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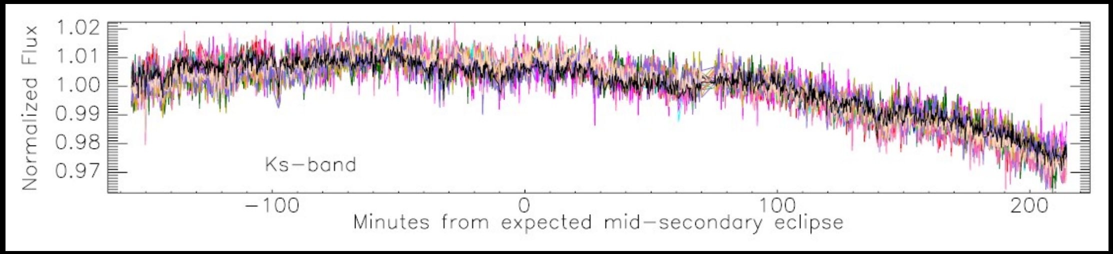
Precise Near-Infrared Red Photometry and its application to the Thermal Emission of hot Jupiters

November 9^{th} 2012

Image Credit: Greg Laughlin

Outline: Precise Near-Infrared Photometry

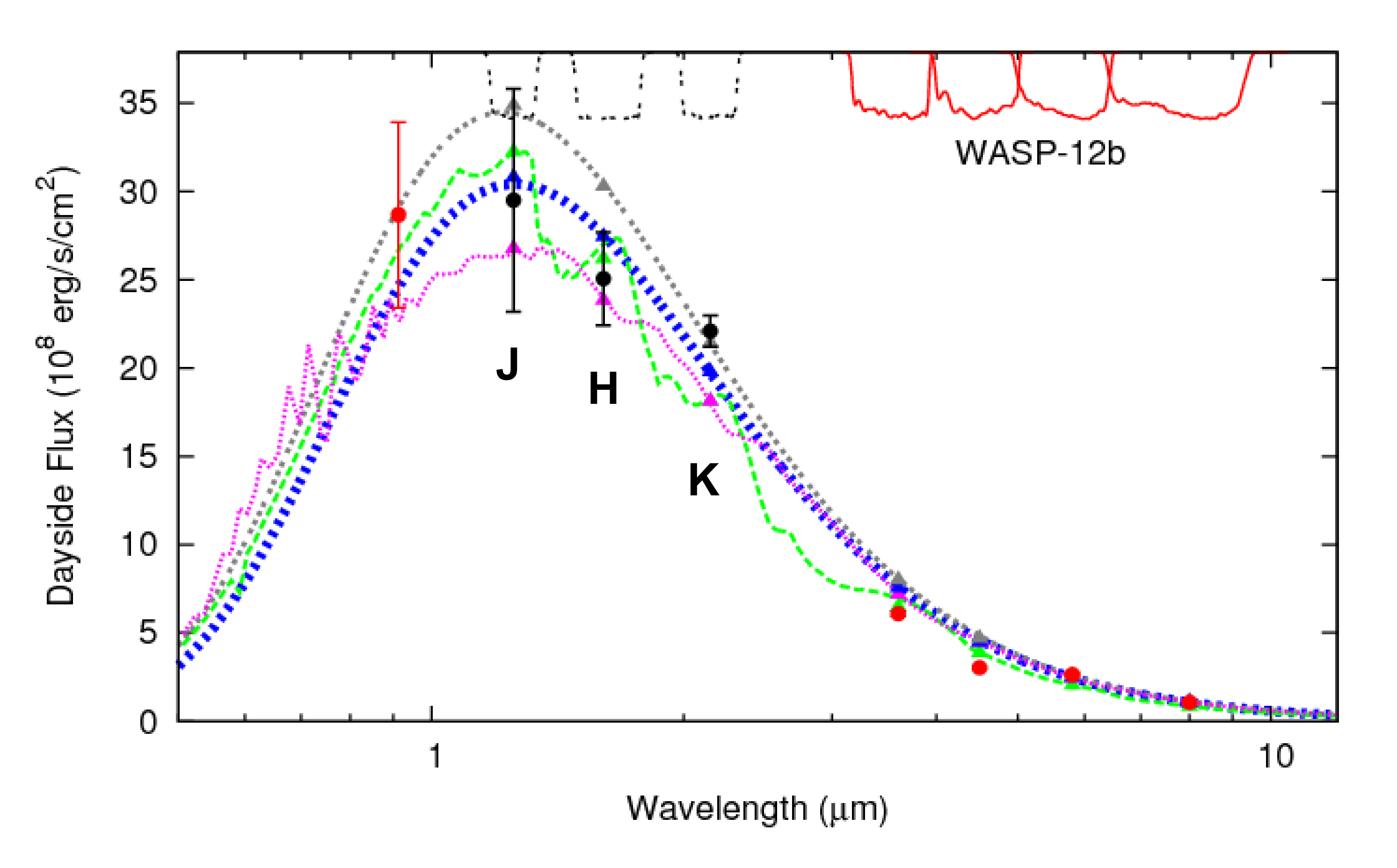
- Precise near-infrared photometry from the ground; limiting systematic effects…
- The application on InGaAs near-infrared detectors to astronomy.
- Lessons learned for hot Jupiters from near-infrared observations.



SU320HX-1.7 SWIR camera

Why the Near-infrared?

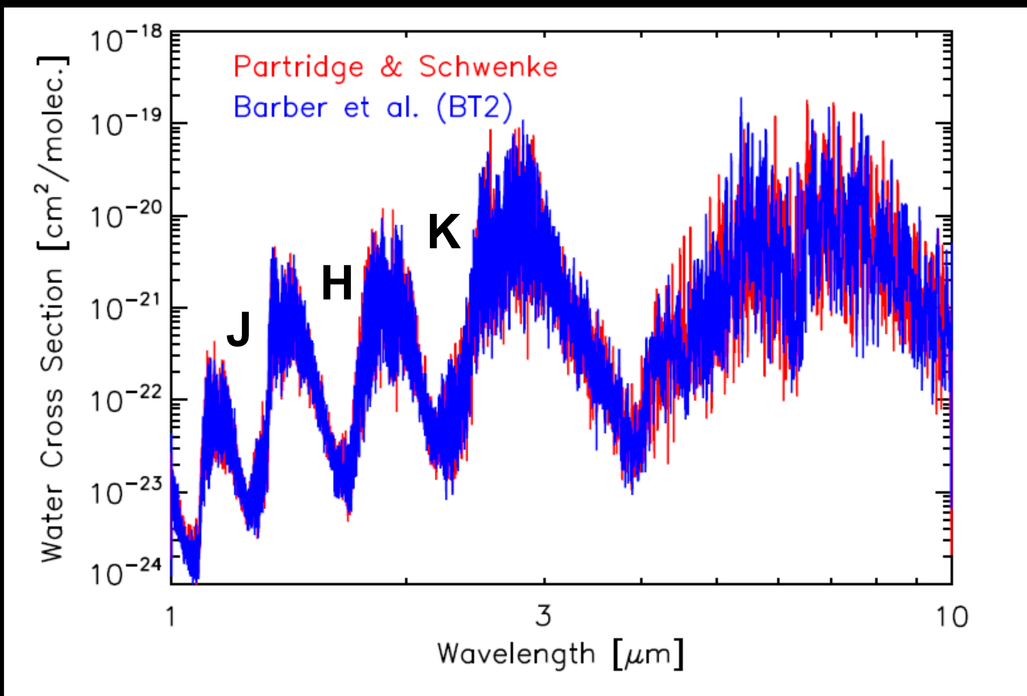
- For the hottest hot Jupiters the Spitzer mid-infrared wavelengths are at longer wavelengths than the blackbody peaks of these planets.
- The near-infrared J, H & K-bands often bracket the blackbody peaks of these planets.

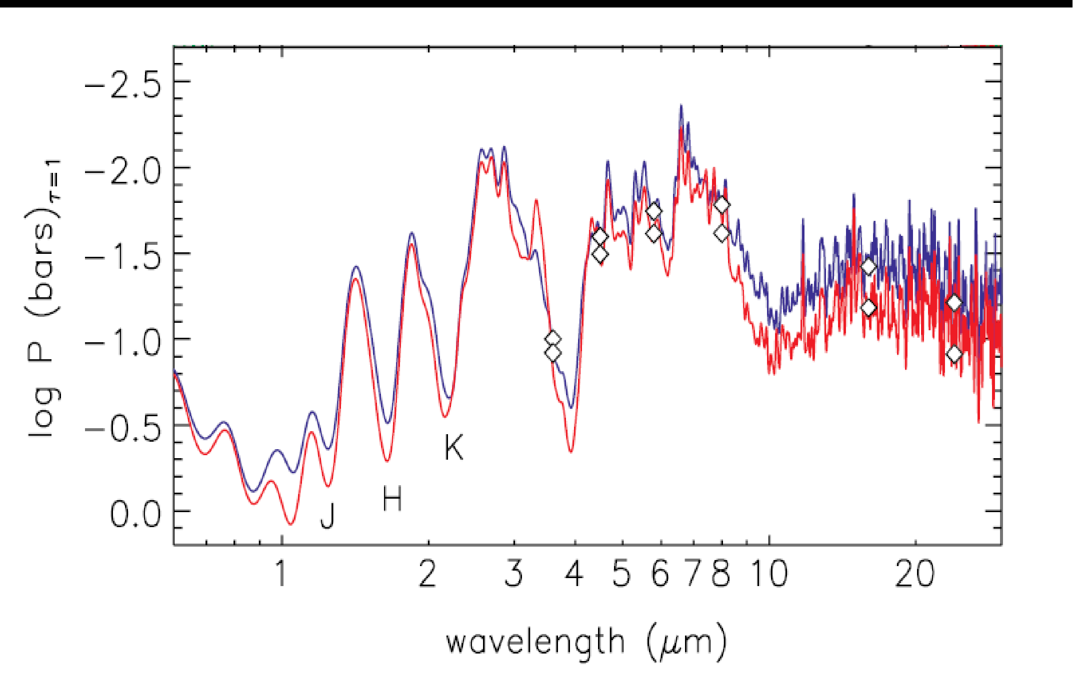


Above: Near- and mid-infrared detections for the highly irradiated hot Jupiter WASP-12b. Detections from Croll et al. (2010c), Lopez-morales et al. (2010) & Campo et al. (2011).

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.

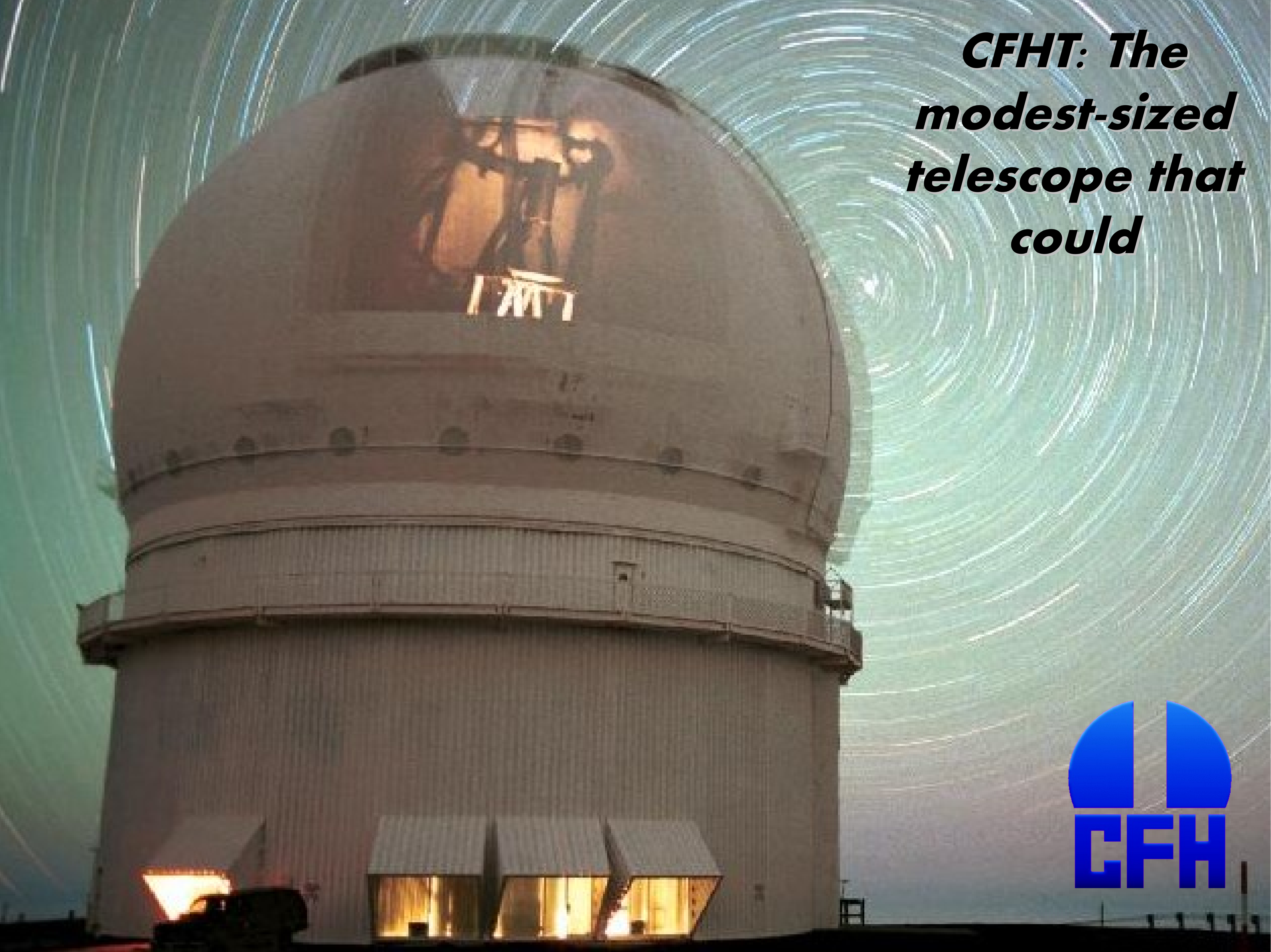




Left: The near-infrared J, H & Ks-bands are holes in the water opacity. Figure from Shabram et al. (2010).

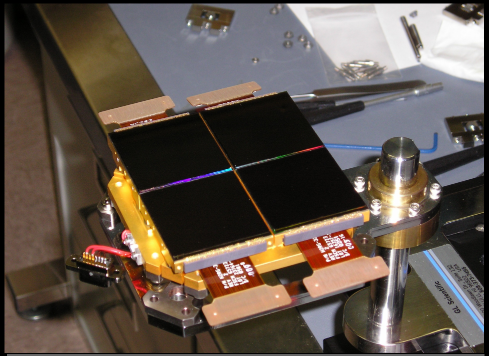
Right: J, H & Ks-band observations probe much deeper pressures and thus deeper depths in the atmospheres of hot Jupiters than the Spitzer/IRAC wavelengths. Figure from Barman et al. (2008).

CFHT: The modest-sized telescope that could



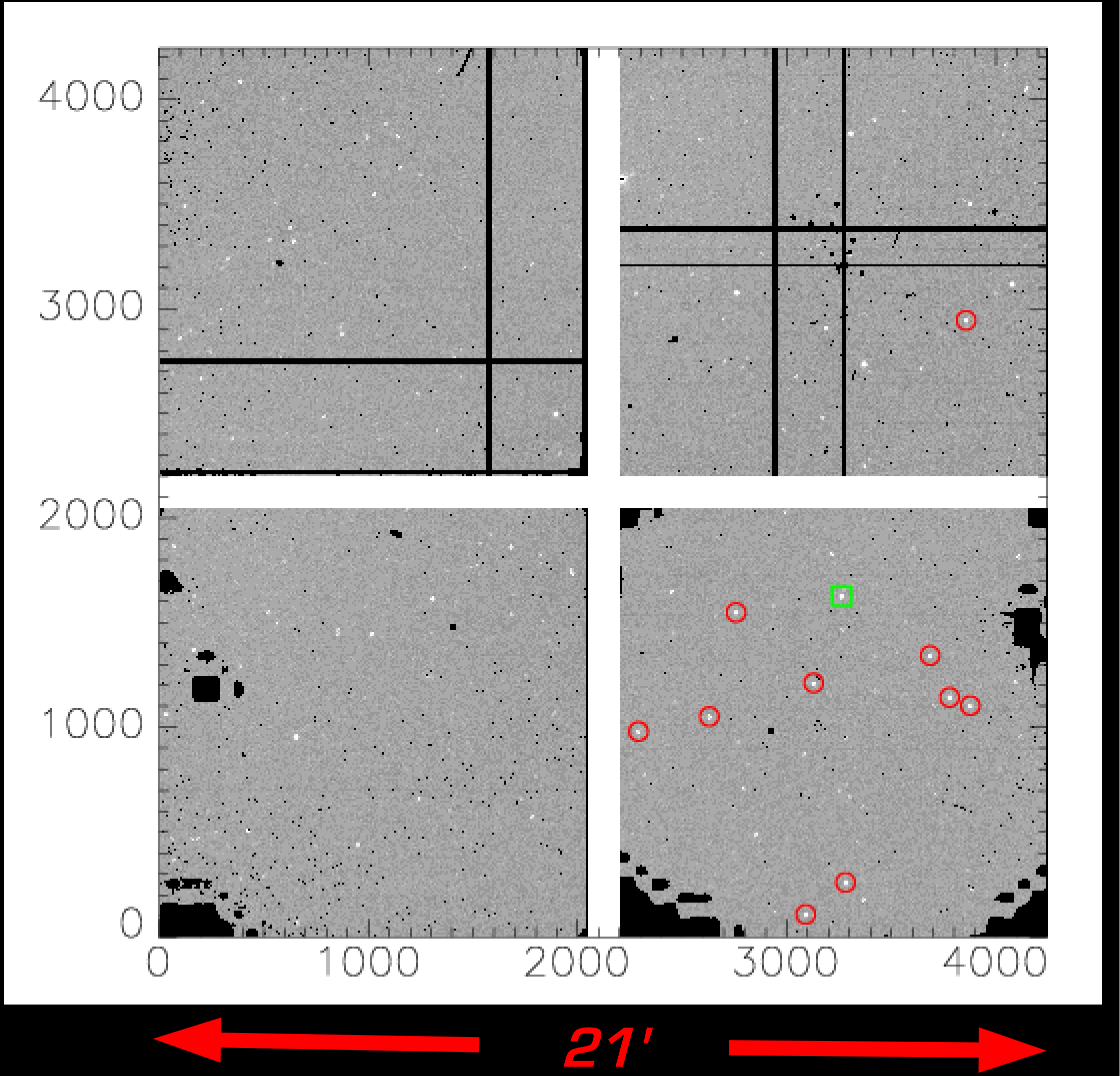
WIRCam Near-IR Defocused Photometry

- 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).

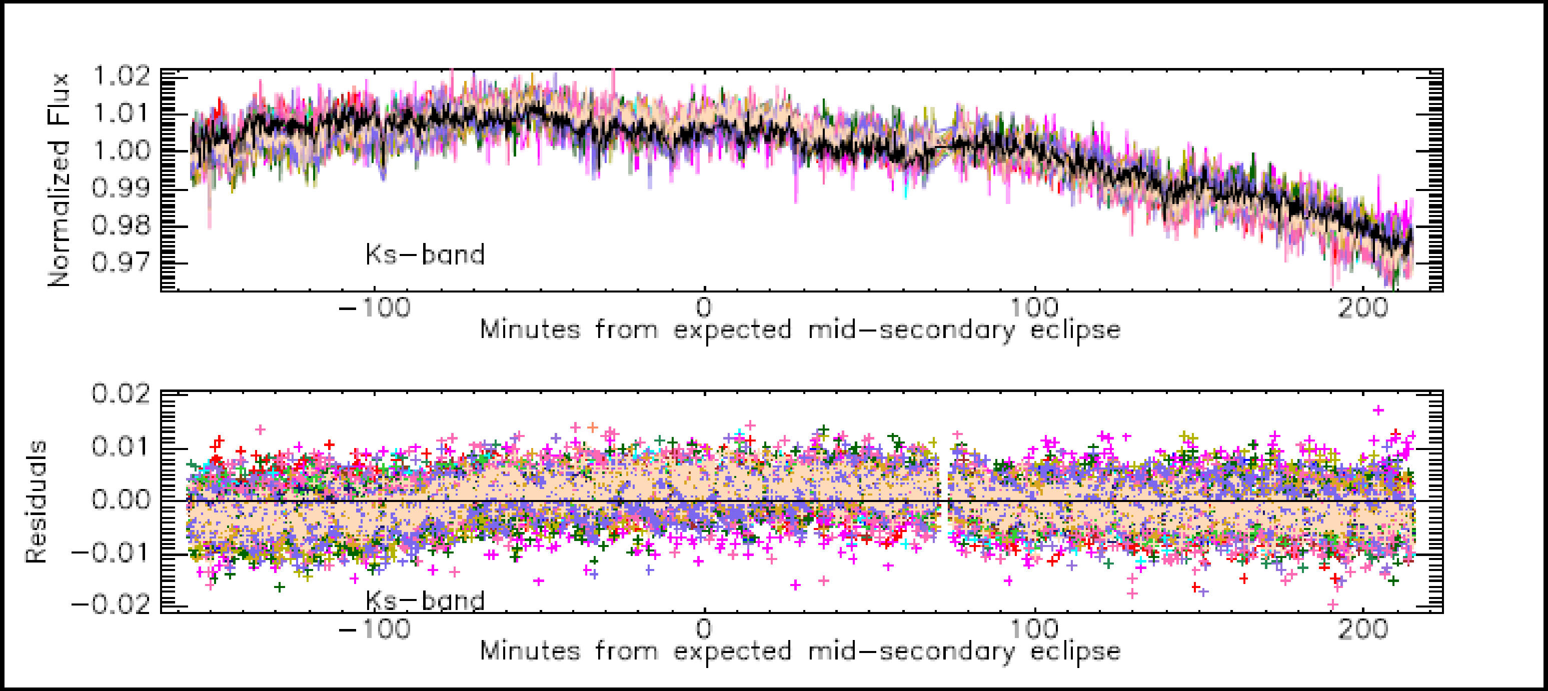
Bottom: We also observe significantly out of focus, so that the light is spread over a donut.



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.

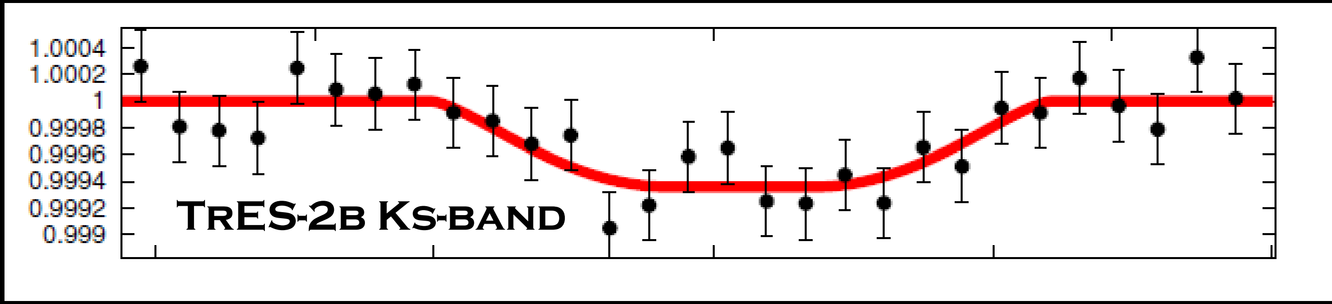


The flux and the residuals of the target star (black), and the reference stars (various colours).

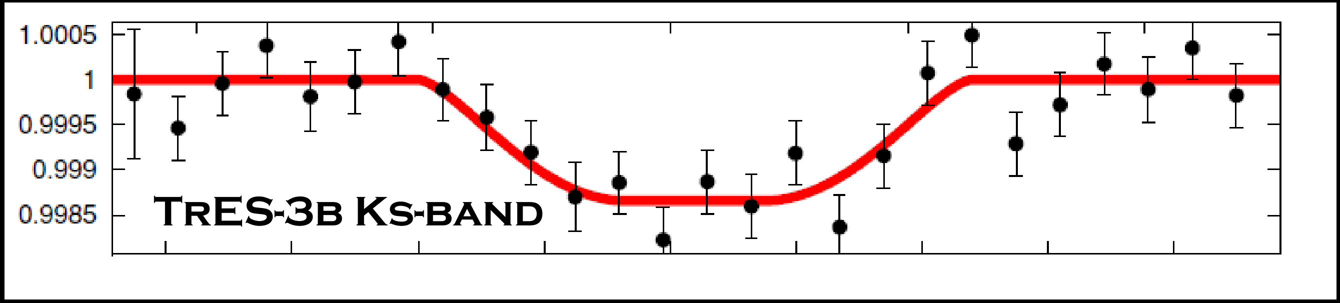
WIRCam Near-IR Detections

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

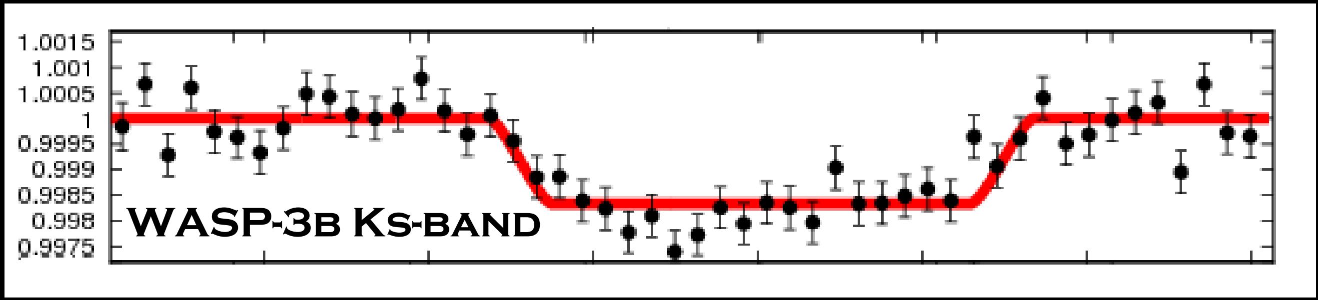
- A 5σ detection of the Ks-band (2.15 micron) thermal emission of TrES-2b equal to 6×10^{-4}.



- A 8σ detection of the Ks-band thermal emission of TrES-3b (13×10^{-4}), and an upper limit on its H-band thermal emission.



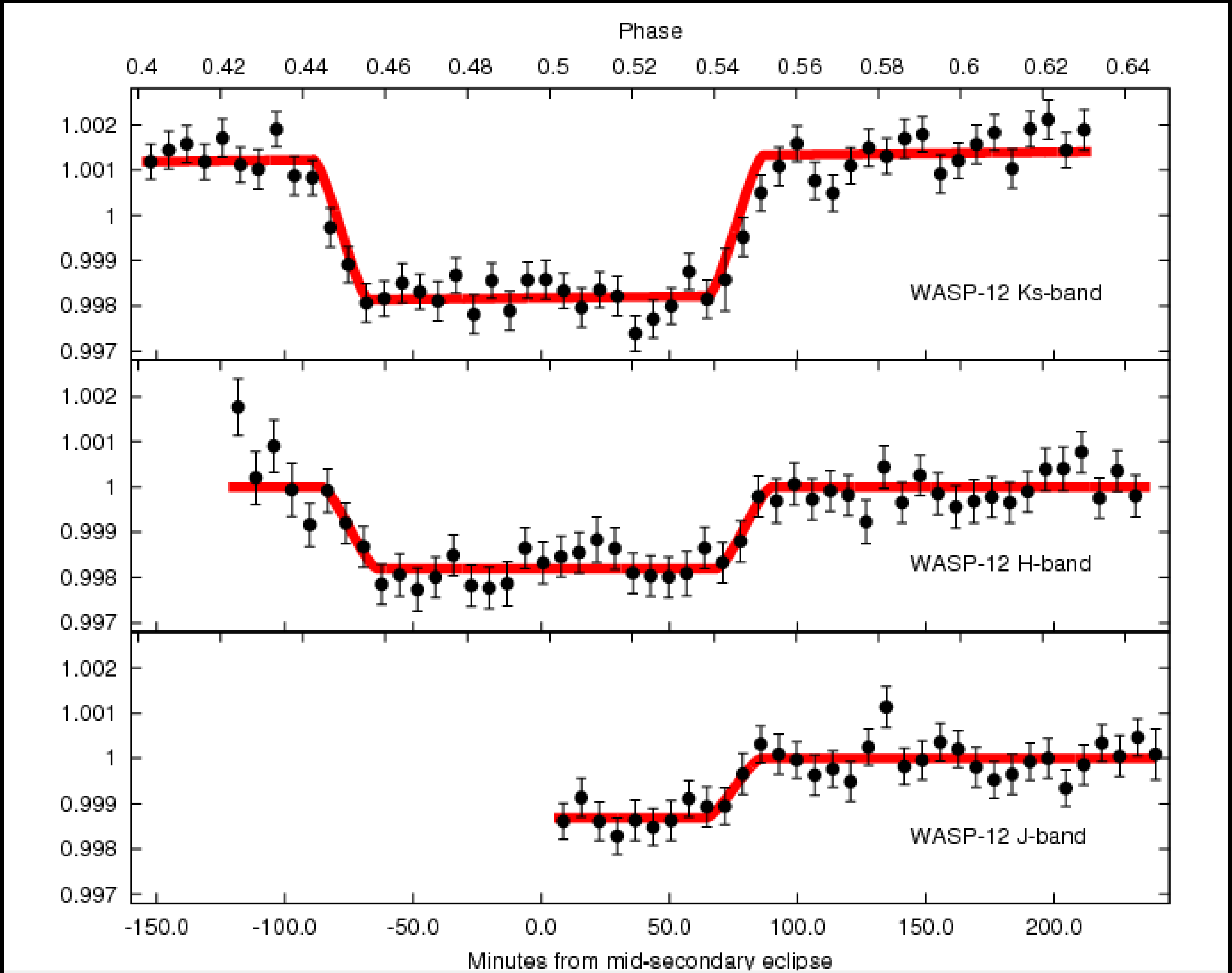
- Two detections (12σ total) of the Ks-band thermal emission of WASP-3b.



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.



WIRCam Large Program:

Thermal Emission of Transiting Exoplanets

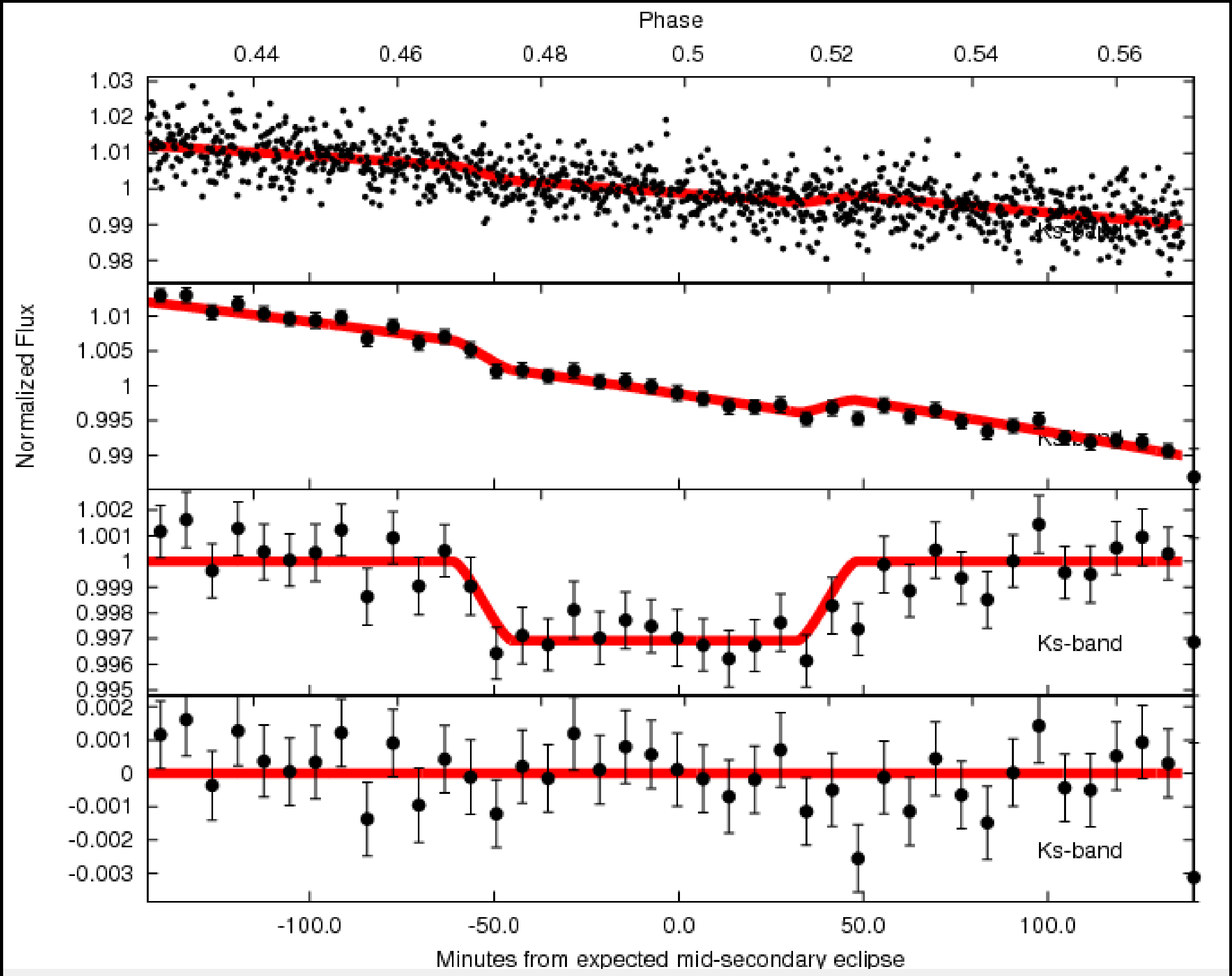
Ray Jayawardhana, Bryce Croll, Ernst de Mooij, Loic Albert, Aldo Bonomo, David Lafreniere, Jonathan Fortney, Magali Deleuil, Claire Moutou.

~150 hours

- Determine the systematics that limit the precision of near-infrared photometry from the ground.
- To survey the near-infrared emission of a great number of hot Jupiters exposed to varying levels of incident flux, stellar activity, etc.
- Over the past two years we've observed the following targets: TrES-2 (Ksx2), Qatar-2 (Ks), Qatar-1 (Ks), WASP-14 (KCont), TrES-3 (Ks, H, J), WASP-12 (Ksx3, KCont, Hx2, Jx2, Y, [Transit in Ks, J]), WASP-33 (KCont, LowOH), HAT-P-23 (Ksx2), WASP-3 (Ksx2, H), WASP-43 (Ksx3), HAT-P-7 (Ks), WASP-2 (Ks), KIC 12557548 (Transit in Ks). 11 or so detections across four targets.

Qatar-2b in Ks

Croll et al. In Prep.



Top: the unbinned photometry.

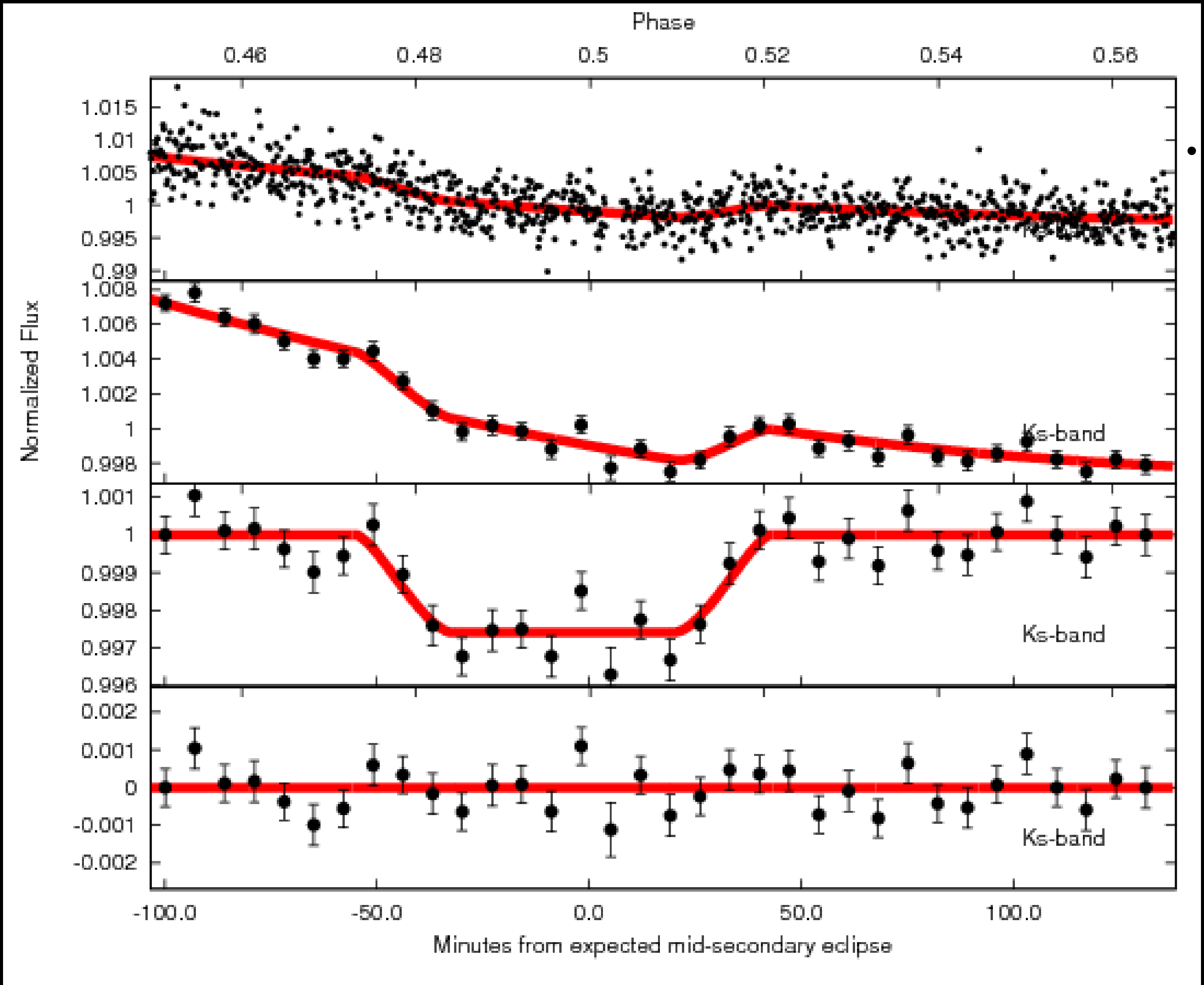
Second from top: the binned photometry.

Second from bottom: the binned photometry after subtracting the background.

Bottom: residuals from the best-fit eclipse.

Qatar-1b in Ks

Croll et al. In Prep.



- Top: the unbinned photometry.

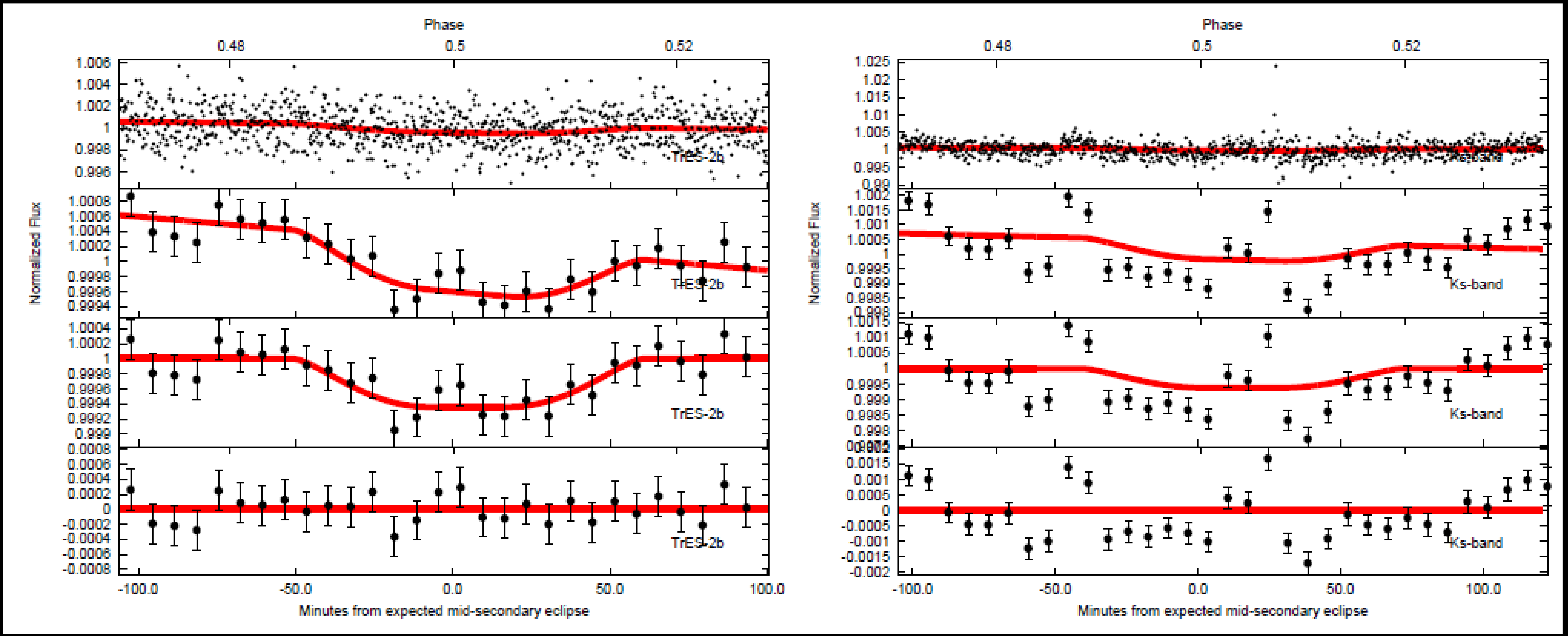
Second from top: the binned photometry.

Second from bottom: the binned photometry after subtracting the background.

Bottom: residuals from the best-fit eclipse.

Disentangling Instrumental and Atmospheric effects

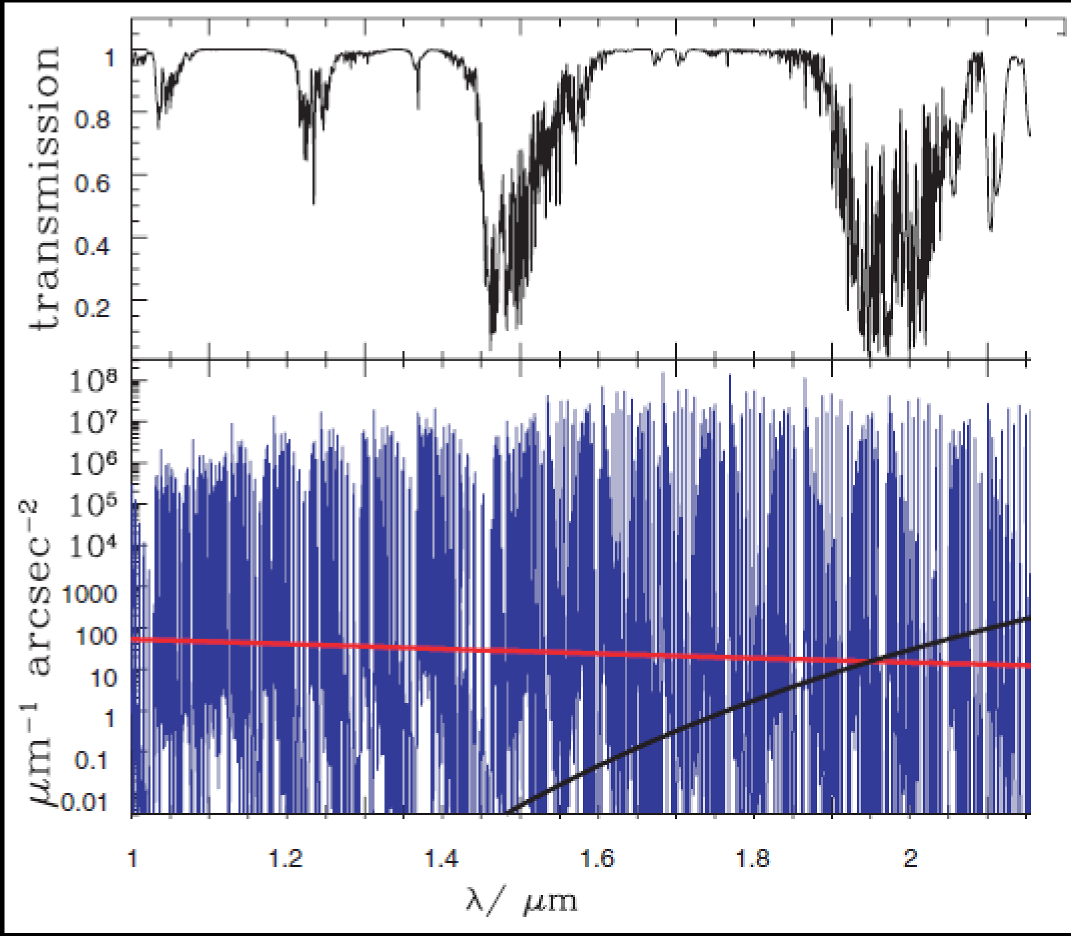
- Reobservations of the same target at different epochs have resulted in accurate data on one occasion and inaccurate data on another.
- The instrumental or atmospheric explanation for this discrepancy is unclear.



Our CFHT/WIRCam Ks-band observations of TrES-3b obtained on two occasions: June 10th, 2010 (left), and July 4th 2010 (Right).

Near-infrared limiting systematics

- The dominant systematics across the near-infrared are expected to be:
  - in Ks-band thermal emission (telescope and atmosphere).
  - in H-band, Airglow (radiated by excited levels of the hydroxyl radical [OH-]).
  - in J-band, scattering from molecules in the atmosphere.
  - in Y and z-band, water vapour variability.



Top Panel: Atmospheric Transmission in the Near-infrared. Bottom Panel: Sky OH emission (Blue), zodiAcal scattered light (red), and Telescope thermal emission (black). Figure from Ellis & Bland-Hawthorn (2008).

Airglow emission as the limiting systematic?

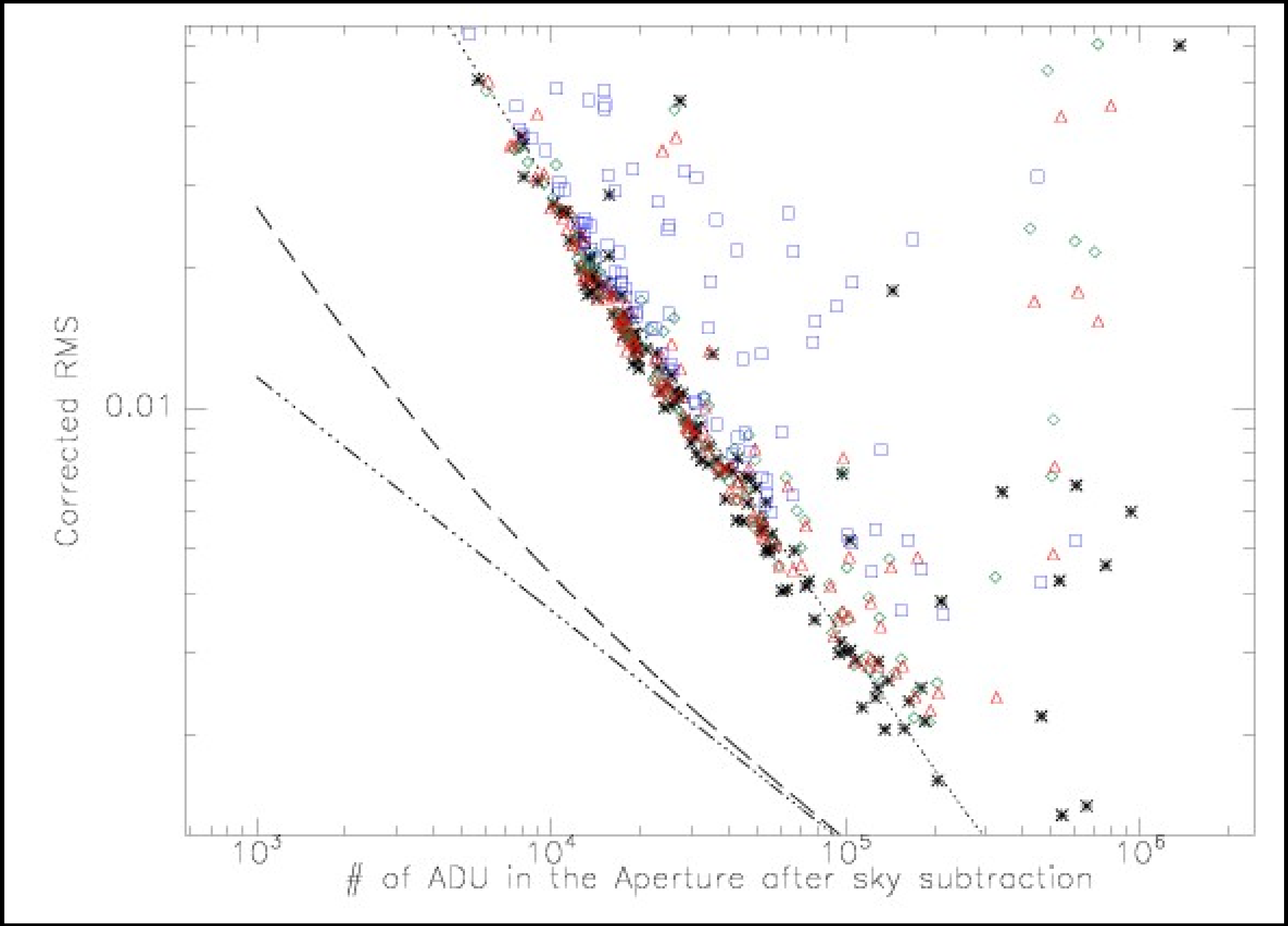
- Airglow is known to vary on large and small angular scales, and also on 5-15 minute timescales (Moreels et al. 2008).
- They are also known to be affected by gravity waves in the ionosphere (Glass et al. 1999).

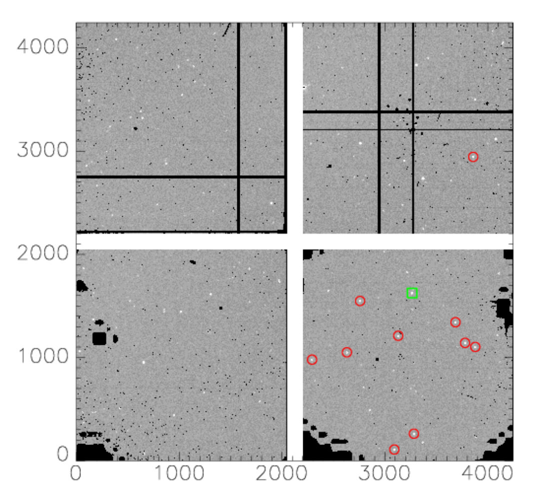
CFHT SkyCam of the Mauna Kea skies.

Limiting systematic of near-infraed data

Croll et al. in prep.

- The limiting systematic that affects the precision of observations from night to night is not obvious (although sky background plays a prominent role, it does not explain the variation in night-to-night precision).

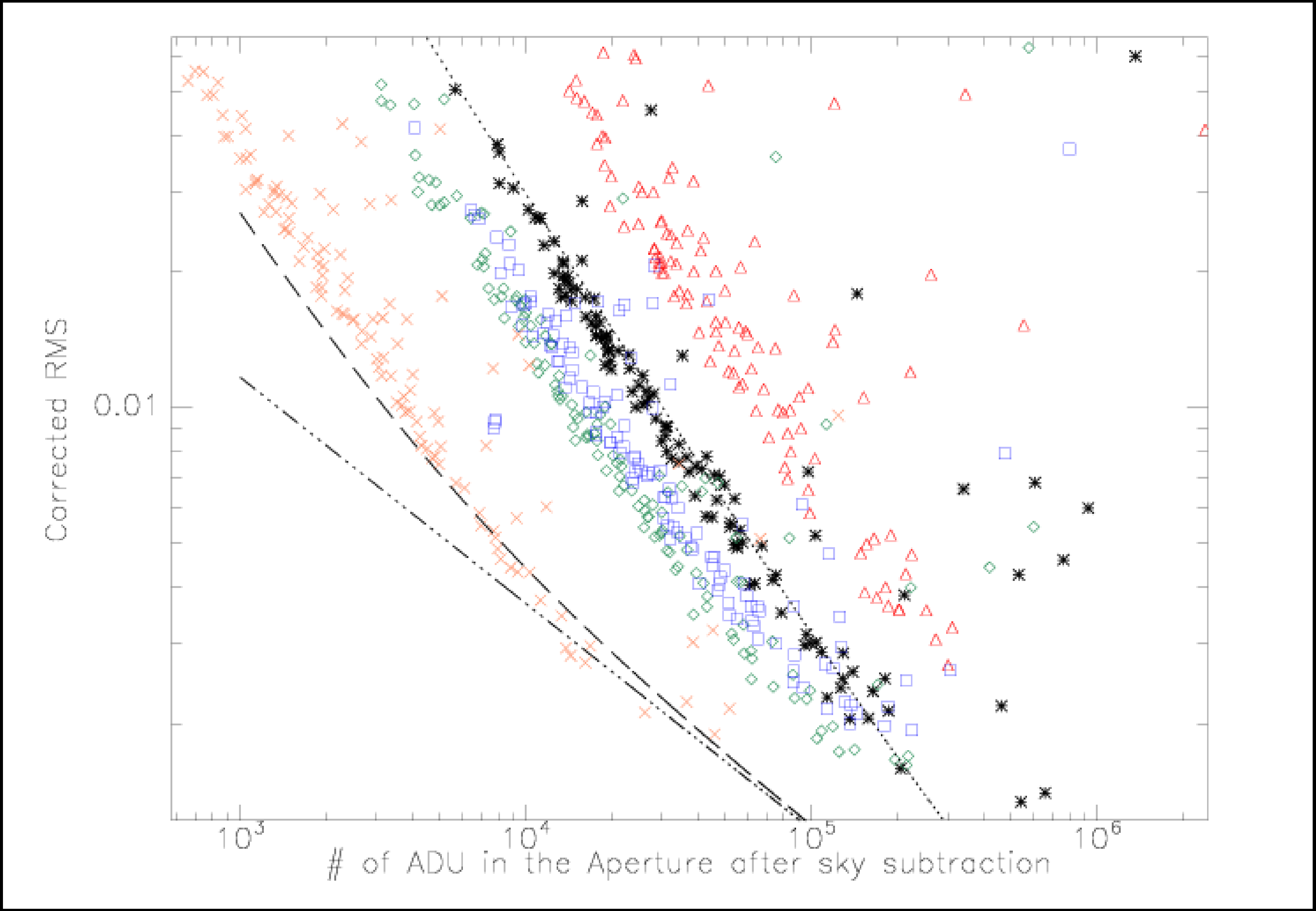




RMS of all the reference stars of WASP-12b in Ks-band over four epoch of observations (Blue, Red, Black, and Green).

Limiting systematic of near-infraed data

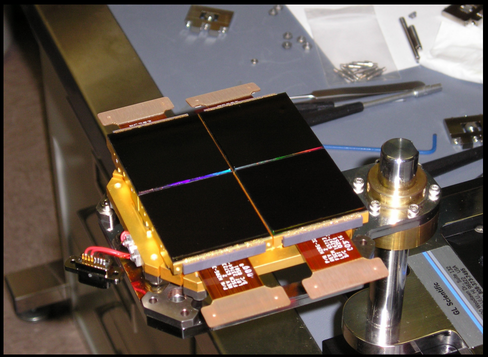
Croll et al. in prep.



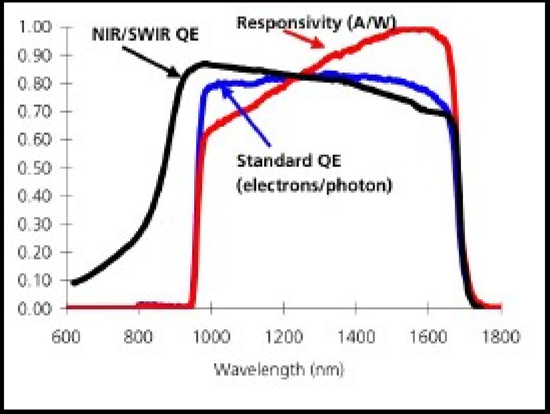
RMS of observations of WASP-12b in various bands (Black=Ks, Blue=J, Red=H, Green=Y, and Orange=KCont).

NEAR-INFRARED DETECTORS

- Existing Near-infrared detectors (JHK) usually use mercury cadmium telluride (HgCdTe; MerCad Telluride) detectors. Cooled to -190 Celsius.
- Indium Gallium Arsenide (InGaAs) are a much cheaper alternative (10-20x cheaper; they only have to be cooled to -30 to -60 Celsius) that have been developed for military/night-vision purposes. Recently, lower noise versions of these cameras have begun to be developed that may be suitable for astronomical observations.



TOP: THE FOUR CHIPS THAT MAKE UP THE WIDE-FIELD INFRARED CAMERA (WIRCAM) A MERCAD TELLURIDE DEVICE.



INGAAS CAMERAS ARE QUANTUM EFFICIENT FROM 0.9 – 1.7 MICRONS, ALLOWING YJH-BAND OBSERVATIONS.

SU320HX-1.7 SWIR camera

BOTTOM: AN INGAAS CAMERA.

InGaAs Cameras

Peter Sullivan, Bryce Croll & Rob Simcoe

- InGaAs cameras have been used previously with astronomical observations with little success (The Robo-AO system had a hard time detecting a 6th magnitude star on a 1.5m telescope with their InGaAs Camera [Nick Law, electronic communication]).
- We received a grant to purchase one or two of these InGaAs cameras and experiment with whether they are suitable for astronomical observations (first generation instruments suffered from high read noise and high dark current).
- We started by begging, borrowing and stealing these cameras, but recently acheived first-light on a custom-built camera.

Figure 1: (Left) the Xenics Xeva-320-1.7 InGaAs camera. (Right) the Princeton Instruments PioNIR camera.

The Dream Team

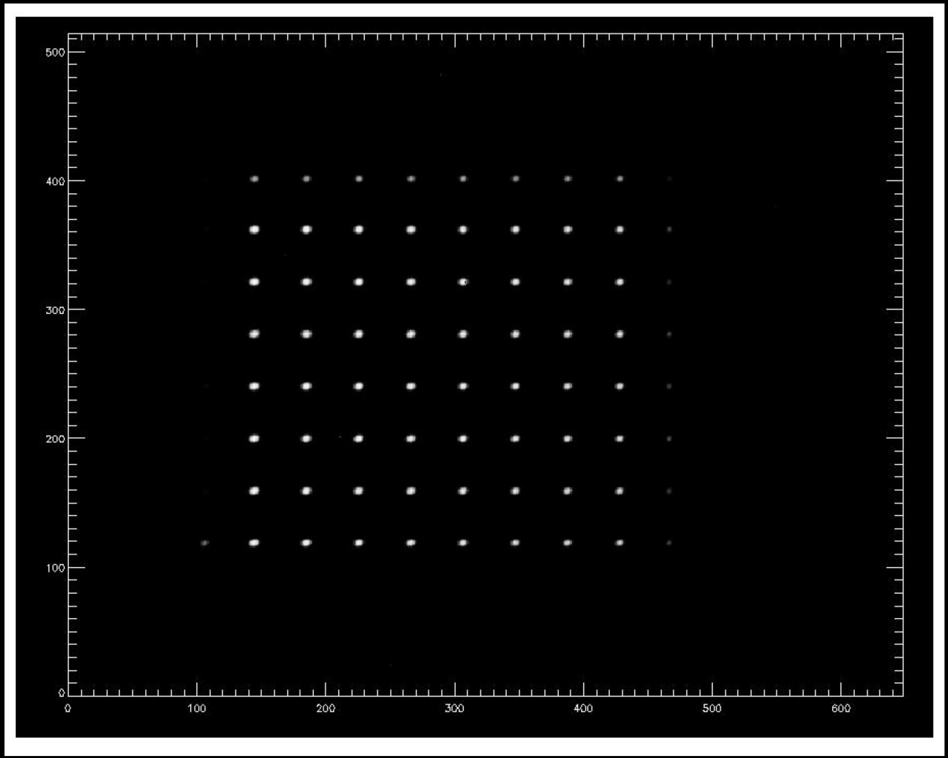
Top: Peter Sullivan

Bottom: Rob Simcoe

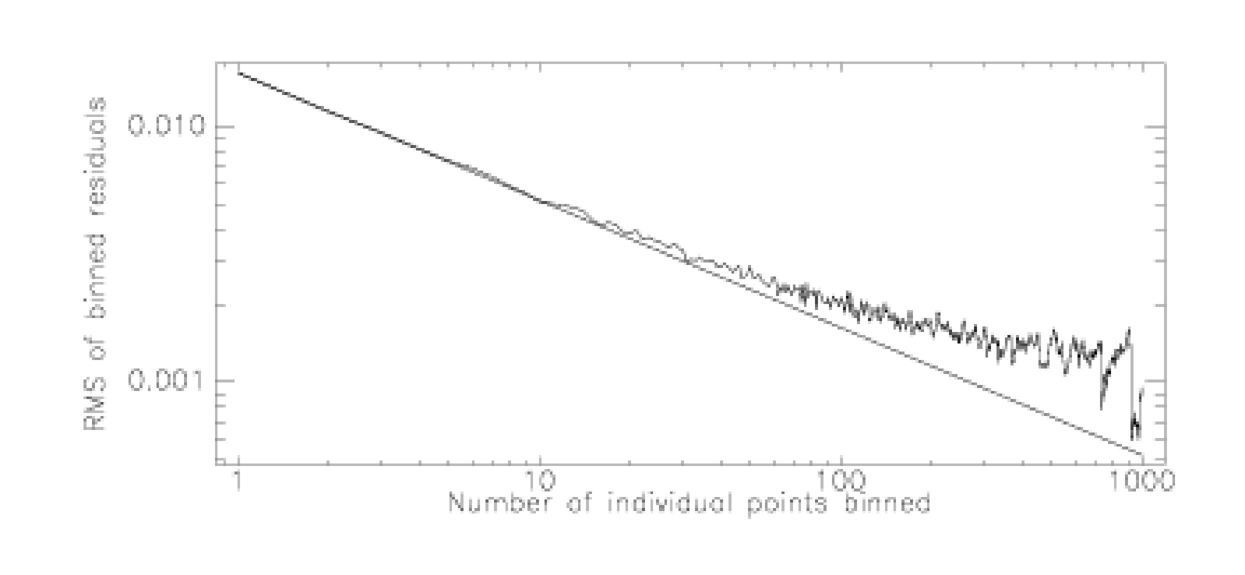
Right: Myself

Laboratory Lenslet Tests
Sullivan, Croll & Simcoe (In Prep.)

- Lenslet array tests (right top) indicate that we achieve promising precision with artificial sources.
- Our lenslet data bins down near the Gaussian-noise expectation with increasing bin size (right bottom).



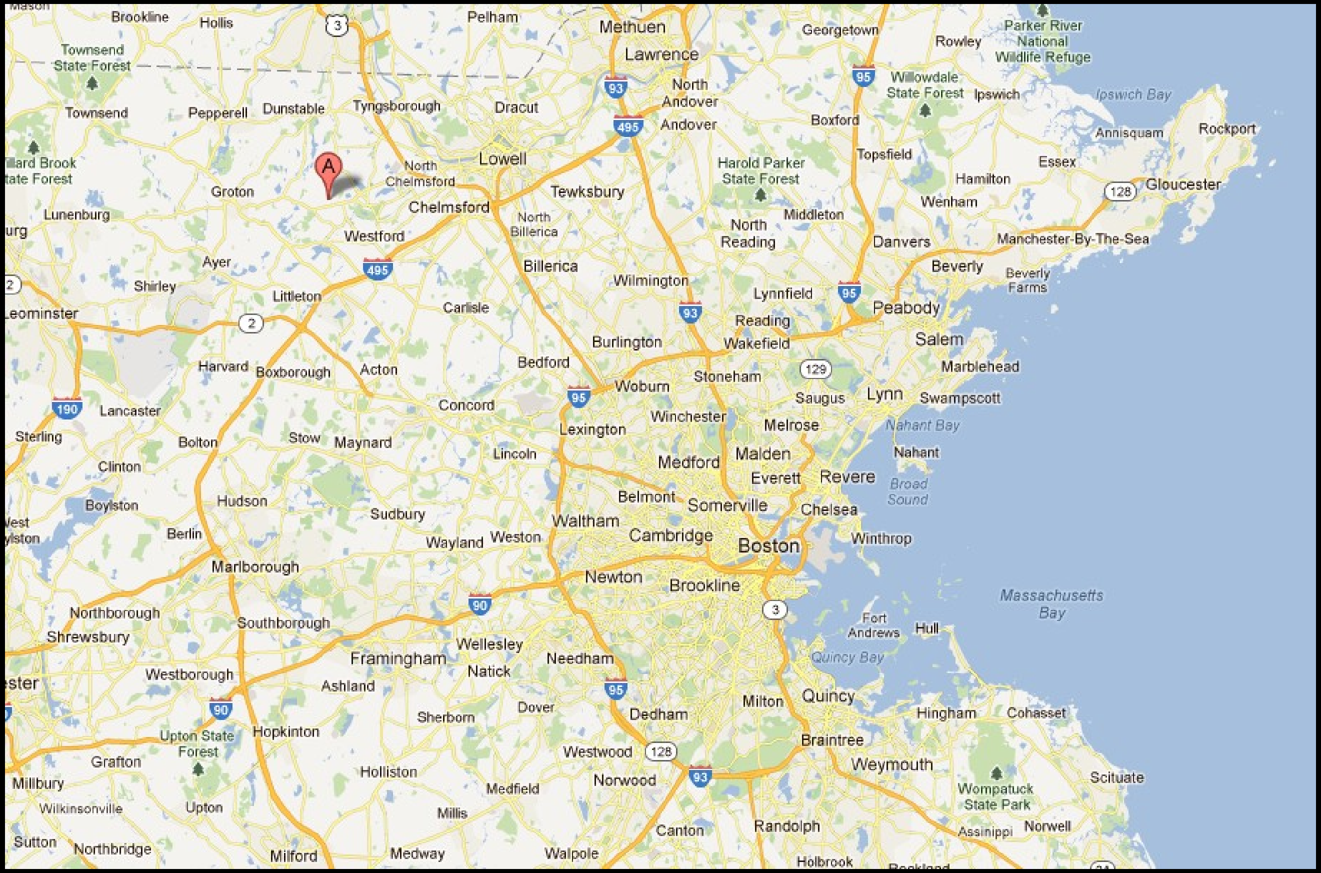
Top: InGaAs observations of the Lenslet Array.



Bottom Right: Our lenslet photometry bins down near the Gaussian noise expectation.

Observations at Wallace Observatory

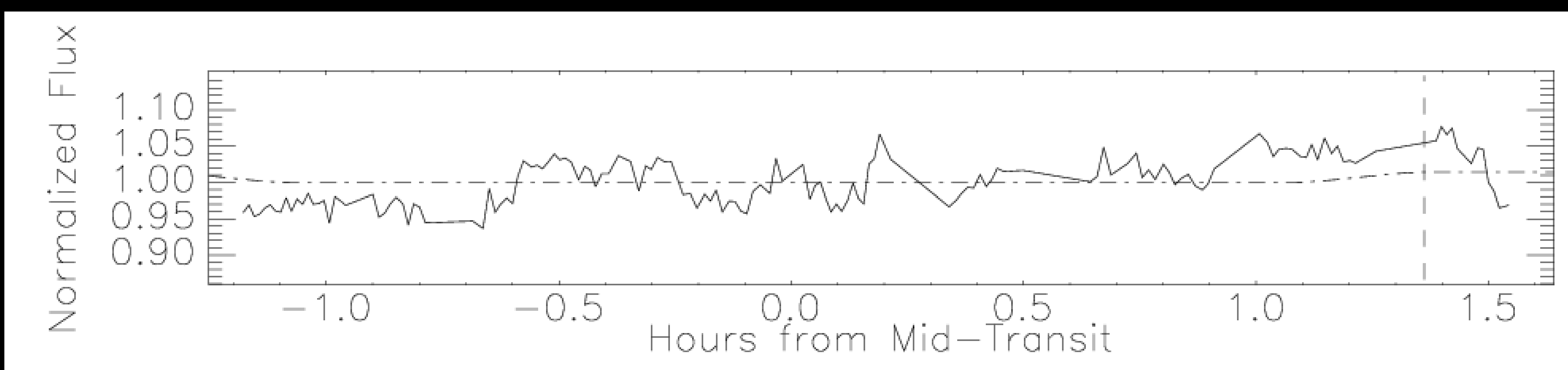
- We recently attached our new camera to the Wallace 24-inch (MIT observatory by Lowell, MA) on a relatively clear night – 3.5” seeing.



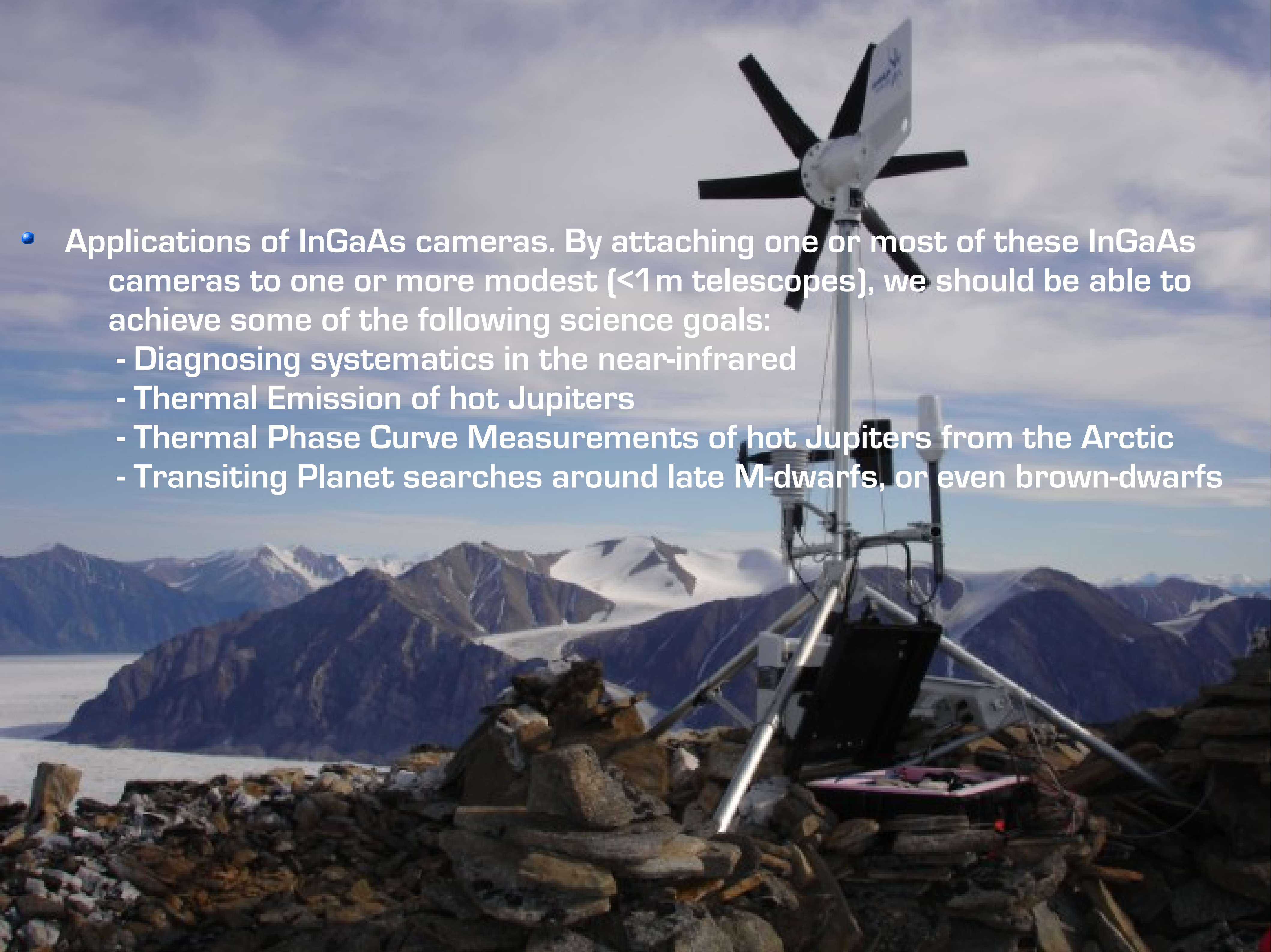
Wallace Observations of the Transit of WASP-33

- We attempted (and failed) to detect the 1% transit depth of the bright star WASP-33 (J~7.5).
- Growing pains associated with using these higher read-noise and dark current detectors.

Top: InGaAs observations of WASP-33 and a nearby reference star.

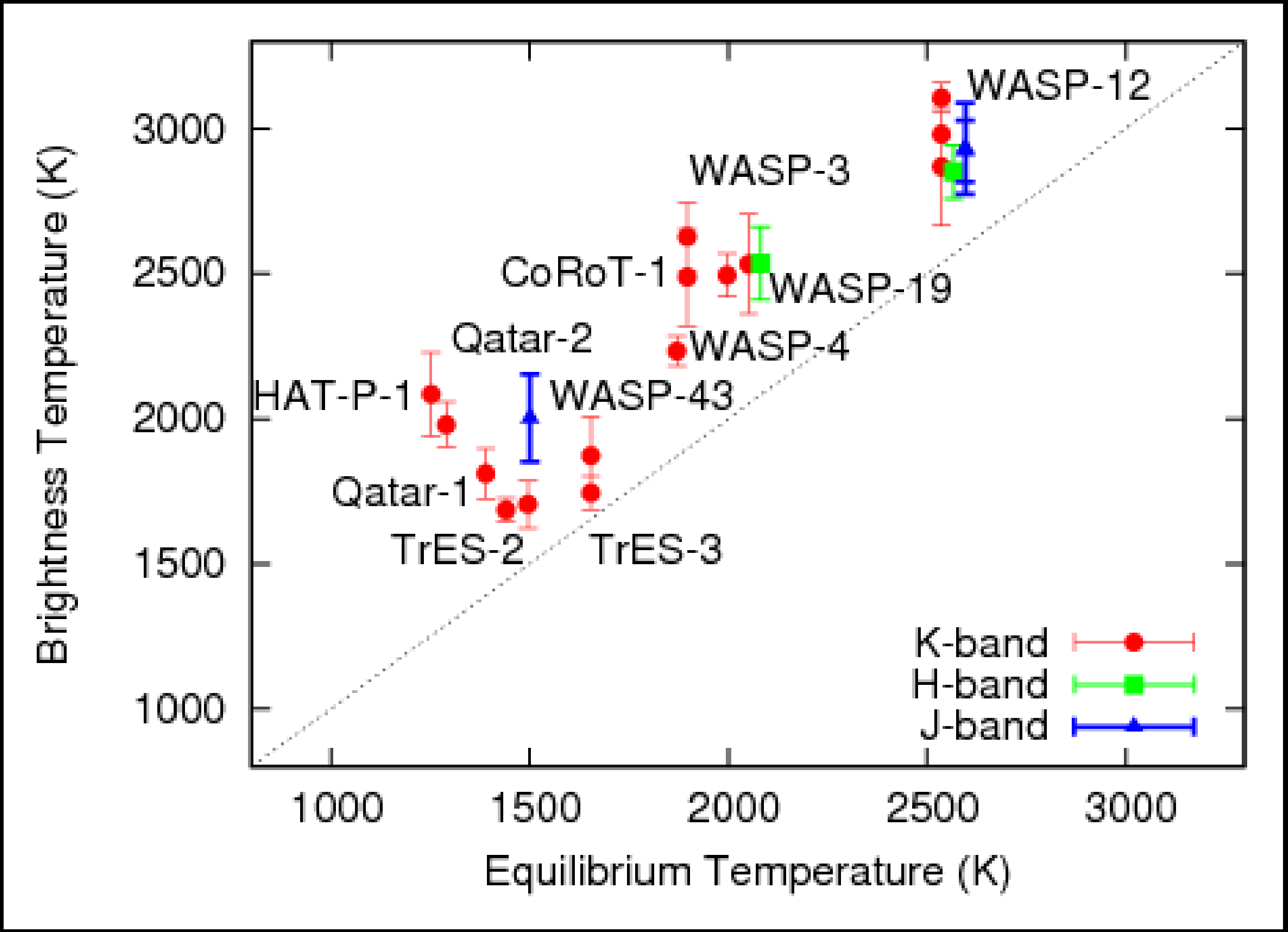


Bottom: InGaAs observations of the transit of WASP-33. We fail to detect the Transit.



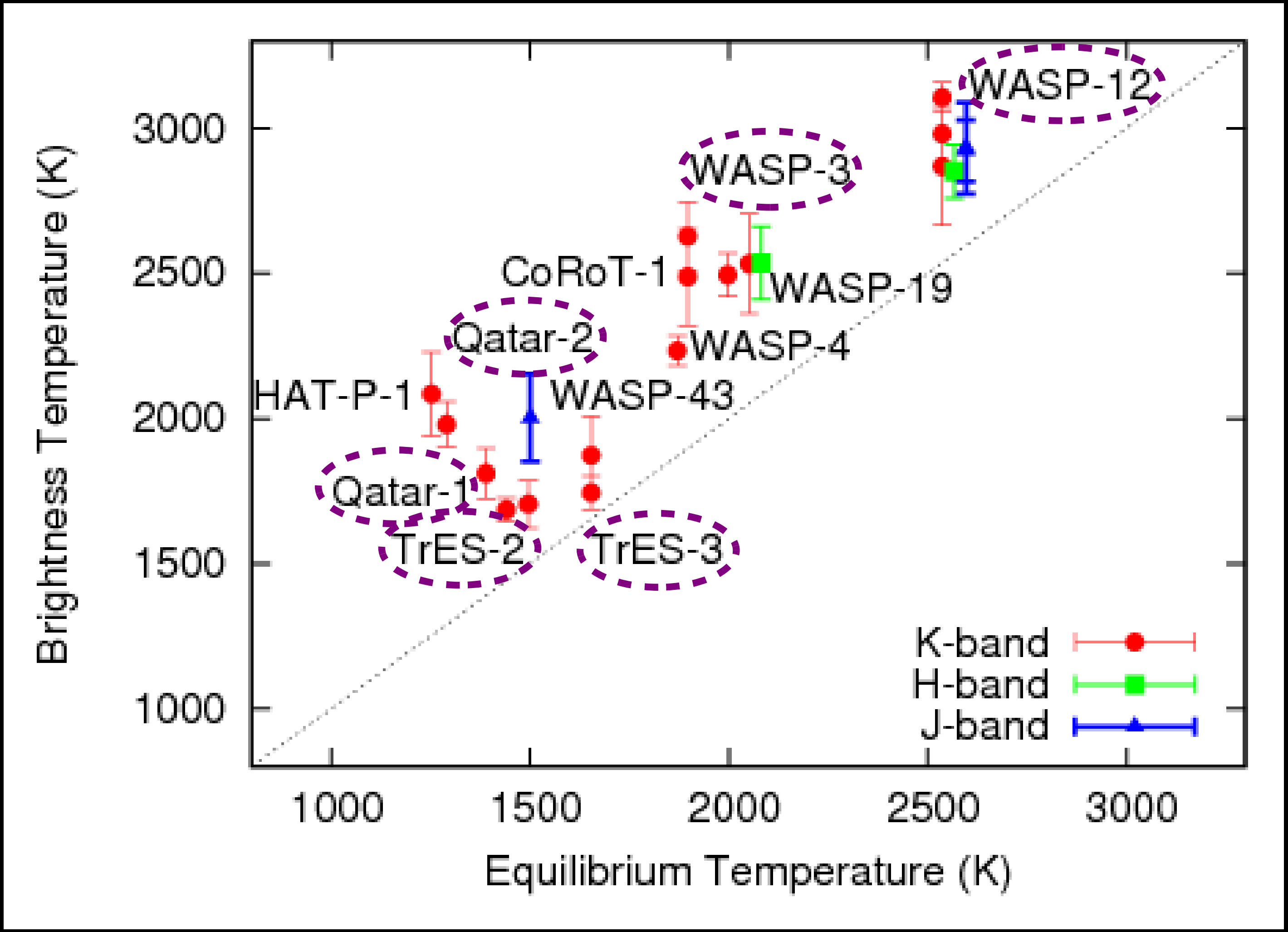
- Applications of InGaAs cameras. By attaching one or most of these InGaAs cameras to one or more modest (<1m telescopes), we should be able to achieve some of the following science goals:
  - Diagnosing systematics in the near-infrared
  - Thermal Emission of hot Jupiters
  - Thermal Phase Curve Measurements of hot Jupiters from the Arctic
  - Transiting Planet searches around late M-dwarfs, or even brown-dwarfs

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, Gillon et al. (2012). The various Swain et al. Results are excluded.

Overview of Near-IR (JHK) Detections

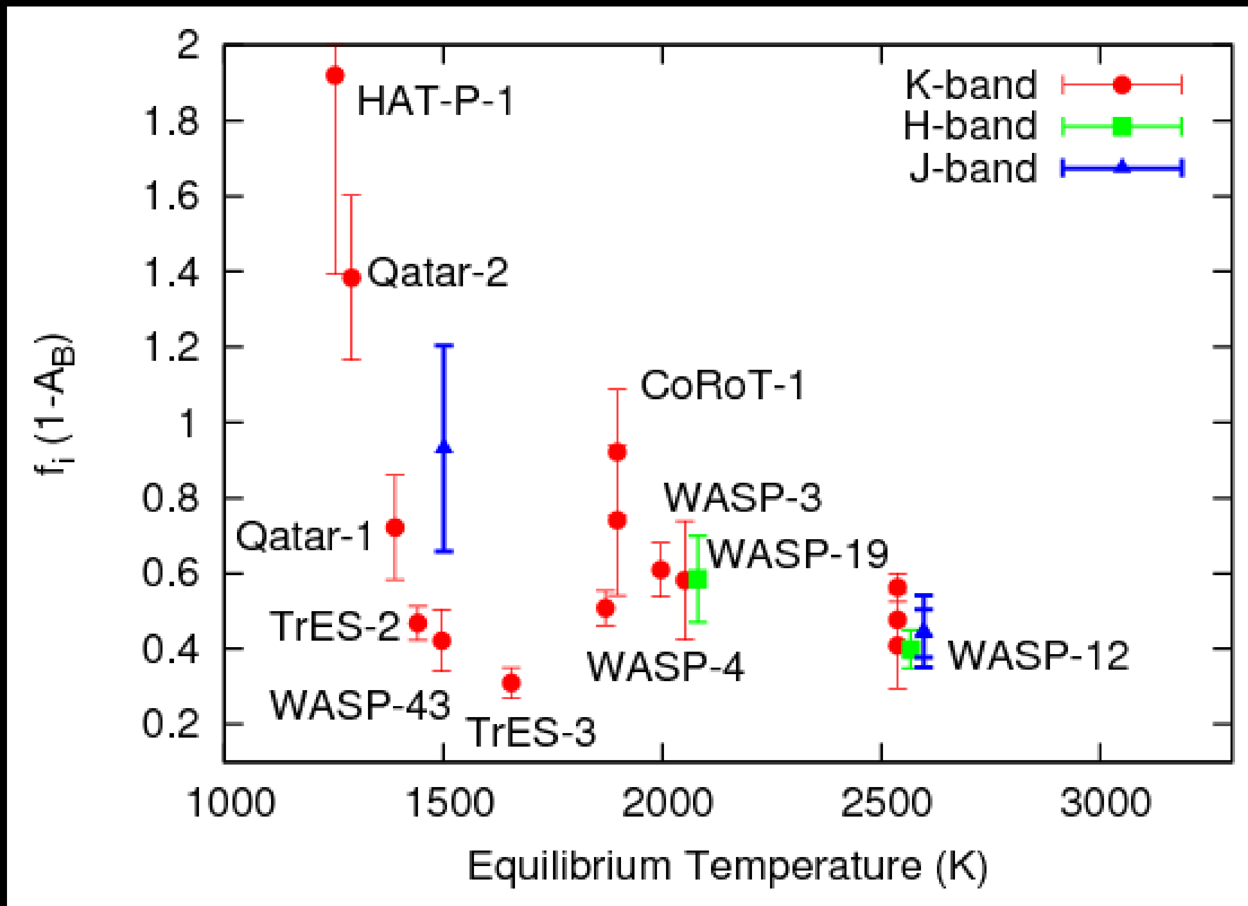


Brightness temperature of the thermal emission of hot Jupiters in the JHK bands. Broadband Detections from: de Mooij & Snellen (2009), Rogers et al. (2009), Gillon et al. (2009), Anderson et al. (2010), Gibson et al. (2010), Croll et al. (2010a,b,2011, in prep.), de Mooij et al. 2011, Caceres et al. 2011, Gillon et al. (2012).

Overview of Near-IR (JHK) Detections

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

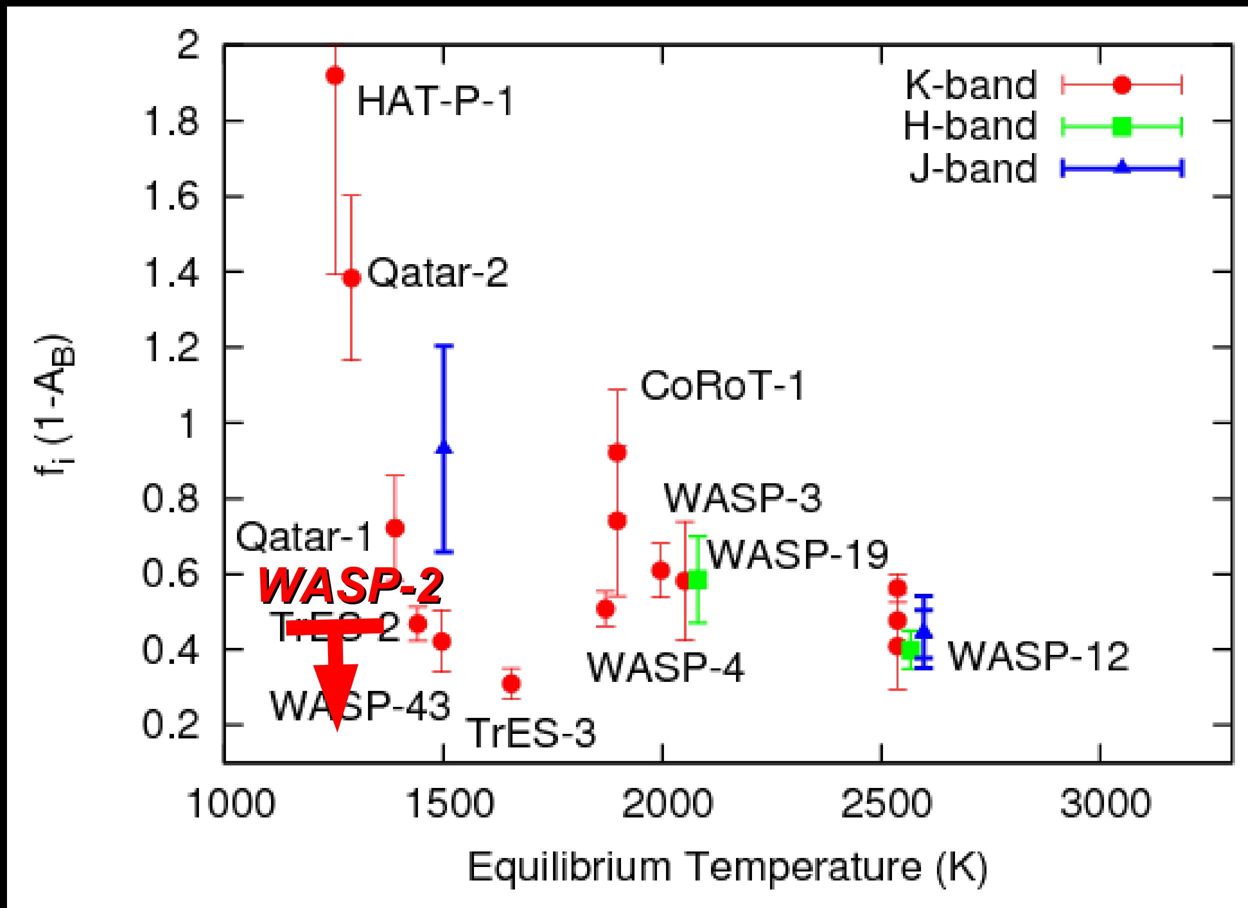
Higher Near-Infrared Brightness Temperatures



The reradiation factor (f) of the thermal emission of hot Jupiters in the JHK bands. Broadband 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, Gillon et al. (2012).

Overview of Near-IR (JHK) Detections

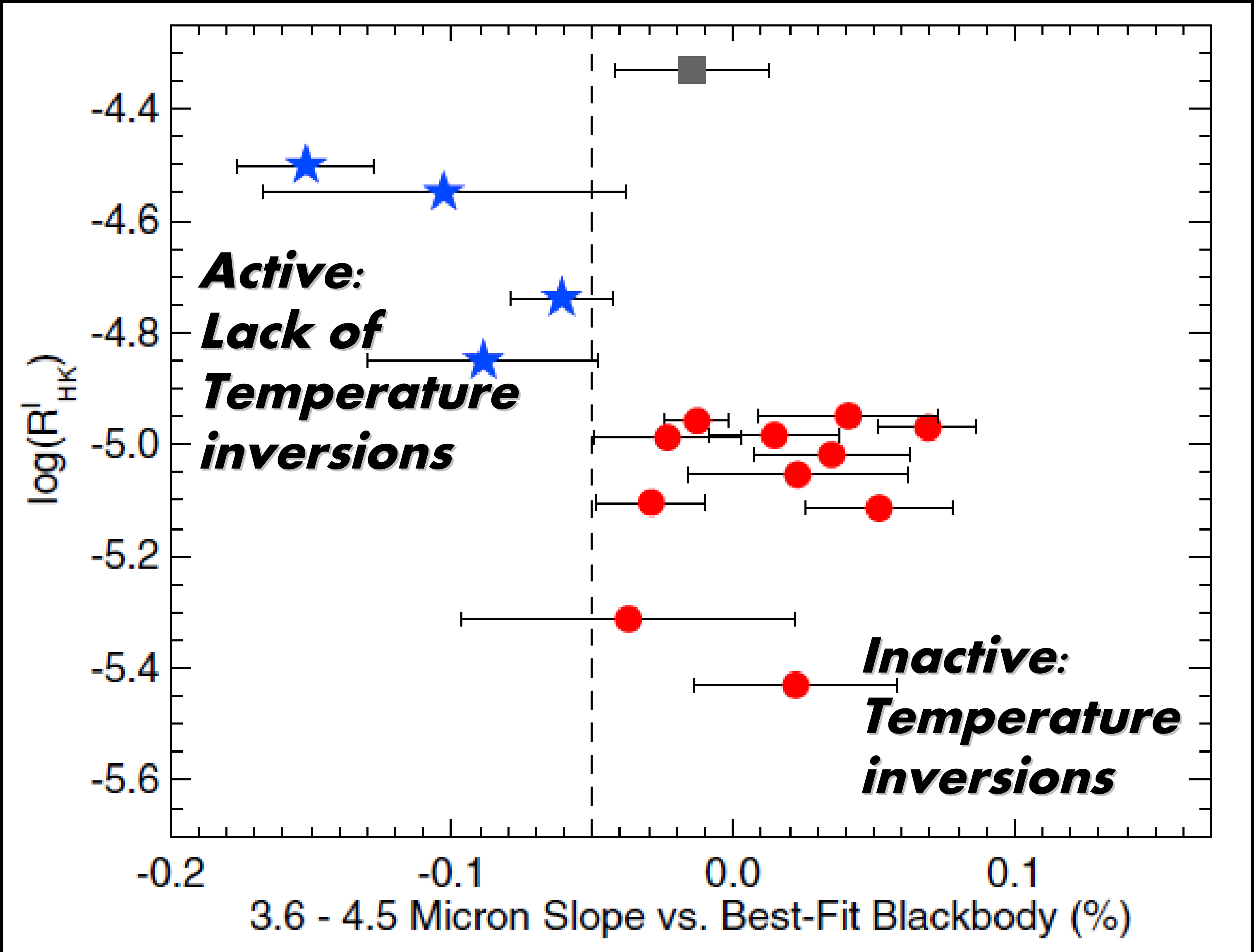
$$T_{B} = T_{*} \left(\frac{R_{*}}{a}\right)^{1/2} [f_{i}(1 - A_{B})]^{1/4},$$



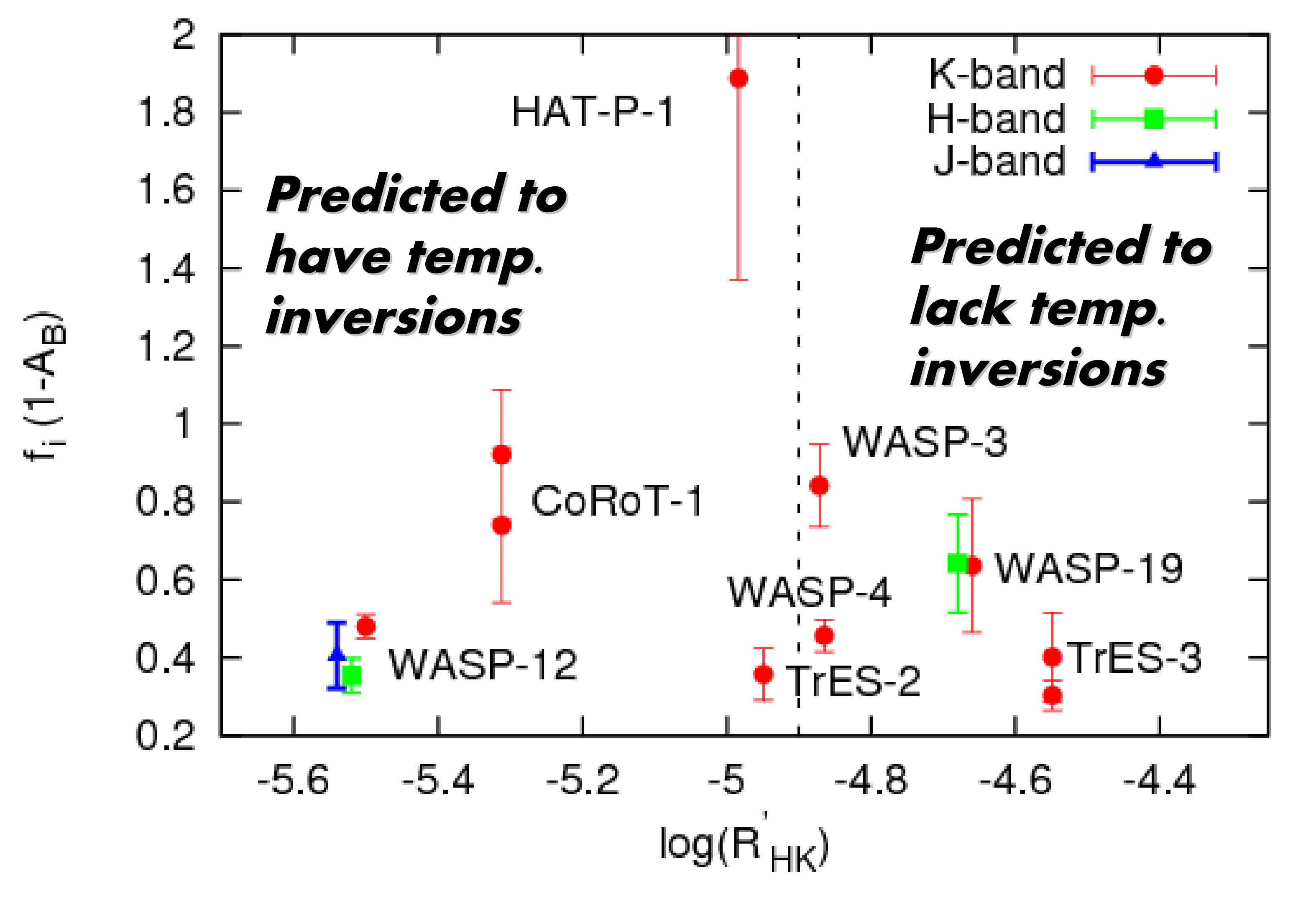
The reradiation factor (f) of the thermal emission of hot Jupiters in the JHK bands. Broadband Detections from: de Mooij & Snellen (2009), Rogers et al. (2009), Gillon et al. (2009), Anderson et al. (2010), Gibson et al. (2010), Croll et al. (2010a,b,2011, in prep.), de Mooij et al. 2011, Caceres et al. 2011, Gillon et al. (2012).

Correlation of Temperature Inversions with Activity

Knutson et al. (2010)



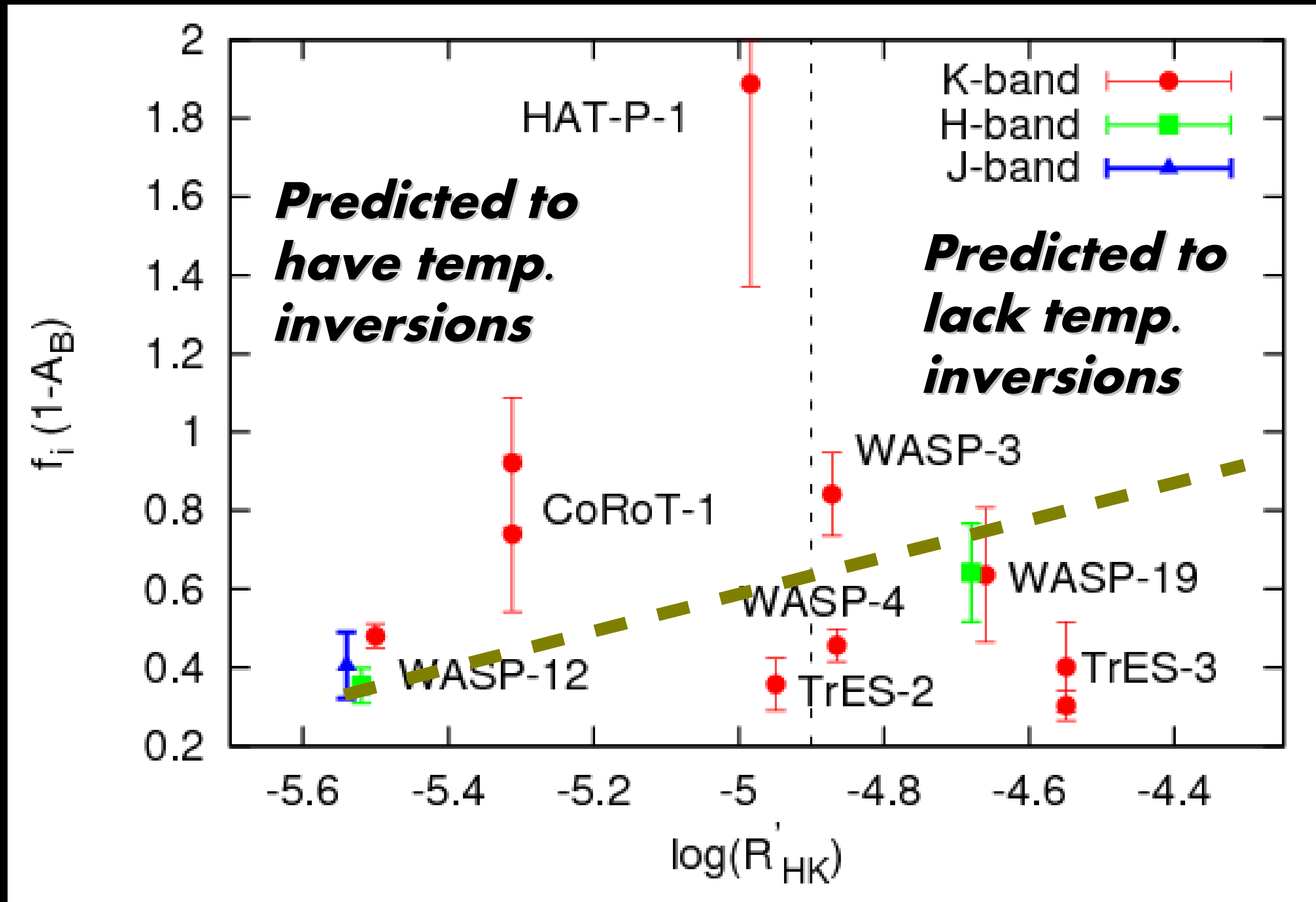
Overview of Near-IR (JHK) Detections



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.

Overview of Near-IR (JHK) Detections

Higher Brightness Temperatures



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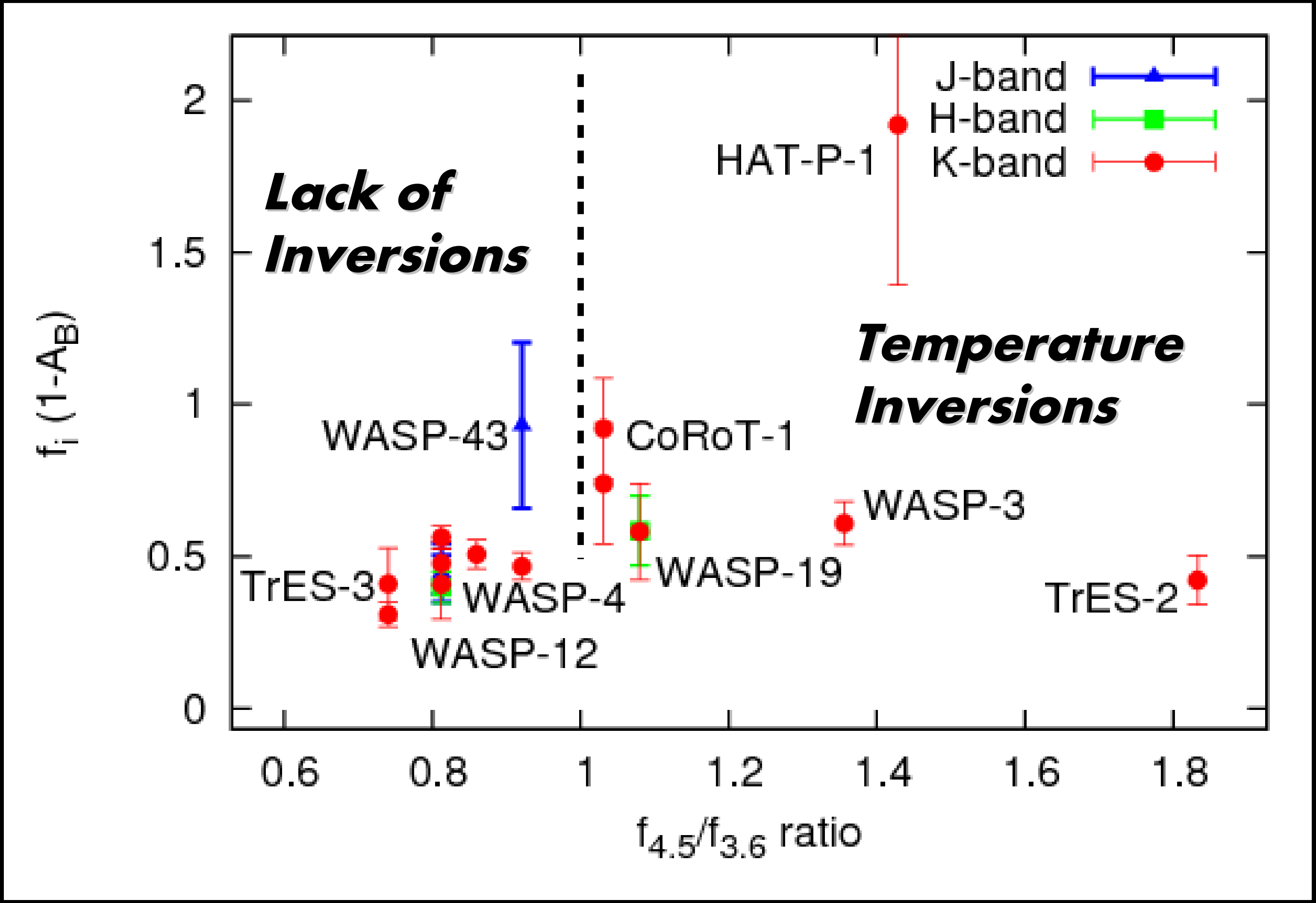
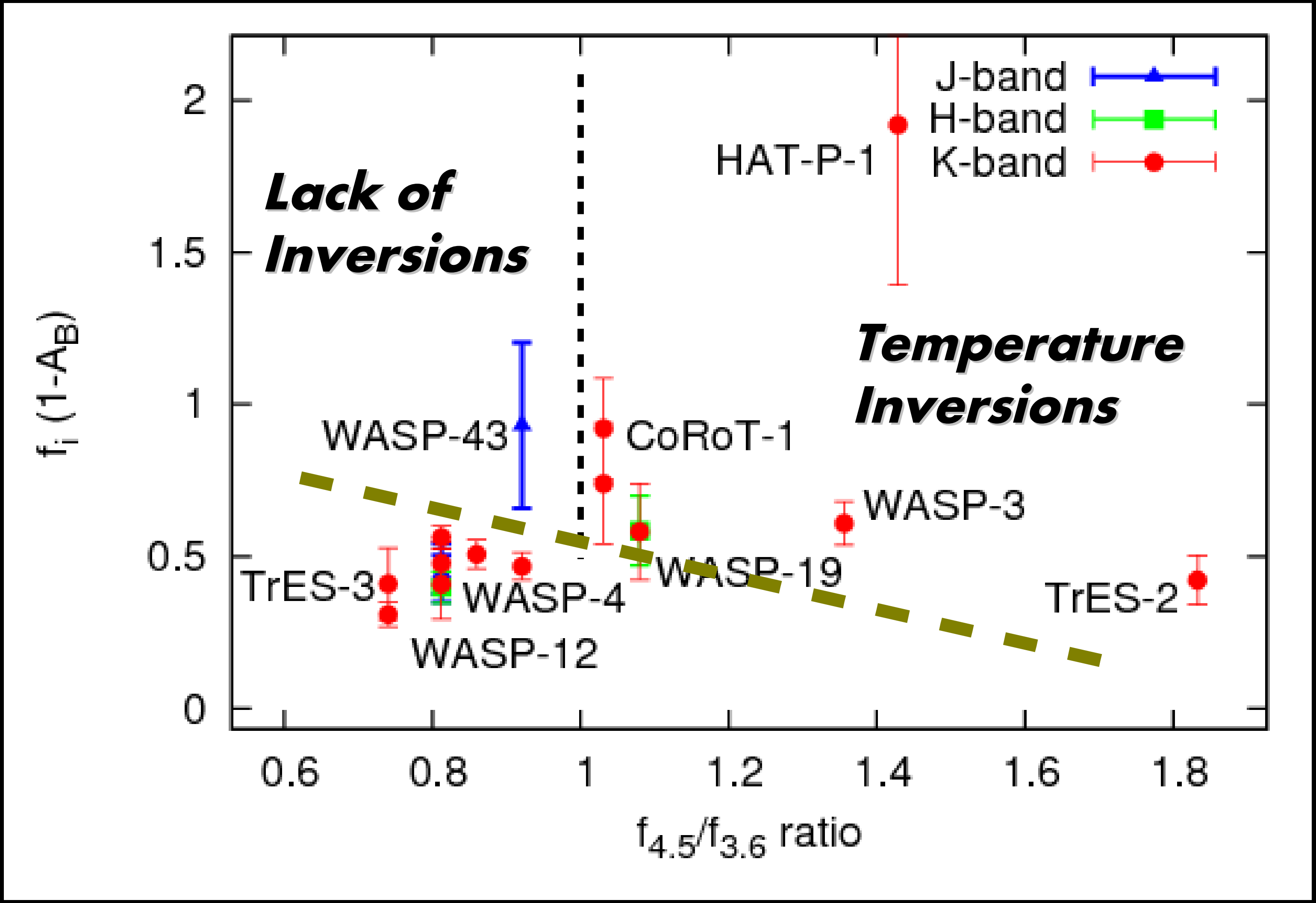
Overview of Near-IR (JHK) Detections



Near-infrared reradiation factor (f) versus the ratio of the 4.5 to 3.6 micron reradiation factors (a proxy for temperature inversions). Spitzer Results from: Fressin et al. (2010), O'Donovan et al. (2010), Todorov et al. (2010), Campo et al. (2011), Beerer et al. (2011), Cowan et al. (2012), Blecic et al. (2012), Anderson et al. (2012).

Overview of Near-IR (JHK) Detections



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Summary

- The limiting systematic of ground-based near-infrared photometry is still unclear.
- InGaAs near-infrared cameras show promise and the science possibilities, when combined with an array of modest-sized telescopes, include transit searches around late M-dwarfs, and brown dwarfs.
- It is unclear what the combination of all the broadband near-infrared thermal emission detections of hot Jupiters tell us about hot Jupiters as an ensemble, rather than as individual objects.