Transmission Spectroscopy

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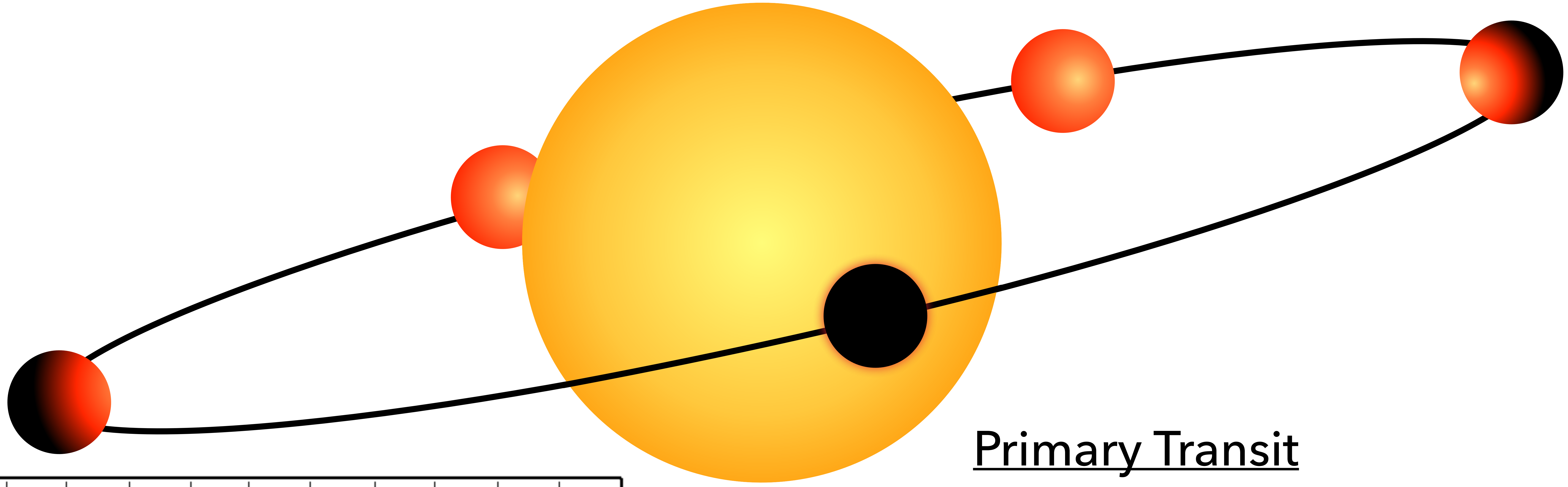
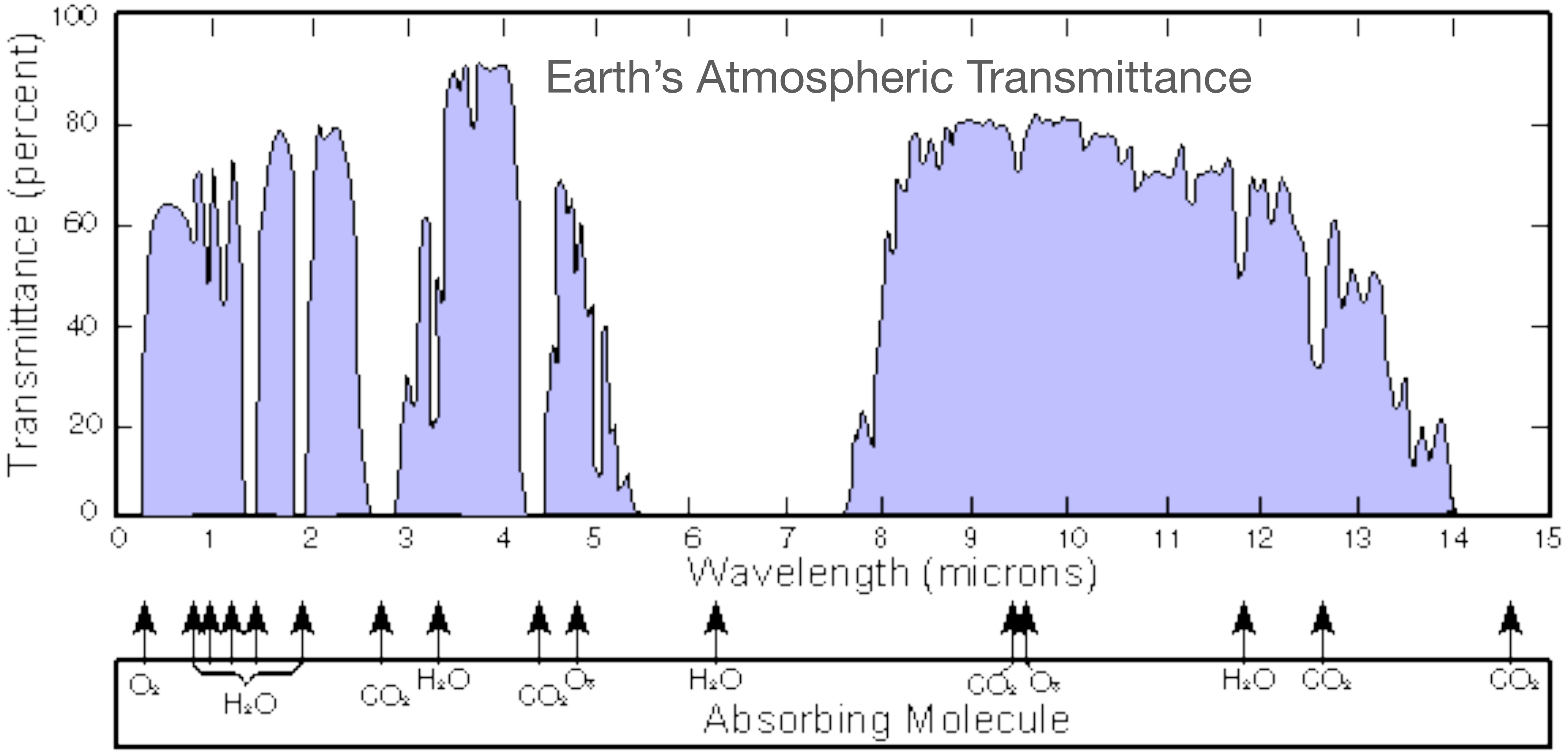
UK Research and Innovation
Horizon Europe Funding

Image compilation: HRWakeford

Transmission Spectroscopy

Measure of atmospheric absorption and transmission during transit





Primary Transit

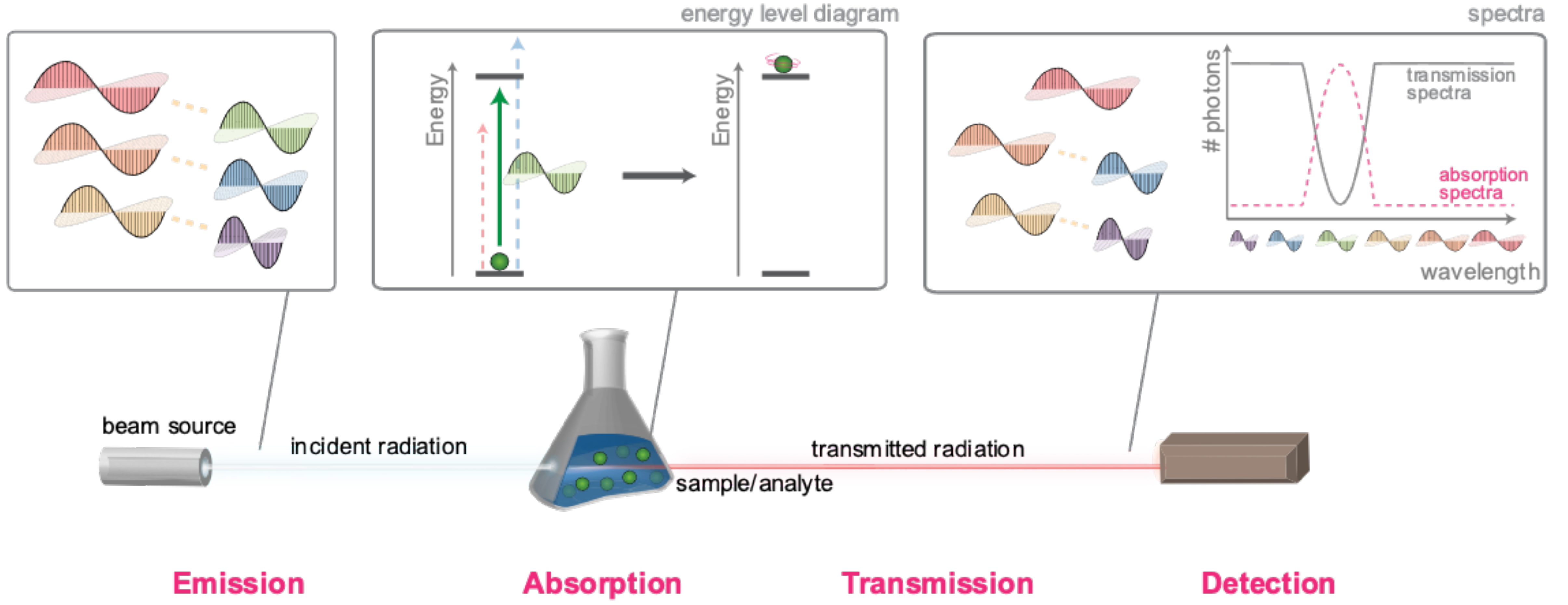
The planet passes in front of the star

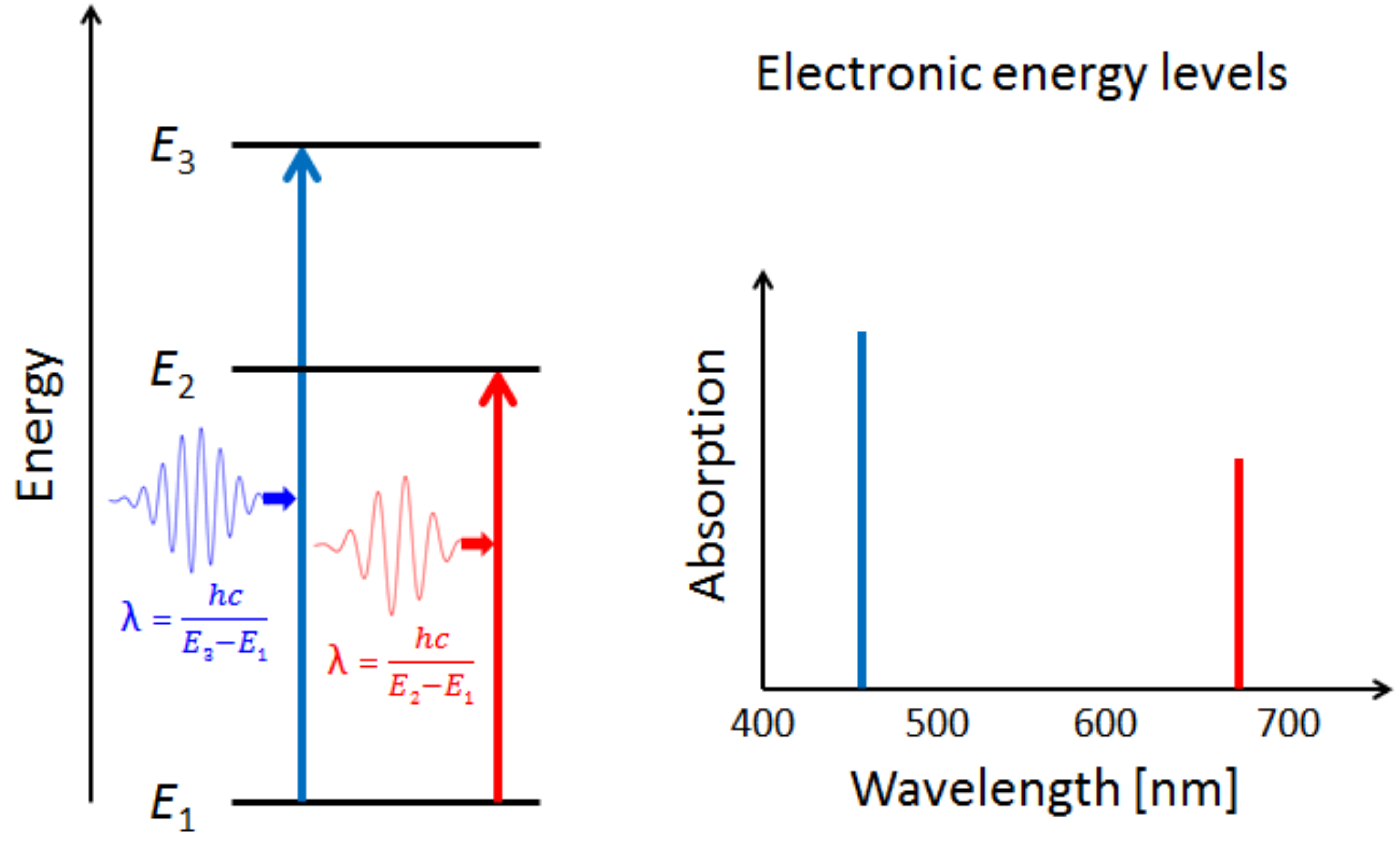
Absorption (transmission) through the planets atmosphere can be measured by the change in area blocked

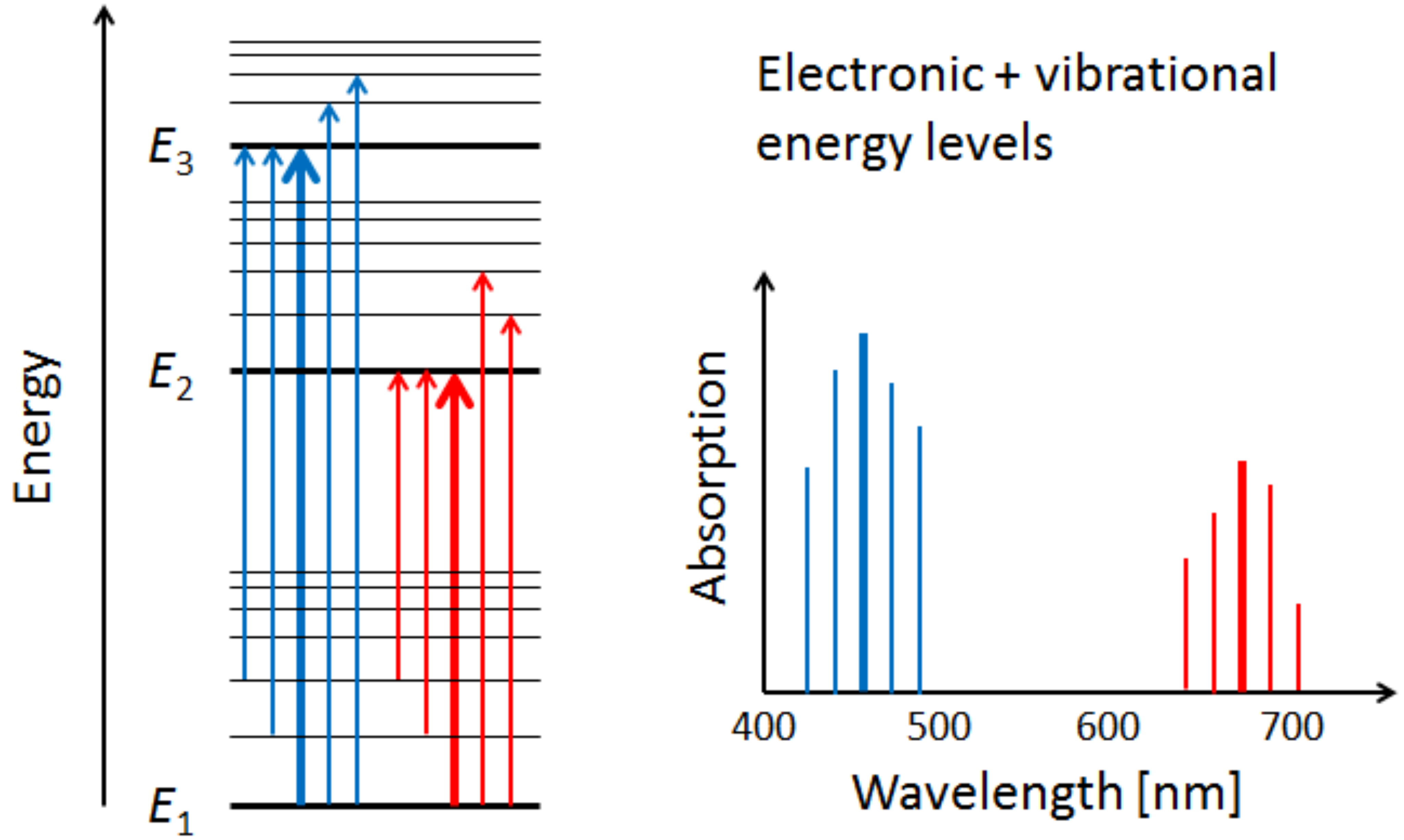
Absorption and Energy Levels

The process where photons are transformed into internal energy

On a quantum mechanical level, a molecule can only absorb or emit energy of wavelength λ if it has energy levels separated by a transition energy







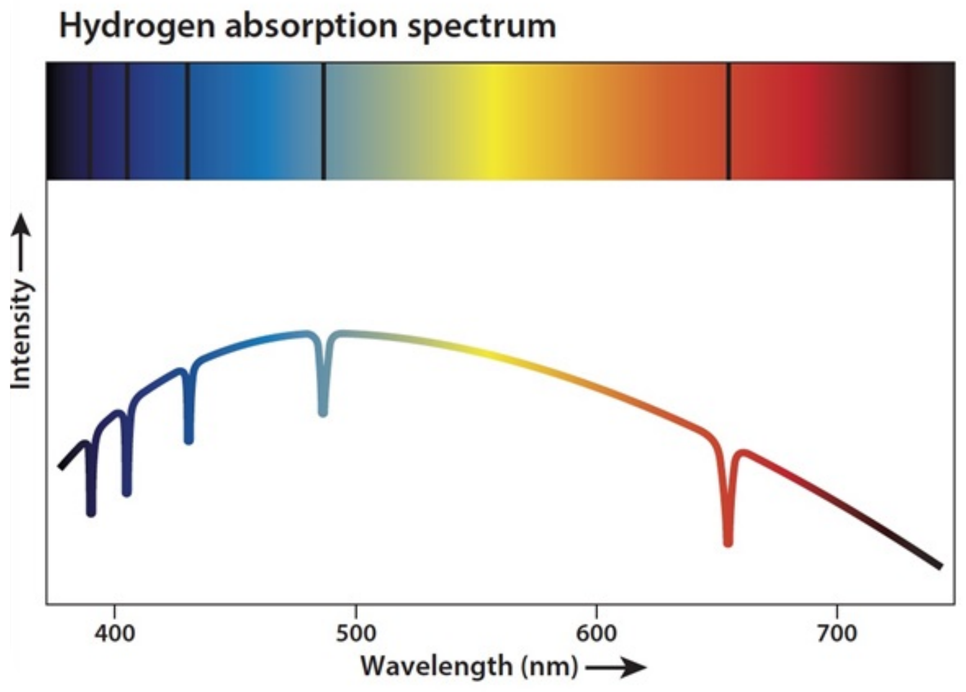
Photon Energies Tell You About Absorption Properties

Different energy scales in atoms and molecules correspond to different process

Electron motion:

$$\Delta E \sim 1000\,\mathrm{eV} - 1\,\mathrm{eV}$$
$$\lambda \sim 1\,\mathrm{nm} - 1\,\mu\mathrm{m}$$

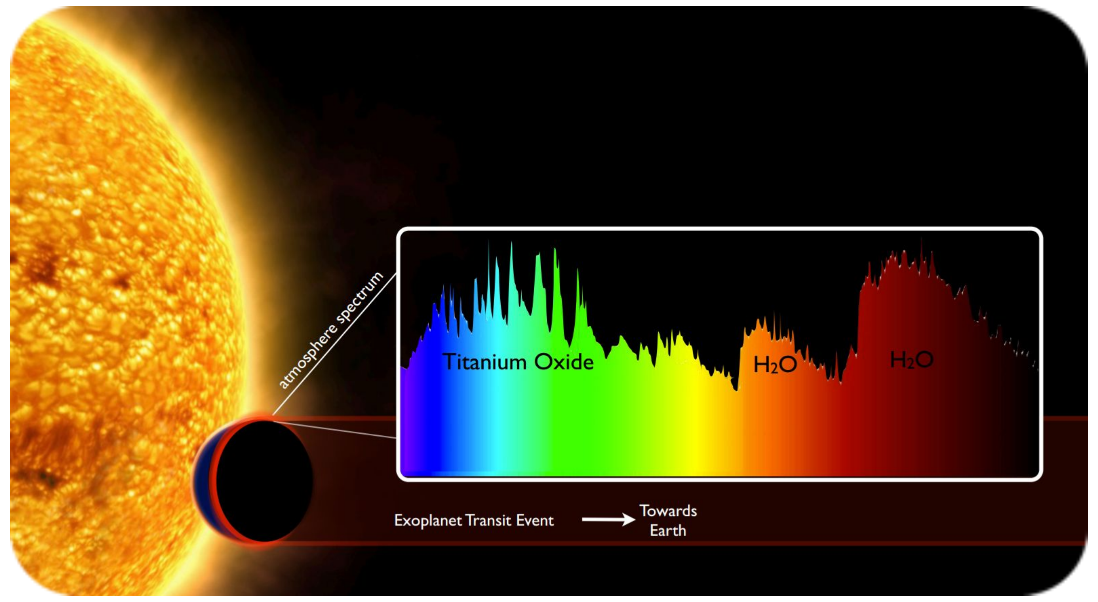
UV - Optical



Ro-vibrational overtones:

$$\Delta E \sim 1\,\mathrm{eV} - 100\,\mathrm{meV}$$
$$\lambda \sim 1\,\mu\mathrm{m} - 10\,\mu\mathrm{m}$$

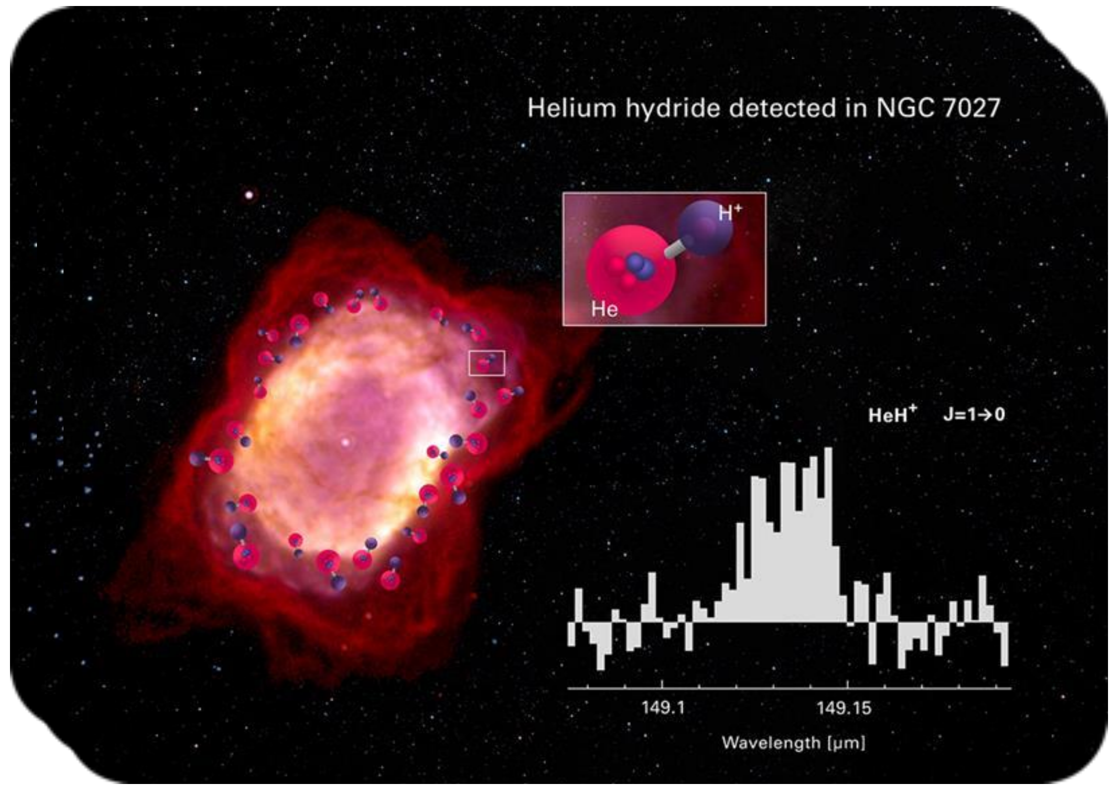
Near- to Mid-IR



Molecular Vibration:

$$\Delta E \sim 100\,\mathrm{meV} - 0.1\,\mathrm{meV}$$
$$\lambda \sim 10\,\mu\mathrm{m} - 1\,\mathrm{cm}$$

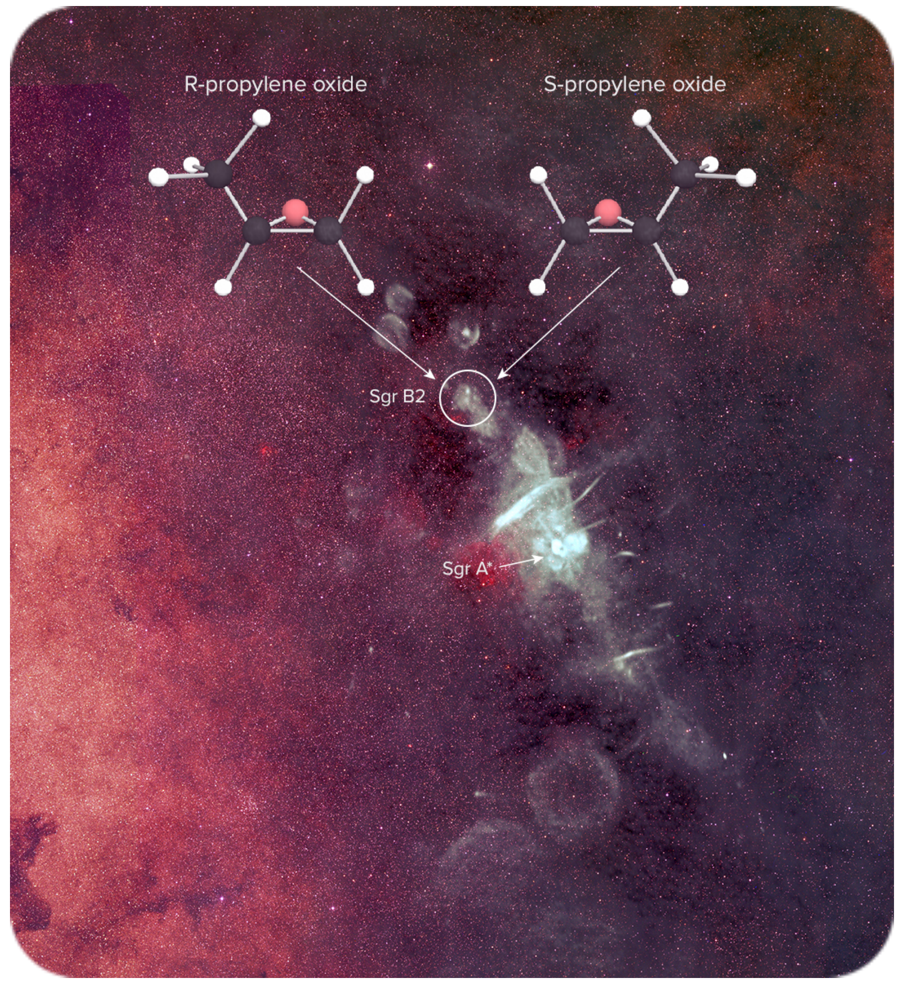
IR - sub-mm & radio



Molecular Rotation:

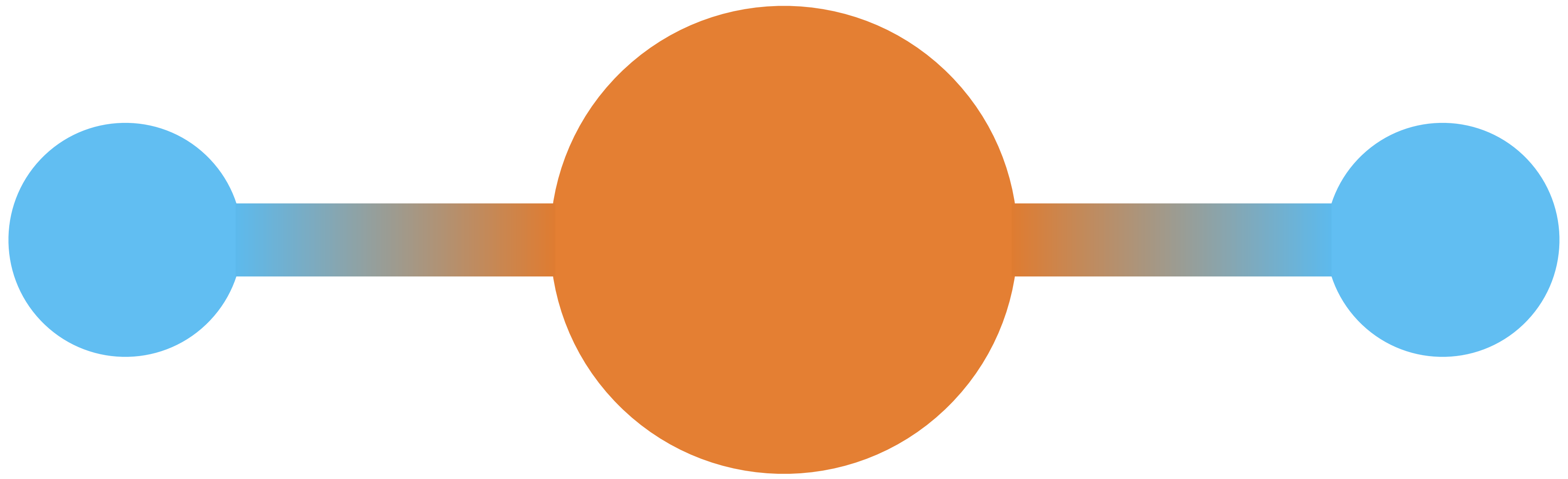
$$\Delta E \sim 0.01\,\mathrm{meV}$$
$$\lambda \sim 10\,\mathrm{cm}$$

Radio



Infrared Absorption

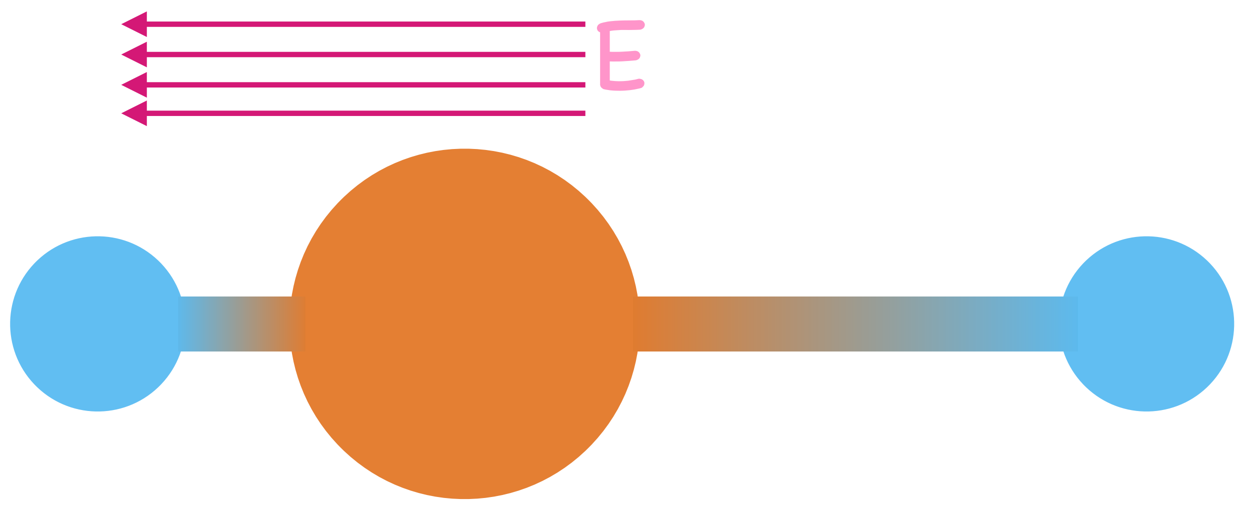
A vibrational mode can only be induced if the molecule has an electric dipole



Electric dipole = structural separation of +ve and -ve charges

Molecules with a pronounced dipole moment will absorb in the infrared

- The wavelength of infrared radiation has a wavelength larger than a typical molecule
- As far as the molecule is concerned, the electric field of the IR radiation represents a uniform external field.
- Within this field all positive charges are pushed in one direction and all the negative charges are pushed in the opposite direction.
- This motion produces a fluctuation on the dipole moment which is how the IR radiation induces a vibration.



Absorption in the Earth's Atmosphere

The size of the atmosphere looks different at different wavelengths

Absorption in the Earth's Atmosphere

The size of the atmosphere looks different at different wavelengths

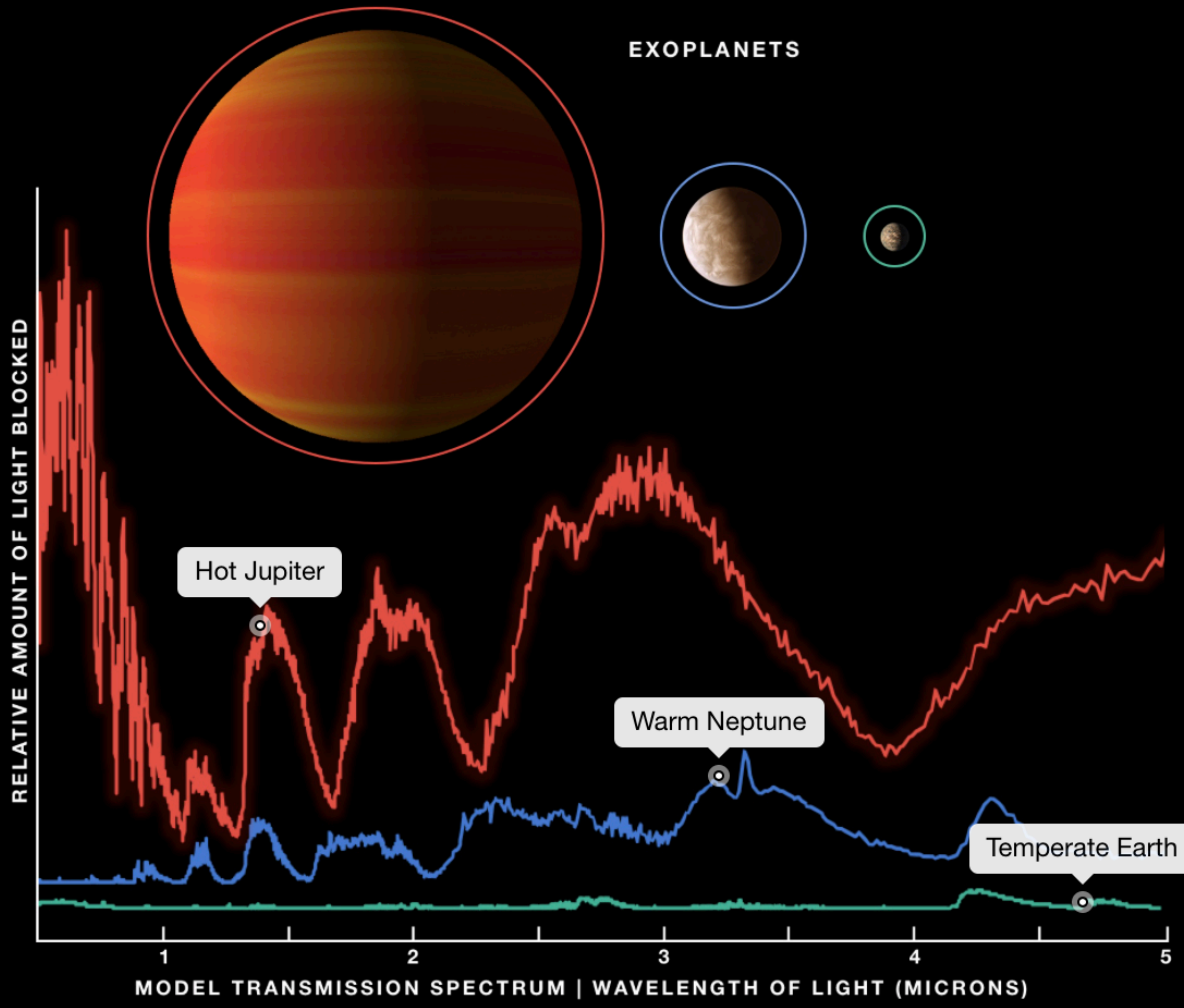
Absorption in the Earth's Atmosphere

The size of the atmosphere looks different at different wavelengths

Credit: Himawary/Simon Proud/Vivien Parmentier

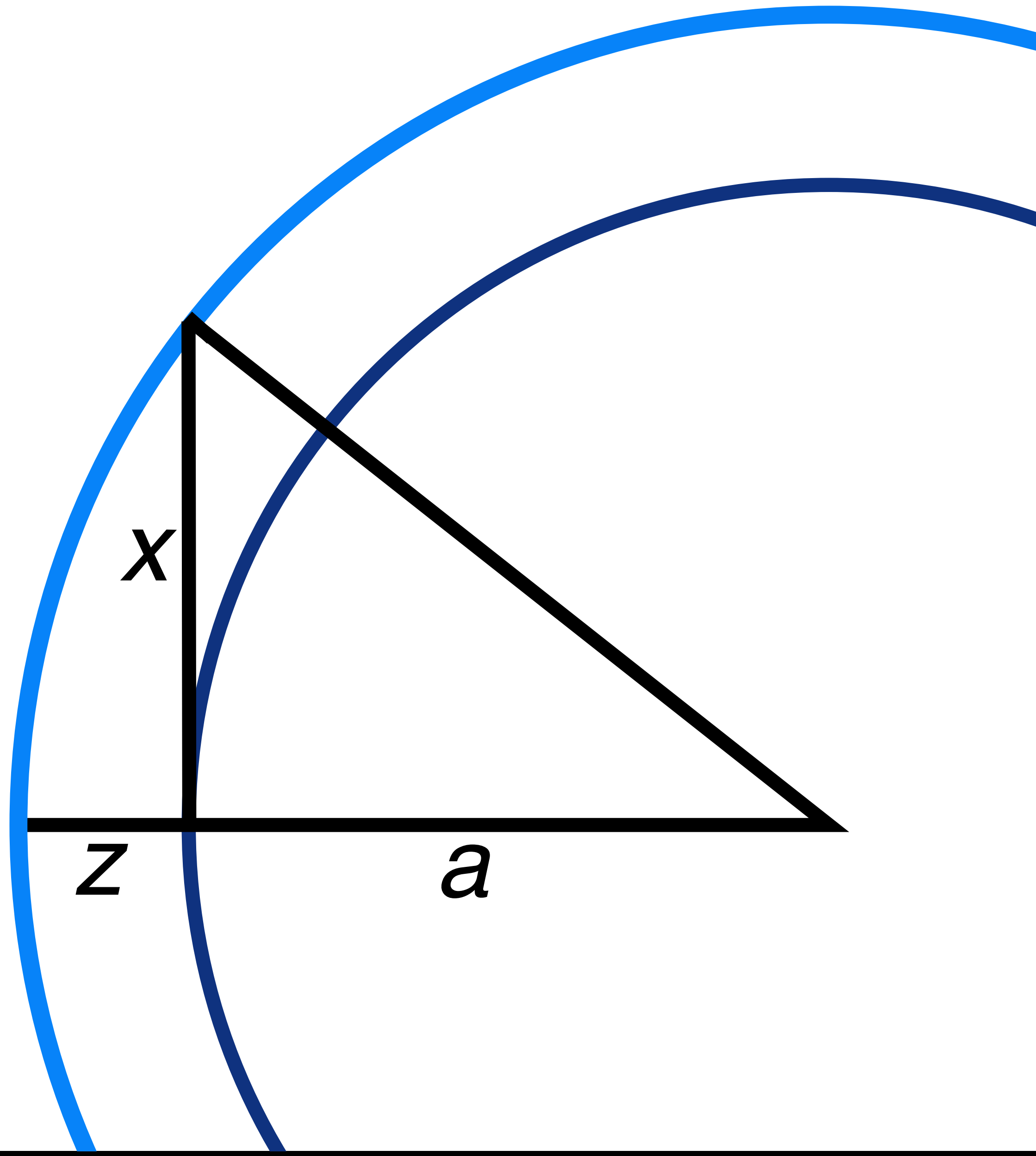
Predicting the Size of Atmospheric Features

The more atmosphere, the more signal transmitted



- The larger the atmosphere the easier the measurement will be.
- The larger the cross section of the molecule the larger the impact on the spectrum for small amounts

The slant geometry measured in transit often increases absorption significance by over 30x



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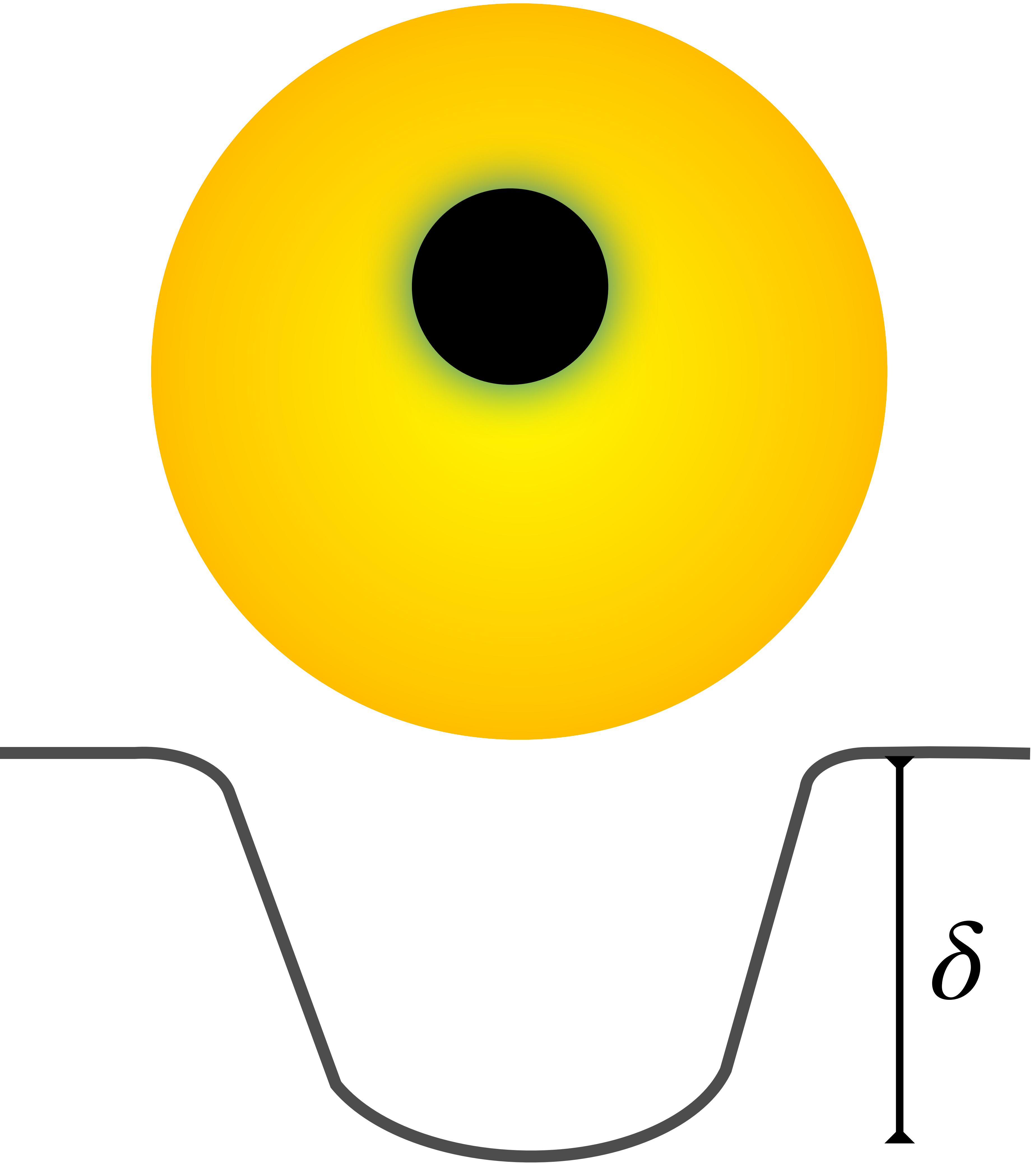
Measured Transit Depth

The atmosphere adds a more area blocked by the planet



$$\delta = \frac{A_p}{A_*} = \frac{\pi R_p^2}{\pi R_*^2} = \left(\frac{R_p}{R_*}\right)^2$$

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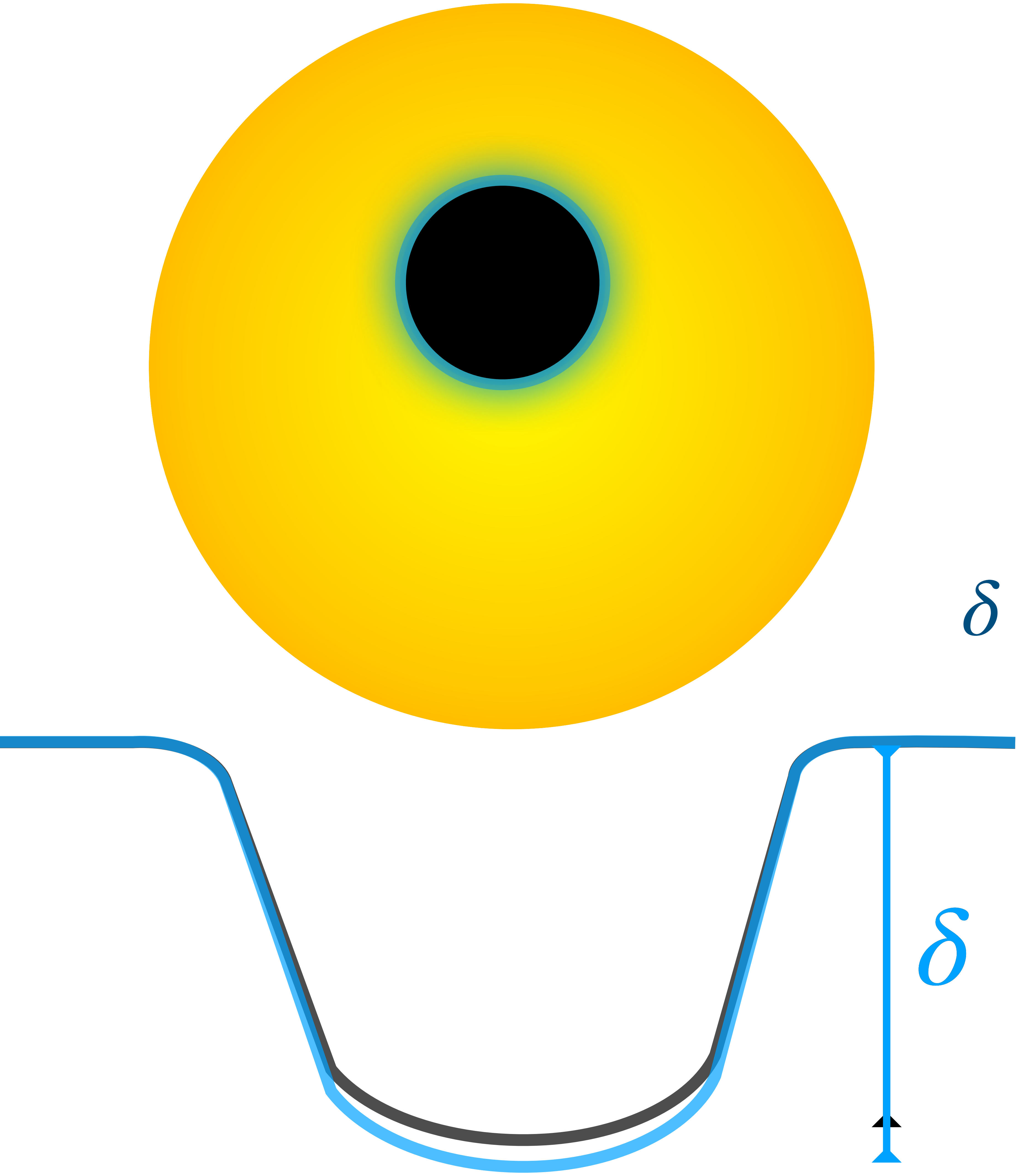
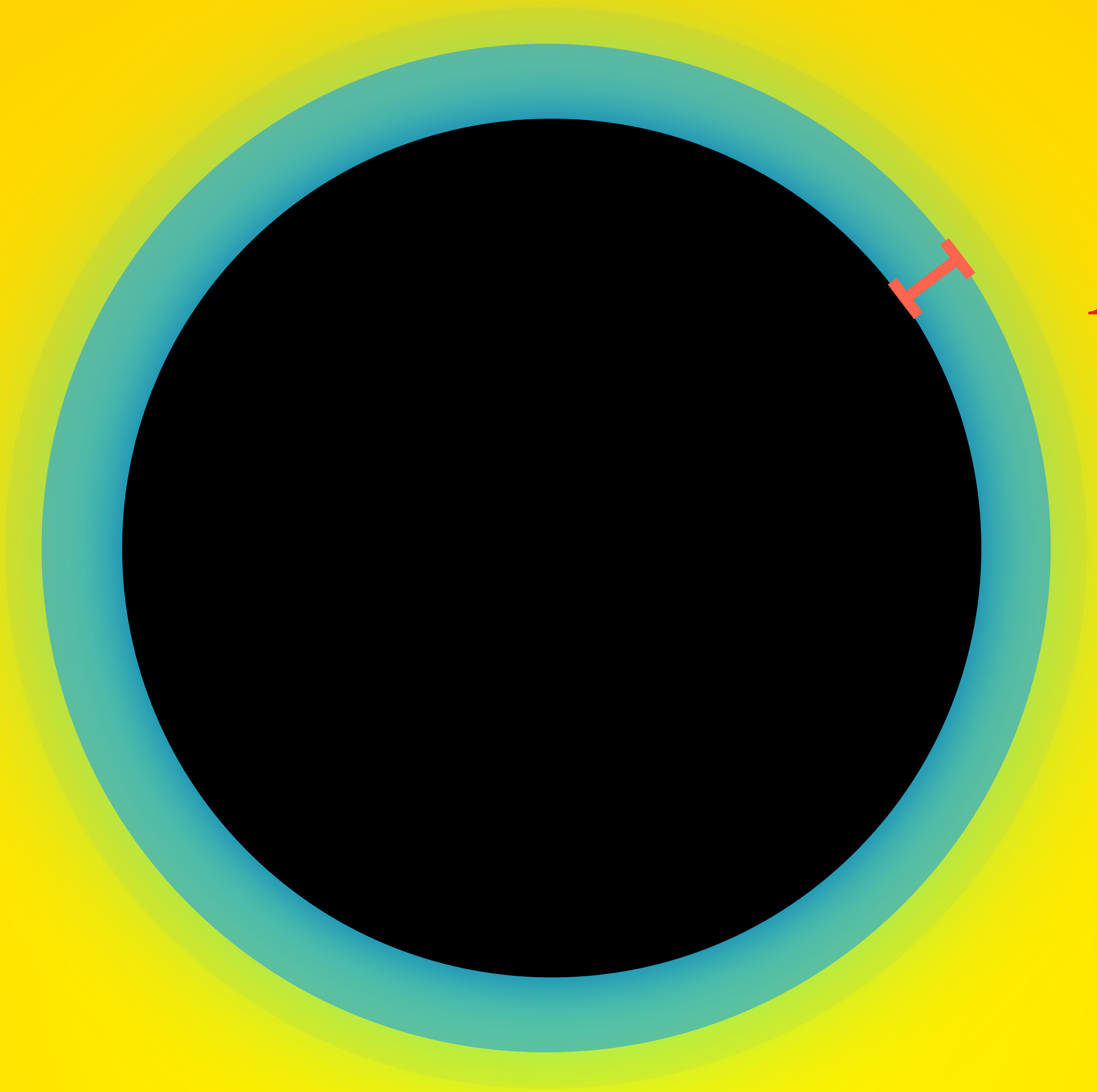


$$\delta = \frac{A_p}{A_*} = \frac{\pi R_p^2}{\pi R_*^2} = \left(\frac{R_p}{R_*}\right)^2$$

$$\delta = \frac{A_p + A_{atm}}{A_*} = \frac{\pi\left(R_p + H_{atm}\right)^2}{\pi R_*^2} \approx \left(\frac{R_p}{R_*}\right)^2 + \frac{2R_pH_{atm}}{R_*^2}$$

Atmospheric Scale Height

Height at which pressure decreases by a factor of e (exponent)



$$H = \frac{k_B T_{eq}}{\mu g_p}$$

H = Atmospheric Scale Height

k_B = Boltzmann Constant

T = Planetary Temperature

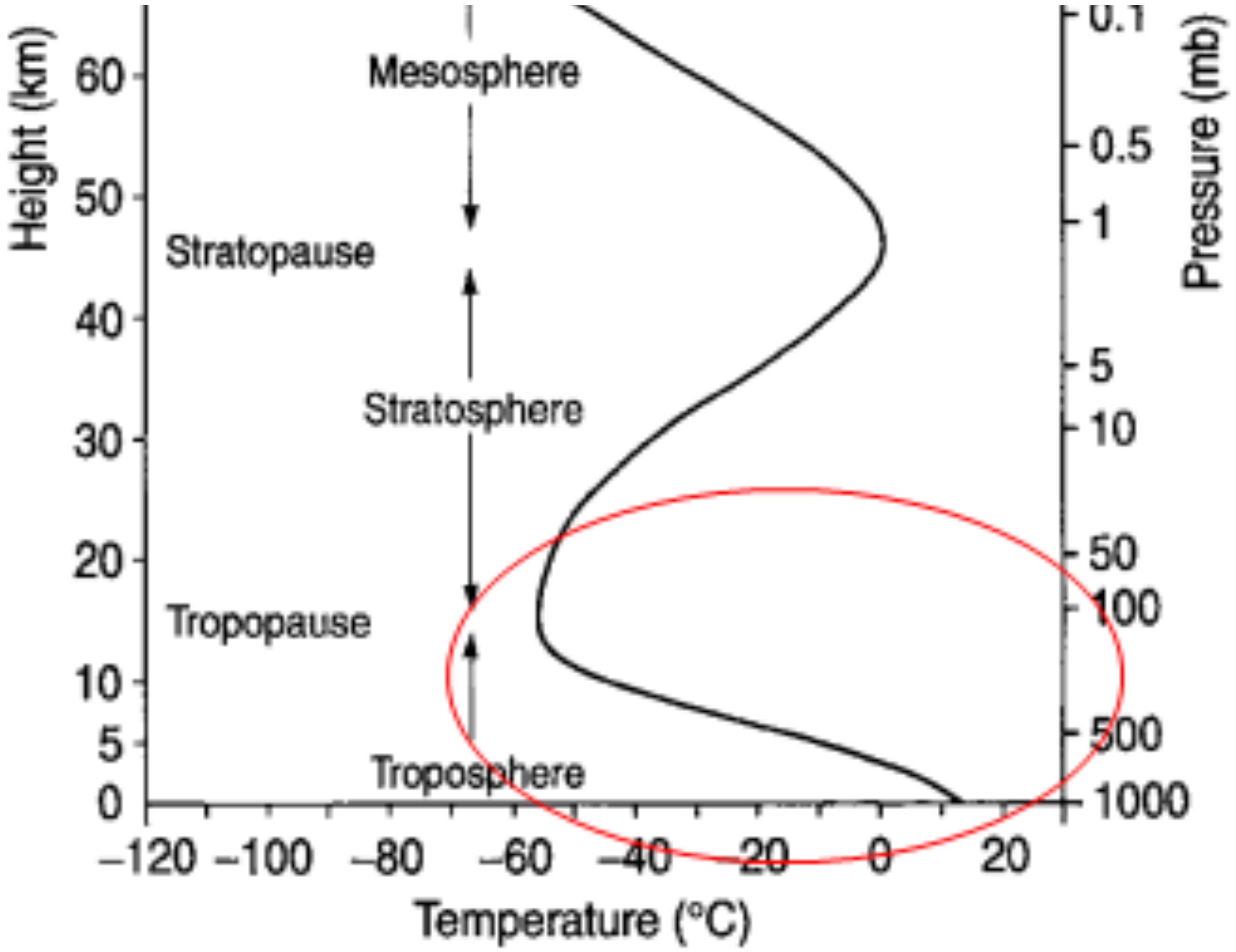
μ = Atmospheric Mean Molecular Weight

g = planet gravity

Atmospheric Pressure Structure

Hot air rises but it also gets colder as you go up, how does that work?

Change in pressure with altitude causes a change in the temperature



As you go up in the atmosphere the pressure drops and how it does this is important.

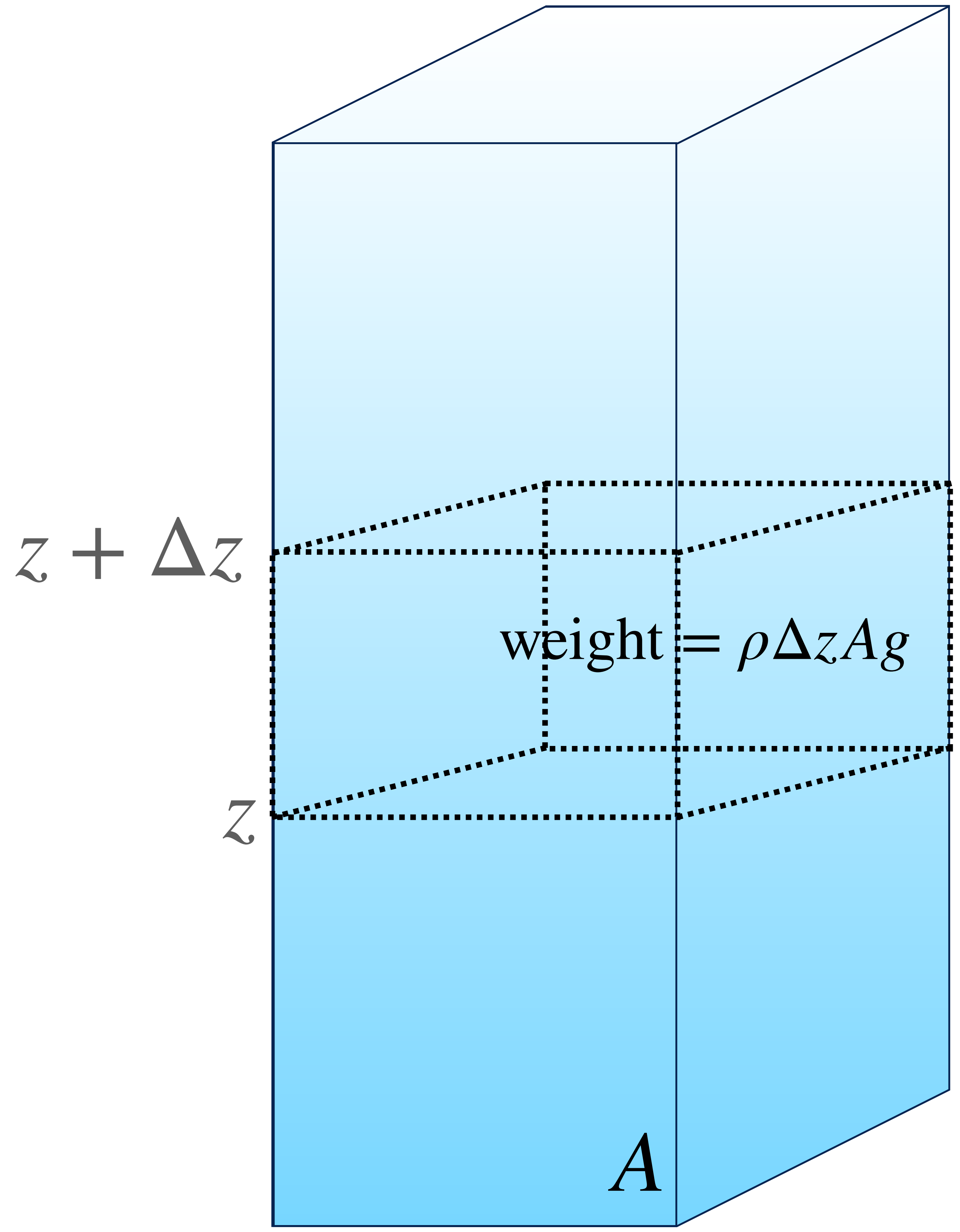
Consider a Column of Air

How does the pressure change with height, z?

The pressure for a column of air is just due to the weight of that air

$$\text{weight} = \rho A g \Delta z$$

$$P(z) - P(z + \Delta z) = \frac{\rho(z) A g \Delta z}{A} = \rho(z) g \Delta z$$



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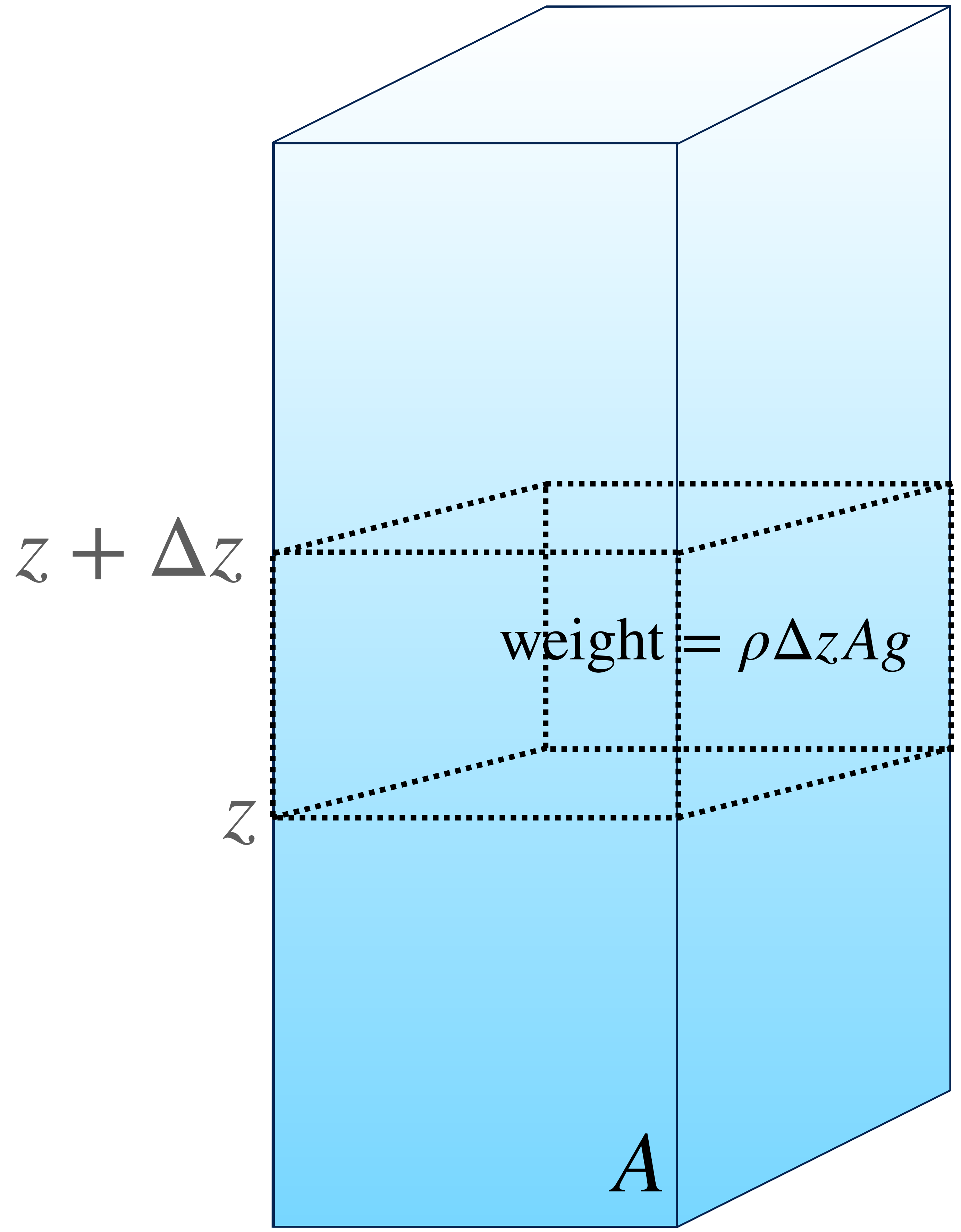
This assumes that density is constant. Therefore, Δz must be very small



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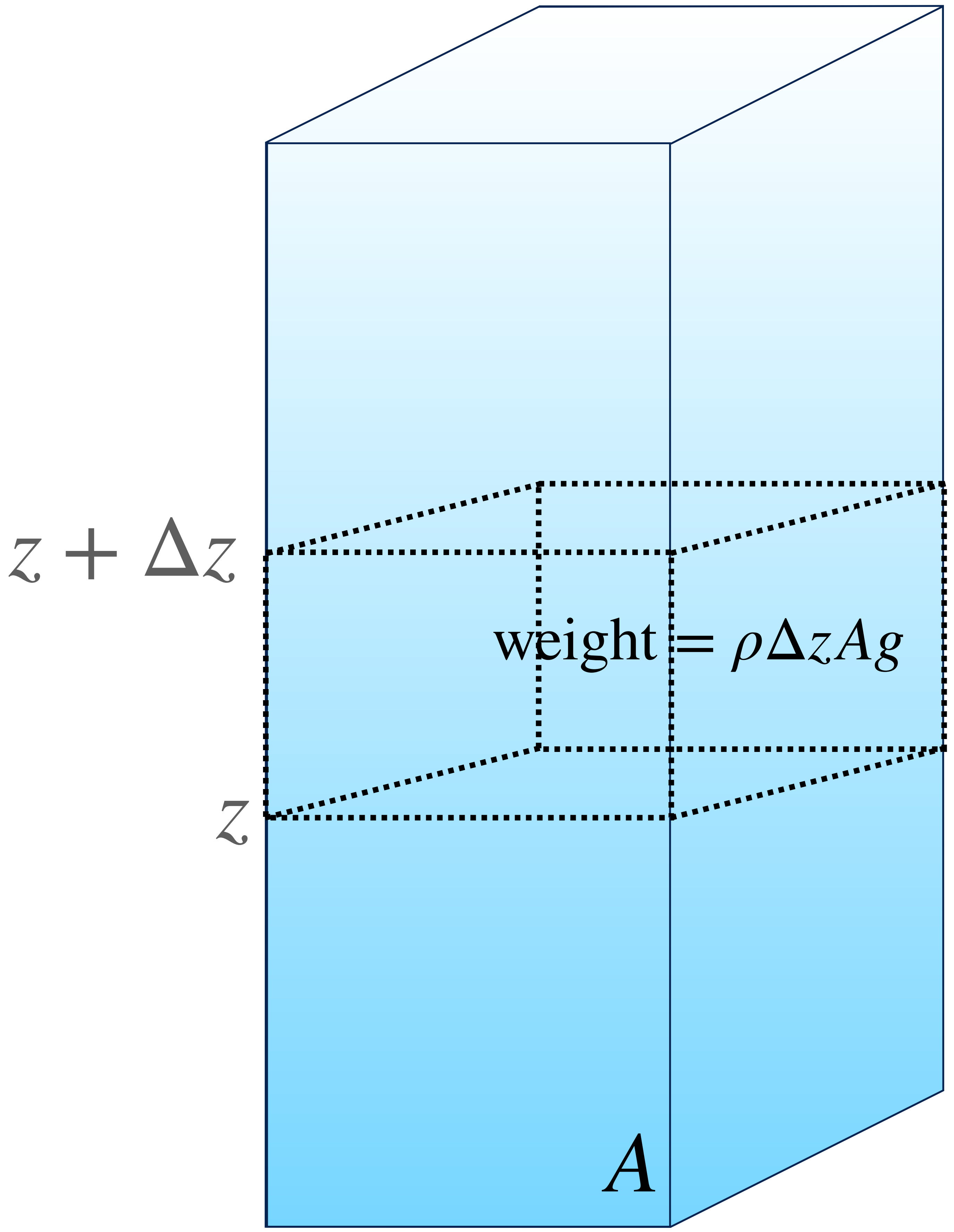
At the limit where $\Delta z \to 0$



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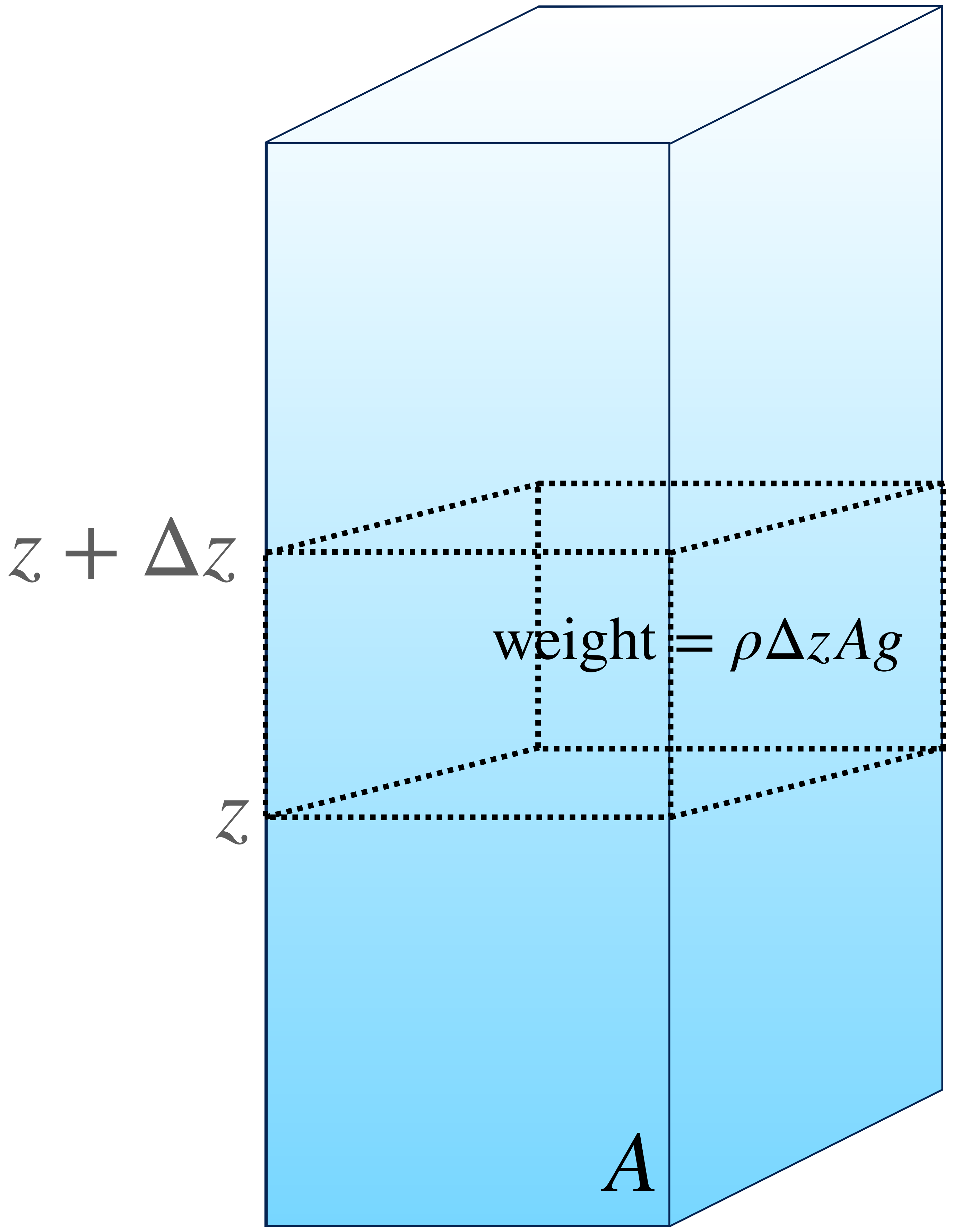
This assumes that density is constant. Therefore, Δz must be very small

At the limit where $\Delta z \rightarrow 0$

$$\frac{\partial P}{\partial z} = -\rho g$$



Hydrostatic Equilibrium

In the limit that the air is not moving we can say it is in hydrostatic equilibrium

Change in pressure with increased altitude, is decreasing as density times gravity

$$\frac{\partial P}{\partial z} = -\rho g$$

This works for any situation where only the force acting is gravity

If the air is not moving this is then said to be in
Hydrostatic Equilibrium

<u>Treating it as an ideal gas:</u>

$$PV = nRT = nk_BN_AT$$

Pressure

$$\frac{\partial P}{\partial z} = -\frac{g}{R' \, T}P$$

Density

$$\frac{\partial(\rho T)}{\partial z} = -\frac{g}{R'}\rho$$

Have to keep T in the derivative as it may change with altitude

Atmospheric Scale Height

Height at which pressure decreases by a factor of e (exponent)

$$\frac{\partial(\rho T)}{\partial z} = -\frac{g}{R'}\rho$$

If we fix T (for Earth average T = 287 K)

We get the rate of change of density with height is equal to minus constant times density

If we differentiate density with height we get, $\rho(z) = \rho_0 e^{-\frac{z}{H}}$

where,

$$H = \frac{R'\,T}{g} = \frac{RT}{M_{air}g} = \frac{k_B T}{\mu g}$$

SCALE HEIGHT

This is the length scale of the atmosphere where P and ρ changes by e

Optical Depth and Absorption Cross Sections

How much stuff the light will pass through

Optical depth (τ) is a dimensionless measure of how far the light has penetrated down into the atmosphere from the top

Roughly how much ‘ stuff ’ the light will pass through

It takes into account the modifying effects of both mass extinction and density, at a specific wavelength

$$\tau_\nu = \int_z^{z_{\rm top}} \kappa_\nu(z')\rho_a(z')\,{\rm d}z'$$

Mass extinction coefficient

Density of gas

Altitude

Optical Depth and Absorption Cross Sections

How much stuff the light will pass through

Optical depth (τ) is a dimensionless measure of how far the light has penetrated down into the atmosphere from the top

Roughly how much ' stuff ' the light will pass through

At slant geometries this becomes:

$$\tau(\lambda, z) \approx \sigma(\lambda)\, n(z) \sqrt{2\pi R_p H}$$

- $\sigma(\lambda)$: Absorbing cross section
- $n(z)$: Volume density
- $2\pi R_p H$: Area of atmosphere

Such that the Earth's atmosphere at slant geometries is 75x that at normal to the planet. Hot Jupiters range from ~35-90x normal

Effective Altitude

Height at which pressure decreases by a factor of e (exponent)

We can then calculate the effective altitude of a planetary atmosphere by assuming it is in hydrostatic equilibrium with a constant density profile and gravity we get,

Species abundance

Pressure base

Species cross section

Effective altitude of transmission

$$z(\lambda) = H \ln\left(\frac{\xi_{\rm abs} P_{\rm z=0} \sigma_{\rm obs}(\lambda)}{\tau_{\rm eq}} \times \sqrt{\frac{2\pi R_p}{k_B T_p \mu g_p}}\right)$$

Scale height

Optical depth

Getting Transmission Spetra from Data

An introduction

Exoplanet distribution compared to the solar system

1000+ exoplanets have both Mass and Radius measurements

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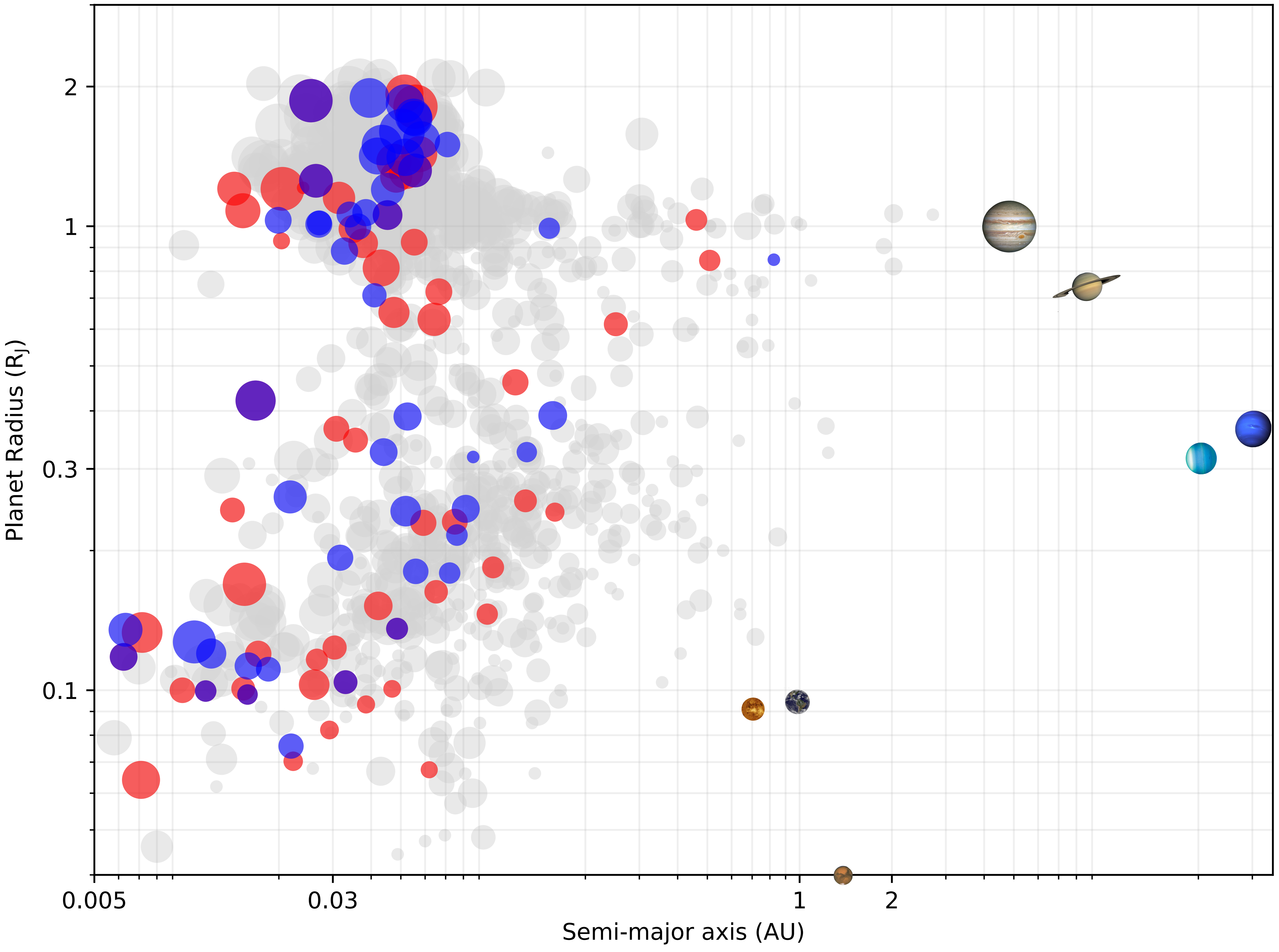
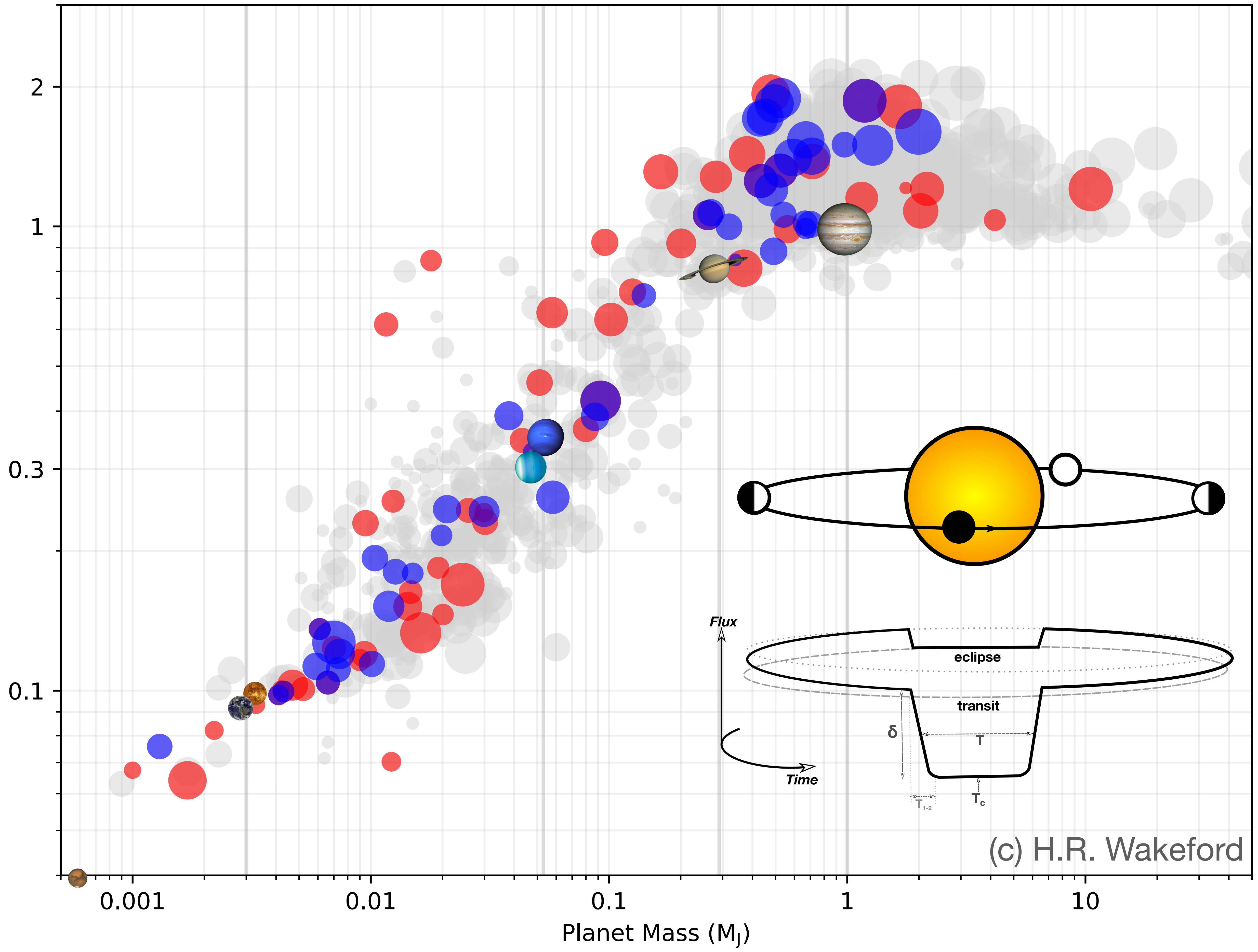
Transiting Exoplanet Atmospheres

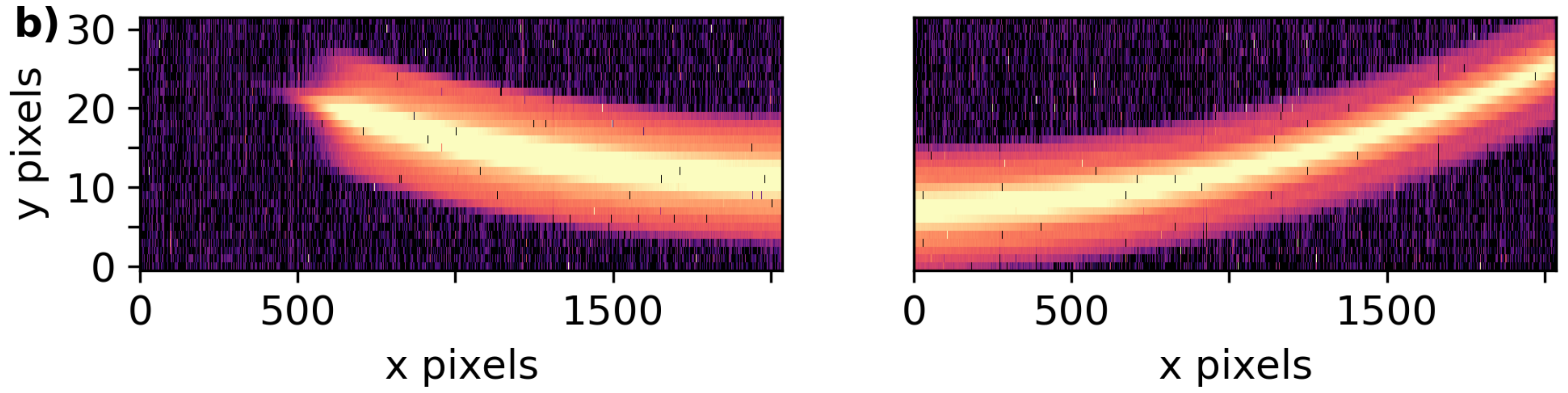
How do we measure the atmosphere of a transiting exoplanet?



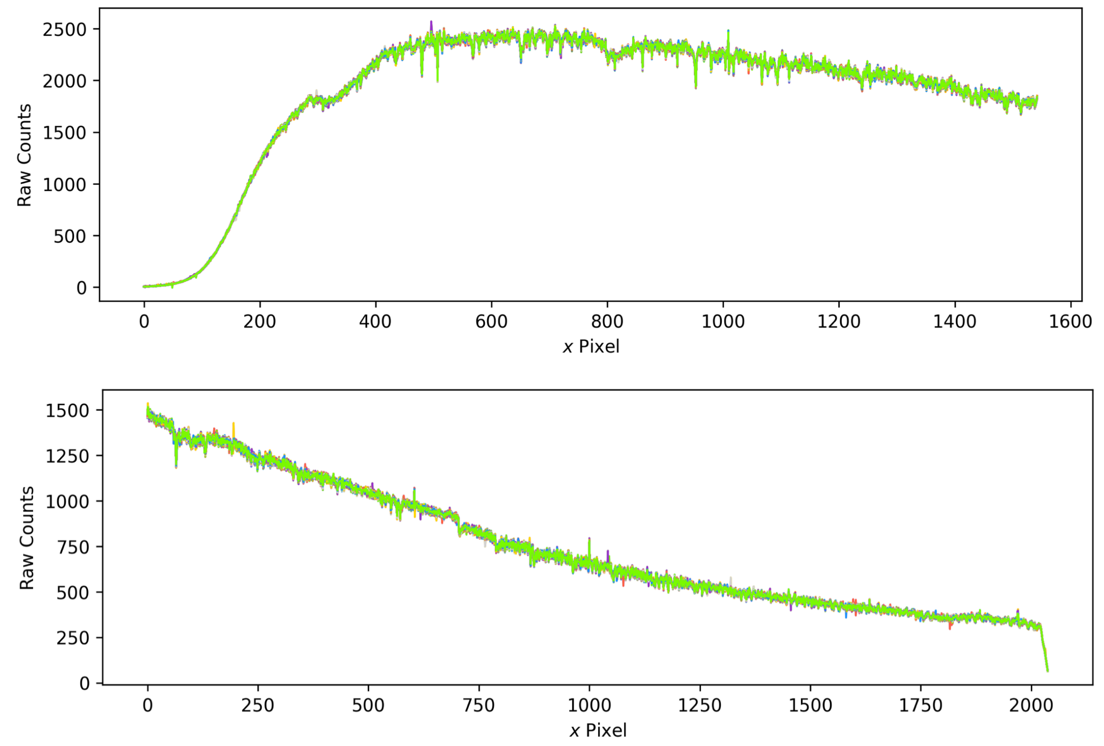


From Observations to Light Curves to Spectra

Measuring the change in transit depth as a function of wavelength



From 2D images
to
1D stellar spectra



Images from Alderson+ (2023, Nature) & Rustamkulov+ (2023, Nature)

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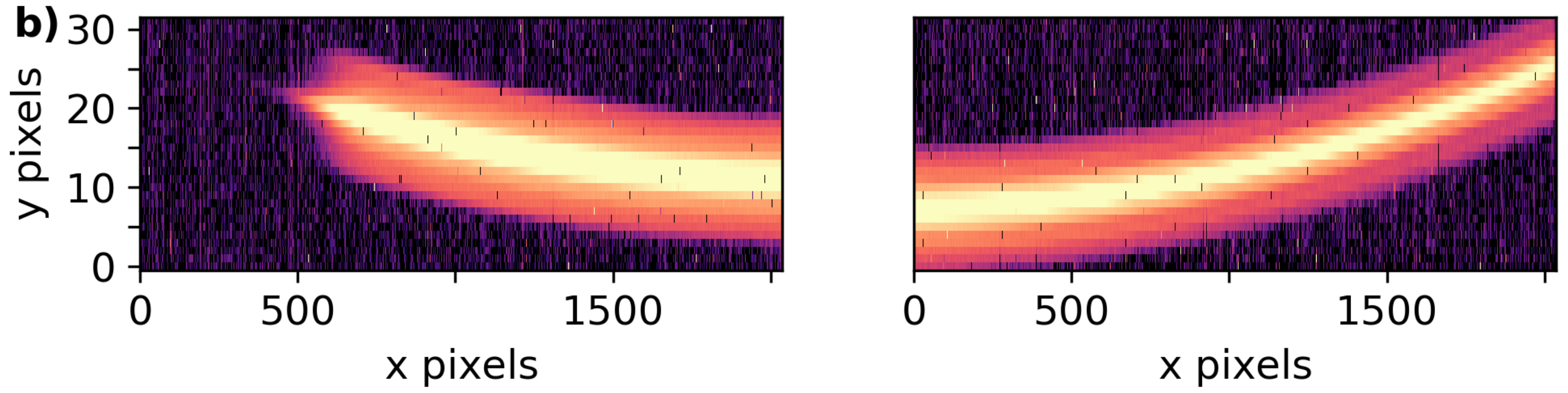

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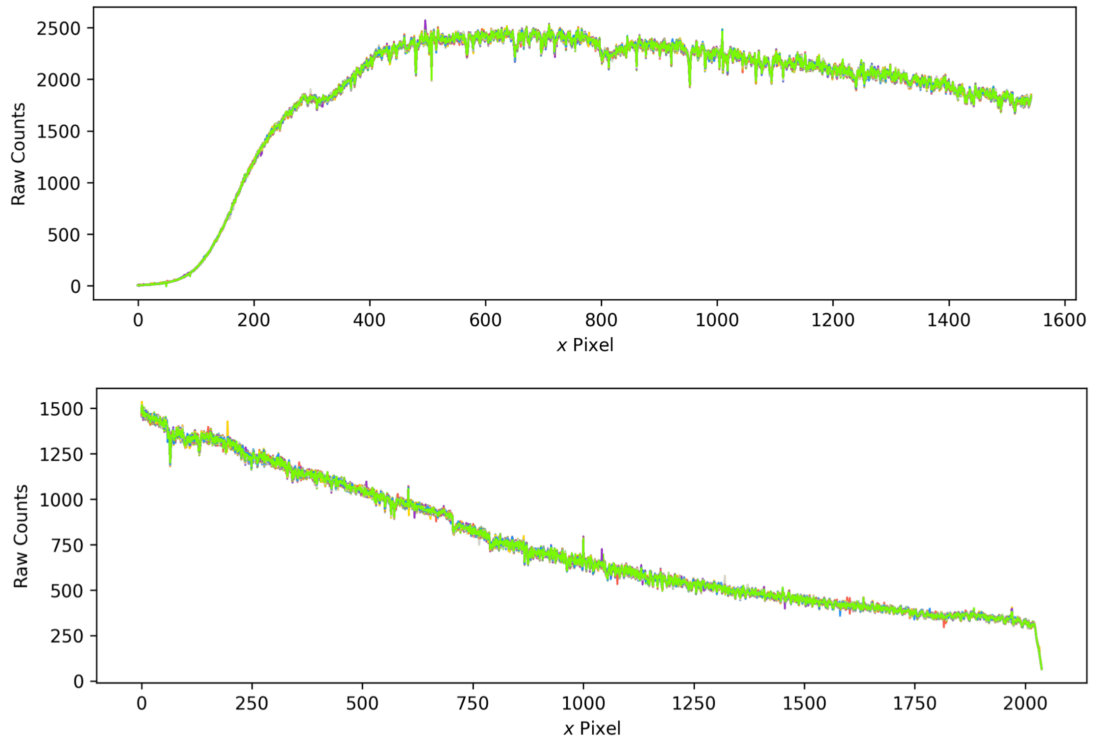

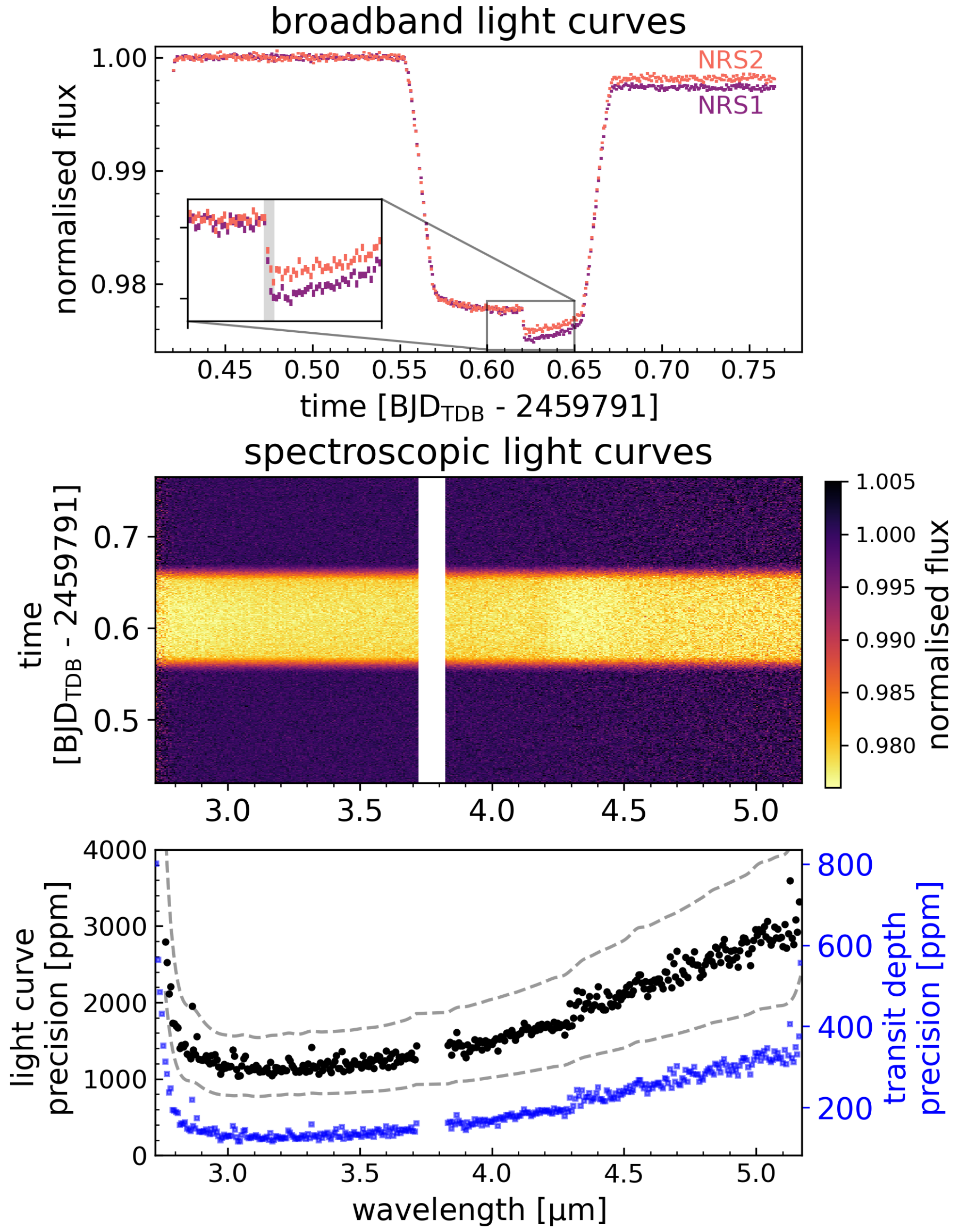

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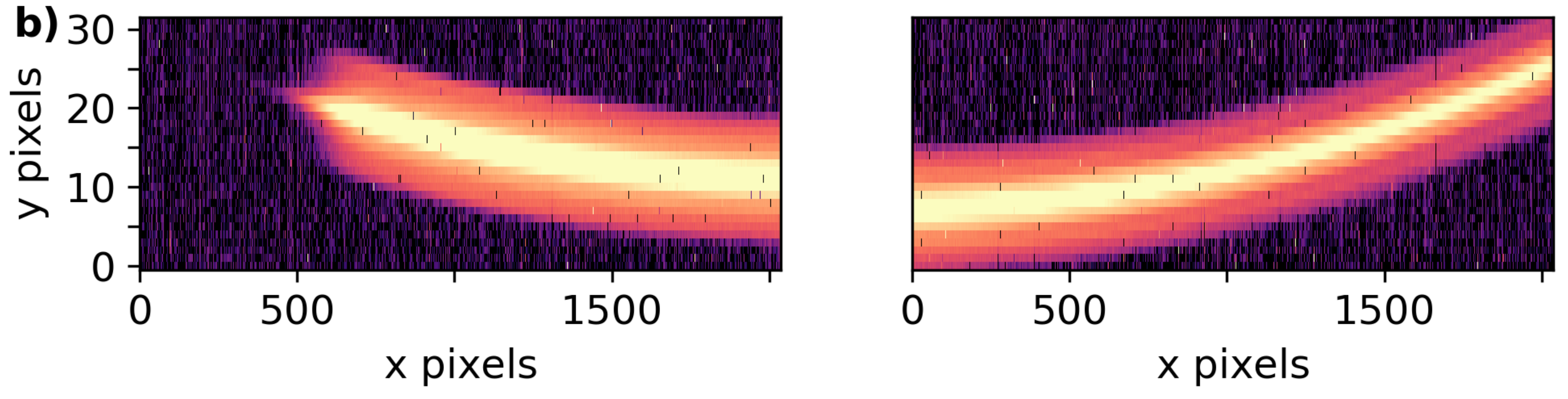

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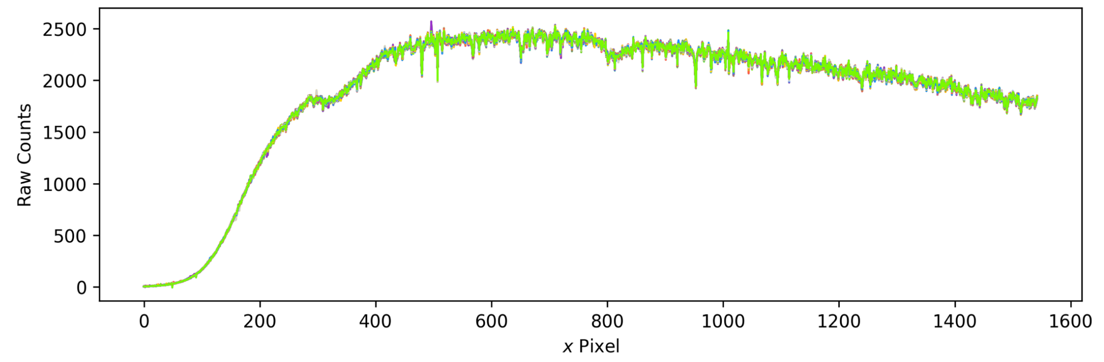

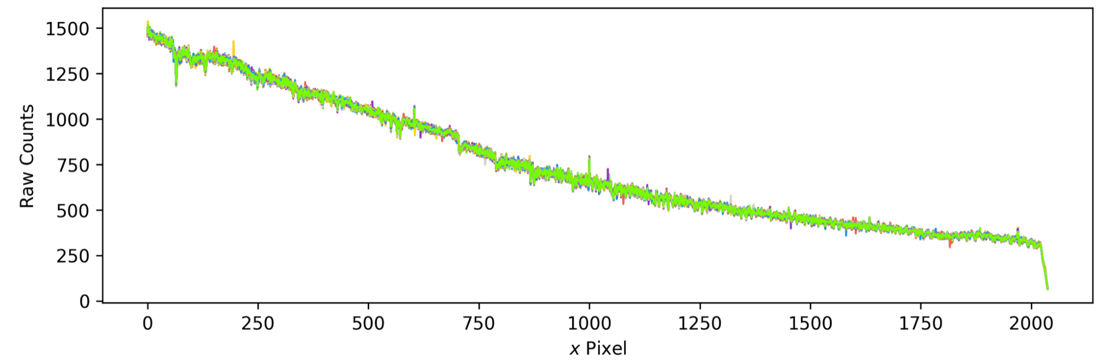

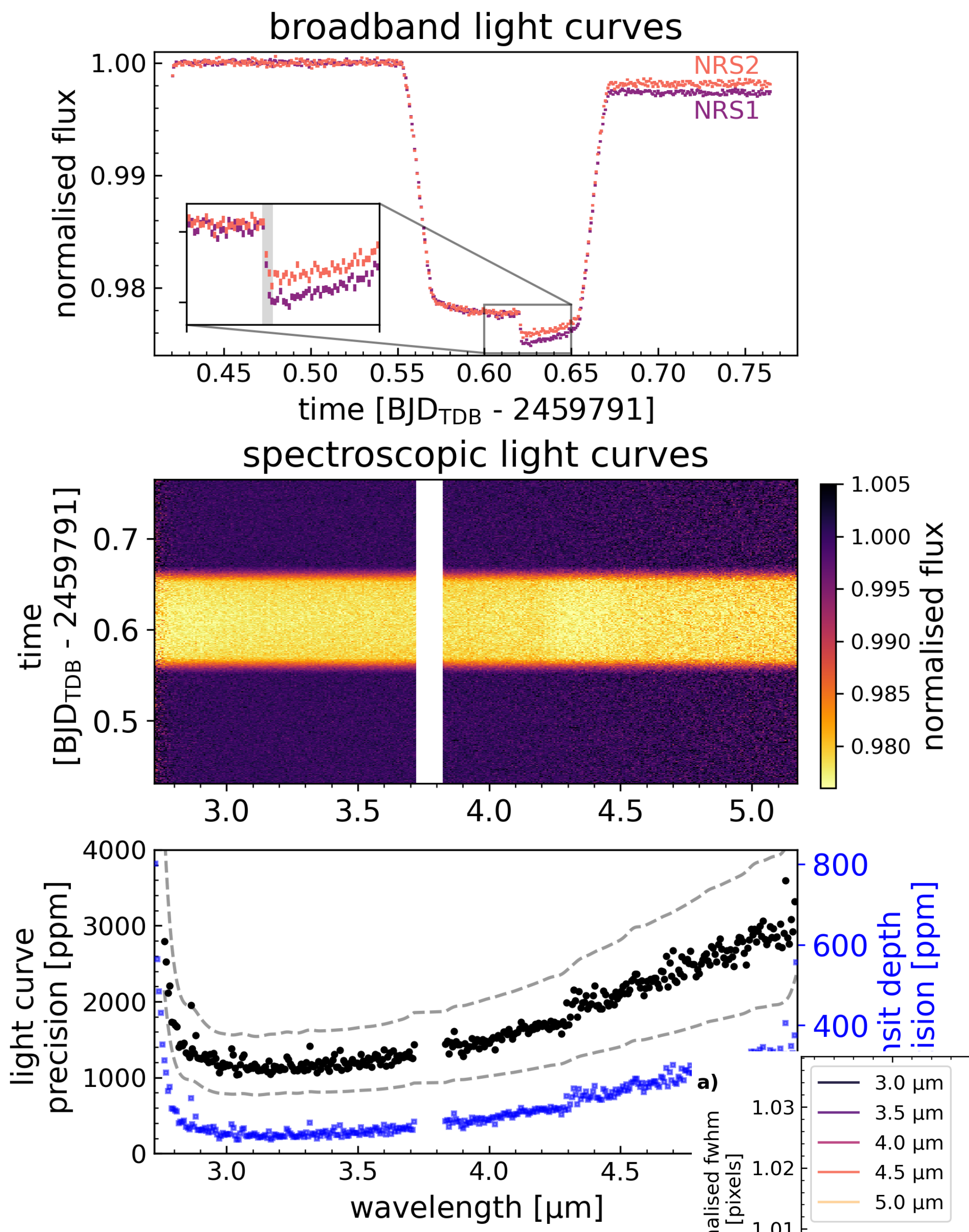

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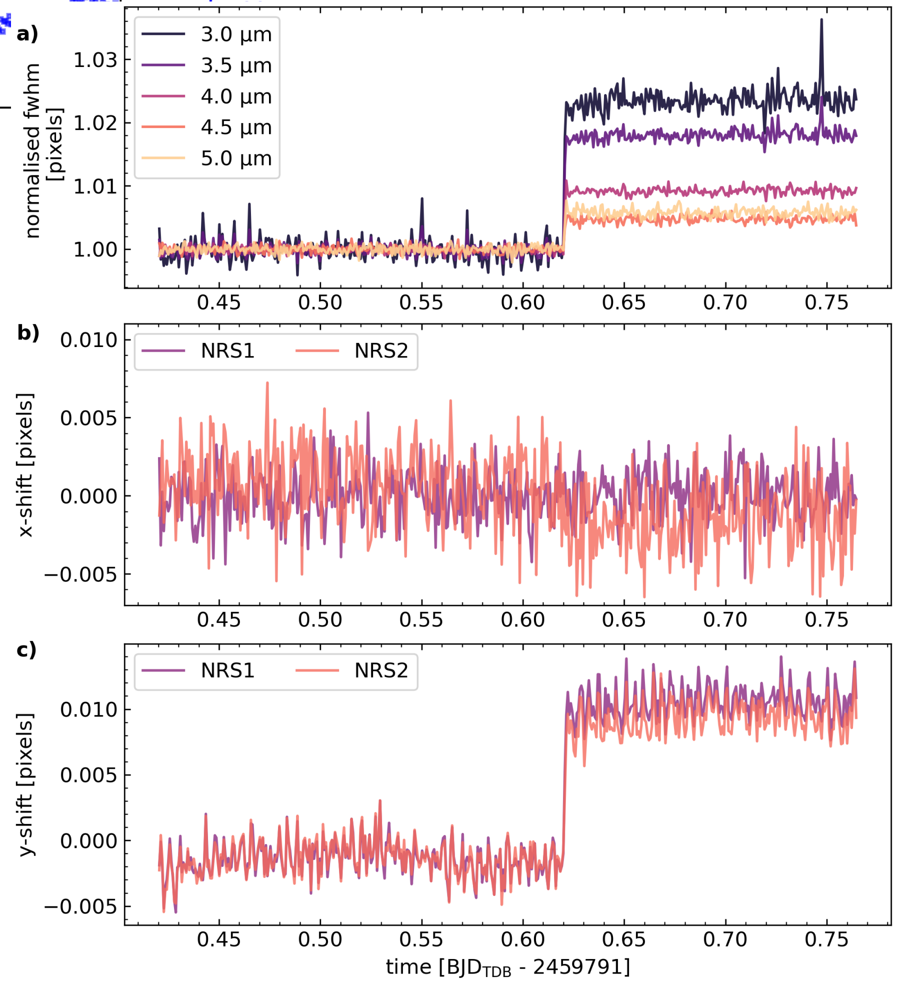
Detrending parameters



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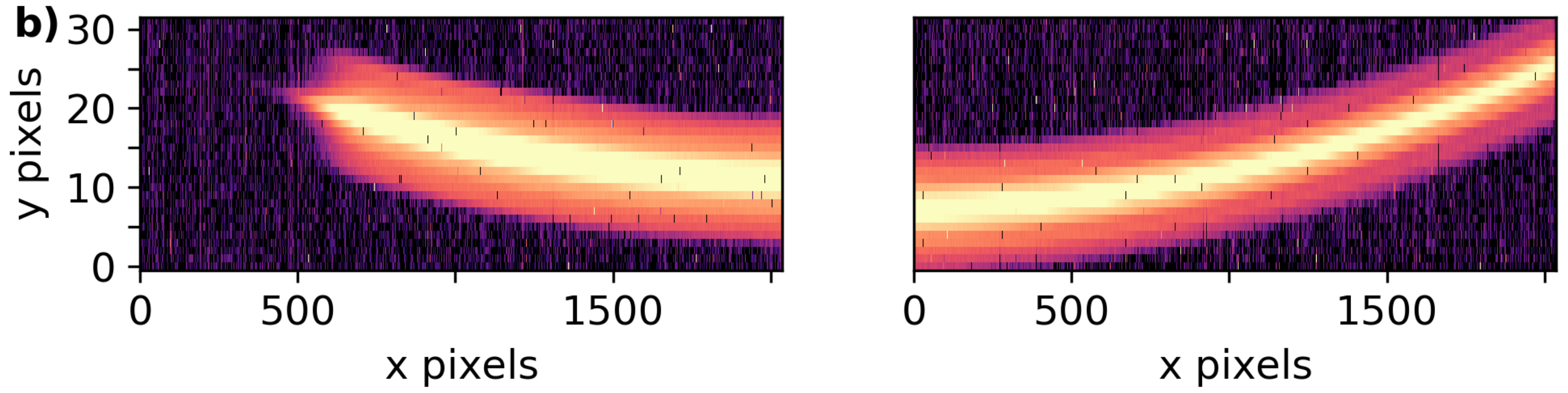

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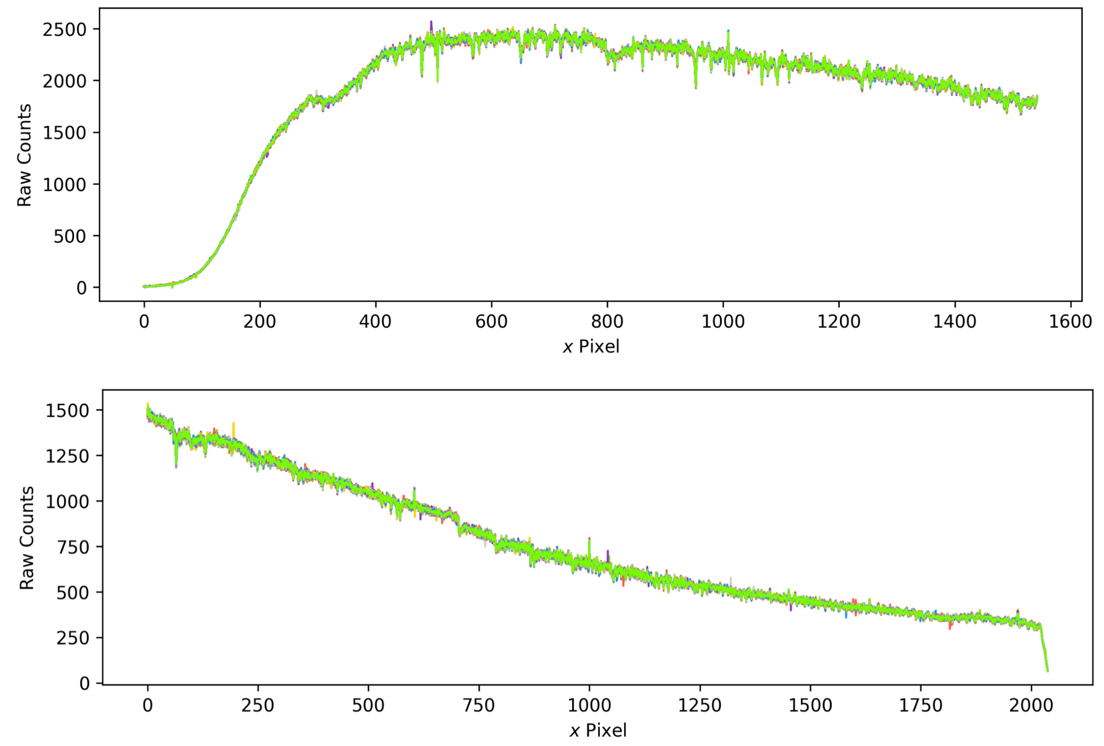

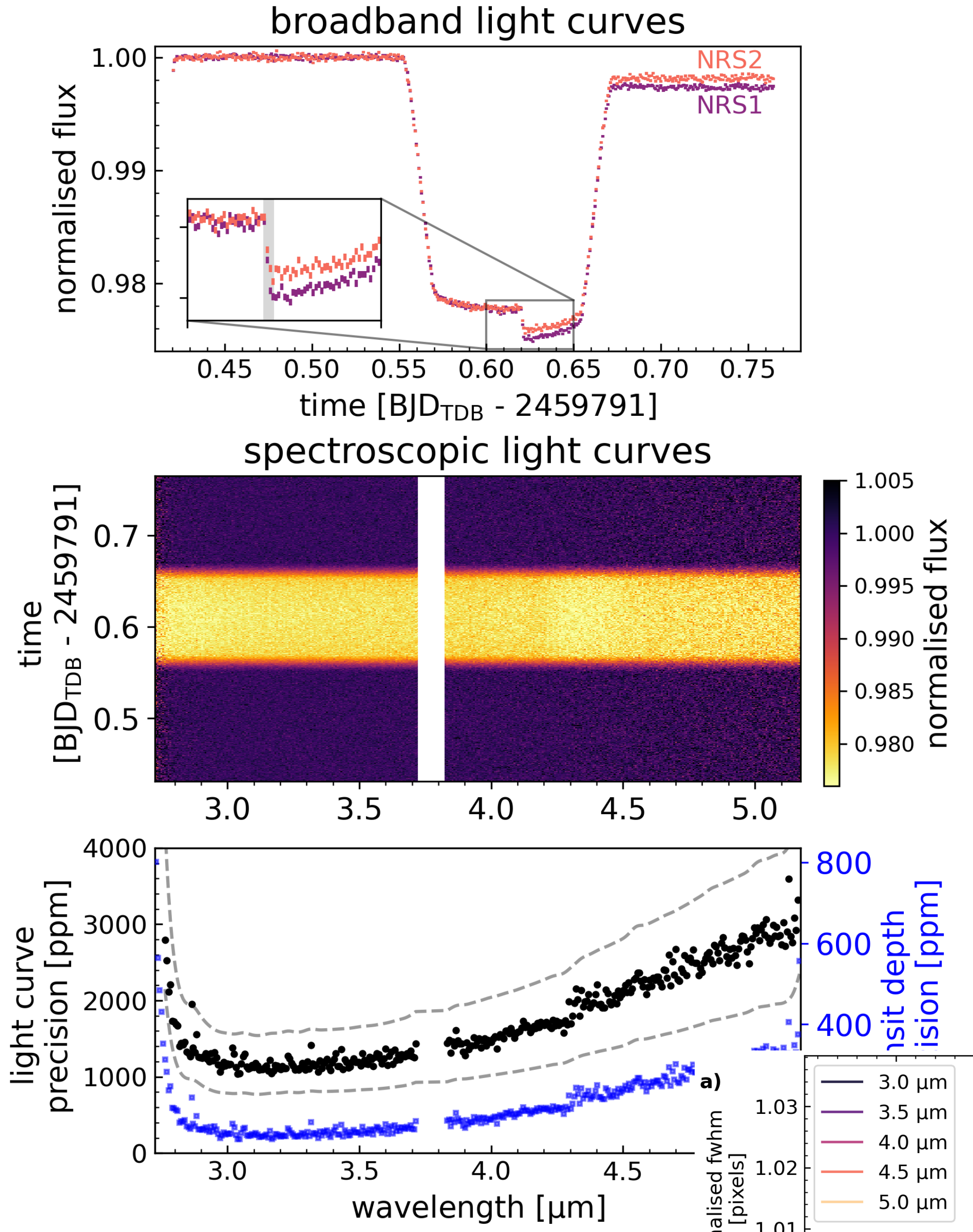

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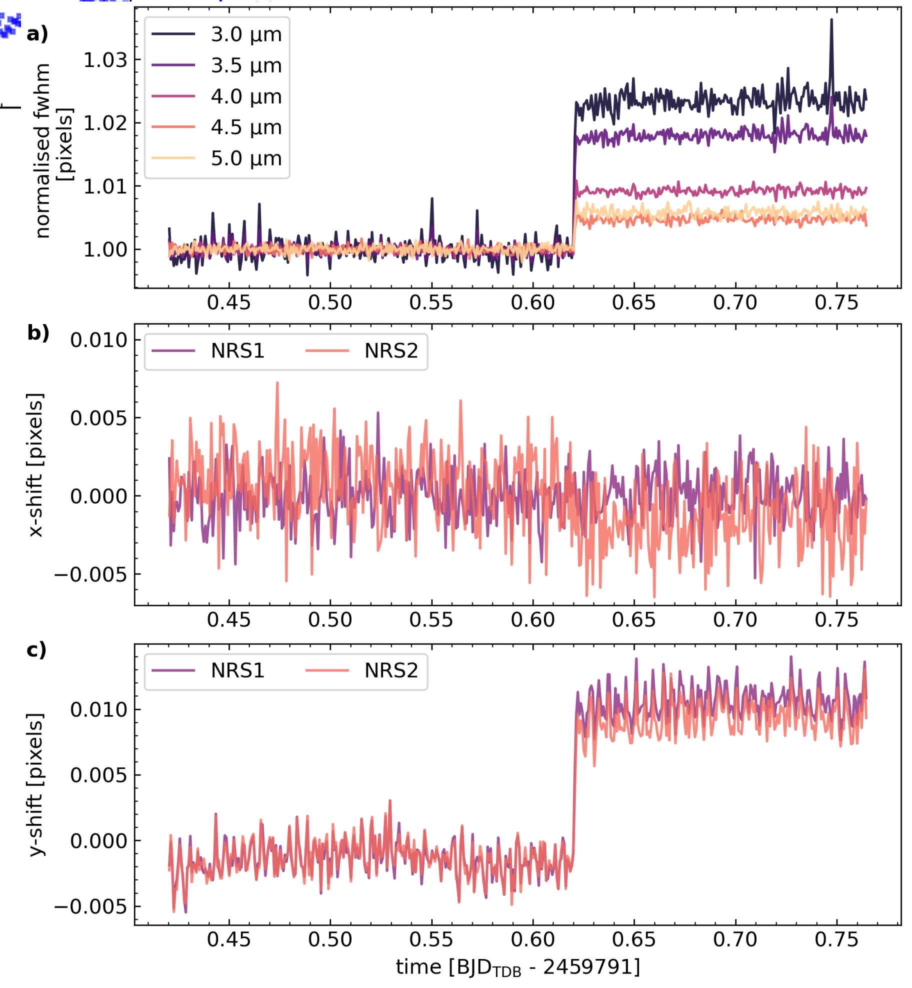
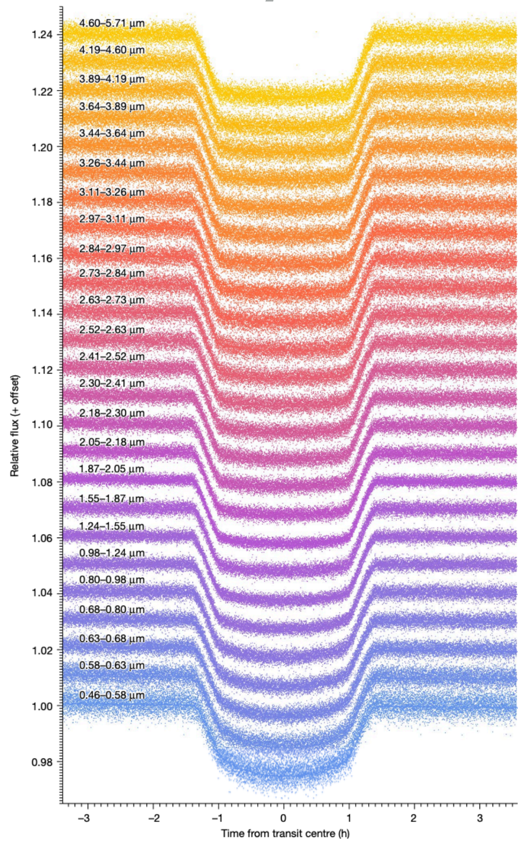


Fitted light curve



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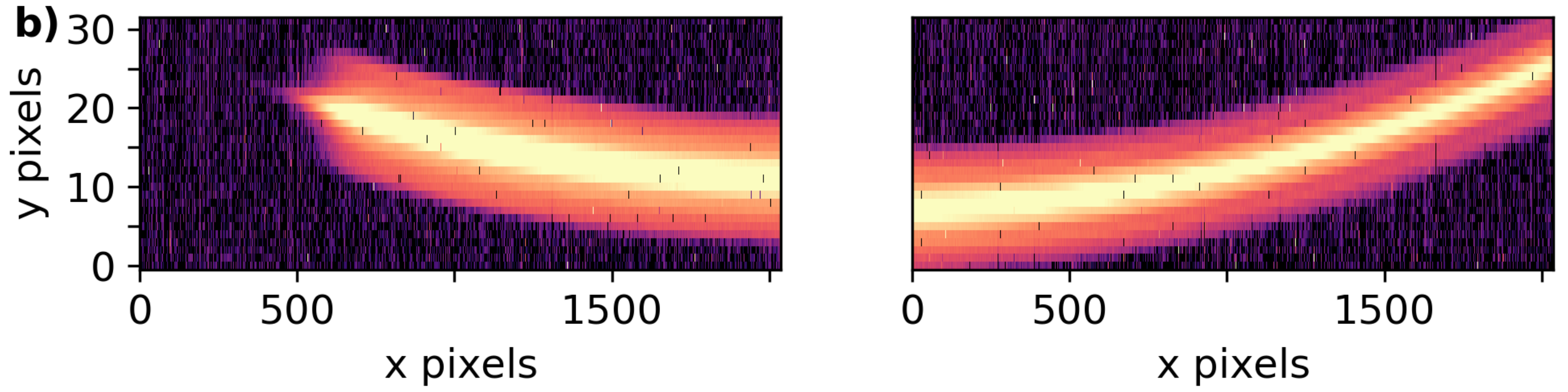

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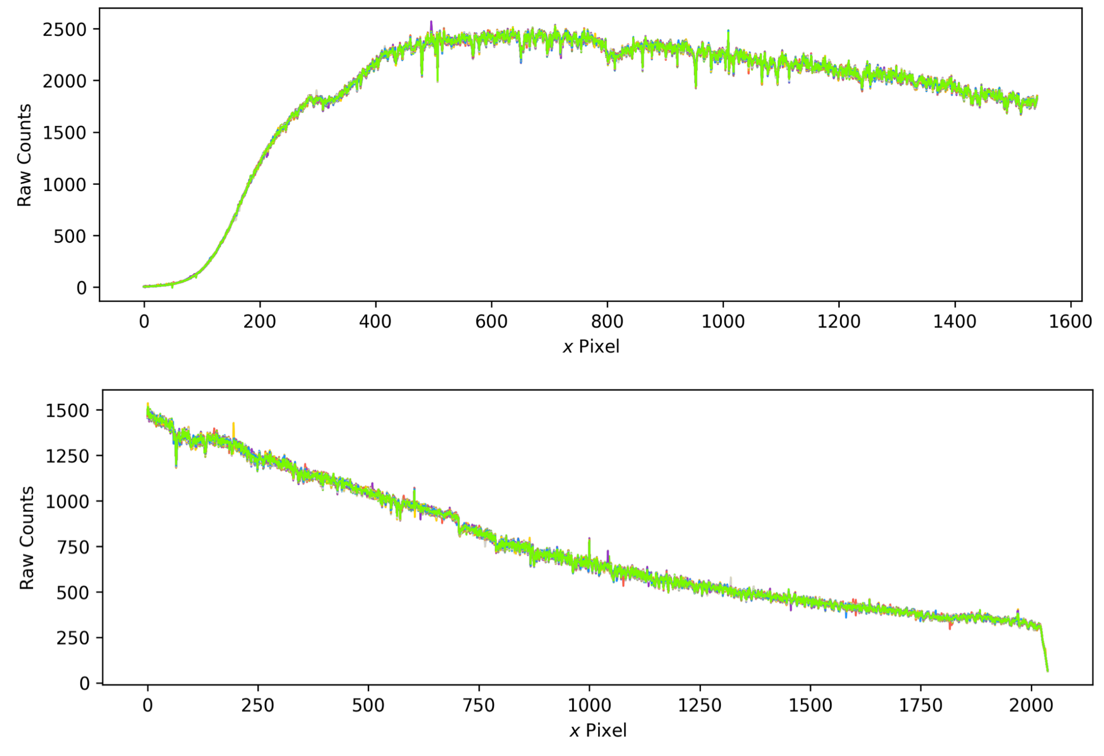

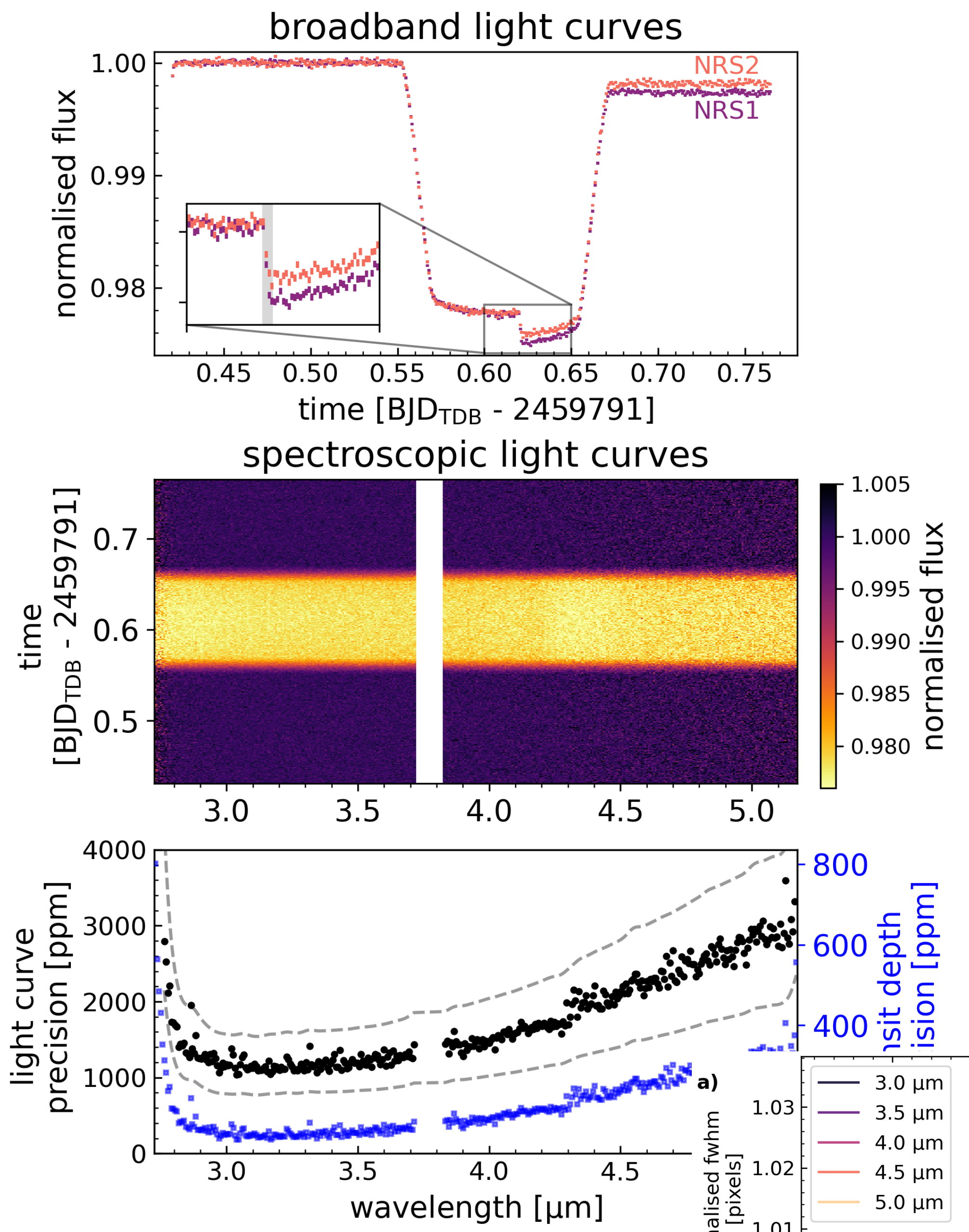

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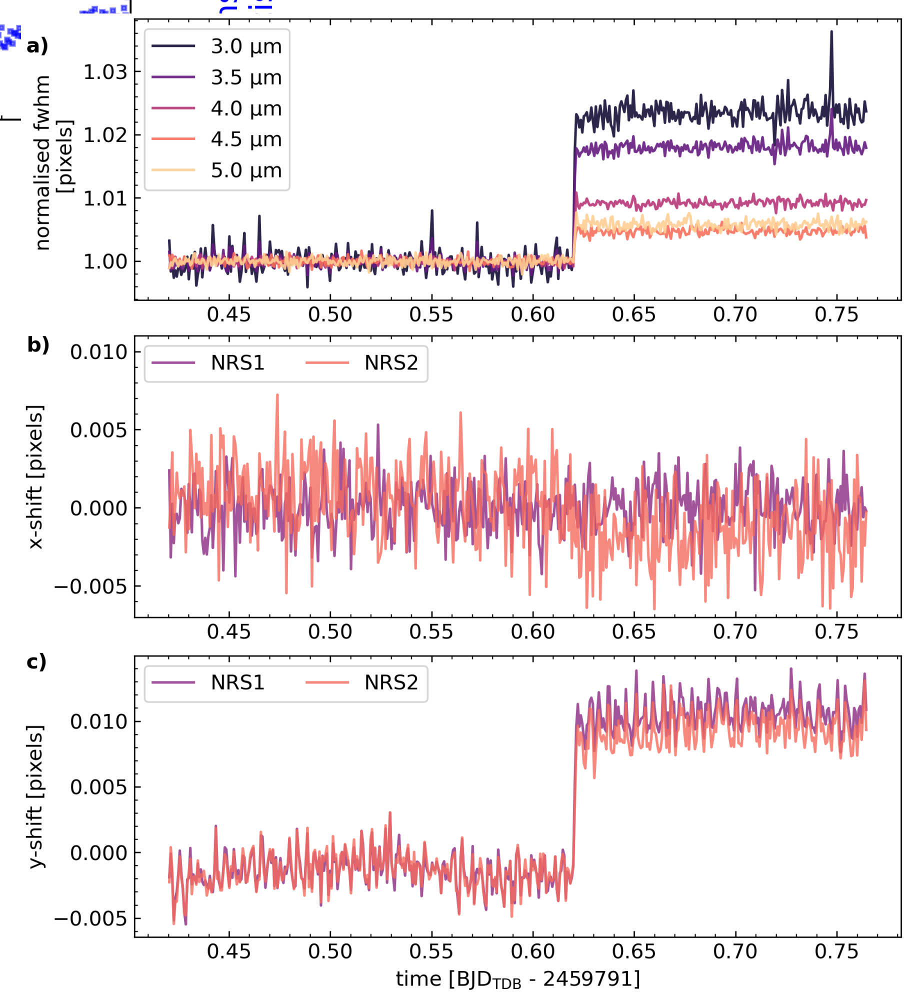

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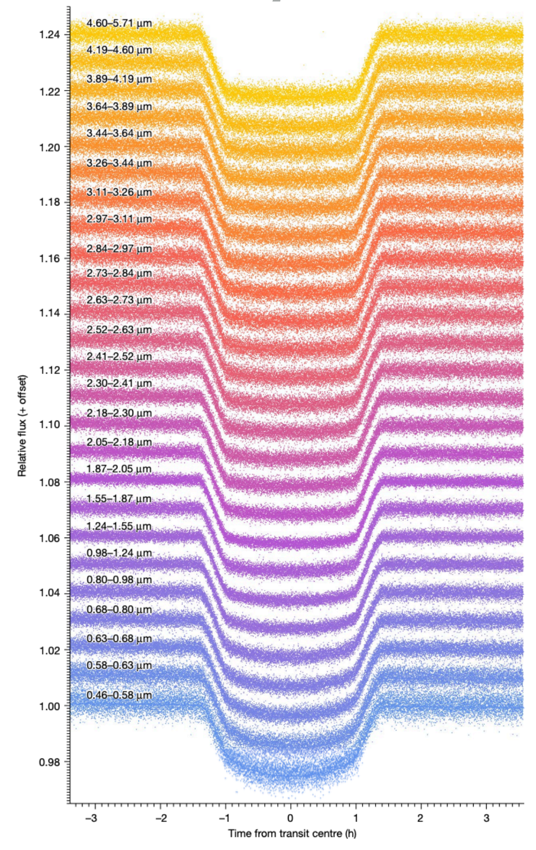
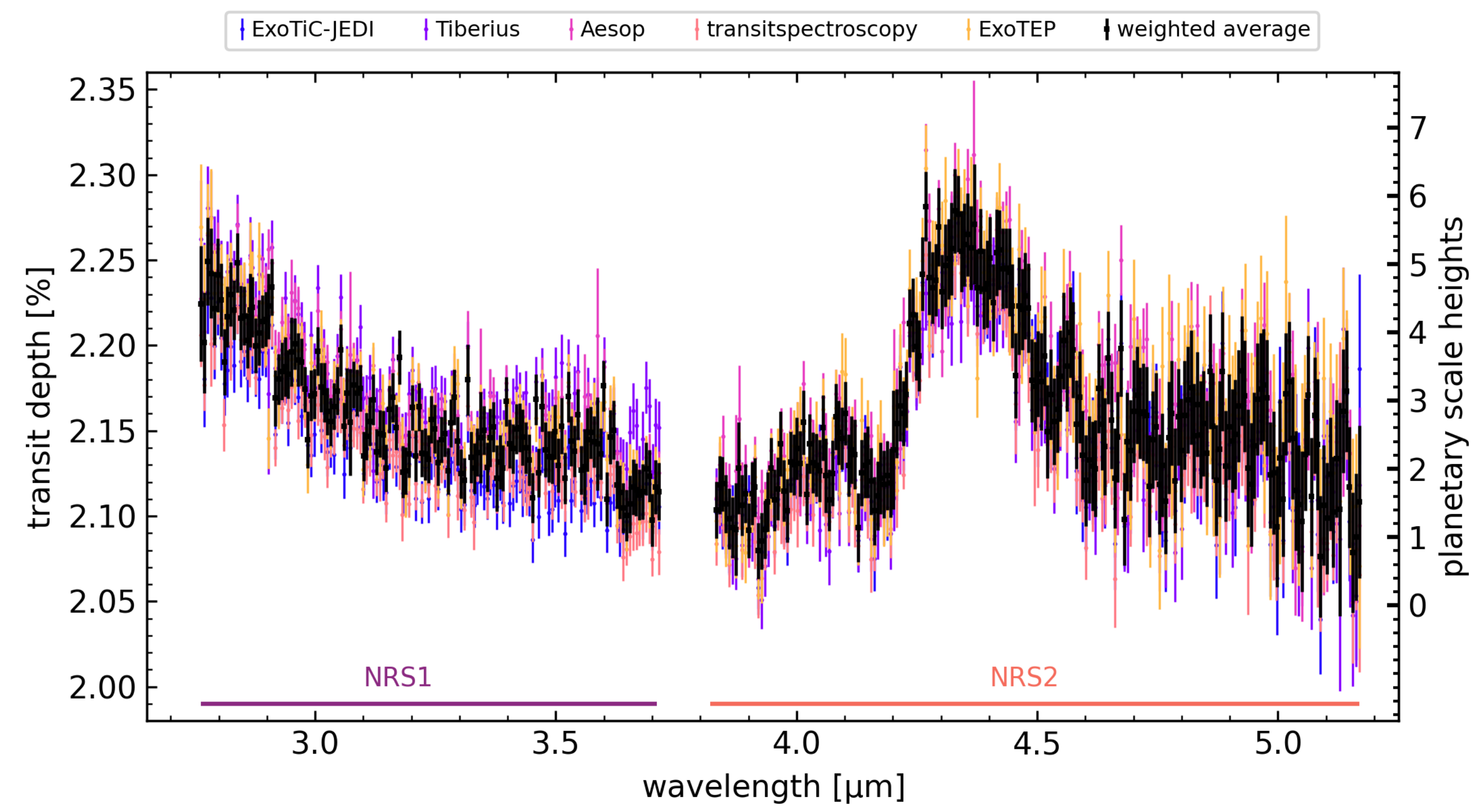


Planetary spectrum



Images from Alderson+ (2023, Nature) & Rustamkulov+ (2023, Nature)

Fitting Your Light Curve Systematics

Accurately treating systematics is key even when not apparent in the data

Systematic Model

Simple

Single systematic models

Common-mode wavelength independent model

Complex

Marginalization

Jitter decorrelation

GP

Solver

Least-square minimizer

MCMC/ nested sampler

GP

Fastest

Slow

Faster

Parameter Estimation

Single uncertainty on parameters

Output covariance matrix

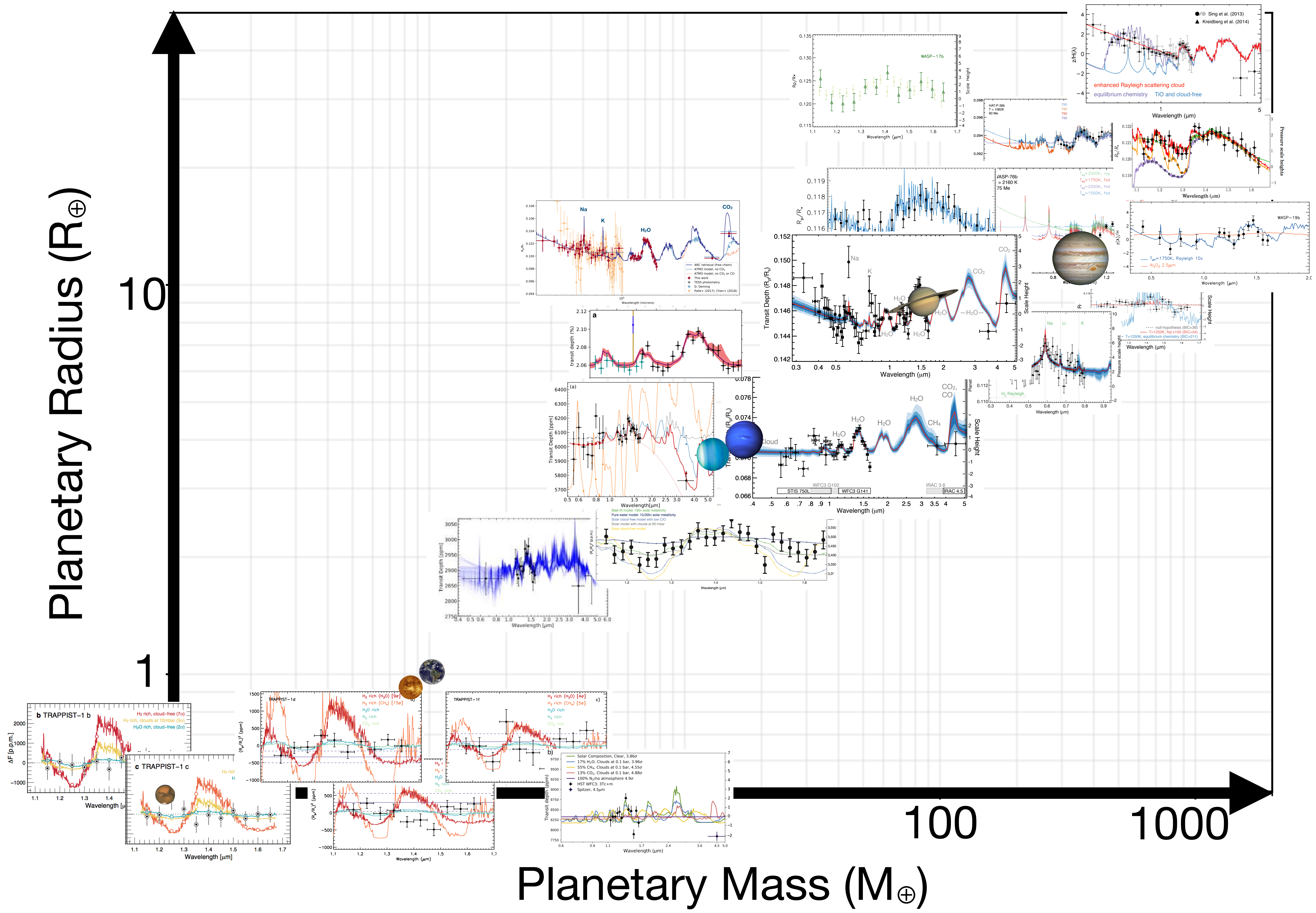
Full posterior of estimated parameters

Correlation between parameters

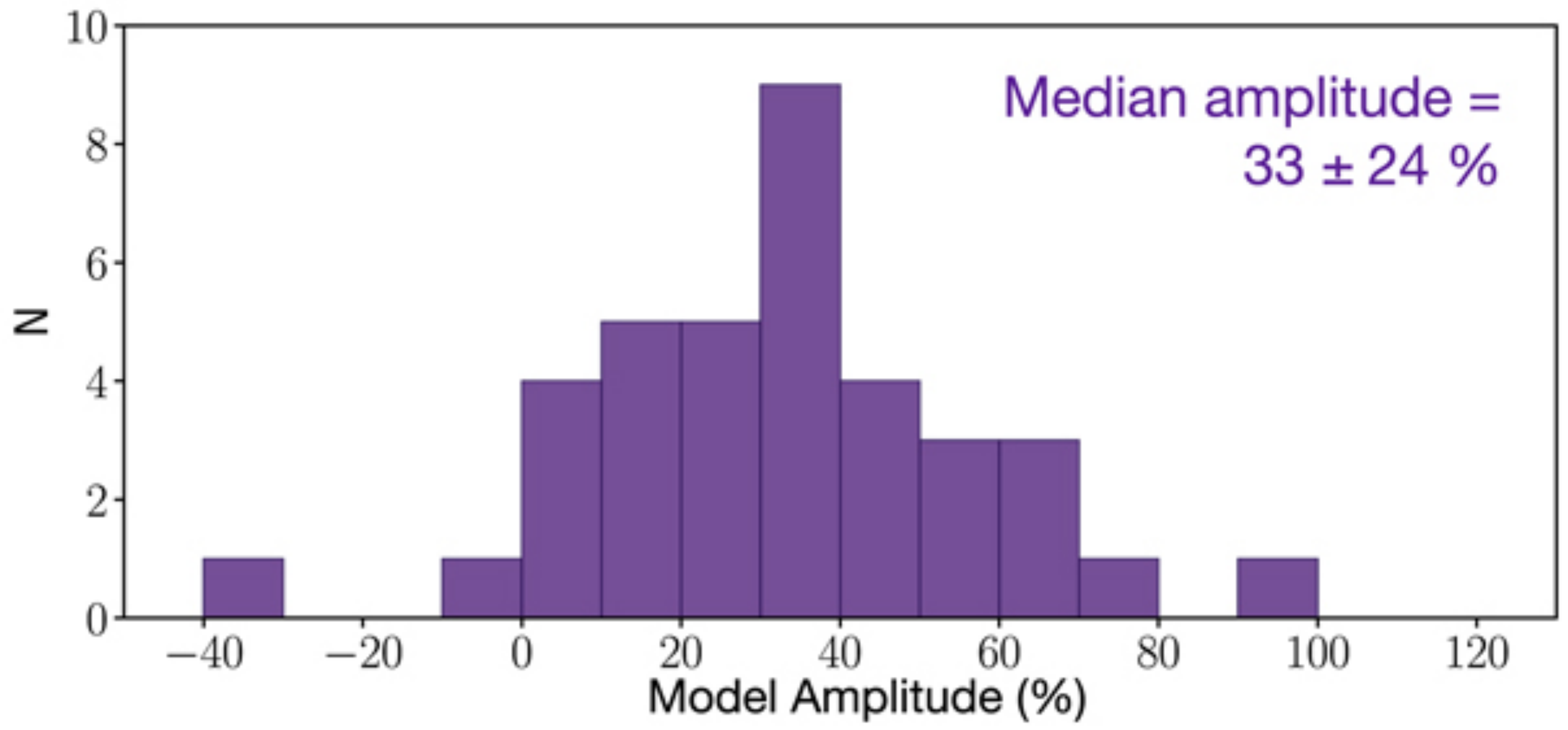
The larger suite of models considered, the smaller the space assigned to the probability that none of your models can explain your data.

Transmission Spectra with Hubble

Cloudy with a chance of water



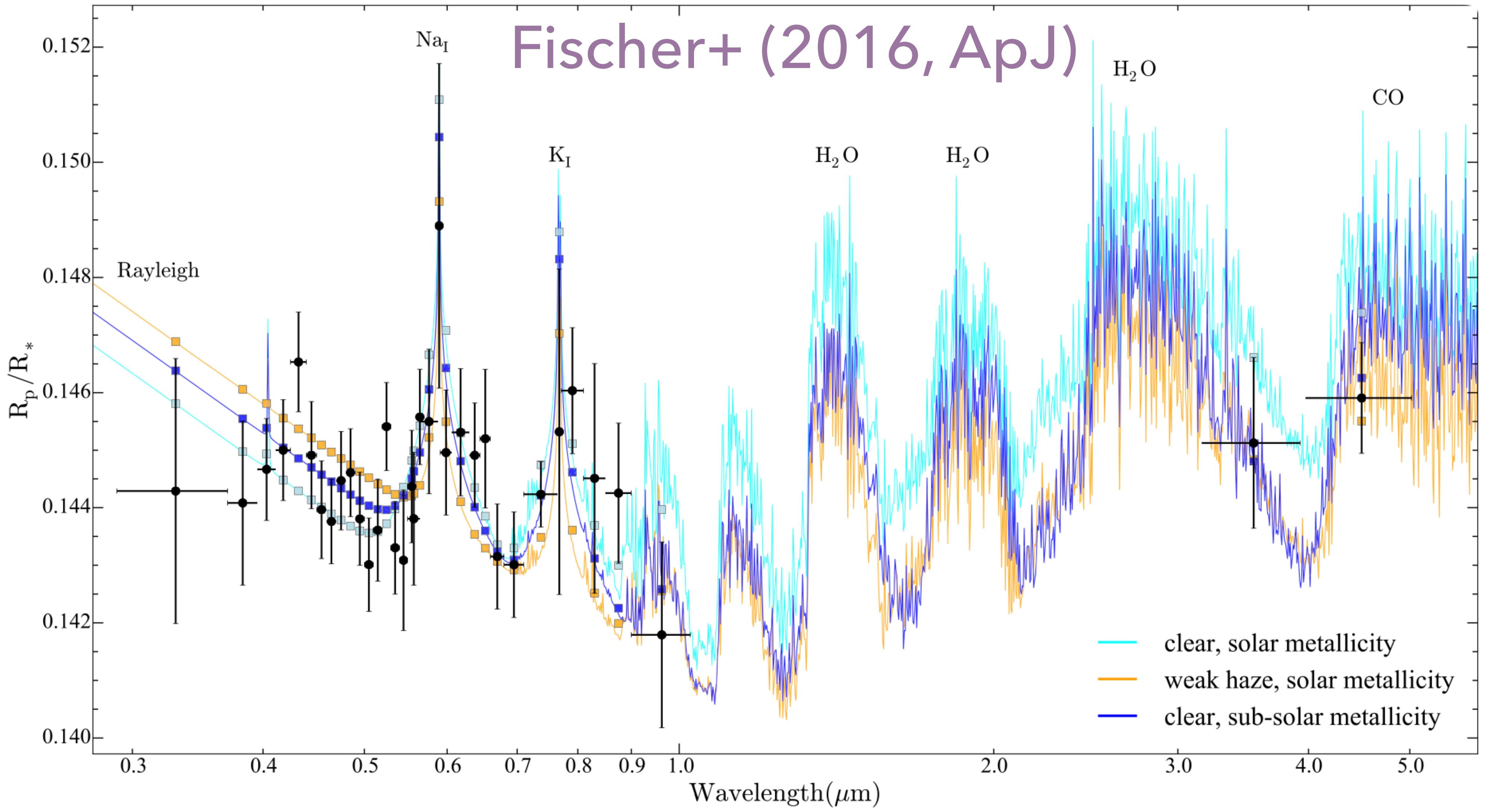
Water vapor has been measured in over 80% of planets



But it is often muted to around 1/3 of expected

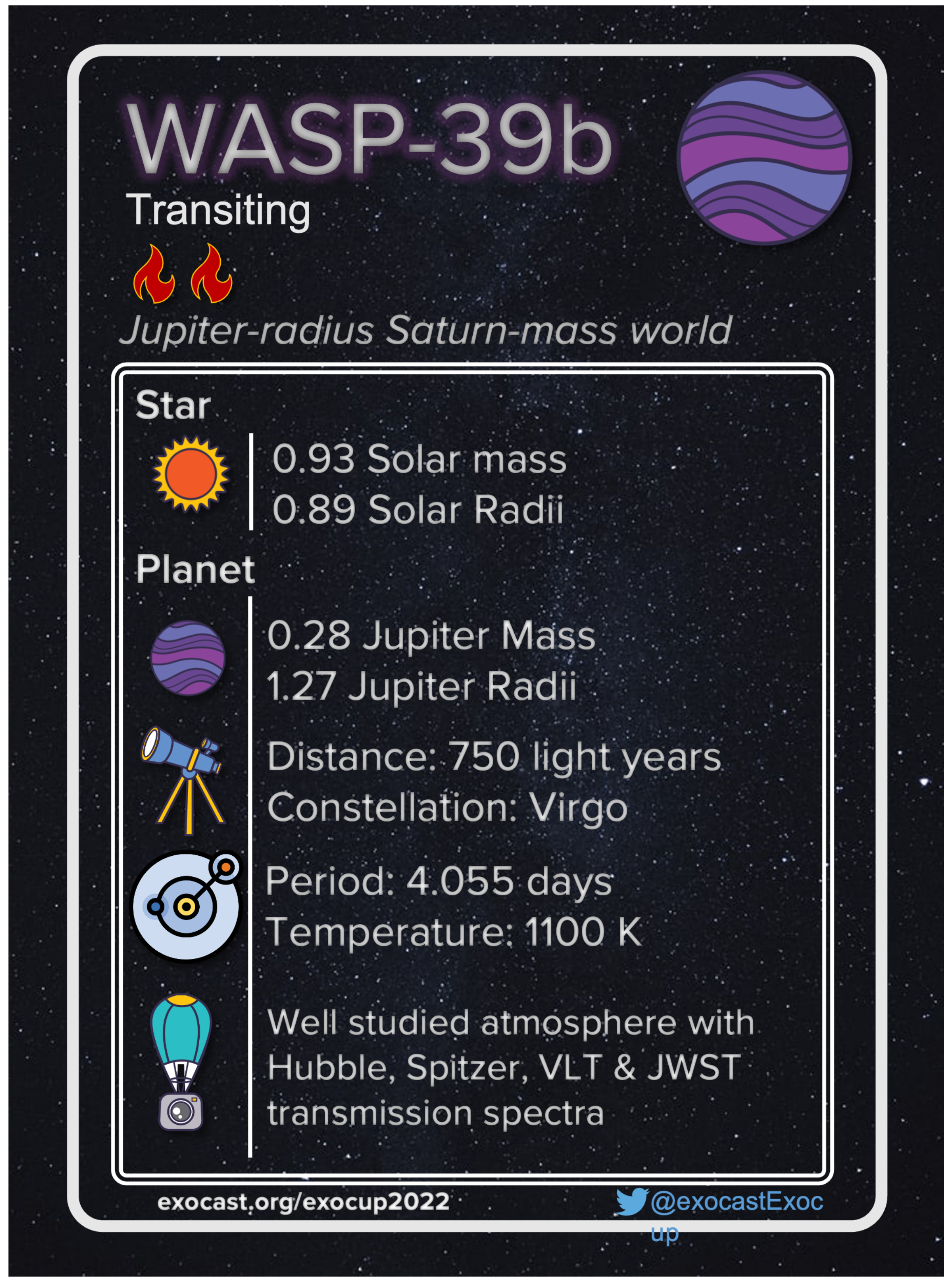
Panchromatic Transmission of WASP-39b

Previous work and predictions



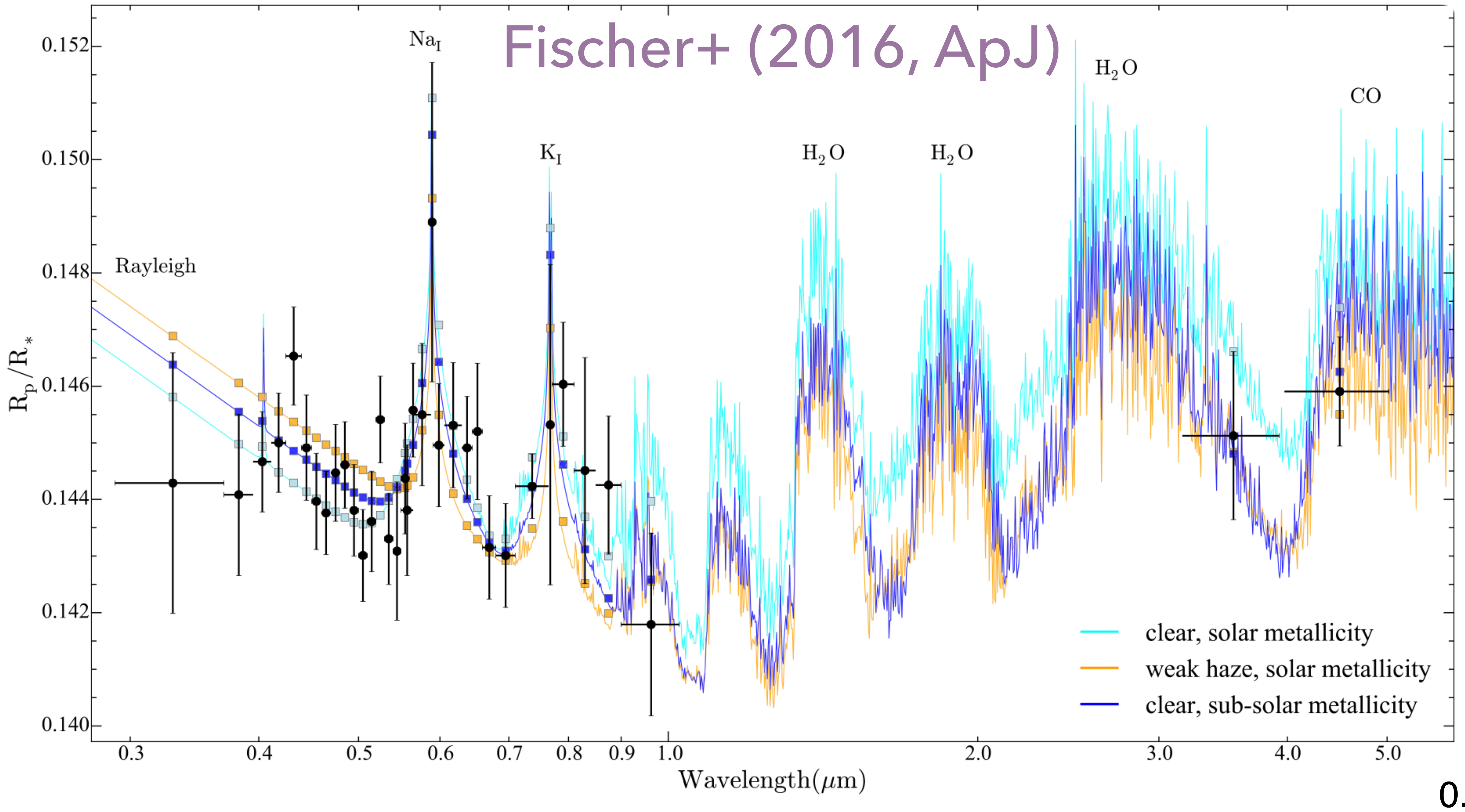
Clear Na and K features suggest an atmosphere with minimal high altitude cloud opacity

Prediction -—> strong H_2O features in near-IR



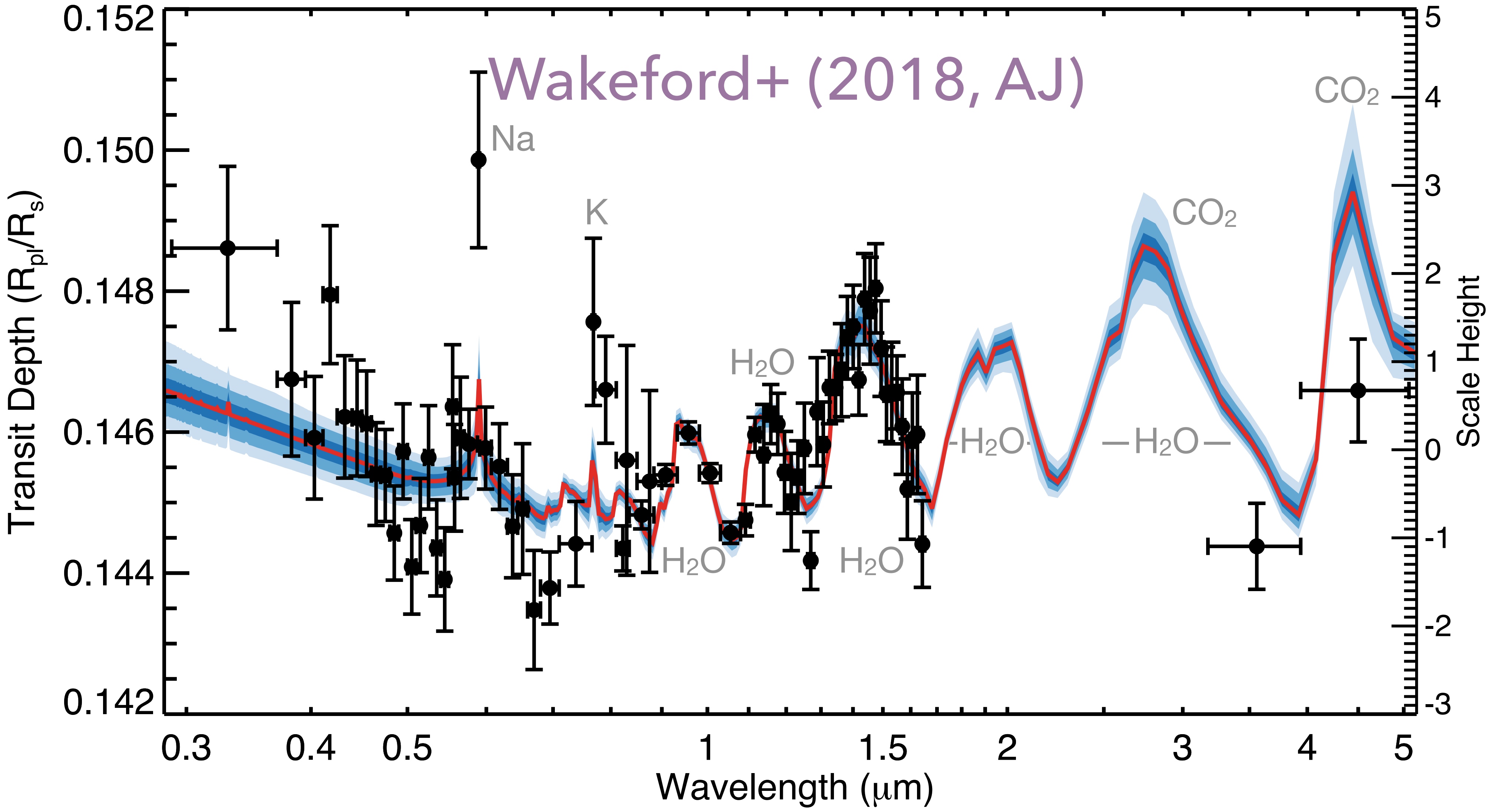
Panchromatic Transmission of WASP-39b

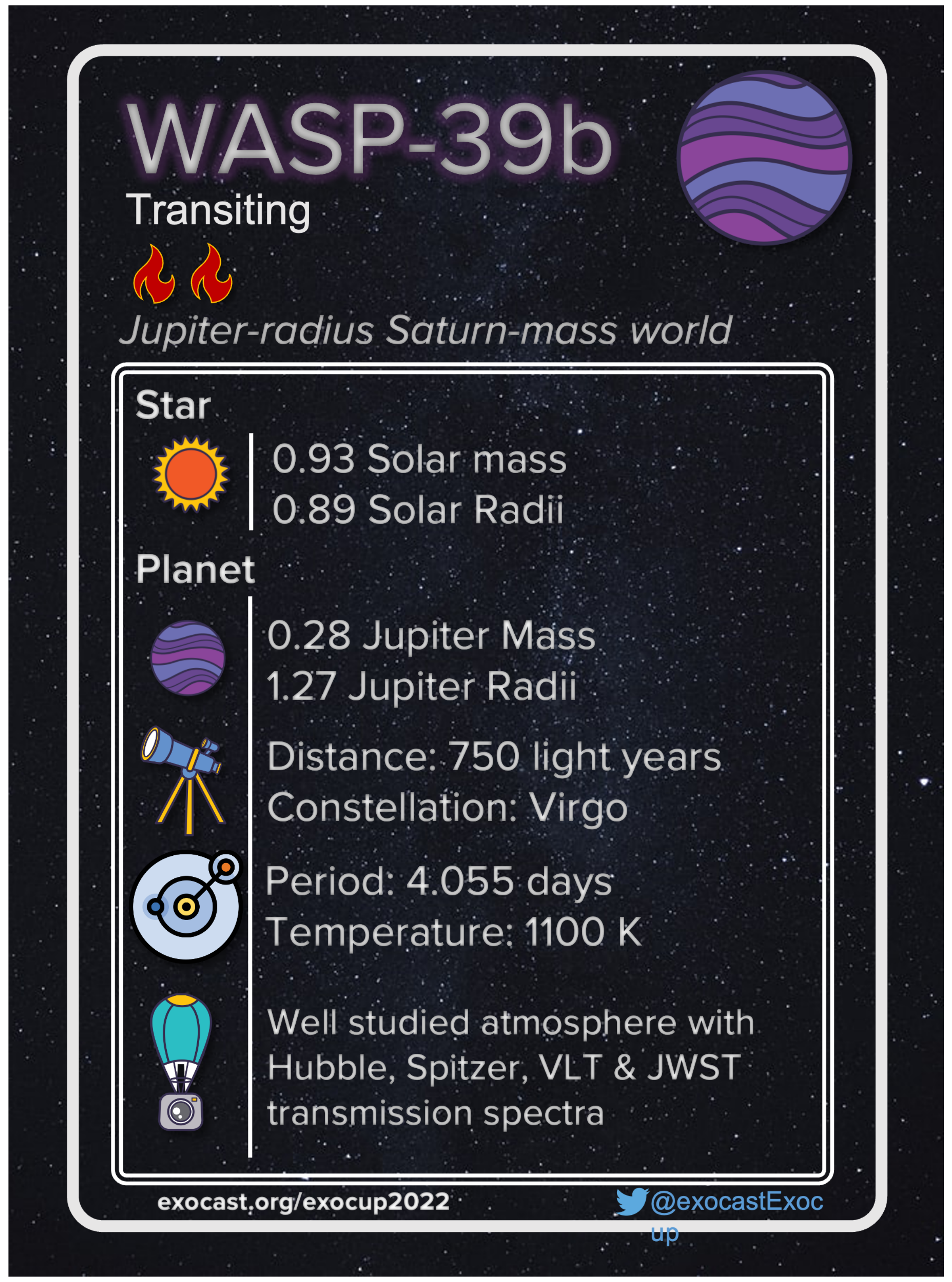
Previous work and predictions



Clear Na and K features suggest an atmosphere with minimal high altitude cloud opacity

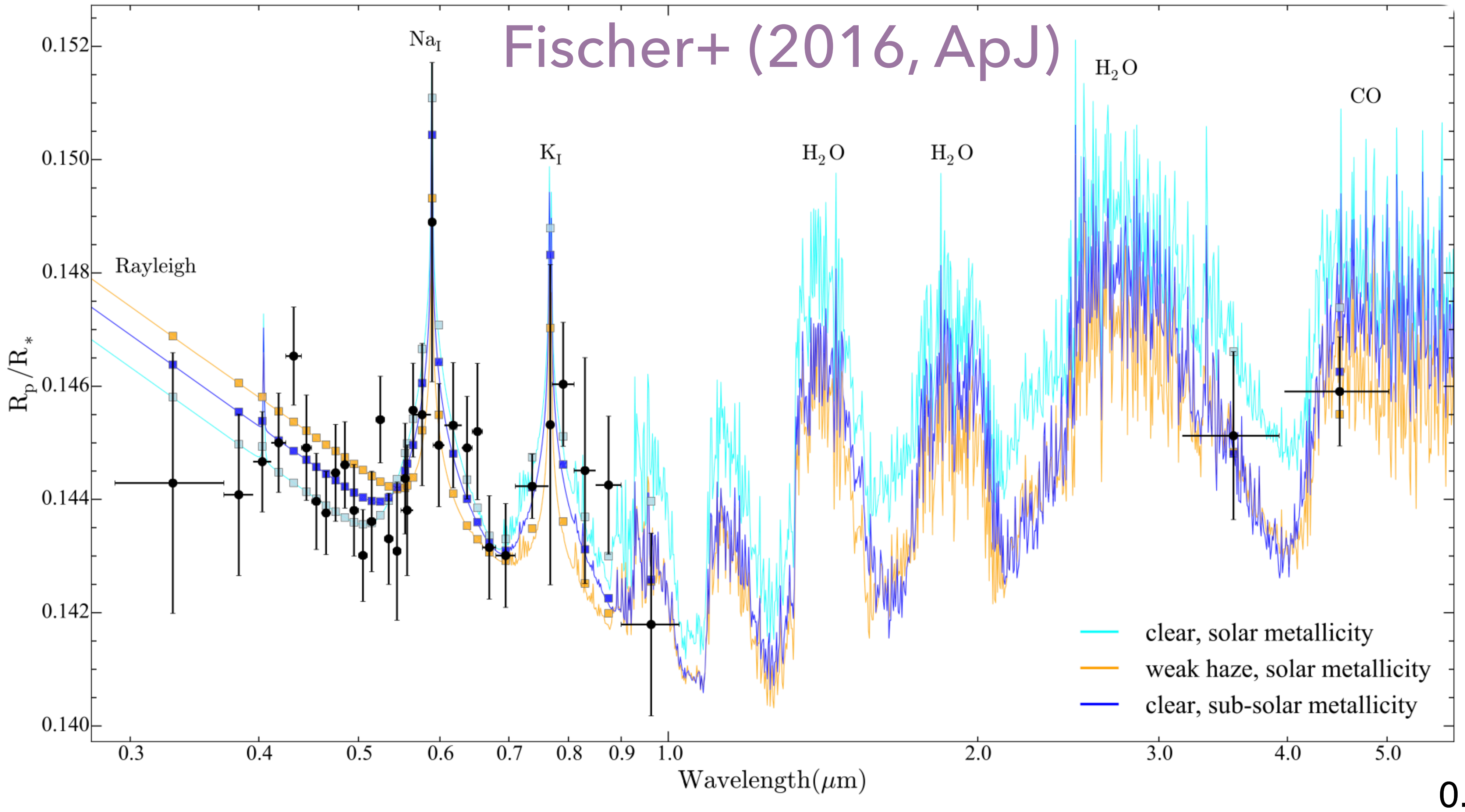
Prediction -—> strong H_2O features in near-IR





Panchromatic Transmission of WASP-39b

Previous work and predictions

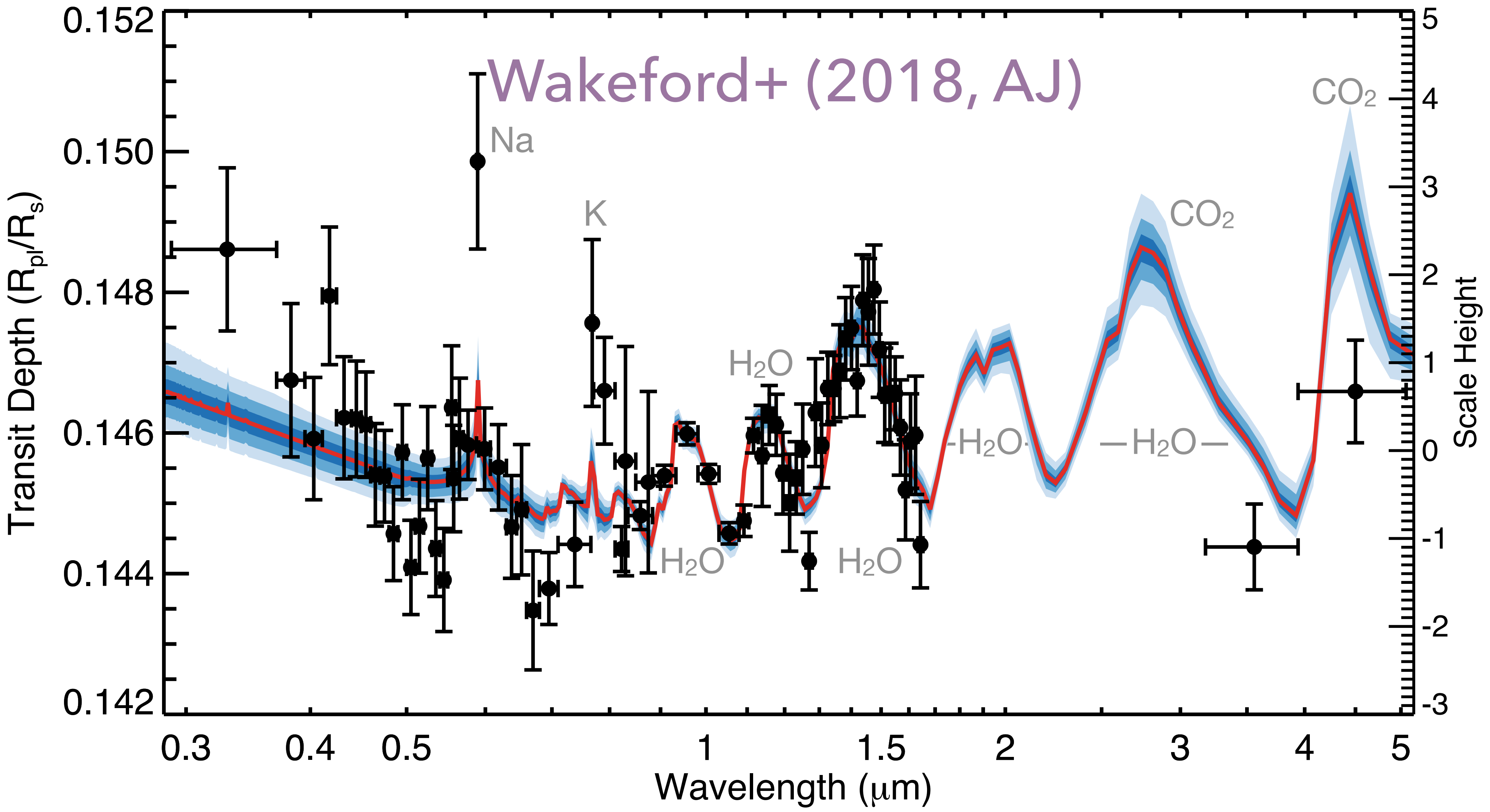


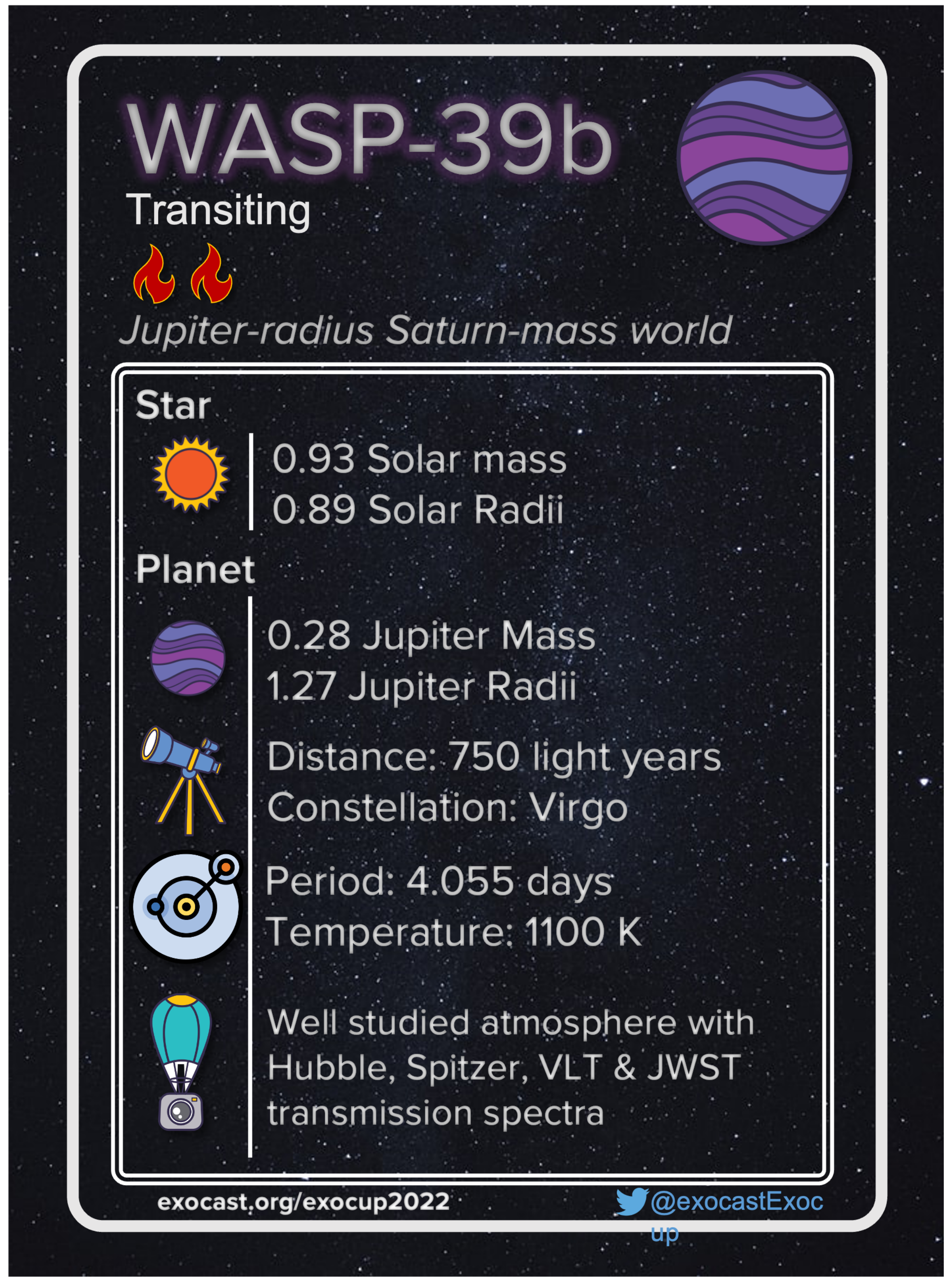
HST/WFC3 IR grisms show three distinct H_2O absorption features with indication of super solar metallicity

Prediction -—> strong absorption by CO_2 in the IR with JWST

Clear Na and K features suggest an atmosphere with minimal high altitude cloud opacity

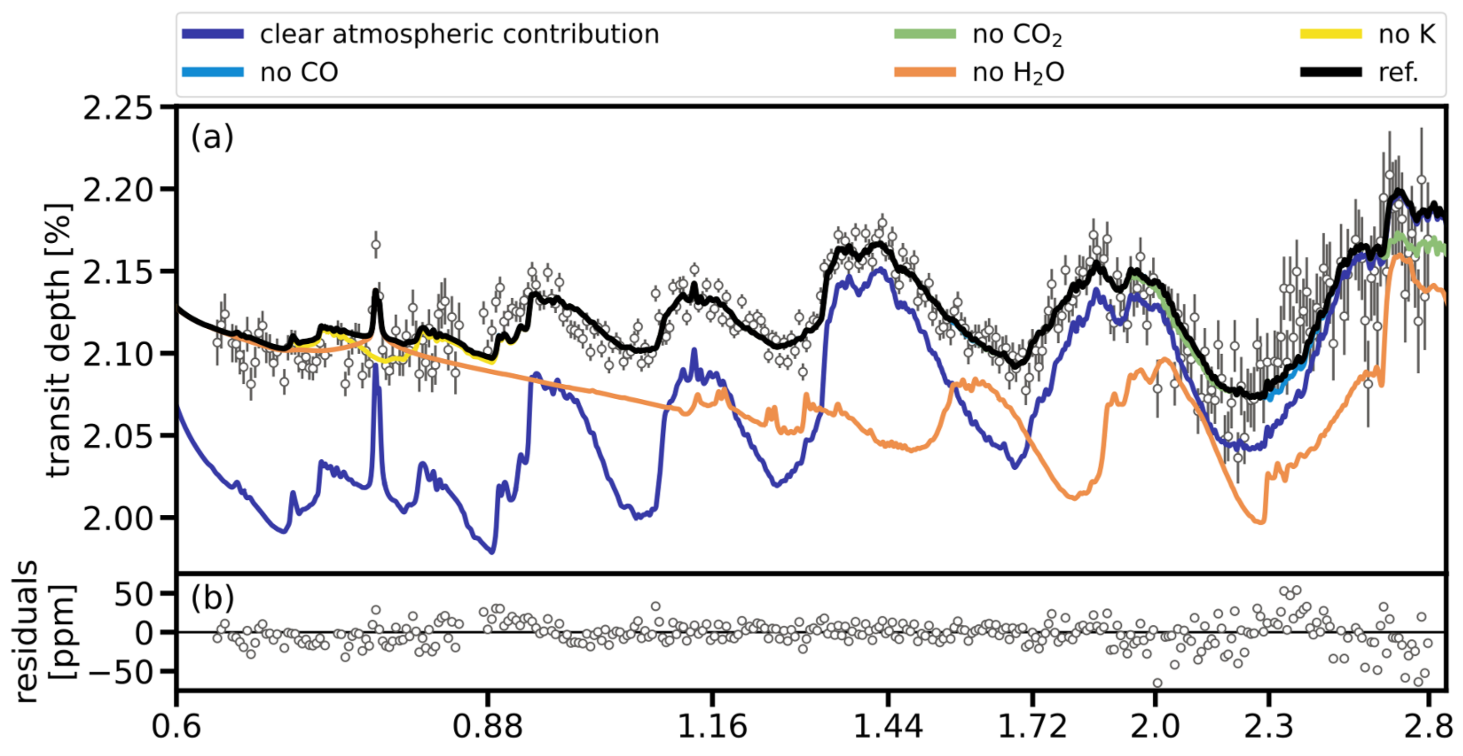
Prediction -—> strong H_2O features in near-IR



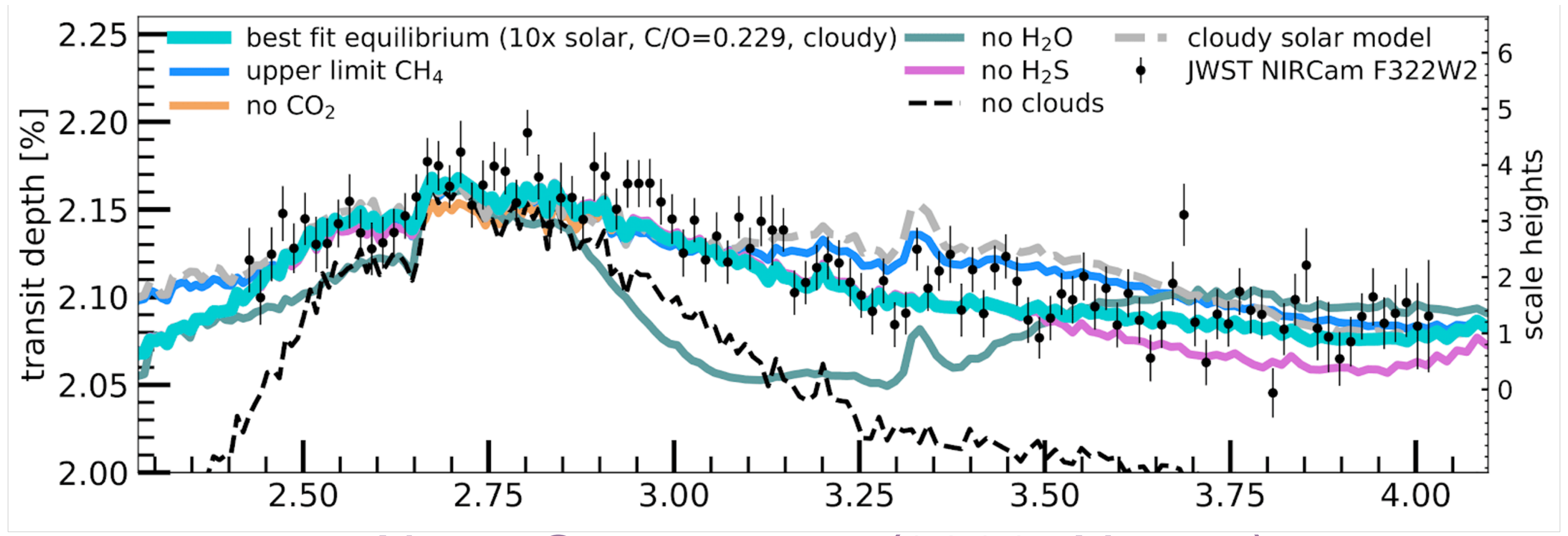


WASP-39b Panchromatic Transmission Spectrum

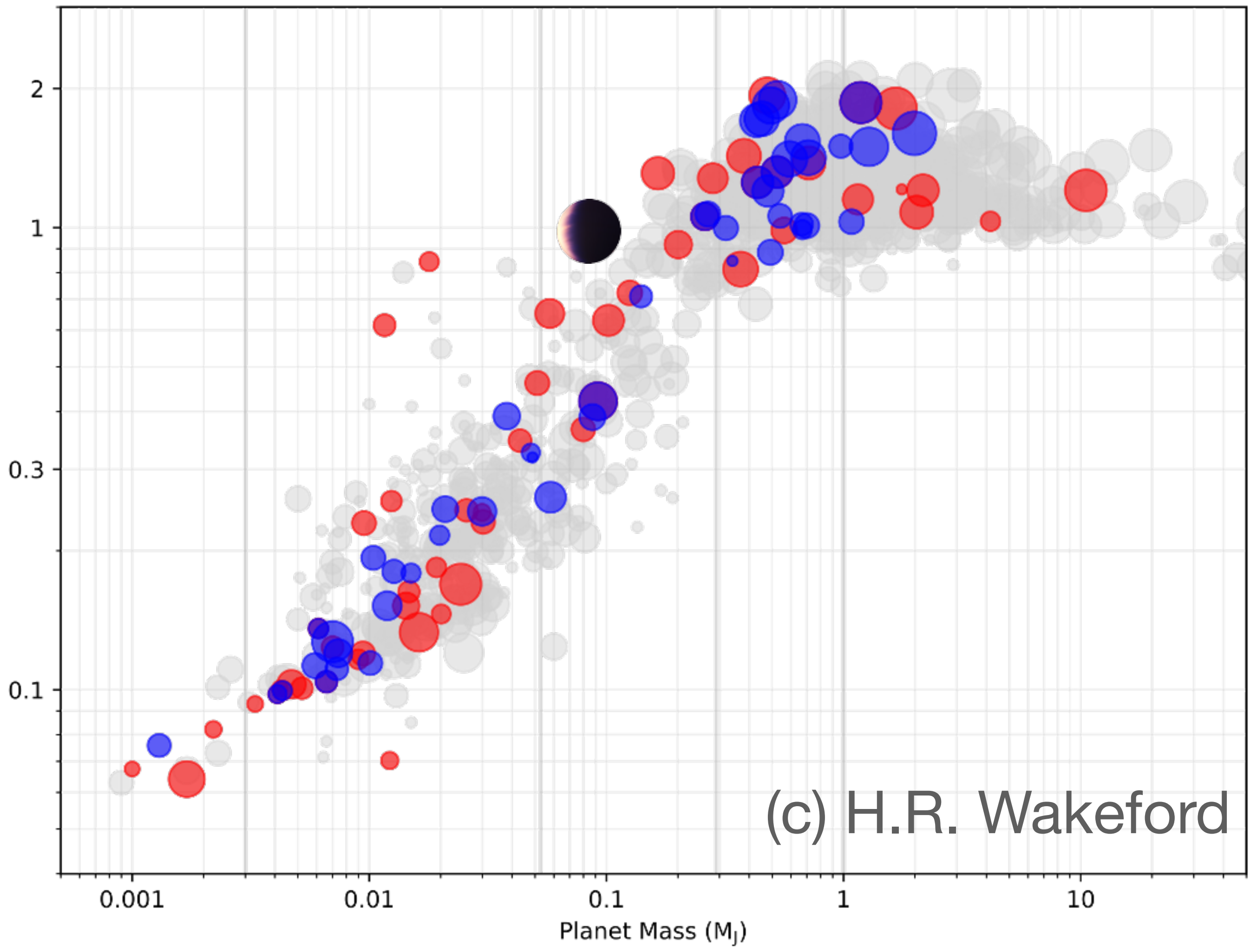
ERS 1366 Transiting Exoplanet Community ERS Program

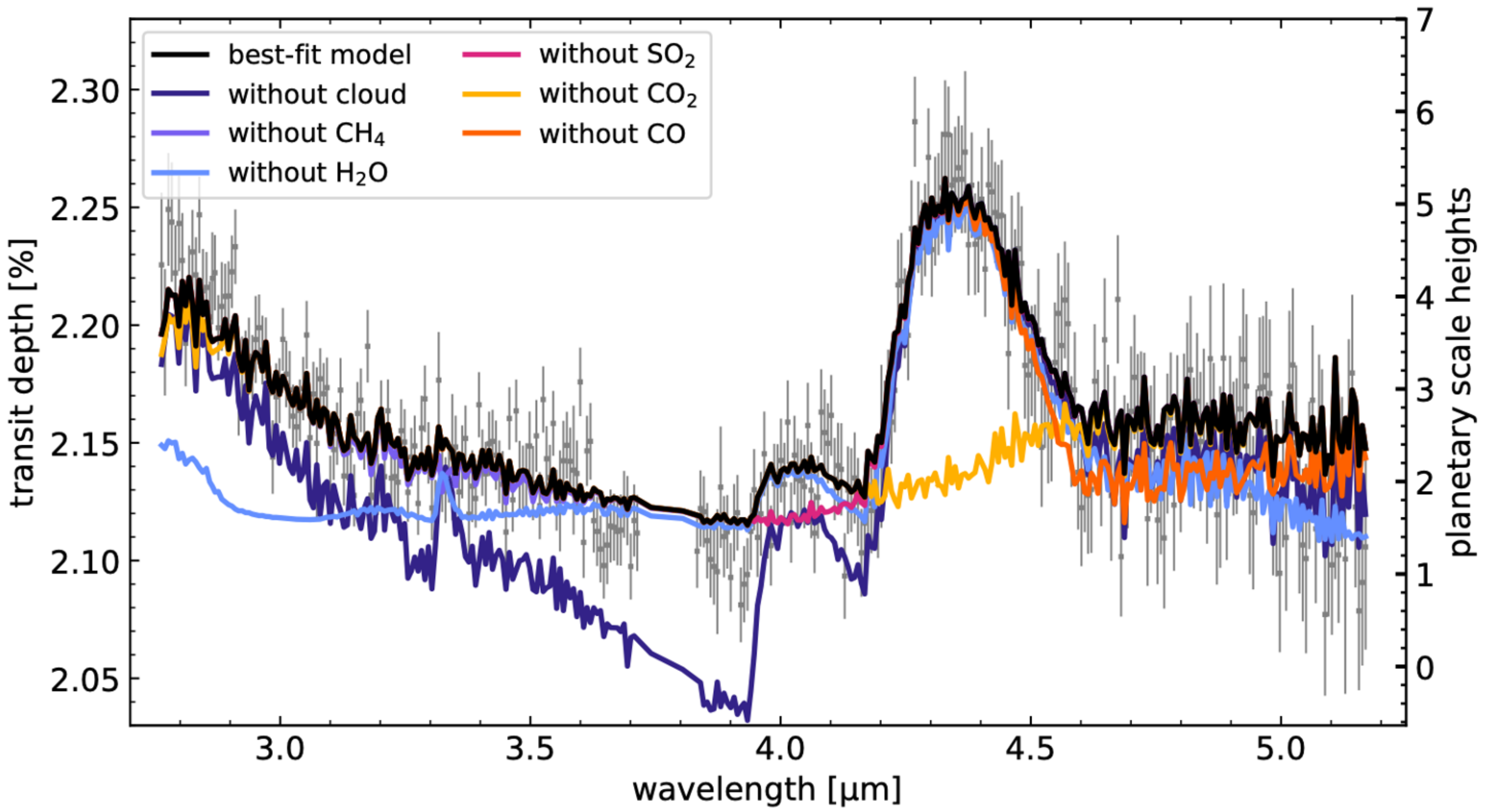


Feinstein, Radica+ (2023, Nature)

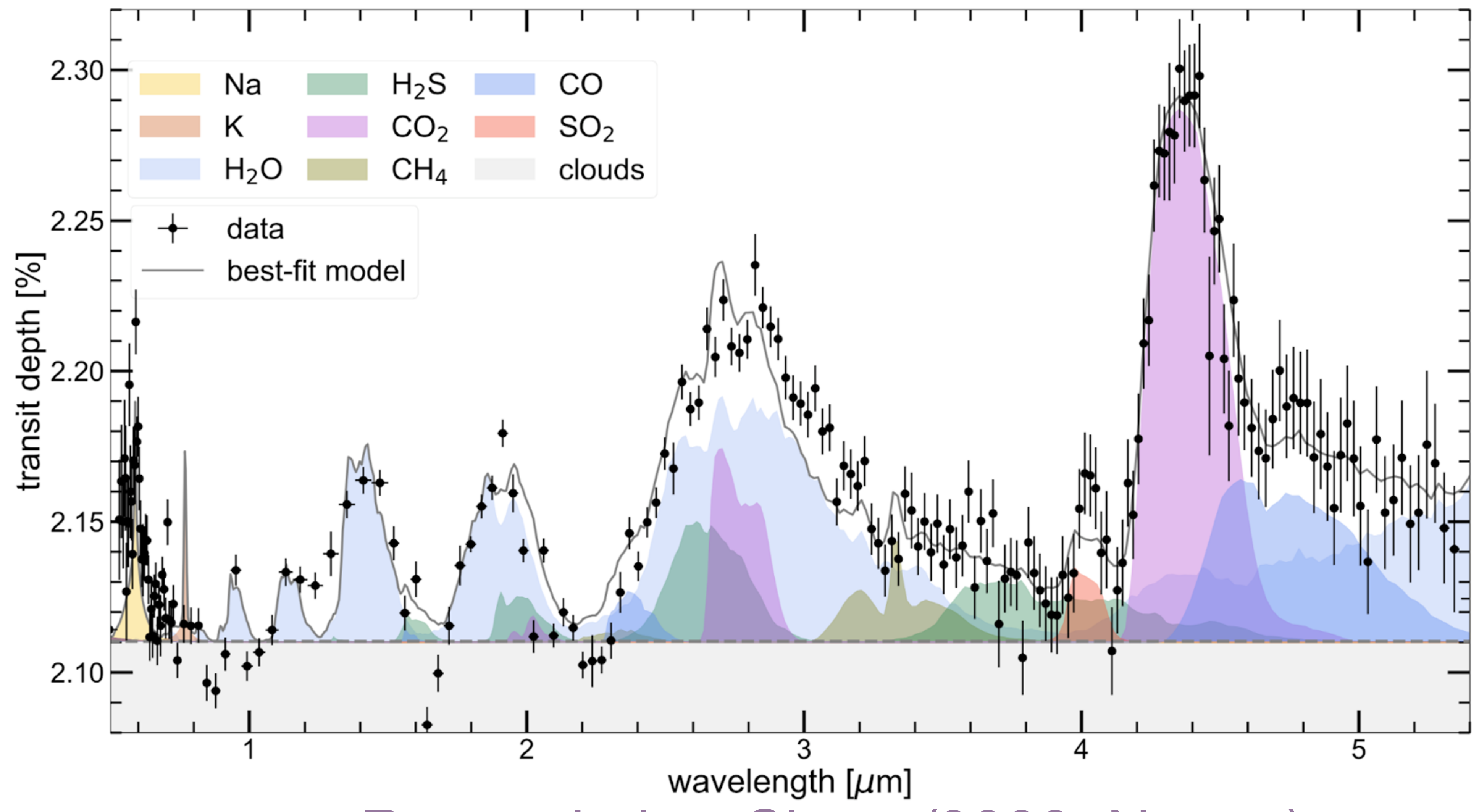


Ahrer, Stevenson+ (2023, Nature)





Alderson, Wakeford+ (2023, Nature)



Rustamkulov, Sing+ (2023, Nature)

Spectrum from 0.6 — 5.2 μm

- Detection of K, H_2O, CO_2, CO, SO_2, aerosol opacity
- [M/H] > solar
- C/O < solar

ERS Panchromatic Transmission of WASP-39b

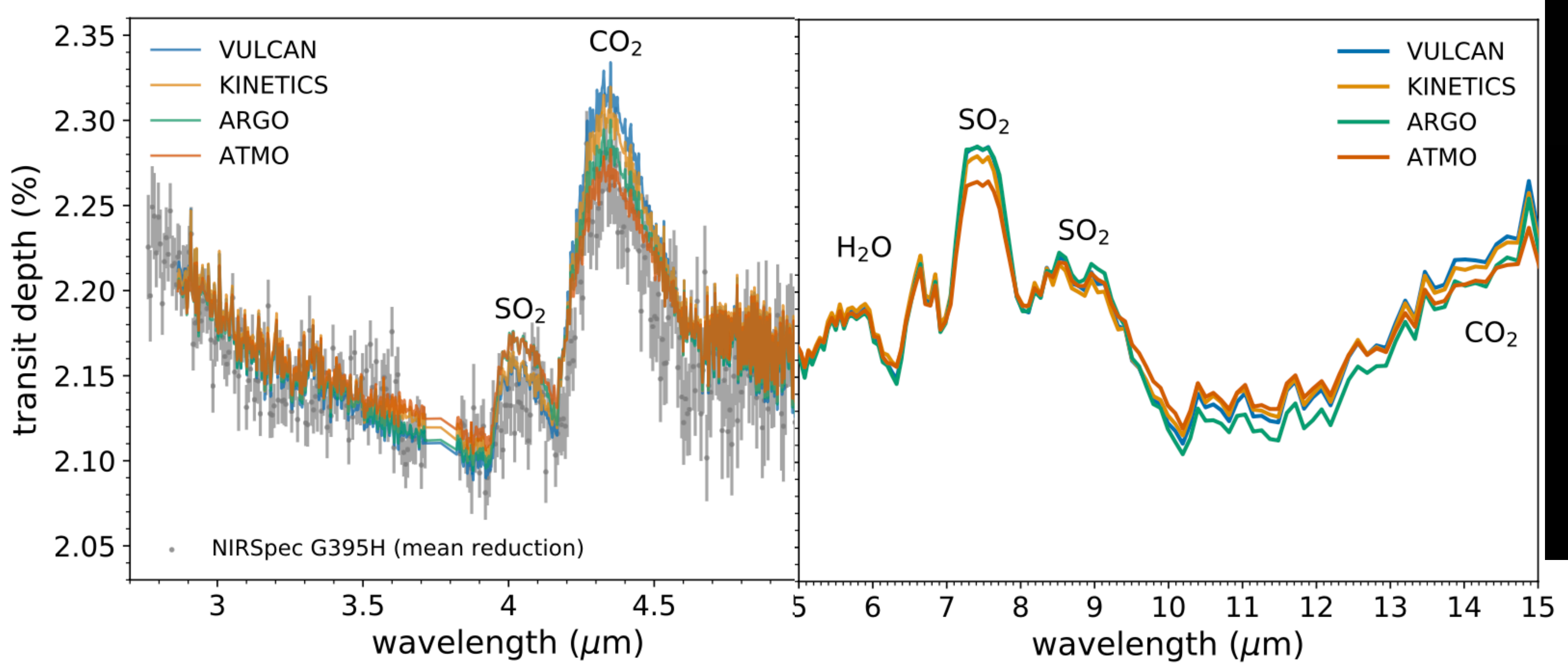
Discovery of SO_2 photochemistry in the atmosphere of WASP-39b

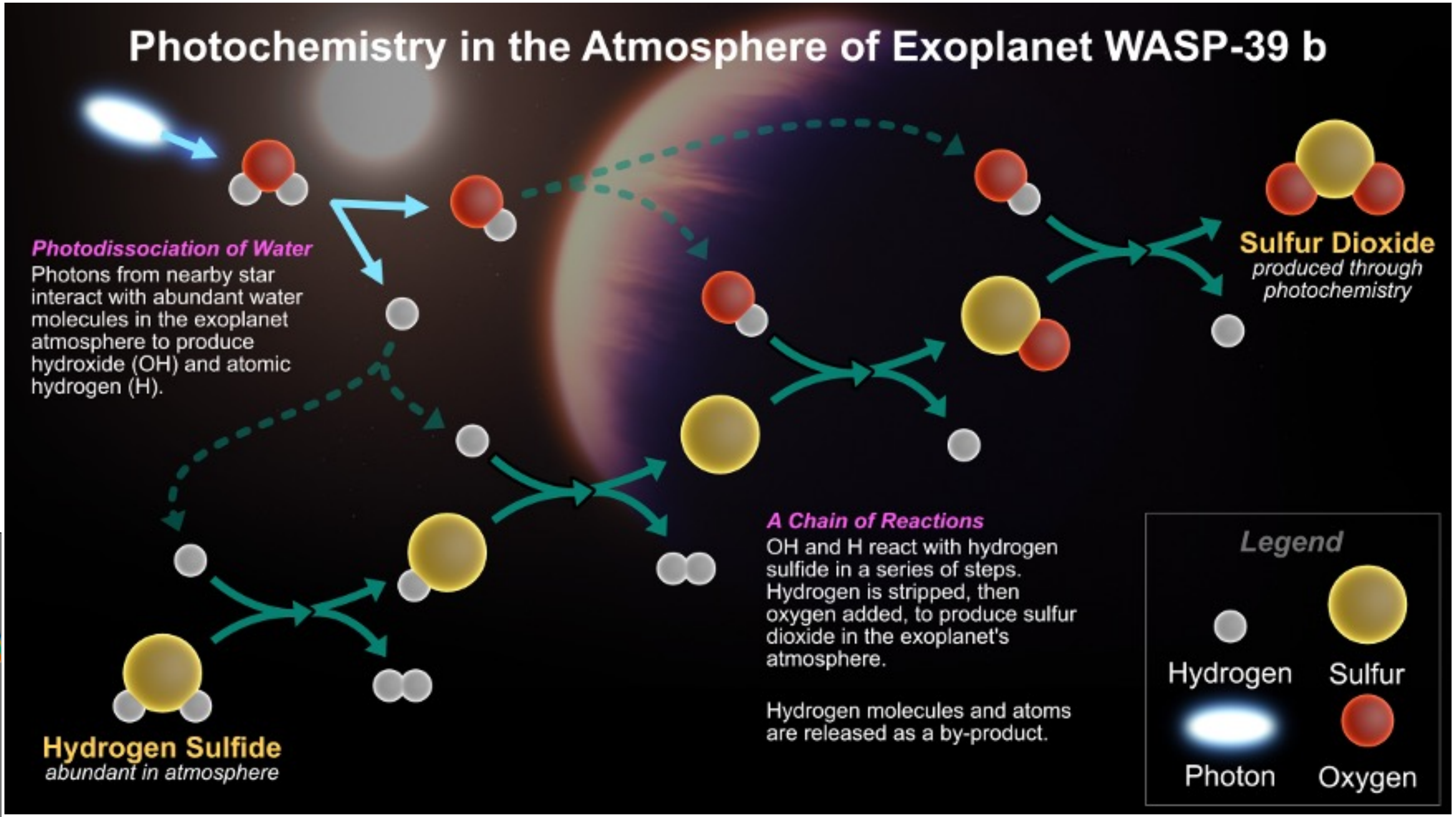
Developed the SO_2 chemical pathway

Confirm SO_2 absorption at 2.6σ in PRISM data & 4.5σ in G395H data

Stronger signatures of SO2 are expected with MIRI

Tsai, Lee et al. 2023, Nature

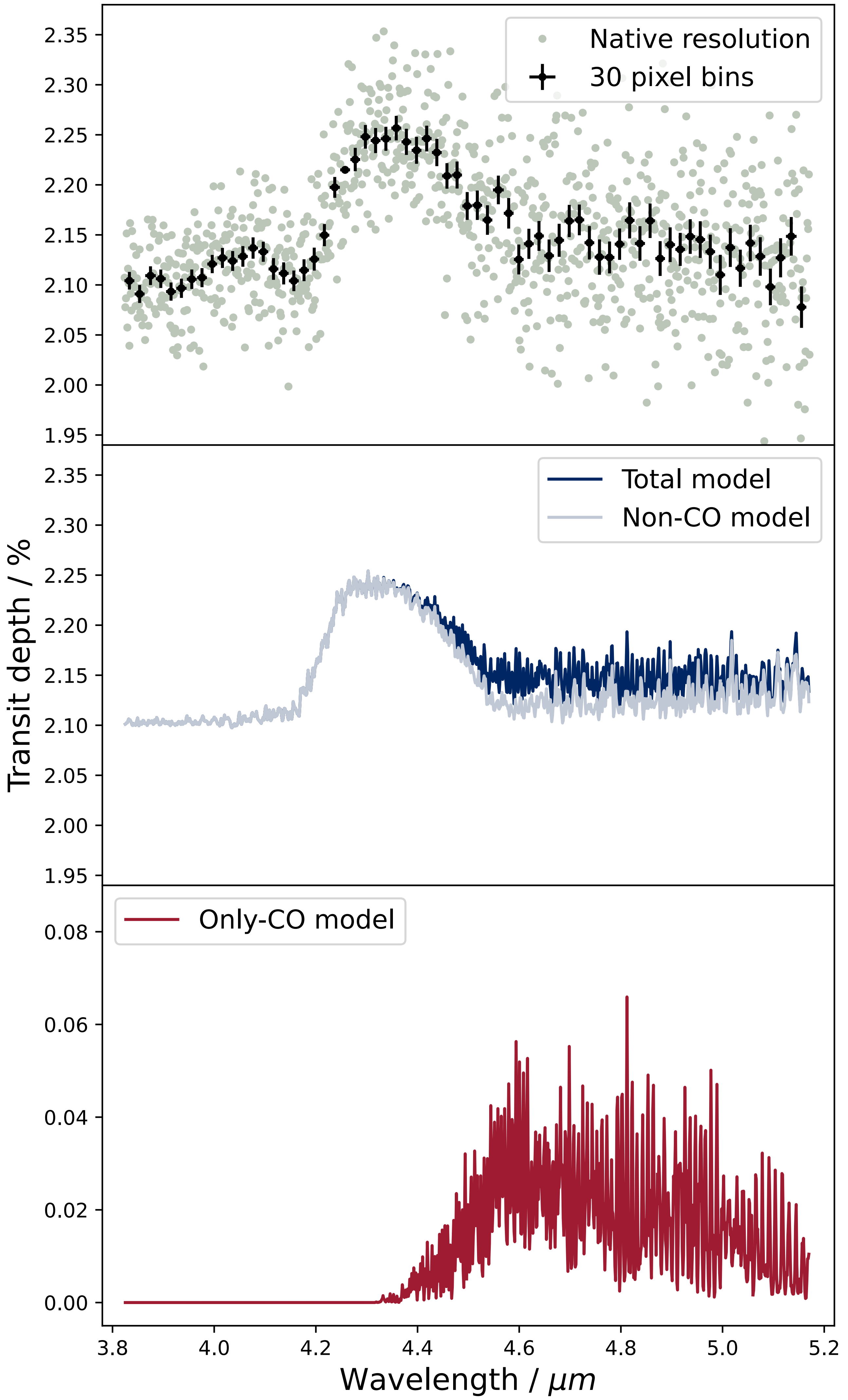




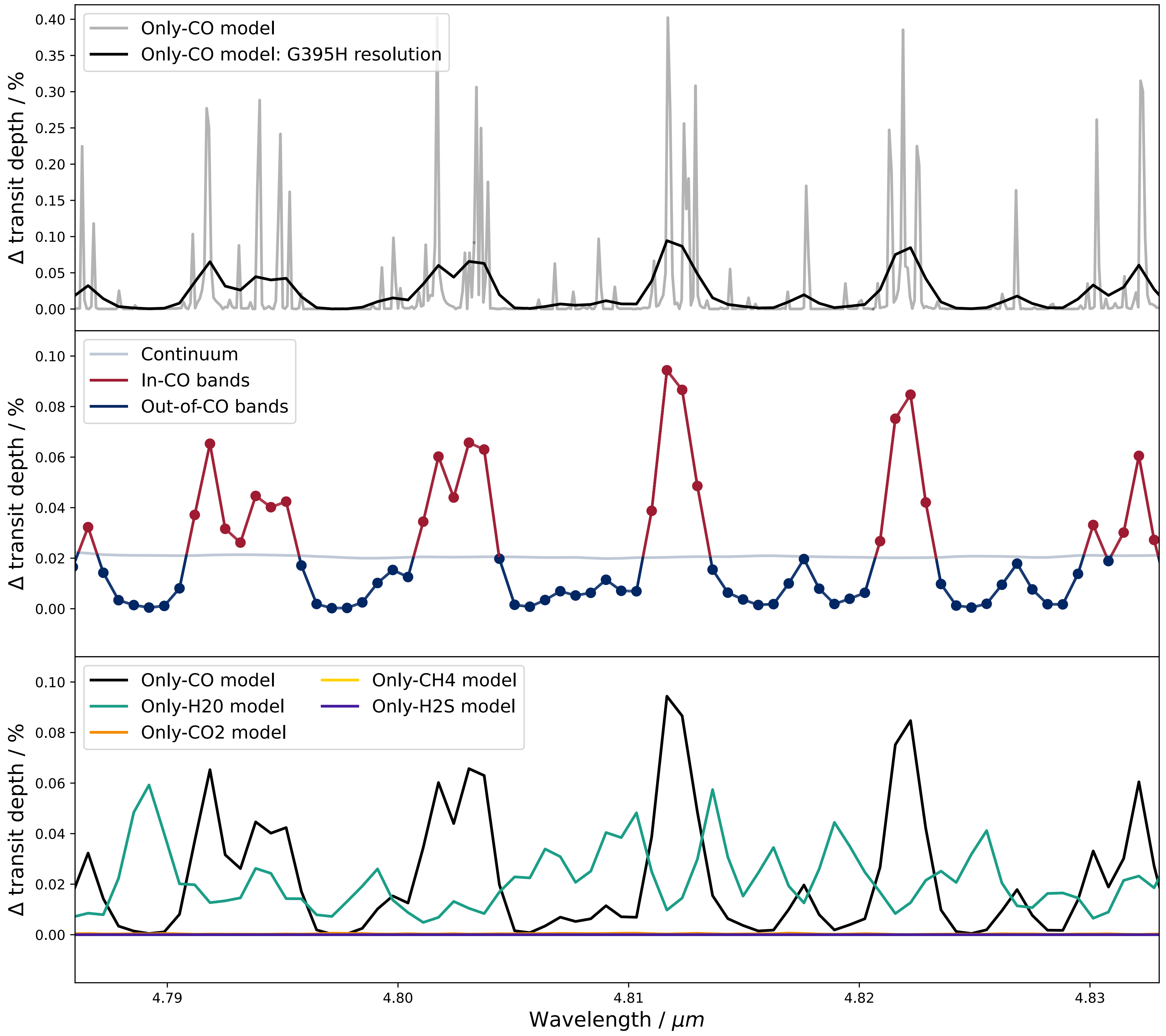
Net: $H_2S + 2H_2O \rightarrow SO_2 + 3H_2$

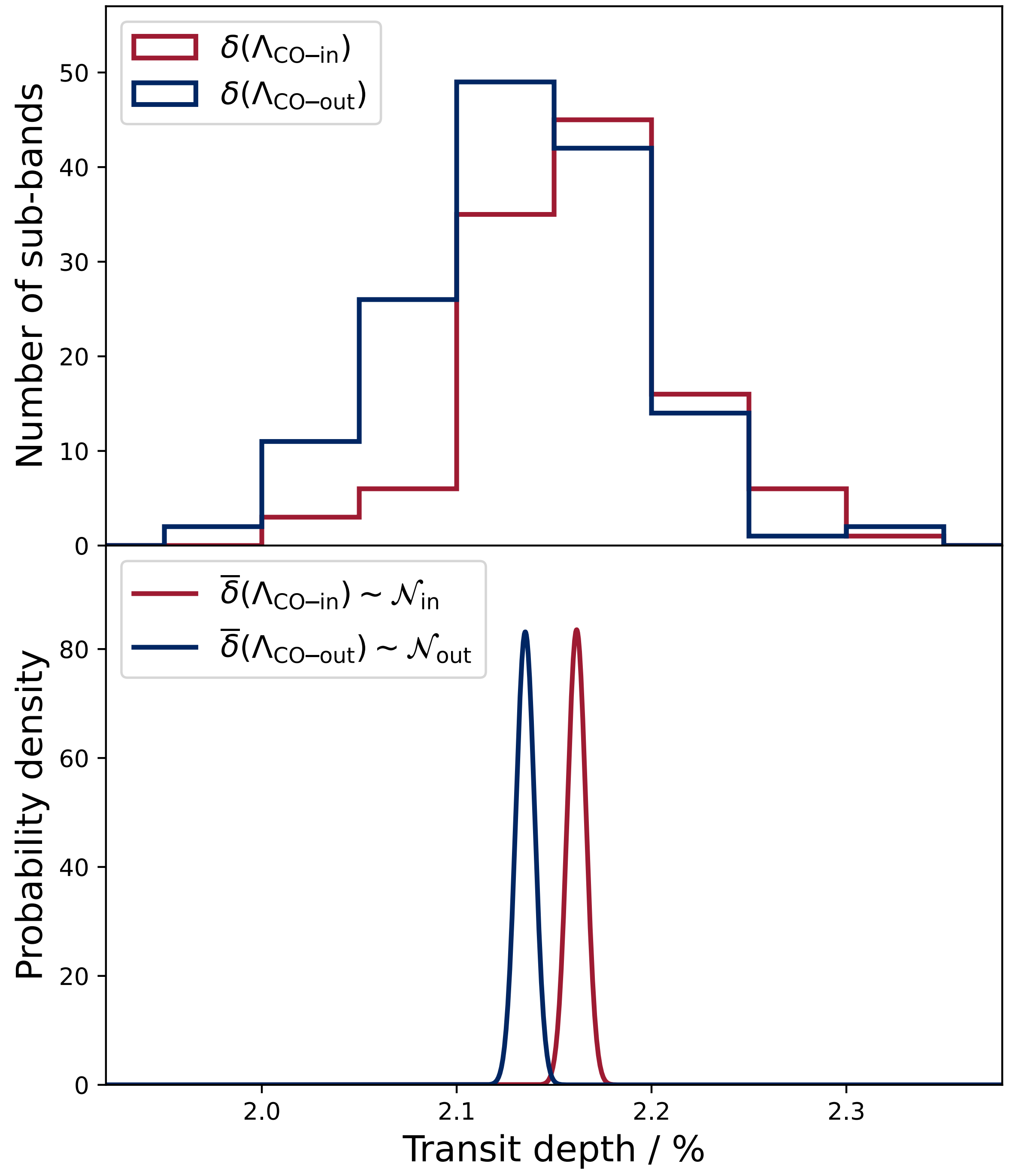
Panchromatic Transmission of WASP-39b [Ancillary]

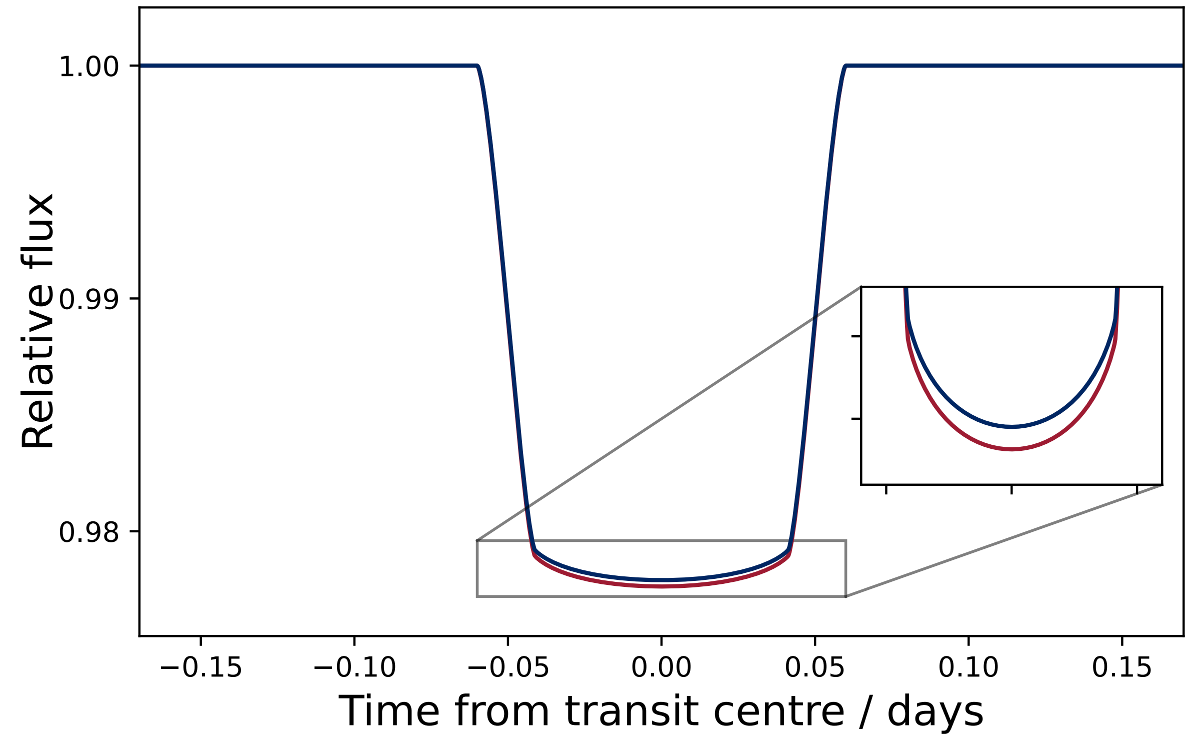
NIRSpec/G395H High-Resolution CO



Ar R~2700 we detect a 264 ± 68 ppm signal of the CO fundamental band structure







[Grant, Lothringer et al. 2023, ApJL]

Atmospheric Scale Height

Height at which pressure decreases by a factor of e (exponent)

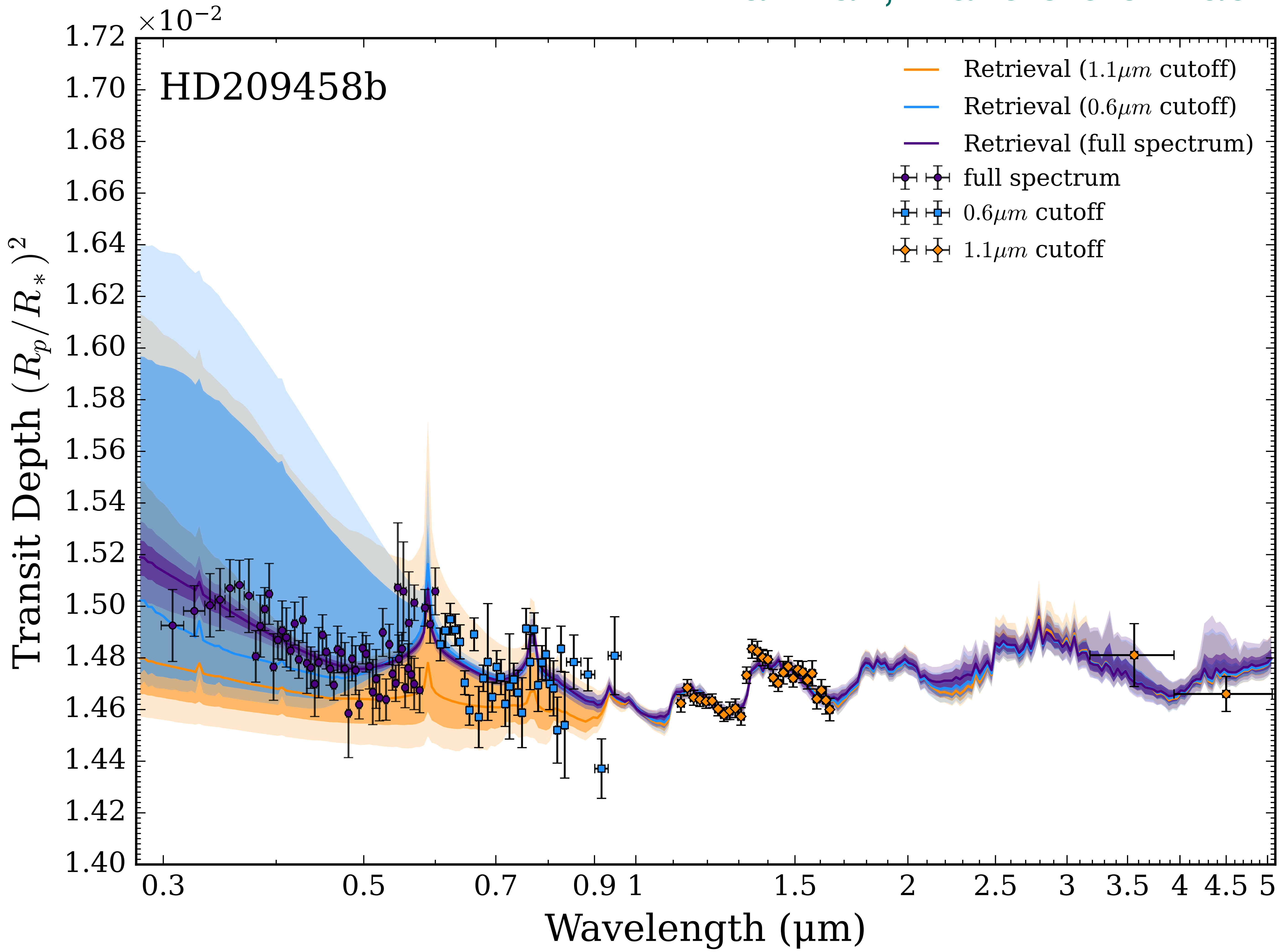
Transiting Exoplanet Atmospheres

How do we measure the atmosphere of a transiting exoplanet?

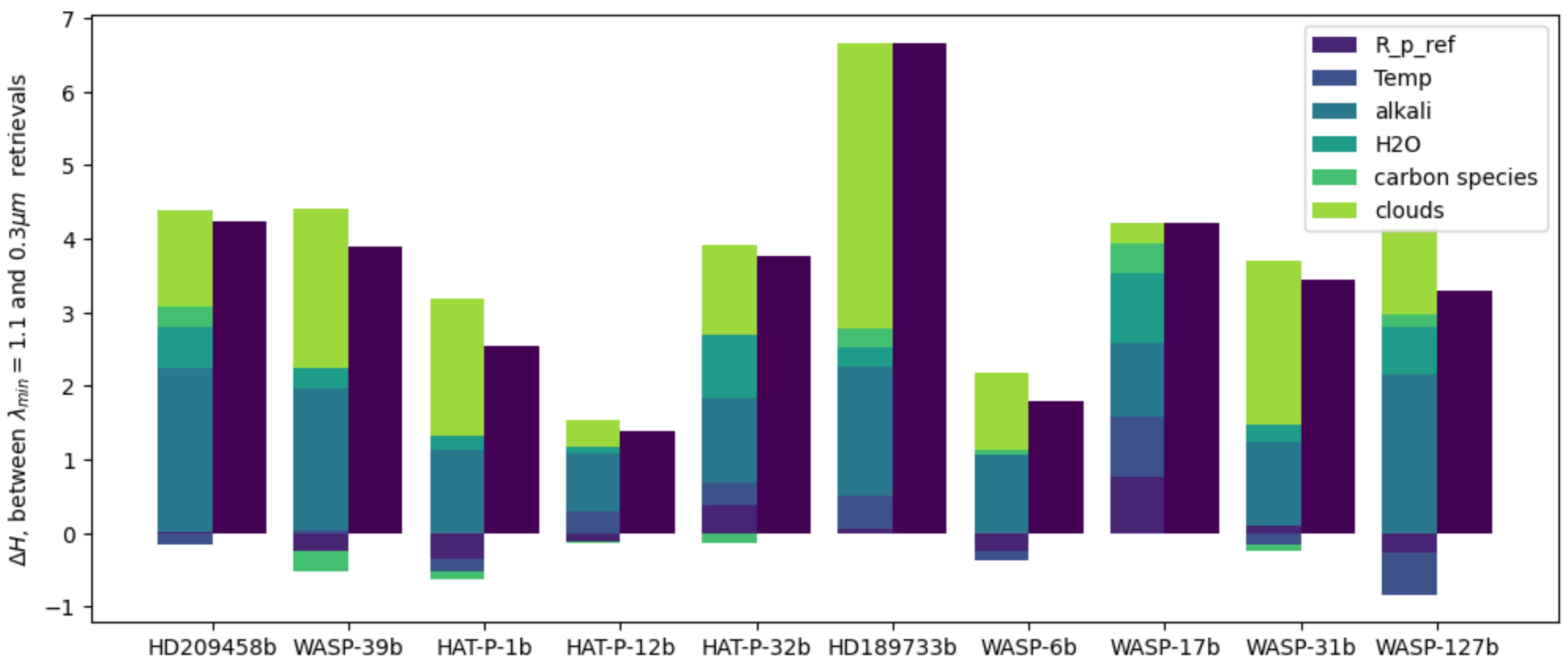
Evaluate the impact of exoplanet aerosols

The UV-Optical will play a core role in assessing aerosols in exoplanet spectra

Fairman, Wakeford & MacDonald (in prep)



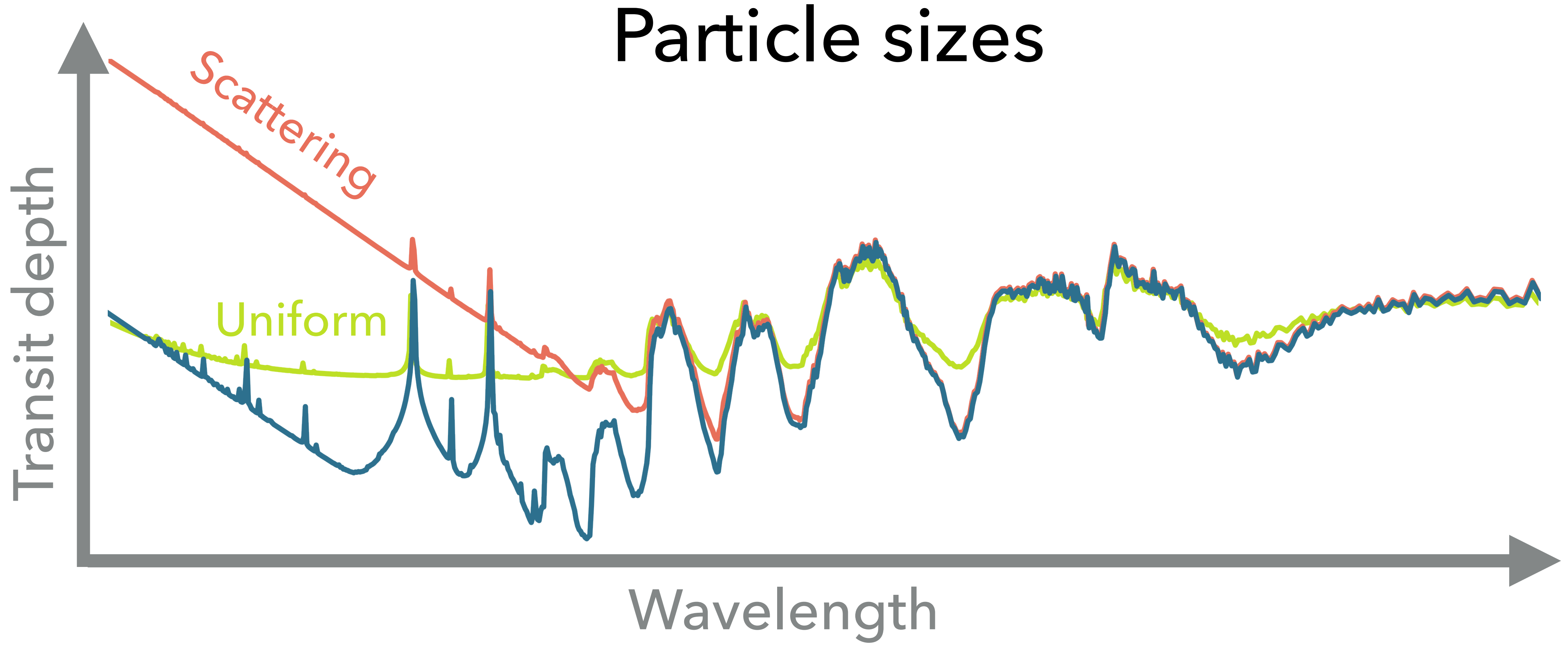
Evaluating the wavelength dependence of retrieved exoplanet properties shows that without information below 0.6 (JWST's blue limit) we cannot properly account for the impact of aerosols on the spectra



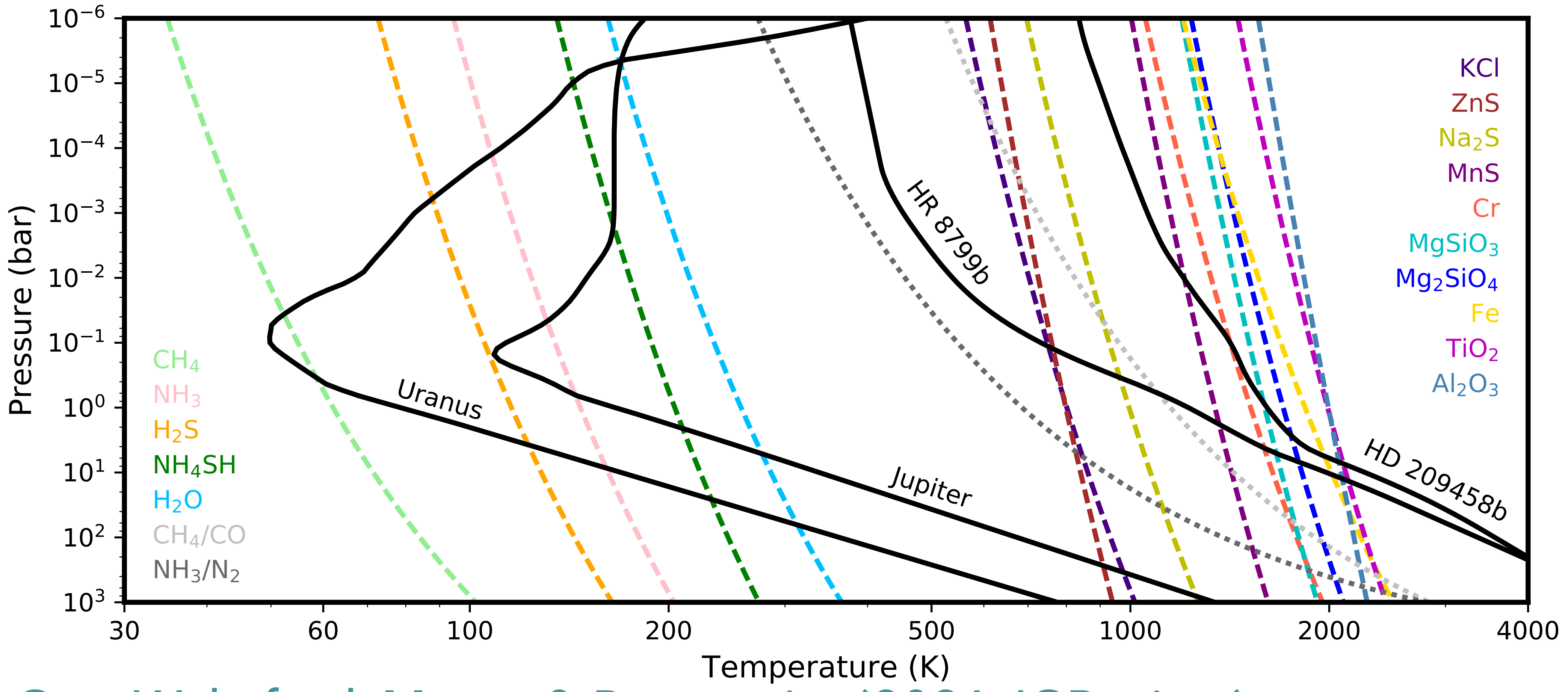
Aerosols will be impacted by Temperature, Chemistry, and Dynamics

How do we measure the atmosphere of a transiting exoplanet?

Particle sizes

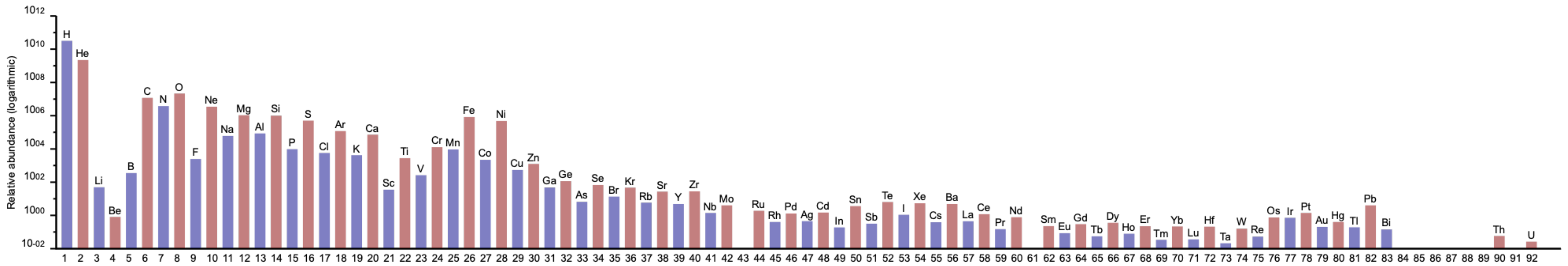


Temperature

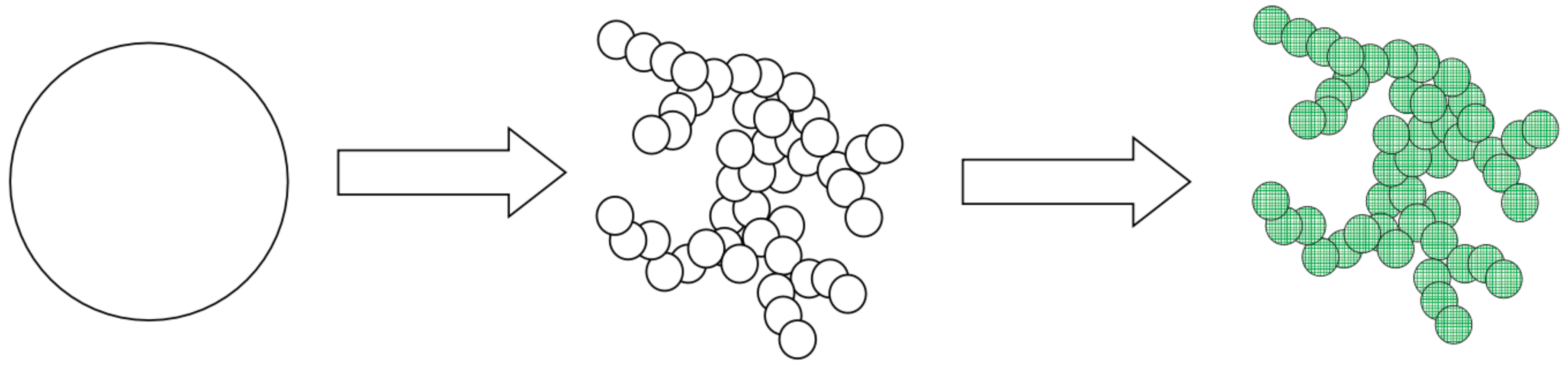


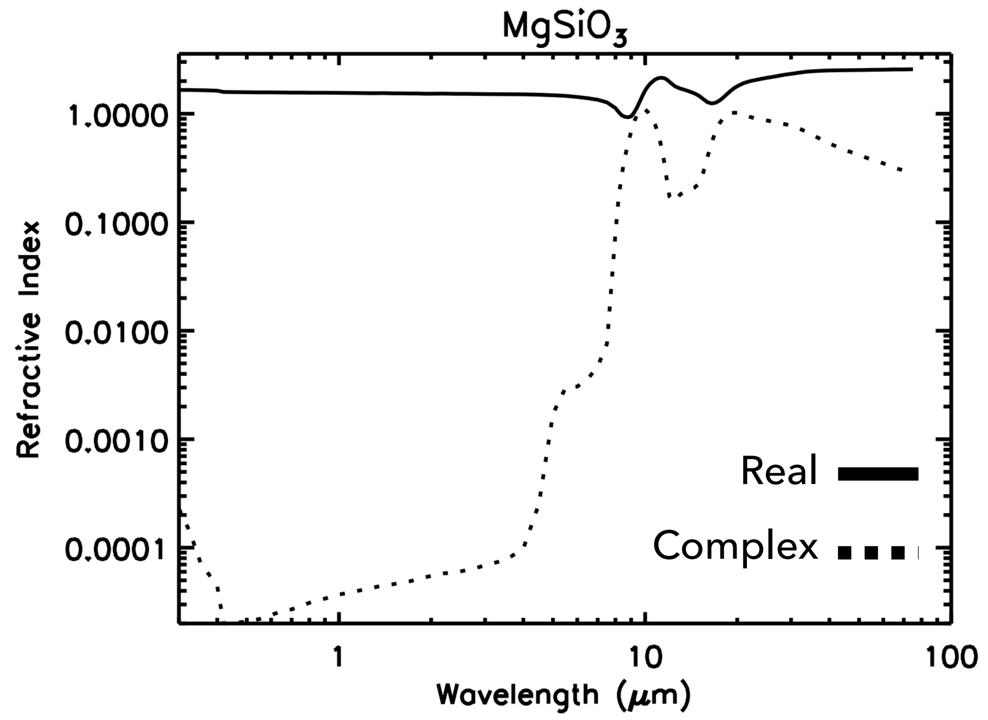
Gao, Wakeford, Moran & Parmentier (2021 JGReview)

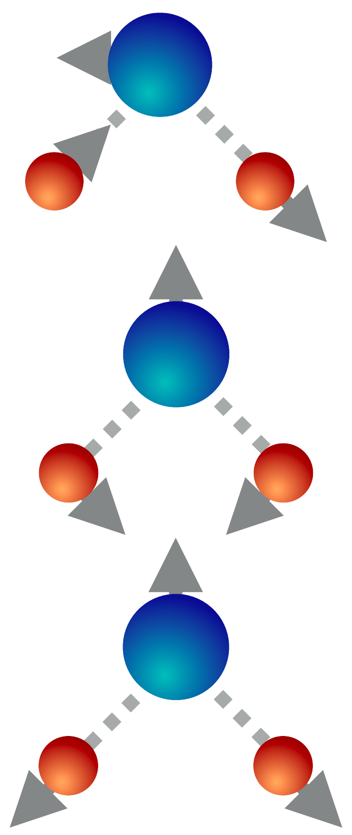
Availability



Chemical properties







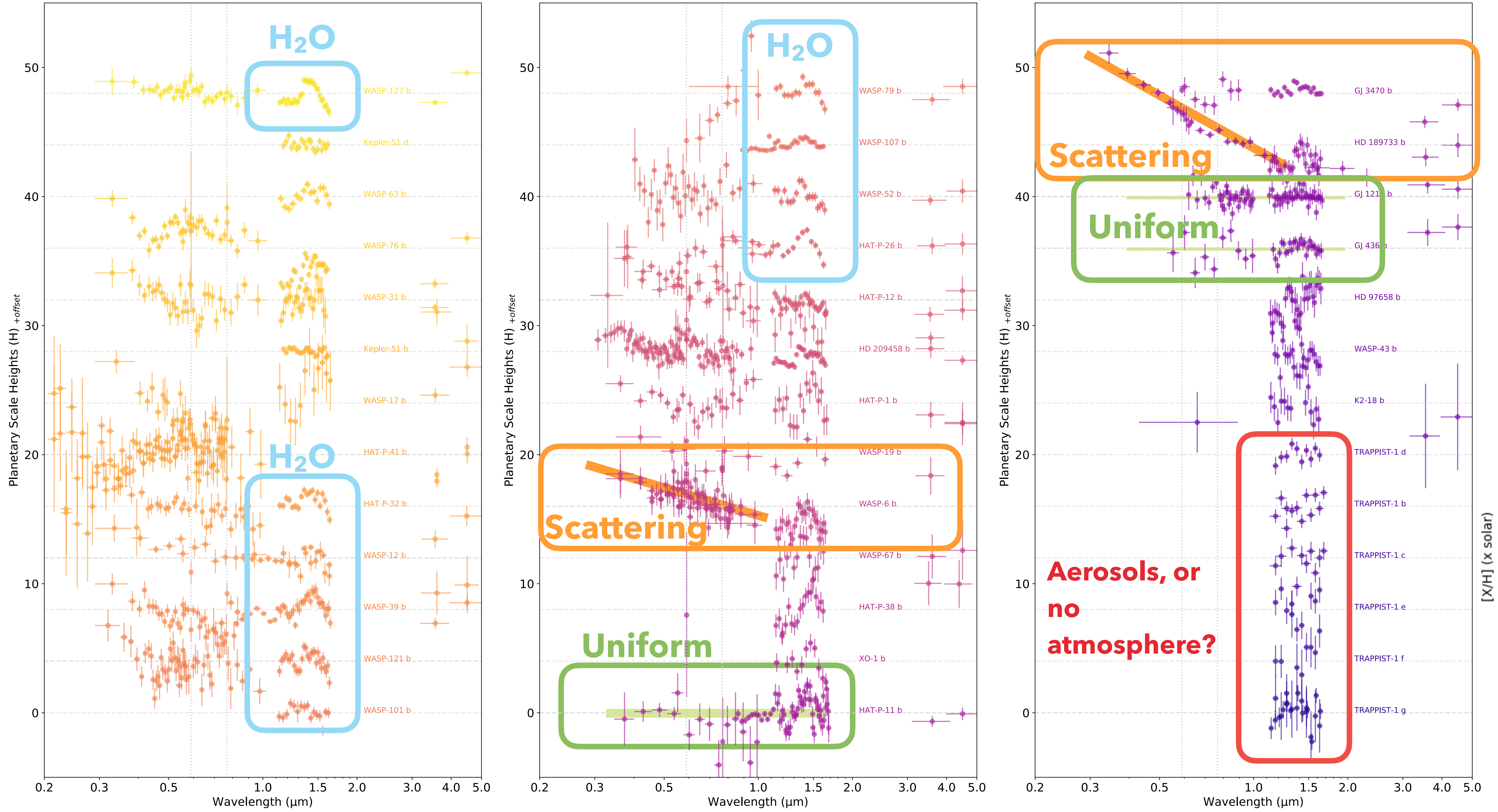
Wakeford & Sing (2015, A&A)

Transiting Exoplanet Atmospheres

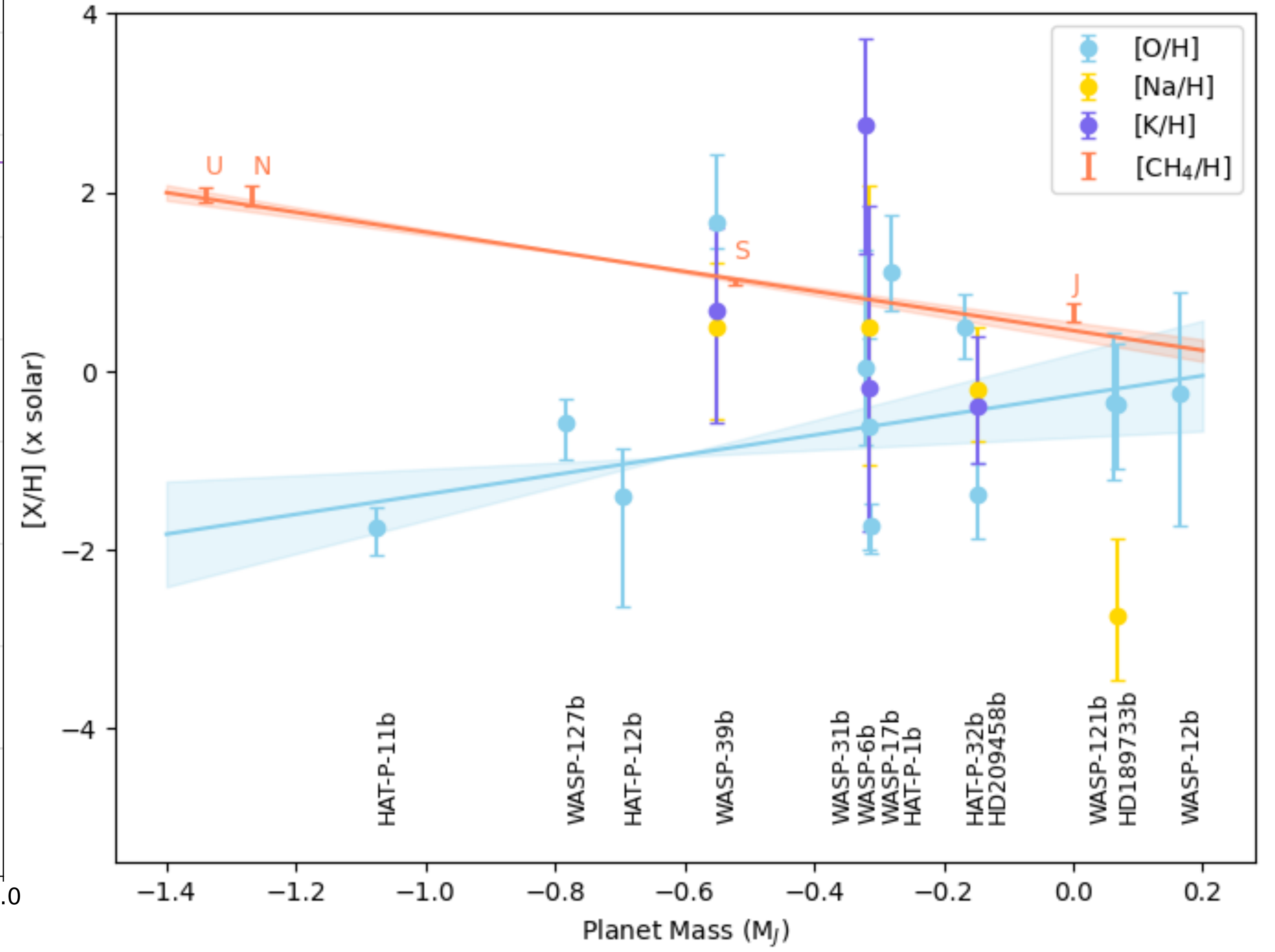
How do we measure the atmosphere of a transiting exoplanet?

What have we seen?

Atoms, Molecules, and Aerosols



Hubble gave us a look at Na, K, & H_2O and hints at aerosols.
JWST will give us carbon-species and cloud composition and location



You can now find all these and more on NASA Exoplanet Archive!

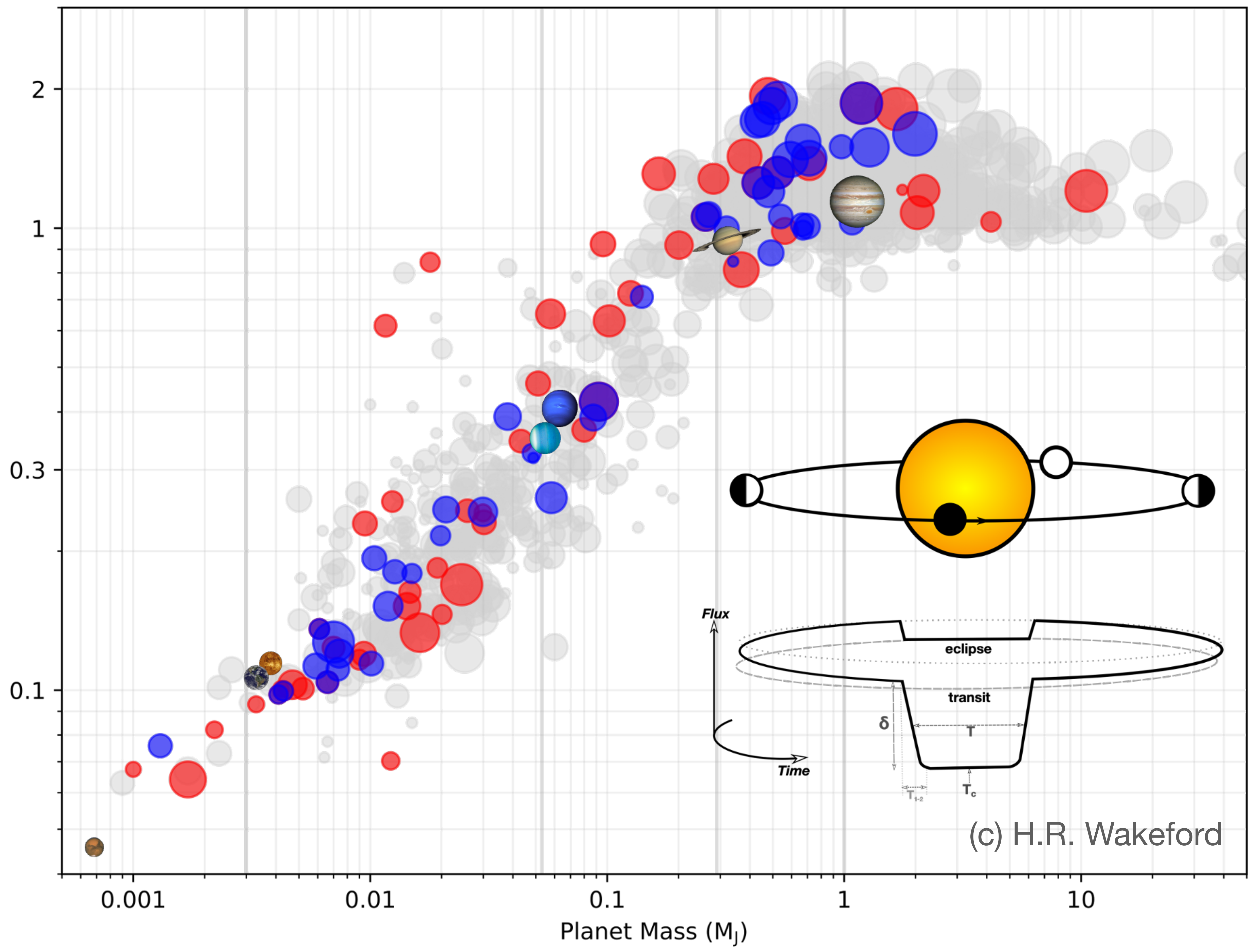
Fairman, Wakeford & MacDonald (in prep)

Transiting Exoplanets with JWST: Cycle 1 & 2

111 individual exoplanets, +200 observation set-ups

Some high level thoughts:

- Lots of love for NIRSpec/G395H observations
- Multiple large programs looking at small worlds to understand small scale atmospheres
- GTO & ERS performed comprehensive deep dives on a handful of planets (could we get this through a TAC?)
- Exciting complementary brown dwarf science
- **A HORDE of amazing ECRs leading the charge!!**



A look to the future of exoplanets with JWST

Exciting science and opportunities

We will see SO_2 again in places we don't expect

We will start to resolve cloud features in the IR and get a better handle on C/O importance

There is still a lot to learn about the instruments in different SNR regimes