What Can We Learn About Exoplanetary Atmospheres in the Optical?

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PLATO 2.0 Science Workshop, ESTEC, 30th July 2013

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Geneva exoplanet group

Oxford exoplanet group

Exeter exoplanet group

Observational background I: spectra of exoplanetary atmospheres

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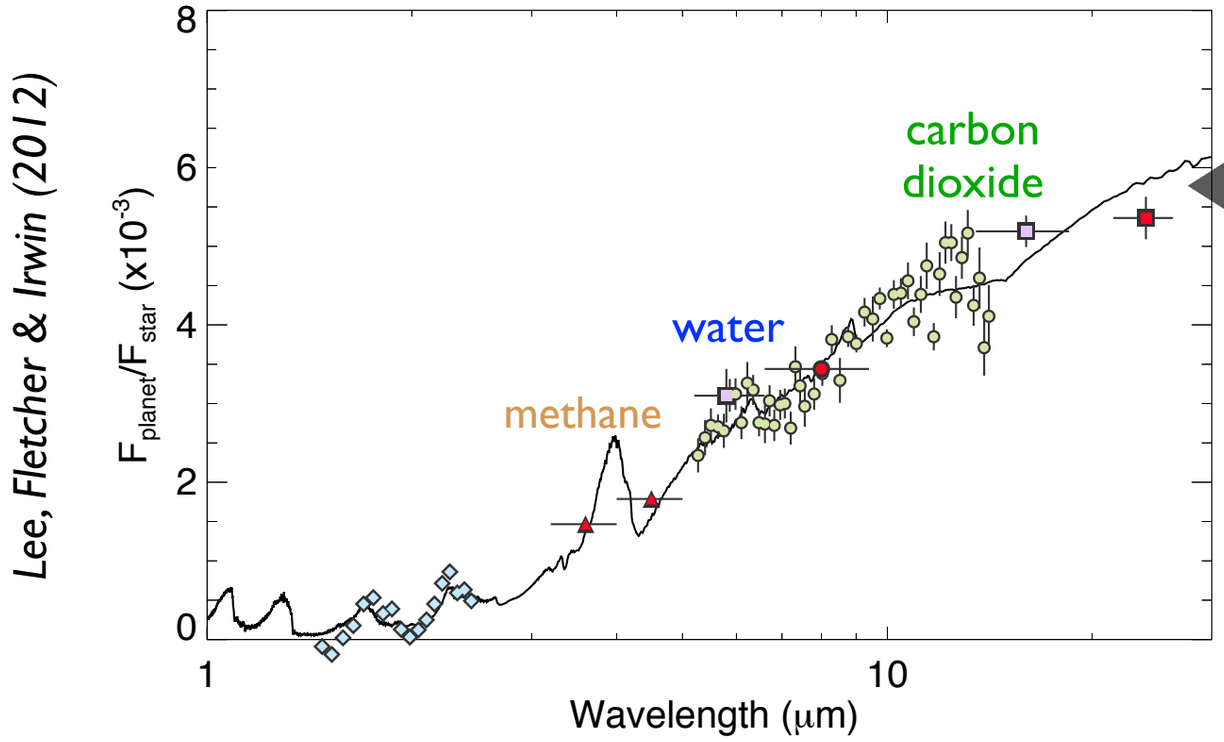
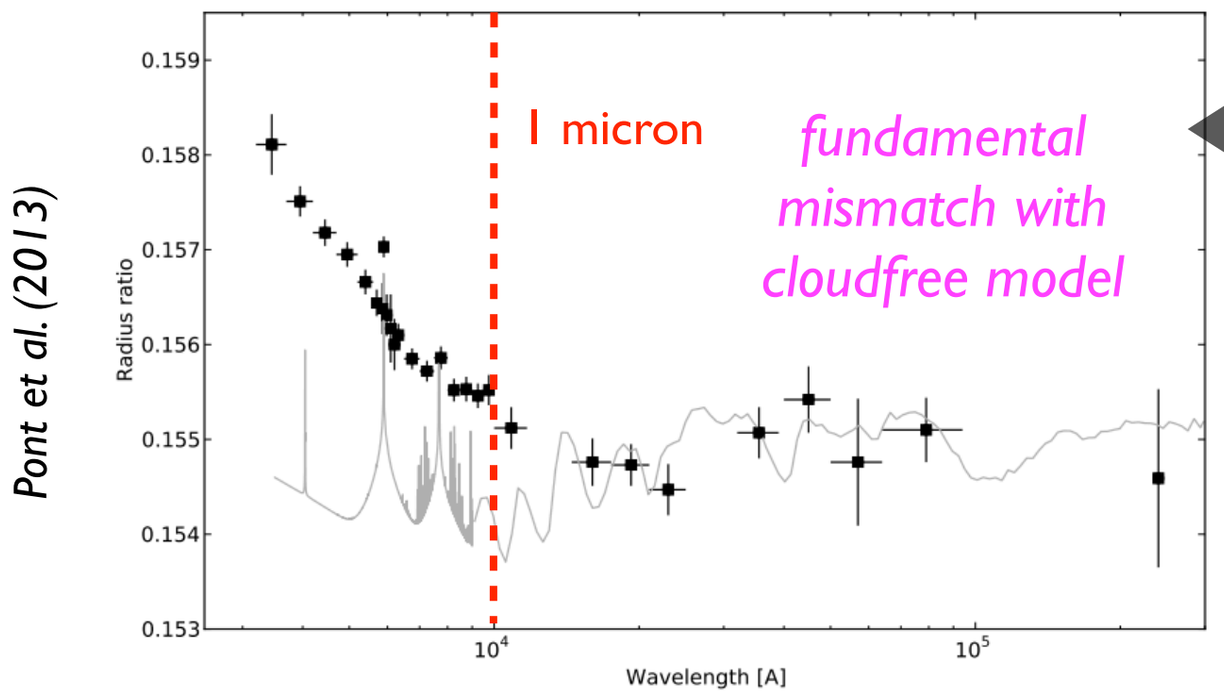


HD 189733b
eclipse spectrum
(dayside)

Molecular features mostly appear in the infrared



HD 189733b
transit spectrum
(day-night terminators)

Featureless slope in the optical consistent with Rayleigh scattering by clouds

Observational background II: the prevalence of clouds

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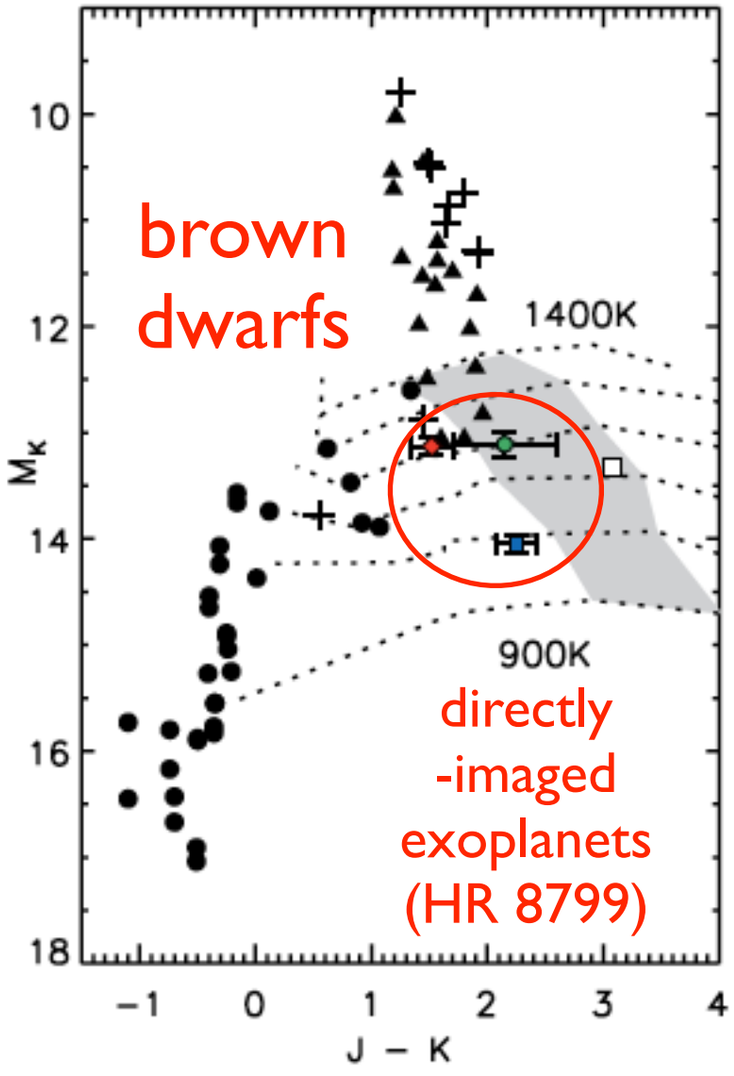
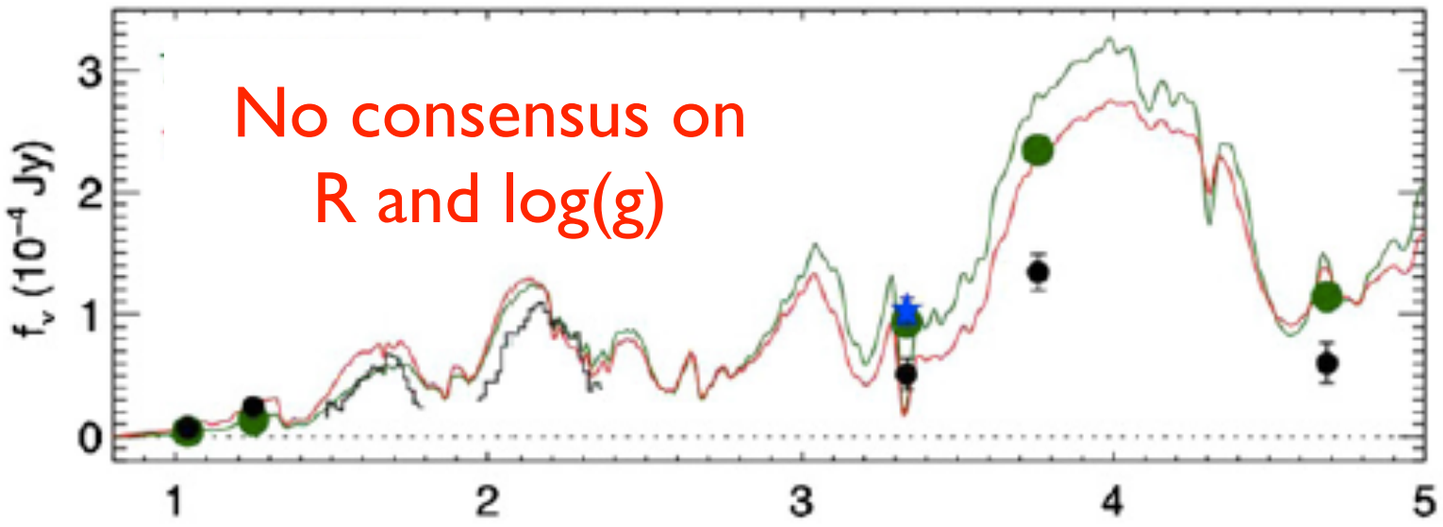


color-magnitude diagram (Barman et al. 2011)



*Spectra and photometry of gas giant **HR 8799b** (Marley et al. 2012)*

Clouds have long plagued our understanding of brown dwarfs, and are **emerging as a major theme** in the study of directly-imaged exoplanets, super Earths and hot Jupiters.

Observational background III: an infinity of mass-radius relationships

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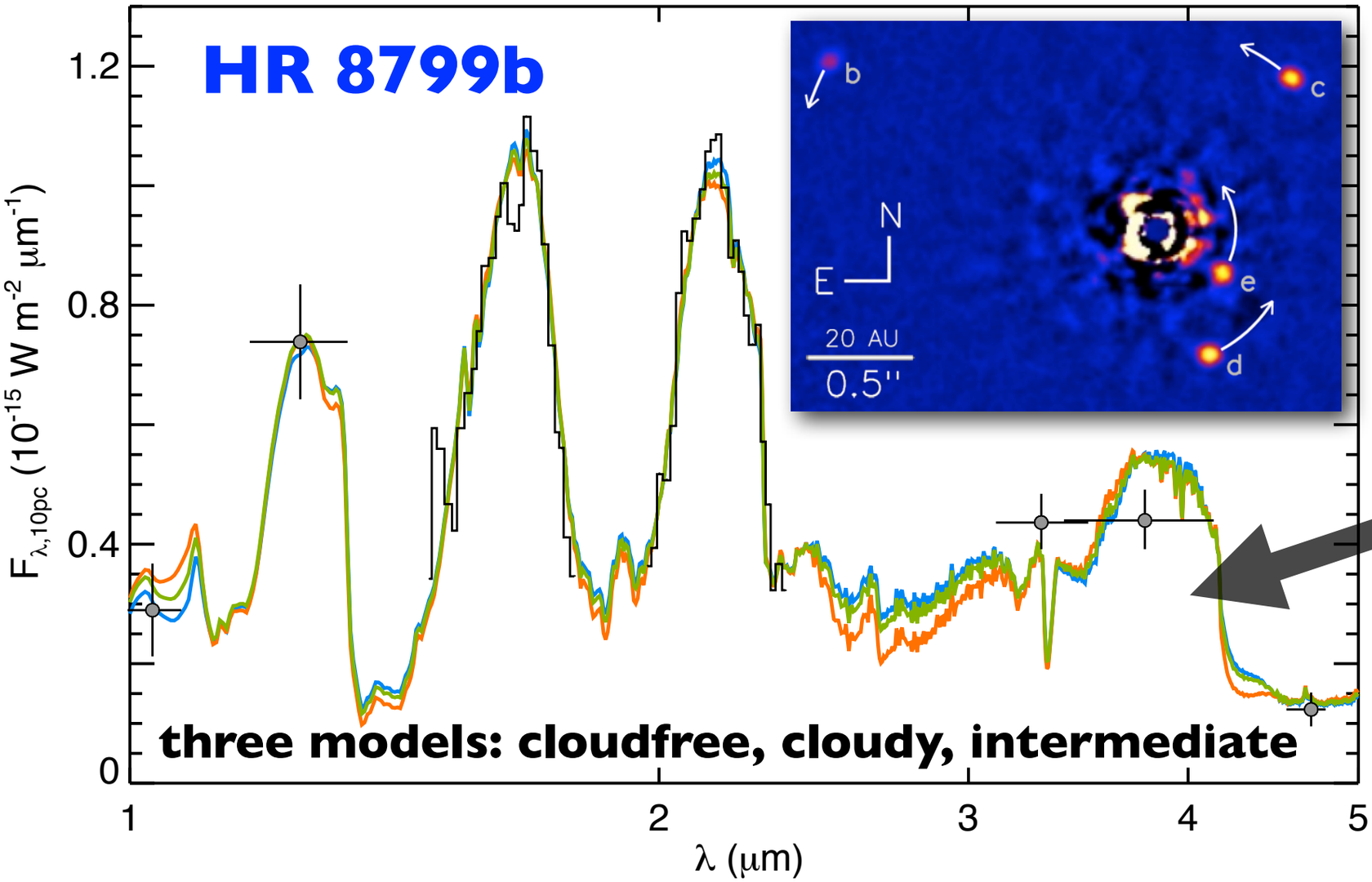

Can you tell which of these models have mean molecular weights of 2.9, 3.8 and 5.0?

Inferred radius, mass, metallicity and abundances differ depending on the **cloud properties**.
Fits are **indistinguishable via chi-square comparison**!
(e.g. Burrows, Heng & Nampaisarn 2011)

atmospheric retrieval analysis by Lee, Heng & Irwin (2013)

How can transit/eclipse measurements at optical wavelengths be useful for understanding exo-atmospheres?

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- Optical eclipse: geometric albedo
- Optical transit: convert relative to absolute abundances
- Optical phase curve: reflectivity (clouds)

Application I: measuring the geometric albedo

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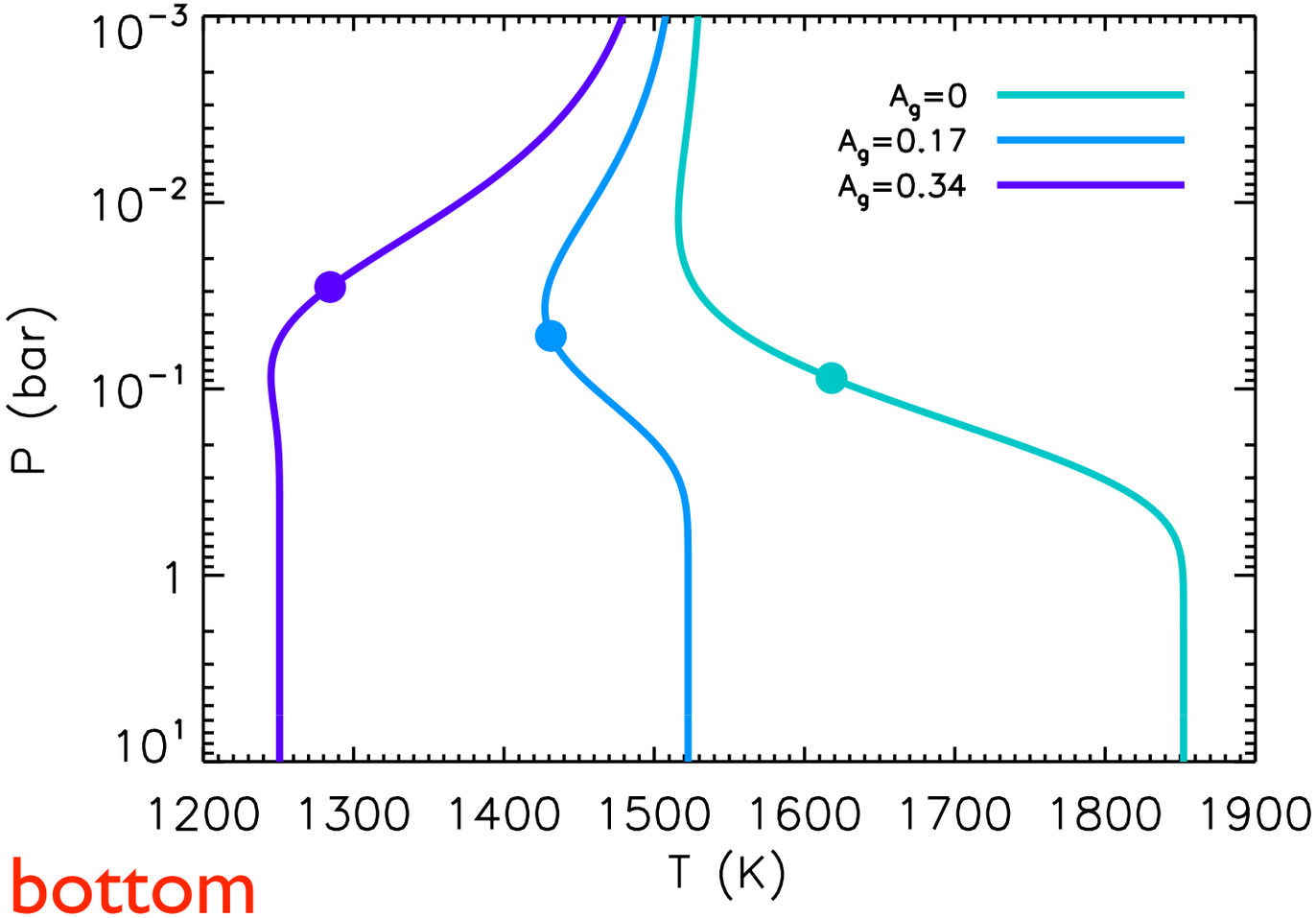
top



bottom

*Examples of **temperature-pressure profiles** in model atmospheres*

Heng et al. (2012)

Two effects:

1. the amount of starlight penetrating the atmosphere

2. the depth of the penetration

thermal structure of atmosphere

See also: Sudarsky et al. (2000), Fortney et al. (2008), Dobbs-Dixon et al. (2012)

Application I: measuring the geometric albedo

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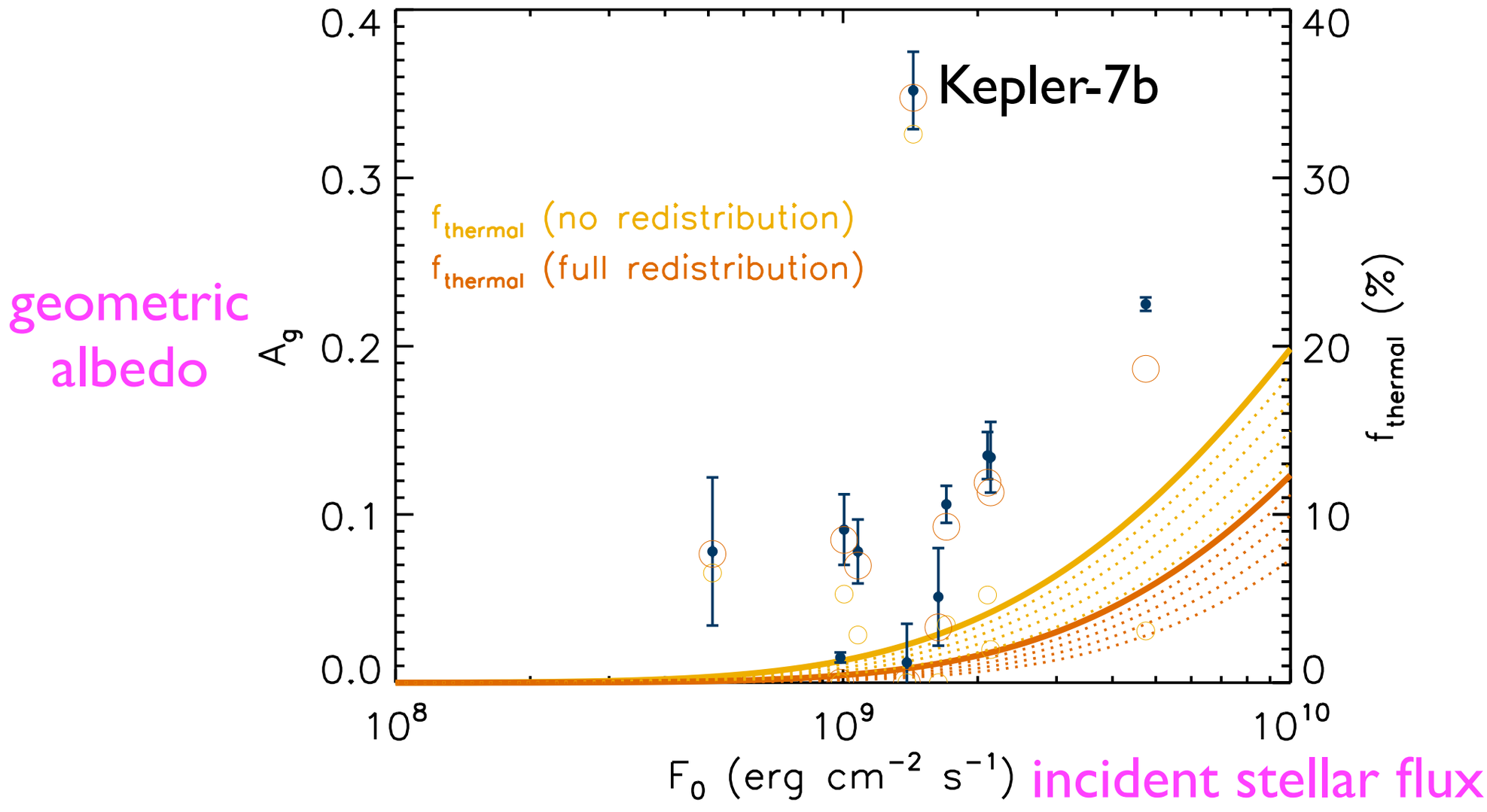

Q0-14 Kepler data (bandpass: 0.4-0.9 microns)

Caveat: contamination by thermal emission!

Heng & Demory (2013)

Application I: measuring the geometric albedo

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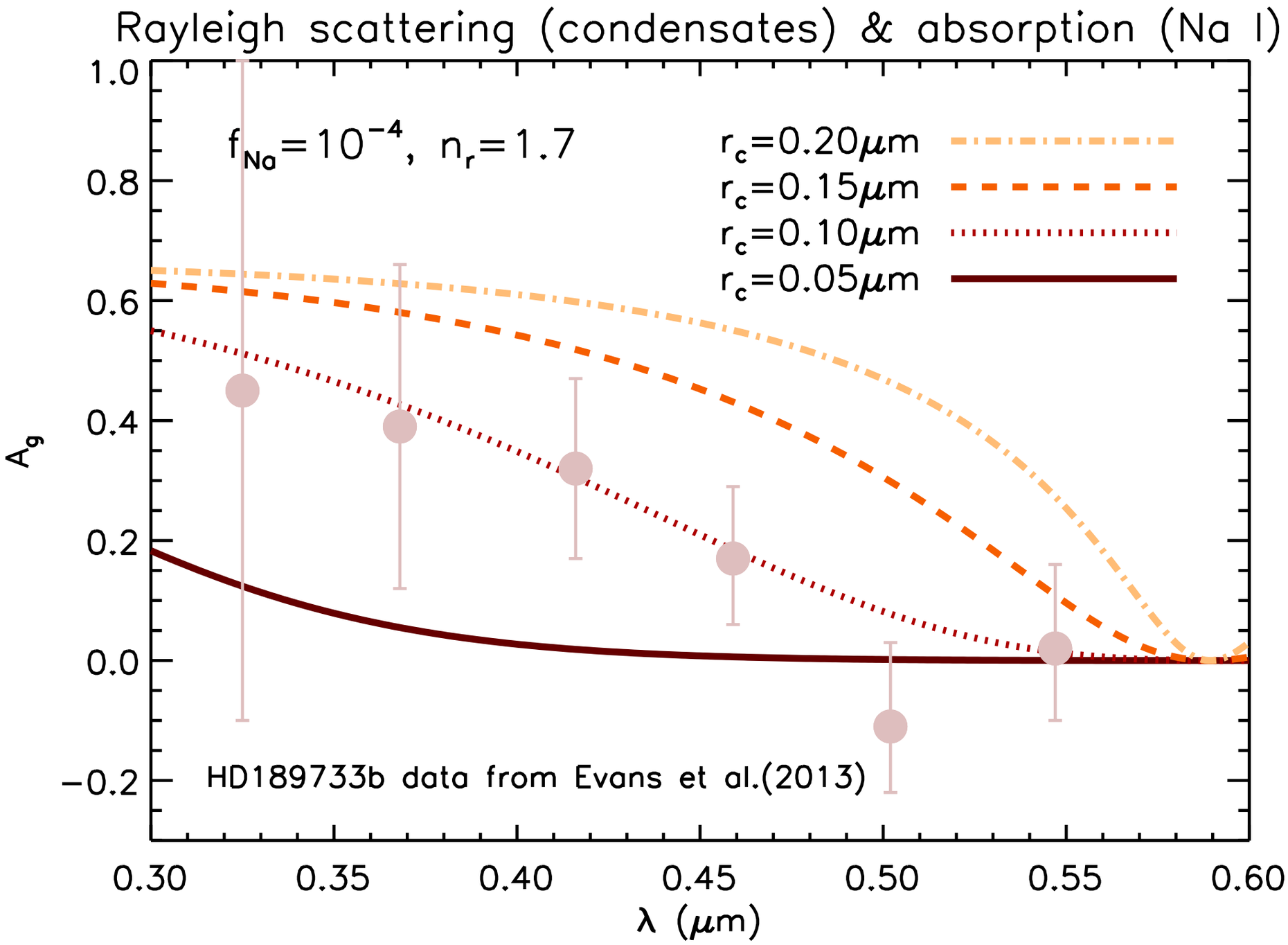

albedo spectrum of HD 189733b by Evans et al. (2013) using HST-STIS

Heng & Demory (2013)

Application I: measuring the geometric albedo

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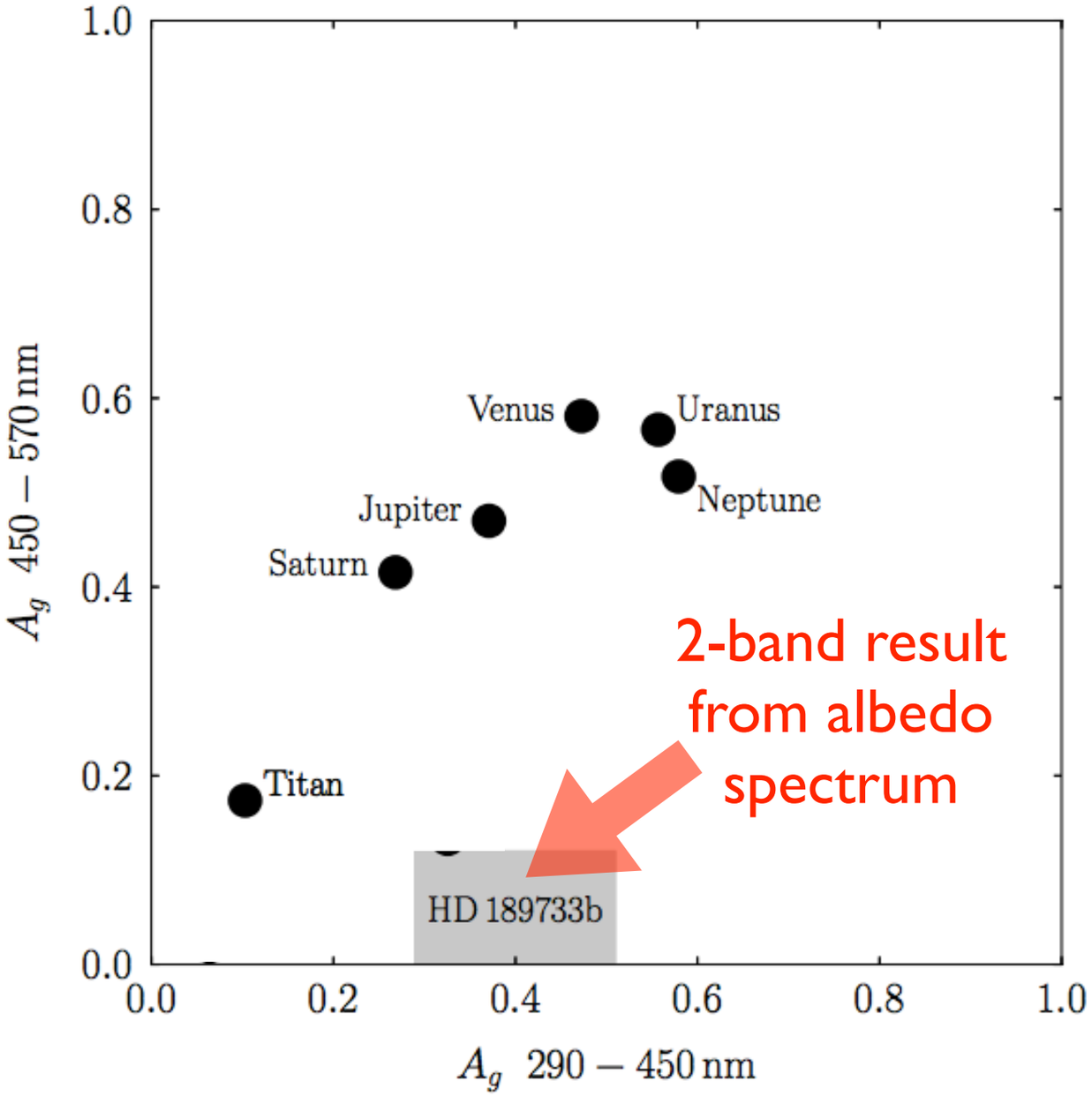
green



blue

Even with just two optical wavebands, comparative exoplanetology of atmospheres can be done

Evans et al. (2013)

Application II: obtaining absolute abundances from transits

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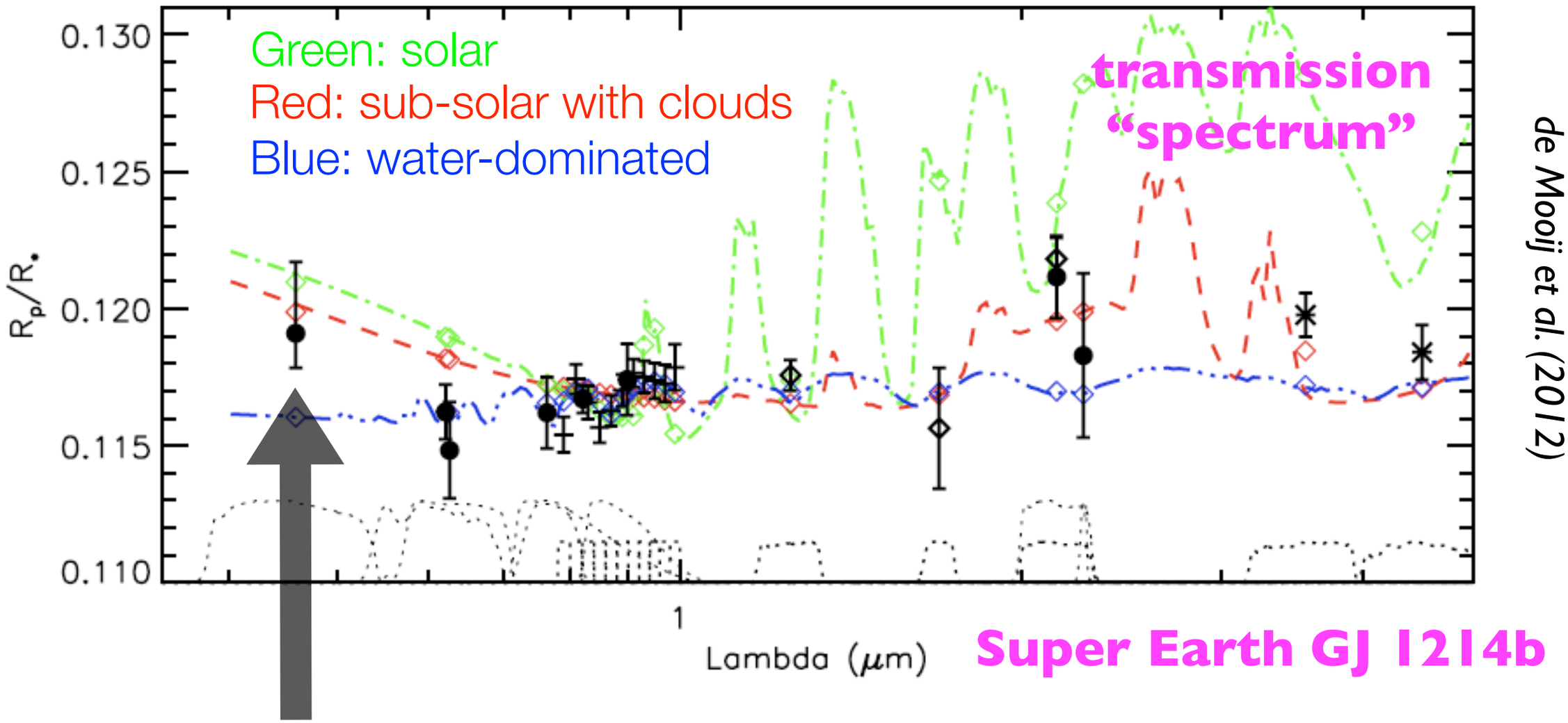

Optical data point (~0.45 micron) helps distinguish between hydrogen- and water-dominated atmospheres

Application II: obtaining absolute abundances from transits

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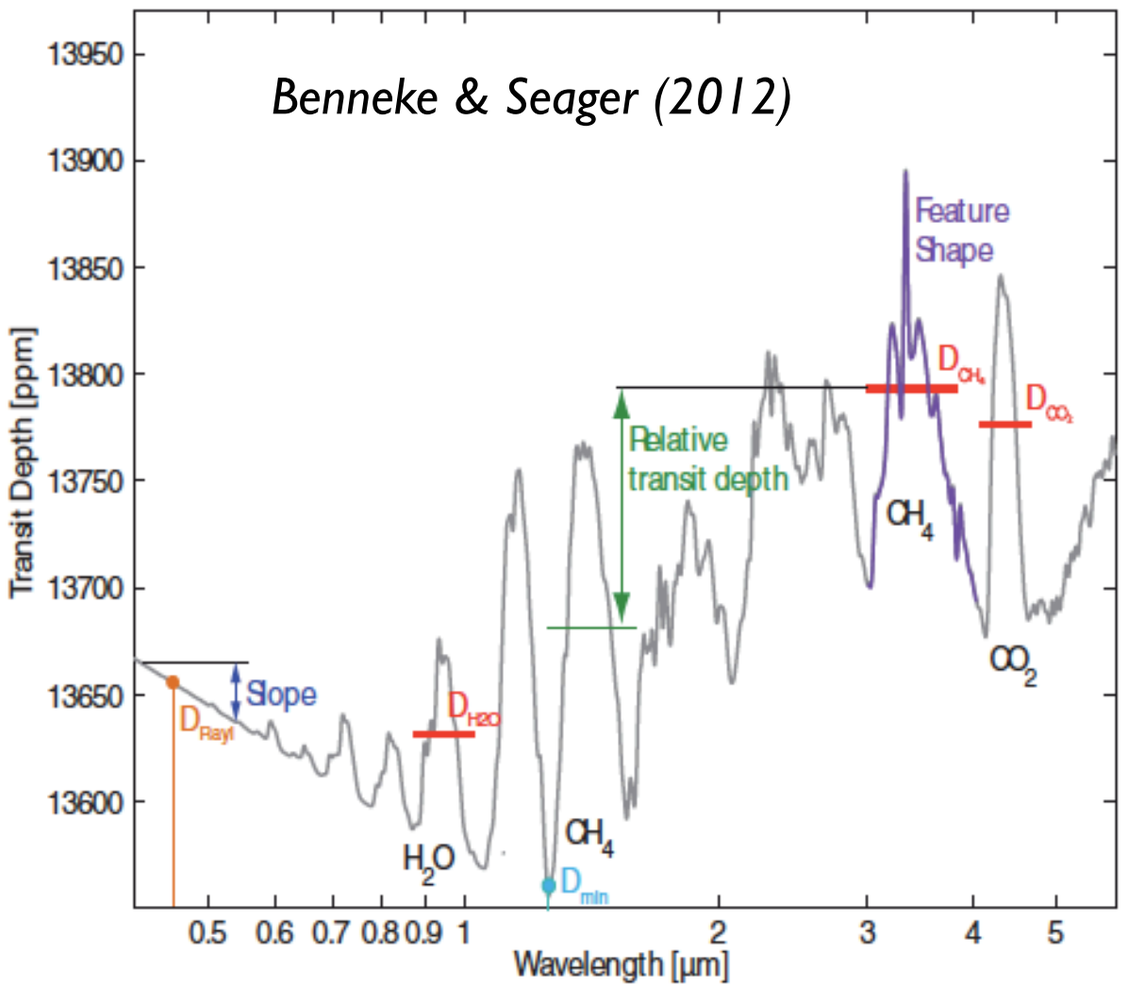

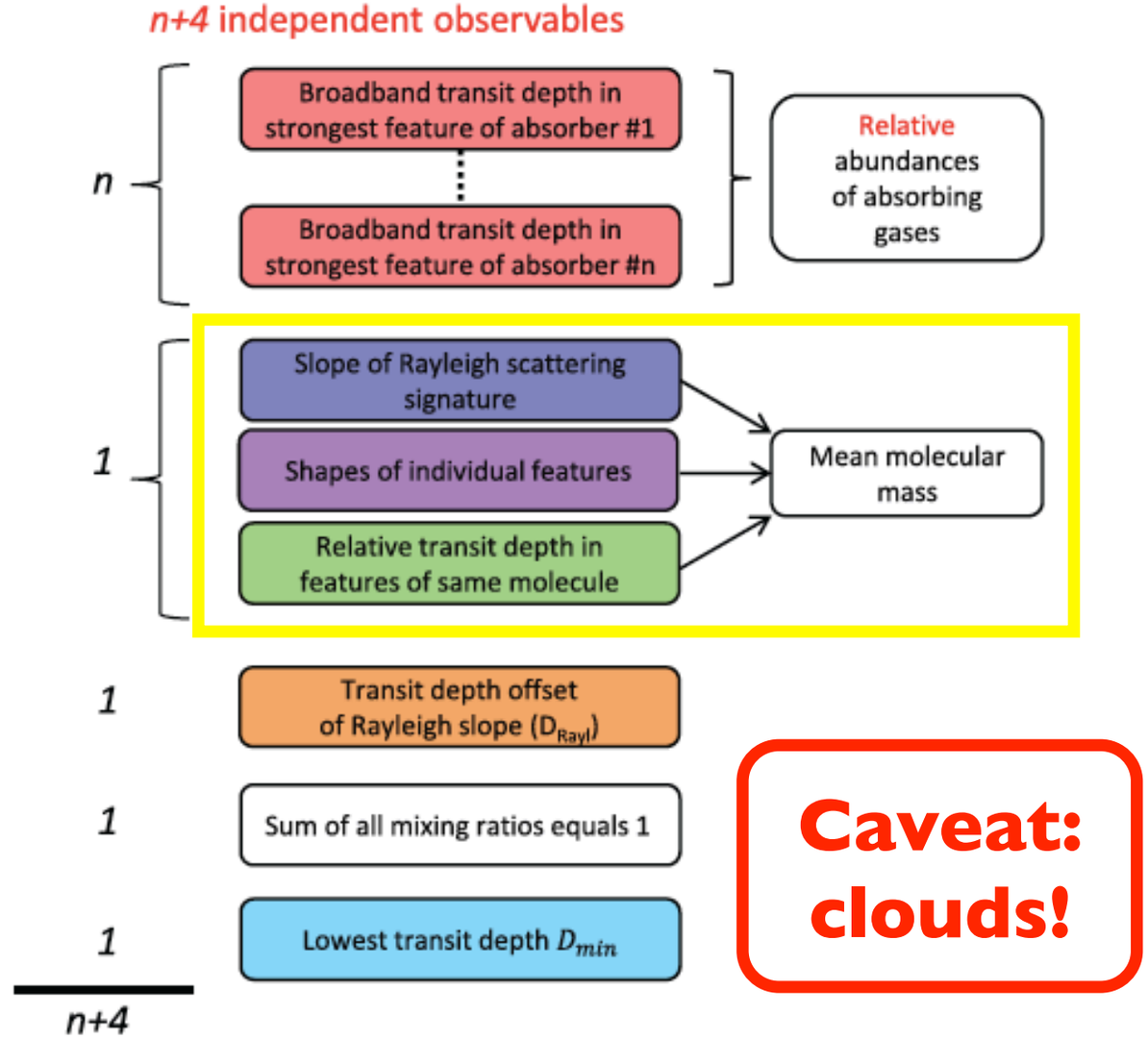

Measuring either the **Rayleigh slope in the optical** (PLATO)
or the **shape of the molecular features in the infrared**
(EChO, JWST) constrains the **mean molecular mass**

Application III: optical phase curves

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Optical flux vs. orbital phase ***(phase curve)***

deconvolution
(Cowan & Agol 2008)

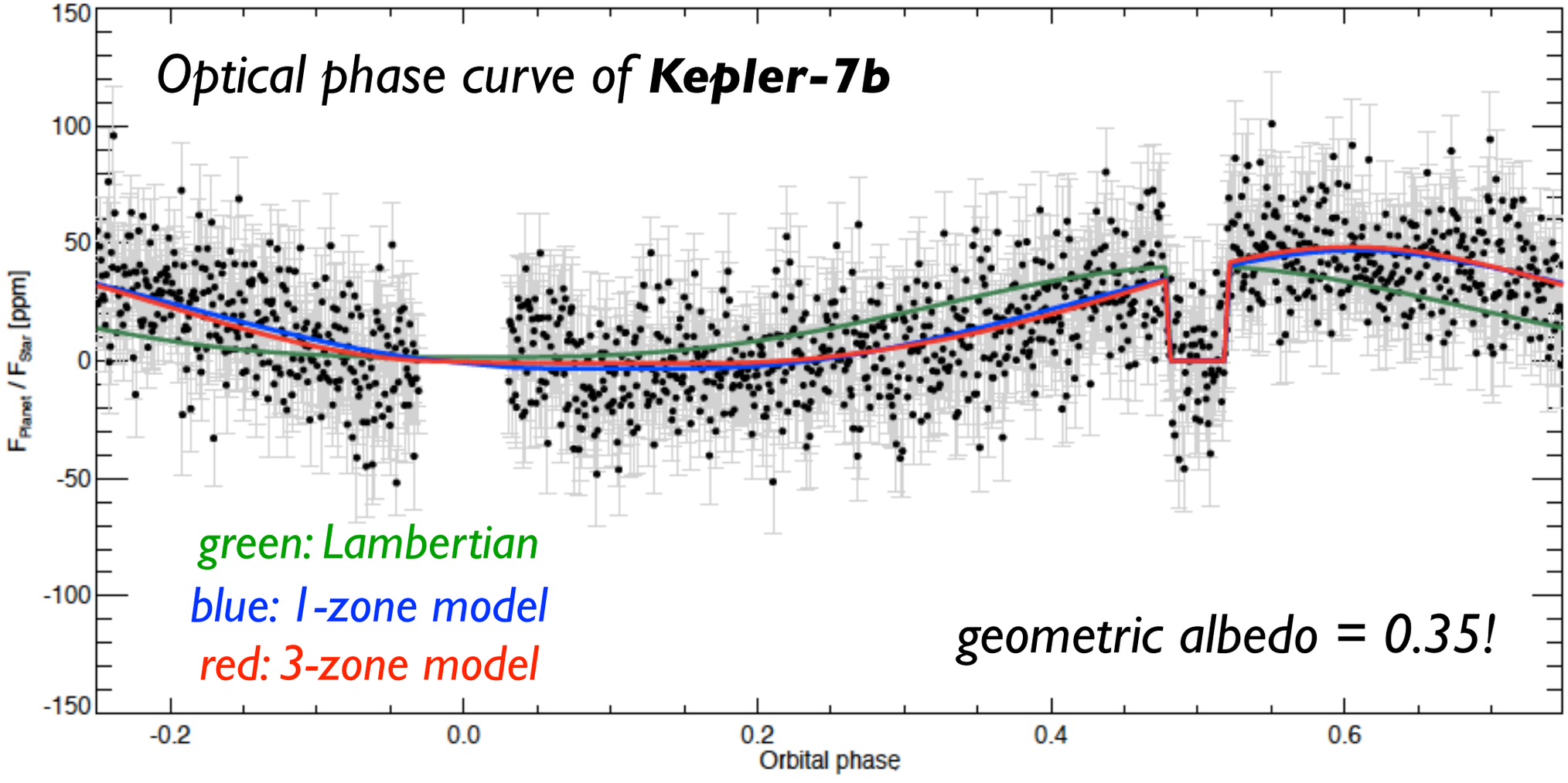
Optical flux vs. longitude ***(brightness map)***

Abundance of clouds as a function of longitude

Heng & Demory (2013)
Demory et al. (2013)

Reflectivity of atmosphere as a function of longitude

Application III: optical phase curves



Demory et al. (2013)

The high albedo of Kepler-7b requires the presence of clouds.
Phase curve peaks **after** eclipse. Brightness map peaks **west** of substellar point!

The need for a holistic approach: clouds, dynamics, radiation, chemistry

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Stellar irradiation

(sets circulation strength, T-P profile)

strength and depth of circulation are highly sensitive to stellar flux

albedo of clouds sets location of photon deposition layer

(and out of all this)

Spectra (!)

Dynamics

(provides background state of [v, T, P] and sets lofting properties of flow)

Clouds

(modify T-P profile via radiative forcing)

affects formation and whether cloud particles are lofted

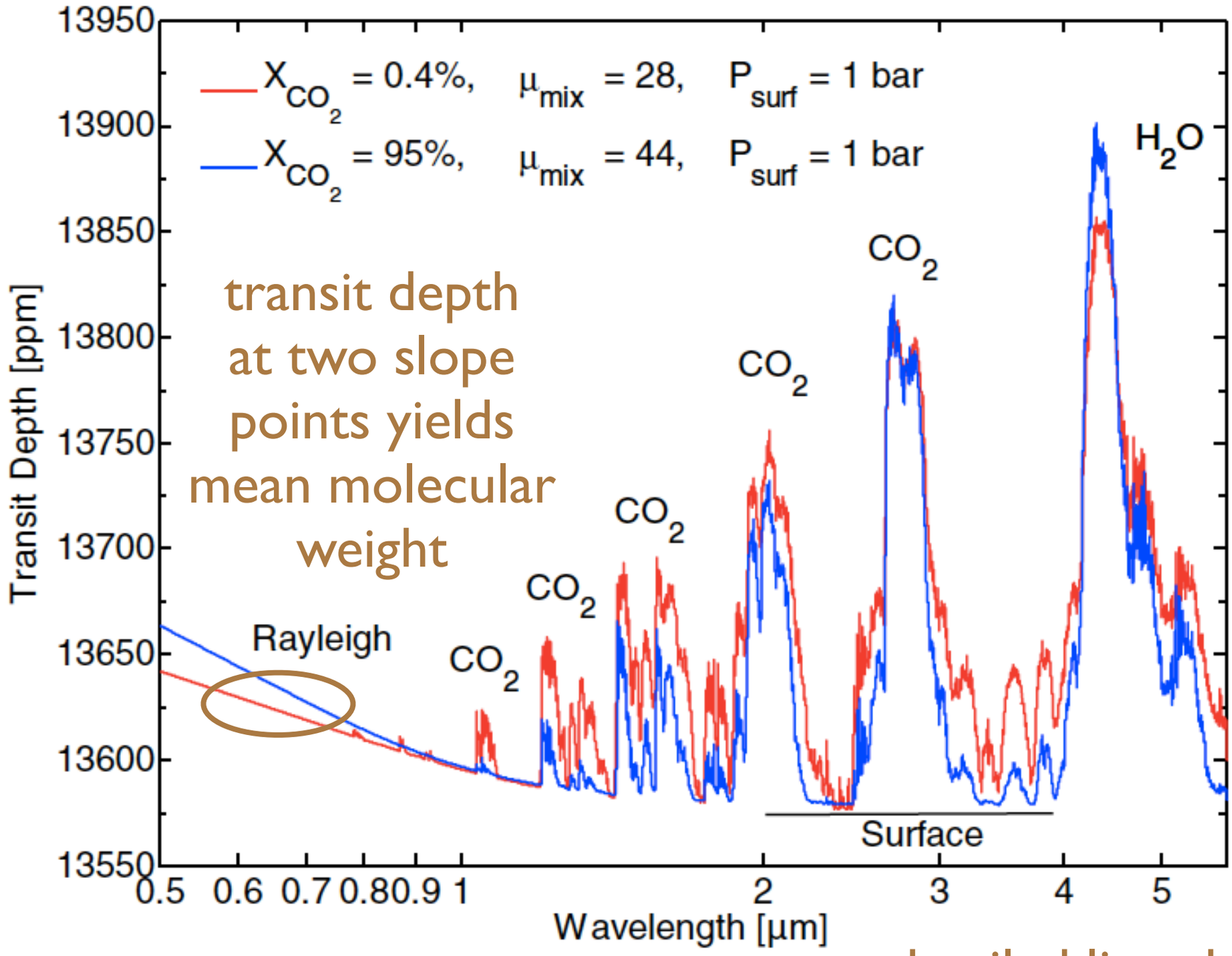
Optical measurements constrain some of these feedback loops!

Summary

- Optical transits, eclipses and full-orbit phase curves contain important information about exoplanetary atmospheres.

- Optical information will help break degeneracies associated with clouds and prepare us for interpretation of JWST spectra.

Upcoming: Heng & Showman (2014),
Annual Reviews of Earth and Planetary Science,
"Dynamics of Exoplanetary Atmospheres"



detailed line shape also yields mean molecular weight (needs R~50)

Red: nitrogen-dominated

Blue: carbon dioxide-dominated

Benneke & Seager (2012)