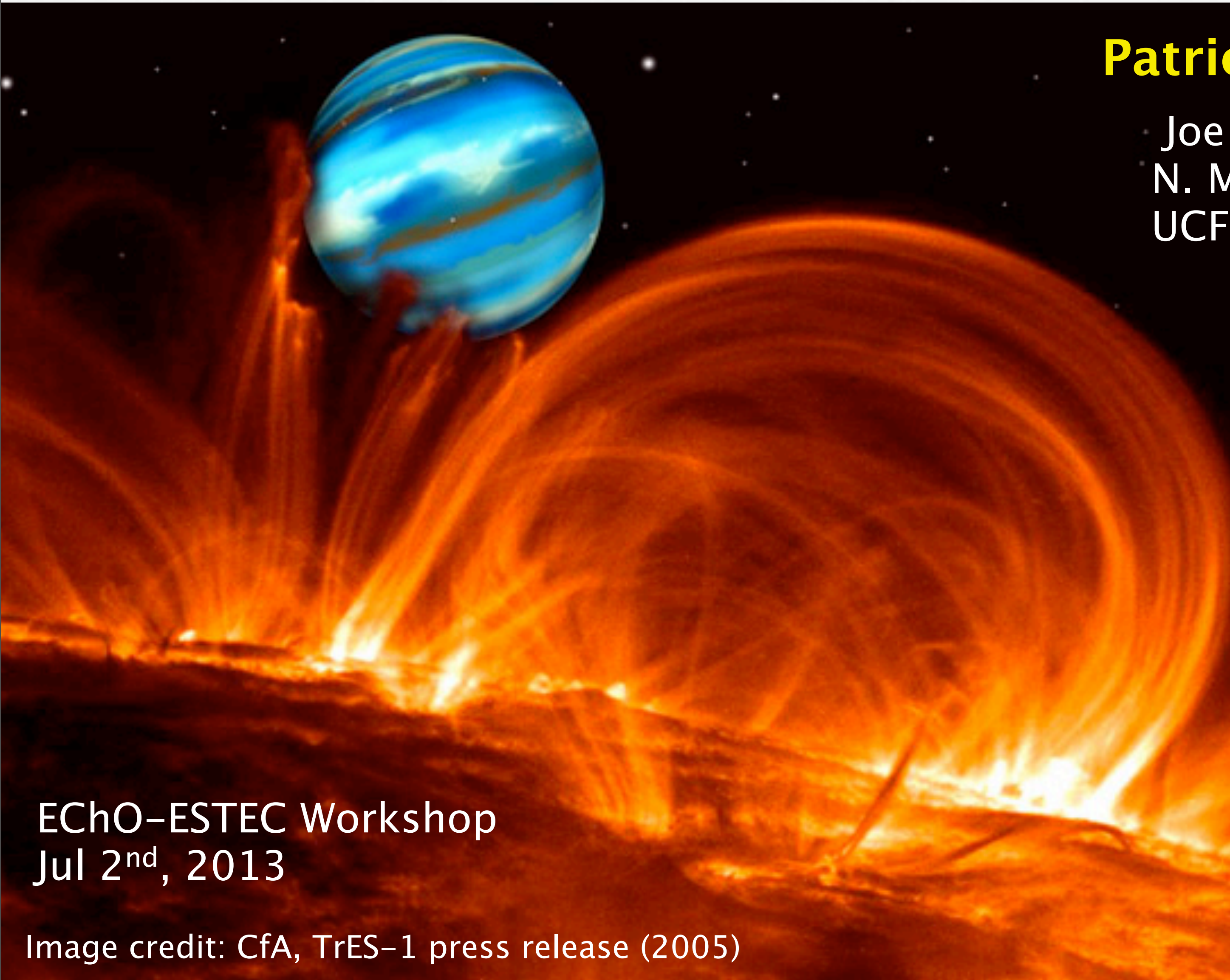
Extracting Faint Eclipse Signals: Spitzer Observations of TrES-1

Patricio E. Cubillos

Joe Harrington

N. Madhusudhan (Yale)

UCF exoplanet group



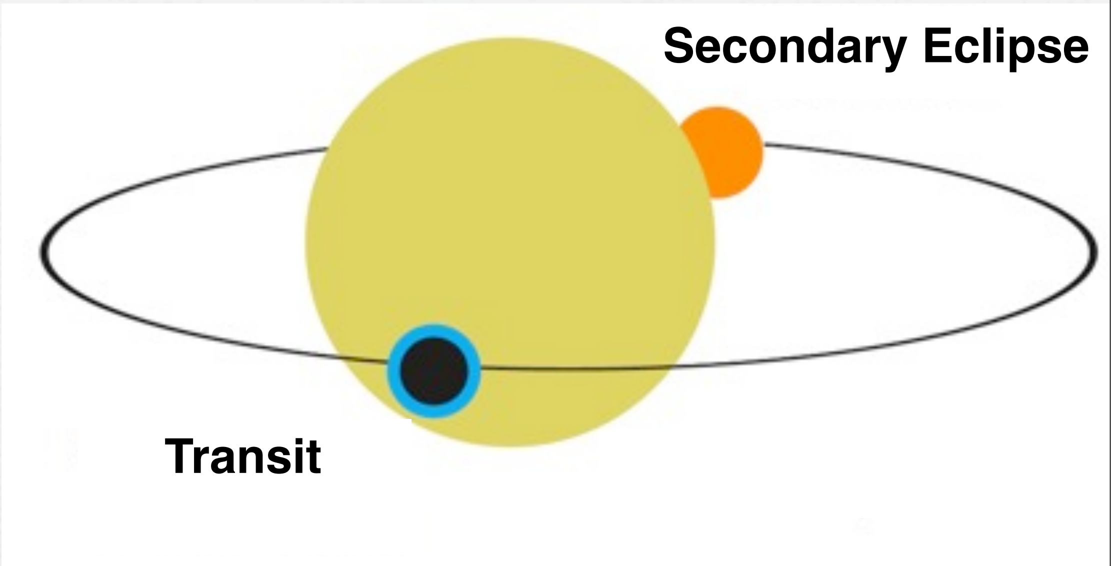
ECHO-ESTEC Workshop

Jul 2nd, 2013

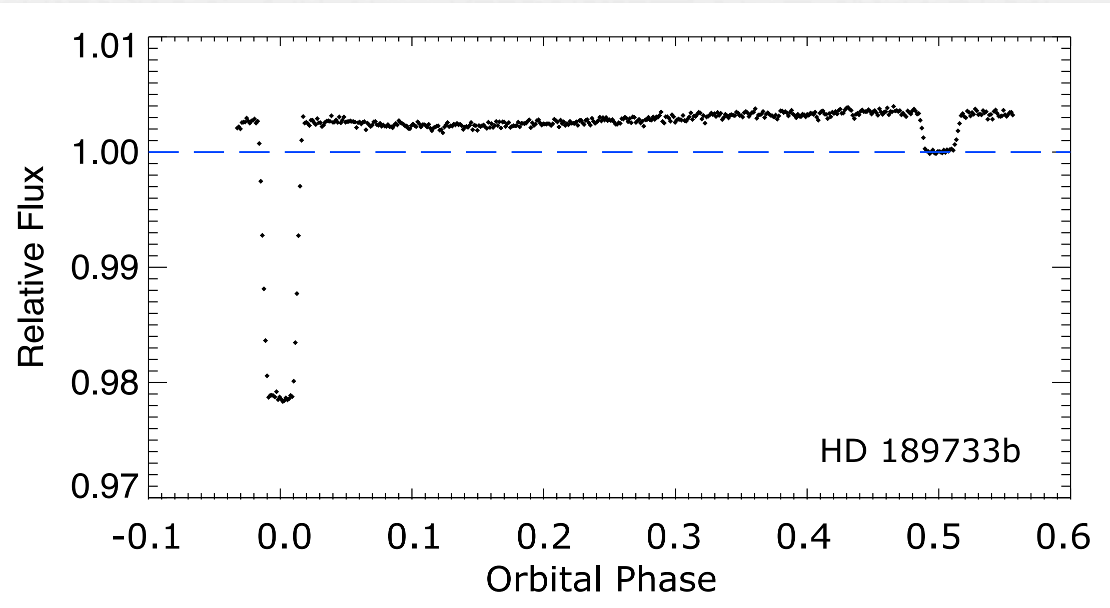
Image credit: CfA, TrES-1 press release (2005)

Transiting Exoplanets Observations:

– IR observations measure the planet's thermal emission.



Seager & Deming (2010)



Knutson et al. (2009)

$$\text{Eclipse depth} = \frac{\Delta F}{F} \approx \frac{F_p}{F_s}$$

The TrES-1 System:

- First transit-discovered exoplanet

Alonso et al. (2004)

- First occultation detection

Charbonneau et al. (2005)

- 3 day, circular orbit, T_{eq} ~1150 K

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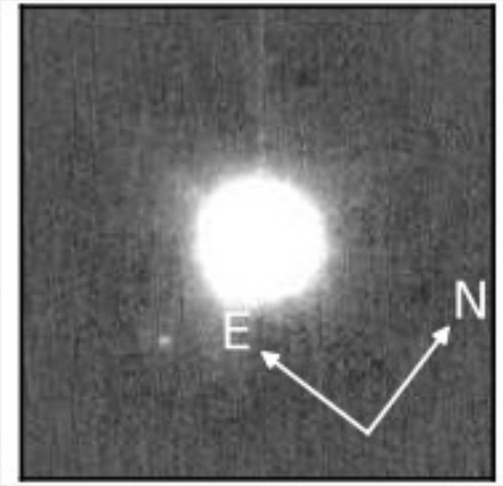

Adams et al. (2013)

Δmag = 7.7 (2 μm)

Separation = 2.3”

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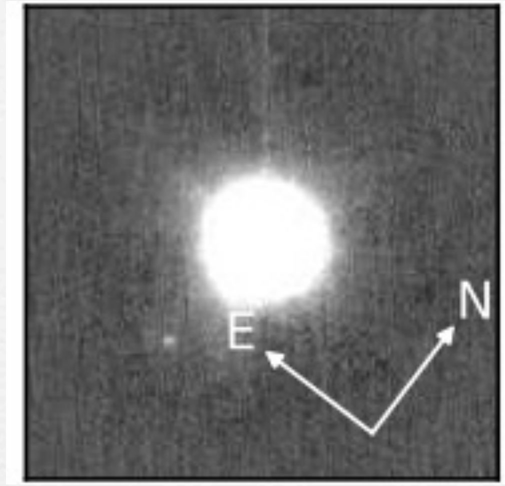

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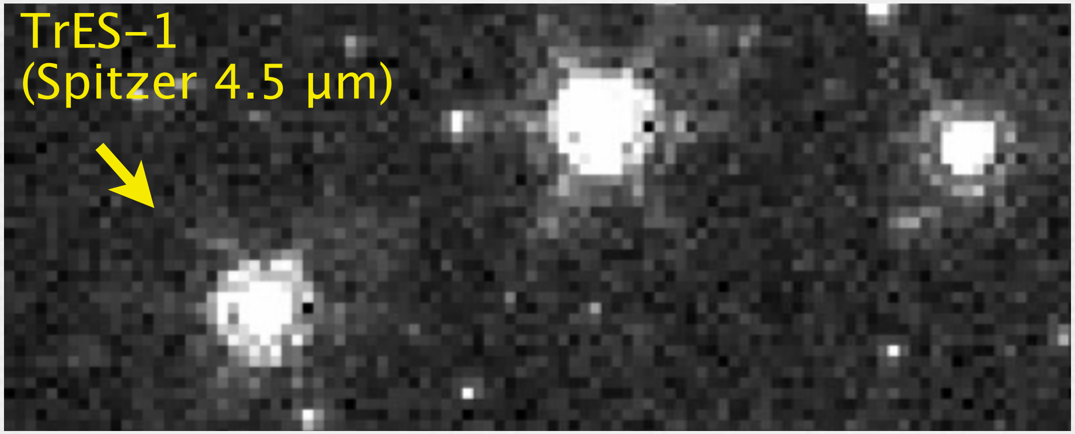

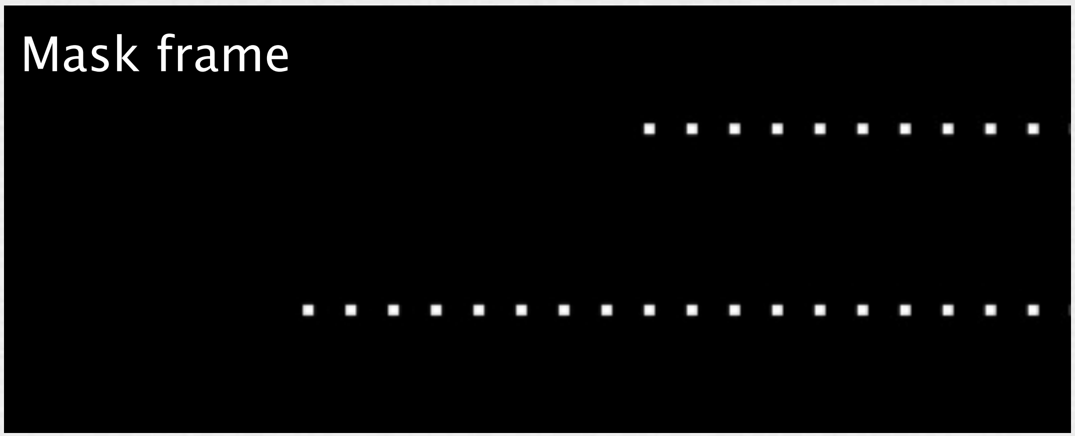

Spitzer occultations at:

- 3.6, 4.5, 5.8, 8.0, and 16 μm.

POET: Photometry for Orbits, Eclipses, and Transits

Cubillos et al. (2013a), Stevenson et al. (2012), Blecic et al. (2013), Nymeyer et al. (2011), Campo et al. (2011)

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- Centering (position determination):
  - Gaussian fitting
  - PSF fitting
  - Least asymmetry
  - Center of light
- Aperture or optimal photometry.

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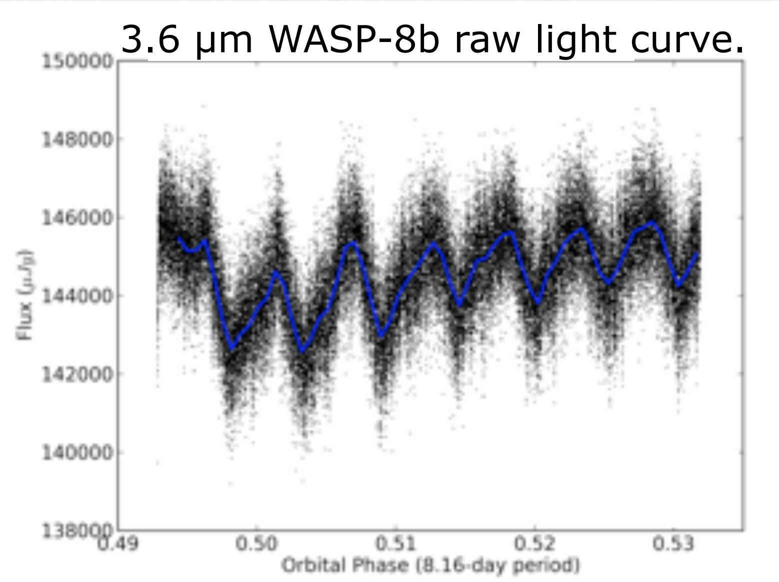
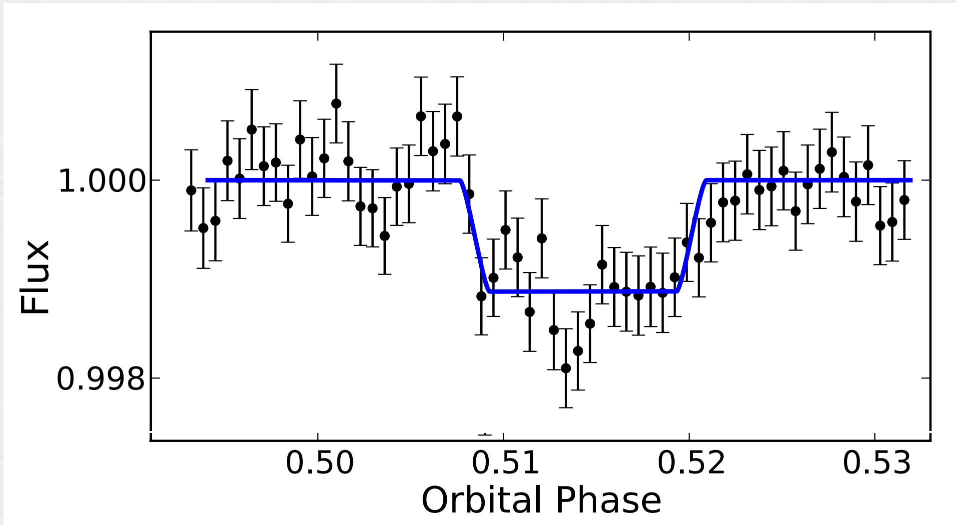
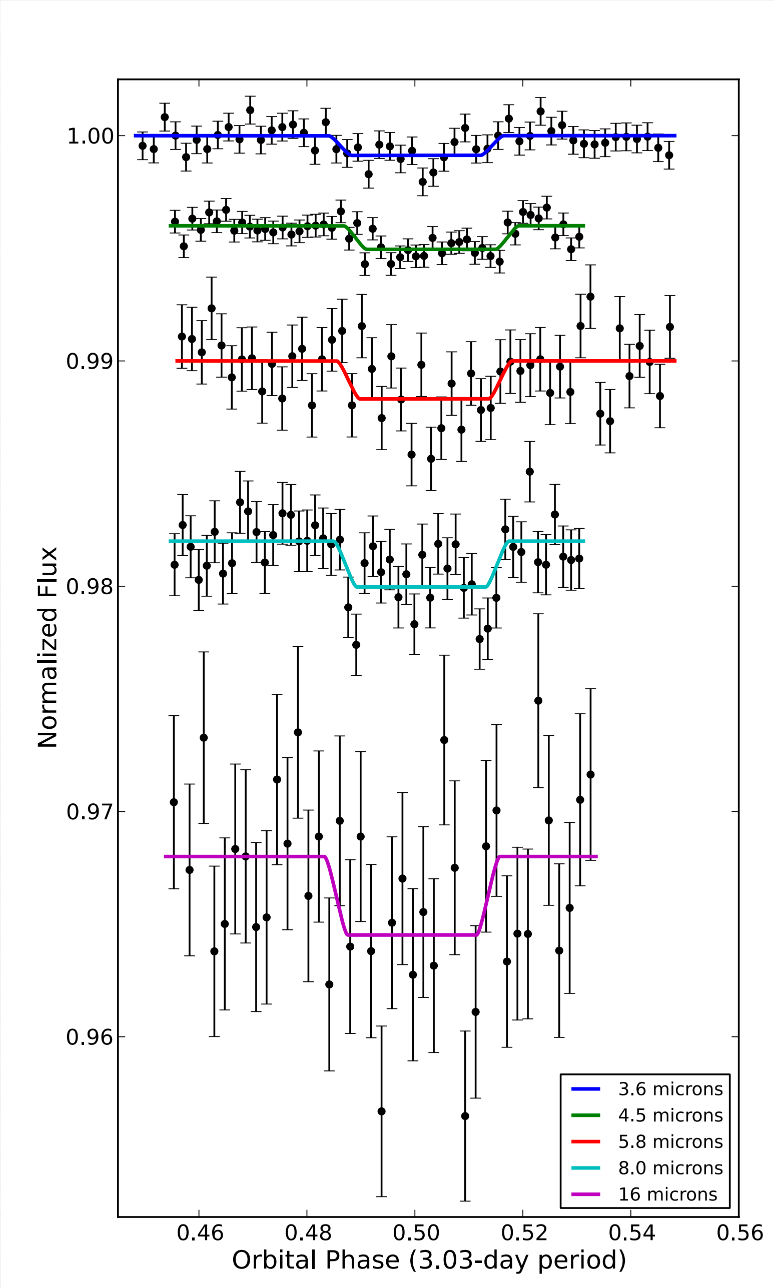
- Centering (position determination):
  - Gaussian fitting
  - PSF fitting
  - Least asymmetry
  - Center of light
- Aperture or optimal photometry.
- Light-curve modeling.
- MCMC, now with Differential Evolution

Braak (2006), Cubillos et al. (2013b, in prep)





Light Curve Results



Waveband (μm)	Depth (%)	Brightness temp. (K)
3.6	0.088 ± 0.023	1253
4.5	0.105 ± 0.024	1142
5.8	0.169 ± 0.043	1250
8.0	0.204 ± 0.043	1128
16	0.35 ± 0.12	1423

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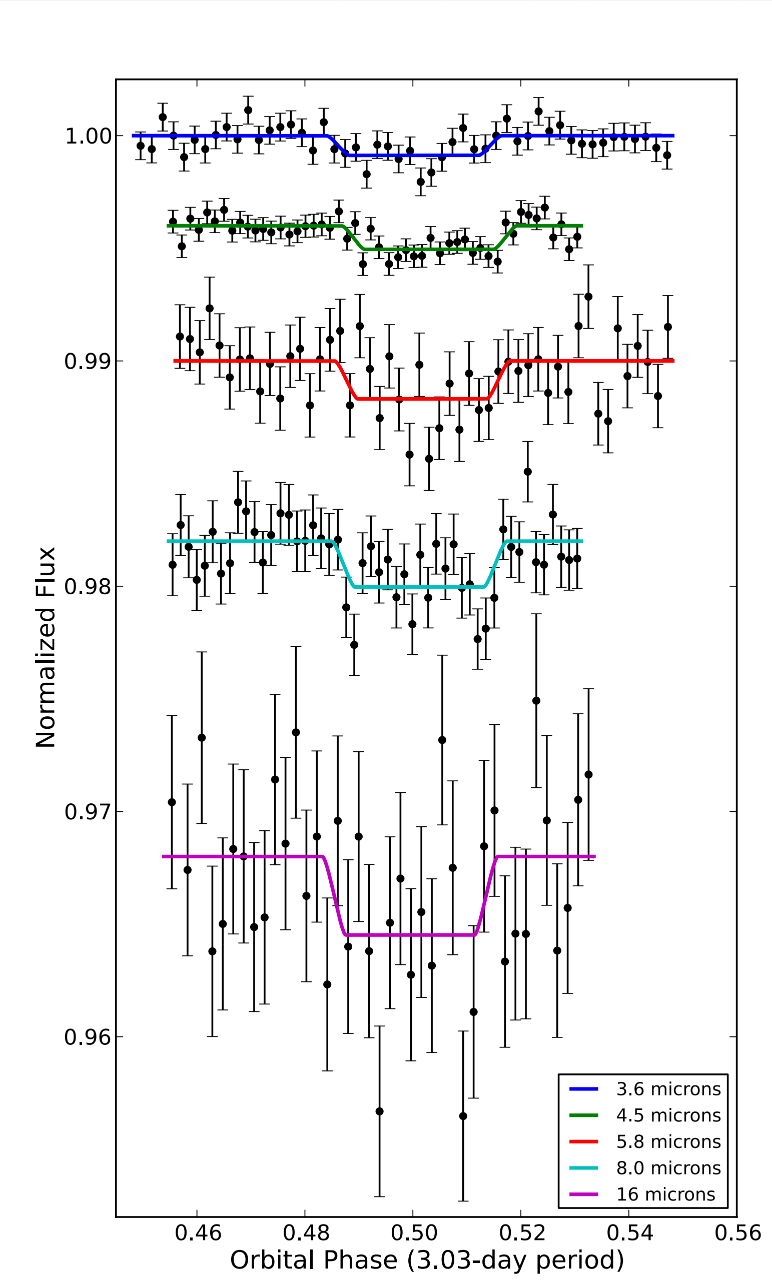

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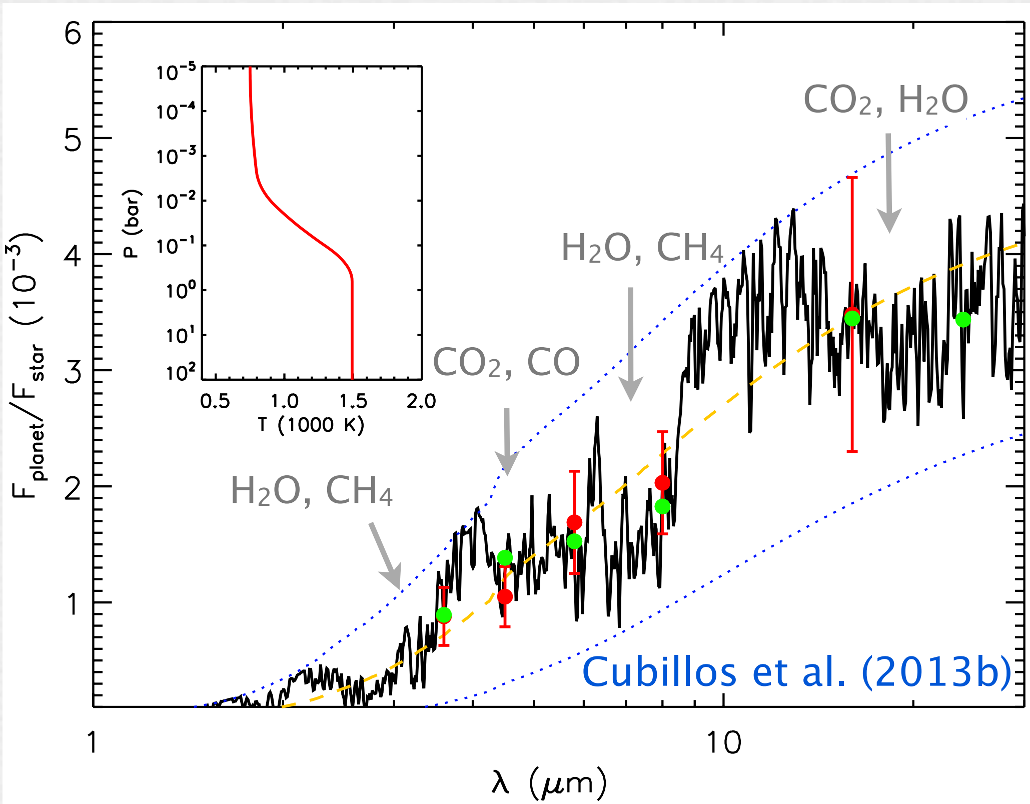
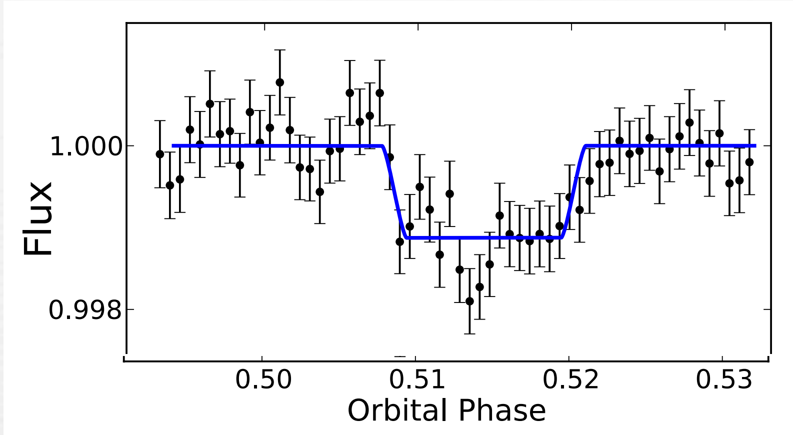
(Madhusudhan & Seager 2009, 2010)



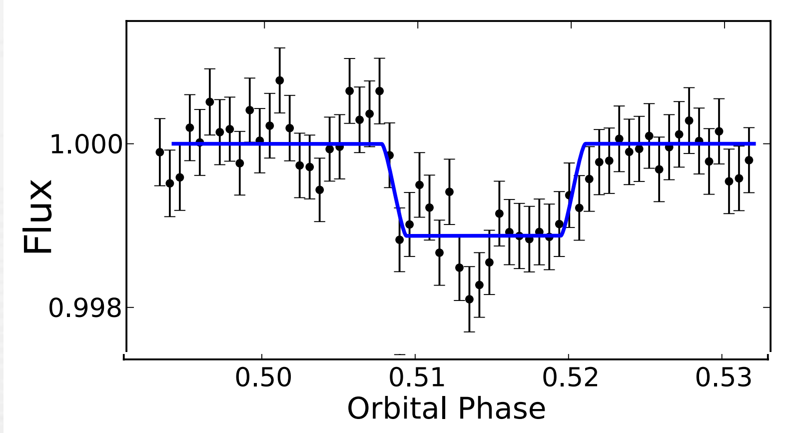
Correlated noise estimators:

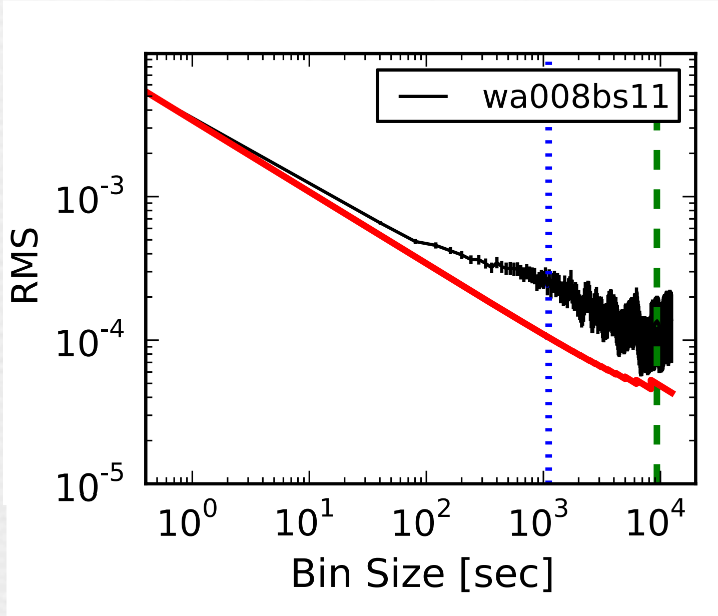


Correlated noise estimators:

– RMS vs Bin size plot: Winn et al. (2008)

$$\sigma_N = \frac{\sigma_1}{\sqrt{N}}\sqrt{\frac{M}{M-1}}$$





Correlated noise estimators:

- RMS vs Bin size plot: Winn et al. (2008)

$$\sigma_N = \frac{\sigma_1}{\sqrt{N}}\sqrt{\frac{M}{M-1}}$$

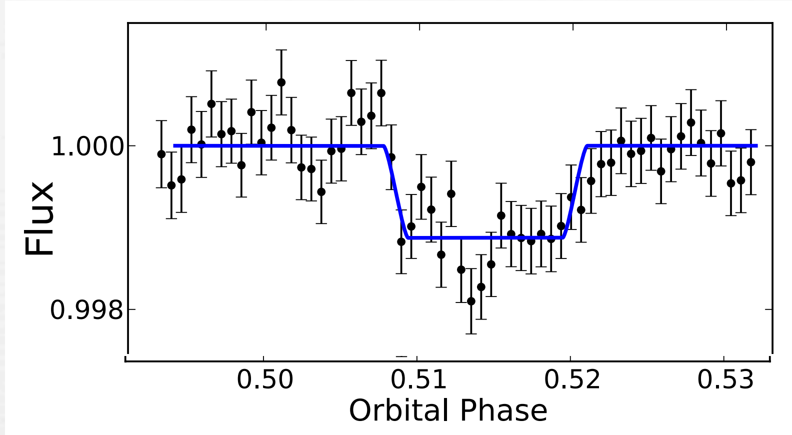
- Prayer beads: Bouchy et al. (2005)

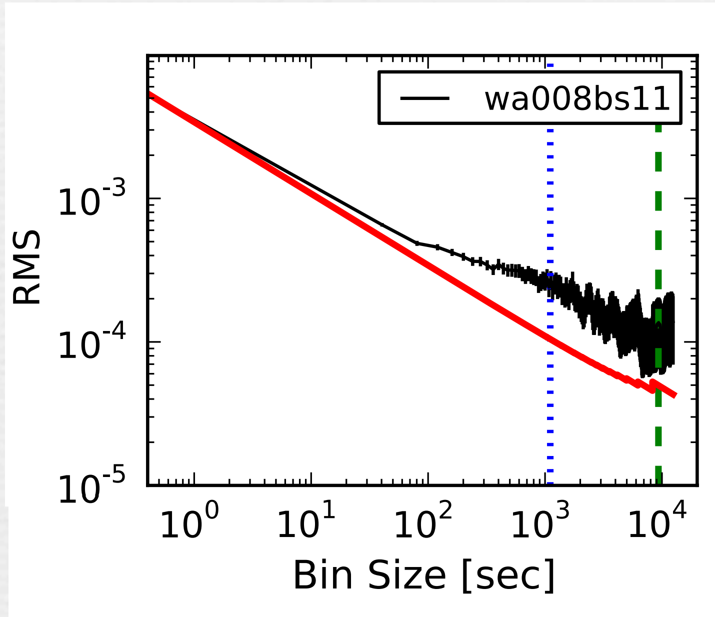
  Fit-residuals are sequentially shifted

  Calculate new best fit: p_i

  Shift again and refit

  parameter uncertainty = $\mathrm{std}(\{p_\mathrm{i}\})$





RMS vs bin size:

The simplest test:

- Create random normal-distributions
- Plot RMS vs bin size

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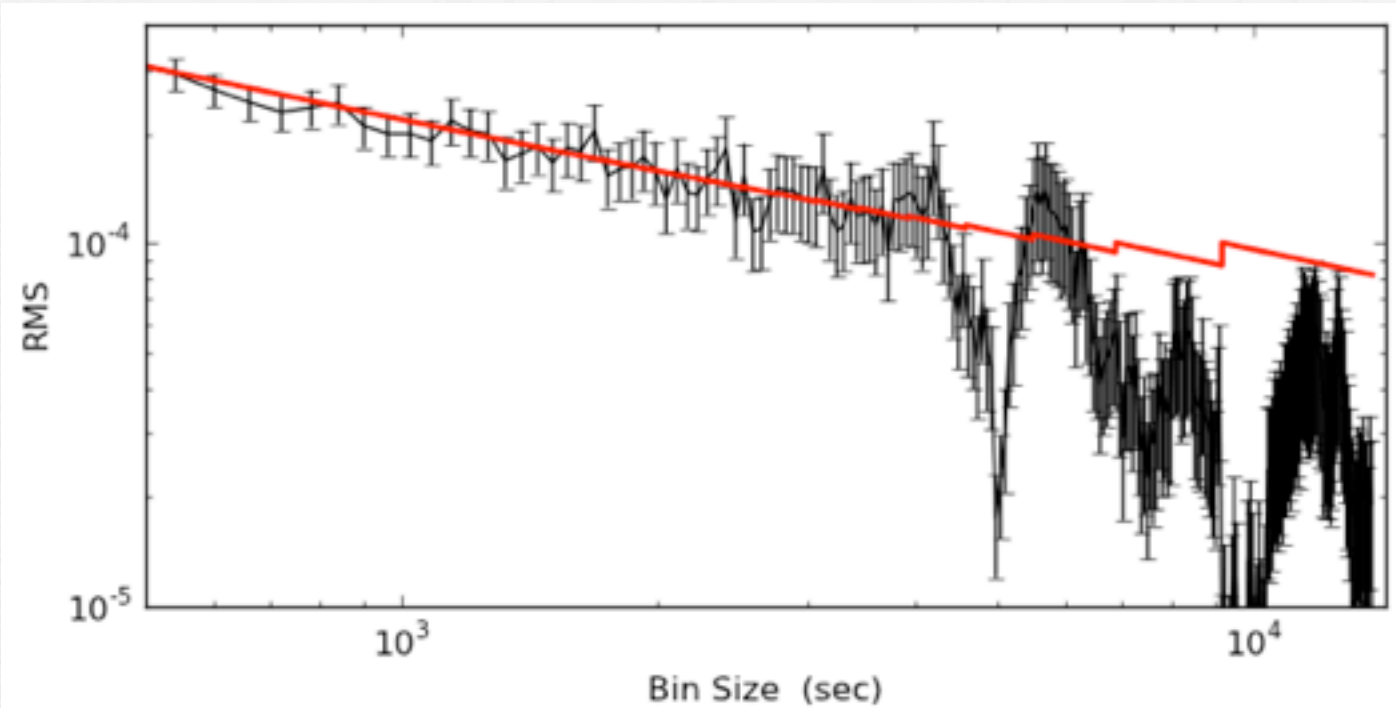

- Often (~35%) the curves show large deviations

Prayer beads:

- Literature search:
  - No fully statistical description.
  - Some citations: Knutson et al. (2009), Bean et al. (2008), Gillon et al. (2007), Desert et al. (2011), ... --> Moutou et al. (2004)

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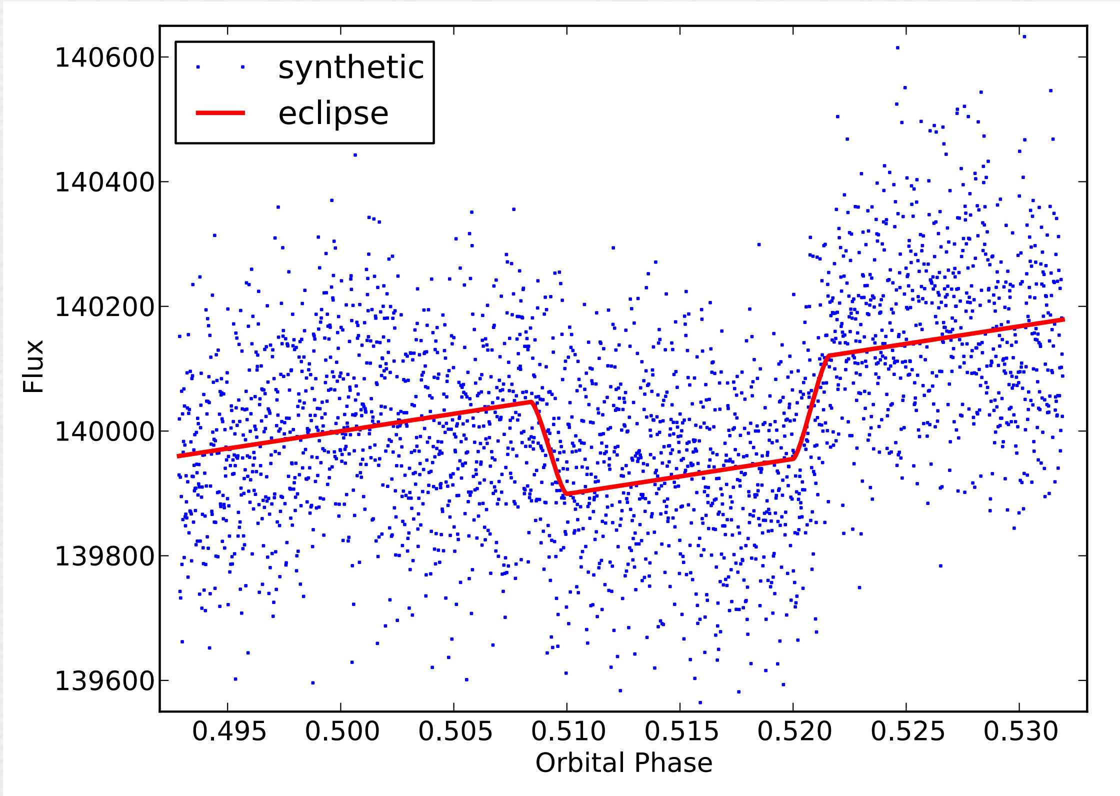
Test:

- Create synthetic light curve:

  eclipse + white noise



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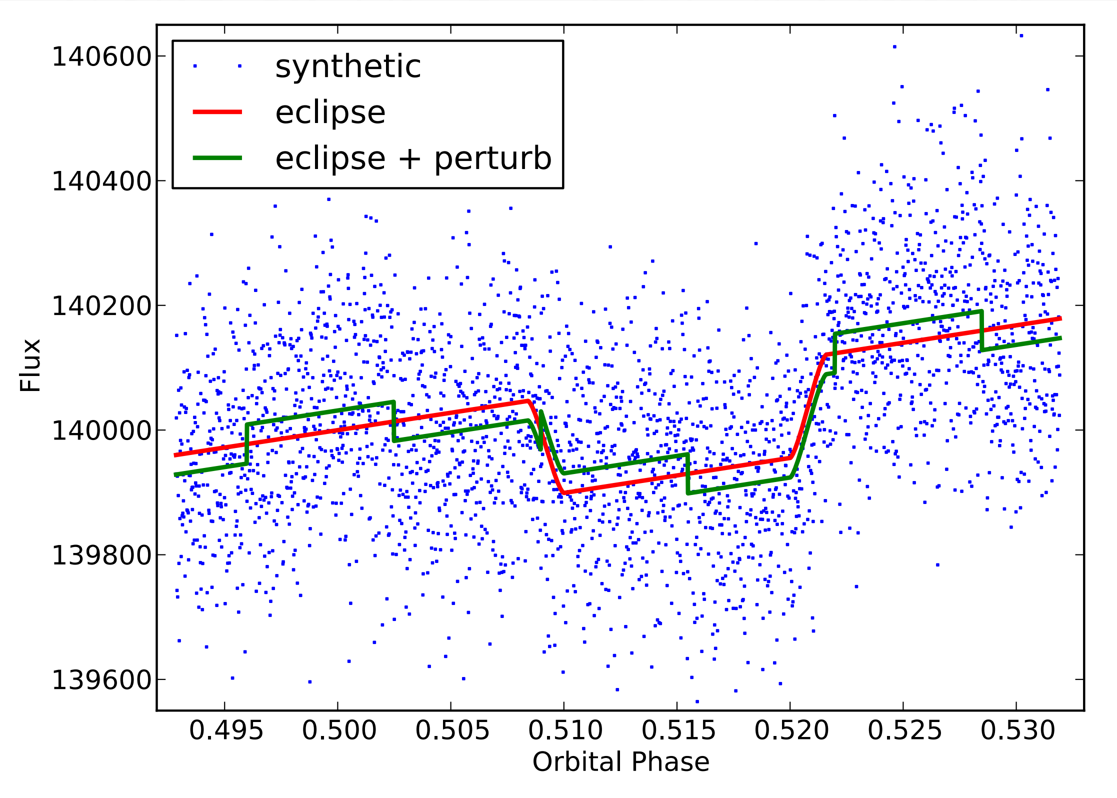
Test:

- Create synthetic light curve:

  eclipse + white noise

  + correlated noise



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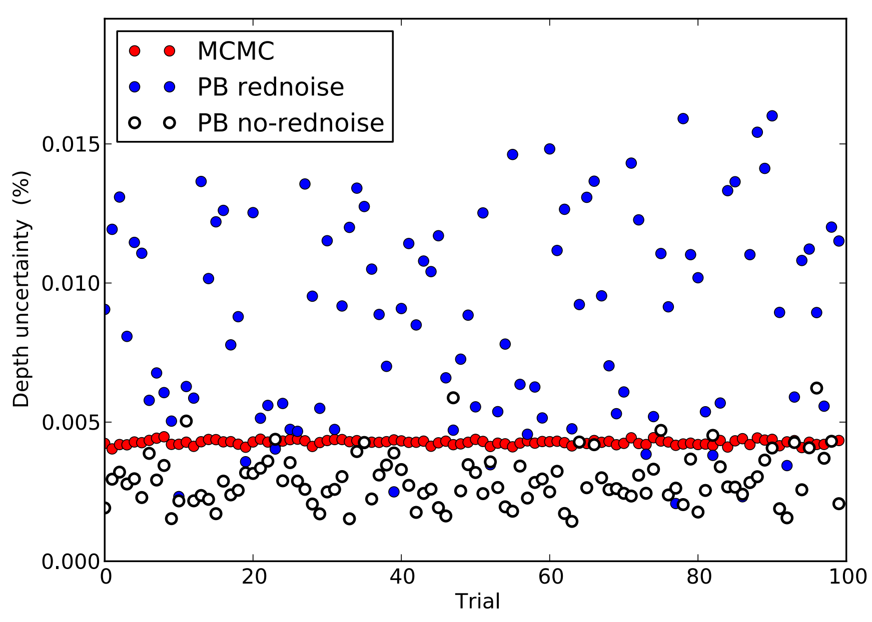
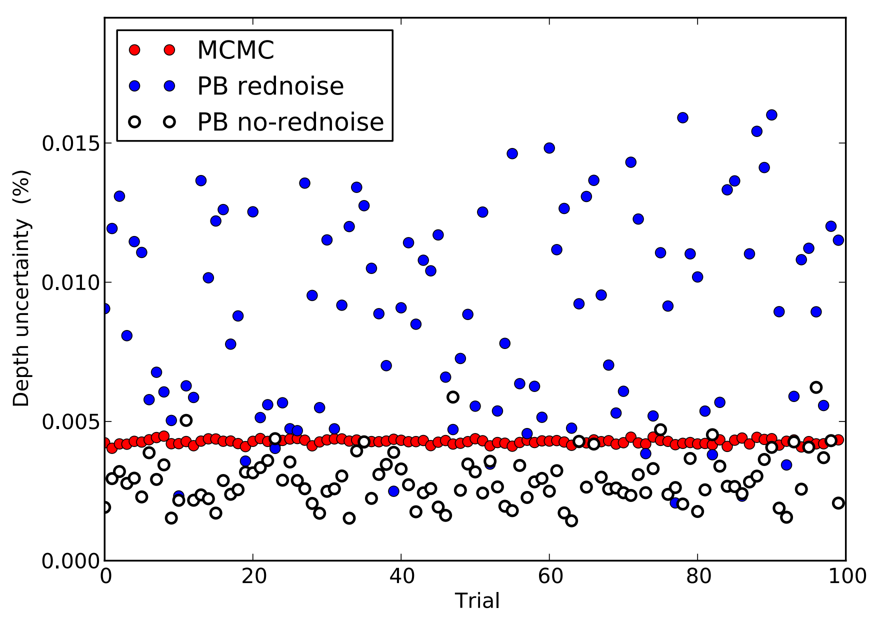


- PB underestimates errors if no correlated noise

Prayer beads:



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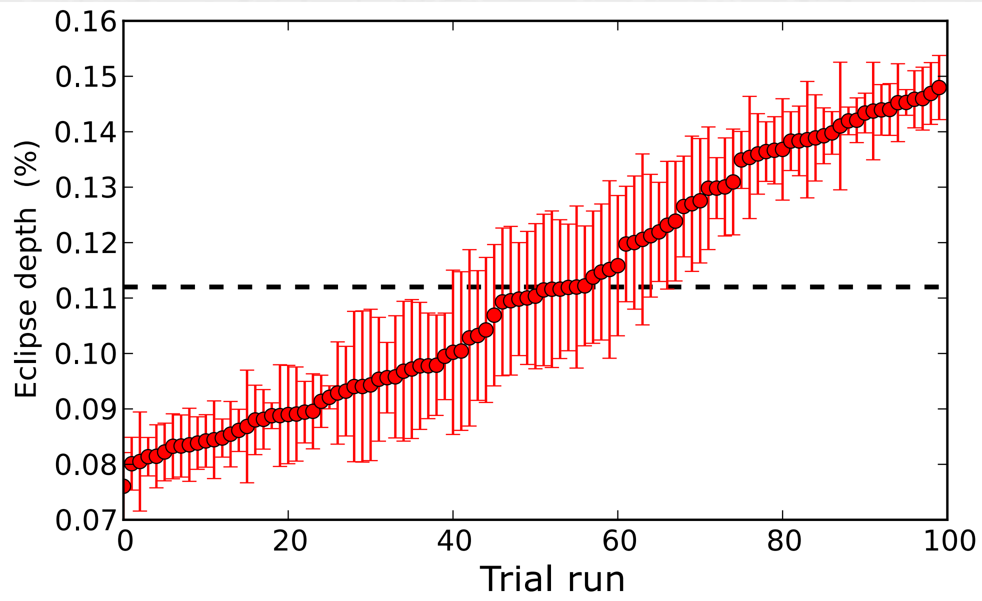
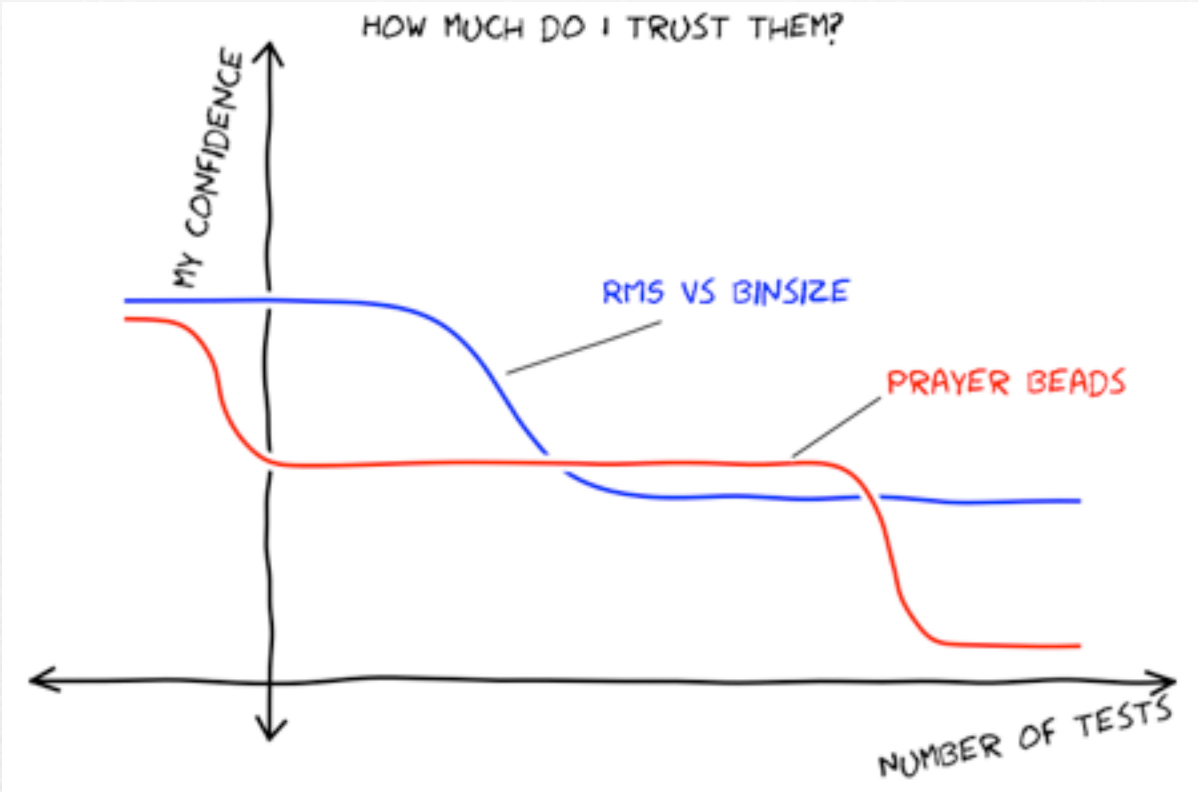


- Doesn’t correctly account for the lack of accuracy

Take-home message:

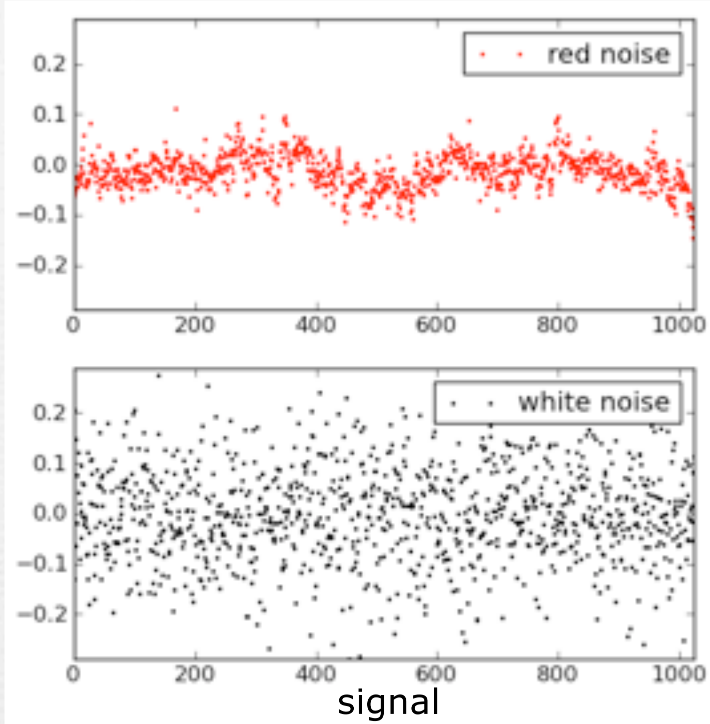


- Assessing correlated noise is important to get appropriate S/N
- Be careful before when using these statistical estimators
- Get to know their limitations

Wavelet-based modeling: Carter & Winn (2009)

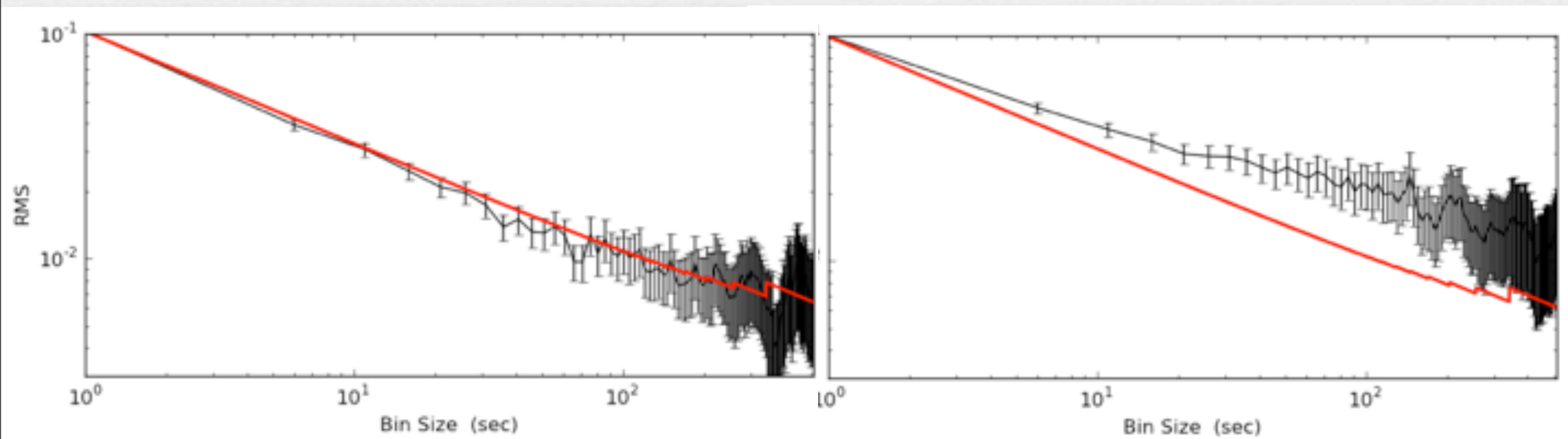
(Work in progress!)

- Using DWT one can create a noise signal with spectral power $\sim 1/f$



- Wavelet-based likelihood:

$$\mathcal{L}=\left\{\prod_{m=2}^{M}\prod_{n=1}^{n_0 2^{m-1}}\frac{1}{\sqrt{2\pi\sigma_W^2}}\exp\left[-\frac{(r_n^m)^2}{2\sigma_W^2}\right]\right\}\left\{\prod_{n=1}^{2n_0}\frac{1}{\sqrt{2\pi\sigma_S^2}}\exp\left[-\frac{(\bar{r}_n^1)^2}{2\sigma_S^2}\right]\right\}$$



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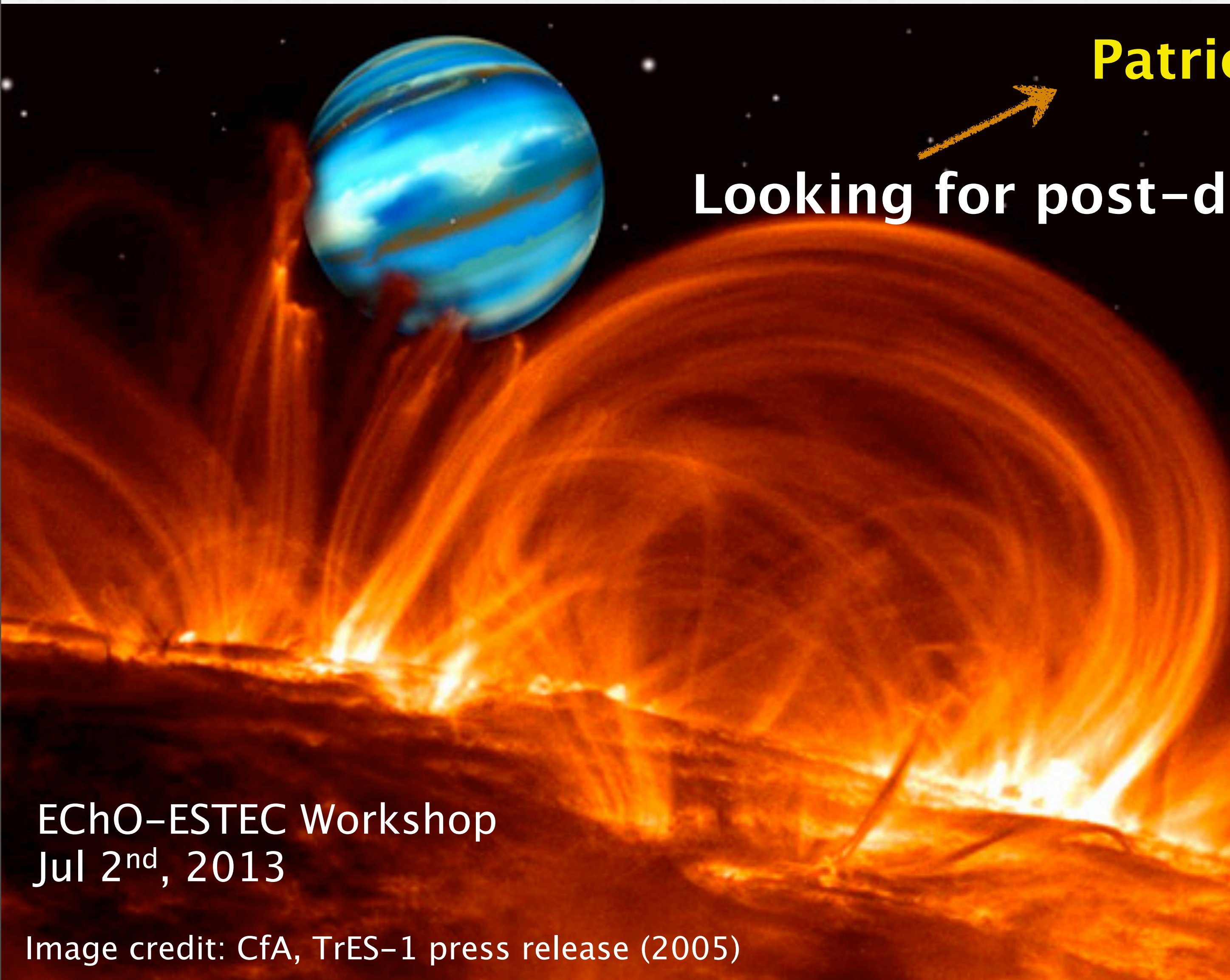

Patricio E. Cubillos

Looking for post-doc for 2014!

ECHO-ESTEC Workshop
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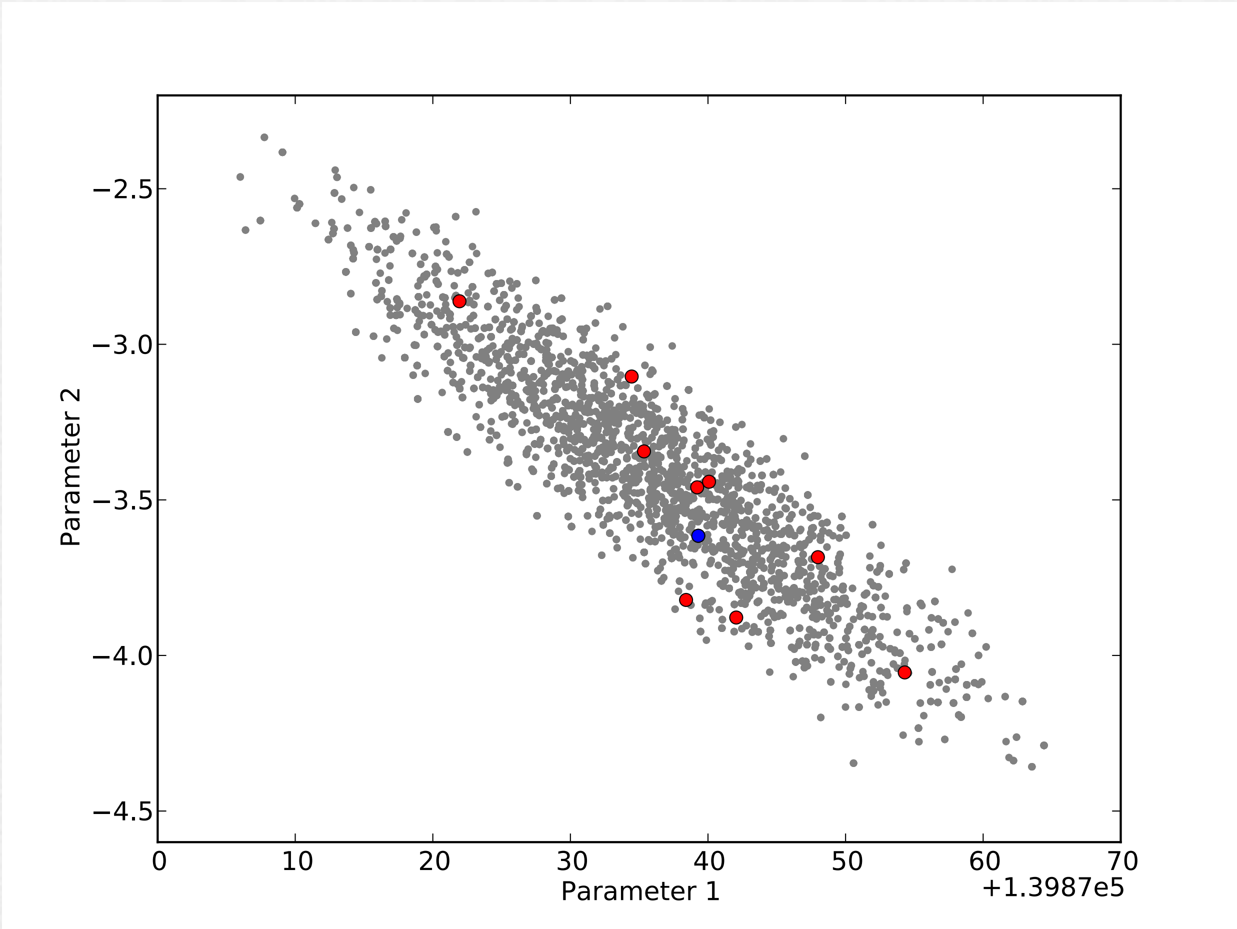
Image credit: CfA, TrES-1 press release (2005)

Differential Evolution Markov Chain: (Braak 2006)

- Usually: Metropolis Random Walk with proposal: $f \sim N(x, w)$
- DE-MC solves problem of scale and orientation of jumps



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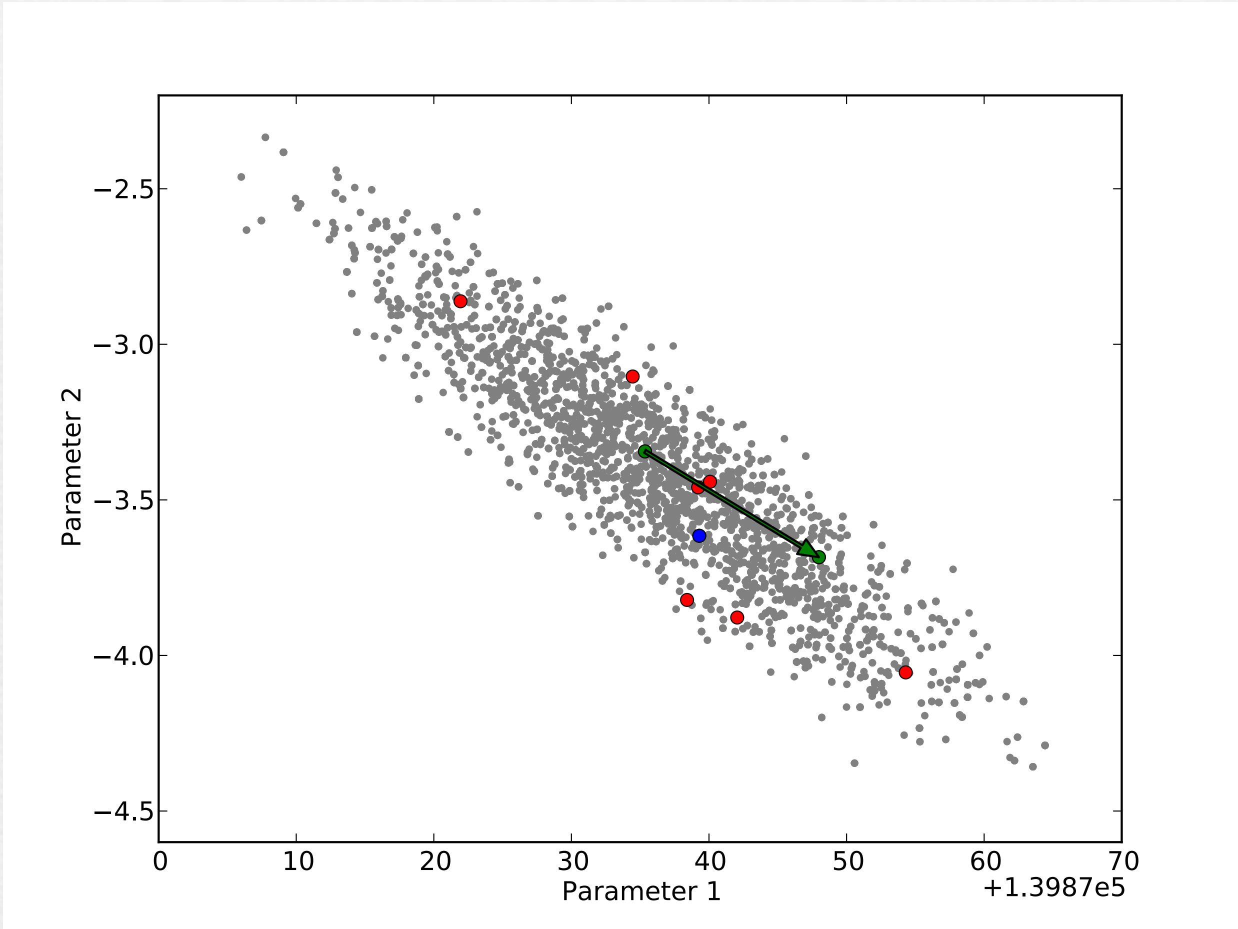

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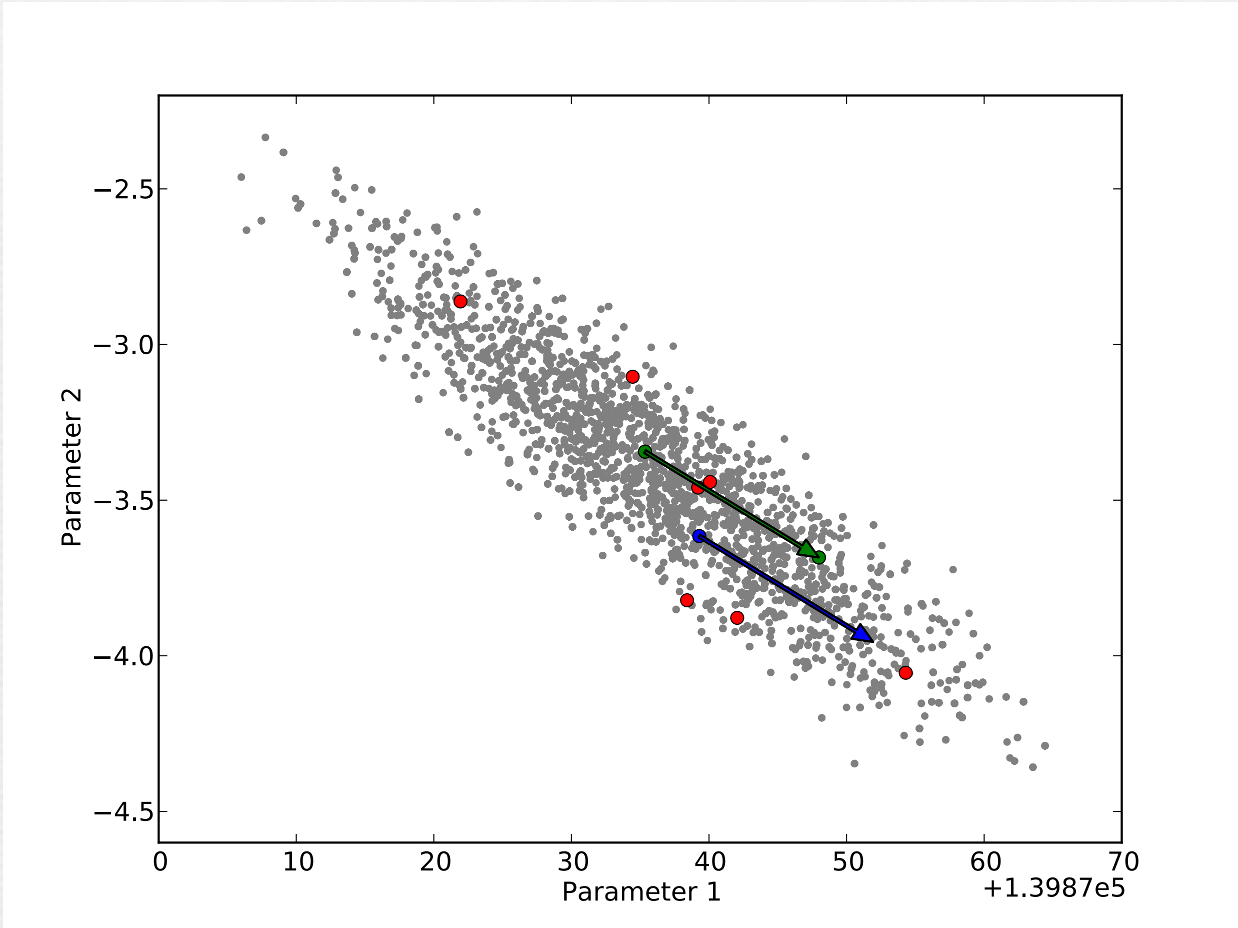
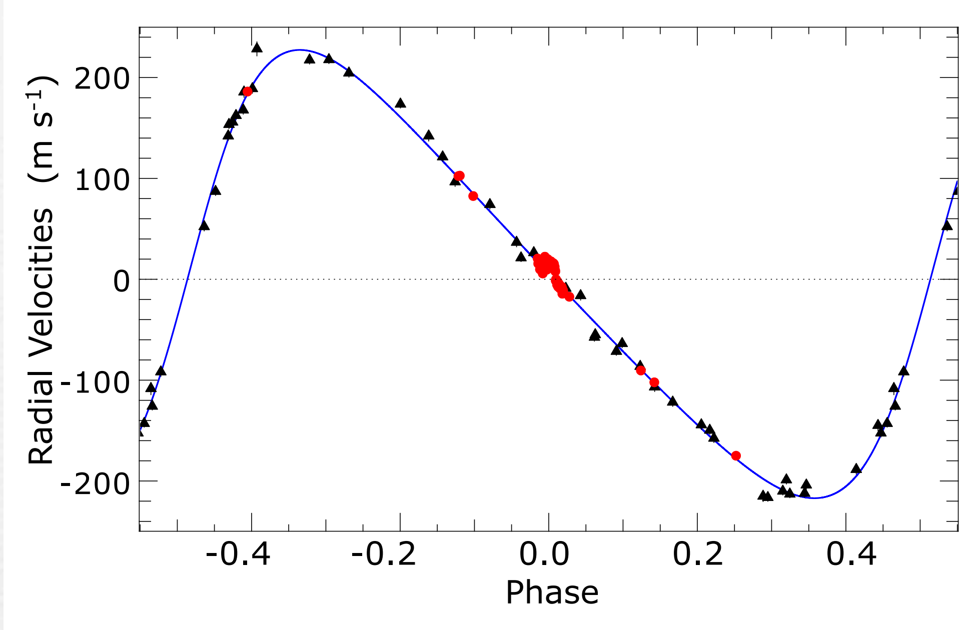


The WASP-8 System:

- Stellar-binary system
- Least-irradiated hot Jupiter observed at secondary eclipse
- Eccentric (e=0.31), 8-day orbit

Queloz et al. (2010)



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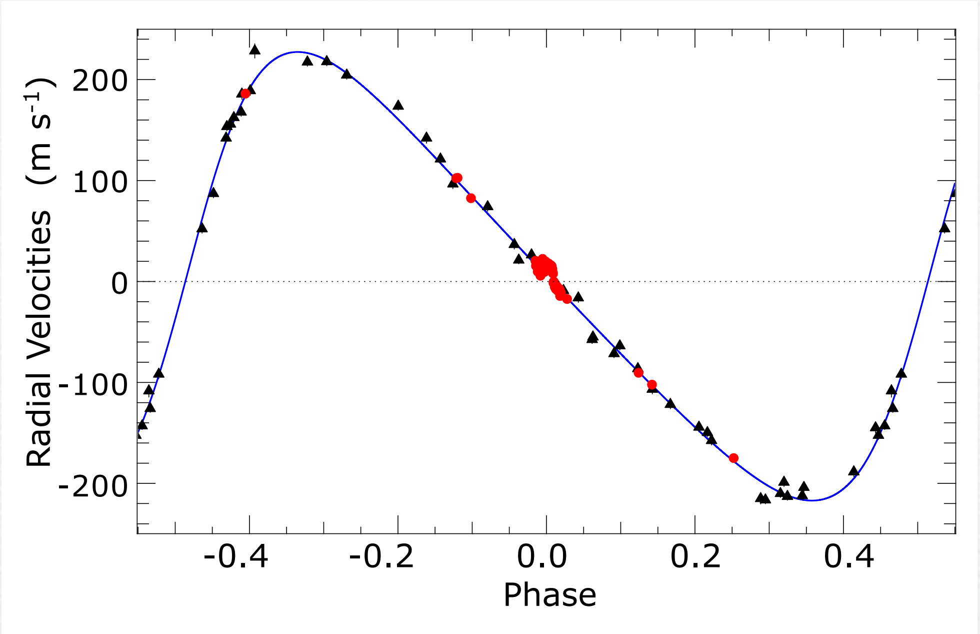
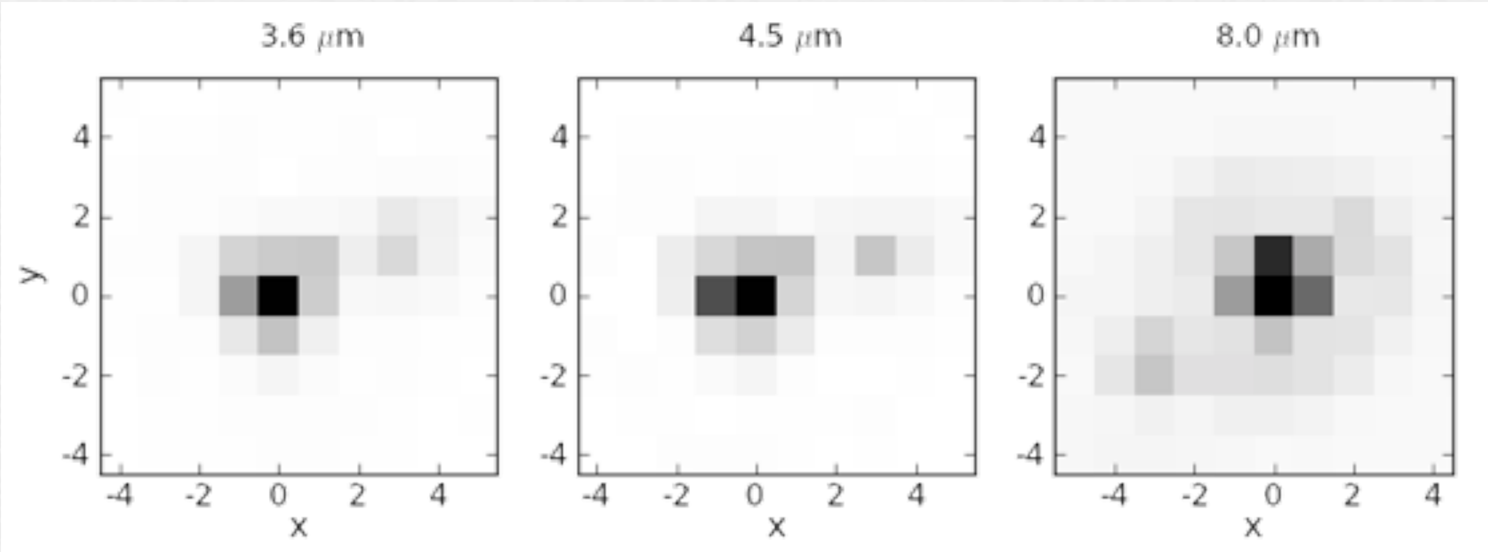
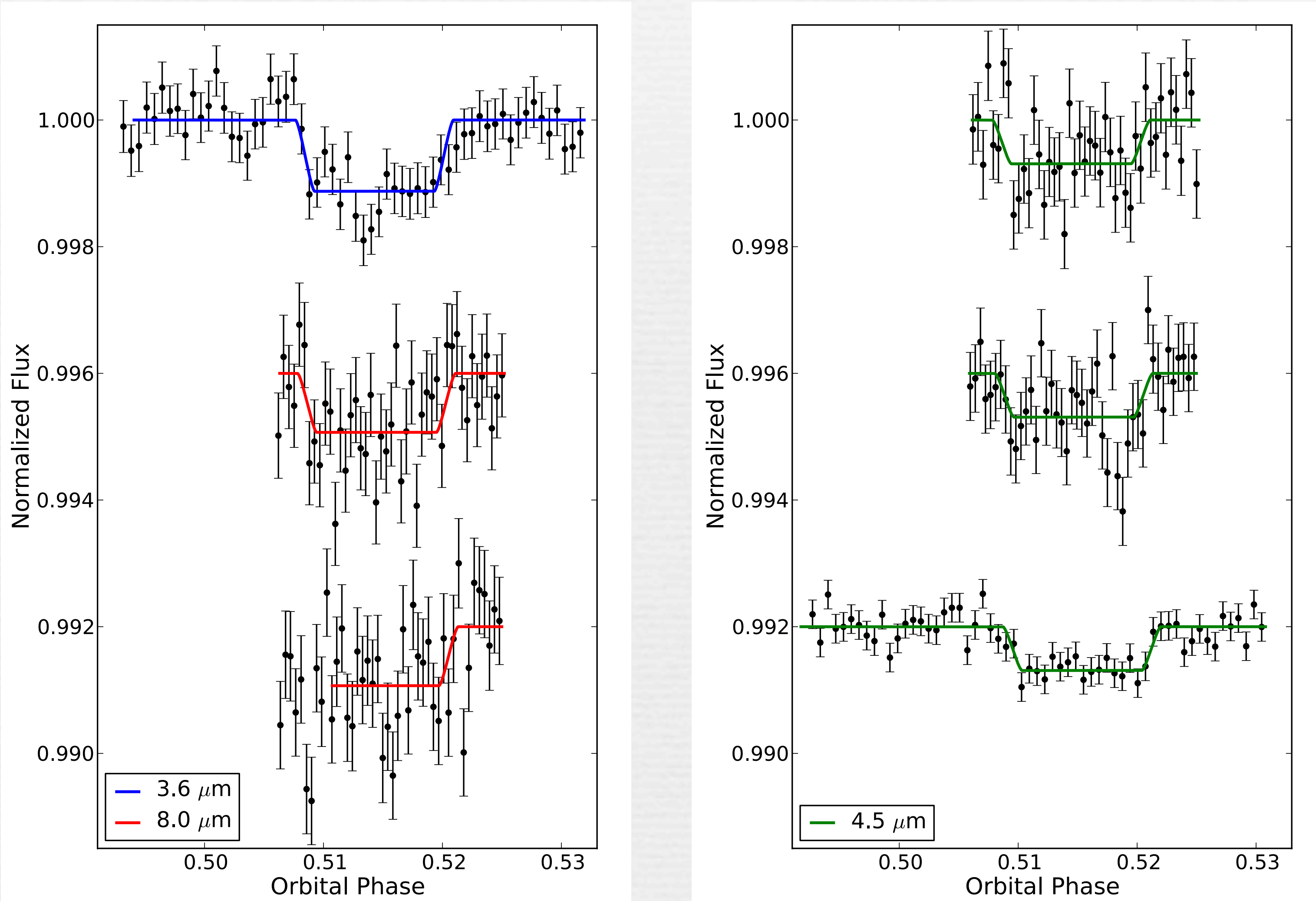


Observations:

- Cold & Warm Spitzer Space Telescope



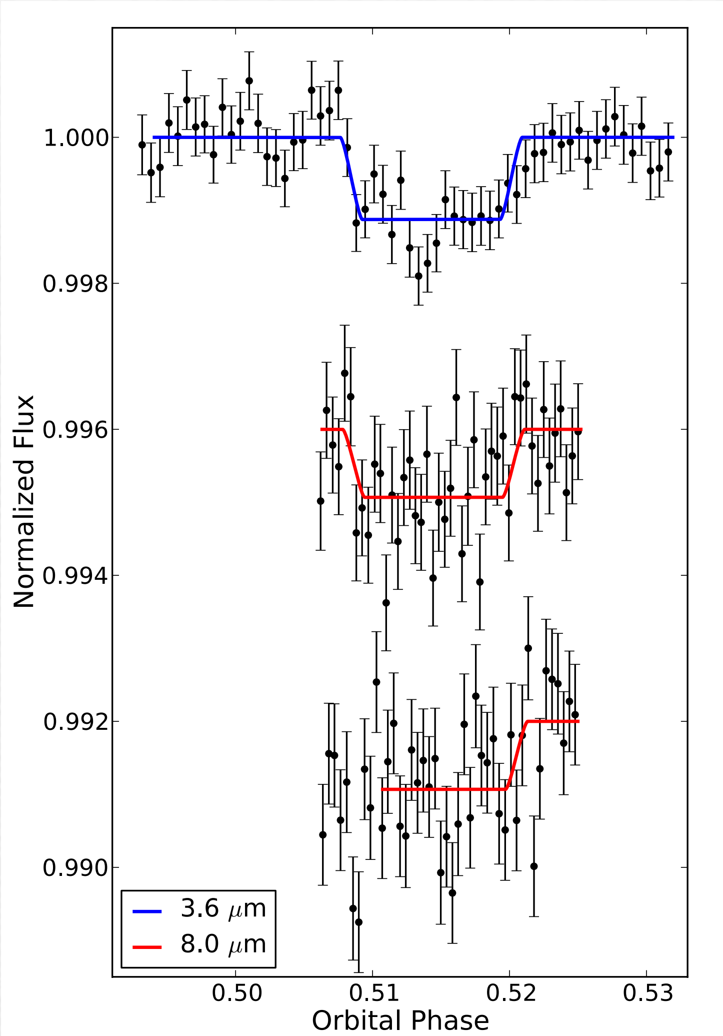
Light Curve Results

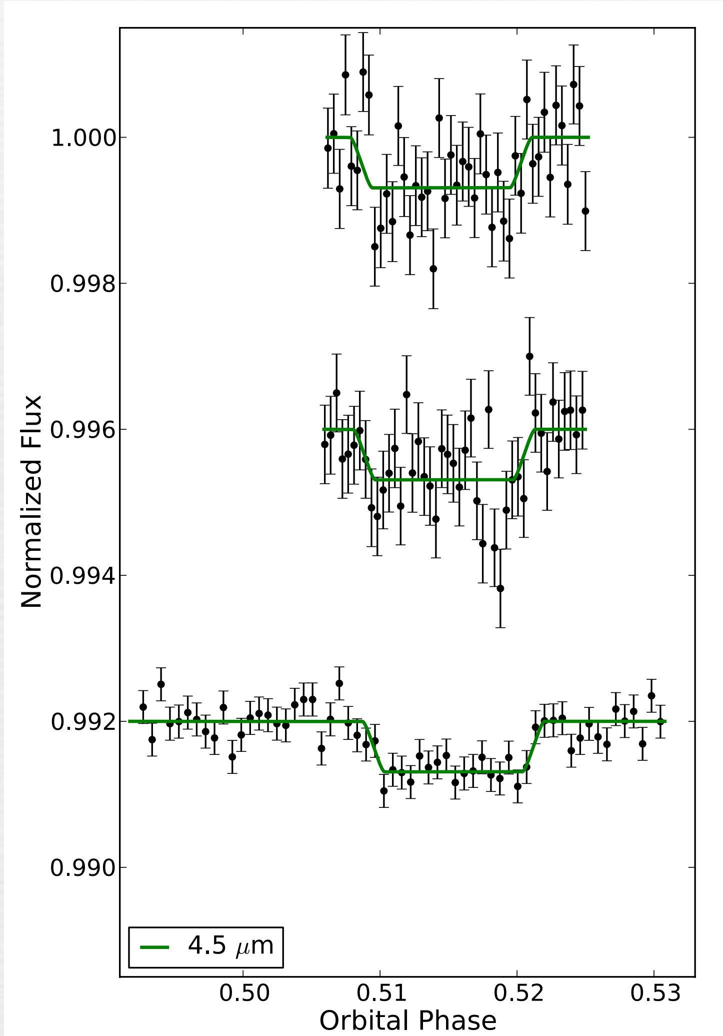


Tuesday, July 23, 13

Light Curve Results

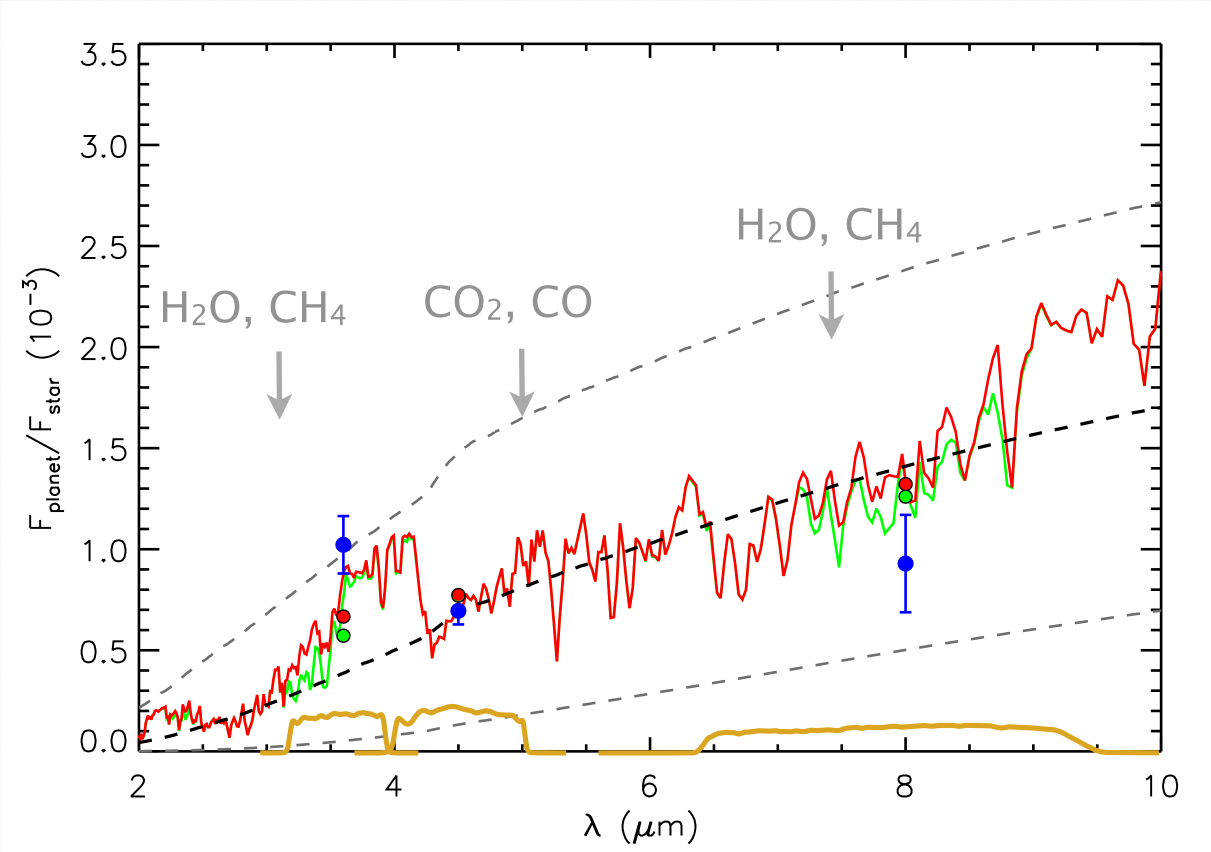
Waveband (µm)	Depth (%)	Brightness temp. (K)
3.6	0.113 +/– 0.018	**1552**
4.5	0.069 +/– 0.007	1131
8.0	0.093 +/– 0.023	938





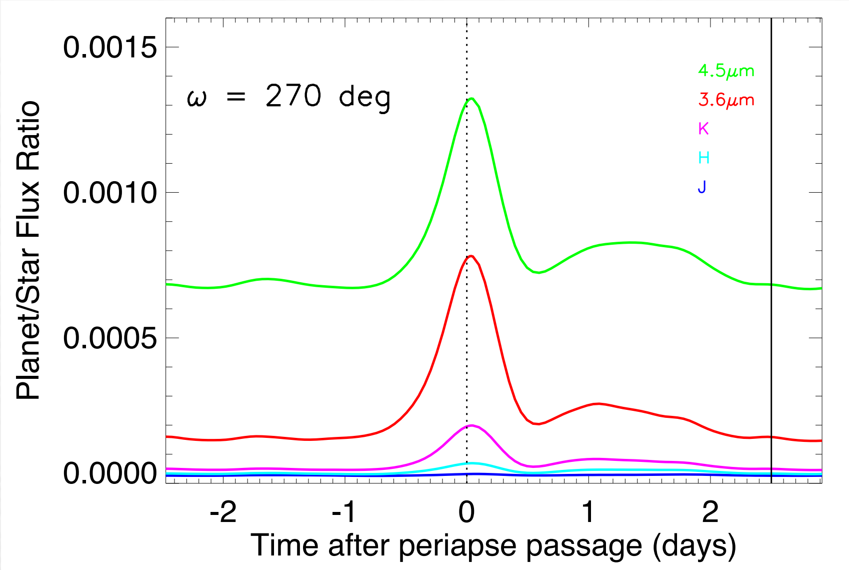
Atmospheric Modeling: (Madhusudhan & Seager 2009, 2010)

- No thermal inversion
- **But**, no model can fit all data points well.



Conclusions (I):

– The eclipse depths cannot be explained by current models.



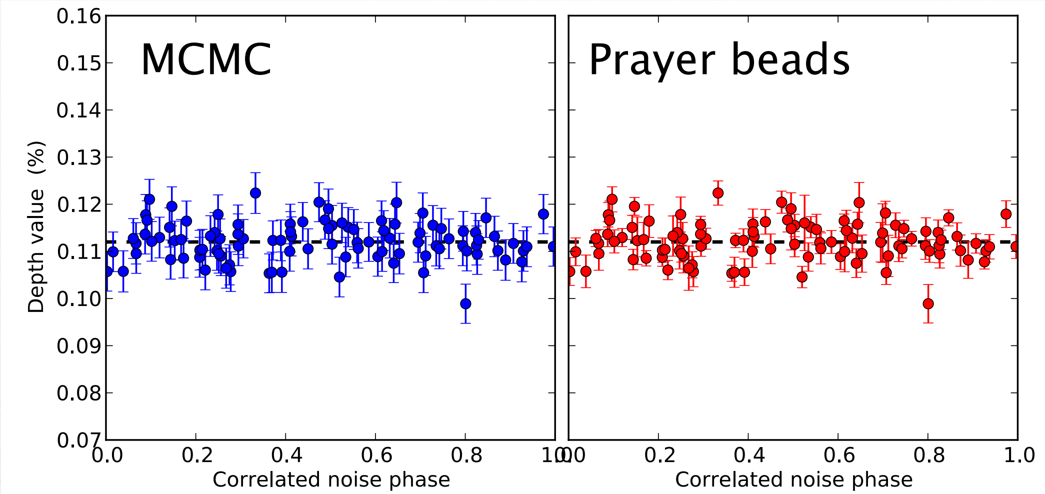
Kataria et al. (2012)

Possible explanations:

1.- Eccentricity might give an answer: Atmosphere shows differential response in **time** and in **strength**.

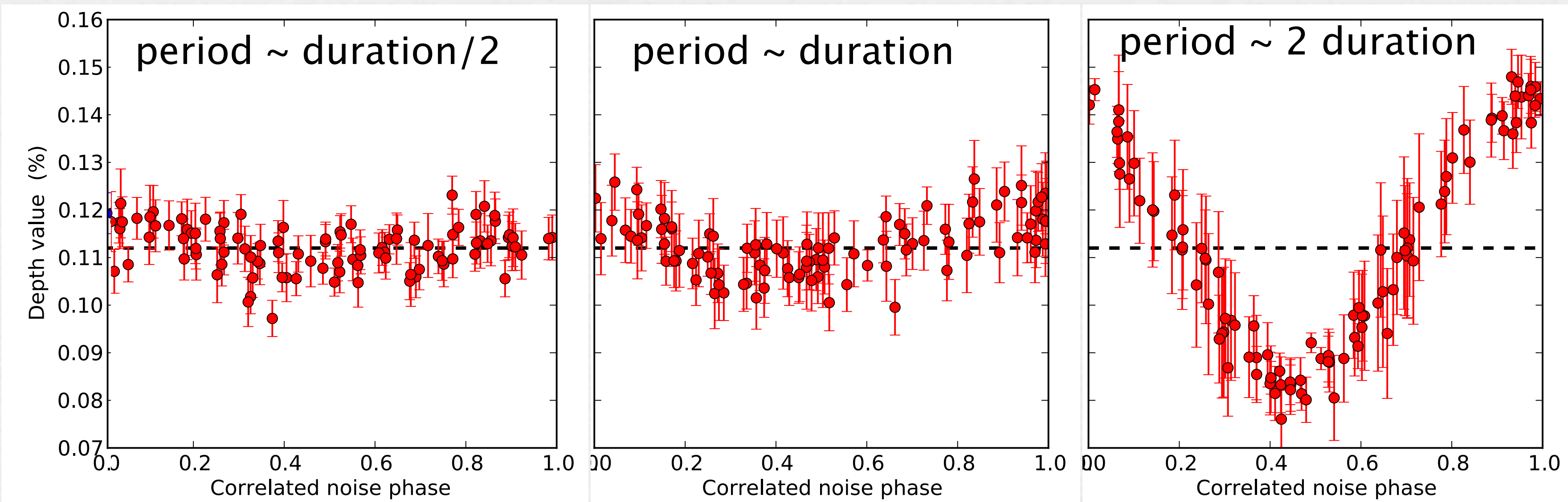
2.- Given the equilibrium temperature (~ 930 K), photochemical processes might alter the planet spectrum.

Prayer beads:



White noise only

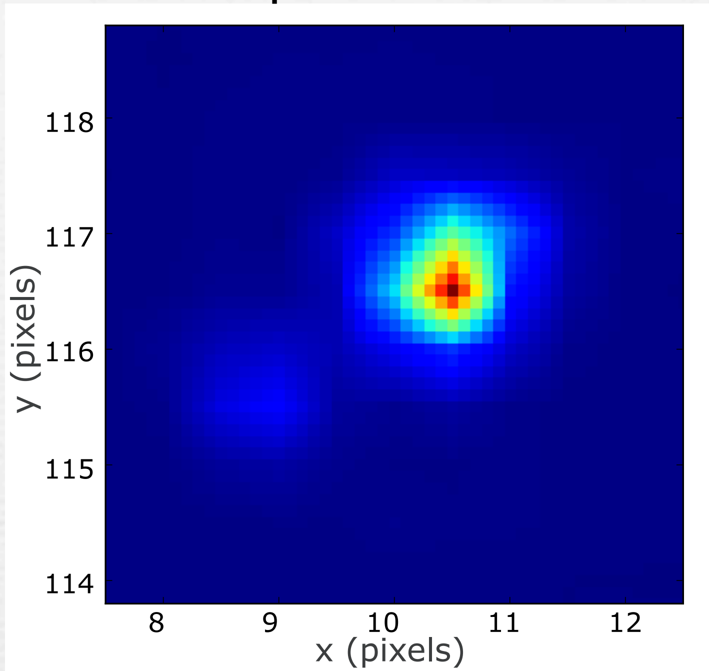
White + Correlated noise:



POET: Photometry

We need to remove the contribution from WASP-8B.

Interpolated data:



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Subtract WASP8-B model from data.

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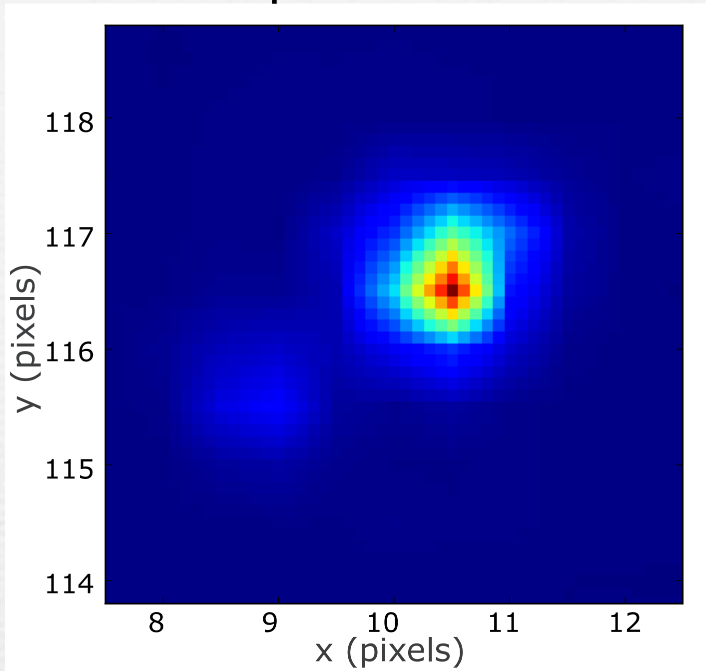

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Discard the pixels within a circular aperture around WASP-8B.
(masks radii: 1.6, 1.8, 2.0 pix.)

Performed 5X-interpolated aperture photometry (Harrington et al. 2007).

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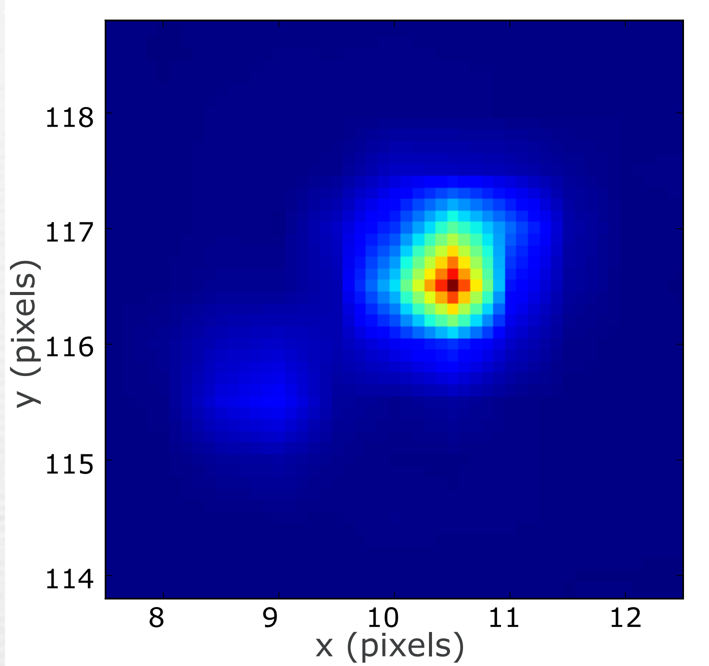

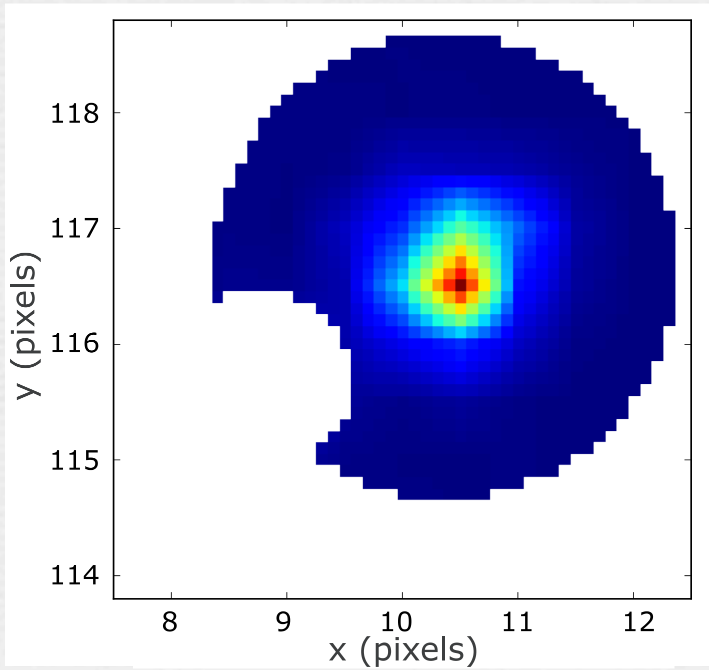

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Methods x Apertures
(4) x (~7) = ~30 light curves.

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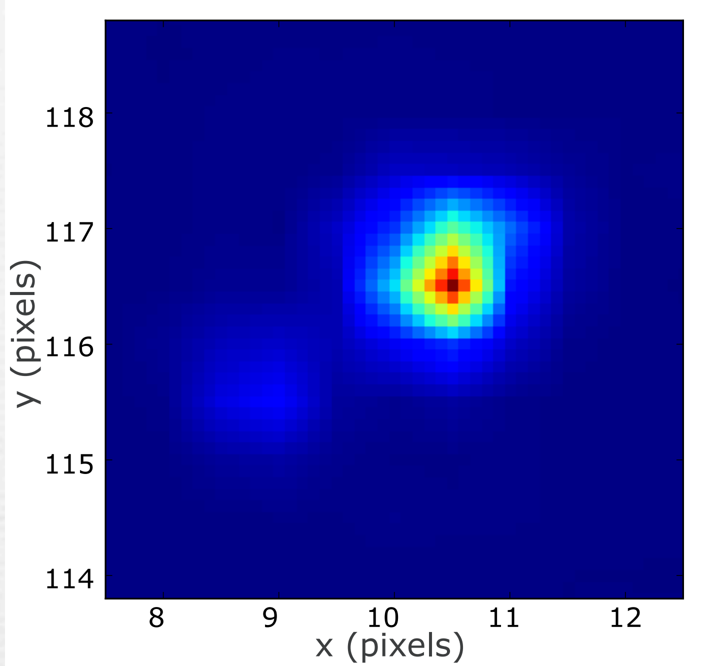
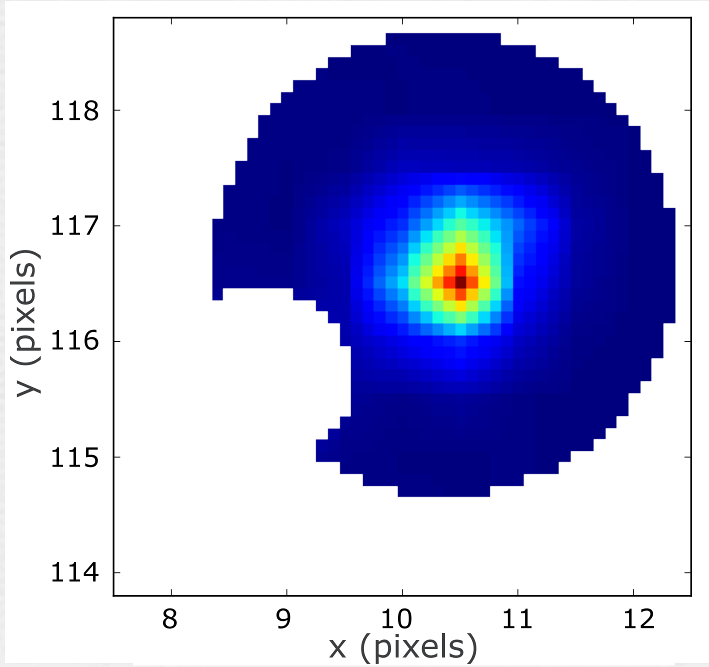
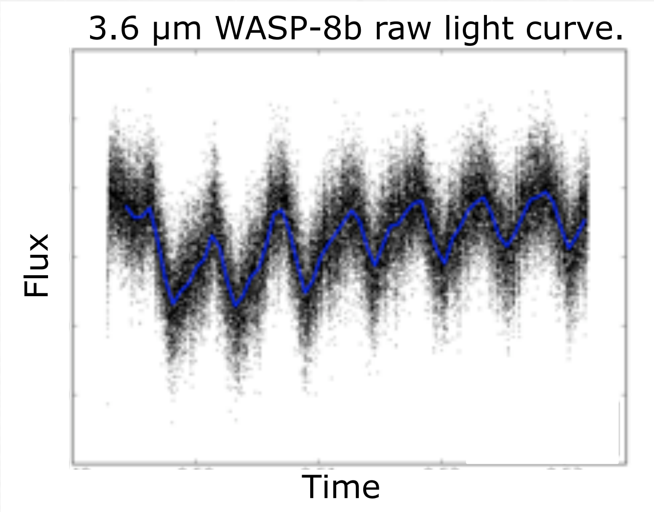
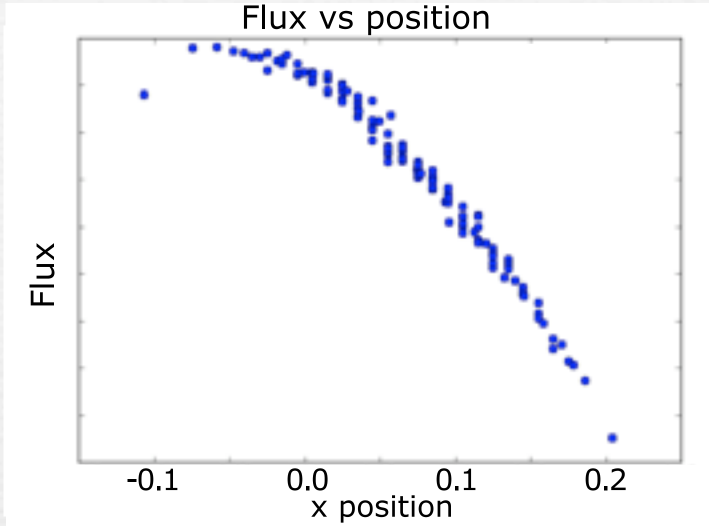




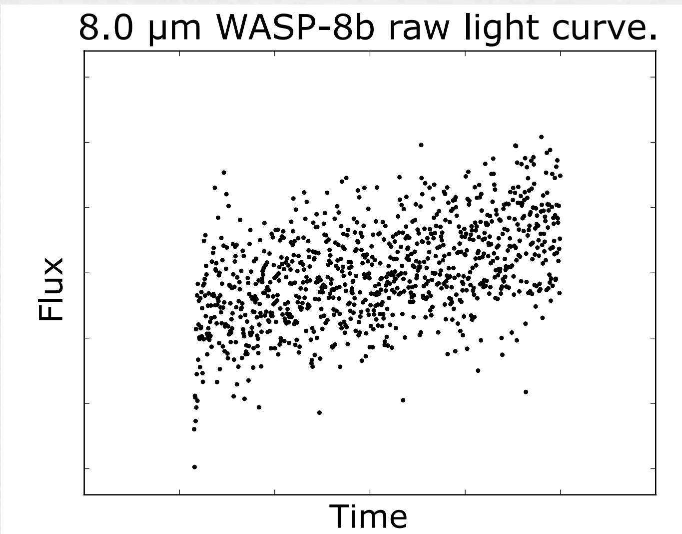
Spitzer Systematics:

1.- Position dependent flux variations ("Intra-pixel effect"). Charbonneau et al. (2005)





2.- Time-dependent pixel sensitivity ("Ramp"). Agol et al. (2010)



Light-curve model:

$$F(x,y,t) = F_s\, E(t)\; M(x,y)\; R(t)$$

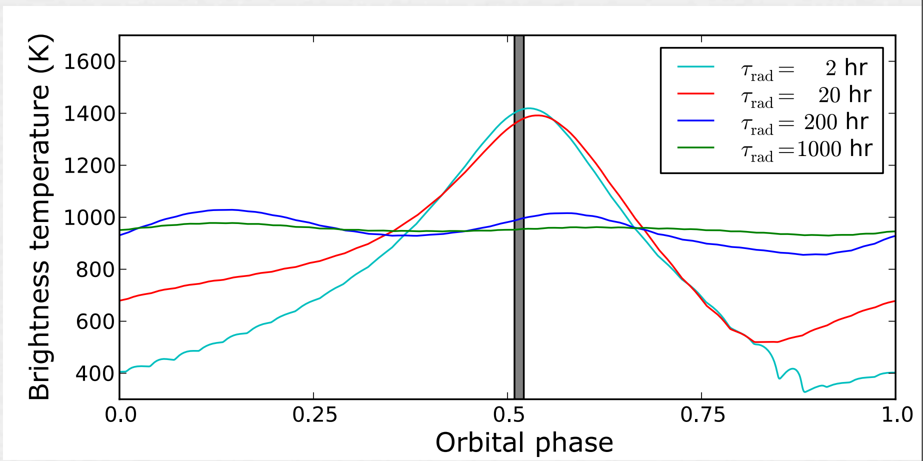
Brightness Temperature:

- Note the 3.6 μm temperature: $T_b \sim 1552$ K
- Equilibrium temperature: $T_{eq} \sim 930$ K
- Equilibrium temp. at periapsis: $T_{eq} \sim 1130$ K

- Modeled the temperature change along the orbit:

$$\frac{dE}{dt} = \left[(1-A)\sigma T_{eff}^4 \left(\frac{R_*}{r(t)}\right)^2 \cos\psi(t) - \sigma T^4\right]$$

Cowan et al. (2011)



- For short radiative times: max $T_{eq} \sim 1400$ K.

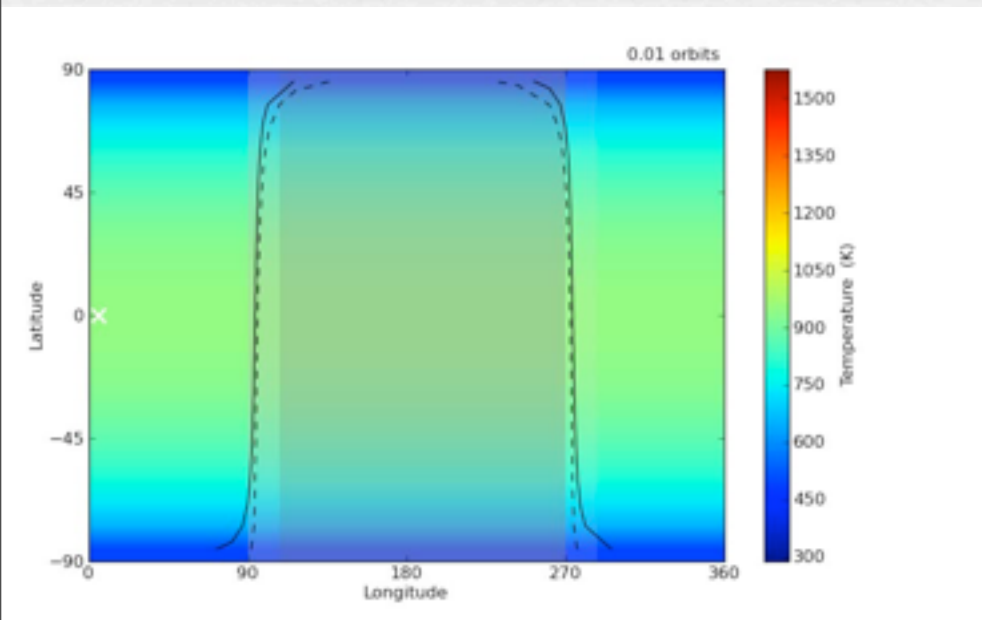
Brightness Temperature:

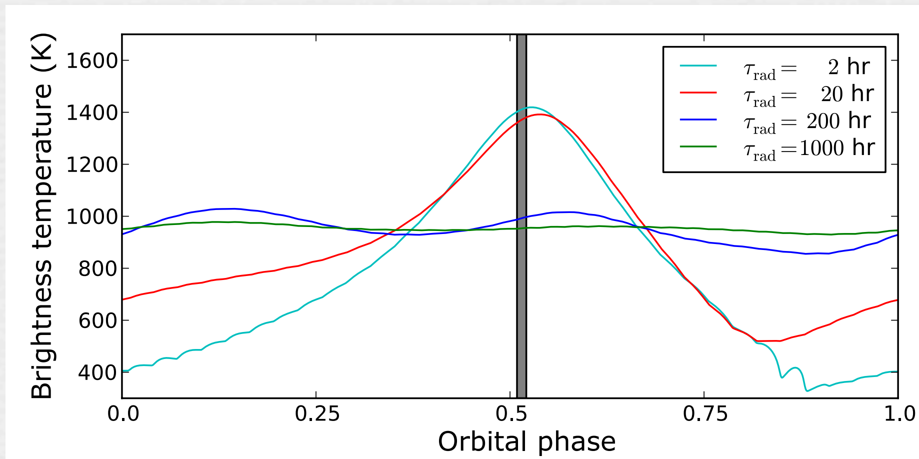
- Note the 3.6 μm temperature: $T_b \sim 1552$ K
- Equilibrium temperature: $T_{eq} \sim 930$ K
- Equilibrium temp. at periapsis: $T_{eq} \sim 1130$ K

- Modeled the temperature change along the orbit:

$$\frac{dE}{dt} = \left[(1-A)\sigma T_{\rm eff}^4 \left(\frac{R_*}{r(t)}\right)^2 \cos\psi(t) - \sigma T^4\right]$$

Cowan et al. (2011)





- For short radiative times: max $T_{eq} \sim 1400$ K.