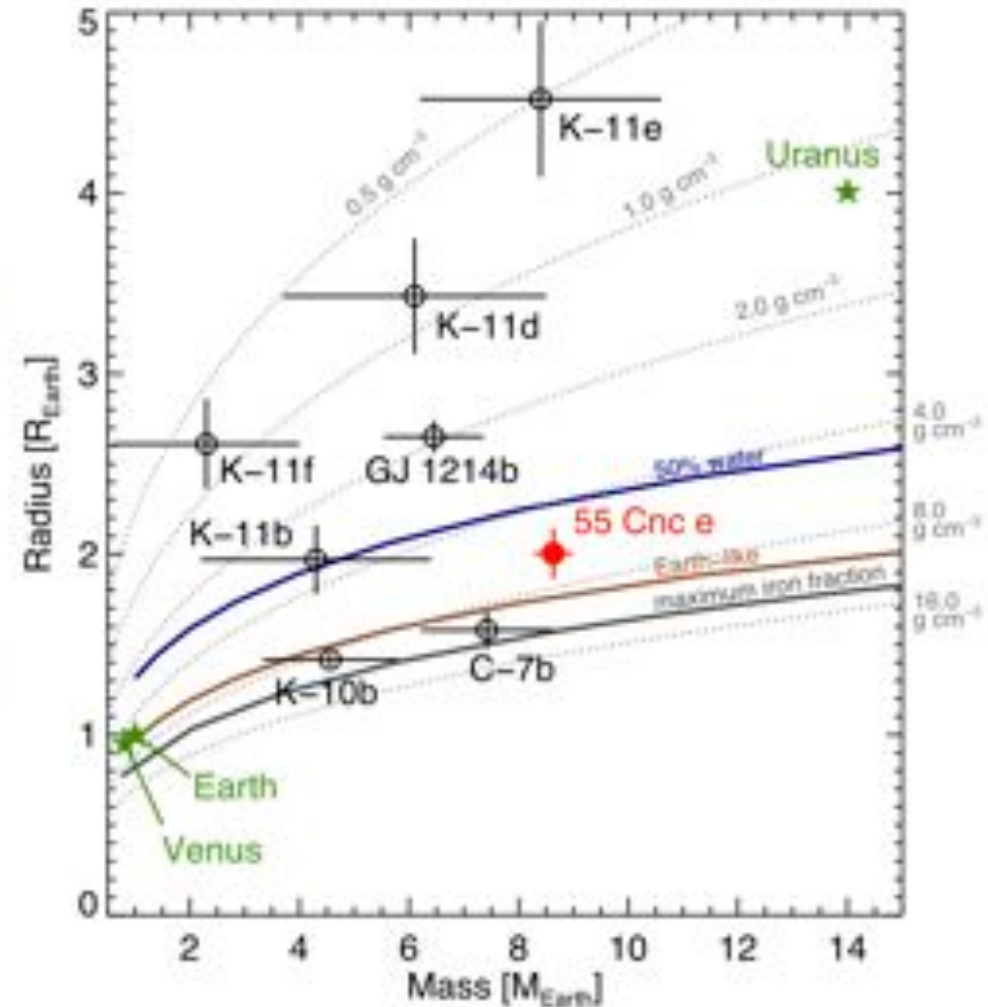
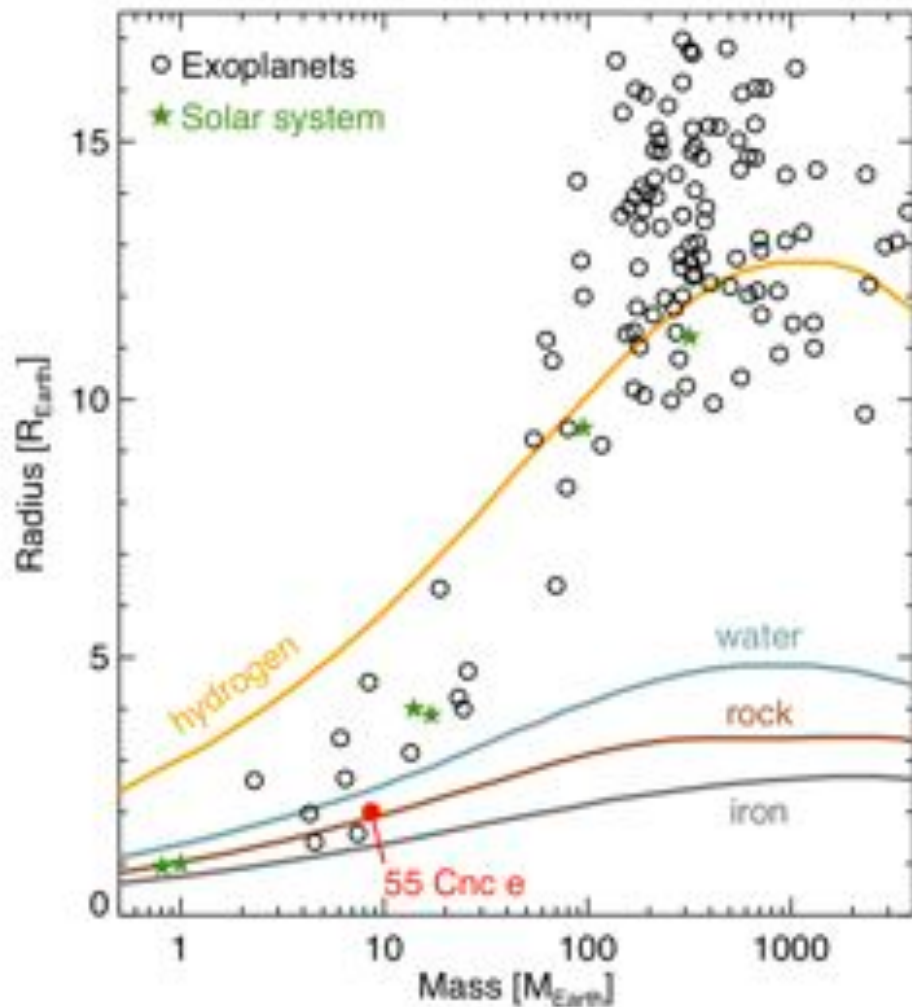


# Characterizing Exoplanets

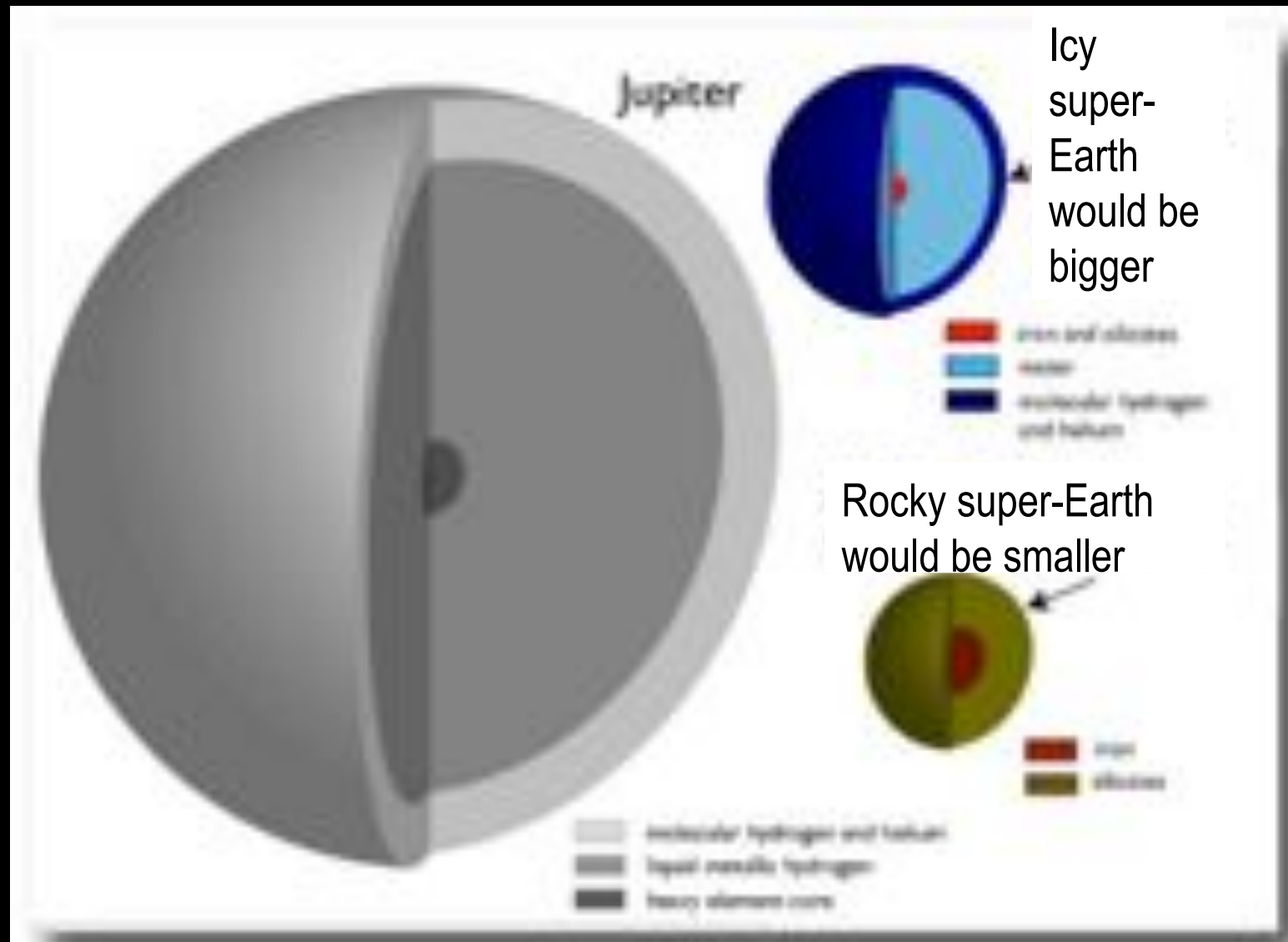
Ray Jayawardhana  
*University of Toronto*

# RV+Transit → Mass-Radius Diagram

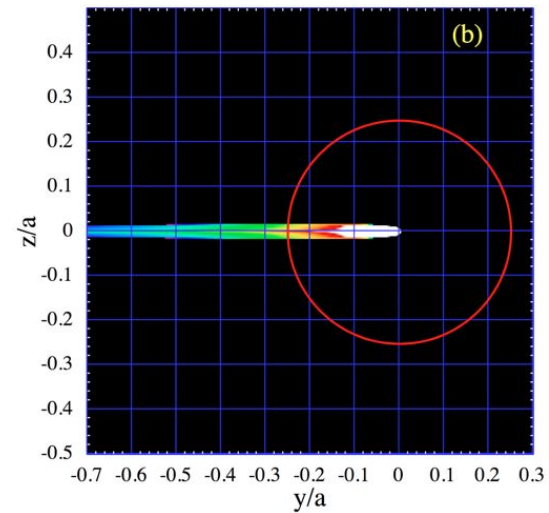
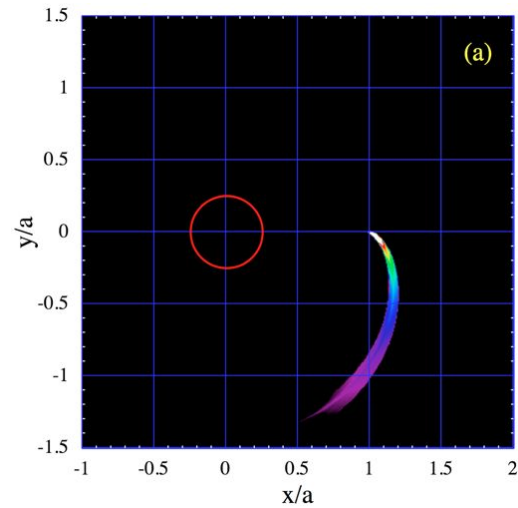
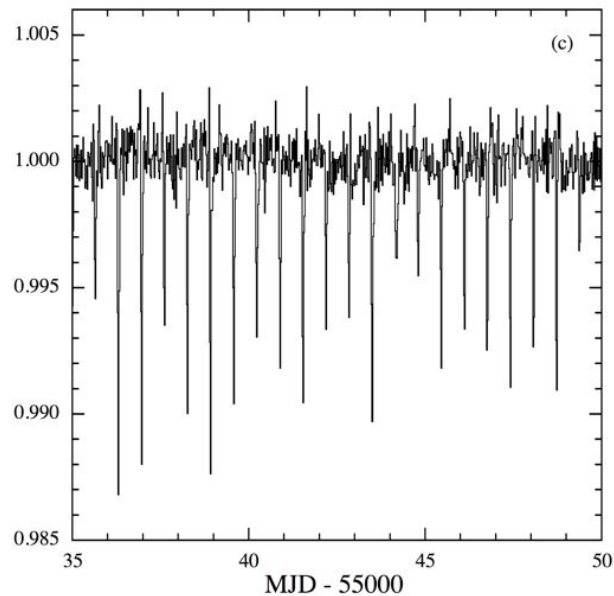
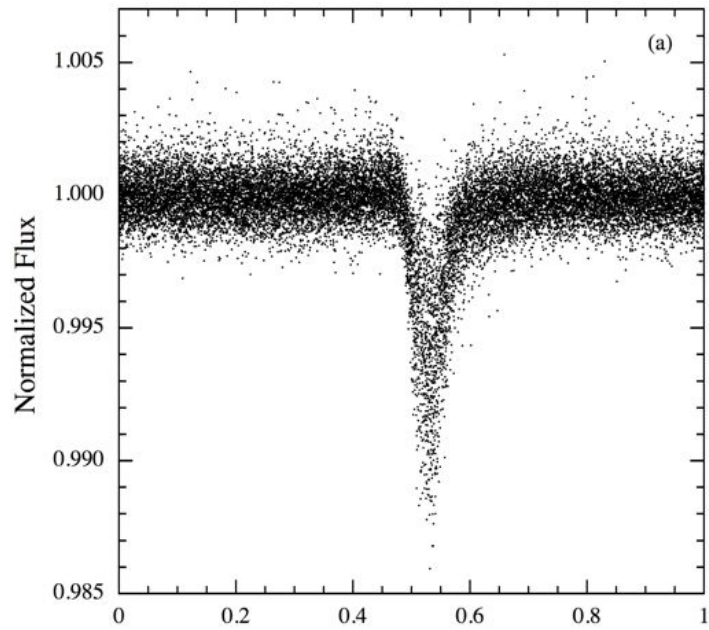


Winn et al. (2011)

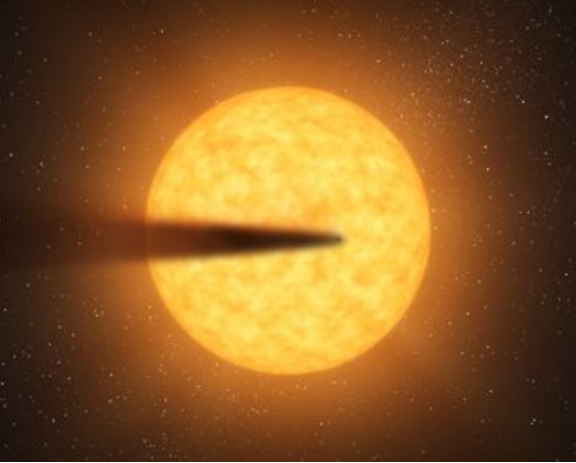
# Super-Earths: Icy or Rocky?



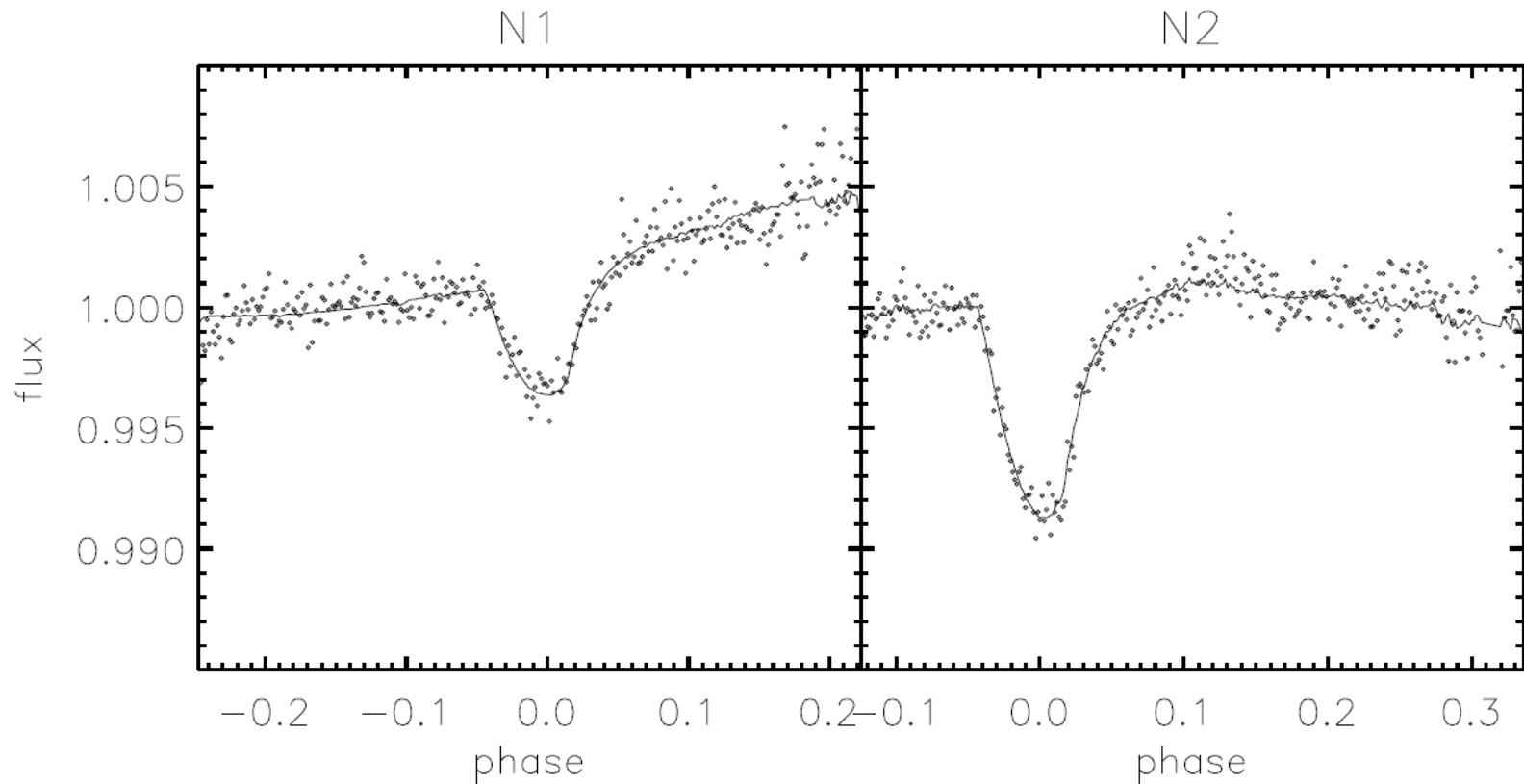
# Evaporating Super-Mercury?



Rappaport et al. (2011)



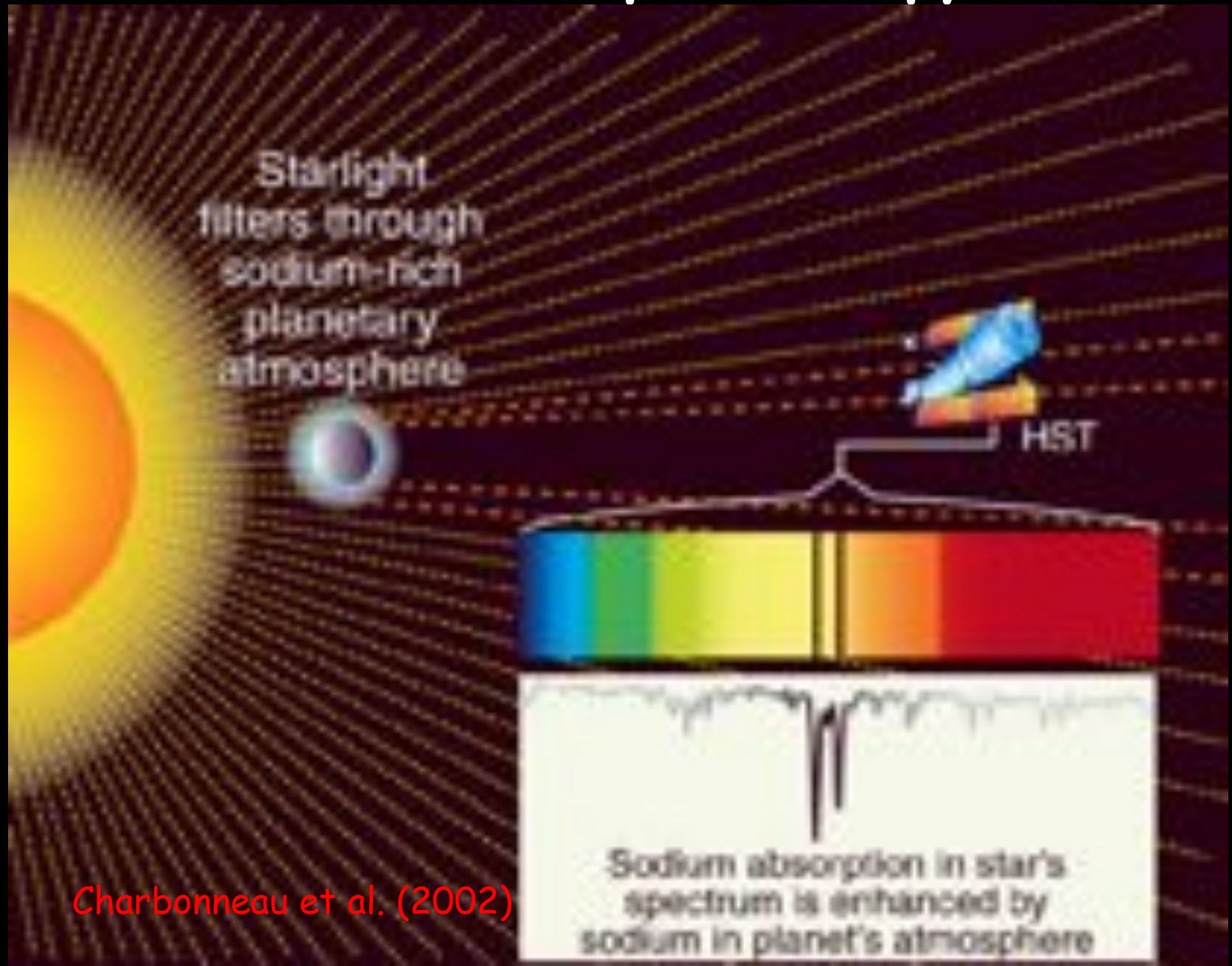
# Differential Spectrophotometry with Gemini North



de Mooij, Silburt, Jayawardhana et al. (in prep)



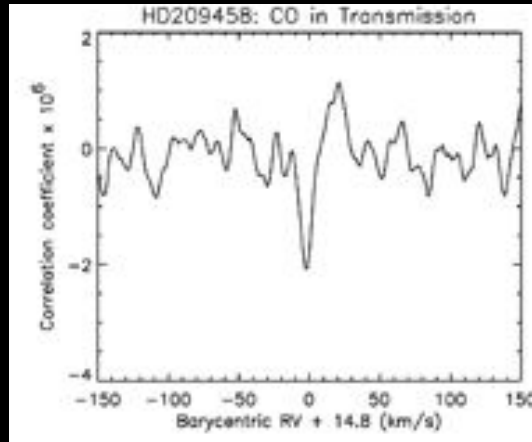
# Transmission Spectroscopy



Charbonneau et al. (2002)

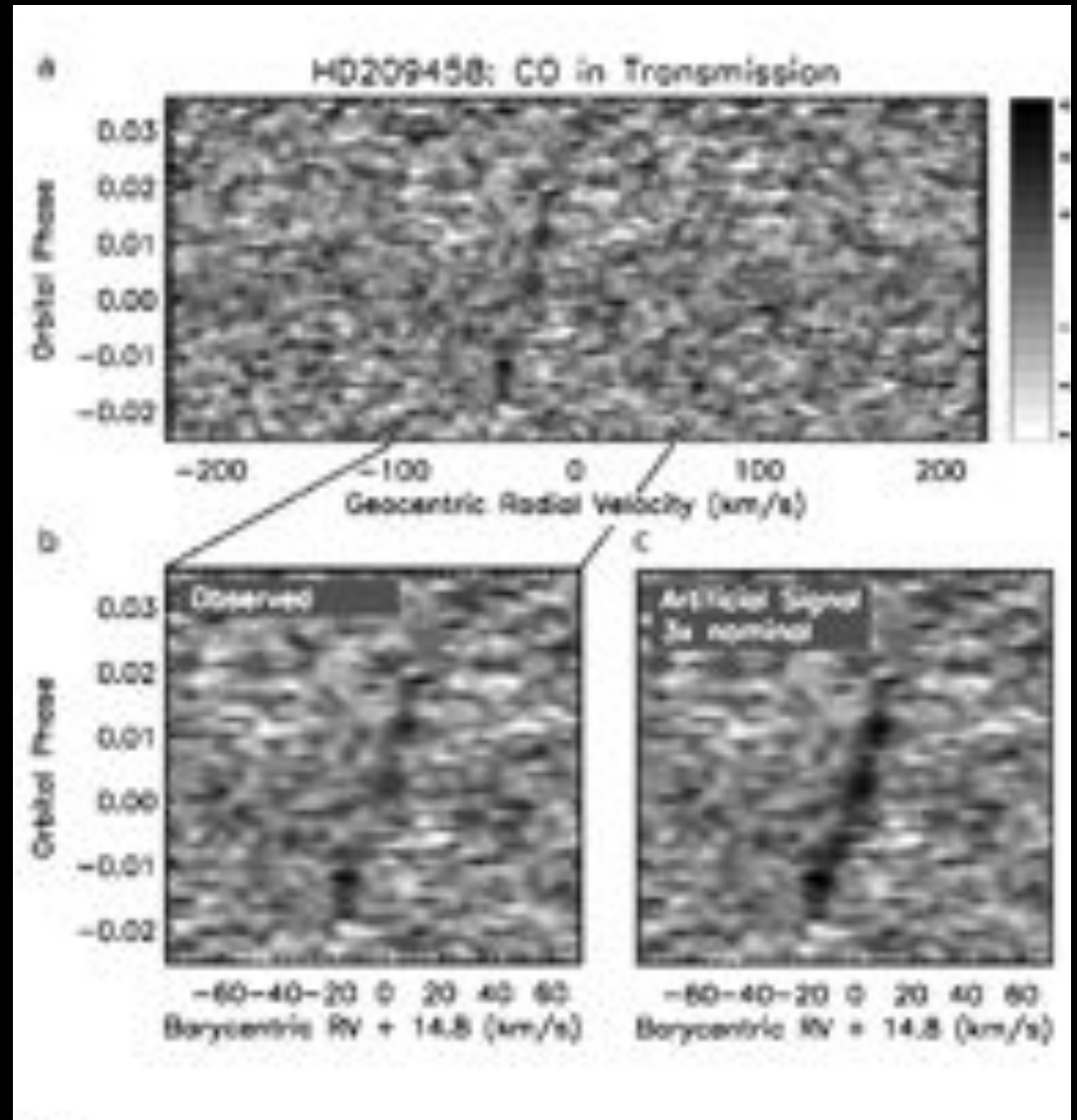
# Transmission Spectroscopy

HD 209458b  
with VLT

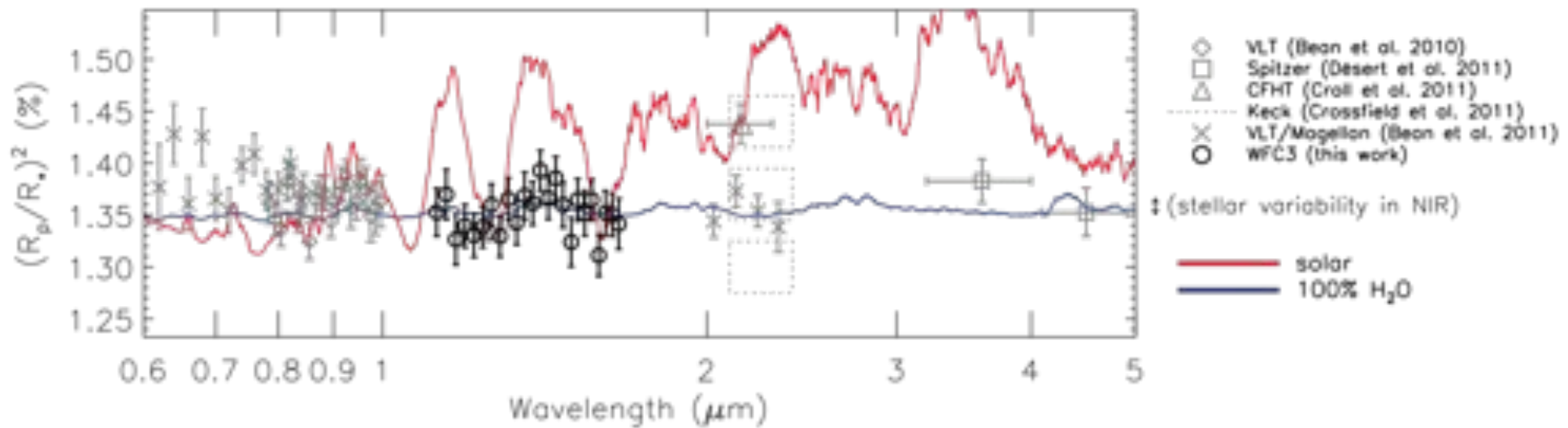
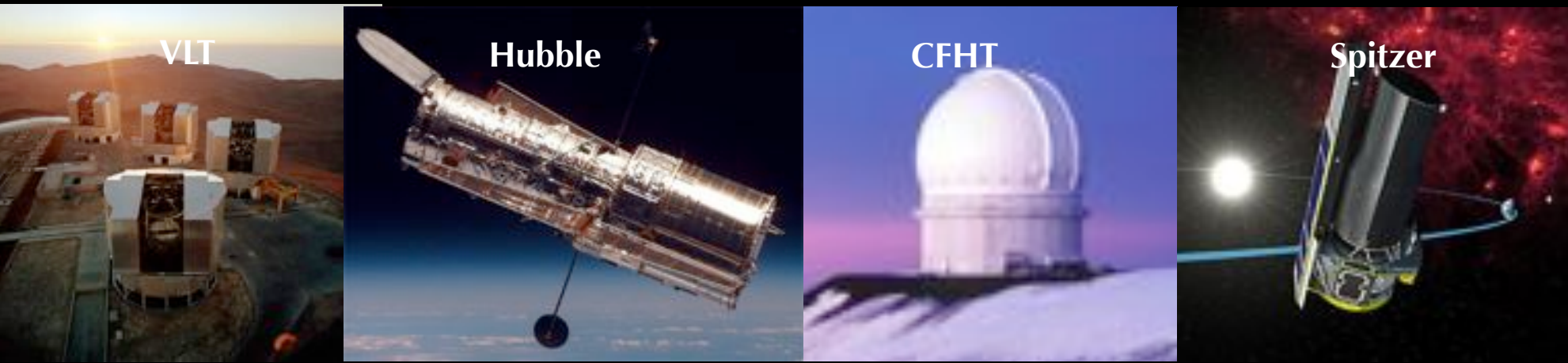


Planet's Orbital Velocity  
from CO line

Snellen et al. (2010)



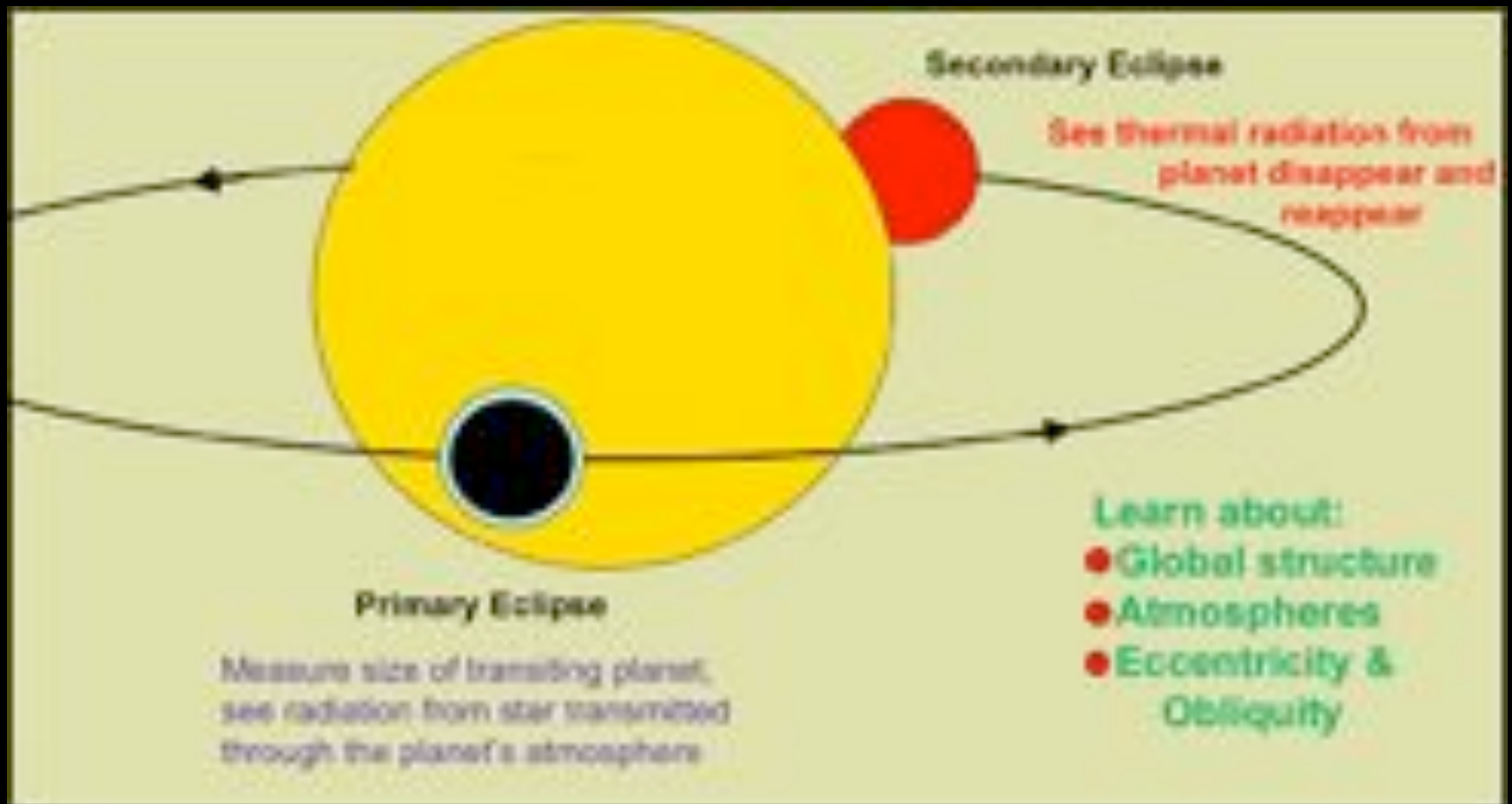
# Characterizing GJ 1214b



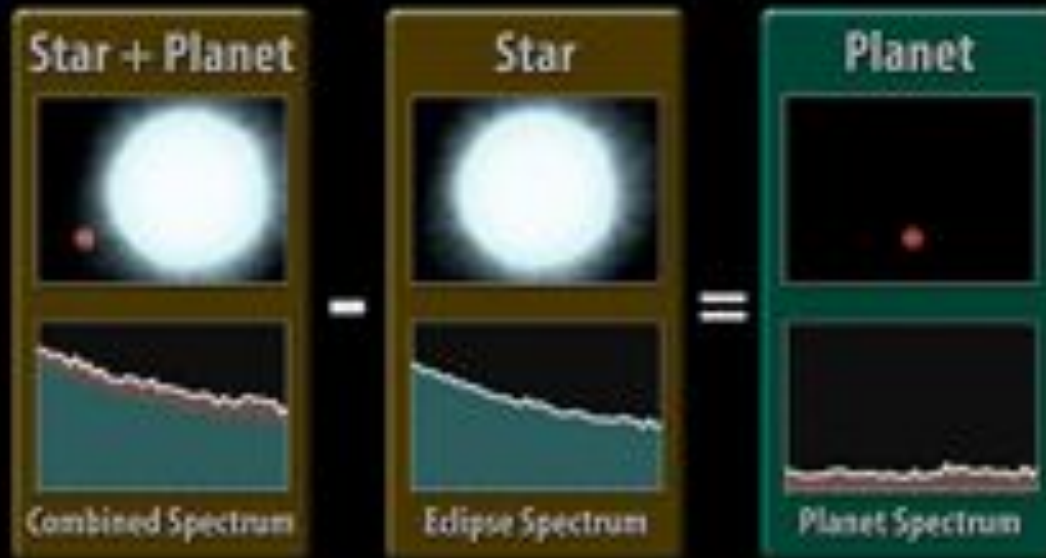
Bean et al. (2011); Desert et al. (2011); Croll et al. (2011);  
Berta et al. (2012); de Mooij et al. (2013)



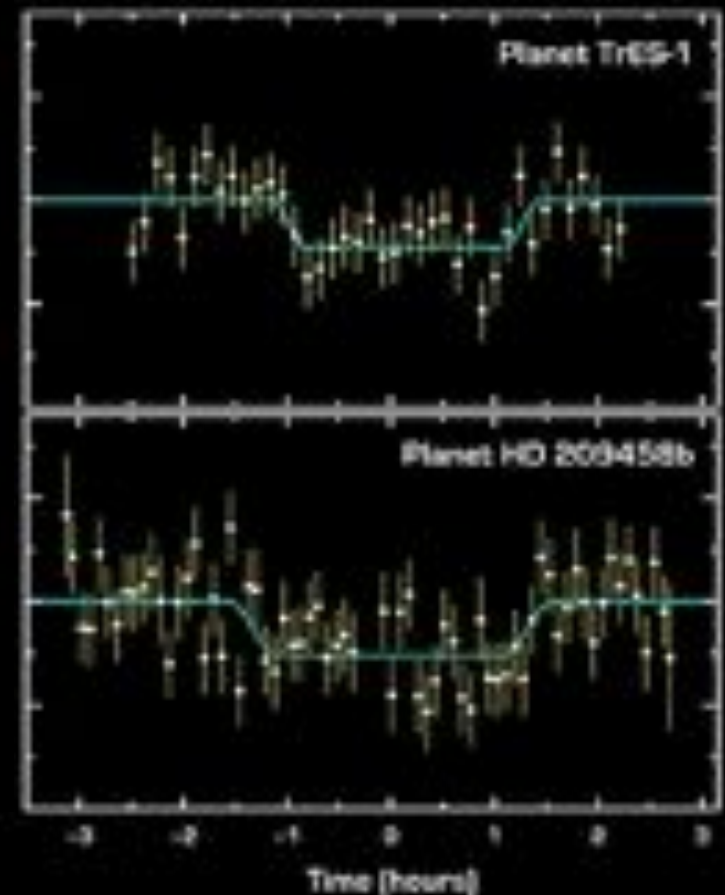
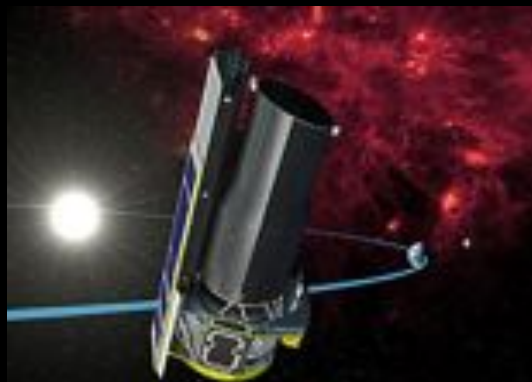
# Characterizing Transiting Planets



**Secondary eclipse: when the planet goes behind the star**



## Isolating a Planet's Spectrum



Planetary Eclipses Spitzer Space Telescope • IRAC • MIPS

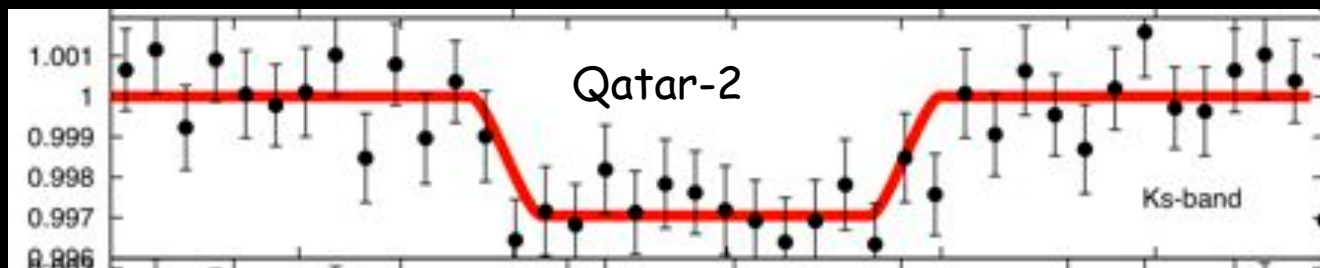
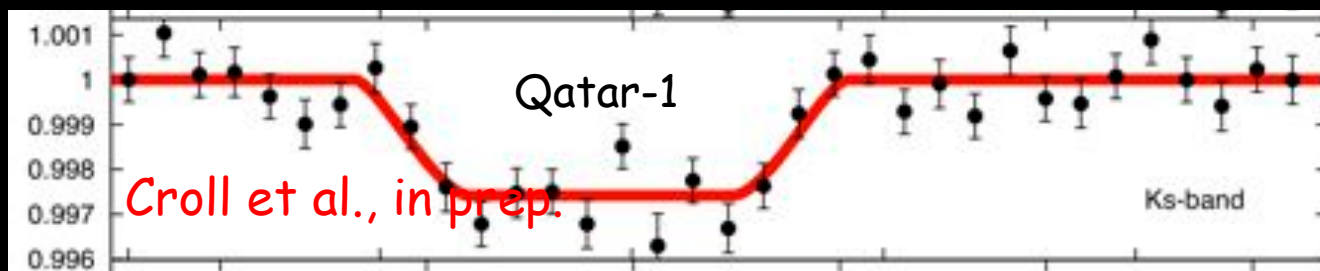
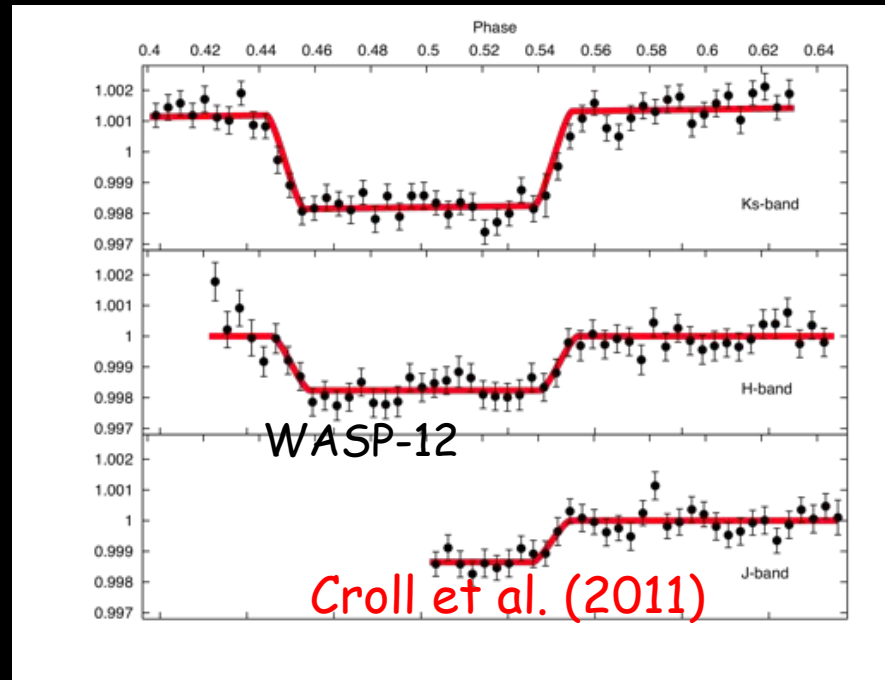
Model: JPL/Caltech / G. Chakrabarti (Harvard-Smithsonian CfA)  
© 2006 (Spitzer Space Telescope)

iss0006-00a

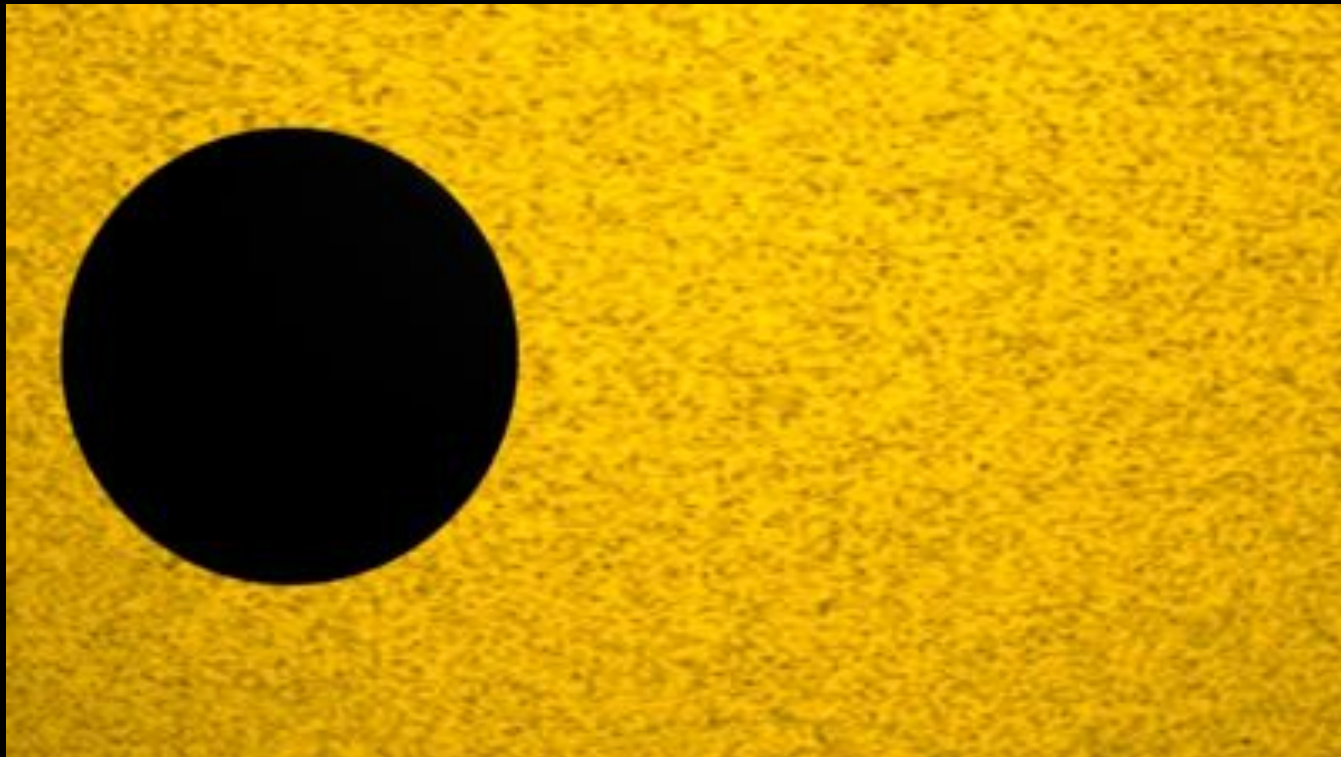
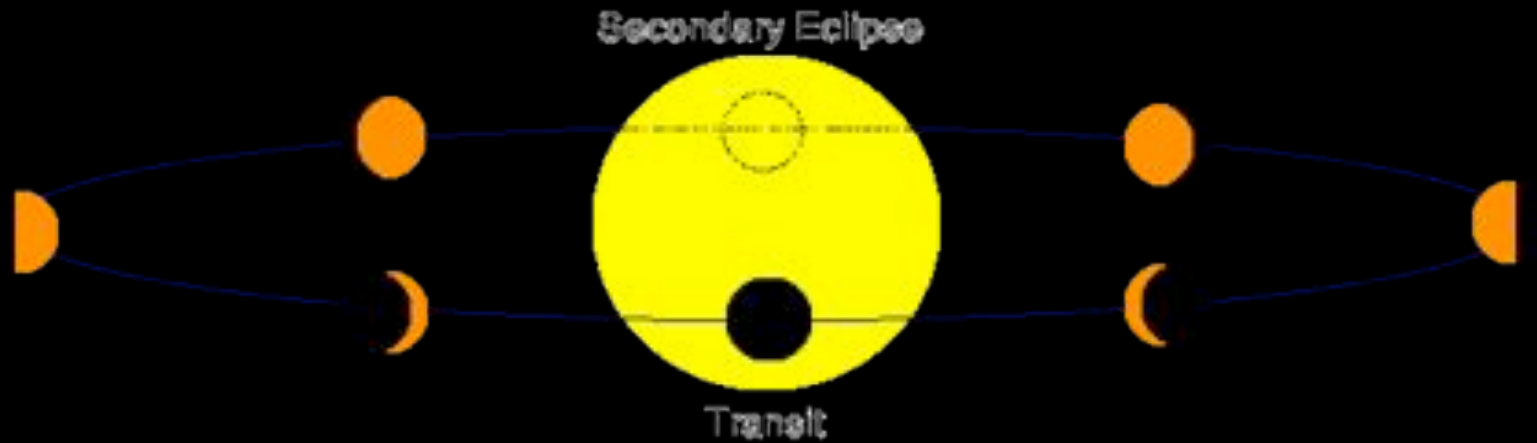
# Secondary Eclipses



Canada-France-Hawaii Telescope

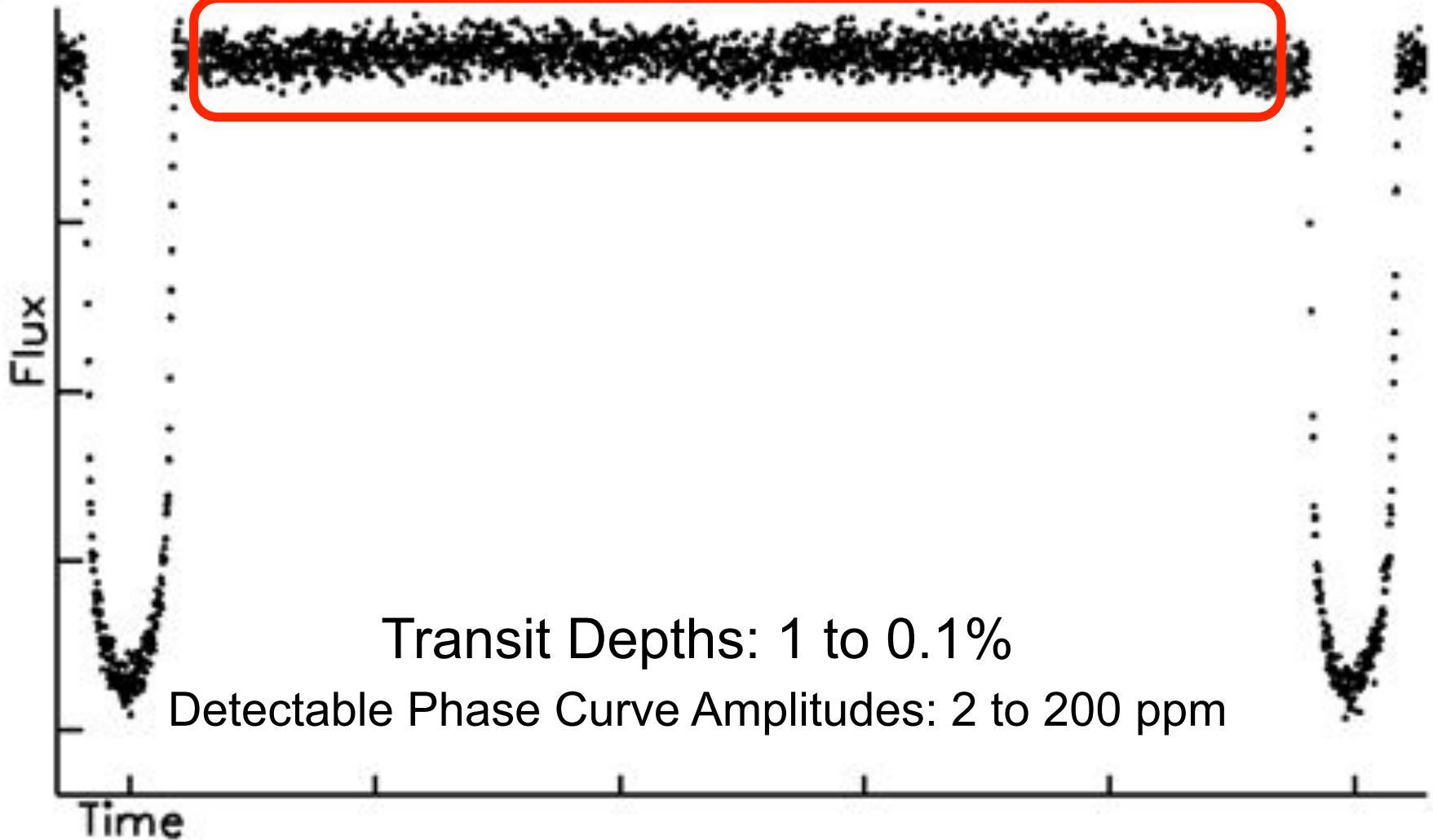


# Phase Curves of Transiting Planets





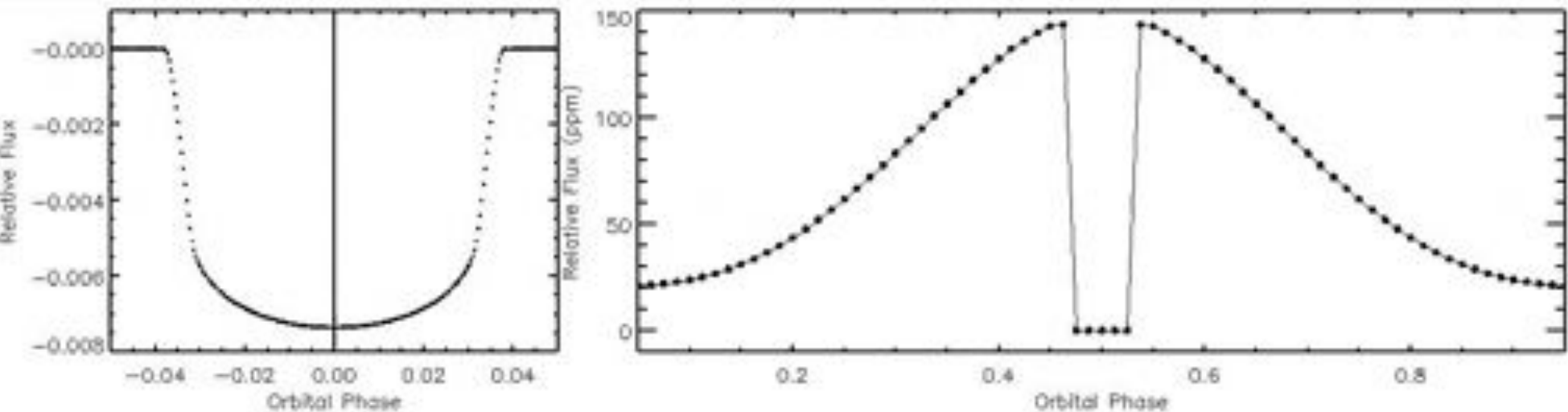
# Light Curve from Kepler



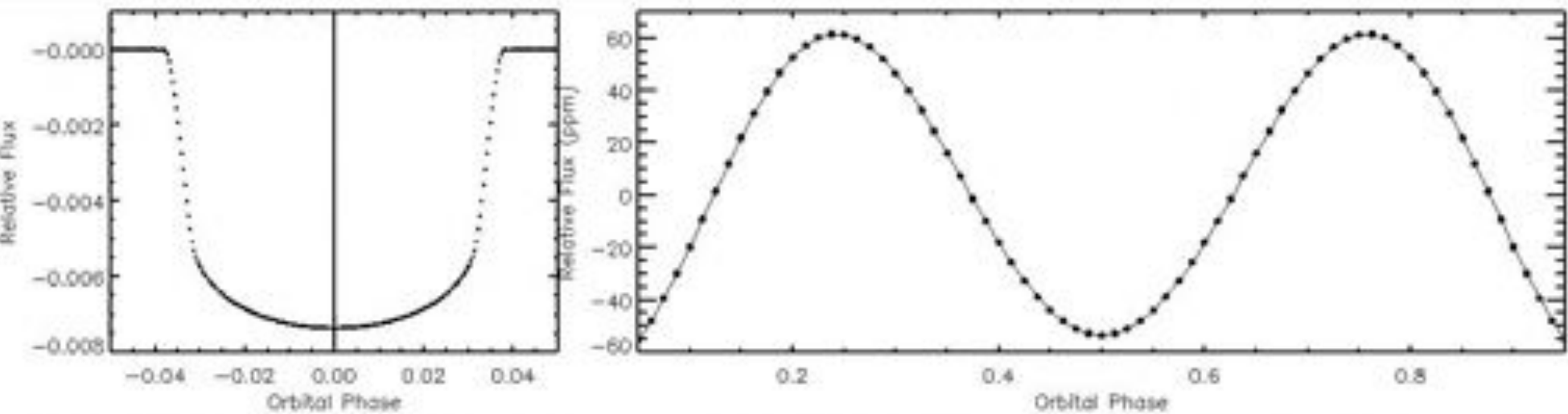
# Phase Curve



# Secondary Eclipse and Reflected Light/Thermal Emission

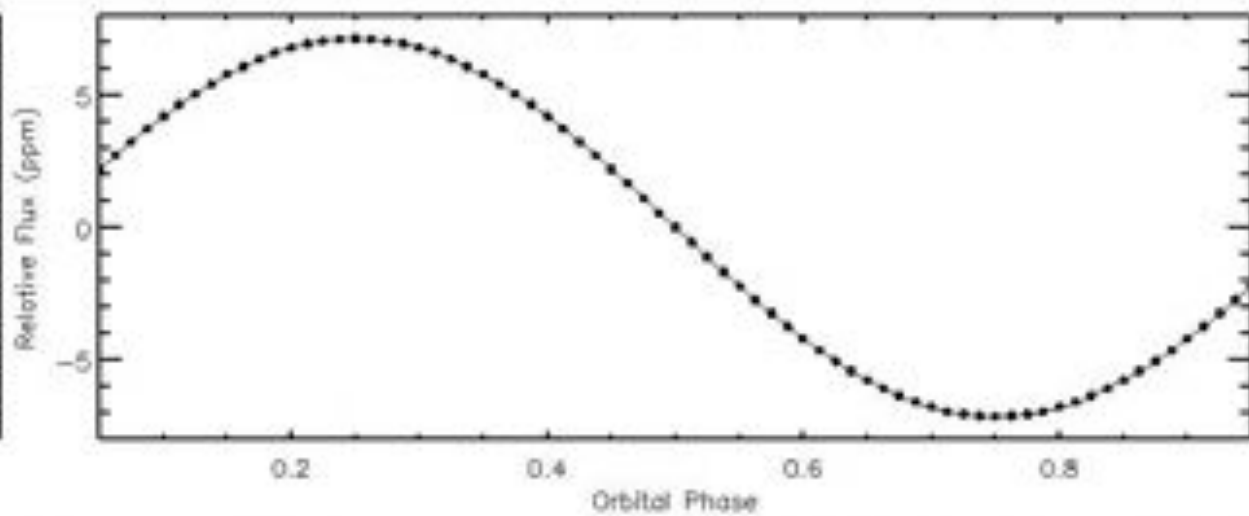
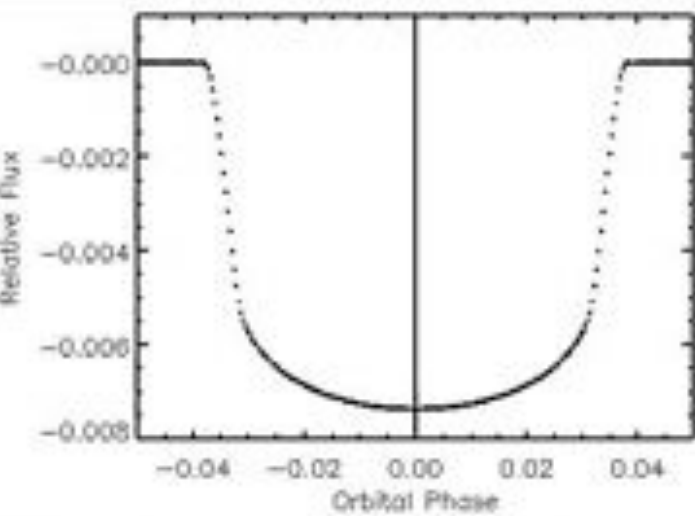


# Ellipsoidal Variations





# Doppler Beaming



# Phase Curve

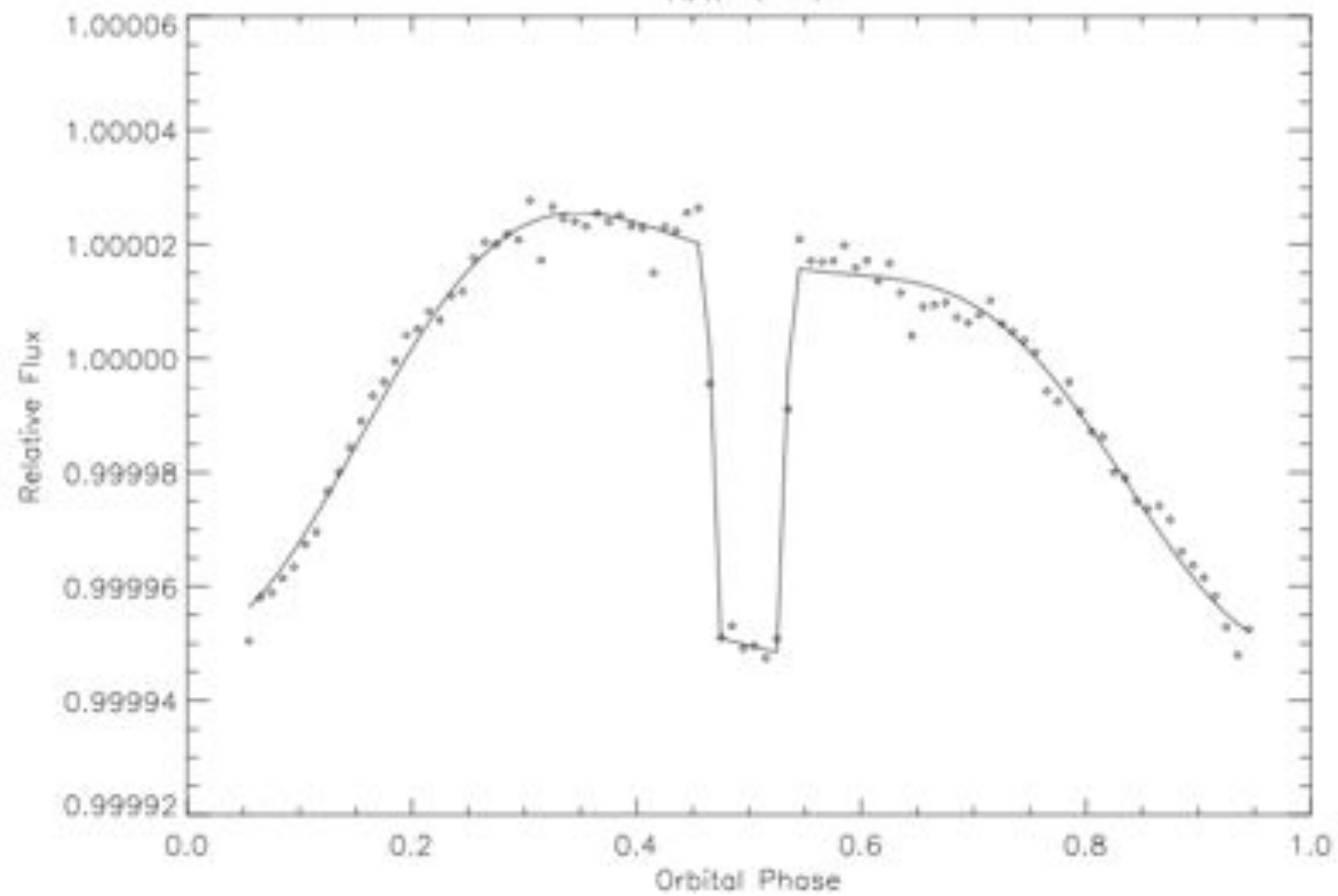
1. Planetary Light  
Reflected Light/Thermal Emission  
Secondary Eclipse
2. Ellipsoidal Variations
3. Doppler Beaming

- **Albedo**
- **Temperature**
- **Heat Distribution**

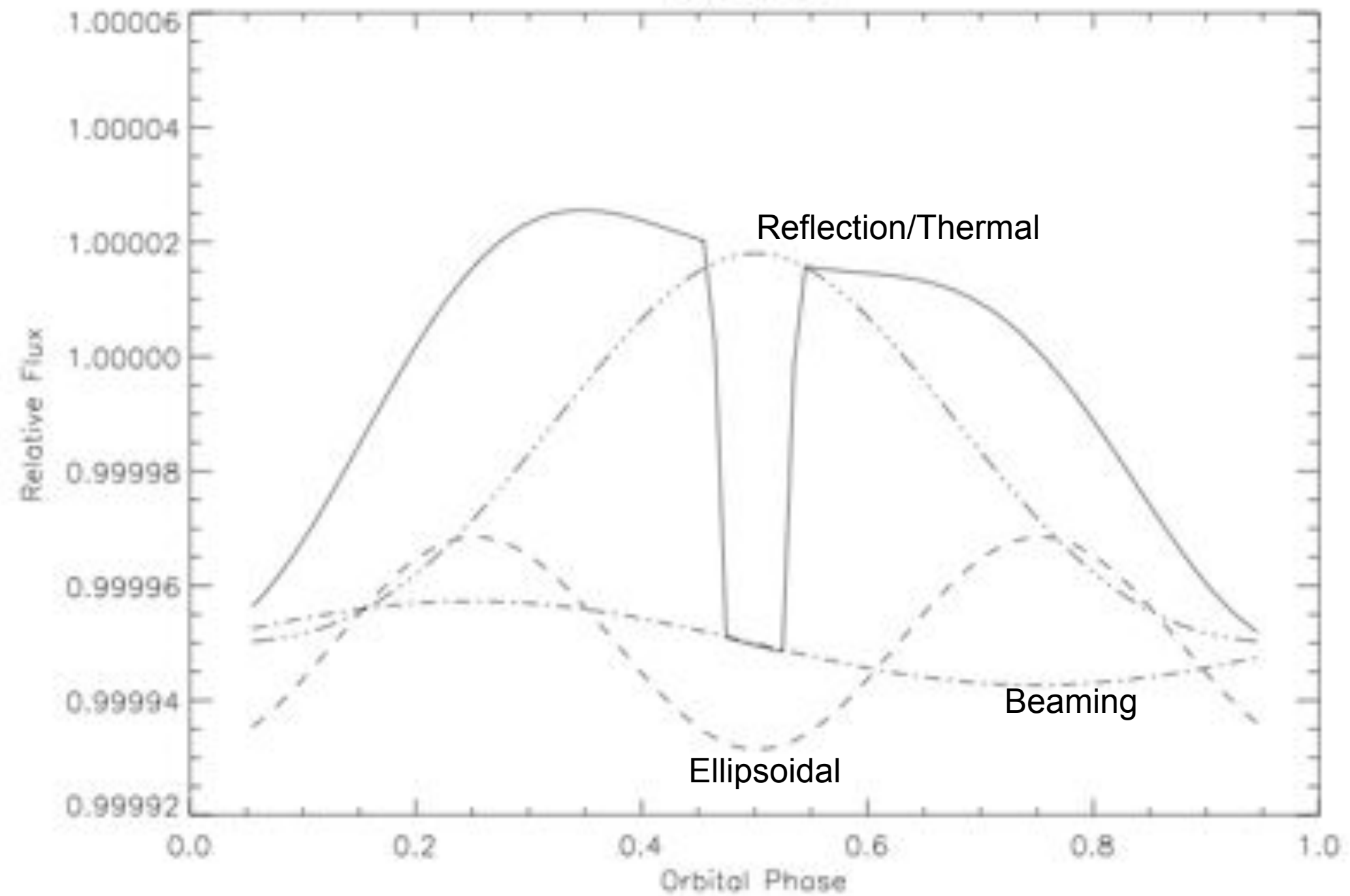
**Mass**



HAT-P-7

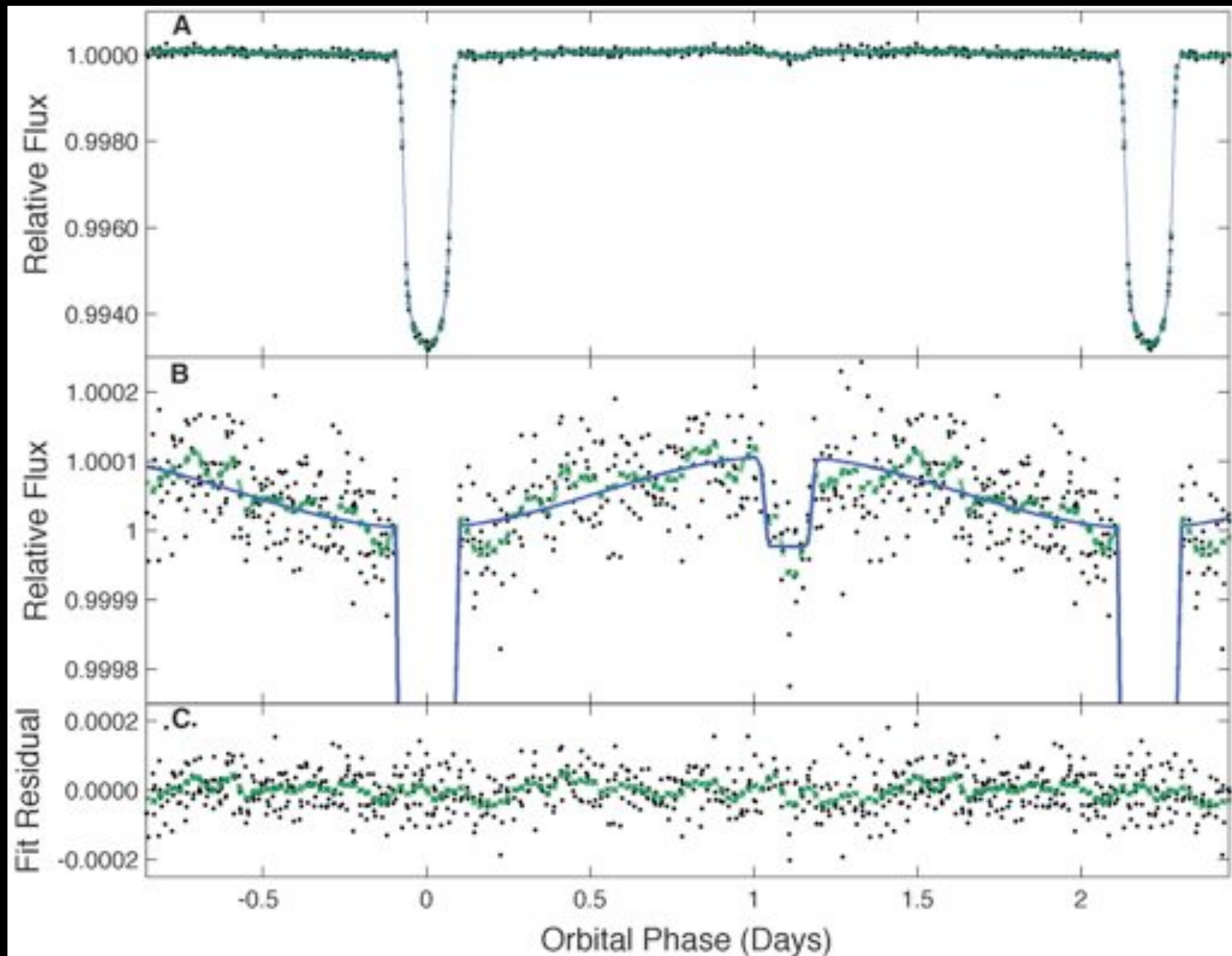


HAT-P-7



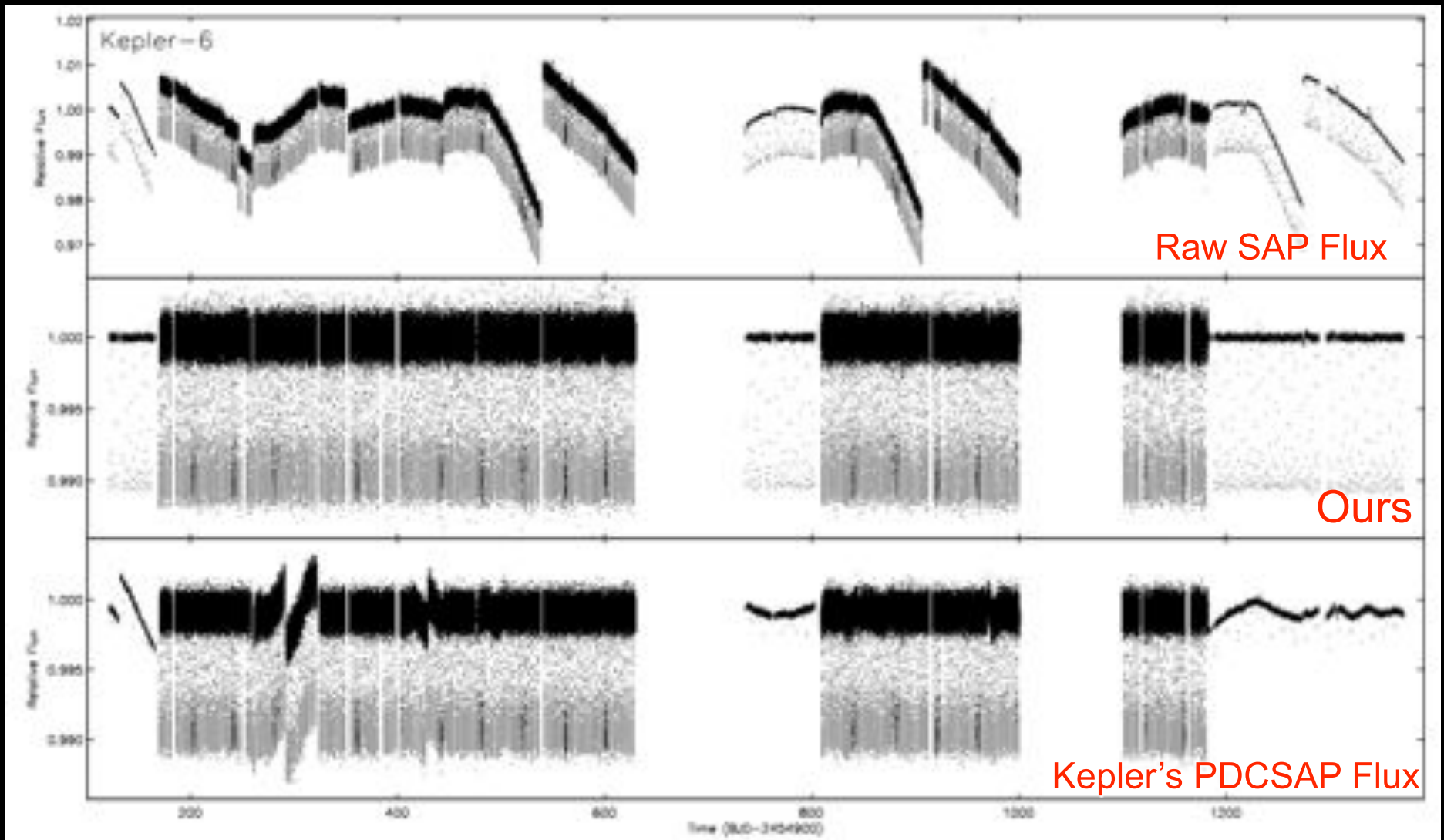


# HAT-P-7b

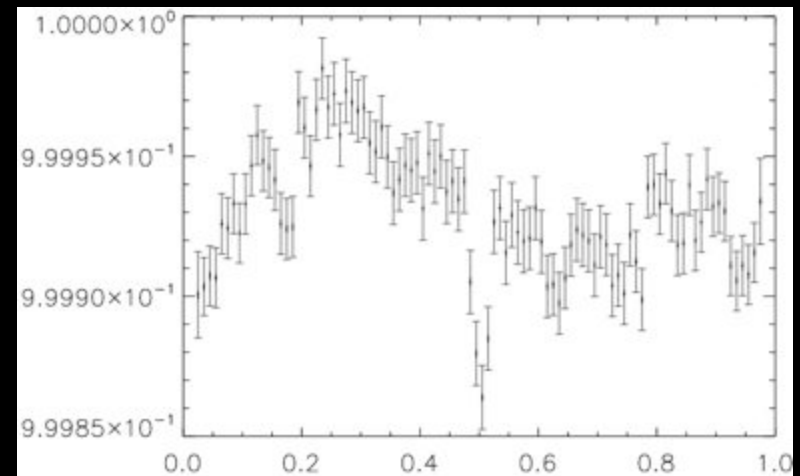
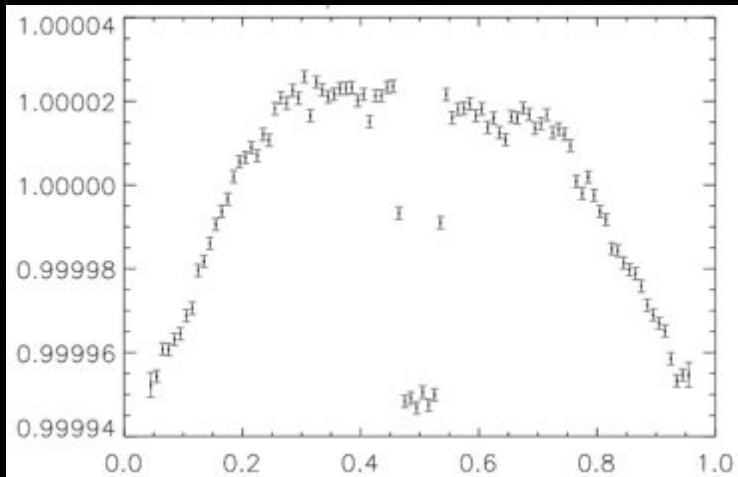
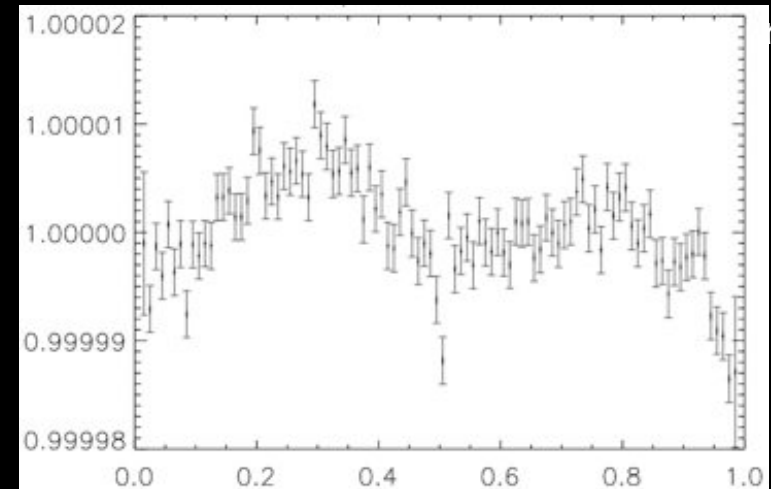
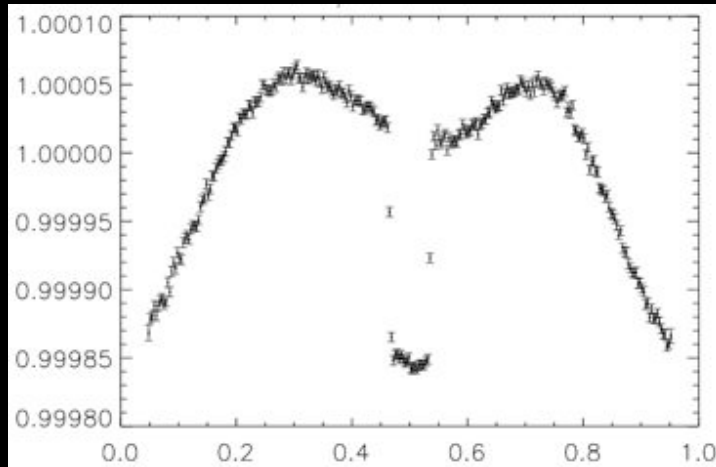


Borucki et al. (2009)

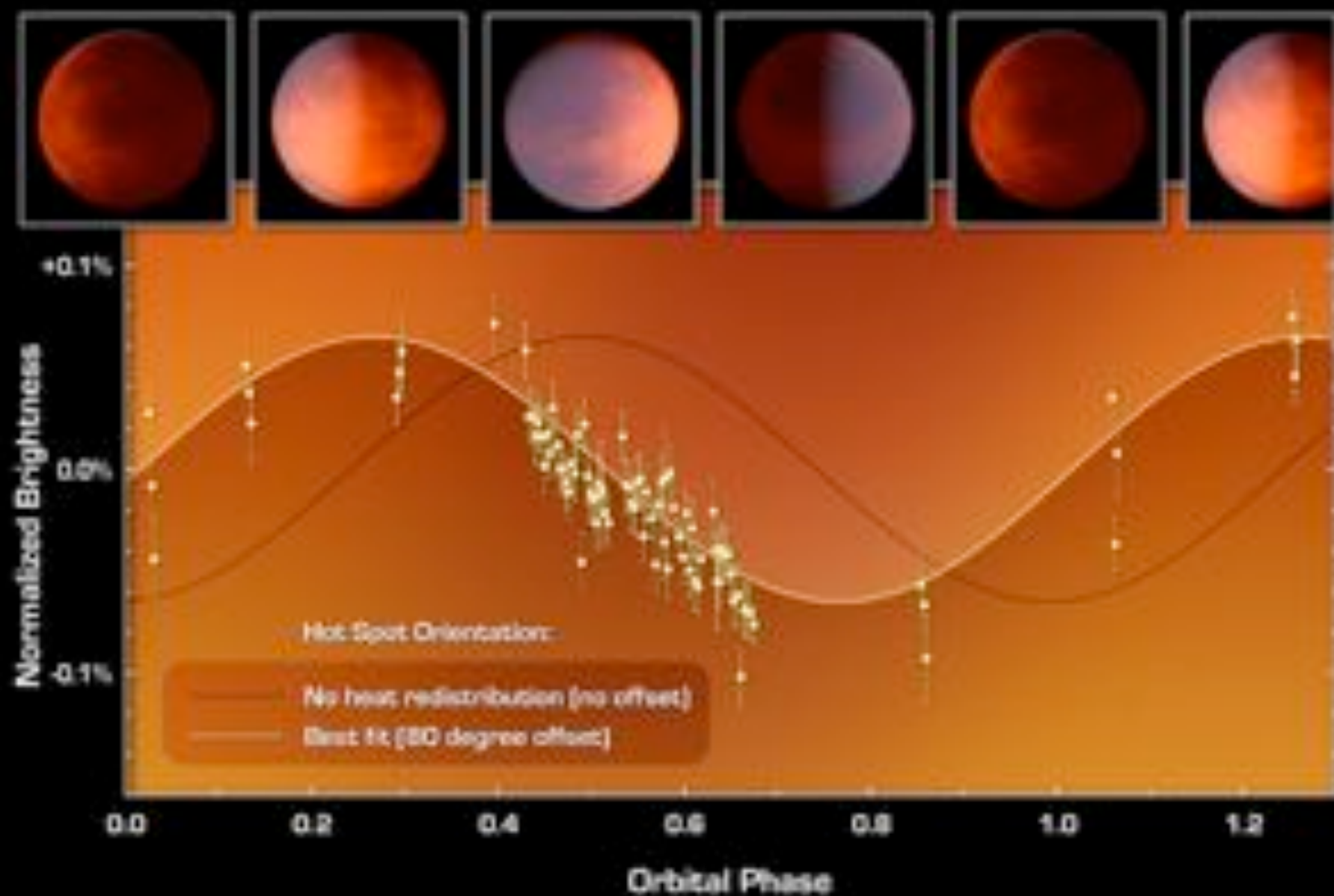
# Removal of Systematics



# Phase Curves of Kepler Planets



Esteves, de Mooij & Jayawardhana (in press)



Hot Spot Exoplanet in Andromeda

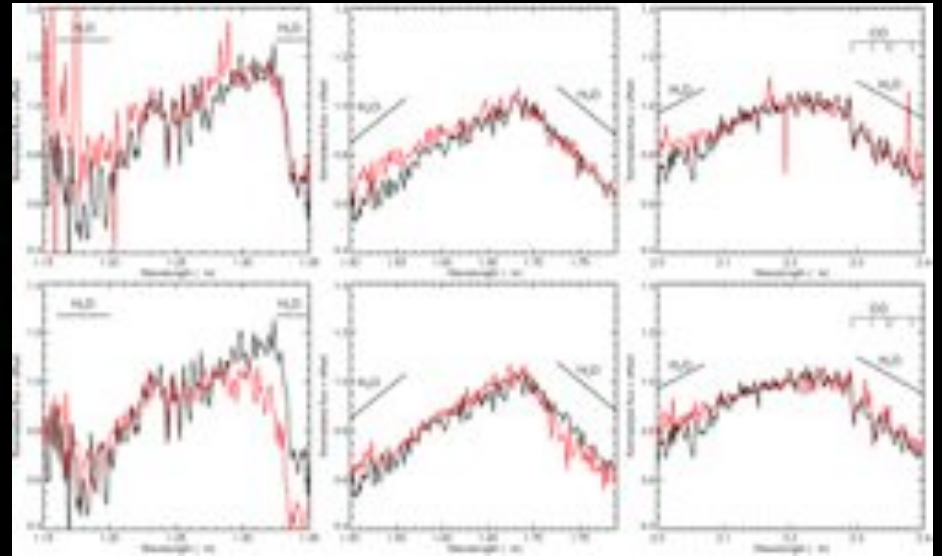
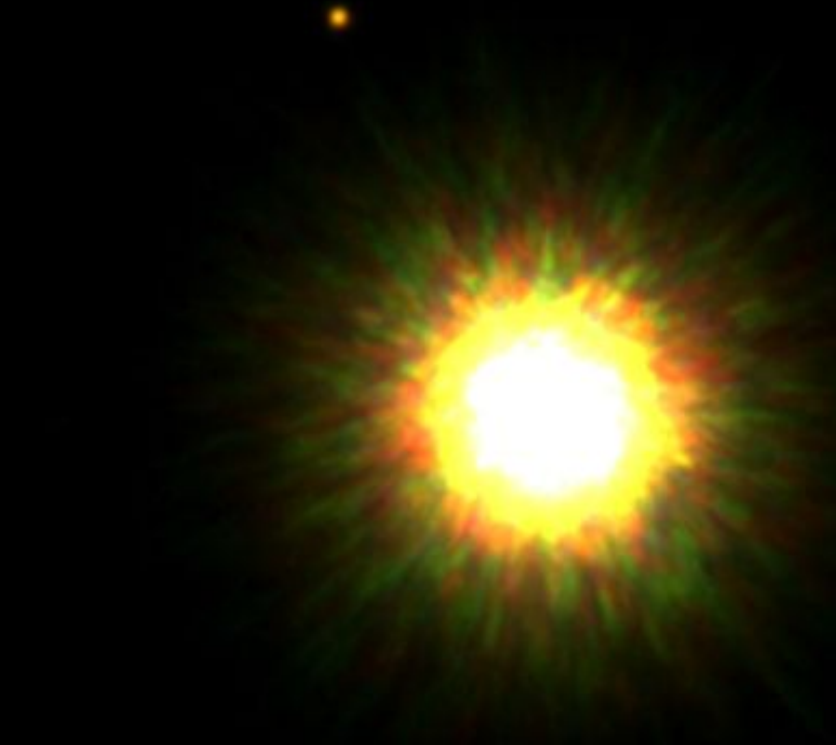
NASA / JPL-Caltech / L. A. M. Crossfield (UCLA)

Spitzer Space Telescope • MIPS

sci.2010.008a

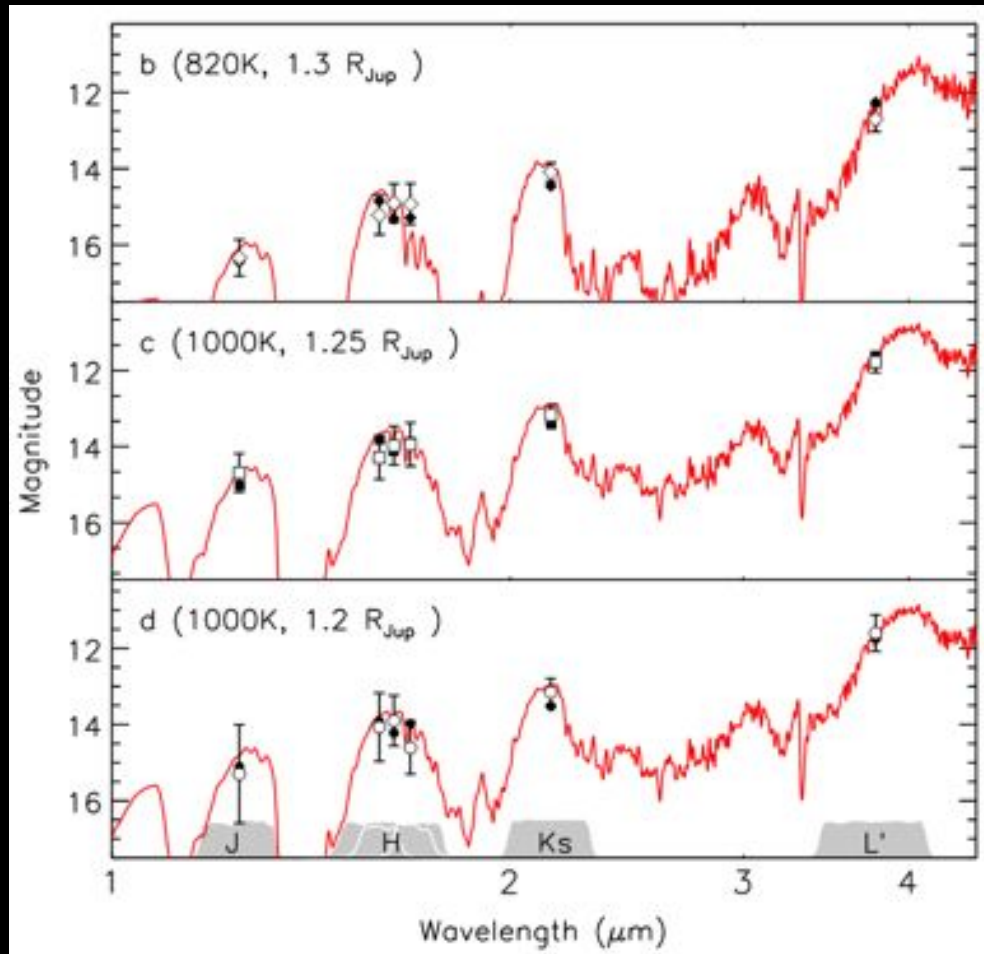


# Directly Imaged Exoplanets



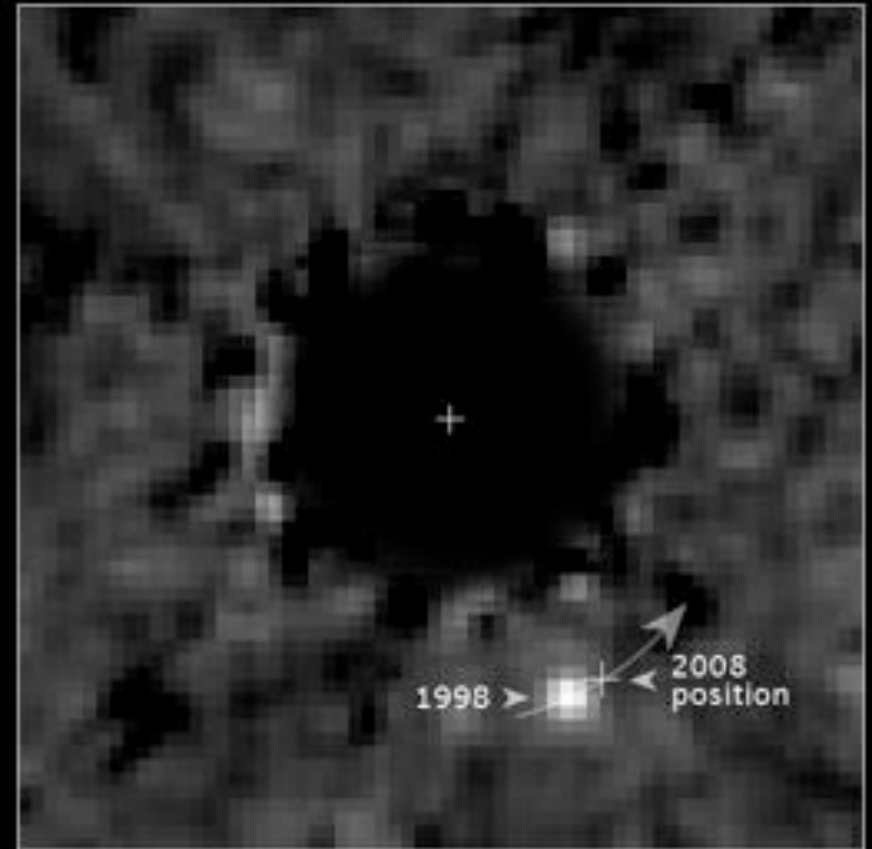
Lafreniere, Jayawardhana & van Kerkwijk (2008, 2010)

# HR 8799 Planets



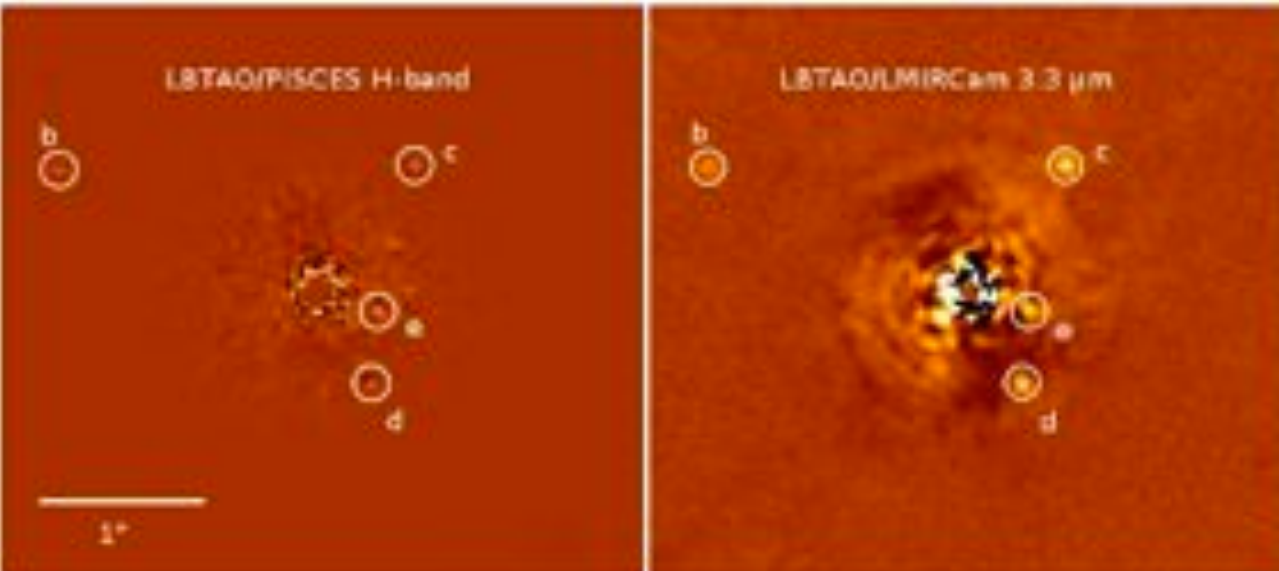
Marois et al. (2008)

Extrasolar Planet HR 8799b • 1998 HST • NICMOS

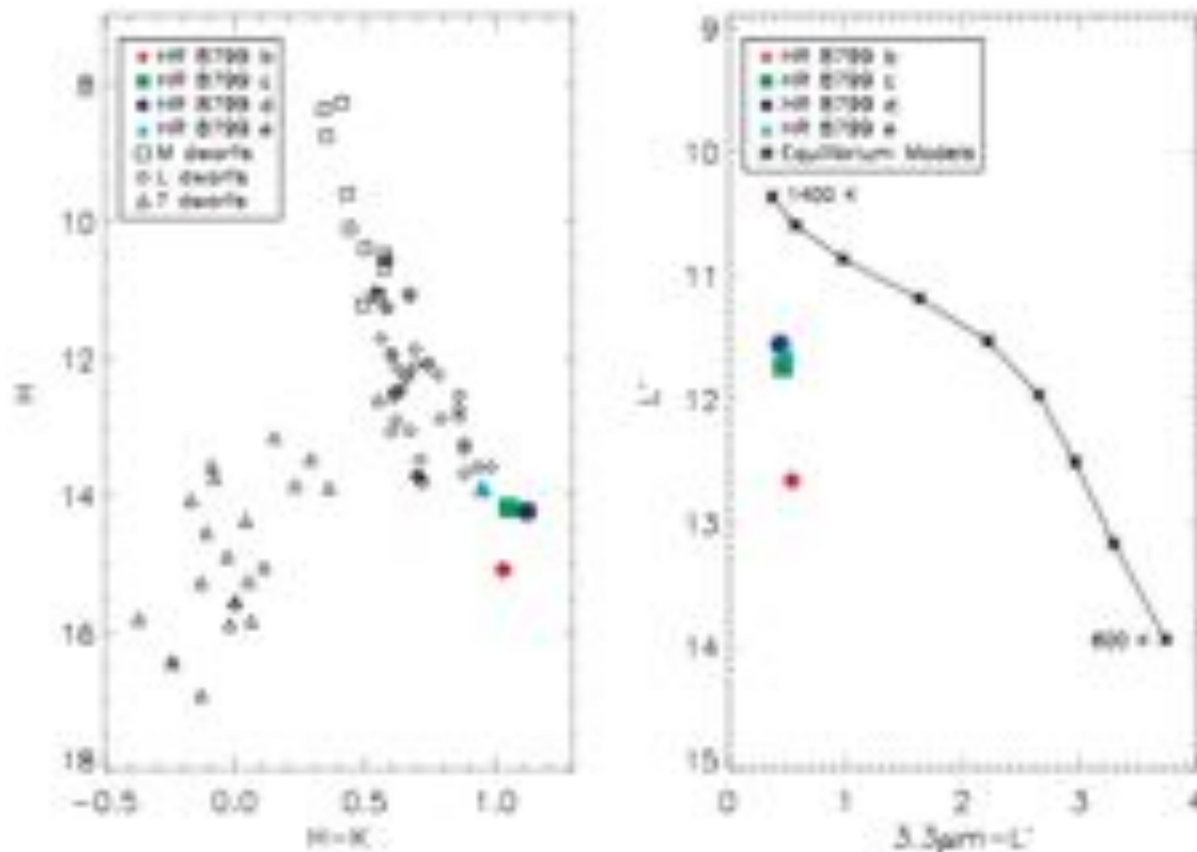


NASA, ESA, and D. Lafrenière (University of Toronto, Canada) STScI-PRC09-15b

Lafreniere et al. (2009)

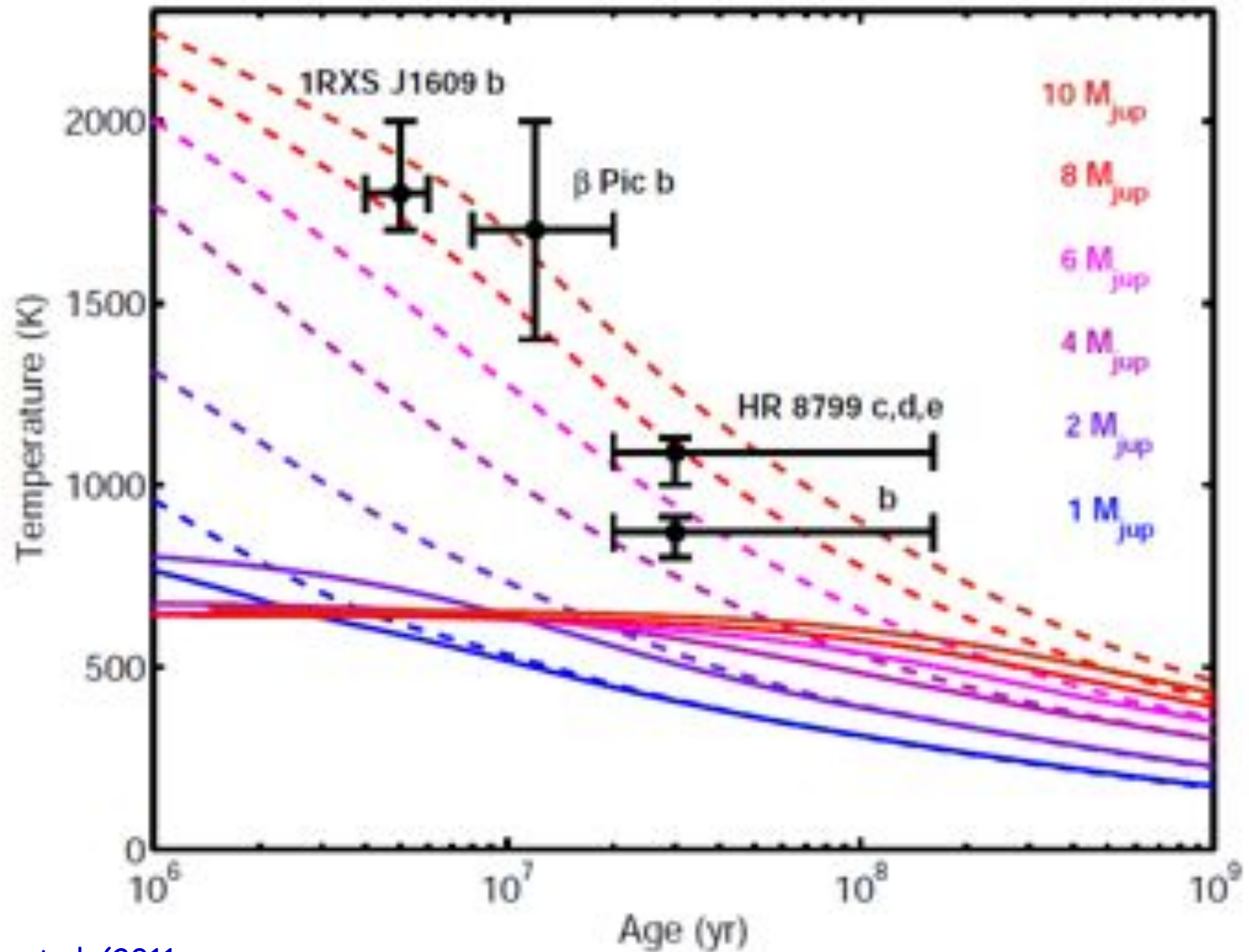


Multi-band  
imaging @ LBT–  
atmosphere  
characterization



Skemer et al. (2012)

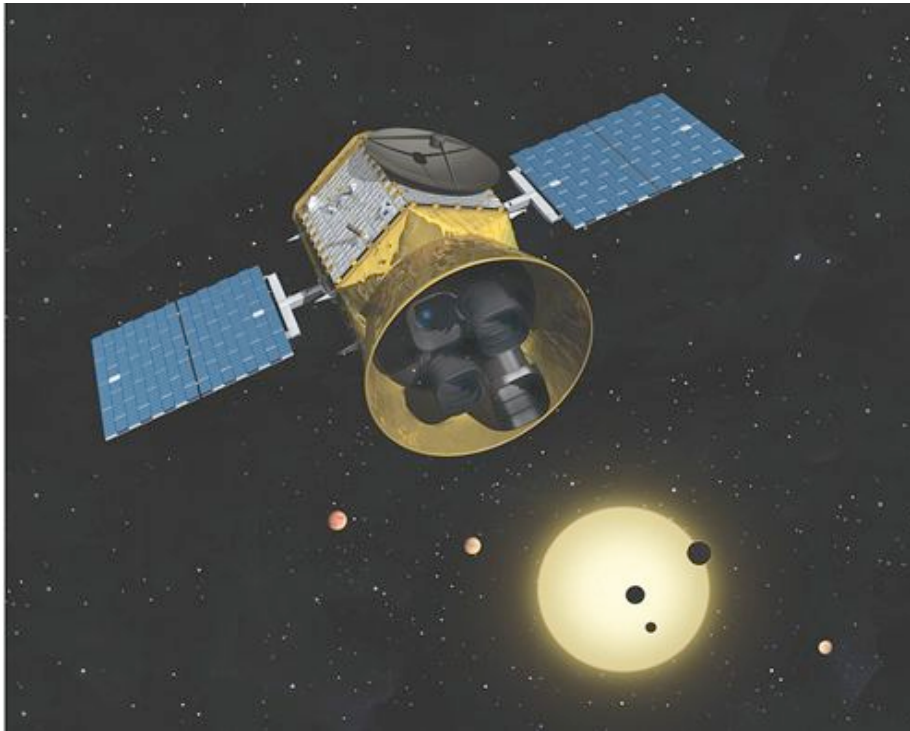
# `Hot Start' versus `Cold Start' Models



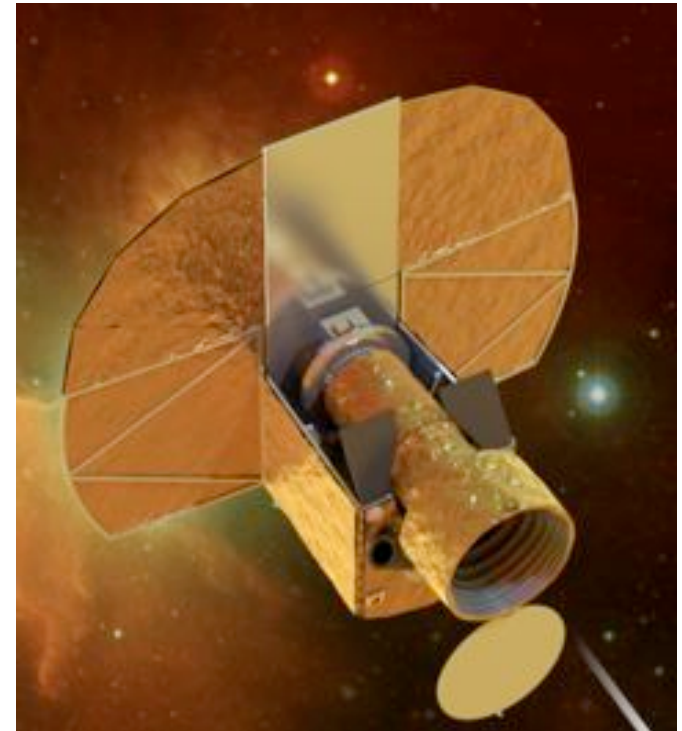
Janson et al. (2011;  
based on Fortney et al., 2008)

# Coming Attractions

**Transiting Exoplanet Survey Satellite  
(TESS, NASA, ~2017)**



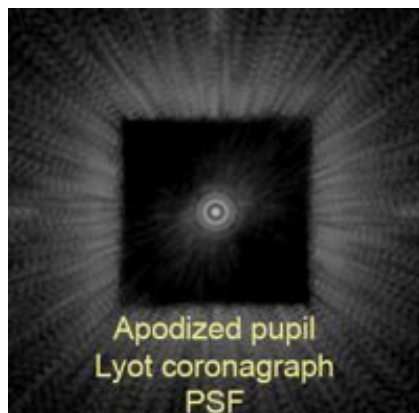
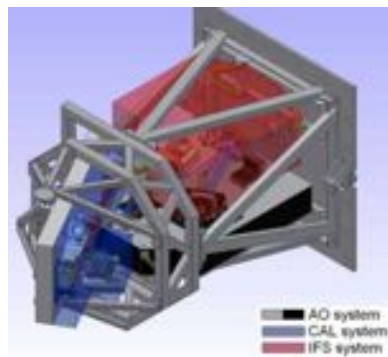
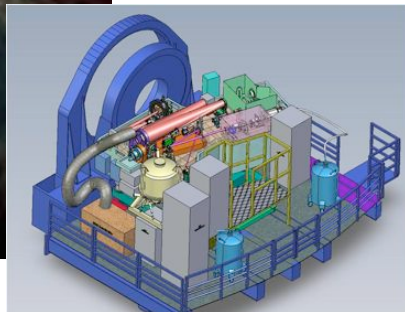
**Characterising Exoplanets Satellite  
(CHEOPS, ESA, ~2017)**







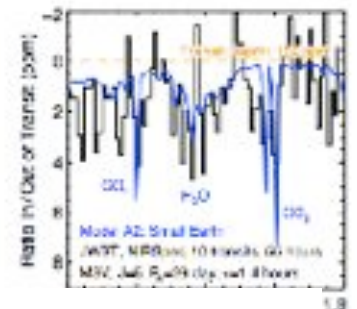
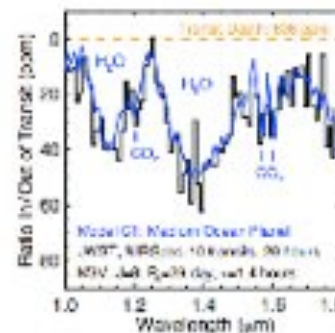
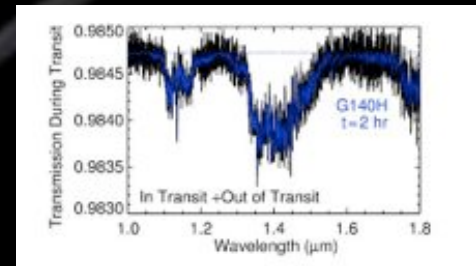
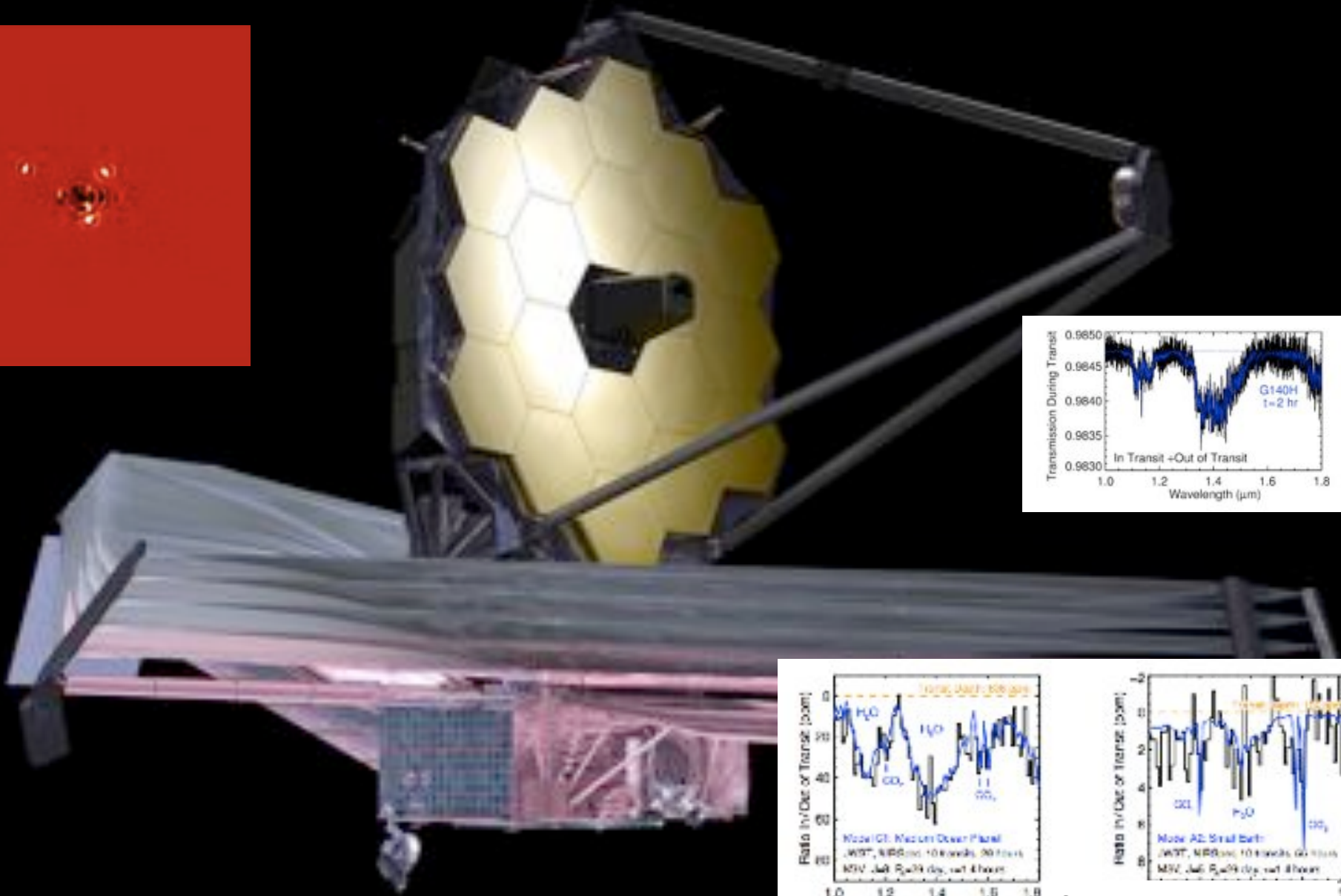
## Extreme AO Imagers



Direct imaging searches of nearest young stars for giant planets in wide orbits with extreme AO instruments on Gemini and VLT by ~2014

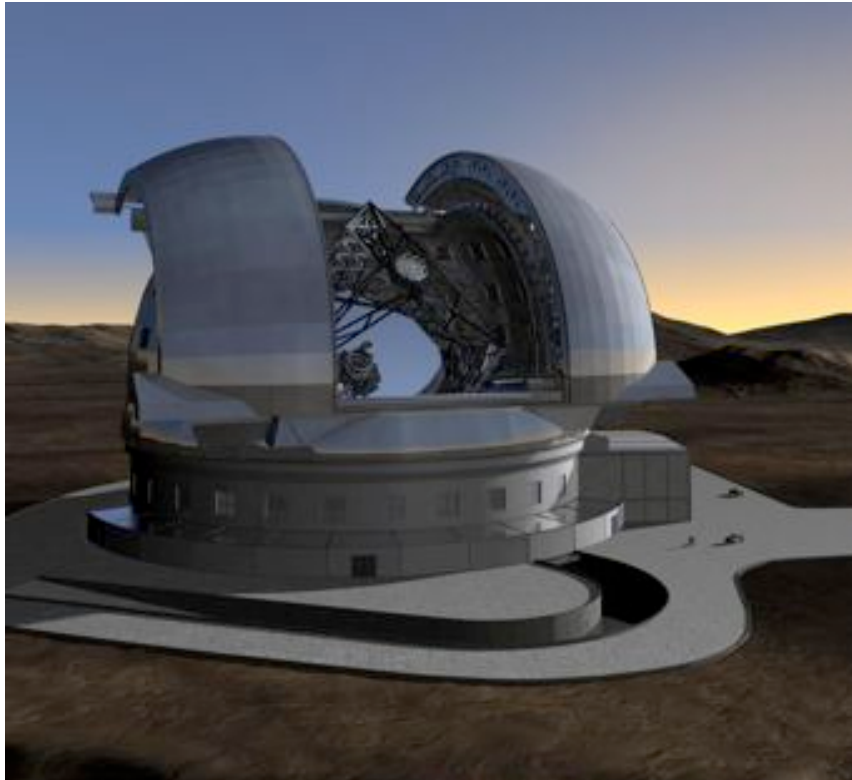
Better sense of planetary system diversity

# James Webb Space Telescope ~2018



Seager et al.

In the longer term



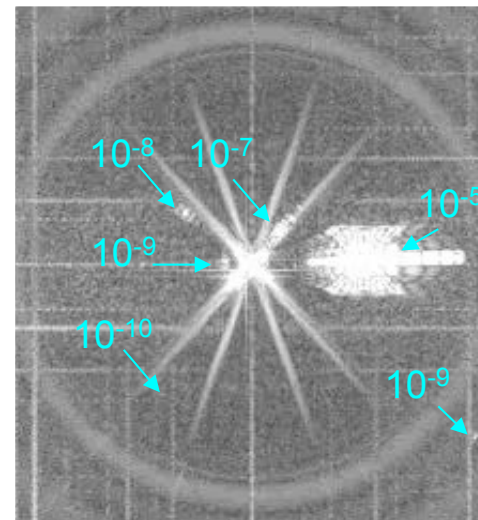
## European Extremely Large Telescope (E-ELT)

Instrument: Planet Imager and Spectrograph with Extreme Adaptive Optics (EPICS)



## Thirty-Meter-Telescope (TMT)

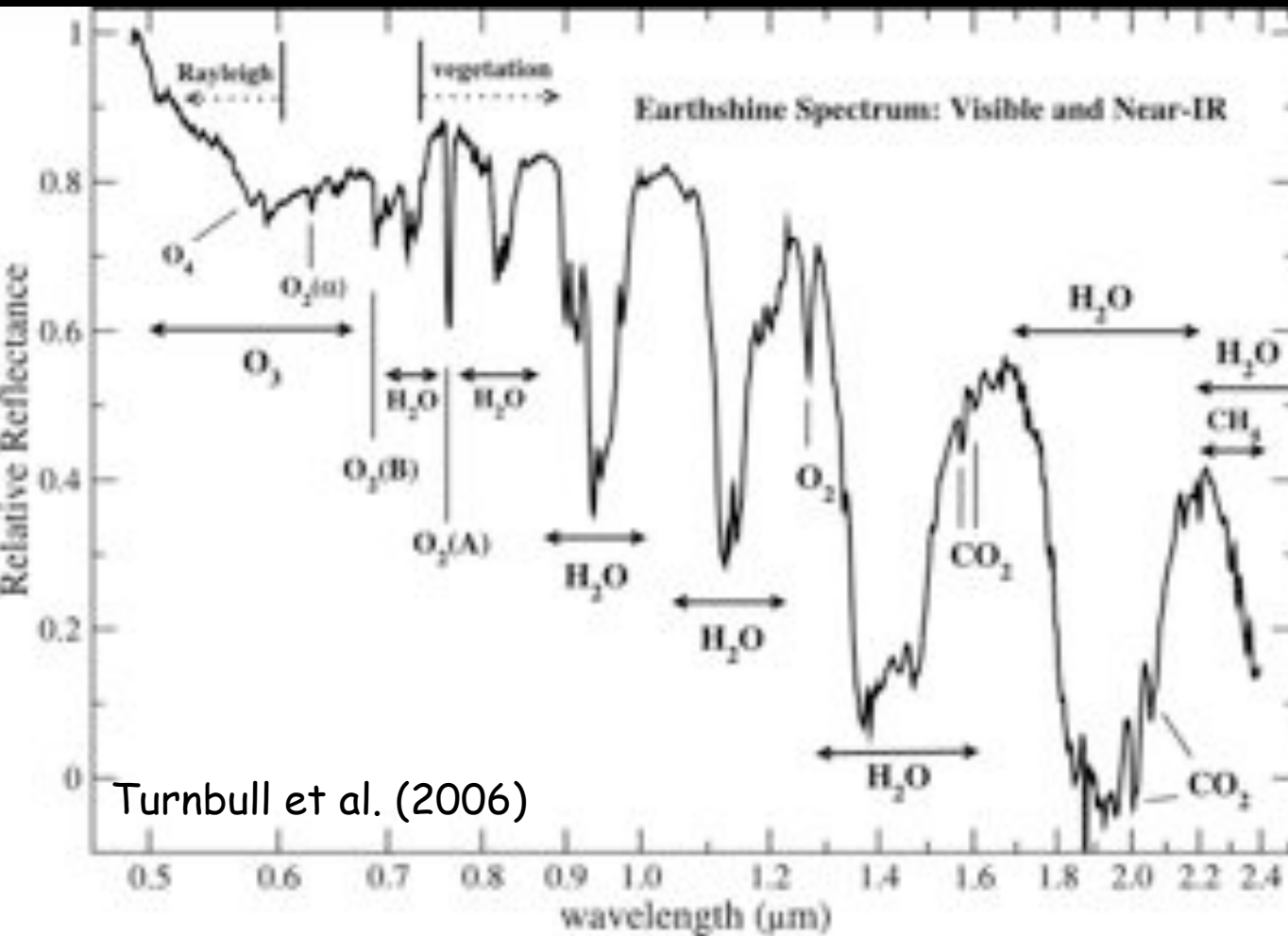
Instrument: Planet Formation Imager (PFI)



Exo-planet imaging in J-band  
Preliminary (EPICS team)



Relative Reflectance

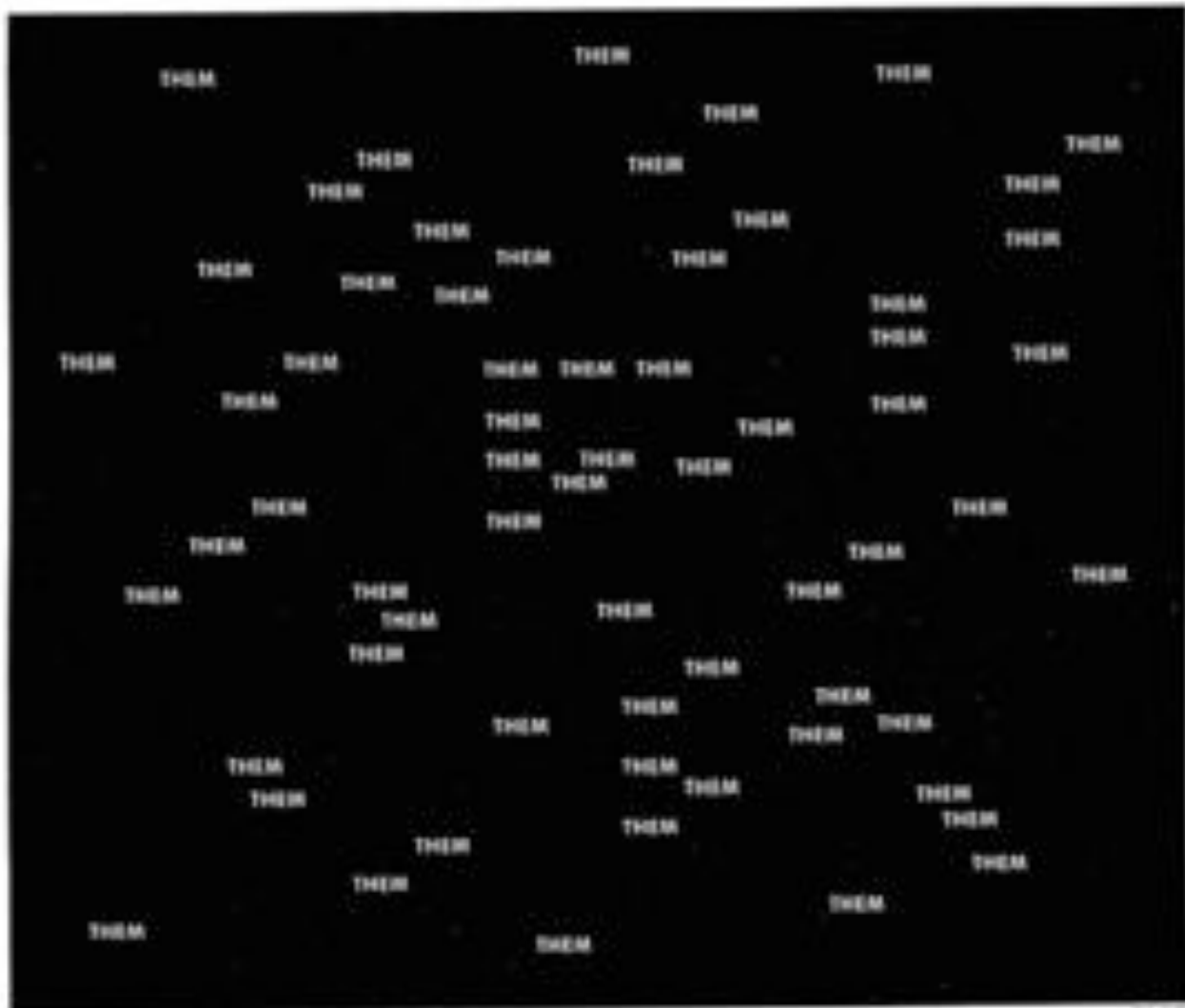


Alan C. Tough









## Alien Life, Coming Slowly Into View

By Ray Jayaram

**I** REMEMBER the first time the concept of another world entered my mind. It was during a walk with my father in our garden in Sri Lanka. He pointed to the Moon and told me that people had walked on it. I was astounded. Suddenly that bright light became a sphere that was cold and dark.

Schoolchildren may feel a similar sense of wonder when they see pictures of a Martian landscape or the

Two and a half years ago, we even managed to capture the first direct pictures of alien worlds. There is something about a photo of an alien planet — even if it only appears as a blurry dot next to a bright, overexposed star — that makes it “real.” Given that stars alone like Hubble’s and to the planetary nebulae built around them, we’ve required powerful optics and clever techniques. The essential tool is adaptive optics technology, which, in effect, takes the trouble out of the stars, thus providing sharper images from telescopes on the ground than would otherwise be possible.

At the core of this grand pursuit is one basic question:

the real life version will almost certainly be a lot less encouraging than the movies depicting alien invasions or crash-landing spacecraft.

The evidence may be circumstantial at first — one spectral line could be interpreted as indicating the presence of water, methane and oxygen — but more could be discovered. Perhaps the construction of new telescopes, to which our debts. Besides, we won’t know whether such “biomarkers” are an indication of alien or civilization. Most people will likely never see in color, more immediate evidence of life here on Earth while we wait for the first.

New York Times  
2011 March 27

The story of an  
unfolding revolution  
that could change  
the way we see  
ourselves and our  
place in the  
universe.

[twitter.com/DrRayJay](https://twitter.com/DrRayJay)

