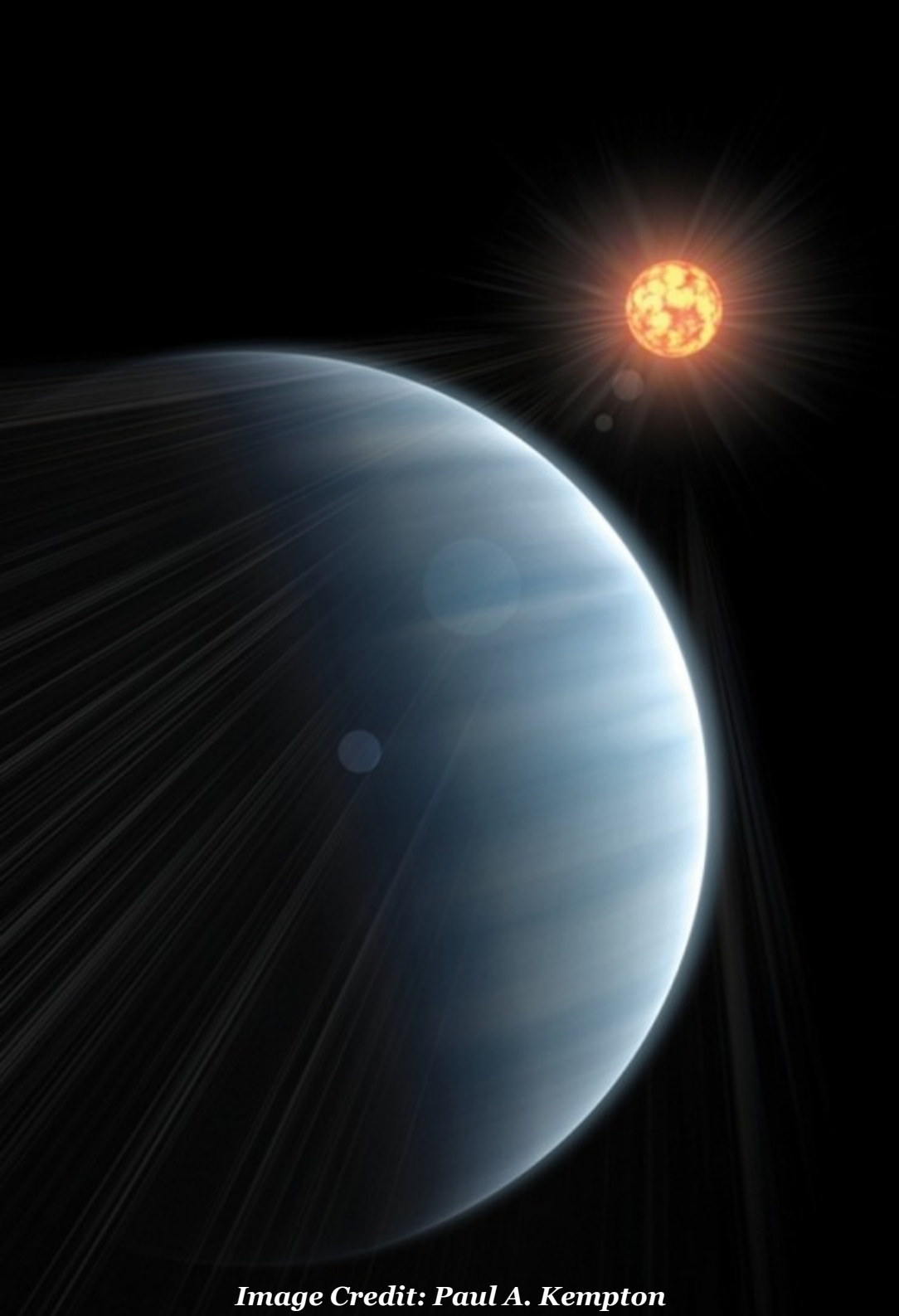


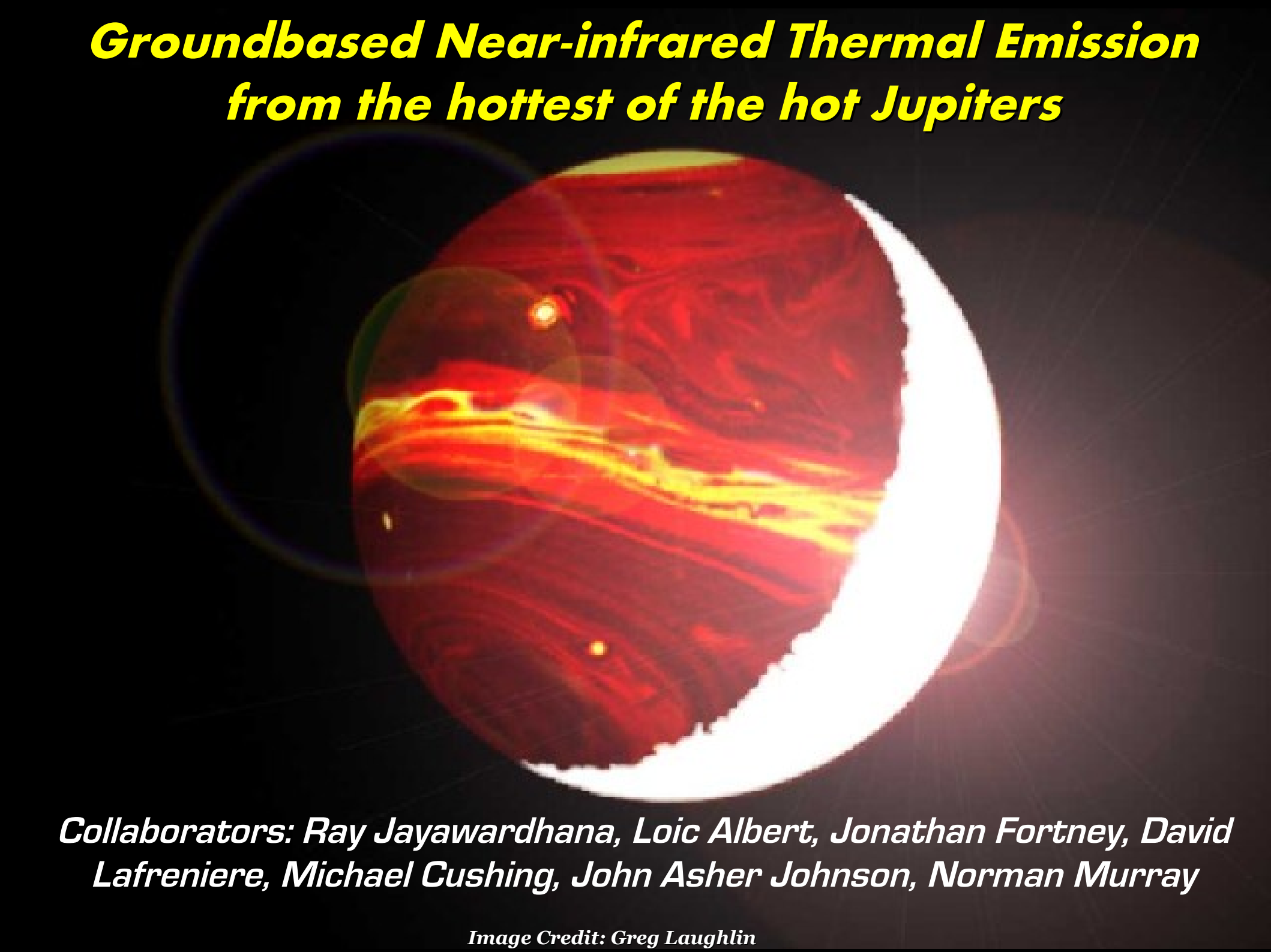
Bryce Croll
University of Toronto

Near-infrared Characterization of the Atmosphere of Exoplanets

May 3rd 2011

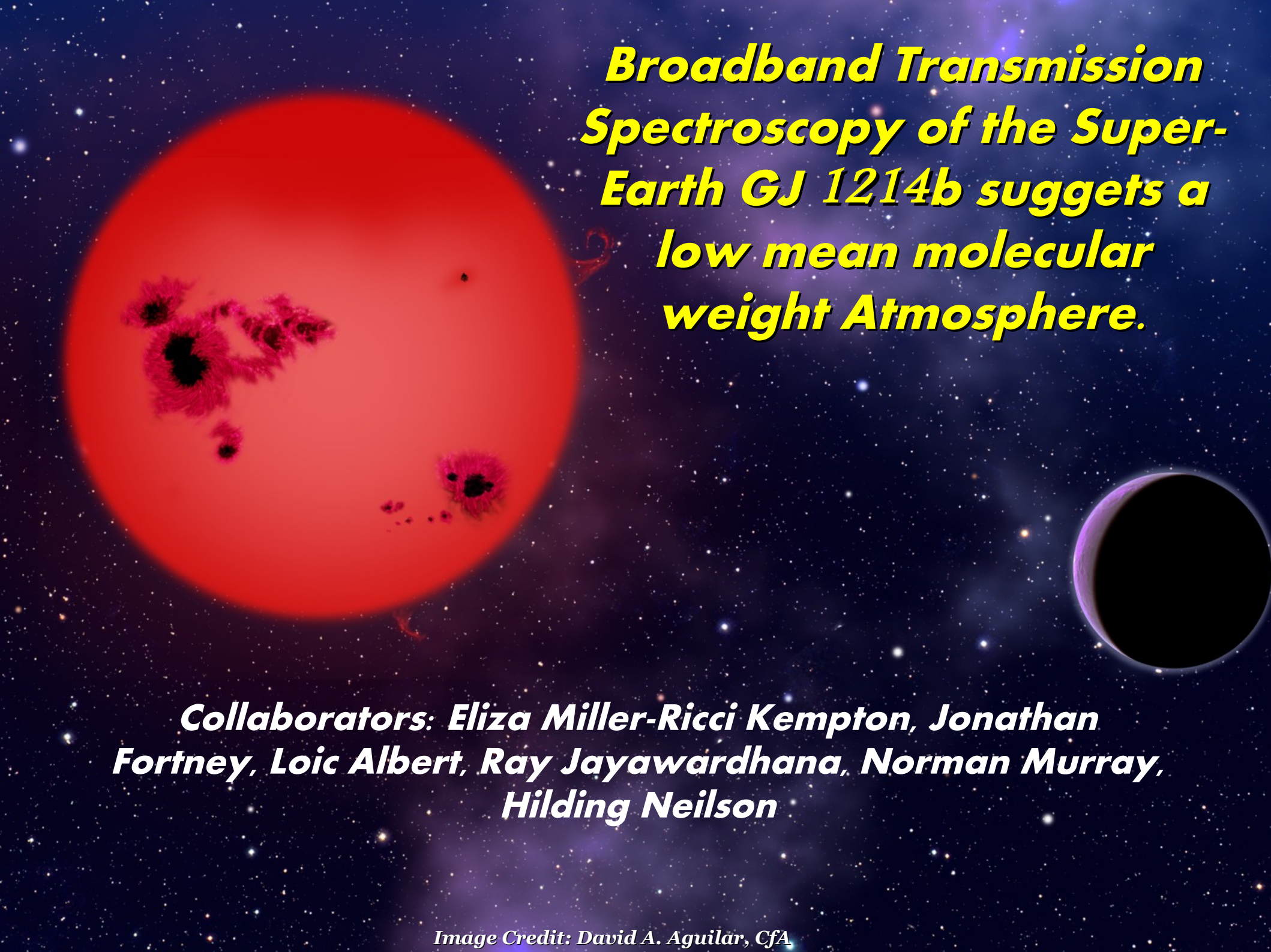
Image Credit: Paul A. Kempton

Groundbased Near-infrared Thermal Emission from the hottest of the hot Jupiters



Collaborators: Ray Jayawardhana, Loic Albert, Jonathan Fortney, David Lafreniere, Michael Cushing, John Asher Johnson, Norman Murray

Image Credit: Greg Laughlin



Broadband Transmission Spectroscopy of the Super-Earth GJ 1214b suggets a low mean molecular weight Atmosphere.

Collaborators: Eliza Miller-Ricci Kempton, Jonathan Fortney, Loic Albert, Ray Jayawardhana, Norman Murray, Hilding Neilson

Image Credit: David A. Aguilar, CfA

Thermal Emission in the Near-IR:

- We've returned the most accurate photometry that has been obtained from the ground to date using the Wide-field Infrared Camera (WIRCam) on the Canada-France-Hawaii Telescope (CFHT).
- We've used these data to detect the secondary eclipses of a number of hot Jupiters from the ground.
- These detections bracket the blackbody peaks of these worlds, leading to the most model-independent constraints on their atmospheres.
- When combined with Spitzer/IRAC detections these observations: constrain the day-to-nightside redistribution of heat, energy budgets, bolometric luminosities, temperature pressure profiles, etc.
- New results!
- What does the ensemble of all the near-infrared detections of hot Jupiters tell us about hot Jupiters as a class?

Artist's View of Extrasolar Planet WASP-12b
NASA, ESA, and G. Bacon (STScI) ▪ STScI-PRC10-15

GJ 1214B: A mini-Neptune?

- We've used WIRCam/CFHT to observe four transits of the super-Earth GJ 1214b.
- We've detected a 4-sigma deeper transit in Ks-band than in J-band for the transiting super-Earth GJ 1214b (the second transiting super-Earth, and the first that we can well-characterize).
- This is likely indicative of a spectral feature. The only way to get a spectral feature this large is if GJ 1214b has a large scale height, low mean molecular weight and thus a hydrogen/helium dominated atmosphere enveloping a rocky core. Other observations suggest the planet must also have hazes and a lack of methane.
- GJ 1214b, the first super-Earth for which we have been able to well characterize its atmospheric characteristics and bulk composition, is arguably better described as a mini-Neptune.

Image Credit: David A. Aguilar, CfA

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- New and upcoming observations!

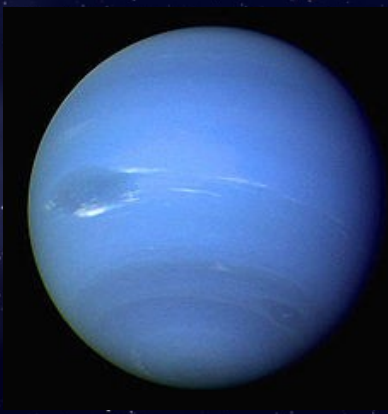
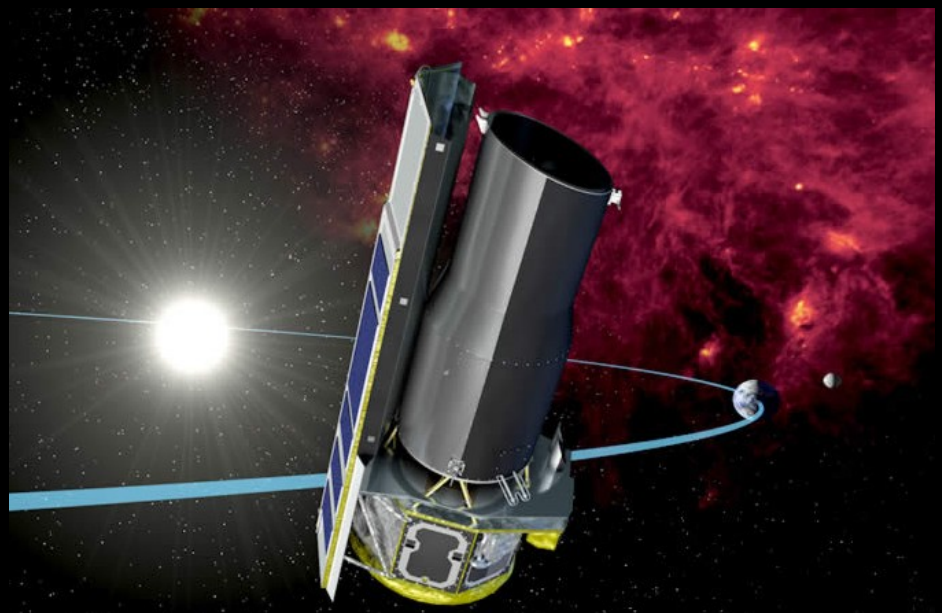


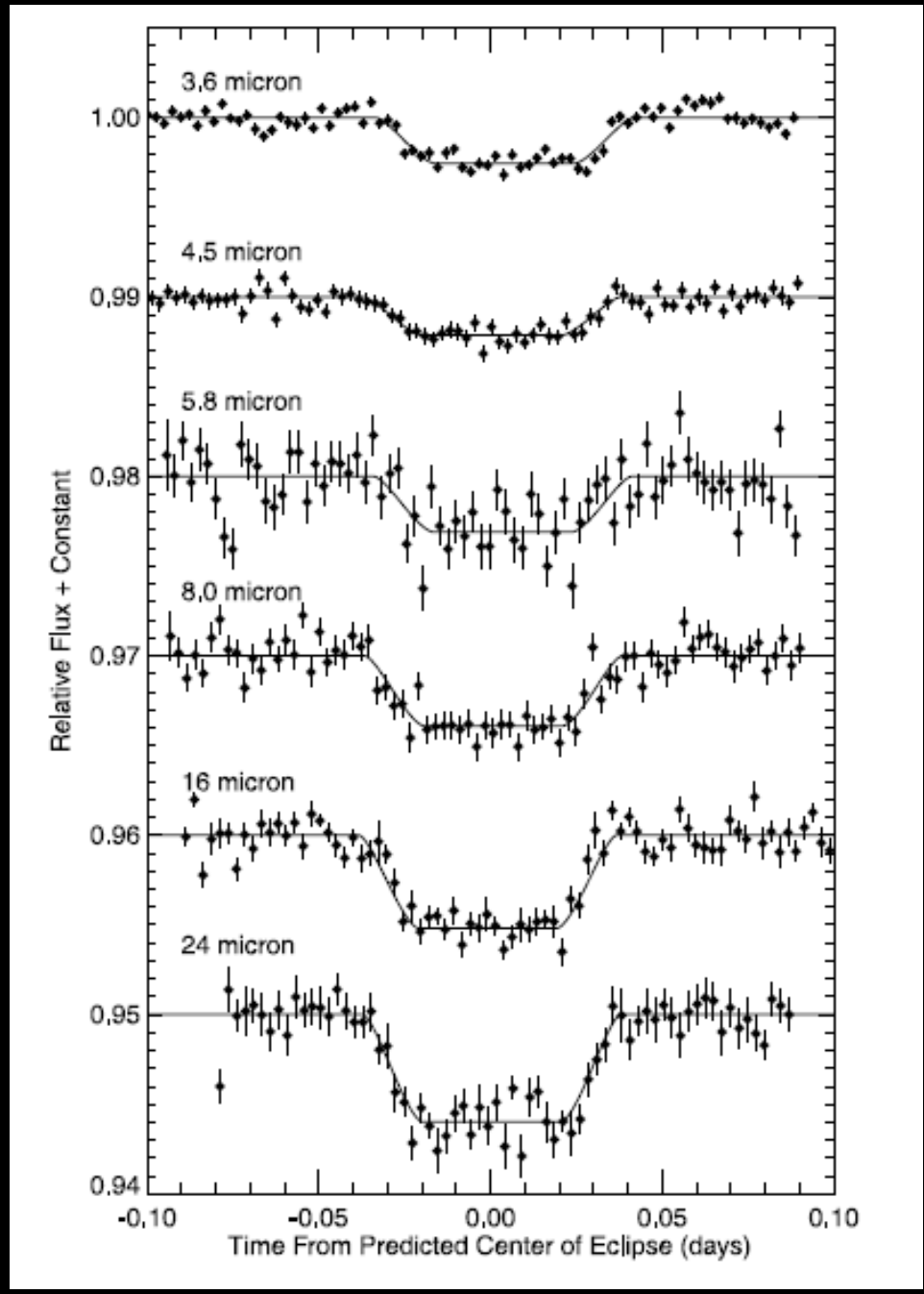
Image Credit: David A. Aguilar, CfA

Thermal Emission with Spitzer

- There have been a series of multi-wavelength thermal emission measurements for hot Jupiters in the mid-infrared from 3.6 – 24 microns (Charbonneau et al. 2008; Knutson et al. 2008, etc.).



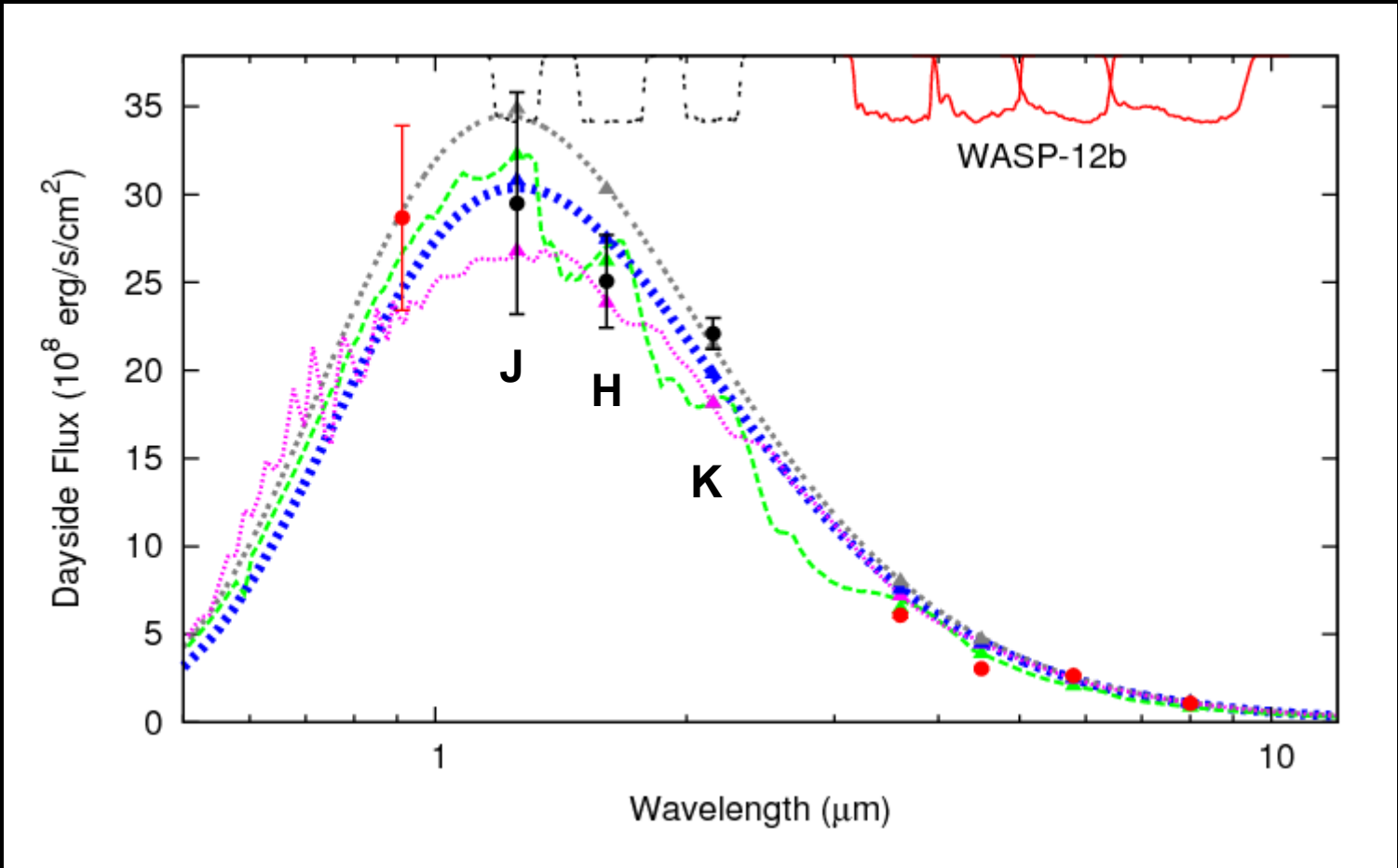
Left: The Spitzer Space Telescope.



Right: detections of the thermal emission of HD 189733 from 3.6 – 24 microns. Figure from Charbonneau et al. (2008).

Why the Near-infrared?

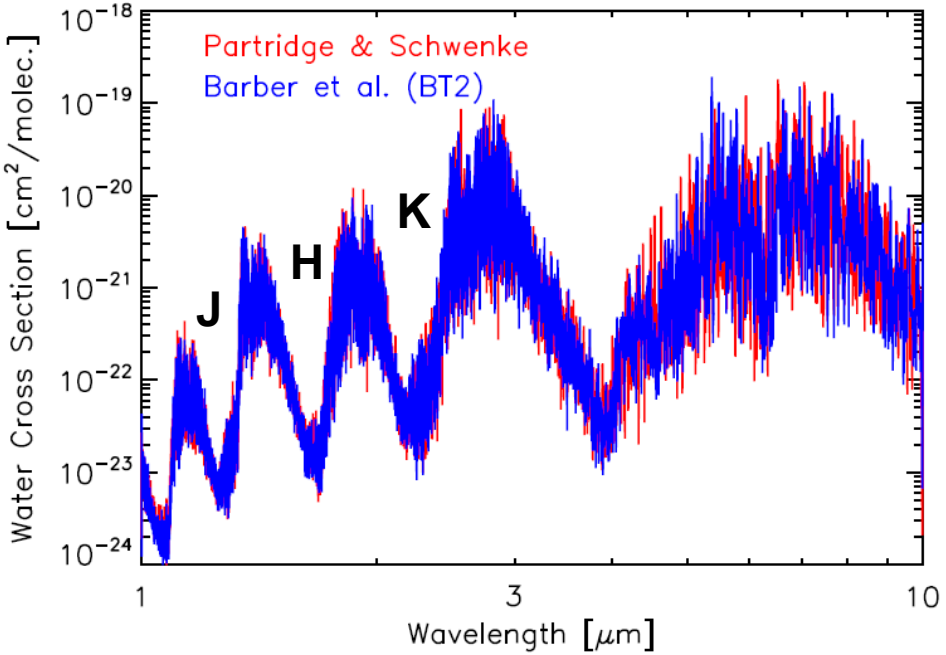
- For the hottest hot Jupiters the Spitzer mid-infrared wavelengths are at longer wavelengths than the blackbody peaks of these planets.
- The near-infrared J, H & K-bands often bracket the blackbody peaks of these planets.

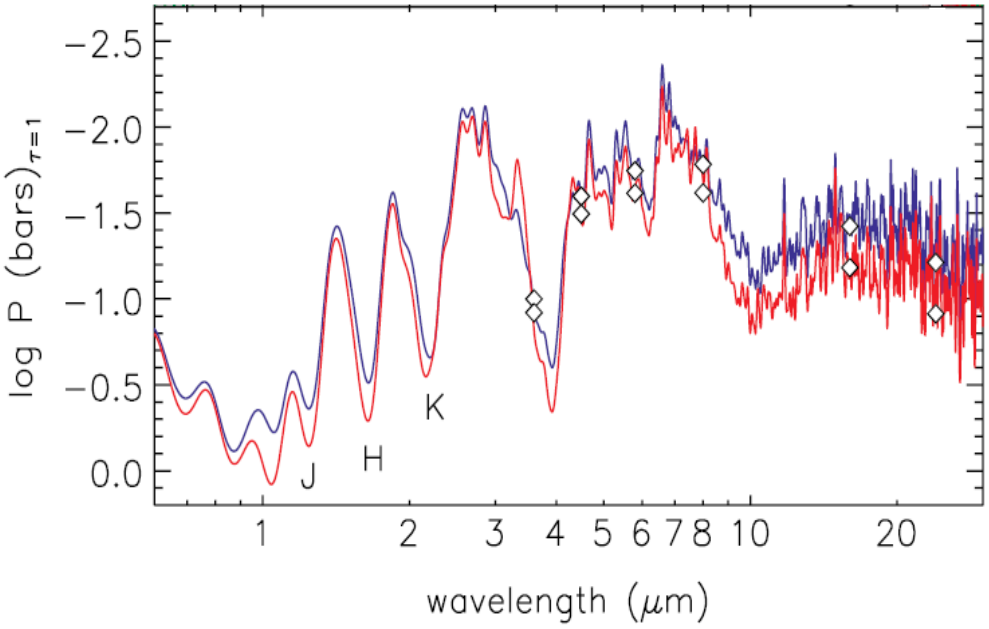


Above: Near- and mid-infrared detections for the highly irradiated hot Jupiter WASP-12b. Detections from Croll et al. (2010c), Lopez-morales et al. (2010) & Campo et al. (2010).

Why the Near-infrared?

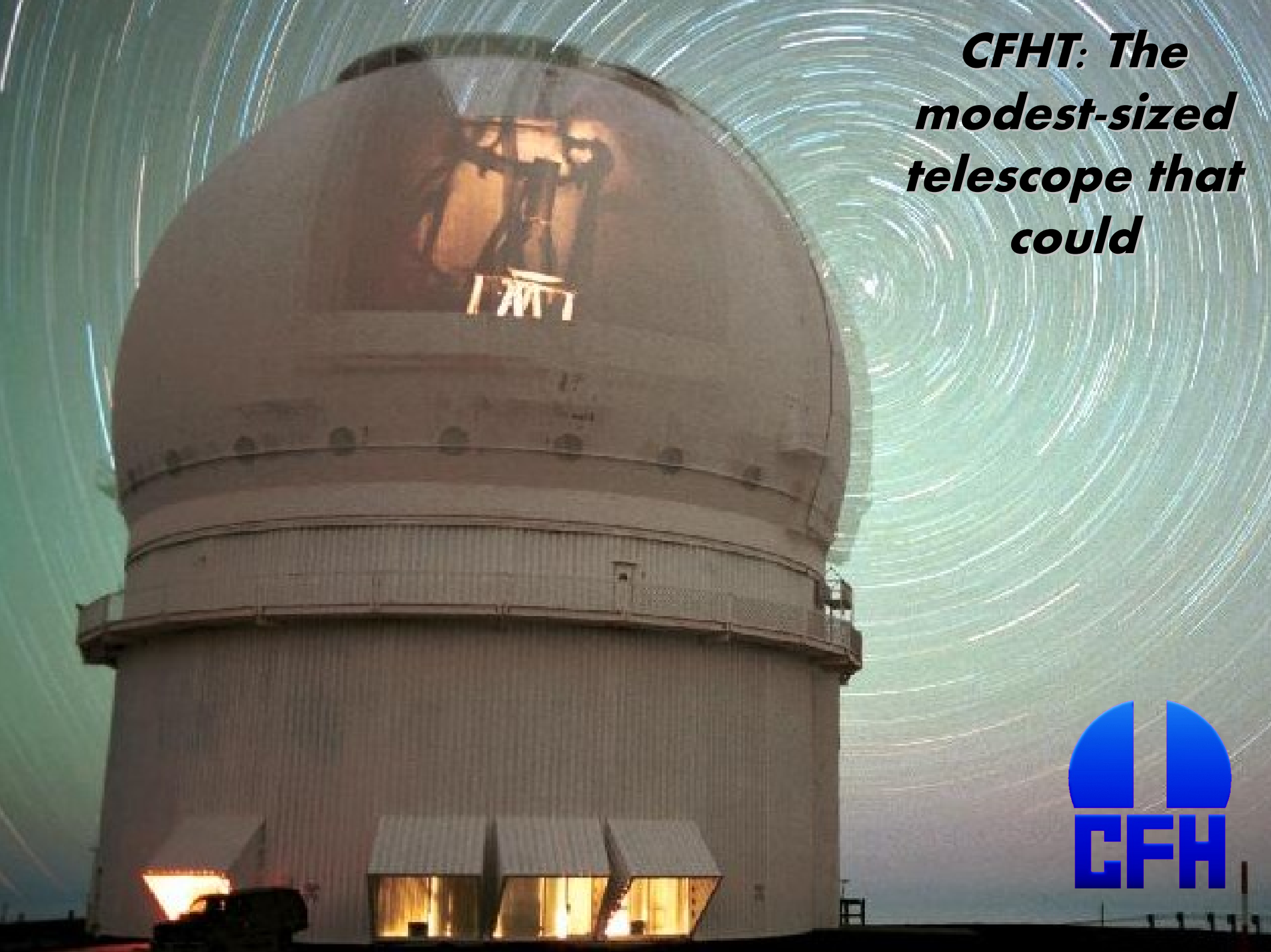
- The near-infrared J, H & K-bands are windows in the water opacity.
- Observations in these wavelengths are thus expected to probe much deeper depths and much greater pressures in the atmospheres of hot Jupiters.





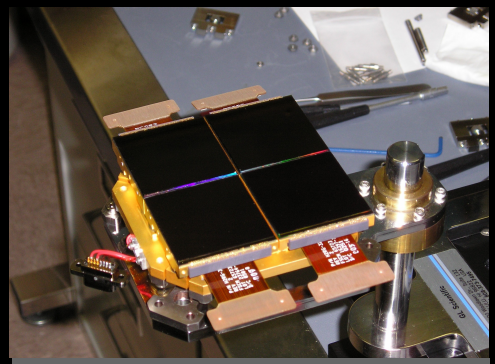
Left: The near-infrared J, H & Ks-bands are holes in the water opacity. Figure from Shabram et al. (2010).

Right: J, H & Ks-band observations probe much deeper pressures and thus deeper depths in the atmospheres of hot Jupiters than the Spitzer/IRAC Wavelengths. Figure from Barman et al. (2008).


CFHT: The modest-sized telescope that could
CFH

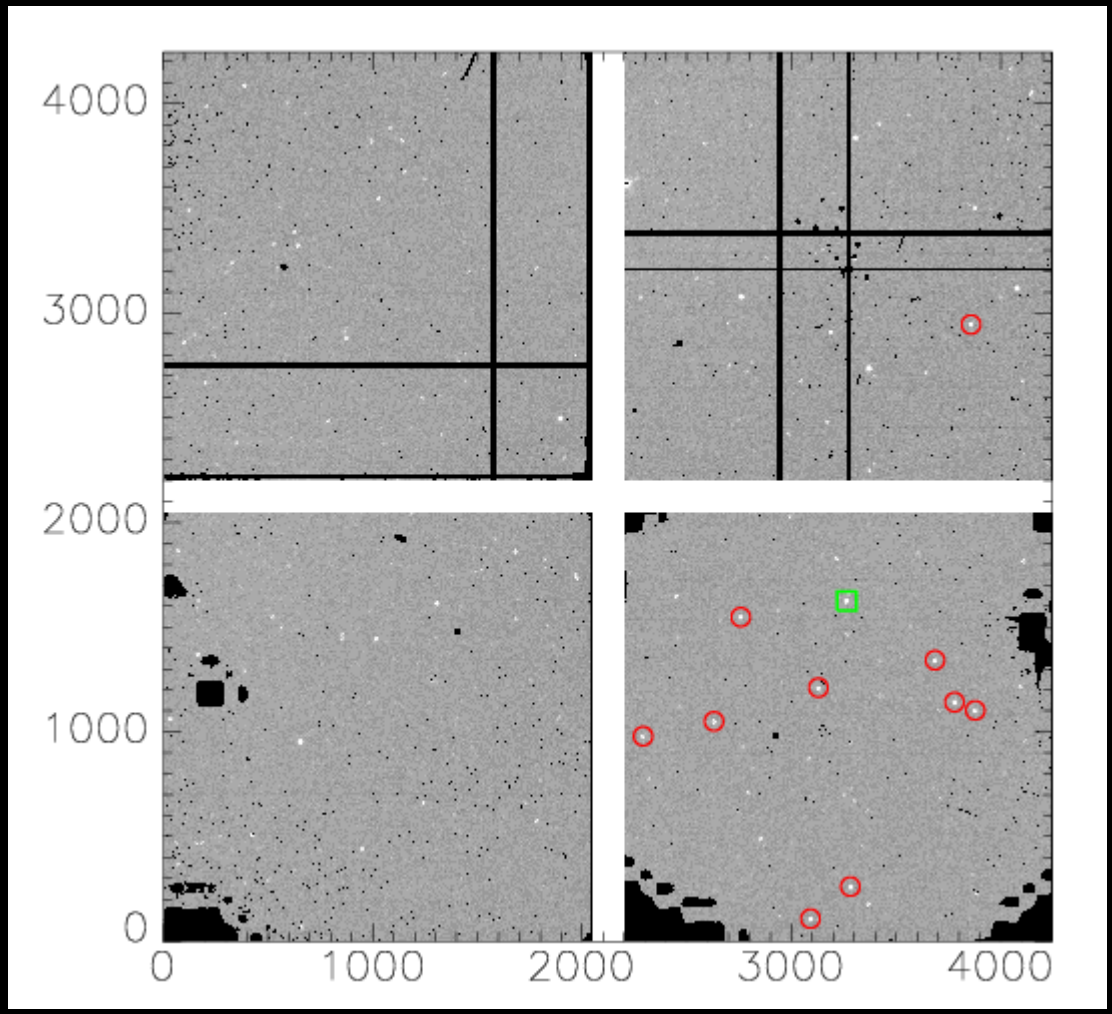
WIRCam Near-IR Defocused Photometry

- WIRCam is optimally suited for these observations as we are able to rapidly read-out the array to avoid saturation, and WIRCam has a wide field of view (21'x21') allowing us to simultaneously observe a great number of reference stars.



Right: The four chips that make up the Wide-field Infrared Camera (WIRCam).

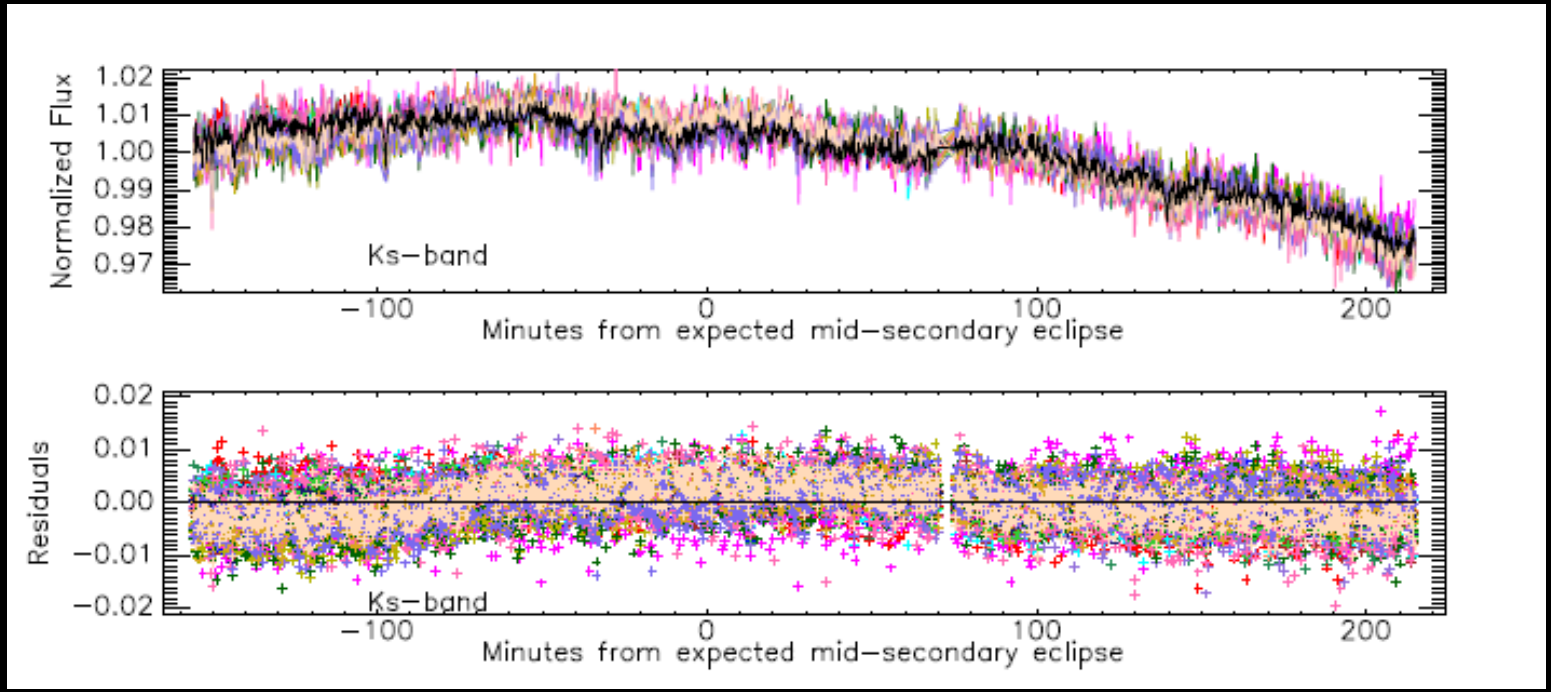
Bottom: We also observe significantly out of focus, so that the light is spread over a donut.



Top: TrES-2b (Green Square), and various reference stars used to correct our photometry (red circles).

Correcting the Raw Photometry

- We perform aperture photometry on the target star and all the suitably bright, unsaturated reference stars.
- We use the reference stars that display the smallest root-mean-square outside of occultation to correct our target for obvious systematic variations in intensity.
- The root-mean-square (RMS) improves from 14 mmag to 0.71 mmag per 1 minute for TrES-2b.

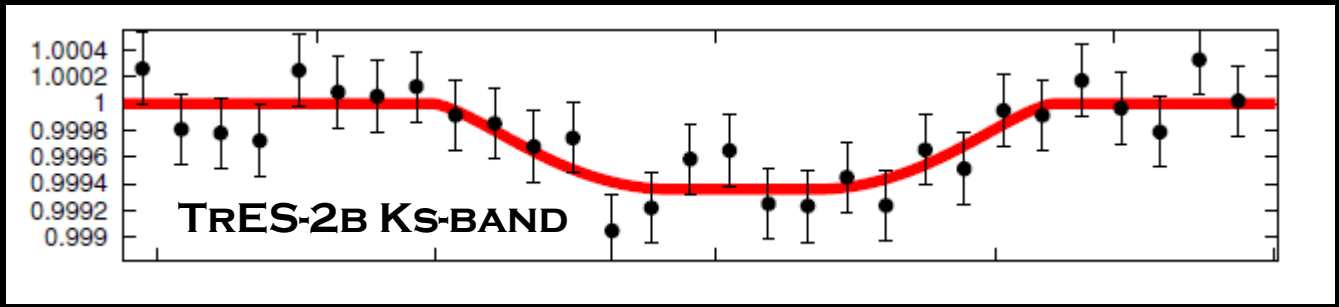


The flux and the residuals of the target star (black), and the reference stars (various colours).

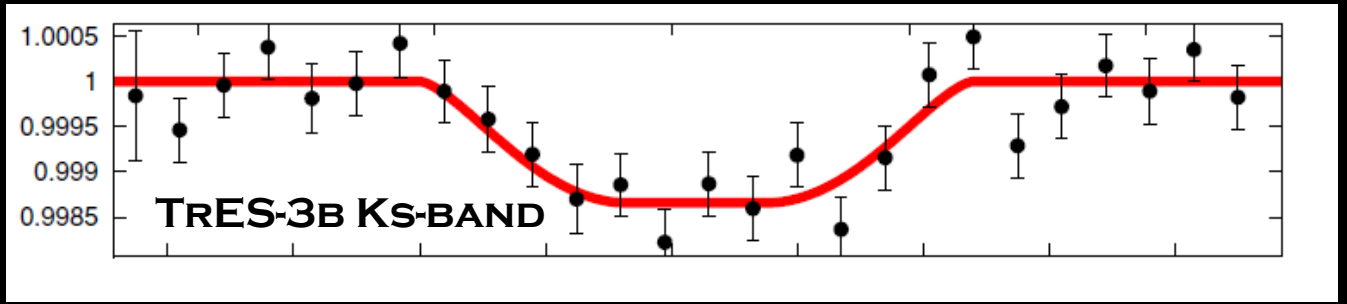
WIRCam Near-IR Detections

Croll et al. (2010a,b,in Prep.)

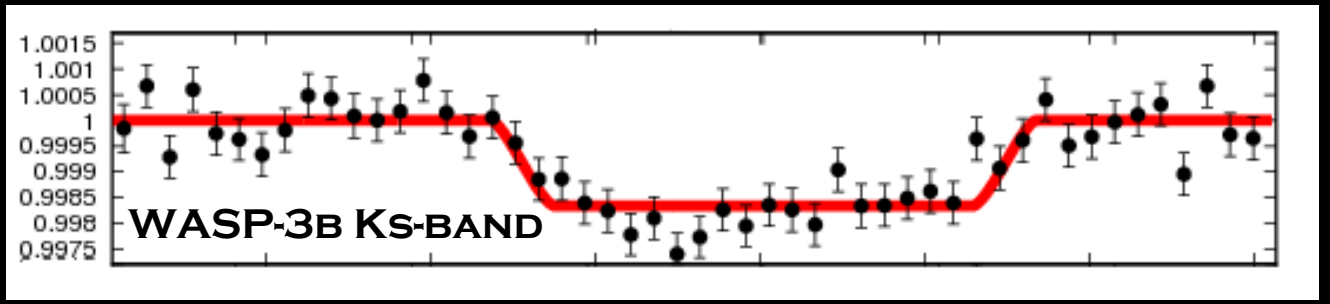
- A 5σ detection of the Ks-band (2.15 micron) thermal emission of TrES-2b equal to $6x10^{-4}$.



- A 8σ detection of the Ks-band thermal emission of TrES-3b ($13x10^{-4}$), and an upper limit on its H-band thermal emission.



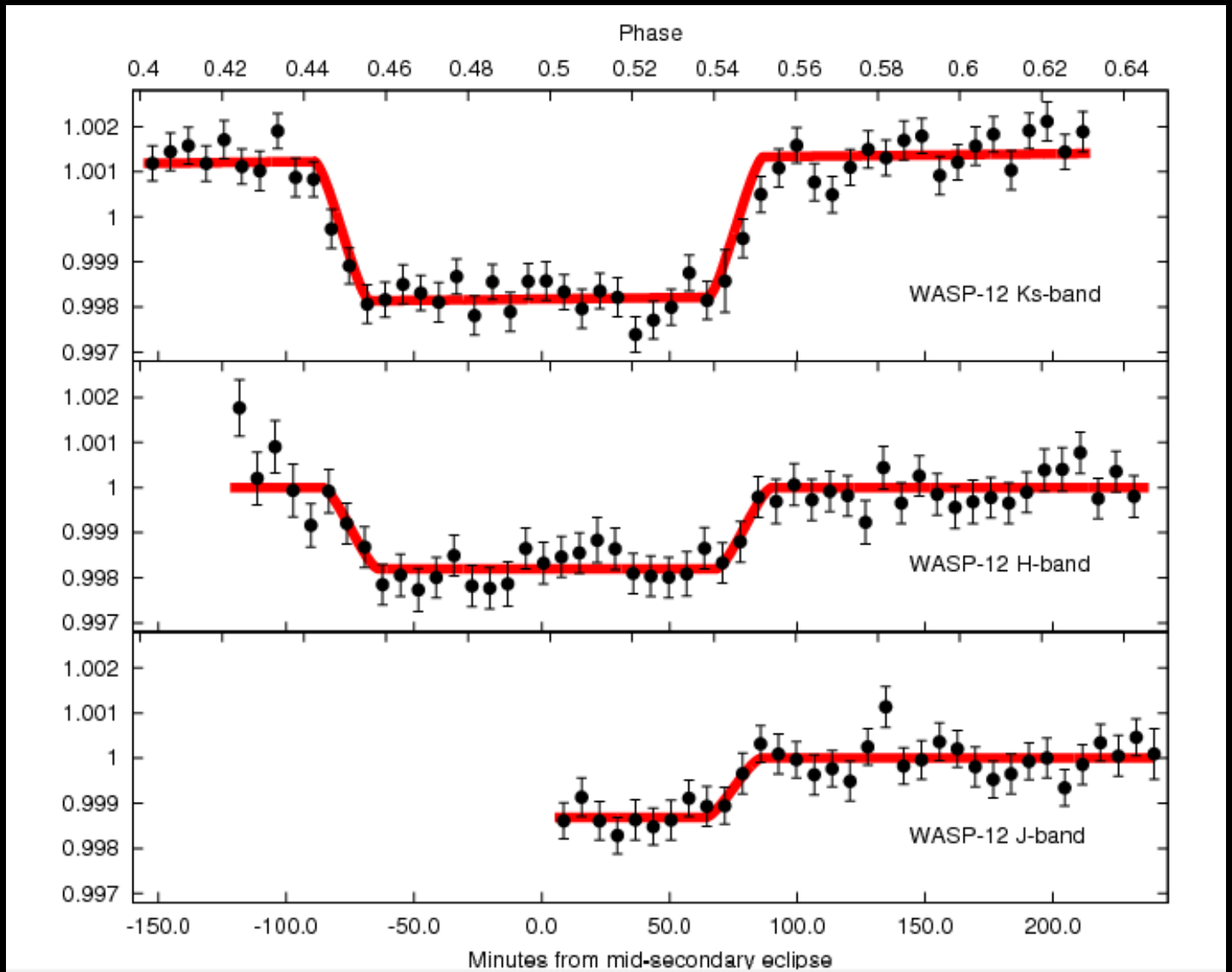
- Two detections (12σ total) of the Ks-band thermal emission of WASP-3b.



WASP-12b in J, H & Ks

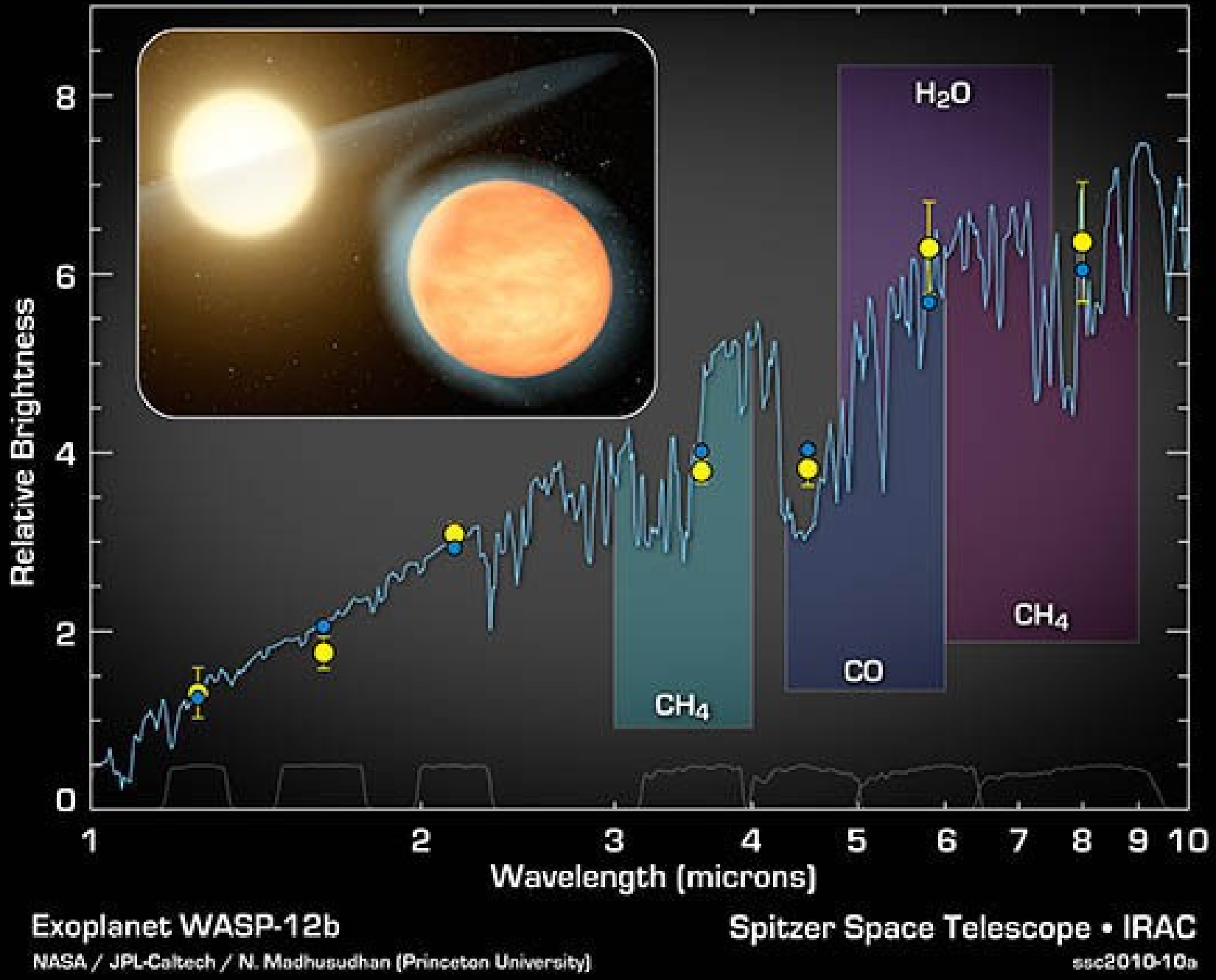
Croll et al. 2011

- We observed a partial eclipse in J-band (1.25 microns) and two full eclipses in H (1.6 microns) and Ks-band (2.15 microns) of the highly irradiated hot Jupiter WASP-12b. We achieved 4-24σ detections of its thermal emission in these bands.



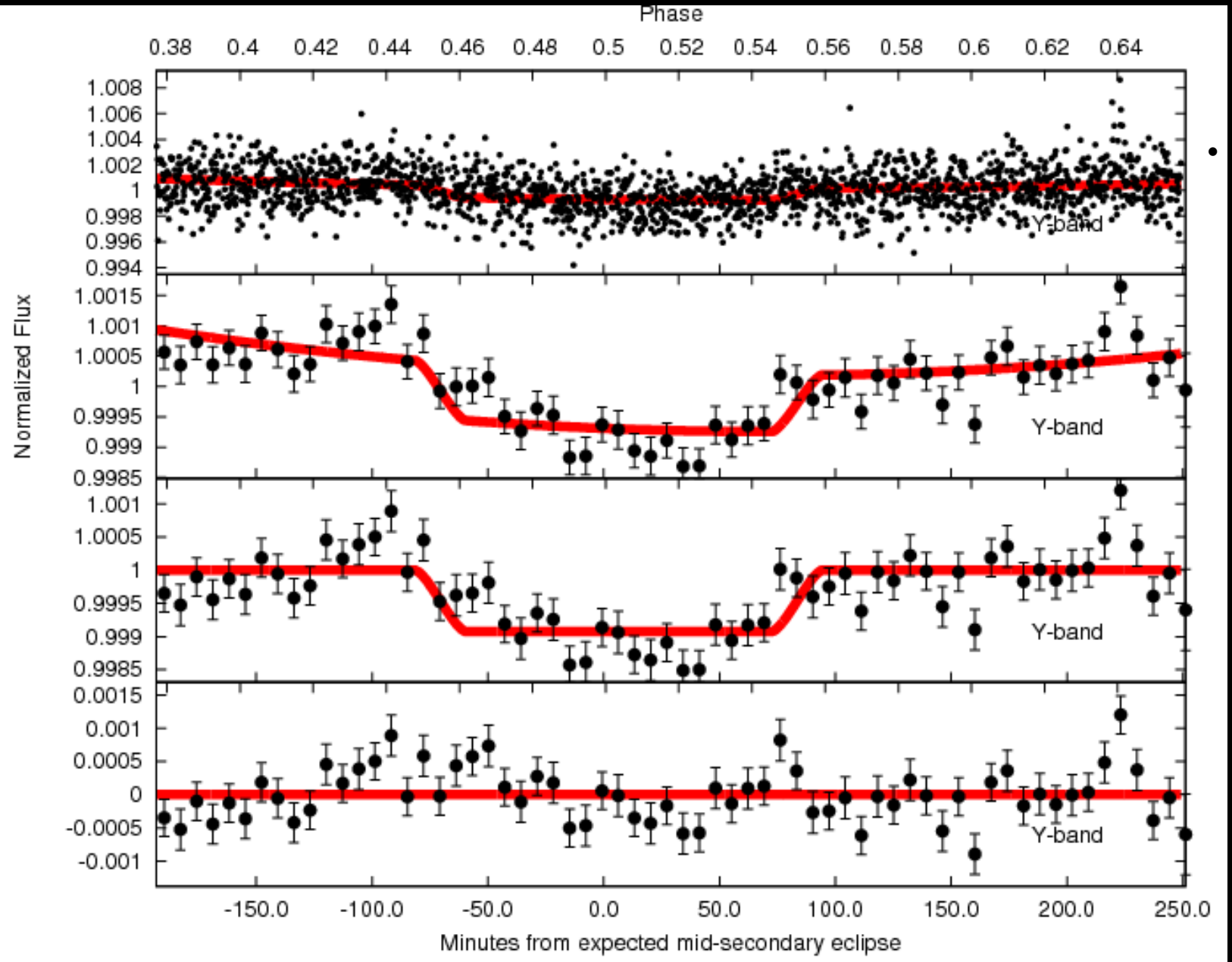
A Carbon-rich Planet?

Madhusudhan et al. 2011



WASP-12 Y-band Eclipse

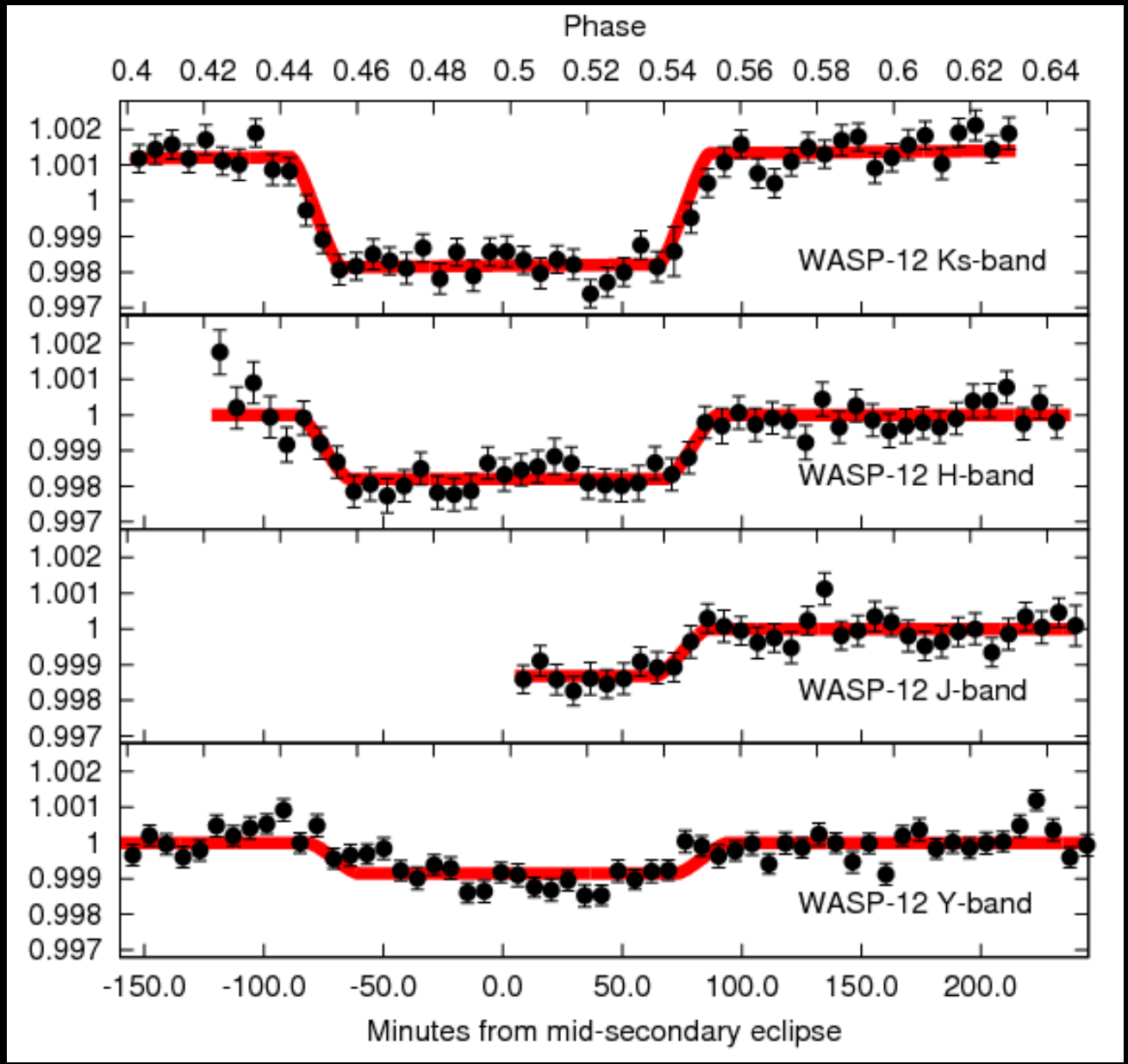
Croll et al. In Prep.



- Top: the unbinned photometry.
- Second from top: the binned photometry.
- Second from bottom: the binned photometry after subtracting the background.
- Bottom: residuals from the best-fit eclipse.

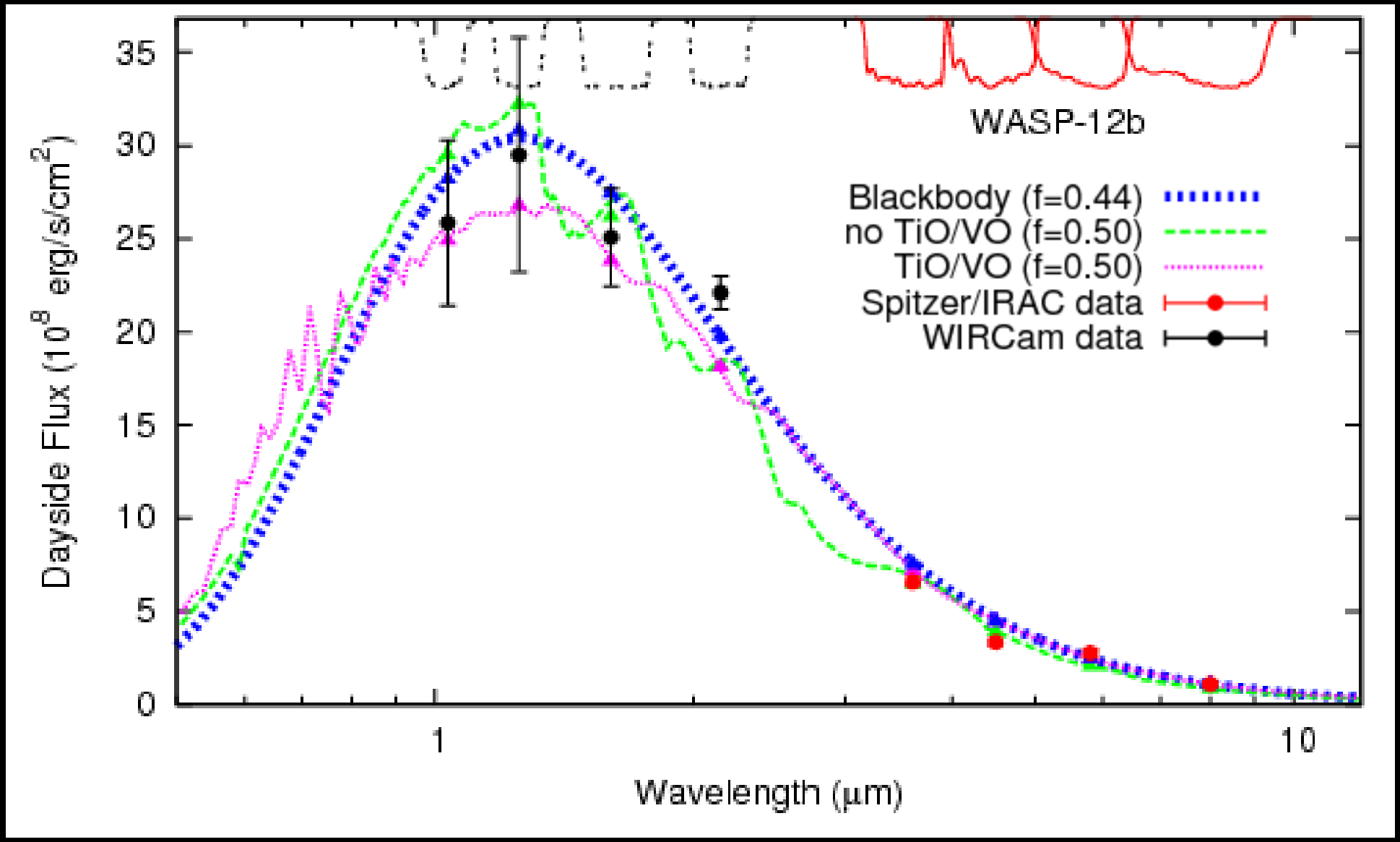
The New WASP-12b Near-IR Family Portrait

Croll et al. In Prep.

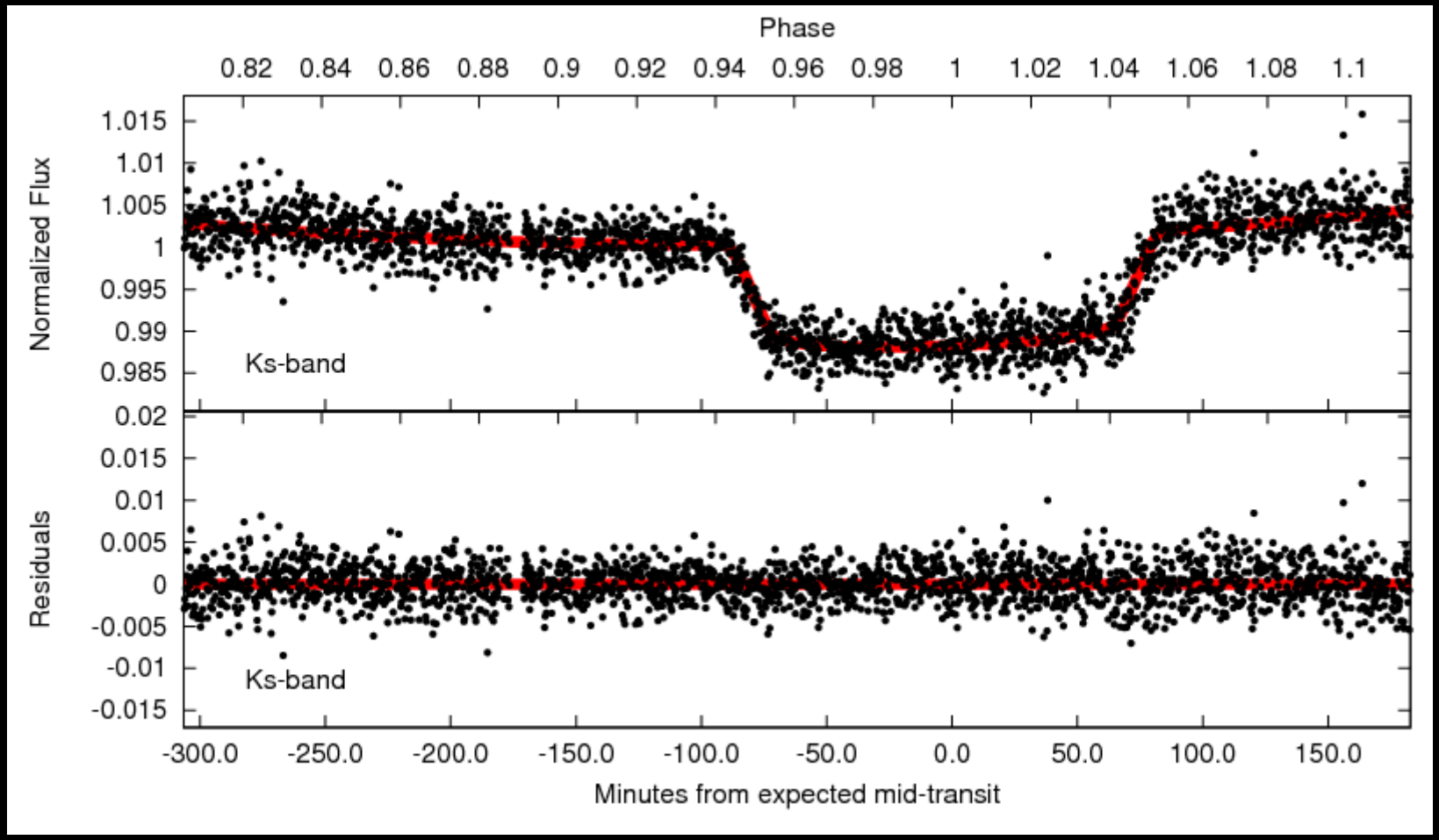


WASP-12 Redux

Croll et al. In Prep.



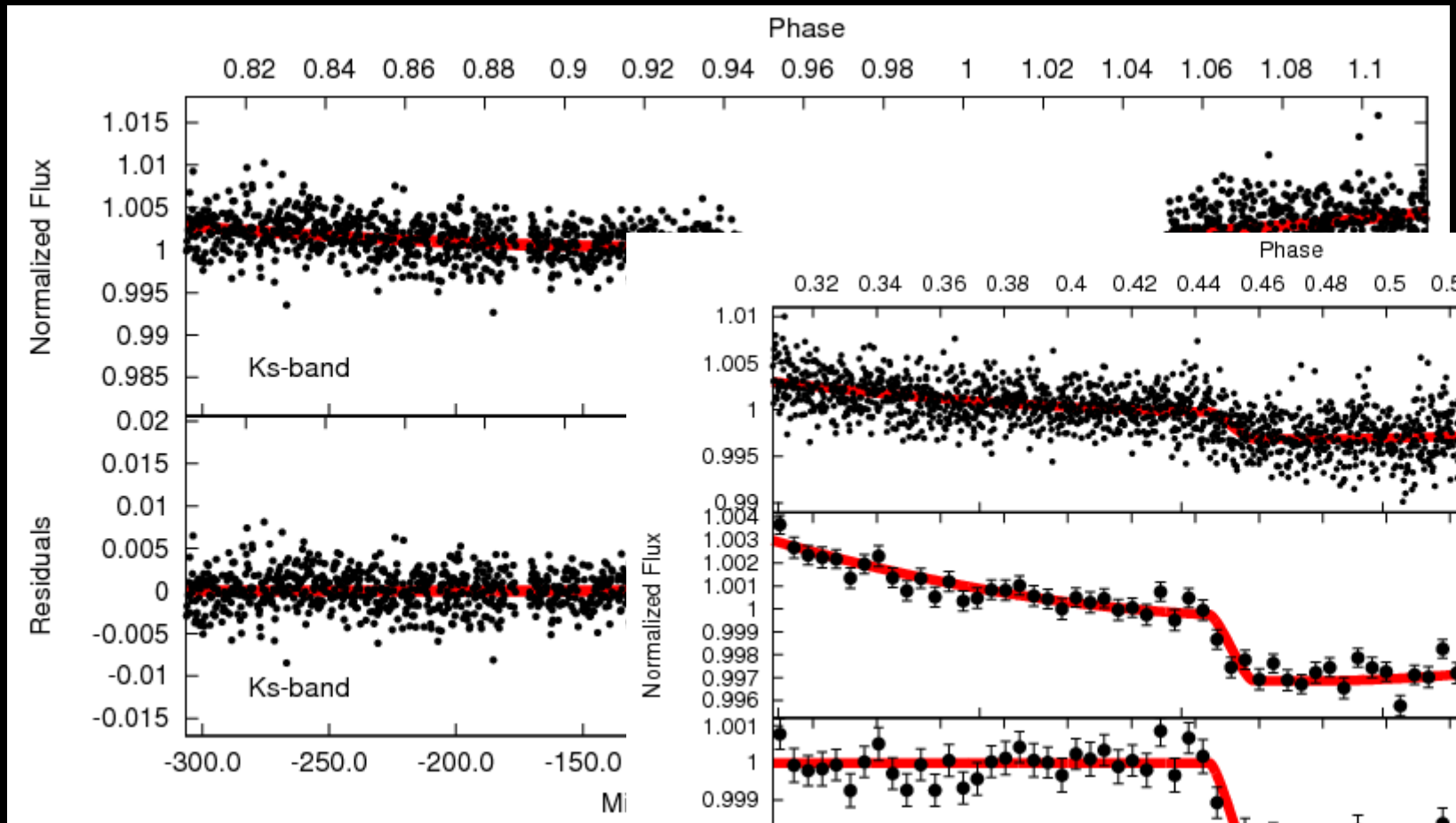
WASP-12 Phase Curve?
Croll et al. In Prep.

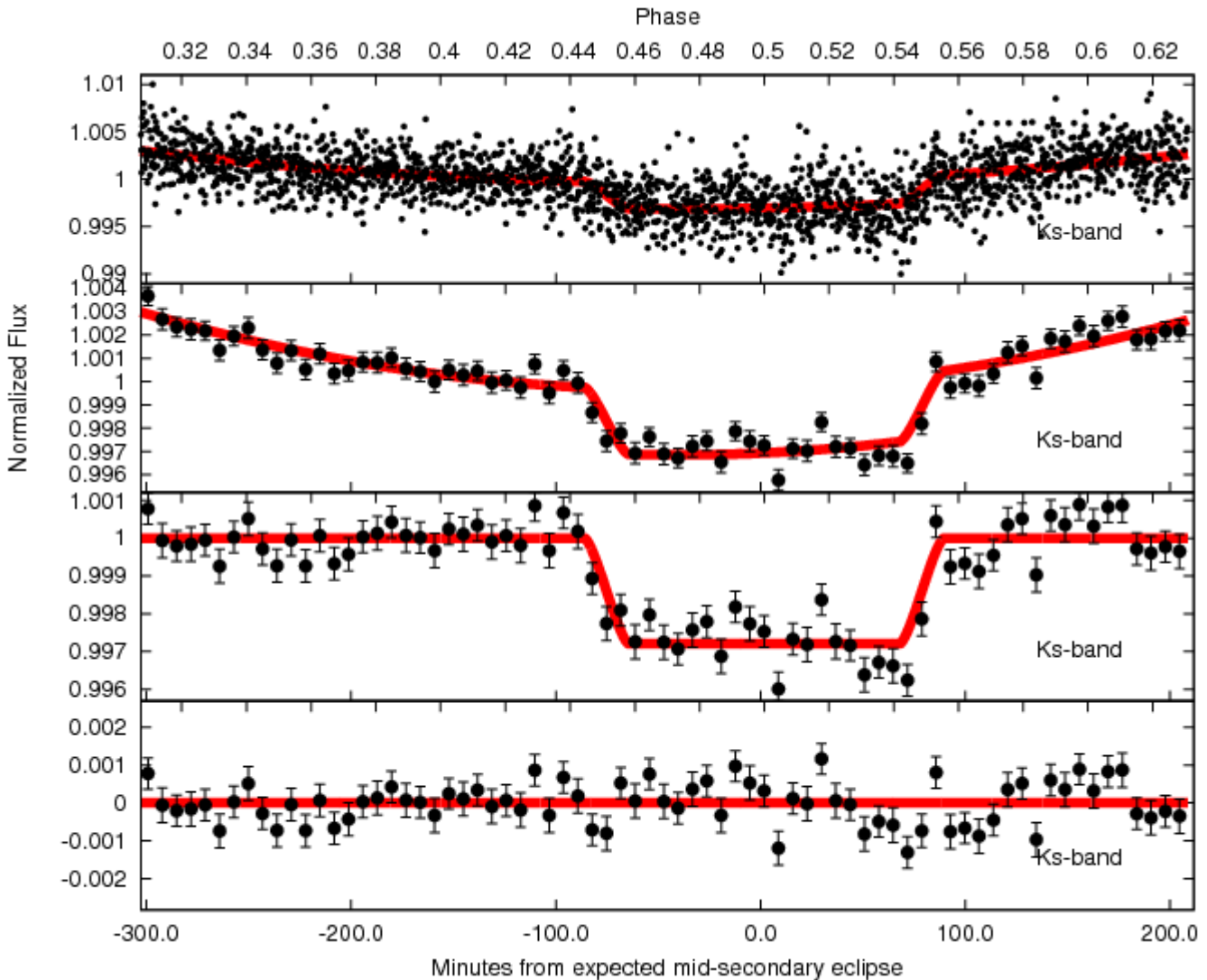


- A Ks-band transit of WASP-12b

WASP-12 Phase Curve?

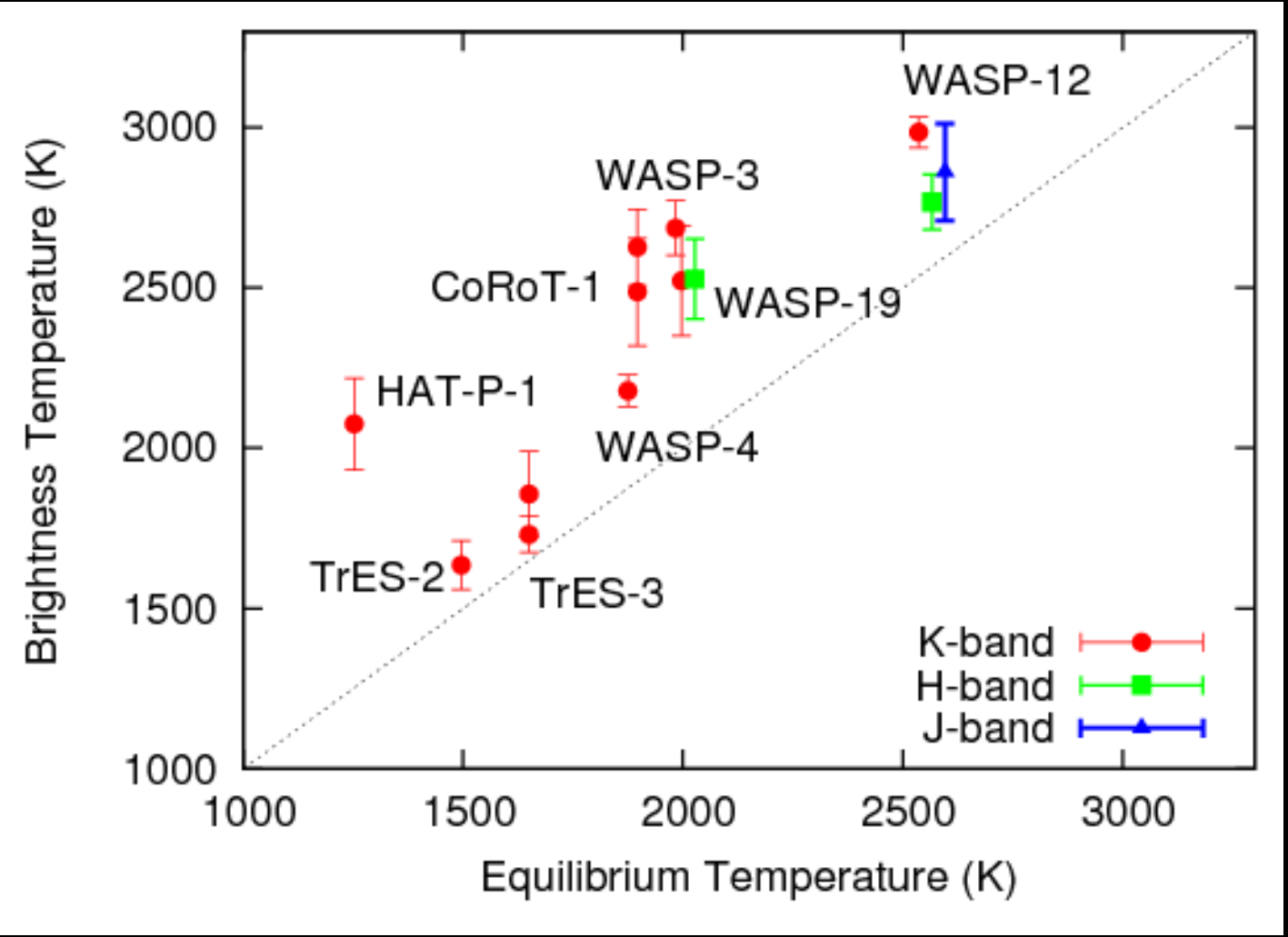
Croll et al. In Prep.





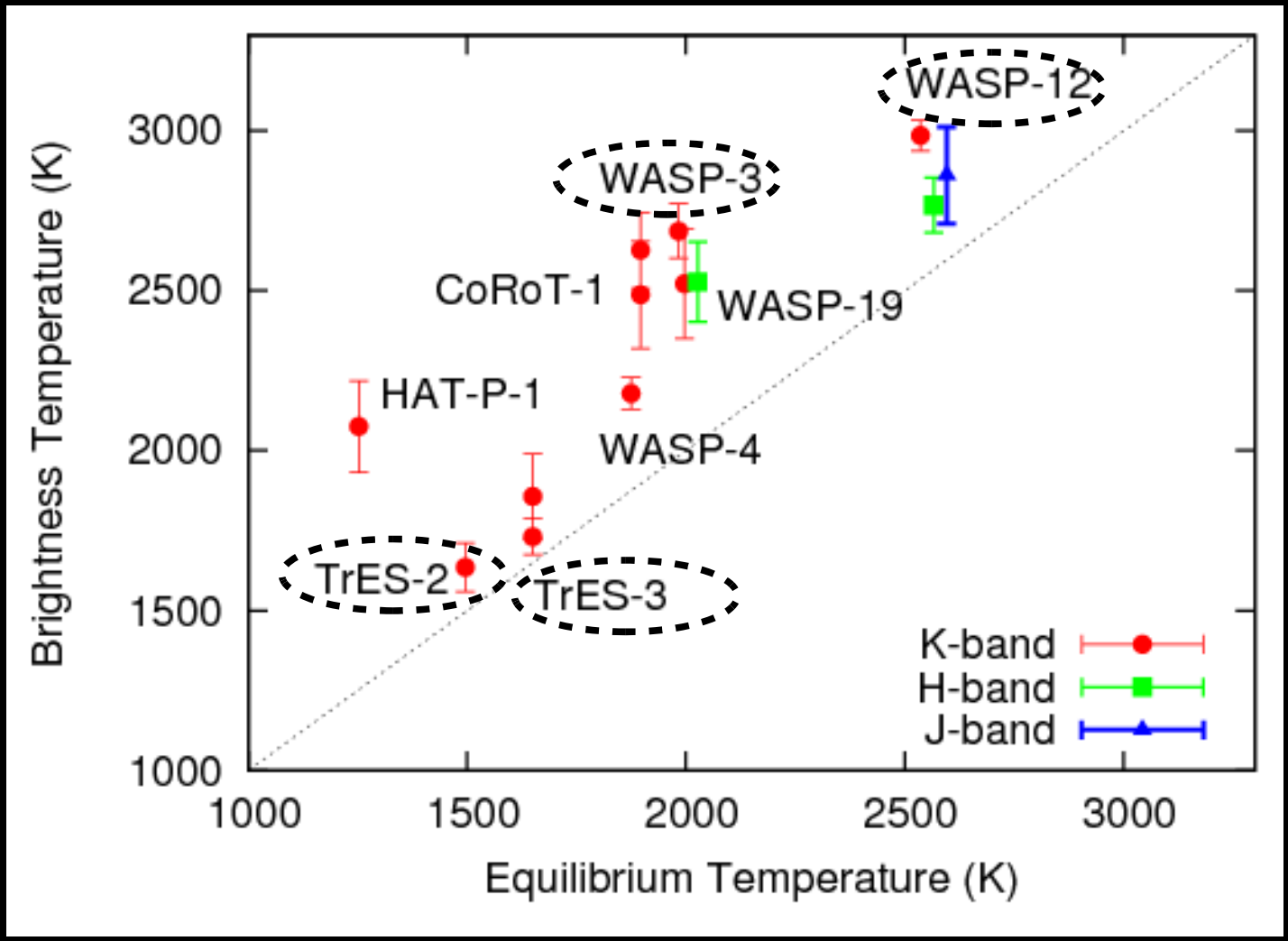
- A Ks-band transit of WASP-12b.
- Another Ks-band eclipse of WASP-12b.

Overview of Near-IR (JHK) Detections



Brightness temperature of the thermal emission of hot Jupiters in the JHK bands. Detections from: de Mooij & Snellen (2009), Rogers et al. (2009), Gillon et al. (2009), Anderson et al. (2010), Gibson et al. (2010), , Croll et al. (2010a,b,2011, in prep.), de Mooij et al. 2011, Caceres et al. 2011. The various Swain et al. Results are excluded.

Overview of Near-IR (JHK) Detections



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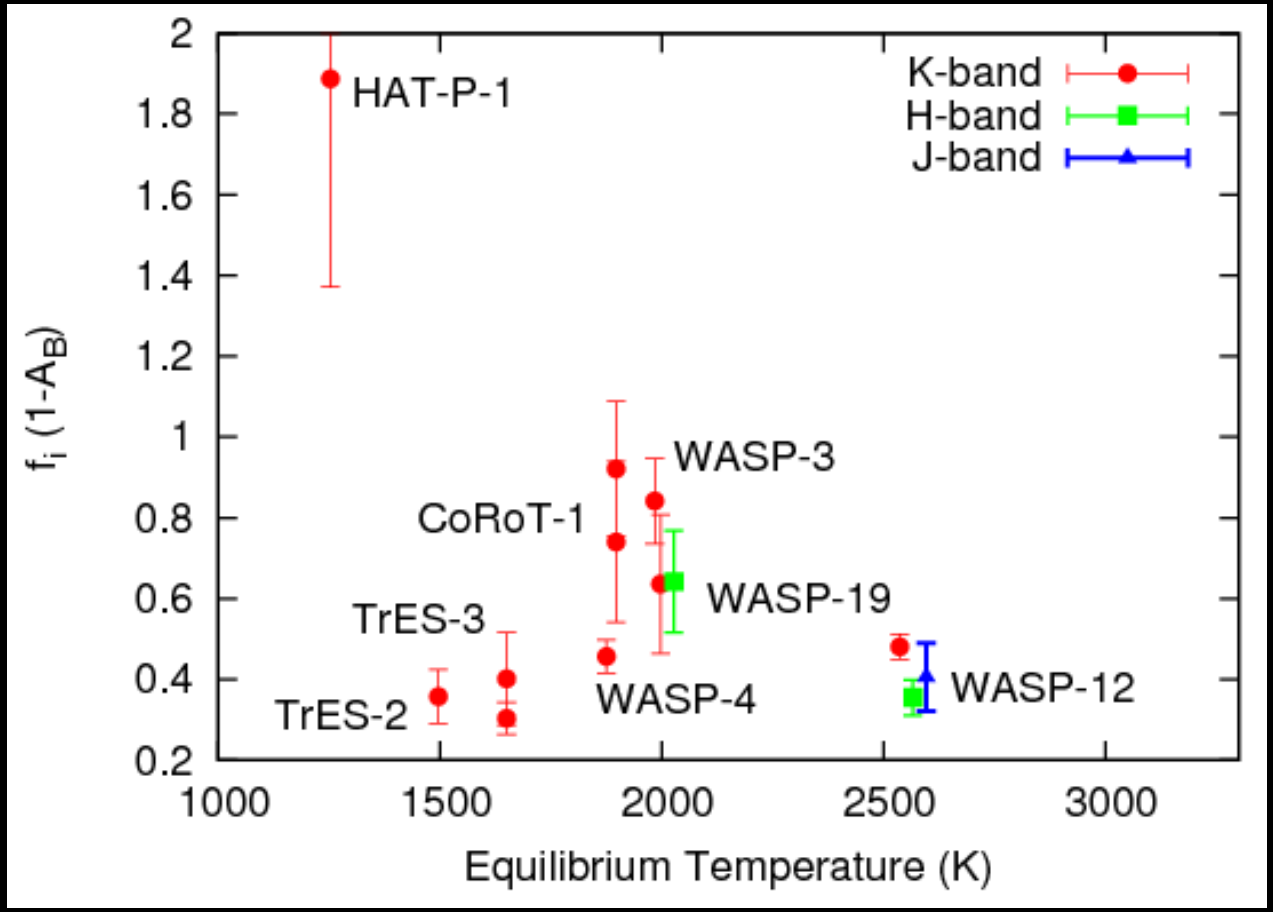
Overview of Near-IR (JHK) Detections

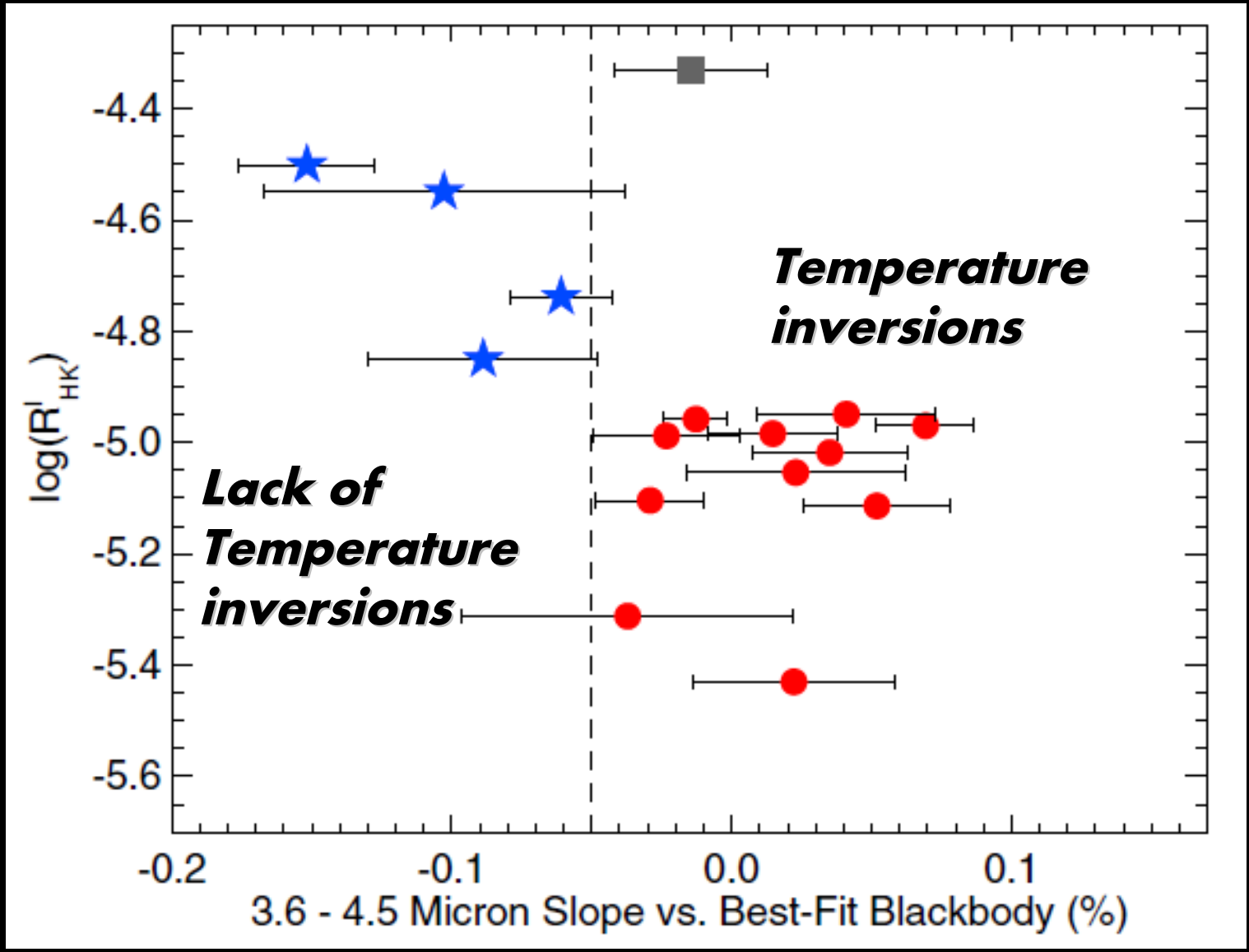
$$T_B = T_* \left(\frac{R_*}{a}\right)^{1/2} [f_i(1 - A_B)]^{1/4},$$



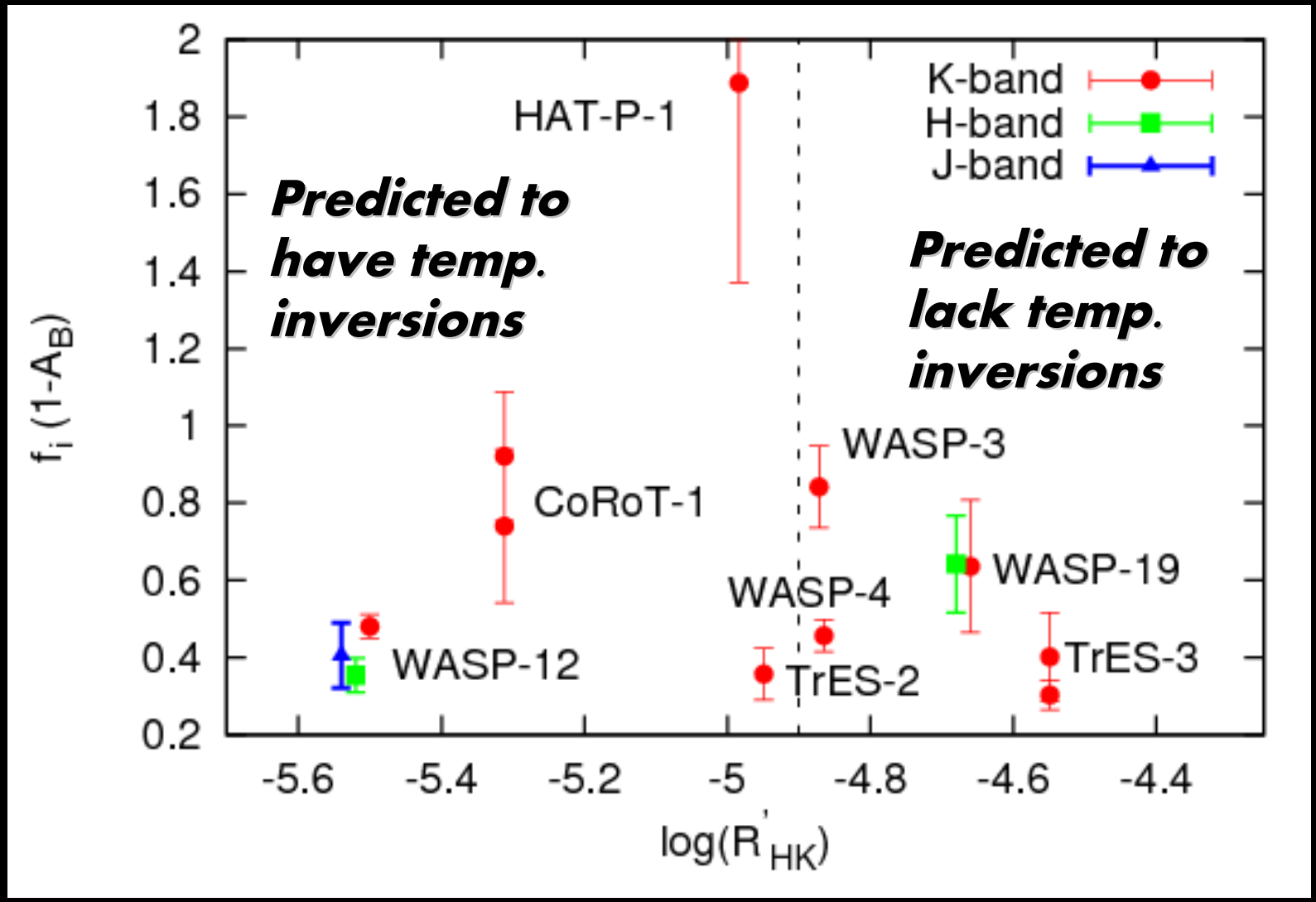
The reradiation factor (f) of the thermal emission of hot Jupiters in the JHK bands. Detections from: de Mooij & Snellen (2009), Rogers et al. (2009), Gillon et al. (2009), Anderson et al. (2010), Gibson et al. (2010), , Croll et al. (2010a,b,2011, in prep.), de Mooij et al. 2011, Caceres et al. 2011. The various Swain et al. results are excluded.

Correlation of Temperature Inversions with Activity

Knutson et al. (2010)

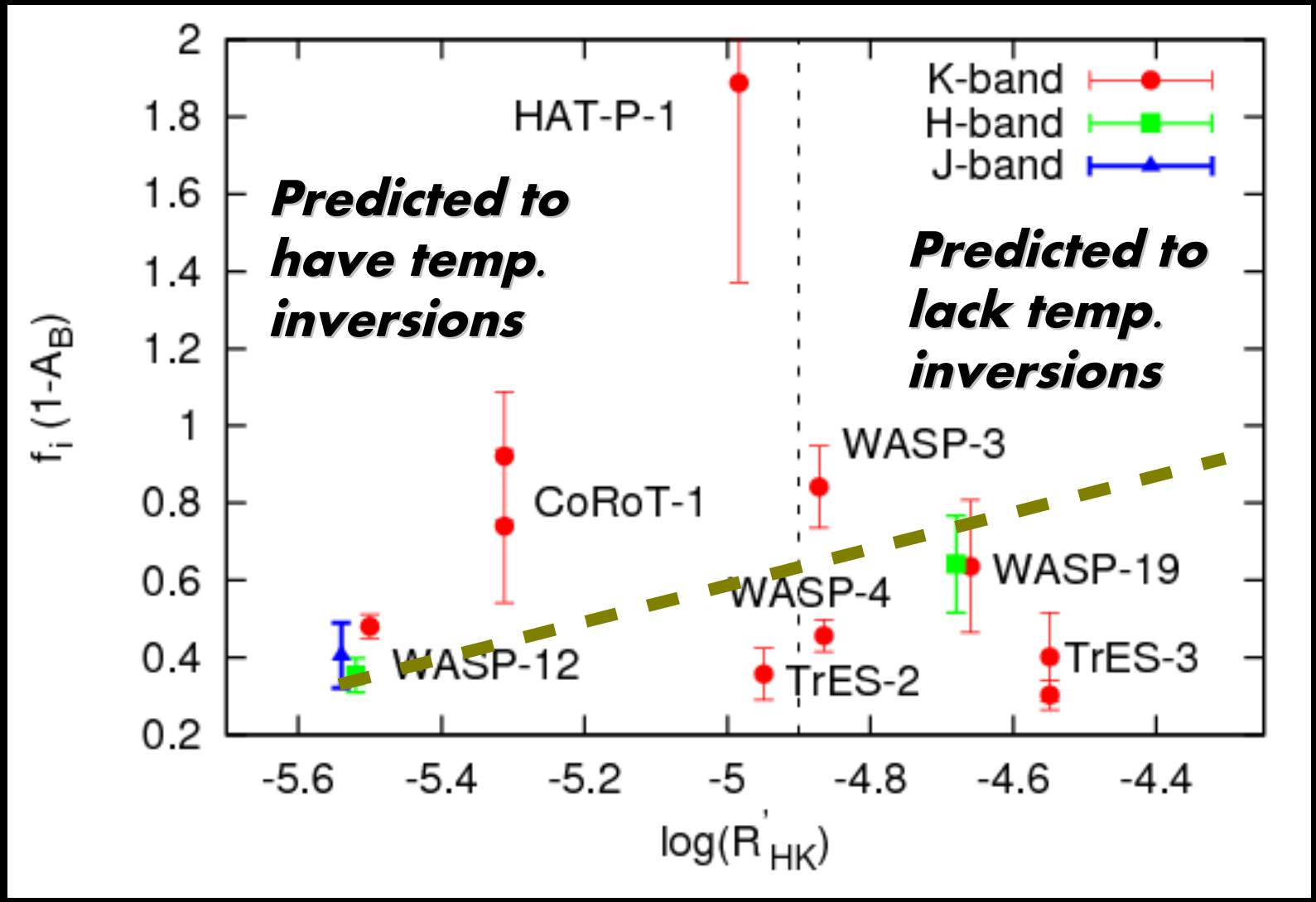


Overview of Near-IR (JHK) Detections



The reradiation factor (f) versus the Ca II H & K activity index: de Mooij & Snellen (2009), Rogers et al. (2009), Gillon et al. (2009), Anderson et al. (2010), Gibson et al. (2010), , Croll et al. (2010a,b,2011, in prep.), de Mooij et al. 2011, Caceres et al. 2011. The various Swain et al. Results are excluded.

Overview of Near-IR (JHK) Detections



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Near-infrared observations suggest the atmosphere of GJ 1214b may have a low mean molecular weight

Croll et al. (2011)

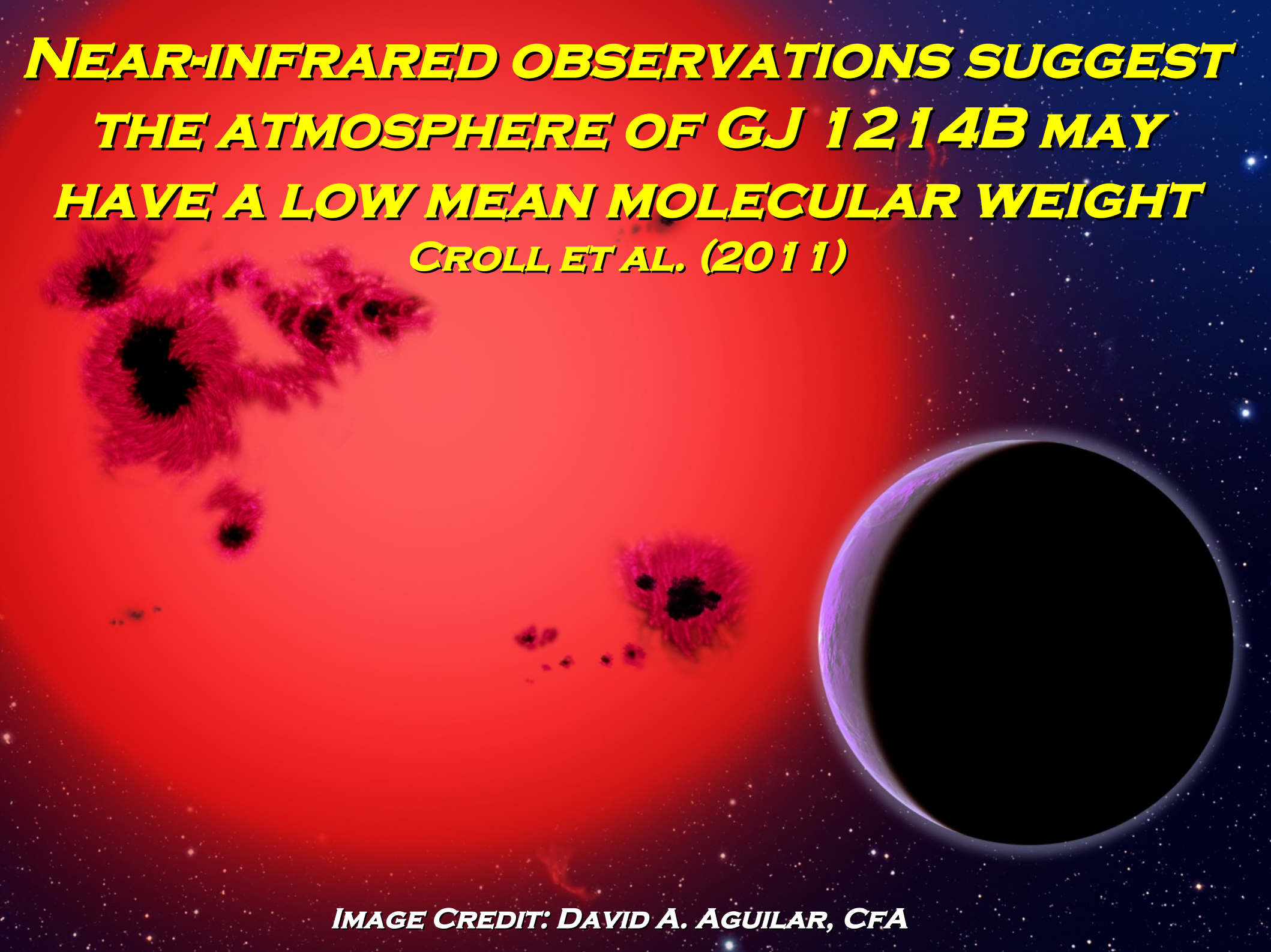
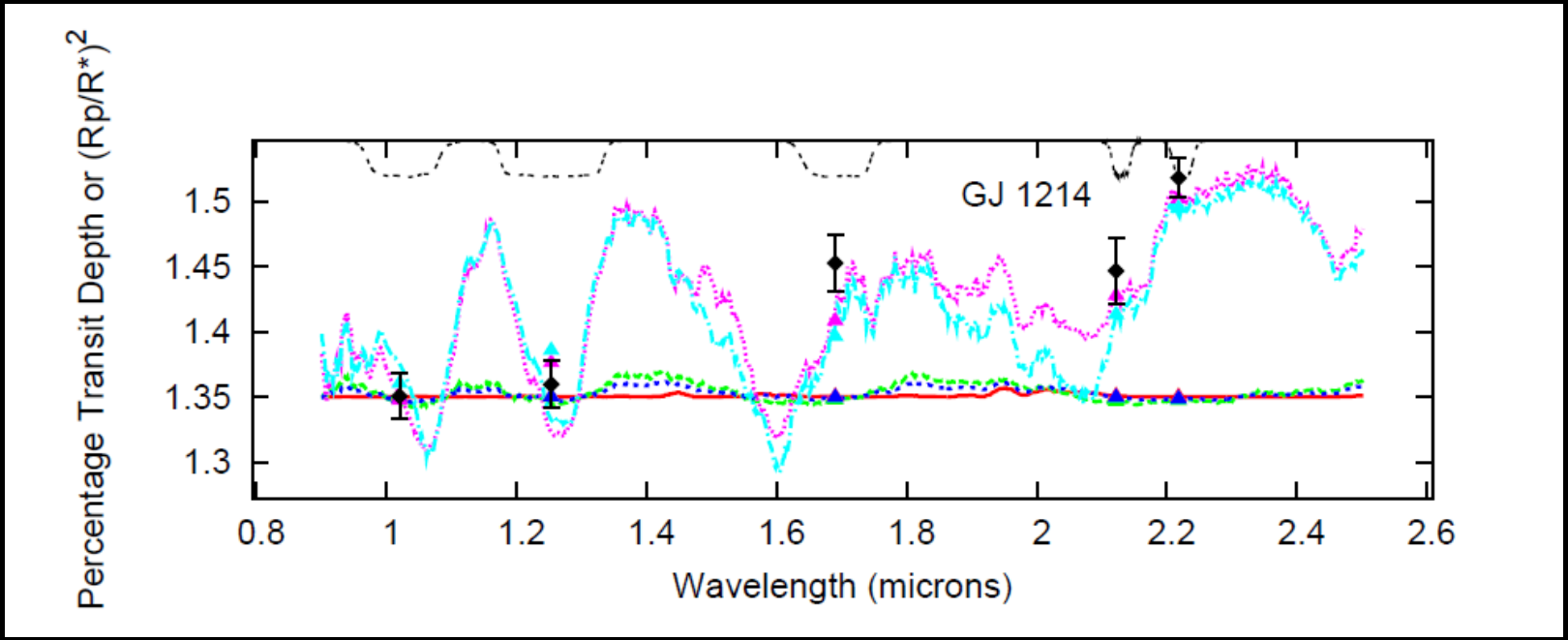


Image Credit: David A. Aguilar, CfA

Spectral Features in the Near-IR

- GJ 1214b was predicted to have prominent spectral features in the near- and far-infrared (Miller-Ricci & Fortney 2010).
- Depending on the composition of GJ 1214b these features were predicted to be readily detectable (for a hydrogen/helium atmosphere) or very difficult (for heavier mean molecular compositions).

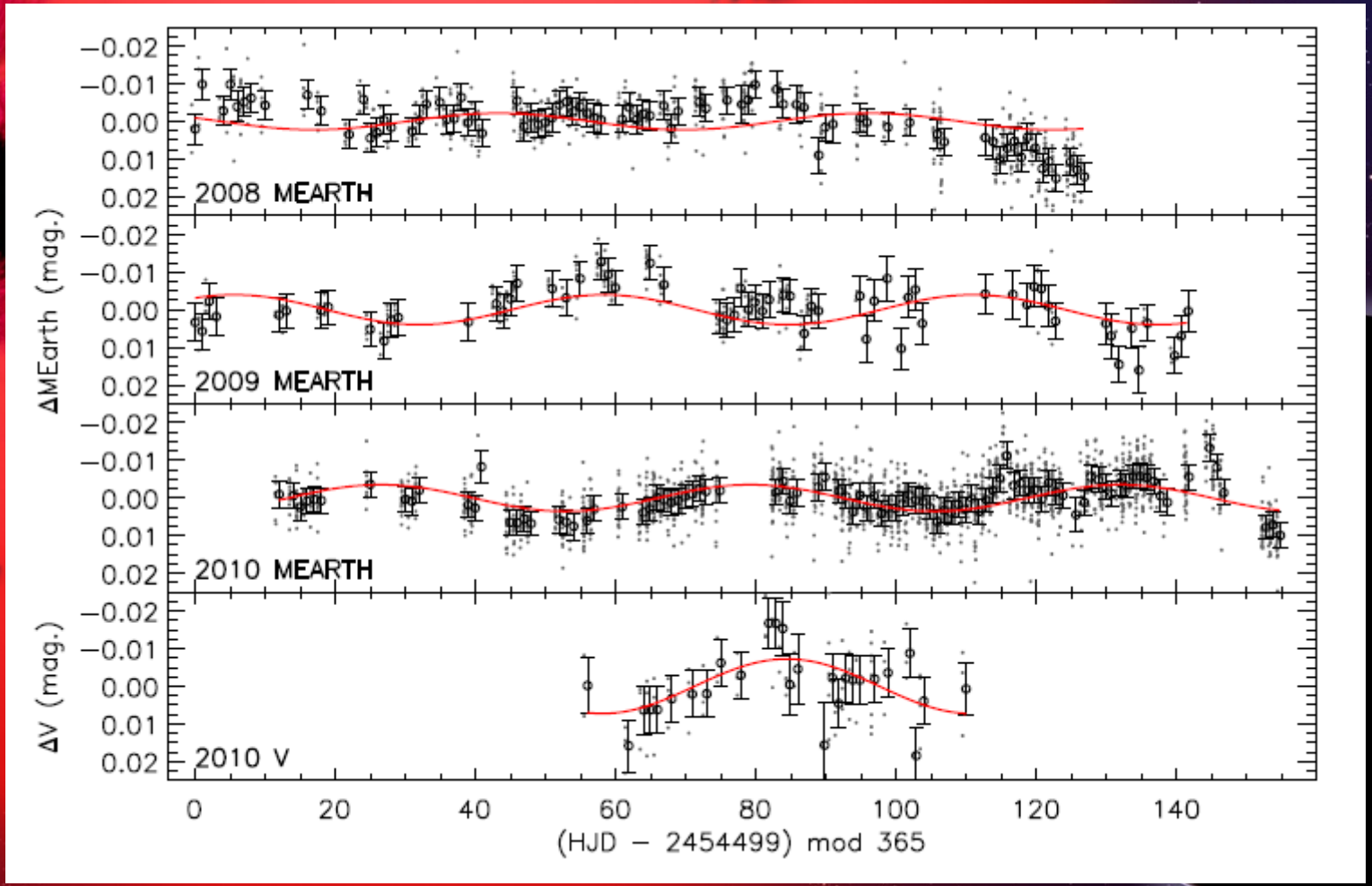


$$H = \frac{kT}{Mg}$$

Predicted spectral features for a Hydrogen/Helium dominated atmosphere (cyan & Magenta curves) and for heavier elemental compositions such as a Water-world (Green Curve). The black points were our predicted precision with WIRCam.

Effects due to Spots?

- Transit depth measurements obtained at different epochs will display slighted different depths due to rotational modulation if the flux of the star varies from epoch to epoch.



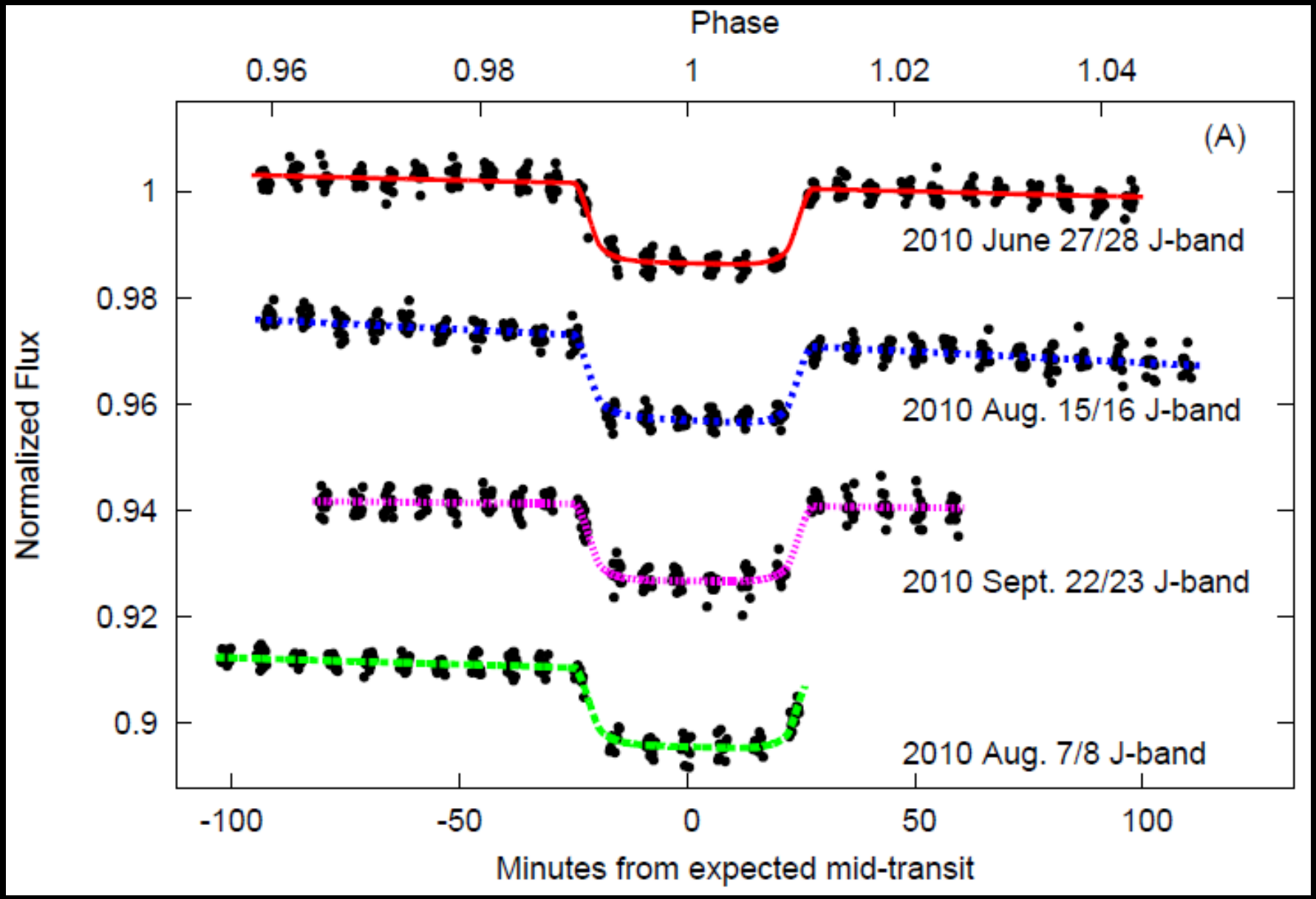
Above: rotational modulation observed on GJ 1214 (Berta et al. 2010).

Image Credit: David A. Aguilar, CfA

Near-IR photometry of GJ 1214b

Croll et al. 2011

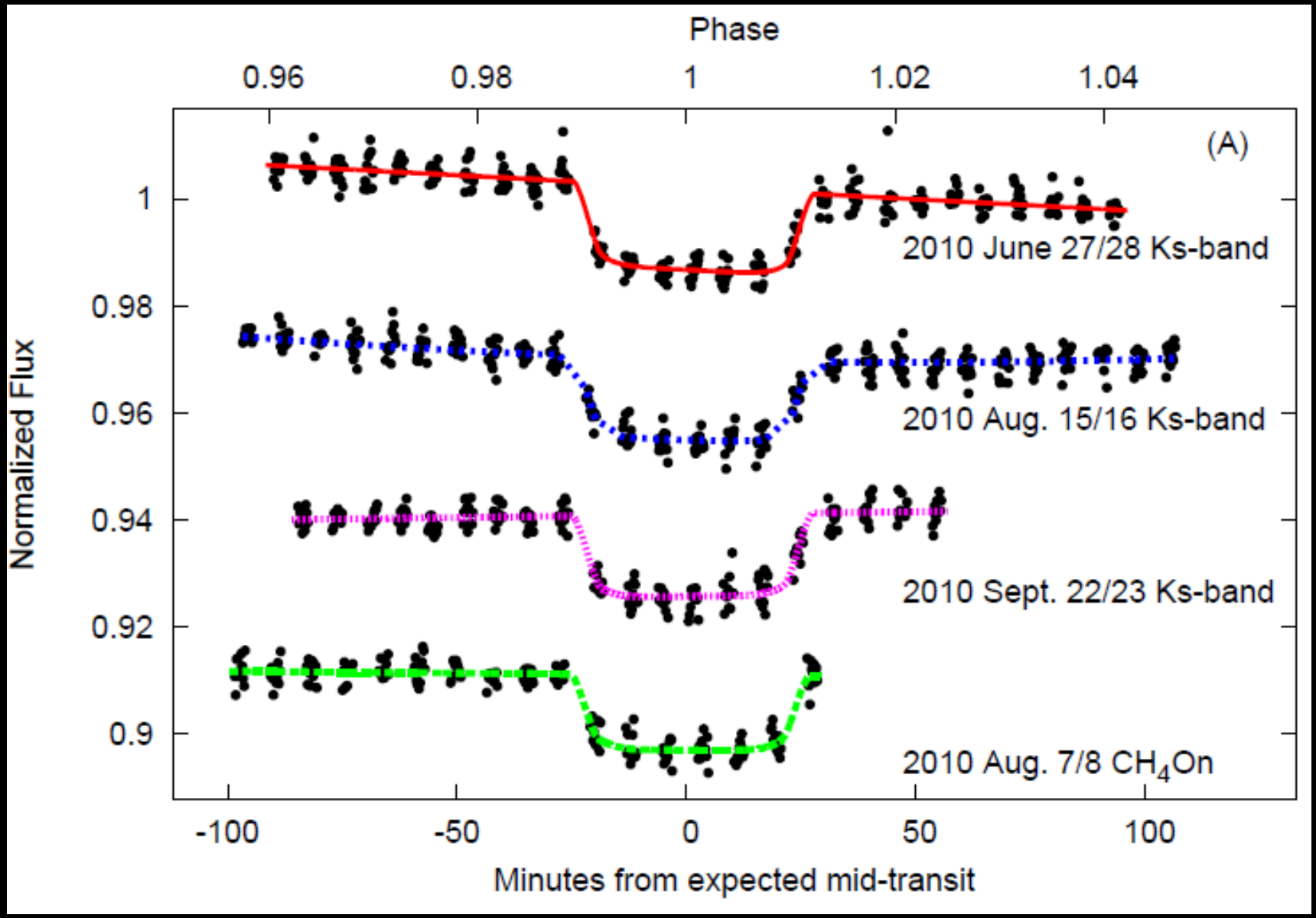
- We observed four transits of GJ 1214b in J-band (1.25 microns) and nearly simultaneously in another band.



Near-IR photometry of GJ 1214b

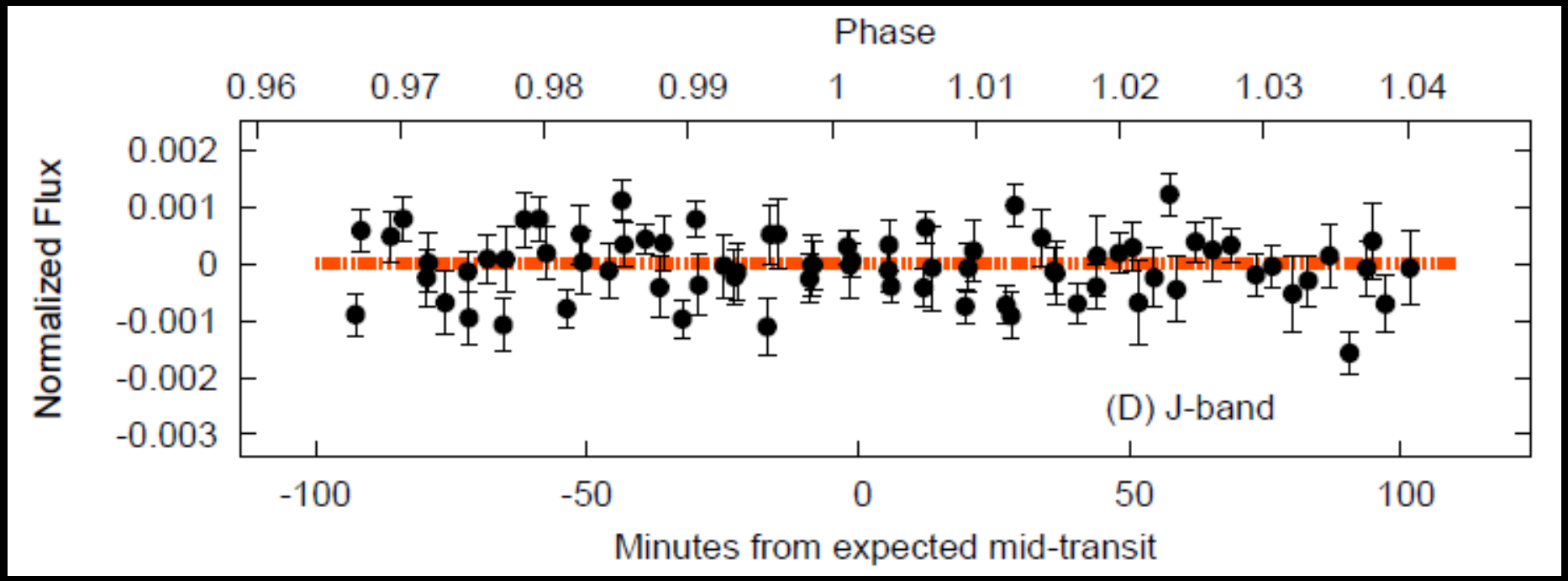
Croll et al. 2011

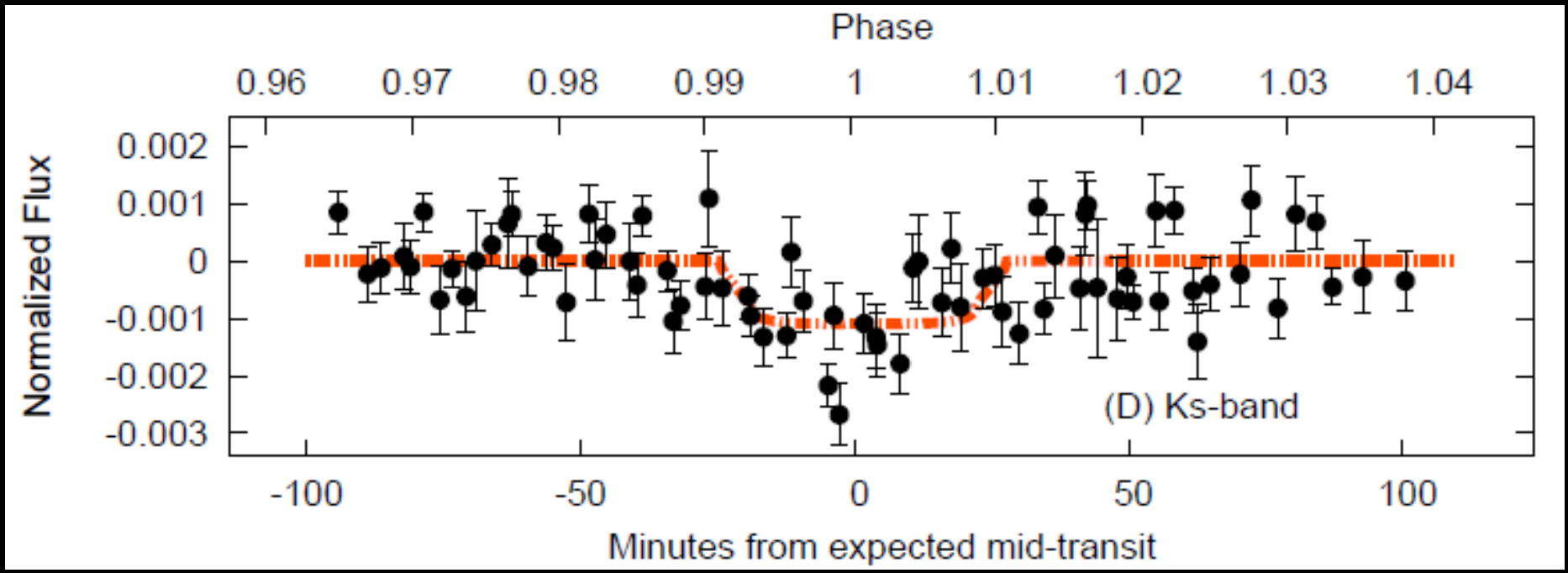
- We observed three transits in Ks-band (2.15 microns) and one transit in the CH_4On filter (1.69 microns).



Extra Absorption in Ks-band?

Croll et al. 2011

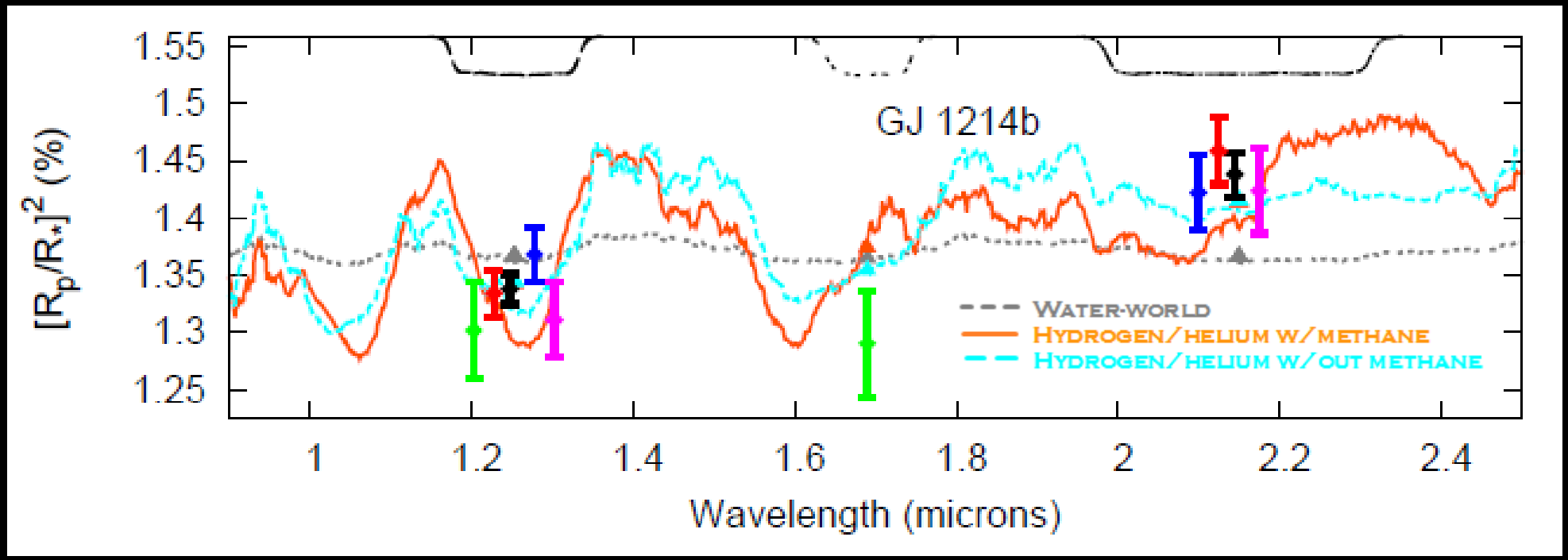




GJ 1214b has a low mean molecular weight

Croll et al. submitted

- Our observations argue for a greater transit depth in Ks-band than in J-band (4σ detection).
- A spectral feature this large is only possible if its atmosphere has a large scale-height, a low mean molecular weight, and thus a hydrogen/helium dominated atmosphere.
- Terrestrial atmospheres are ruled out at >2σ.



The best-fit transit depths from our analysis. The black points are the weighted mean of the J and Ks-band observations. Each coloured set of points was observed simultaneously.

A Steamy super-Earth?

- Bean et al. (2010) presented exquisite VLT photometry and argued that GJ 1214b is either a cloudy/hazy hydrogen/helium dominated planet or a water-world...

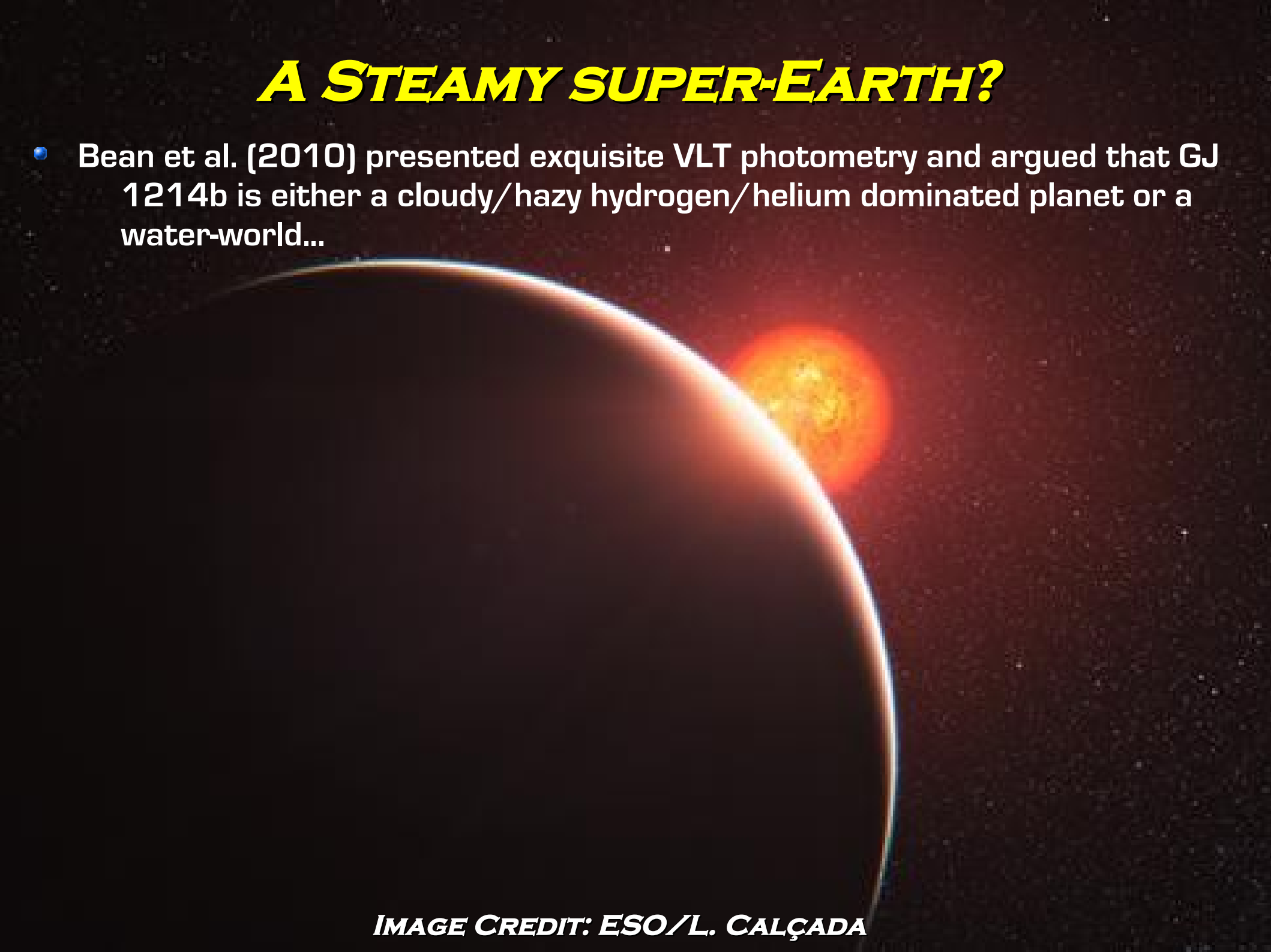
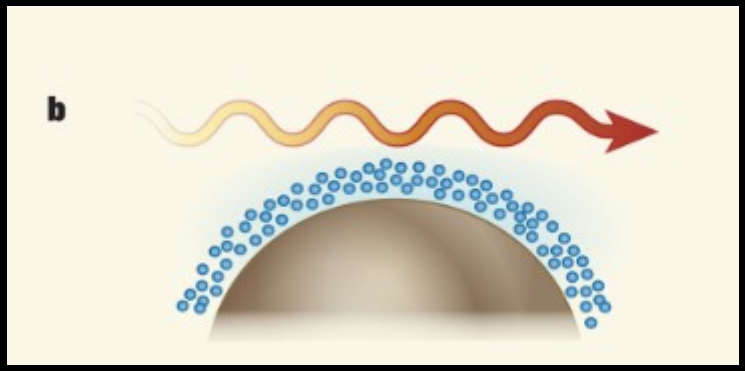
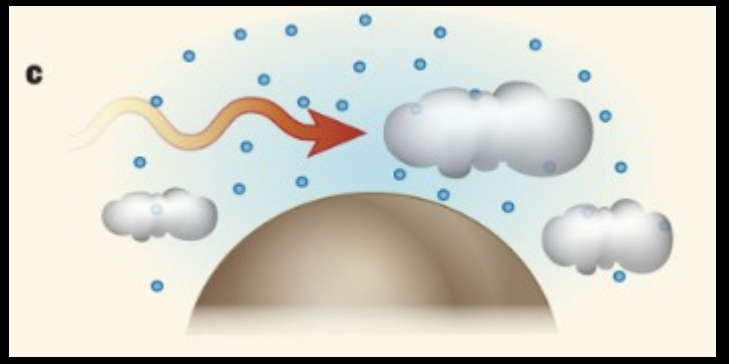


Image Credit: ESO/L. Calçada

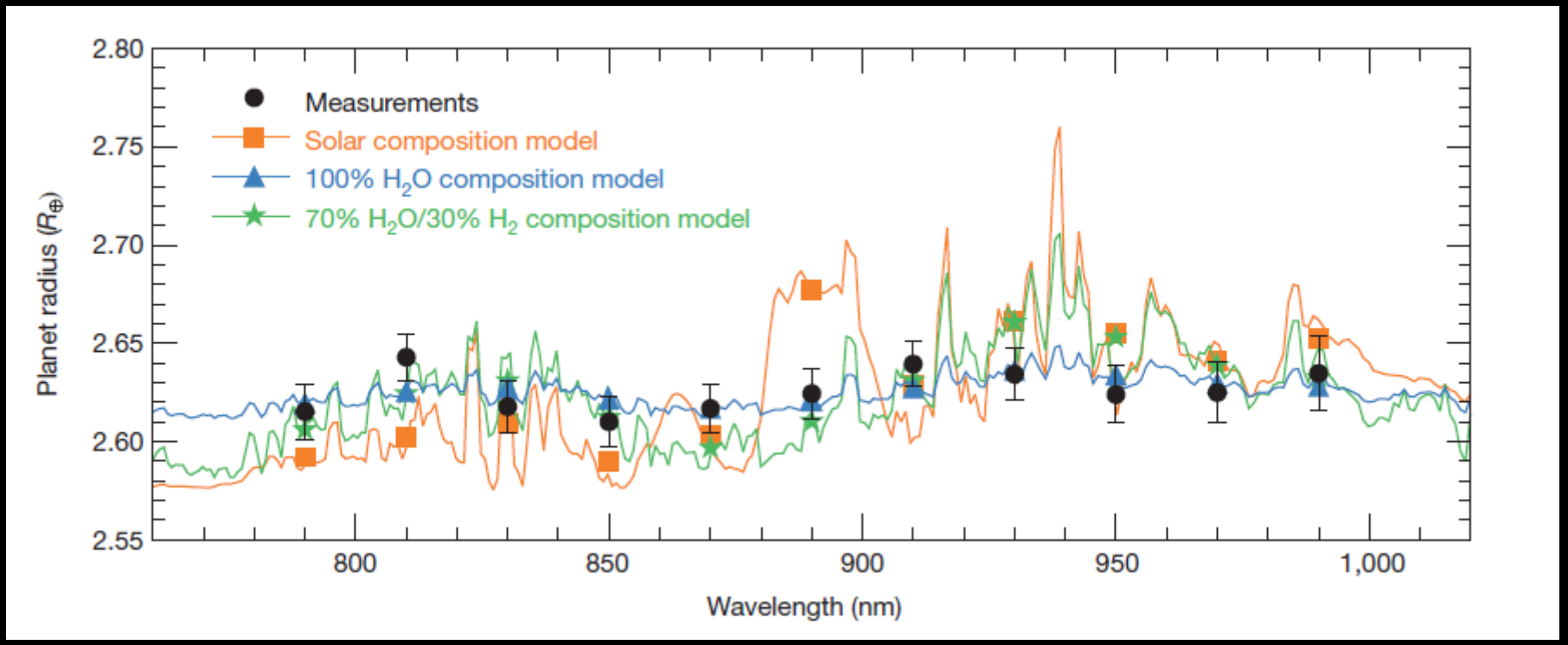
VLT Photometry of GJ 1214B

Bean et al. (2010)





From Bean et al. (2010) the planet should be water-dominated (left), or hydrogen/helium-dominated with clouds/hazes (figure from Deming 2010).



VLT Spectrophotometry argues that GJ 1214b must have a hazy/cloudy hydrogen atmsophere, or be water-dominated.

Spitzer/IRAC Observations of GJ 1214b
Desert et al. (2011)

- Desert et al. (2011) lack of transit depth variations argue for a water-world composition; if the planet has a hydrogen/helium dominated composition it must be depleted in methane.

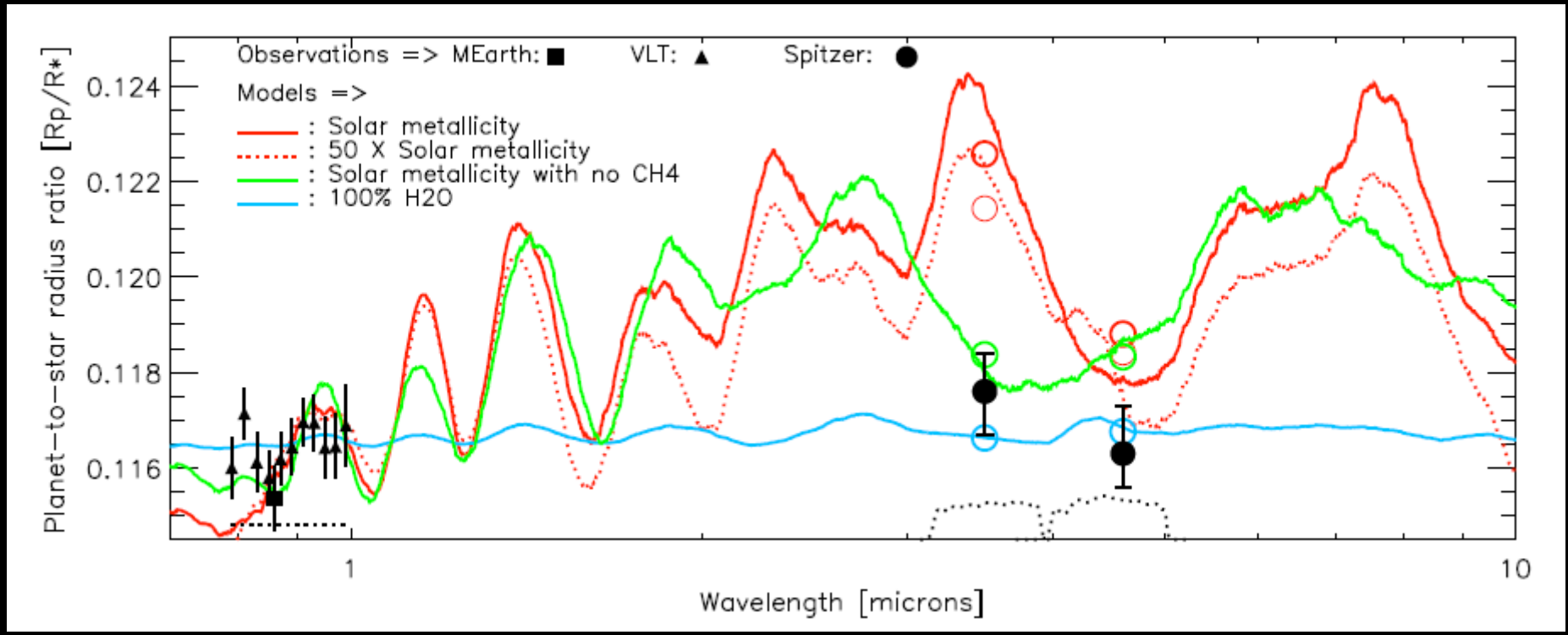


Figure from Desert et al. (2011). Spitzer/IRAC 3.6 and 4.5 micron observations of GJ 1214b

GJ 1214B's Atmospheric Composition

- The water-world possibility is only viable if my Ks-band point is an outlier.
- A hazy methane-free hydrogen/helium atmosphere explains all the observations to date and provides the best-fit to the data.
- The transmission spectrum could simply be more complicated than we expect. More modelling is encouraged!

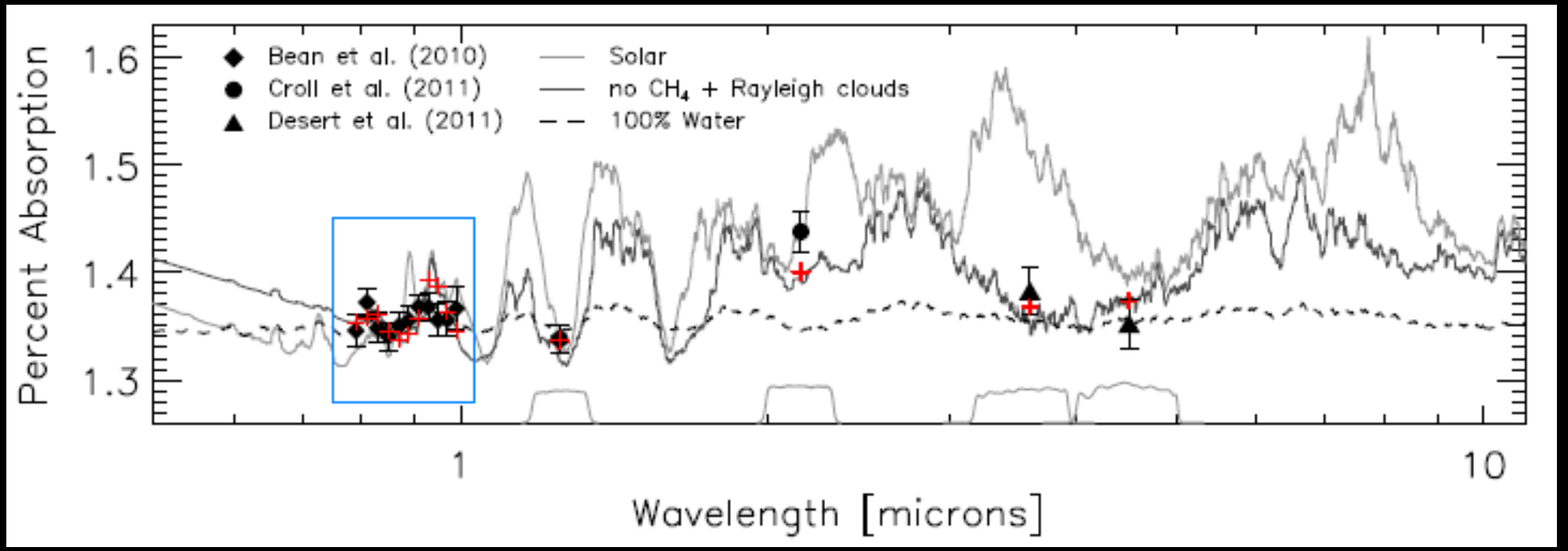
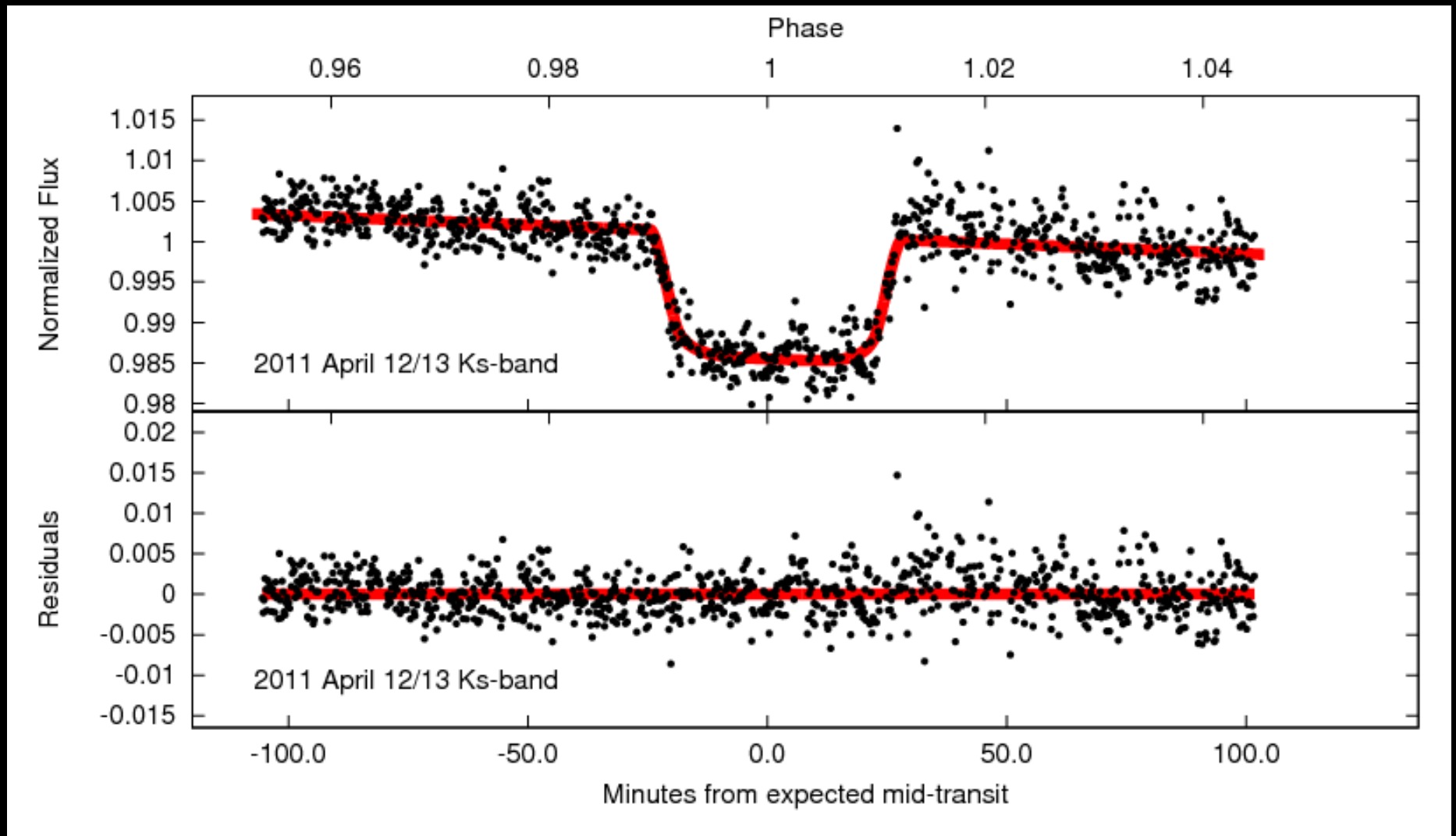


Figure from Miller-Ricci Kempton et al. (2011): Compilation of the GJ 1214B Transit Depths to date across a wide wavelength range.

Recent Ks-band Observations of GJ 1214b

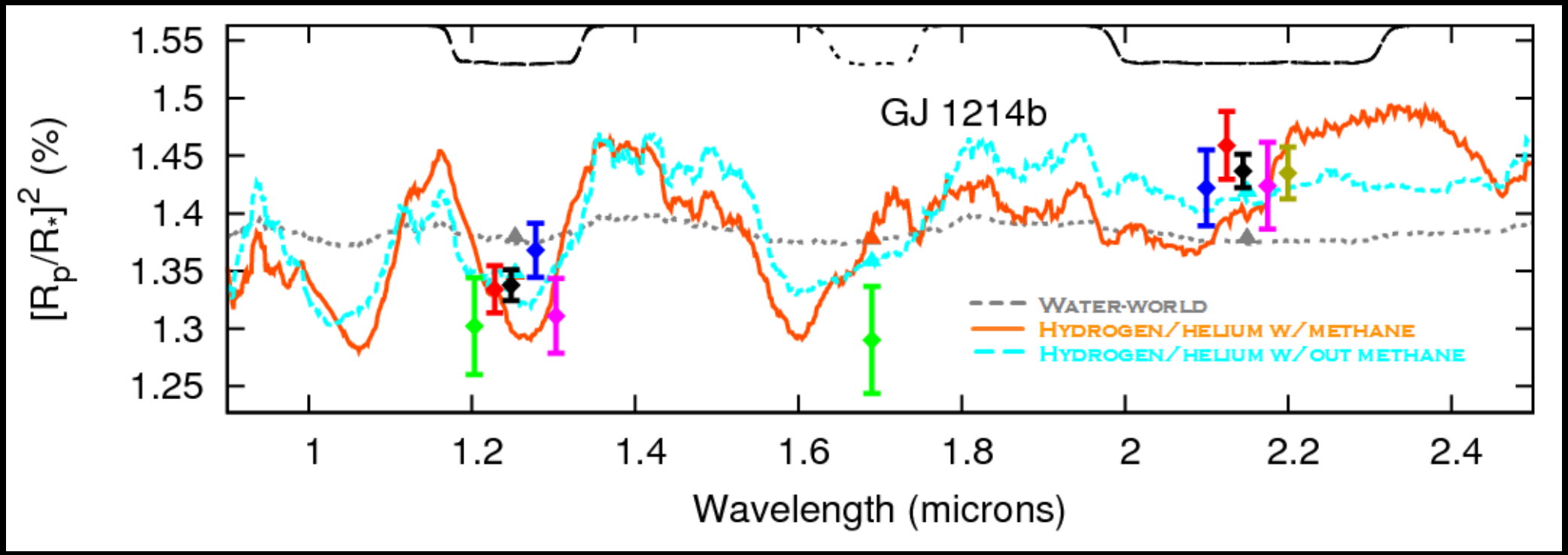
Croll et al. In Prep.

- Single-band observations only in Ks-band.
- However MEarth long-term monitoring indicates the star may be more spotted than last year.



The GJ 1214B Transmission Spectrum Refined

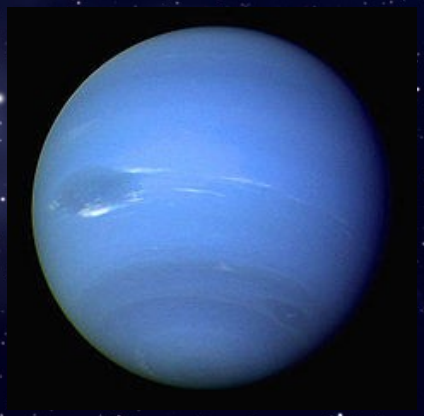
Croll et al. In Prep.



- Rules out the water world model at > 3-sigma.
- 6-sigma difference between the J and Ks-band depths.
- Three more CFHT/WIRCam transits of GJ 1214B in the next two weeks!

Summary: GJ 1214b, a Mini-neptune?

- From our near-simultaneous observations in J-band and Ks-band we have been able to demonstrate an increased transit depth in Ks-band.
- This is likely indicative of a spectal absorption feature near ~2.15 microns.
- The only way to get a feature this large is for the scale height of GJ 1214b's atmosphere to be large, and its mean molecular weight to be low.
- GJ 1214b, the first super-Earth we have been able to characterize, is arguably better described as a Mini-Neptune with a hydrogen/helium atmosphere depleted in methane, a rocky core, and hazes.
- *Even more* observations of this object across a wide wavelength regime are still required.



Near-infrared thermal emission Summary

- Using CFHT/WIRCam we`ve detected the thermal emission of a number of hot Jupiters right at their blackbody peaks – with many more to come in the YJHK bands!
- Unfortunately what these near-infrared observations reveal about hot Jupiters as a class is still to be determined.

Thanks for your attention & thumbs-up for staying to the end of the session