The Relevance of Optical Data for Understanding Exoplanetary Atmospheres

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Review Talk at CoRoT-Kepler Joint Meeting 2014

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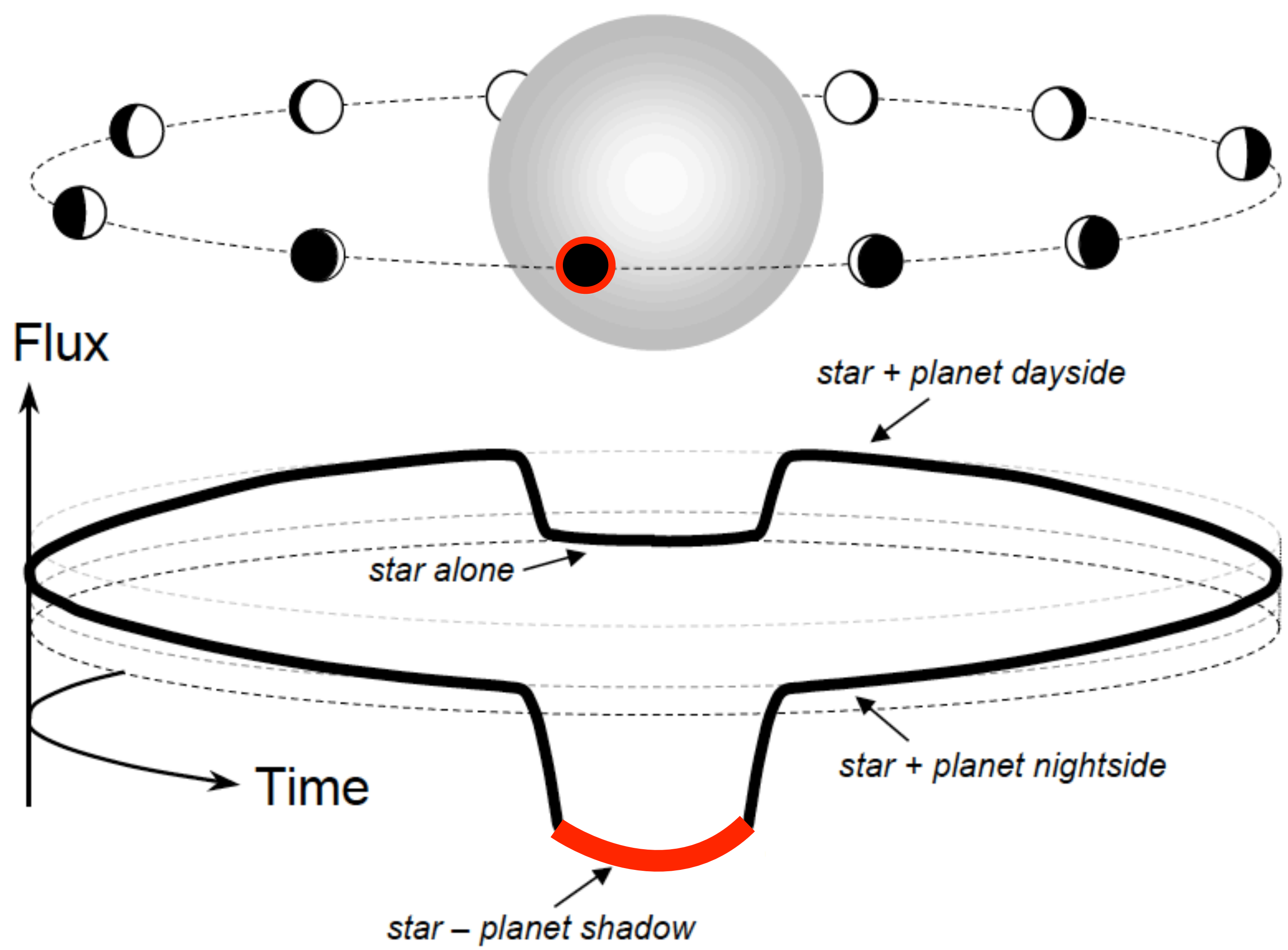
Agenda

- What do optical data have to say about exoplanetary atmospheres?
- What trends do models and simulations predict?
- What types of observational and theoretical advances do we need to make in the future?

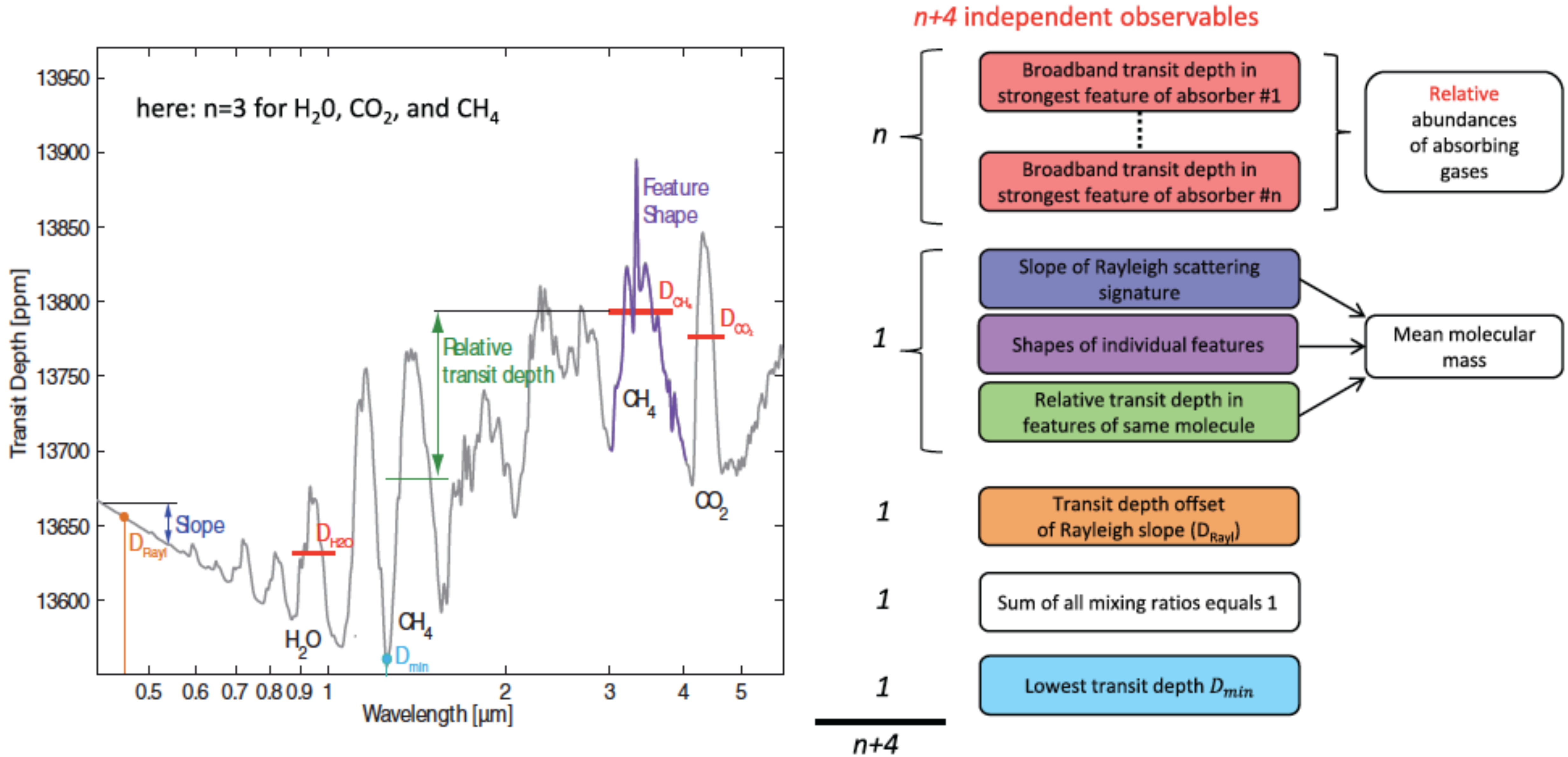


Transit:

absorption spectrum

(through atmospheric limbs)

Original schematic from Winn (2010)

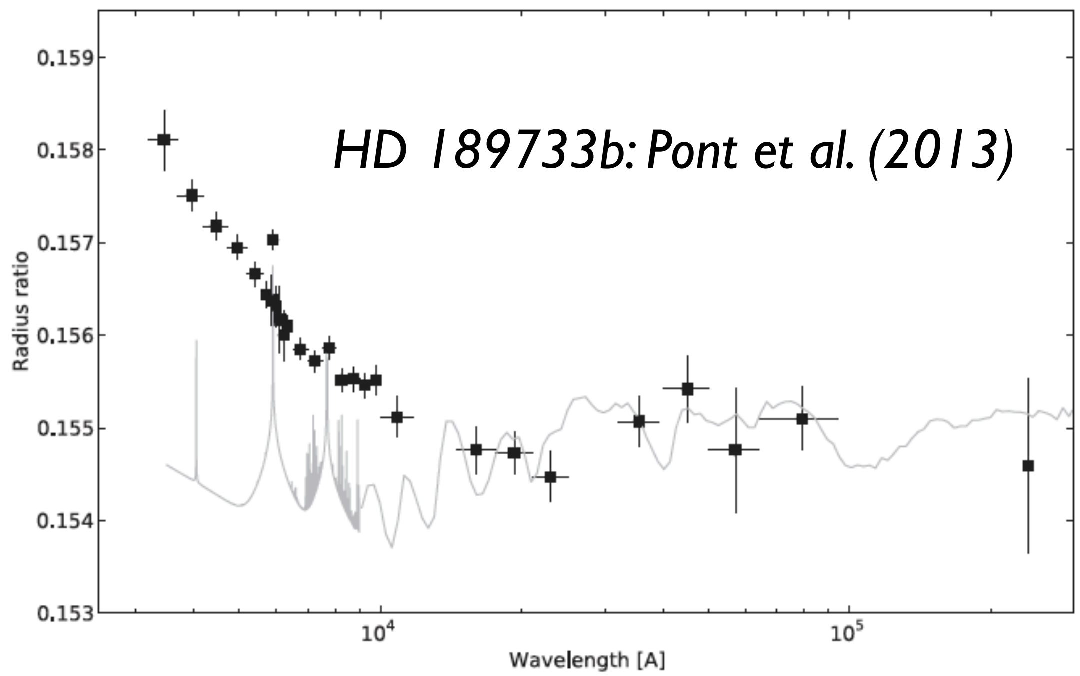


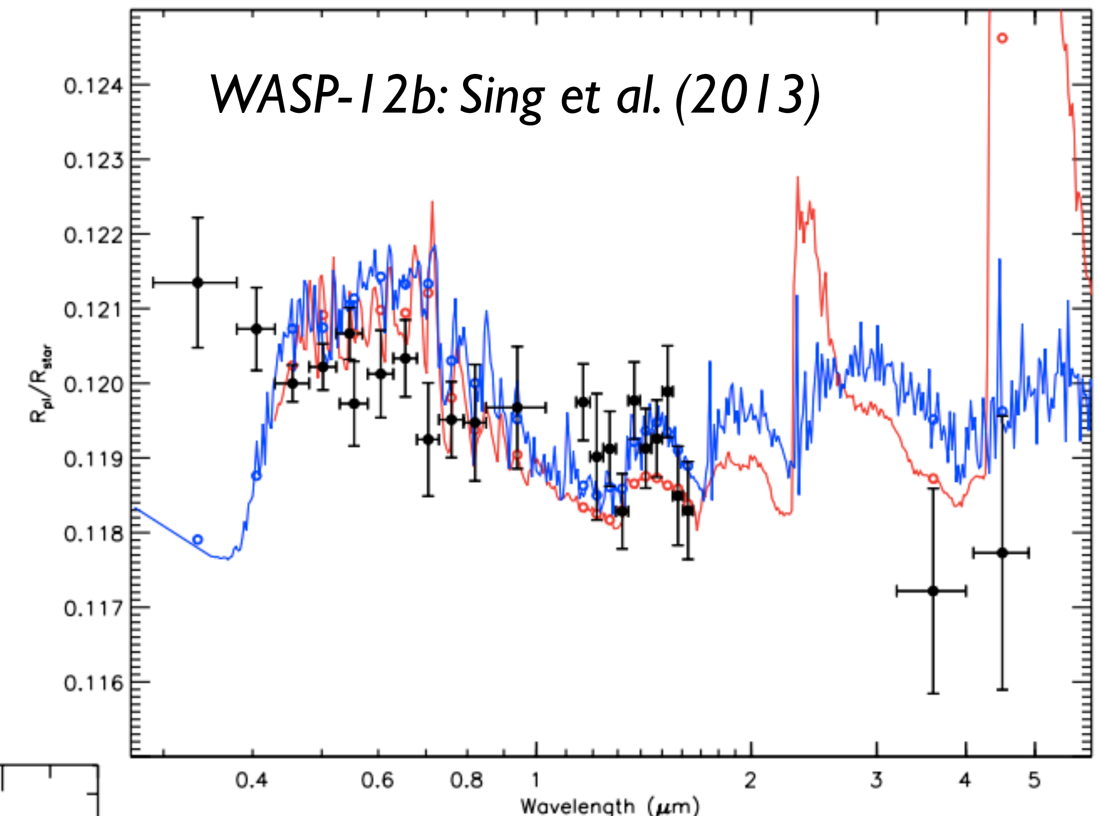
Benneke & Seager (2012)

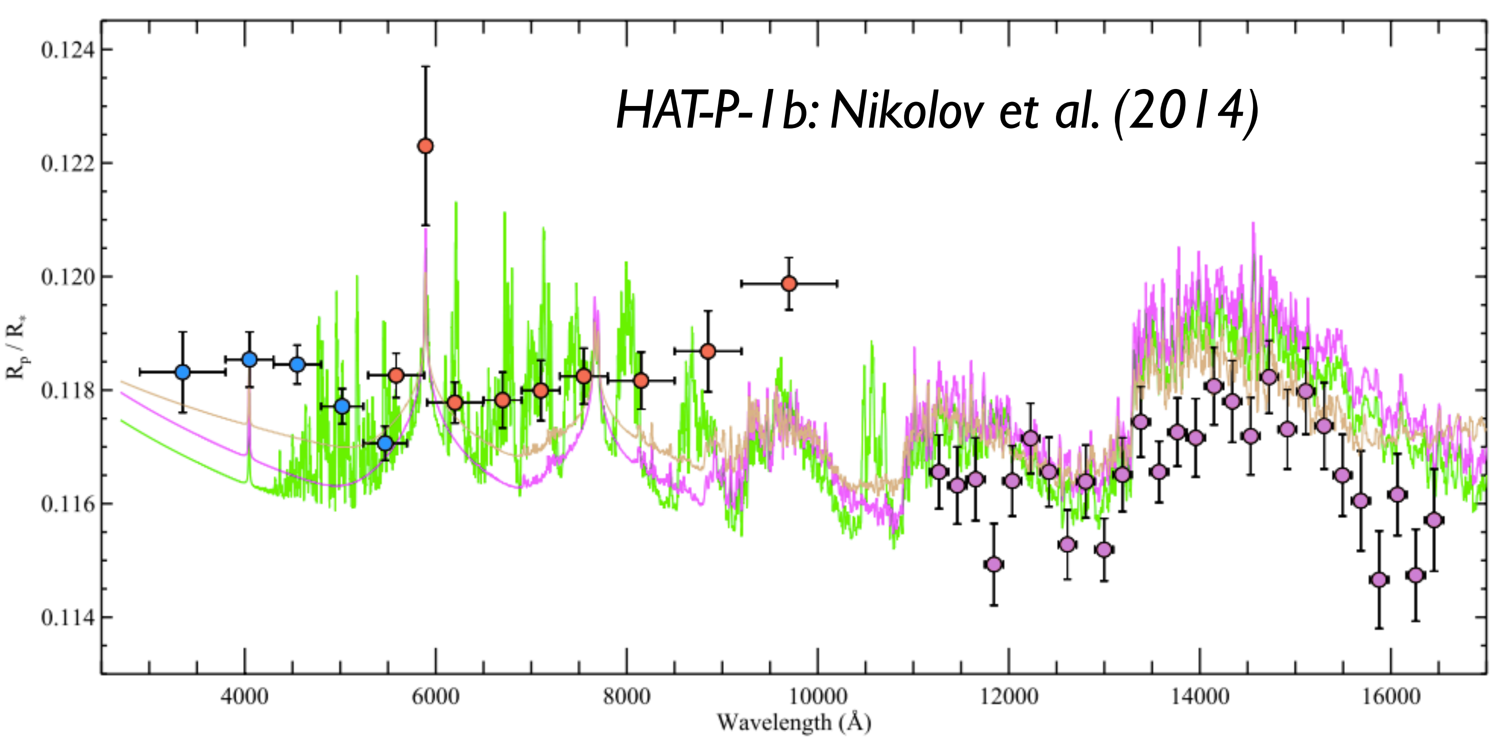
Measuring the Rayleigh scattering slope in the optical yields the mean molecular mass (and hence the main constituent) of the atmosphere.

Caveat: cloudfree!

Transit spectra suggest that some exoplanets are cloudy (while others are not)



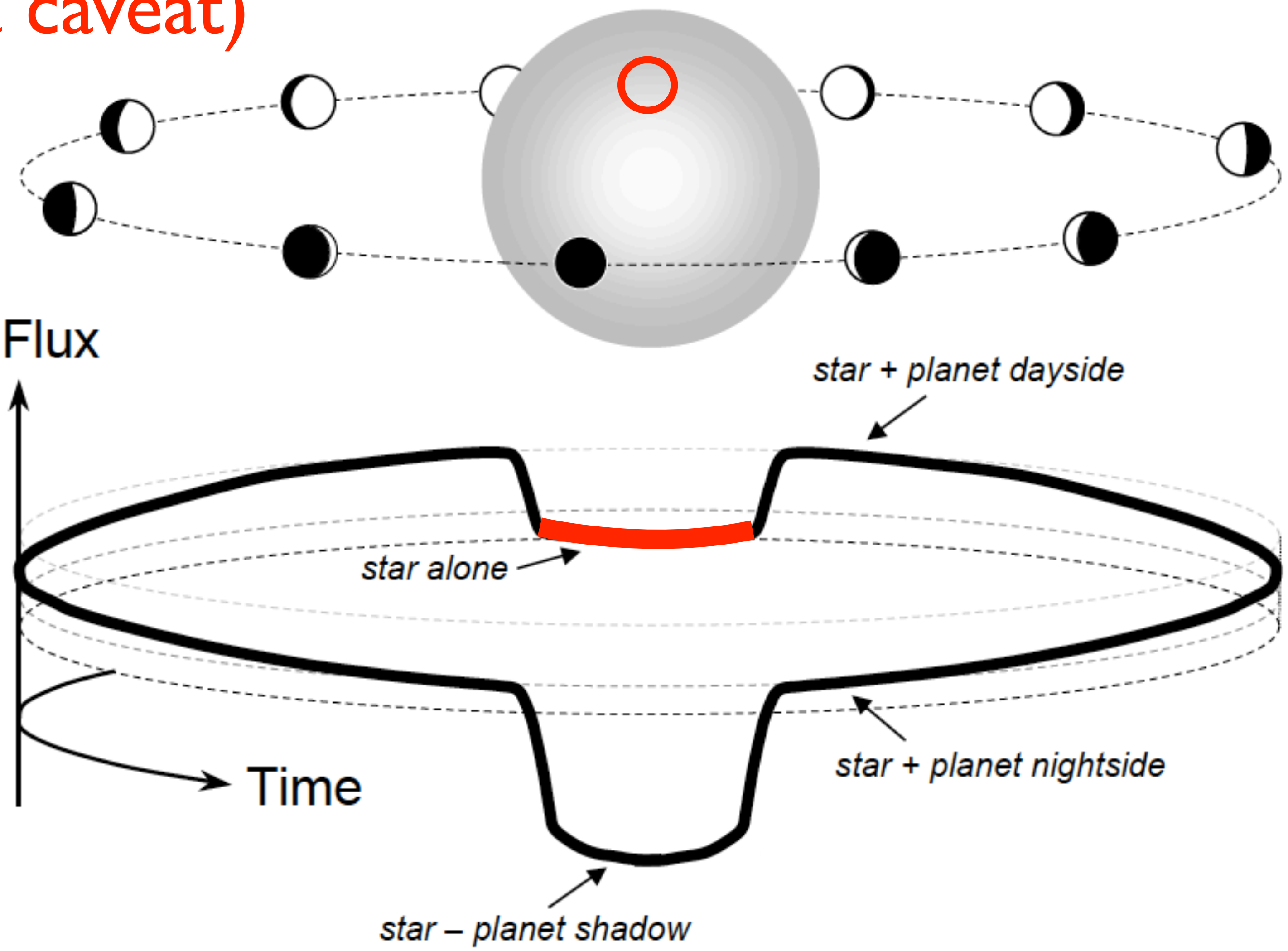




It is unclear if cloudiness correlates with any quantity.

Eclipse:
measurement of
reflected light
(but with a caveat)

albedo at zero phase:
geometric albedo



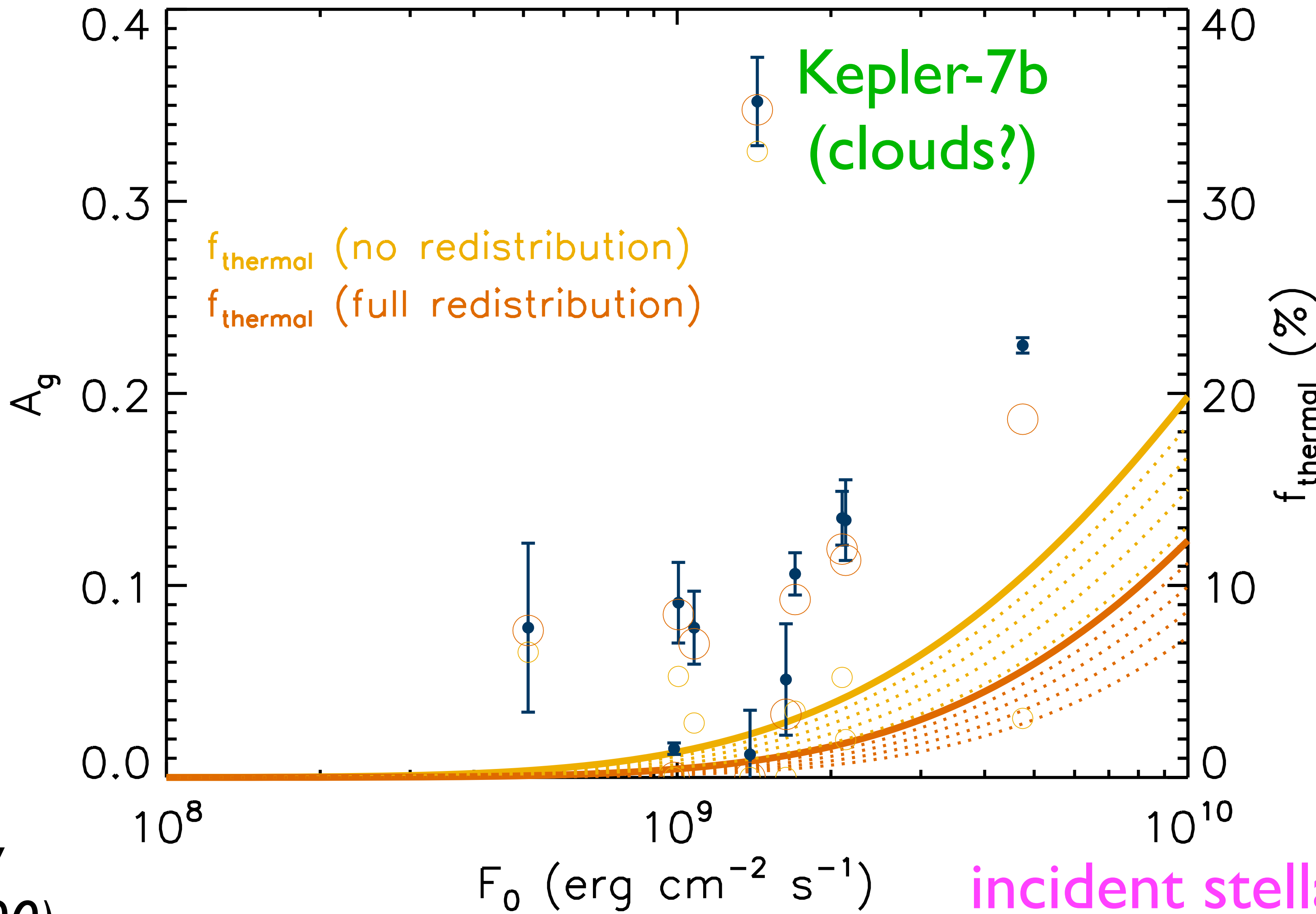
Albedos are interesting because:

1. energy budget of atmosphere
2. vertical profile of absorption of stellar irradiation in atmosphere

Original schematic from Winn (2010)

Measurements of the optical eclipses yield the geometric albedo

geometric albedo (Kepler bandpass)

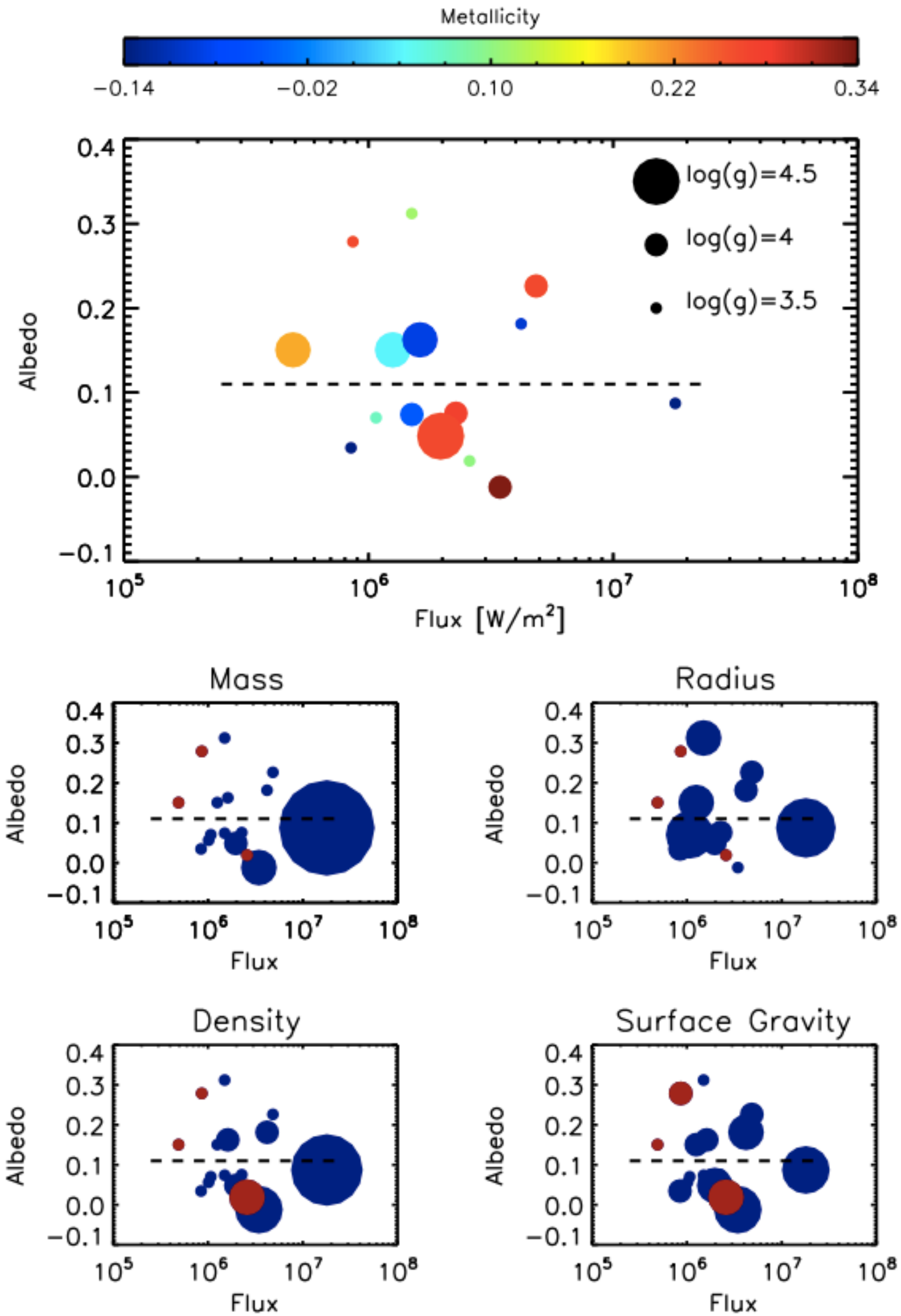


incident stellar flux

Heng & Demory (2013, ApJ, 777, 100)

No obvious trend with stellar irradiation.

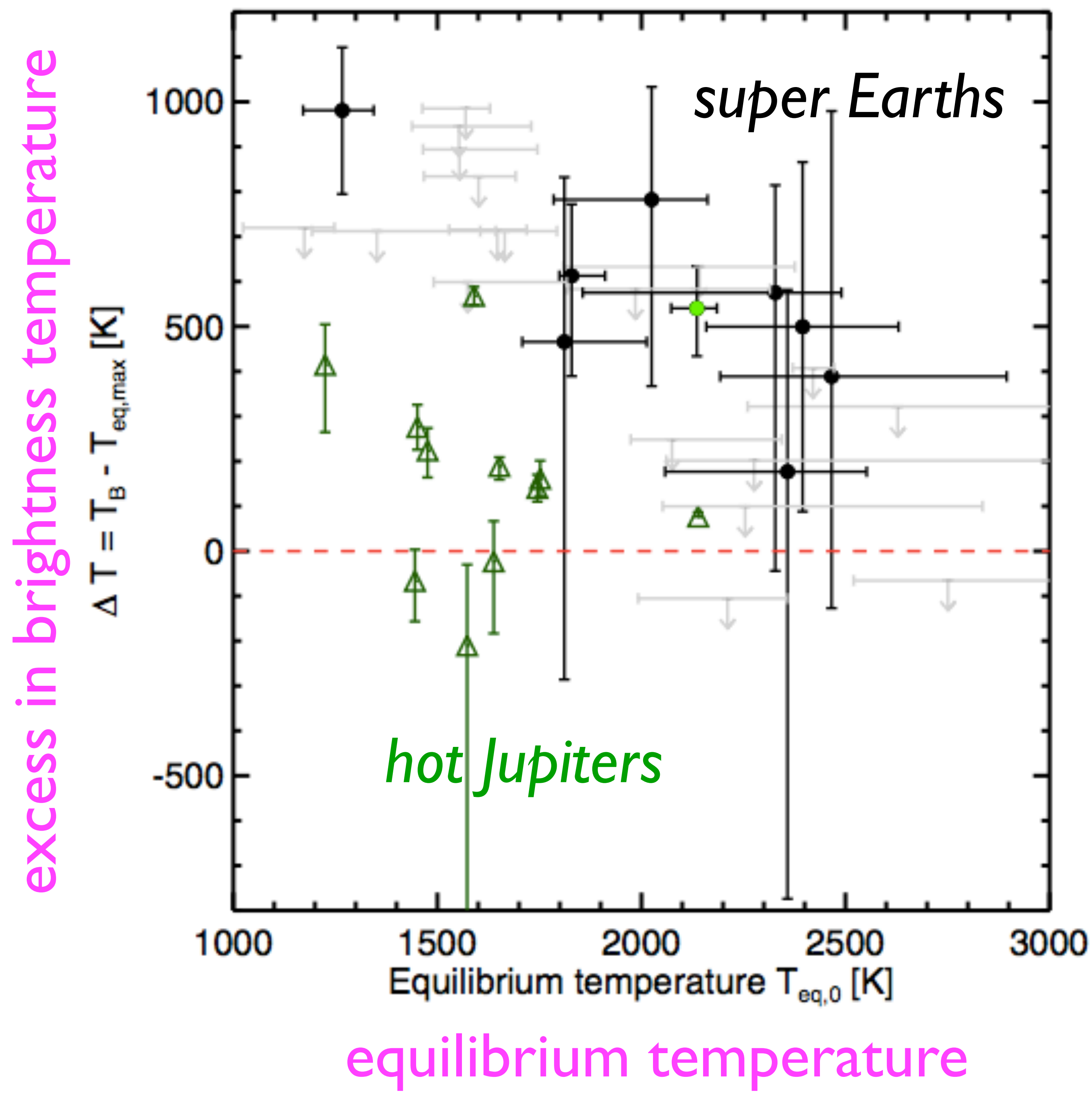
Corrected for contamination by thermal emission (for the hottest objects).



No obvious trend of geometric albedo with metallicity, mass, radius, density or surface gravity. Why?

Angerhausen et al. (2014, arXiv:1404.4348)

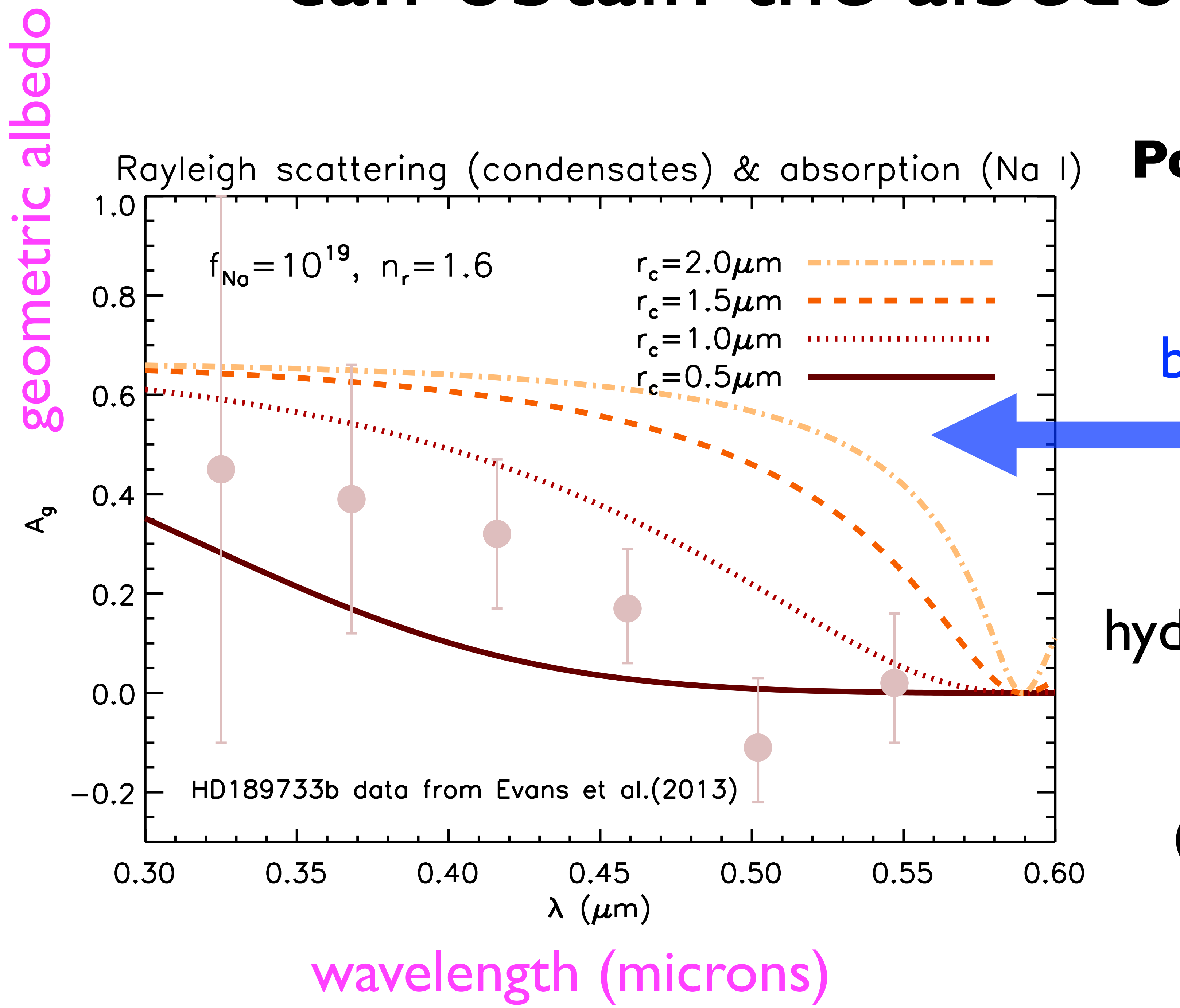
Measurements of the optical eclipses yield the geometric albedo



Super Earths appear to be more reflective as a population, compared to hot Jupiters. Why?

Demory (2014, ApJL, 789, L20)

For the case of HD 189733b, one can obtain the albedo spectrum



Possible interpretations:

1. Rayleigh scattering by condensates + sodium (shown in left panel)

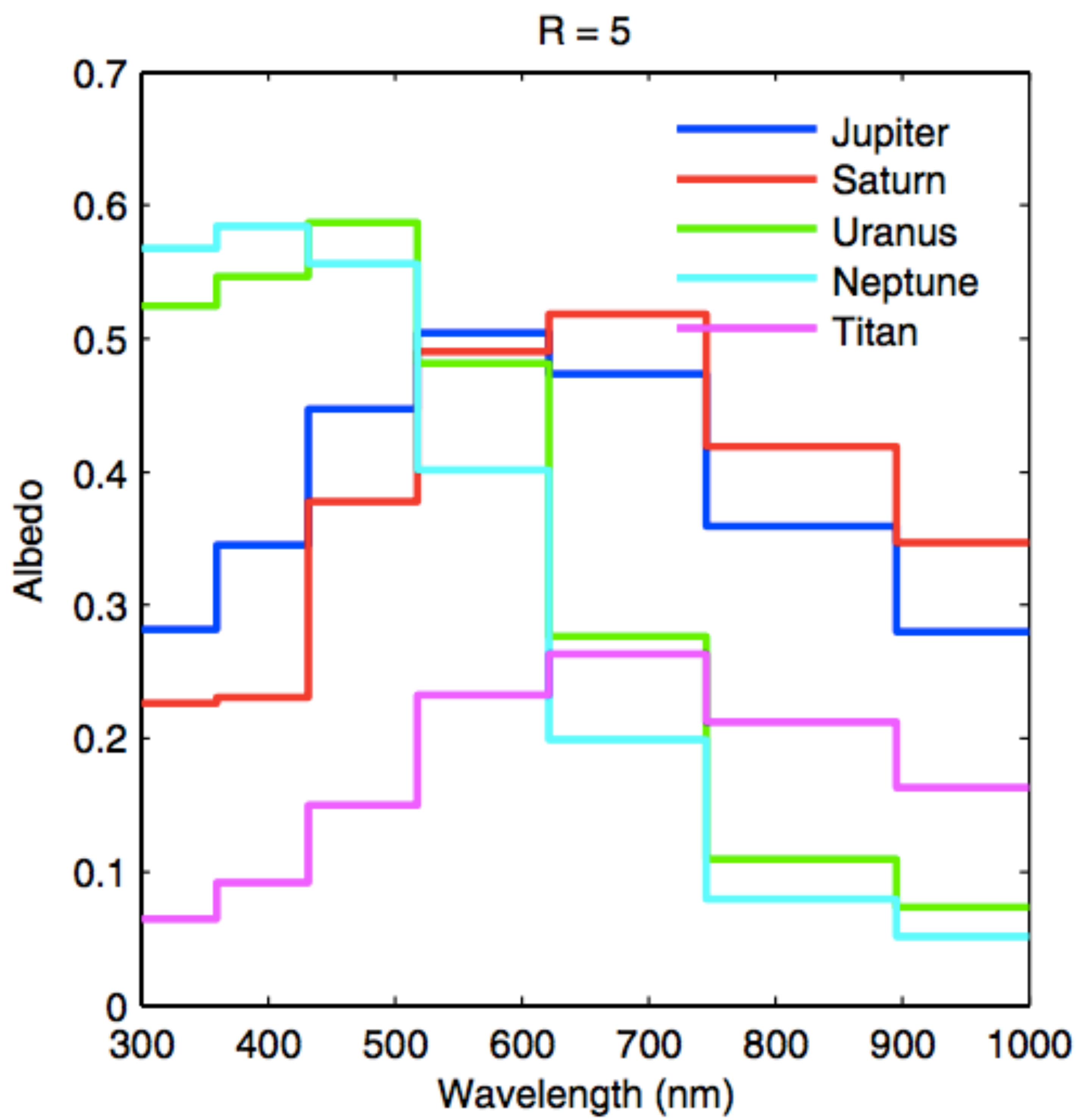
2. Rayleigh scattering by hydrogen molecules + sodium

3. Silicate carbide grains (10 nm) without sodium

Evans et al. (2013, ApJL, 772, L16)

See also work by Marley et al. (1999), Sudarsky et al. (2000, 2005), Cahoy et al. (2010)

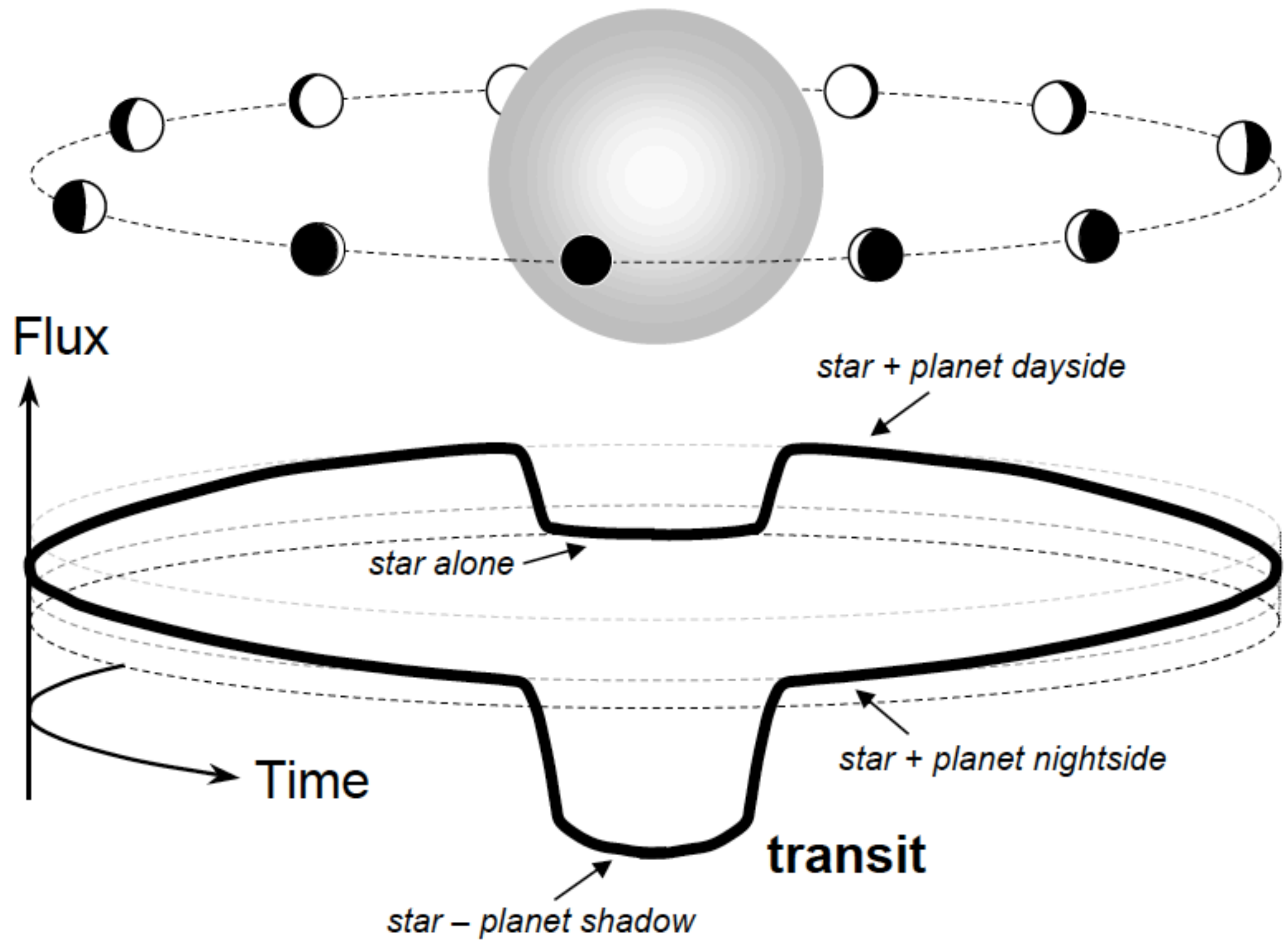
Even coarse albedo spectra may help us to identify different planet types



The ice and gas giants of our Solar System may be distinguished even using coarse (R=5) optical spectra.

Data rebinned from Karkoschka et al. (1994)

Cahoy et al. (2010, ApJ, 724, 189)

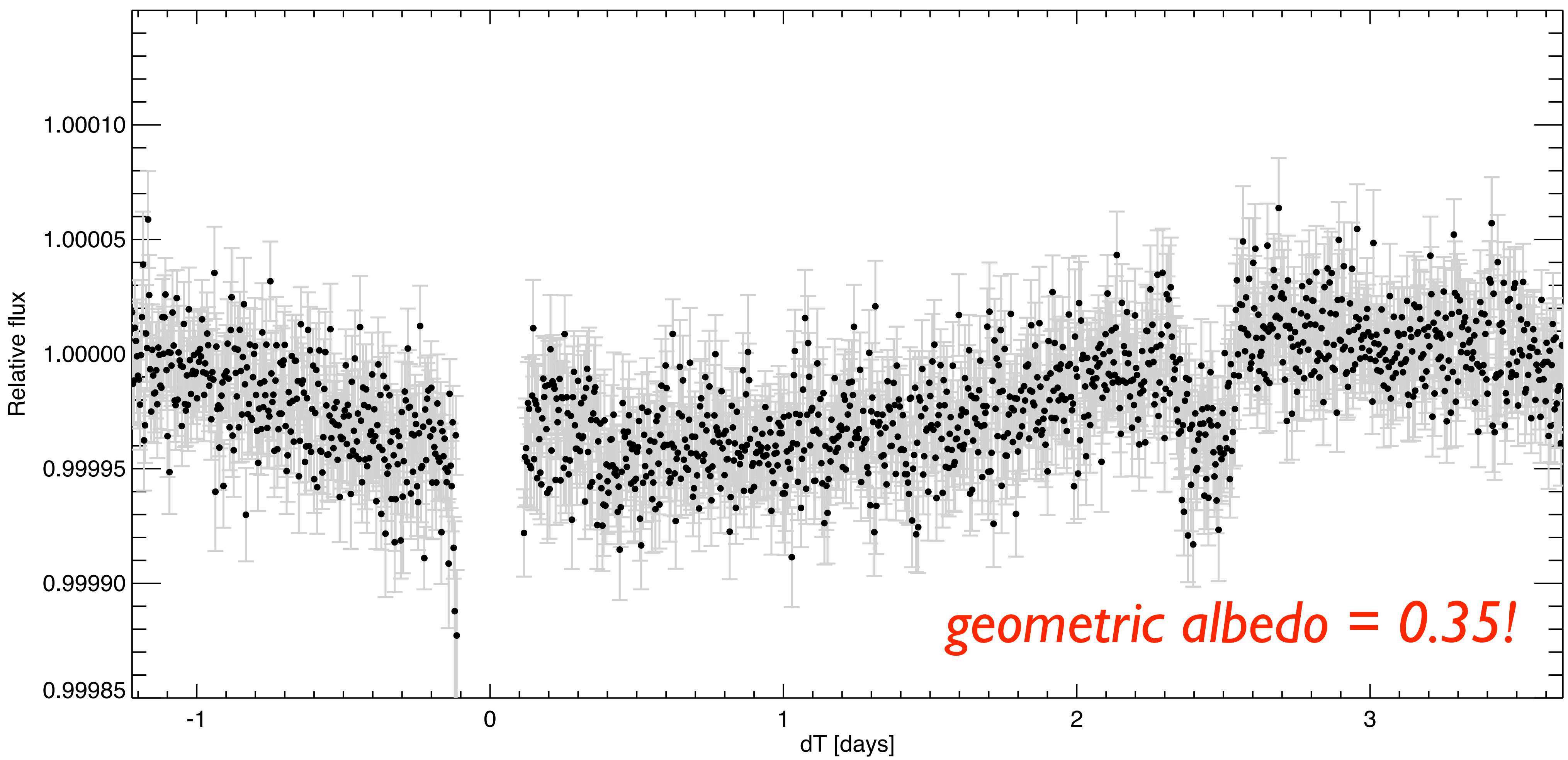


Phase Curve:

how the reflectivity of the exoplanetary atmosphere changes across longitude (relative abundance of clouds)

Original schematic from Winn (2010)

Optical phase curve of Kepler-7b: evidence for varying clouds across longitude



Demory et al. (2013, 776, L25)

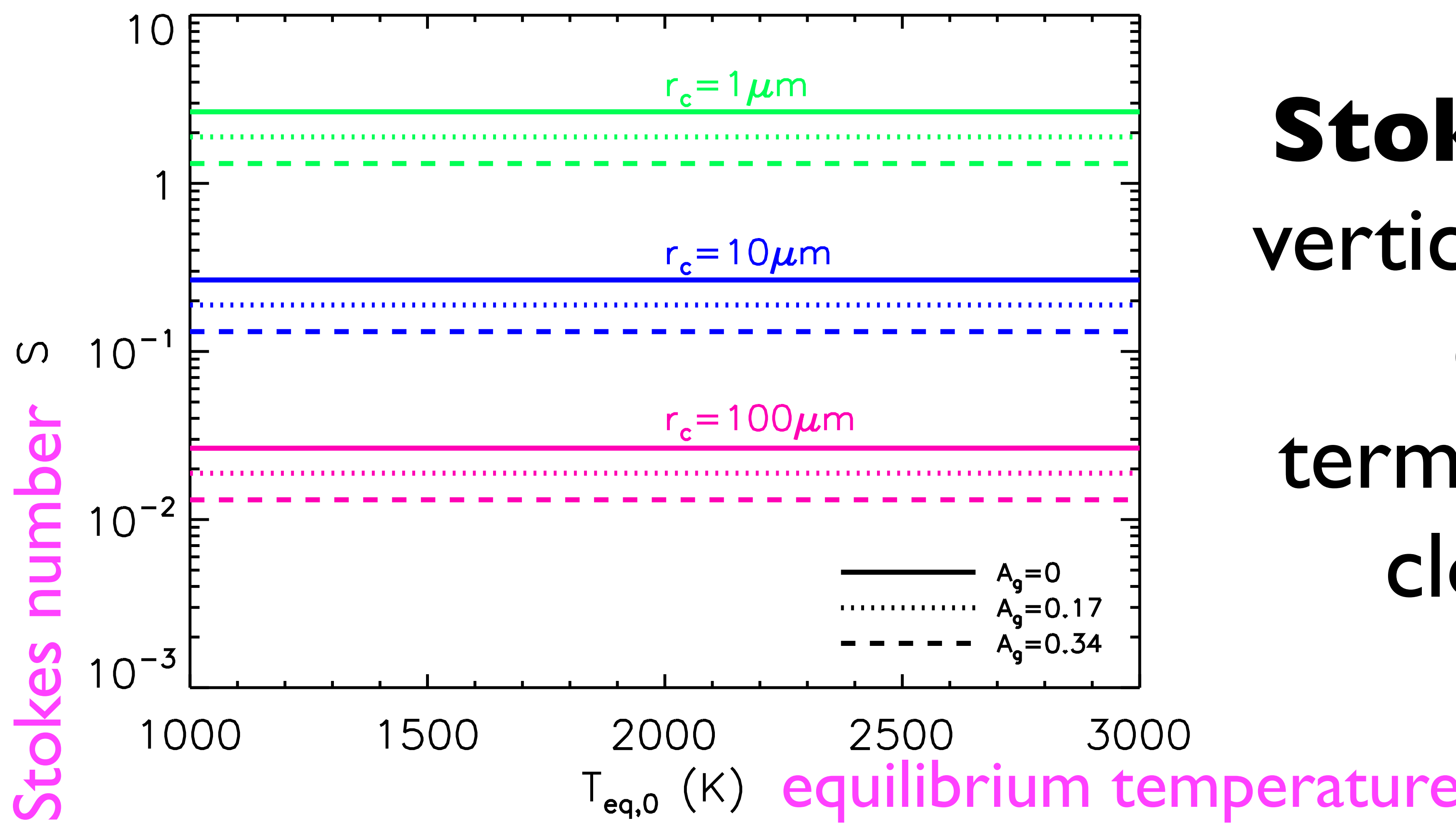
Only example where the phase curve peaks **after** secondary eclipse.

Unknown: do profiles of thermal emission (IR phase curve) and reflected light (optical phase curve) coincide?

What the observations tell us so far

- **Transmission spectra:** some exoplanetary atmospheres are cloudy, while others are not. Reasons are unclear/unknown.
- **Geometric albedos:** there appears to be no correlation with any property of the exoplanet.
- Super Earths appear to be more reflective as a population than hot Jupiters. Why?
- **Why we care:** because the inference of atmospheric abundance and thermal structure from spectra is degenerate with cloudiness.

What do simple models and scaling laws predict?



Stokes number: vertical flow velocity divided by terminal velocity of cloud particle

$$S \approx \frac{2.7 \mathcal{M}_z \gamma P}{\rho_c r_c g}$$

$$\sim 1 \left(\frac{\mathcal{M}_z}{10^{-3}} \frac{\gamma}{7/5} \frac{P}{0.1 \text{ mbar}} \right) \left(\frac{\rho_c}{3 \text{ g cm}^{-3}} \frac{r_c}{1 \ \mu\text{m}} \frac{g}{10^3 \text{ cm s}^{-2}} \right)^{-1}$$

if photon deposition layer does not depend on irradiation, then S is flat

Heng & Demory (2013, ApJ, 777, 100)

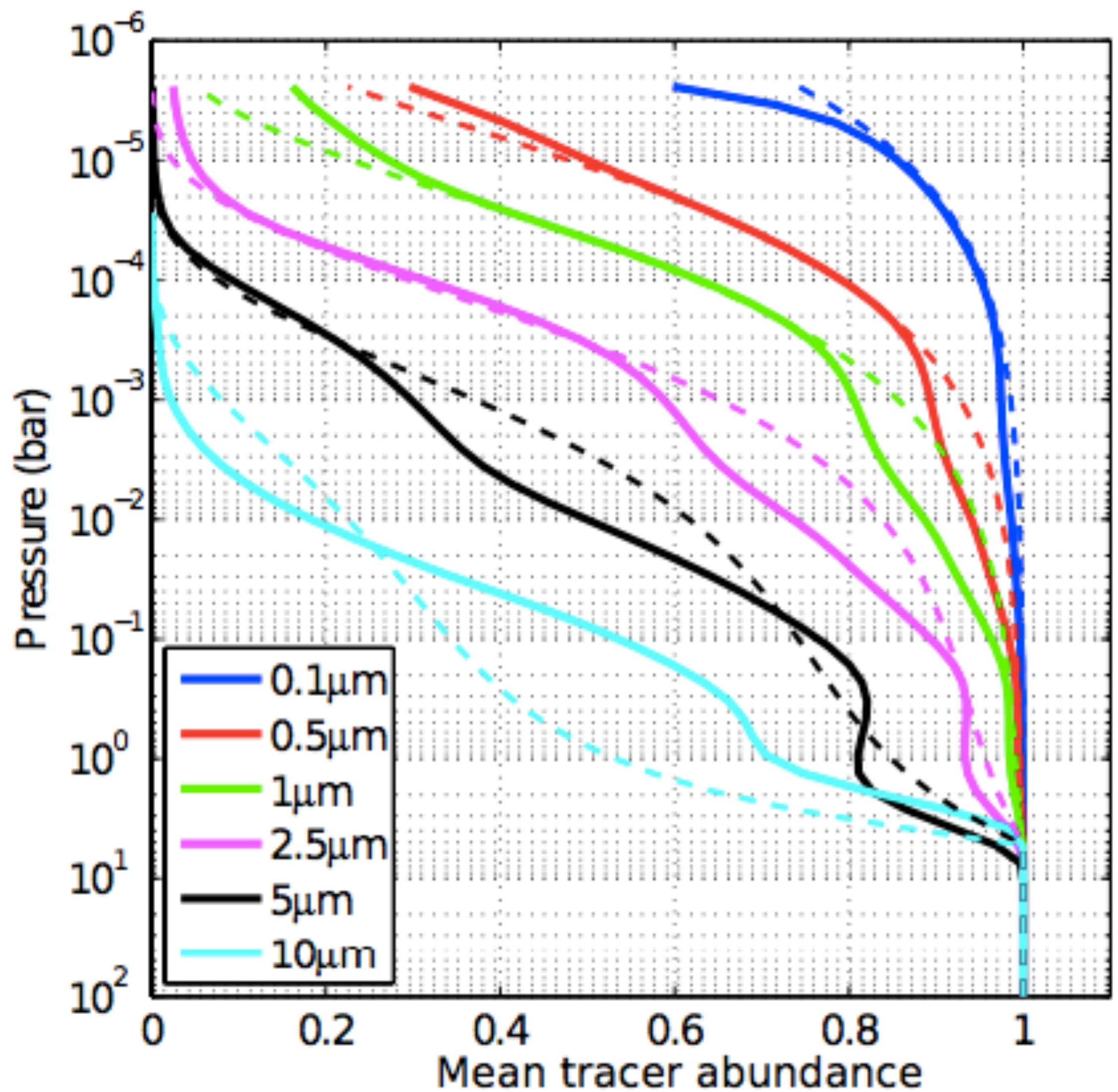
What do simple models and scaling laws predict?

- **Sinusodial optical phase curve:** large cloud particles (~10 microns).
- **Flat optical phase curve:** small cloud particles (<<1 micron).
- **High albedo, small infrared phase offset:** expected from sampling atmosphere at higher altitudes.
- **Low albedo, small infrared phase offset:** expected for highly irradiated objects.

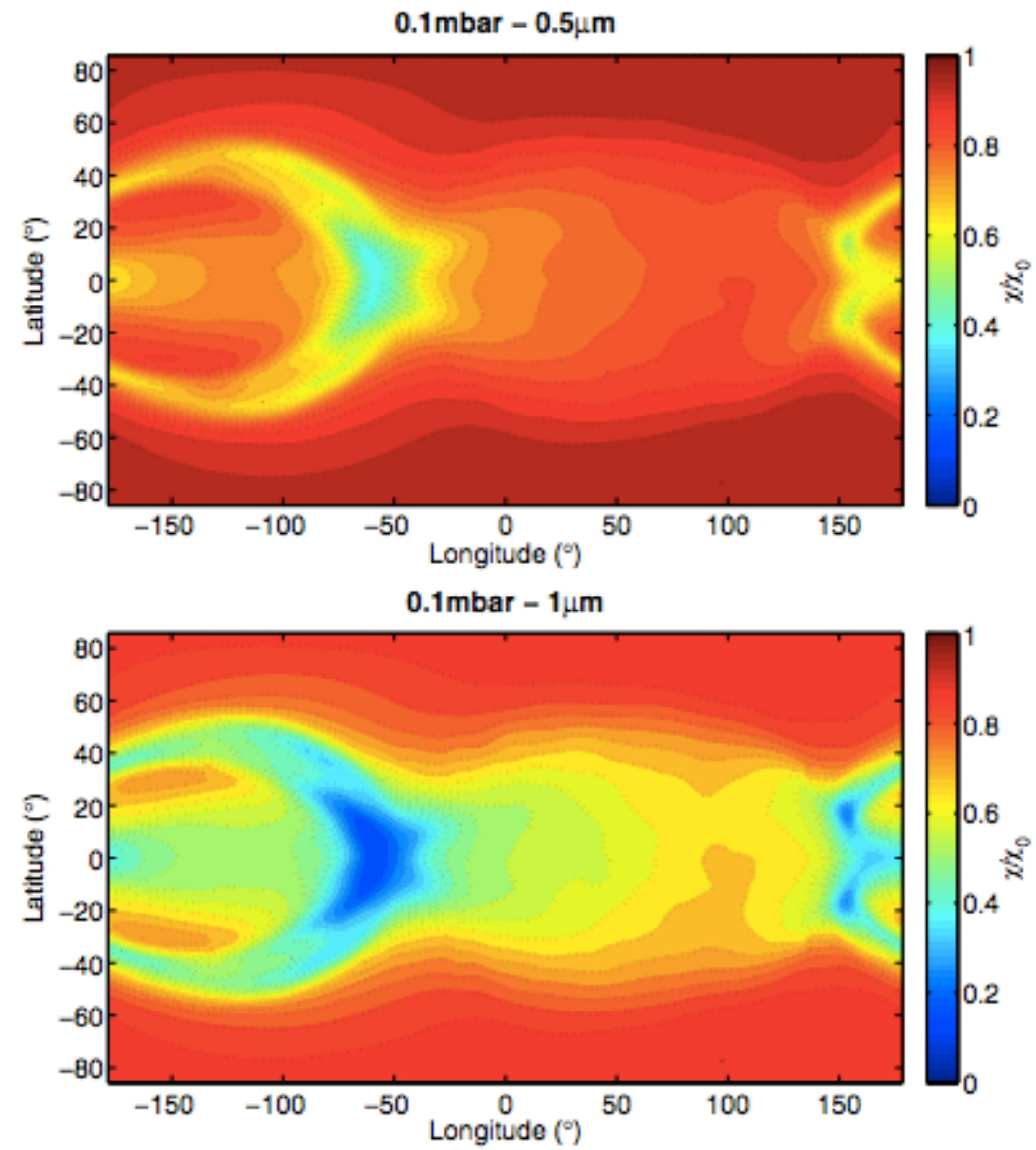
Key point: if we find exceptions, we learn something!

Heng & Demory (2013, ApJ, 777, 100)

What do 3D GCMs predict?



Mean tracer abundances depend on vertical flow.

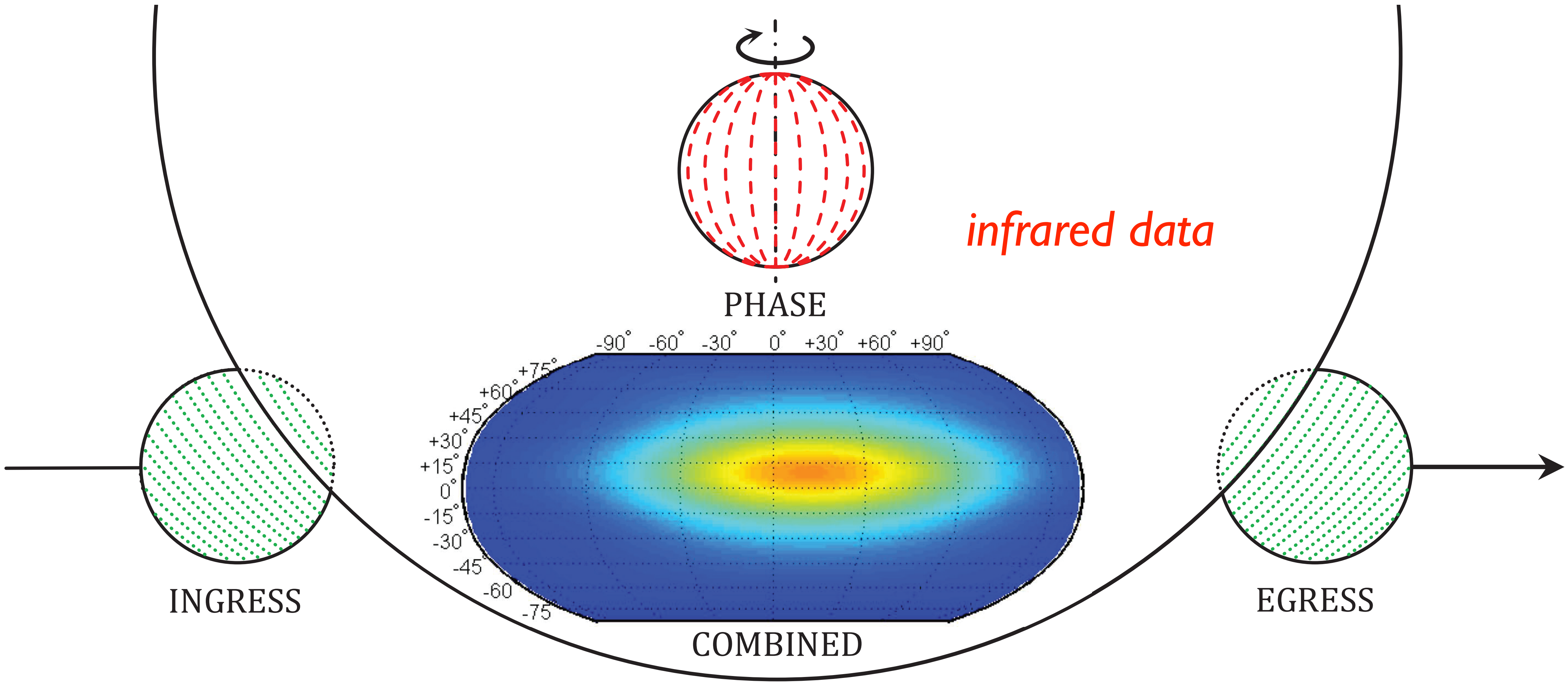


Specific tracer abundances vary with temperature.

See talk by V. Parmentier

Parmentier et al. (2013)

Can eclipse mapping be performed in the optical?



See also Majeau et al. (2012a,b)

de Wit et al. (2012, A&A, 548, A128)

What observations do we need for the future?

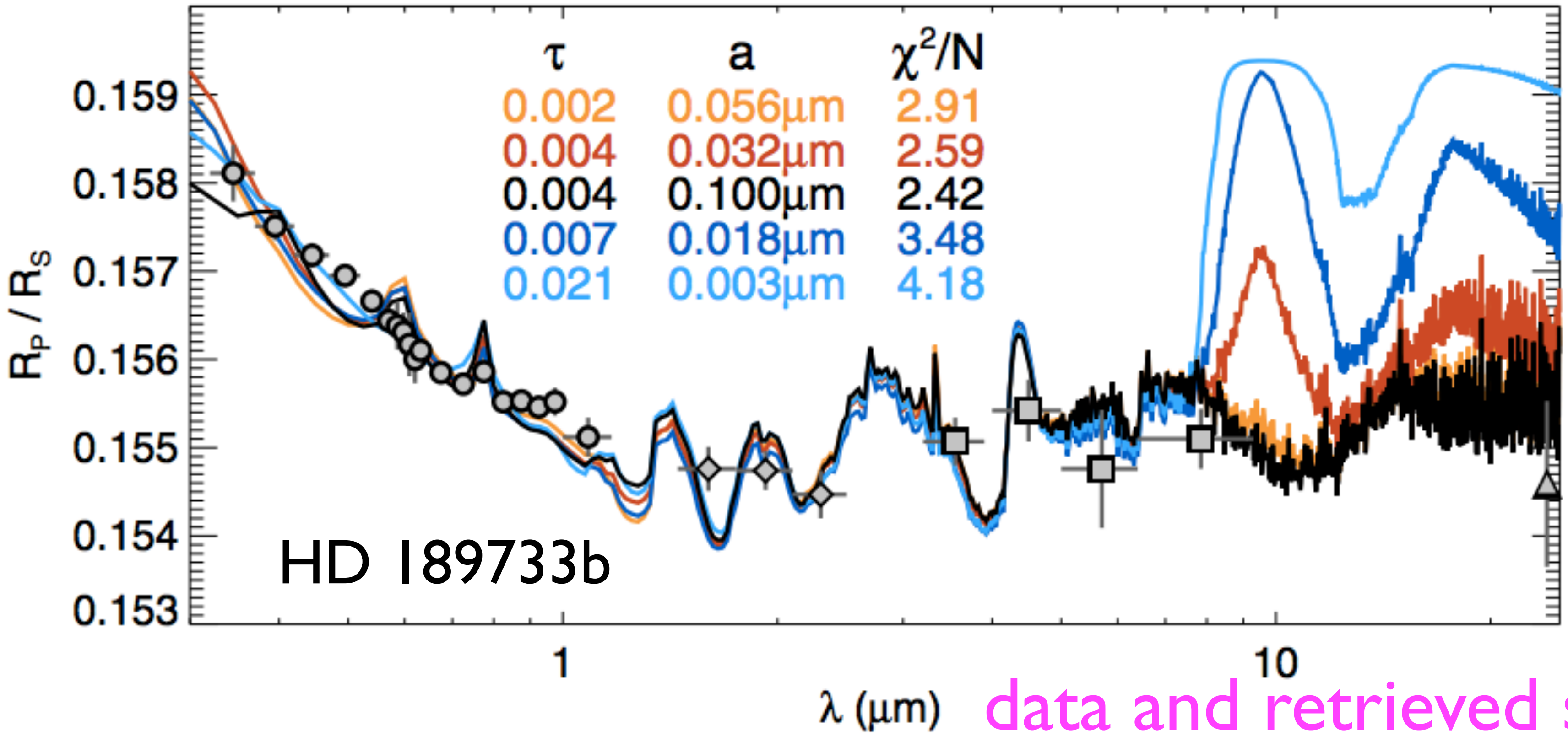
- **A larger sample of optical eclipses:** Measure geometric albedo for hot Jupiters, Neptunes and Earths across a range of exoplanet and stellar properties.
- **Recognize the value of optical phase curves:** Measure optical phase curves at high precision for a sample of objects with no thermal contamination.
- **Measure both optical and infrared phase curves:** Examine profiles of thermal emission vs. reflected light.
- **Perform eclipse mapping in the optical:** Perhaps clouds on hot Jupiters are also patchy?

See talk by R. Jayawardhana

What models do we need to construct for the future?

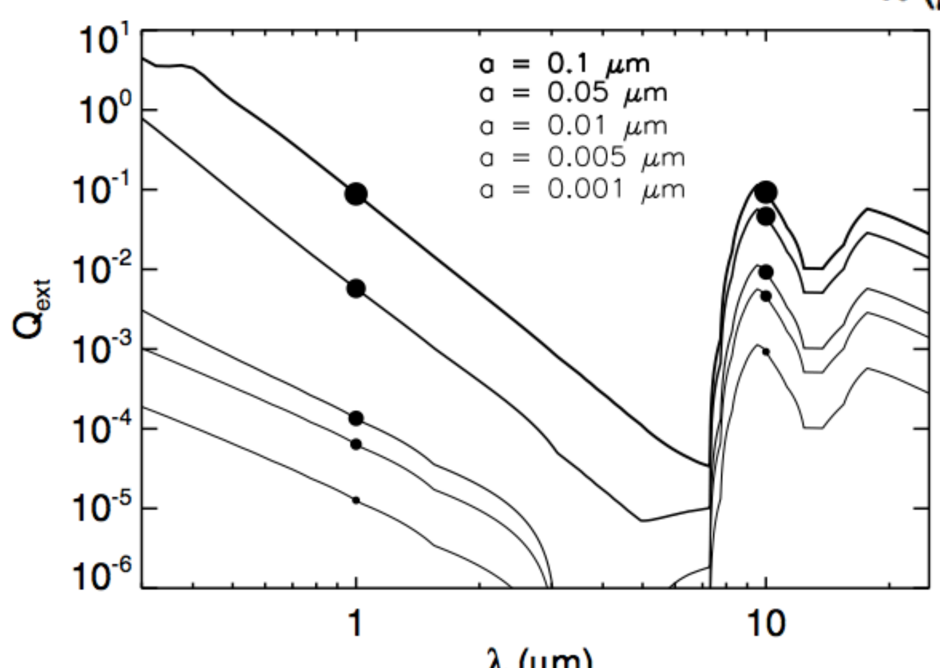
- **Simple, phenomenological cloud model:** Small number of meaningful parameters, can be used in GCMs and retrieval codes.
- **More realistic clouds in GCMs:** The clouds are dynamically affected by the flow, but also feed back radiatively on the entire atmosphere. Need to couple microphysics with large-scale flow.
- **Predictions of optical phase curves:** Need to understand how to decipher basic properties of clouds from high-precision phase curves.

Consequences for atmospheric retrieval studies



data and retrieved solutions

Retrieved solutions depend very much on the cloud properties.



extinction efficiencies (condensates)

To break the degeneracy due to clouds, we need optical/NIR data (<1 micron) and IR data >8 micron.

Lee et al. (2014, ApJ, 789, 14)

Conclusions

- The utility of optical data for studying exoplanetary atmospheres has been demonstrated, but its full potential has yet to be realized (secondary eclipses, phase curves, eclipse mapping).
- A judicious combination of optical and infrared data will break the degeneracies due to clouds for transiting exoplanets.
- Key question: how will these scientific goals be realized within the observing strategies of TESS, CHEOPS and PLATO?