Bryce Croll

Ex-Sagan Fellow

Boston University

Achieving & the Applications of Precise, Near-infrared, Ground-based Photometry

May 8th 2015

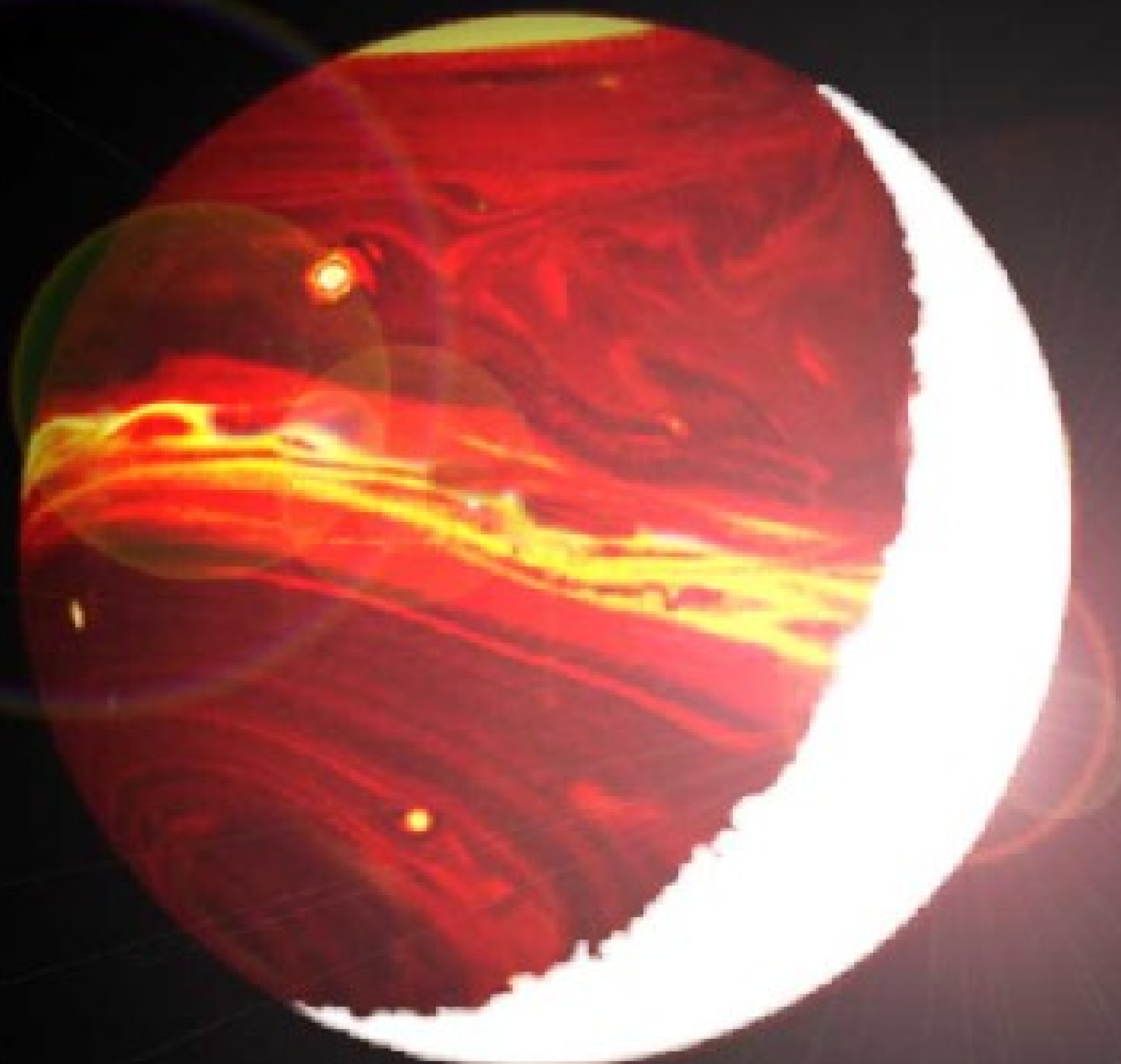


Image Credit: Greg Laughlin

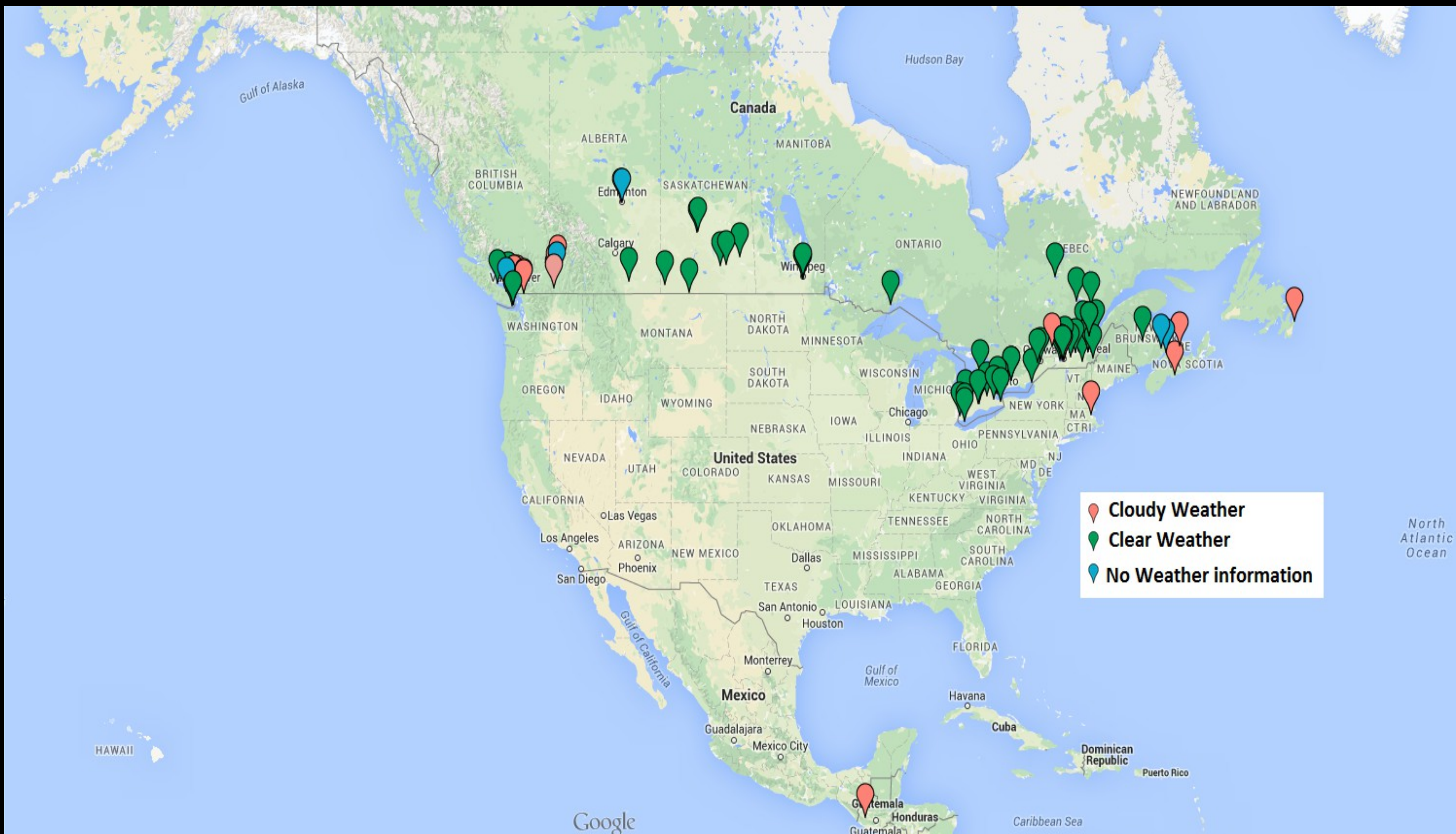
2012 Transit of Venus

- Initiated and coordinated a program to design, buy and distribute 43,000 “Transit of Venus“ Solar Eclipse glasses across Canada so that a great number of Canadians could safely view the Transit of Venus on June 5th, 2012.

Ottawa.

2012 Transit of Venus

- Of these 43,000 glasses, 28,000 were distributed to Canadian amateur organizations, and the remainder were distributed to professional astronomers.



2012 Transit of Venus

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Winnipeg, Manitoba

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London, Ontario.

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Toronto, Ontario.

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2012 Transit of Venus

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Mississauga, Ontario.

The Art of Astrophysics

- Co-organized an Astronomy Art contest at MIT that attracted 49 fabulous entries, and distrbuted $700 in prize money, including a $300 first prize.

The Life of a Star in the Flame Nebula

The Art of Astrophysics

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100 Planetary Nebulas

The Art of Astrophysics

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Postcard from the moon.

The Art of Astrophysics

- All entries were presented at a gallery show.

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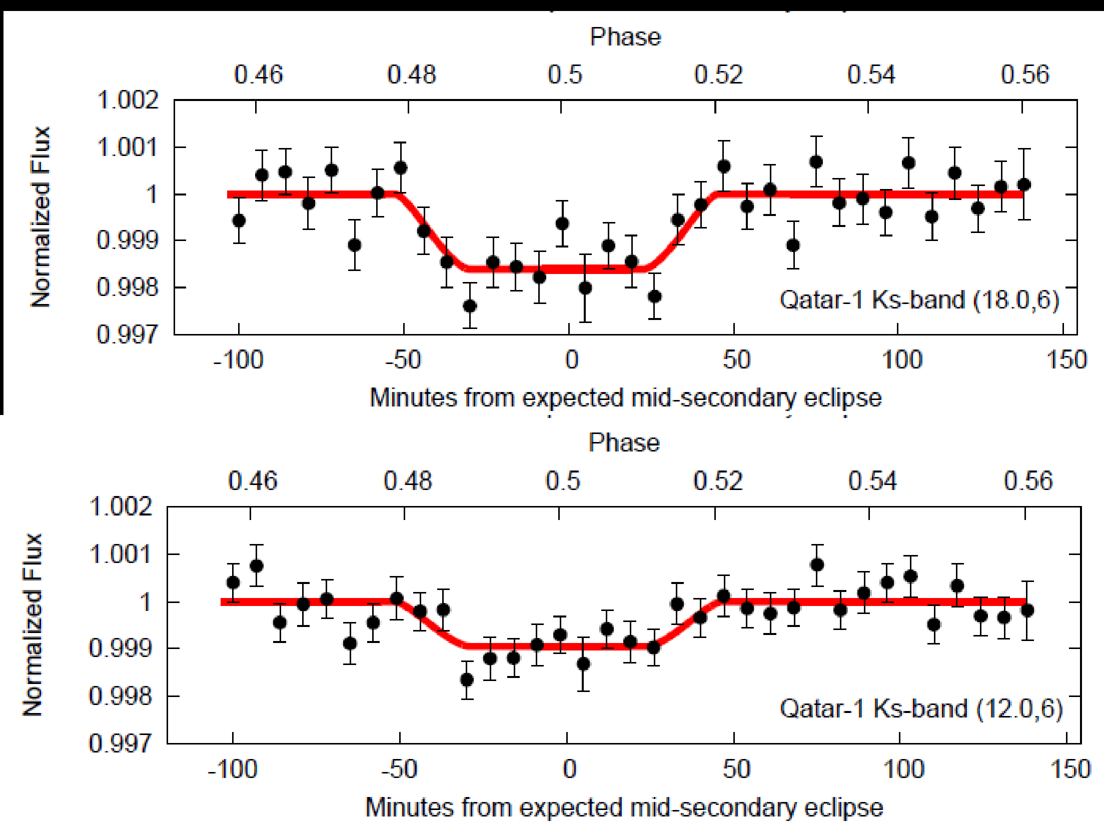
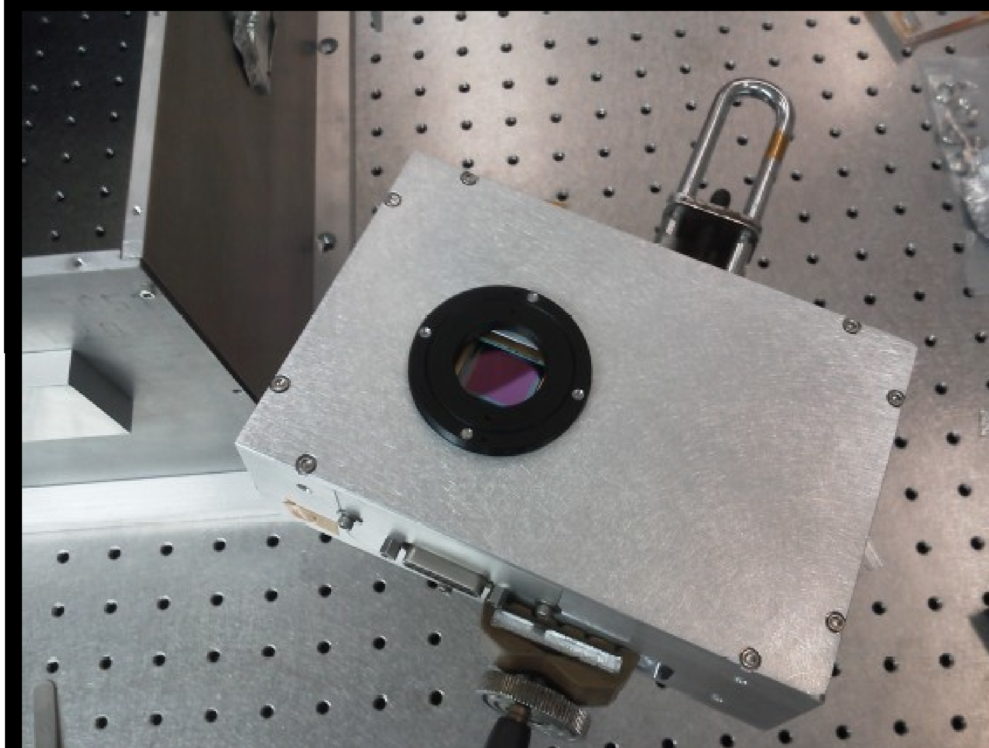
Outline: InGaAs Camera & Precise Near-Infrared Photometry

- Precise near-infrared photometry and how to return repeatable eclipse depths.

- The promising application of Indium Gallium Arsenide (InGaAs) devices to small telescopes.



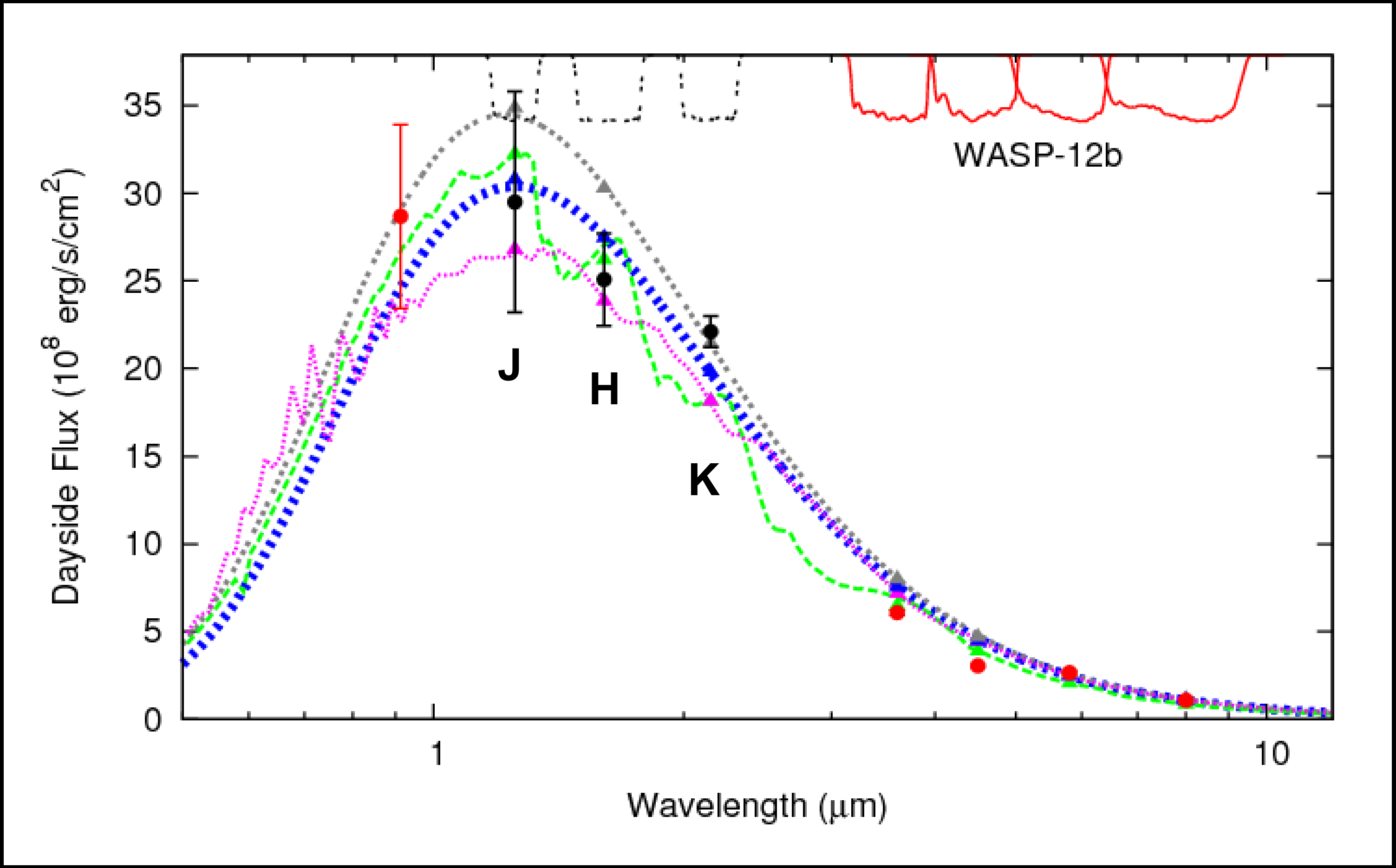


Left: Different reductions return different eclipse depths.

Right: Our InGaAs Camera.

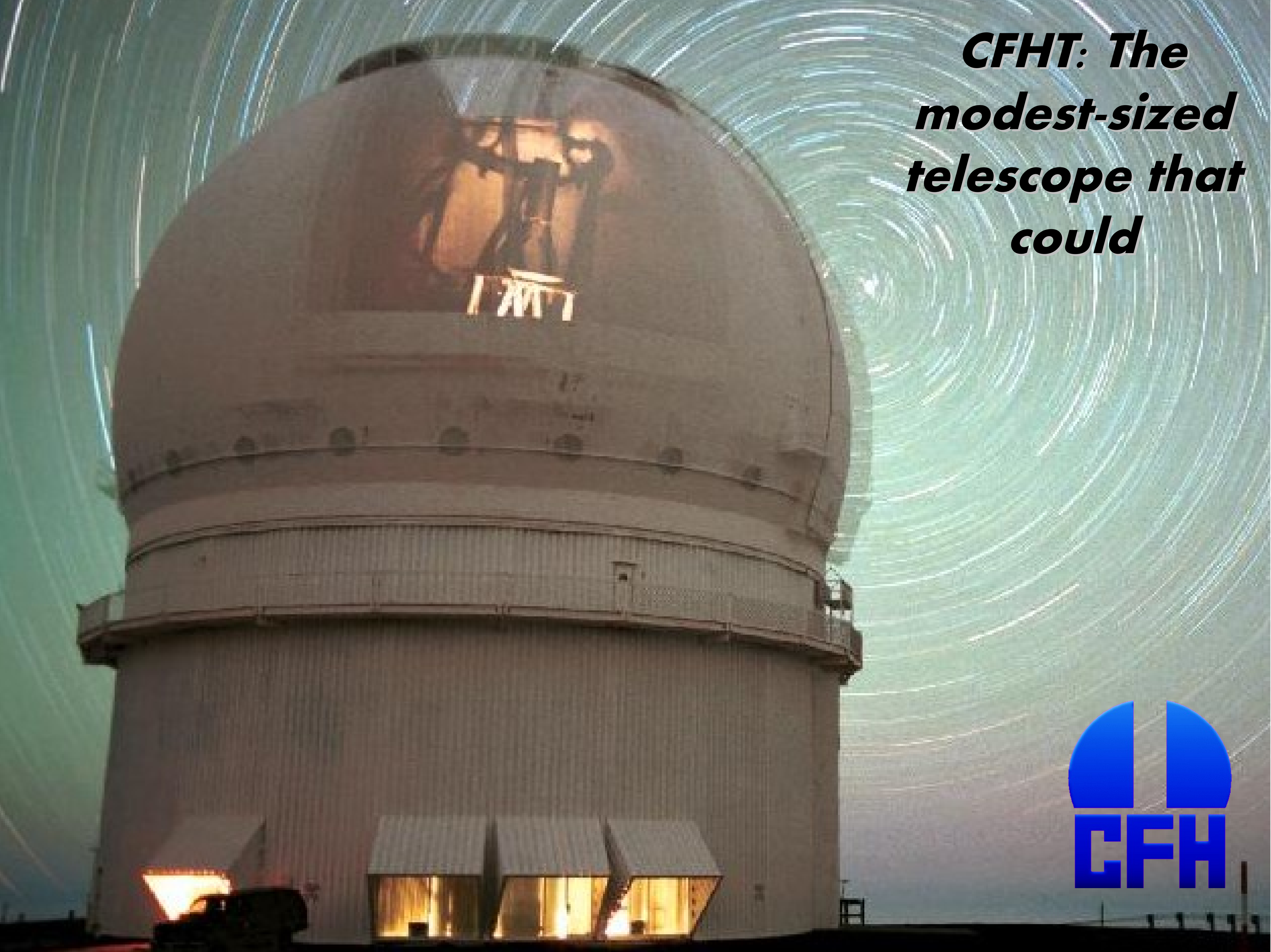
Why Near-infrared from the Ground?

- The J, H & K-bands are water opacity windows allowing one to see deep in these planet's atmospheres; K-band observations are best done from the ground.
- The near-infrared often brackets 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).

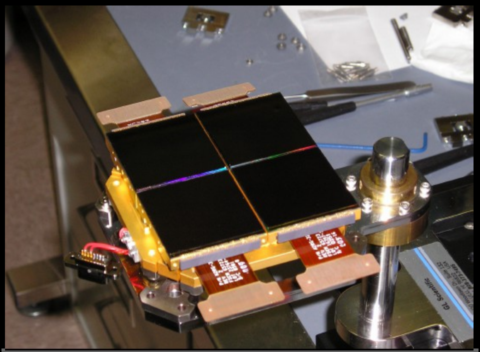
CFHT: The modest-sized telescope that could



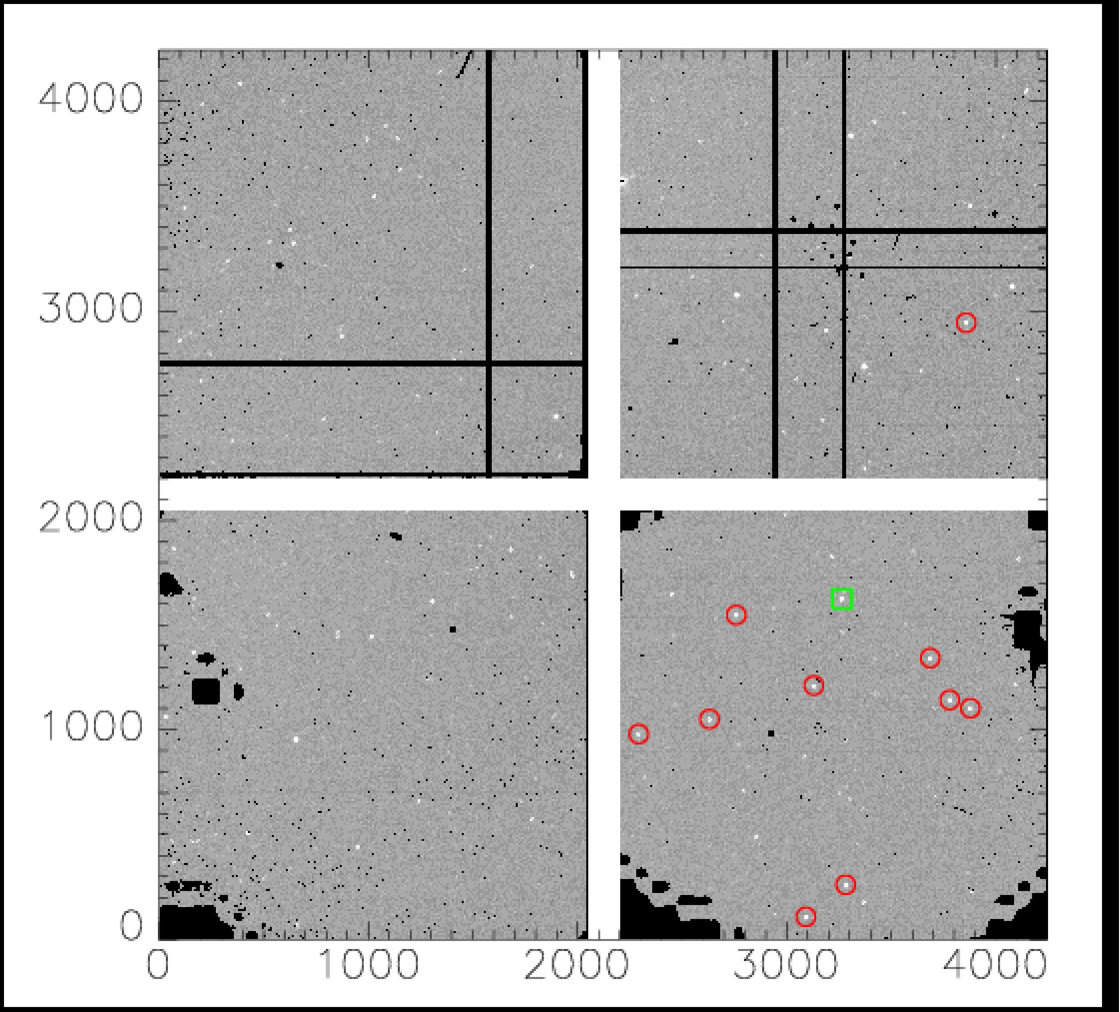
WIRCam Near-IR Defocused Photometry

- 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.

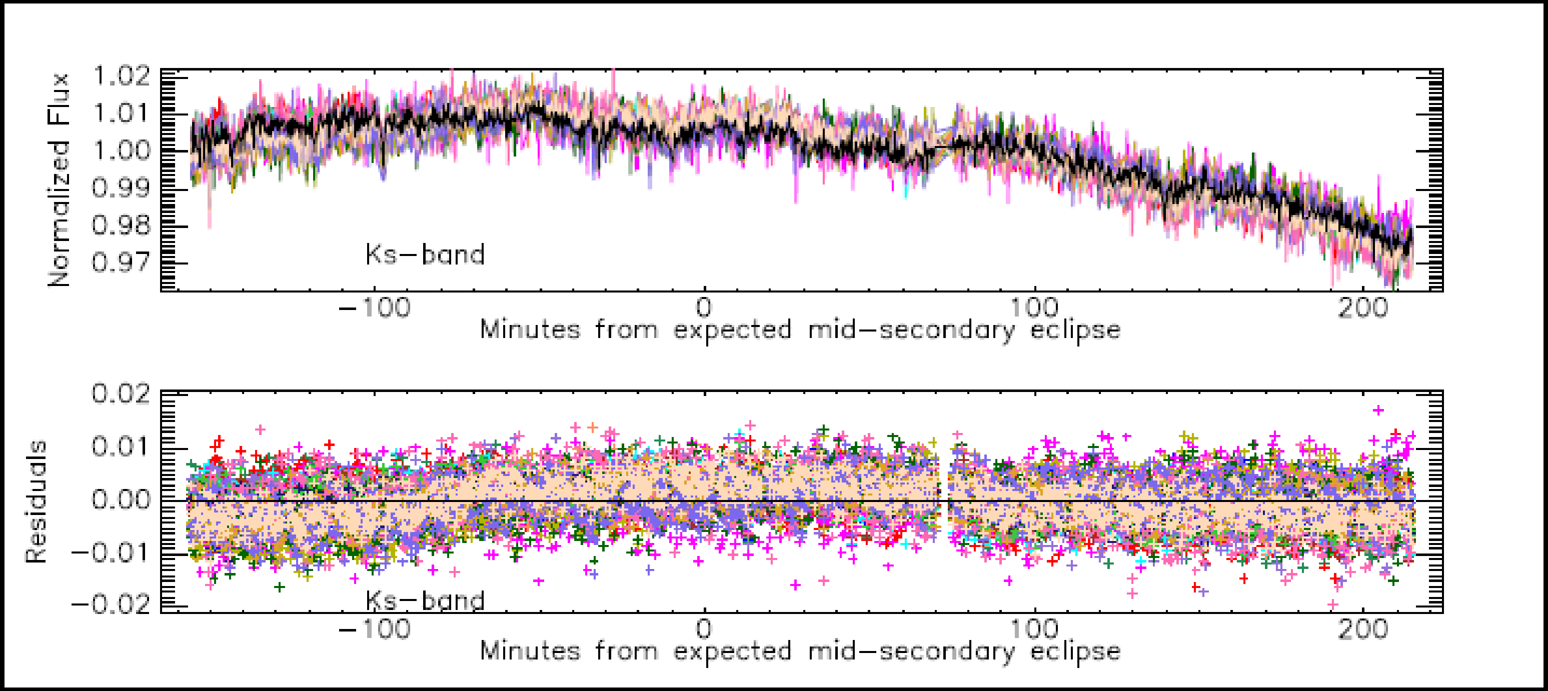


21'

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.



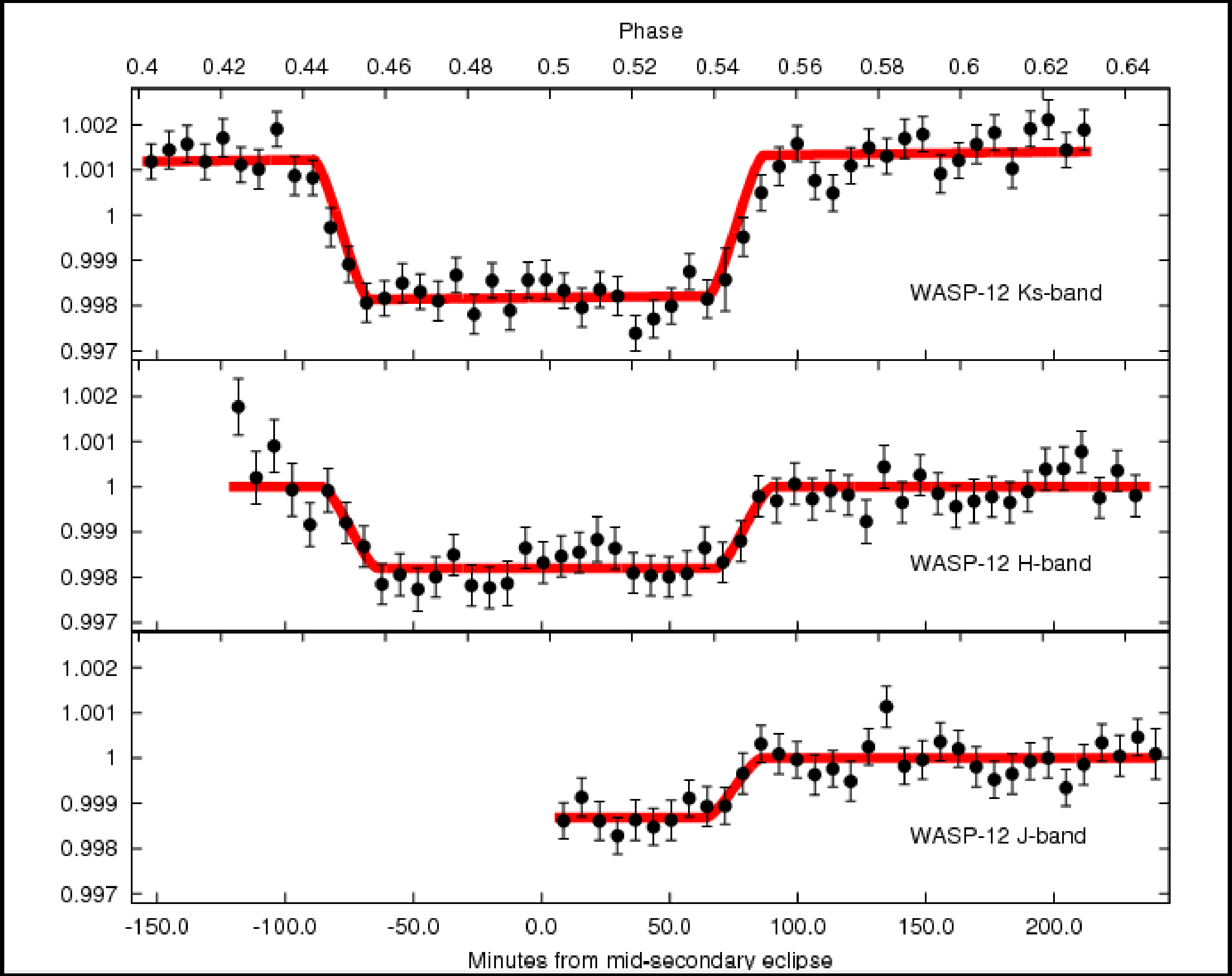
The flux and the residuals of the target star (black), and the reference stars (various colours).

WIRCam Large Program:

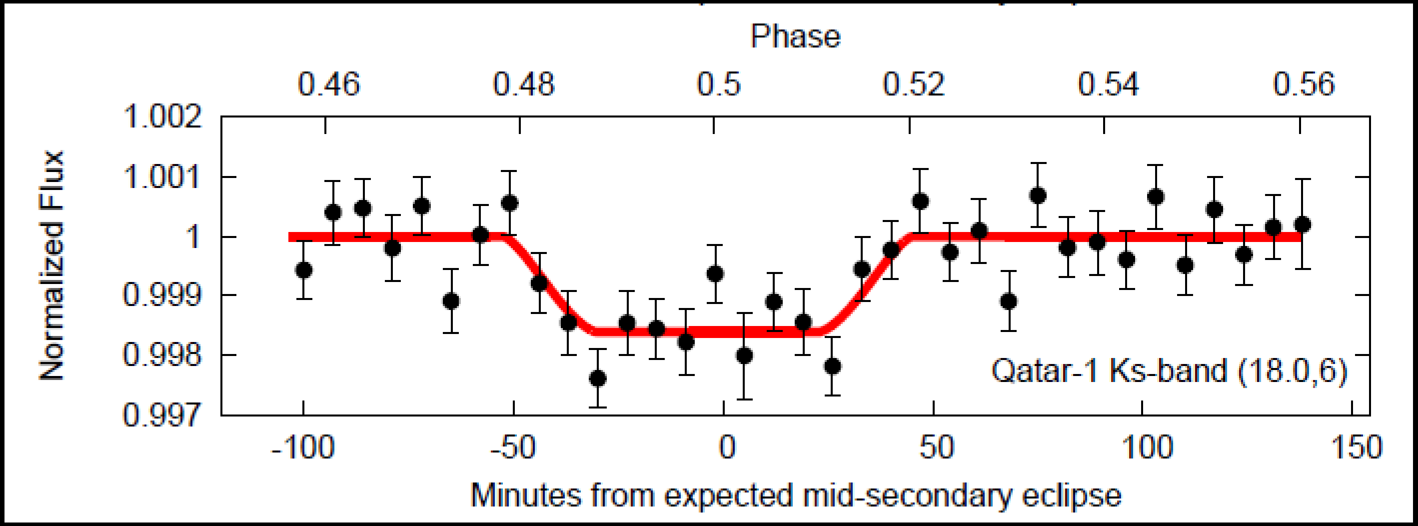
Thermal Emission of Transiting Exoplanets

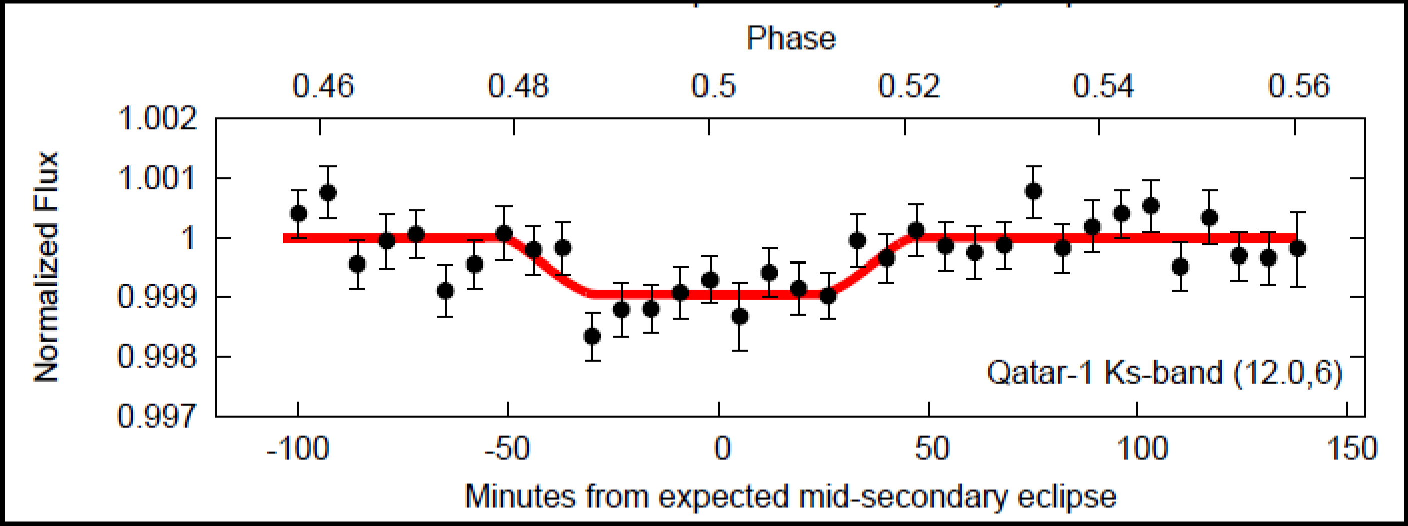
Bryce Croll, Ray Jayawardhana, Loic Albert, Aldo Bonomo, David Lafreniere, Jonathan Fortney, Magali Deleuil, Claire Moutou.

~200 hours



Repeatable Ground-based Near-infrared Eclipse Depths?





Two reductions/analyses of the Ks-band eclipse depth of Qatar-1 in the ks-band. One has a relatively deep depth and one has a shallow depth.

Repeatable Transit Depths?

- Our reported difference between the Ks-band and J-band transit depths of the super-Earth GJ 1214b (Croll et al. 2011), was refuted by other researchers (Bean et al. 2011).
- The Ks-band eclipse depths of TrES-3b disagree at the 2-sigma level (de Mooij & Snellen 2009; Croll et al. 2010b); a ground-based H-band upper-limit appears to disagree with a spacebased HST/WFC3 detection (Croll et al. 2010b; Ranjan et al. 2014).

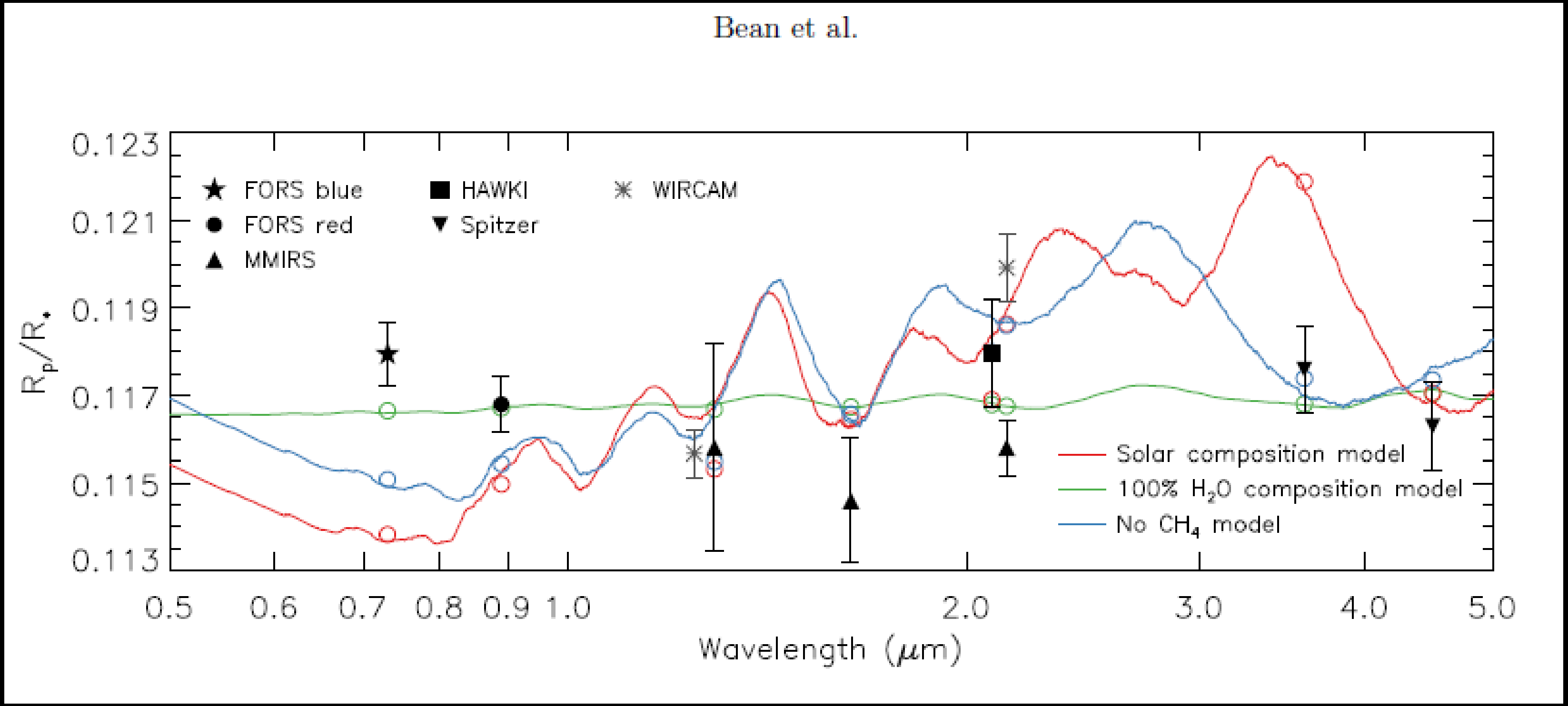
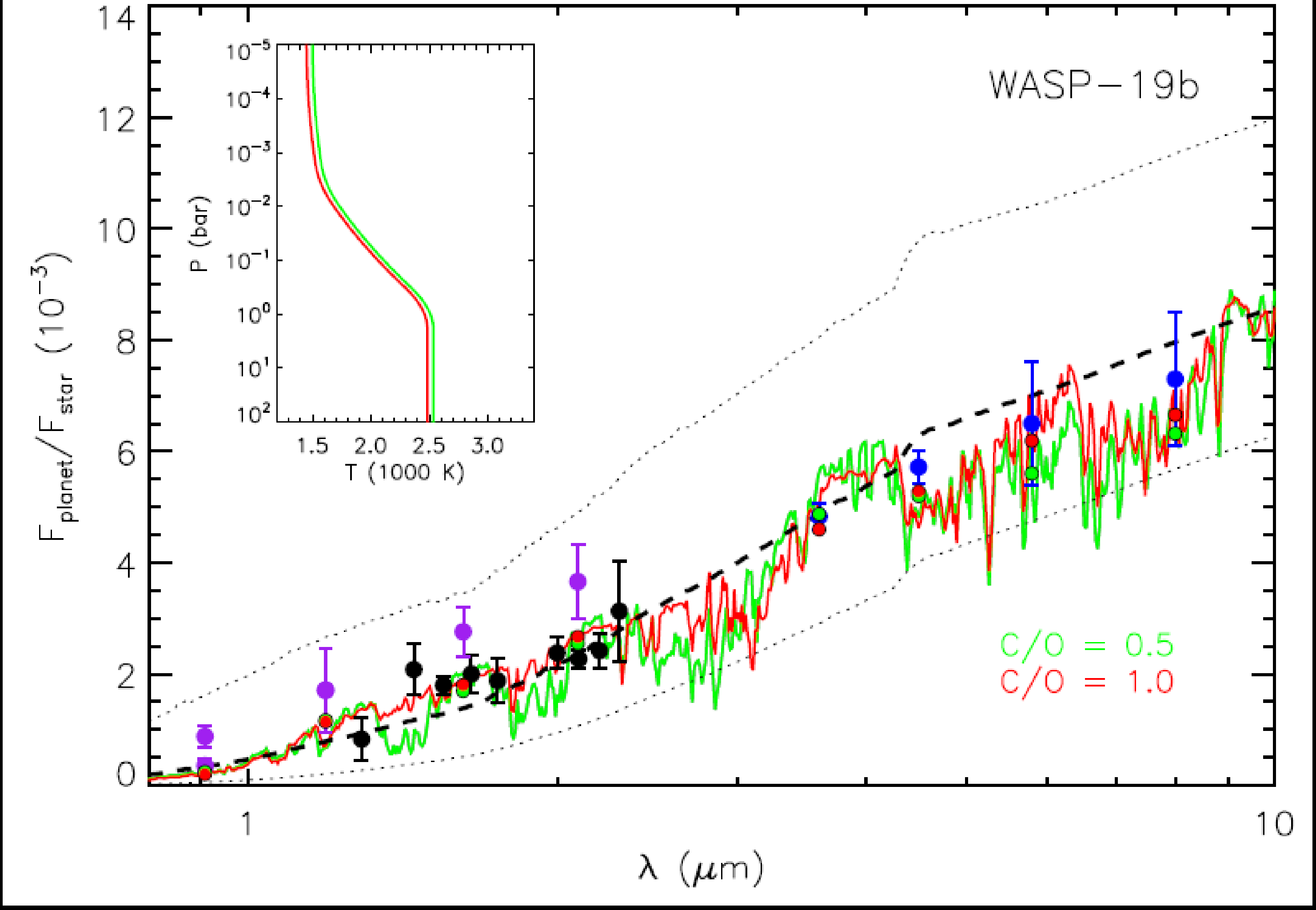


Figure from Bean et al. (2011): Compilation of the GJ 1214b Transit Depths at that time across a wide wavelength range.

Lack of Repeatability in near-infrared eclipse depths?
Bean et al. (2013)

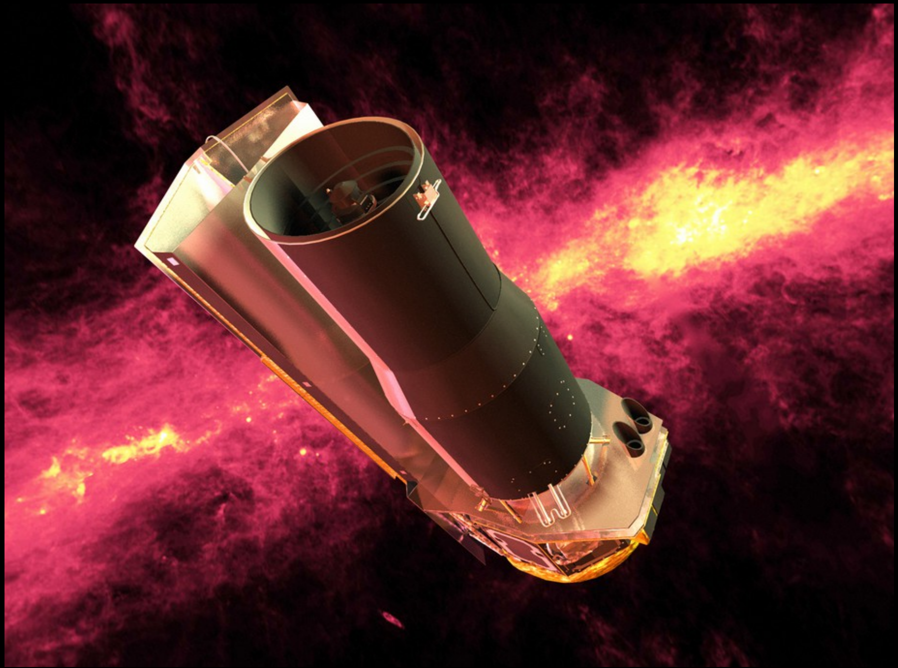
- The eclipse depths from MMIRS/Magellan spectrophotometry of a very hot, hot Jupiter (WASP-19b) agree only at the 2.9-sigma level.



Near-infrared ground-based eclipses (Bean et al. 2013; Anderson et al. 2010; Gibson et al. 2010; Burton et al. 2012; Lendl et al. 2013).

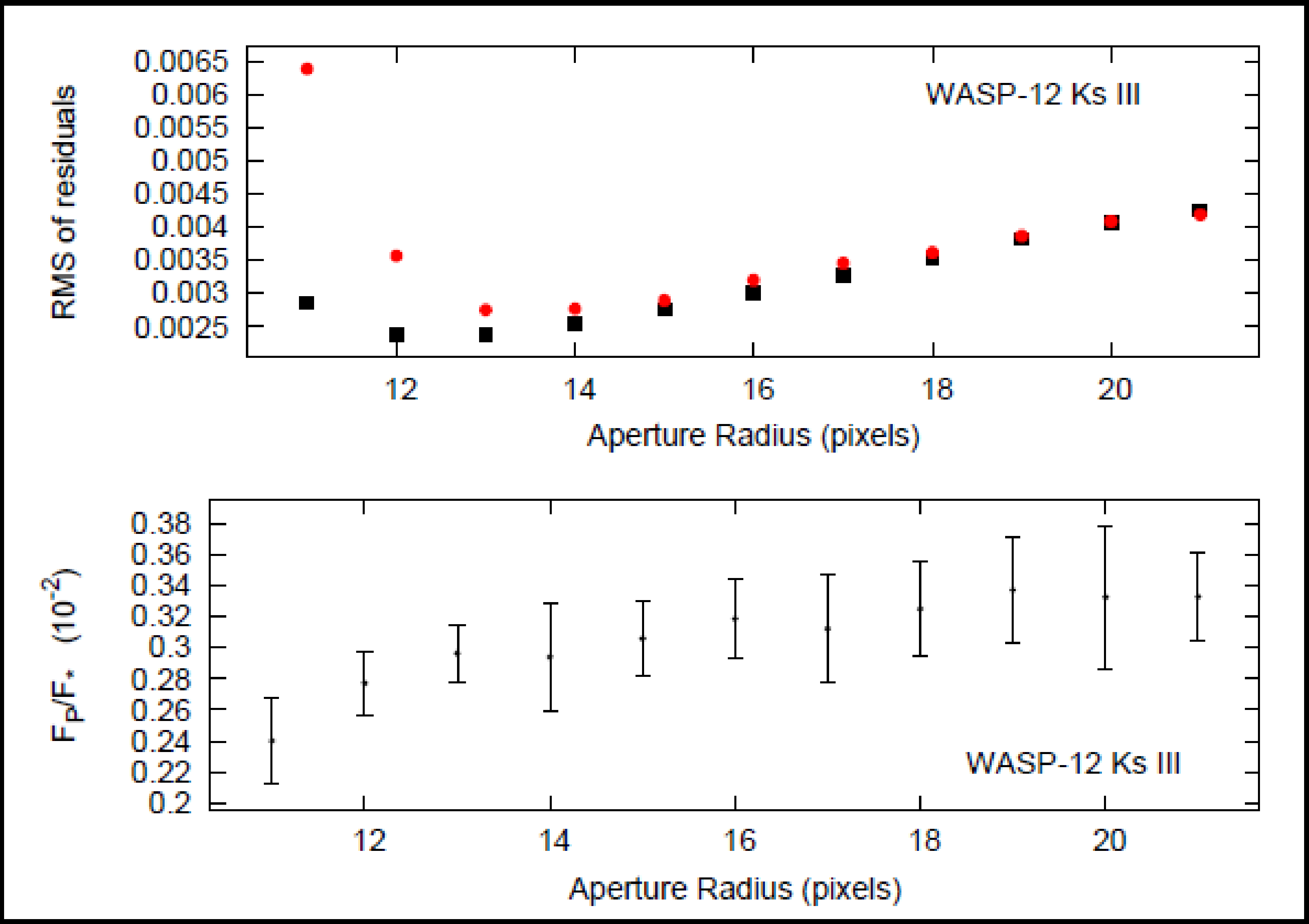
Reliability of Spitzer & HST Eclipses

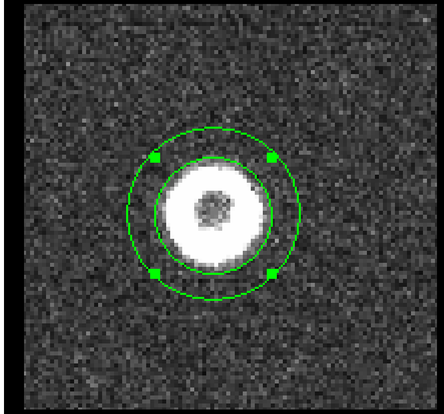
- Other instruments on other telescopes have already undergone a series of revisions in their attempts to return eclipse depths accurate at the sub-millimagnitude level, including:
  - Spitzer/IRAC (e.g. Harrington et al. 2007; Knutson et al. 2009; Knutson et al. 2007; Charbonneau et al. 2008; Stevenson et al. 2010; Knutson et al. 2011; Zellem et al. 2014; Diamond-Lowe et al. 2014).
  - and HST/NICMOS (e.g. Swain, Vasisht & Tinetti. 2008; Swain et al. 2009a; Swain et al. 2009b; Gibson et al. 2011; Mandell et al. 2011; Gibson et al. 2012; Waldmann et al. 2013; Swain et al. 2014).



Fidelity of near-infrared eclipse depths
Croll et al. (2015)

- The eclipse depths measured in some data-sets display trends with aperture radii, or the number of reference stars used.





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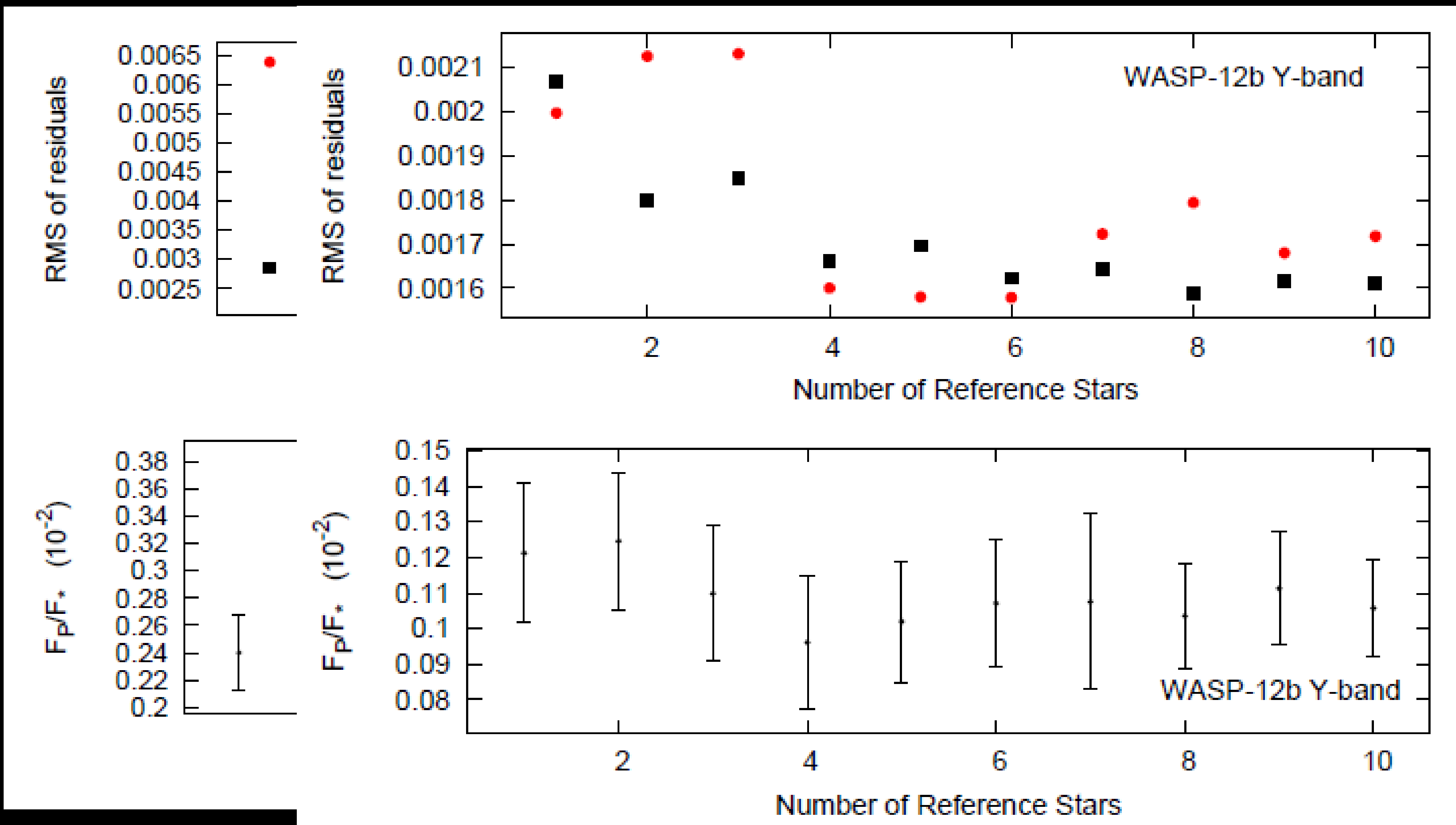
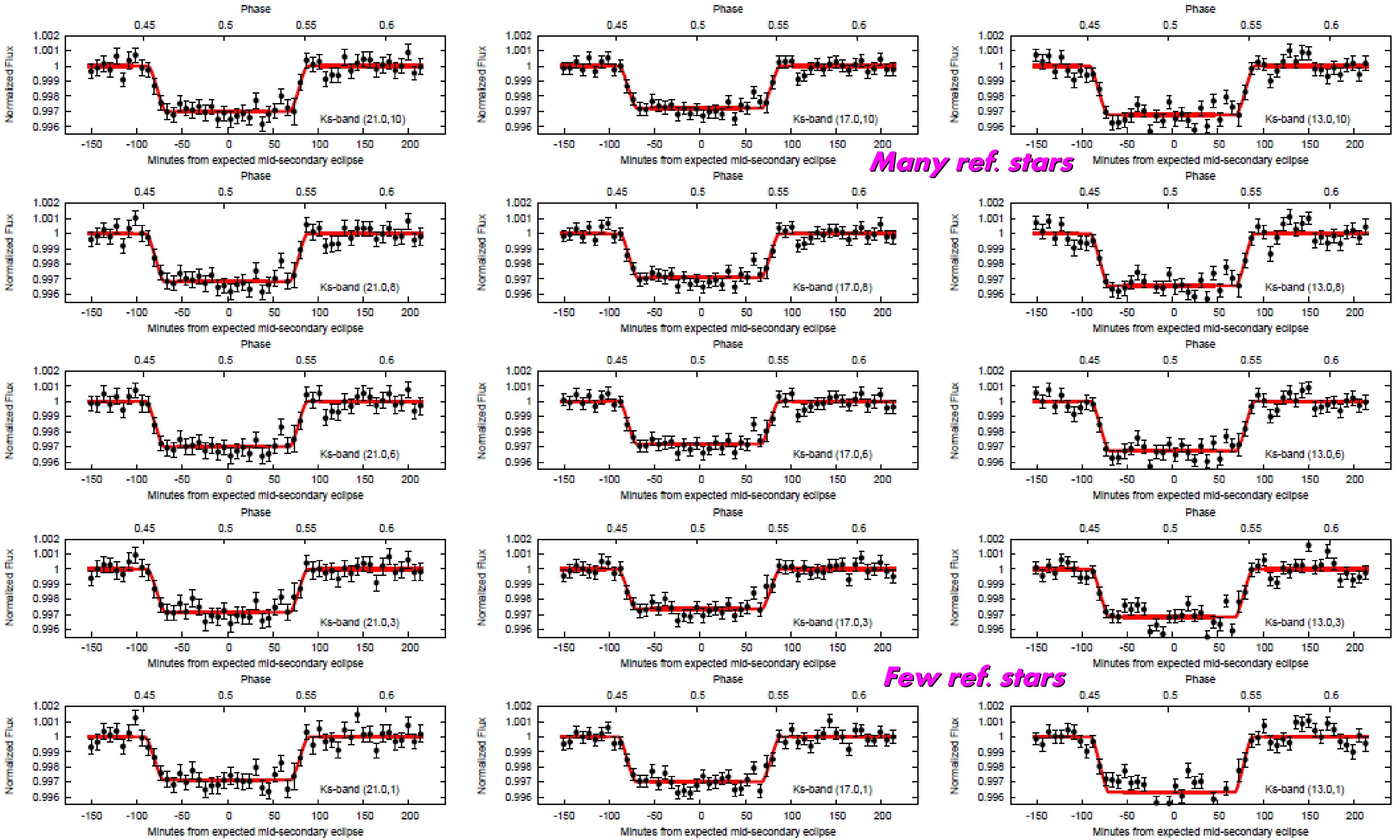


Fidelity of near-infrared eclipse depths

WASP-12 Ks-band (Croll et al. 2015)

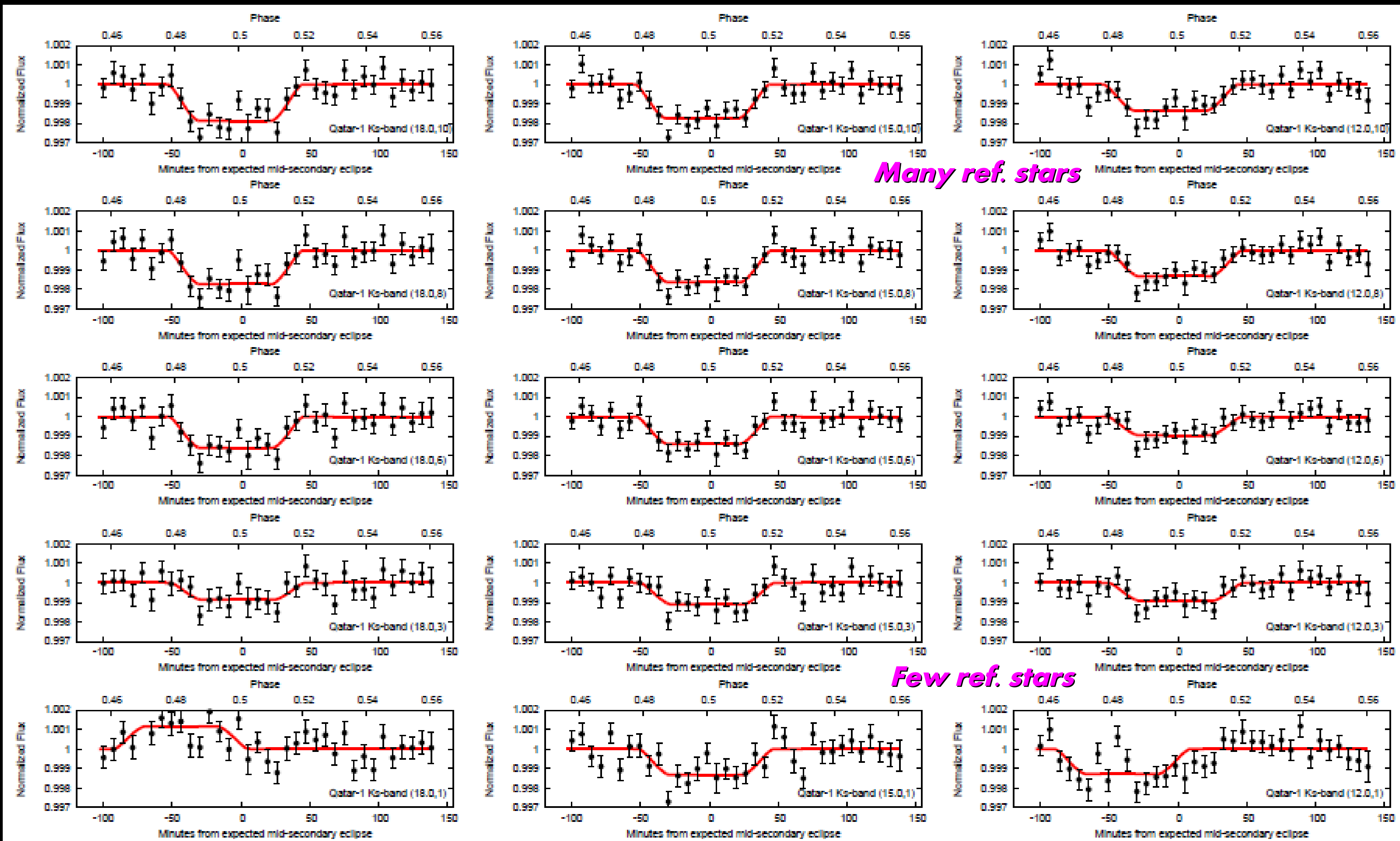


Large Aperture

Small Aperture

Fidelity of near-infrared eclipse depths

Qatar-1 Ks-band (Croll et al. 2015)

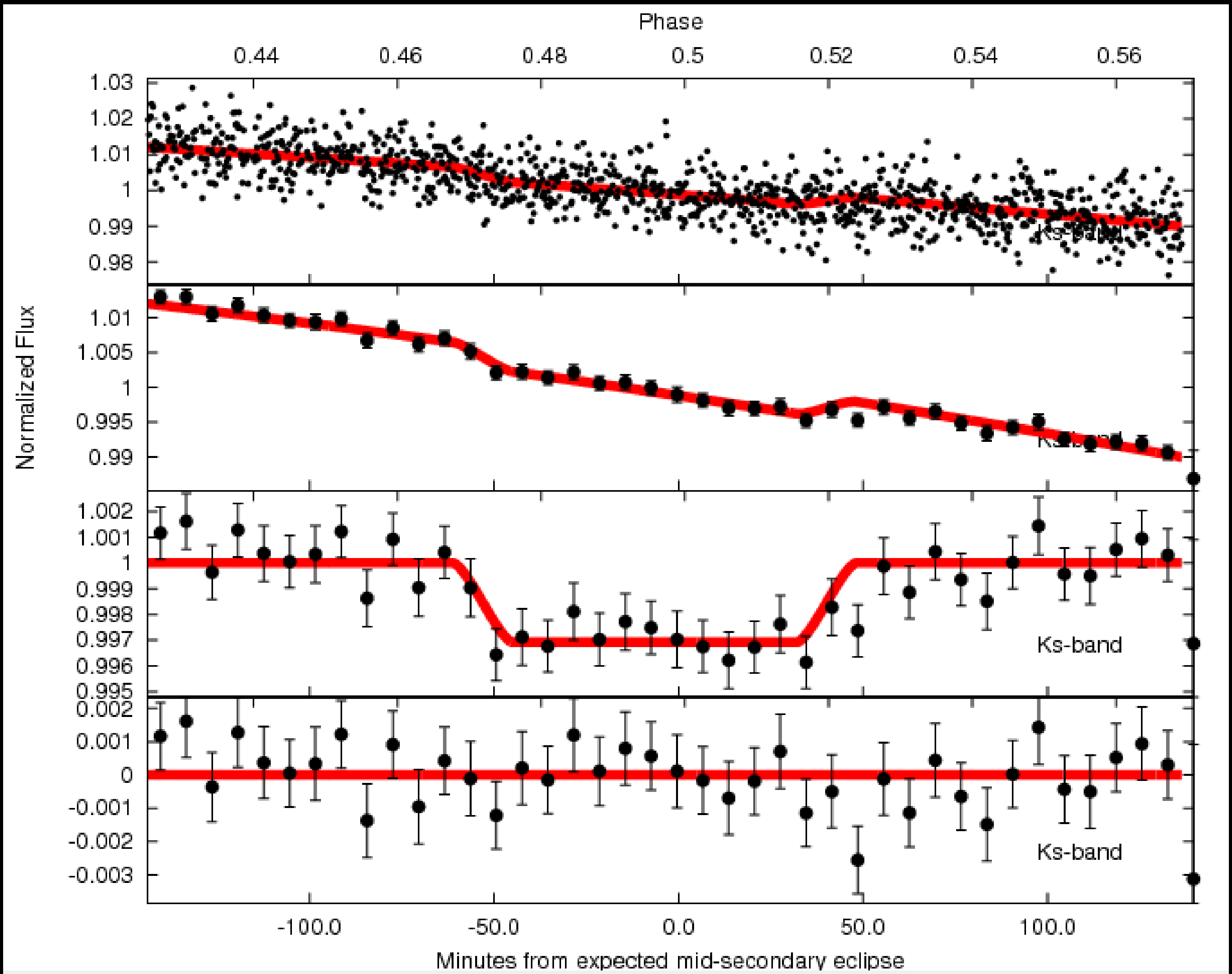


Large Aperture *Small Aperture*

Qatar-2b in Ks

Croll et al. In Prep.

Slide from 2012 Sagan Symposium!



Top: the unbinned photometry.

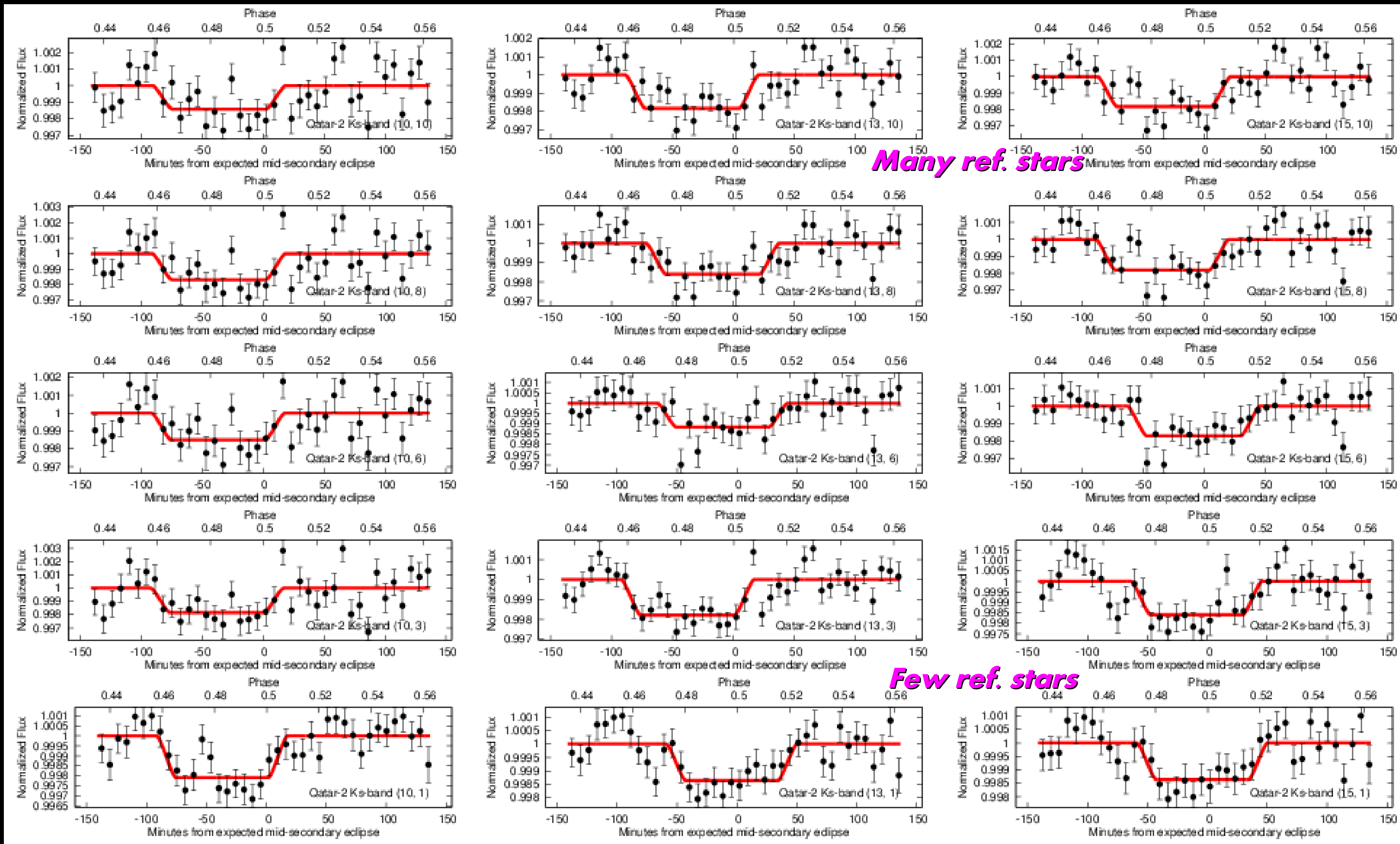
Second from top: the binned photometry.

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

Bottom: residuals from the best-fit eclipse.

Fidelity of near-infrared eclipse depths

Qatar-2 Ks-band

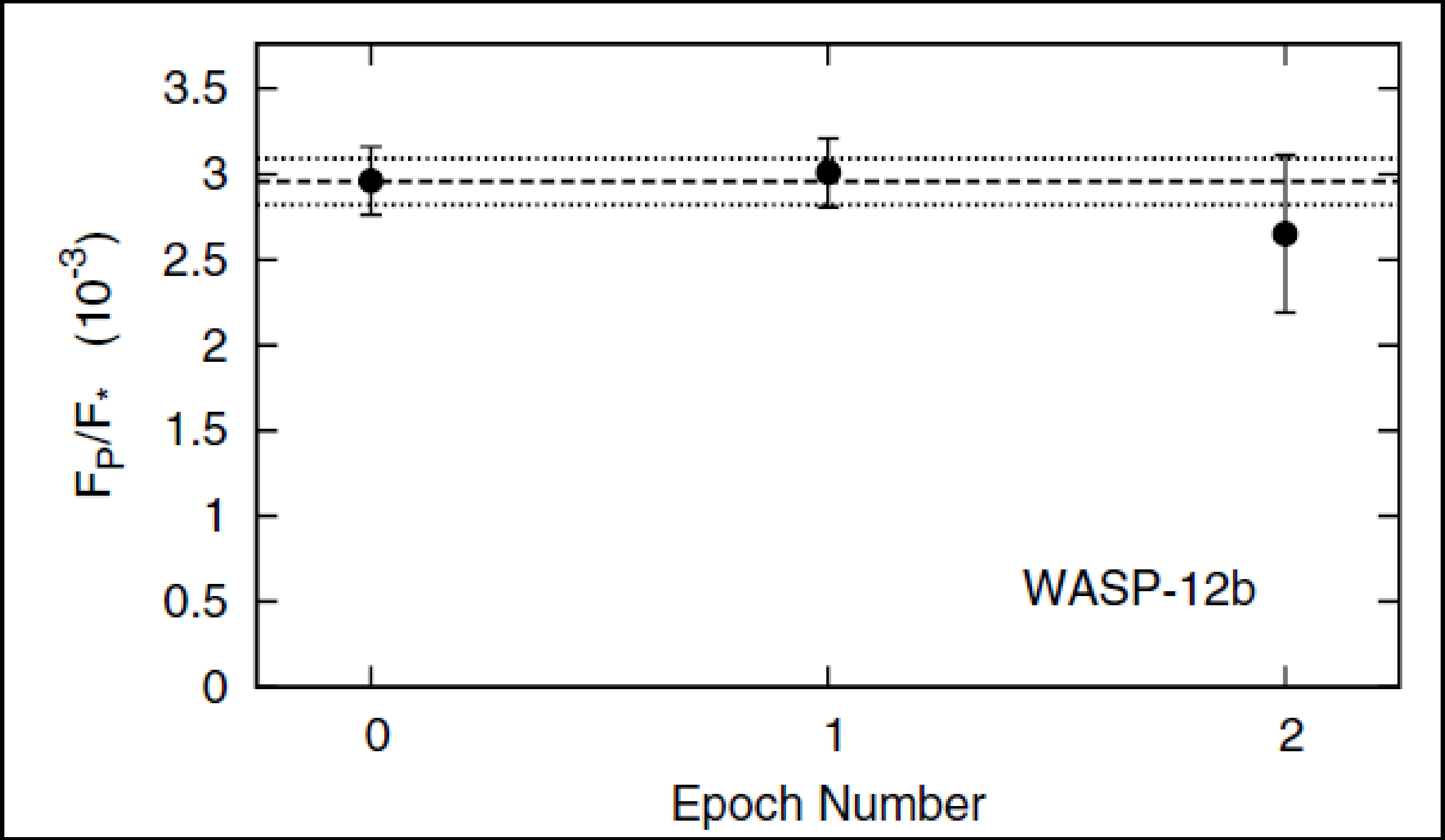


Large Aperture *Small Aperture*

WASP-12b: Repeatability of eclipse depths

Croll et al. (2015)

- We detected WASP-12b`s thermal emission in Ks-band on three occasions. The eclipse depths were consistent to within 1-sigma, arguably demonstrating the validity of our techniques. There is also an independent confirmation of our eclipse depth (Zhao et al. 2011).

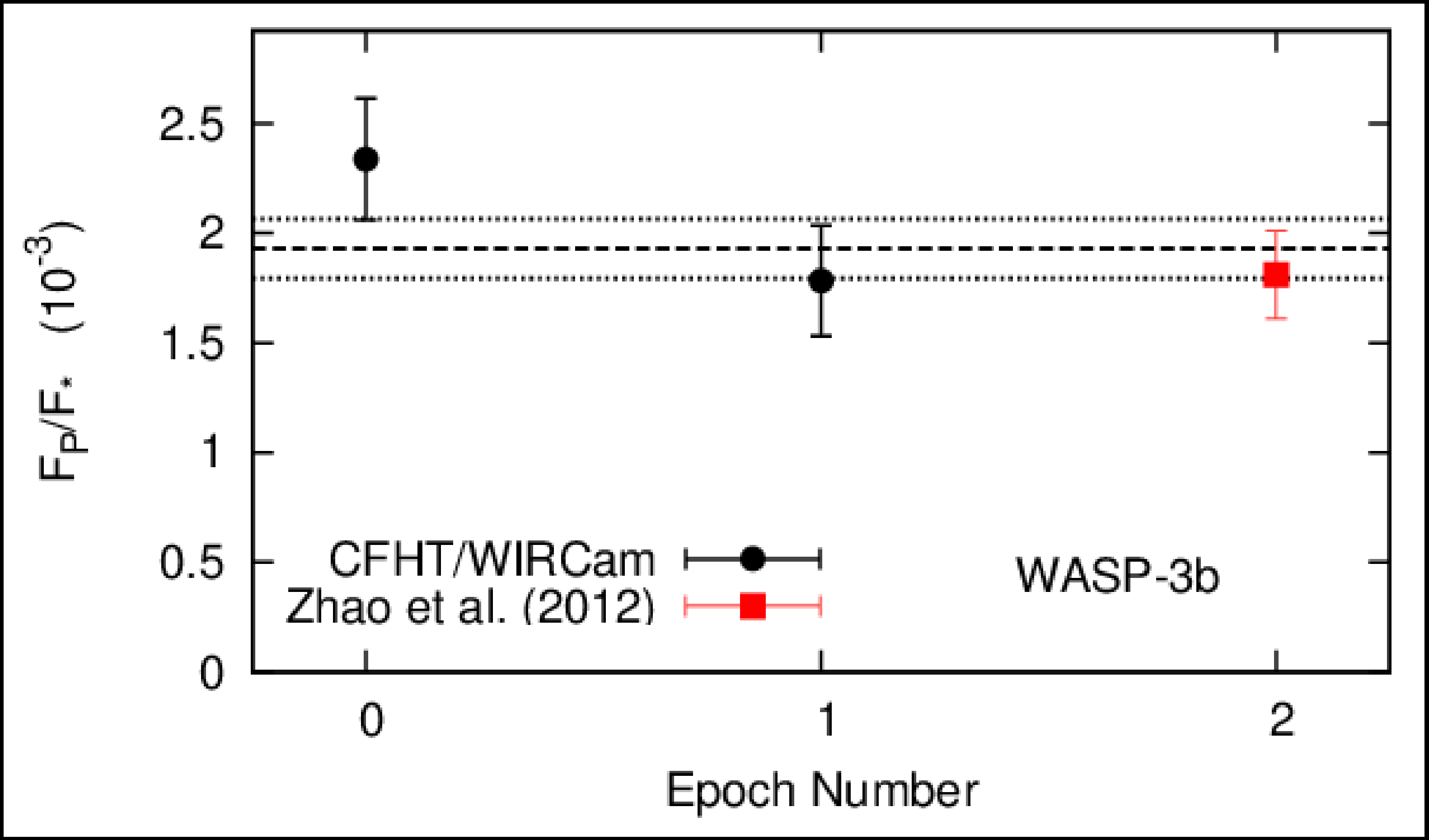


Eclipse depths of our three WASP-12 Ks-band eclipses. The dashed lines indicate the weighted mean, while the dotted lines indicate the 1-sigma errors.

WASP-3b: Repeatability of eclipse depths

Croll et al. (2015)

- The WASP-3b were roughly consistent.

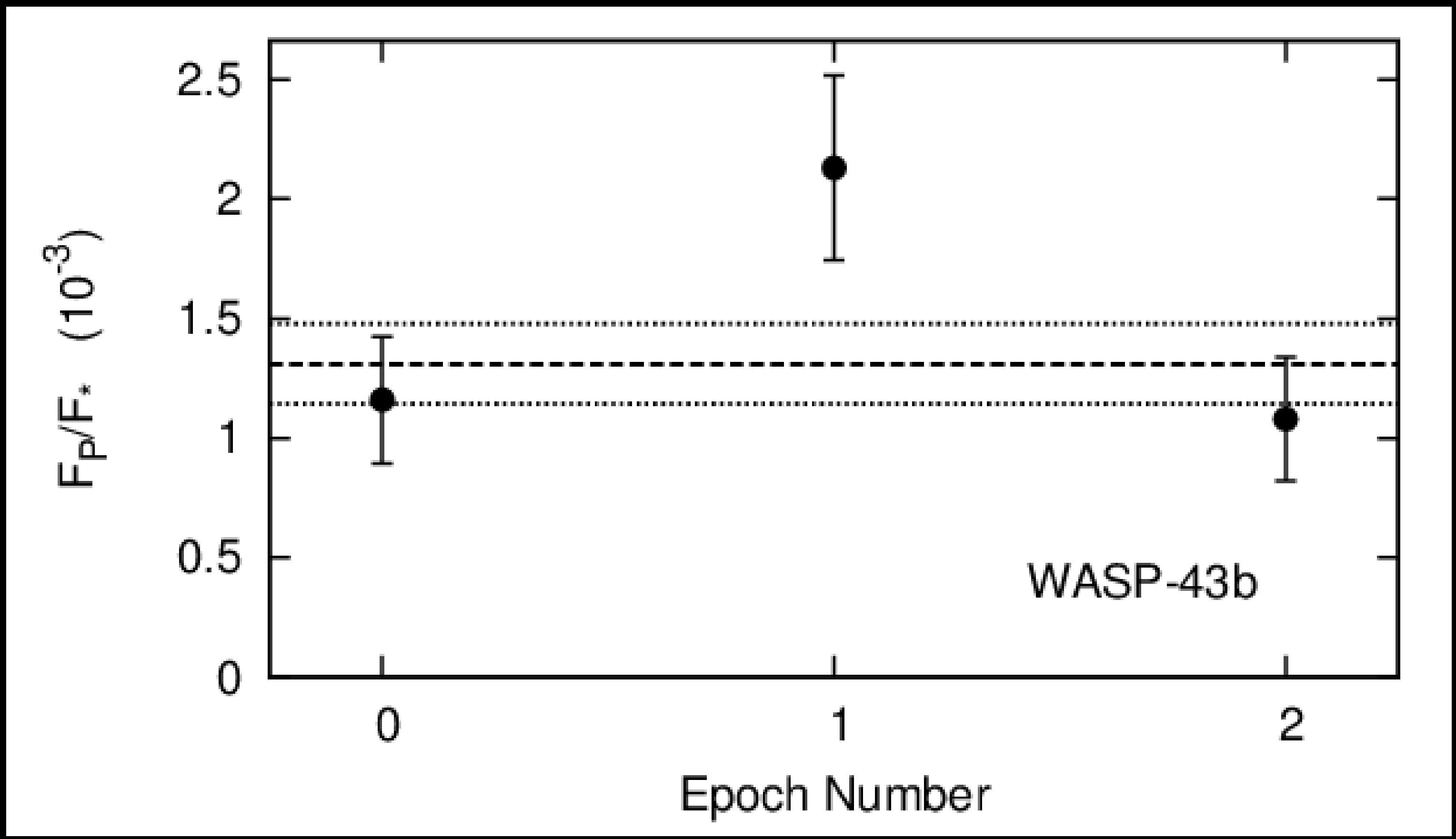


Eclipse depths of our two WASP-3 Ks-band eclipses, and another from Zhao et al. (2012). The dashed lines indicate the weighted mean, while the dotted lines indicate the 1-sigma errors.

WASP-43b: Repeatability of eclipse depths

Croll et al. In Prep.

- Our three WASP-43b Ks-band eclipse depths are roughly consistent (with an outlier at less than 2-sigma).

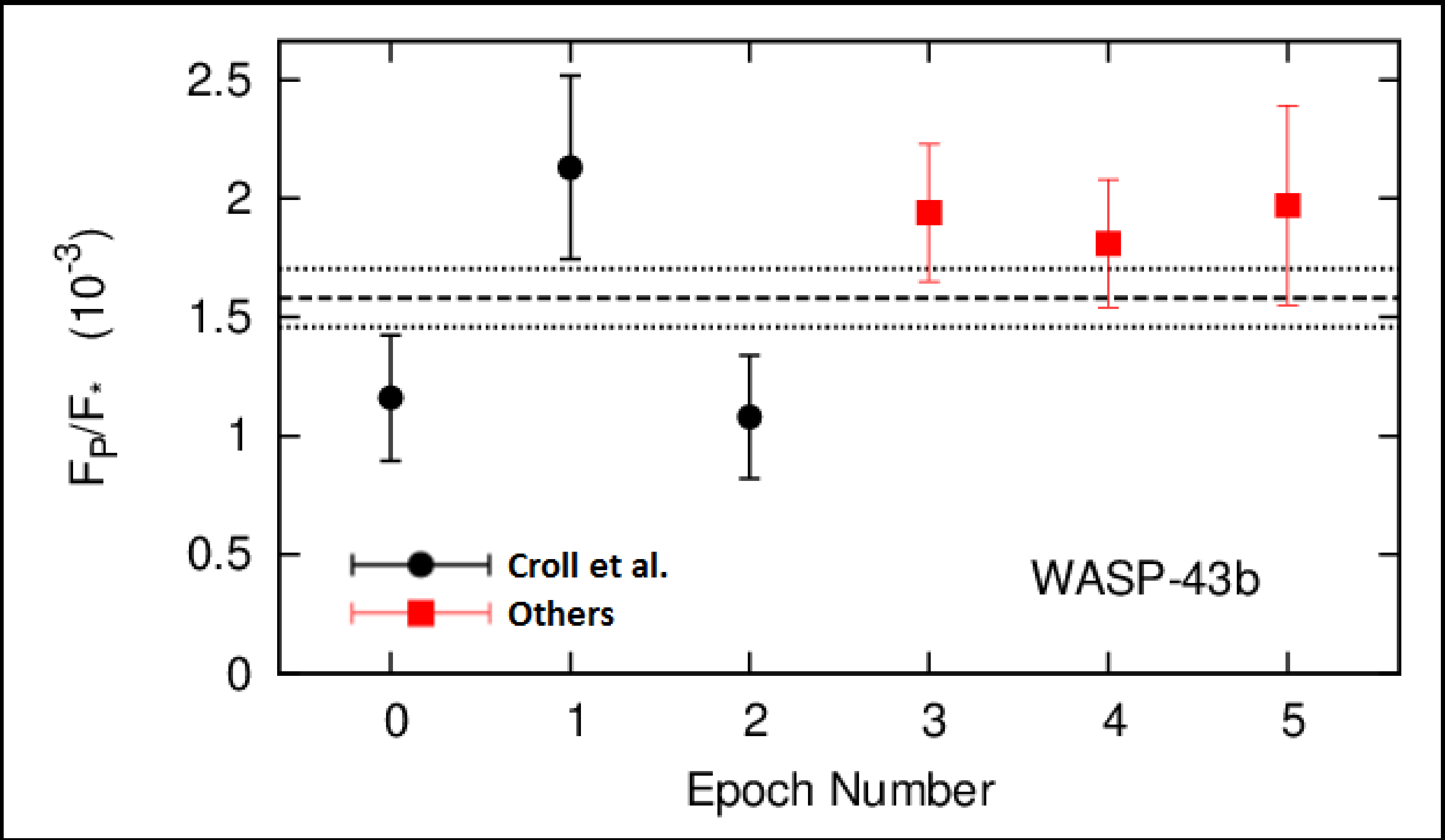


Eclipse depths of our three WASP-43 Ks-band eclipses. The dashed lines indicate the weighted mean, while the dotted lines indicate the 1-sigma errors.

WASP-43b: Repeatability of eclipse depths

Croll et al. In Prep.

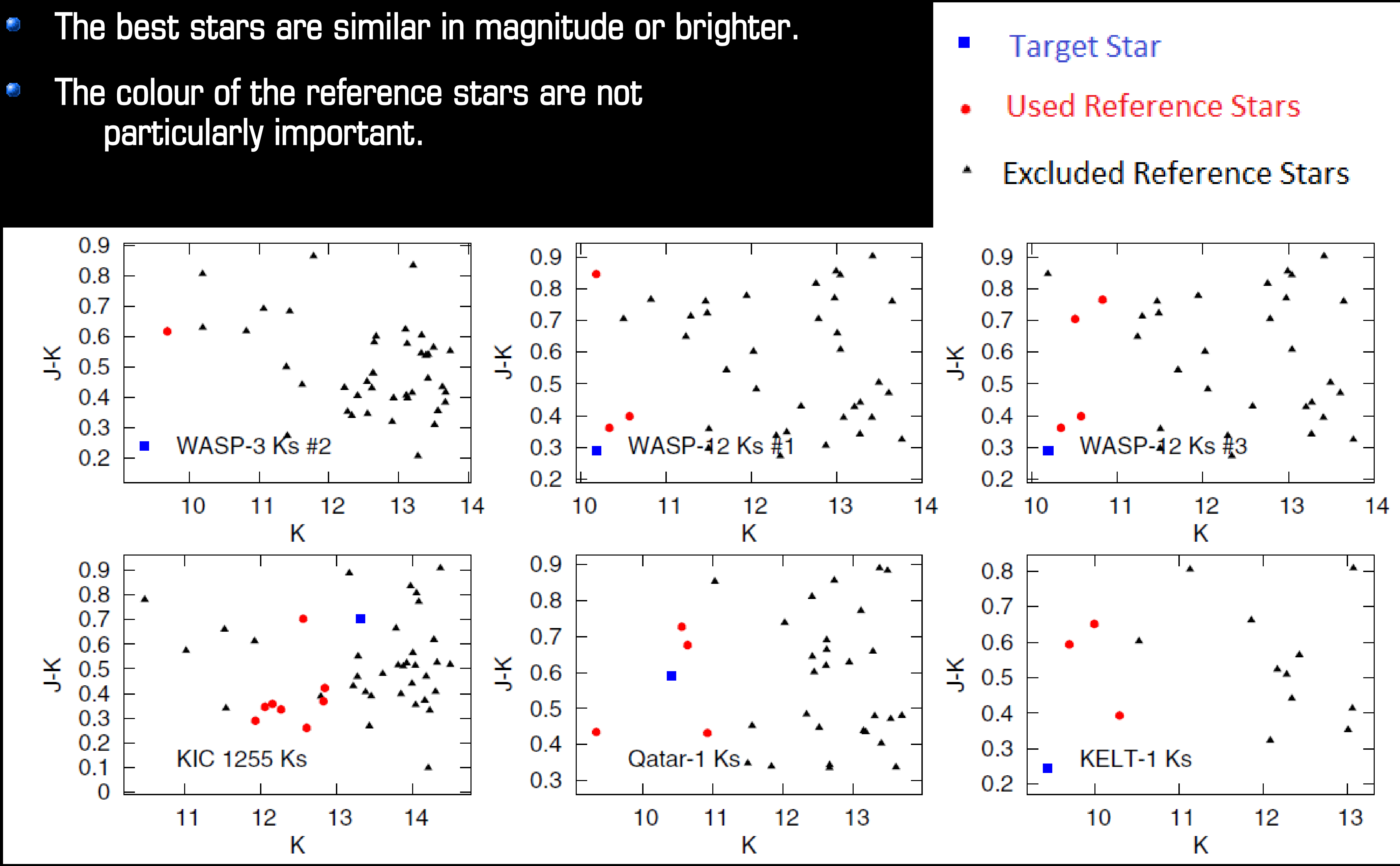
- There is a concern of systematically overestimated eclipse depths (Rogers et al. 2013).



Eclipse depths of our three WASP-43 Ks-band eclipses; red points are from Wang et al. (2013), Zhou et al. (2014), Chen et al. (2014). The dashed lines indicate the weighted mean, while the dotted lines indicate the 1-sigma errors.

Which Reference Stars?

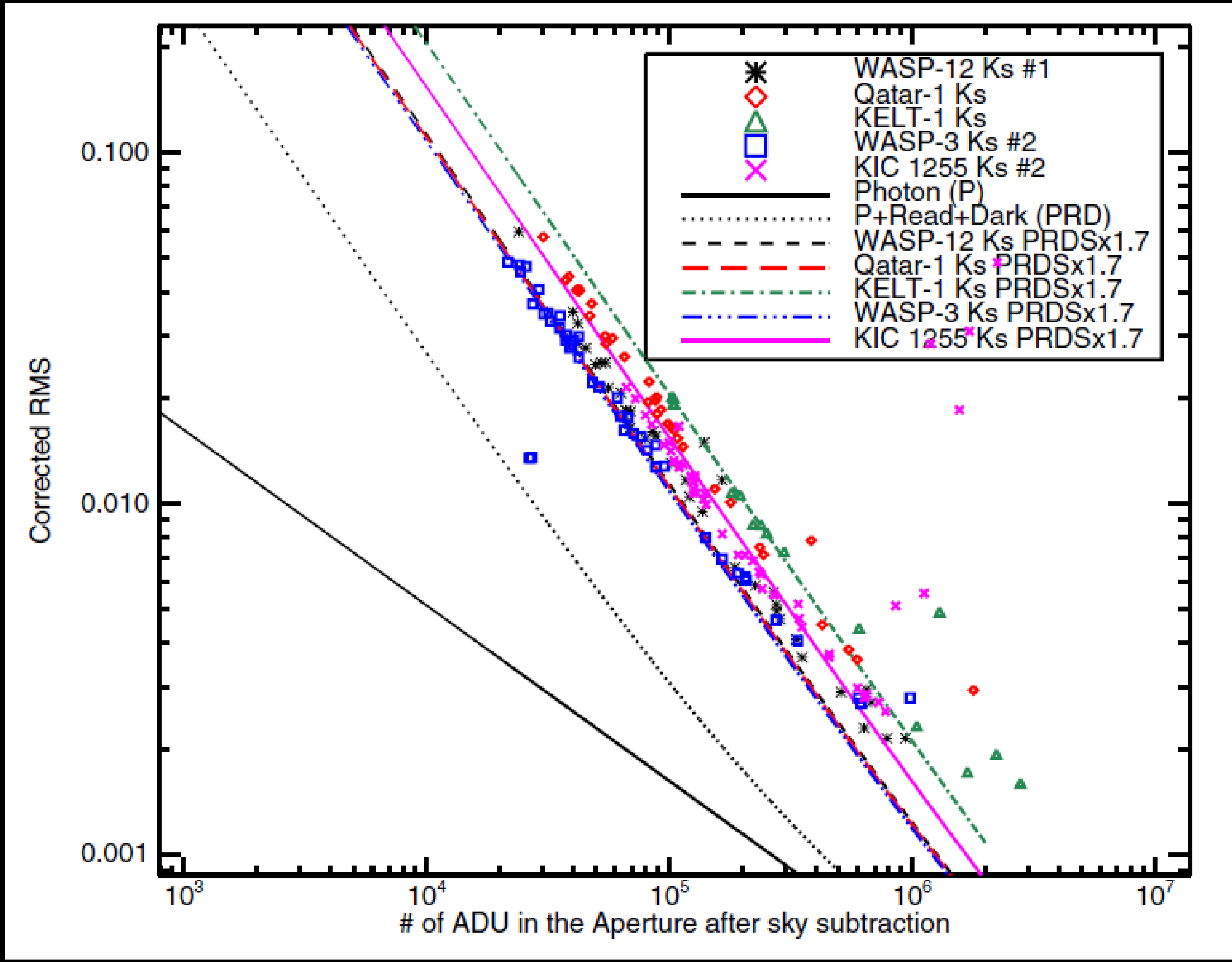
- The reference stars we use for our various Staring Mode data-sets.
- The best stars are similar in magnitude or brighter.
- The colour of the reference stars are not particularly important.

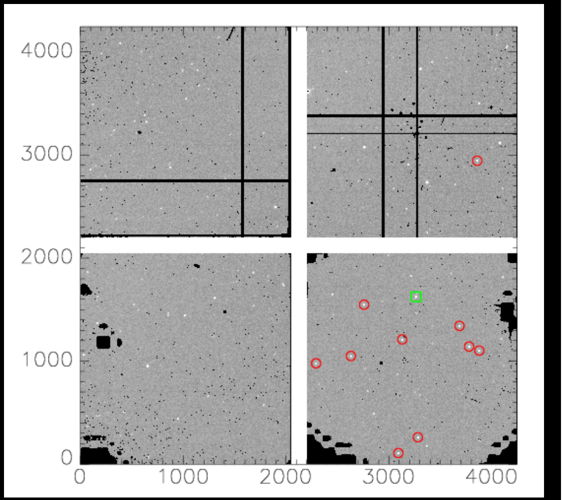


LIMITING SYSTEMATIC OF NEAR-INFRAED DATA

CROLL ET AL. (2015)

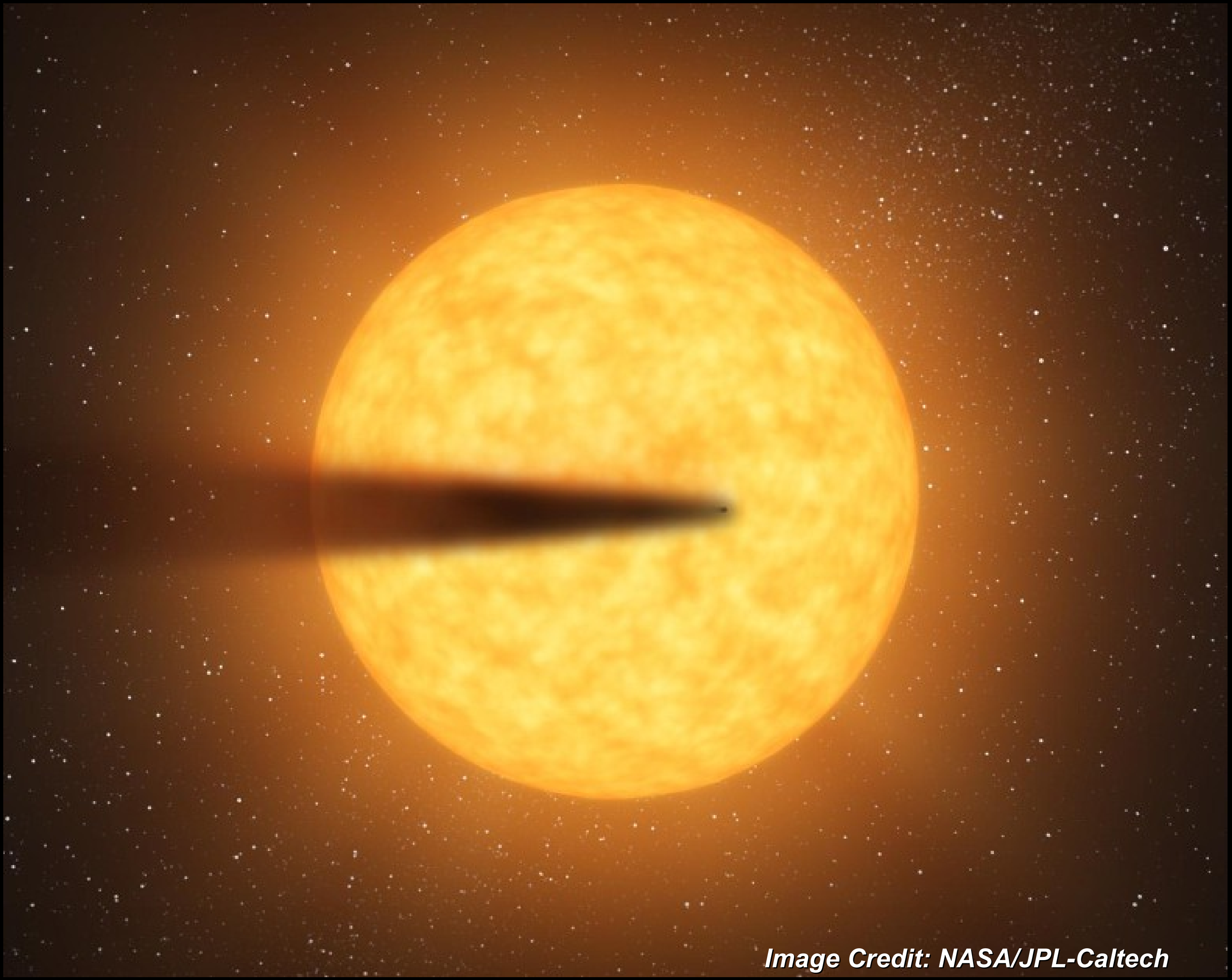
- The great number of reference stars allows us to explore the limiting systematics of near-infrared data.
- For faint stars our data is near the noise limit once all sources of error are taken into account.





RMS OF ALL THE REFERENCE STARS OF WASP-12, QATAR-1, KELT-1, WASP-3 AND KIC 1255 IN THE KS-BAND.

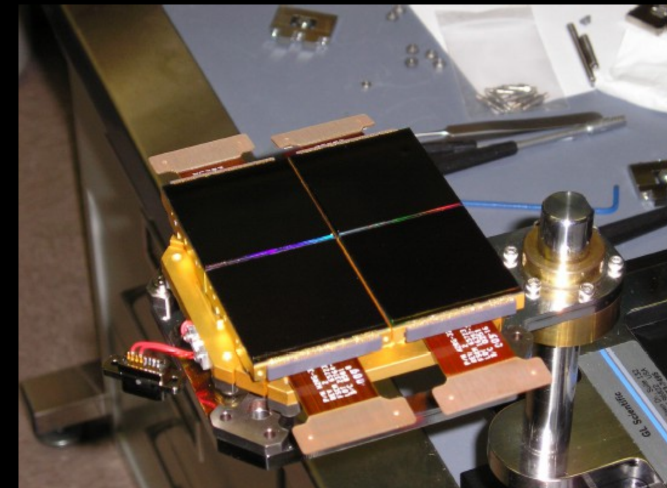
Multiwavelength Observations of the candidate disintegrating sub-Mercury KIC 1255b
Croll et al. 2014



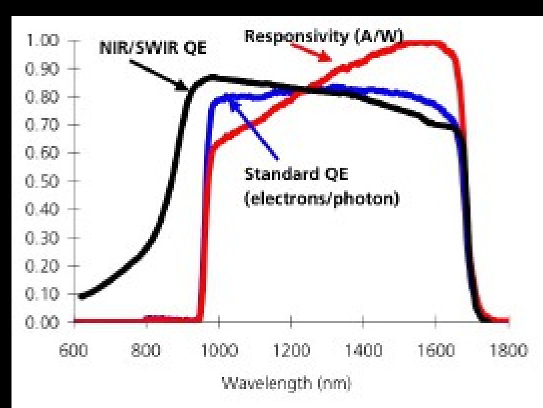
Our near-infrared photometry allows us to constrain the particle sizes in the cometary tail.

Near-infrared Detectors

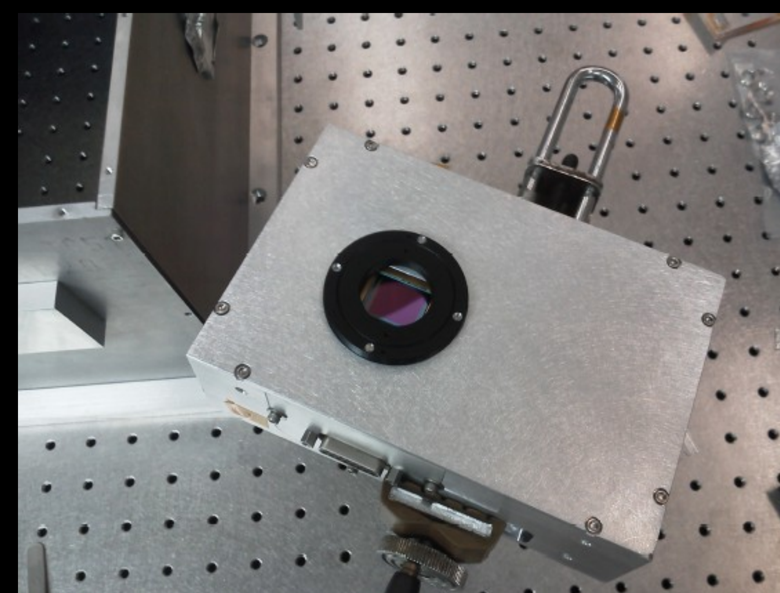
- Existing near-infrared detectors (JHK) usually use mercury cadmium telluride (HgCdTe; MerCad Telluride) detectors cooled to -190 Celsius.
- Indium Gallium Arsenide (InGaAs) are a much cheaper alternative (10-20x cheaper; they only have to be cooled to -30 to -60 Celsius) that have been developed for 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 WIRCam a HgCdTe device.



InGaAs Cameras are quantum efficient from 0.9 – 1.7 microns, allowing YJH-band observations.



Bottom: Our InGaAs Camera.

The Dream Team

Top: Peter Sullivan

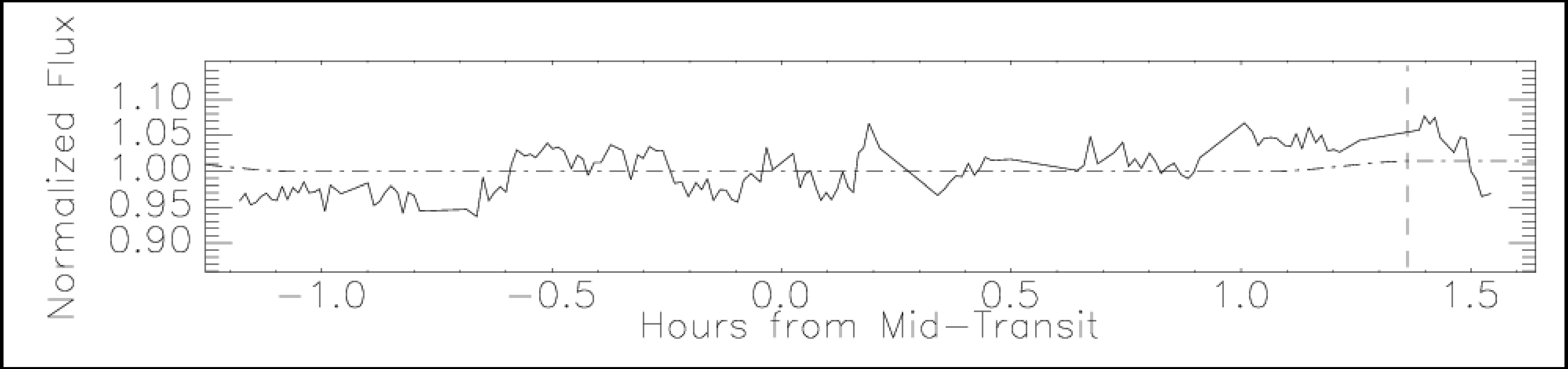
Bottom: Rob Simcoe

Right: Myself

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.

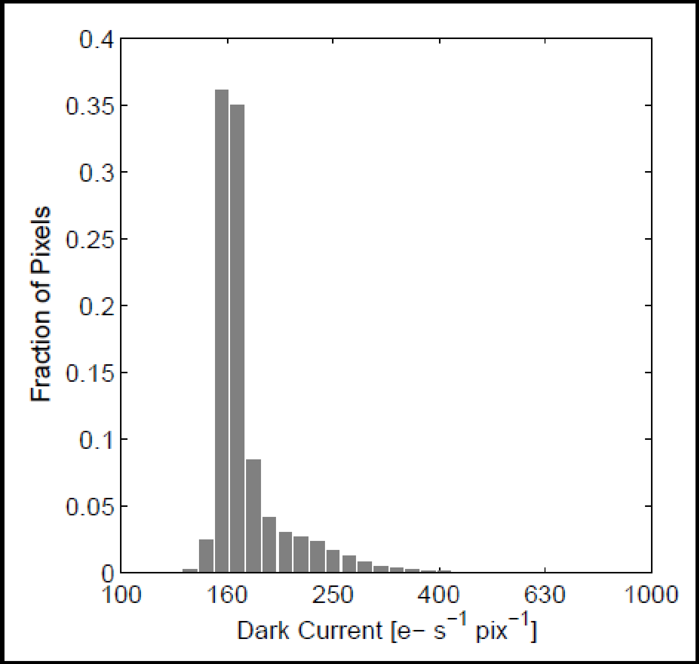


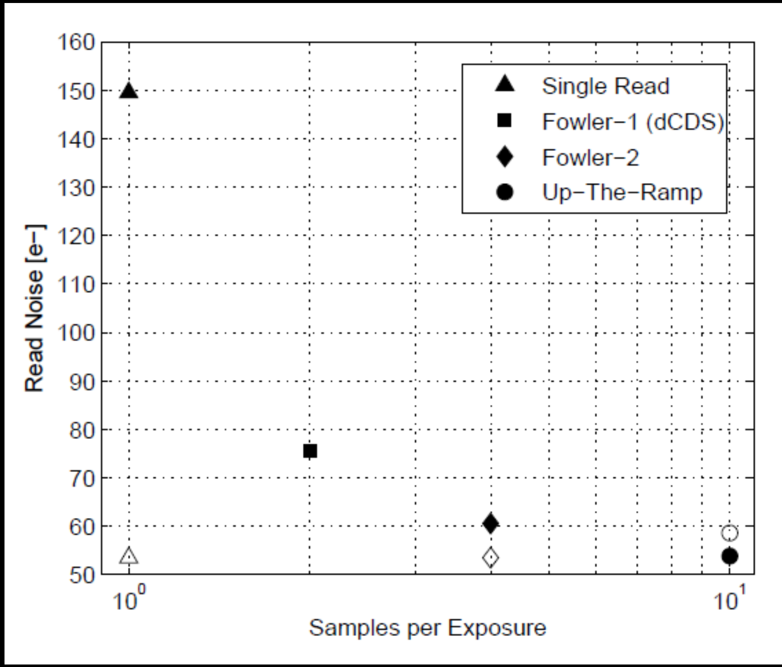
Bottom: InGaAs observations of the transit of WASP-33. We fail to detect the Transit.

The Promise of InGaAs Devices

Sullivan, Croll & Simcoe (2013, 2014)

- HgCdTe devices display low read noise (~10 e-/read), and very low dark current (<1 e-/sec/pixel) at -190 C.
- Our original device displayed reasonable read noise (~50 e-/read), but high dark current (~800 e-/sec/pixel) at -20 C that did not improve as we cooled the device.
- Our next generation chip displayed competitive read noise (~50 e-/read) and competitive dark current (~160 e-/sec/pixel) such that the sky will limit the resulting precision for small telescopes.



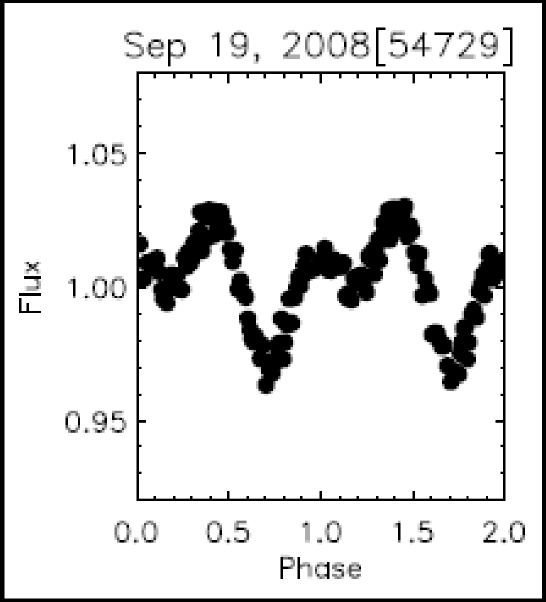


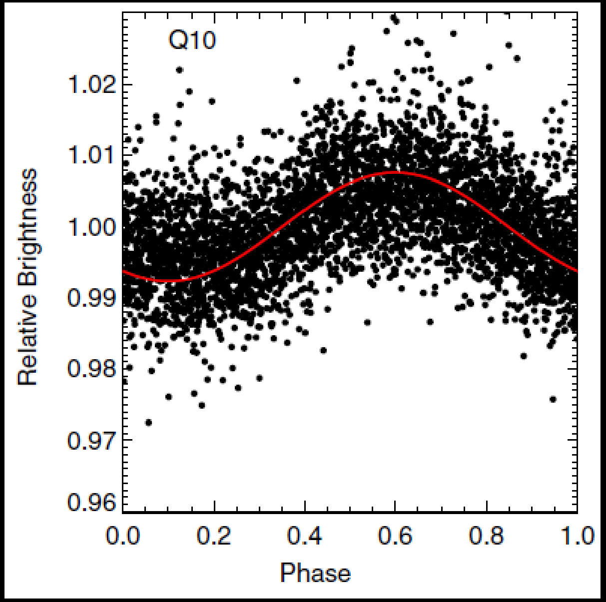
Left: Low Dark current and Right: Low Read Noise for our latest InGaAs chip.

- 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:
  - Thermal Emission of hot Jupiters
  - Thermal Phase Curve Measurements of hot Jupiters from the Arctic.
  - Variability studies of, and transiting planet searches around, late M-dwarfs, & brown-dwarfs.

Brown Dwarf Variability & Searching for Earth-Sized Planets in the Habitable Zone

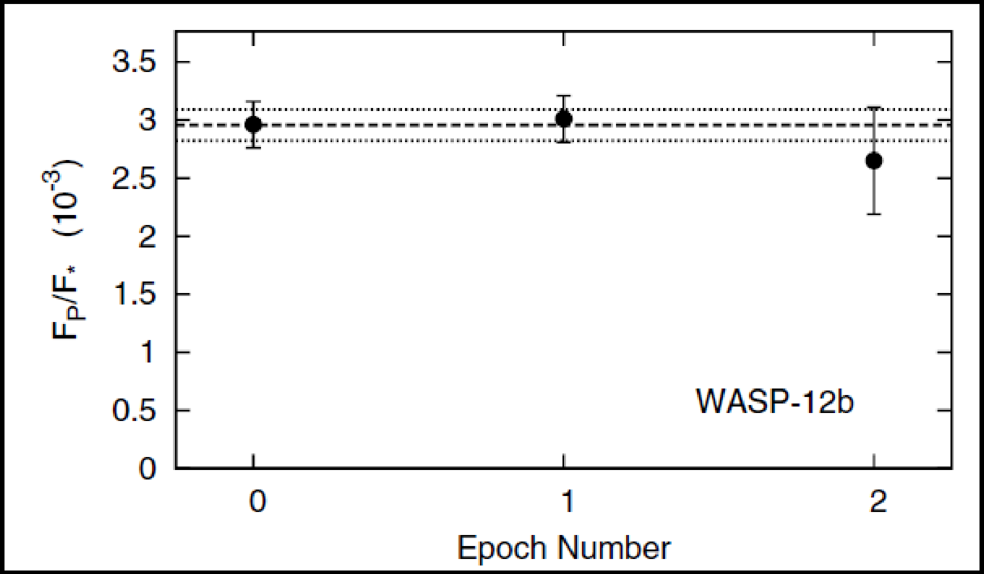
- 25 nights of observations with the Perkins 1.8 m telescope at Lowell of an L-dwarf and an L/T transition BD.
- Our photometry will have the sensitivity to detect Earth-sized planets in the habitable zone; only with rocky planets about ultra-cool dwarfs will atmospheric features/biomarkers be able to be detected with JWST with just a few weeks of observing time (Belu et al. 2013).
- The opportunity to probe variability and the evolution of variability for L/T transition BDs, where the variability is believed to arise from cloud clearings, to L dwarfs where the source of variability is less clear (clouds or spots?).



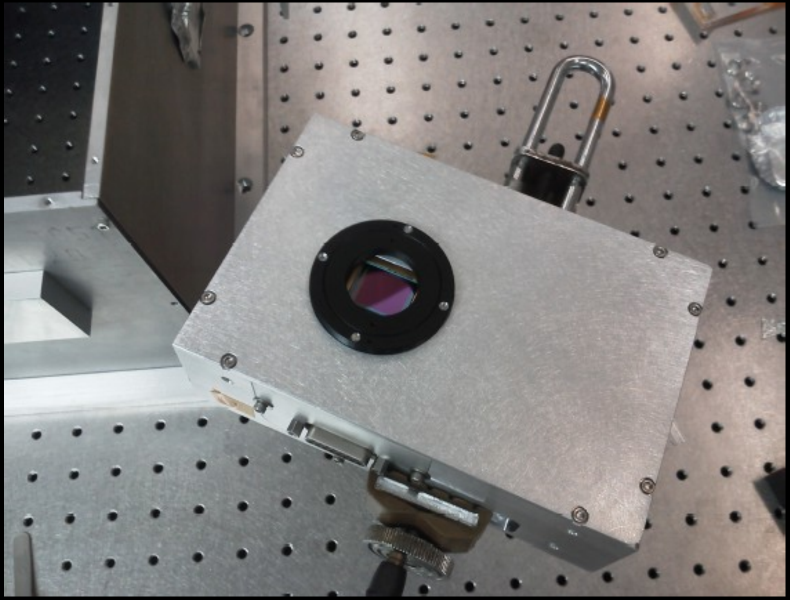


Left: 5% J-band Variability that evolves from Night-to-night of an L/T transition BD, and right: 1% constant variability in the Kepler-band of an L1 dwarf.

SUMMARY



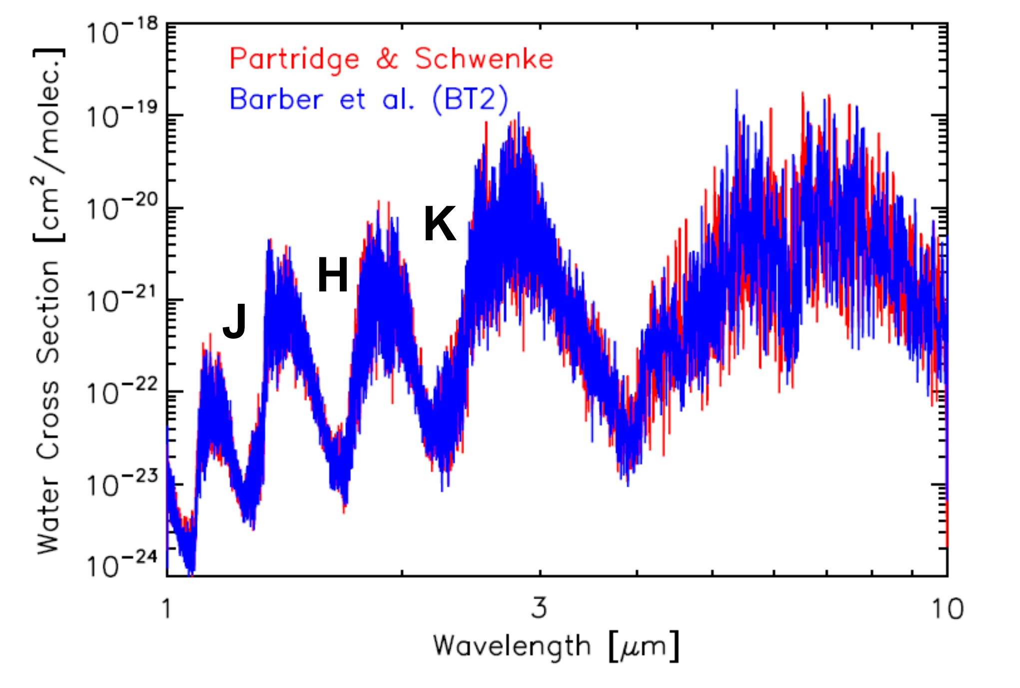
- Accurate ground-based near-infrared photometry.

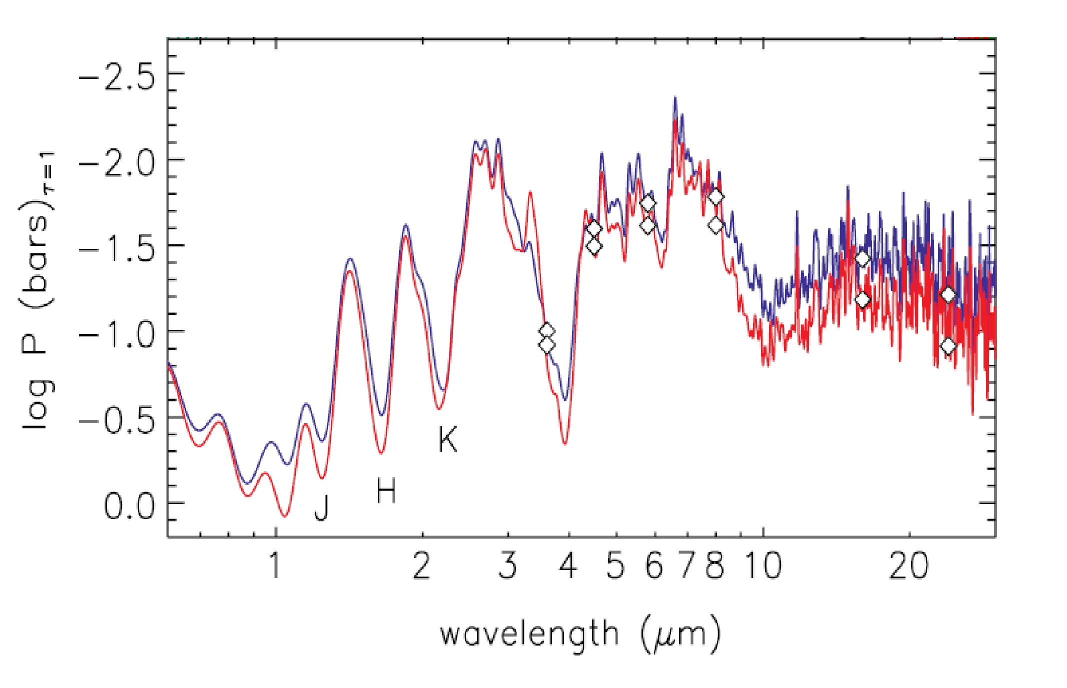


- Do what you want! For me this was some unique public outreach initiatives.
- Promising results from InGaAs cameras on small telescopes.

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.

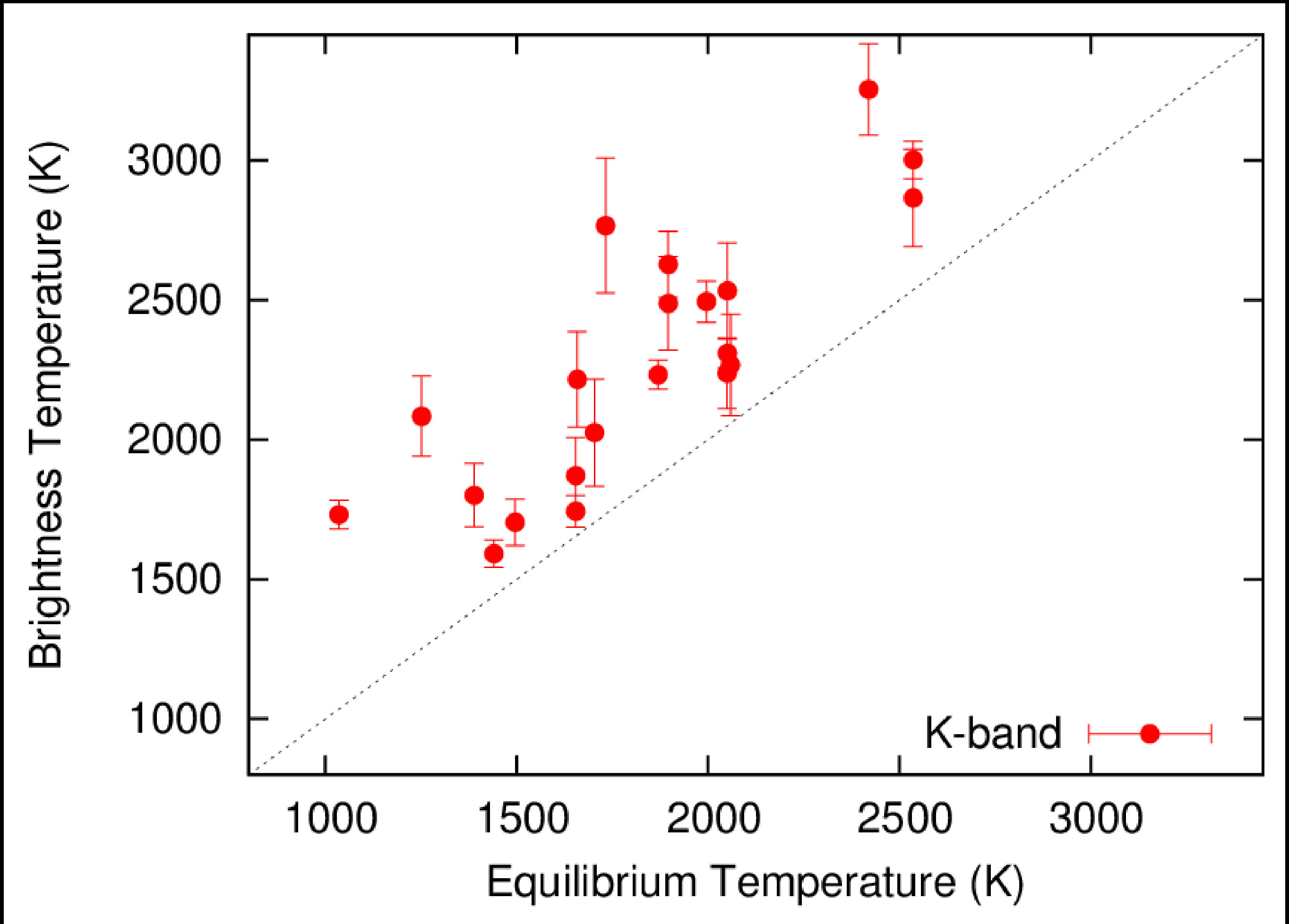




Left: The near-infrared J, H & Ks-bands are holes in the water opacity. Figure from Shabram et al. (2010).

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).

Overview of K-band Hot Jupiter Secondary Eclipse Detections

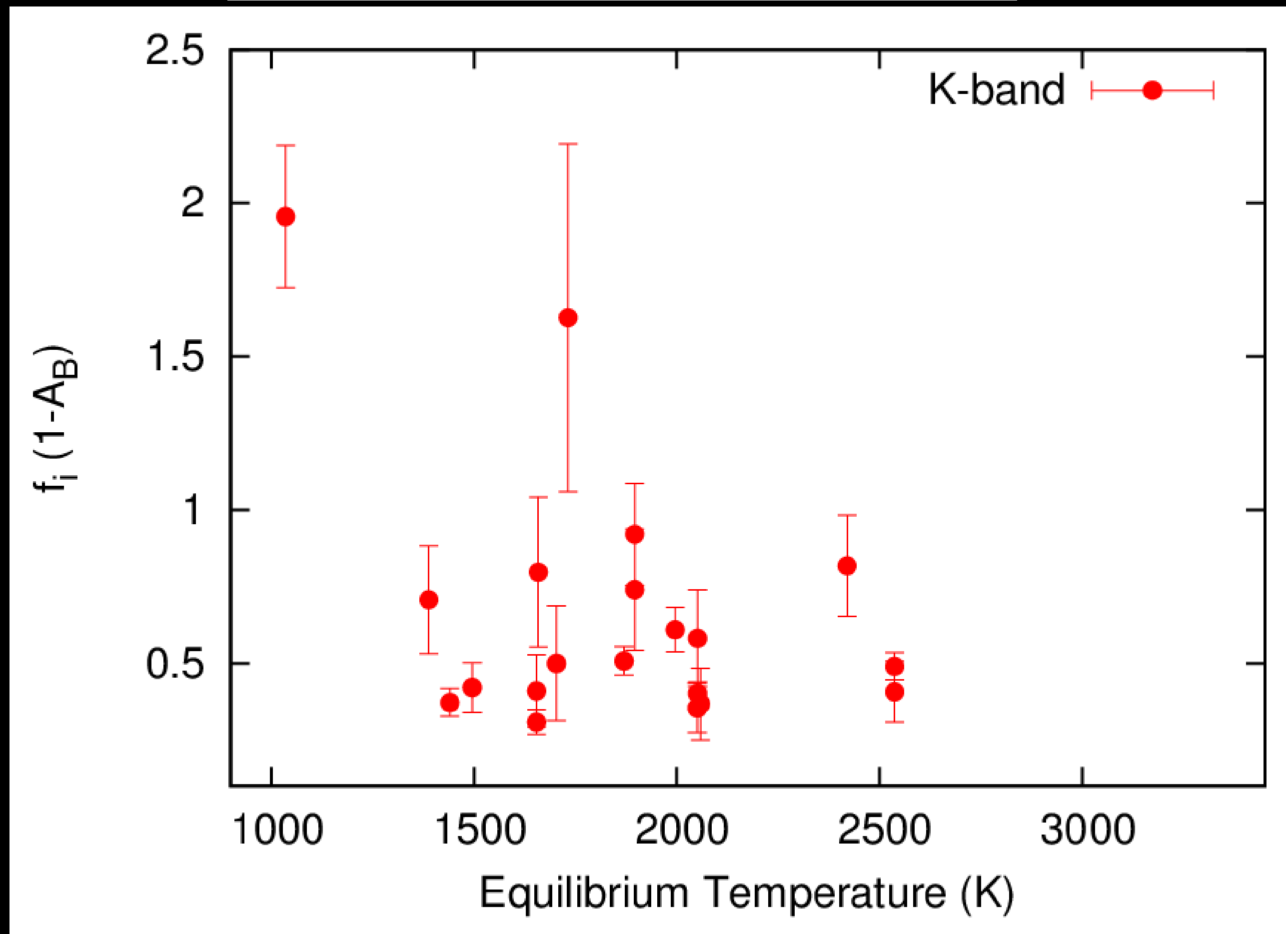


Brightness temperature of the thermal emission of hot Jupiters in the K band. Detections from: de Mooij & Snellen (2009), Rogers et al. (2009), Gillon et al. (2009), Anderson et al. (2010), Gibson et al. (2010), Croll et al. (2010a,b,2011, 2015), de Mooij et al. 2011, Caceres et al. 2011, Gillon et al. (2012), Zhao et al. (2012a,b,2014).

Overview of Near-IR (JHK) Detections

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

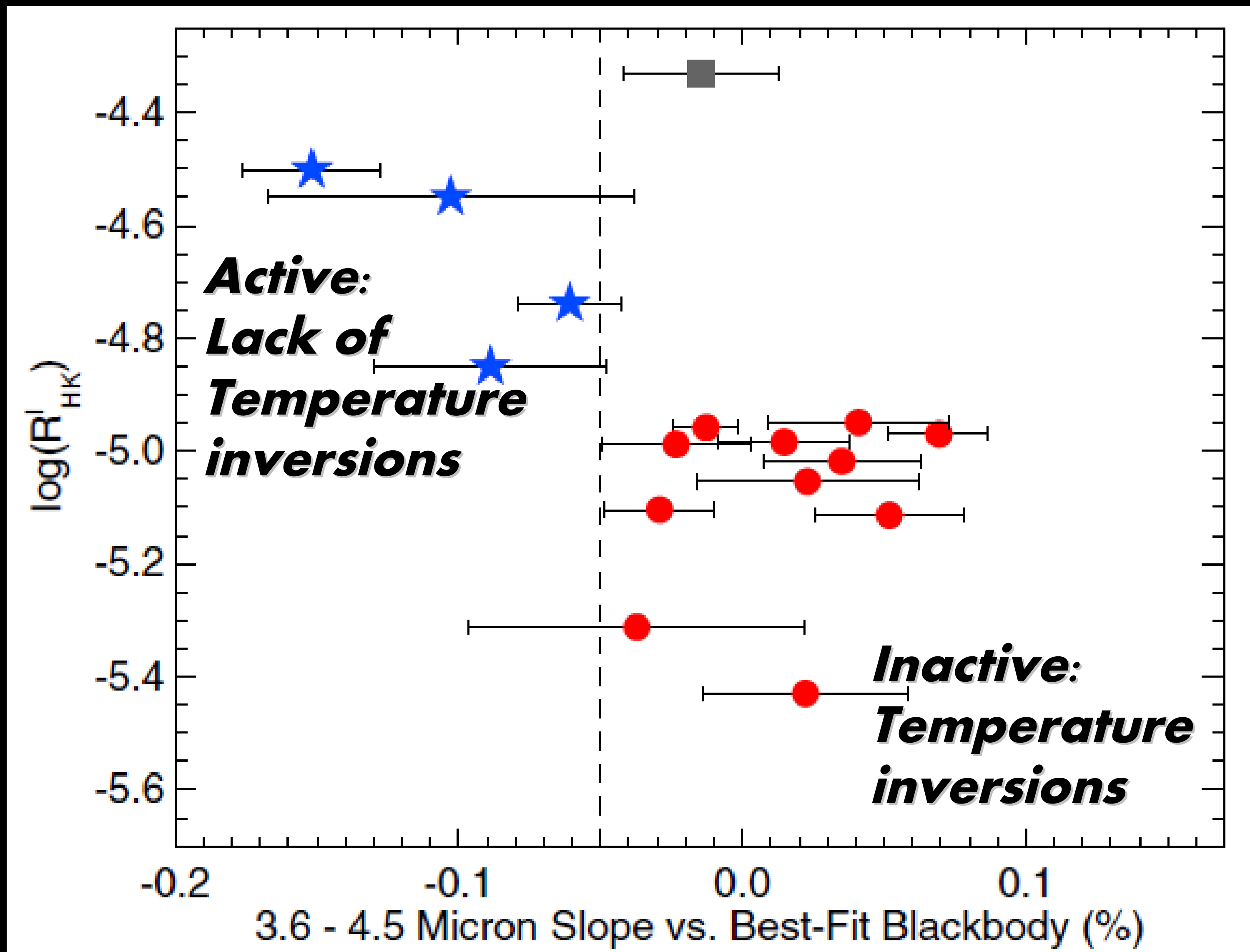
Higher Near-Infrared Brightness Temperatures



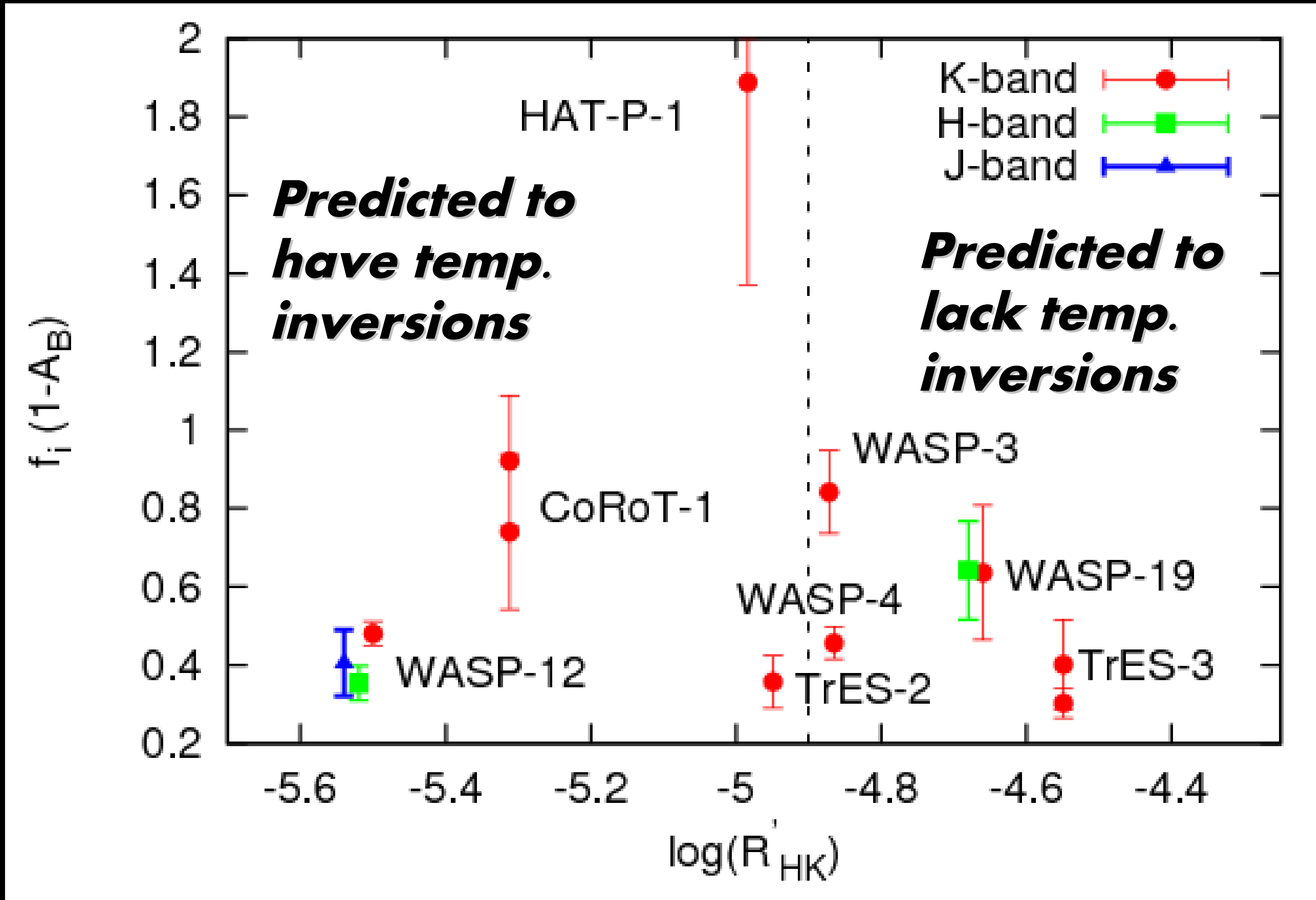
The reradiation factor (f) of the thermal emission of hot Jupiters in the JHK bands. Broadband Detections from: de Mooij & Snellen (2009), Rogers et al. (2009), Gillon et al. (2009), Anderson et al. (2010), Gibson et al. (2010), Croll et al. (2010a,b,2011, in prep.), de Mooij et al. 2011, Caceres et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

Correlation of Temperature Inversions with Activity

Knutson et al. (2010)



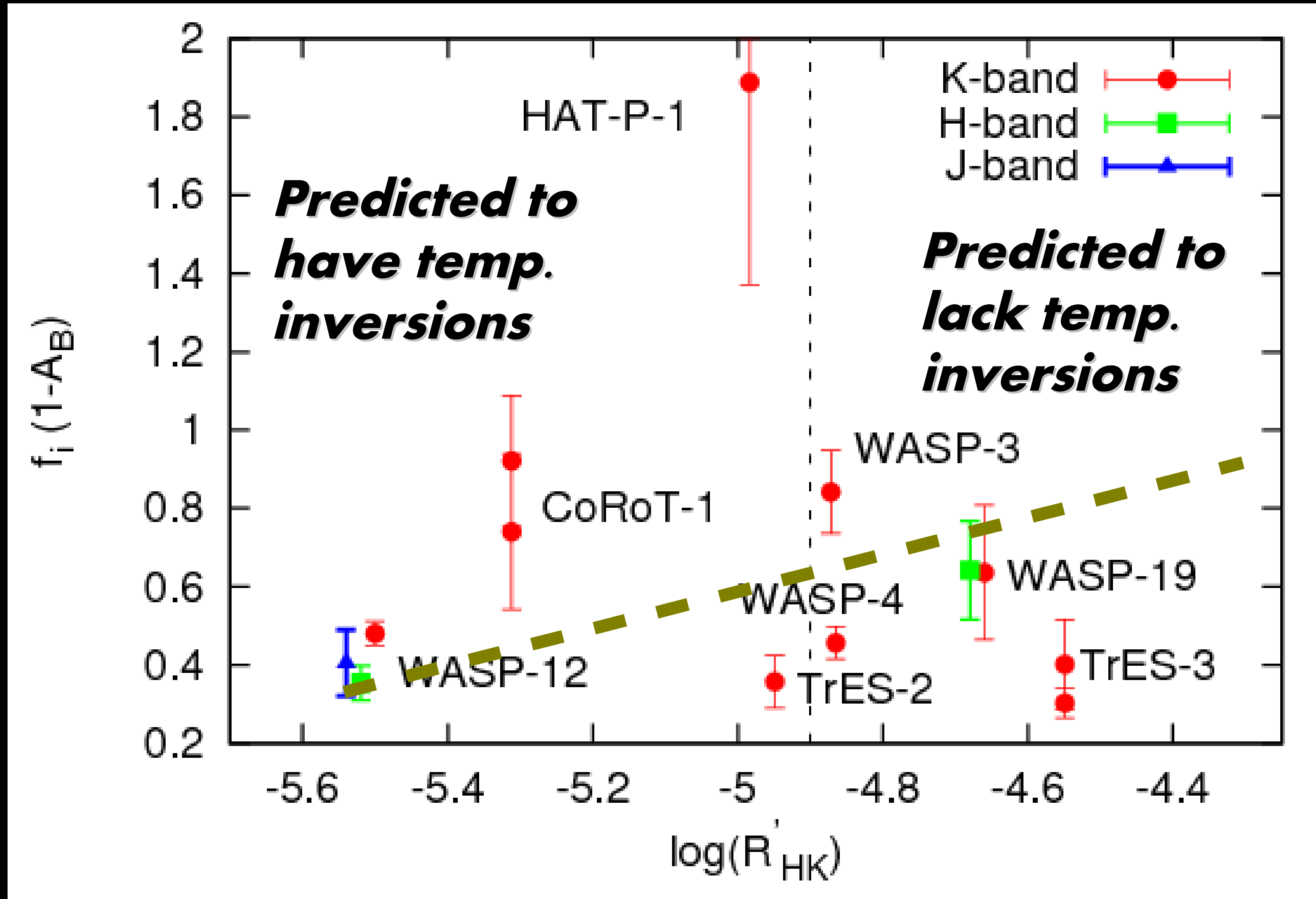
Overview of Near-IR (JHK) Detections



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.

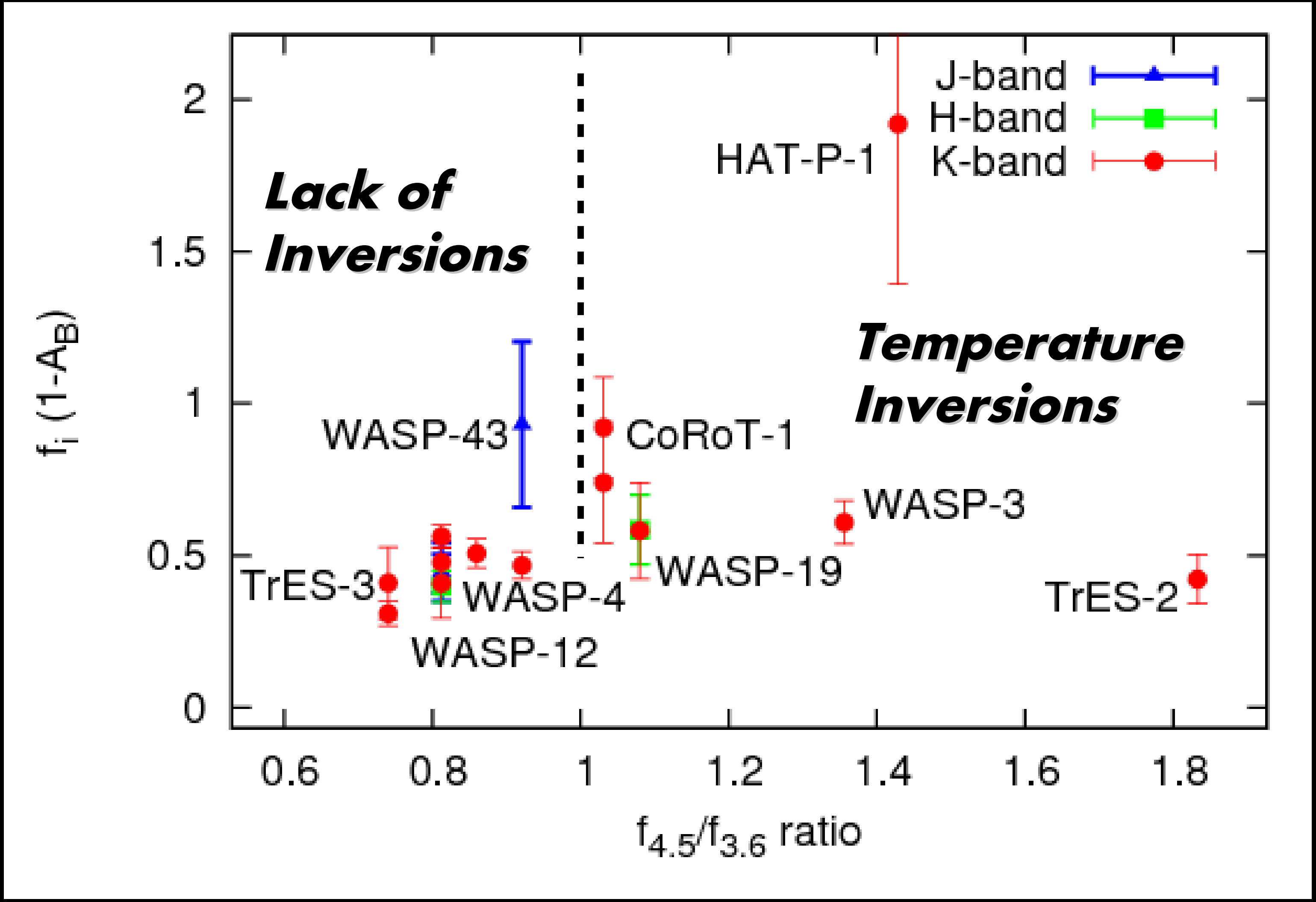
OVERVIEW OF NEAR-IR (JHK) DETECTIONS

HIGHER BRIGHTNESS TEMPERATURES



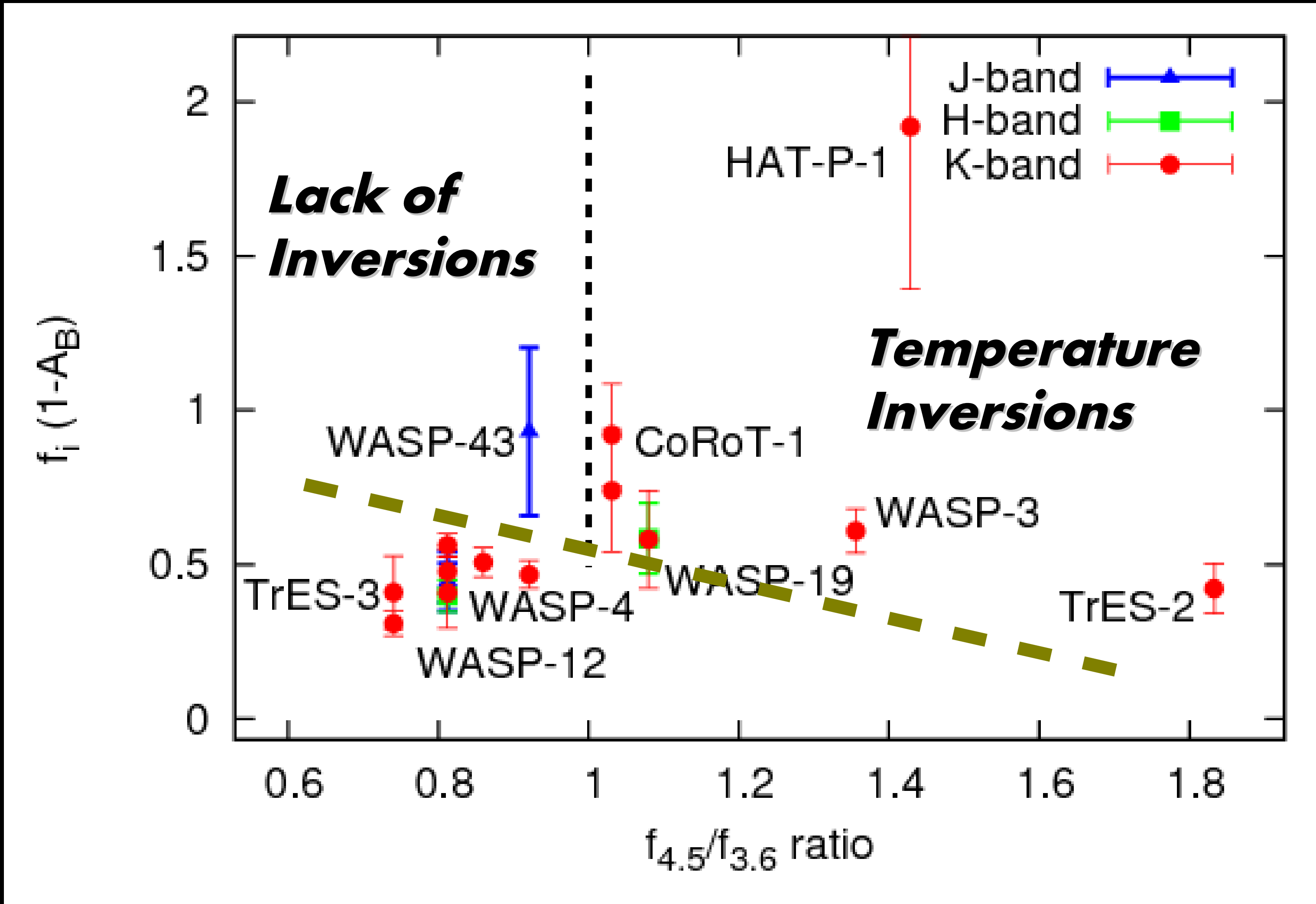
THE RERADIATION FACTOR (f) VERSUS THE CA II H & K ACTIVITY INDEX: DE MOOIJ & SNELLEN (2009), ROGERS ET AL. (2009), GILLON ET AL. (2009), ANDERSON ET AL. (2010), GIBSON ET AL. (2010), , CROLL ET AL. (2010A,B,2011, IN PREP.), DE MOOIJ ET AL. 2011, CACERES ET AL. 2011.

Overview of Near-IR (JHK) Detections

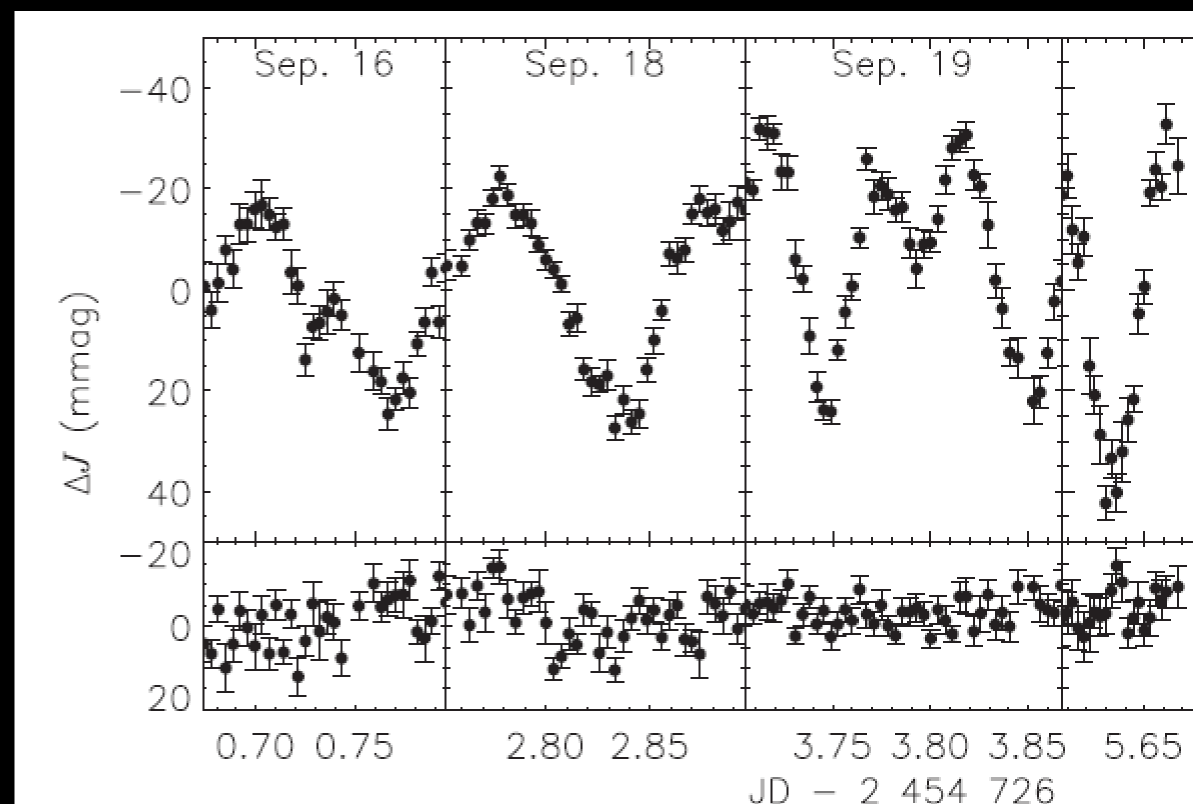


Near-infrared reradiation factor (f) versus the ratio of the 4.5 to 3.6 micron reradiation factors (a proxy for temperature inversions). Spitzer Results from: Fressin et al. (2010), O'Donovan et al. (2010), Todorov et al. (2010), Campo et al. (2011), Beerer et al. (2011), Cowan et al. (2012), Blecic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

Overview of Near-IR (JHK) Detections

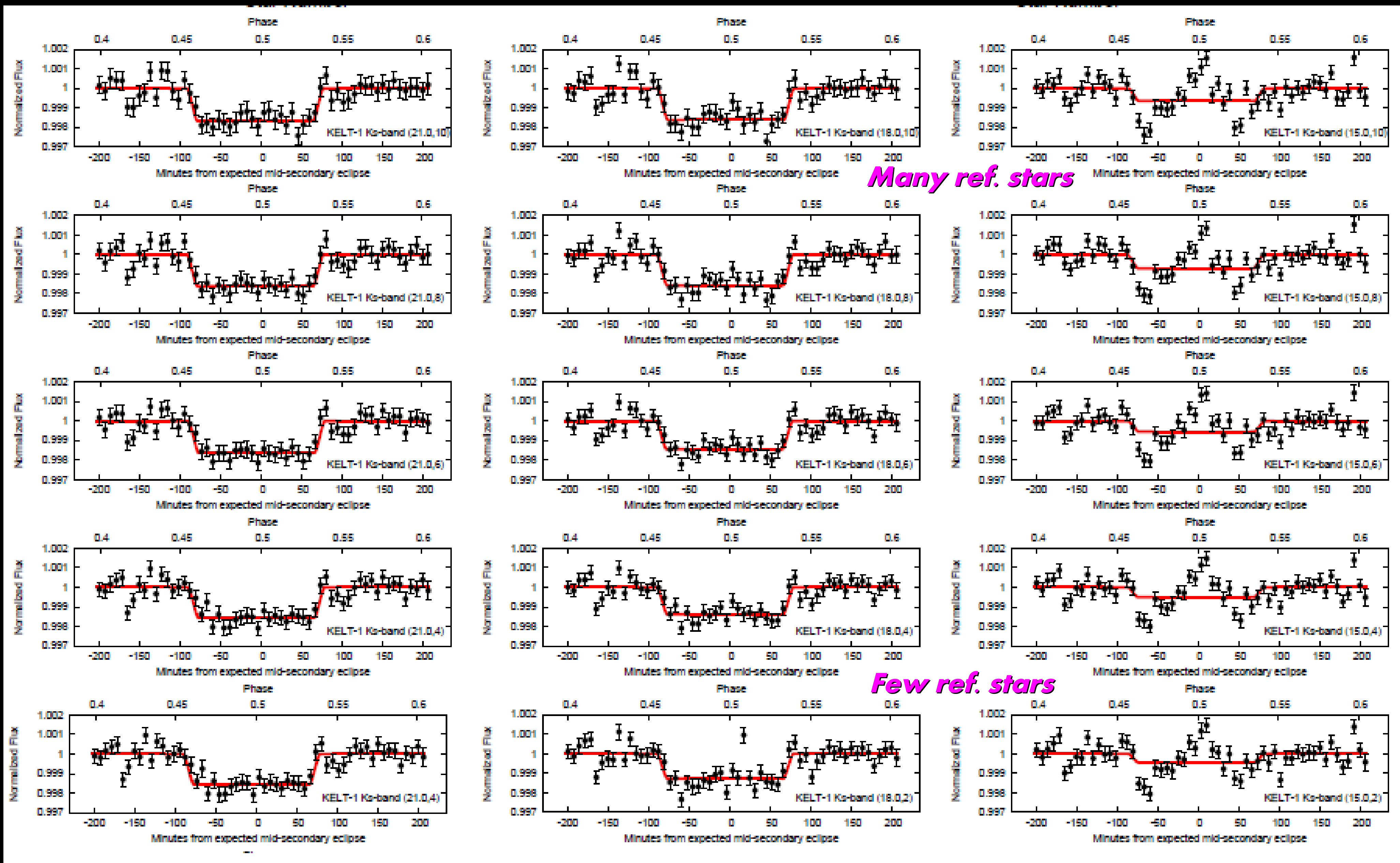


Near-infrared reradiation factor (f) versus the ratio of the 4.5 to 3.6 micron reradiation factors (a proxy for temperature inversions). Spitzer Results from: Fressin et al. (2010), O'Donovan et al. (2010), Todorov et al. (2010), Campo et al. (2011), Beerer et al. (2011), Cowan et al. (2012), Blecic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



Sep. 16
Sep. 18
Sep. 19
−40
−20
0
20
40
ΔJ (mmag)
−20
0
20
0.70
0.75
2.80
2.85
3.75
3.80
3.85
5.65
JD − 2 454 726

FIDELITY OF NEAR-INFRARED ECLIPSE DEPTHS
KELT-1 KS-BAND (CROLL ET AL. 2015)



Large Aperture

Small Aperture

Preparing for the Future of Ground-based, Near-infrared Observations

- The techniques discussed here are laying the ground-work for current & future instruments/telescopes.