Characterizing Planets and Biosignatures from Atmospheric Spectra

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Key Questions

What techniques exist for characterizing exoplanet atmospheres?

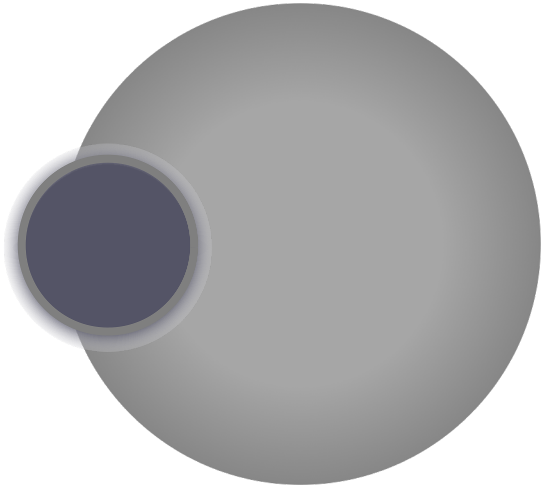
What can different observing techniques tell us about exoplanets and their atmospheres?

Given a spectrum, how do we say something about the state of an exoplanet atmosphere?

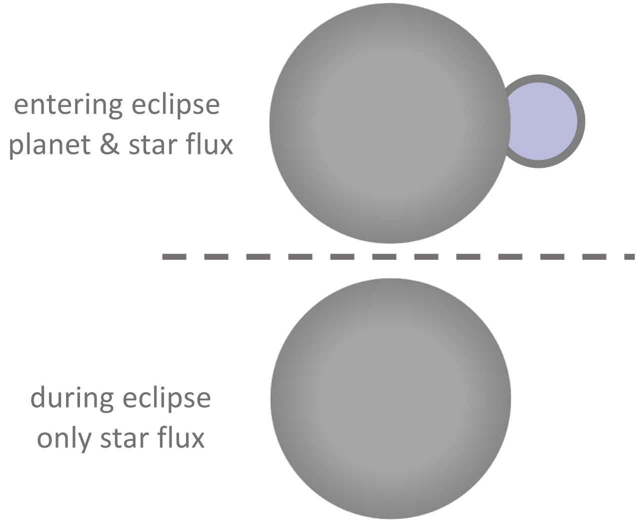
What are the prospects for exoplanet biosignature detections?

What techniques exist for characterizing exoplanet atmospheres?

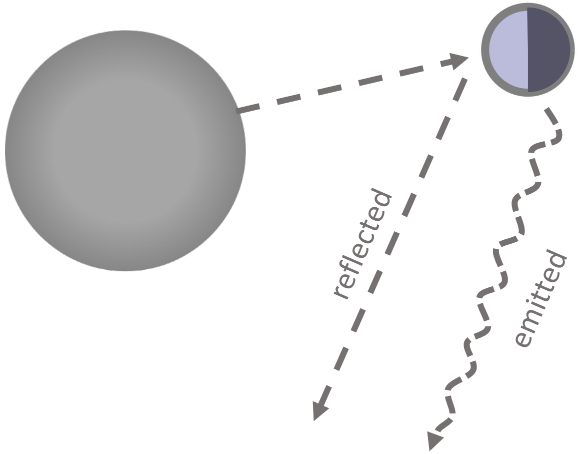
Transit



Secondary Eclipse



Direct Imaging



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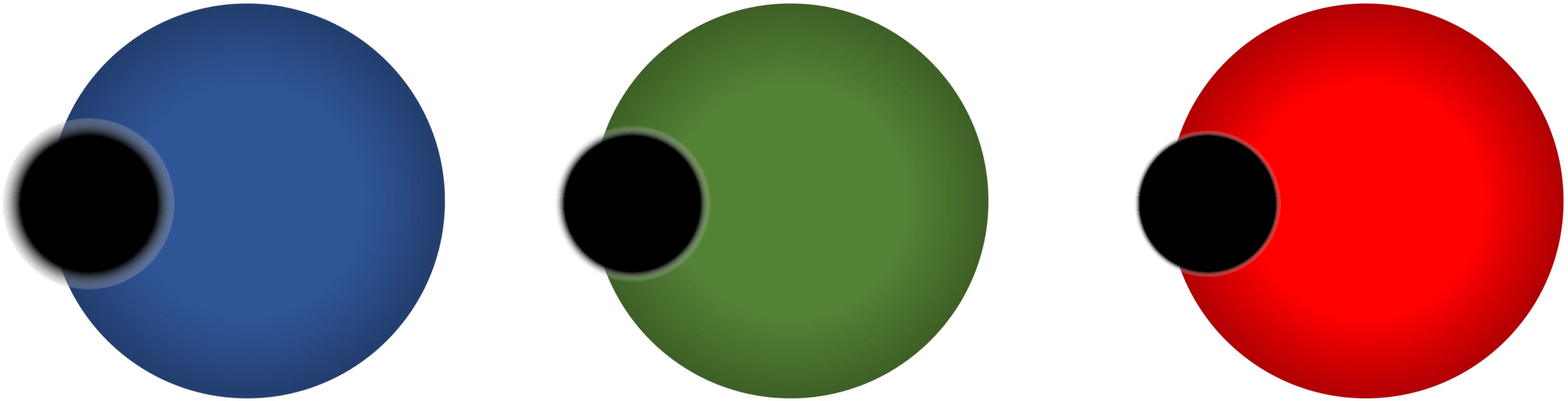

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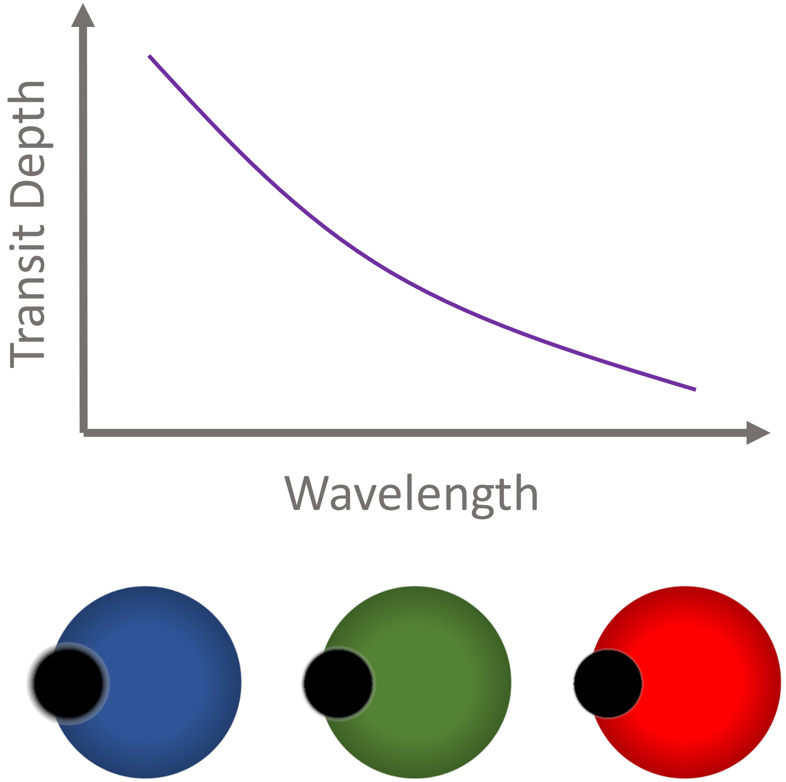
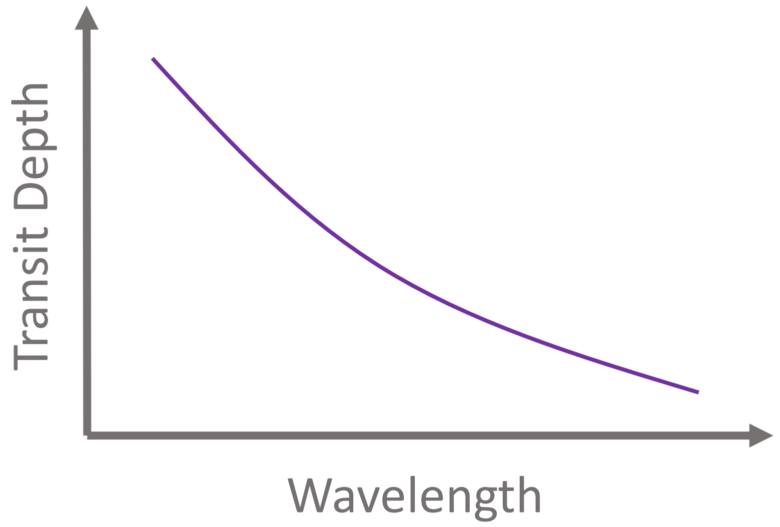
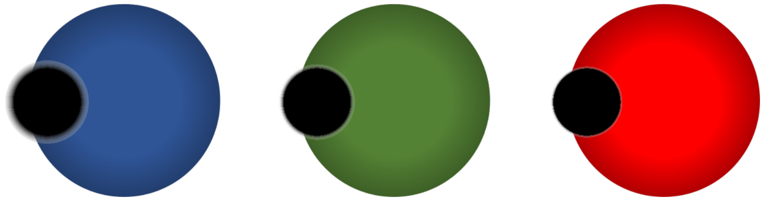


Transit

- dimming of host star scales as $(R_p/R_s)^2$
- planets will appear larger at wavelengths corresponding to higher atmospheric opacity (e.g., molecular absorption features)
- transit spectroscopy relies on non-detections of *stellar* photons that are blocked by atmospheric species or aerosols





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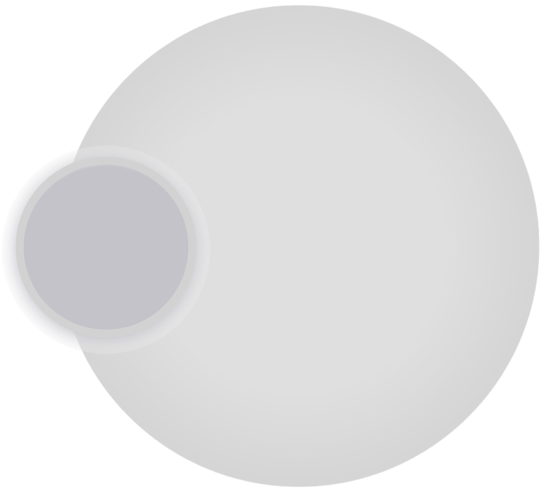
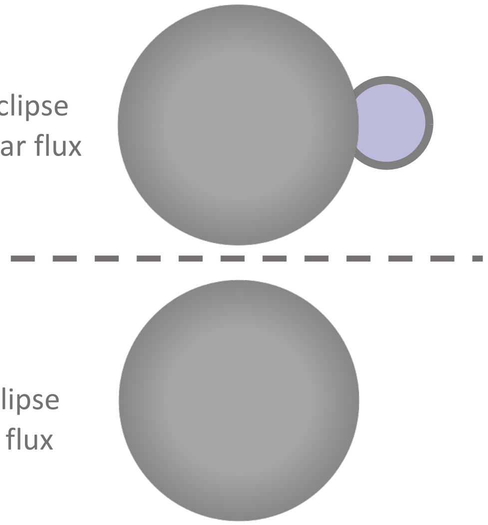


Secondary Eclipse

entering eclipse
planet & star flux

during eclipse
only star flux



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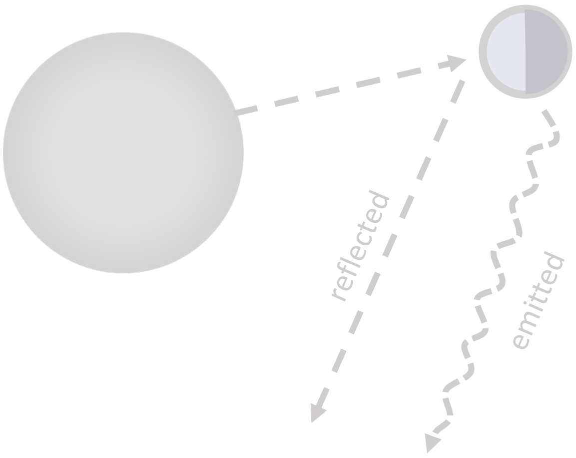

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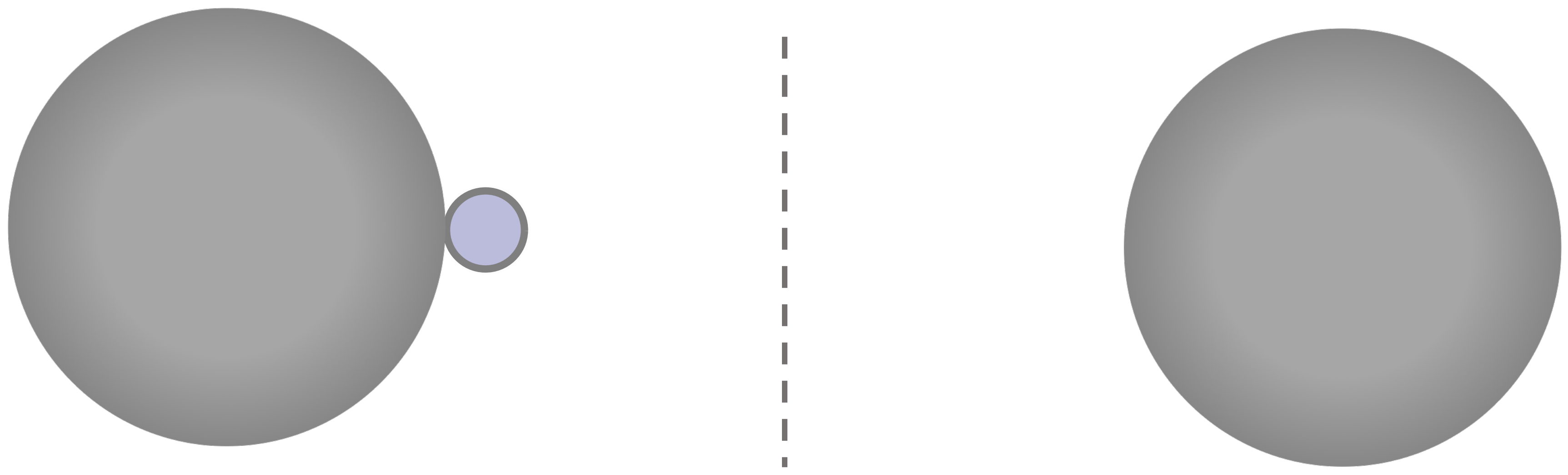
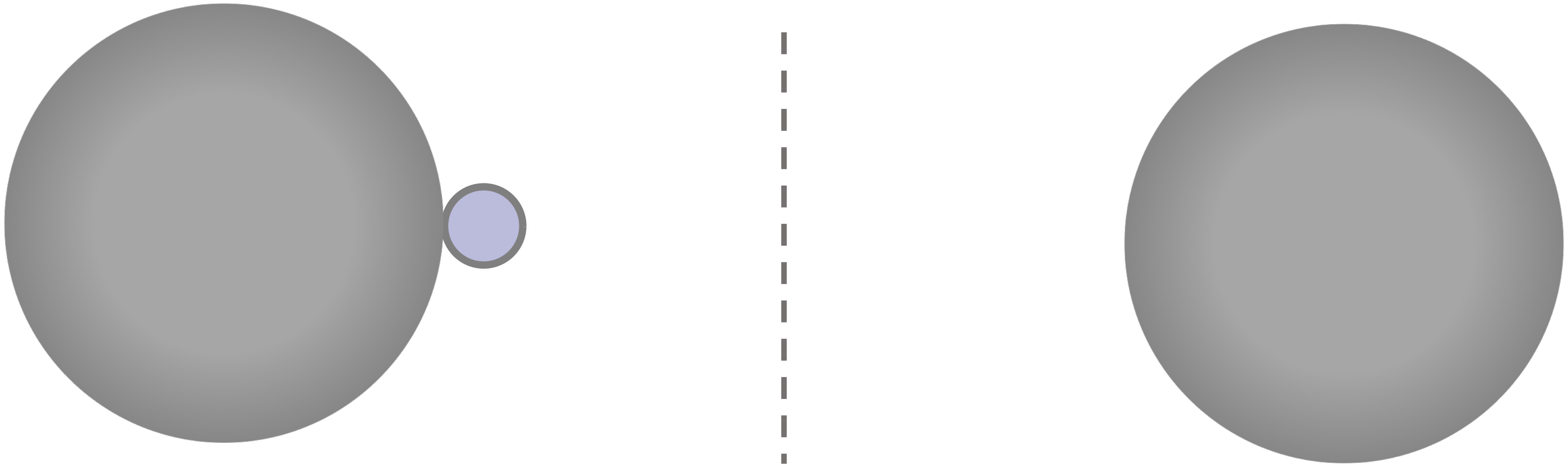


ratio of observations is sensitive to F_p/F_s

Secondary Eclipse

before eclipse | during eclipse

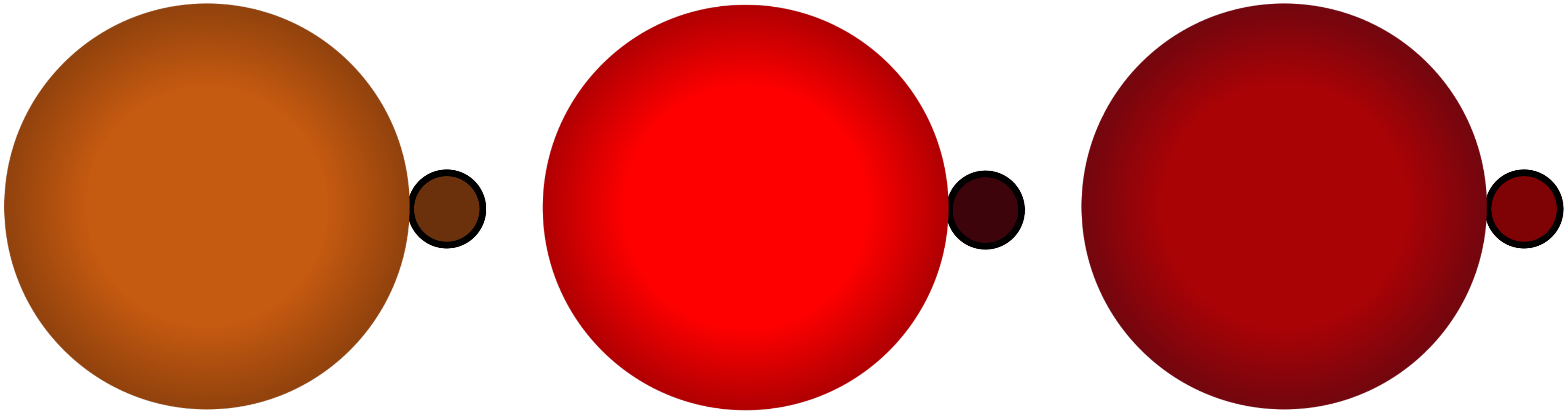


$F_s + F_p$ | F_s

ratio of observations is sensitive to F_p/F_s

note: works “best” at wavelengths where planet *emits*

Secondary Eclipse



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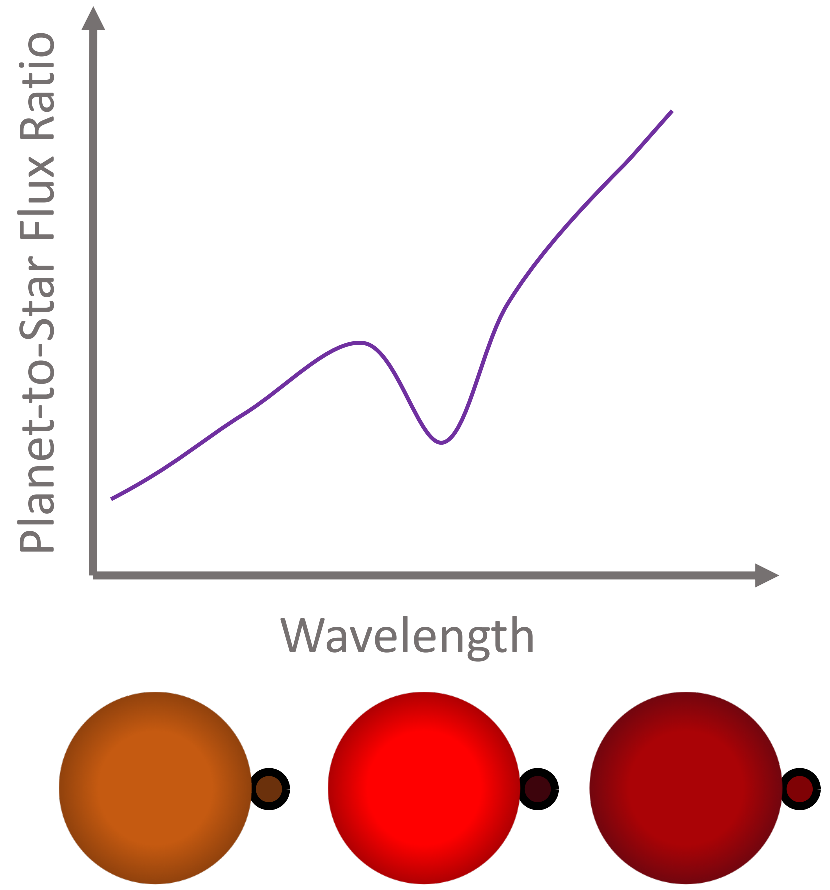
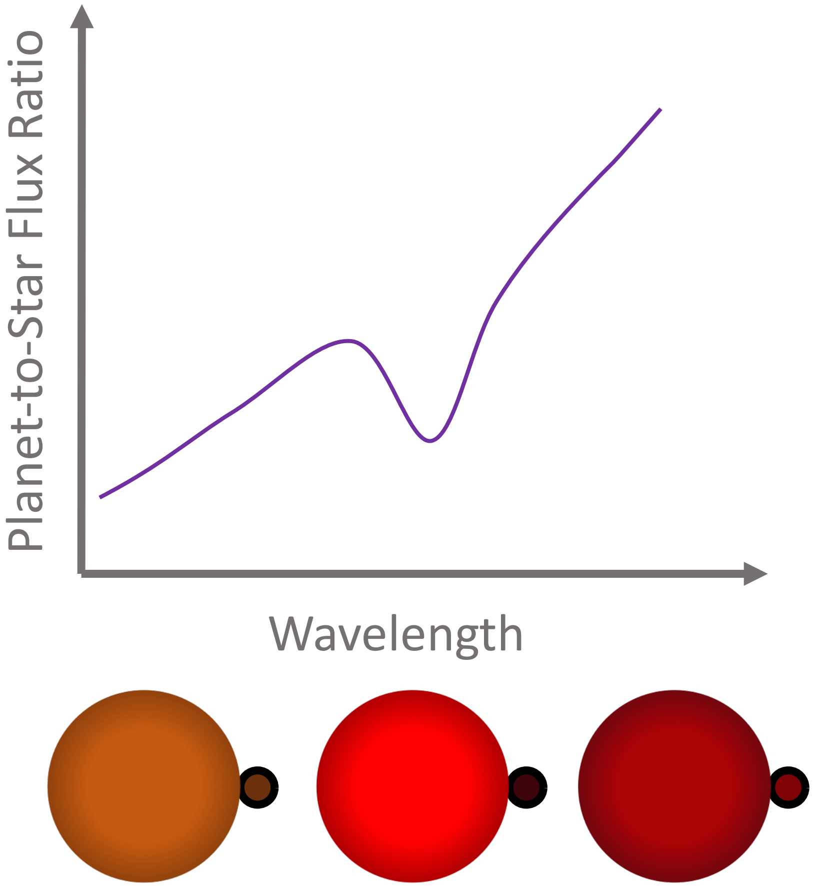


Secondary Eclipse

- scales as $B_\lambda(T_\mathrm{p})/B_\lambda(T_\mathrm{s})$
- expect wavelength-dependence, due to ratio of Planck functions at different temperatures
- deviations from ratio of Planck functions can indicate absorption or emission features



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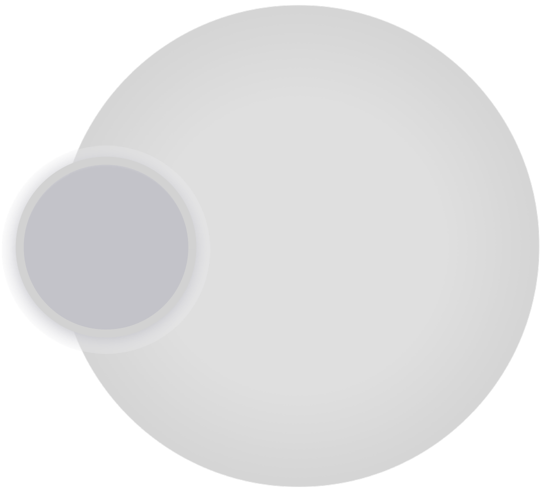
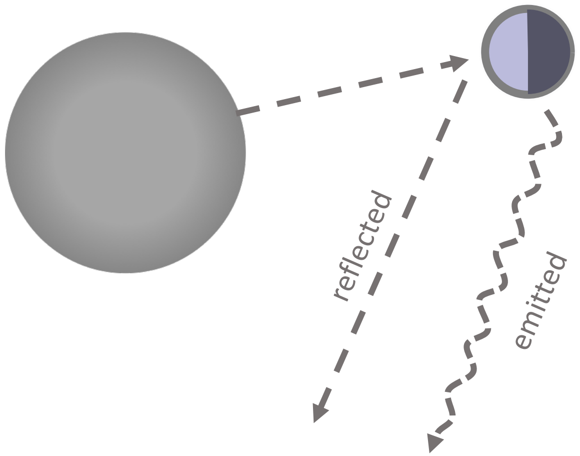
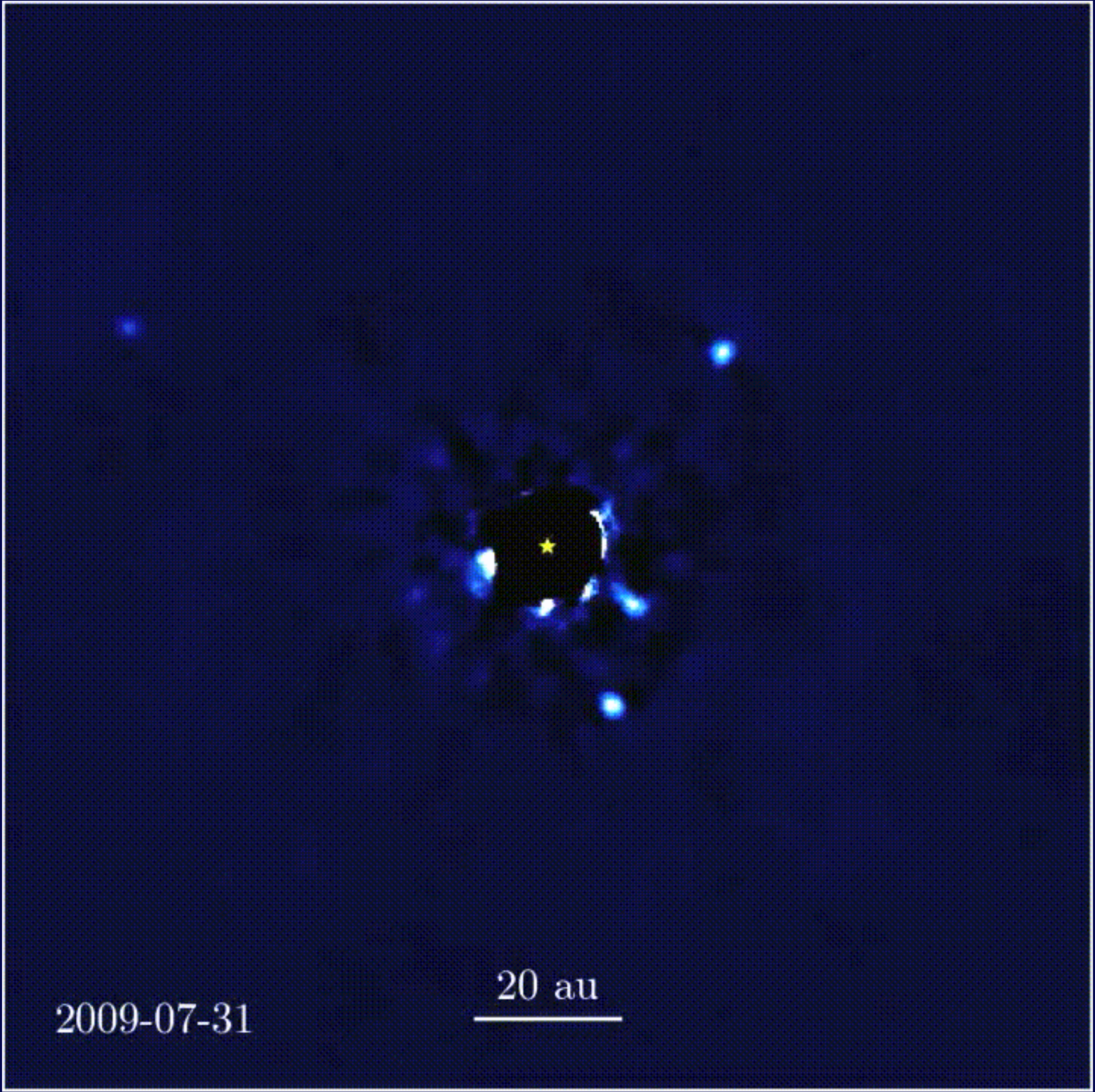


Secondary Eclipse

Direct Imaging

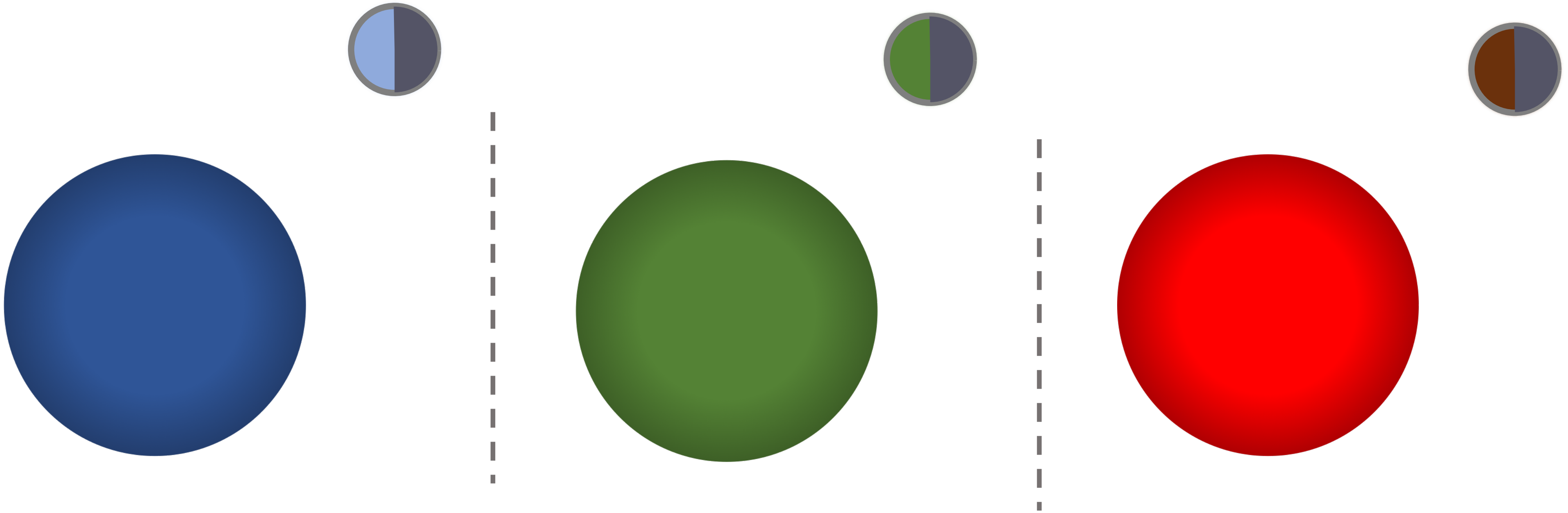


HR 8799



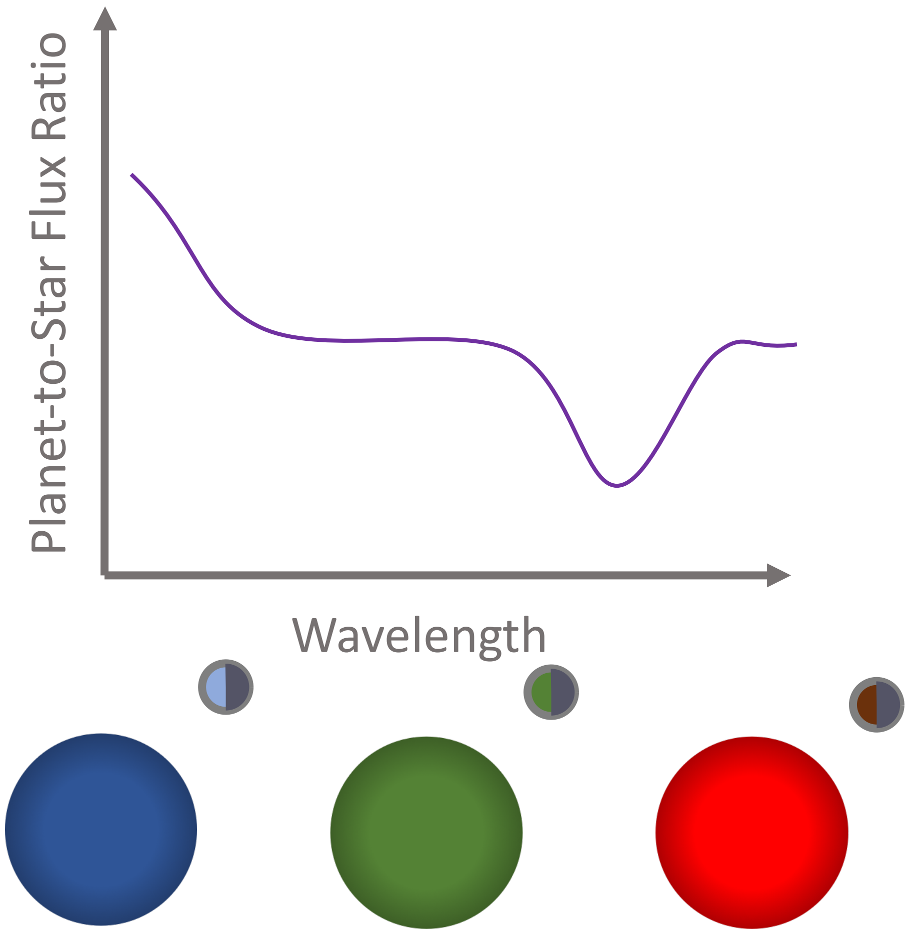
Credit: Jason Wang

Direct Imaging



note: in reflected light, presenting as F_p/F_s divides out stellar spectral variations

Direct Imaging



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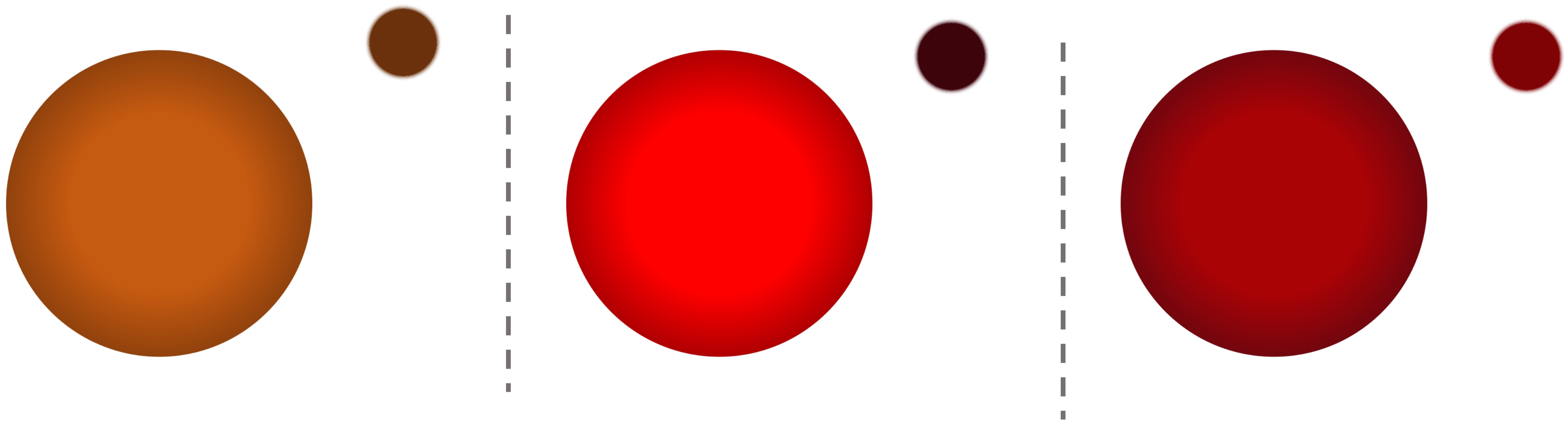
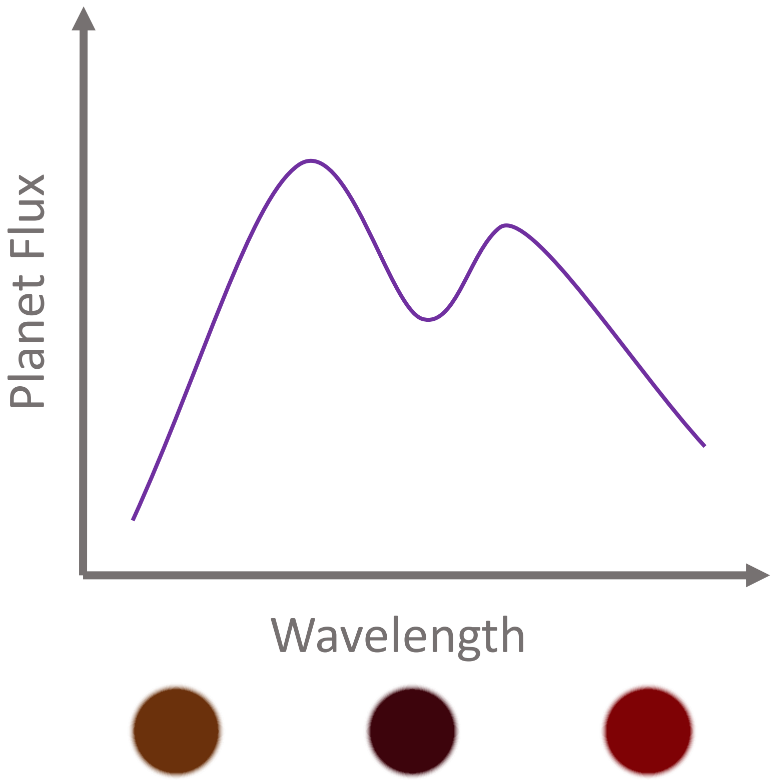


note: looks like secondary eclipse if presented as F_p/F_s

Direct Imaging



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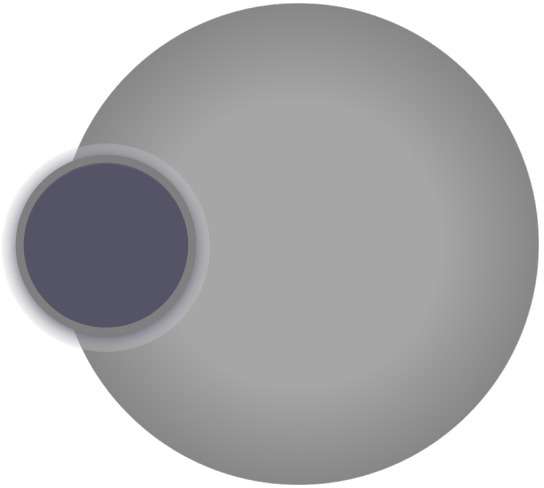

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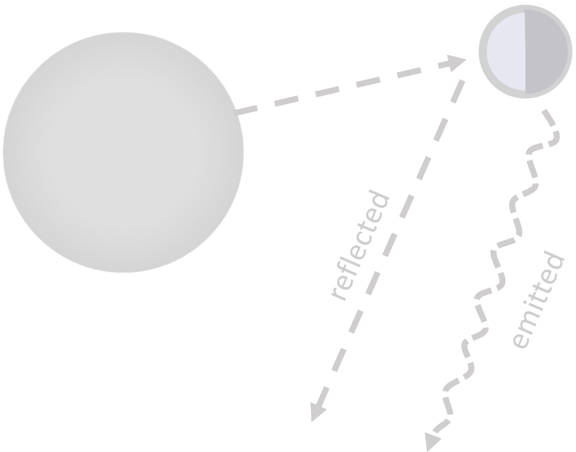
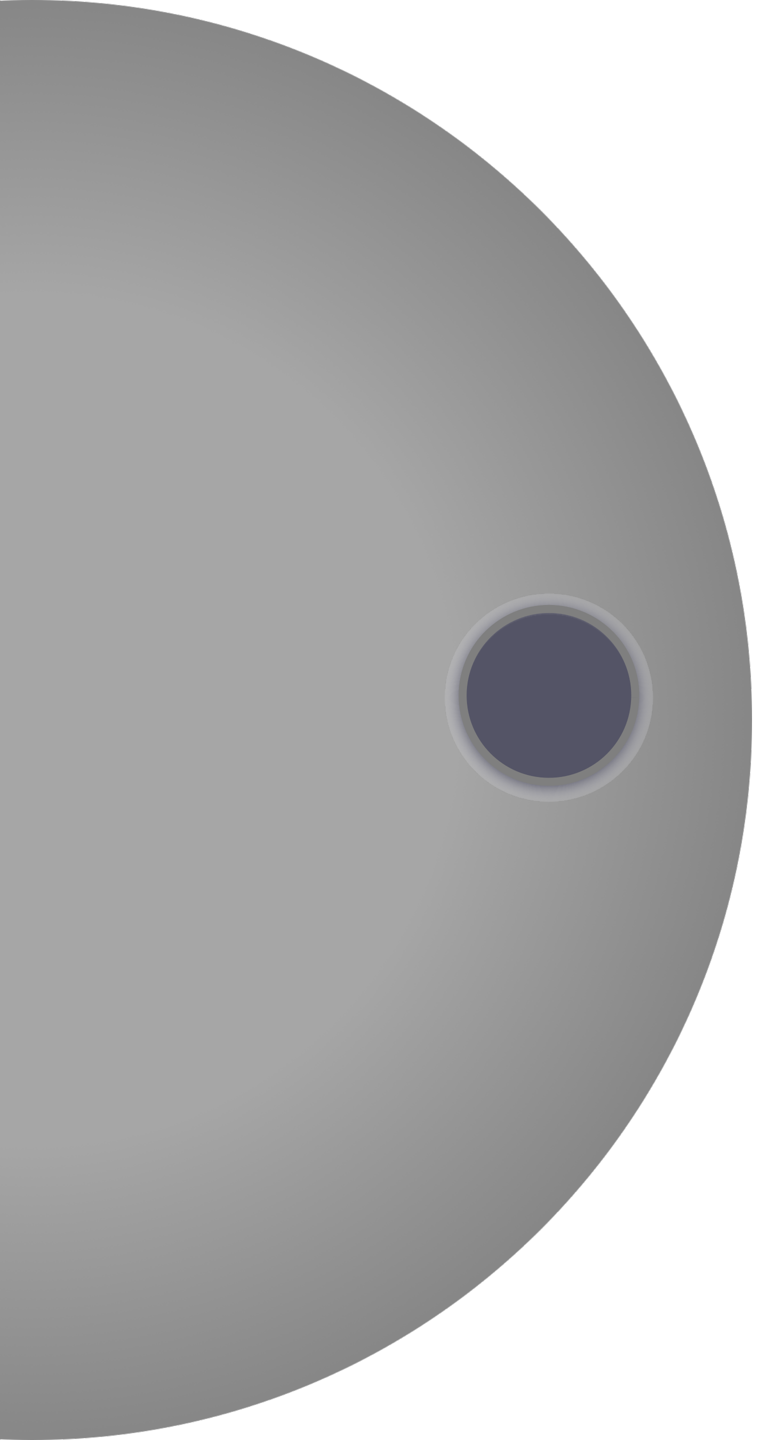
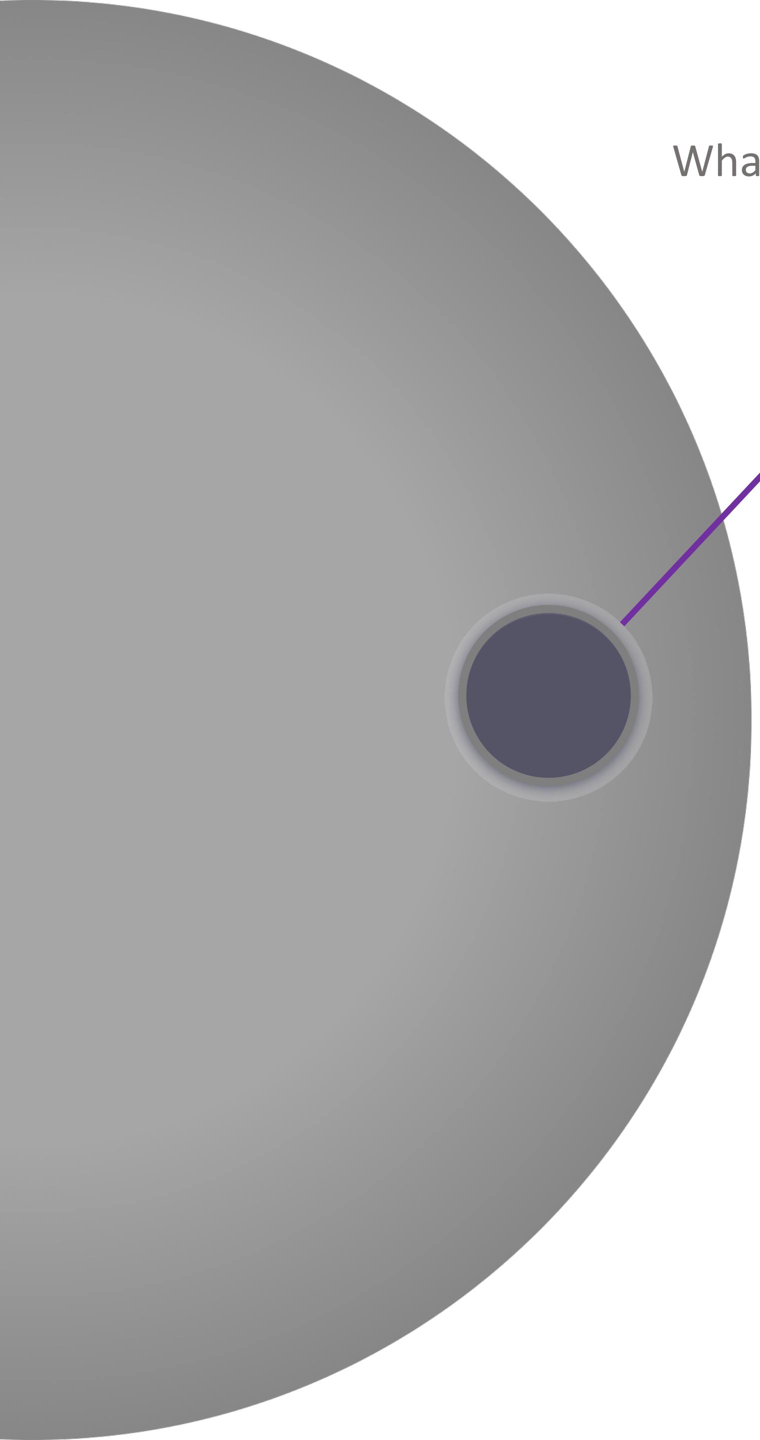
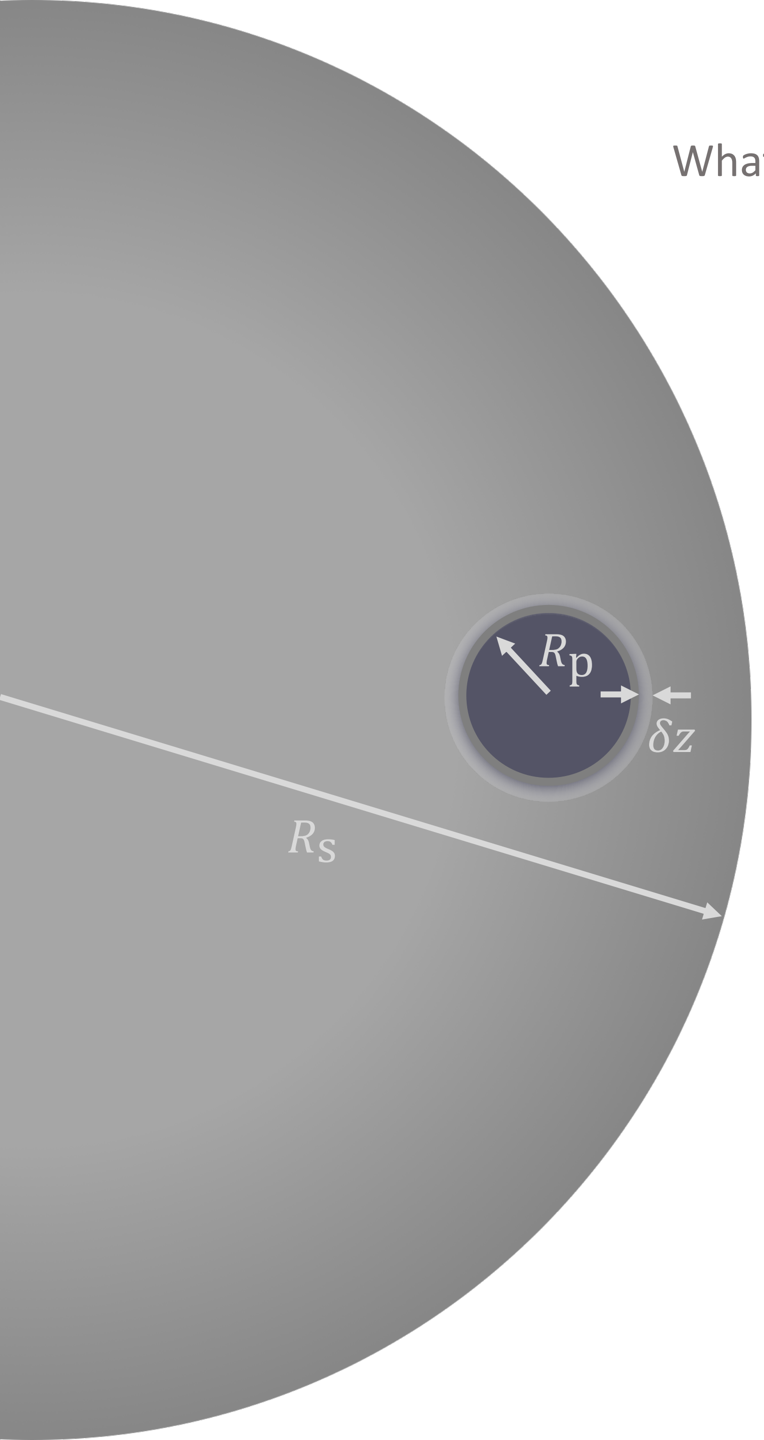




What is the additional transit depth caused by the planetary atmosphere?





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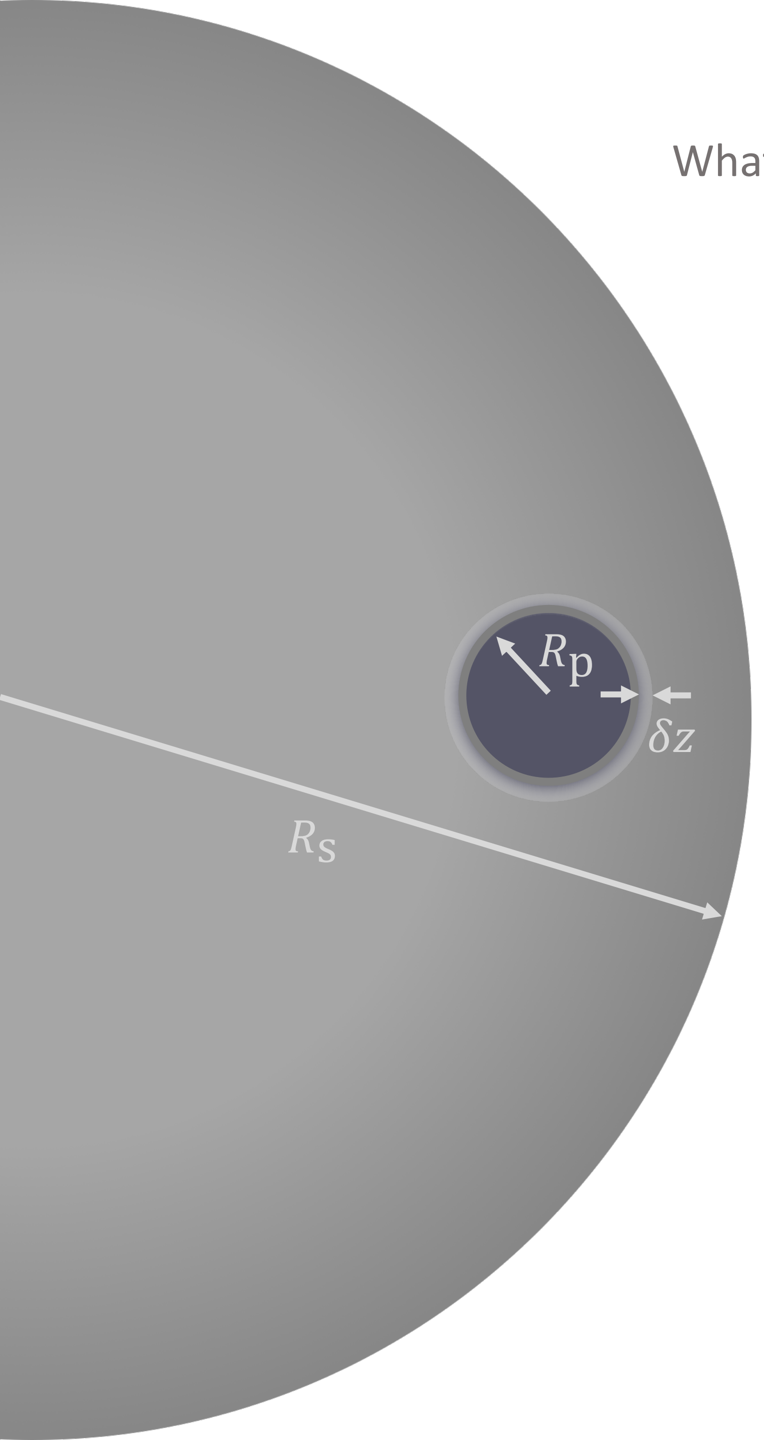
$$\Delta = \frac{\text{area of atmospheric annulus}}{\text{area of stellar disk}} = \frac{2\pi R_\mathrm{p}\delta z}{\pi R_\mathrm{S}^2}$$



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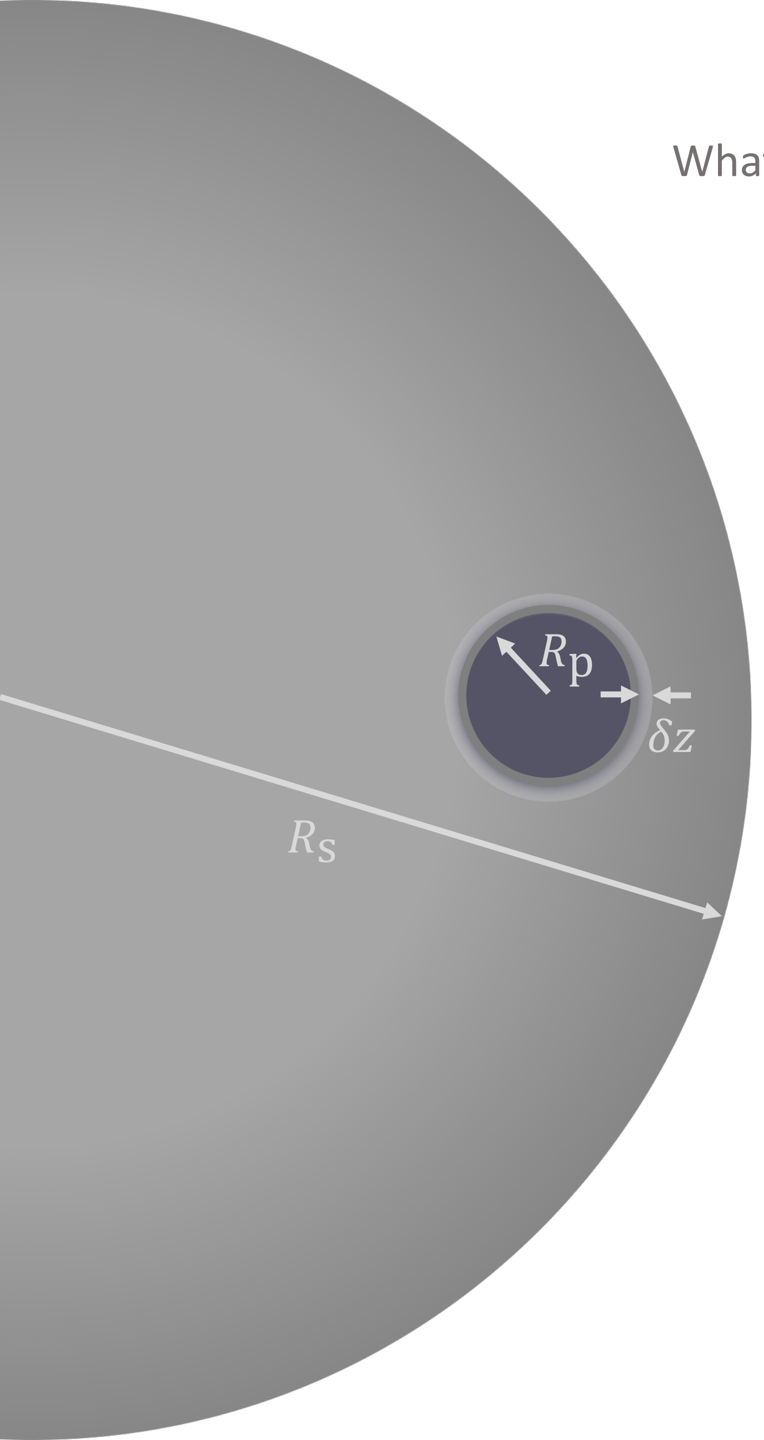

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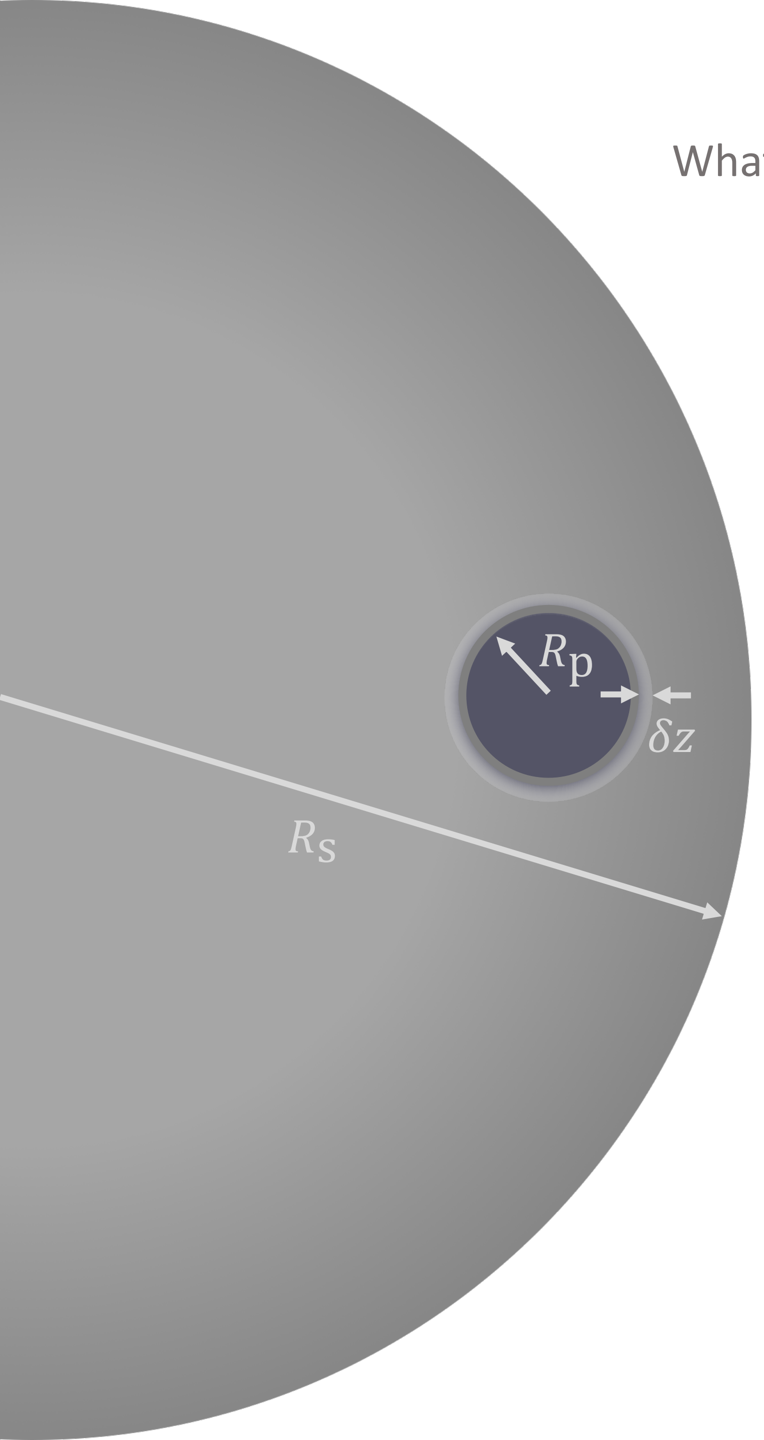
Scales with the pressure scale height:

$$H_p = \frac{k_\mathrm{B}T}{mg}$$



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Scales with the pressure scale height:

Boltzmann constant

atmospheric temperature

$$H_p = \frac{k_{\mathrm{B}} T}{m g}$$

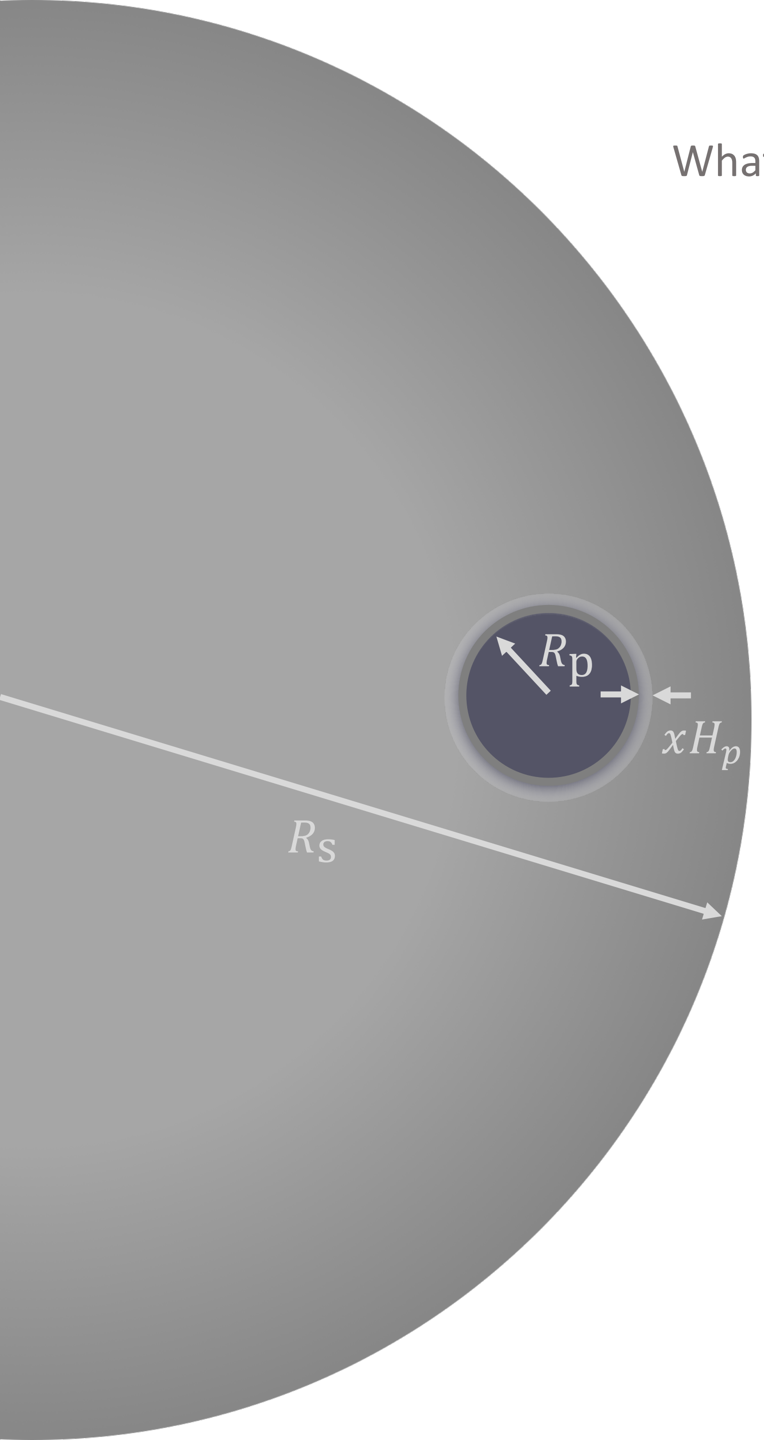
atmospheric mean molecular mass

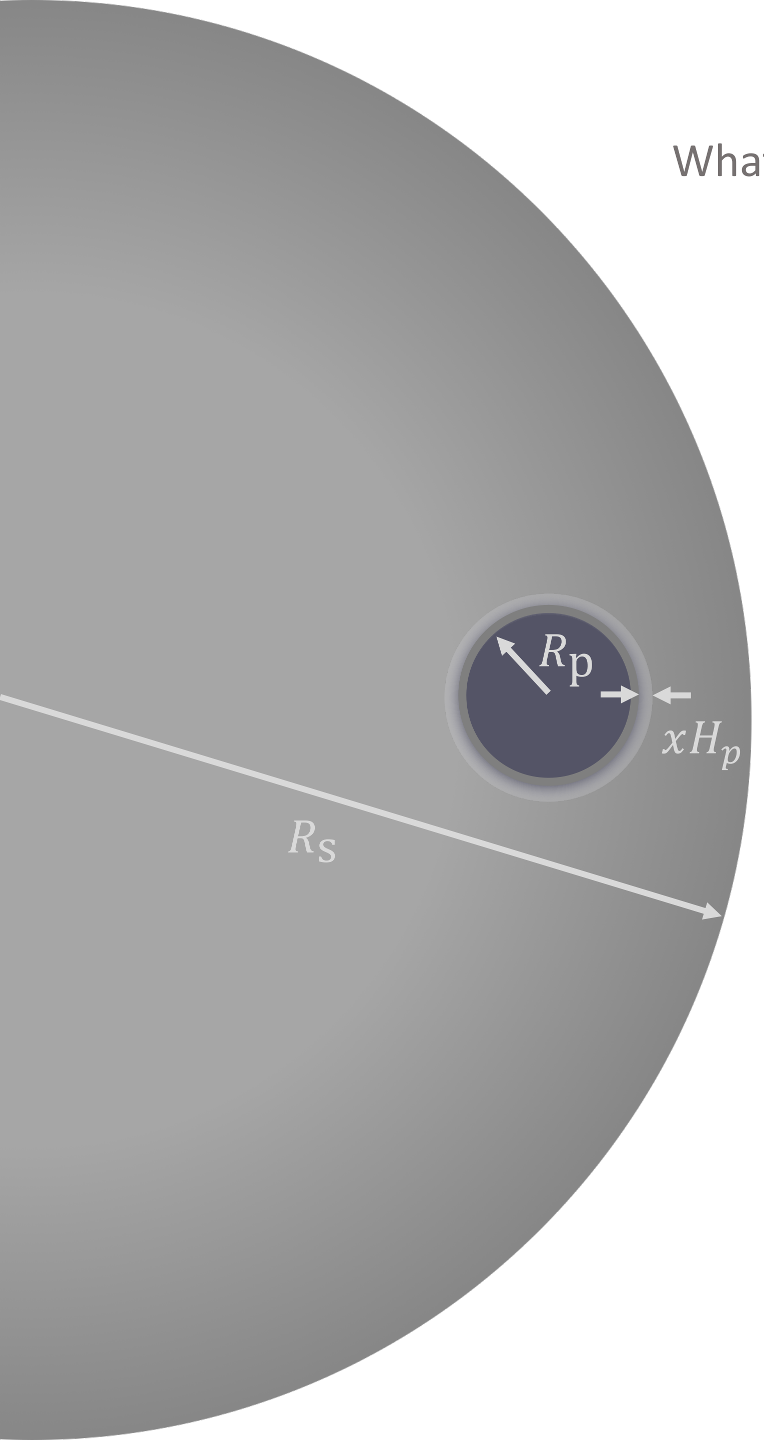
gravitational acceleration

What is the additional transit depth caused by the planetary atmosphere?

$$\Delta = \frac{2R_\mathrm{p}}{R_\mathrm{S}^2} \cdot xH_p = \frac{2R_\mathrm{p}}{R_\mathrm{S}^2} \cdot x\,\frac{k_\mathrm{B}T}{mg}$$

fudge factor to capture how many (or few) atmospheric scale heights represent the thickness of the atmosphere





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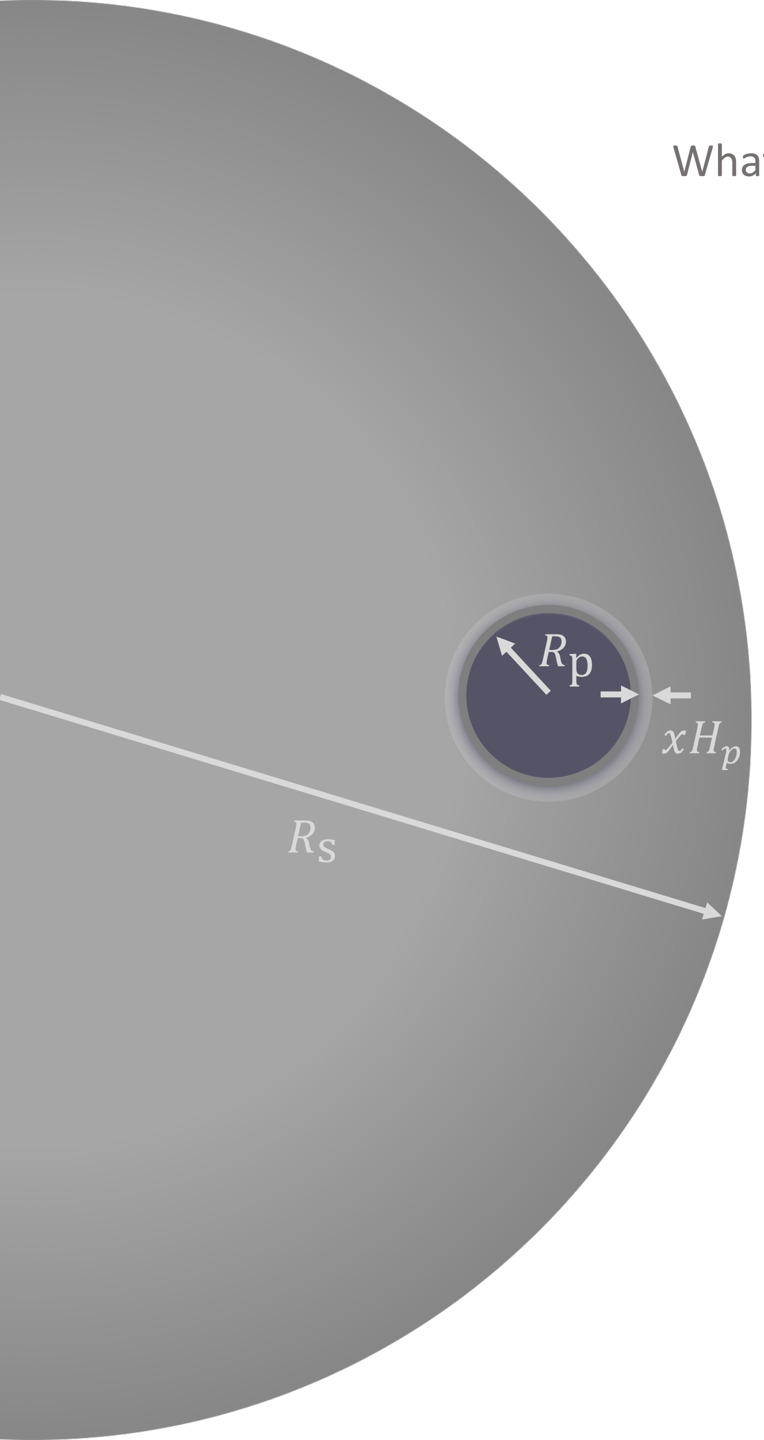
Where does the wavelength dependence come in?



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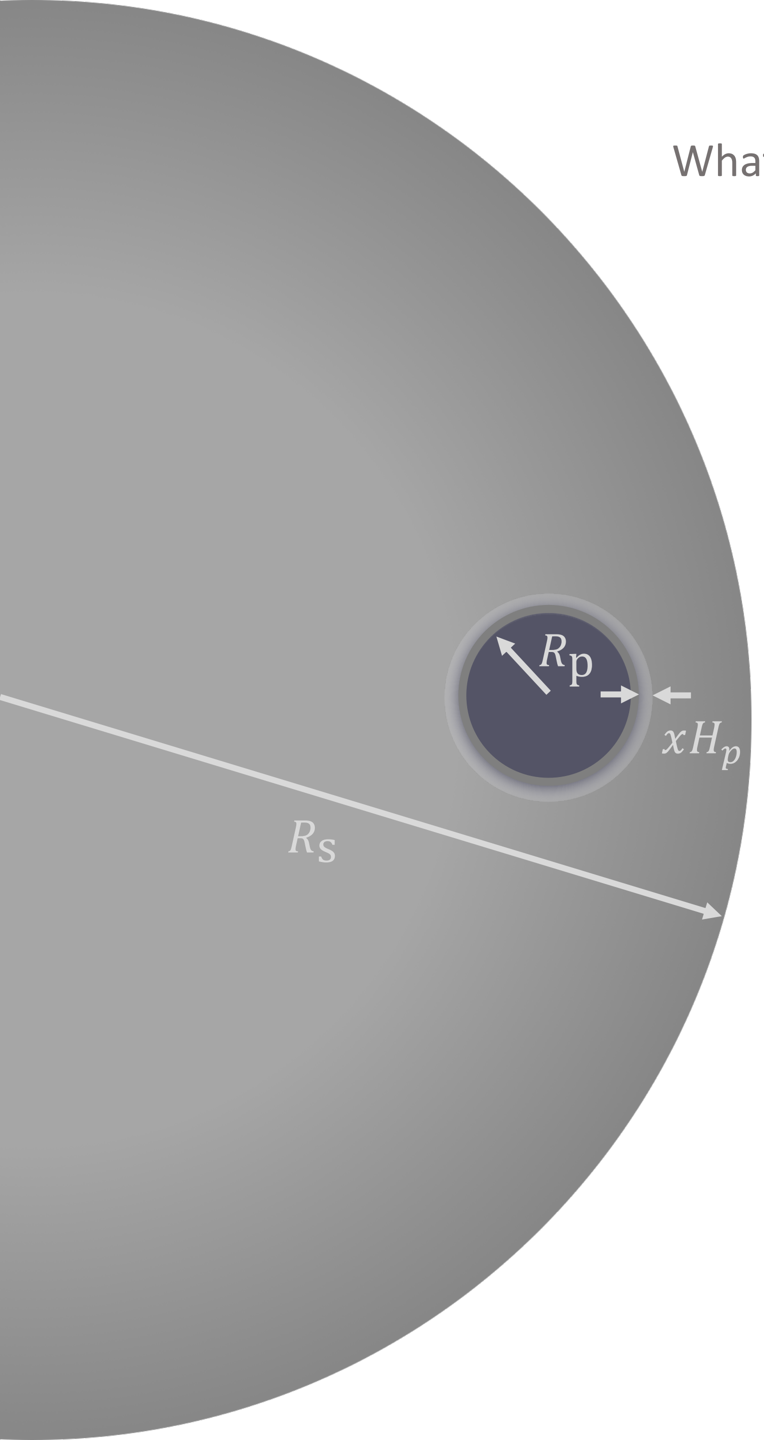

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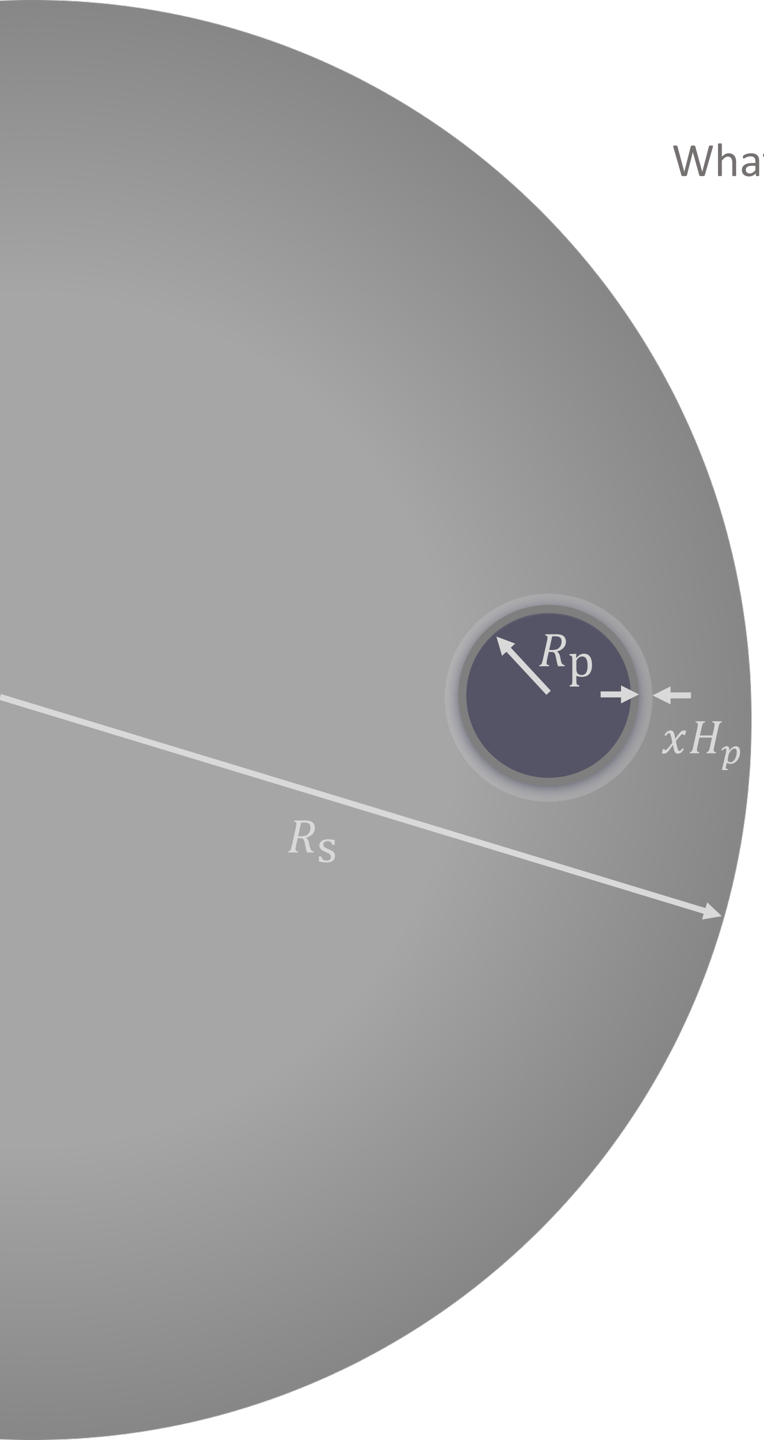
Thus, transit spectra can provide constraints on:

atmospheric opacity
atmospheric temperature
atmospheric bulk composition
surface gravity
planet size



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Thus, transit spectra can provide constraints on:

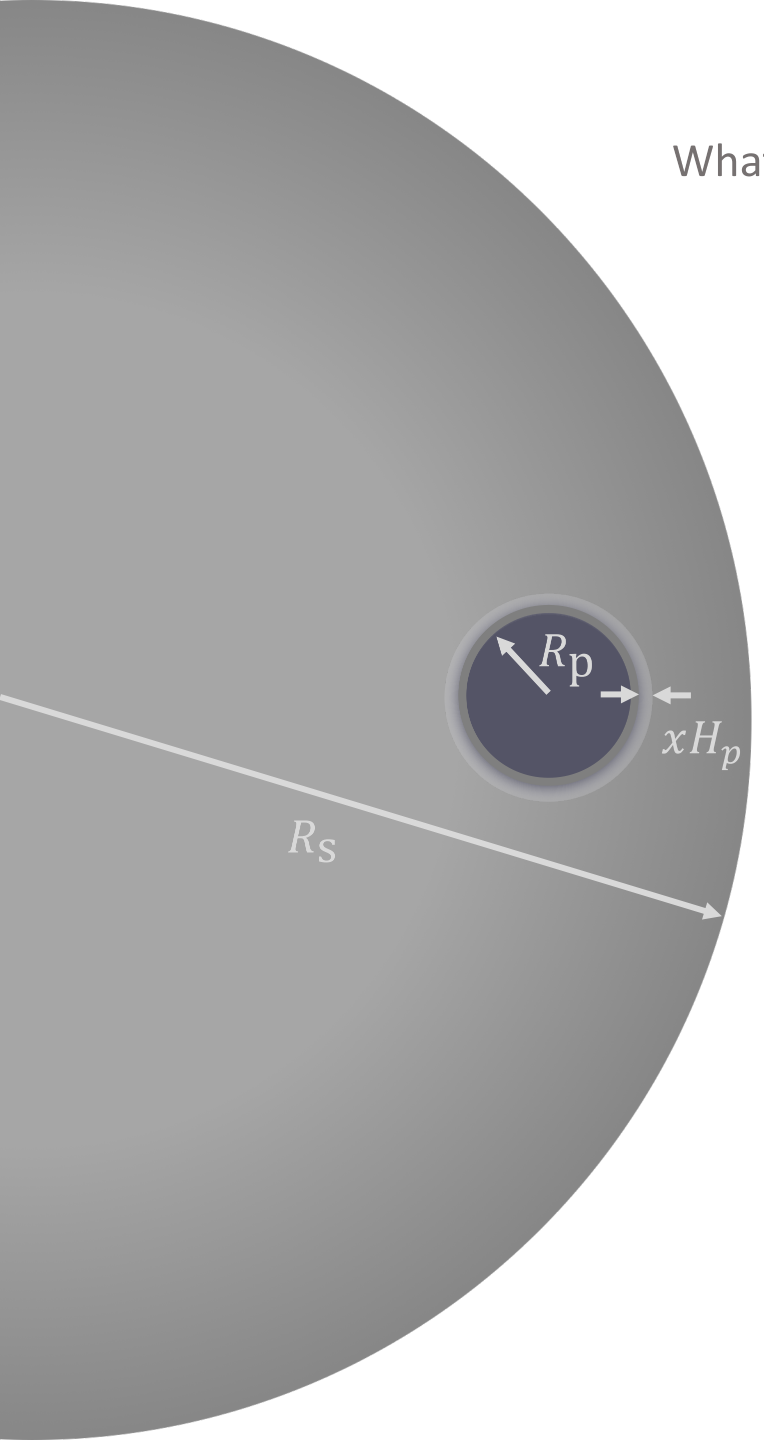
atmospheric opacity → atmospheric trace/bulk gas composition, aerosols, atmospheric pressure

atmospheric temperature

atmospheric bulk composition

surface gravity, planet size → planet mass

See also: de Wit & Seager (2013)



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note: potential for degeneracies!

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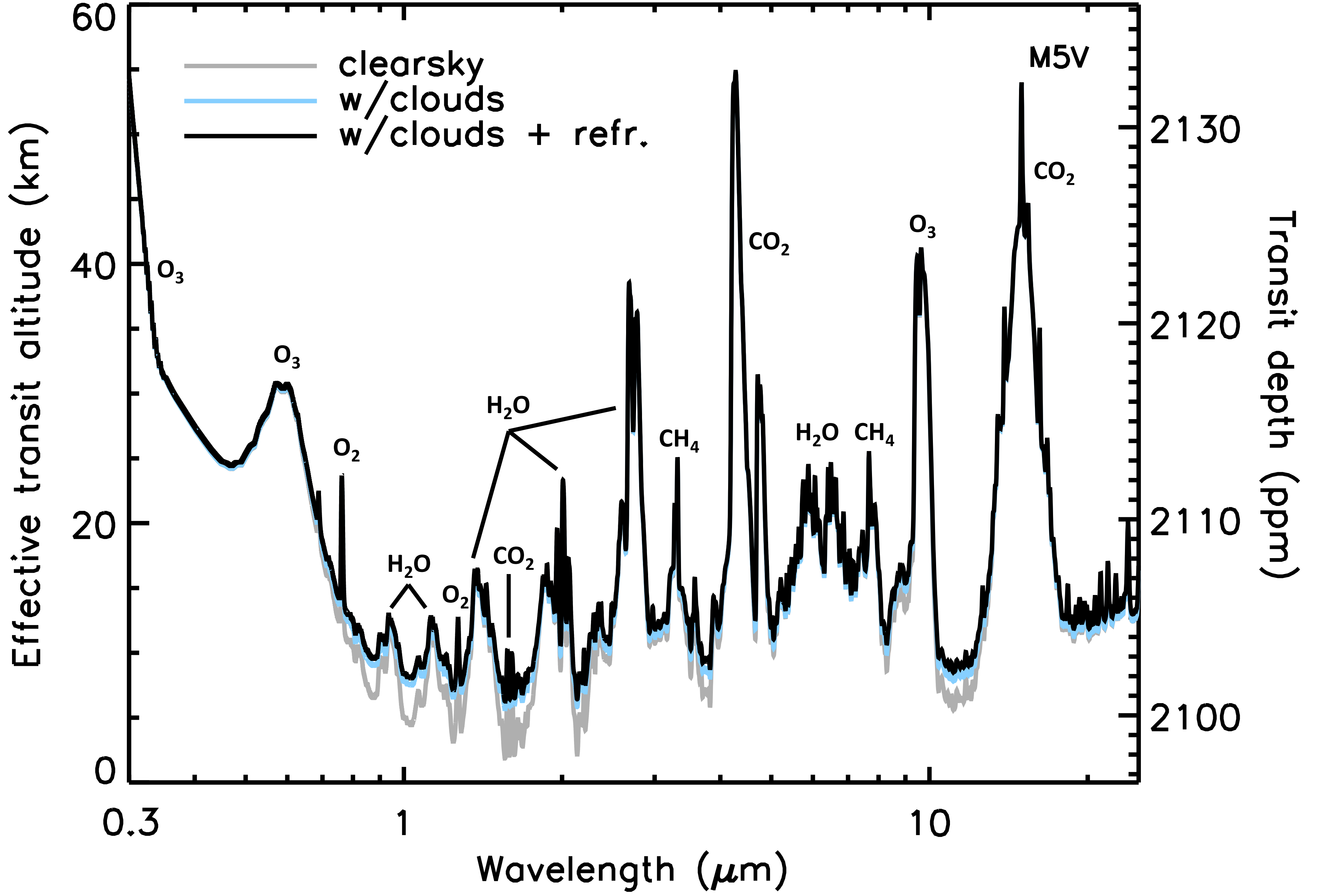
Earth twin transiting M5V



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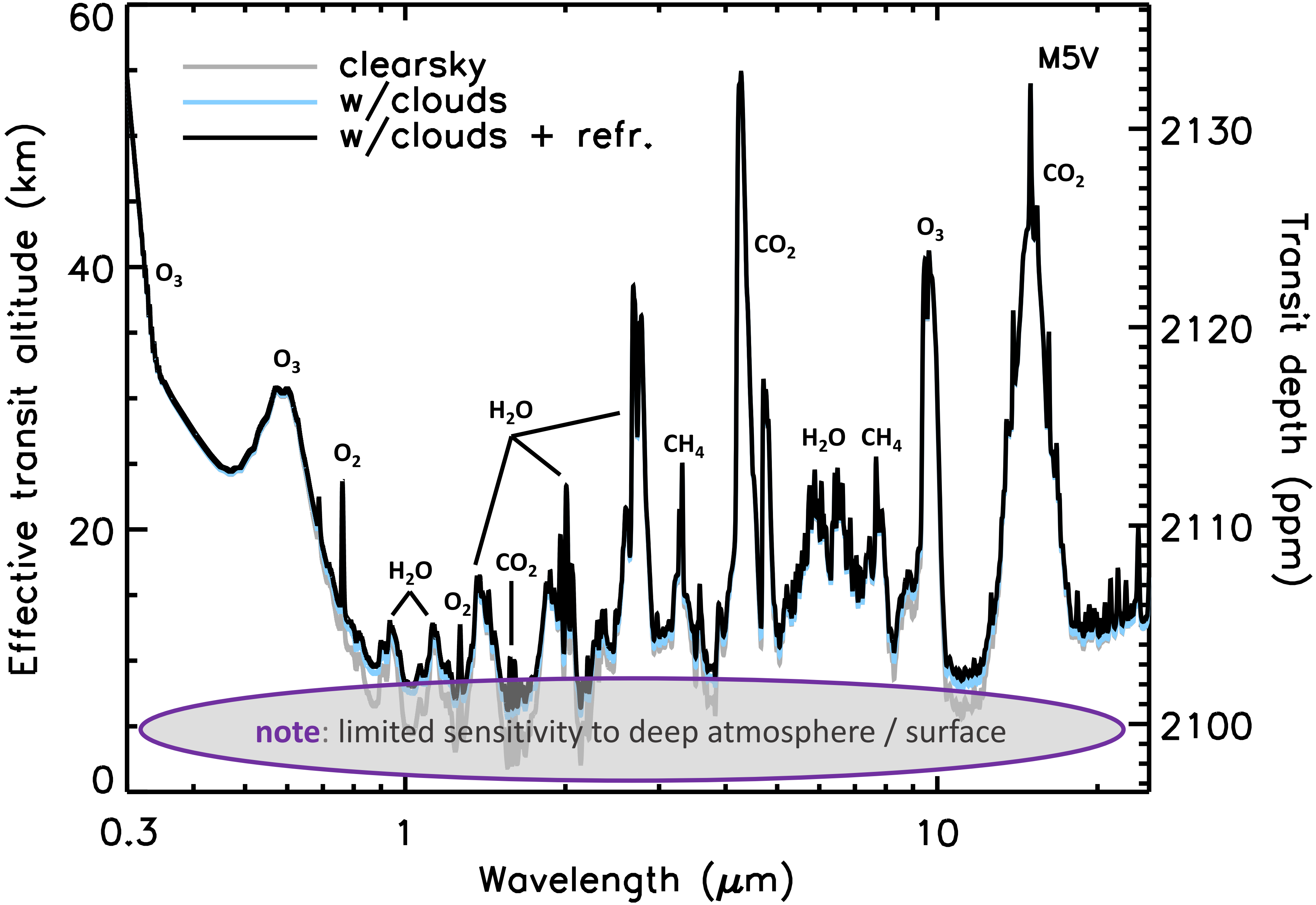

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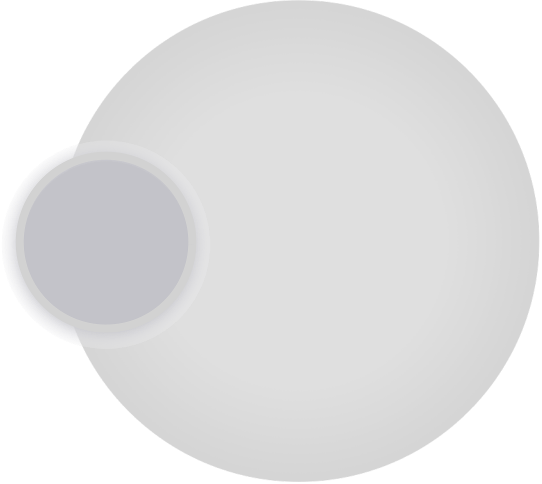

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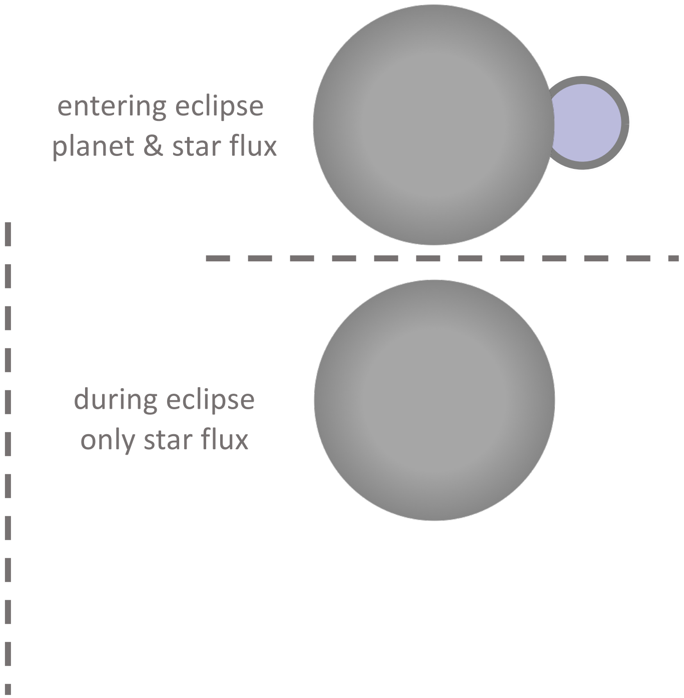

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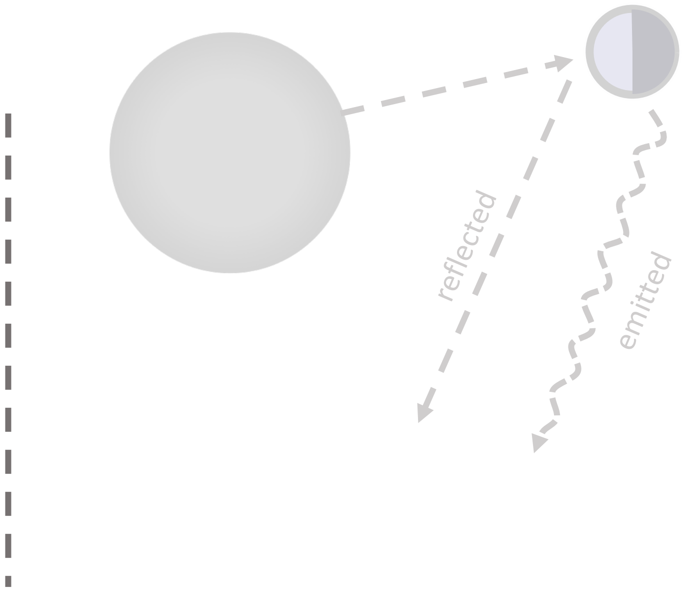

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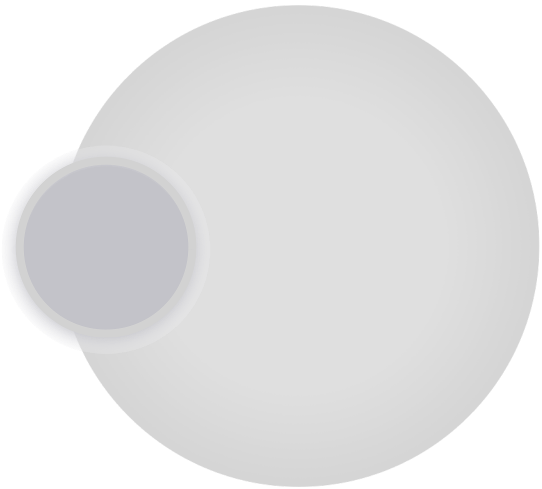

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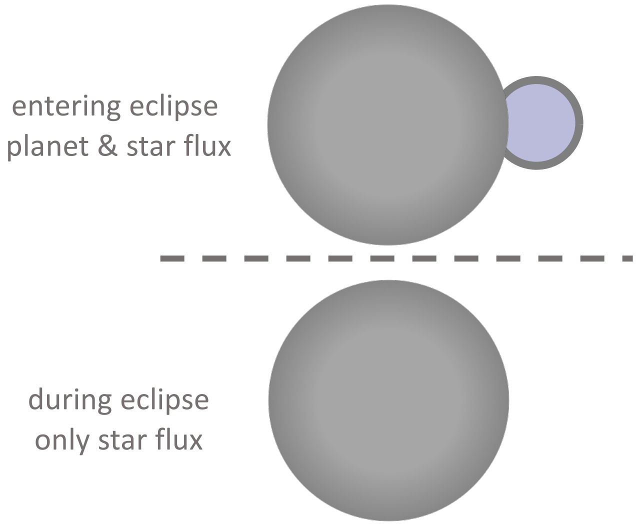

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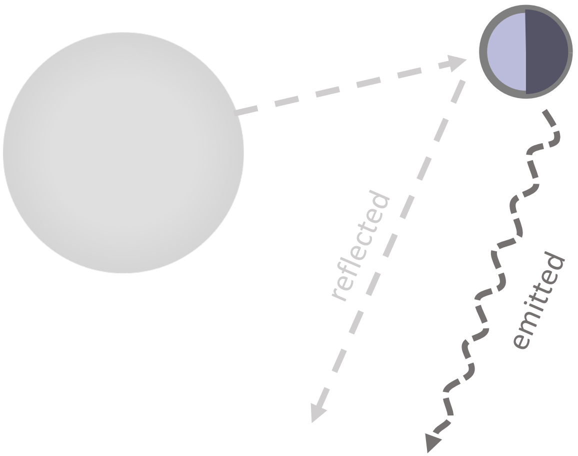
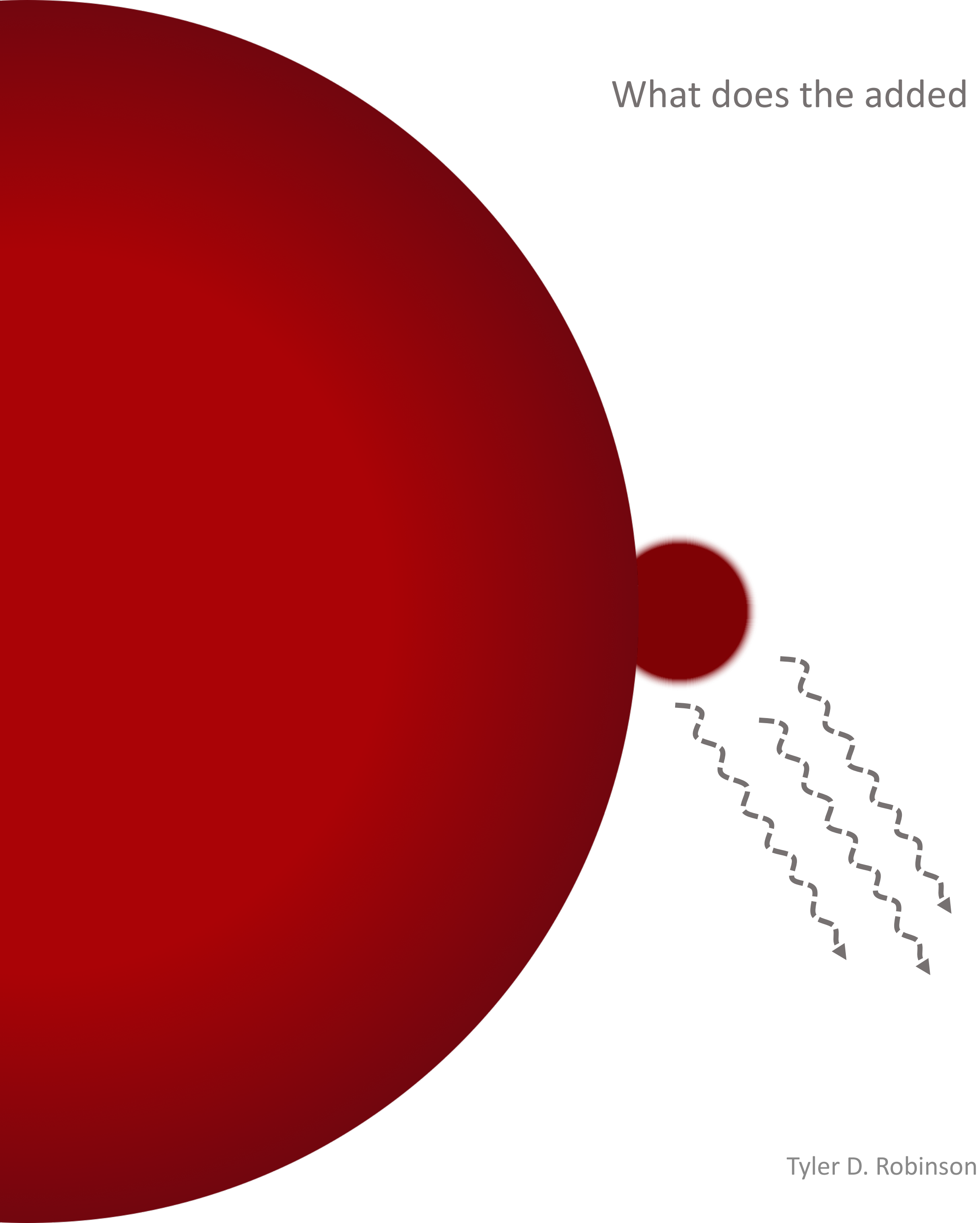


What does the added planet-star system flux due to the planet “look” like?



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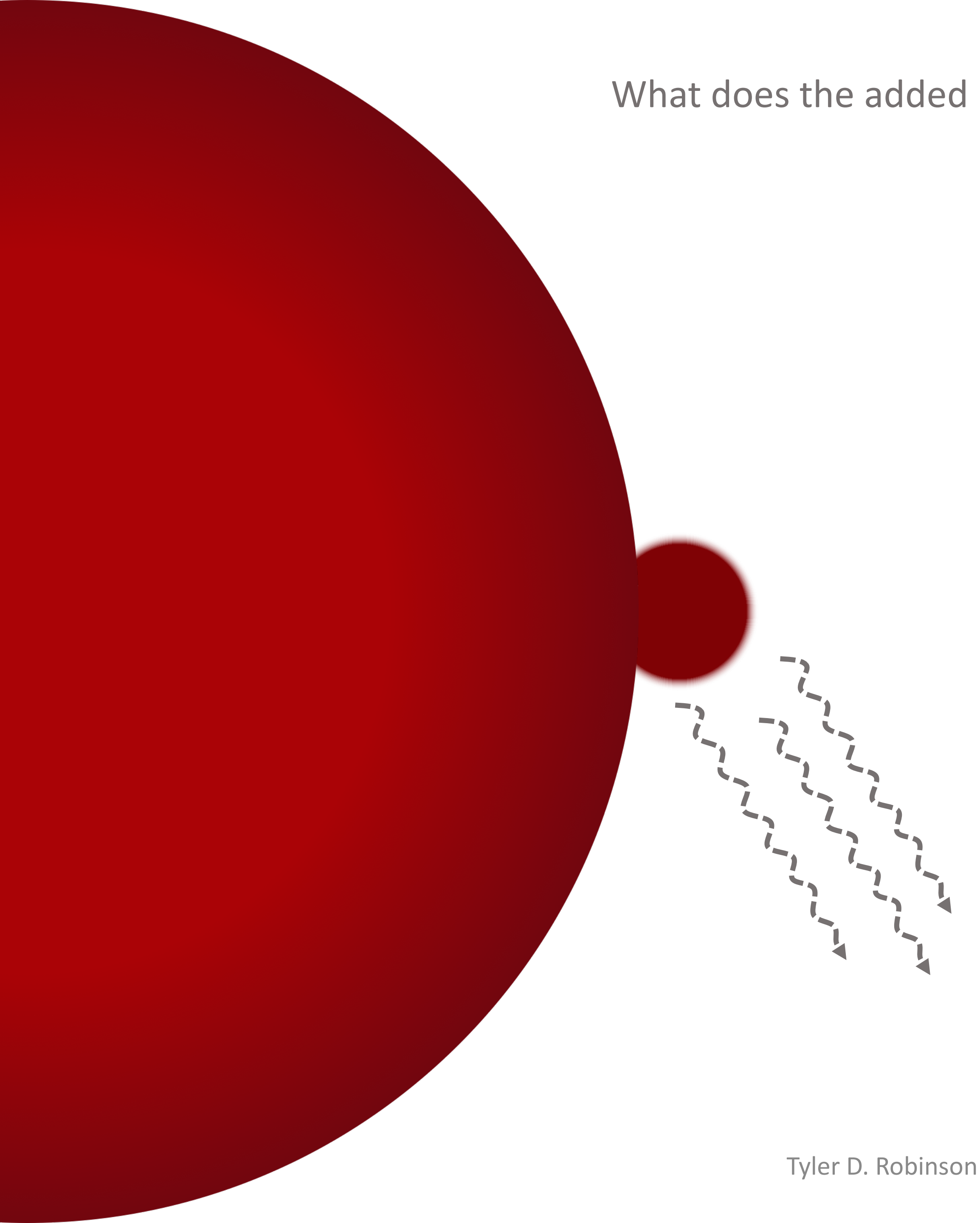
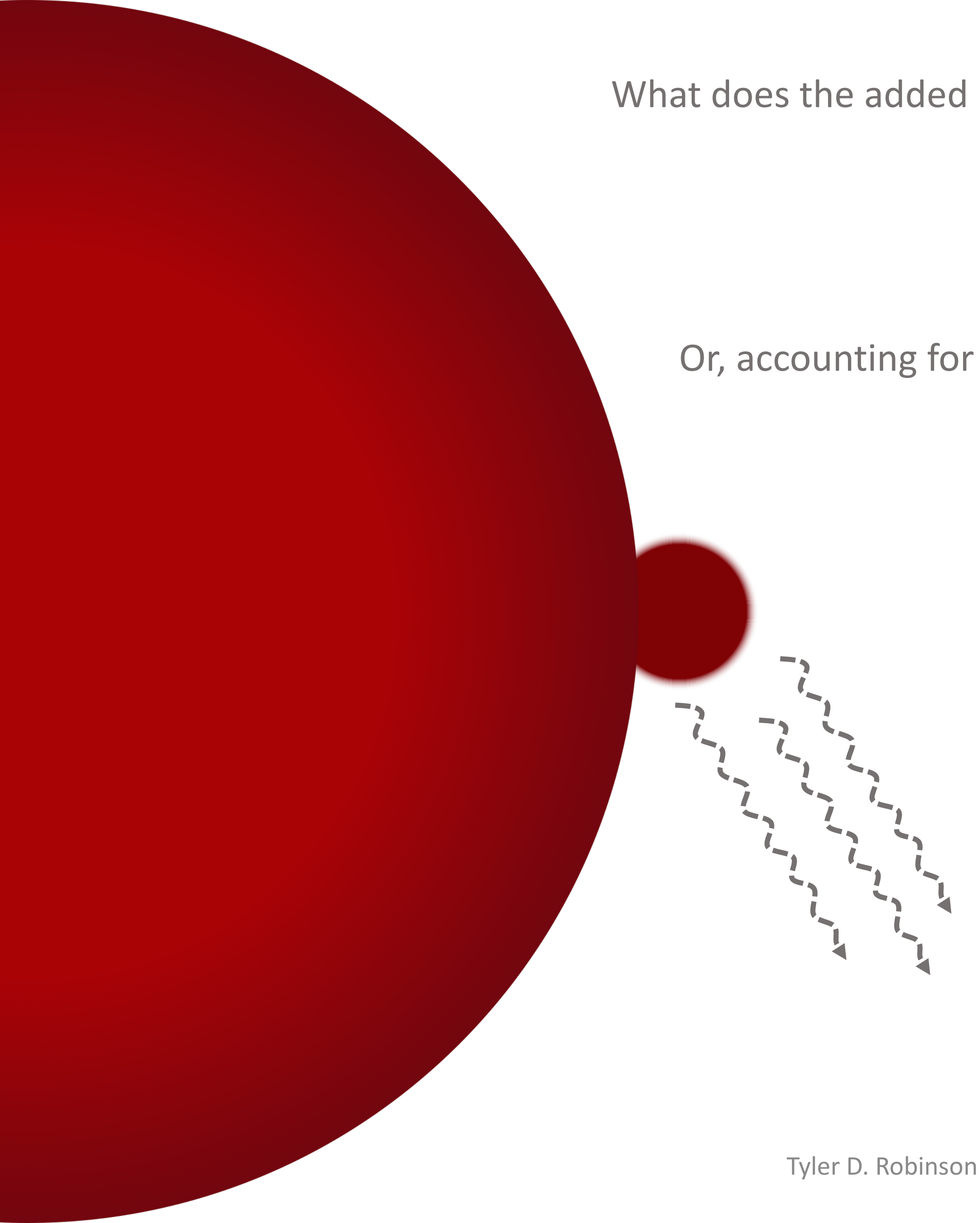




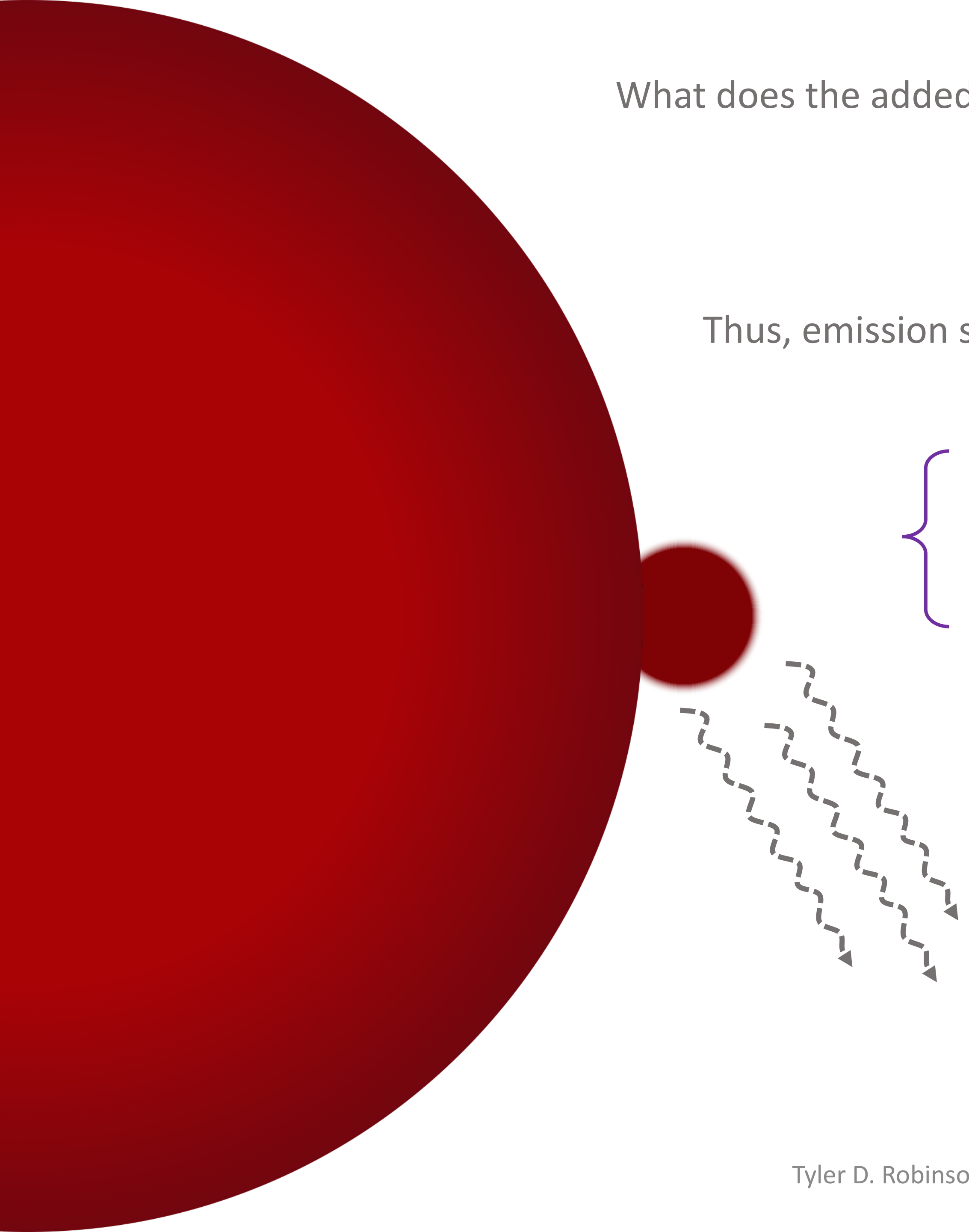
What does the added planet-star system flux due to the planet "look" like?

$$F_{\mathrm{p}} \sim R_{\mathrm{p}}^{2} \cdot B_{\lambda}\left(T_{\mathrm{p}}\right)$$

Or, accounting for the non-blackbody nature of the atmosphere, we'd have:

$$F_{\mathrm{p}} \approx R_{\mathrm{p}}^{2} \cdot \varepsilon_{\lambda} B_{\lambda}\left(T_{\mathrm{p}}\right)$$

atmospheric emissivity



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Thus, emission spectra can provide constraints on:

atmospheric opacity
atmospheric temperature
planet size

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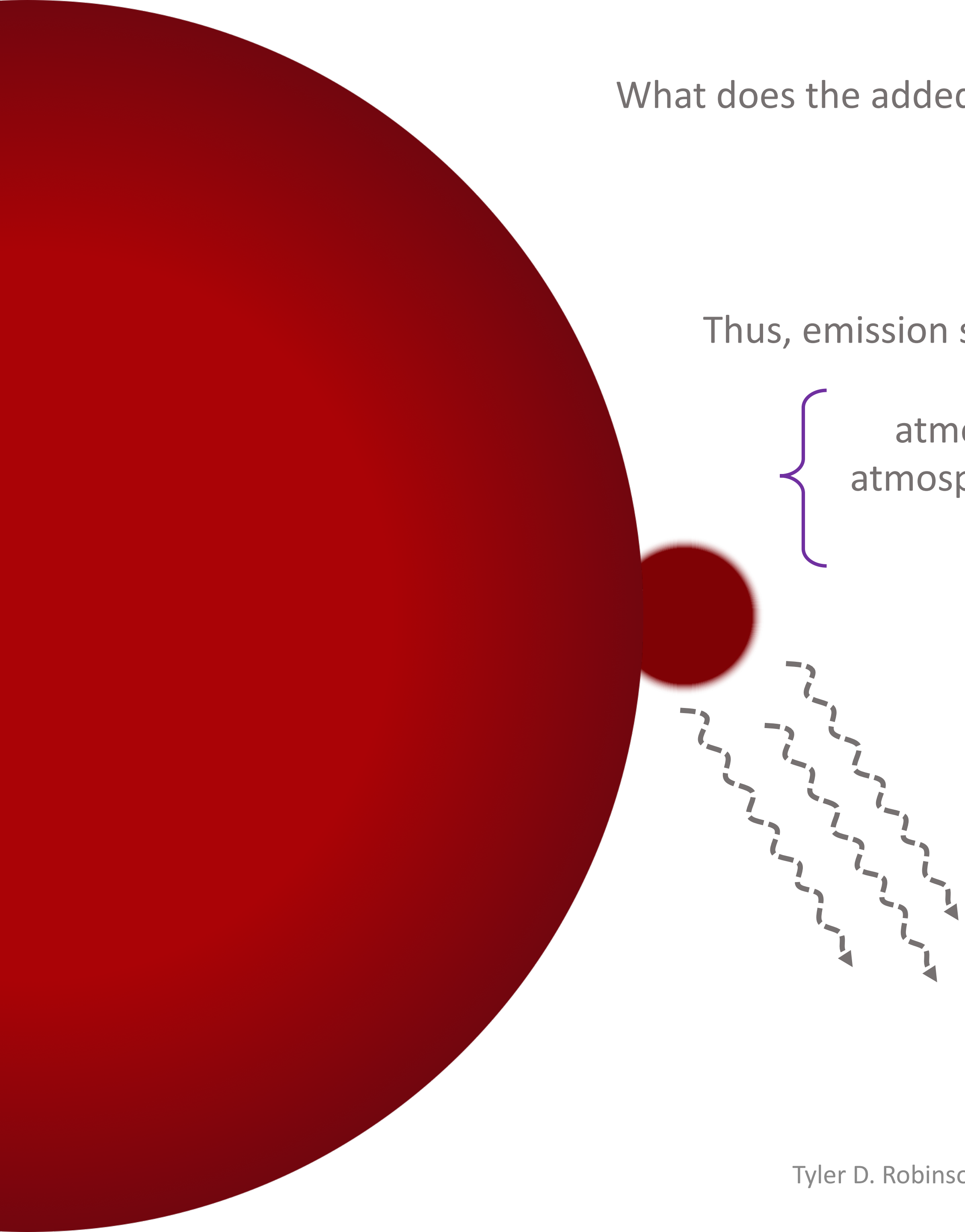

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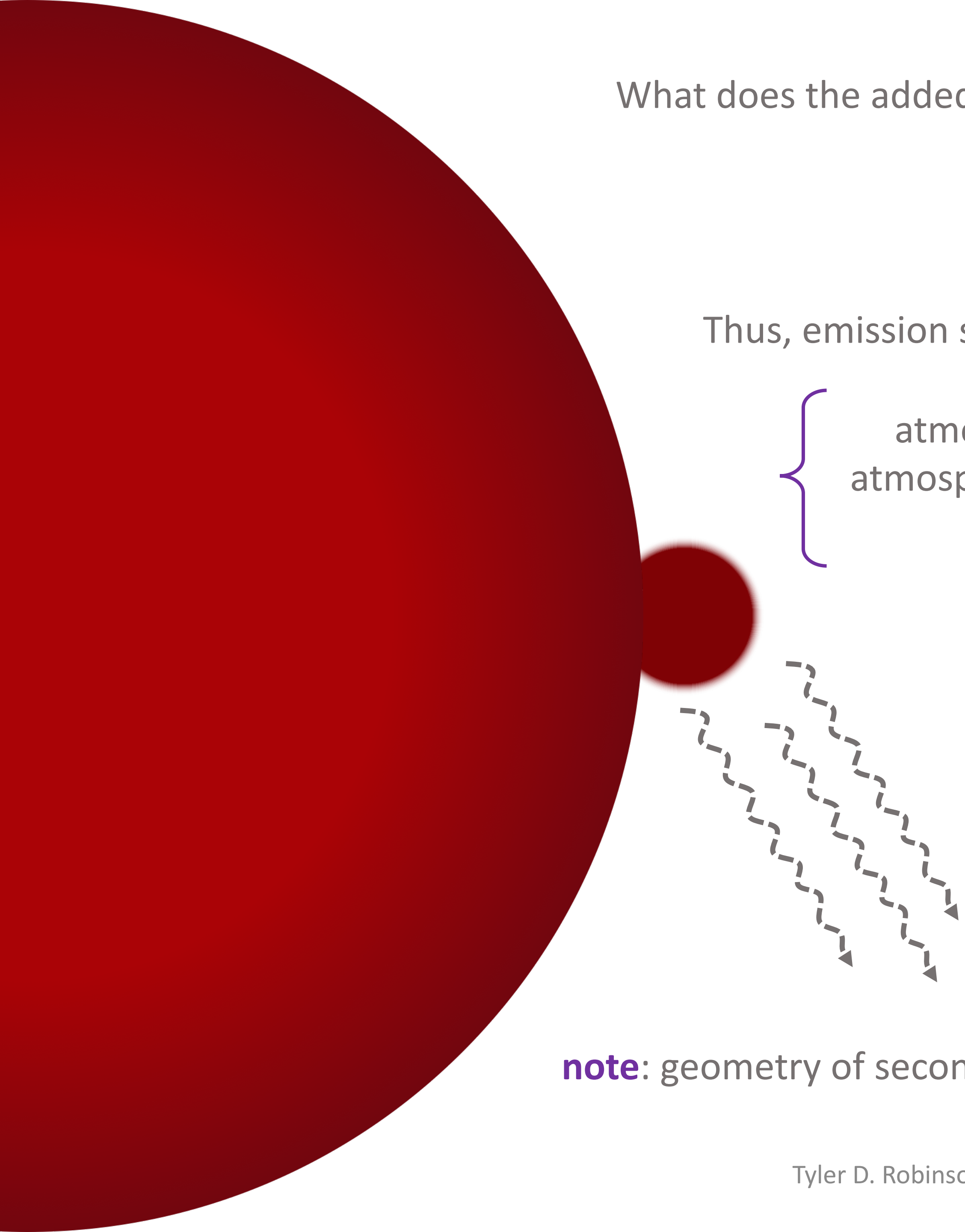
aerosols
atmospheric pressure

lapse rate (i.e., d*T*/d*p*)



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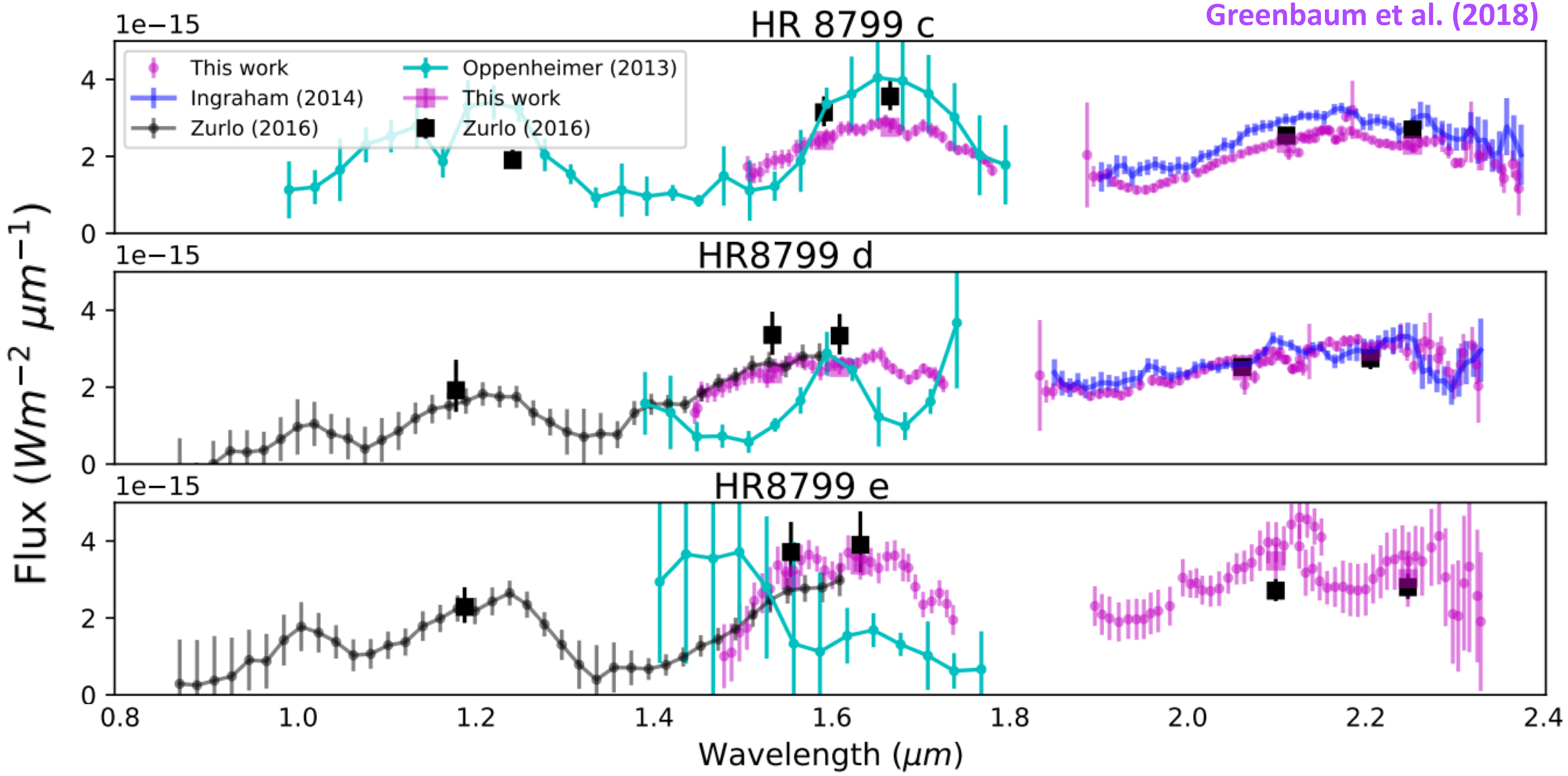
note: geometry of secondary eclipse allows for sensitivity to deep atmosphere / surface

Greenbaum et al. (2018)



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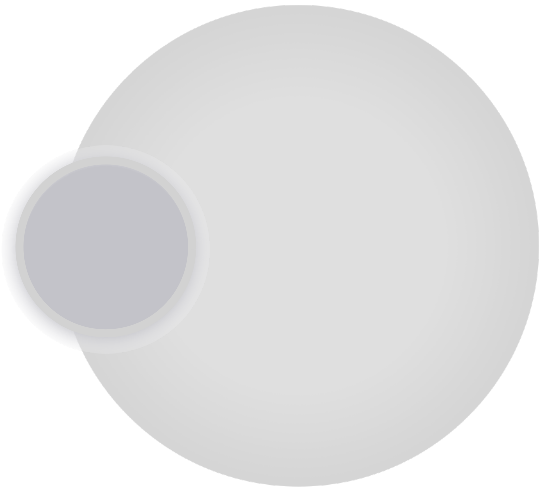

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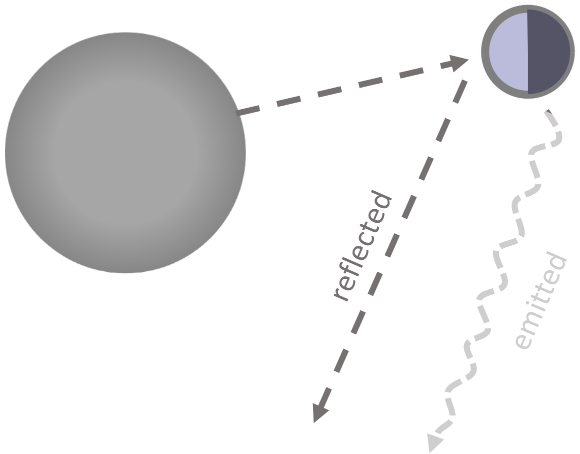
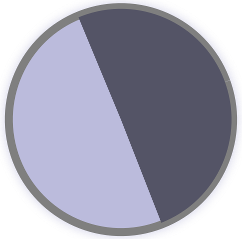
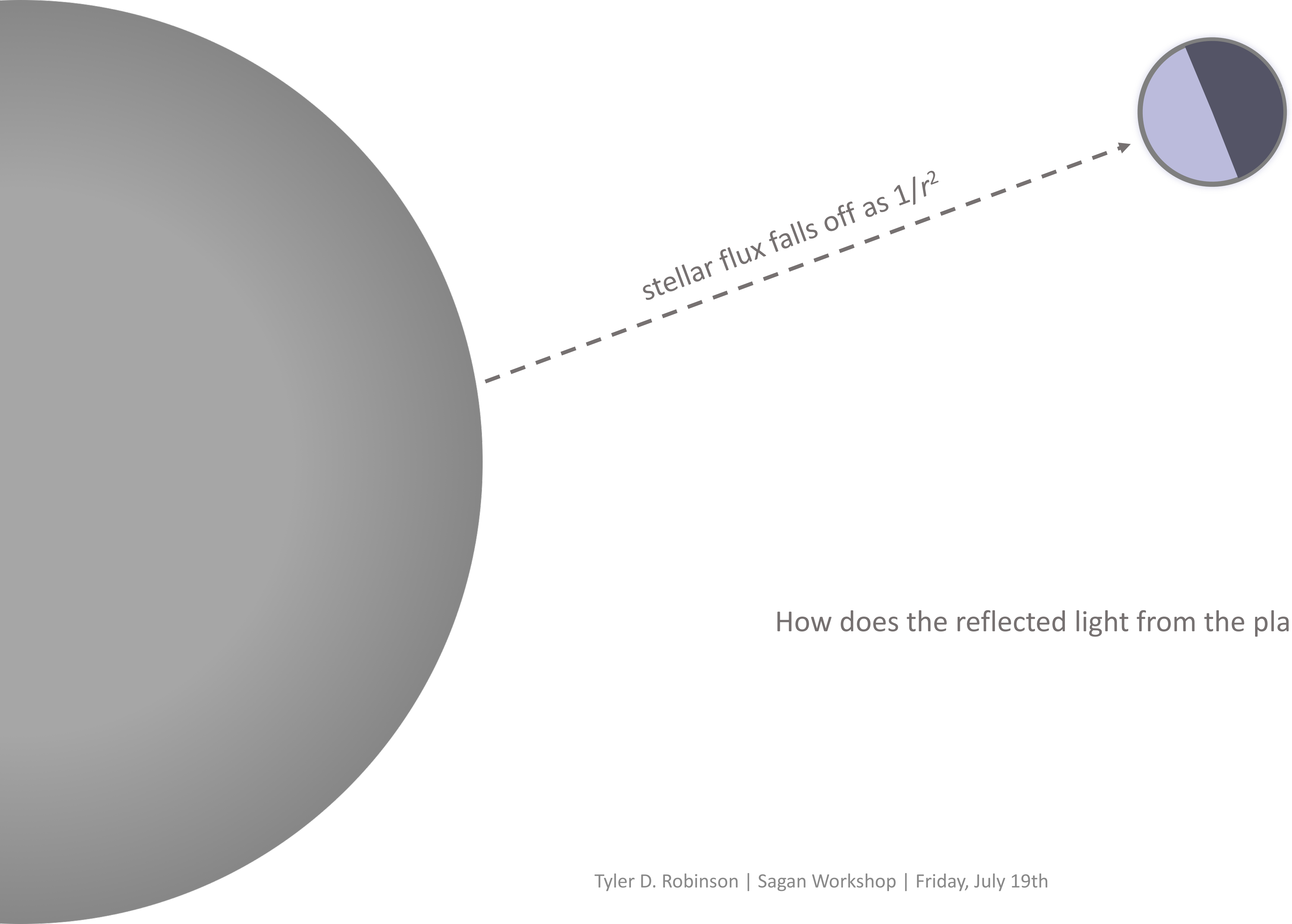
Direct Imaging





How does the reflected light from the planet scale?



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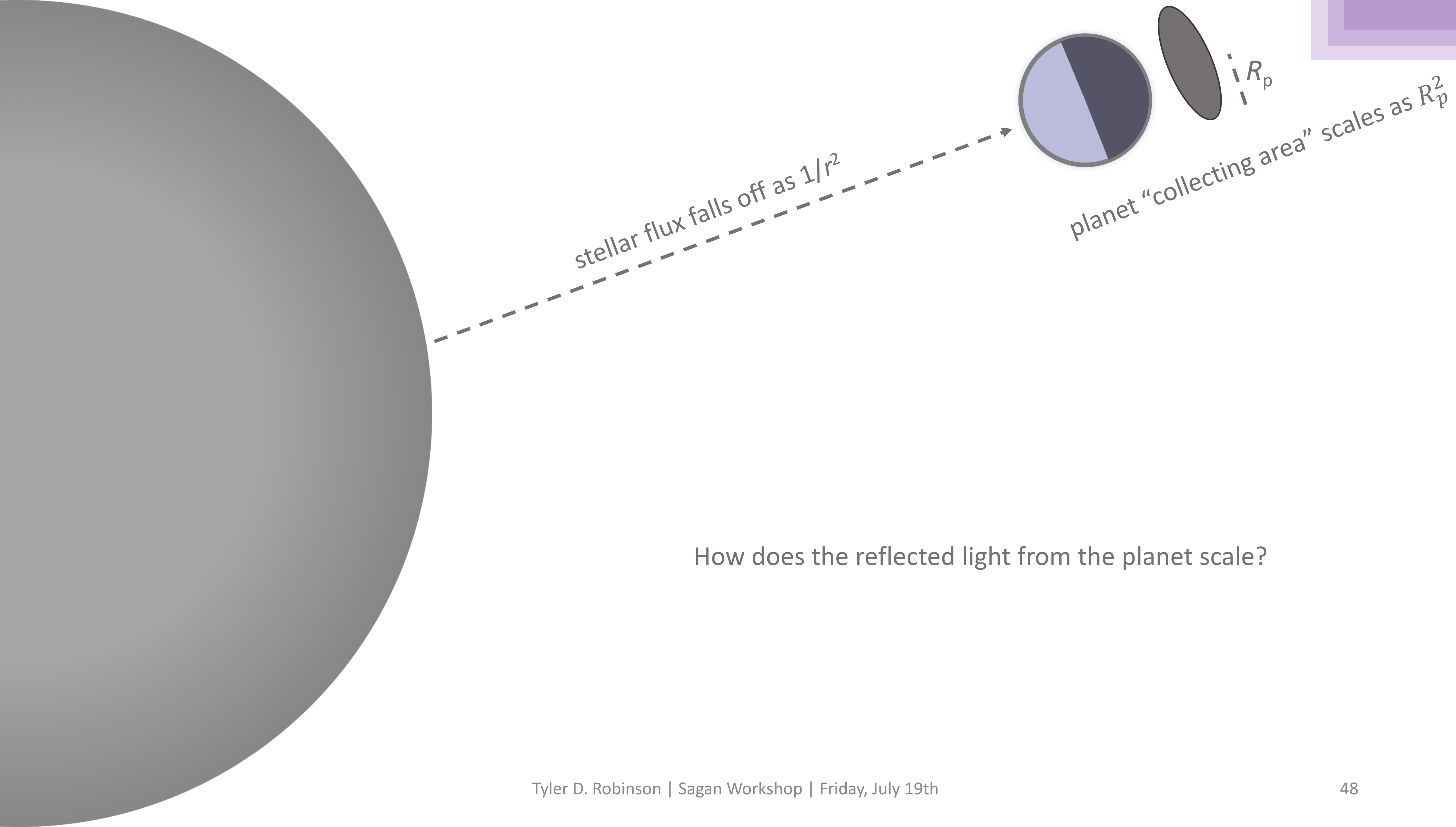

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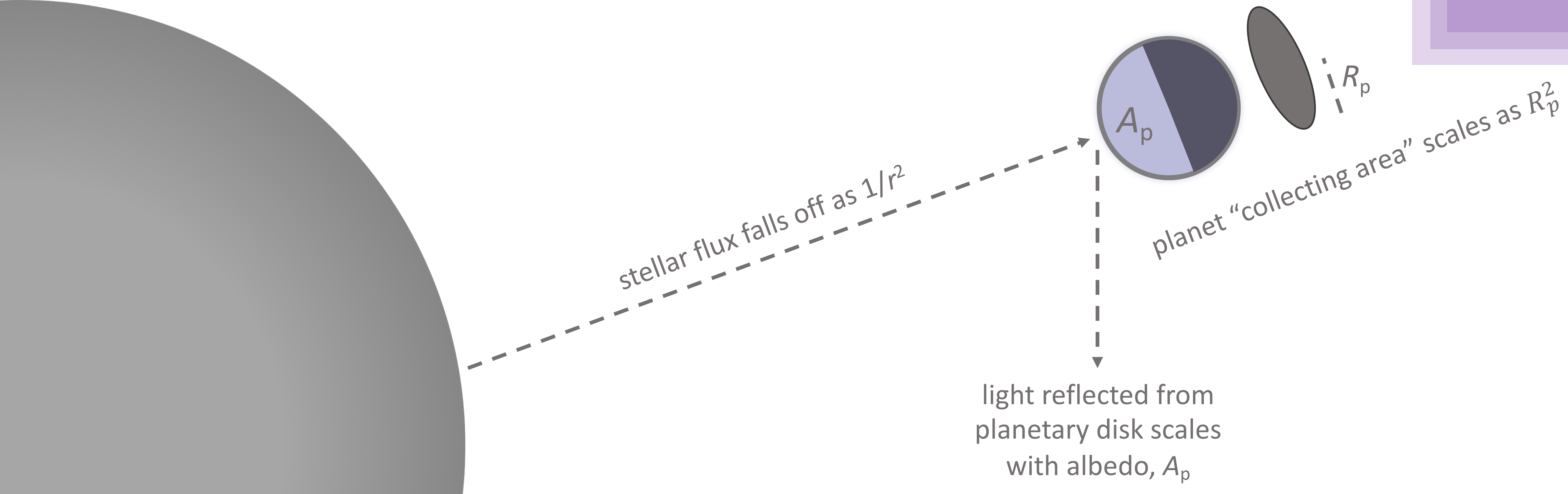
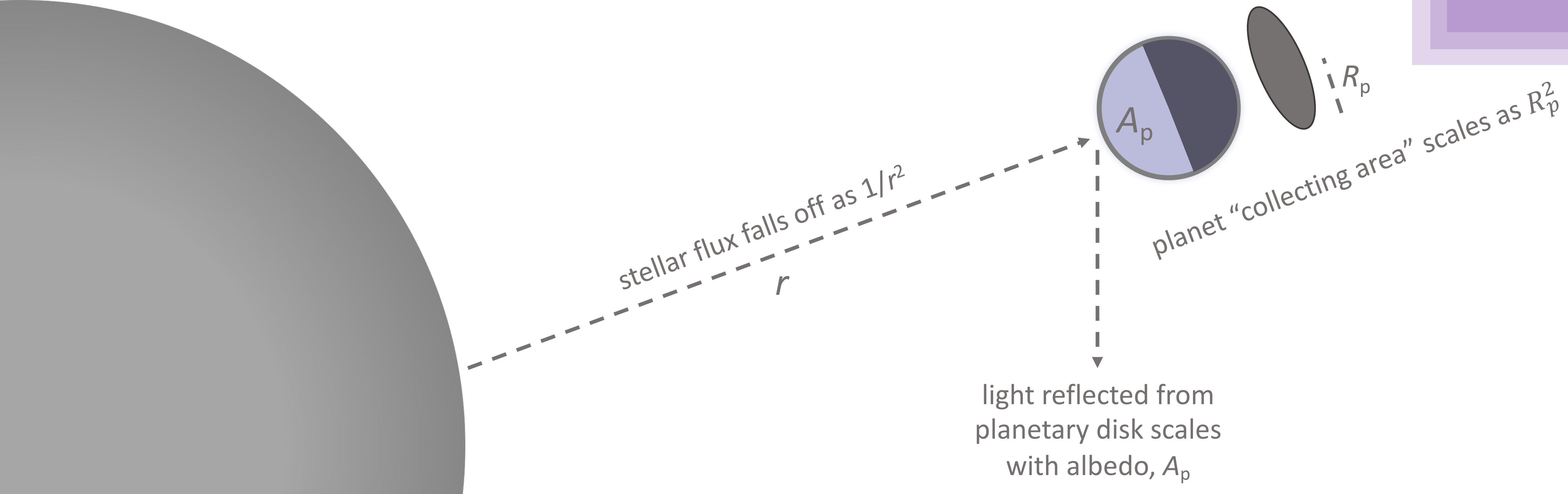
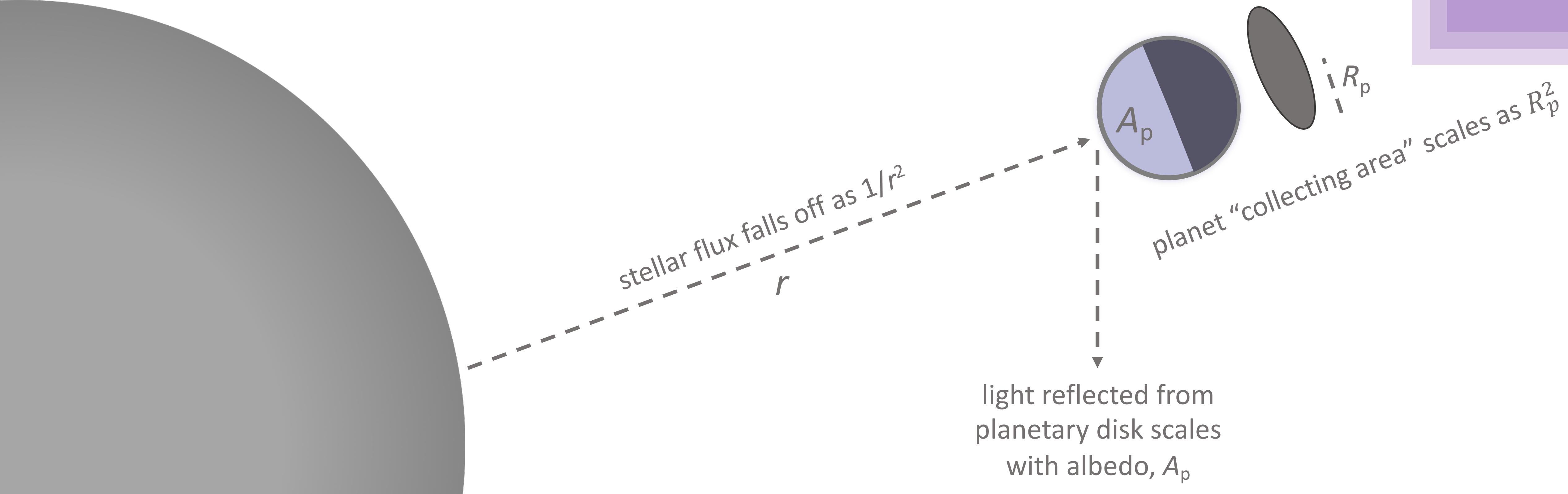


How does the reflected light from the planet scale?



How does the reflected light from the planet scale?

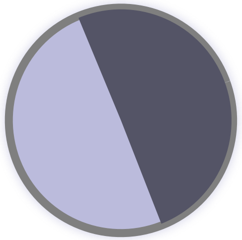
$$\frac{F_\mathrm{p}}{F_\mathrm{s}} = A_\mathrm{p}\phi(\alpha)\frac{R_\mathrm{p}^2}{r^2}$$



How does the reflected light from the planet scale?

$$\frac{F_{\mathrm{p}}}{F_{\mathrm{s}}} = A_{\mathrm{p}}\phi(\alpha)\frac{R_{\mathrm{p}}^2}{r^2}$$

phase function: how the reflectivity scales with phase angle, α

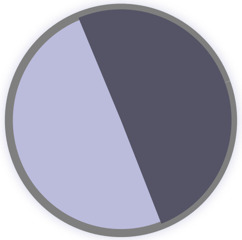


How does the reflected light from the planet scale?

$$\frac{F_\mathrm{p}}{F_\mathrm{s}} = A_\mathrm{p}\phi(\alpha)\frac{R_\mathrm{p}^2}{r^2}$$

Direct imaging in reflected light provides constraints on:

atmospheric opacity
surface reflectance
atmosphere/surface scattering
planet size
orbital distance



How does the reflected light from the planet scale?

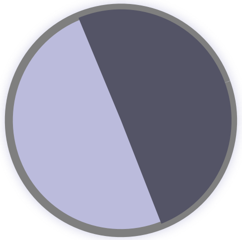
$$\frac{F_{\mathrm{p}}}{F_{\mathrm{s}}} = A_{\mathrm{p}}\phi(\alpha)\frac{R_{\mathrm{p}}^2}{r^2}$$

Direct imaging in reflected light provides constraints on:

atmospheric opacity
surface reflectance
atmosphere/surface scattering
planet size
orbital distance

atmospheric composition
atmospheric pressure
aerosols

surface composition



How does the reflected light from the planet scale?

$$\frac{F_{\mathrm{p}}}{F_{\mathrm{s}}} = A_{\mathrm{p}}\phi(\alpha)\frac{R_{\mathrm{p}}^{2}}{r^{2}}$$

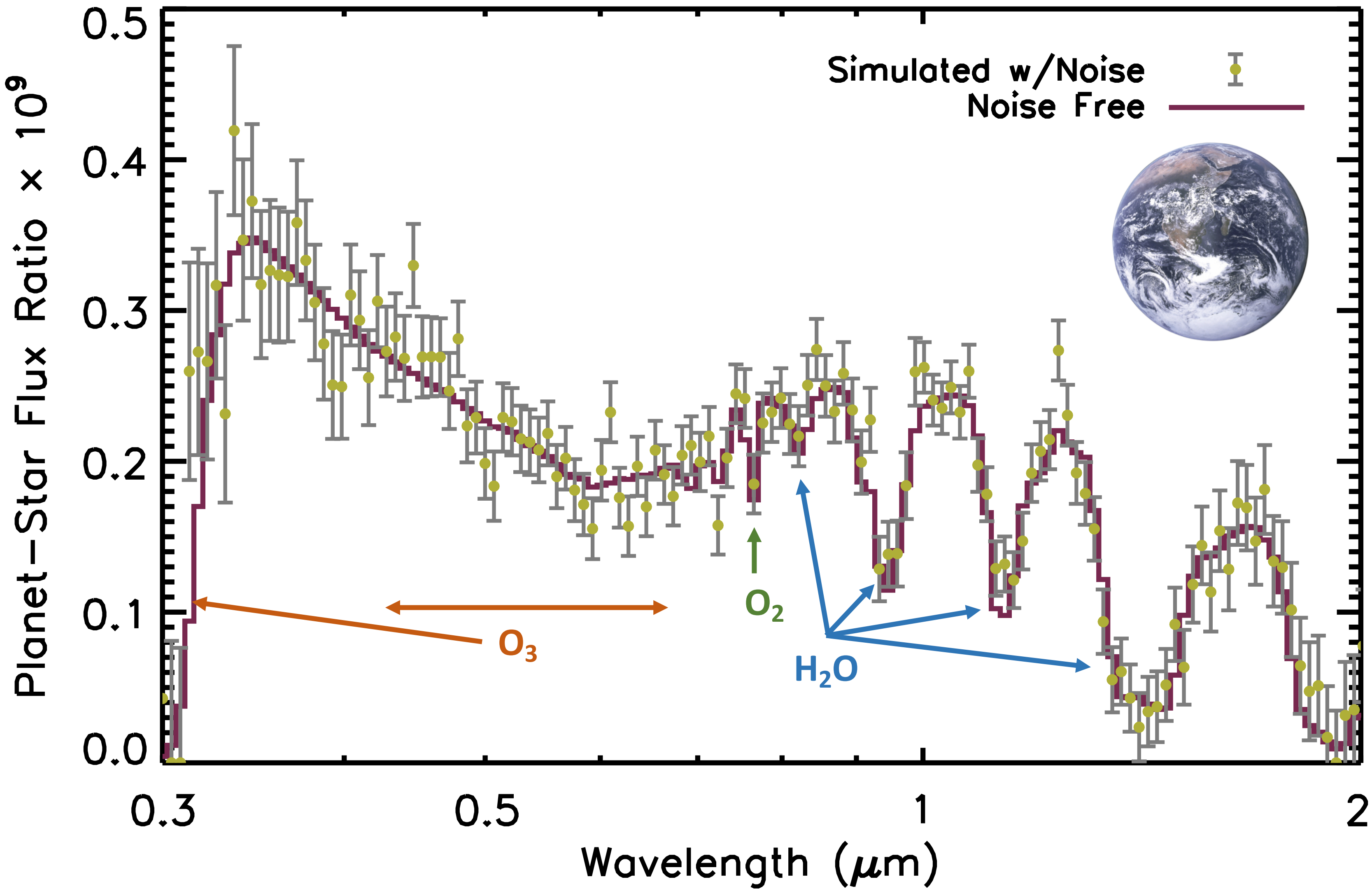
note: potential for degeneracies!

Direct imaging in reflected light provides constraints on:

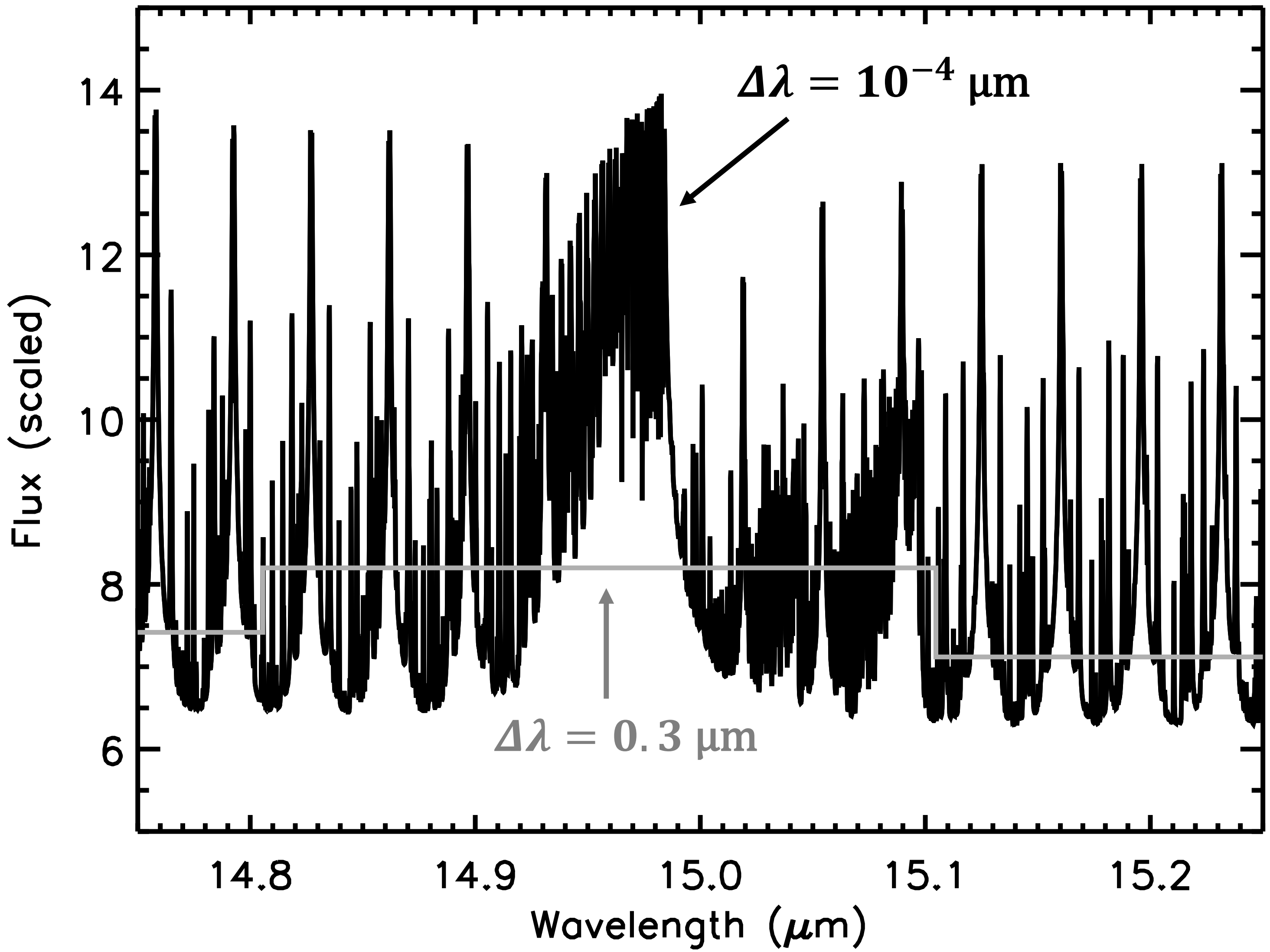
atmospheric opacity
surface reflectance
atmosphere/surface scattering
planet size
orbital distance

atmospheric composition
atmospheric pressure
aerosols

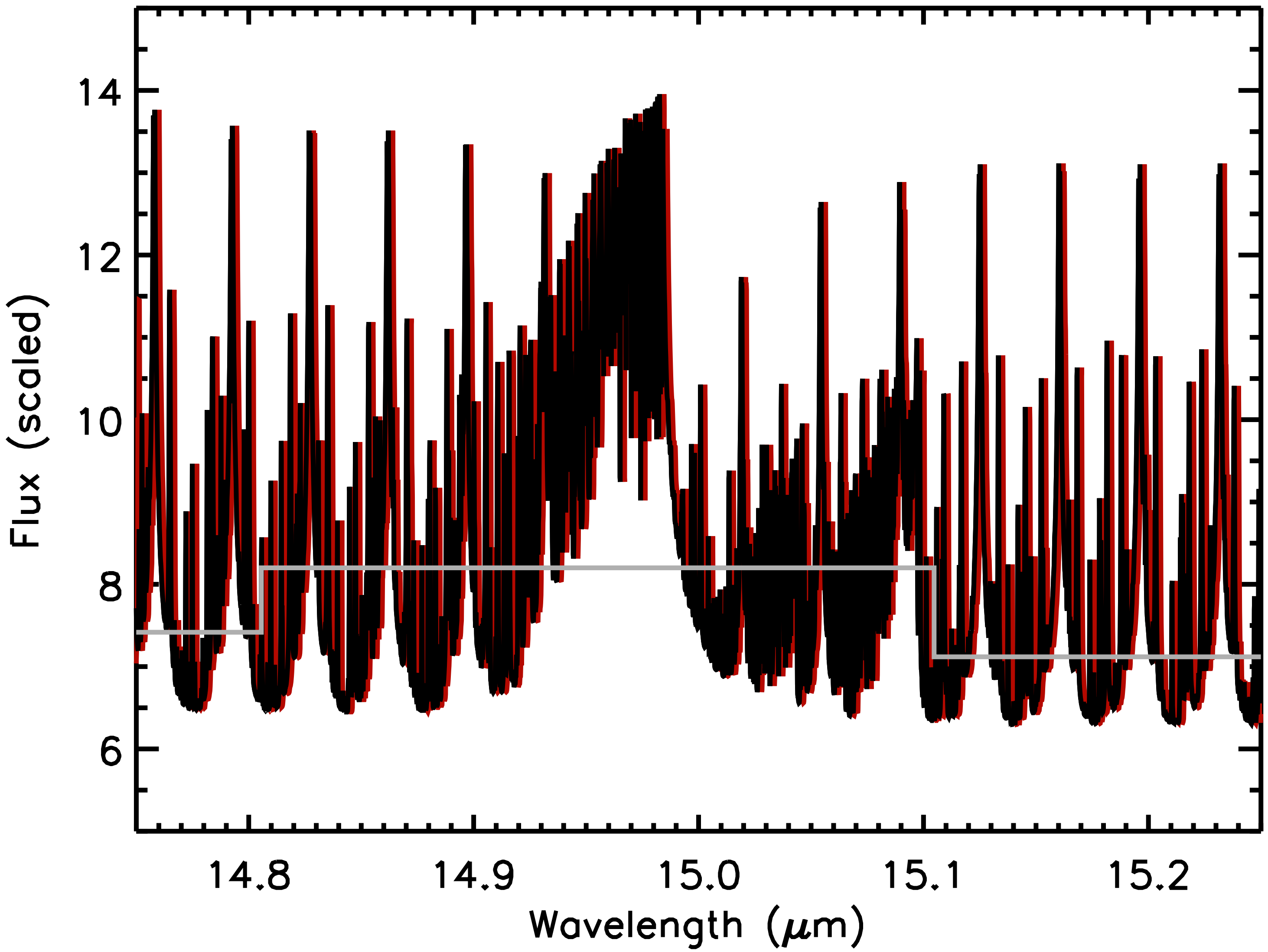
surface composition


Simulated w/Noise
Noise Free
Planet–Star Flux Ratio × 10^9
0.5
0.4
0.3
0.2
0.1
0.0
0.3
0.5
1
2
Wavelength (μm)
O_3
O_2
H_2O

Spectral Resolution

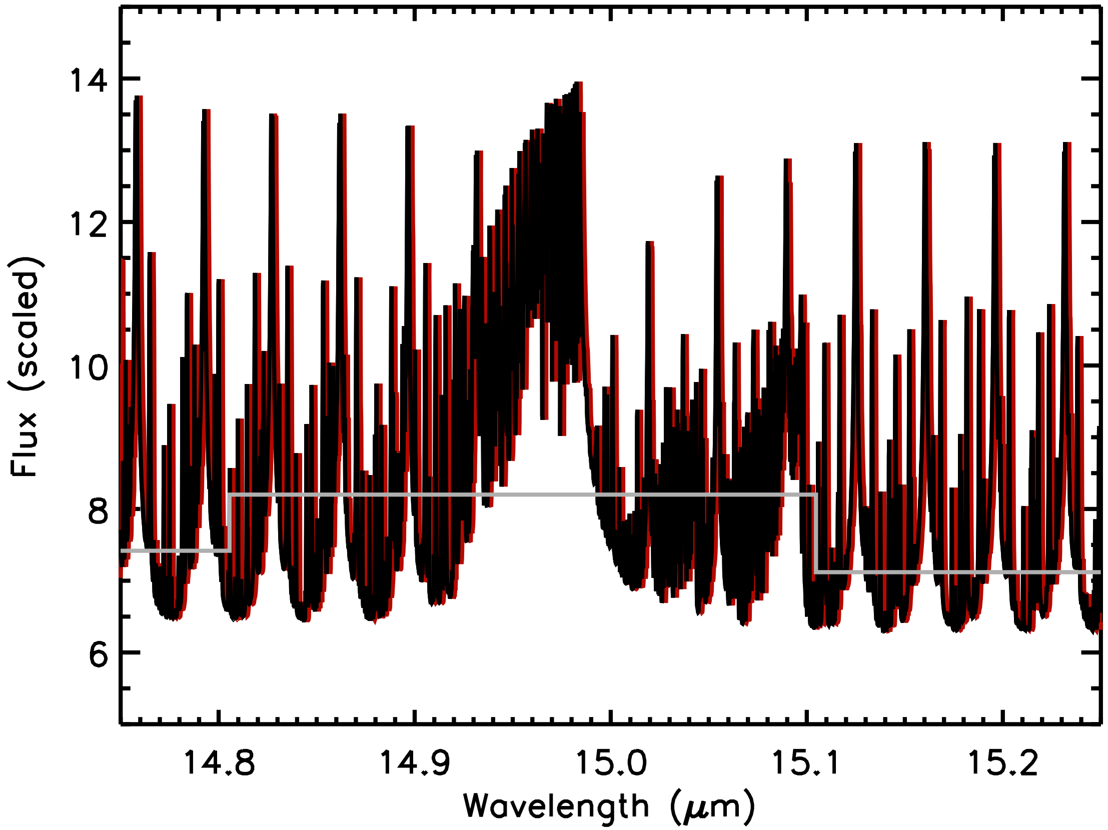


Spectral Resolution



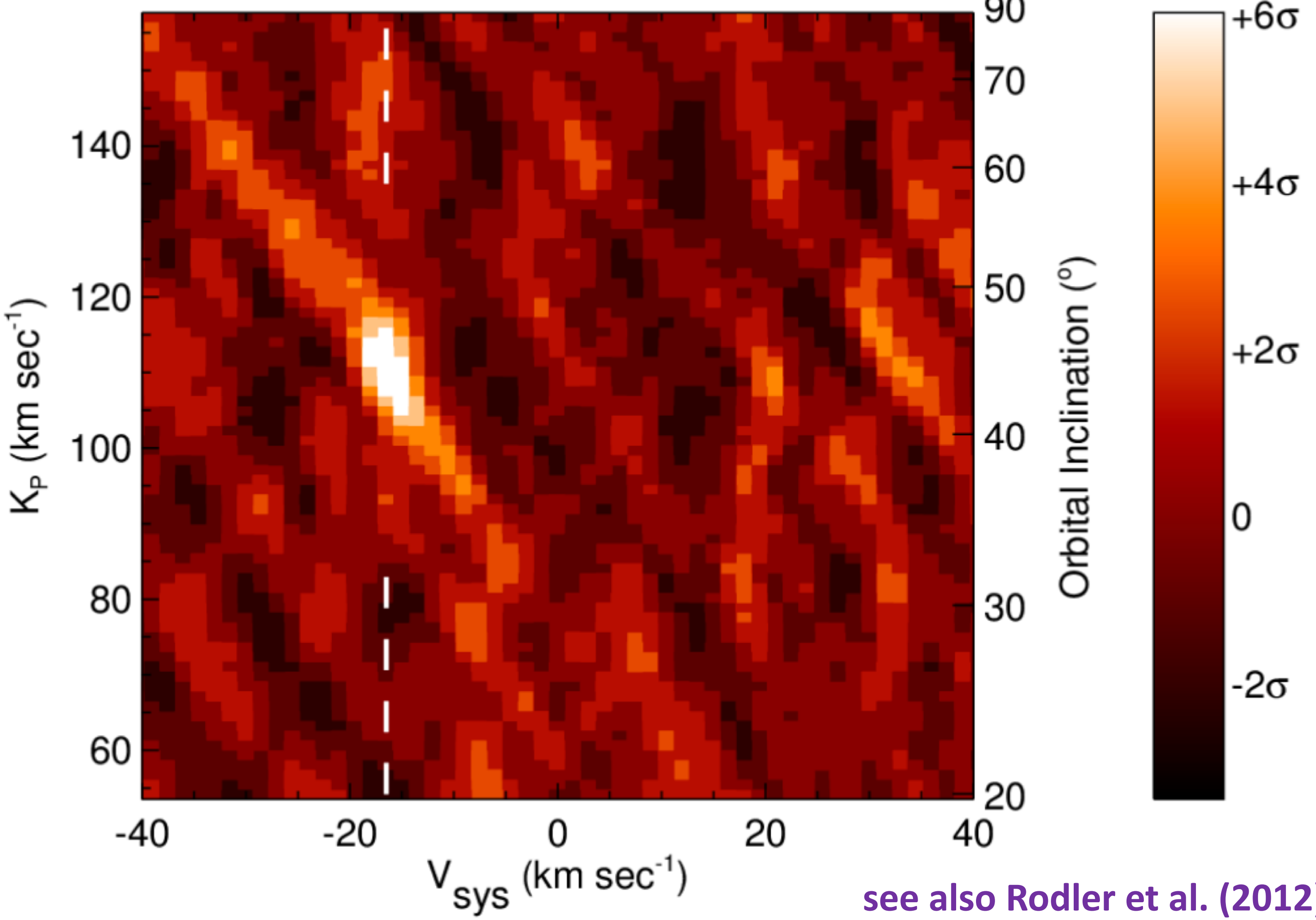
Spectral Resolution

- hi-res observations can be sensitive to Doppler shifts due to orbital motions or planetary winds
- integrating information across wavelength (via a cross-correlation) can yield gas species detections even with low-SNR spectra
- planet light need not be separated from star light
- well-suited to ground-based facilities (larger apertures better enable hi-res observations)



Spectral Resolution

Brogi et al. (2012)

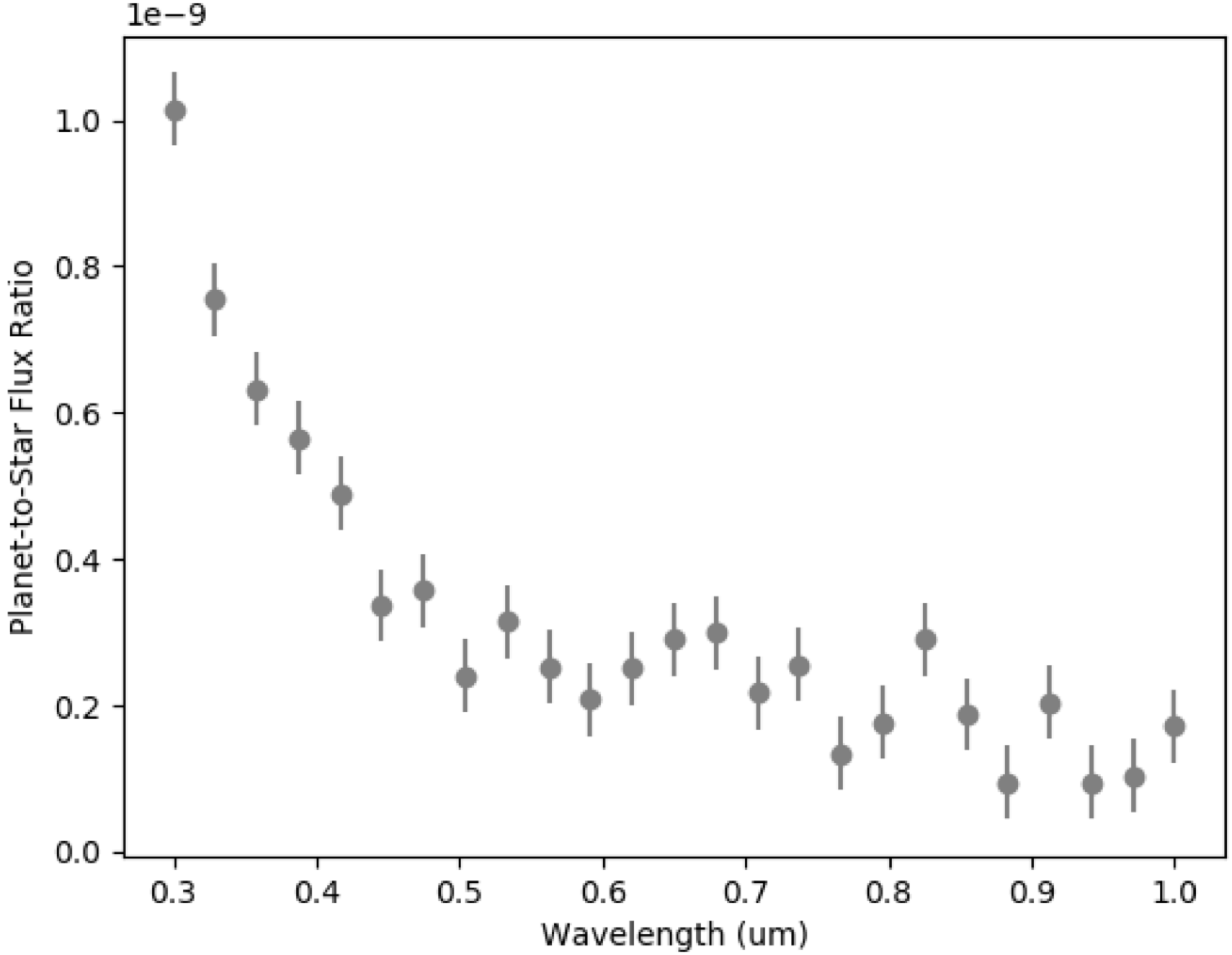


Tau Boötis b

see also Rodler et al. (2012)

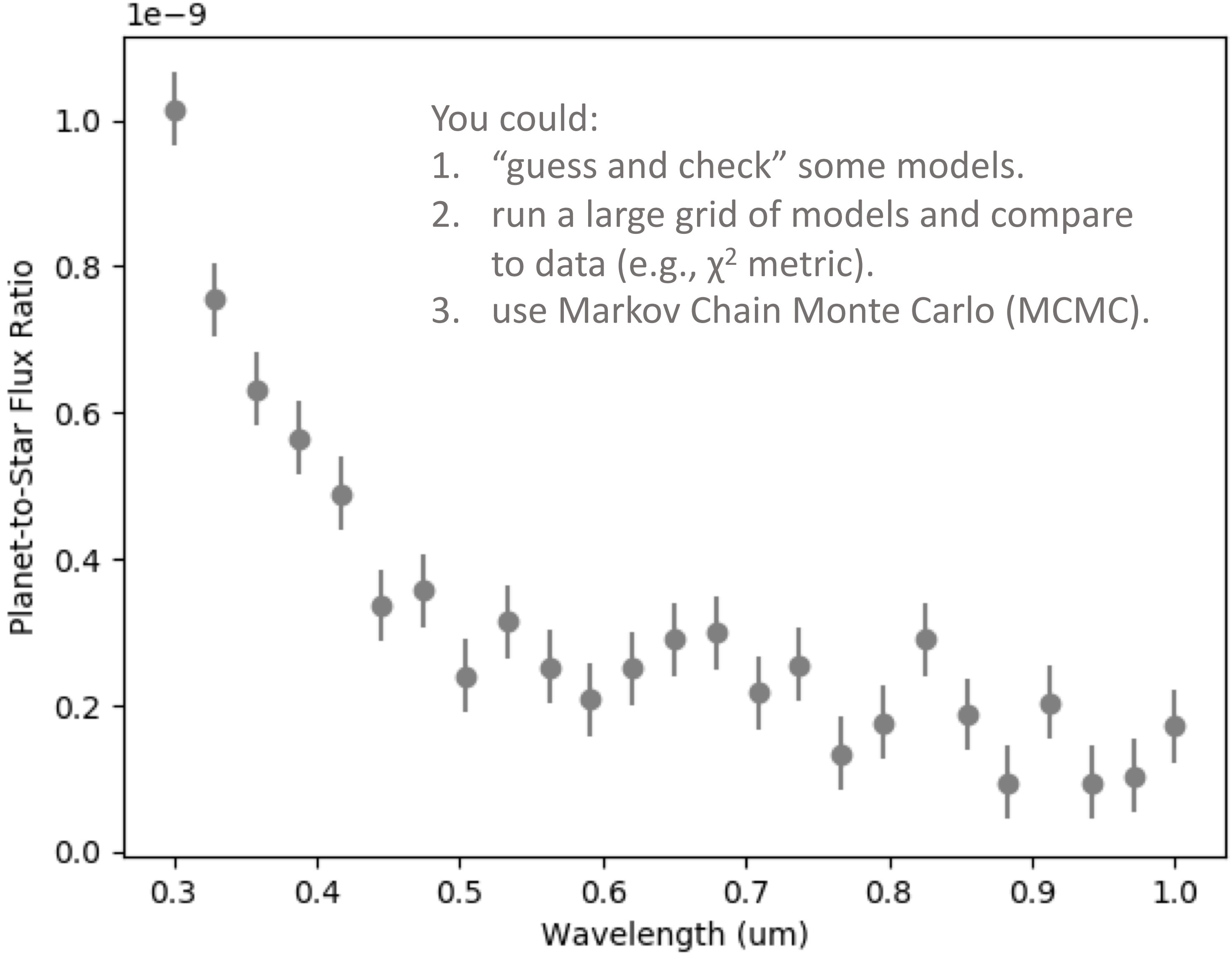
note: *not* even a transiting exoplanet

Given a spectrum, how do we say something about the state of an exoplanet atmosphere?

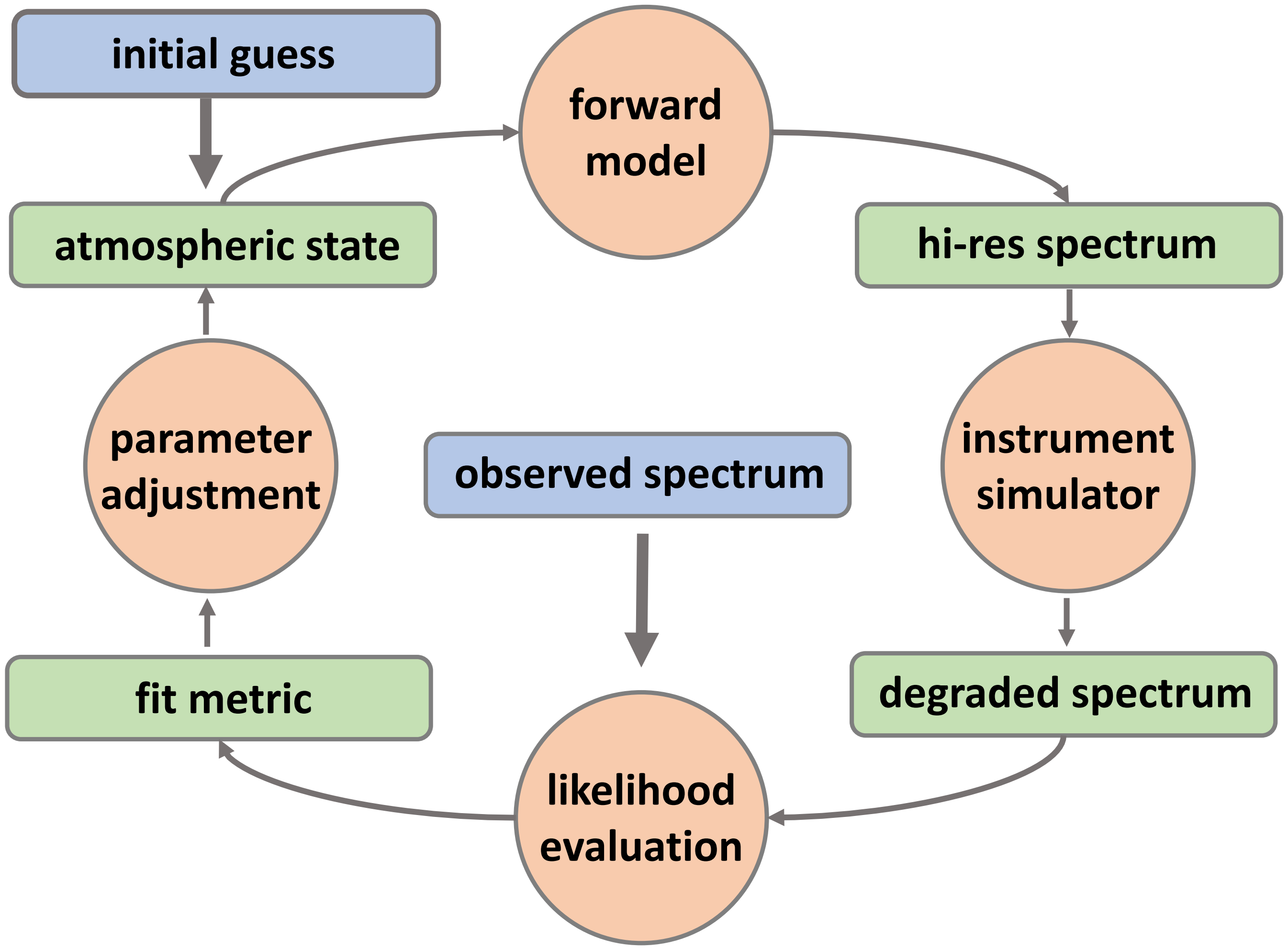

1e−9
1.0
0.8
0.6
0.4
0.2
0.0
Planet-to-Star Flux Ratio
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (um)

You could:

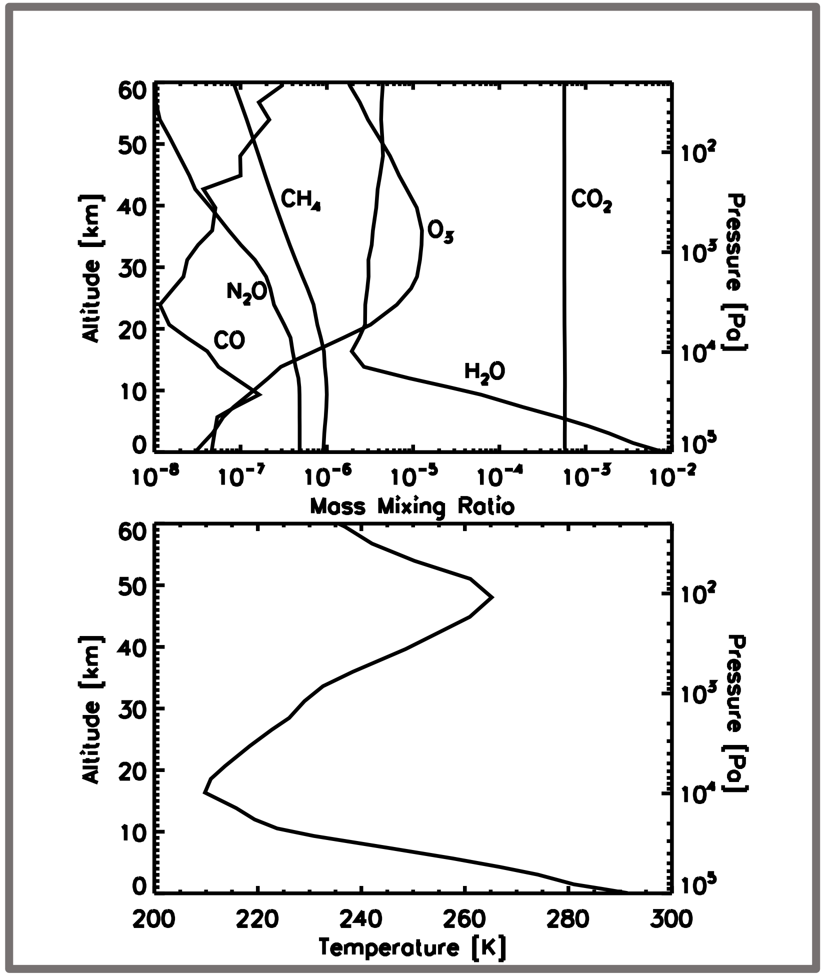
1. “guess and check” some models.
2. run a large grid of models and compare to data (e.g., χ^2 metric).
3. use Markov Chain Monte Carlo (MCMC).



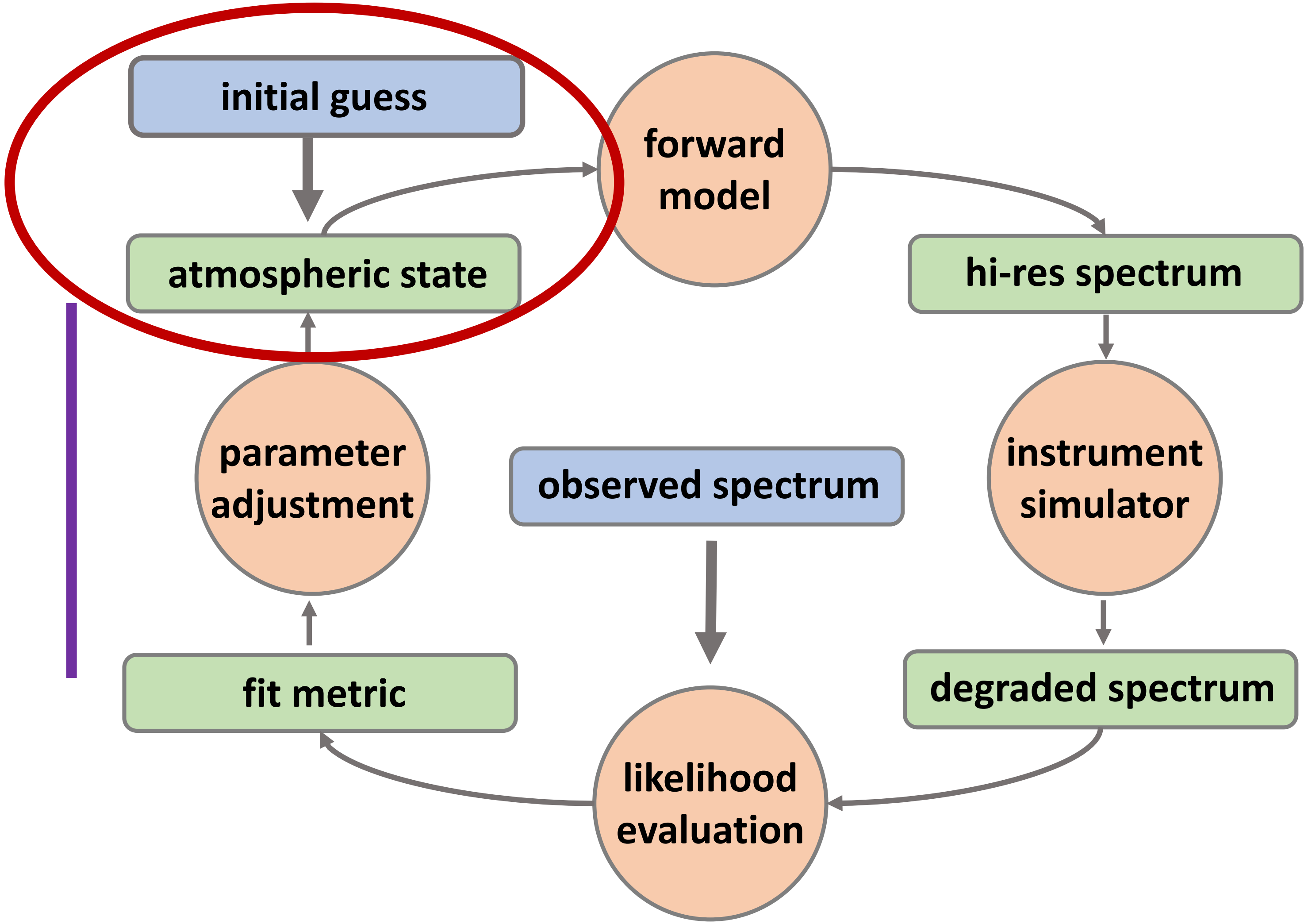
Retrieval


initial guess
forward model
atmospheric state
hi-res spectrum
parameter adjustment
observed spectrum
instrument simulator
fit metric
degraded spectrum
likelihood evaluation

Retrieval



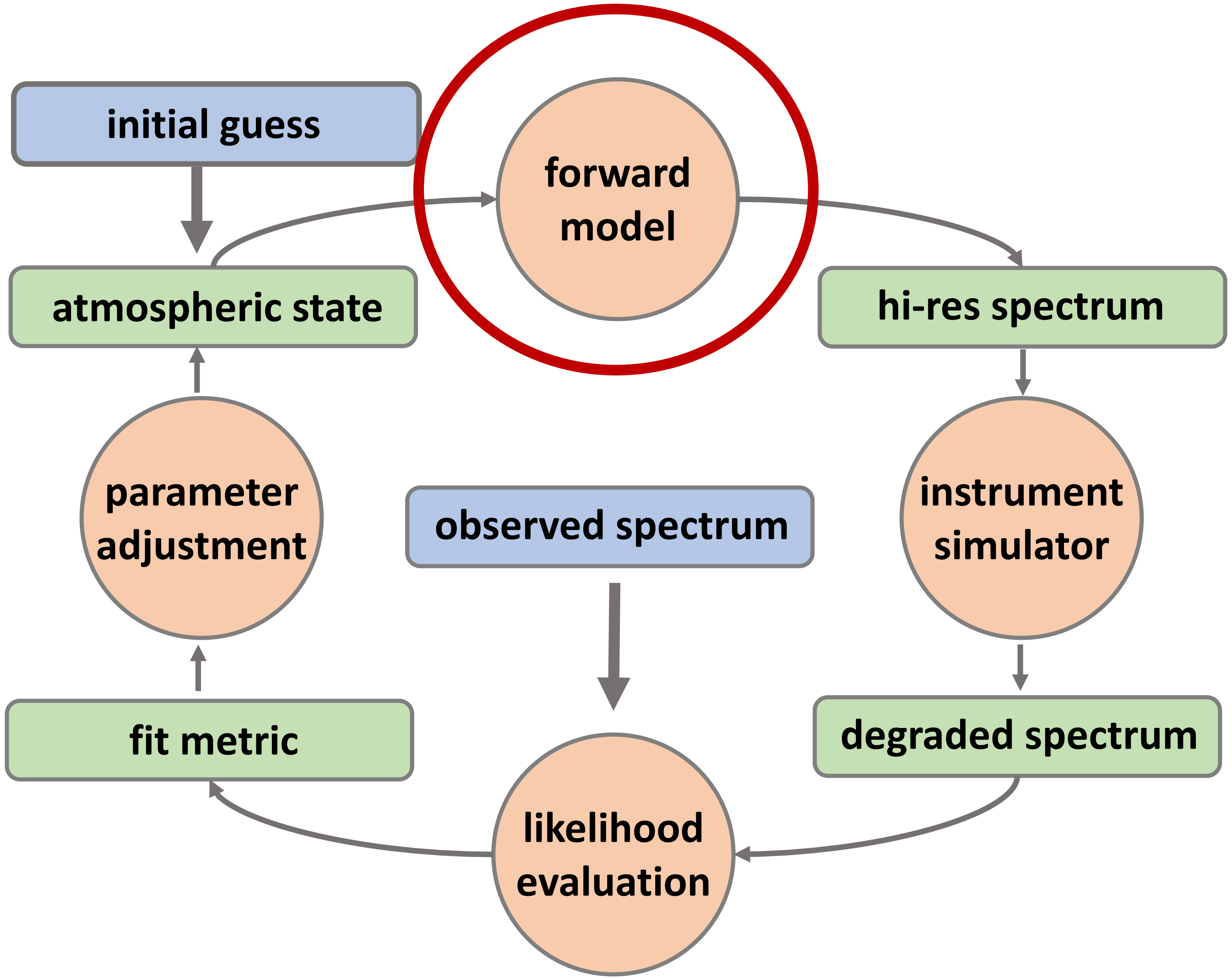
Altitude [km]
Pressure [Pa]
Mass Mixing Ratio
CH4
CO2
O3
N2O
CO
H2O
Temperature [K]



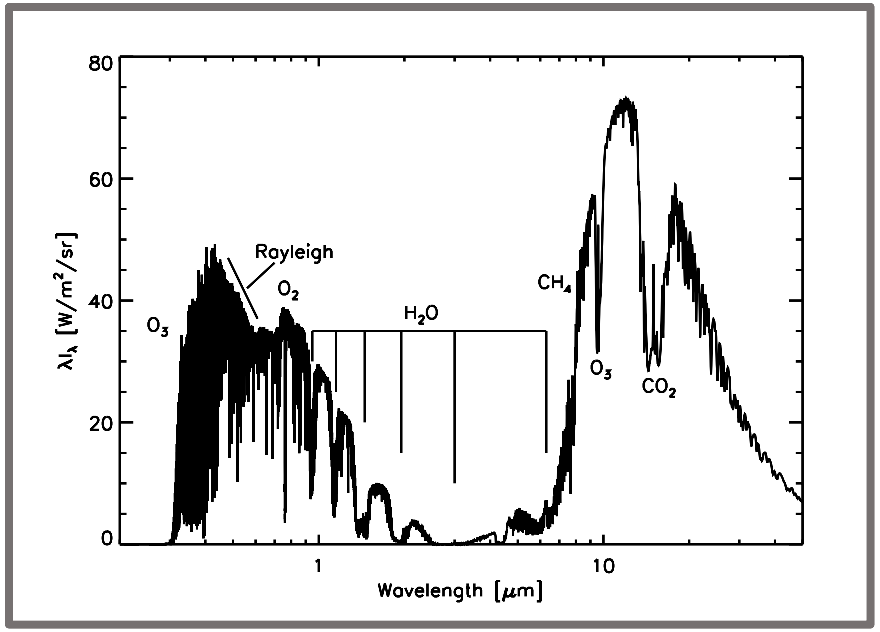
initial guess
atmospheric state
forward model
hi-res spectrum
instrument simulator
degraded spectrum
likelihood evaluation
observed spectrum
fit metric
parameter adjustment

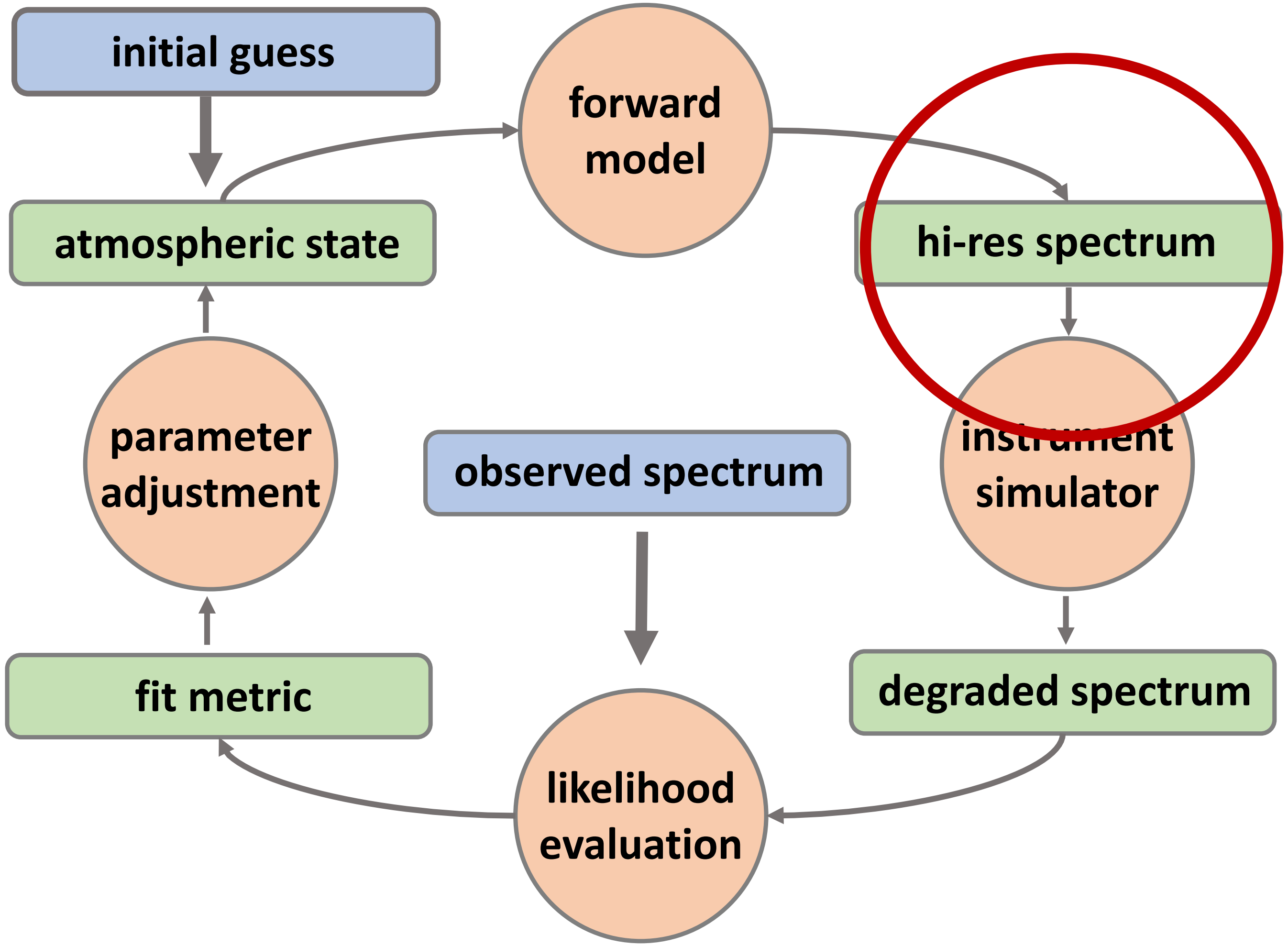
Retrieval

(i.e., a radiative transfer model)

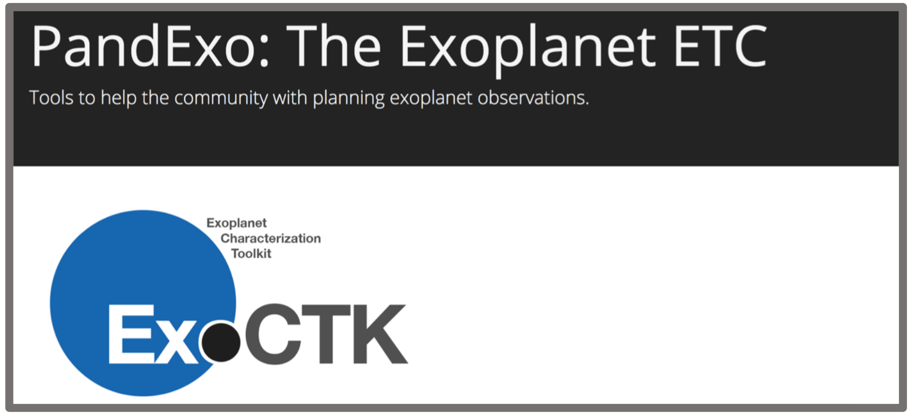


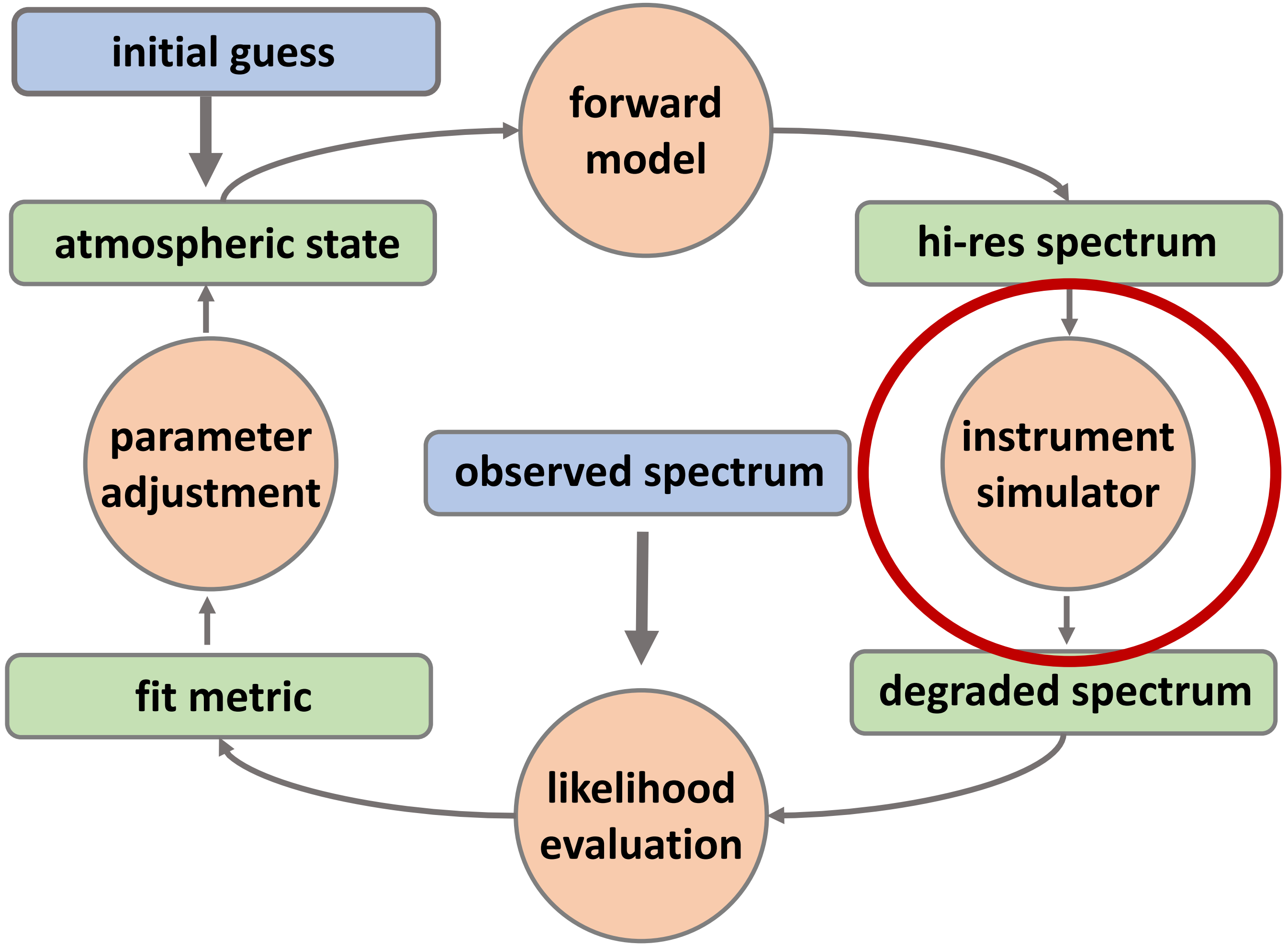
Retrieval


80
60
40
20
0
λI_λ [W/m^2/sr]
Rayleigh
O_2
O_3
H_2O
CH_4
O_3
CO_2
1
10
Wavelength [μm]

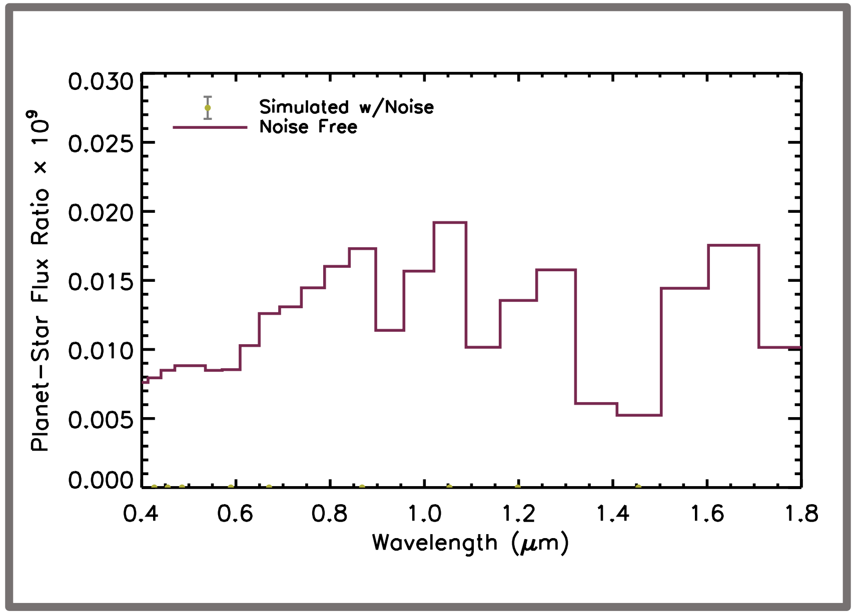

initial guess
forward model
atmospheric state
hi-res spectrum
parameter adjustment
observed spectrum
instrument simulator
fit metric
degraded spectrum
likelihood evaluation

Retrieval

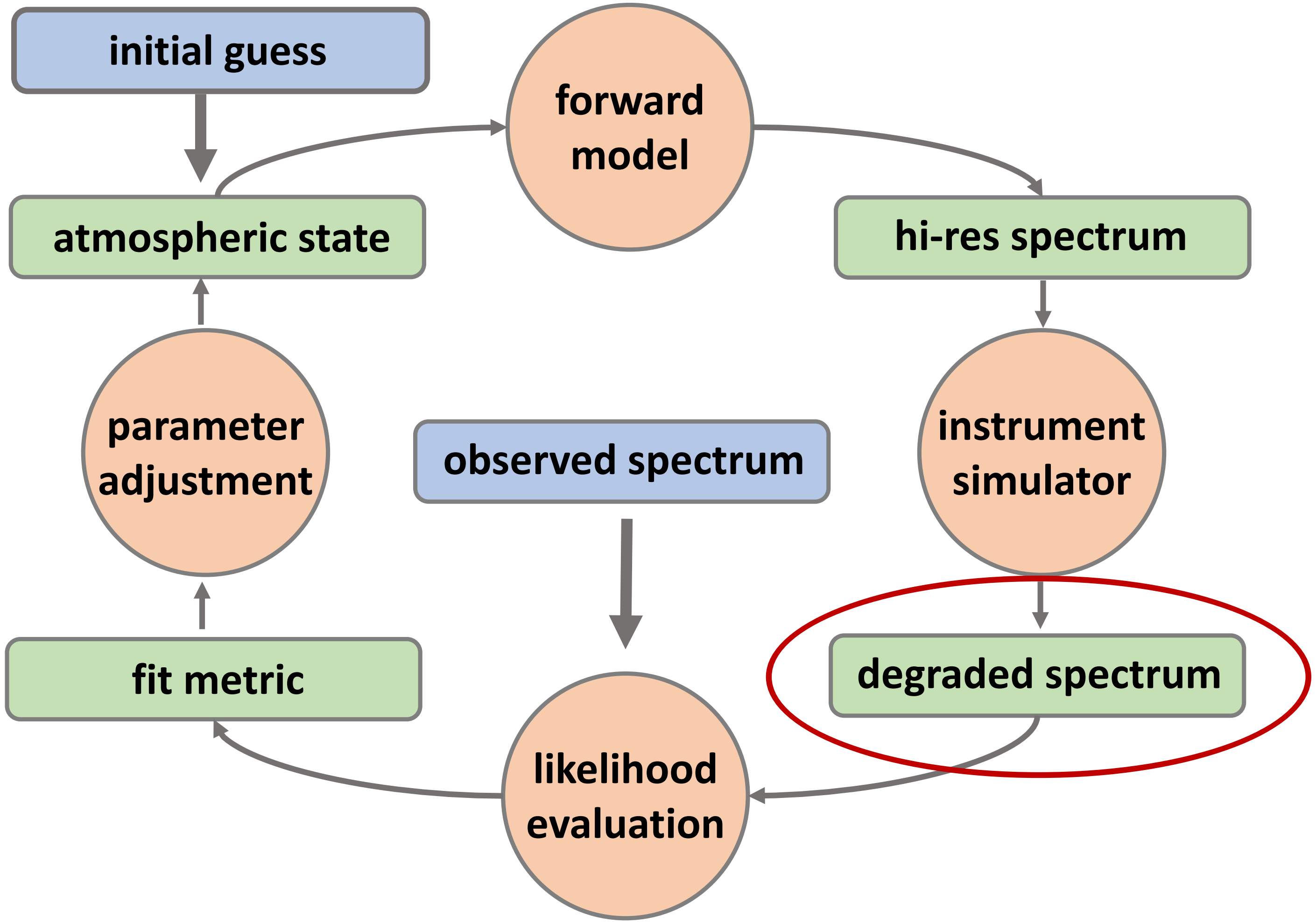

PandExo: The Exoplanet ETC
Tools to help the community with planning exoplanet observations.
Exoplanet
Characterization
Toolkit
ExoCTK


initial guess
forward model
atmospheric state
hi-res spectrum
parameter adjustment
observed spectrum
instrument simulator
fit metric
degraded spectrum
likelihood evaluation

Retrieval



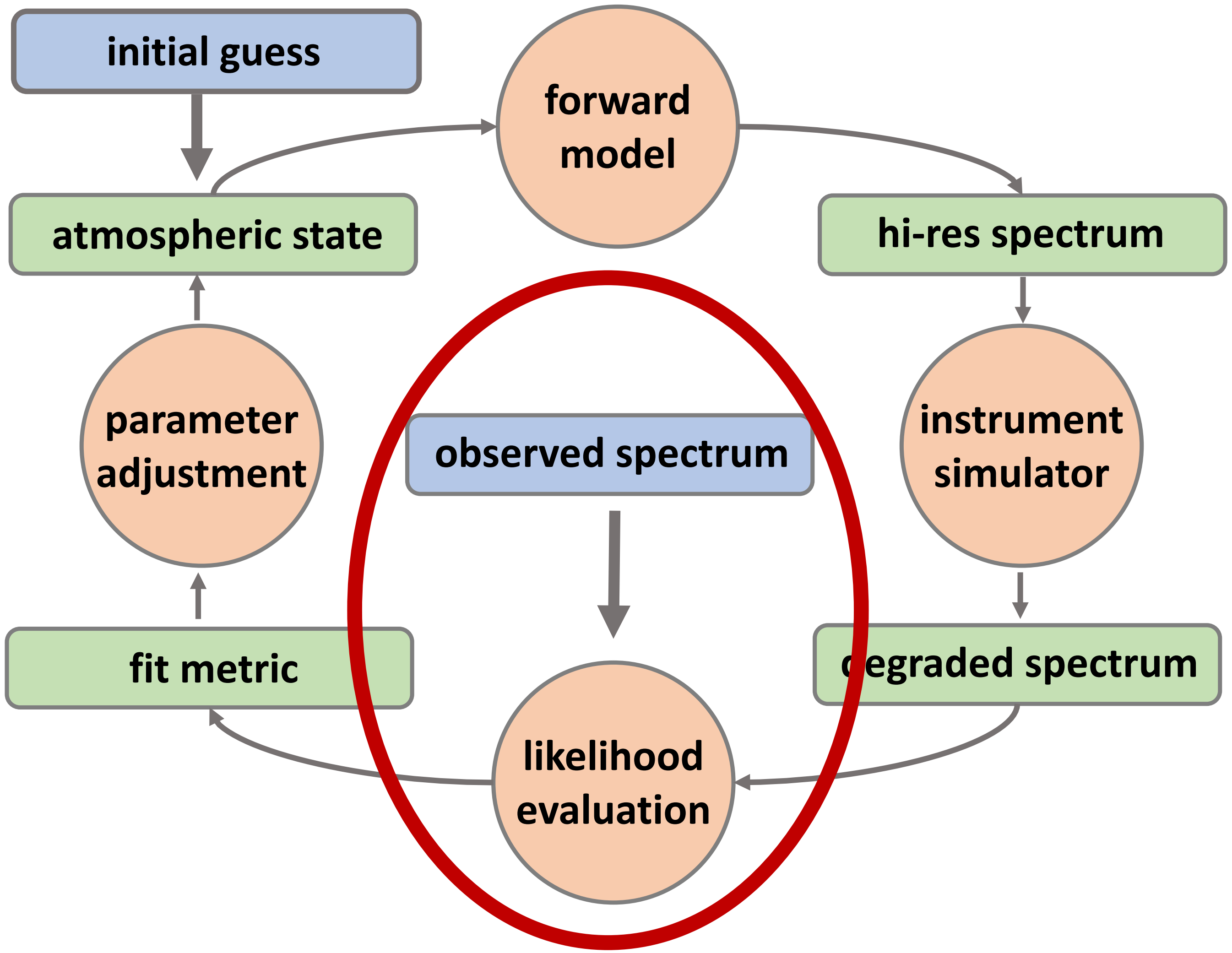
Simulated w/Noise
Noise Free
Planet−Star Flux Ratio × 10⁹
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Wavelength (μm)



initial guess
forward model
atmospheric state
hi-res spectrum
parameter adjustment
observed spectrum
instrument simulator
degraded spectrum
fit metric
likelihood evaluation

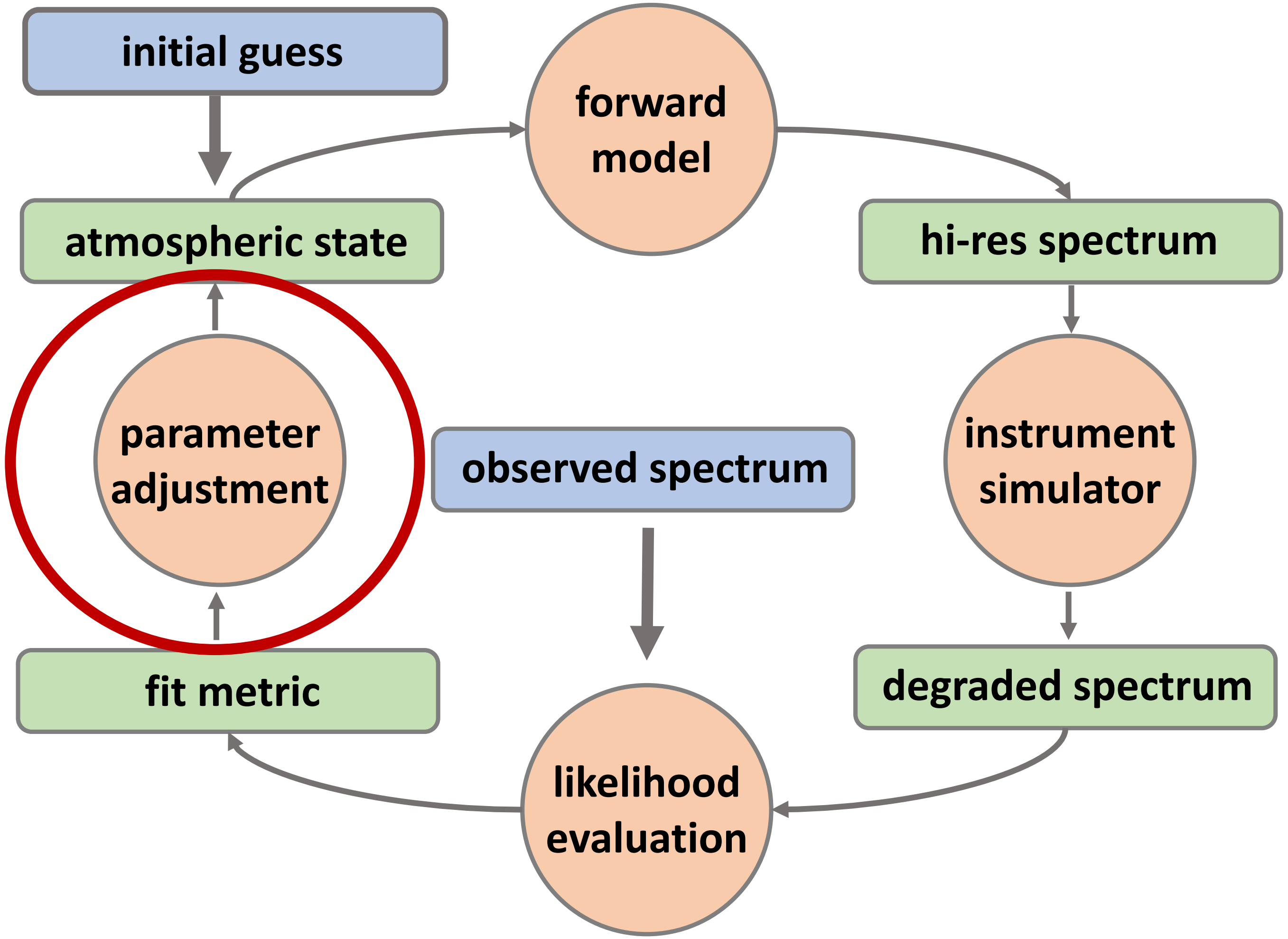
Retrieval

$$(\text{e.g., } \chi^2 = \sum_i \frac{(d_i - m_i)^2}{\sigma_i^2})$$

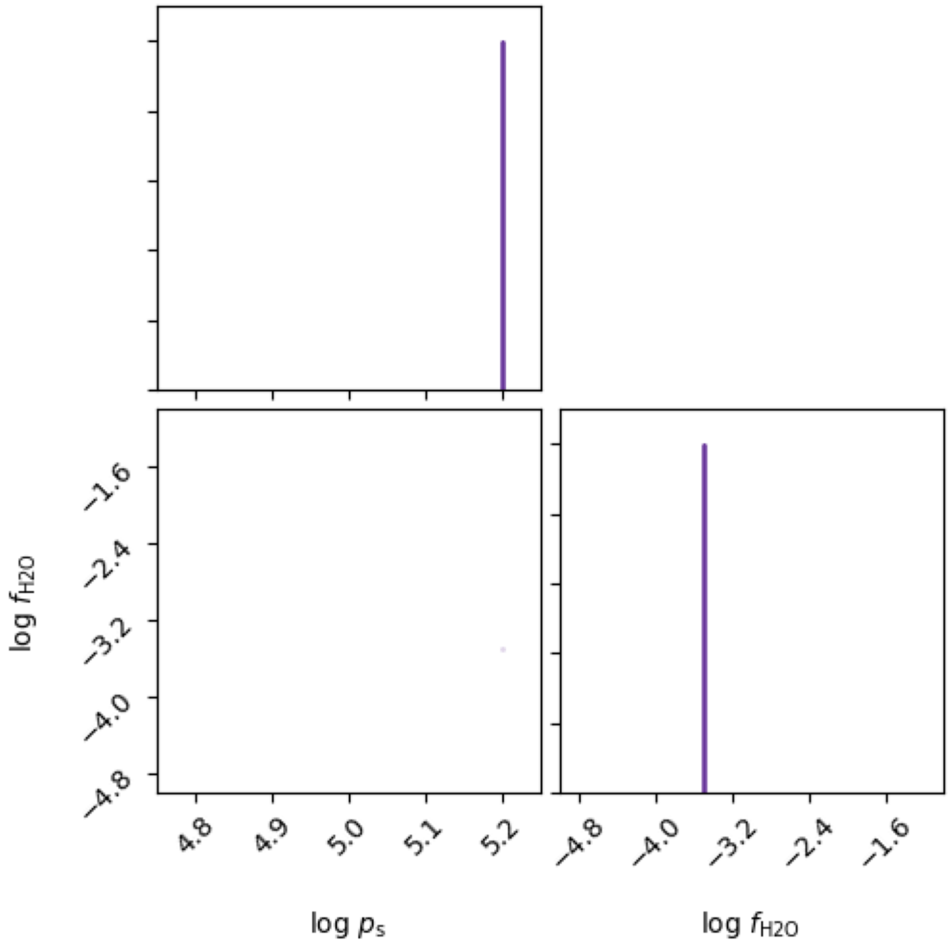


Retrieval

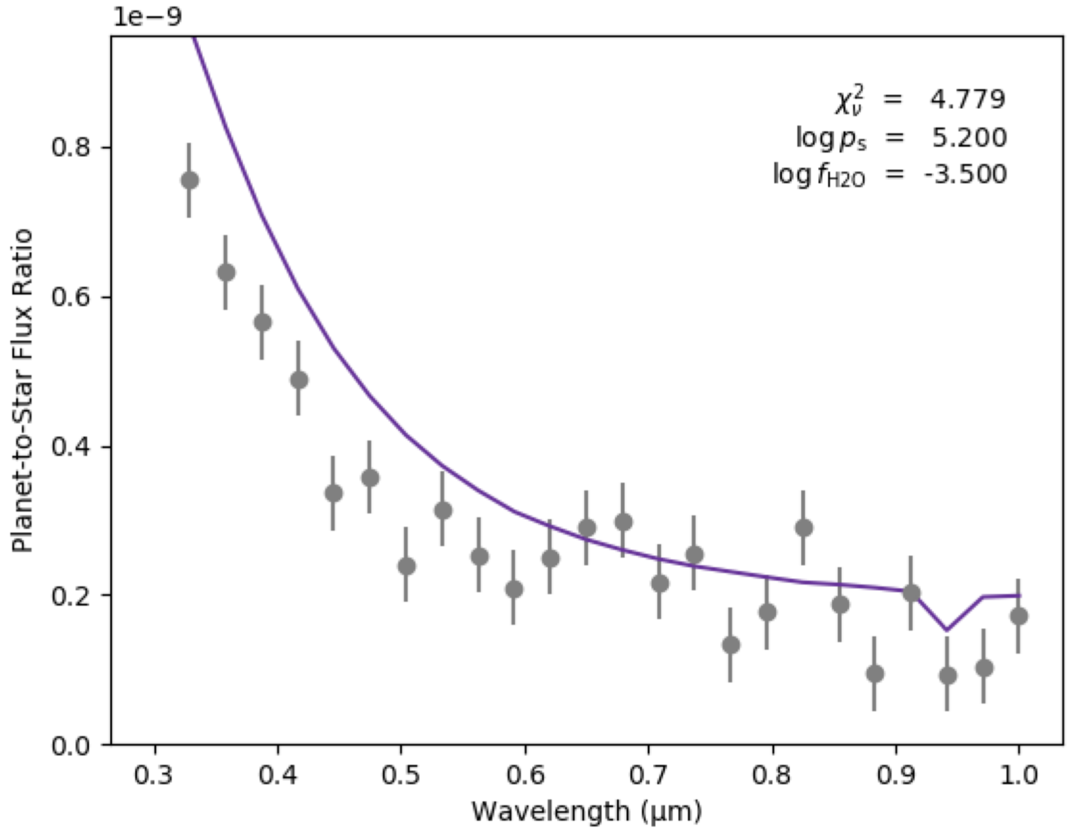
(i.e., sampling algorithm)



Retrieval

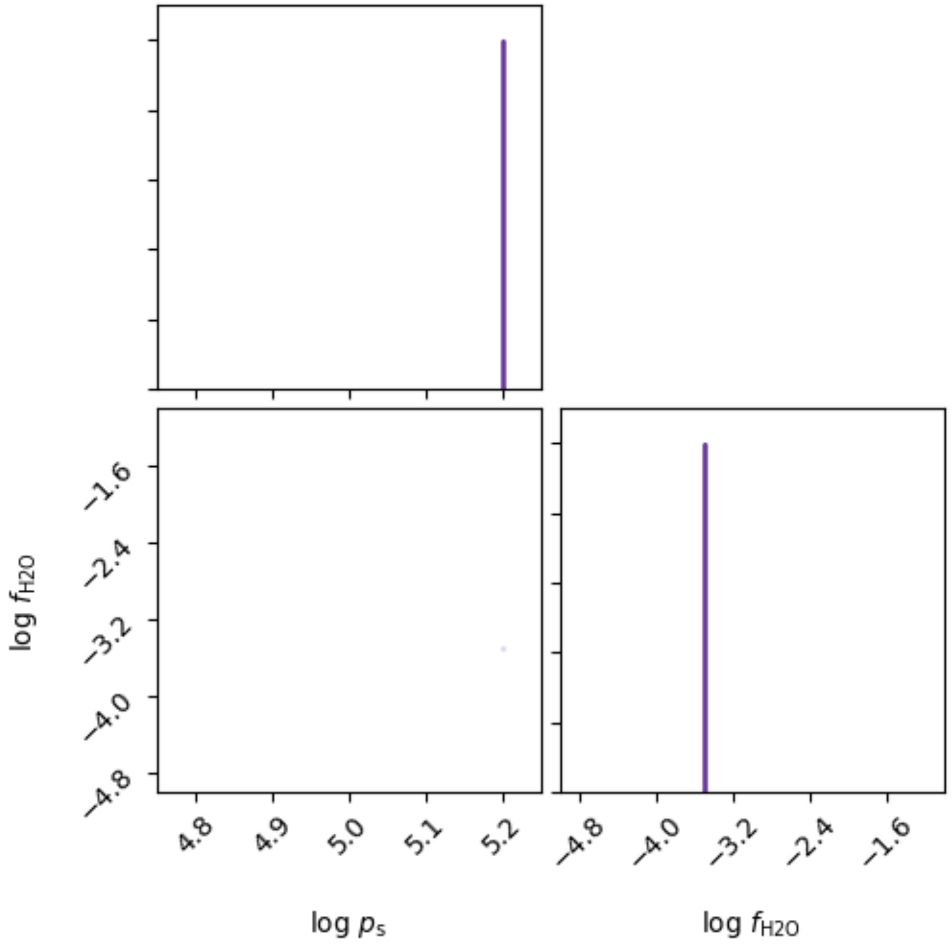


log f_{H2O}
−1.6
−2.4
−3.2
−4.0
−4.8
4.8
4.9
5.0
5.1
5.2
log p_s
−4.8
−4.0
−3.2
−2.4
−1.6
log f_{H2O}

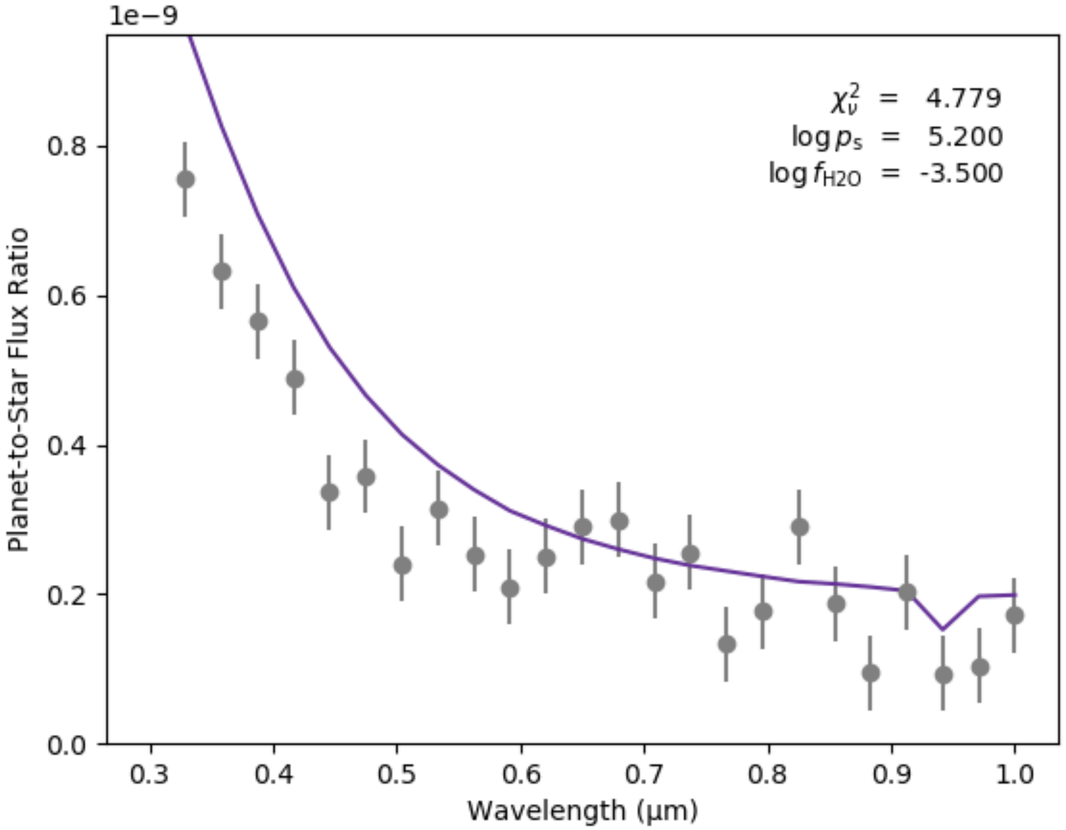


1e−9
χ^2_ν = 4.779
log p_s = 5.200
log f_{H2O} = -3.500
Planet-to-Star Flux Ratio
0.0
0.2
0.4
0.6
0.8
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (μm)

Retrieval

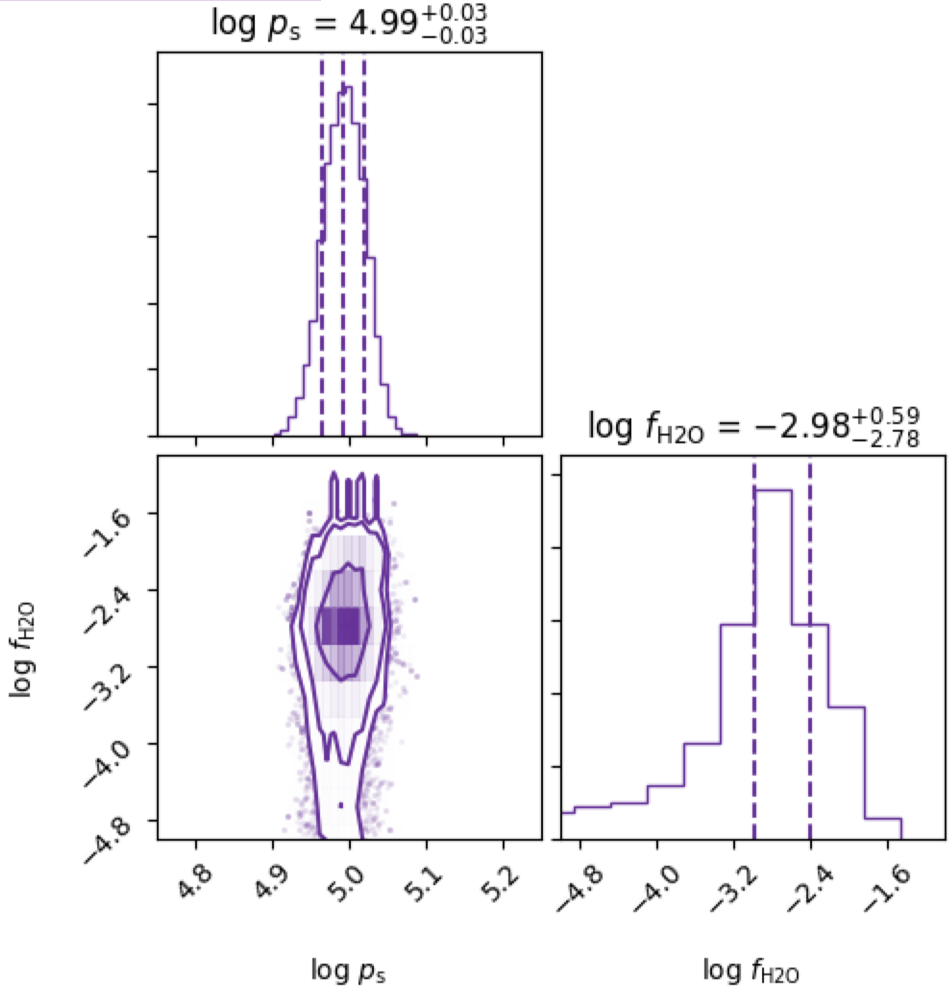


log f_{H2O}
−1.6
−2.4
−3.2
−4.0
−4.8
4.8
4.9
5.0
5.1
5.2
log p_s
−4.8
−4.0
−3.2
−2.4
−1.6
log f_{H2O}

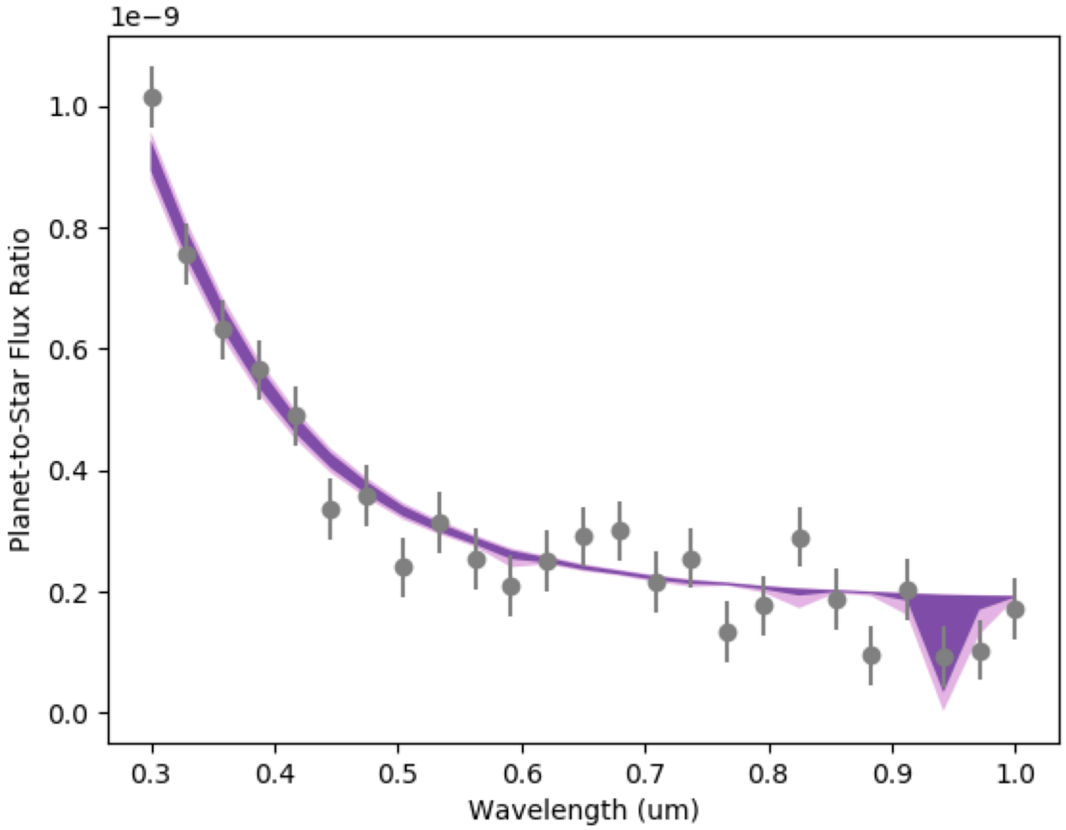


1e−9
χ^2_ν = 4.779
log p_s = 5.200
log f_{H2O} = -3.500
Planet-to-Star Flux Ratio
0.0
0.2
0.4
0.6
0.8
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (μm)

Retrieval

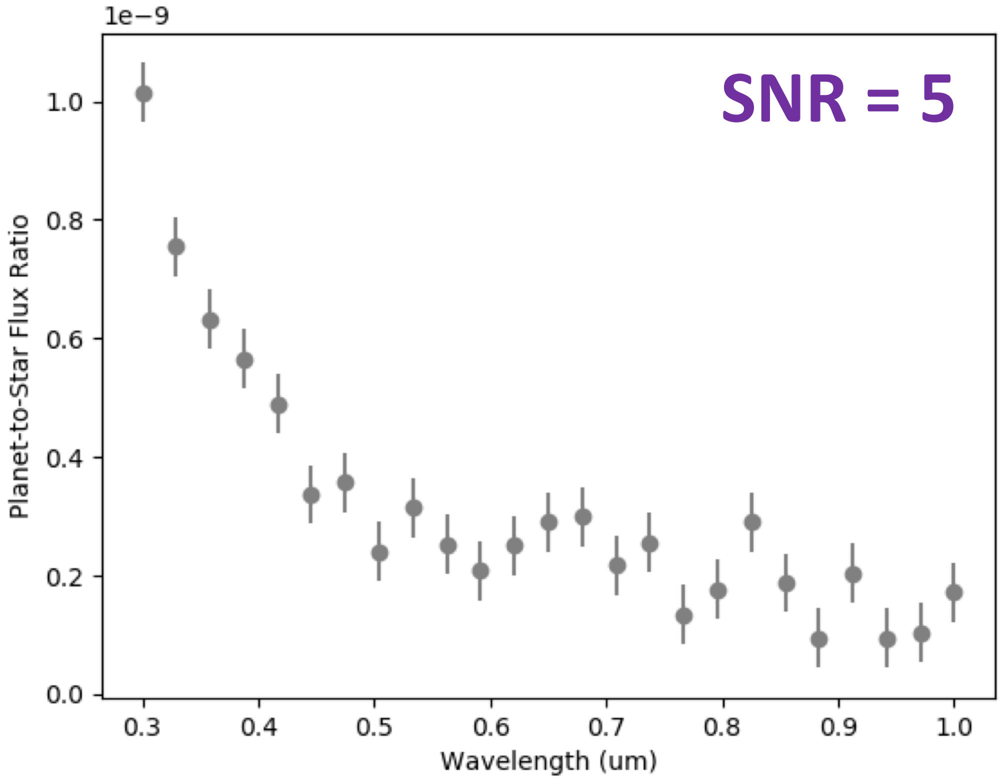


log p_s = $4.99^{+0.03}_{-0.03}$
log f_{H2O} = $-2.98^{+0.59}_{-2.78}$
log f_{H2O}
-1.6
-2.4
-3.2
-4.0
-4.8
4.8
4.9
5.0
5.1
5.2
log p_s
log f_{H2O}



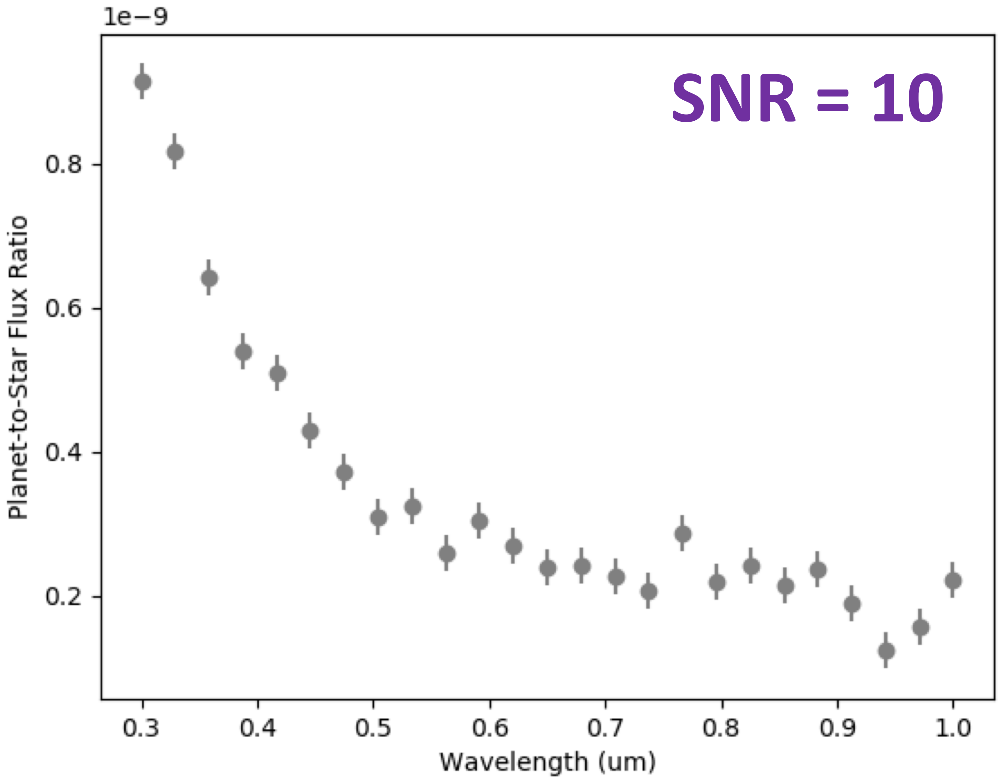
1e−9
Planet-to-Star Flux Ratio
1.0
0.8
0.6
0.4
0.2
0.0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (um)

Retrieval



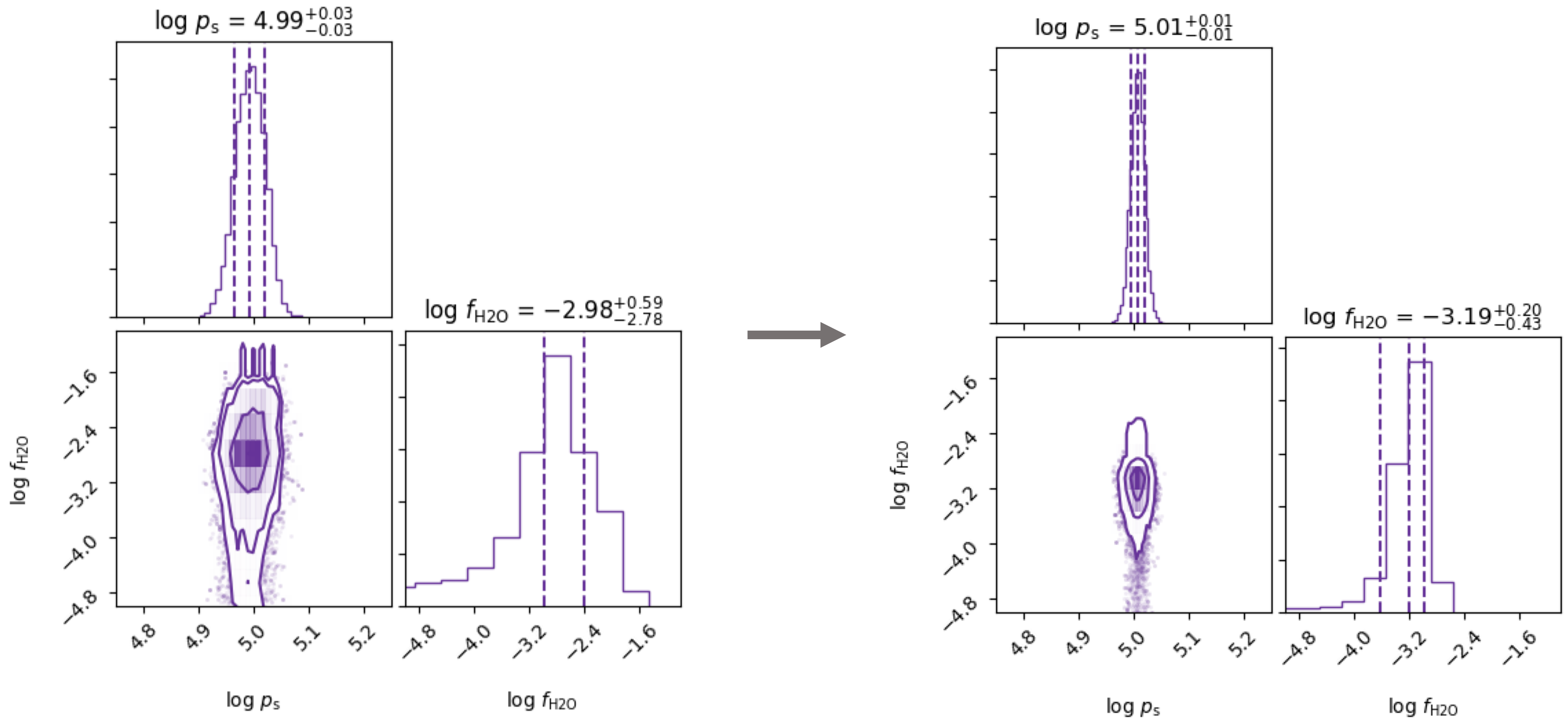
1e−9
SNR = 5
Planet-to-Star Flux Ratio
0.0
0.2
0.4
0.6
0.8
1.0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (um)

?



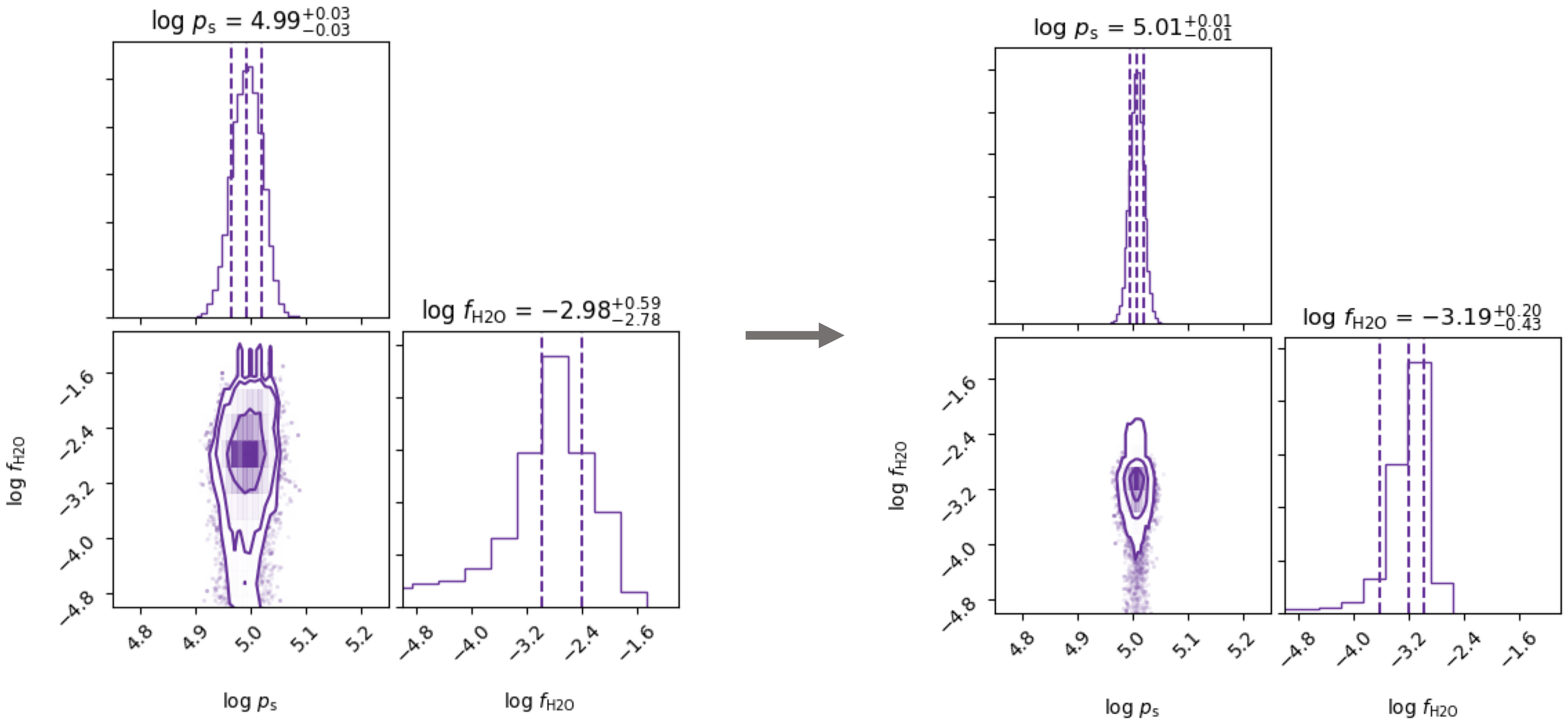
1e−9
SNR = 10
Planet-to-Star Flux Ratio
0.2
0.4
0.6
0.8
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (um)

Retrieval



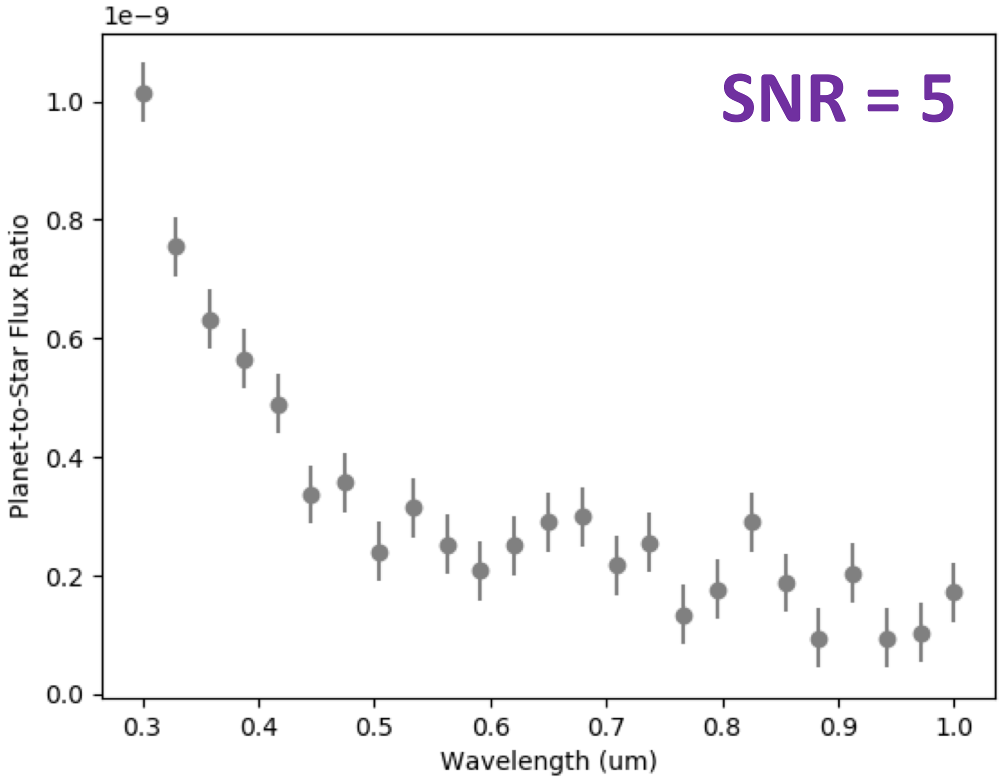
log p_s = $4.99^{+0.03}_{-0.03}$
log f_{H2O} = $-2.98^{+0.59}_{-2.78}$
log f_{H2O}
−1.6
−2.4
−3.2
−4.0
−4.8
4.8
4.9
5.0
5.1
5.2
log p_s
log f_{H2O}
log p_s = $5.01^{+0.01}_{-0.01}$
log f_{H2O} = $-3.19^{+0.20}_{-0.43}$

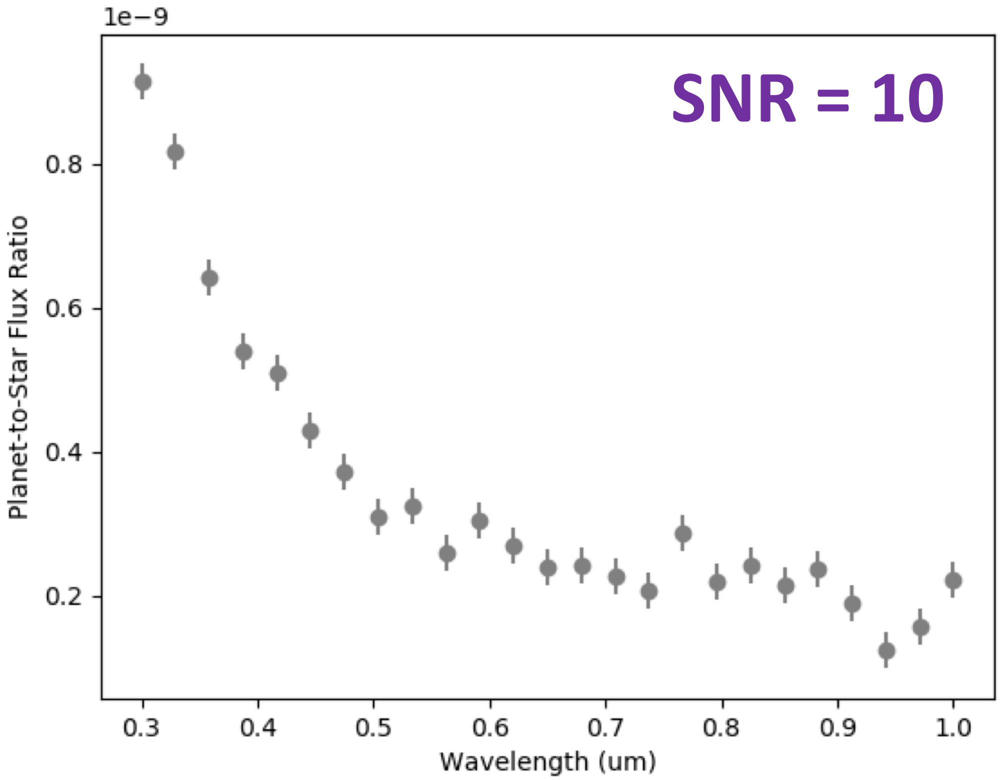
Retrieval



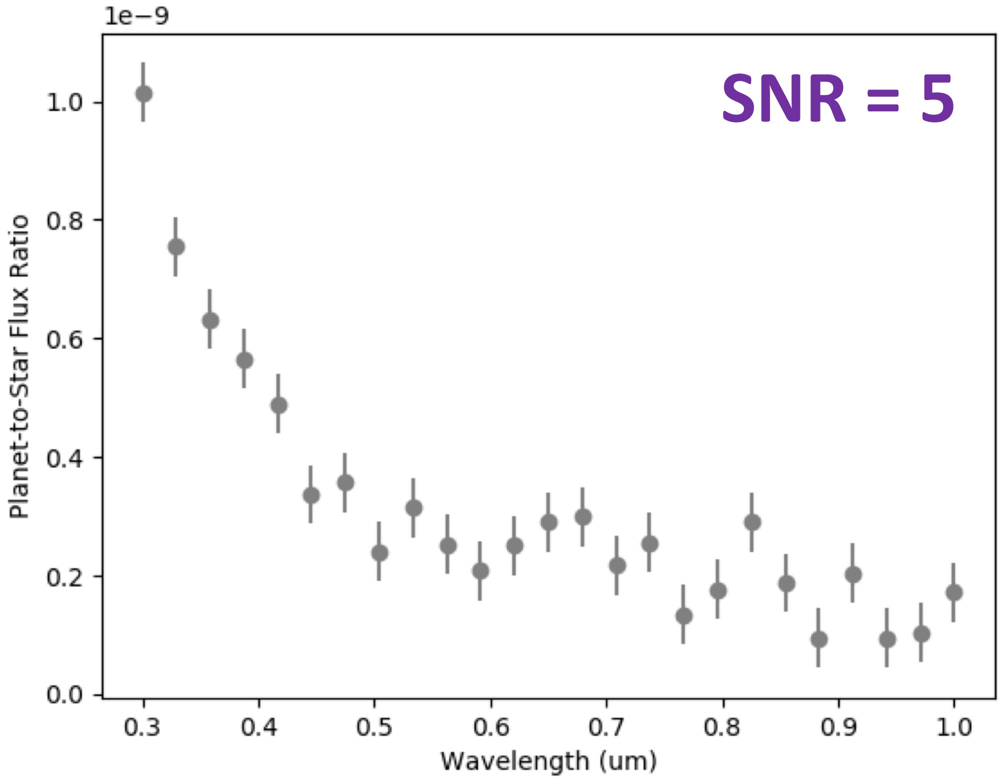
Why did the water vapor constraints improve dramatically, while the surface pressure constraints hardly changed?

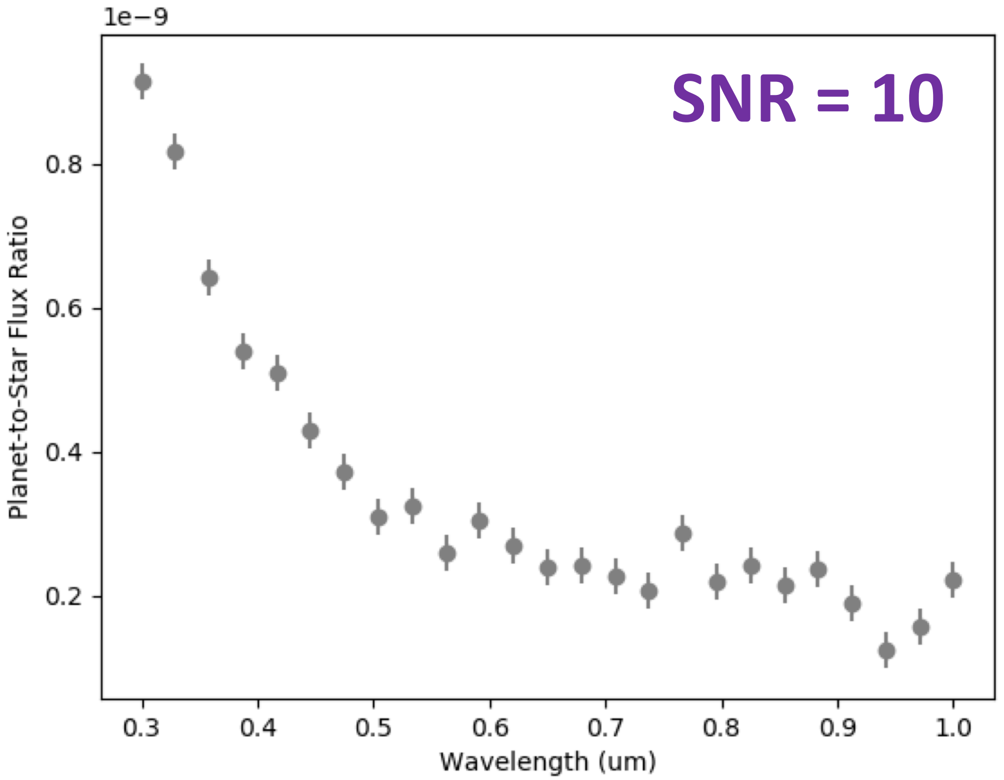
Retrieval


1e−9
SNR = 5
1.0
0.8
0.6
0.4
0.2
0.0
Planet-to-Star Flux Ratio
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (um)


1e−9
SNR = 10
0.8
0.6
0.4
0.2
Planet-to-Star Flux Ratio
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (um)

Retrieval



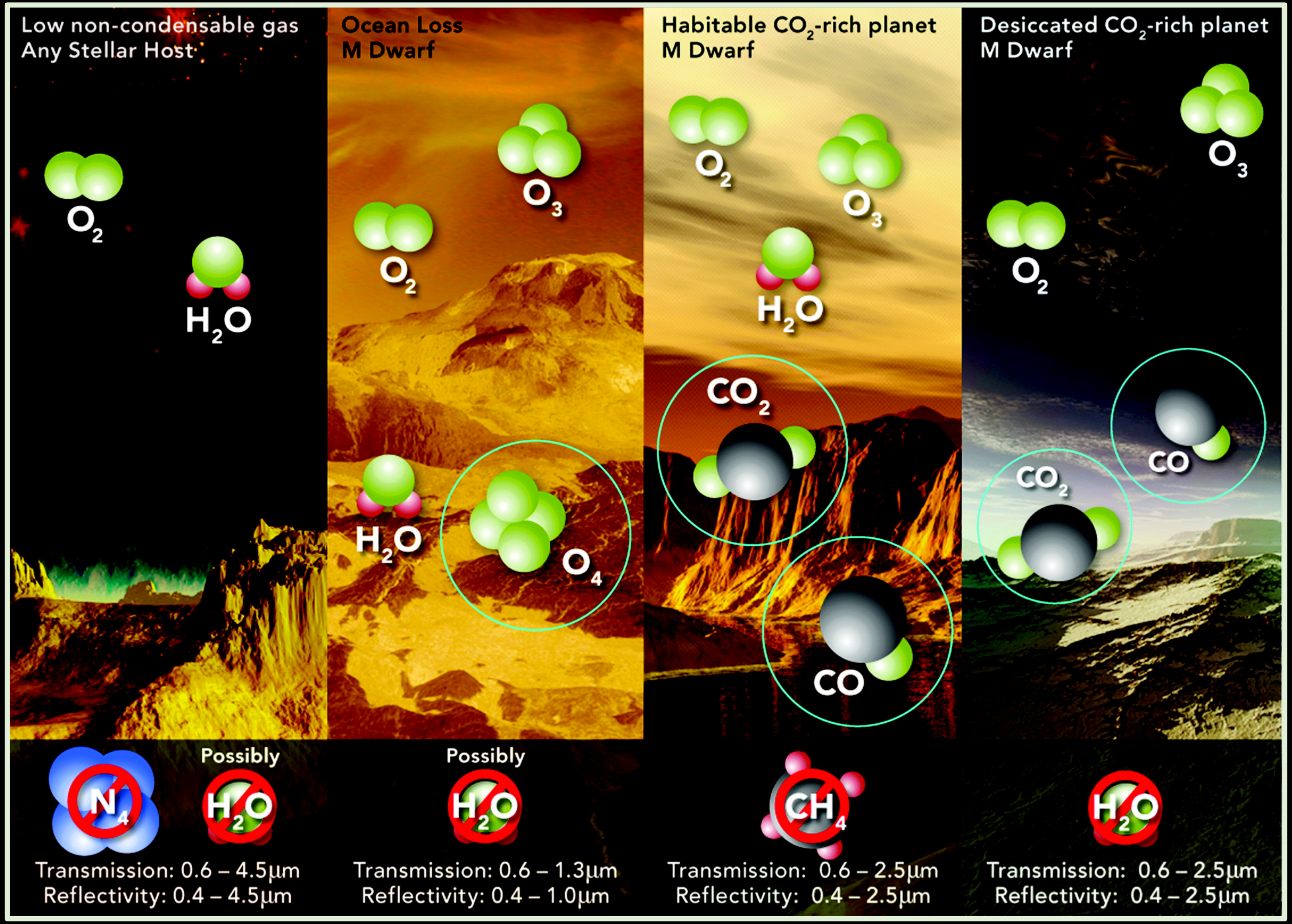


Key point: Atmospheric constraints are sensitive to SNR and spectral resolution in complex, non-linear ways!

What are the prospects for exoplanet biosignature detections?

Oxygen False Positives

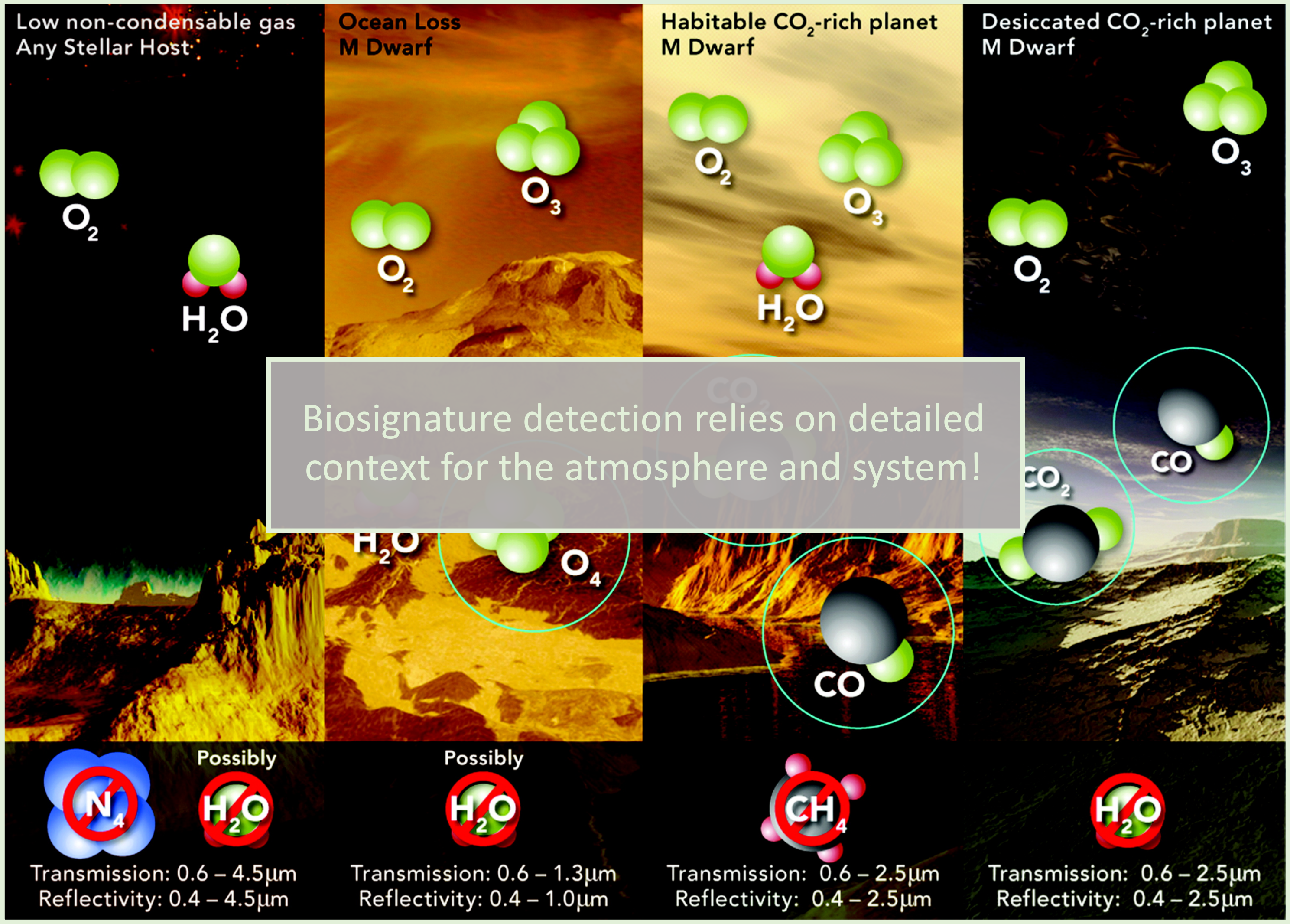
Meadows (2017)



See also: Wordsworth & Pierrehumbert (2014), Luger & Barnes (2015), Tian (2015), Segura et al. (2003, 2005), Hu & Seager (2014), Gao et al. (2015)

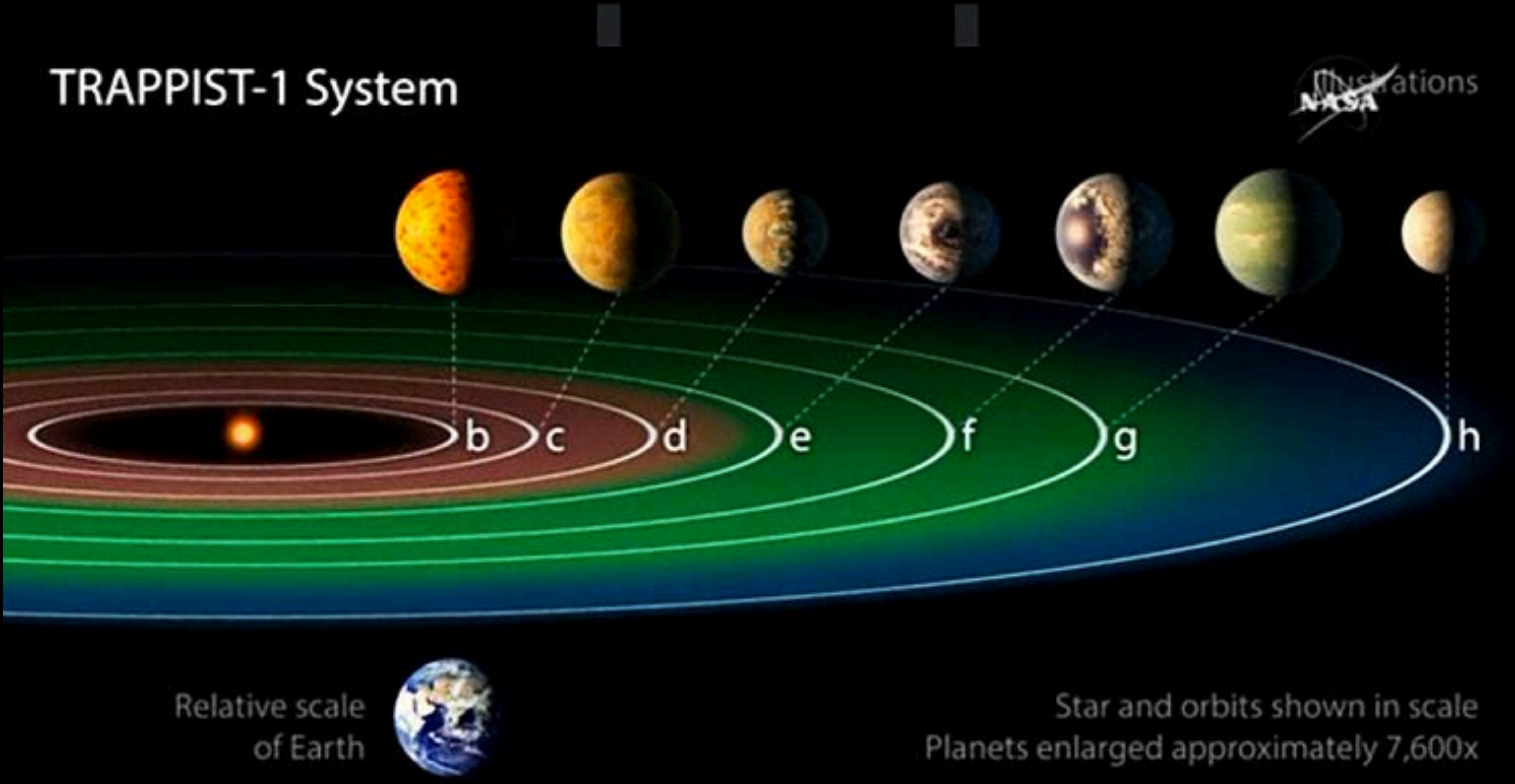
Oxygen False Positives

Meadows (2017)

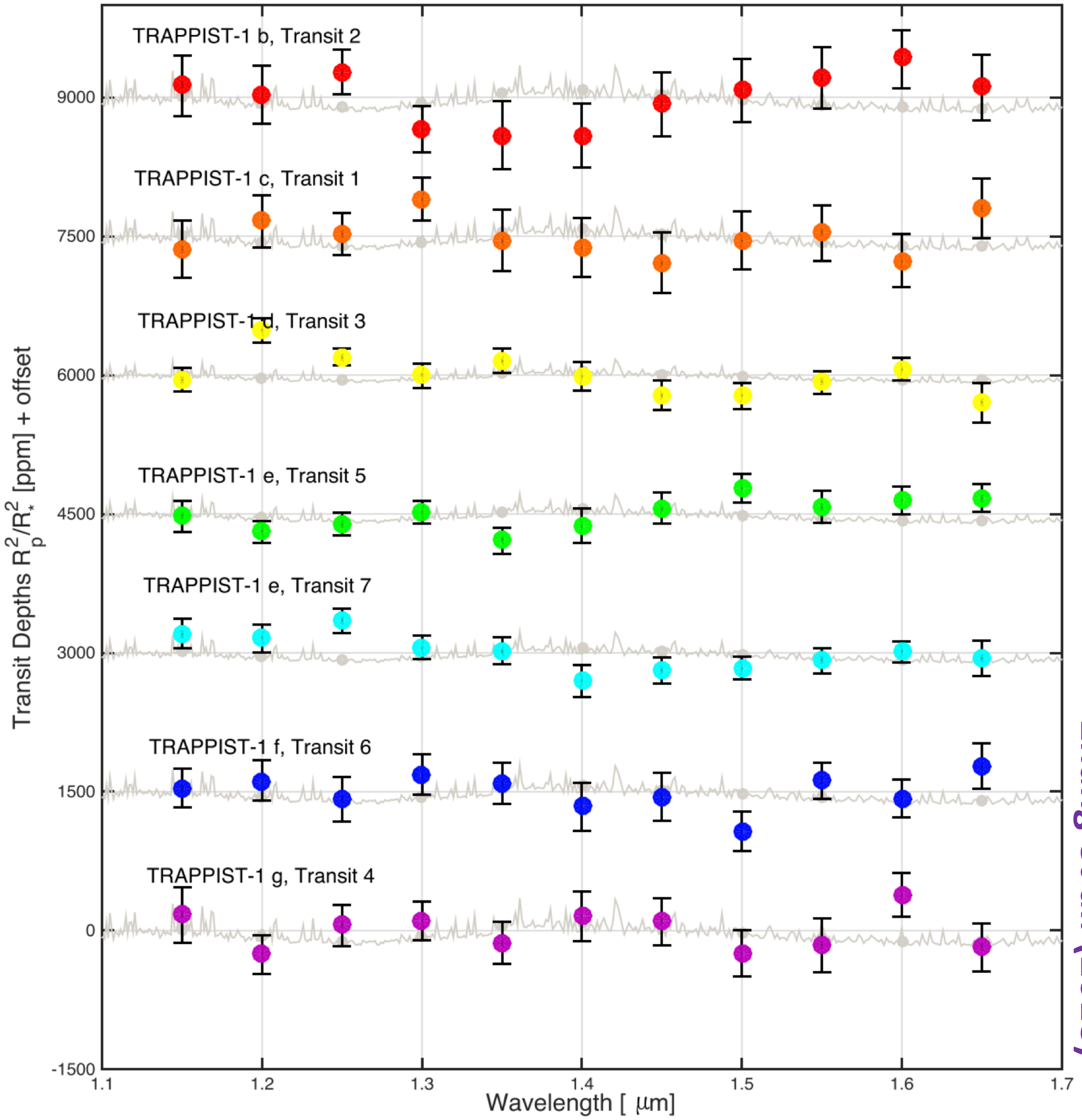


Biosignature detection relies on detailed context for the atmosphere and system!

See also: Wordsworth & Pierrehumbert (2014), Luger & Barnes (2015), Tian (2015), Segura et al. (2003, 2005), Hu & Seager (2014), Gao et al. (2015)


TRAPPIST-1 System
b
c
d
e
f
g
h
Relative scale
of Earth
Star and orbits shown in scale
Planets enlarged approximately 7,600x

HST/WFC3

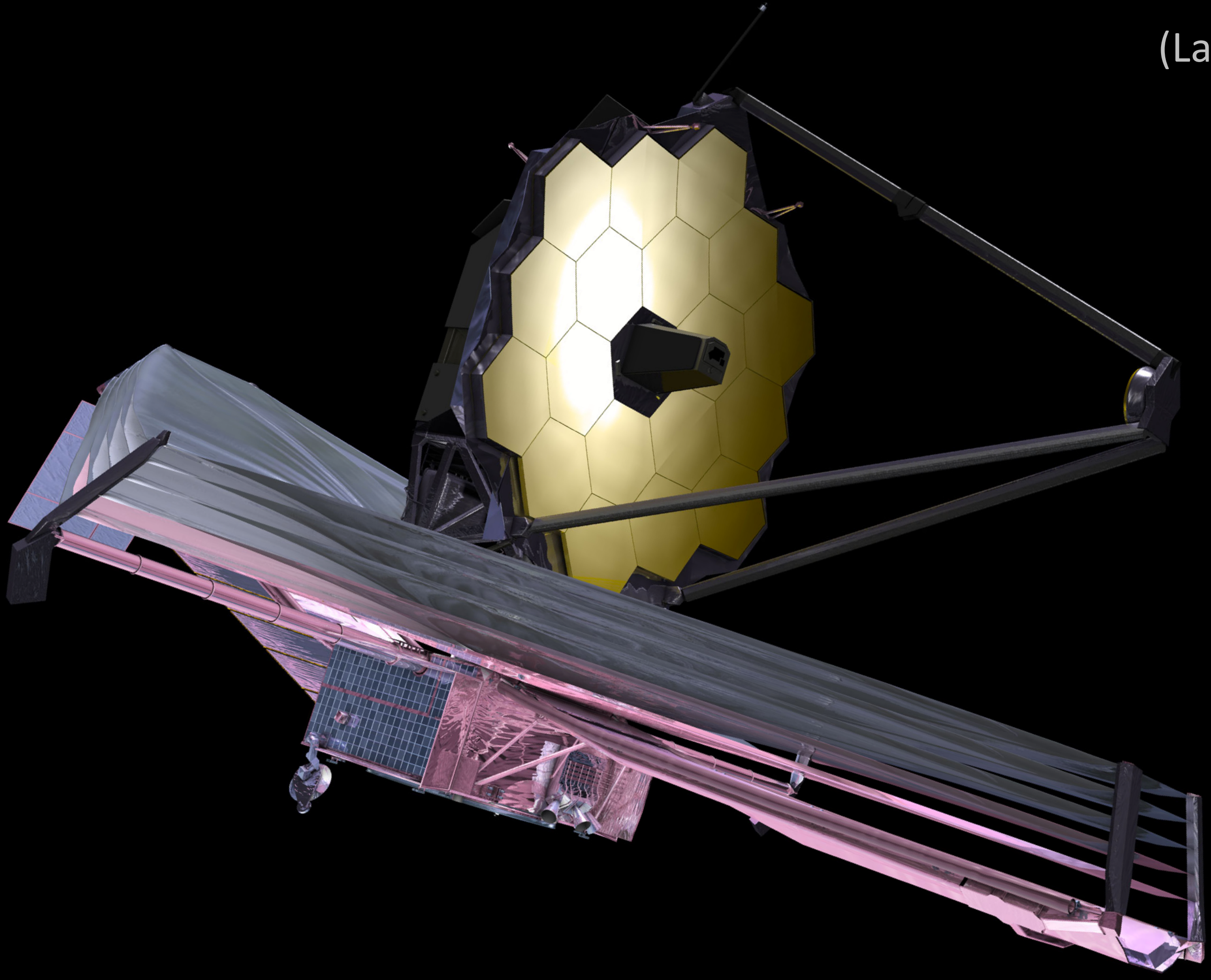


Zhang et al. (2018)

see also: de Wit et al. (2016, 2018)

James Webb Space Telescope

(Launch: March 2021)



JWST Performance

What is the expected performance of JWST for studying temperate, rocky exoplanet atmospheres?

- Valenti et al. (2006) : detection of H_2O and CO_2 only for Earth analogs transiting *very* nearby M dwarfs
- Kaltenegger & Traub (2009) : biosignature detections for Earths orbiting most M dwarf types with 200 hr of obs.
- Deming et al. (2009) : potential to characterize super-Earths, but will struggle to characterize Earth analogs
- Cowan et al. (2015) : roughly 1 year of JWST time to study 3 temperate planets orbiting M5 dwarfs
- Greene et al. (2015) : single transit detections of some species for clear H_2 or H_2O-dominated super Earth atmospheres for early-M host
- Barstow & Irwin (2016) : detection of O_3 for TRAPPIST planets in 30—60 transits
- Morley et al. (2017) : detection of atmosphere for hottest TRAPPIST-1 planets in 10s of transits or eclipses
- Stevenson (2019) : struggle to detect anything but CO_2 for Earth-like TRAPPIST-1 planets
- Lustig-Yaeger et al. (2019) : clearsky CO_2 or abiotic oxygen atmospheres detectable for TRAPPIST-1 planets

JWST Performance

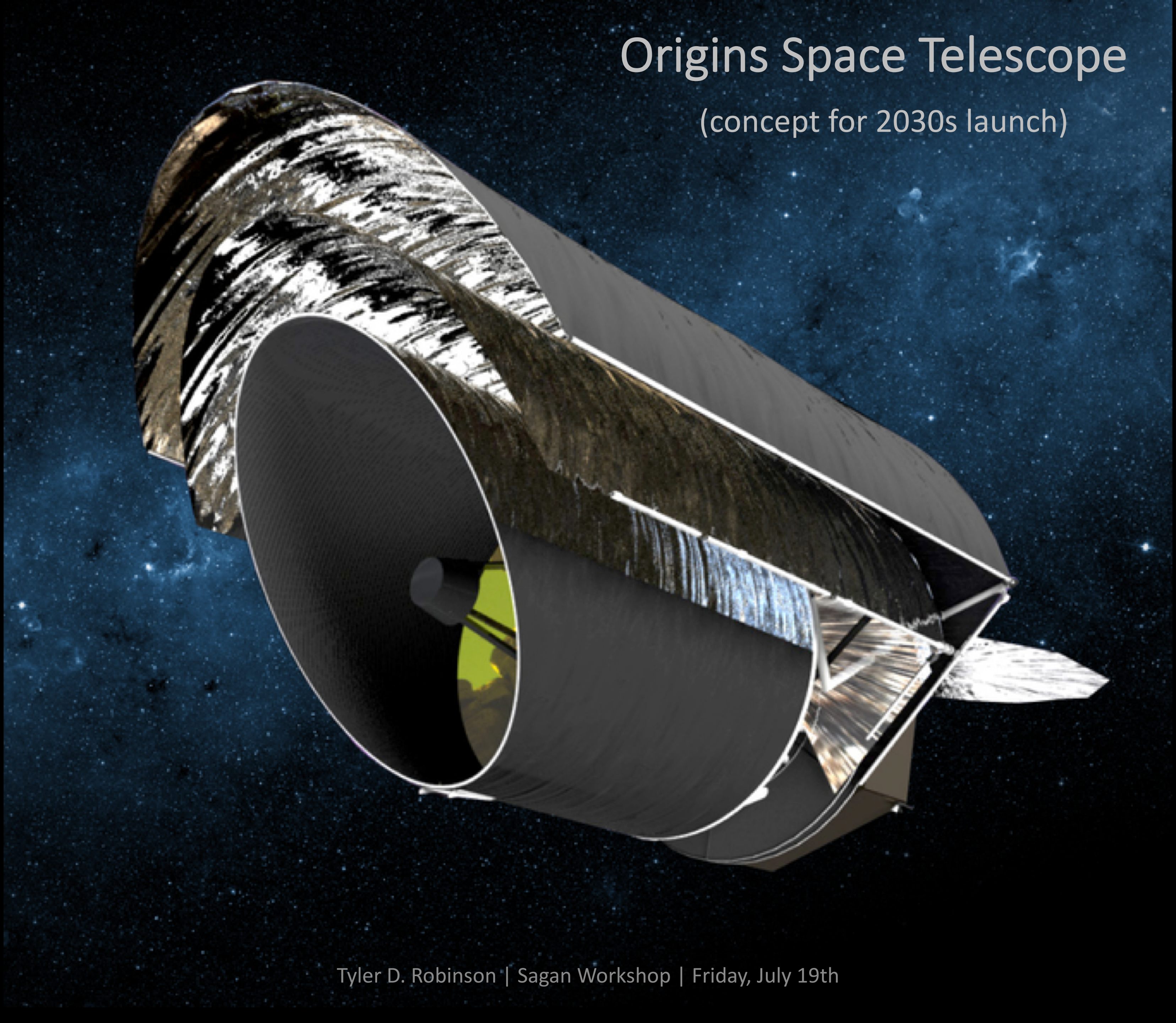
What is the expected performance of JWST for studying temperate, rocky exoplanet atmospheres?

- Valenti et al. (2006) : detection of H_2O and CO_2 only for Earth analogs transiting *very* nearby M dwarfs
- Kaltenegger & Traub (2009) : biosignature detections for Earths orbiting most M dwarf types with 200 hr of obs.
- Deming et al. (2009) : potentia … e to characterize Earth analogs
- Cowan et al. (2015) : roughly 1 … ets orbiting M5 dwarfs
- Greene et al. (2015) : single tra … r H_2O-dominated super Earth atmospheres for early-M host
- Barstow & Irwin (2016) : detection of O_3 for TRAPPIST planets in 30—60 transits
- Morley et al. (2017) : detection of atmosphere for hottest TRAPPIST-1 planets in 10s of transits or eclipses
- Stevenson (2019) : struggle to detect anything but CO_2 for Earth-like TRAPPIST-1 planets
- Lustig-Yaeger et al. (2019) : clearsky CO_2 or abiotic oxygen atmospheres detectable for TRAPPIST-1 planets

We need to ”wait and see” what JWST will deliver to the exoplanet community!

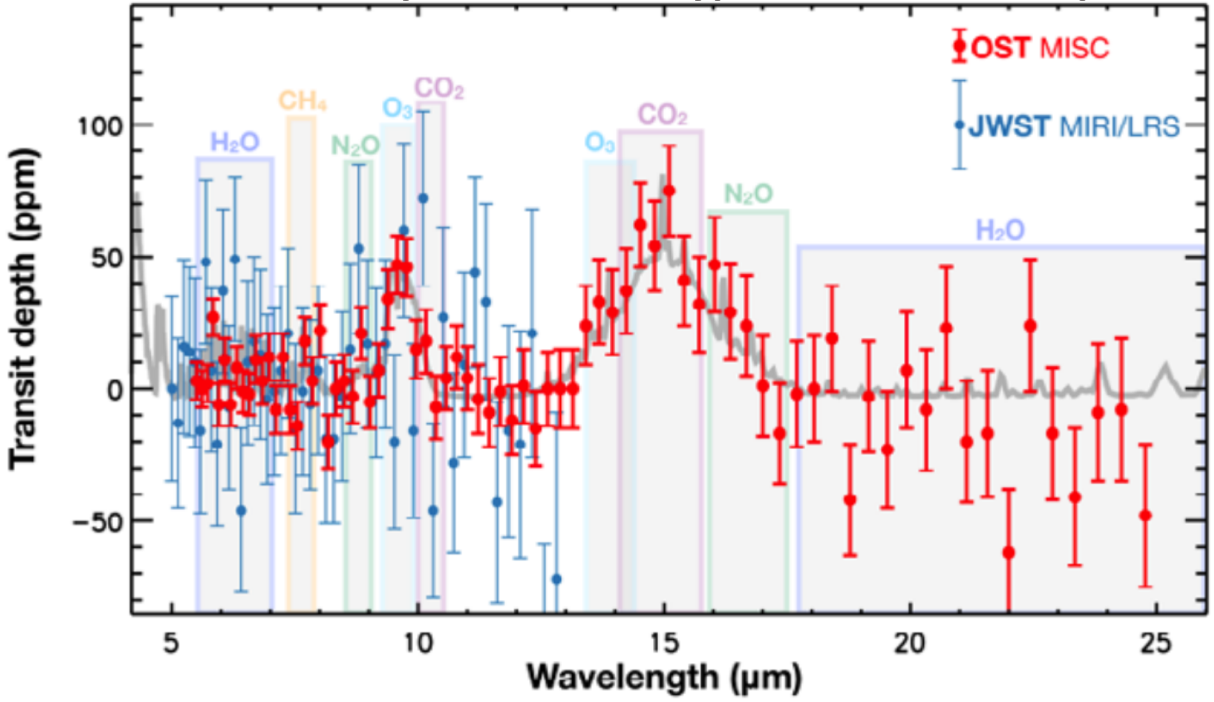
Origins Space Telescope

(concept for 2030s launch)

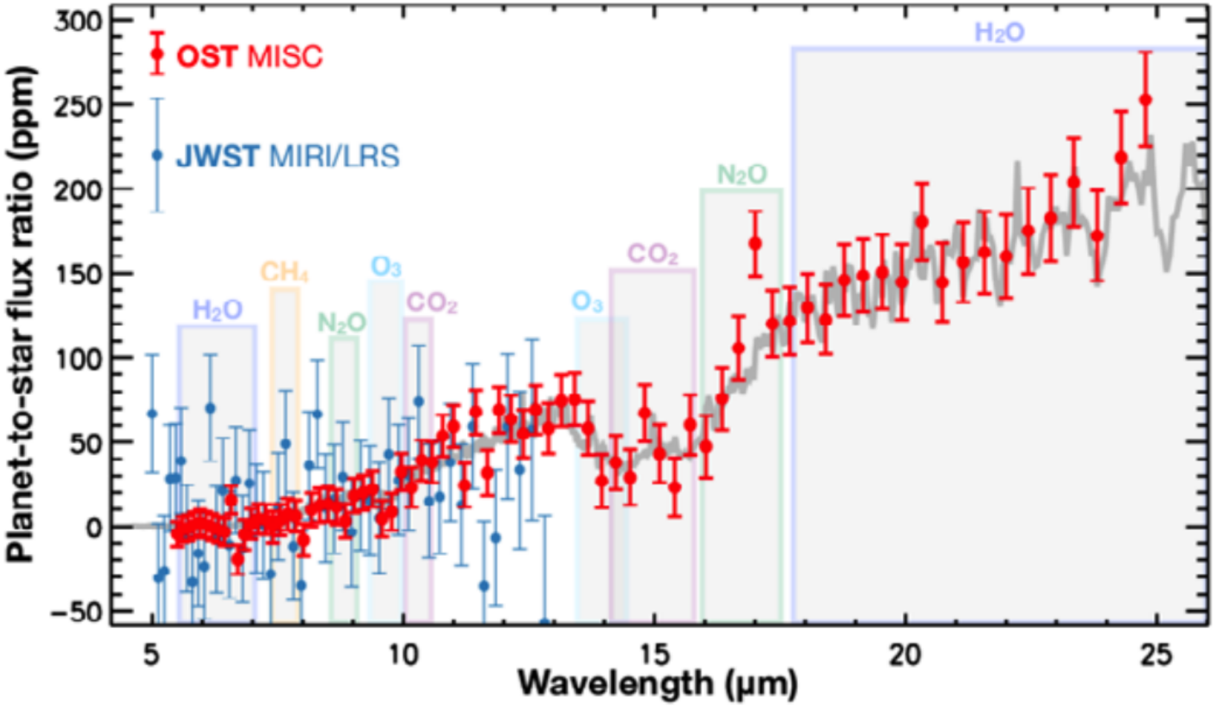


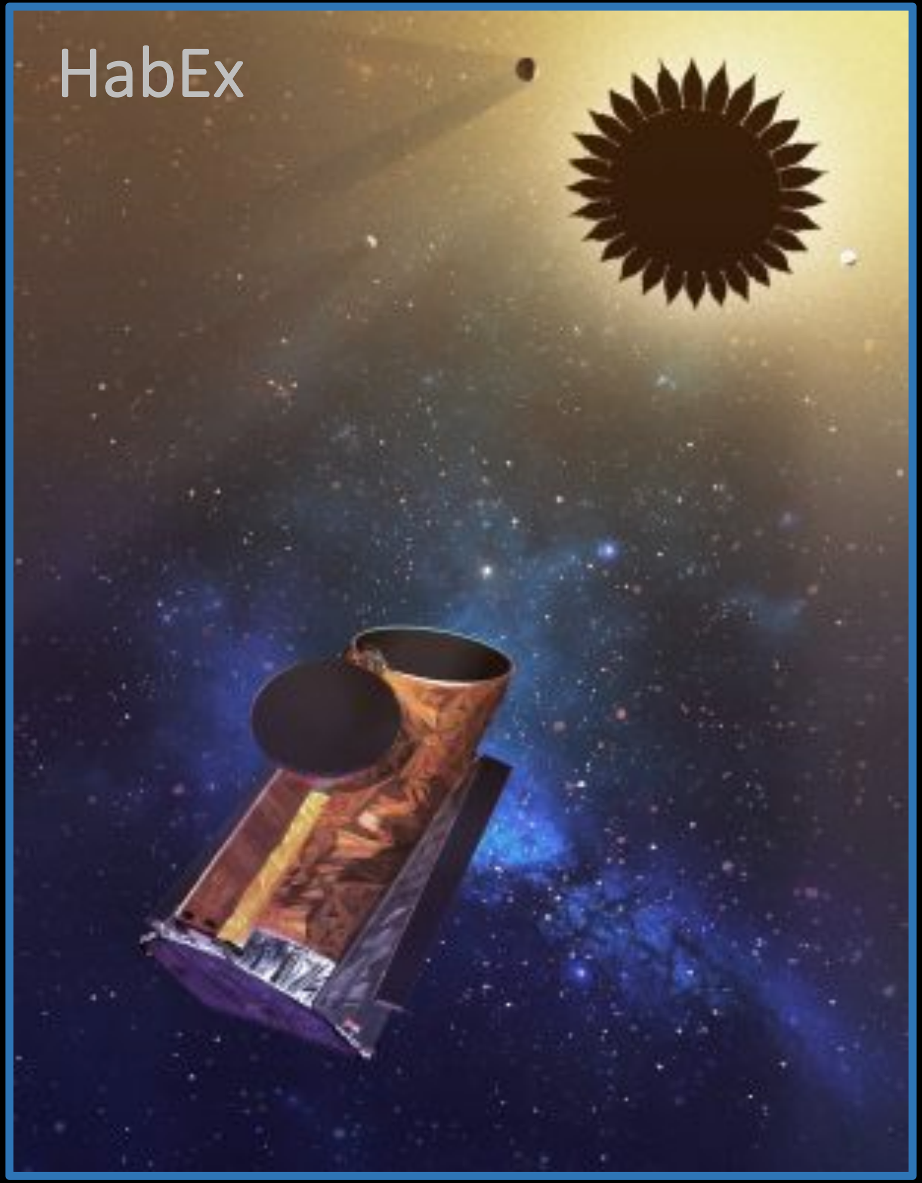
OST Science

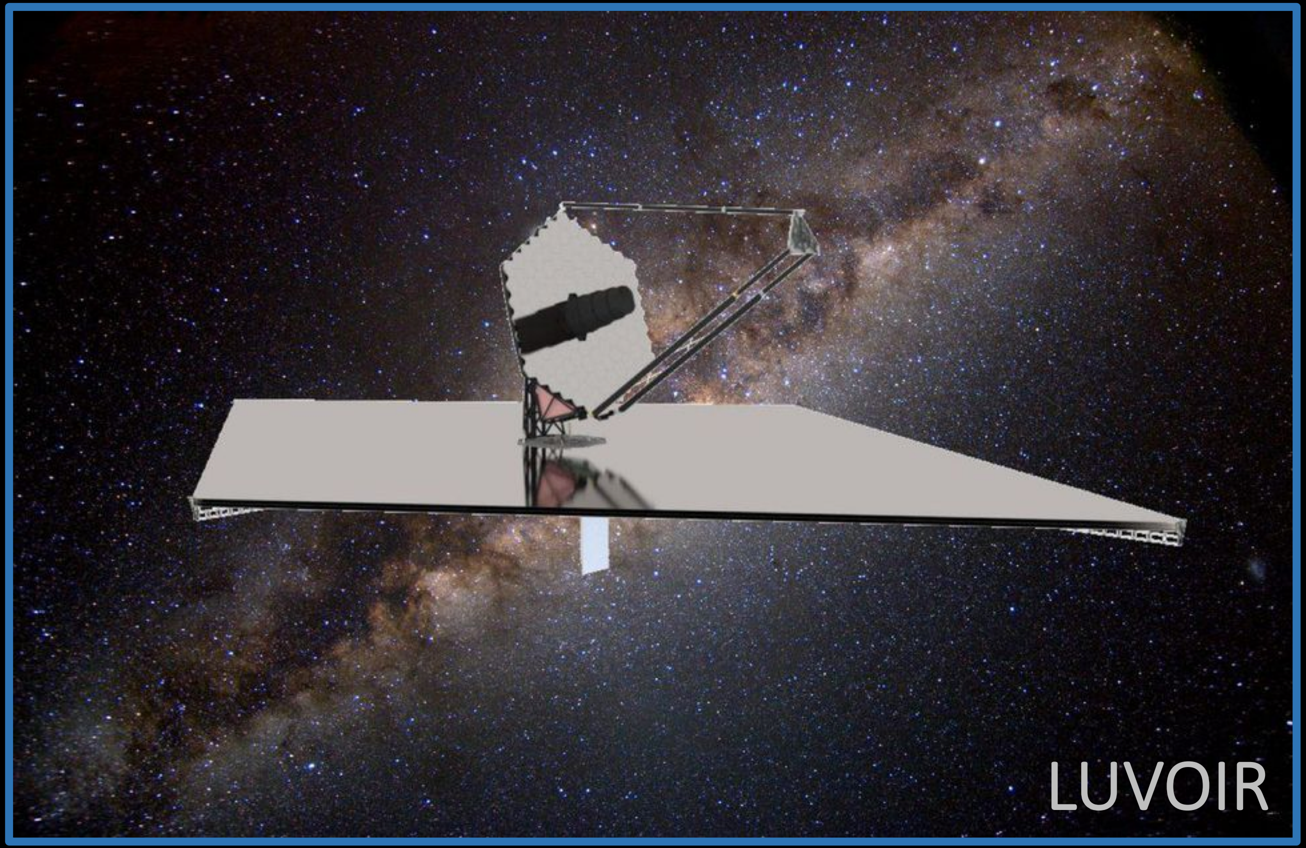
Earth-like exoplanet & late-type M dwarf at 4.2 pc



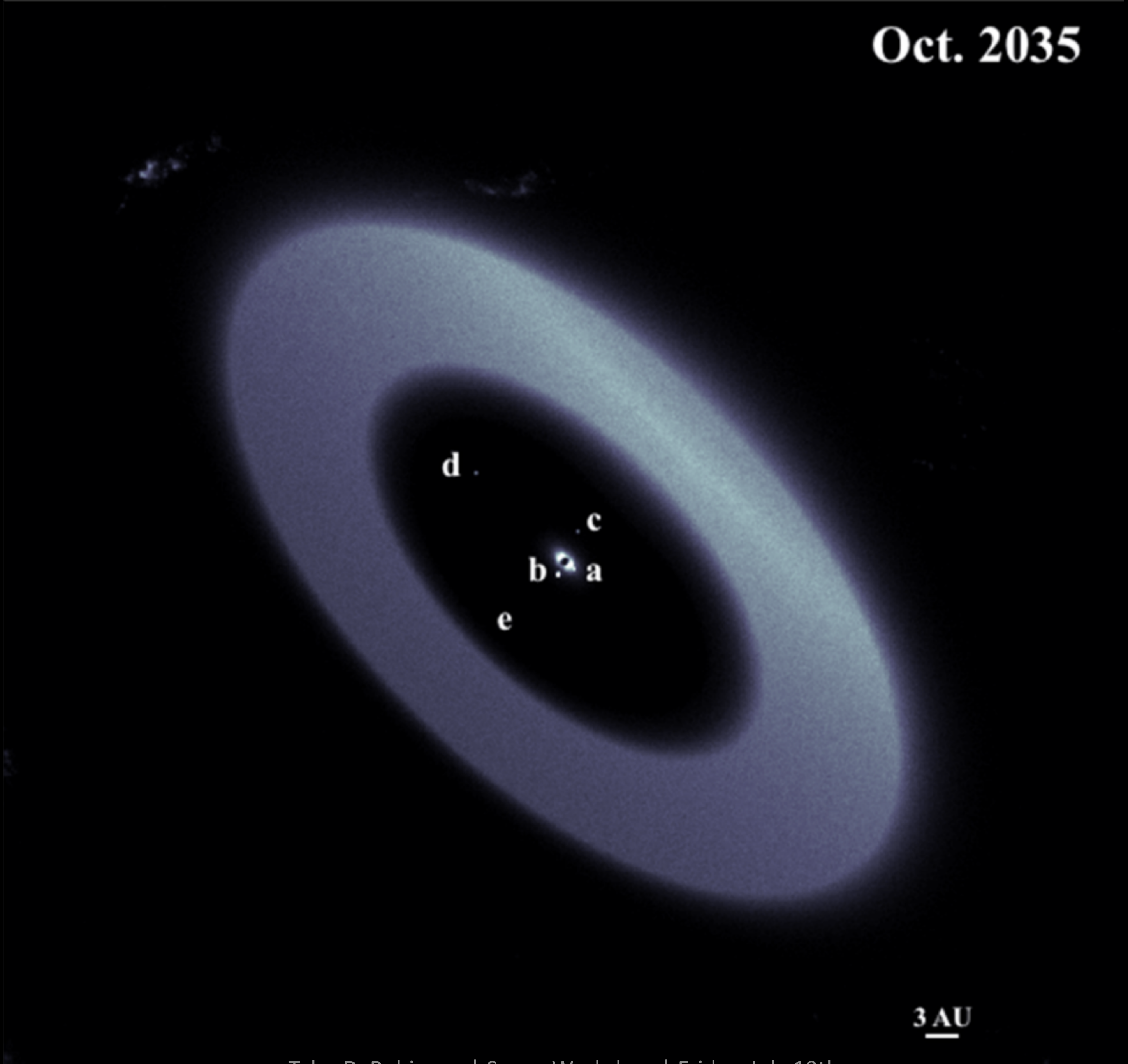
OST Interim Report



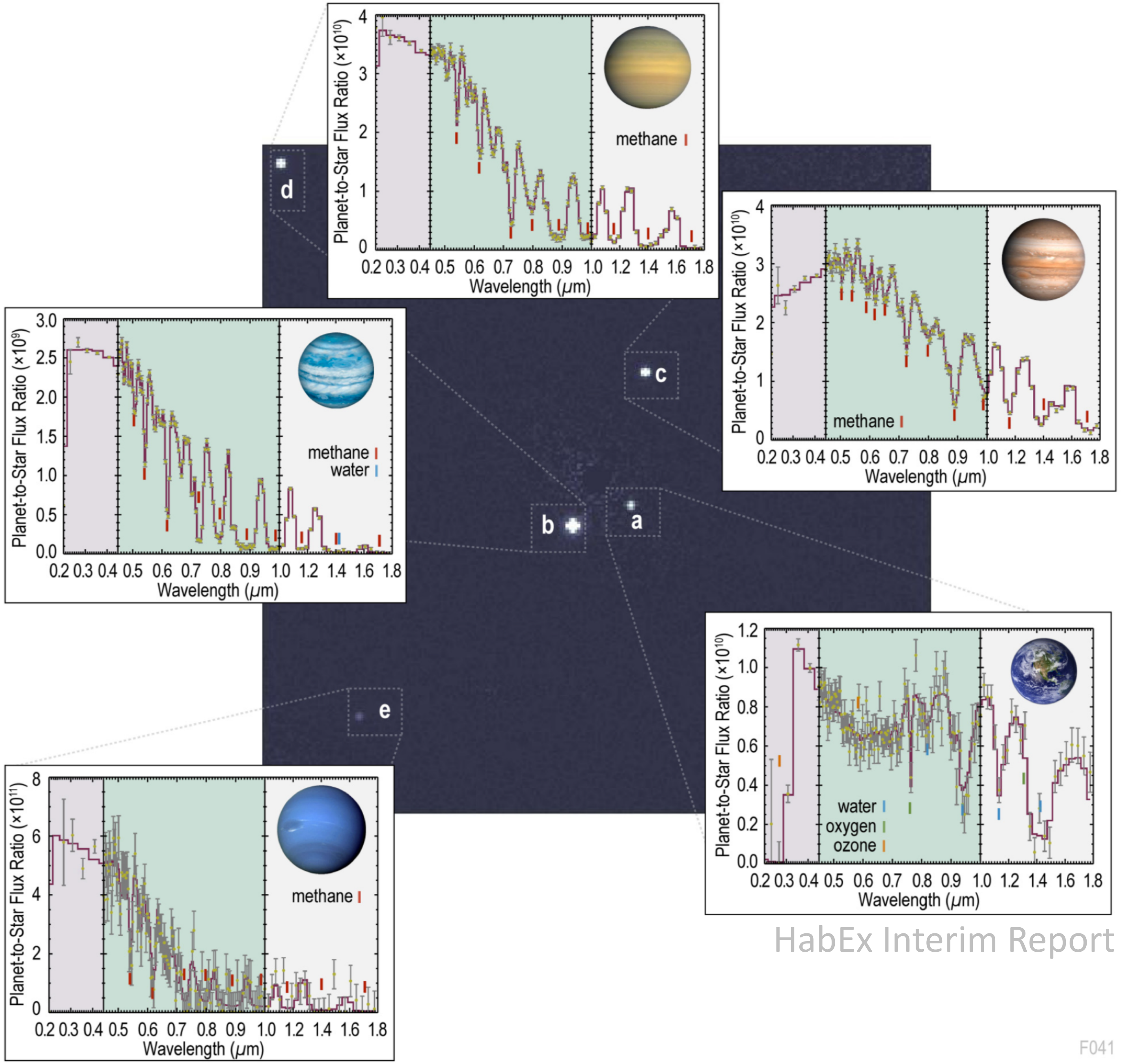




(concepts for 2030s launch)

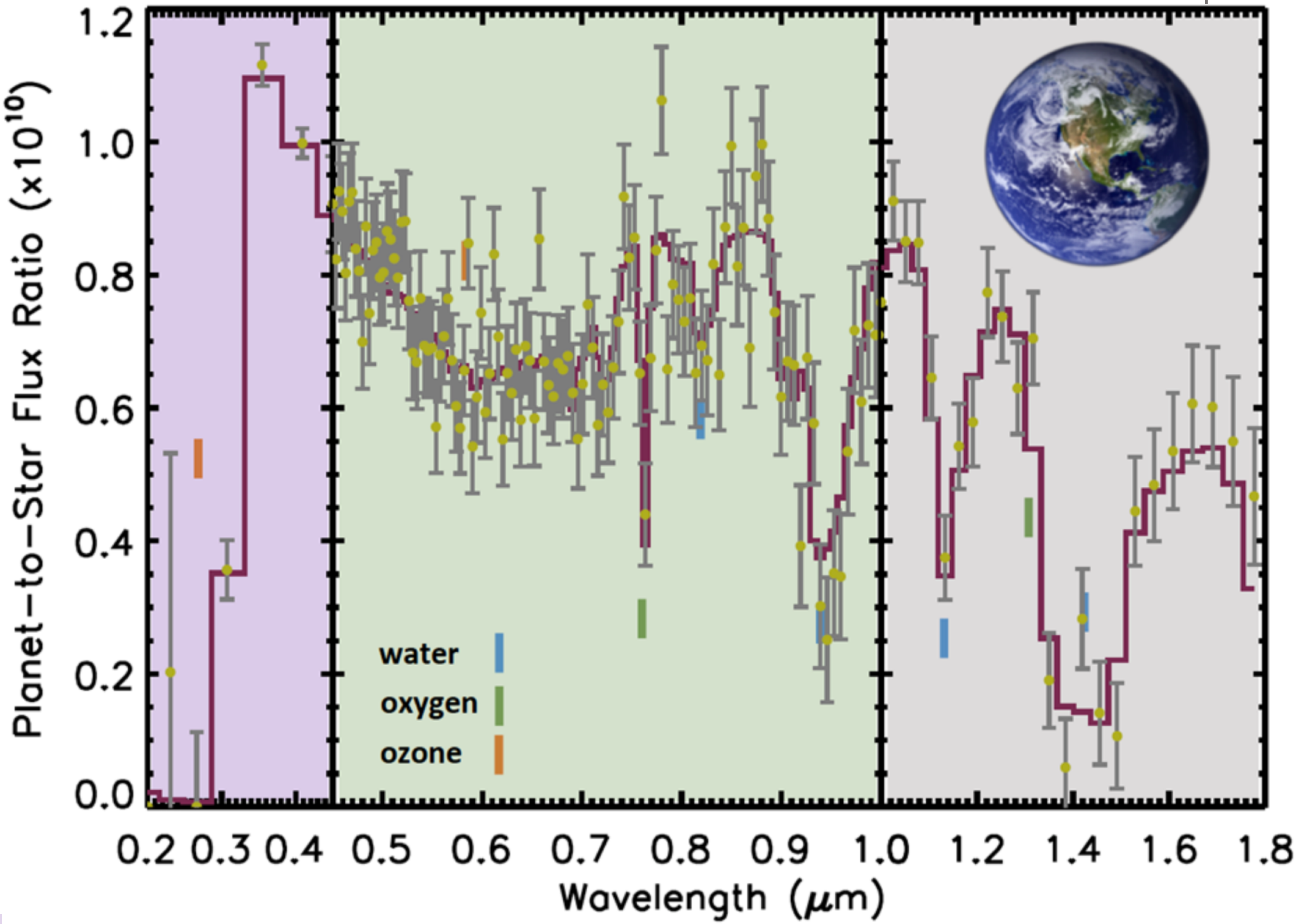


Credit: HabEx Interim Report



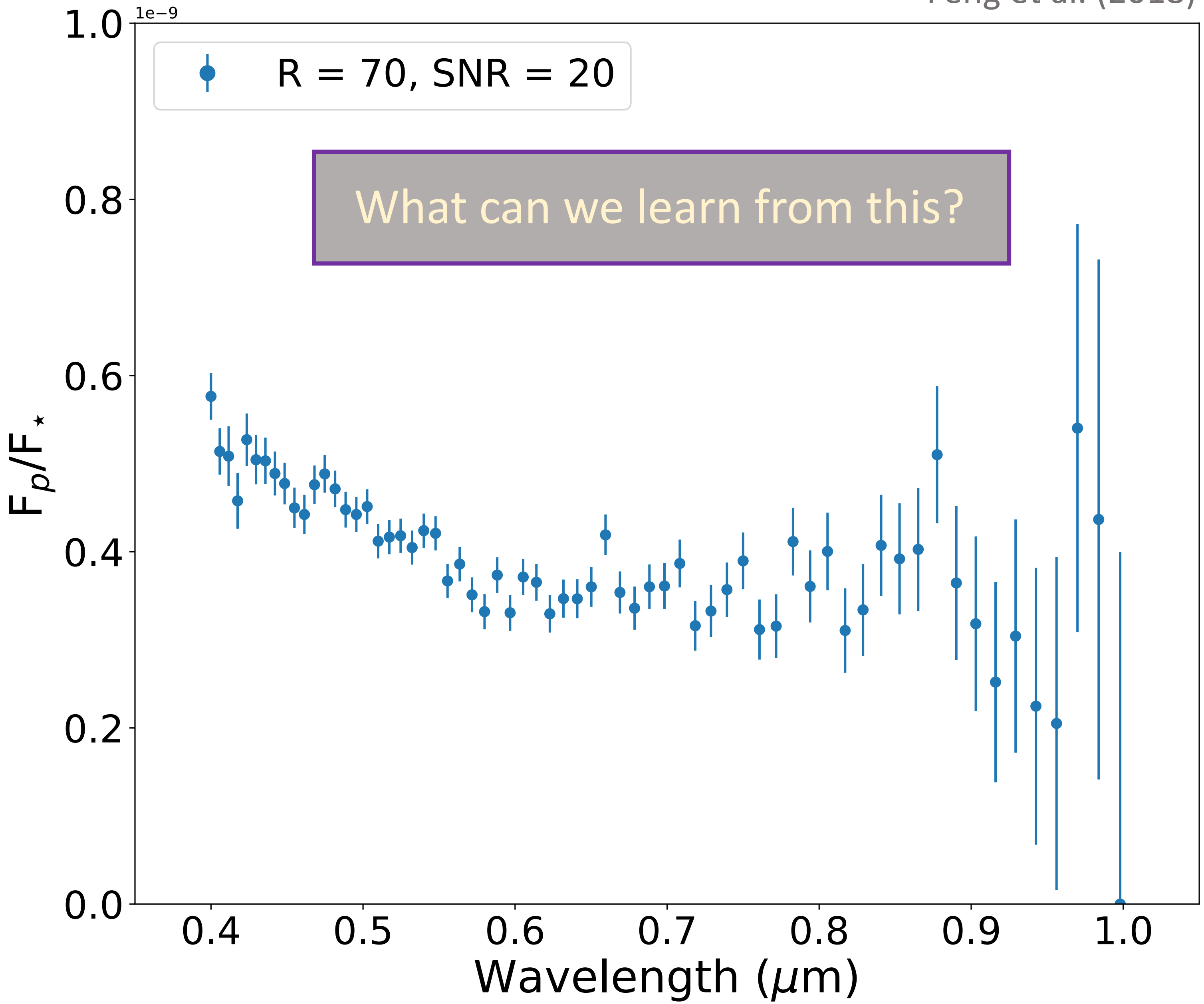
HabEx Interim Report

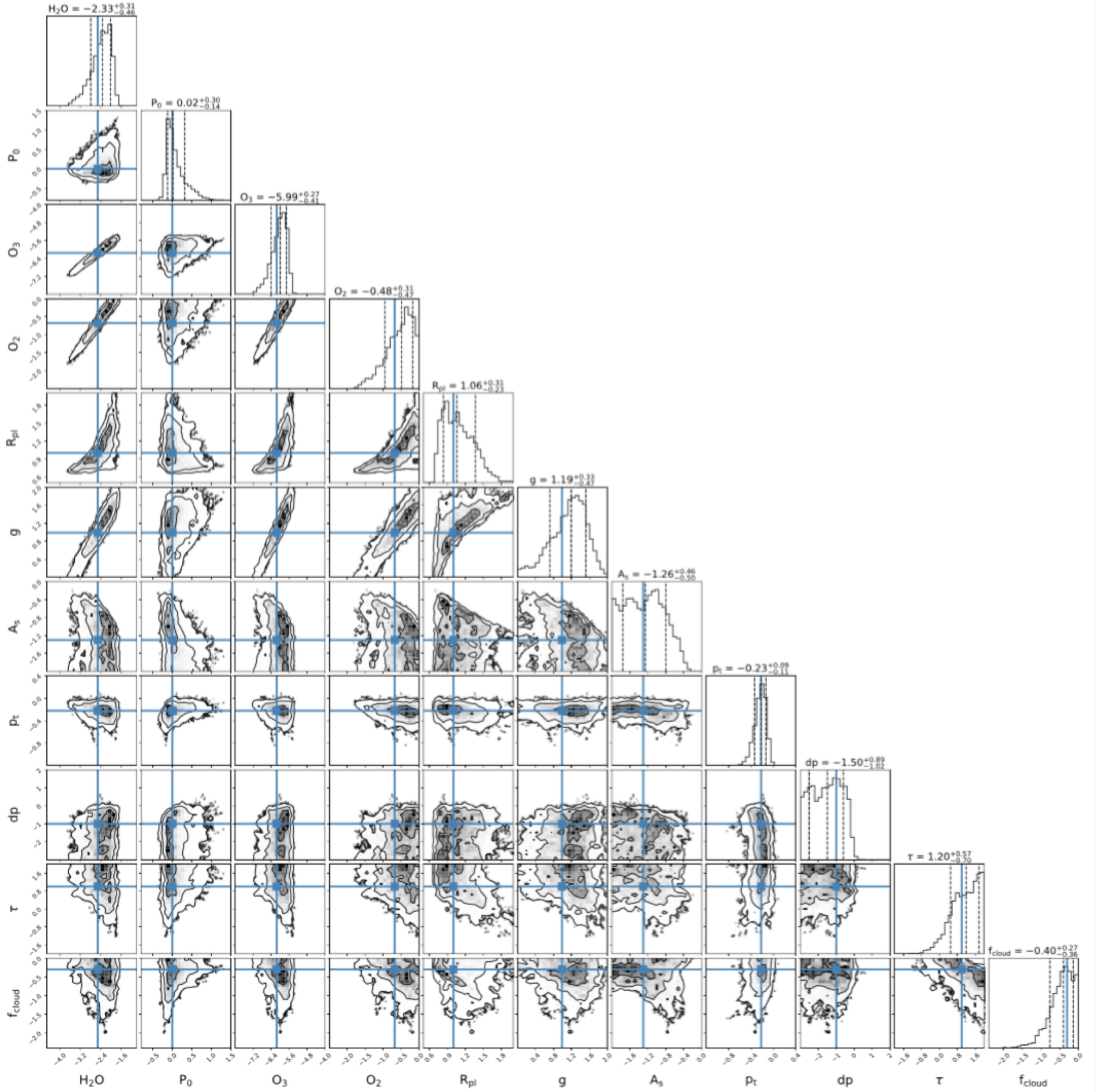
F041



Planet-to-Star Flux Ratio (x10¹⁰)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
water
oxygen
ozone
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.2 1.4 1.6 1.8
Wavelength (μm)

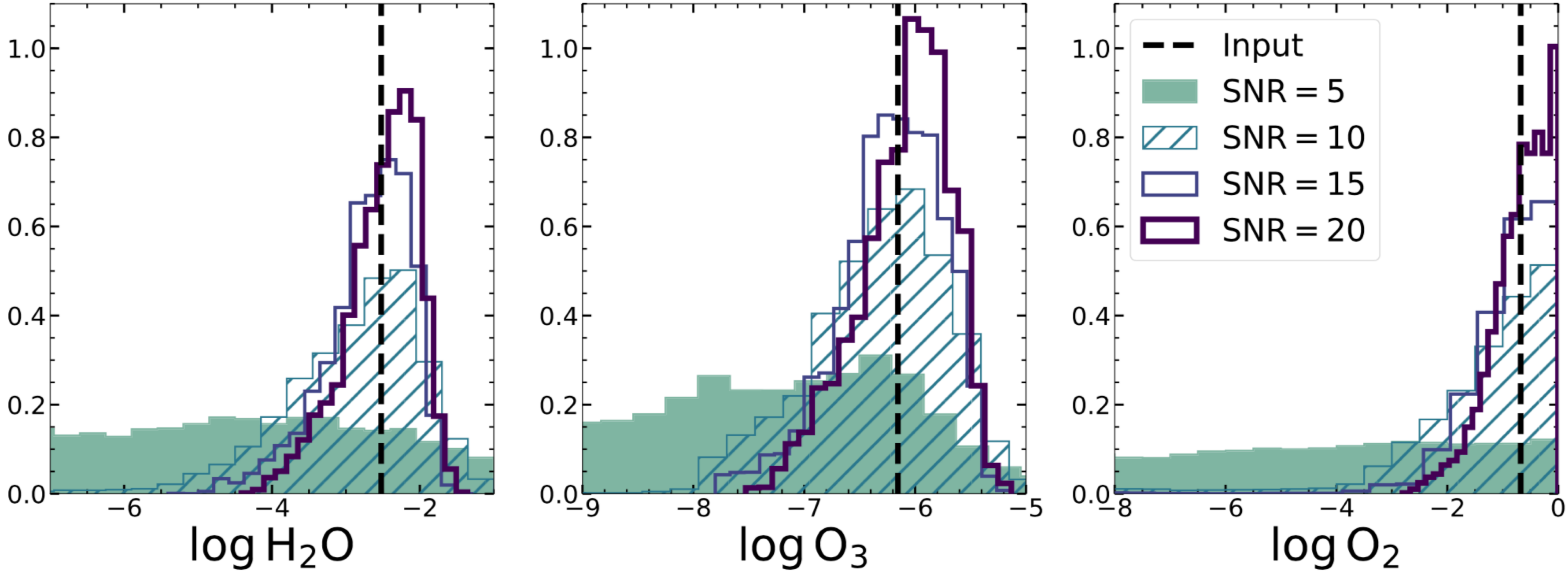
Feng et al. (2018)

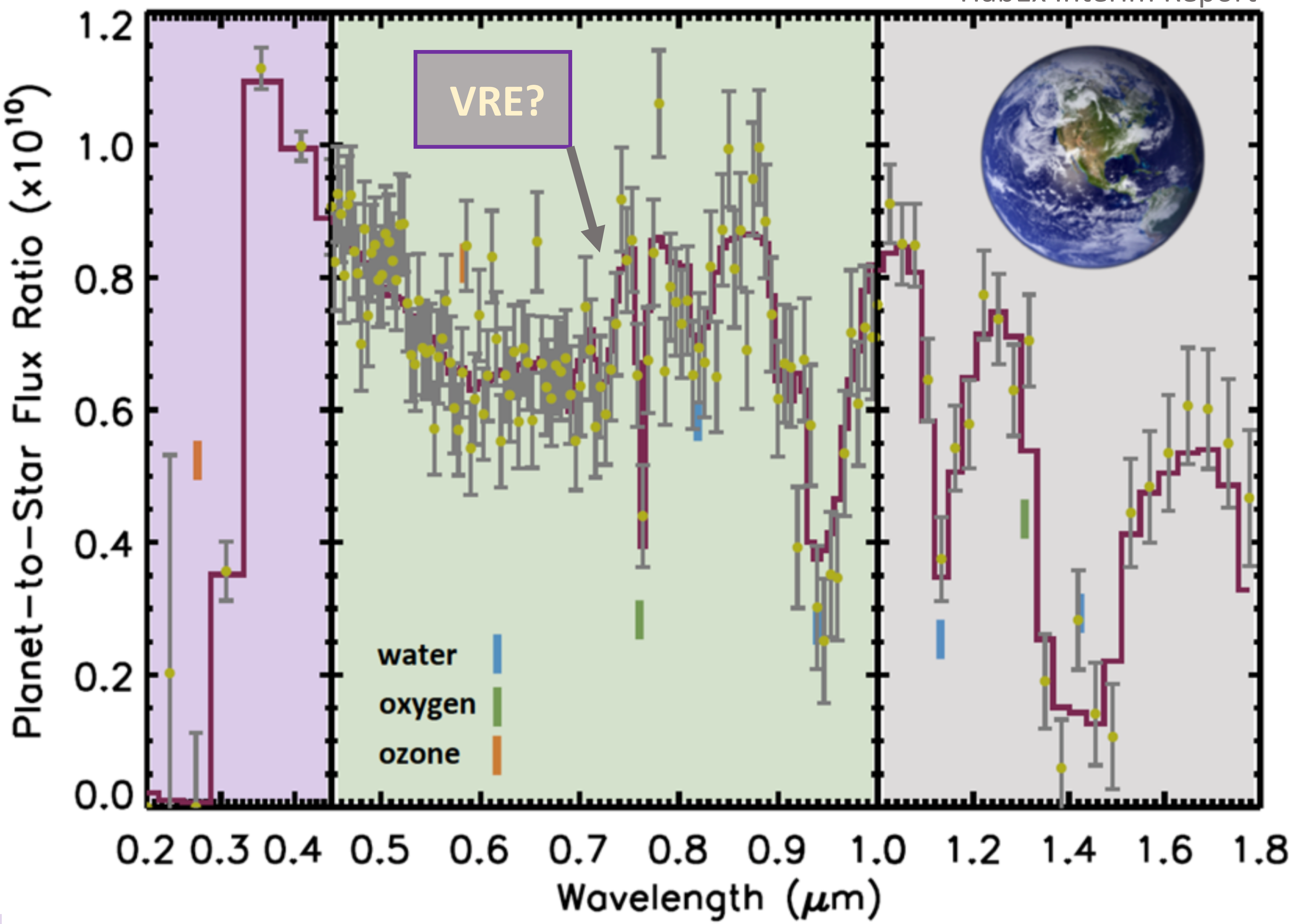




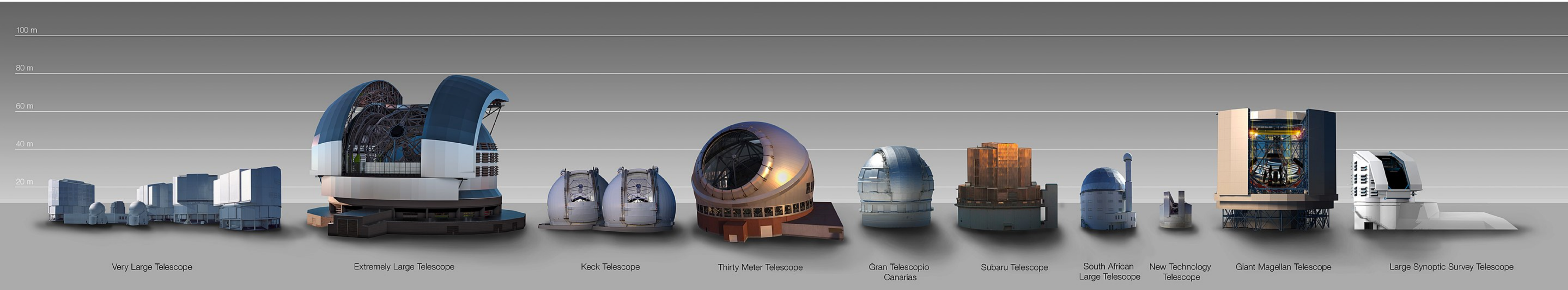
Feng et al. (2018)

Feng et al. (2018)




VRE?
Planet-to-Star Flux Ratio ($\times 10^{10}$)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
water
oxygen
ozone
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.2 1.4 1.6 1.8
Wavelength (μm)

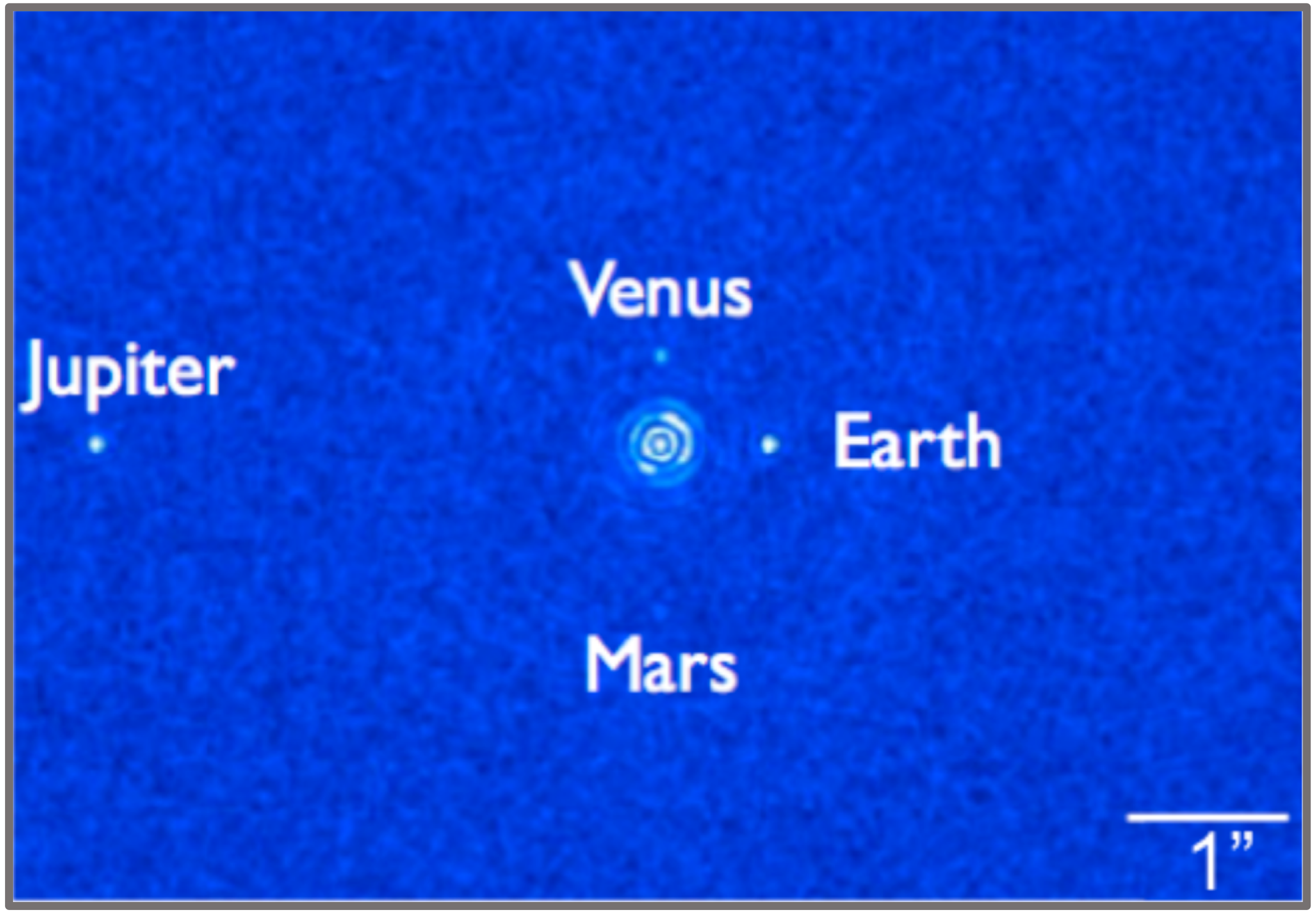
Credit: ESO



100 m
80 m
60 m
40 m
20 m
Very Large Telescope
Extremely Large Telescope
Keck Telescope
Thirty Meter Telescope
Gran Telescopio Canarias
Subaru Telescope
South African Large Telescope
New Technology Telescope
Giant Magellan Telescope
Large Synoptic Survey Telescope

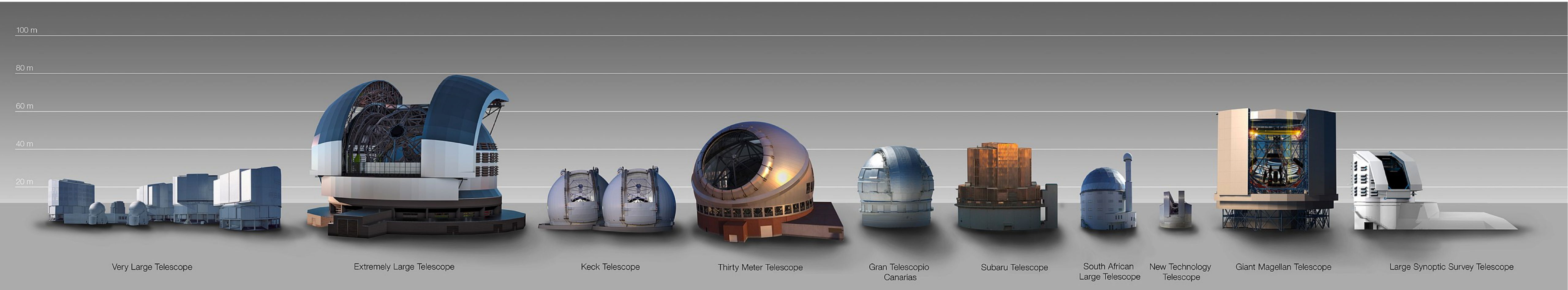
ELTs & Biosignatures

- MIR direct imaging of Earths orbiting AFGK stars



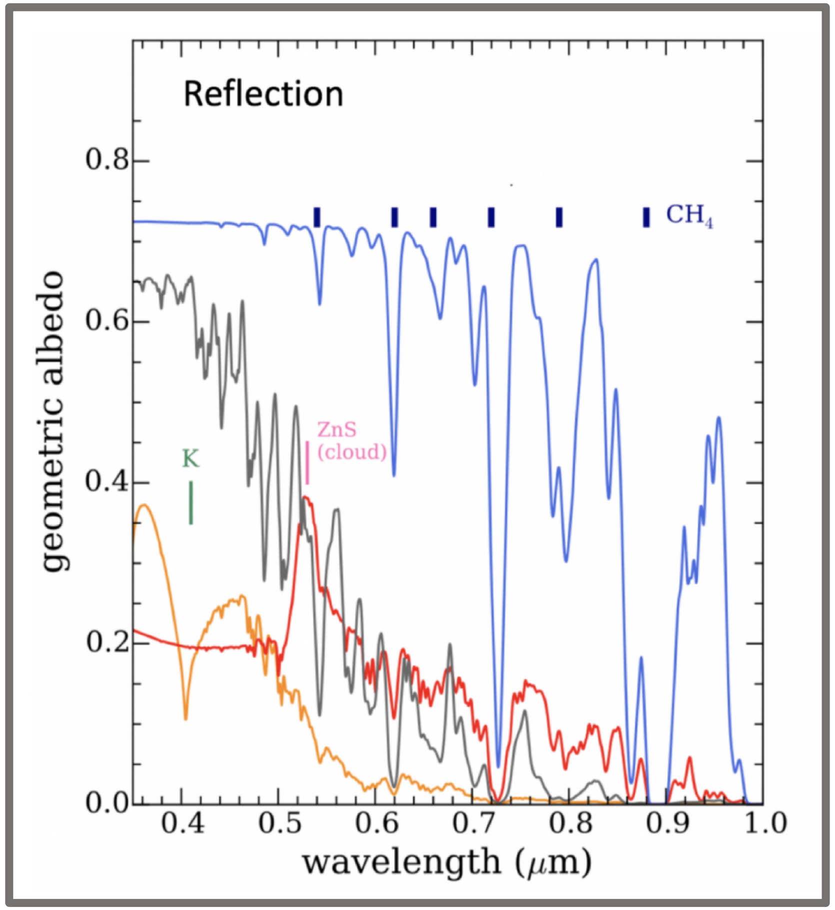
Credit: C. Marois

See also: Currie et al. (2019)

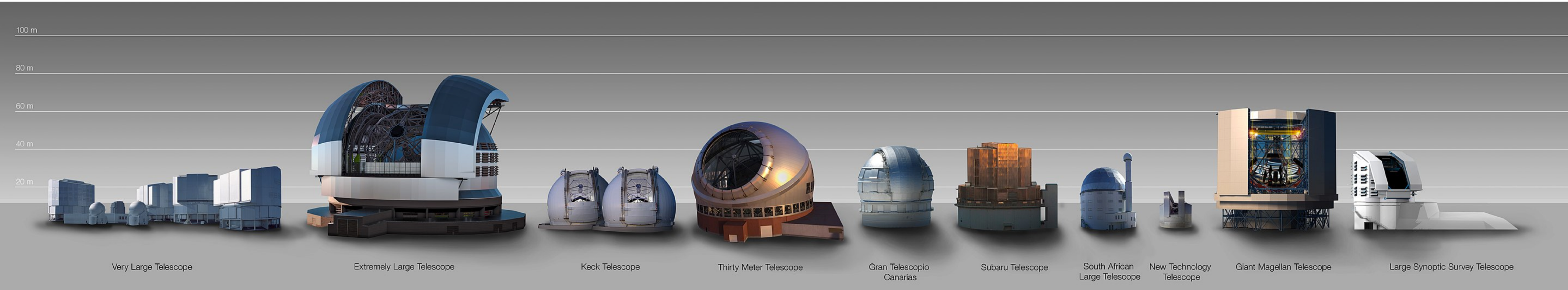


ELTs & Biosignatures

- MIR direct imaging of Earths orbiting AFGK stars
- visible imaging of small, cool worlds orbiting M dwarfs



See also: Wang & Meyer et al. (2019)

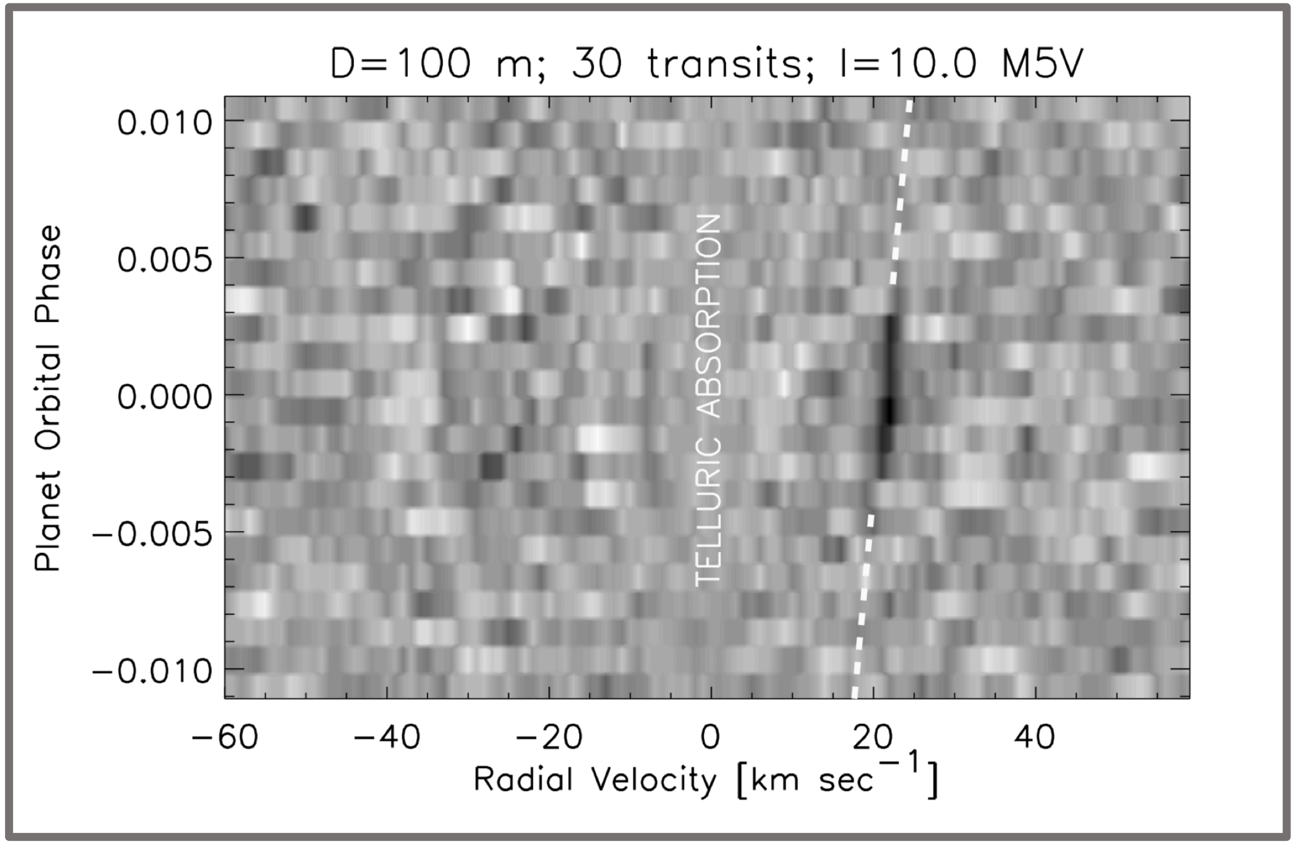


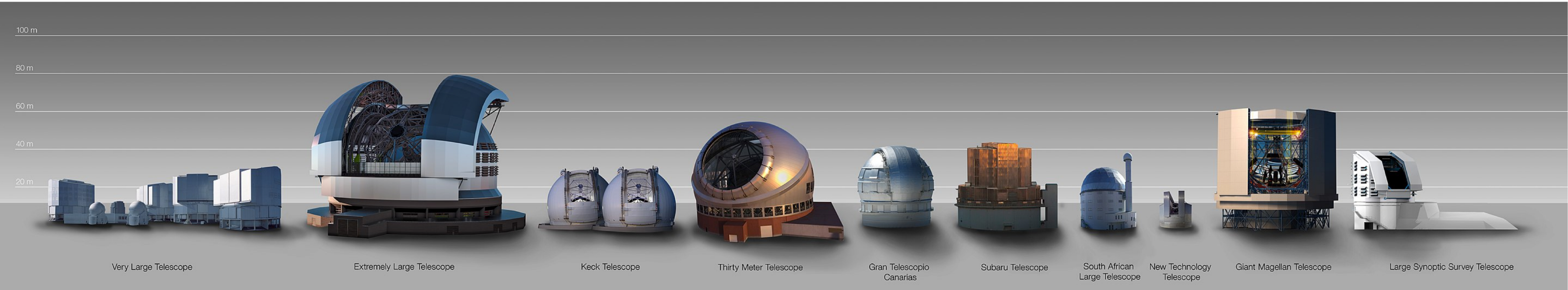
ELTs & Biosignatures

- MIR direct imaging of Earths orbiting AFGK stars
- visible imaging of small, cool worlds orbiting M dwarfs
- high-resolution detection of O_2 for exo-Earths
  - can be combined with high-contrast imaging

See also: Kawahara (2014); Serindag & Snellen (2019)

Snellen et al. (2013)





Key Questions

What techniques exist for characterizing exoplanet atmospheres?

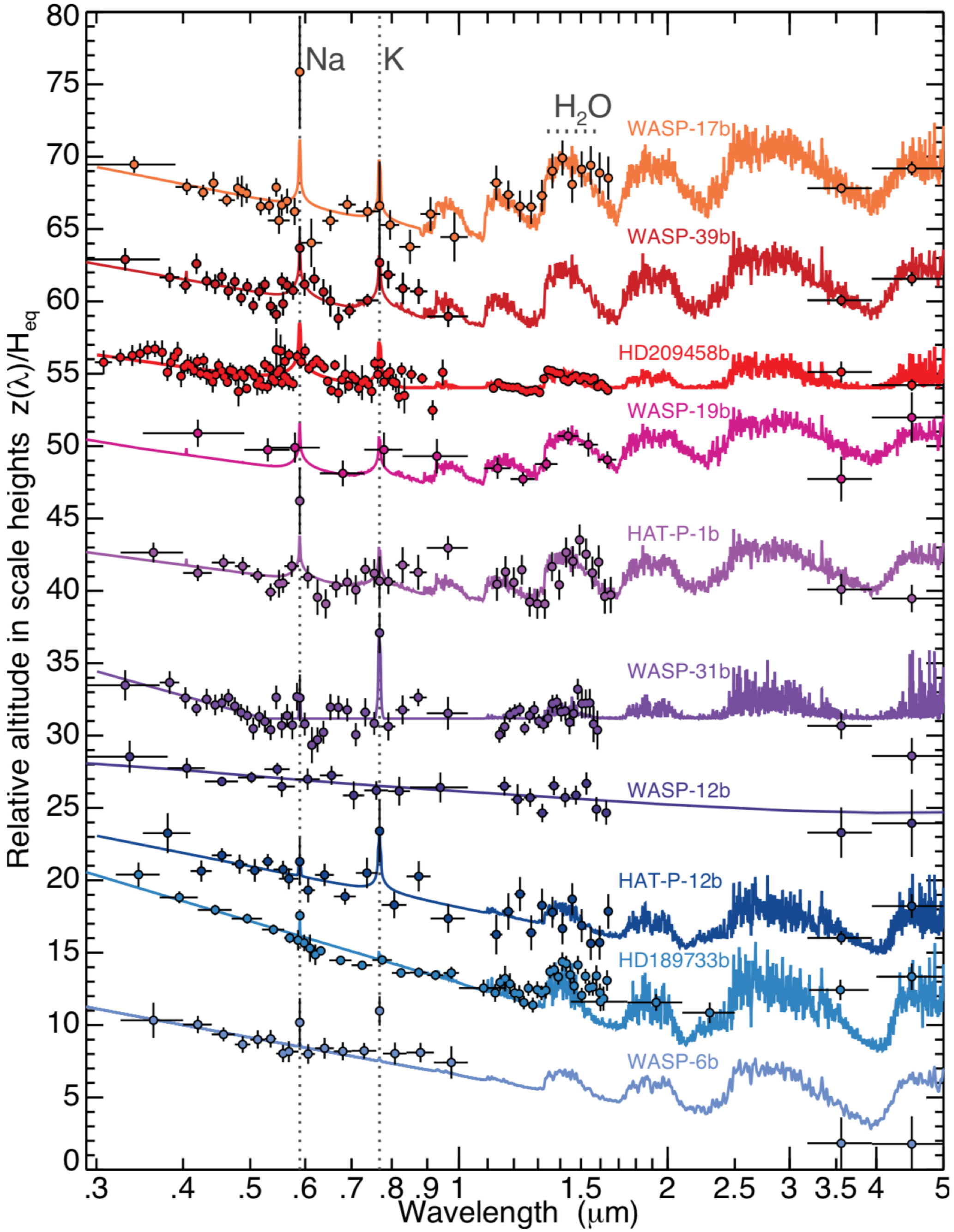
What can different observing techniques tell us about exoplanets and their atmospheres?

Given a spectrum, how do we say something about the state of an exoplanet atmosphere?

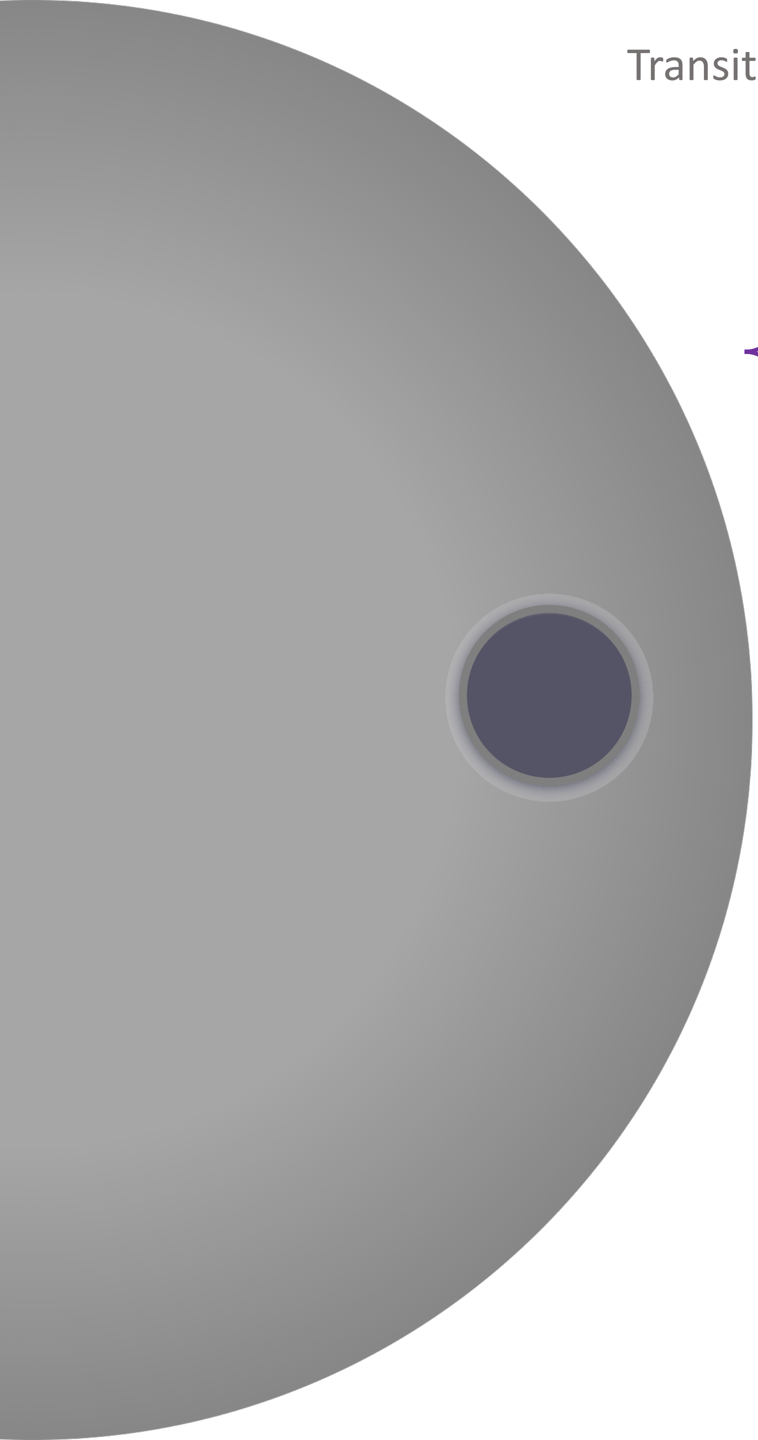
What are the prospects for exoplanet biosignature detections?

Thanks to: Sagan Fellowship Program, NAI & NExSS, NASA Exoplanets Research Program, NASA Exobiology

Transiting Hot Jupiters



Sing et al. (2015)



Transit spectra can provide constraints on:

atmospheric opacity → atmospheric trace/bulk gas composition, aerosols, atmospheric pressure

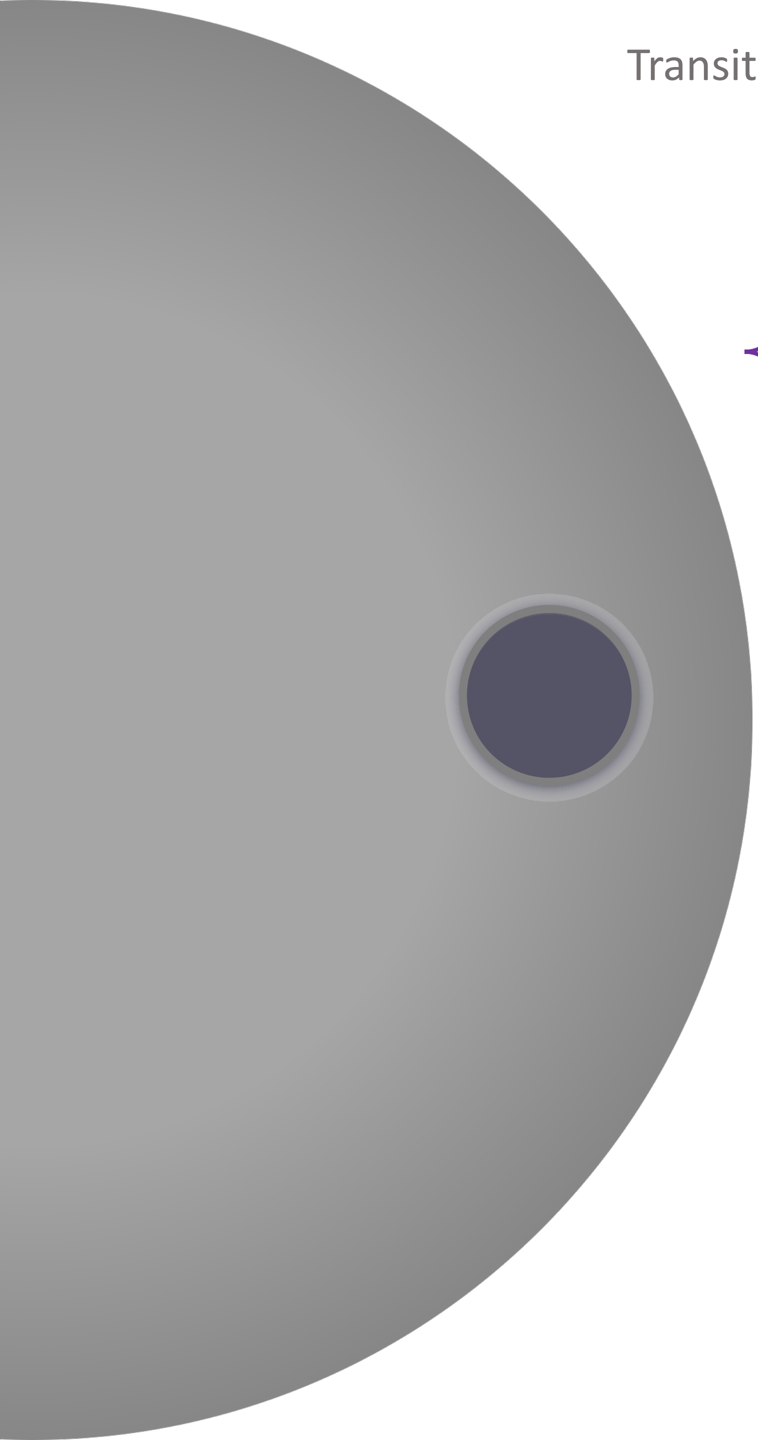
atmospheric temperature

atmospheric bulk composition

surface gravity, planet size → planet mass

recall: transit spectra are more sensitive to lower-pressure atmospheric regions

See also: de Wit & Seager (2013)



Transit spectra can provide constraints on:

atmospheric opacity
atmospheric temperature
atmospheric bulk composition
surface gravity
planet size

→ atmospheric trace/bulk gas composition
aerosols
atmospheric pressure

→ planet mass

recall: transit spectra are more sensitive to lower-pressure atmospheric regions

putting these together: transit spectroscopy has the potential to detect atmospheric chemical biosignatures *if* these signatures are transported and preserved (in some way) in the upper atmosphere

See also: de Wit & Seager (2013)