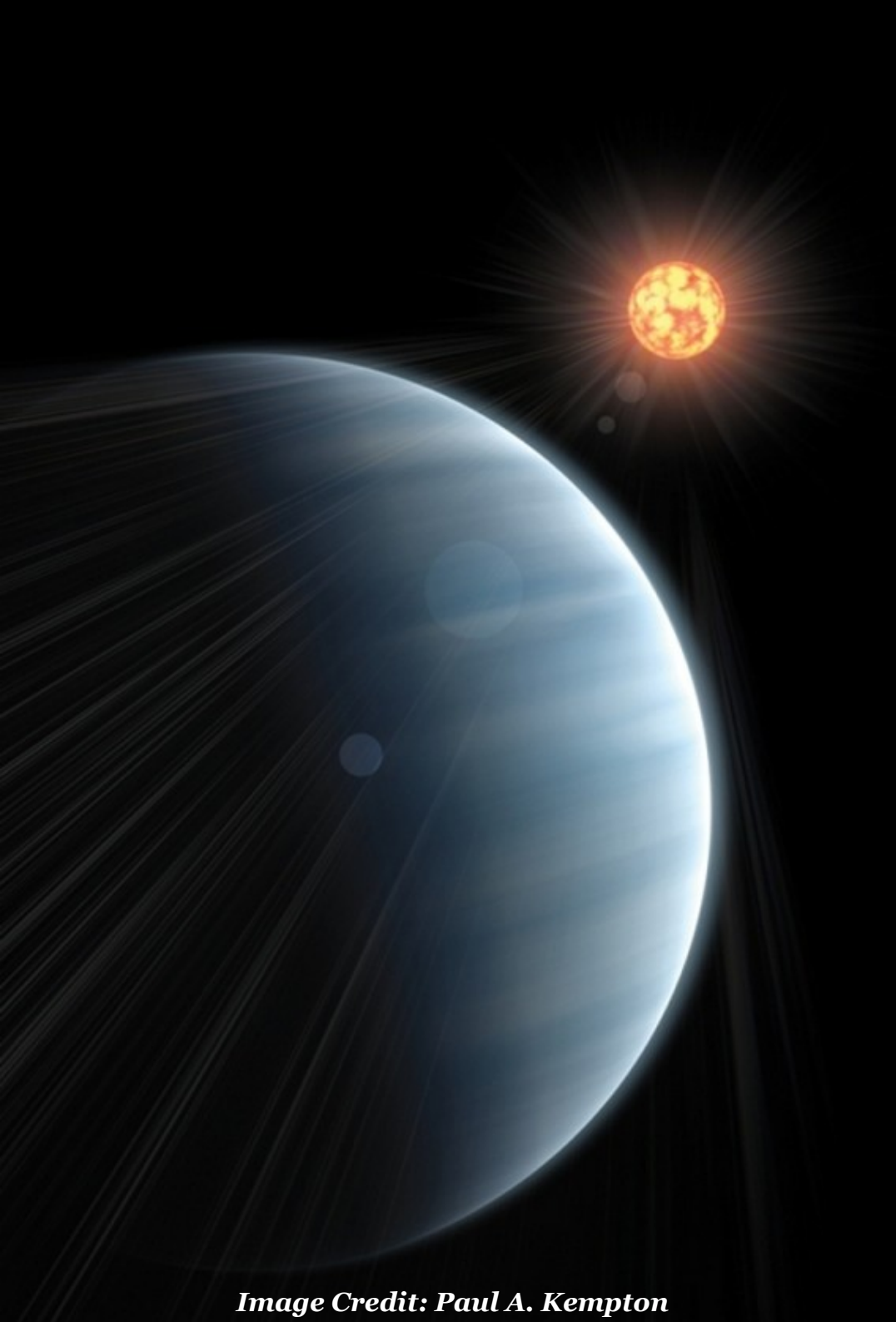


Bryce Croll
Massachussets
Institute of Technology

New near-infrared Observations of the super-Earth GJ 1214b

Sept. 15th 2011

Image Credit: Paul A. Kempton

GJ 1214B: Water world or mini-Neptune?

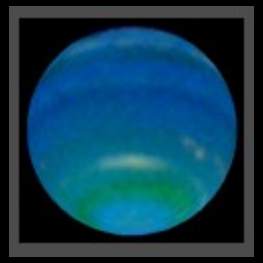
- Using WIRCam/CFHT we've observed an additional five transits in 2011 to add to the four transits we observed in 2010.
- I'll present a preliminary analysis of the four new transits obtained in 2011 that largely continue to support a deeper Ks-band transit.
- A proper investigation of systematic effects are crucial.
- A combination of all the observations to date suggest a relatively flat spectrum, favouring a water-world of hydrogen/helium atmosphere with high altitude clouds.
- More complicated explanations require additional observations to reveal spectral features to remain viable.

Image Credit: David A. Aguilar, CfA

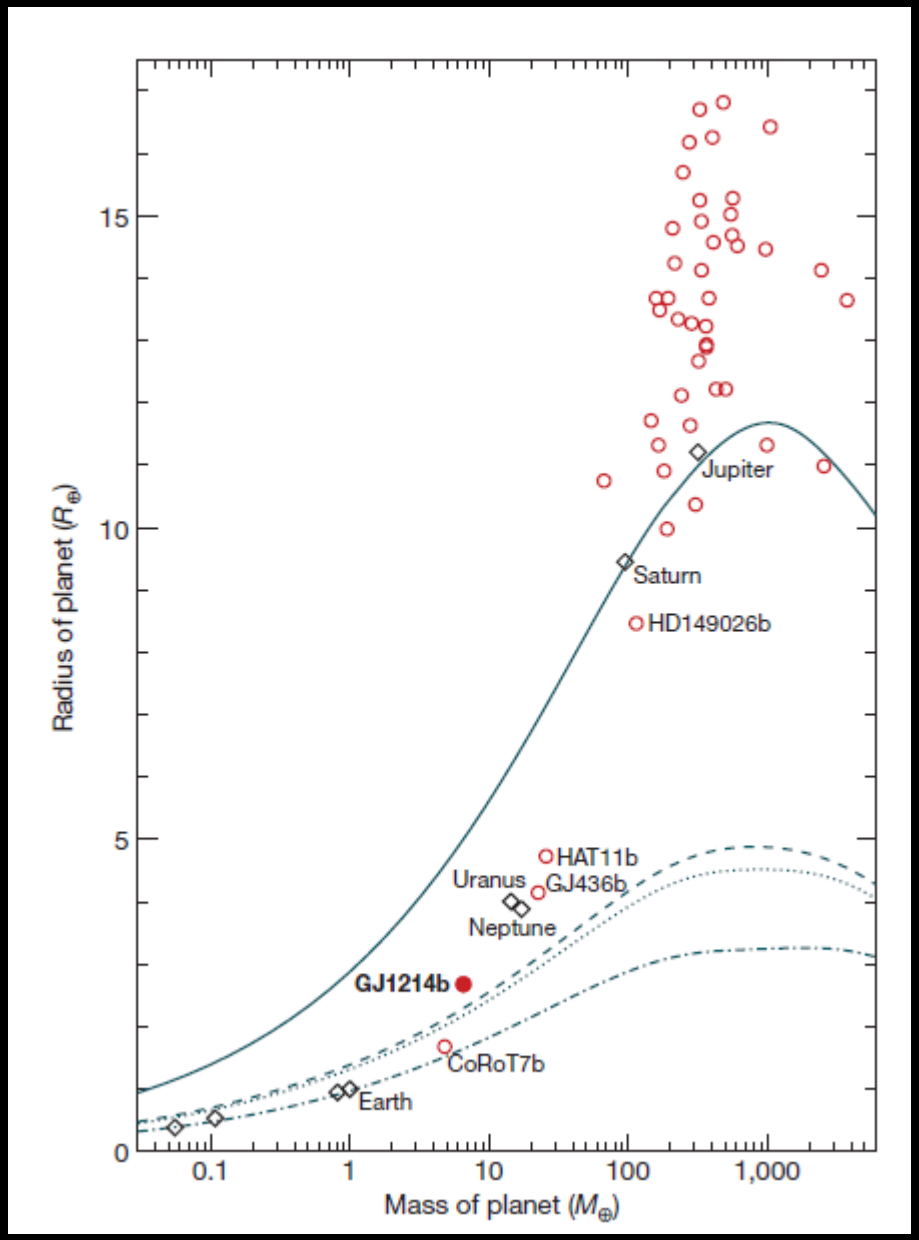
The Super-Earth GJ 1214b

- Super-Earths are planets with masses from 2-10 Earth masses.
- The Super-Earth GJ 1214b (Charbonneau et al. 2009) is the second transiting super-Earth announced, and the first we can readily characterize.

- GJ 1214b may be better understood as a super-Earth if it is composed of an atmosphere similar to terrestrial.



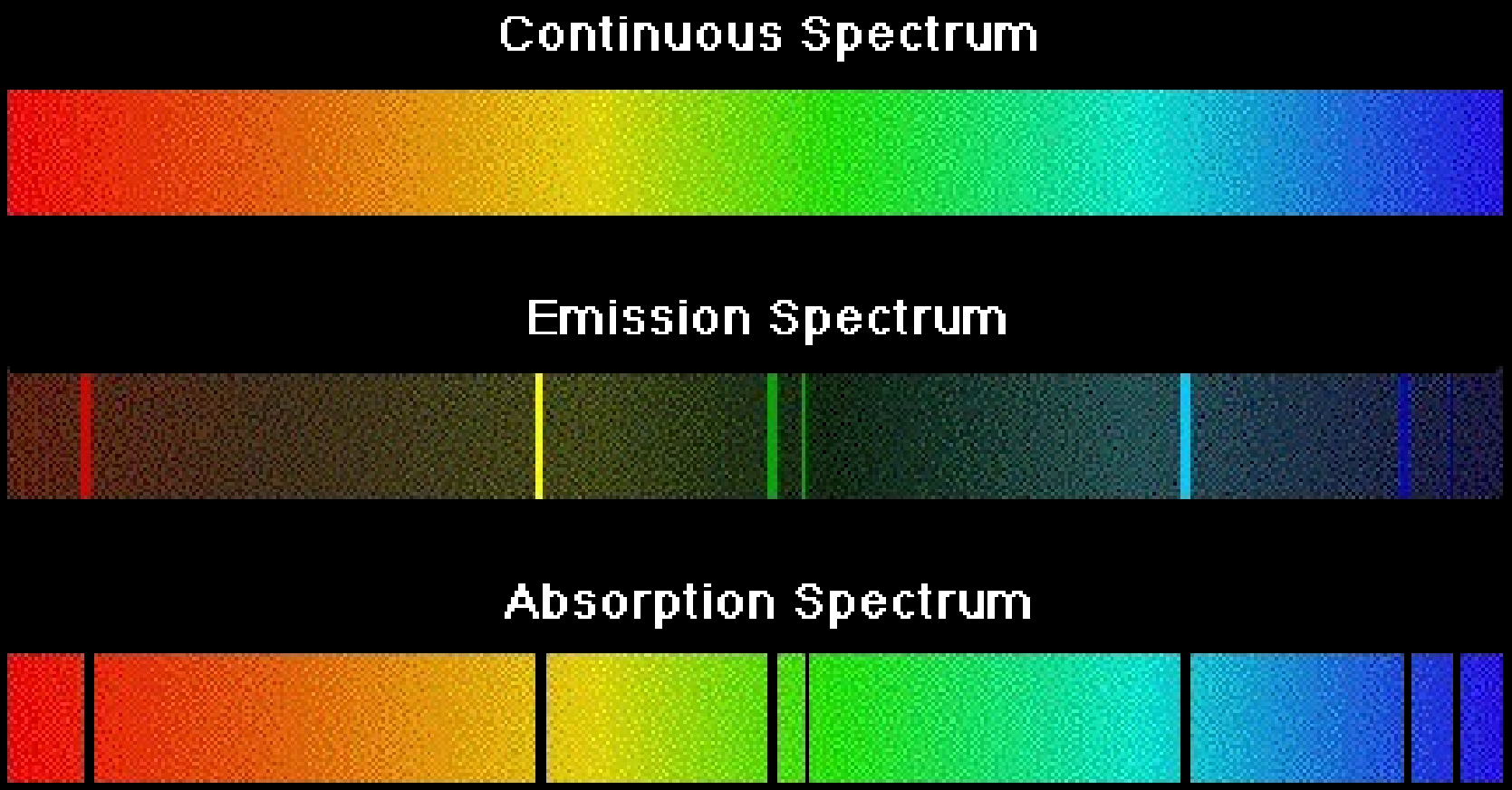
- Or a sub-Neptune if it has a hydrogen/helium dominated atmospheric envelope.



Above: Transiting planets Charbonneau et al. (2009)

Transmission Spectroscopy

- The depth of the transit (and thus the size of the planet) will appear to vary in spectral absorption bands.



Transmission Spectroscopy

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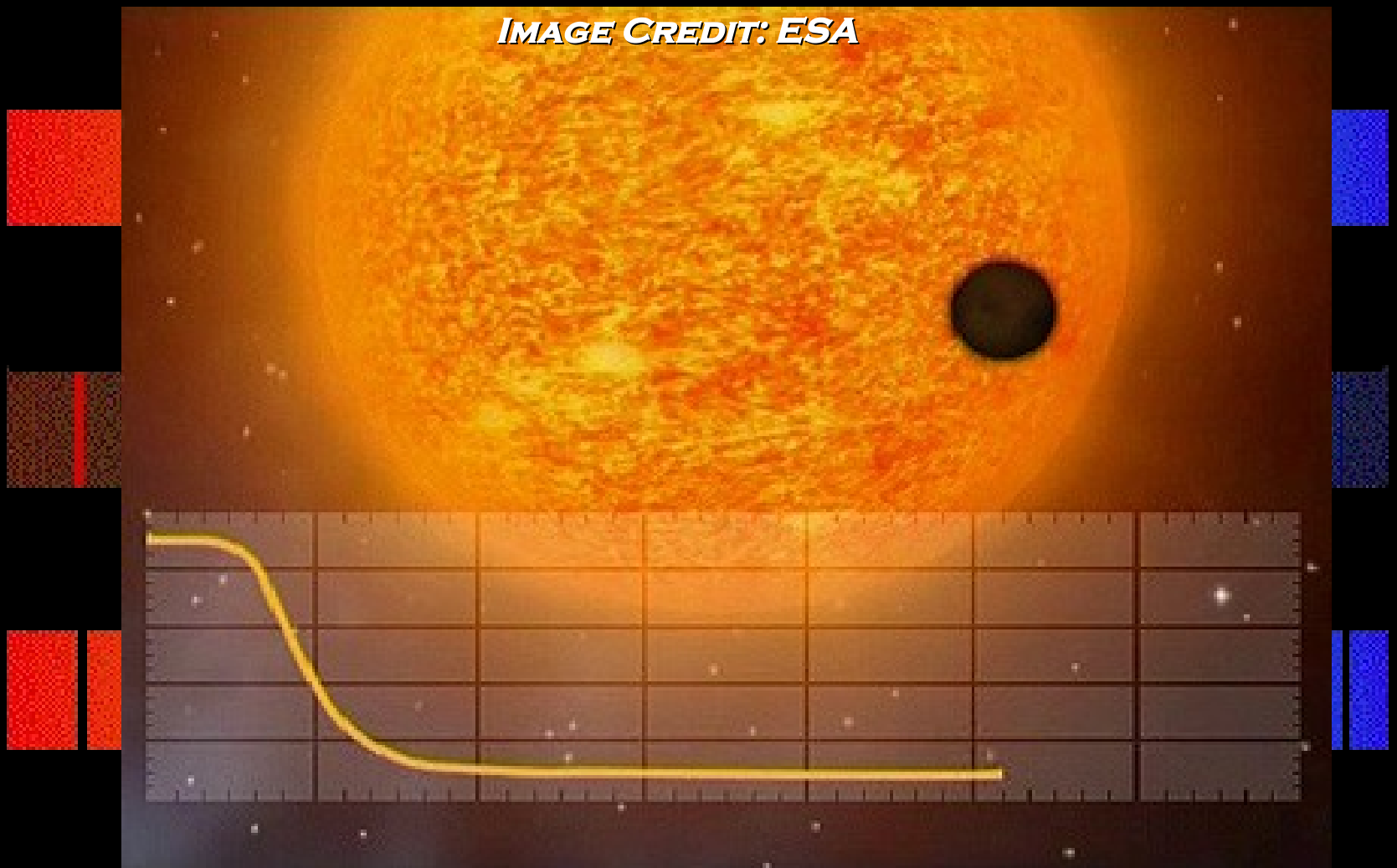

Transmission Spectroscopy

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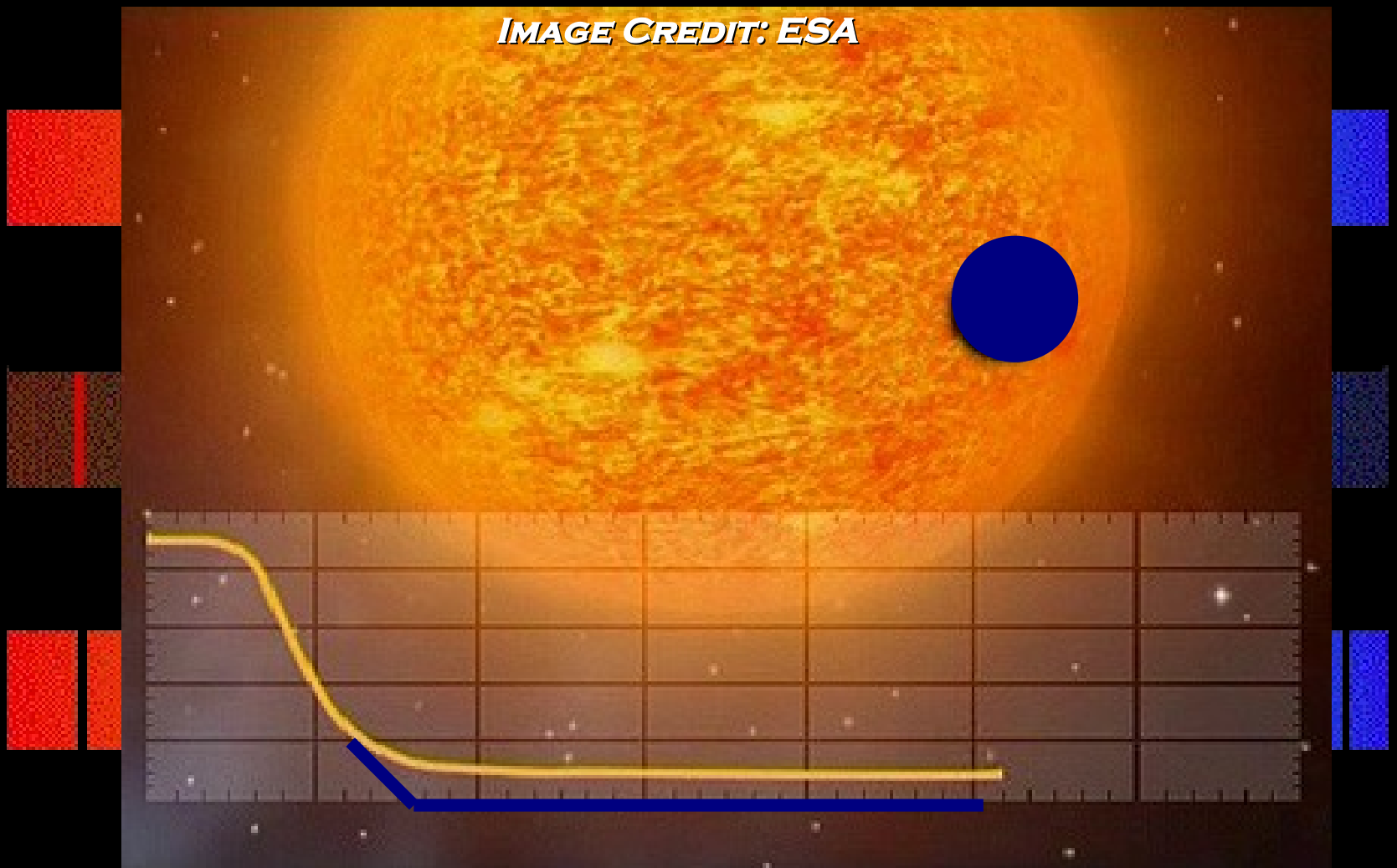
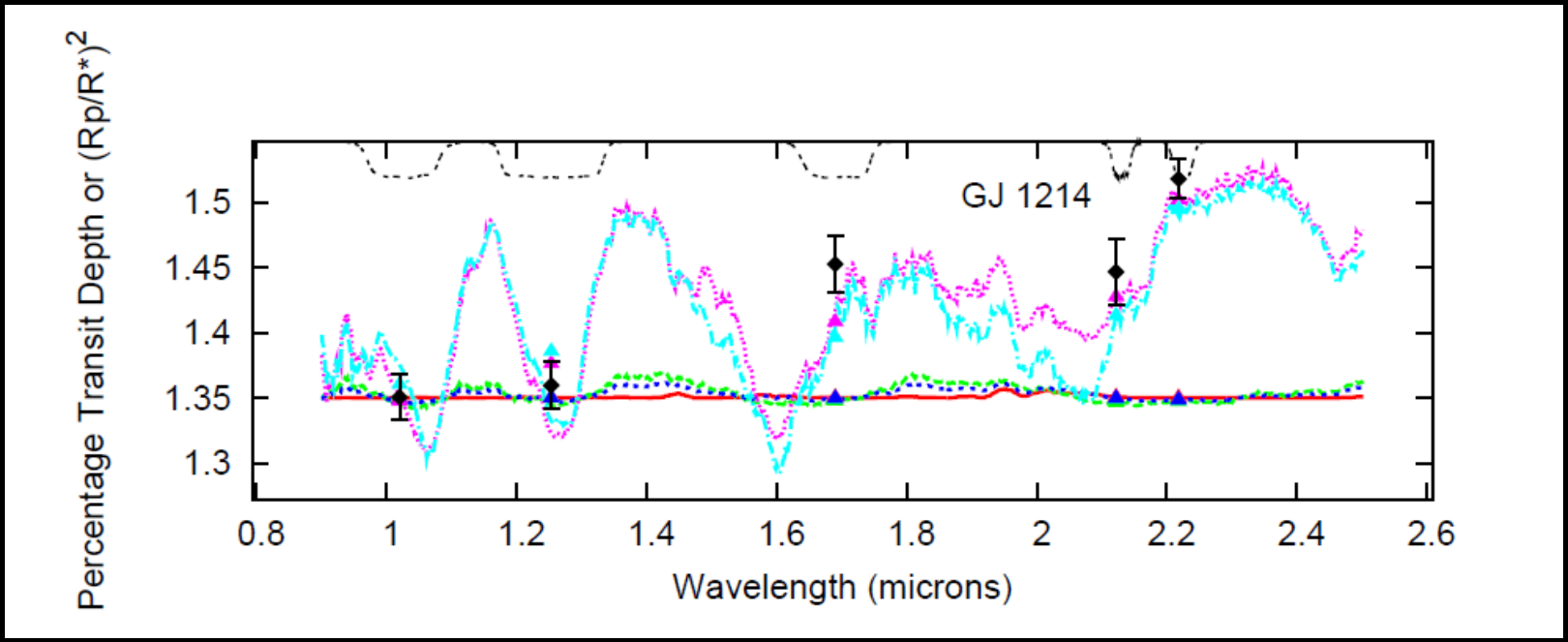


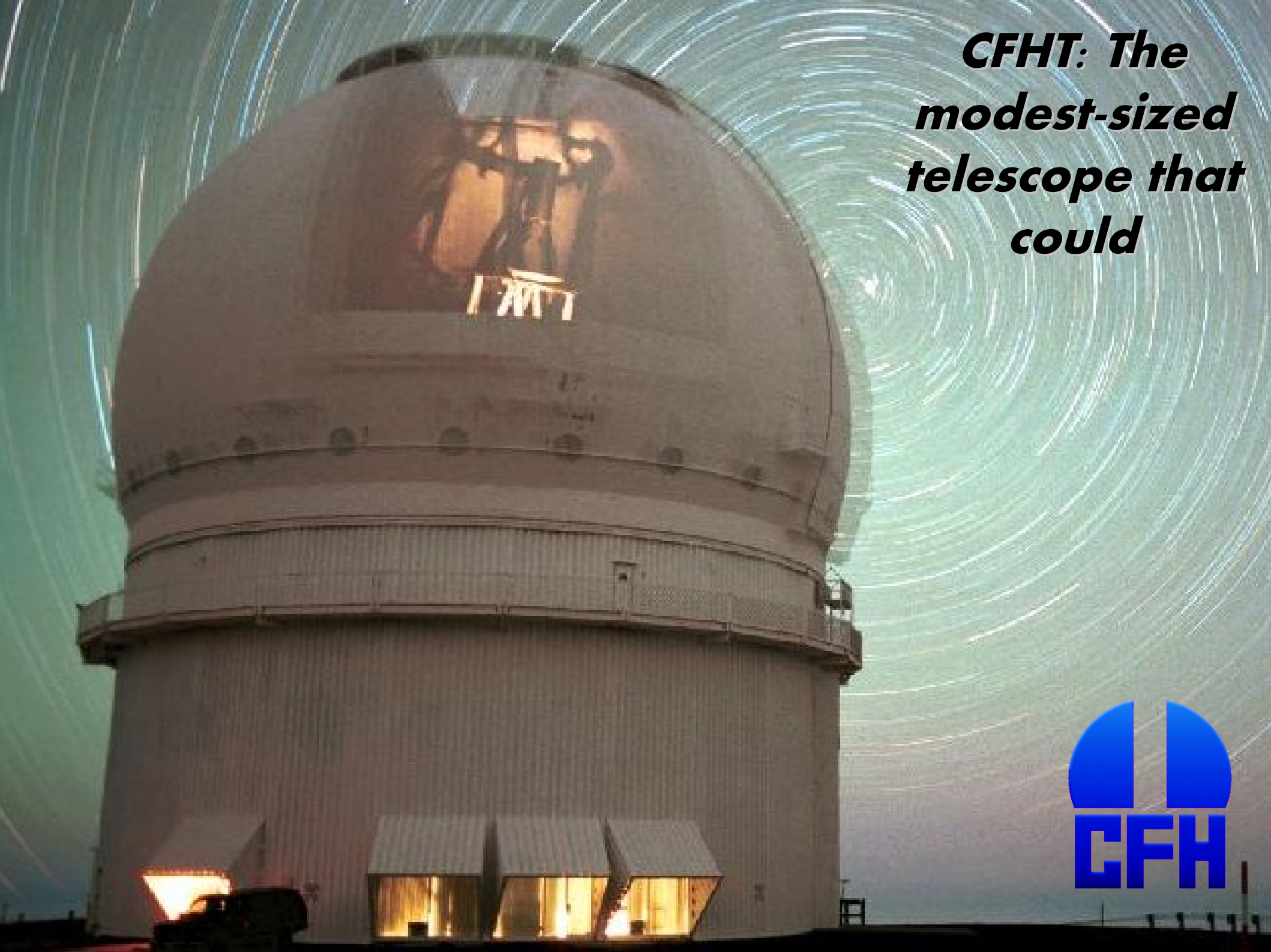
Spectral Features in the Near-IR

- 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).
- This entire analysis assumes a low density for the planet, and thus a certain R*, which has been called into question (Carter et al. 2011).



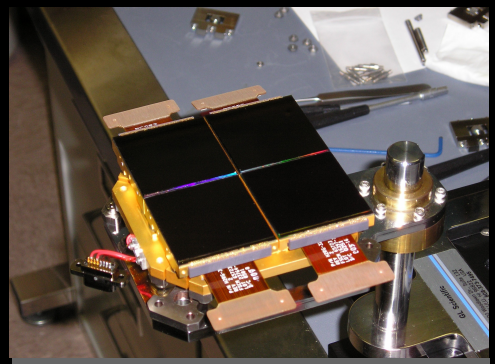
$$H = \frac{kT}{Mg}$$

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.


CFHT: The modest-sized telescope that could
CFH

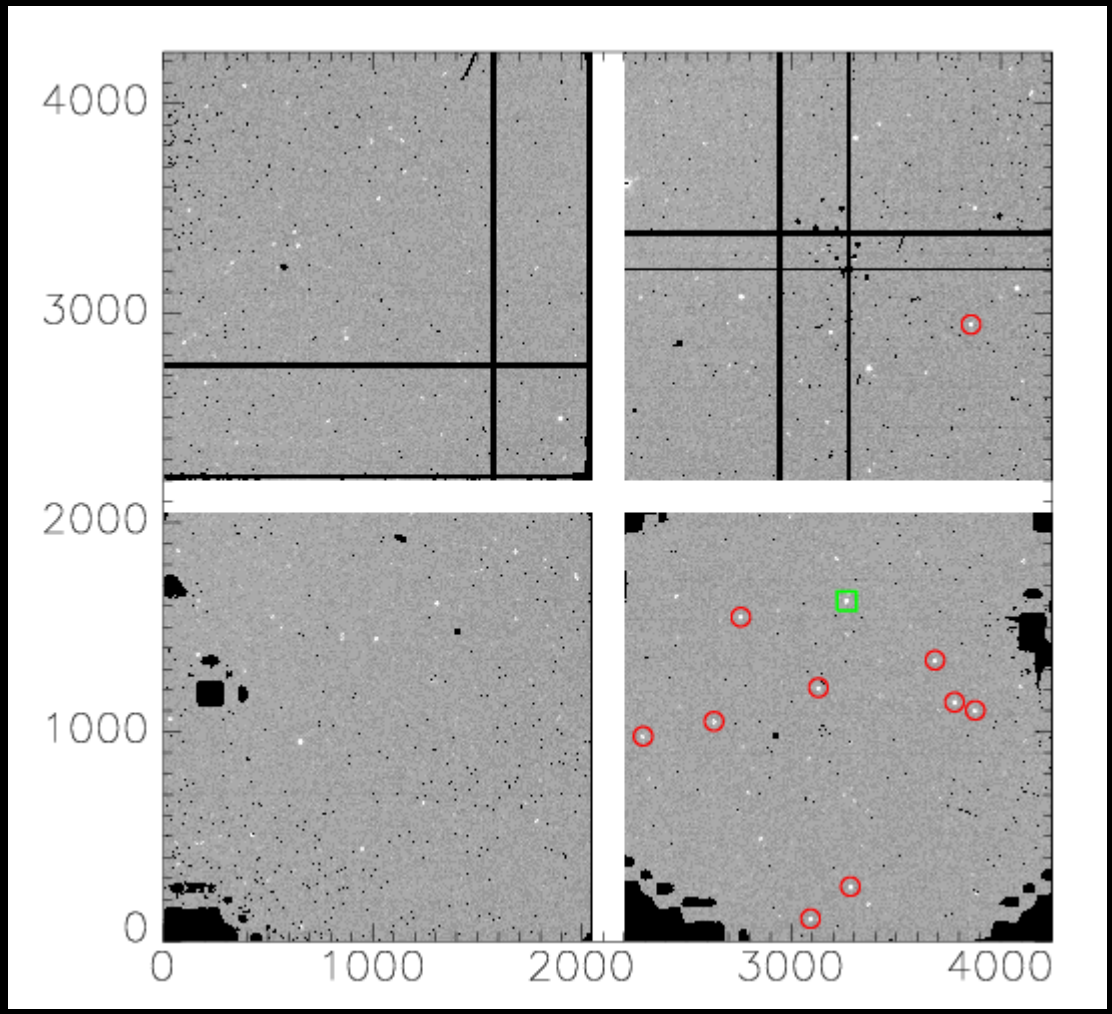
WIRCam Near-IR Defocused Photometry

- 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).

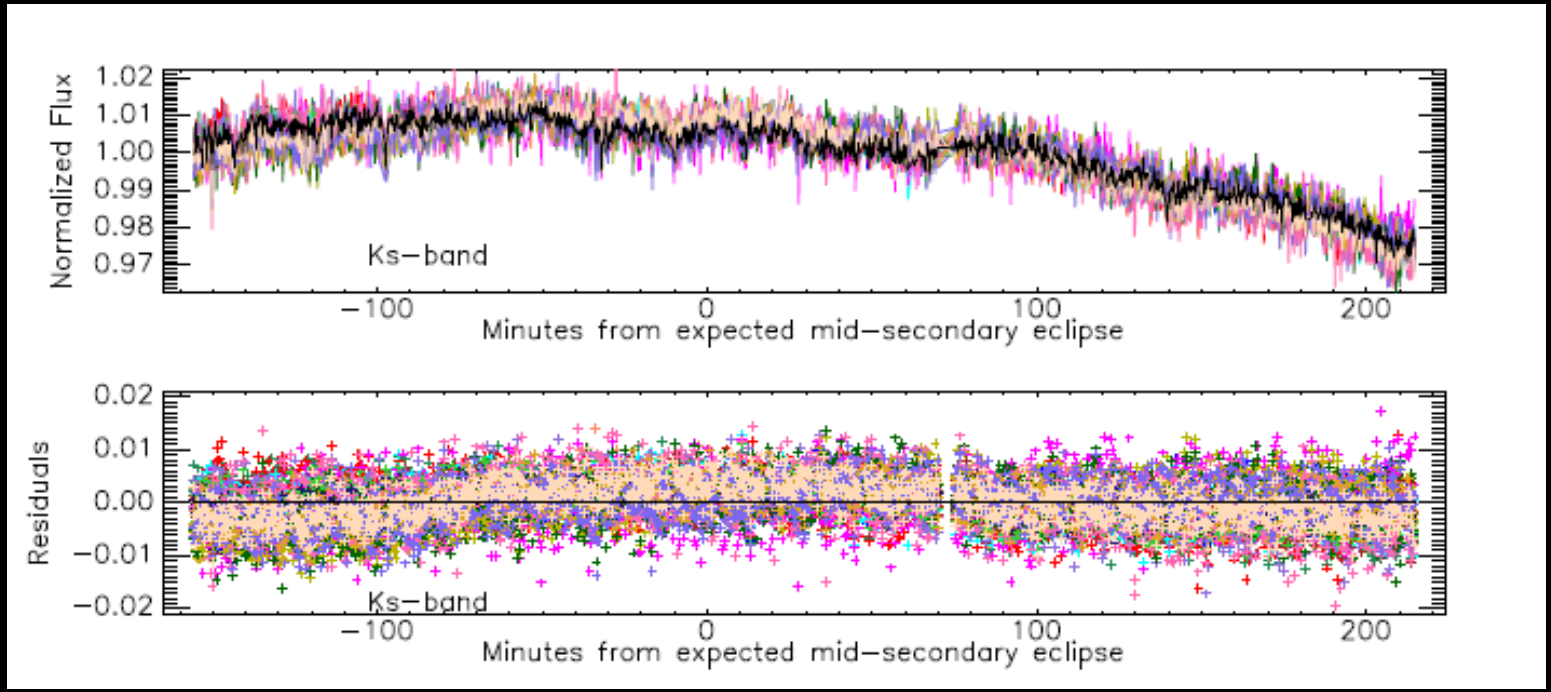
Bottom: We also observe significantly out of focus, so that the light is spread over a donut.



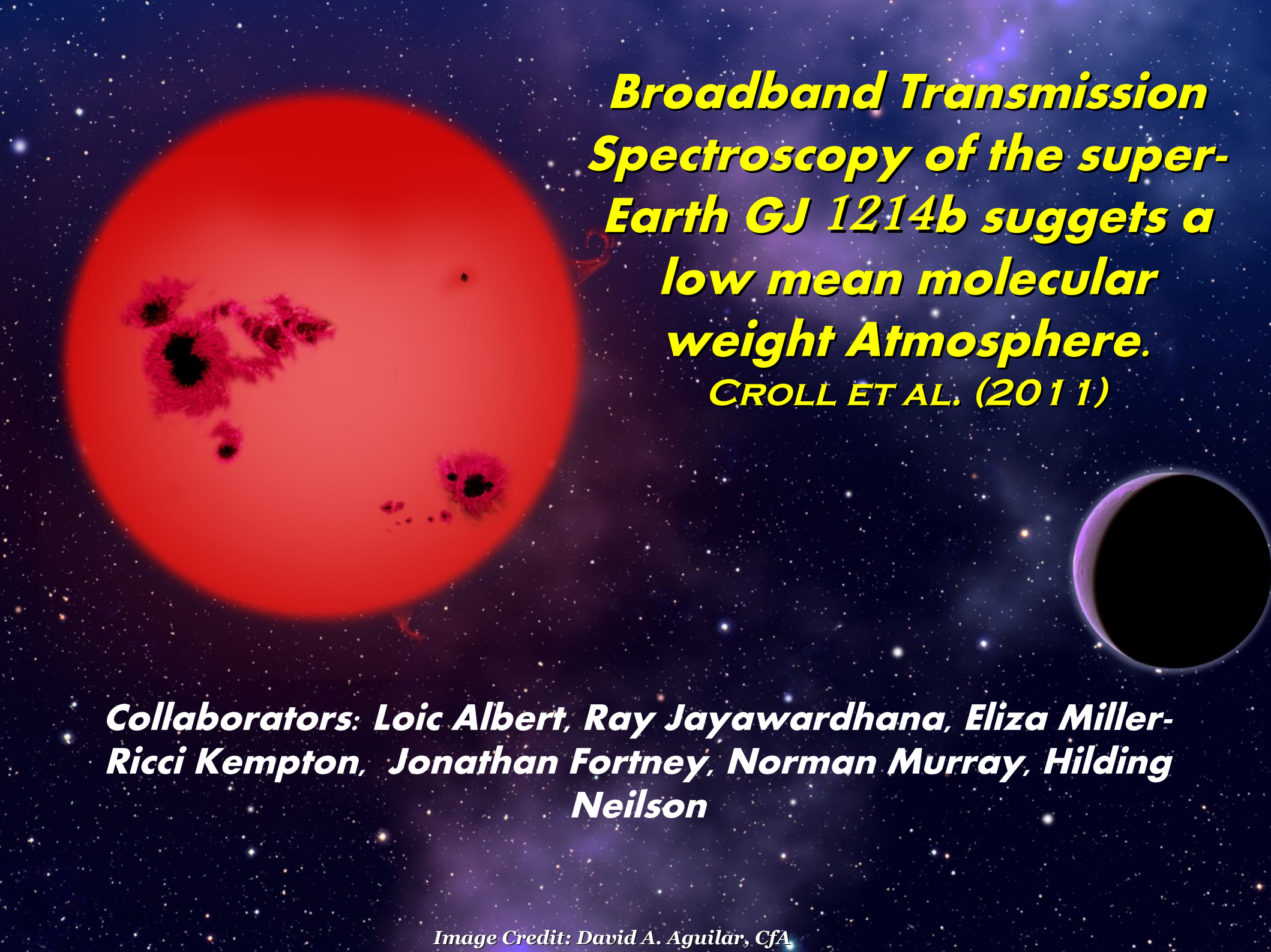
Top: TrES-2b (Green Square), and various reference stars used to correct our photometry (red circles).

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.



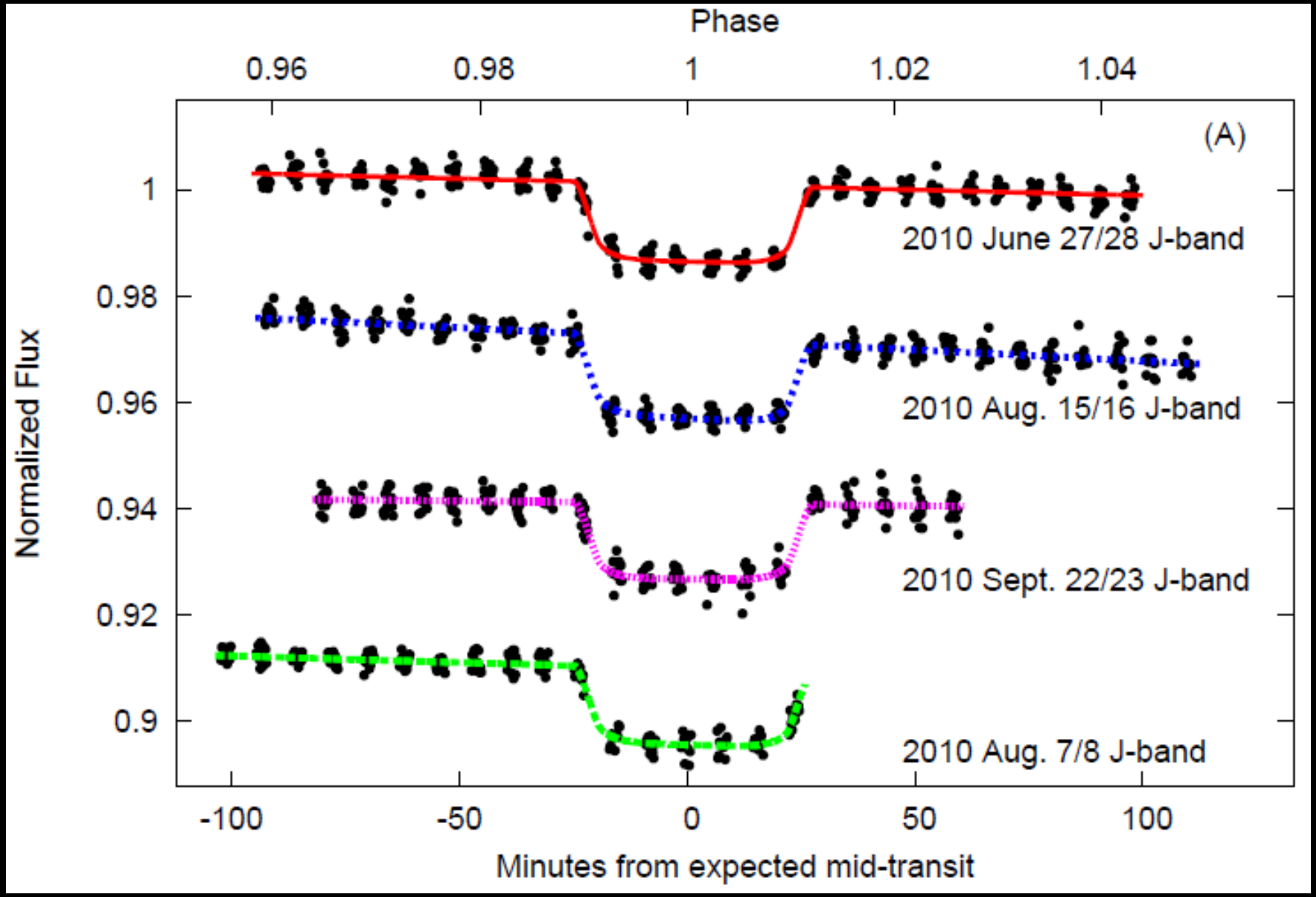
The flux and the residuals of the target star (black), and the reference stars (various colours).


Broadband Transmission Spectroscopy of the super-Earth GJ 1214b suggets a low mean molecular weight Atmosphere.
Croll et al. (2011)
Collaborators: Loic Albert, Ray Jayawardhana, Eliza Miller-Ricci Kempton, Jonathan Fortney, Norman Murray, Hilding Neilson
Image Credit: David A. Aguilar, CfA

2010 Near-IR photometry of GJ 1214b

Croll et al. 2011

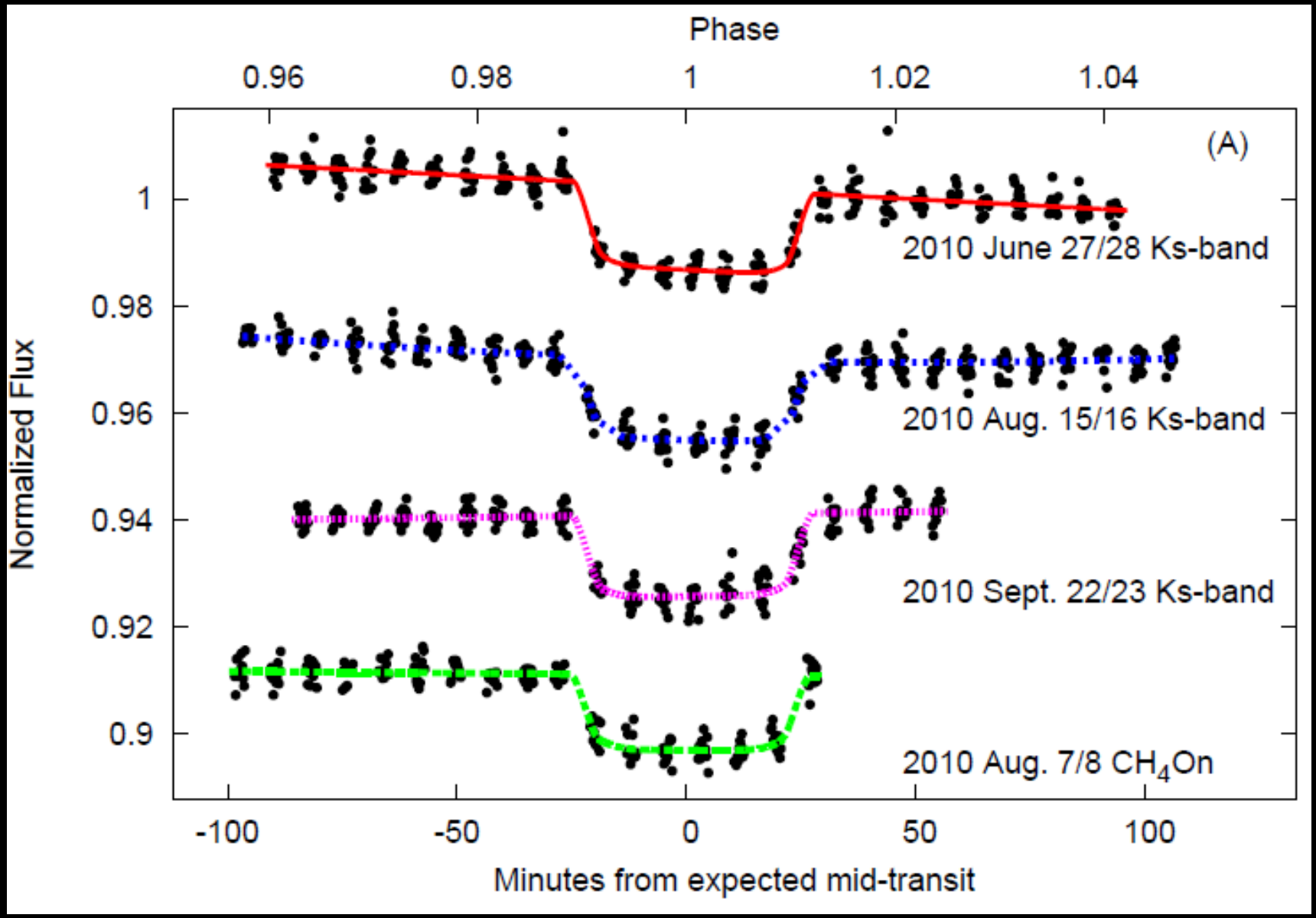
- We observed four transits of GJ 1214b in J-band (1.25 microns) and nearly simultaneously in another band.



2010 Near-IR photometry of GJ 1214b

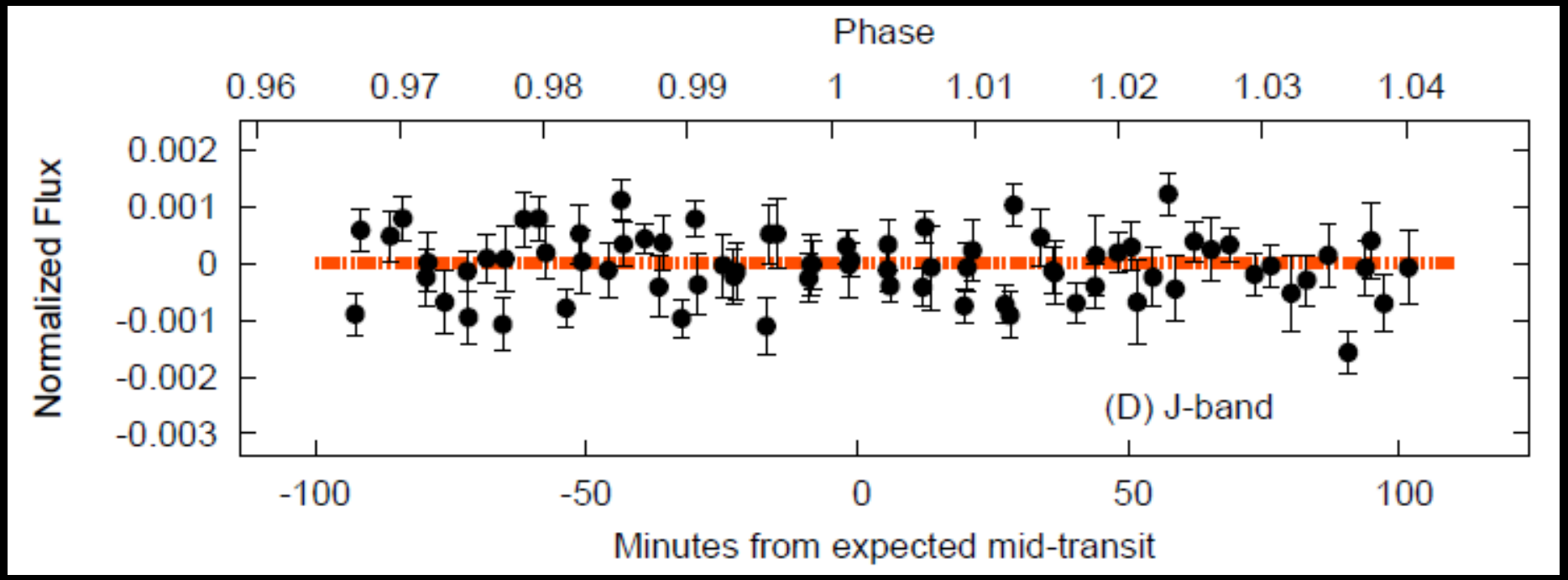
Croll et al. 2011

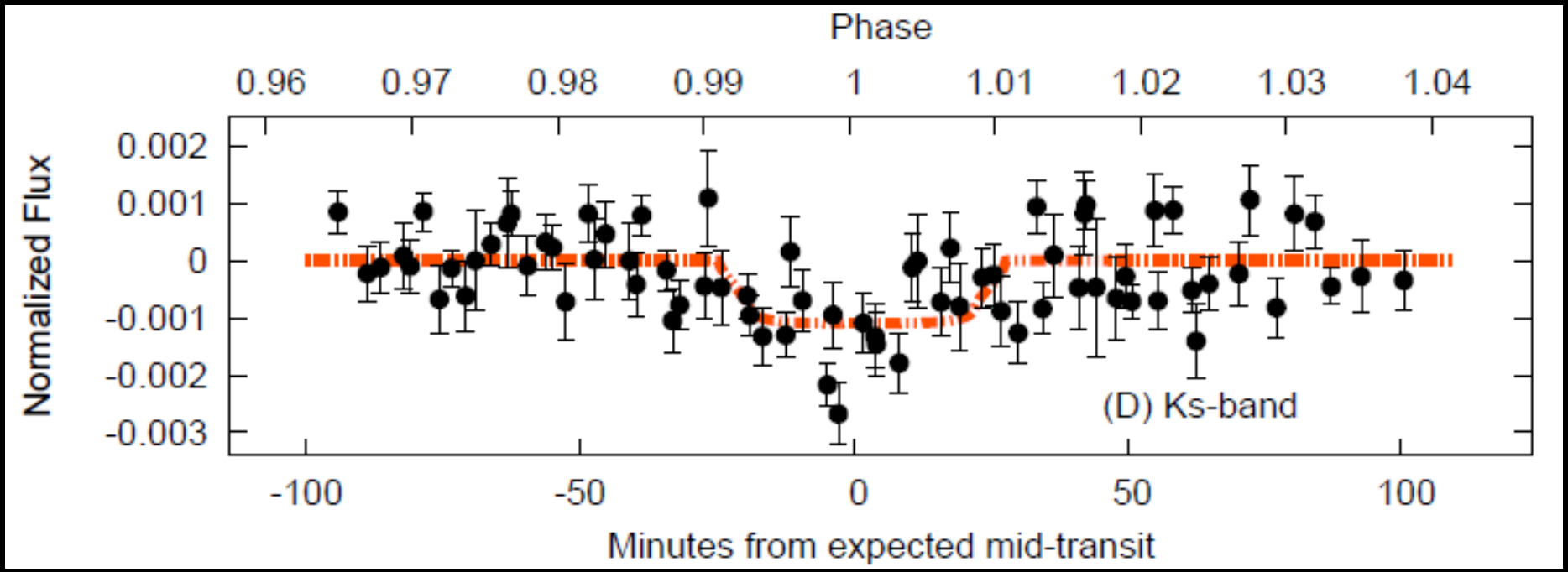
- We observed three transits in Ks-band (2.15 microns) and one transit in the CH_4On filter (1.69 microns).



2010: Extra Absorption in Ks-band?

Croll et al. 2011

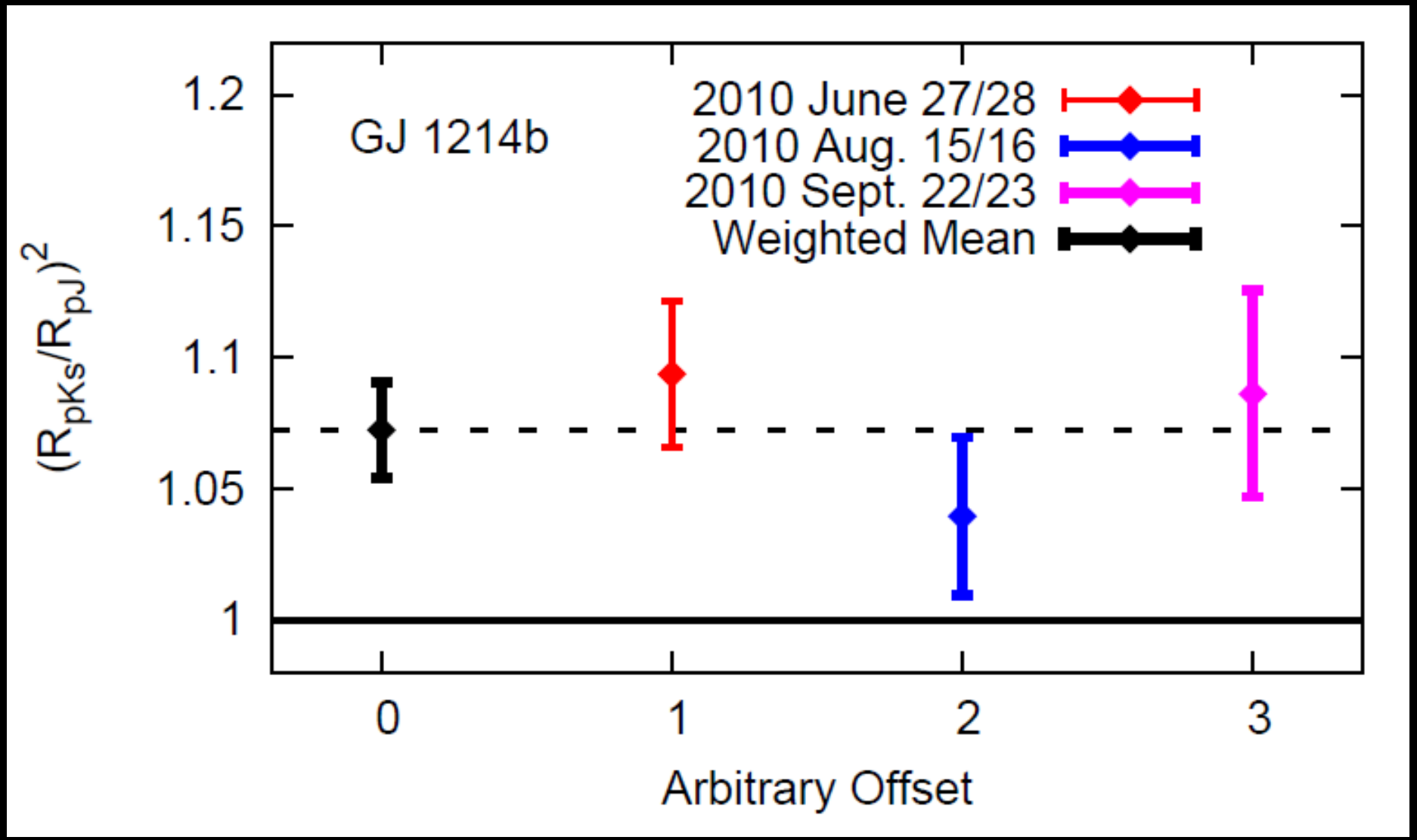




2010: Extra Absorption in Ks-band?

Croll et al. 2011

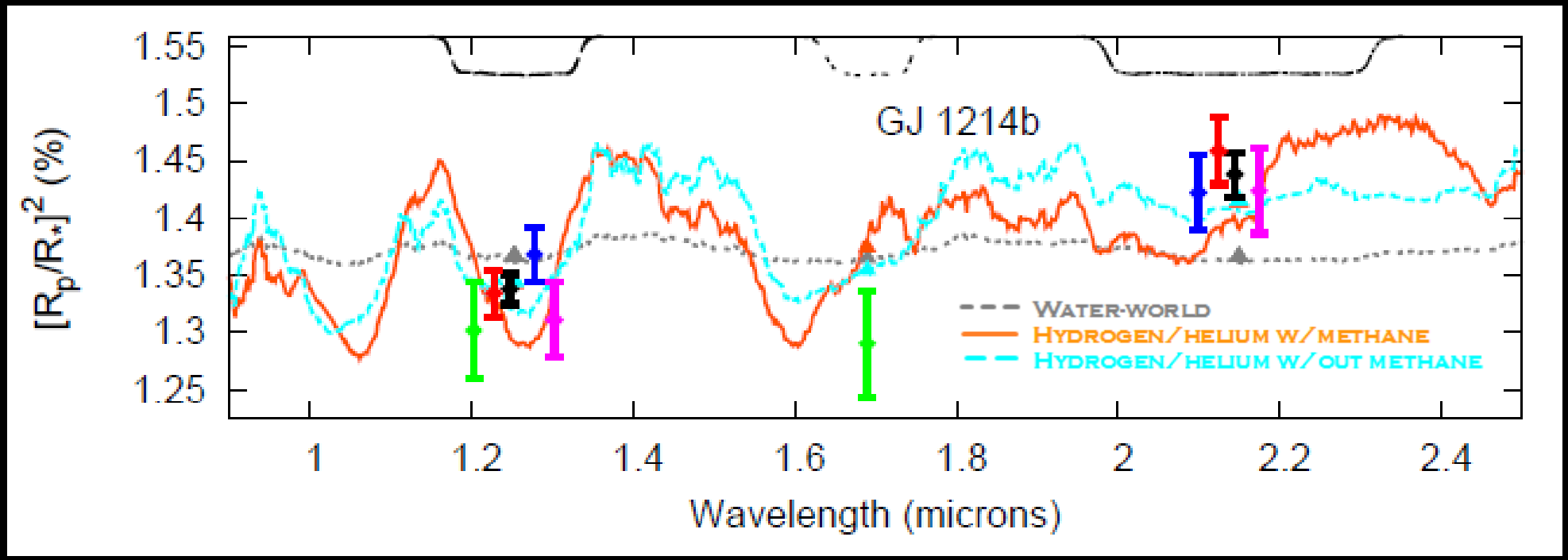
- A 4σ detection of a deeper transit (and thus absorption) in Ks-band (2.15 microns) as compared to J-band (1.25 microns).



The best-fit Ks-band transits display a deeper depth than the best-fit J-band transits (4σ).

GJ 1214b: A low mean molecular weight Atmosphere?
Croll et al. 2011

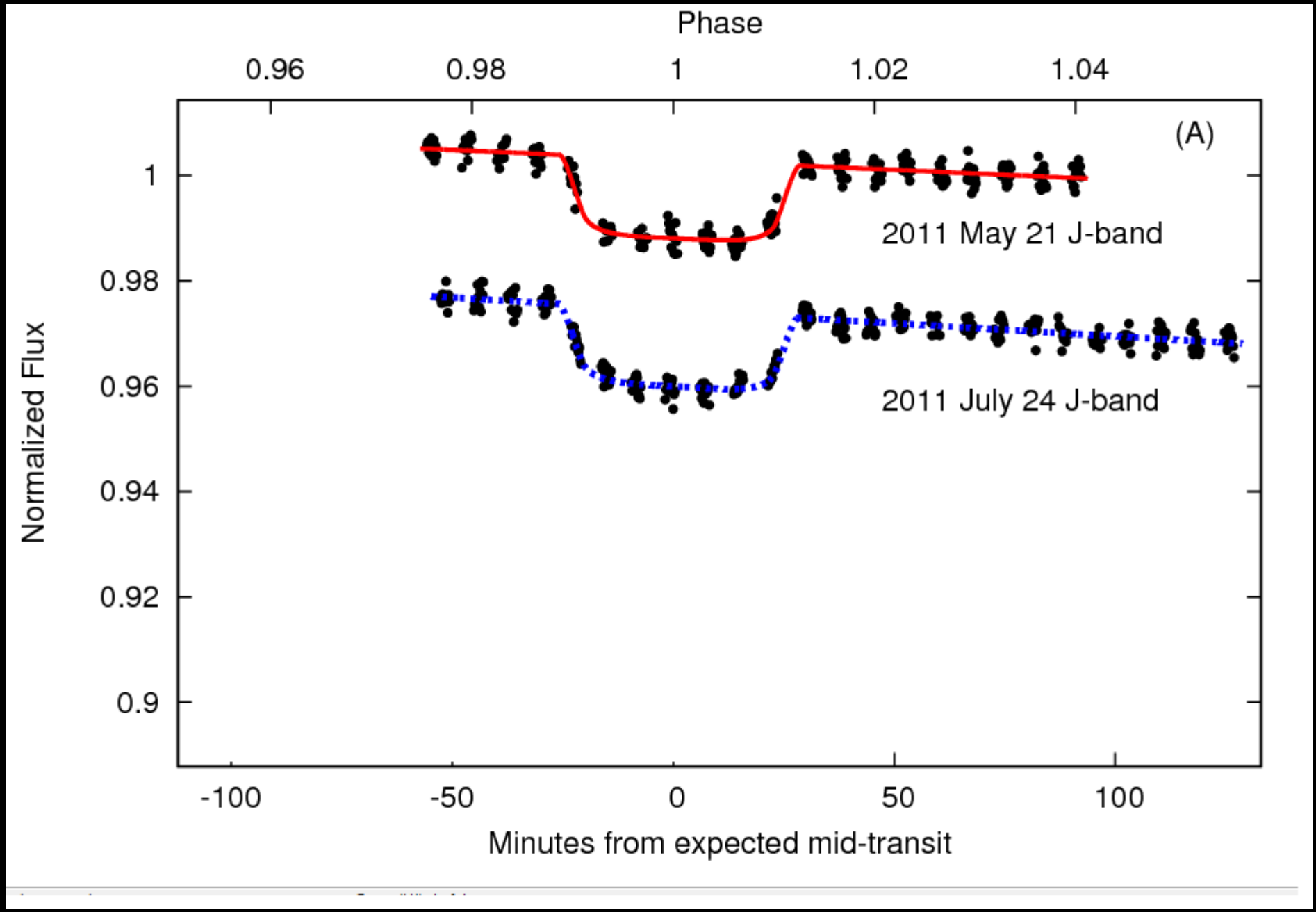
- Our observations argue for a greater transit depth in Ks-band than in J-band (4σ detection).
- A spectral feature this large is only possible if its atmosphere has a large scale-height, a low mean molecular weight, and thus a hydrogen/helium dominated atmosphere.



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.

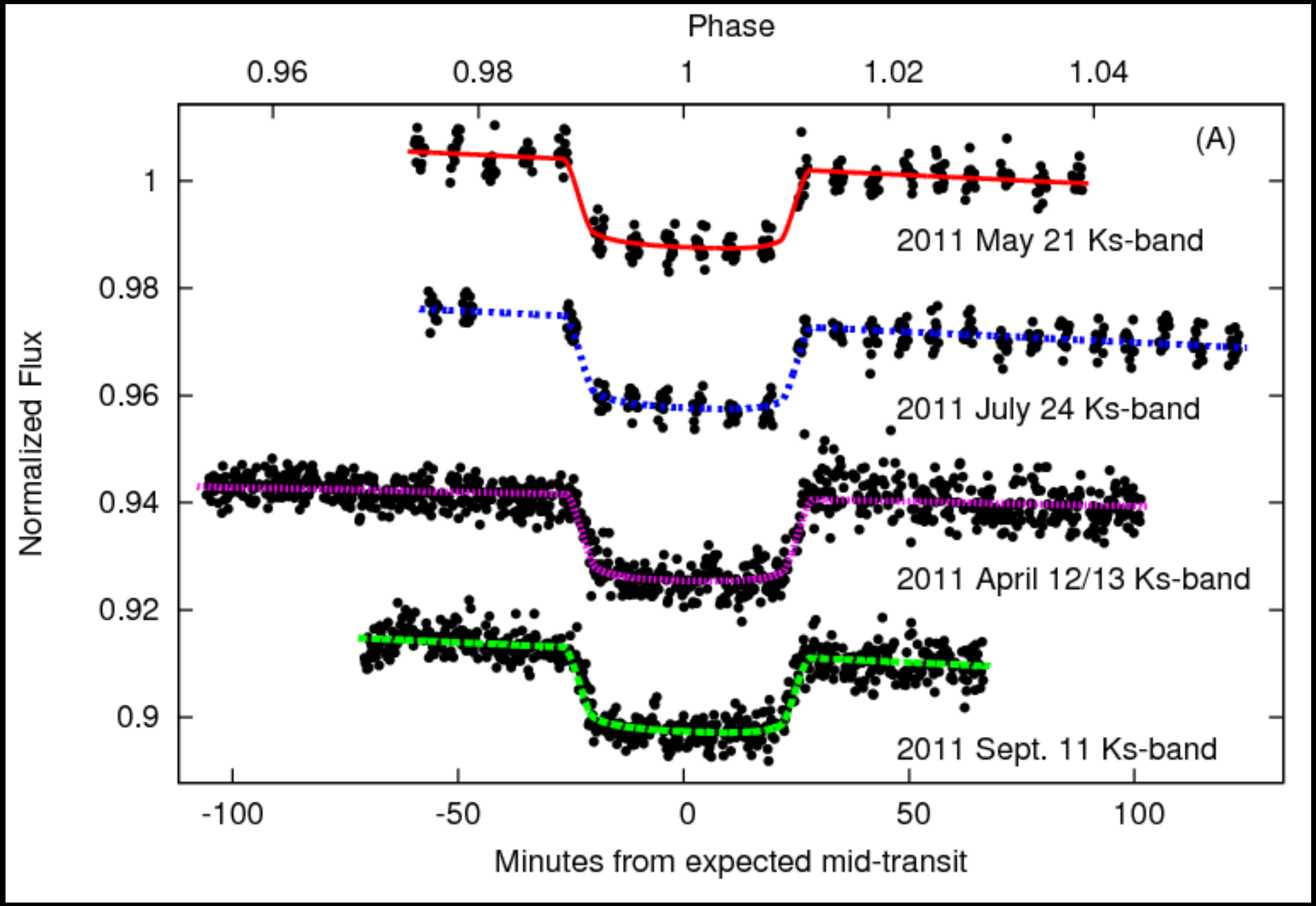
2011 Near-IR photometry of GJ 1214b

Croll et al. In prep.



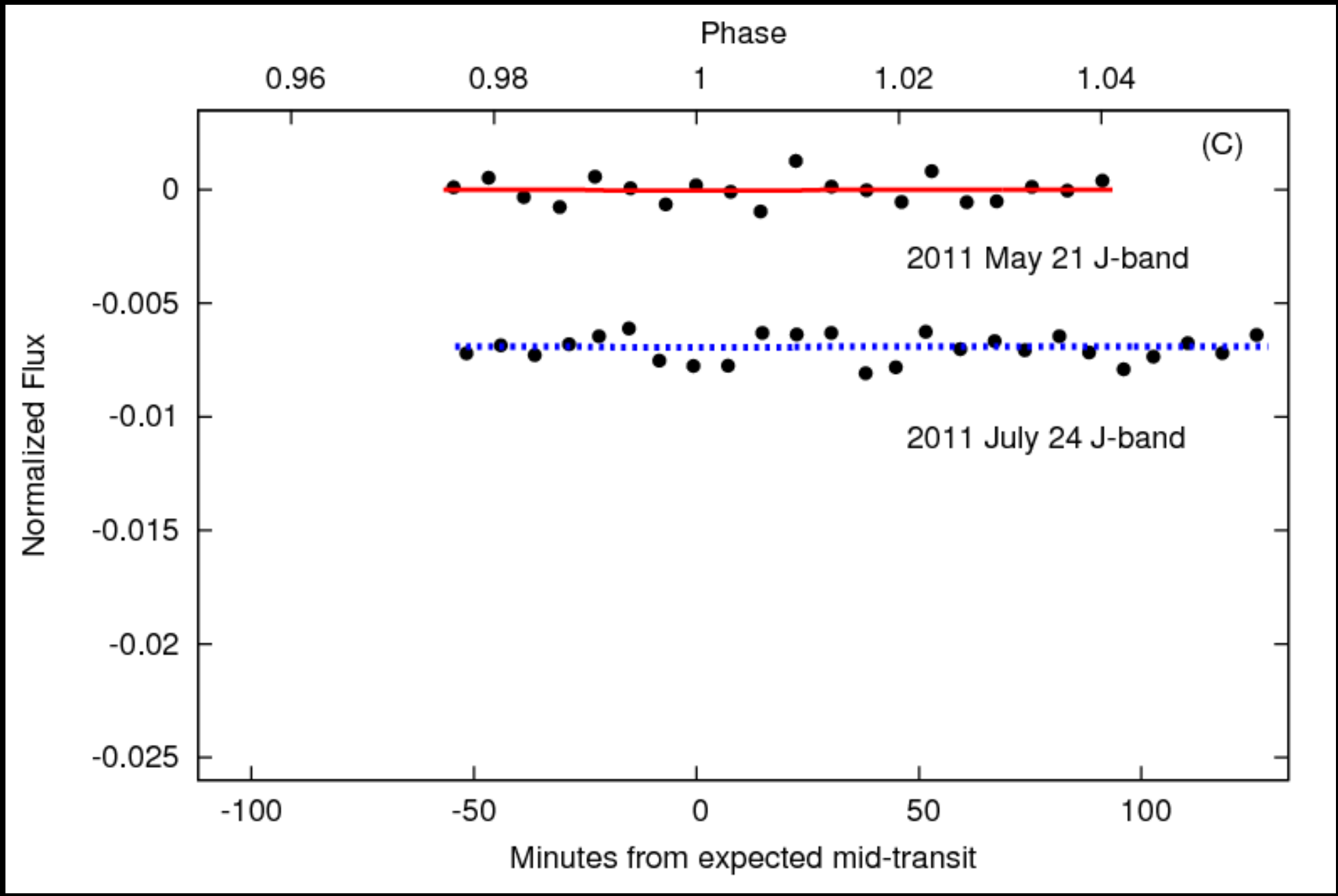
2011 Near-IR photometry of GJ 1214b

Croll et al. In prep.



2011: Residuals from the J-band Depths

Croll et al. In prep.



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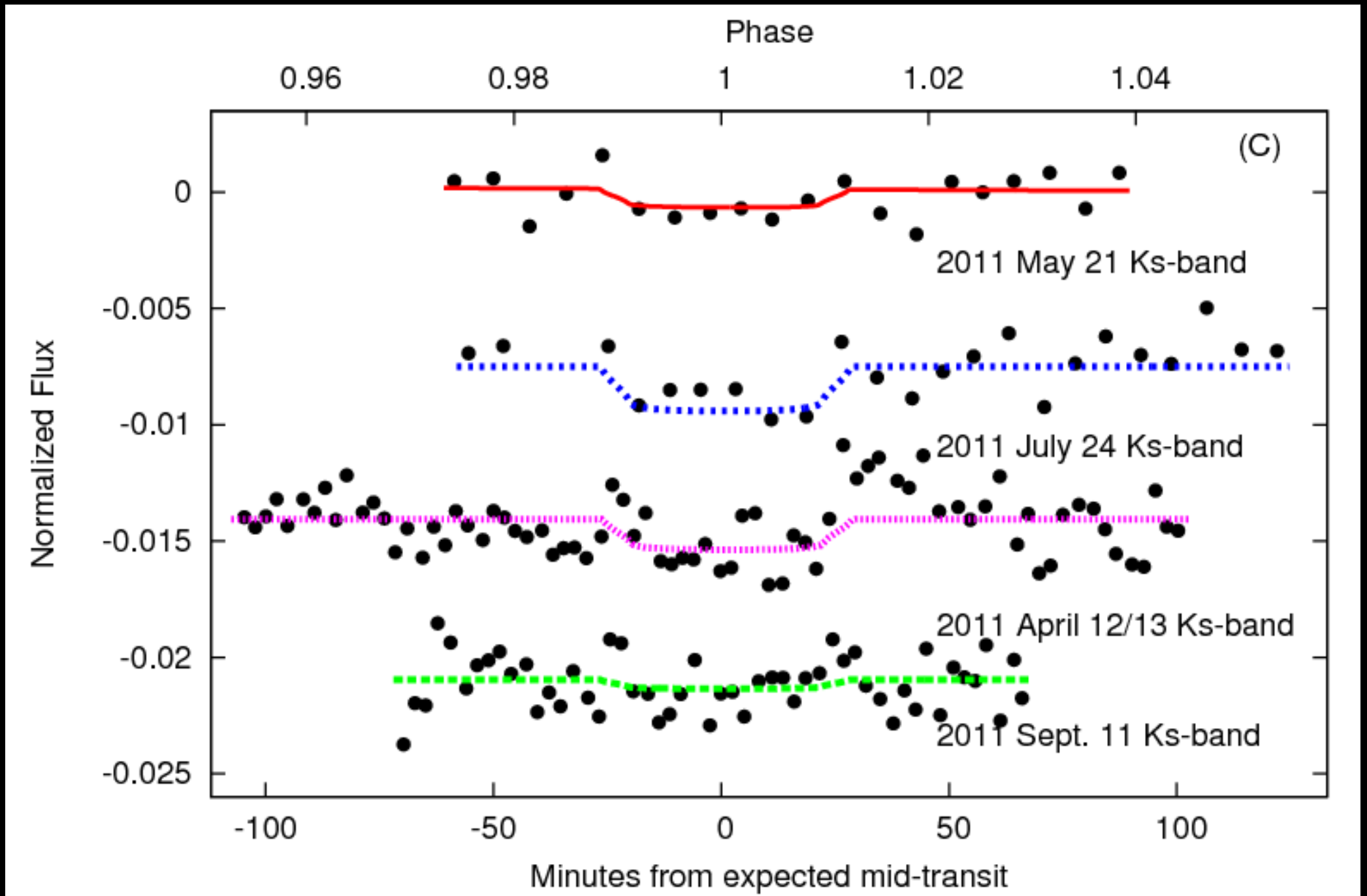

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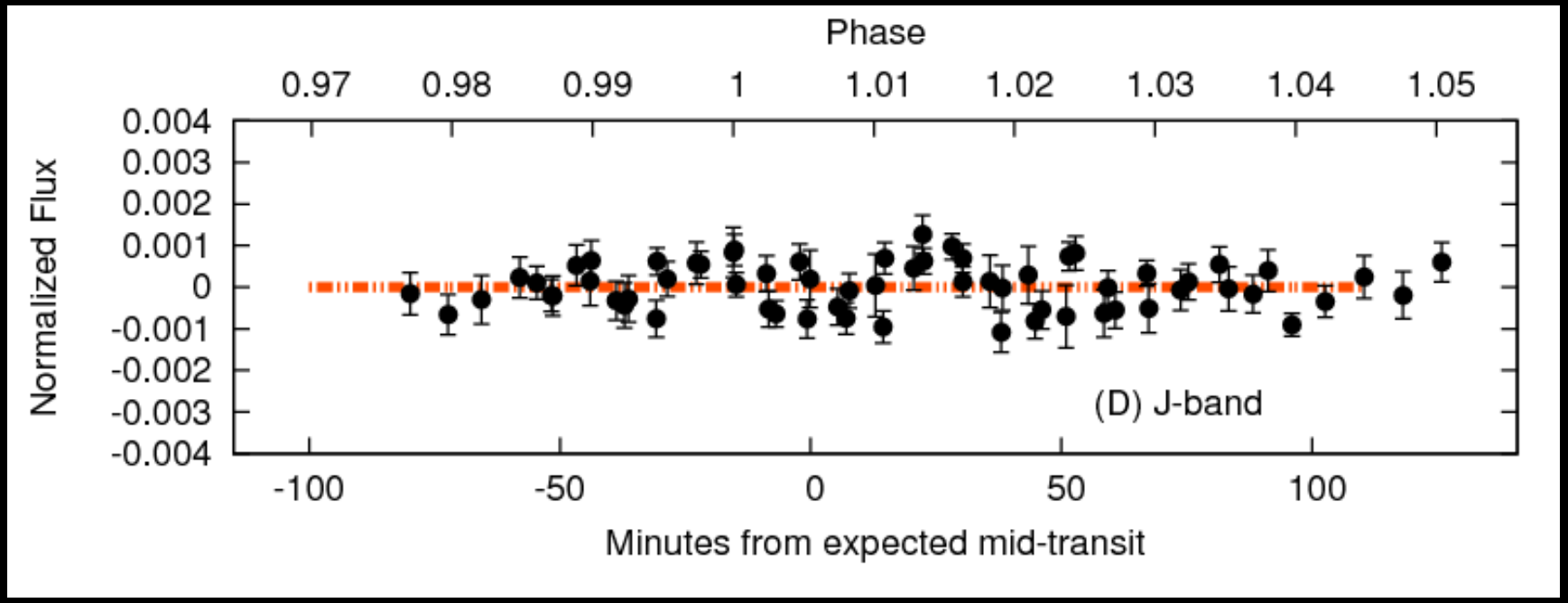
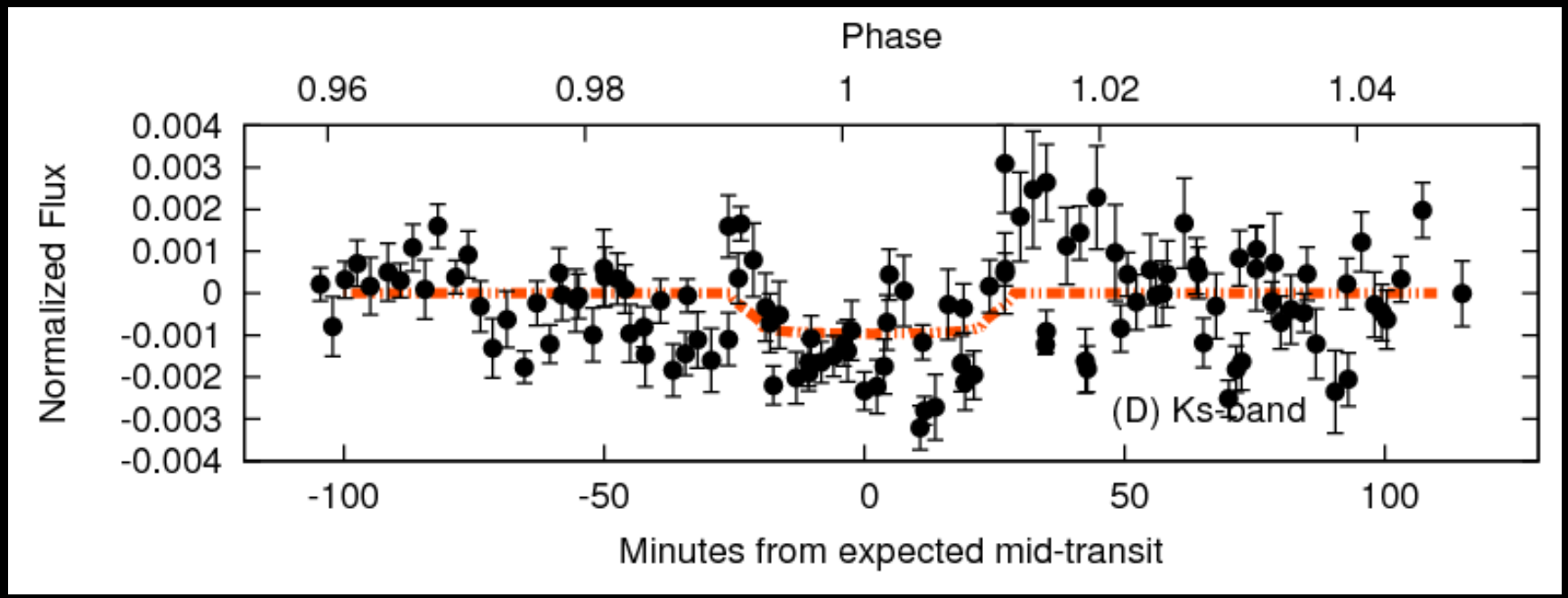
Croll et al. In prep.

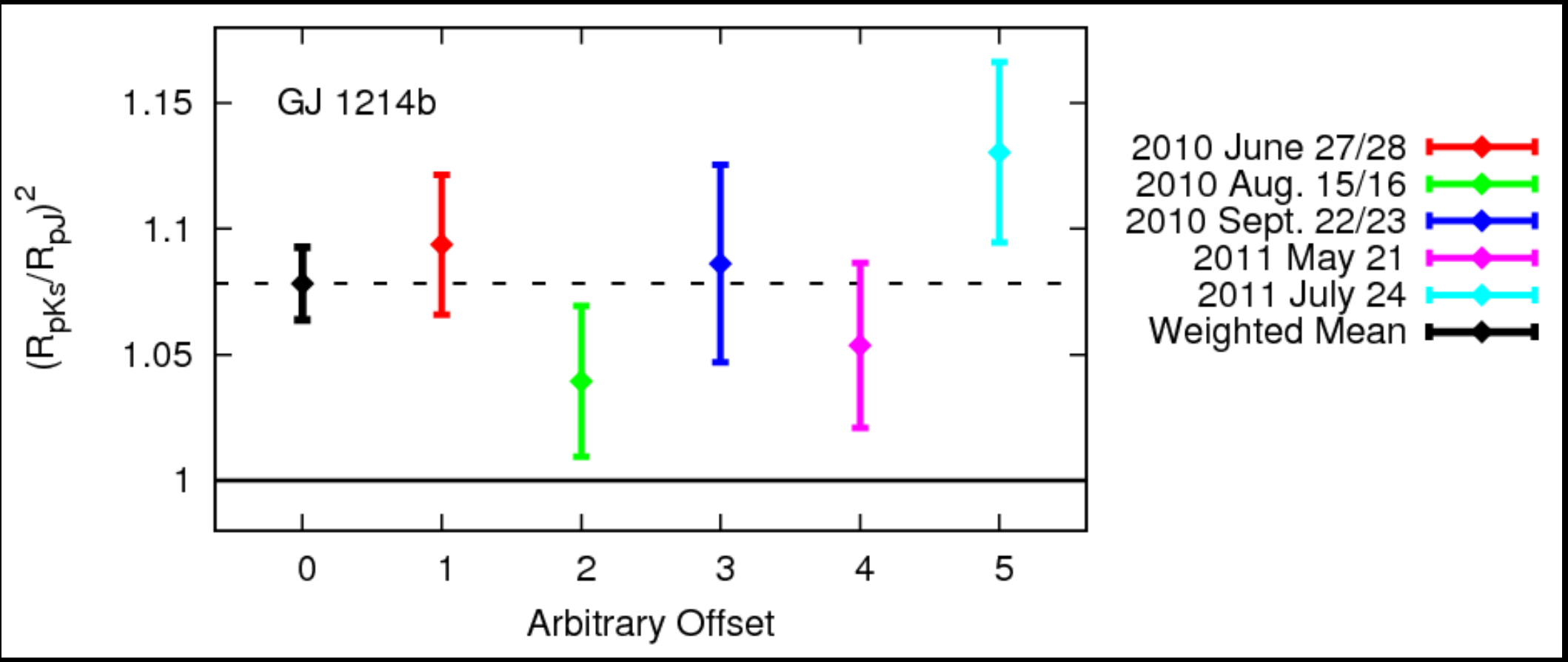




2010/2011: Ratio of Ks to J-band Transit Depths

Croll et al. In prep.

- The Ks-band (2.15 microns) transits are deeper than the J-band (1.25 microns) transits observed nearly simultaneously by greater than 5σ.

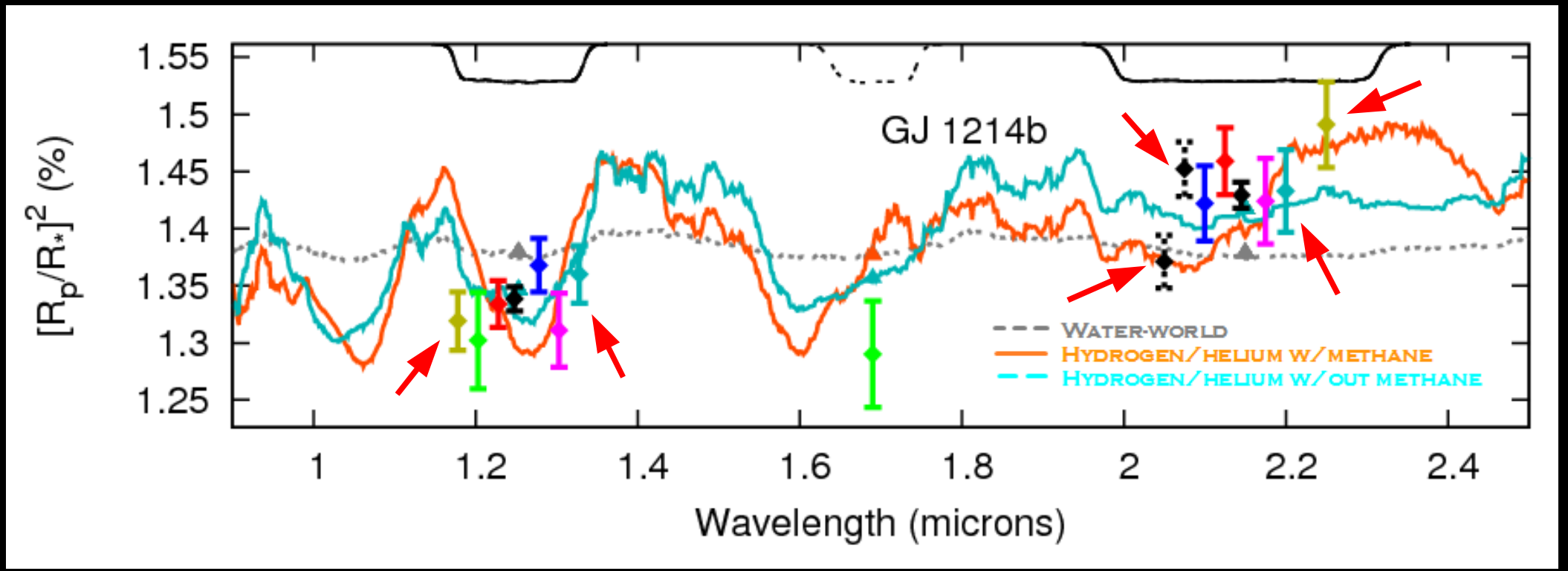


GJ 1214b: A low mean molecular weight Atmosphere?

Croll et al. In prep.

- A weighted mean of all the CFHT/WIRCam J-band and Ks-band transits to date suggests that our Ks-band observations are deeper by greater than 7-sigma.

2011 Transits: red arrows



A Steamy super-Earth?

- Bean et al. (2011) presented exquisite VLT/FORS2 and Magellan/MMIRS spectrophotometry and VLT/HAWKI photometry that ruled out a deeper Ks-band depth and argued that GJ 1214b is either a cloudy/hazy hydrogen/helium dominated planet or a water-world...

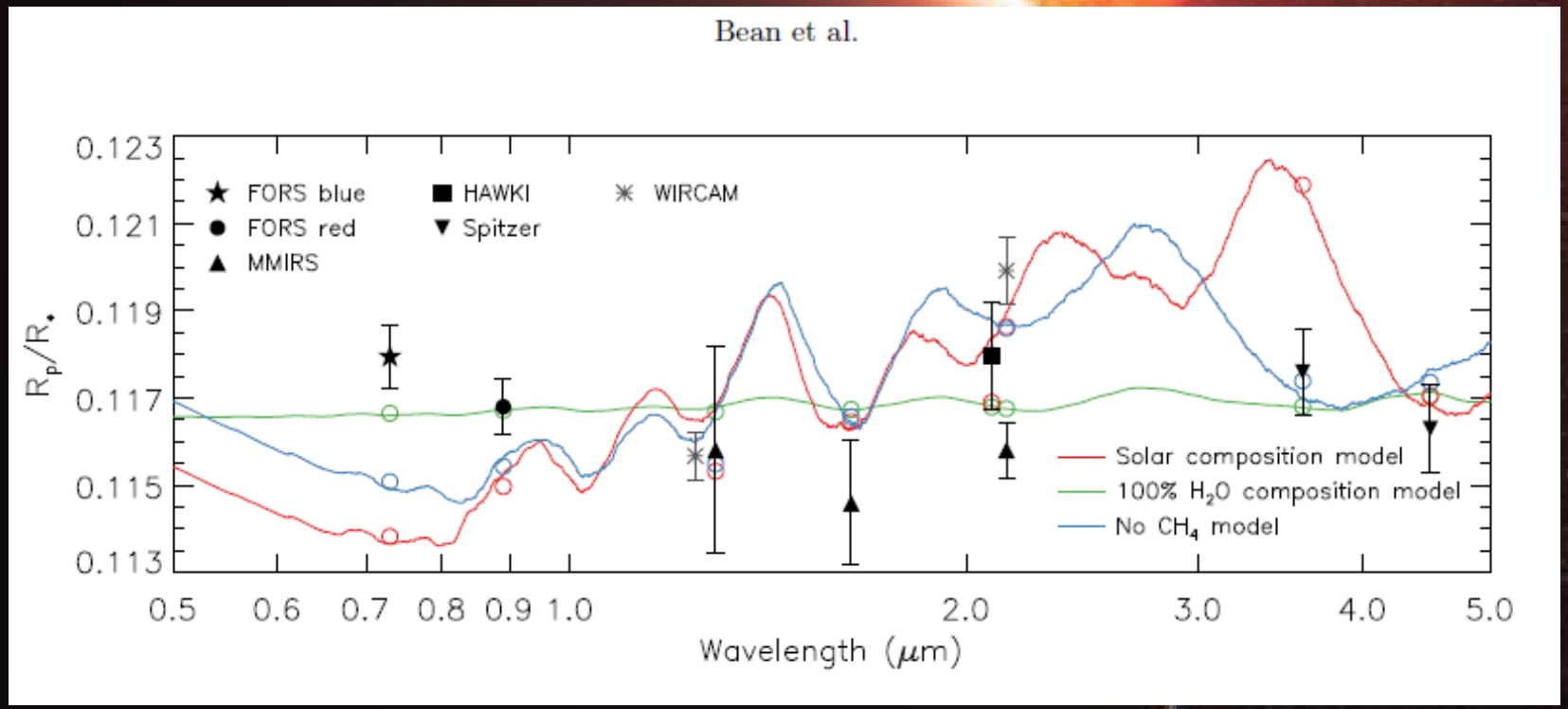


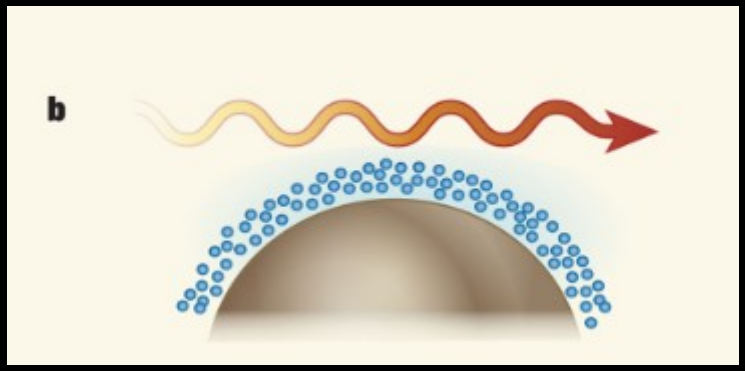
Image Credit: ESO/L. Calçada

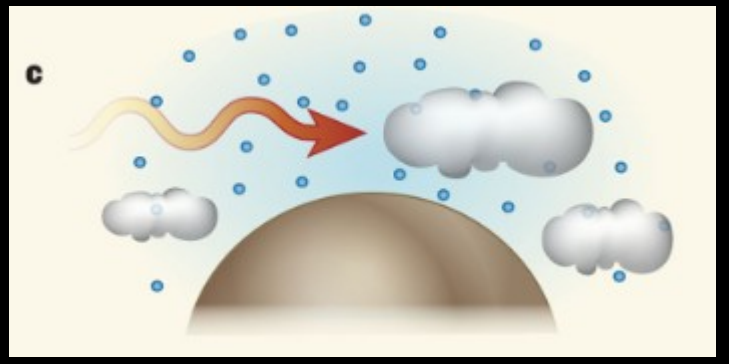
Possible Systematics with CFHT/WIRCam Staring Mode data

- Switching the filter back and forth. However the J-band photometry appears robust and it is difficult to imagine a systematic induced by switching the filter that only affects the Ks-band photometry. Also, although it is difficult to extrapolate from just two points, the combination of our two transits where we observe solely in Ks-band display a similar combined depth to our Ks-band weighted mean – however, our most recent Ks-band transit does display the smallest depth yet, only 1-sigma deeper than our J-band mean.
- Non-linearity correction. However our J-band photometry reaches similar count levels to our Ks-band photometry. Thus any discrepancy in the non-linearity correction should be similar in both bands. Not applying the non-linearity correction at all still returns significantly deeper Ks-band depths.
- It is difficult to imagine how other systematics (variations with airmass, colour of the reference star versus the target star) would induce a transit depth difference in the Ks-band but not the J-band photometry, as the transit depth is already a differential measurement.

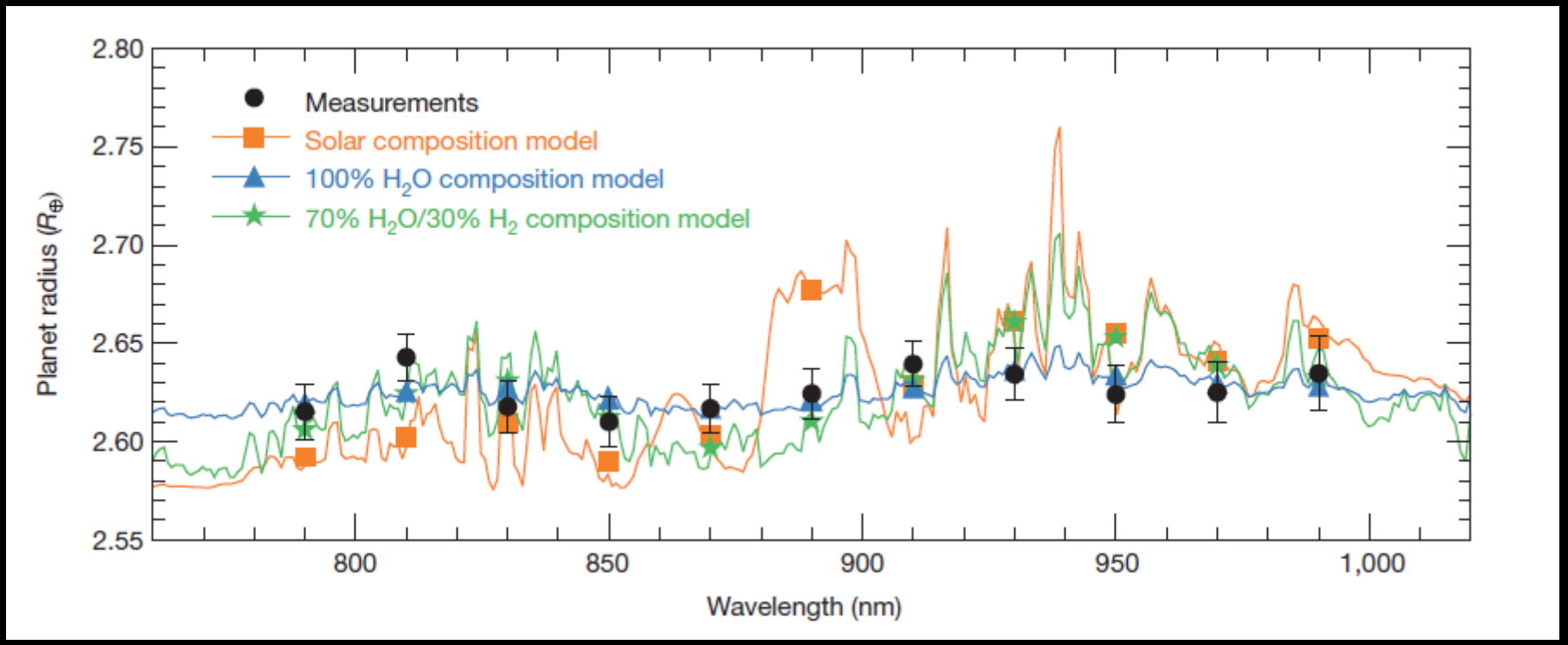
VLT Photometry of GJ 1214B

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.

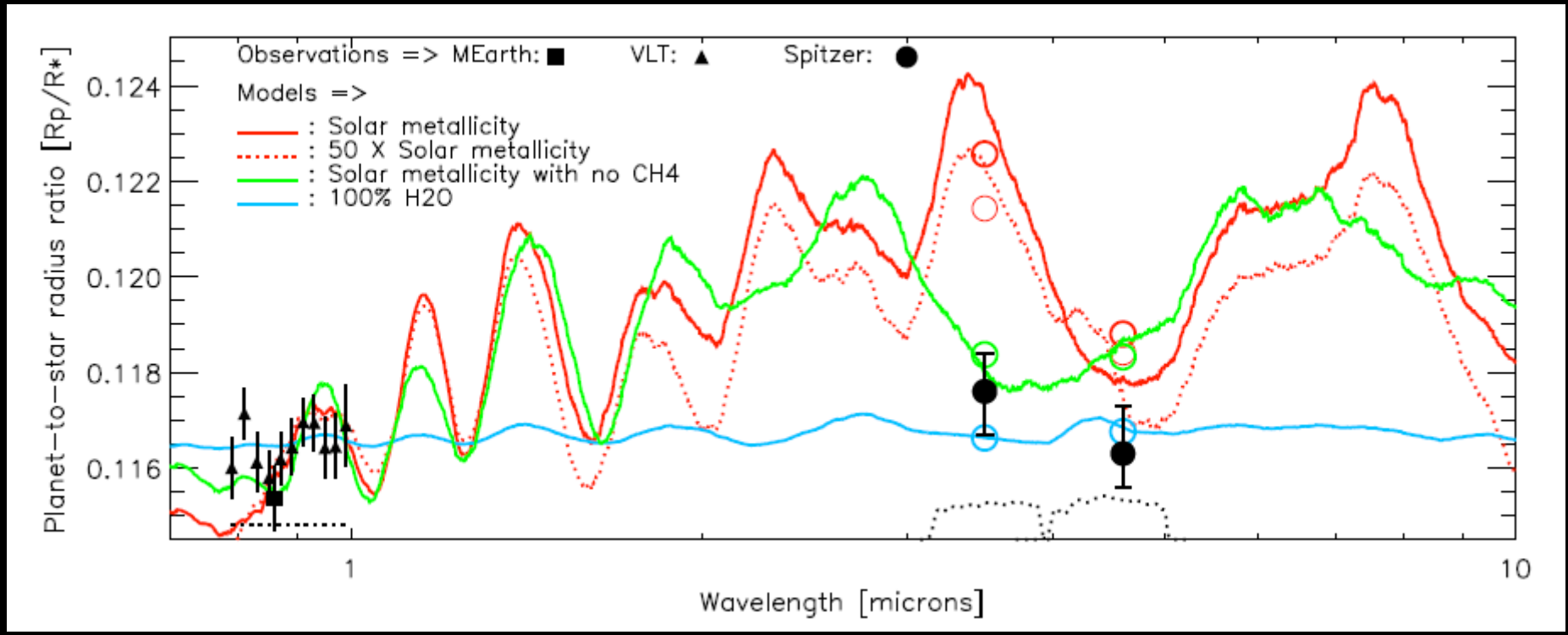
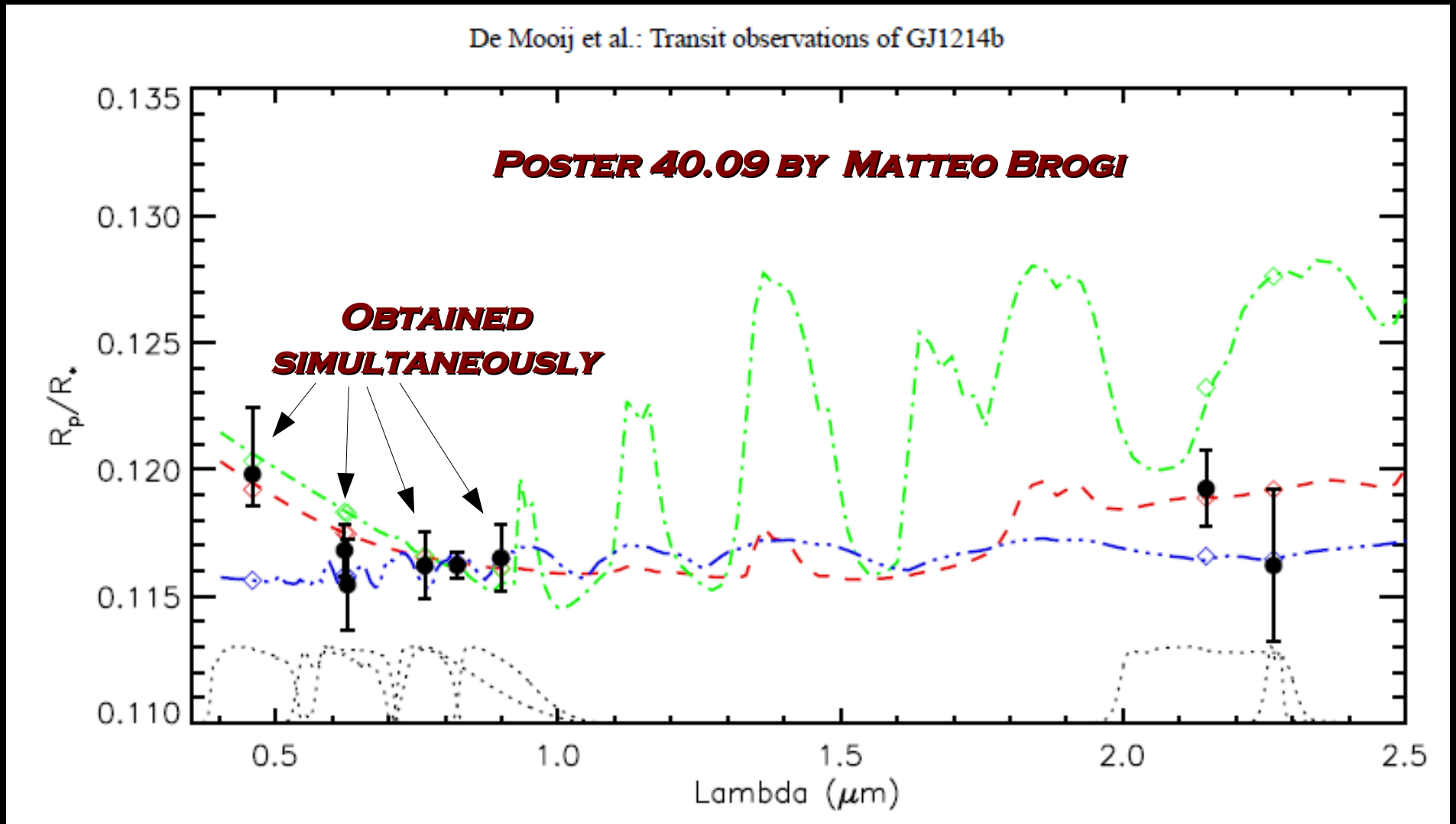


Figure from Desert et al. (2011). Spitzer/IRAC 3.6 and 4.5 micron observations of GJ 1214b

Additional groundbased observations of GJ 1214b

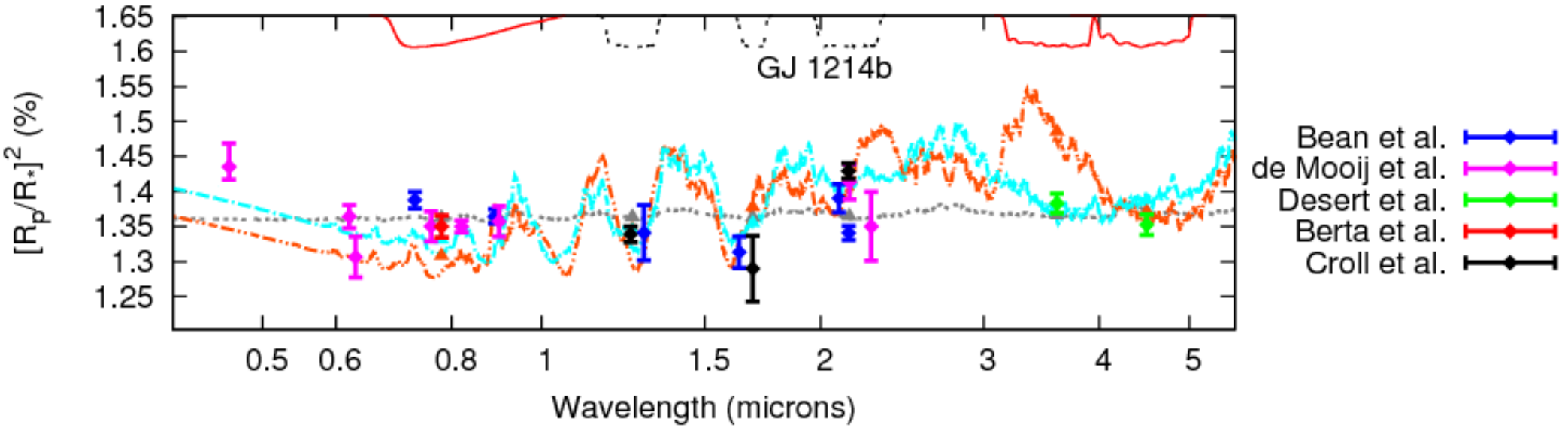
de Mooij et al. (submitted)

- Photometry obtained with the Isaac Newton Telescope (INT), the MPI/ESO telescope, the Nordic Optical Telescope (NOT) and the William Herschel Telescope (WHT).



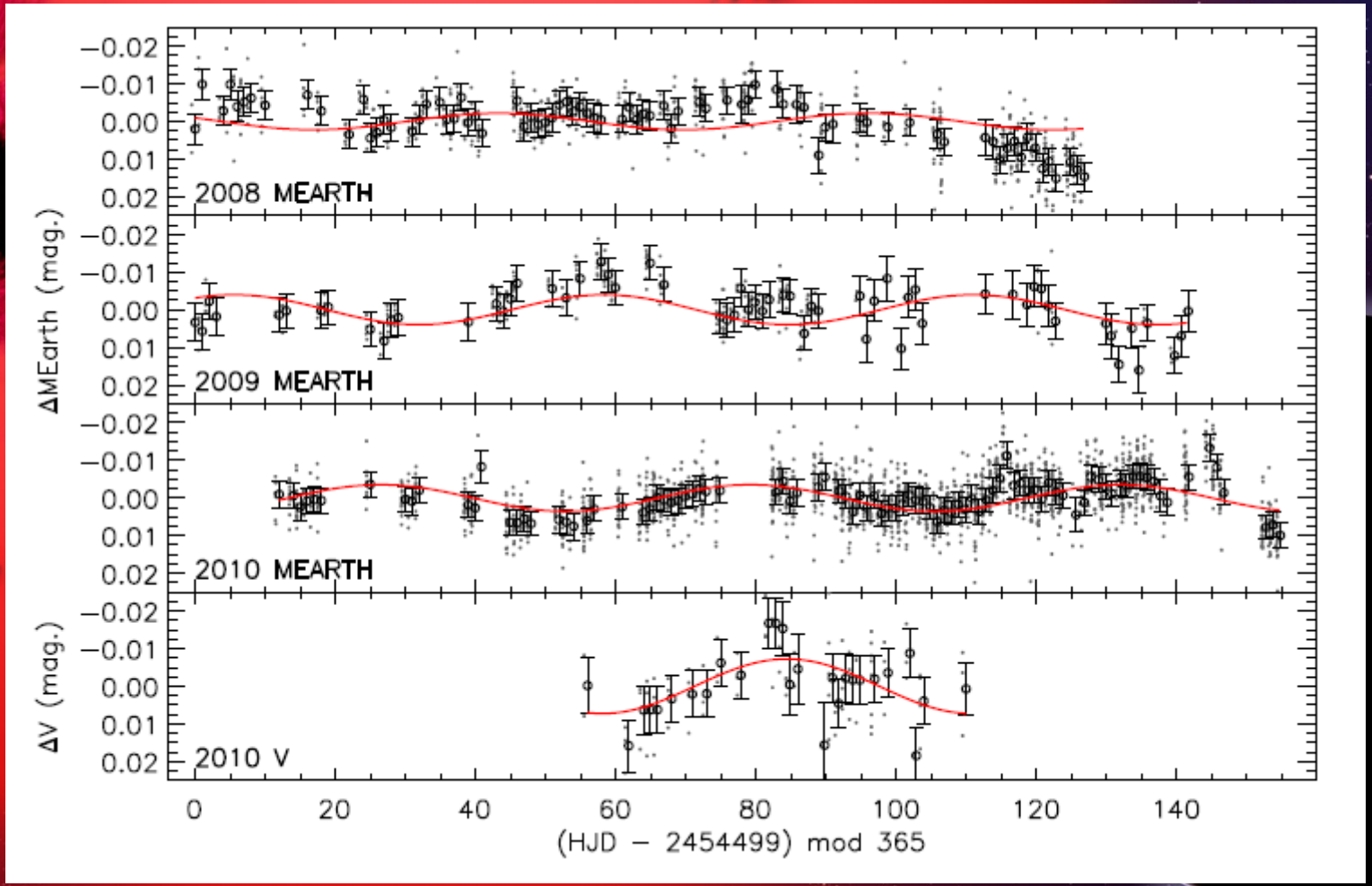
GJ 1214B's Atmospheric Composition

- A combination of all the observations to date suggests a relatively flat spectrum. Thus a *water-world* scenario or a *hydrogen/helium atmosphere with a high altitude cloud layer* remains the preferred scenarios.
- A hazy methane-free hydrogen/helium atmosphere remains a plausible scenario, but requires follow-up observations that discover additional spectral features to remain viable.
- A single discrepant point is not sufficient justification to justify an obscure physical scenario.



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

Effects of Unocculted spots

- Even though the Spitzer infrared points show remarkable agreement with the optical values, the planet to star radius ratio may be significantly higher than in the optical, if GJ 1214 is continually spotted (de Mooij et al. submitted). This would favour a hydrogen/helium dominated atmosphere.

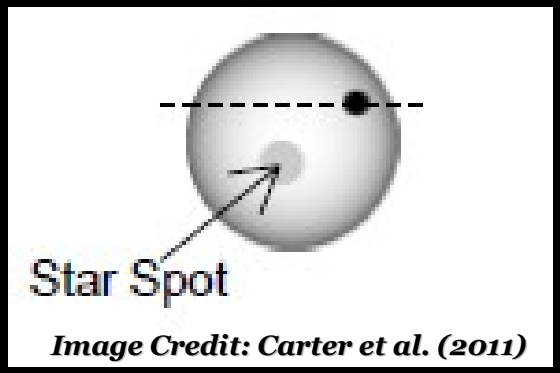
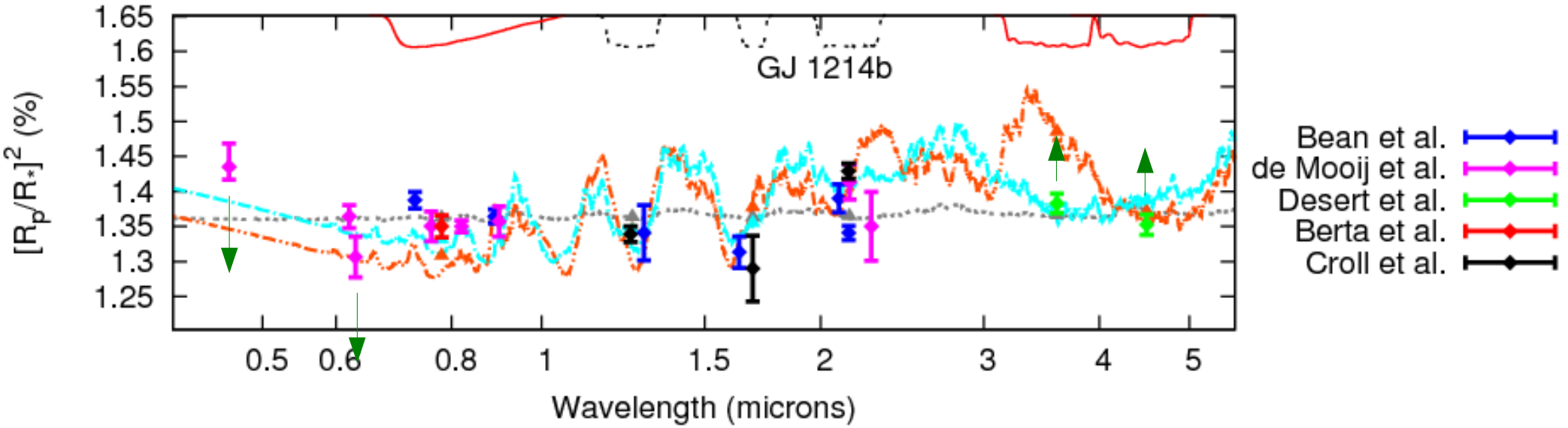


Image Credit: Carter et al. (2011)



Summary: GJ 1214b, Water-world or Mini-neptune?

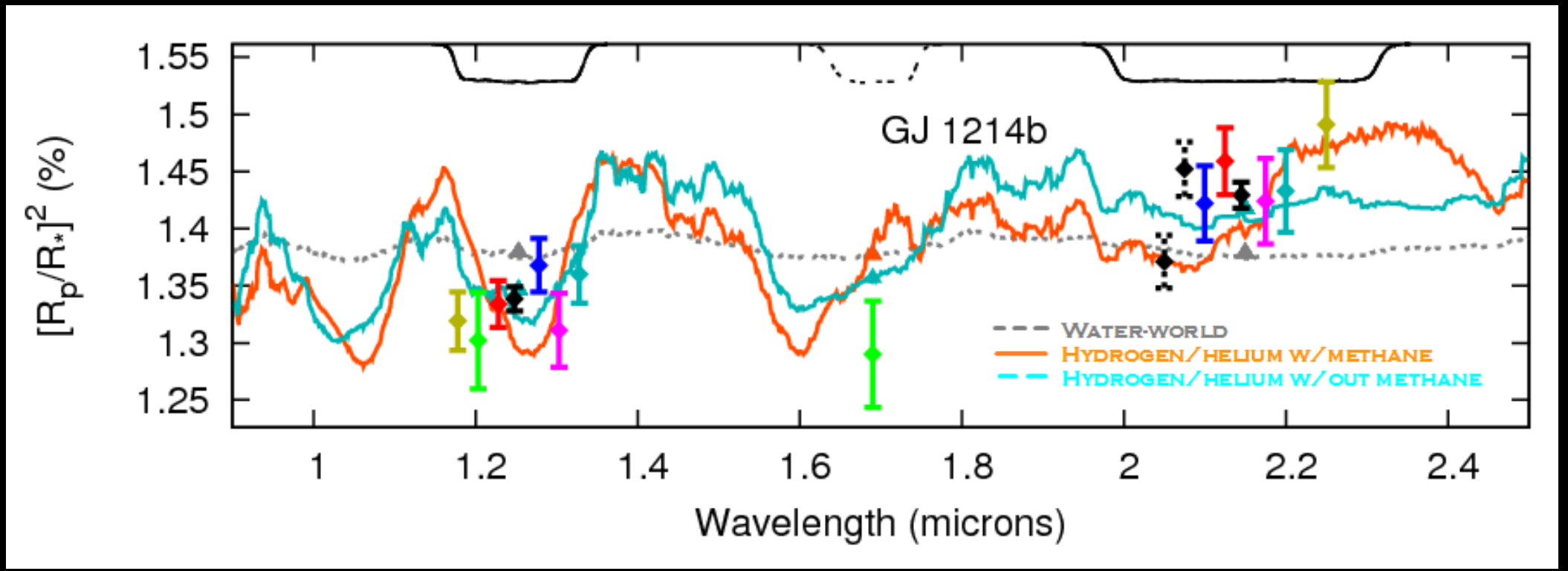
- Despite that our CFHT/WIRCam observations display a deeper Ks-band than J-band transit depth, the combination of all the observations to date reveal a relatively flat spectrum, thus favouring a water-world or hydrogen/helium atmosphere with a high altitude cloud layer.
- A more complicated hydrogen/helium dominated atmosphere remains viable, but requires additional observations to confirm near-infrared spectral features or short wavelength scattering features.
- Either way, it is important to validate these broadband photometric and spectrophotometric techniques to facilitate future observations of exoplanets, including exo-Earths.

Image Credit: David A. Aguilar, CfA

GJ 1214b: A low mean molecular weight Atmosphere?

Croll et al. In prep.

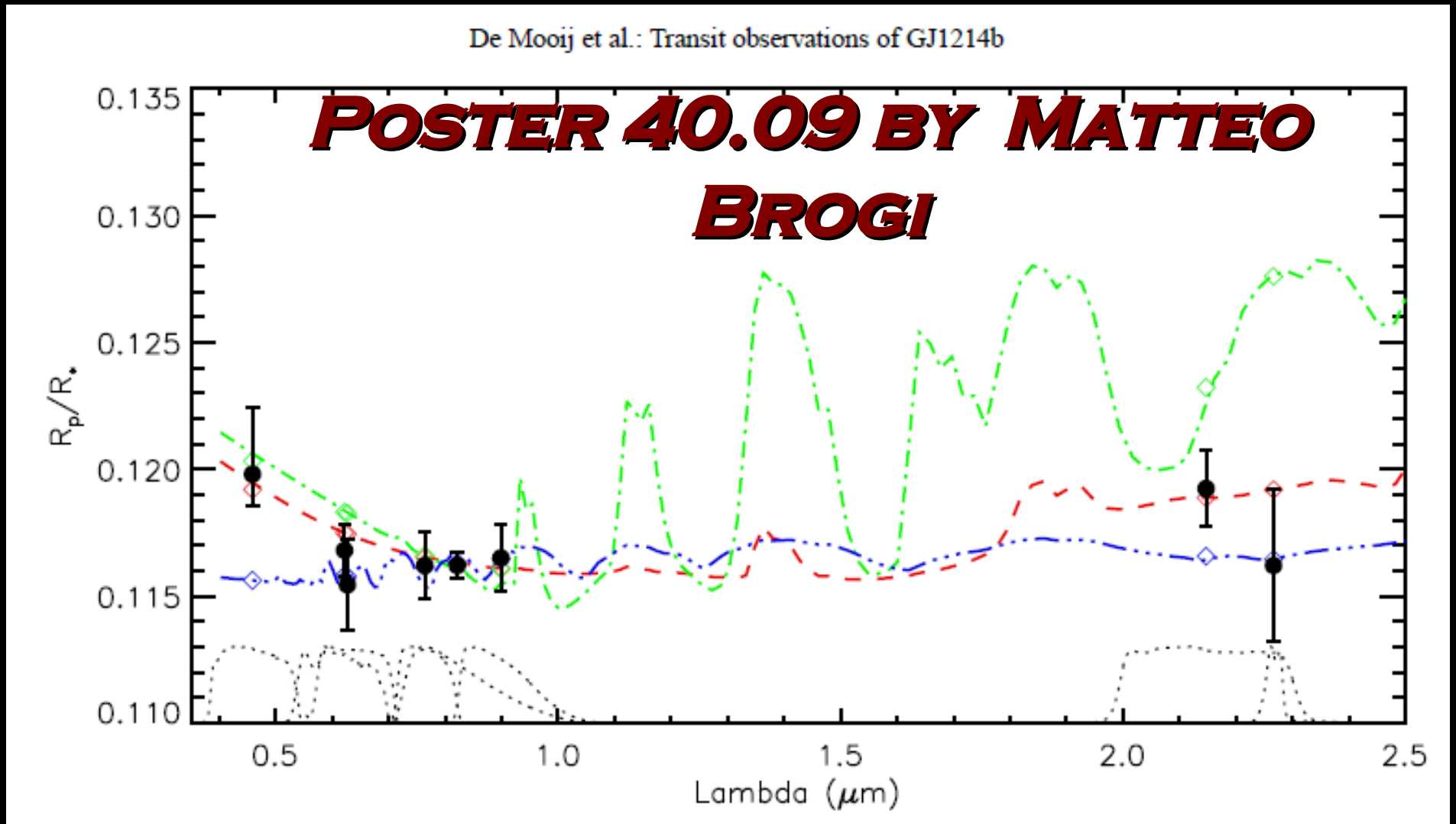
- A weighted mean of all the CFHT/WIRCam J-band and Ks-band transits to date suggests that our Ks-band observations are deeper by greater than 7-sigma.



Additional groundbased observations of GJ 1214b

de Mooij et al. (submitted)

- Photometry obtained with the Isaac Newton Telescope (INT), the MPI/ESO telescope, the Nordic Optical Telescope (NOT) and the William Herschel Telescope (WHT).



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!

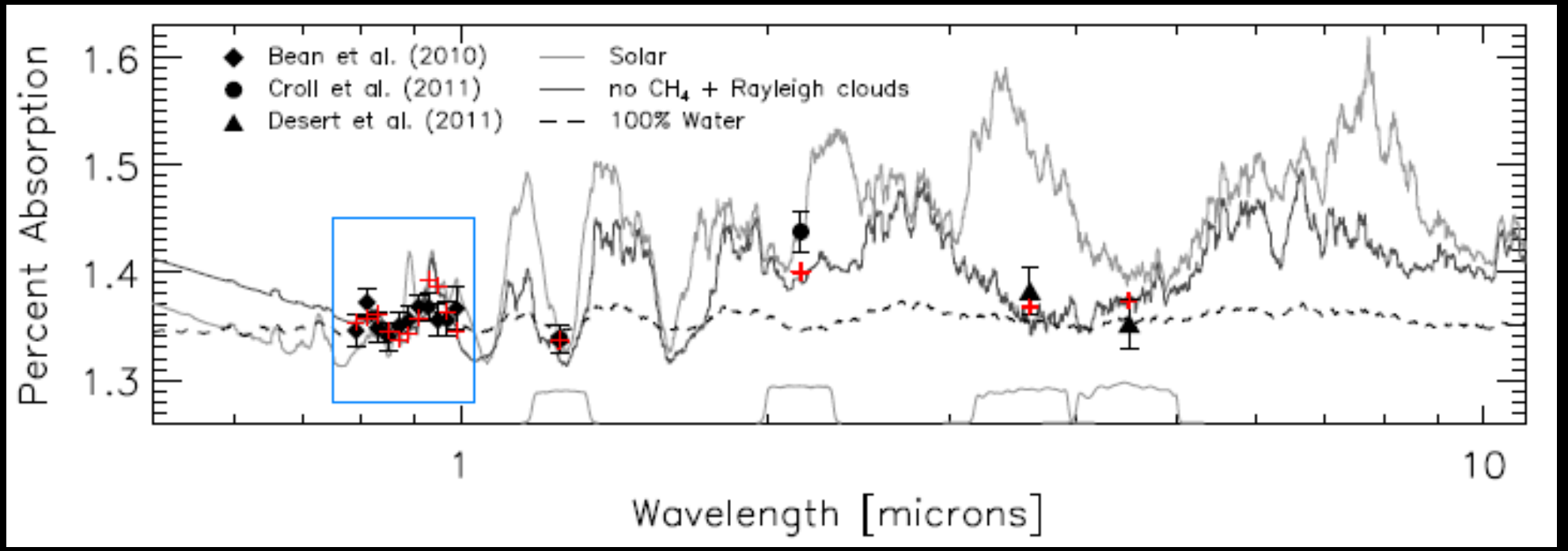


Figure from Miller-Ricci Kempton et al. (2011): Compilation of the GJ 1214B Transit Depths to date across a wide wavelength range.

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

Croll et al. (2011)

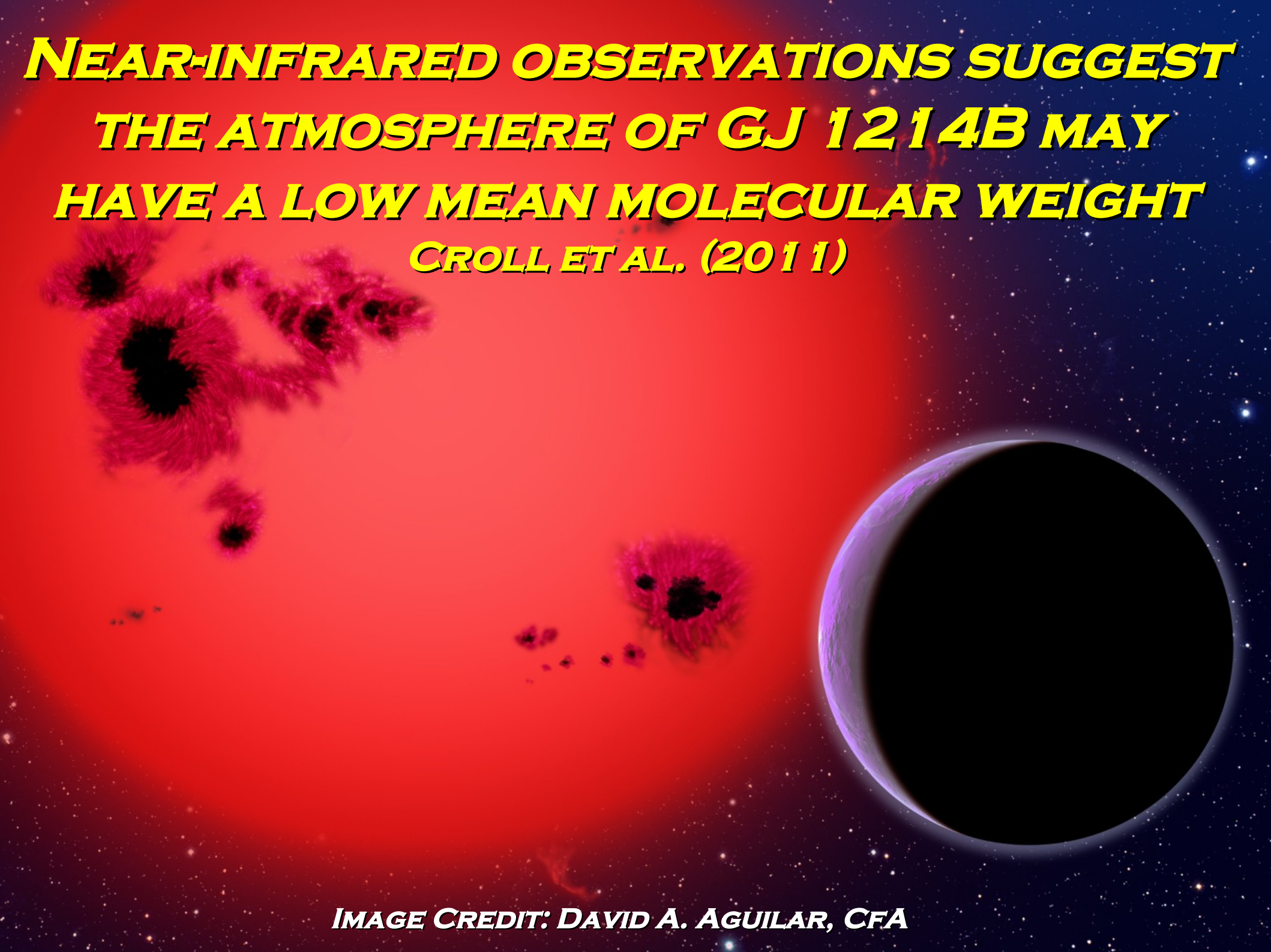


Image Credit: David A. Aguilar, CfA

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.
- New and upcoming observations!

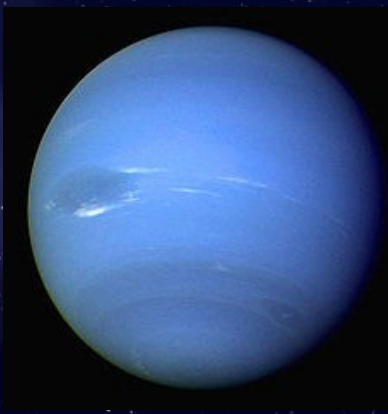


Image Credit: David A. Aguilar, CfA

The GJ 1214B Transmission Spectrum Refined

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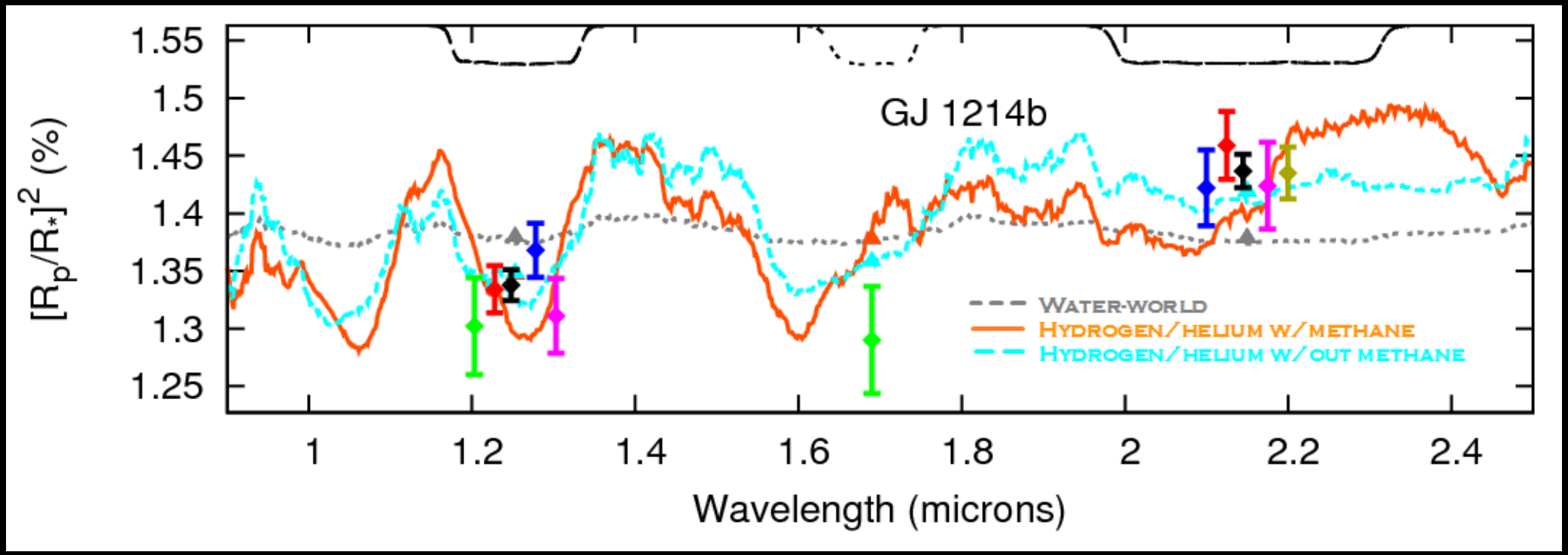

- Rules out the water world model at > 3-sigma.
- 6-sigma difference between the J and Ks-band depths.
- Three more CFHT/WIRCam transits of GJ 1214B in the next two weeks!

Recent Ks-band Observations of GJ 1214b

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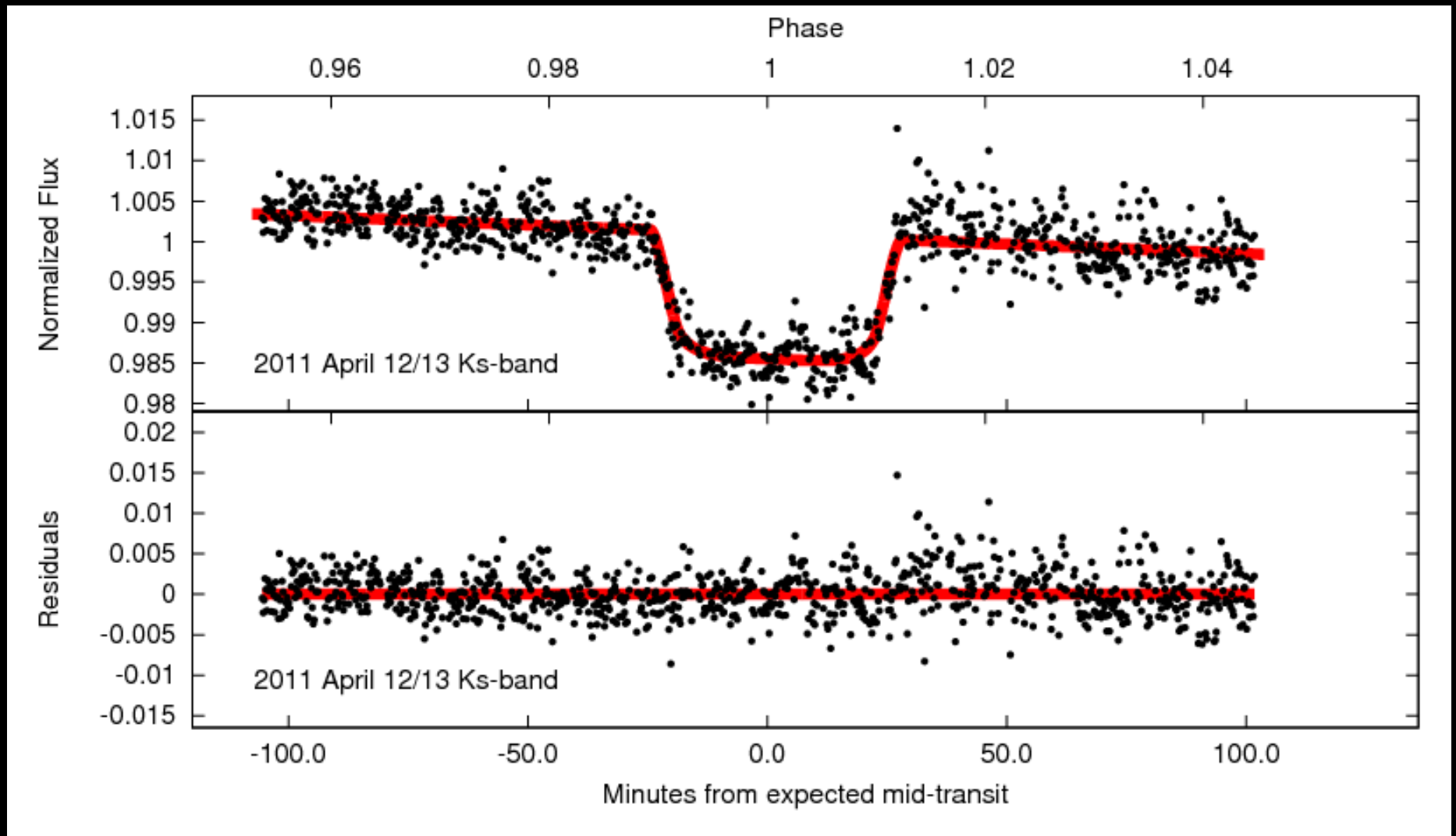
- Single-band observations only in Ks-band.
- However MEarth long-term monitoring indicates the star may be more spotted than last year.



A Large Rocky Core

Rogers & Seager (2010) & Nettelmann et al. (2010)

- From the observational constraints on the planet's mass (6.55 $M_{\oplus}$) and radius (2.68 $R_{\oplus}$), and thus density (Charbonneau et al. 2009) we can infer the bulk composition of GJ 1214b.
- The hydrogen/helium envelope makes up a small percentage of the mass.
- GJ 1214b, by mass, could have a great deal of water and a small amount of iron/silicates, or a very small amount of water and a very large amount of iron/silicates.
- Either way, GJ 1214b must have a large rocky core.

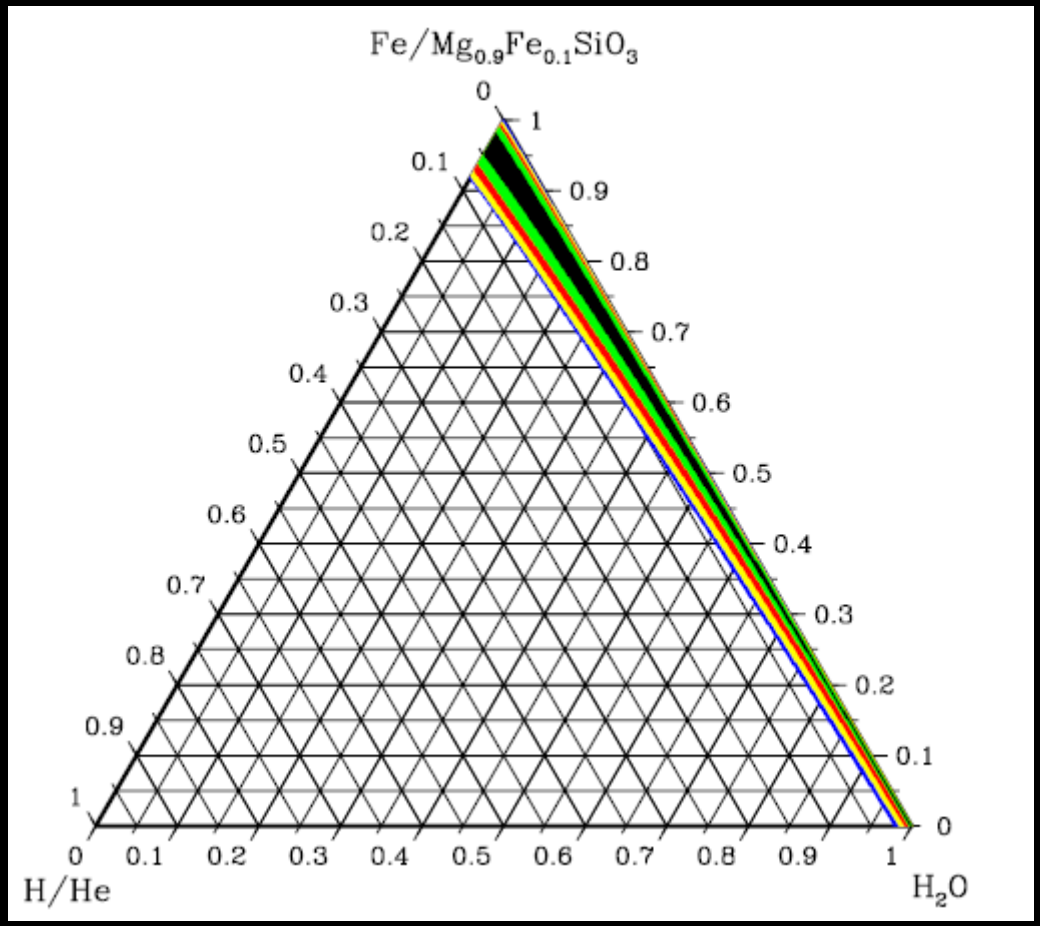
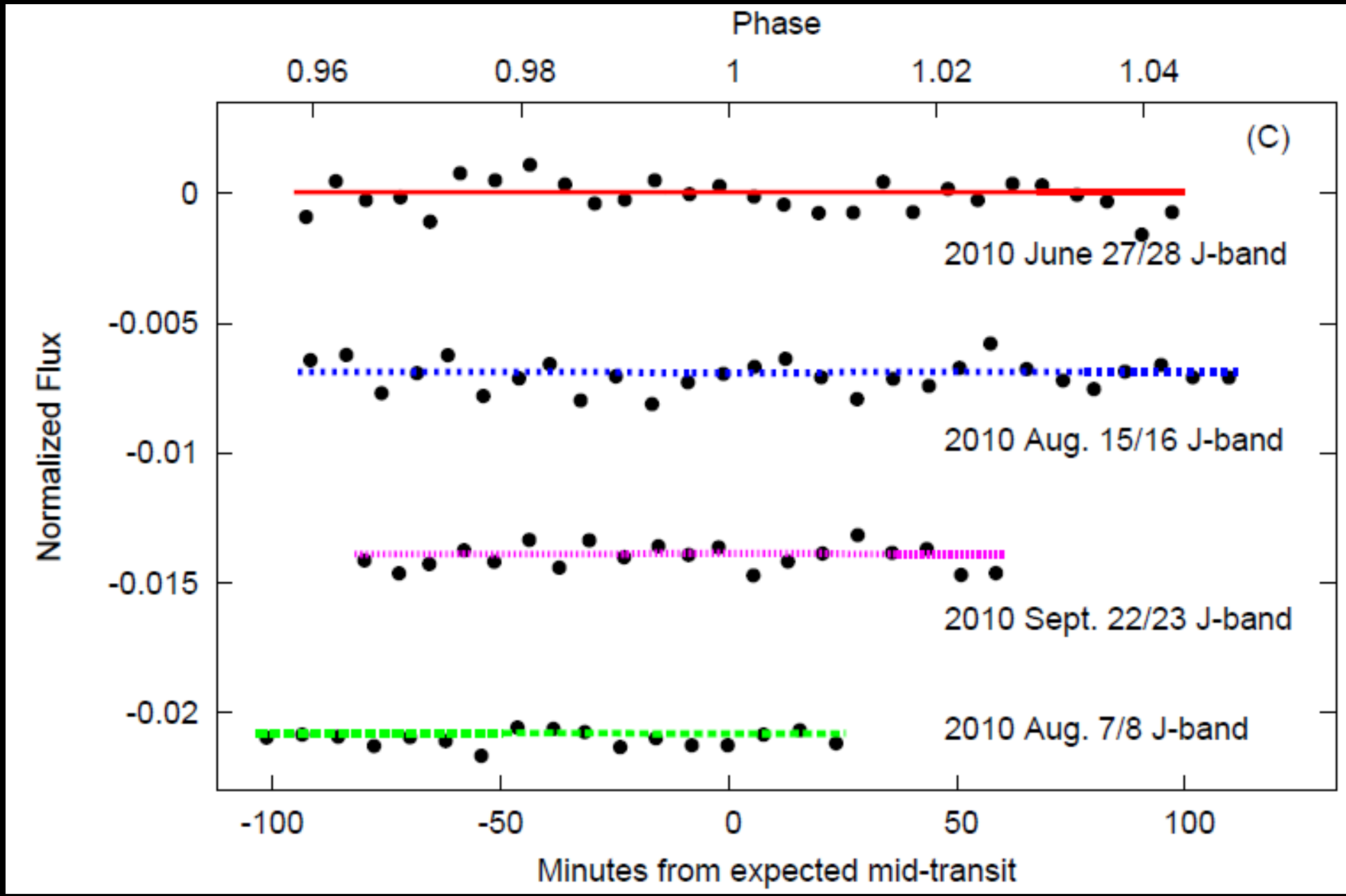


Figure from Rogers & Seager (2010).

Extra Absorption in Ks-band?

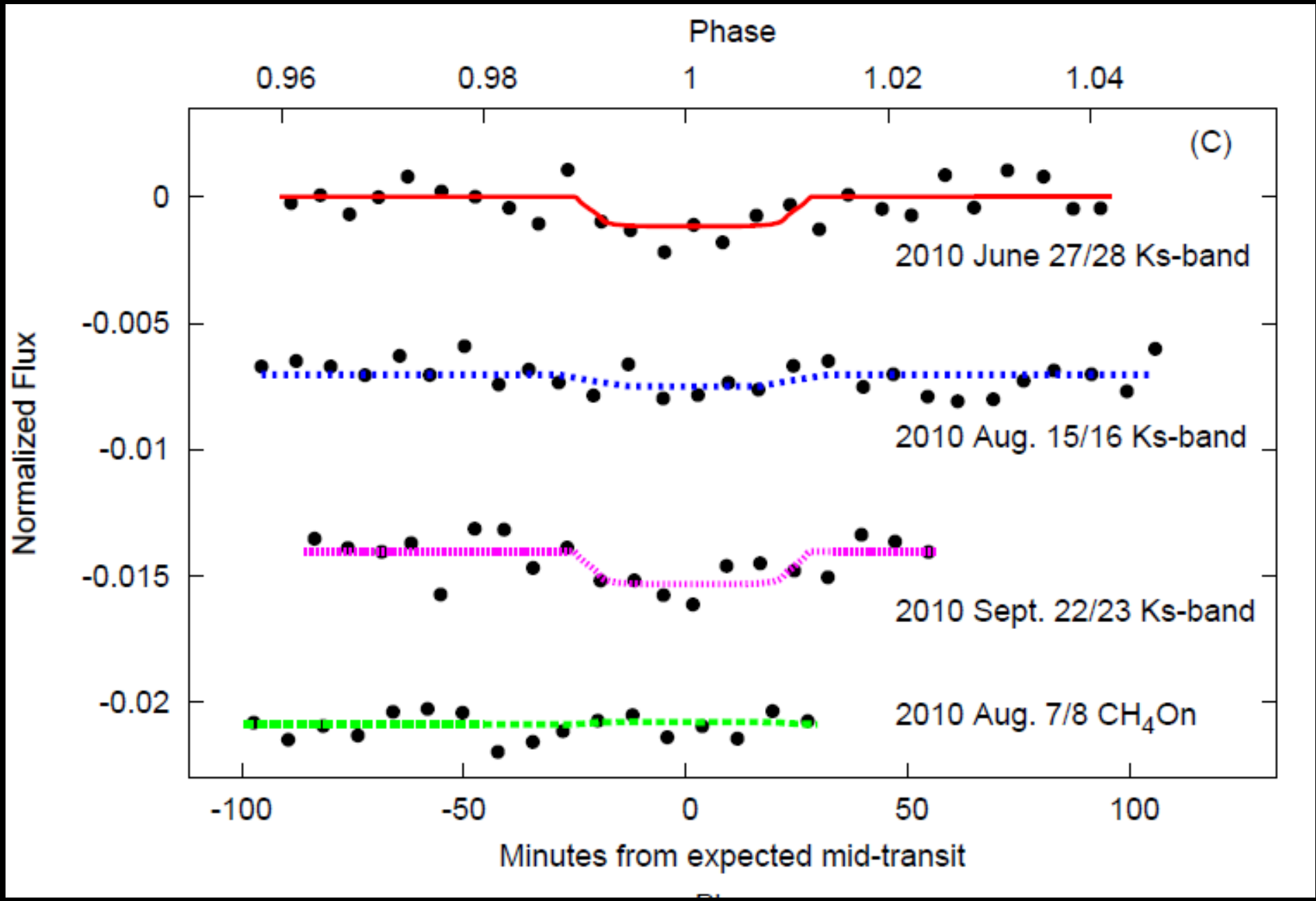
Croll et al. 2011



Residuals from the best-fit J-band Transit Depths.

Extra Absorption in Ks-band?

Croll et al. 2011



Residuals of the Ks and CH_4On data from the best-fit J-band Depths.