Interpretation of exoplanet phase curves

…of close-in gas giants at optical wavelengths

…with a focus on atmospheric characterization

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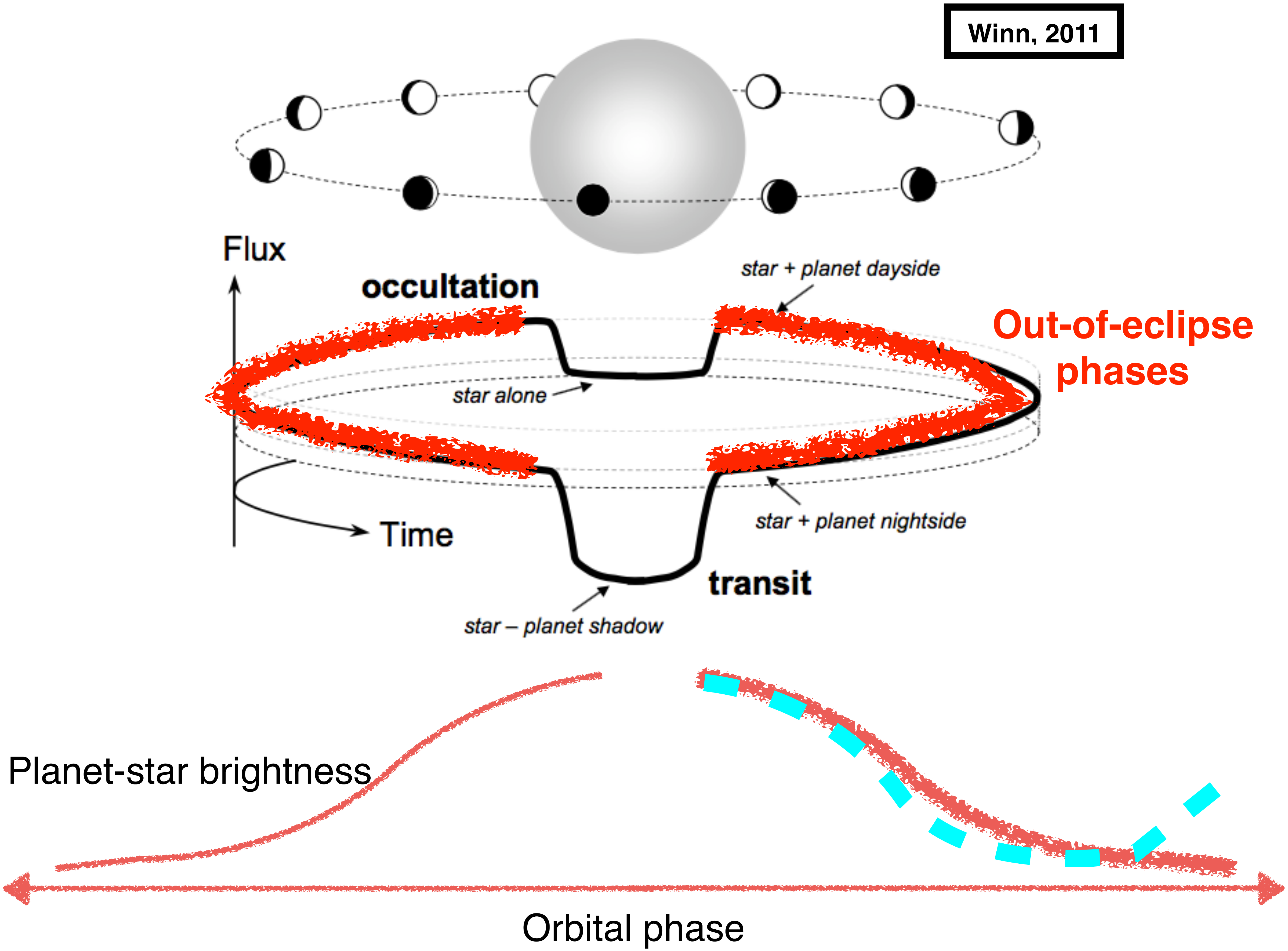
What's a phase curve?



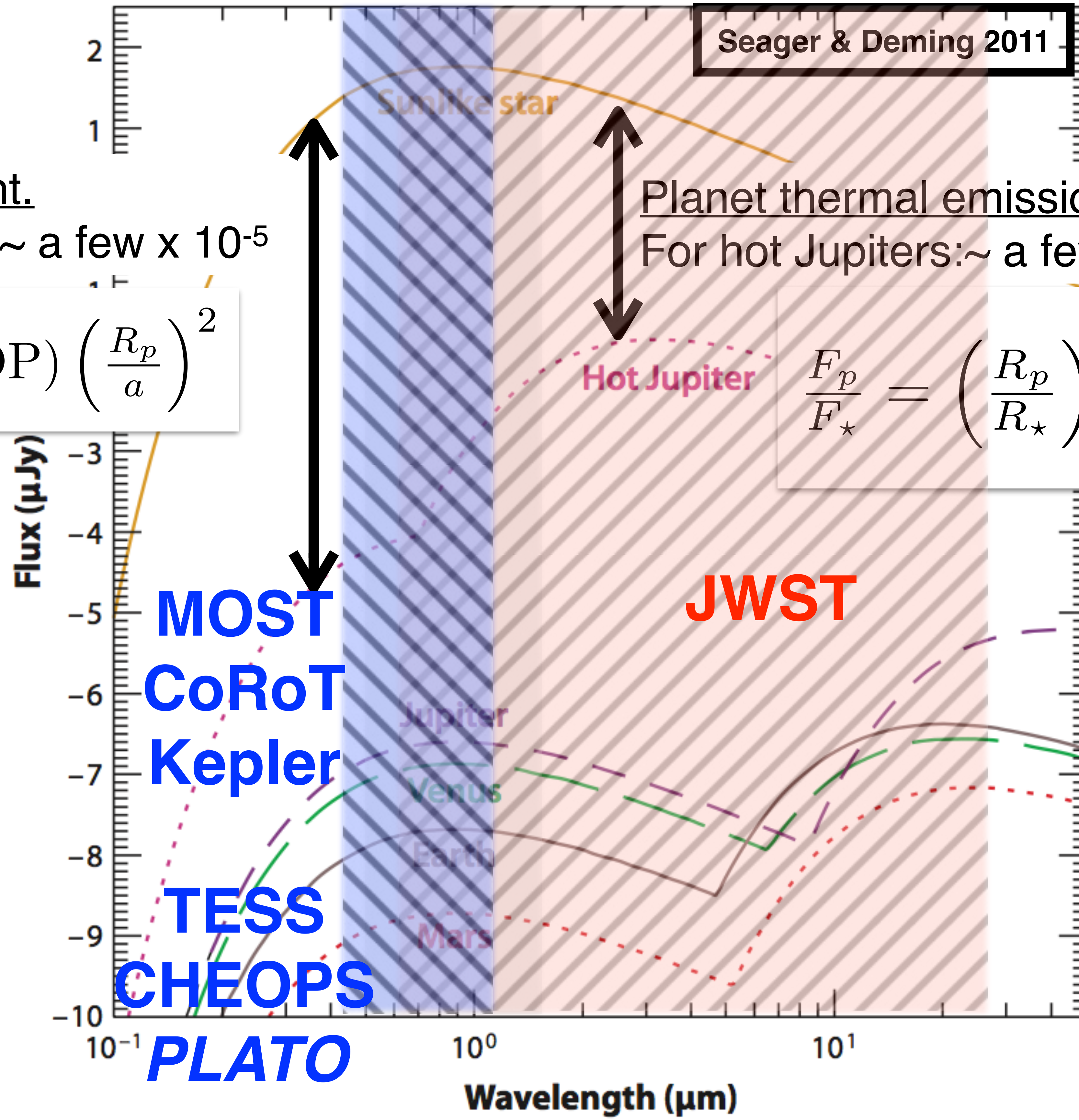
Planet-to-star contrast

Reflected starlight.
For hot Jupiters: ~ a few x 10^{-5}

$$\frac{F_p}{F_\star} = A_g \Phi(\mathrm{OP}) \left(\frac{R_p}{a}\right)^2$$

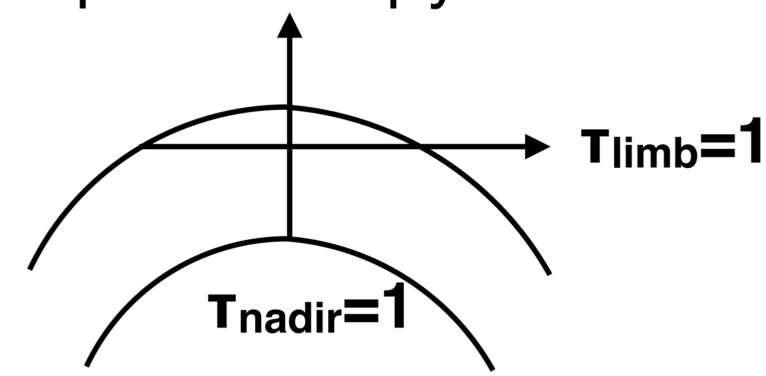
Planet thermal emission.
For hot Jupiters:~ a few x (10^{-4} – 10^{-3})

$$\frac{F_p}{F_\star} = \left(\frac{R_p}{R_\star}\right)^2 \frac{B(T_p)}{B(T_\star)}$$



Why investigating phase curves?
(if interested in atmospheres)

- Remote sensing technique complementary to transmission spectroscopy.
  - Transits: τ_{limb}~1 – – > probing τ_{nadir}<<1
  - Phase curve & occultation– – > probing τ_{nadir}>>1



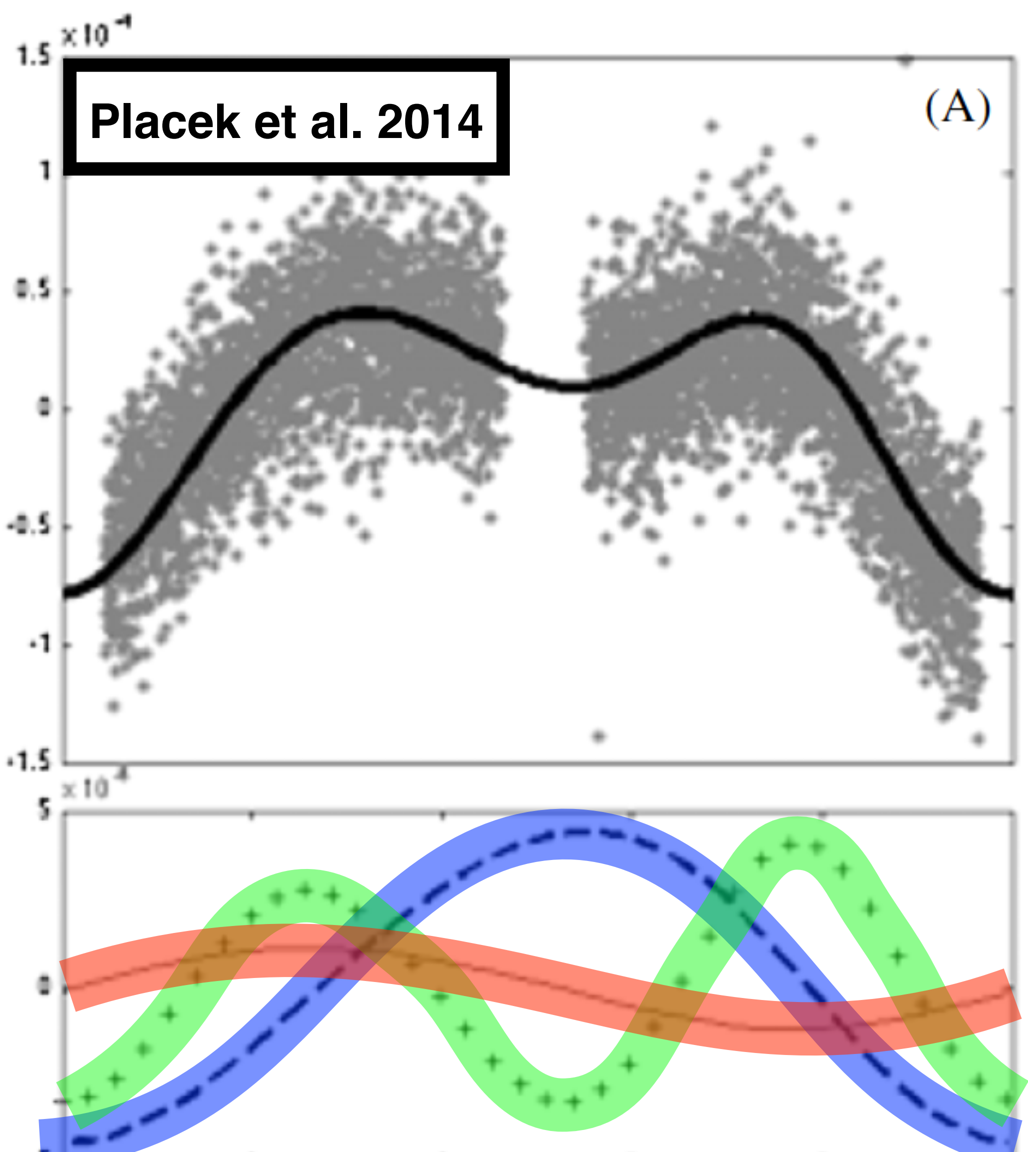
- Brightness changes in orbital phase and in wavelength are complementary.

– – > Day & nightside.

- Provides insight into:
  - Atmospheric composition (Gas/Condensates).
  - Winds dynamics.
  - Energy budget.

Some cautionary considerations
(if interested in atmospheres)

- Spatially-resolved planet-star system.
- Measured brightness modulations caused by:
  - **Planet atmosphere.**
  - But also **Doppler beaming** and **star tidal distortion**.



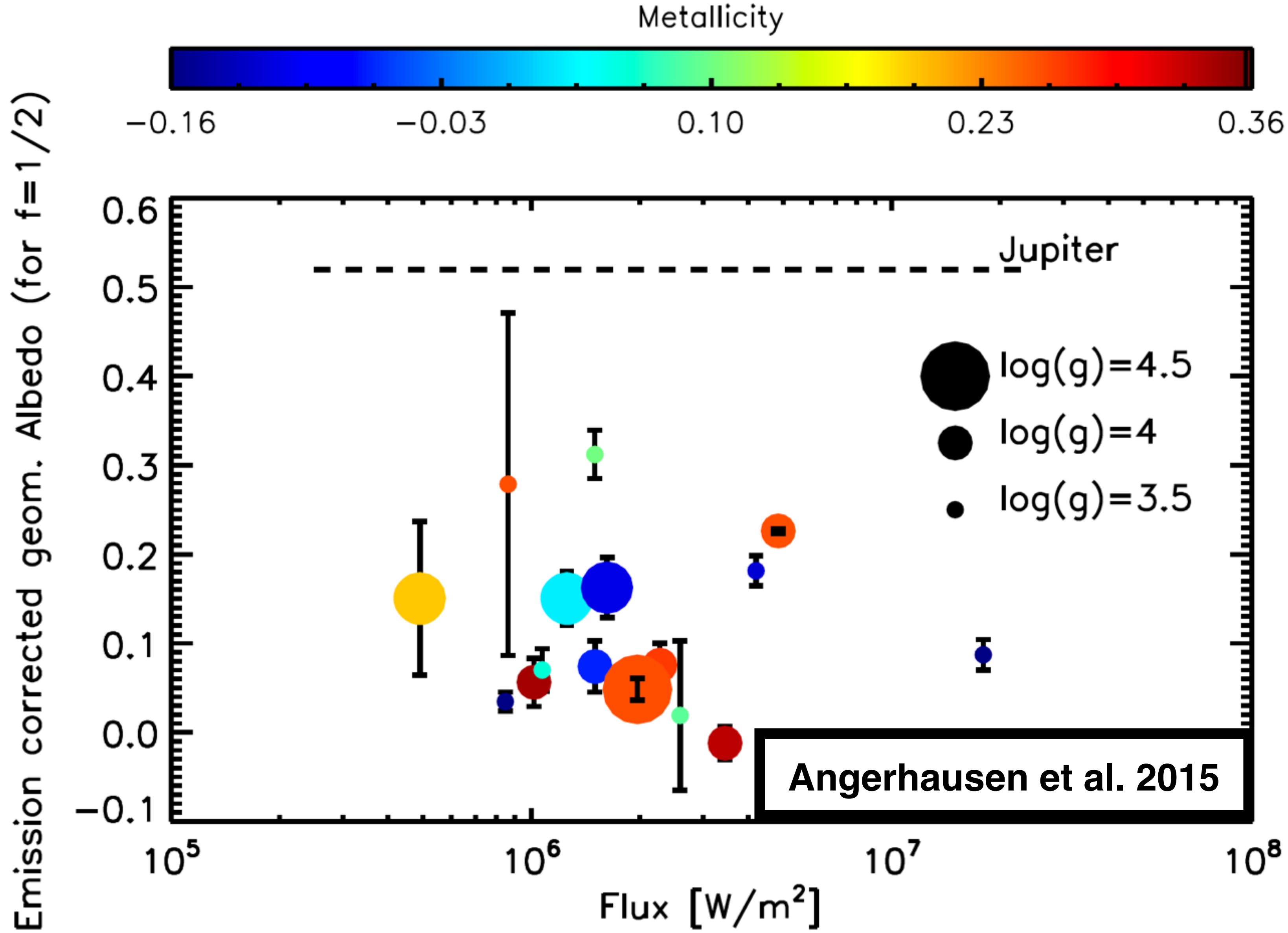
$$\frac{F_p}{F_\star}(\phi) = f_{\mathrm{Doppler}}(\phi) + f_{\mathrm{ellipsoidal}}(\phi) + f_{\mathrm{atmosphere}}(\phi)$$

How well are the non-atmospheric terms known?

(Jackson et al., 2012; Shporer, 2017)

Representation is not orthogonal

Geometric albedos. Large planets



- Hot Jupiters (15-20 of them) are ***typically*** dark in the ***optical***.
- Uncertainty due to lack of IR measurements.
- **Kepler-7b is exceptional**: IR data + very reflective.

Other Refs.: Angerhausen et al. 2015; Coughlin & López Morales, 2012; Demory et al. 2011, 2013; Esteves et al. 2013, 2015; Evans et al. 2013; Faigler & Mazeh, 2011; Gelino & Kane, 2014; Heng & Demory, 2013; Kipping & Spiegel, 2014; Kipping & Bakos, 2011; Lillo-Box et al., 2016; Snellen et al., 2009;

Albedos. Not-so-large planets

super-Earths to sub-Saturns — occultations

A_g~0.16—0.30 for 27 super-Earths candidates (R_p=1–2 R_E) — Demory, 2011

>0.06—0.11 for hot Jupiters

A_g~0.22 for aggregate population (R_p=1–6 R_E)

Sheets & Deming, 2014; short cadence data

A_g~ 0.11 ± 0.06 for aggregate population (R_p=1–2 R_E)

A_g~ 0.05 ± 0.04 for aggregate population (R_p=2–4 R_E)

A_g~ 0.11 ± 0.08, for aggregate population (R_p=4–6 R_E)

Sheets & Deming, 2017; long cadence data

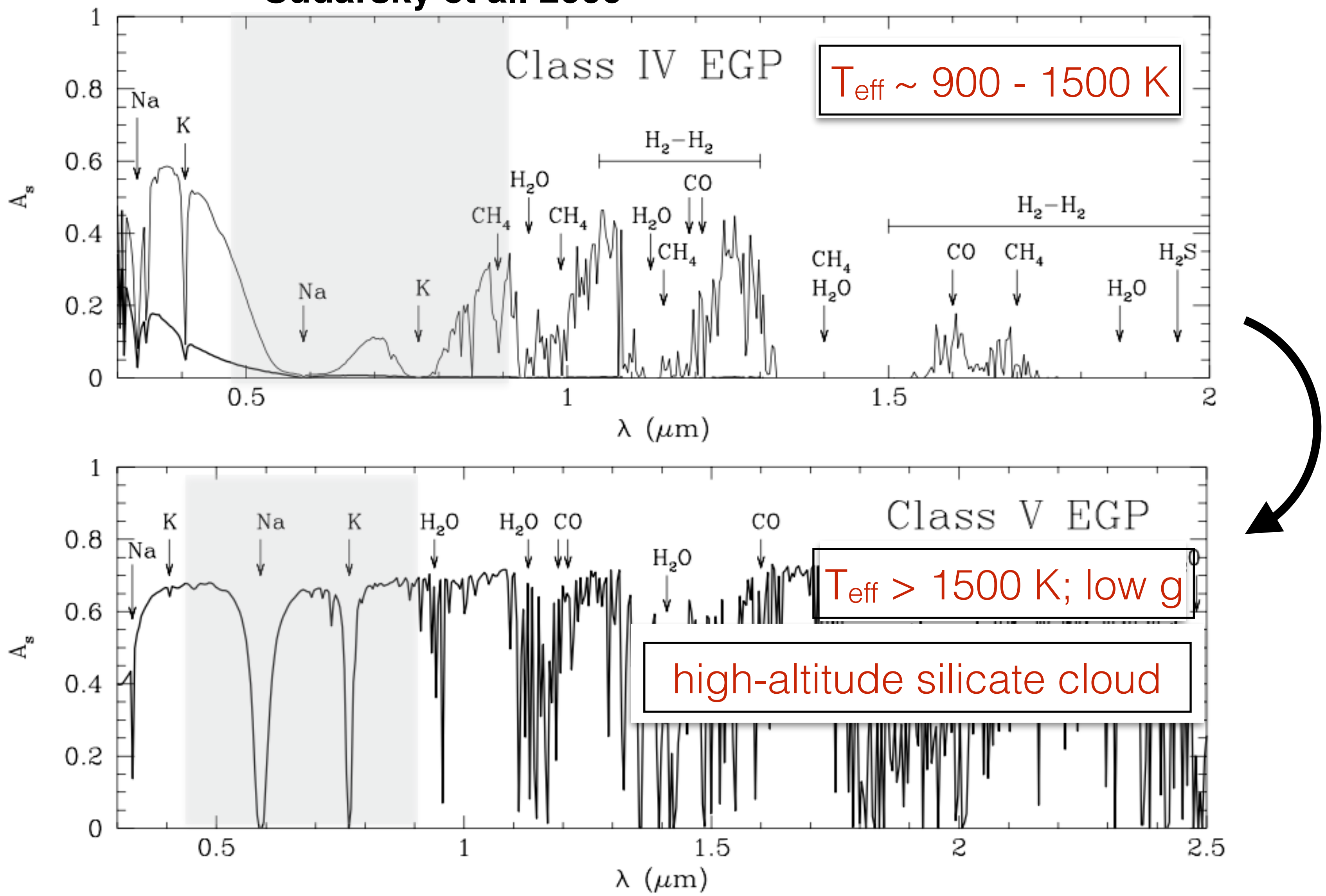
<— — **Ag~0.61±0.17**
Kepler-10b

$\boxed{\textbf{A}_\textbf{g}\textbf{\textasciitilde 0.39 for HAT-P-11b}\text{ (}R_p\text{=4.3 }R_E\text{; Huber et al. 2017)}}$

Outliers are valuable!!

How to interpret this? Clouds?

Sudarsky et al. 2000



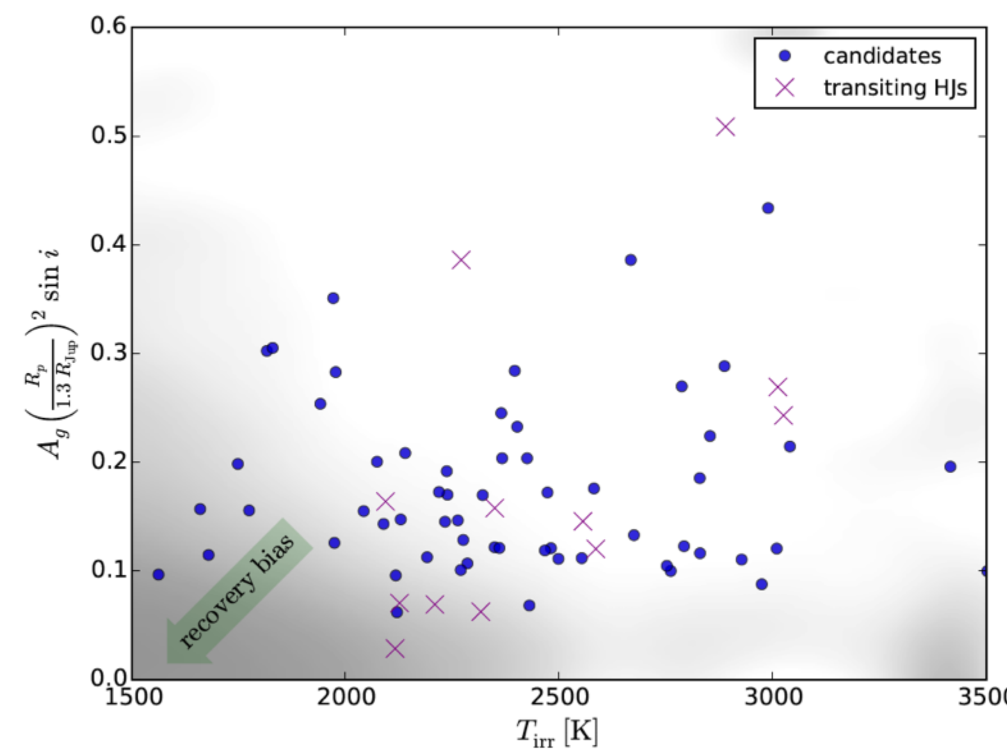
We need **statistics**
to understand how reflectance depends on T_{eq}, ρ, metallicity, etc.

Non-transiting hot Jupiters

A larger sample of (non-transiting) planets would help (Jenkins & Doyle, 2003).

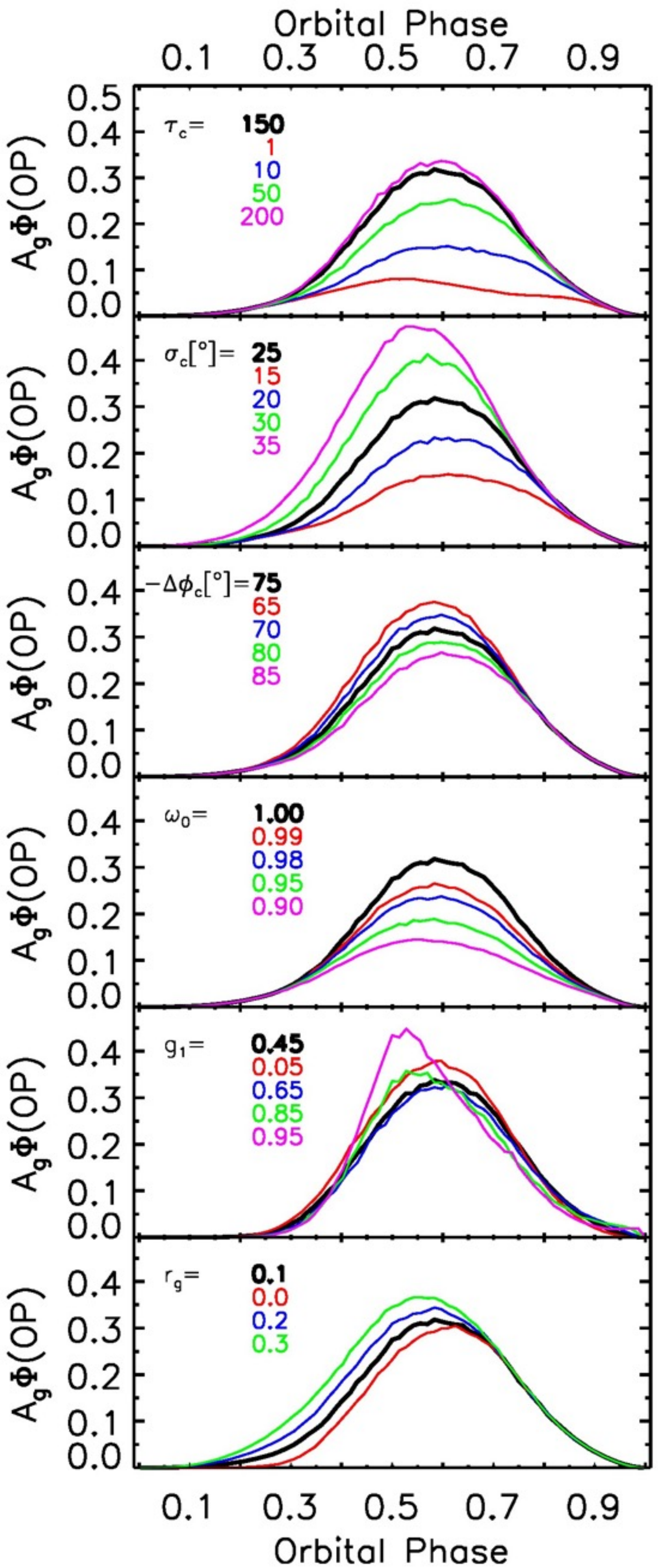
Millholland & Latham 2017

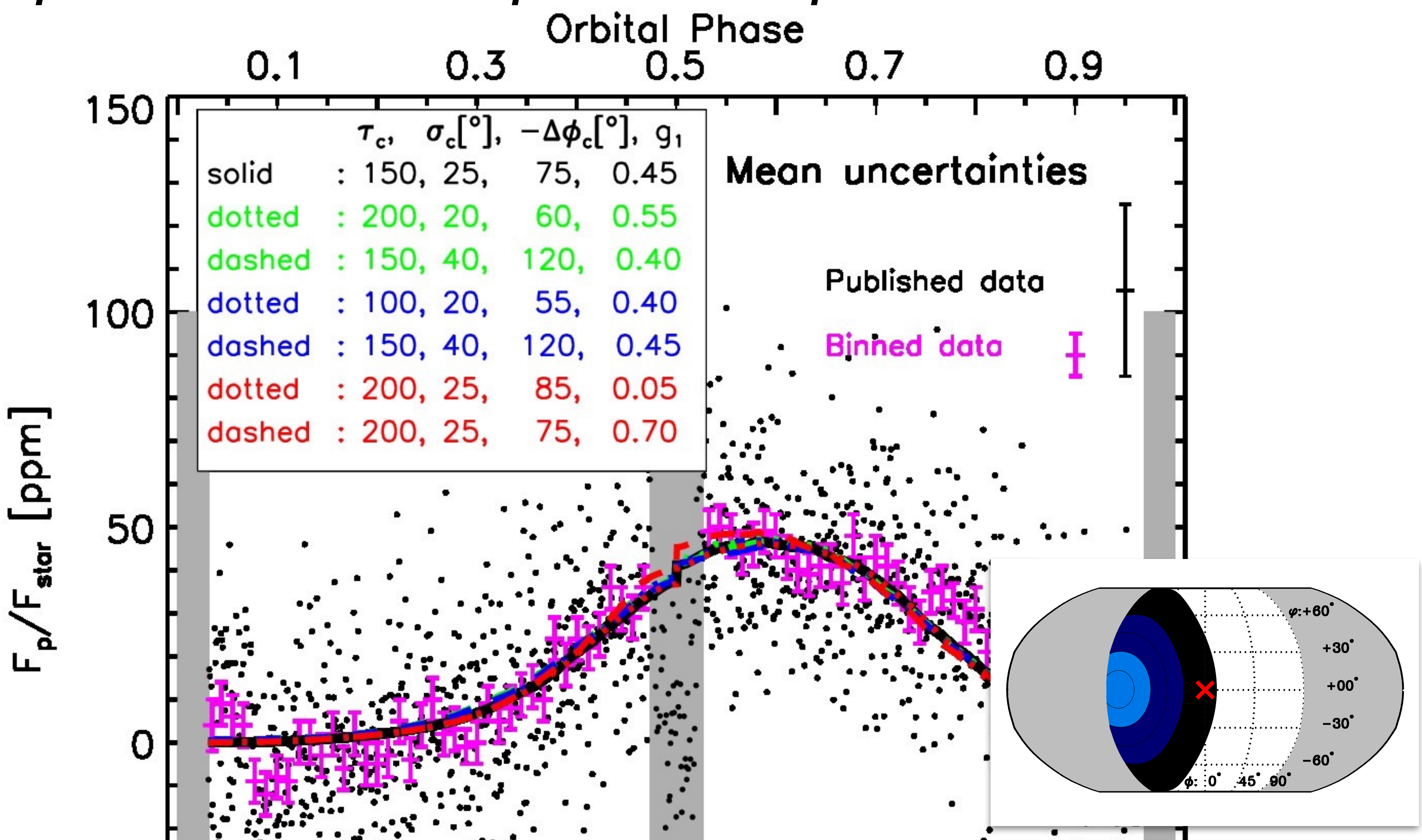
60 non-transiting planet ***candidates***



Reflected starlight. Phase curve shape

Interpretation of Kepler-7b's phase curve



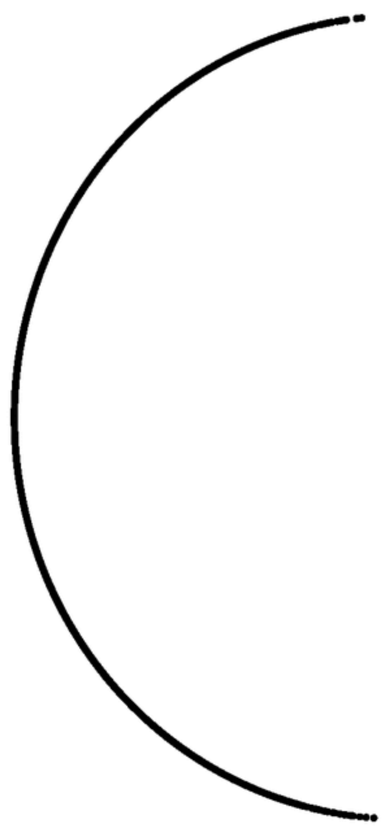


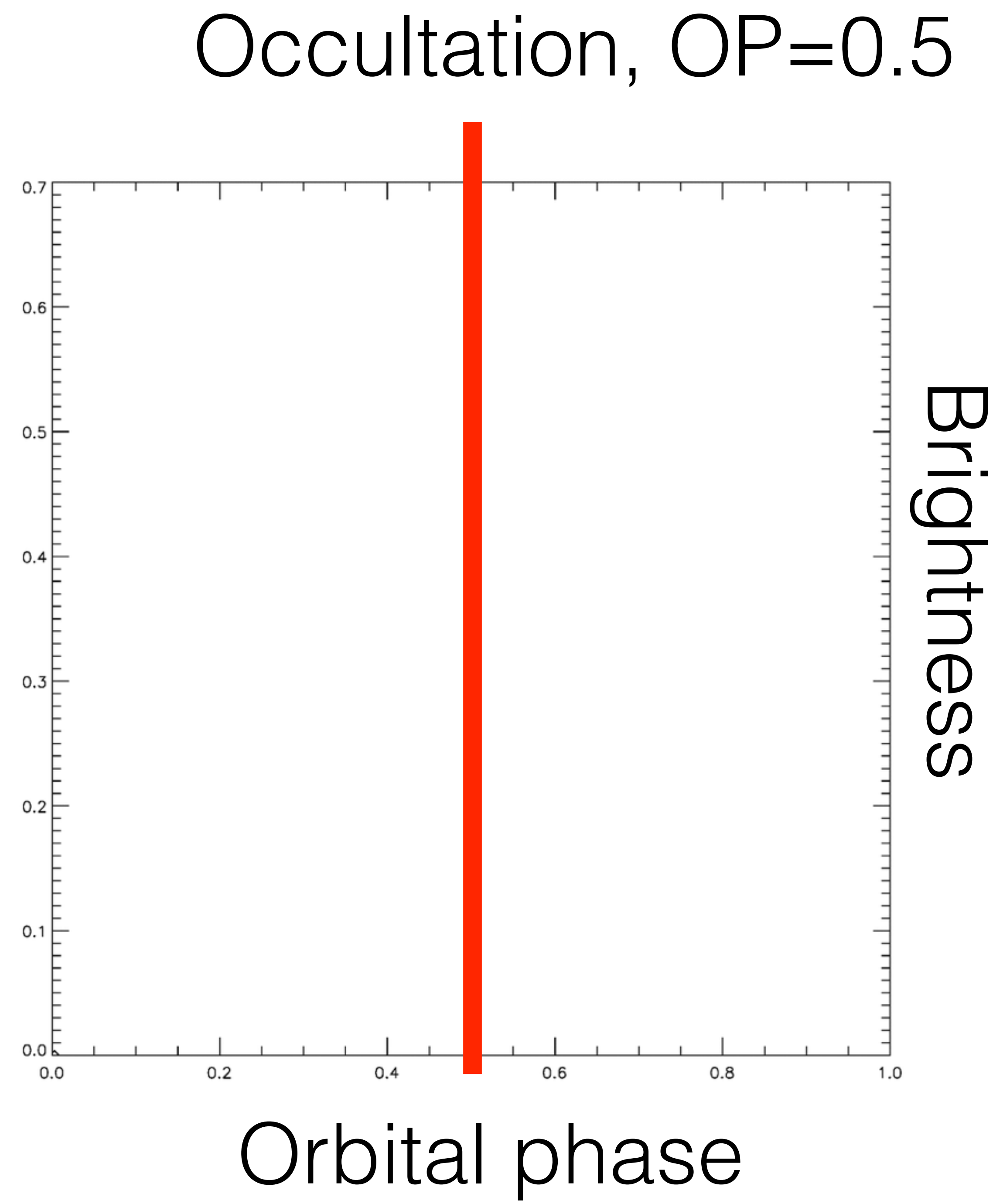
García Muñoz & Isaak, 2015. Data from Demory et al. (2013)

- Cloud offset west from substellar point;
- Particulates are small, r<1μm, & of
- conservative composition (e.g. silicates);
- Non-cloudy surface is very dark.

Reflected starlight. Phase curve shape

Interpretation of Kepler-7b's phase curve





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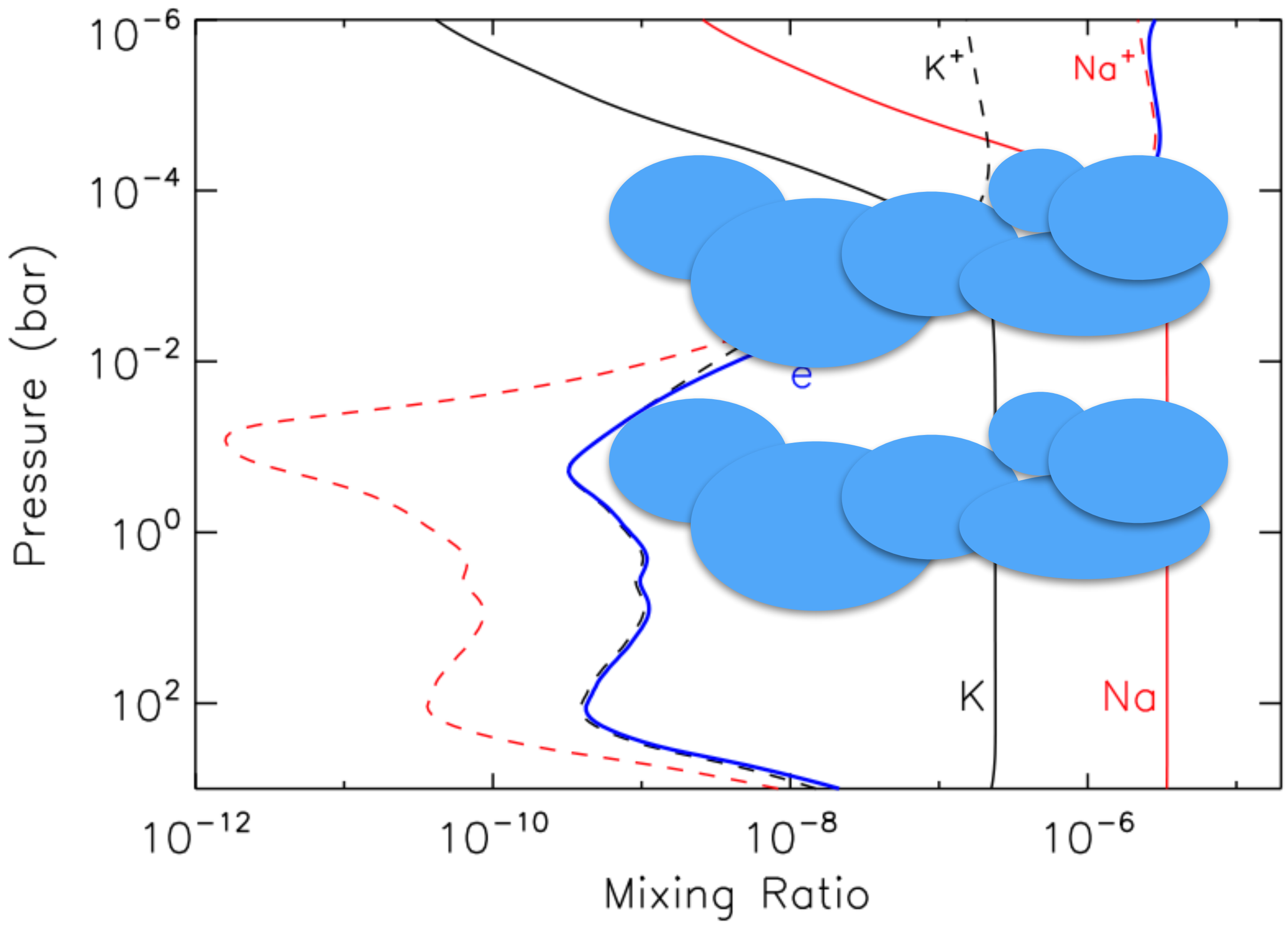
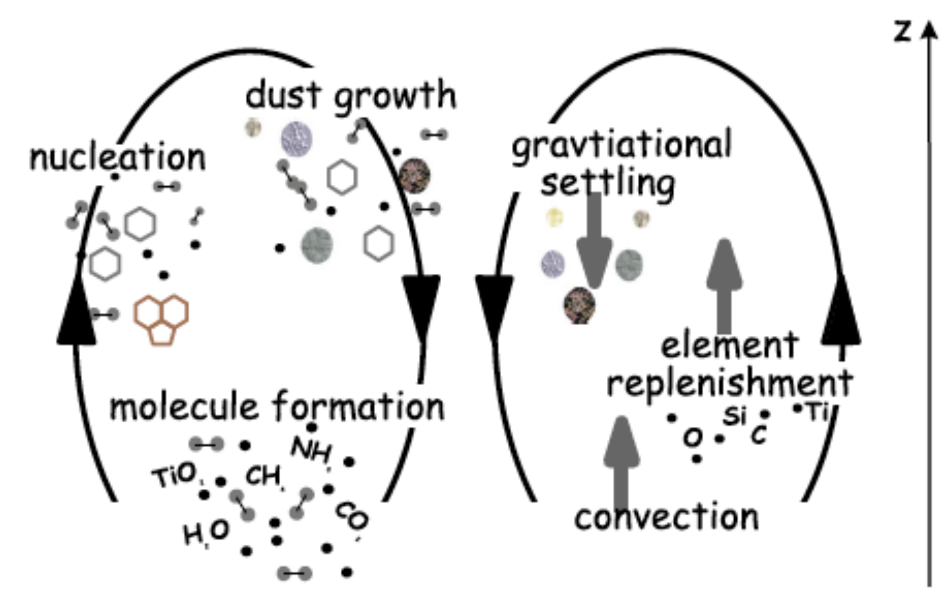


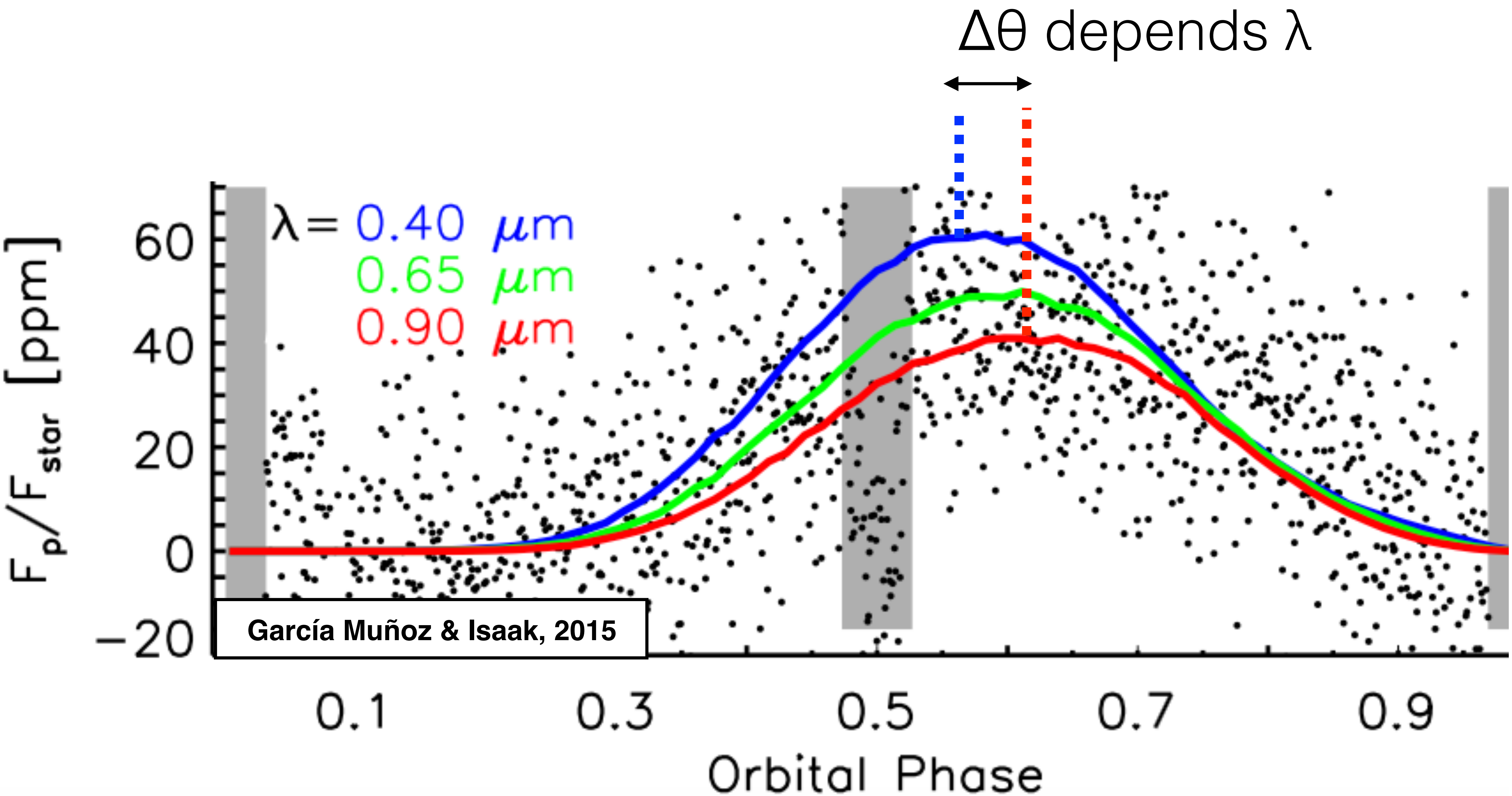
Lavvas et al. 2014



Woitke & Helling, 2004

Reflected starlight. Phase curve shape

Interpretation of Kepler-7b's phase curve



See J. L. Grenfell's poster.

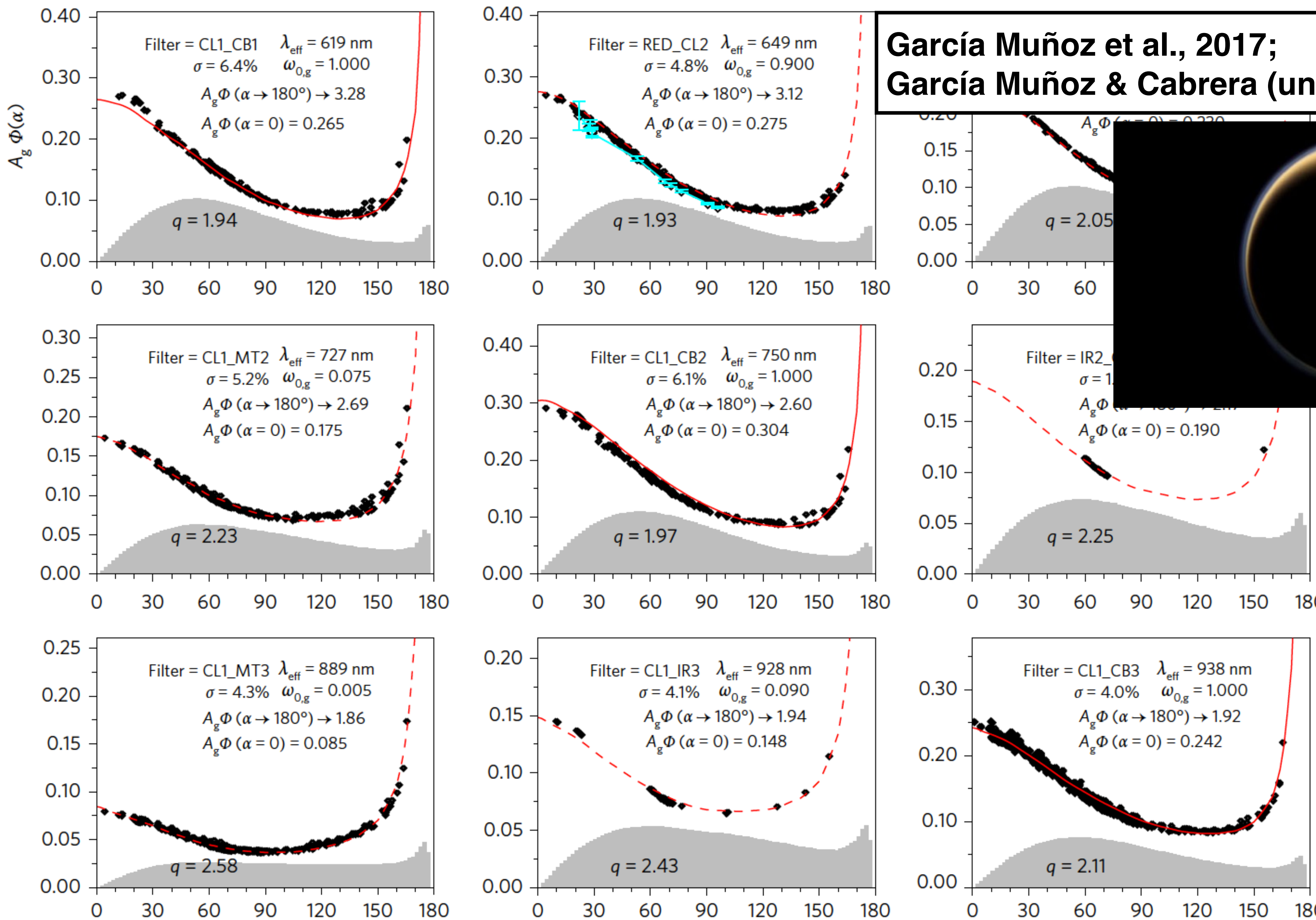
See also Lee et al. 2017 for phase curve predictions in TESS & CHEOPS passbands

Reflected starlight. Puffy planets

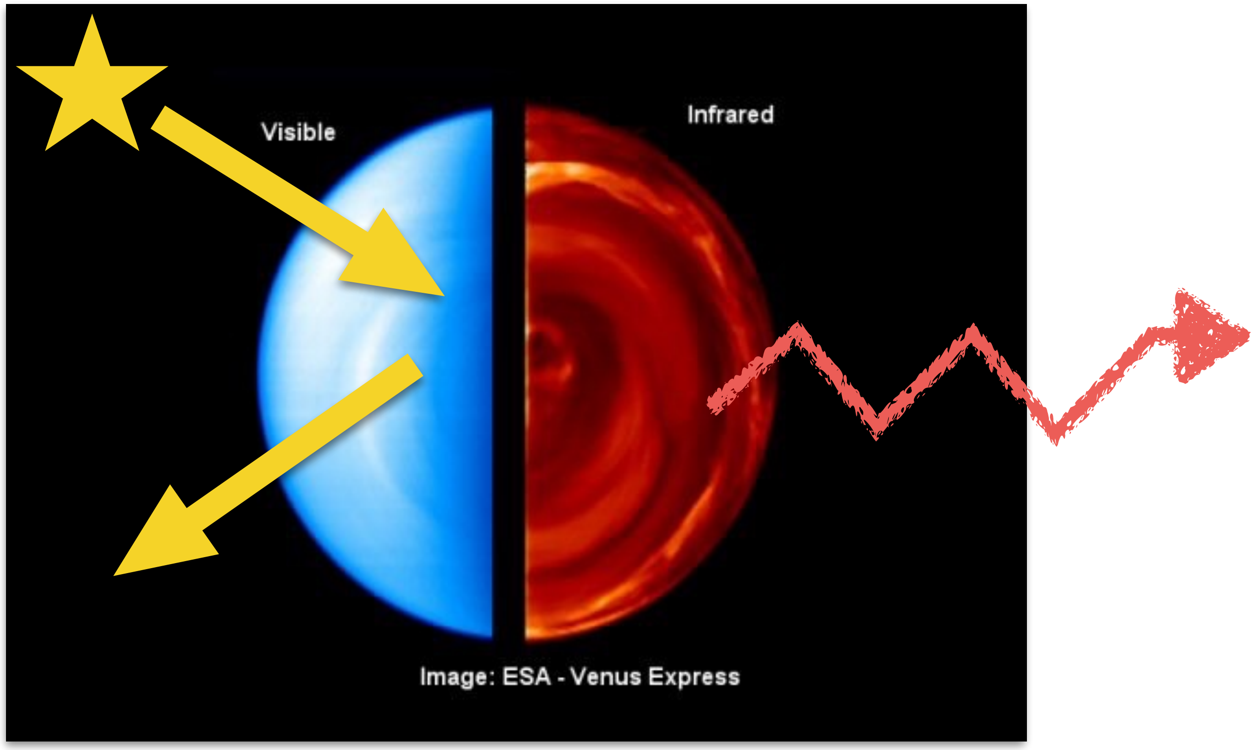
@ **Titan**, brightness increases at very large phase angles.

Diagnostics for H/R$_p$, aerosol stratification & aerosol size —> @ exoplanets?

García Muñoz et al., 2017;
García Muñoz & Cabrera (under review)



Energetics of hot Jupiters



Balance:

$$P_{dep} = P_{emi}$$

$P_{dep} = P_{inc} - P_{sca} \sim (1 - A_B)\, P_{inc}$

P_{emi} = *thermal emission*

P_{dep} & P_{emi} are needed:

- **In all directions**
- **At all relevant wavelengths**

——> Both optical & IR phase curves needed

——> Bond albedo A_B & Circulation efficiency $\varepsilon = \tau_{rad}/\tau_{adv}$

Energetics of hot Jupiters

Current treatments use one of these approaches:

- **Only IR data (occultations/phase curves)**
- **IR + optical occultations**
- **Only optical phase curves**

Inconsistencies amongst approaches and in Bond (IR) vs. geometric albedos (optical)

A_B~0.35 but **A_g~0.1** (Schwartz & Cowan, 2015)

Good news: JWST will be providing spectroscopic IR phase curves

— —> For the same targets, optical phase curves are needed!!

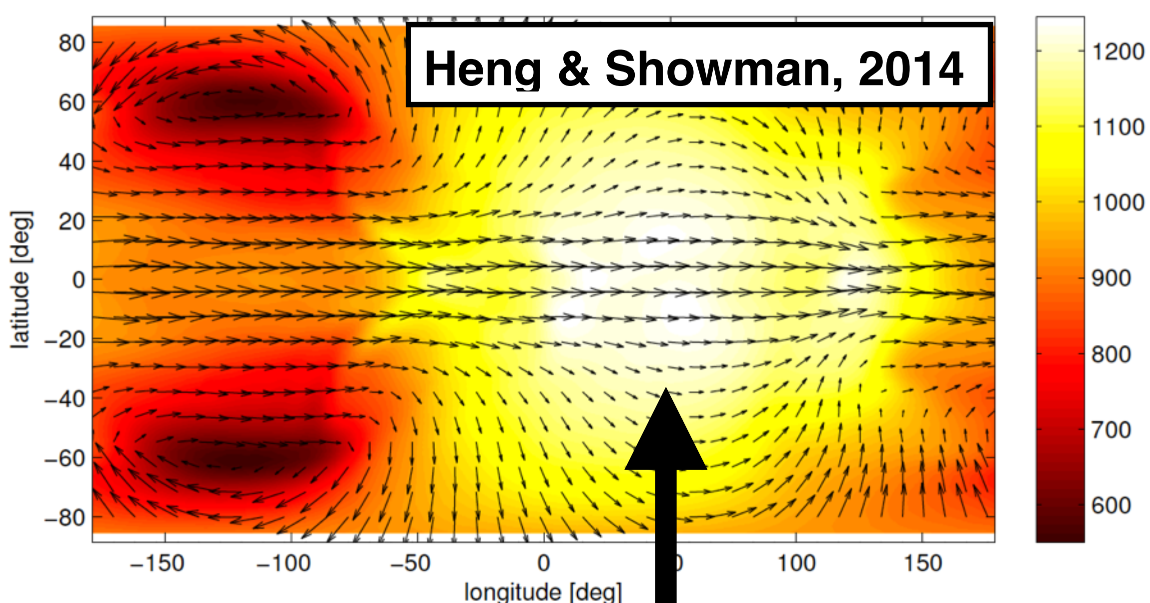
Refs.: Cowan & Agol, 2011; Hu et al. 2015; Schwartz & Cowan, 2015; Schwartz et al. 2017; Shporer & Hu, 2015; von Paris et al., 2015

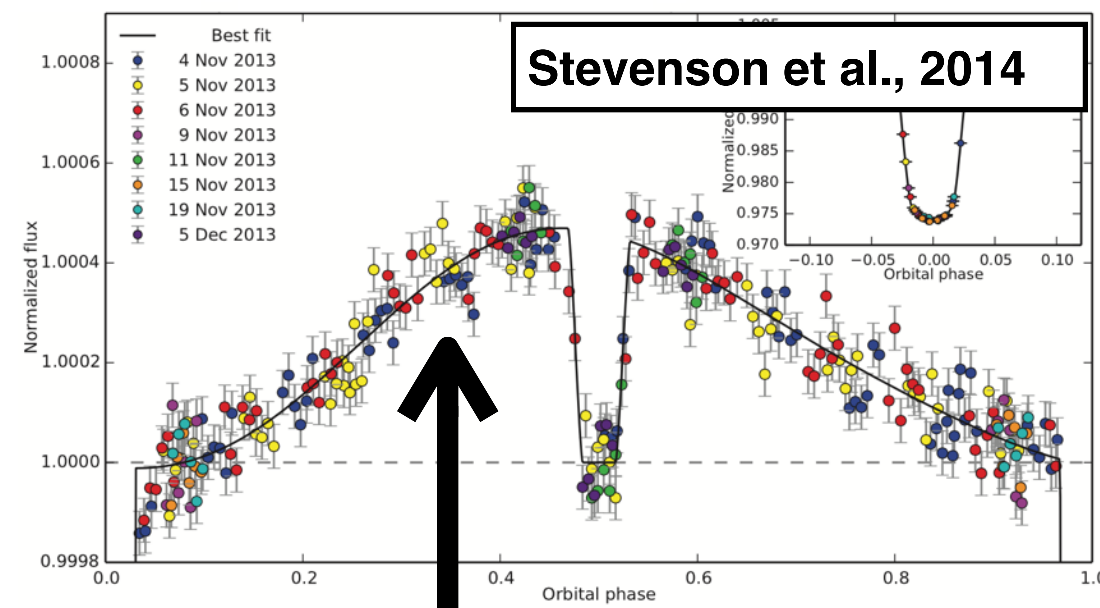
Energetics of hot Jupiters

GCMs: Energy balance— wind dynamics.

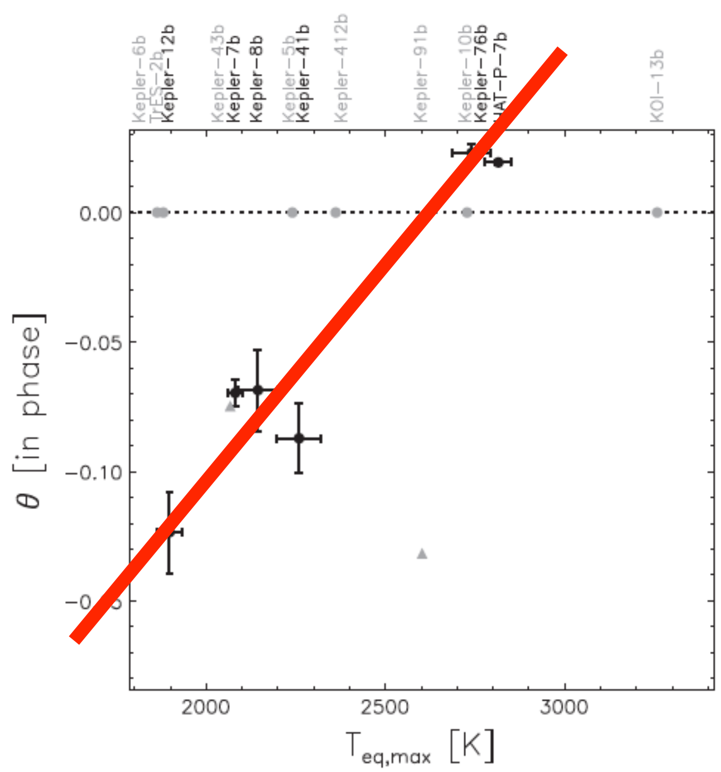
Super-rotation. Hot-spot is offset westwards of substellar point.

Evidence for this in the IR and in the optical.





Δθ>0



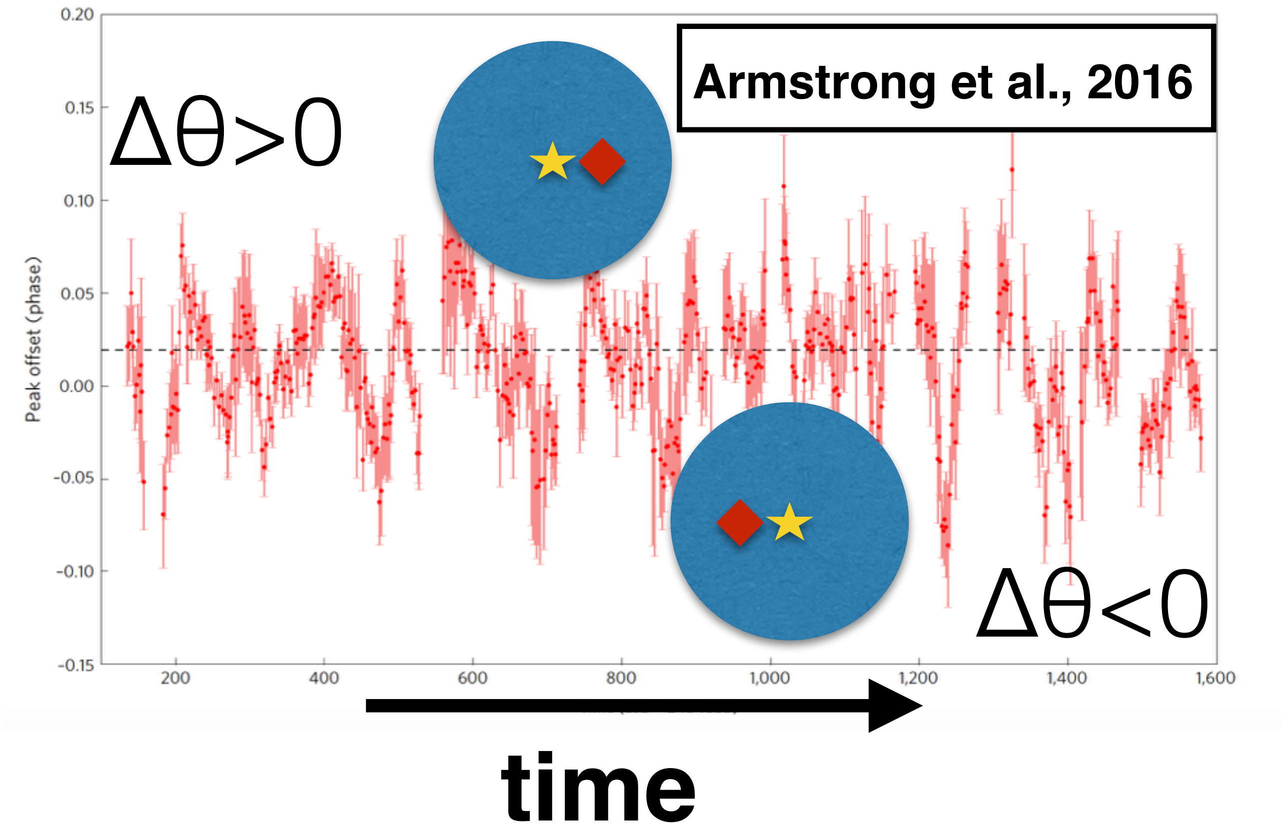
Confirmed by theory.

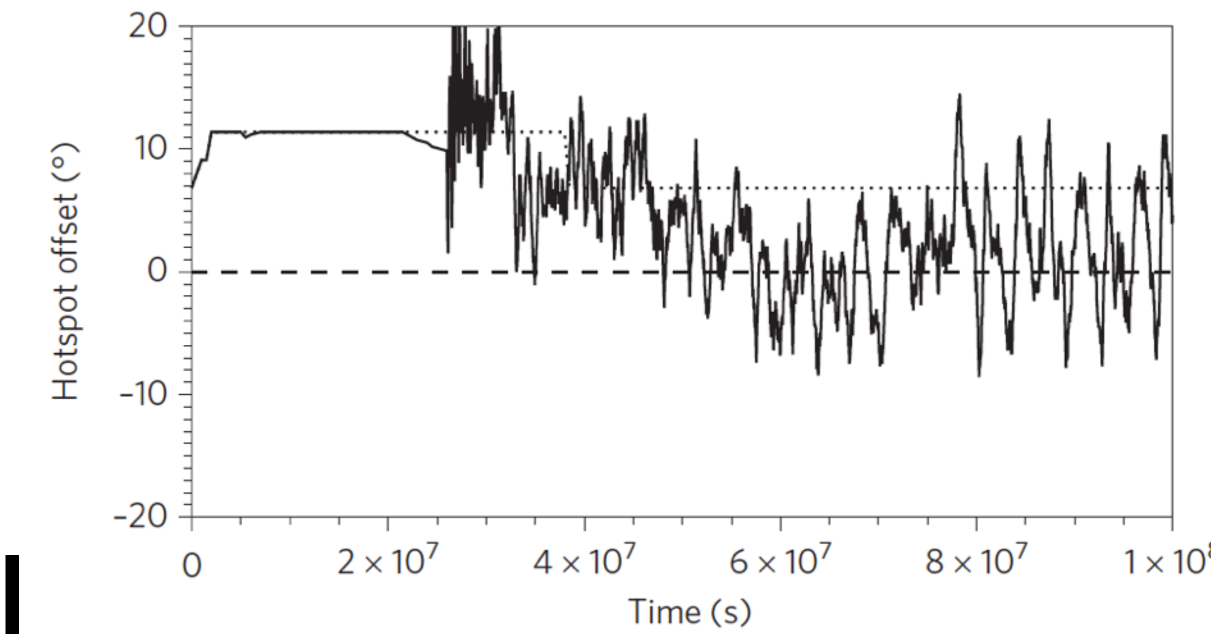
Δθ>0 occurs for hottest planets. Offset hot spot.

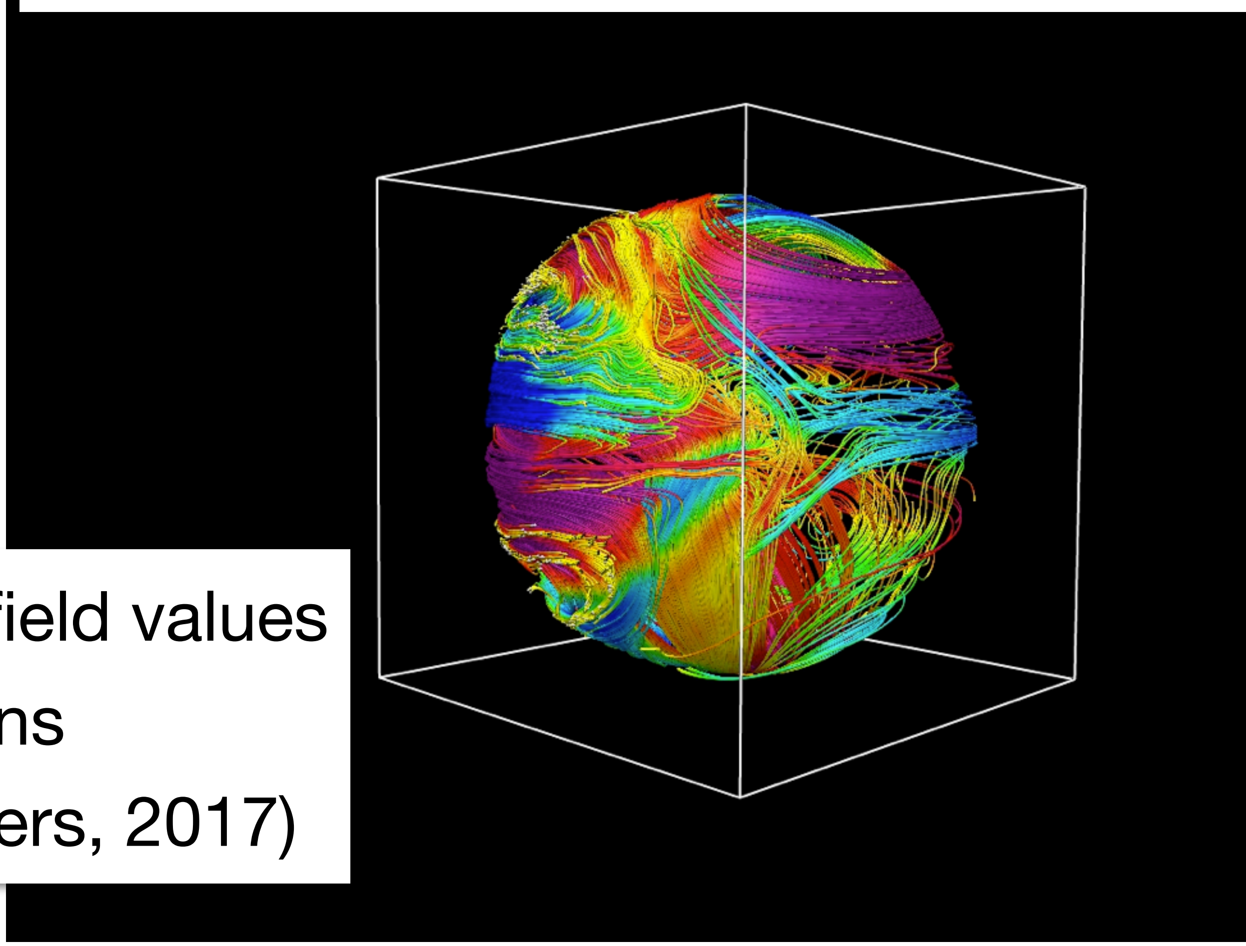
Δθ<0 occurs for coolest planets.

Time variability & MHD

HAT-P-7b (T>2,500K)







Oscillating behavior is limited to a range of B field values

——> Diagnostics for MHD interactions

Prediction: WASP-12b, -19b (Rogers, 2017)

The PLATO opportunity for phase curves

- Long-baseline (2 years + 2 years + …).
  - **— —>** Extra sensitivity.
  - **— —>** Reveal time-variable phenomena.

- Bright targets. Amenable to multi-technique investigations.
  - **— —>** Investigate individual planets.
  - **— —>** Investigate populations.

- 2 Fast cameras with Blue/Red filters **— —> *see J. Lee Grenfell's poster.***
  - Disentangle reflected starlight from thermal emission for some targets.
  - Investigate scattering properties at two wavelengths.

- Synergy between PLATO (500-1000 nm, launch 2026) and JWST (0.6-28 μm, launch 2018). Spectrally-resolved phase curves for selected (bright) targets.

- Synergy with large ground-based observatories (e.g. E-ELT). Albedos to be investigated from the ground.