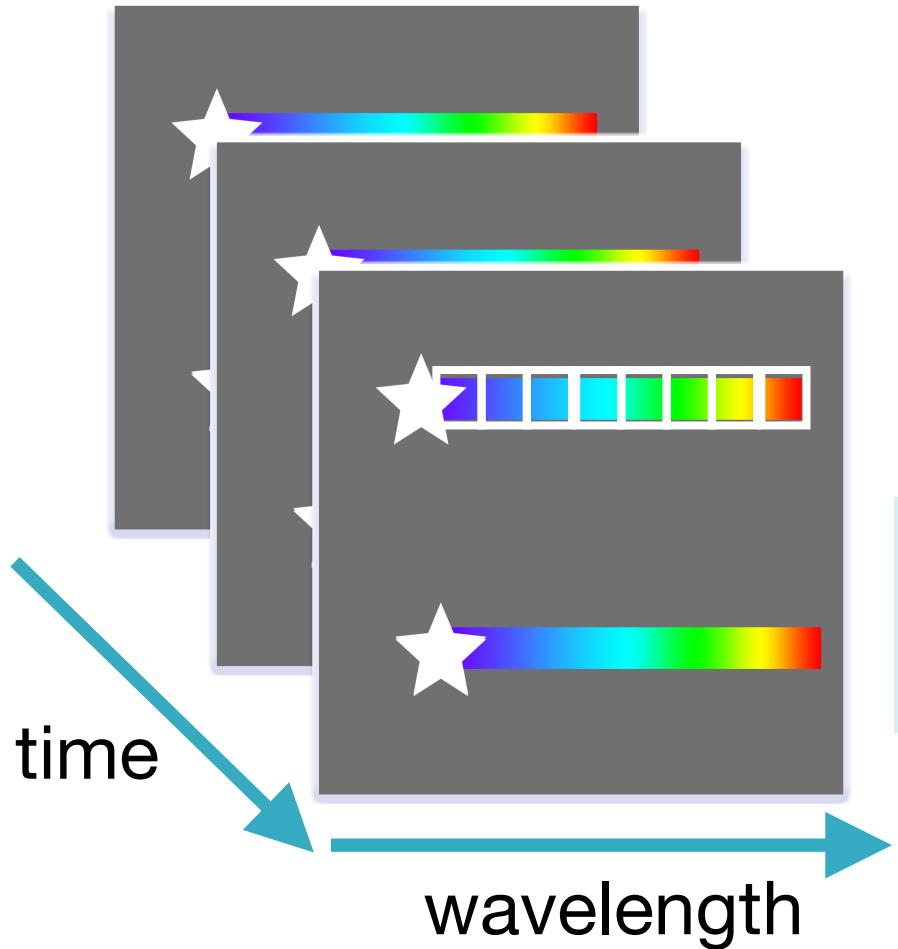


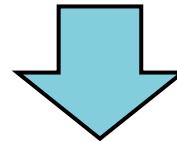
Image on each detector



Data analysis (MOIRCS) - Spectroscopy

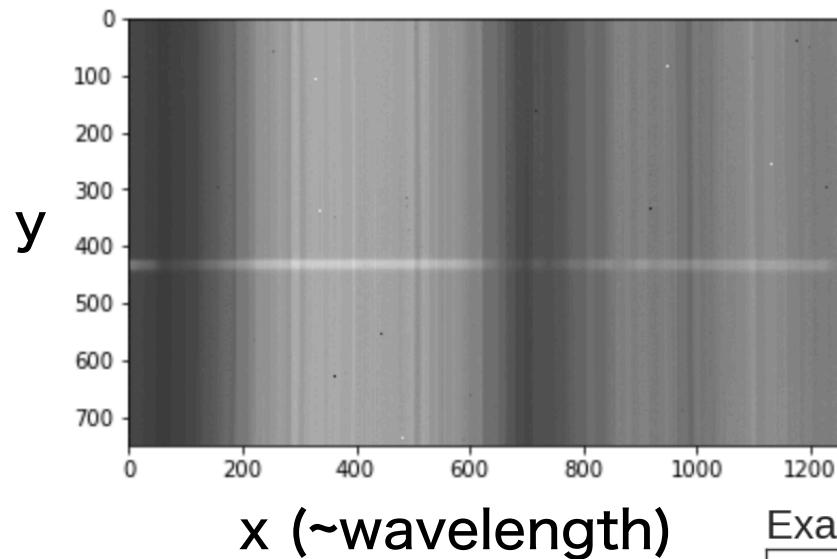


Integrate with respect to
wavelength region

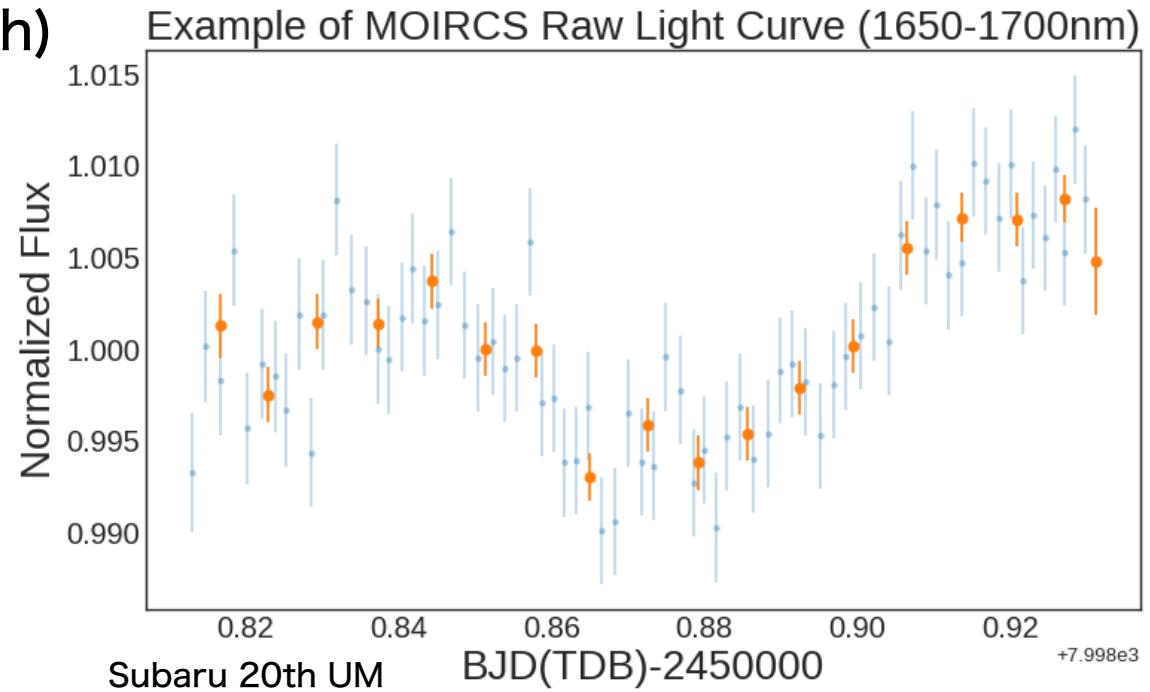


Light Curve
per wavelength

Data Analysis (MOIRCS) - Spectroscopy

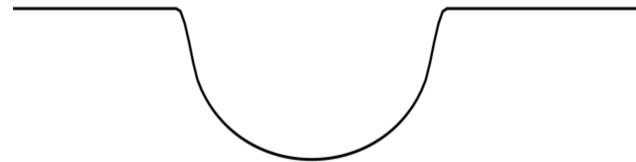


Reduction
Aperture photometry
Wavelength Calibration



Data Analysis – Model Fitting

Transit model



Trend model



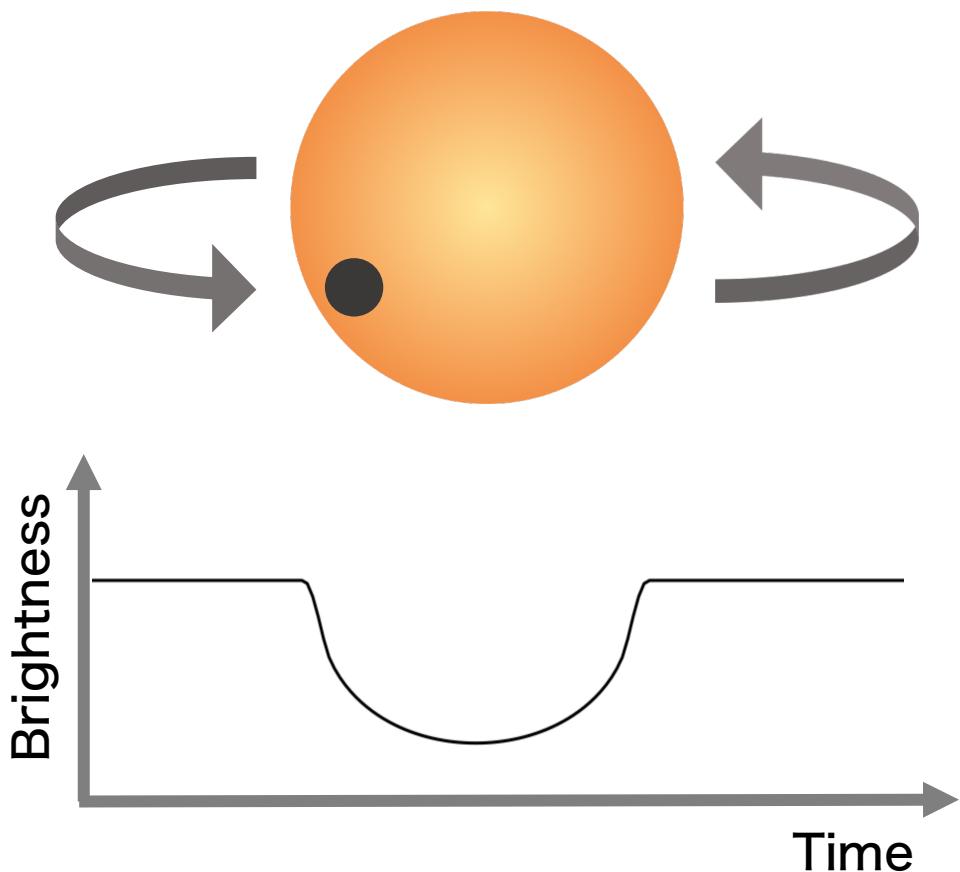
Calculating the likelihood of the data
given each model



Parameter estimation
with Markov Chain Monte Carlo method

Data Analysis – Transit Model

(PyTransit by Parviainen)



Parameters

Center time T_c

Radius ratio R_p / R_s

Semimajor axis a / R_s

Impact parameter b

Limb Darkening
Parameter (u_1, u_2)

From theoretical calculation
(LDTK by Parviainen)

Data Analysis – Trend Model (Gaussian Process)

Hyper parameter

$$\text{kernel} = \alpha^2 \exp\left(-\frac{dx^2}{2\tau^2}\right)$$

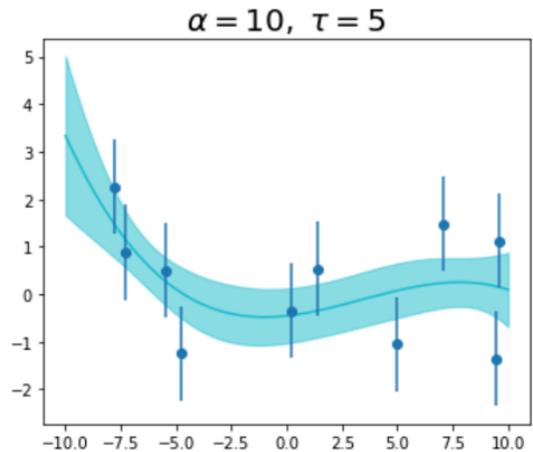
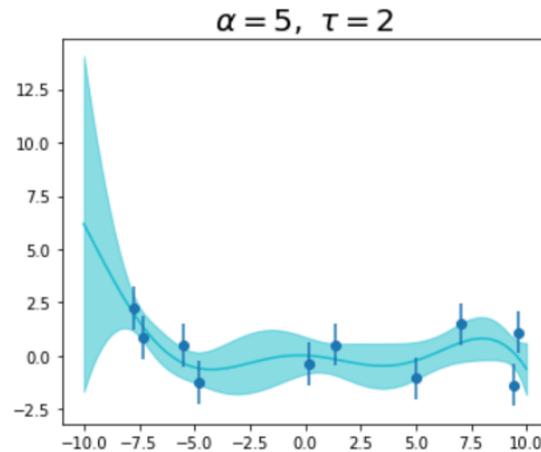


$$C = \begin{pmatrix} var[x_1] & cov[x_1, x_2] & \dots & cov[x_1, x_n] \\ \vdots & var[x_2] & & cov[x_2, x_n] \\ cov[x_n, x_1] & cov[x_n, x_2] & \ddots & var[x_n] \end{pmatrix}$$

Covariance matrix

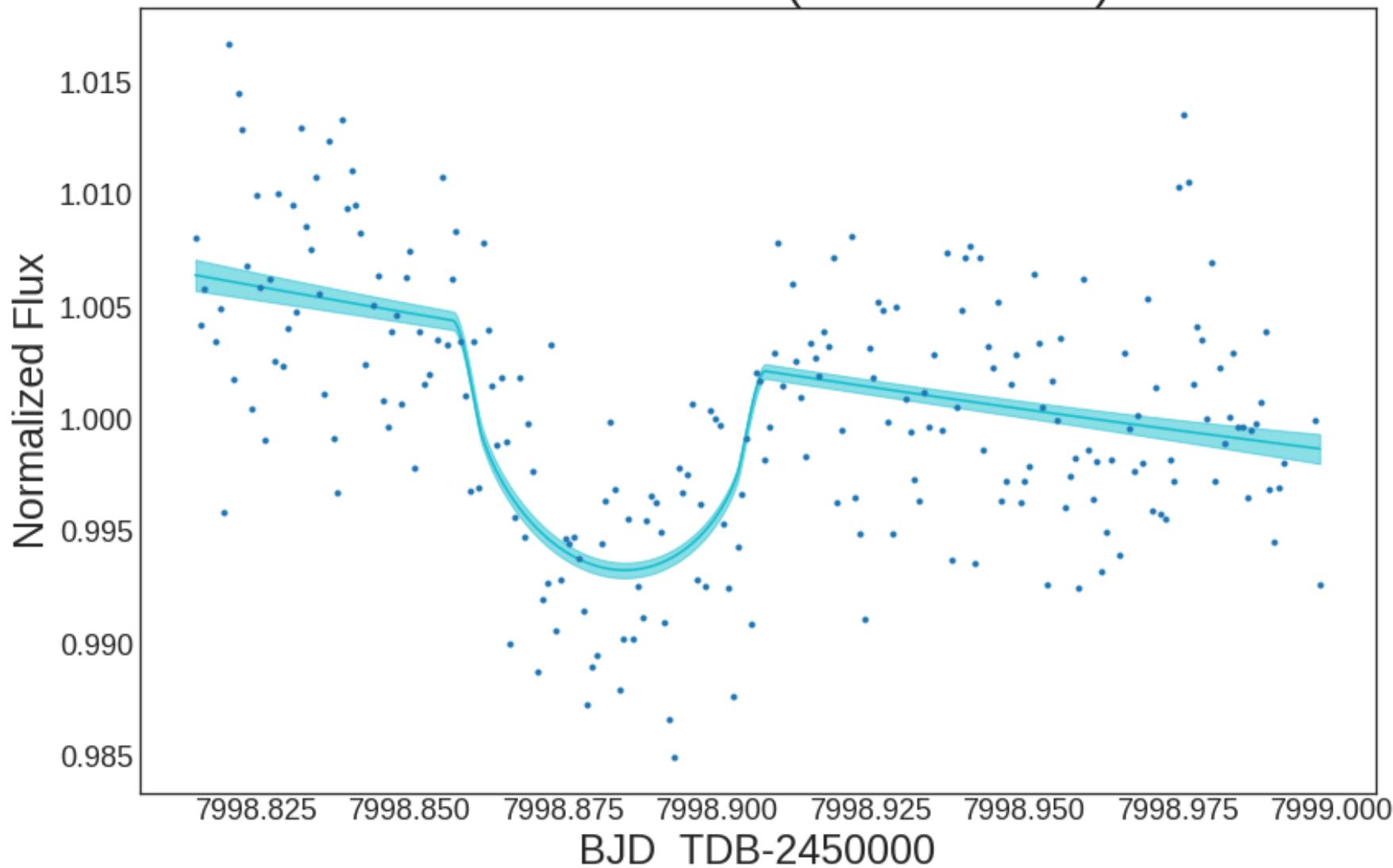


Trend

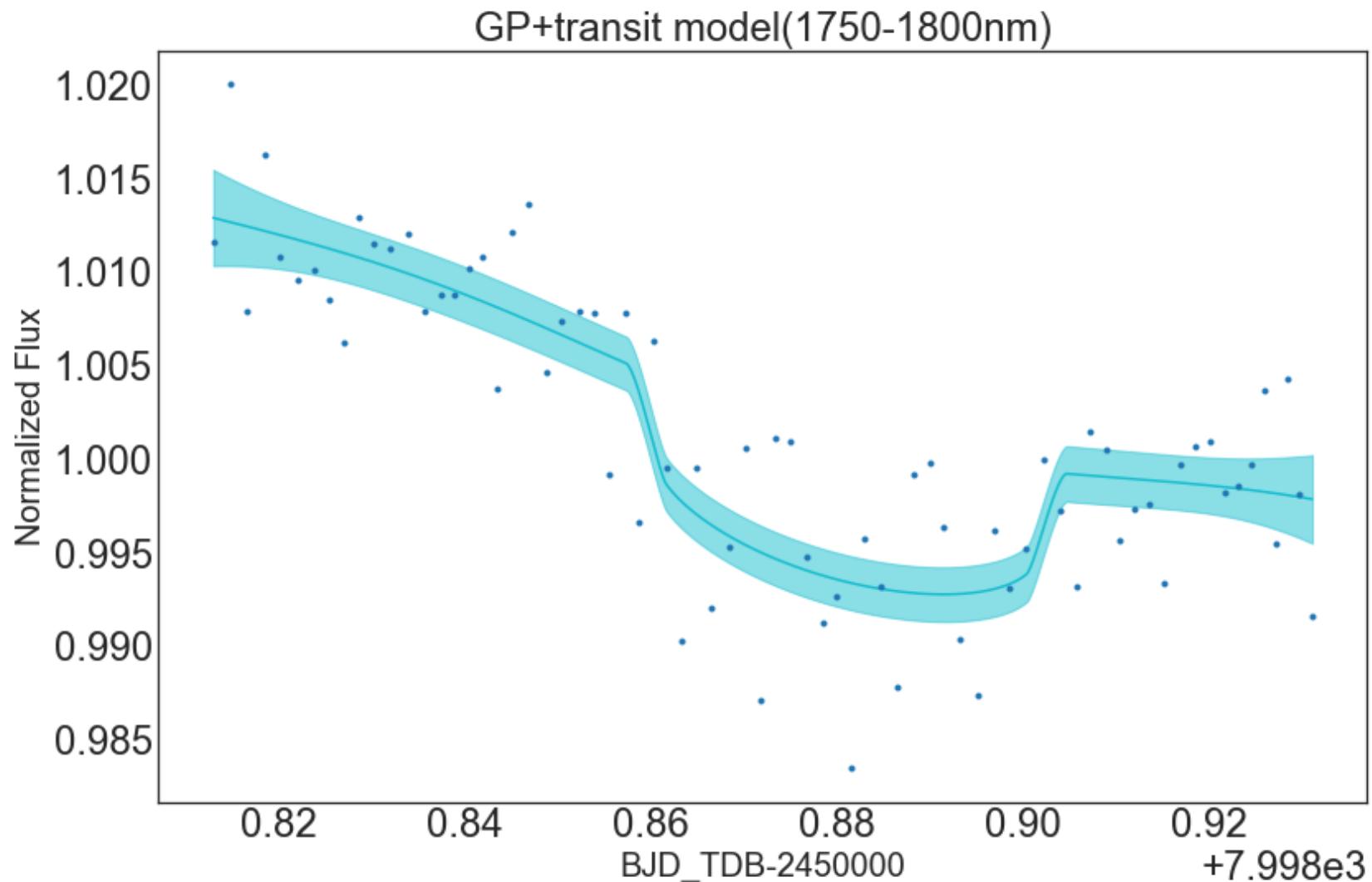


Result (GMOS-N) - Photometry

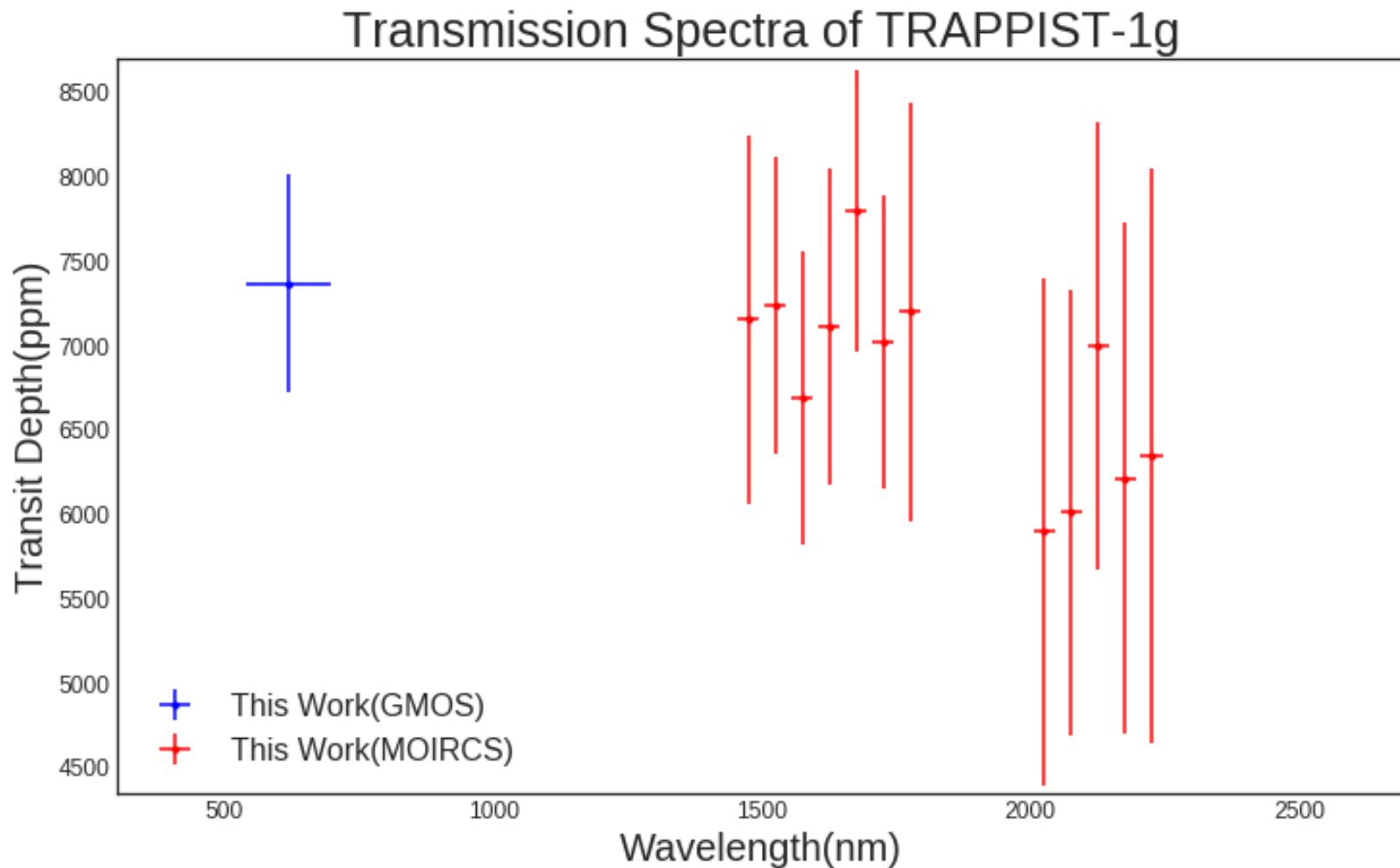
GP+transit model(GMOS-rband)



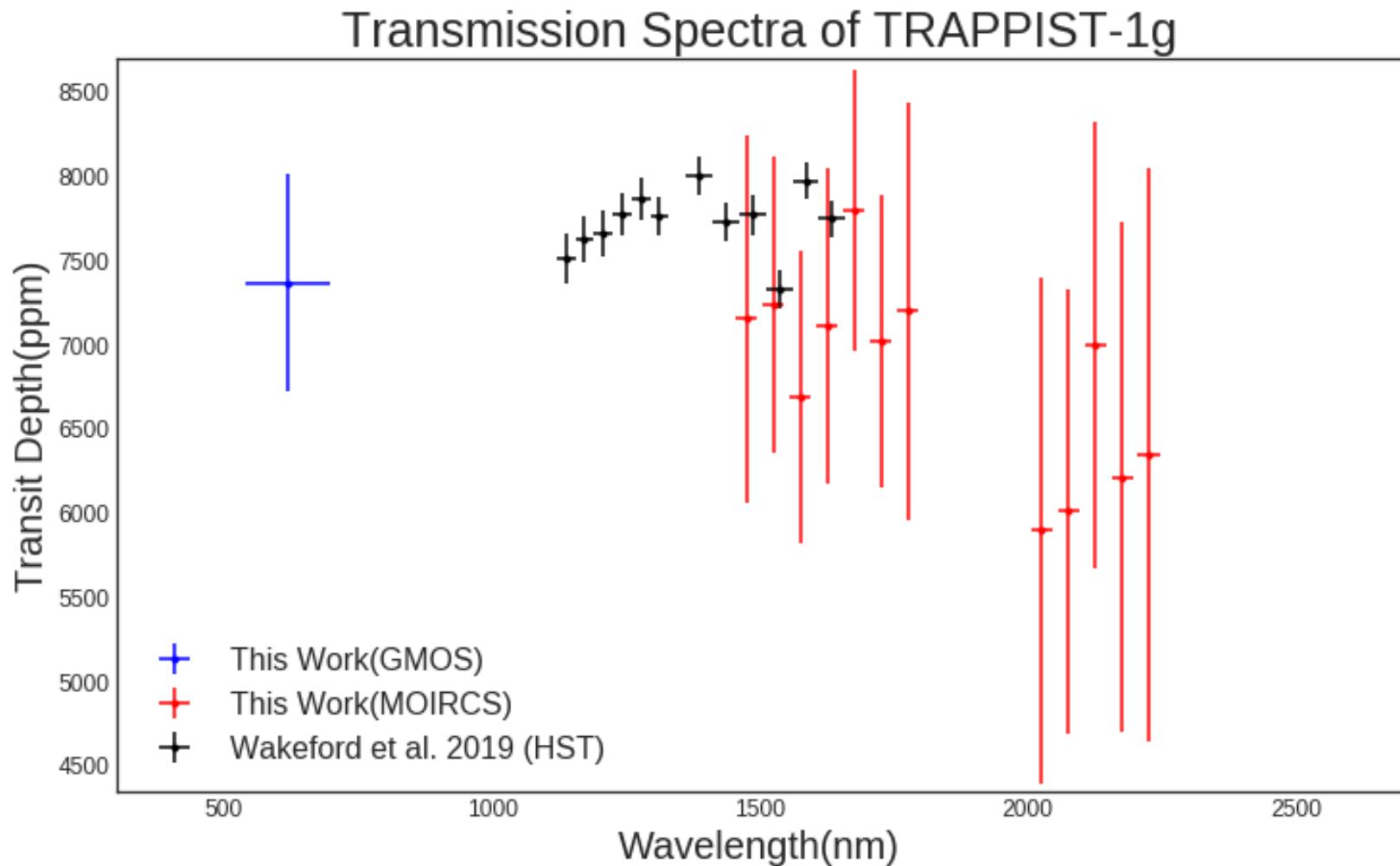
Result (MOIRCS) - Spectroscopy



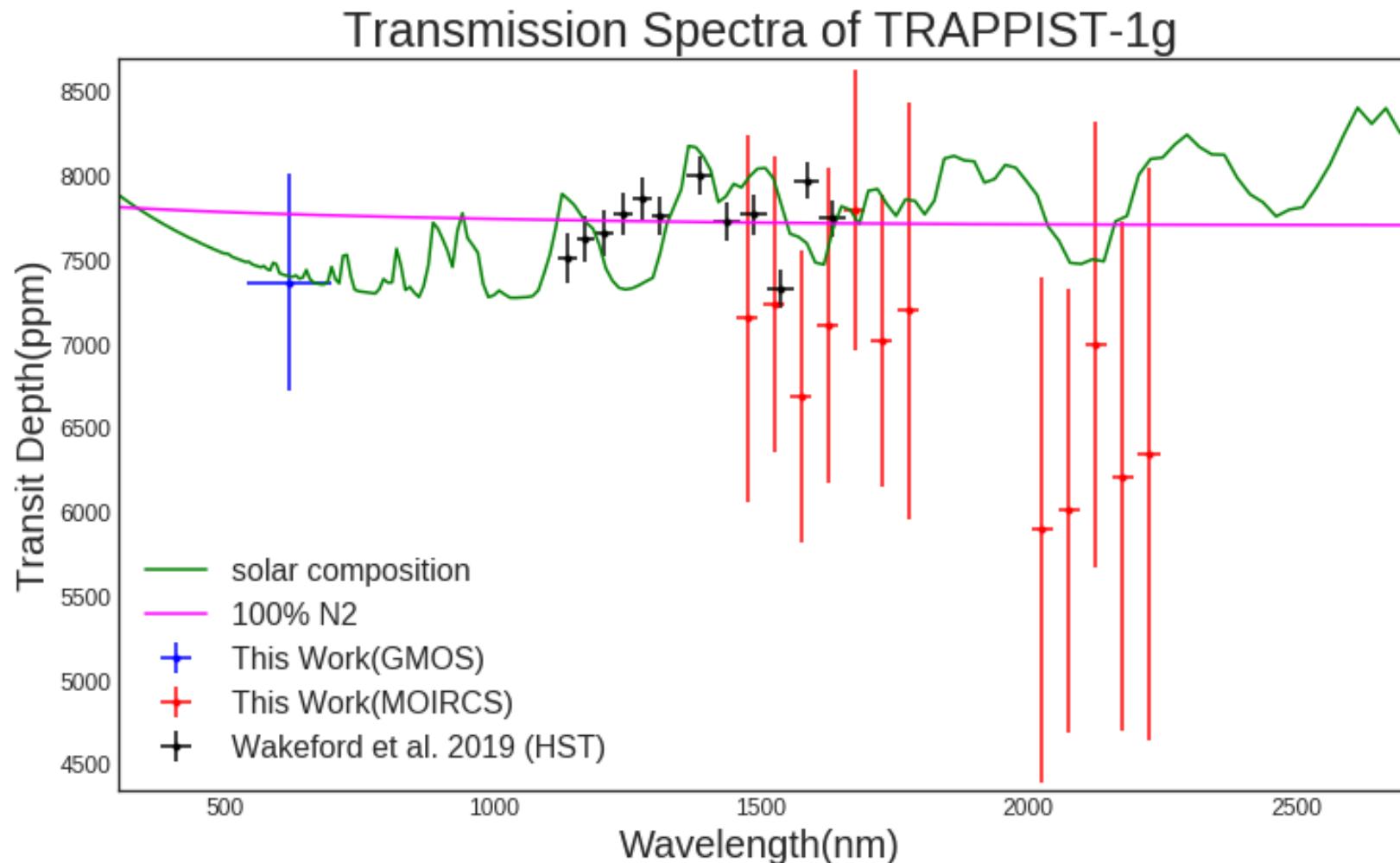
Result – Transmission Spectra



Result – Transmission Spectra



Result – Transmission Spectra

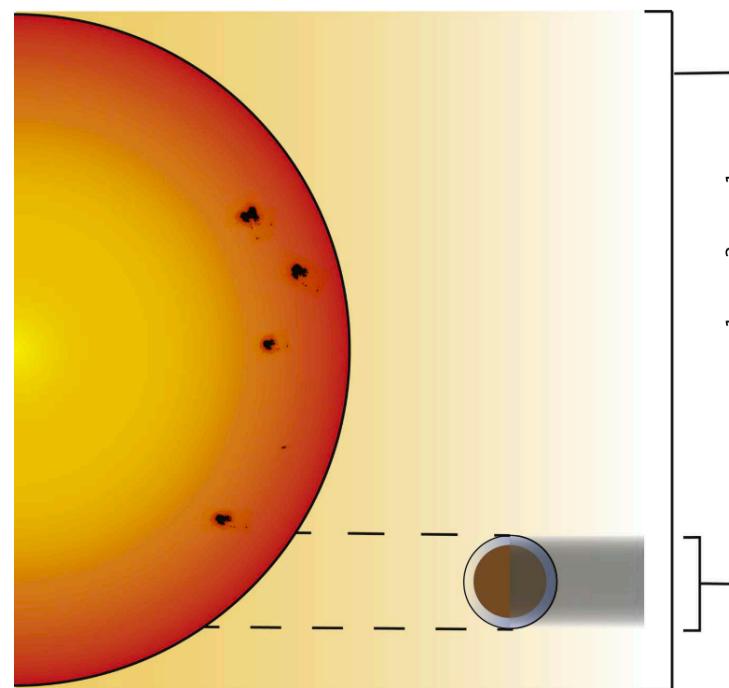


Results

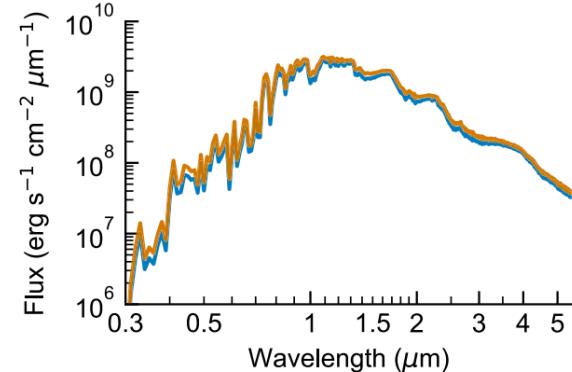
- We got the relatively **flat & shallower** transmission spectrum of TRAPPIST-1g atmosphere, and it was consistent with the results using HST.
- The estimated errors were bigger than predicted.
(Probably because of the observational setting.)
- It was the **first** observational result of TRAPPIST-1g transit in r-band from ground based telescope.

The Effect of Inhomogeneous Stellar Surface

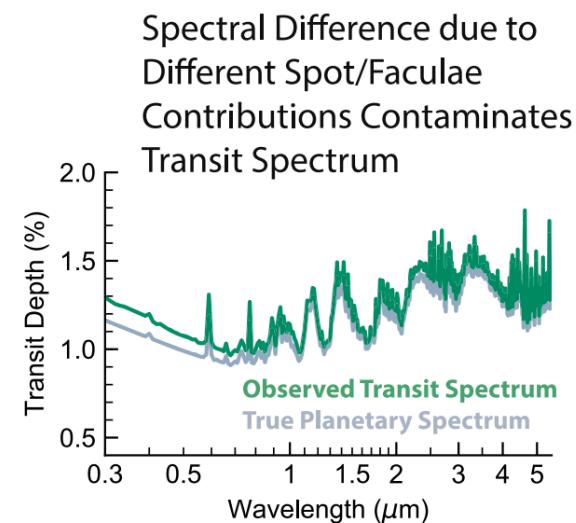
Transit Light Source Effect (Rackham et al. 2018)

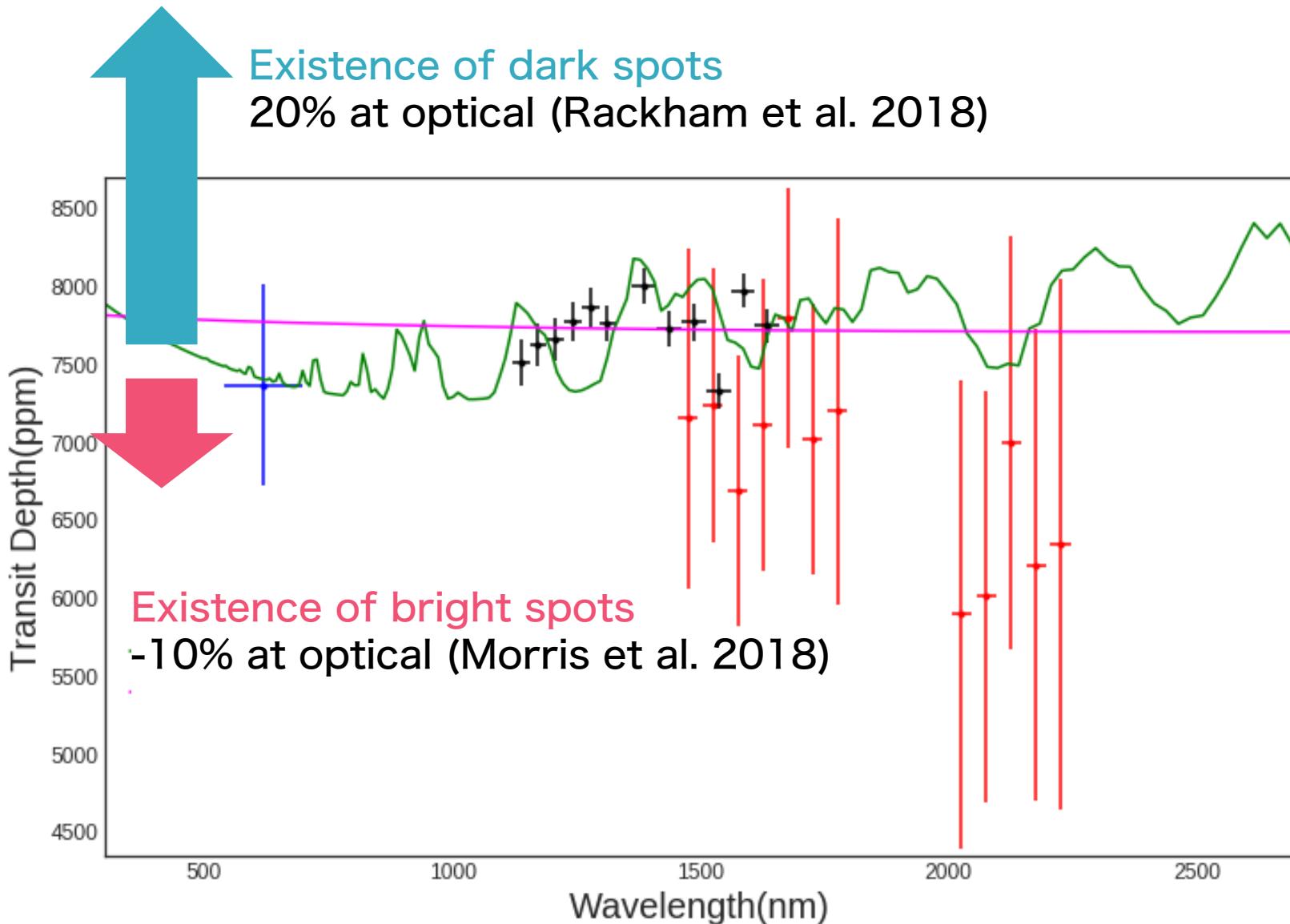


Pre-transit Stellar Disk is the
Assumed Light Source



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





Possible Observation with Subaru / SWIMS (from S20B?)

SWIMS allows **wider-wavelength** spectroscopy.

Instrument	Wavelength[um]	Resolution
MOIRCS – zJ500 grism	0.9 - 1.78	~460
MOIRCS - HK500 grism	1.3 - 2.3	~ 530
SWIMS – zJ grism	0.9 – 1.4	~ 700 - 1200
SWIMS – HK grism	1.4 – 2.5	~ 600 – 1000

Simultaneous!

Future study

- Ground-based transit spectroscopy of **TESS planets**, using Subaru / SWIMS must be possible, to detect primordial atmospheres around Super-Earth sized planets.
- Wider-wavelength range transmission spectroscopy is important to constrain **transit light source effect**.