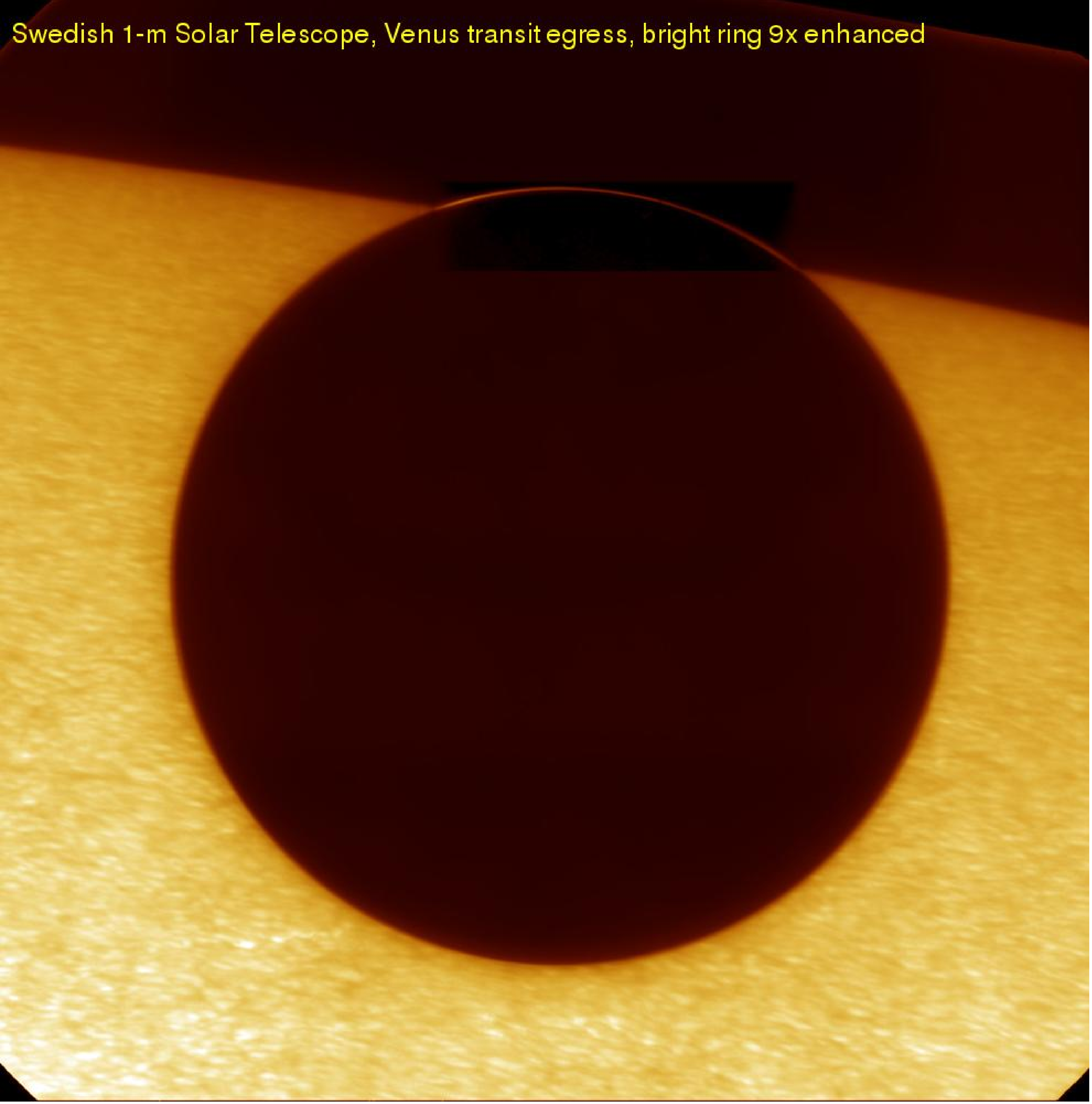


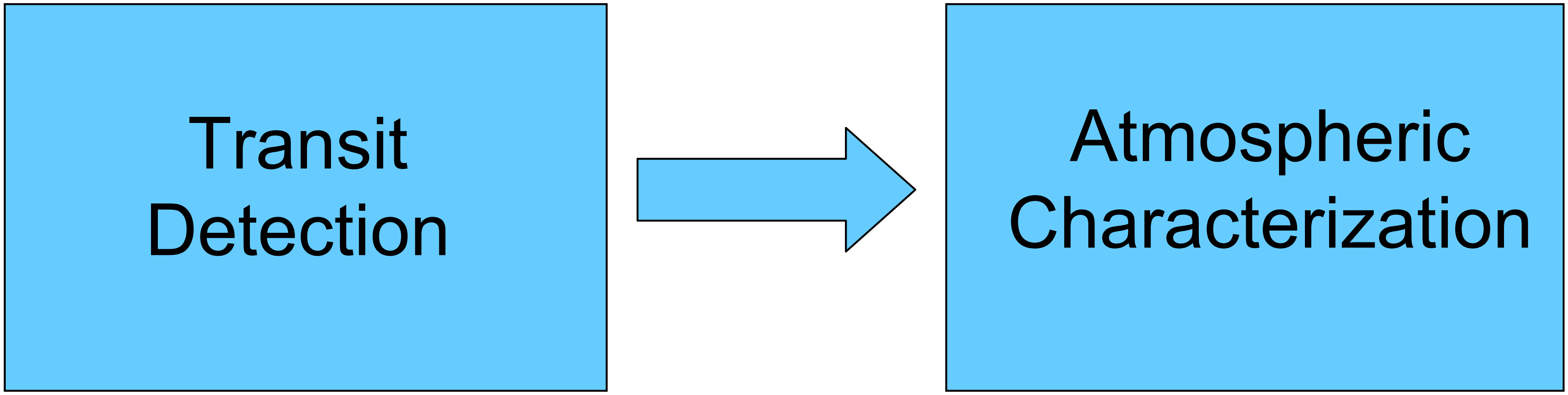
A Transitory Overview

David Charbonneau

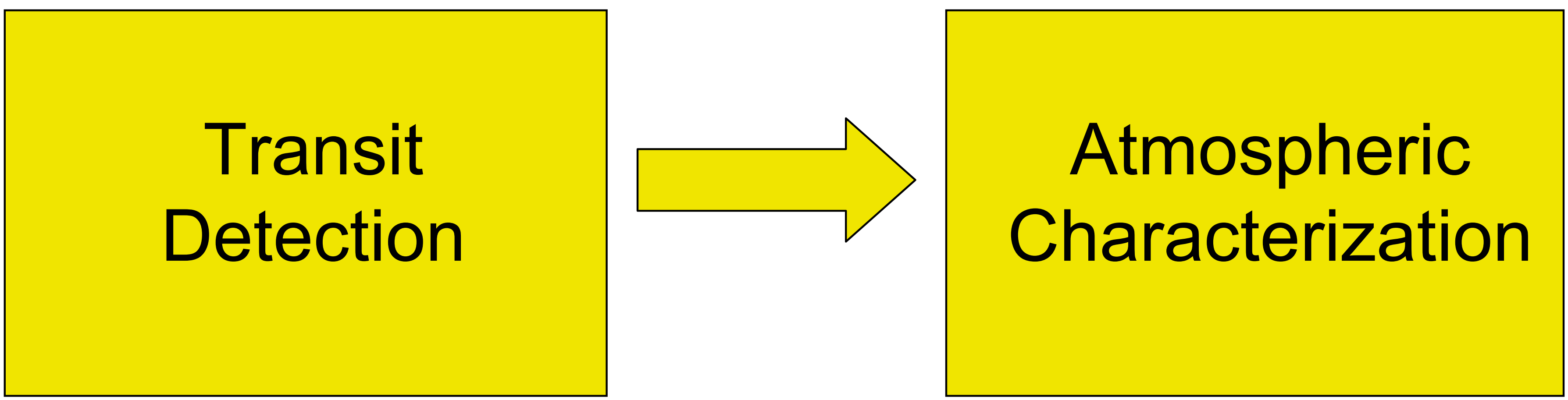
Harvard University

29 March 2010

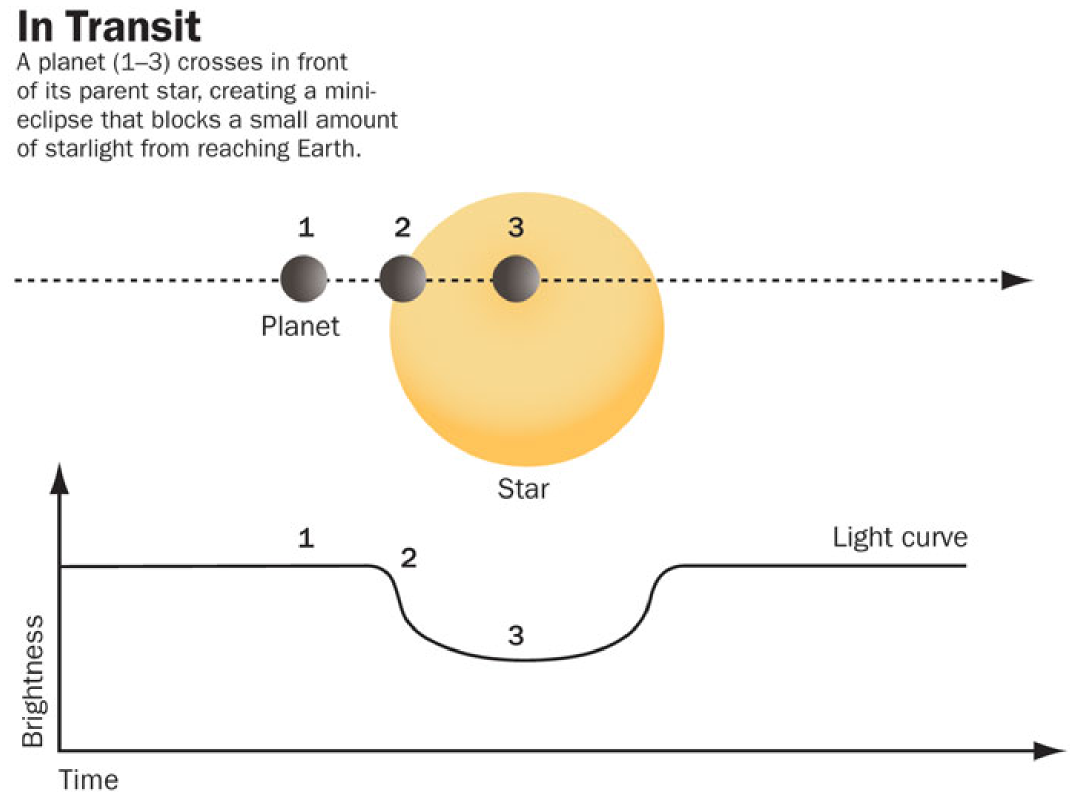
1999 – 2009: **Hydrogen + Helium Worlds**



2009+ : **Rock + Ice Habitable Worlds**



Why All the Fuss About Transiting Exoplanets?



- They permit direct **estimates of the masses and radii**.
- They permit **studies of the exoplanetary atmospheres**.
- They will enable the first**studies of the spectra of habitable worlds** beyond the Solar system.

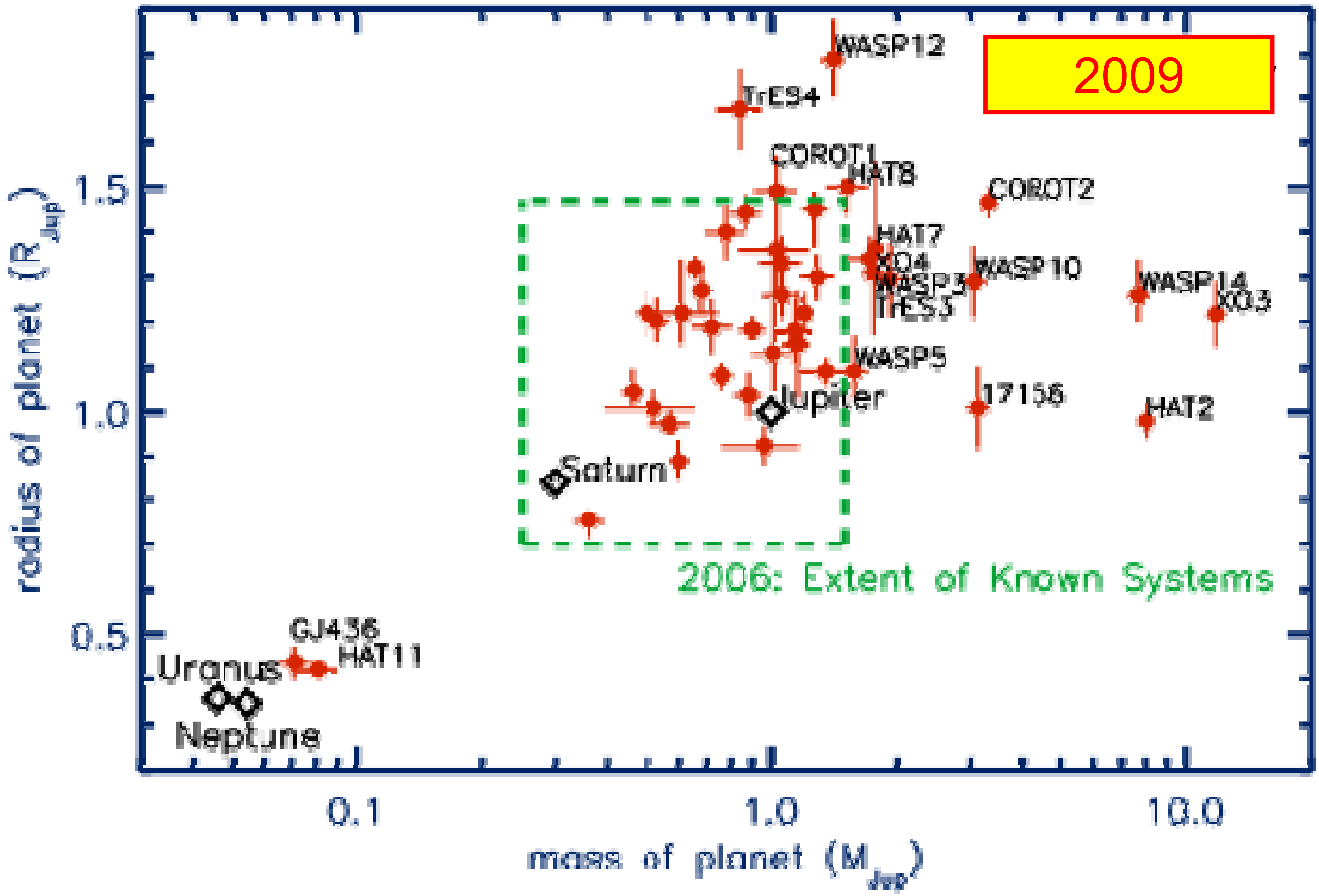
Giant Planet Masses and Sizes (Entire Universe)

1999

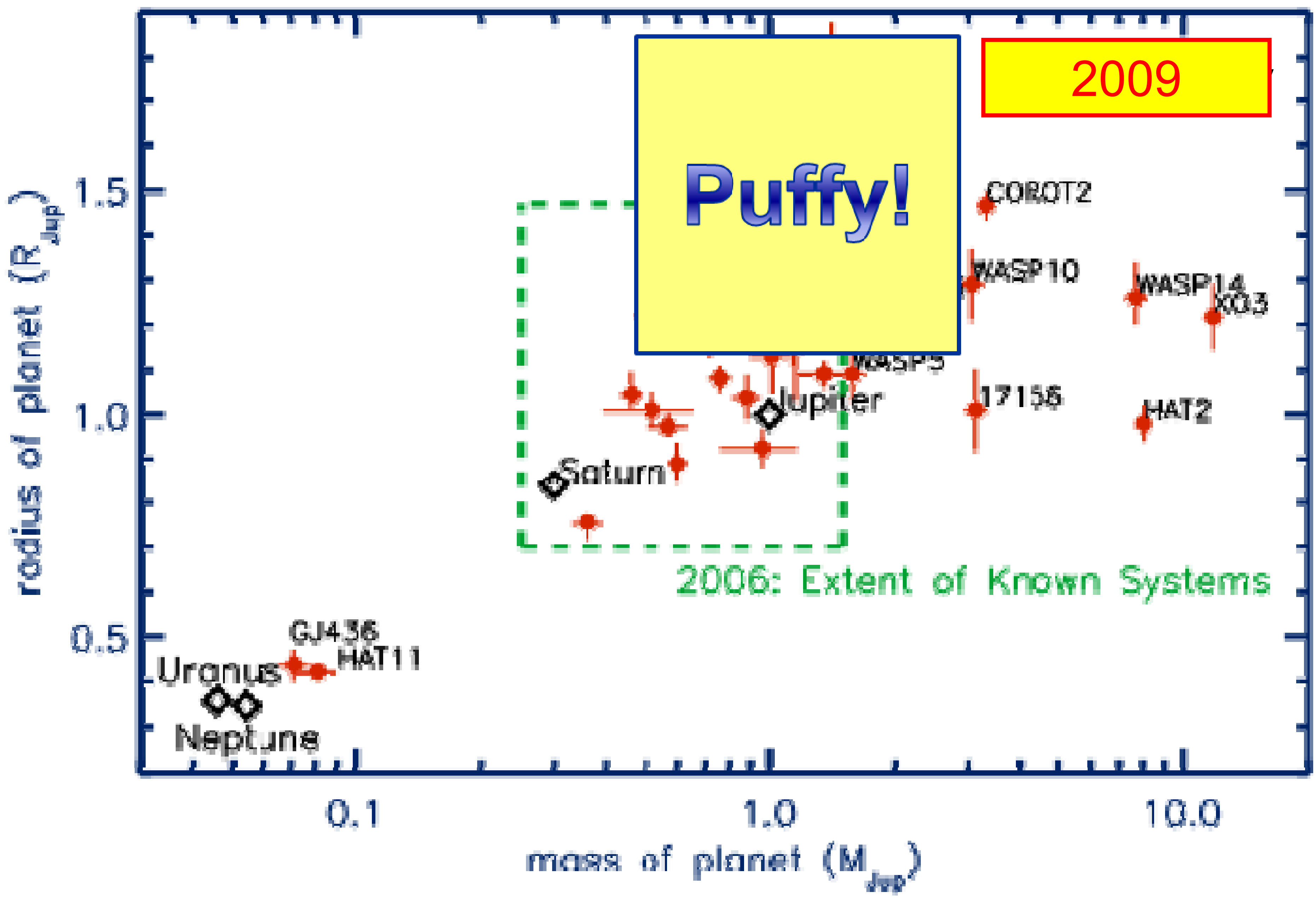
HD 209458b

Jupiter

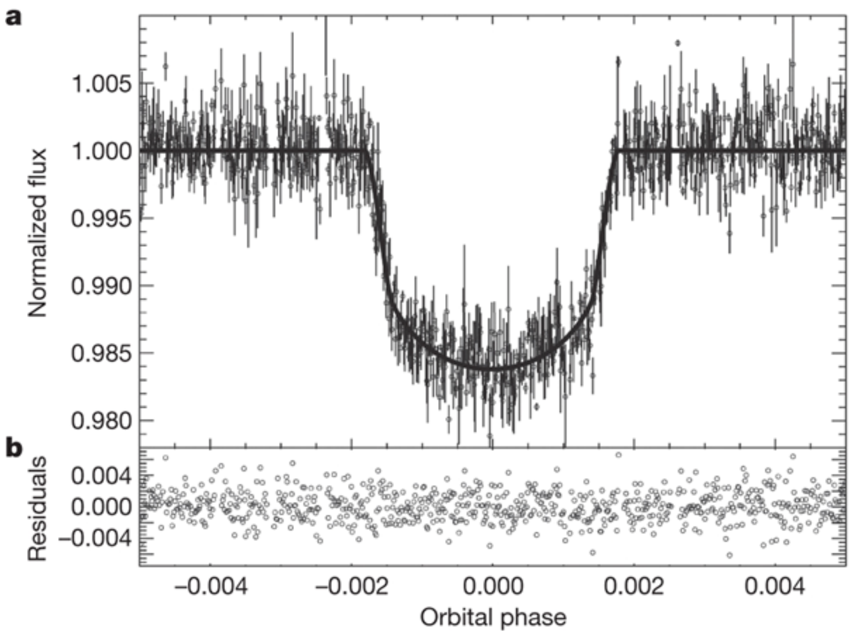
A Decade of Labor:
Giant Planet Masses and Sizes



The Puffy Planet Puzzle Remains

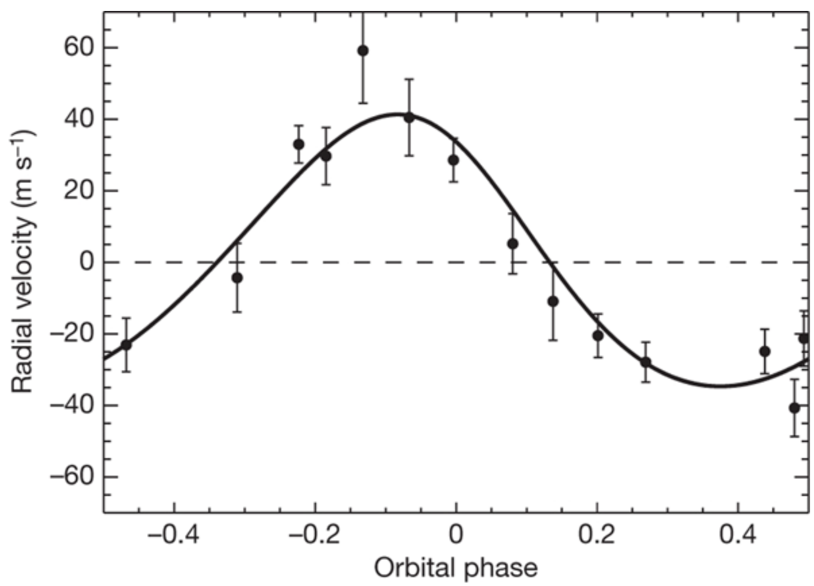


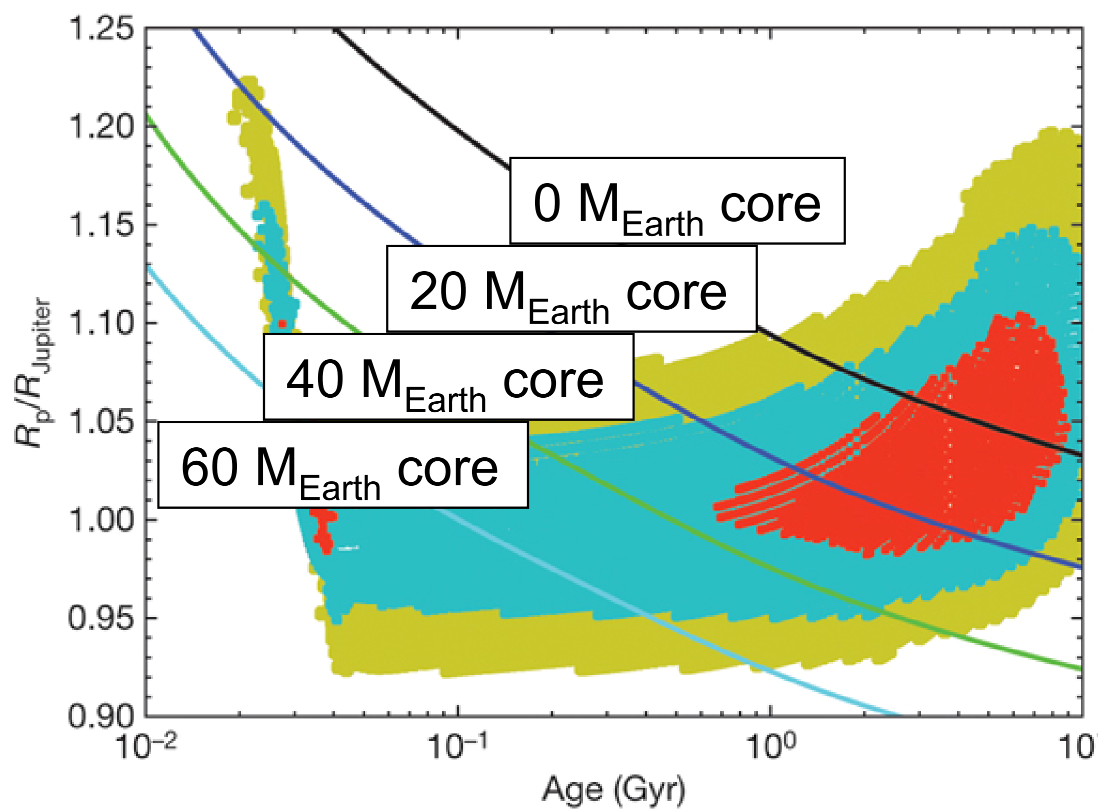
Welcome CoRoT-9b: The First Sensible Transiting Jupiter



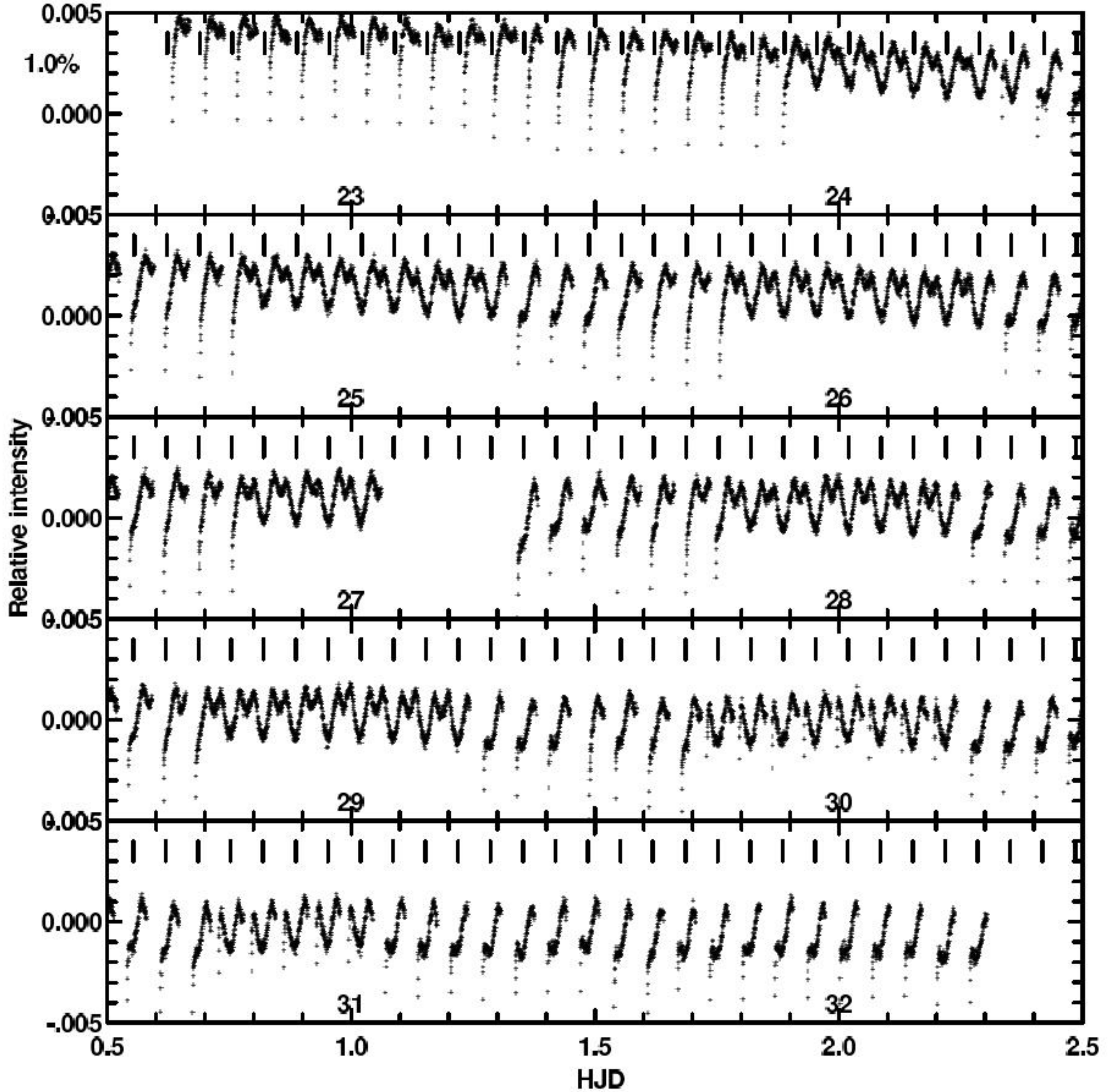
Largest Published Periastron 0.36 AU
Deeg et al. (2010)

All models for the inflated hot Jupiters invoke physical effect resulting from proximity to star. CoRoT-9b is a chance to test this assumption!





Asteroseismology
+ Transits
The Case of HD17156



Goals:

1. Two independent estimates of mean stellar density

2. Decent Estimate of System Age

Plan:

Observe HD17156 for 10 days and 3 additional transits with HST/FGS

PI: Ron Gilliland

Gilliland et al. 2010
Nutzman et al. 2010

Asteroseismology + Transits The Case of HD17156

<u>Goals:</u>

1. Two independent estimates of mean stellar density
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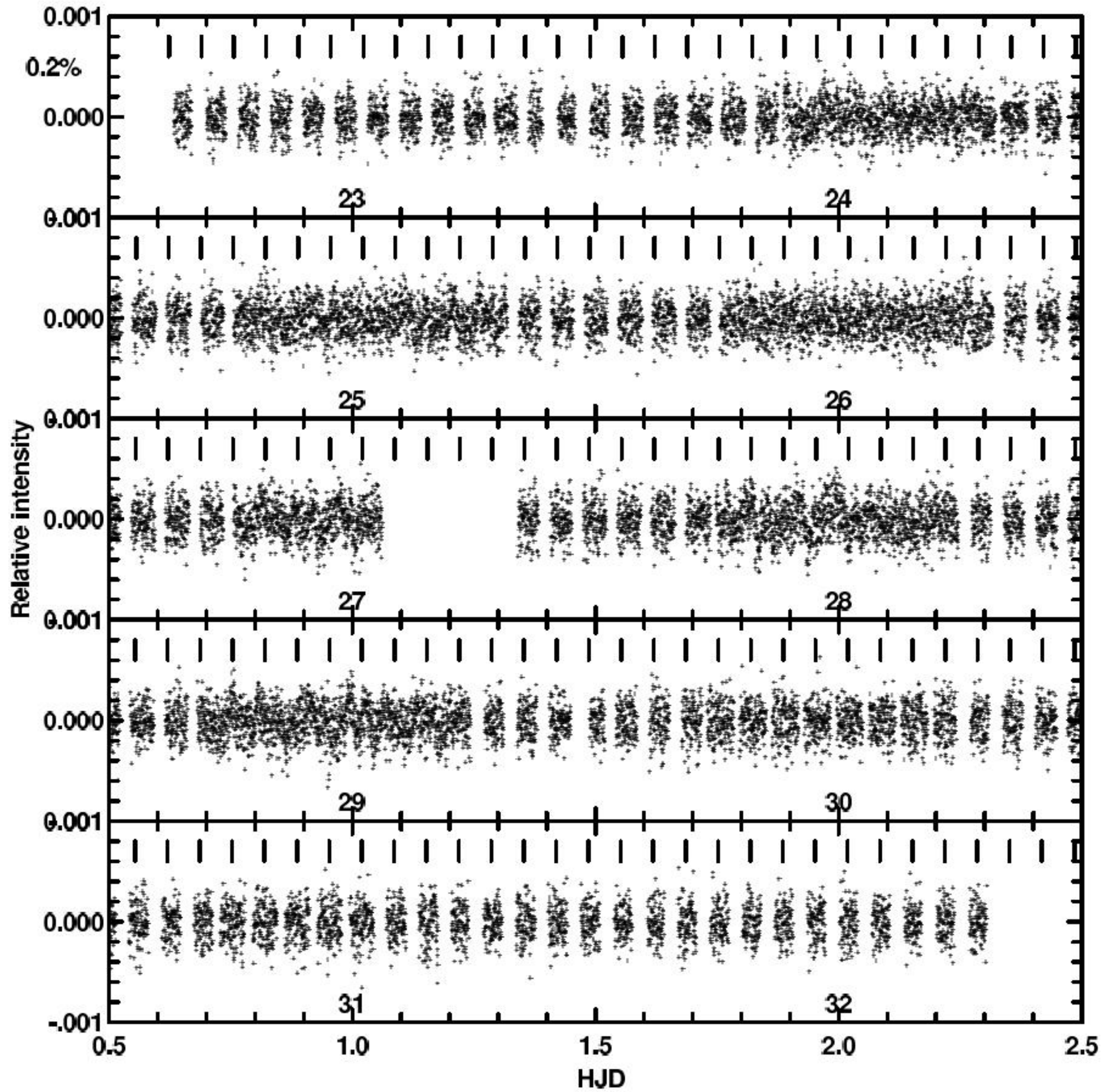
<u>PI:</u> Ron Gilliland



Gilliland et al. 2010
Nutzman et al. 2010

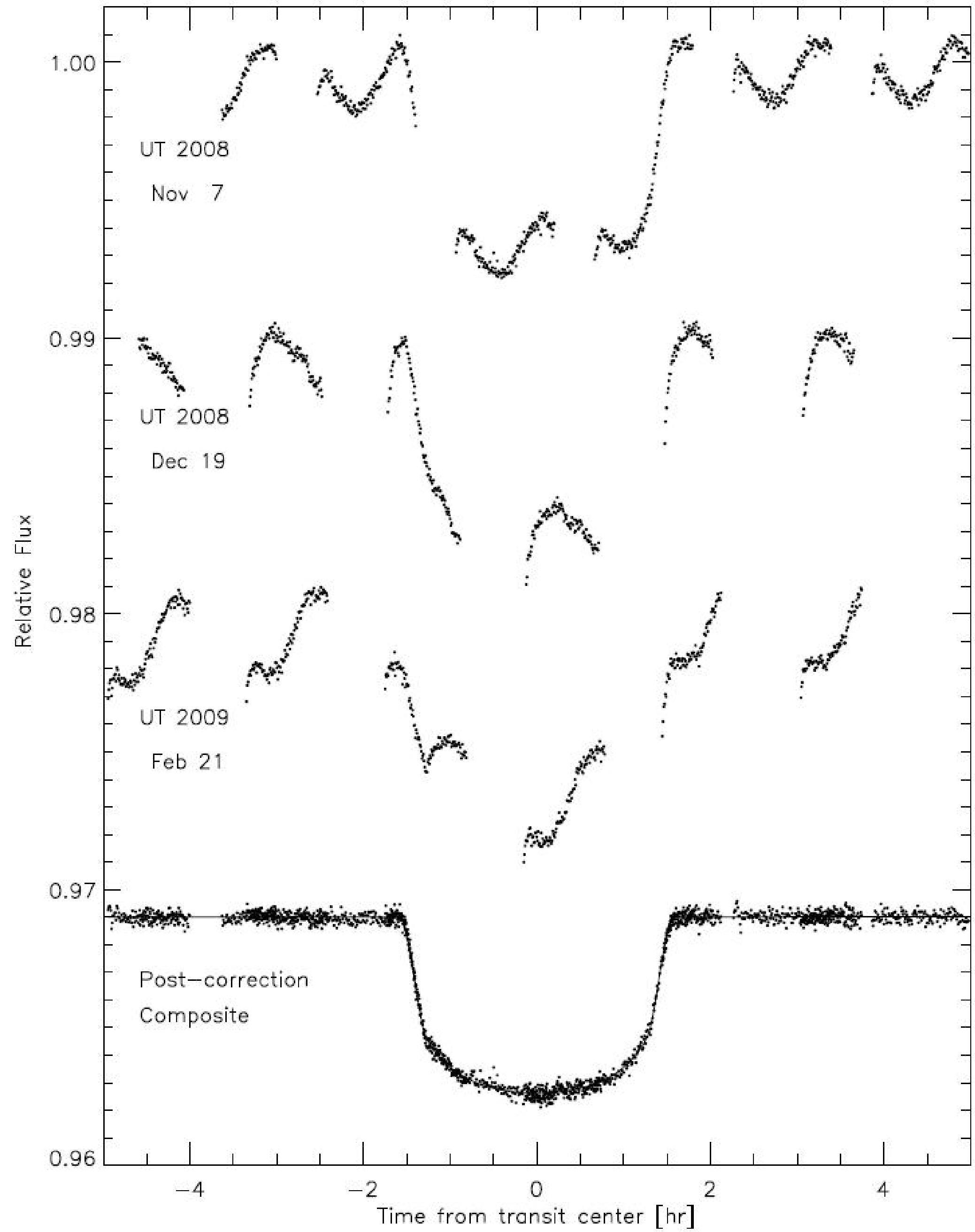
Asteroseismology
+ Transits
The Case of HD17156

Asterseismology:
$\rho_* = 0.5308 +/- 0.004$ g cm^{-3}

Transit Photometry:
$\rho_* = 0.522 +/- 0.019$ g cm^{-3}

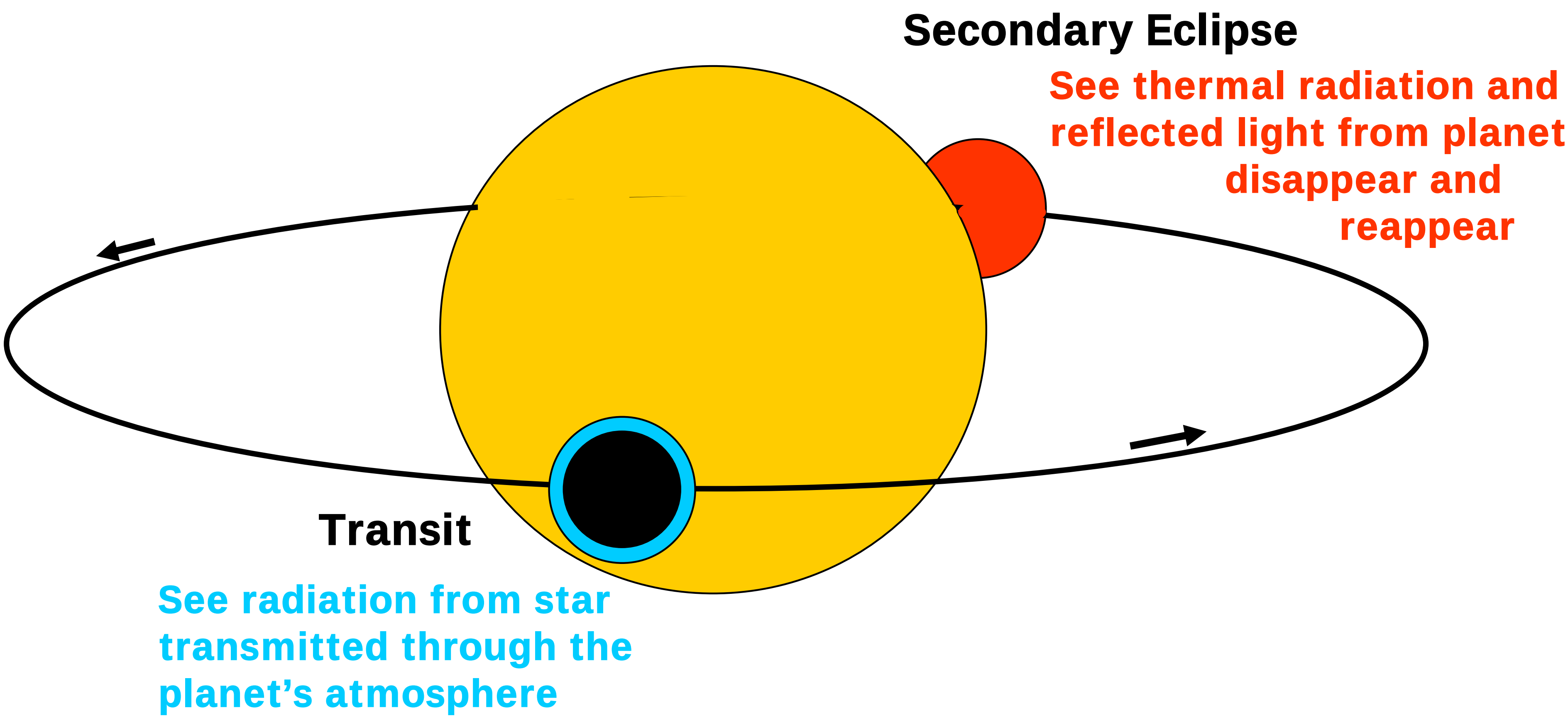
Age:
$3.37^{+0.20}_{-0.47}$Gyr

Radius of planet
$1.0870 +/- 0.0066\ R_{Jup}$
<u>including</u> M_* uncertainty



Gilliland et al. 2010
Nutzman et al. 2010

Transits Allows Studies of the Atmospheres That Are Not Possible for Non-Transiting Planets



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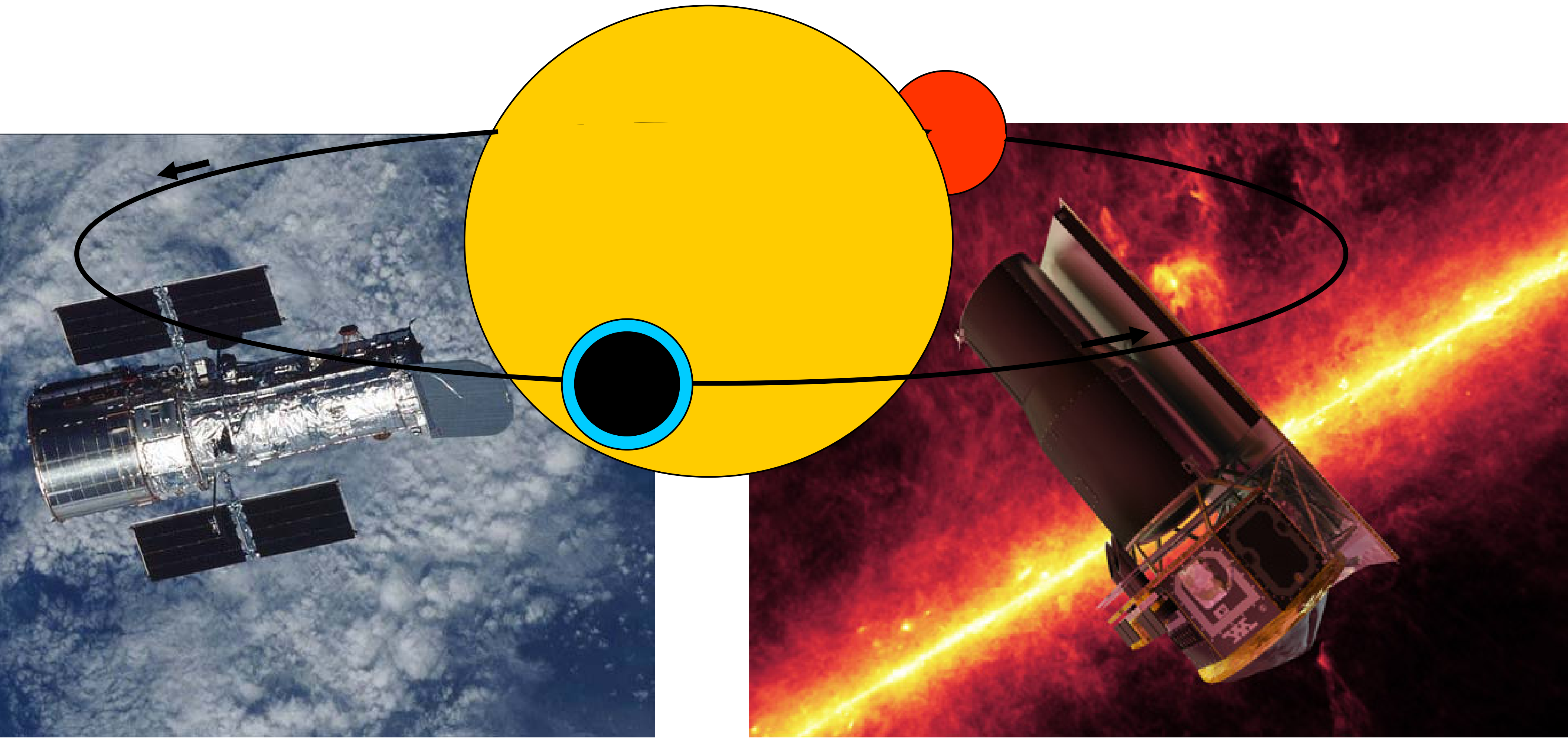

The Infrared Spectrum of the Dayside of a Hot Jupiter

Grillmair, Burrows, Charbonneau, et al. Nature (2008)

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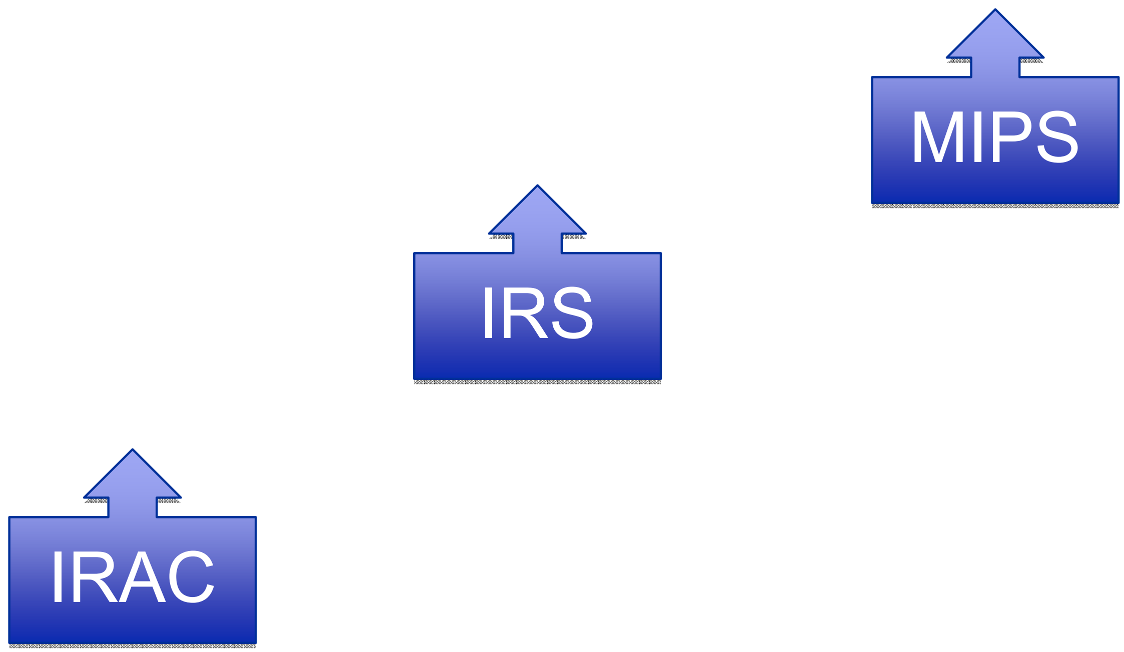


Grillmair, Burrows, Charbonneau, et al. Nature (2008)

We Almost Missed This Opportunity…
Let's Not Do That For JWST

2002

HD 209458b

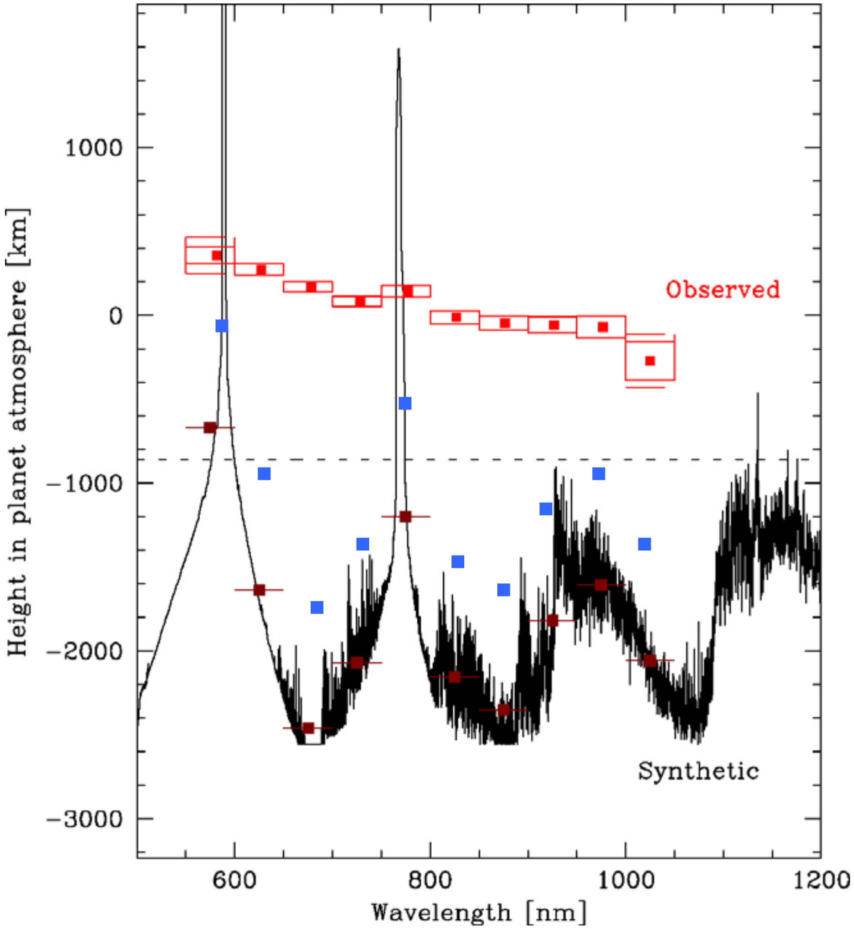
SIRTF Launch Imminent

Jupiter

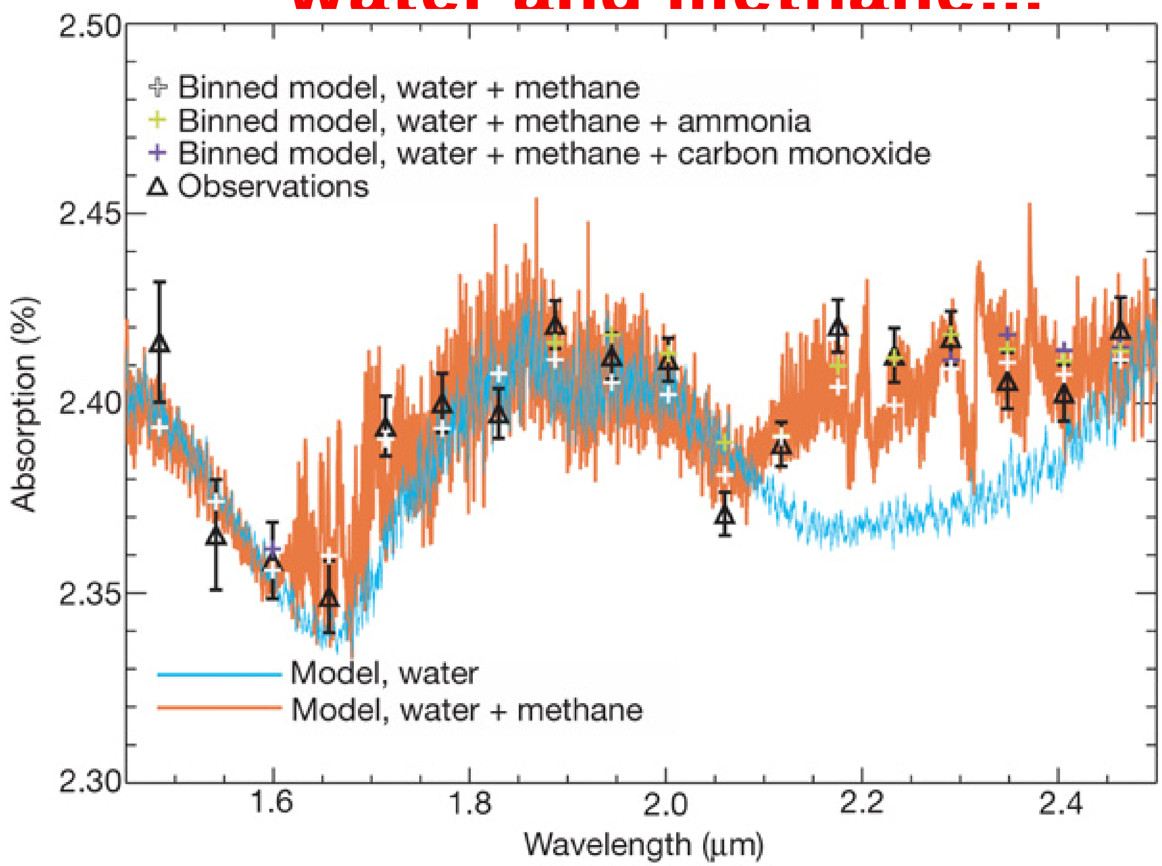
HST Transmission Spectroscopy of theSame Exoplanet

Visible spectrum indicates hazes…

Infrared spectrum reveals water and methane…

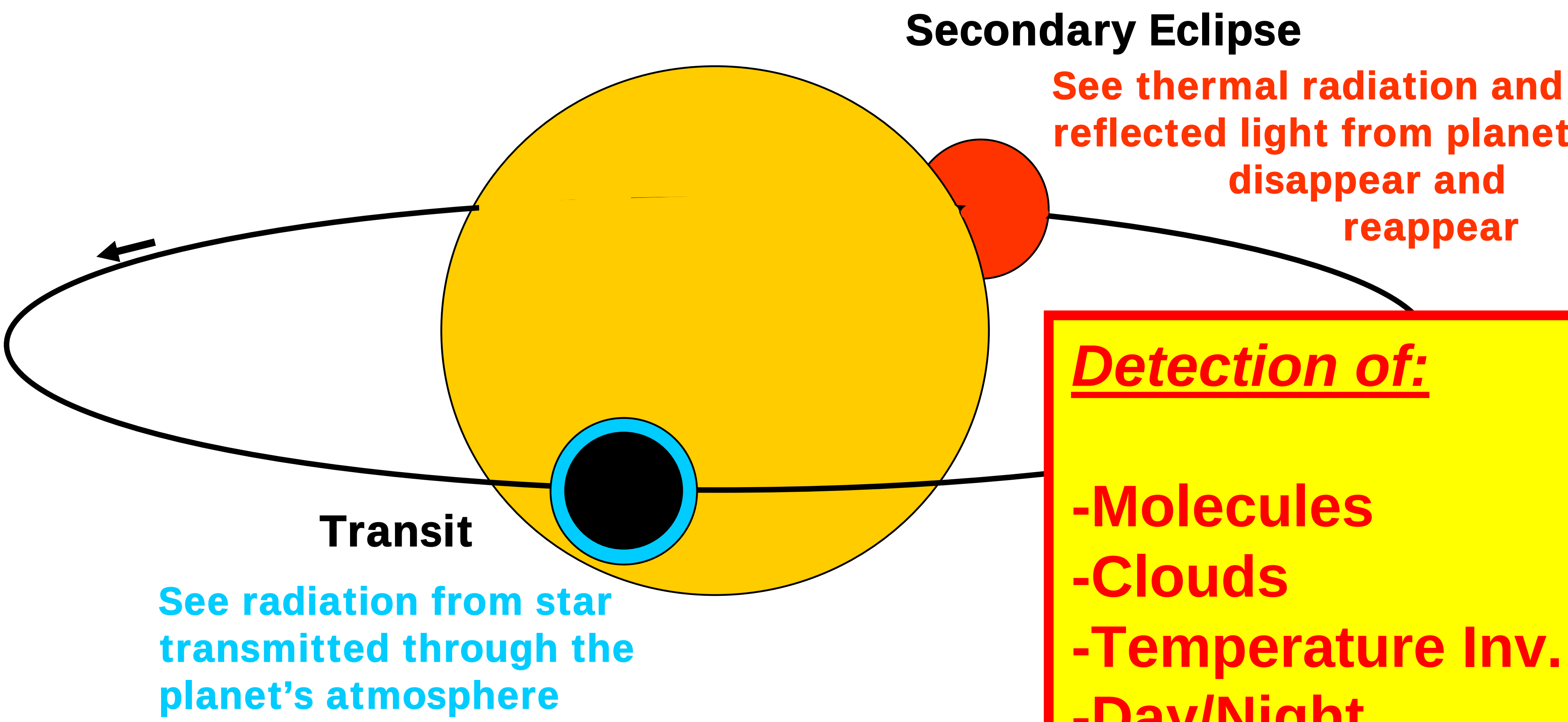


Pont et al. (2007)
Hubble Space Telescope/ACS



Swain et al (2008)
Hubble Space Telescope/NICMOS

Transits Allows Studies of the Atmospheres That Are Not Possible for Non-Transiting Planets



<u>Detection of:</u>

- -Molecules
- -Clouds
- -Temperature Inv.
- -Day/Night Contrast

A Brief History of Progress in Comparative Exoplanetology

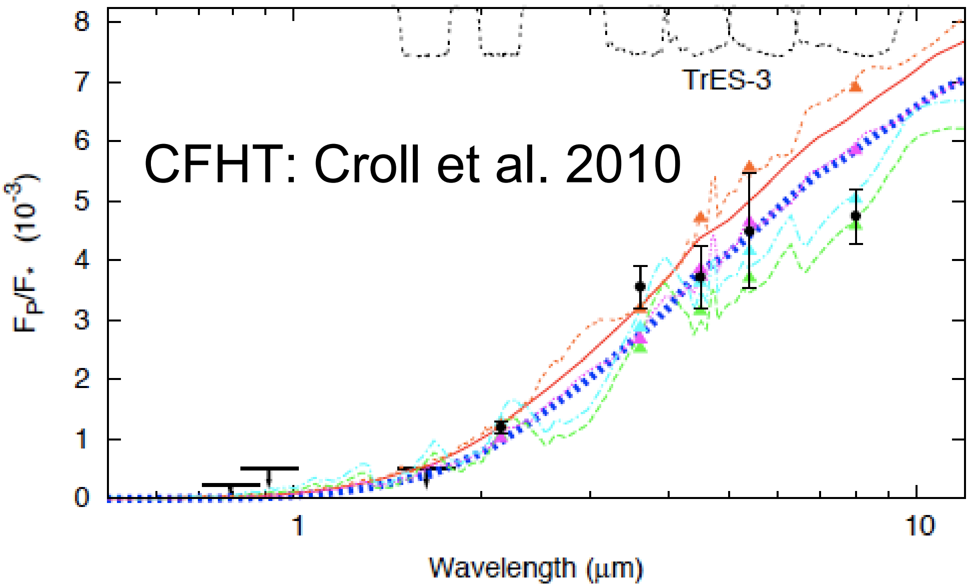
Transit Detection → Mass Determination → Atmospheric Characterization

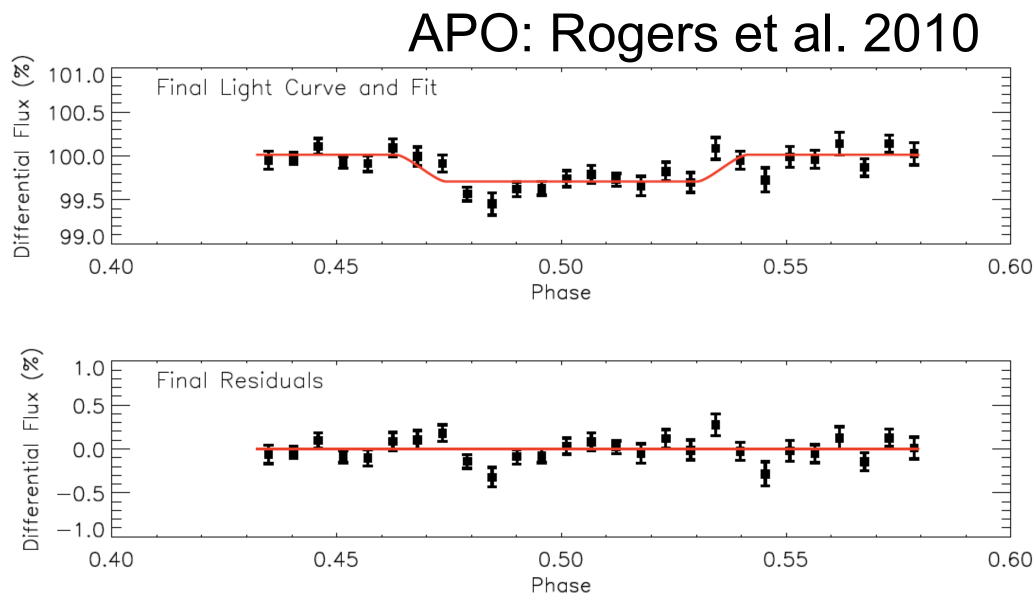
Ground Based

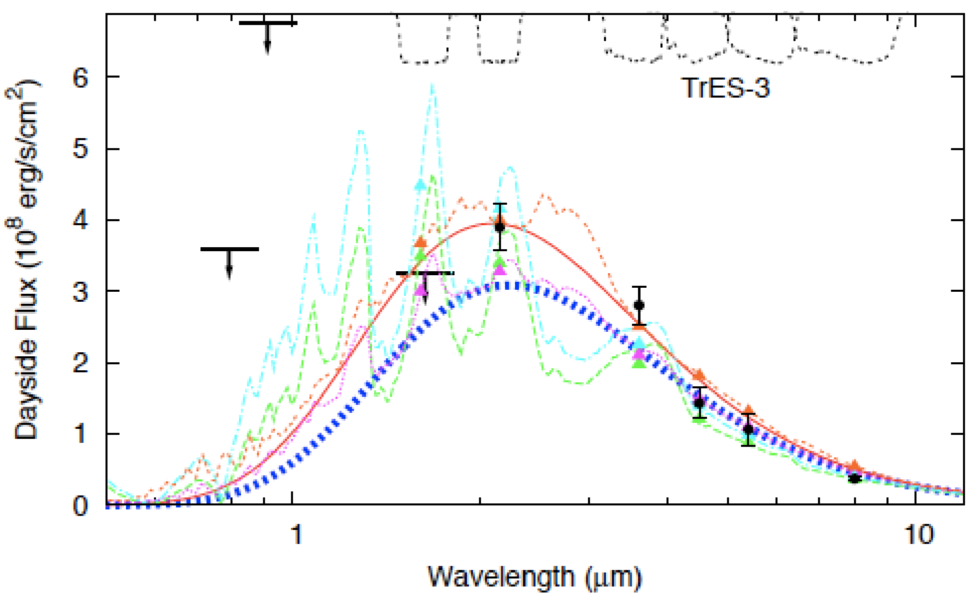
Ground Based

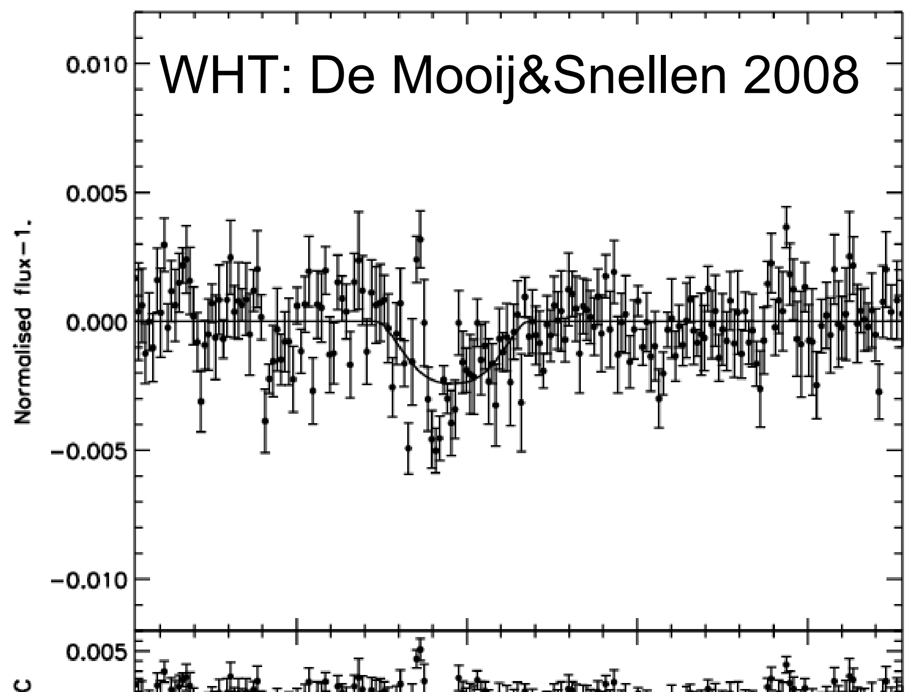
Space Based

Ground-based Detections Probe Peak of Hot Jupiter Emission

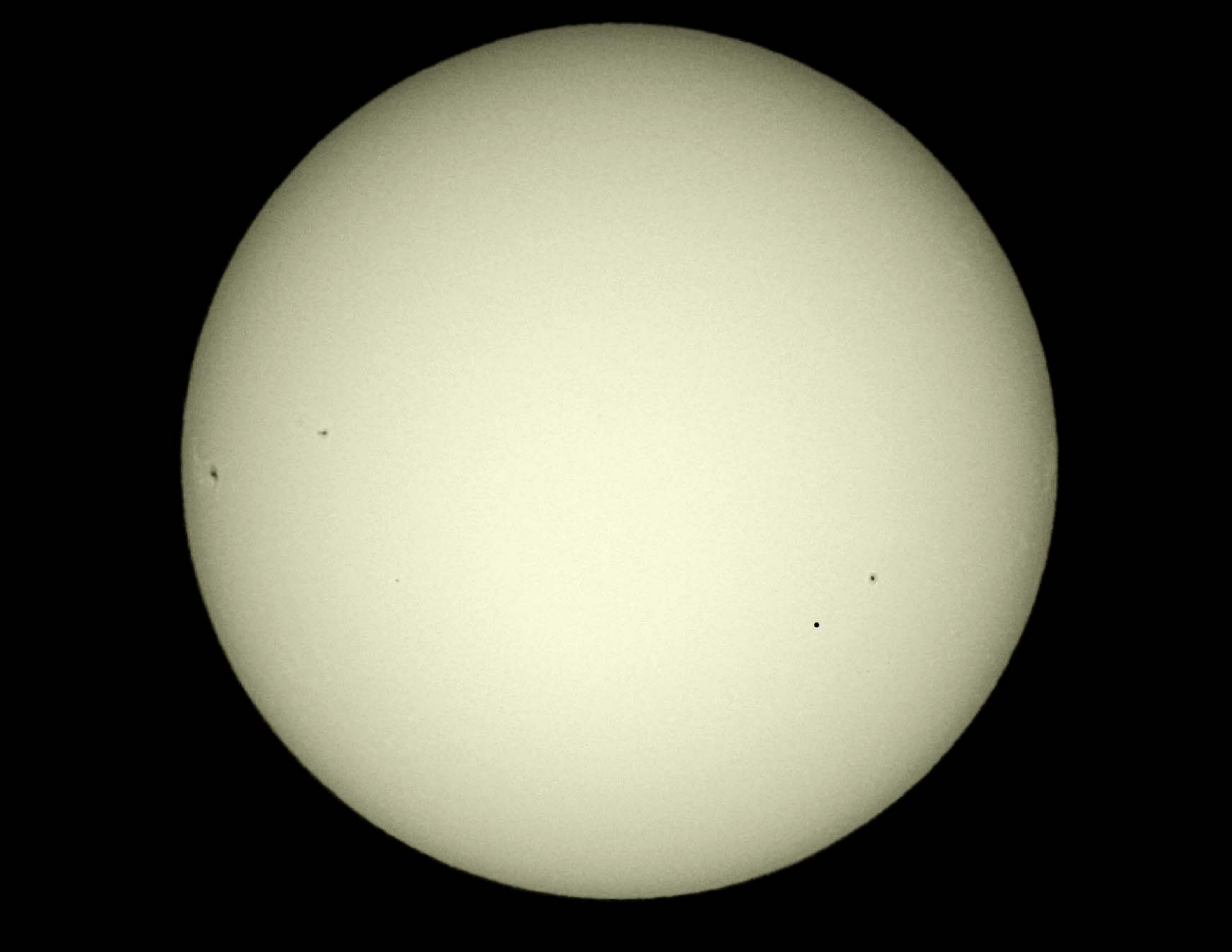






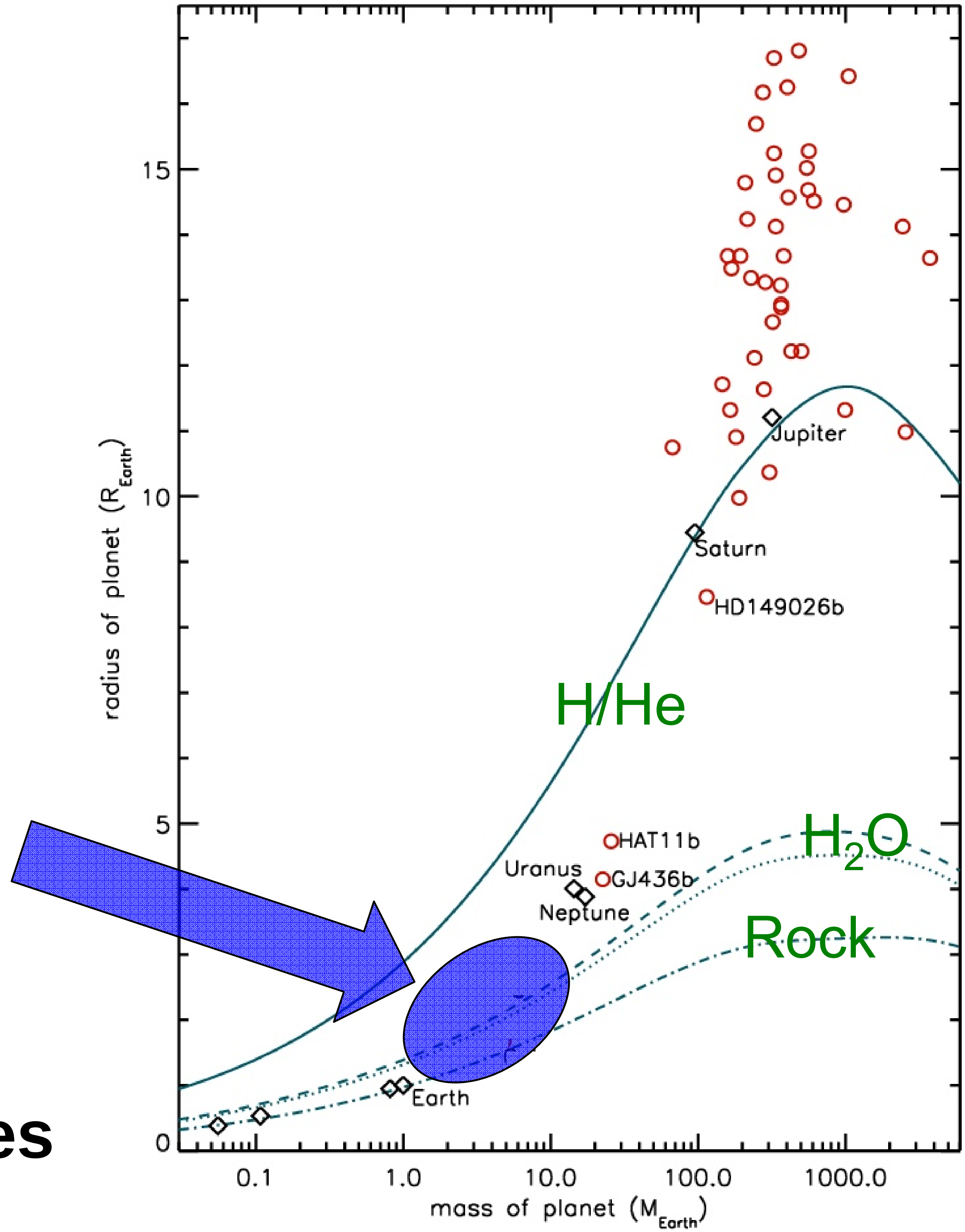


How can we use these techniques
to study the atmosphere
of a habitable exoplanet?



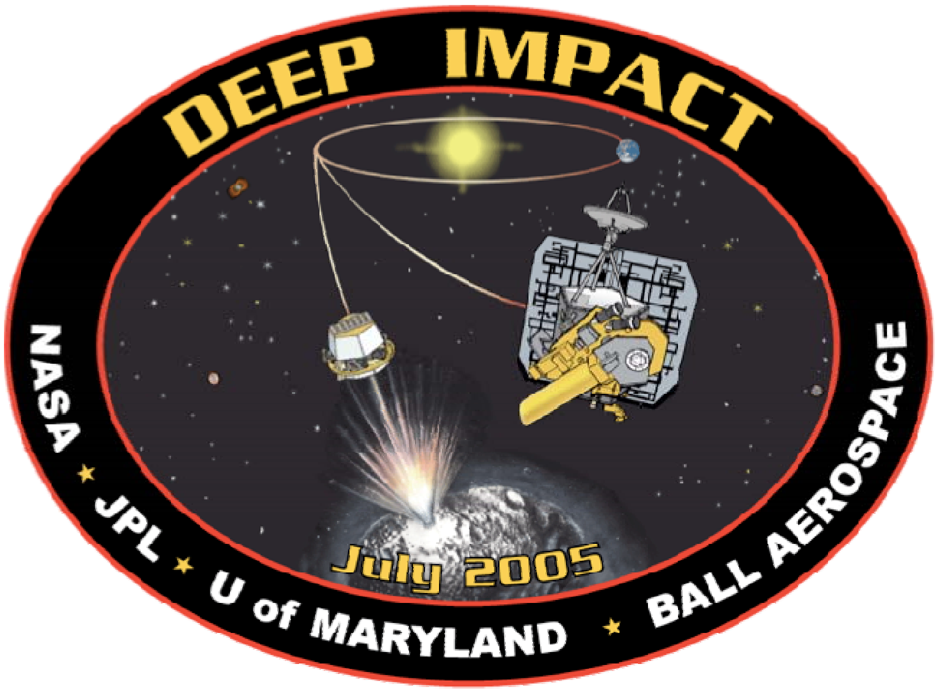
A Diversity of Worlds

Super-Earths



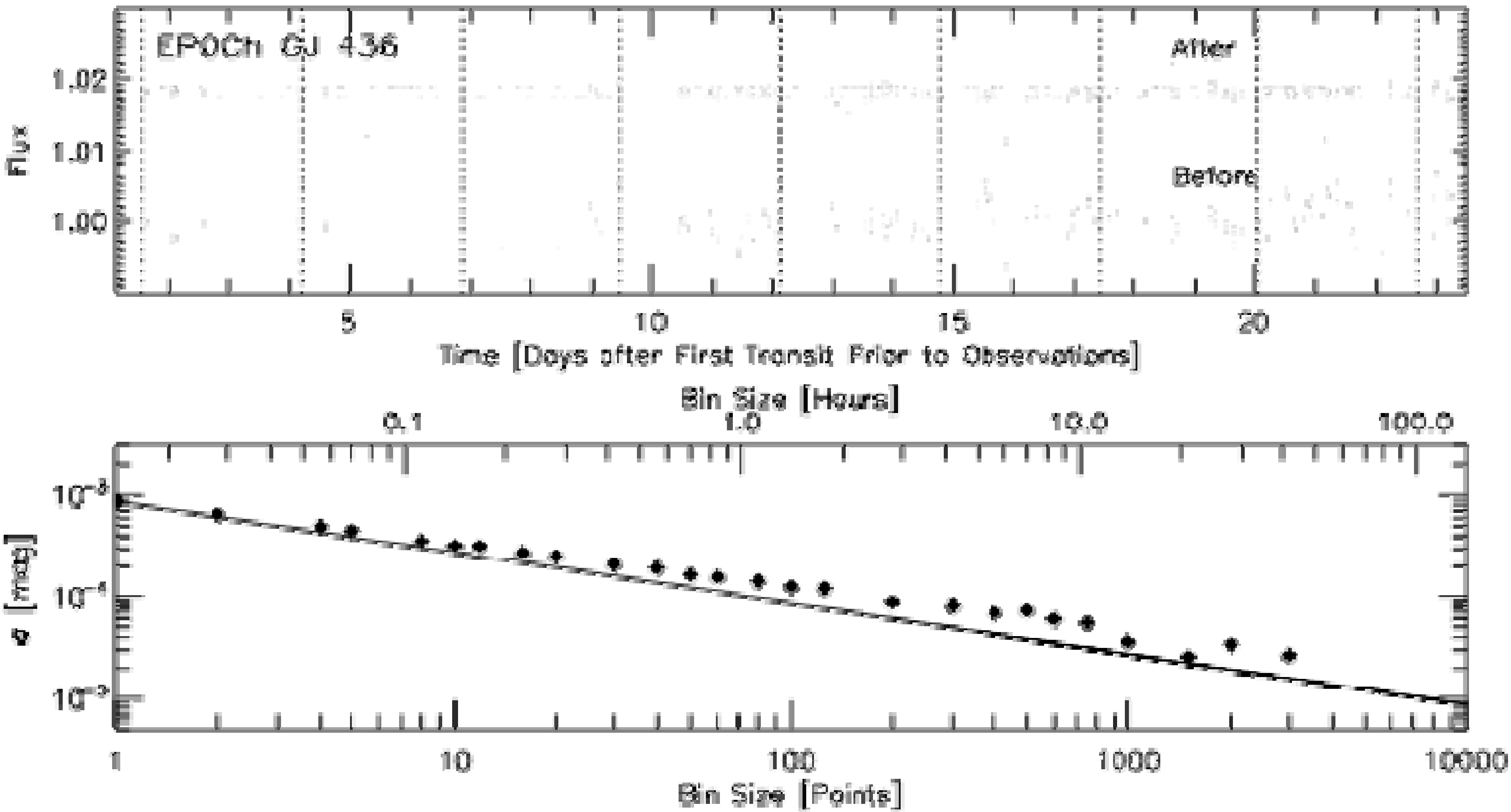
Mass range:
2 – 10 Earth masses

Plan #1: Use Transiting Planets As Guide to Edge-On Systems



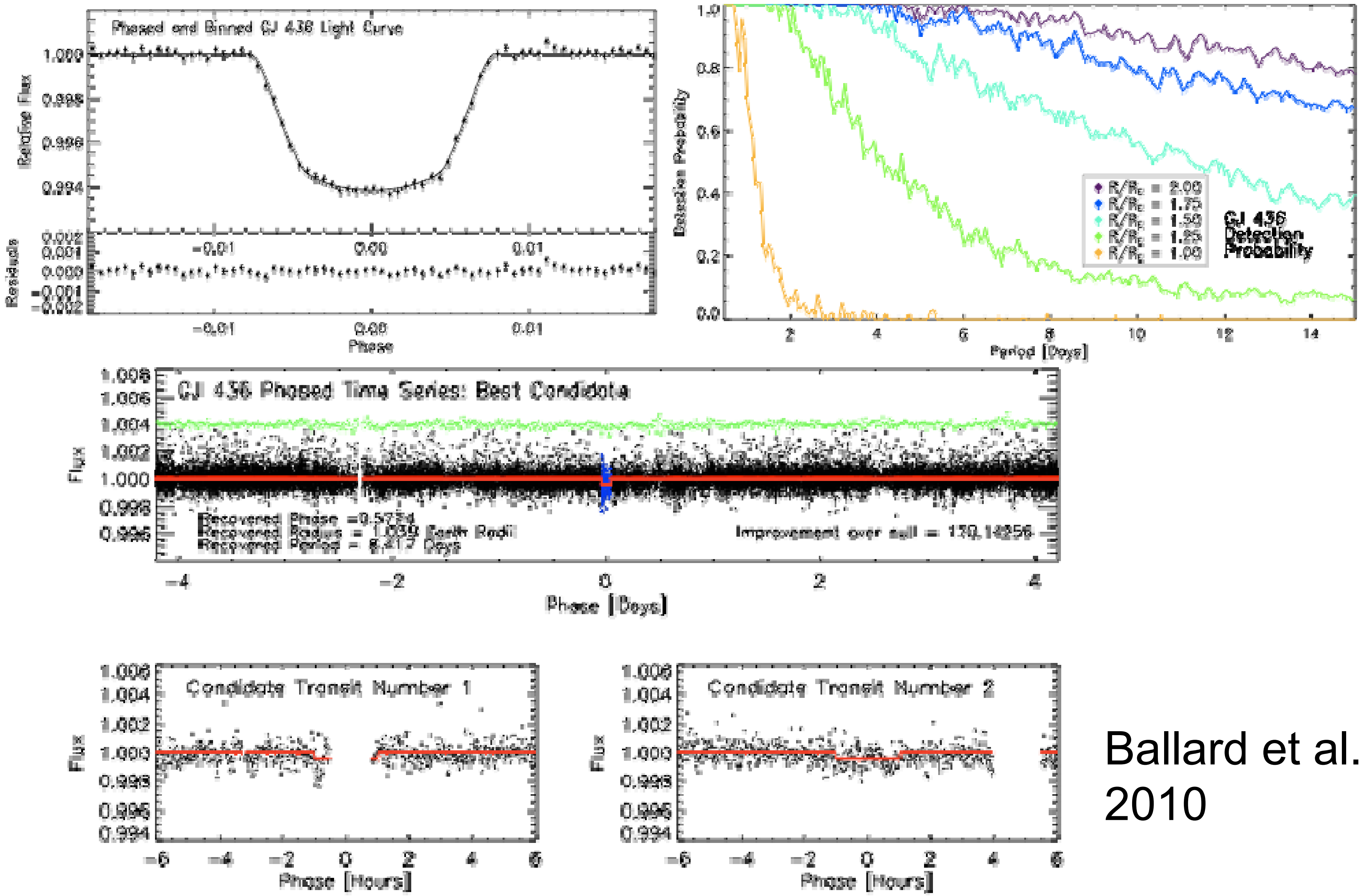
The NASA EPOXI Mission reused the Deep Impact Spacecraft to survey 7 known systems for small planets that could be detected either by their photometric transits or their dynamical influence on the known exoplanet.

NASA EPOXI Observations of GJ 436



Ballard et al. 2010

NASA EPOXI Constraints on GJ 436c



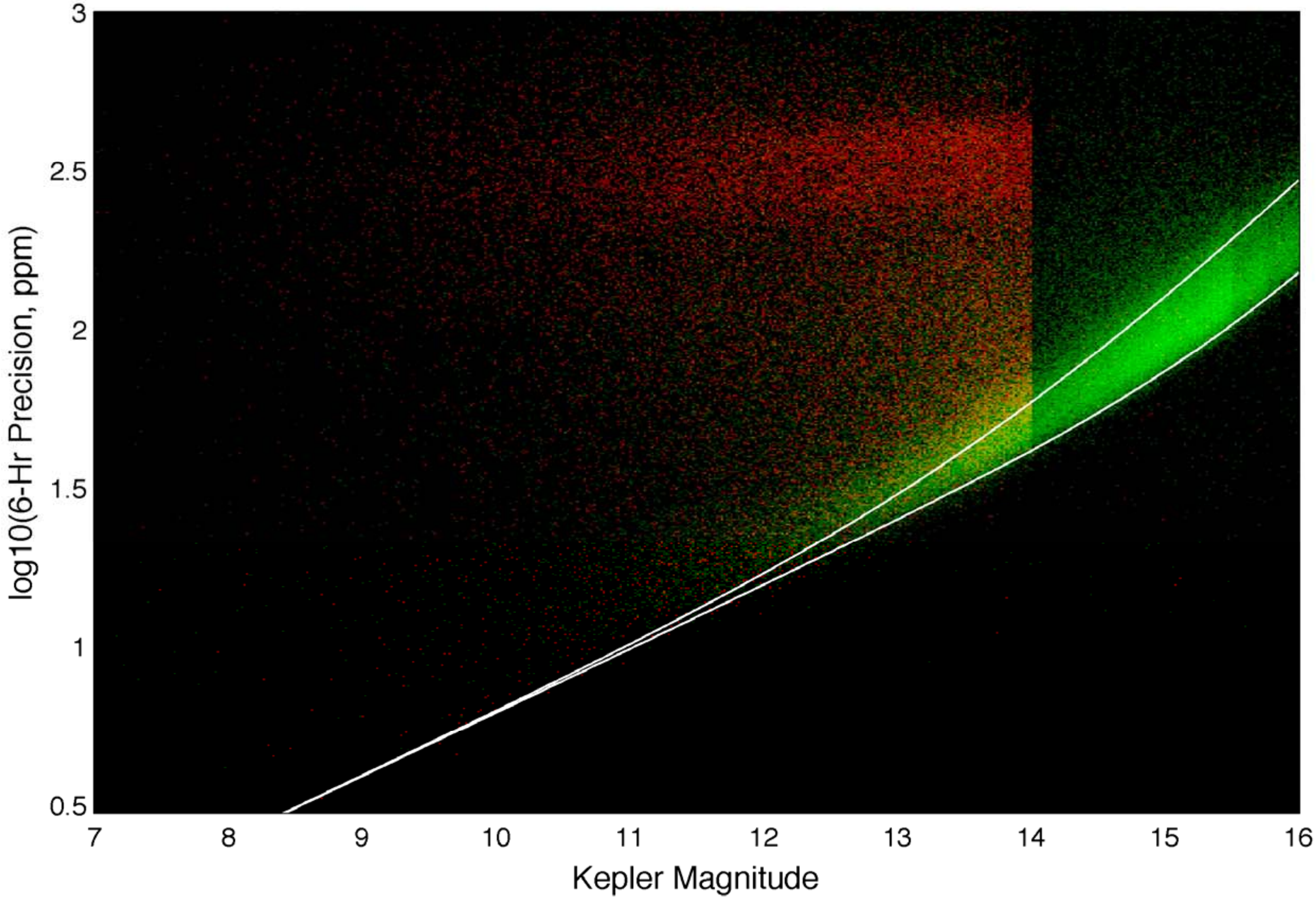
Ballard et al. 2010

Plan #2: Build Dedicated Spacecraft to Survey Large Numbers of Stars for Transiting Rocky Exoplanets

- French Space Agency with European Partners
- Monitor 60,000 stars for 150 days
- Sensitivity tosuper-Earths

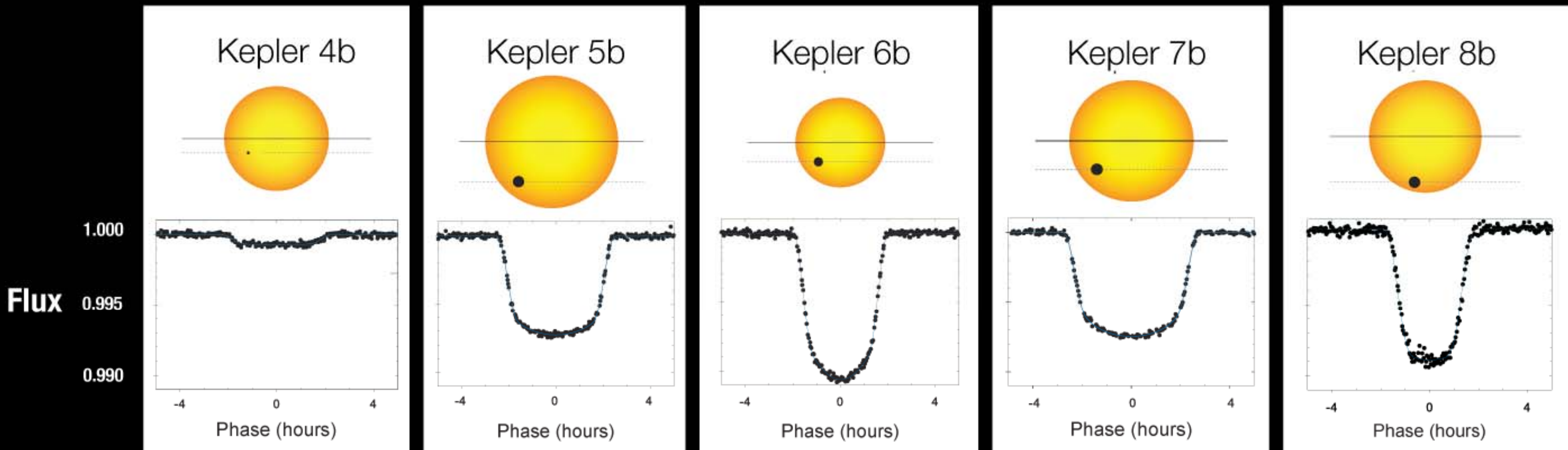
- NASA
- Will monitor 170,000 stars for 4 years
- Will determine rate-of-occurrence of *true* Earth analogs

Kepler: COMBINED DIFFERENTIAL PHOTOMETRIC PRECISION



Measured 6-hour precision of the Q0 data set. A strong separation in photometric variability can be seen between the dwarfs (green points) and the red giants (red points). The two curves bound the upper and lower measurement uncertainties propagated through the data processing pipeline.

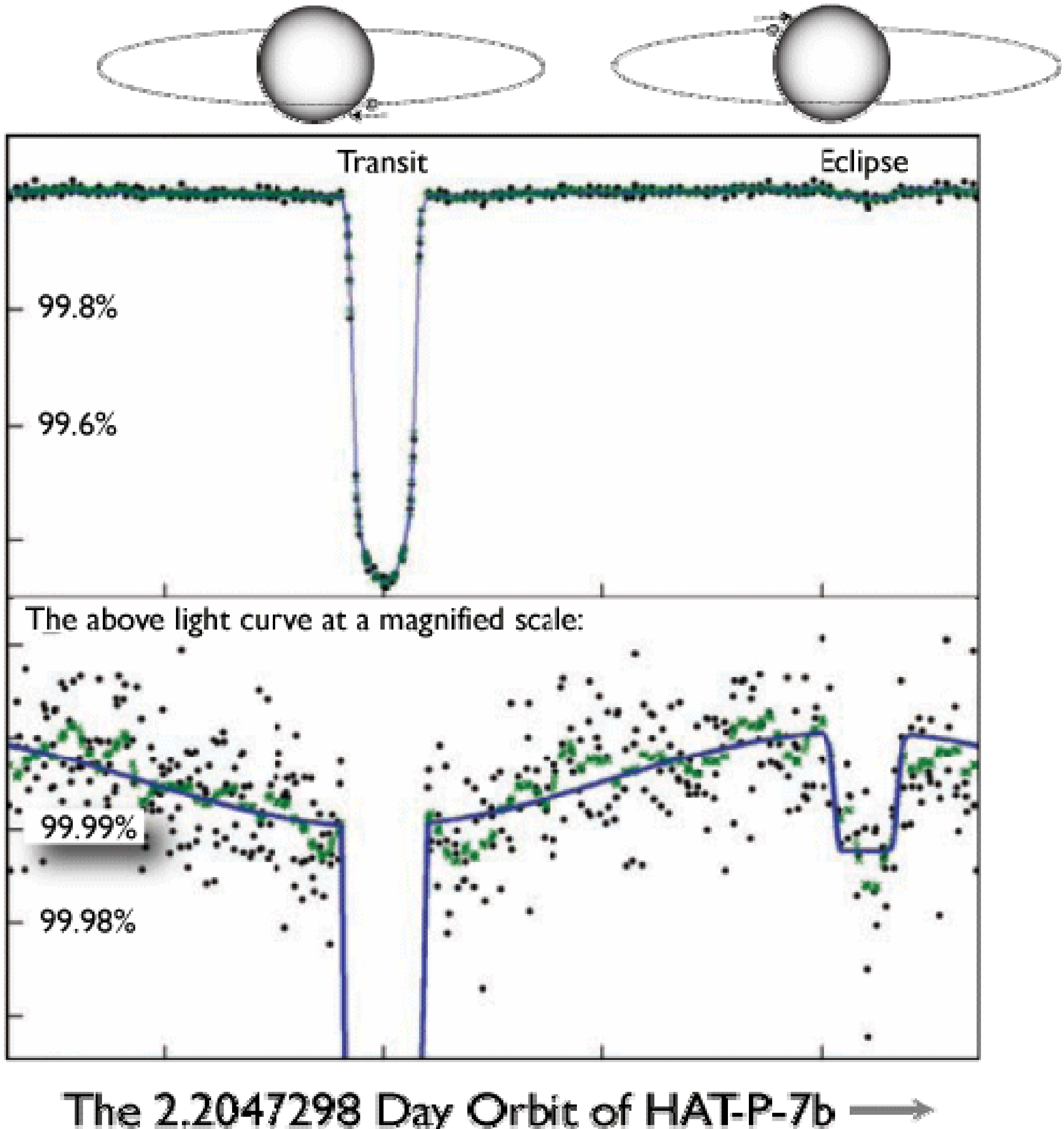
Transit Light Curves



Orbital Period (days)	*3.2 days*	*3.5 days*	*3.2 days*	*4.9 days*	*3.5 days*
Size (R_E)	*4.31*	*18.8*	*15.0*	*16.9*	*18.3*

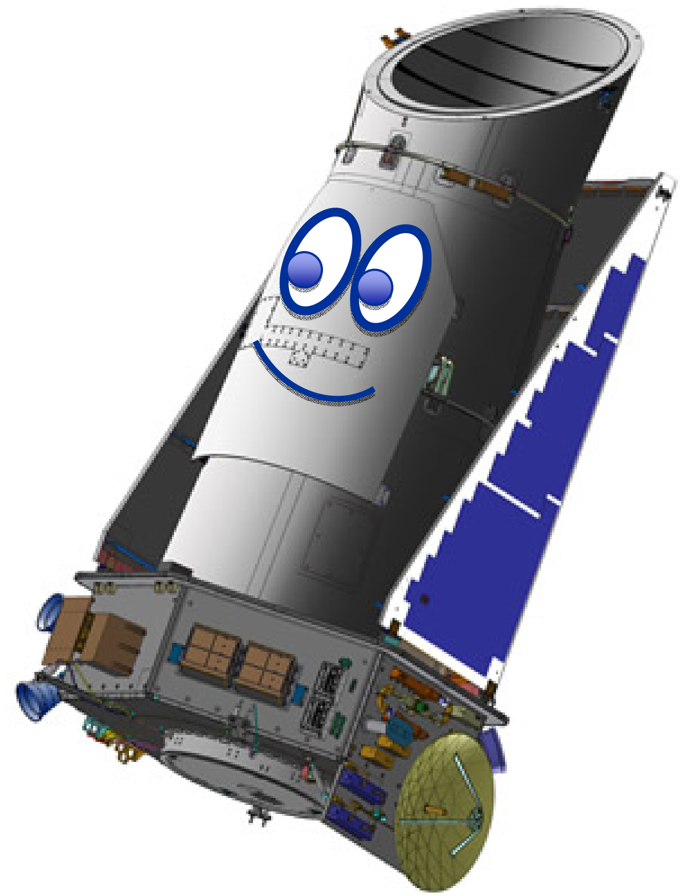
Kepler Mission Photometry of the Known Exoplanet HAT-P-7

Borucki et al. Science (2009)

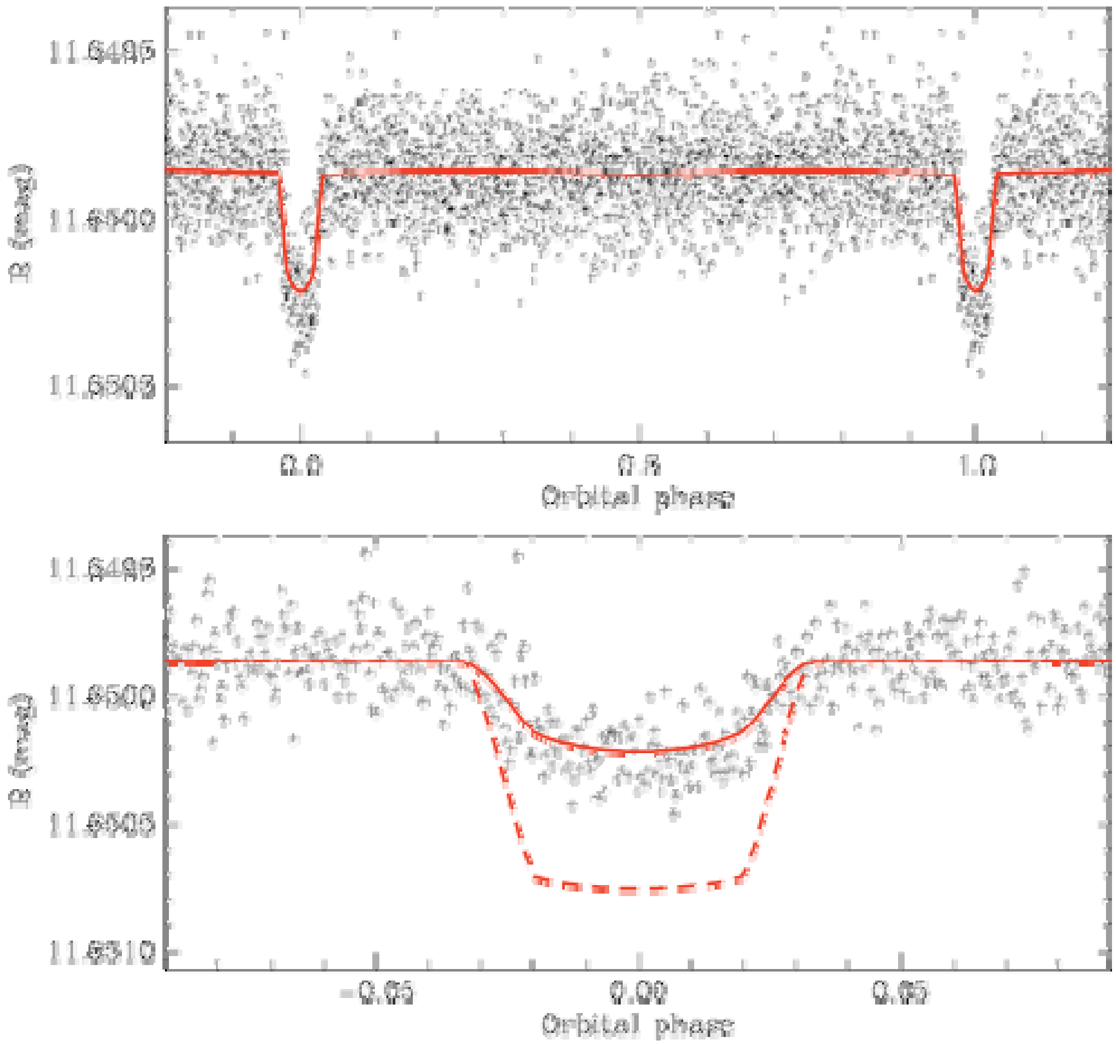


It is unlikely that we will obtain the RV orbit for terrestrial planets discovered by Kepler.

Thus we need to be prepared to use another approach...



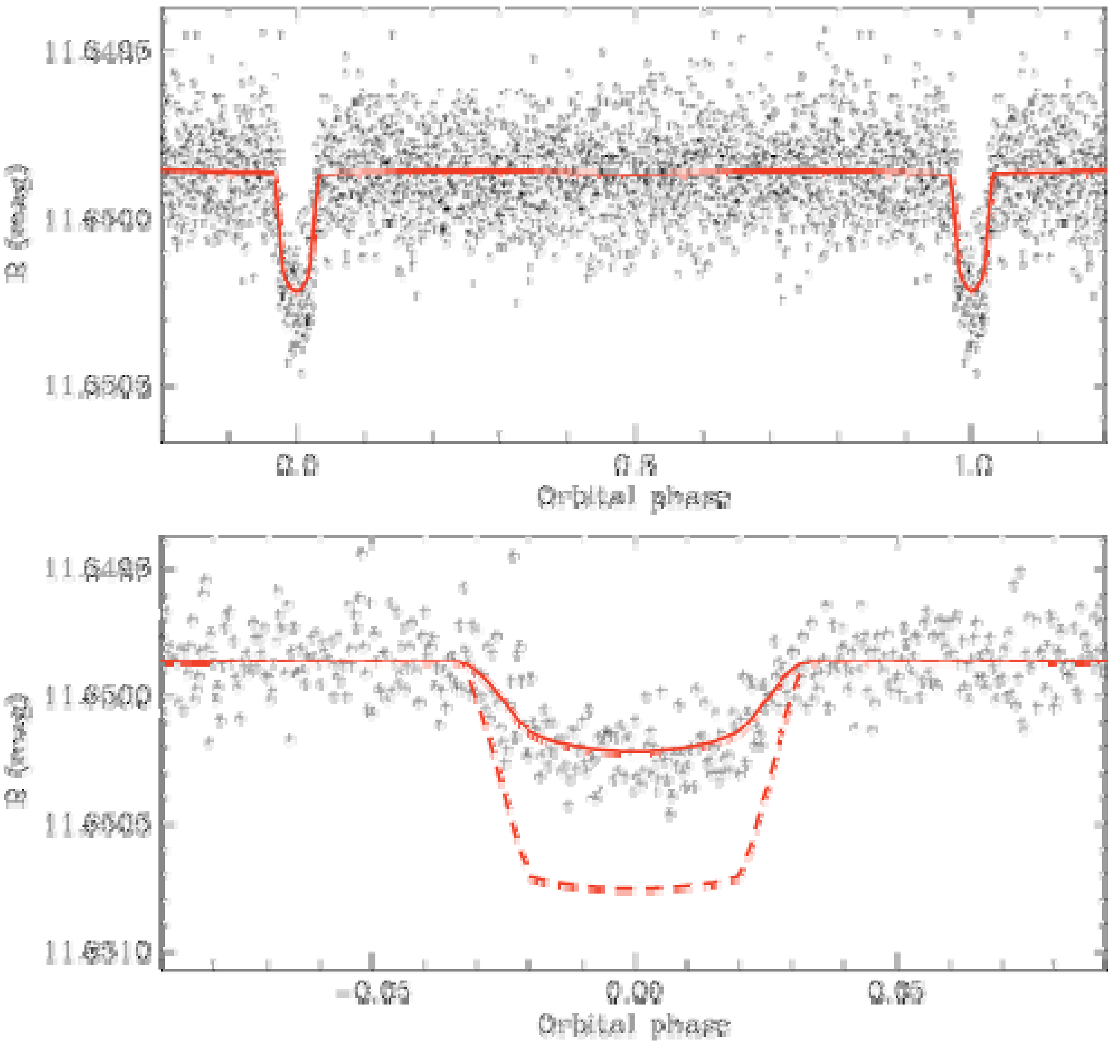
Excluding False Positives for CoRoT-7

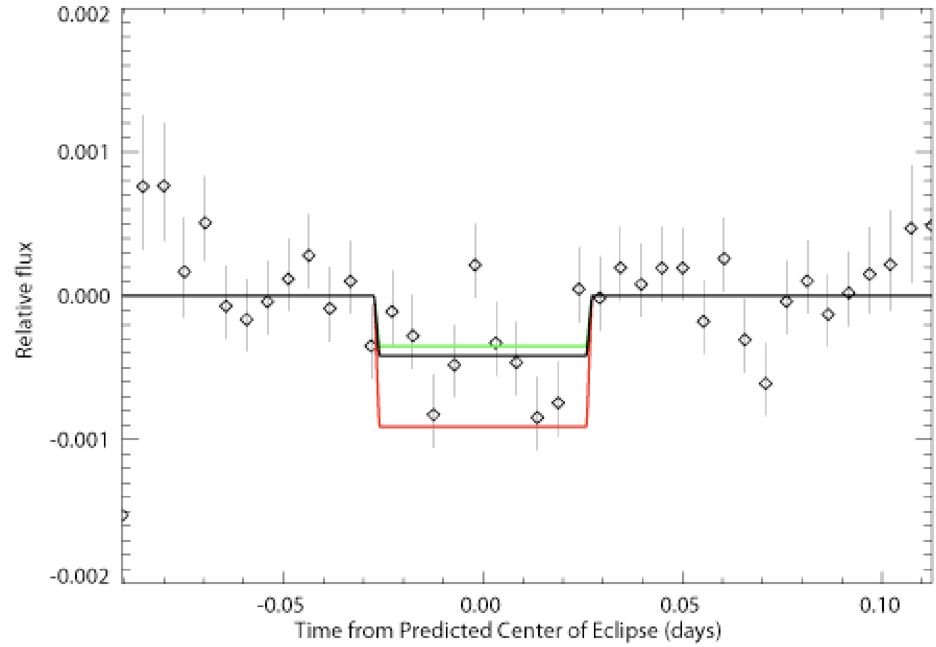


- Use Blender software to identify plausible blend scenarios and predict the signal at infrared wavelengths

Fressin et al. 2010

Excluding False Positives for CoRoT-7





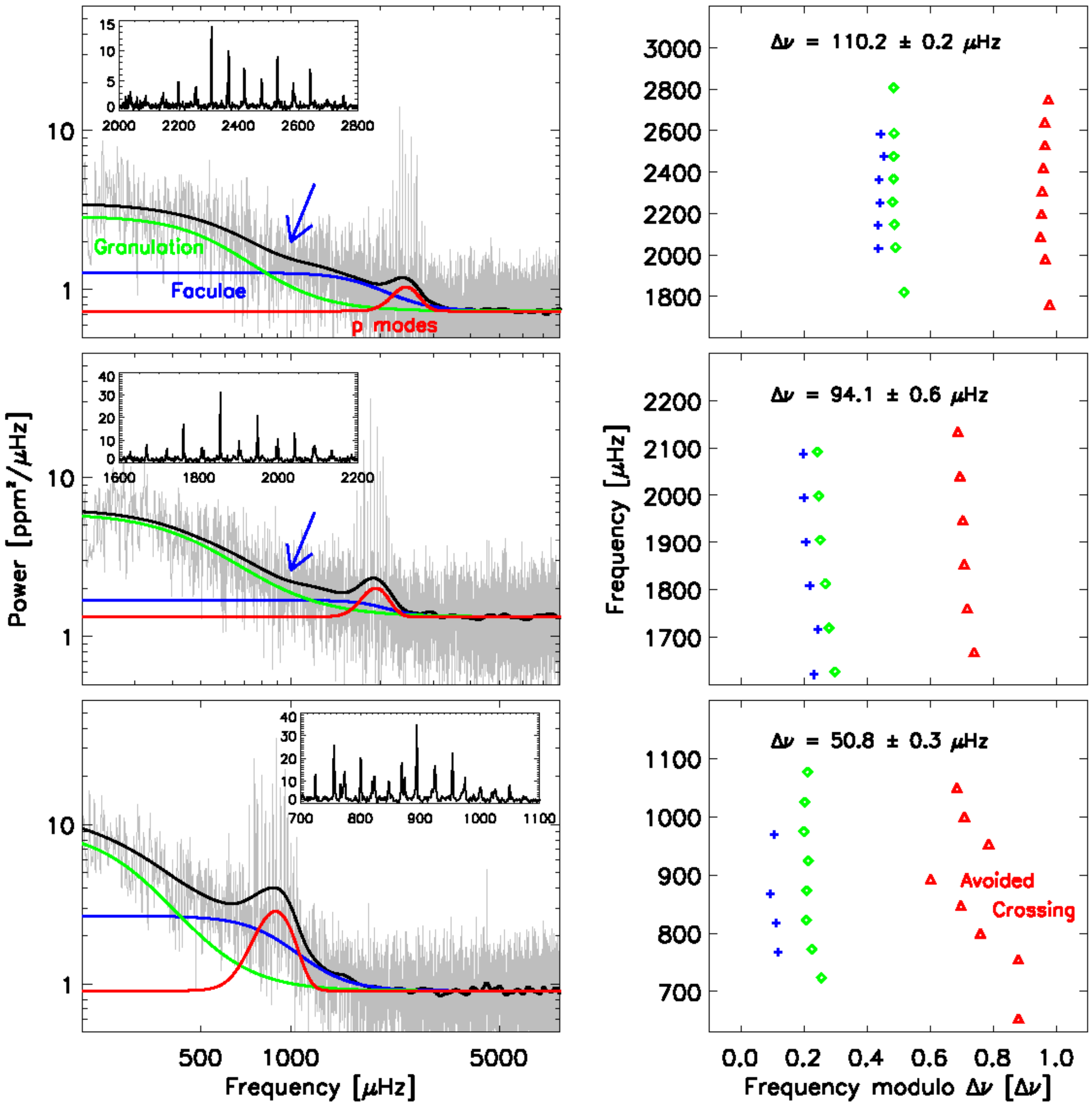
Spitzer lightcurve rules out blend resulting from eclipsing binary.

Fressin et al. 2010

ASTEROSEISMOLOGY RESULTS

Kepler

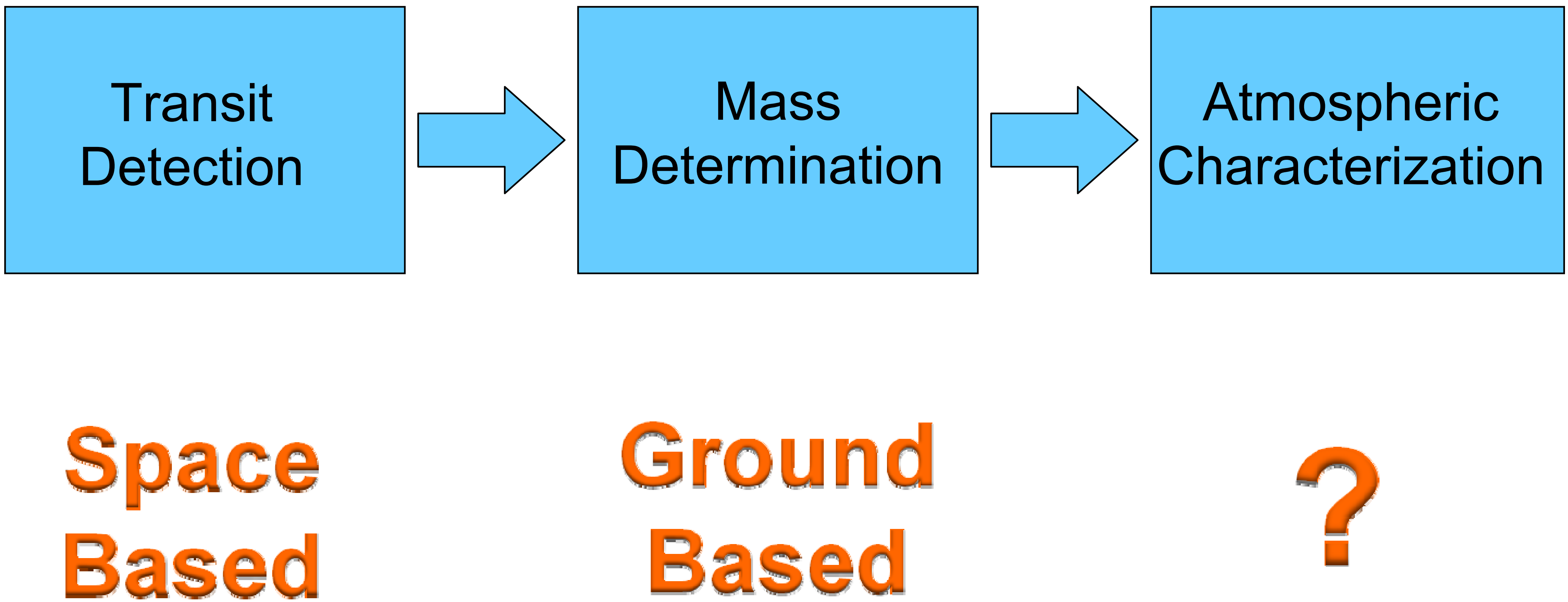
A Search for Earth-size Planets



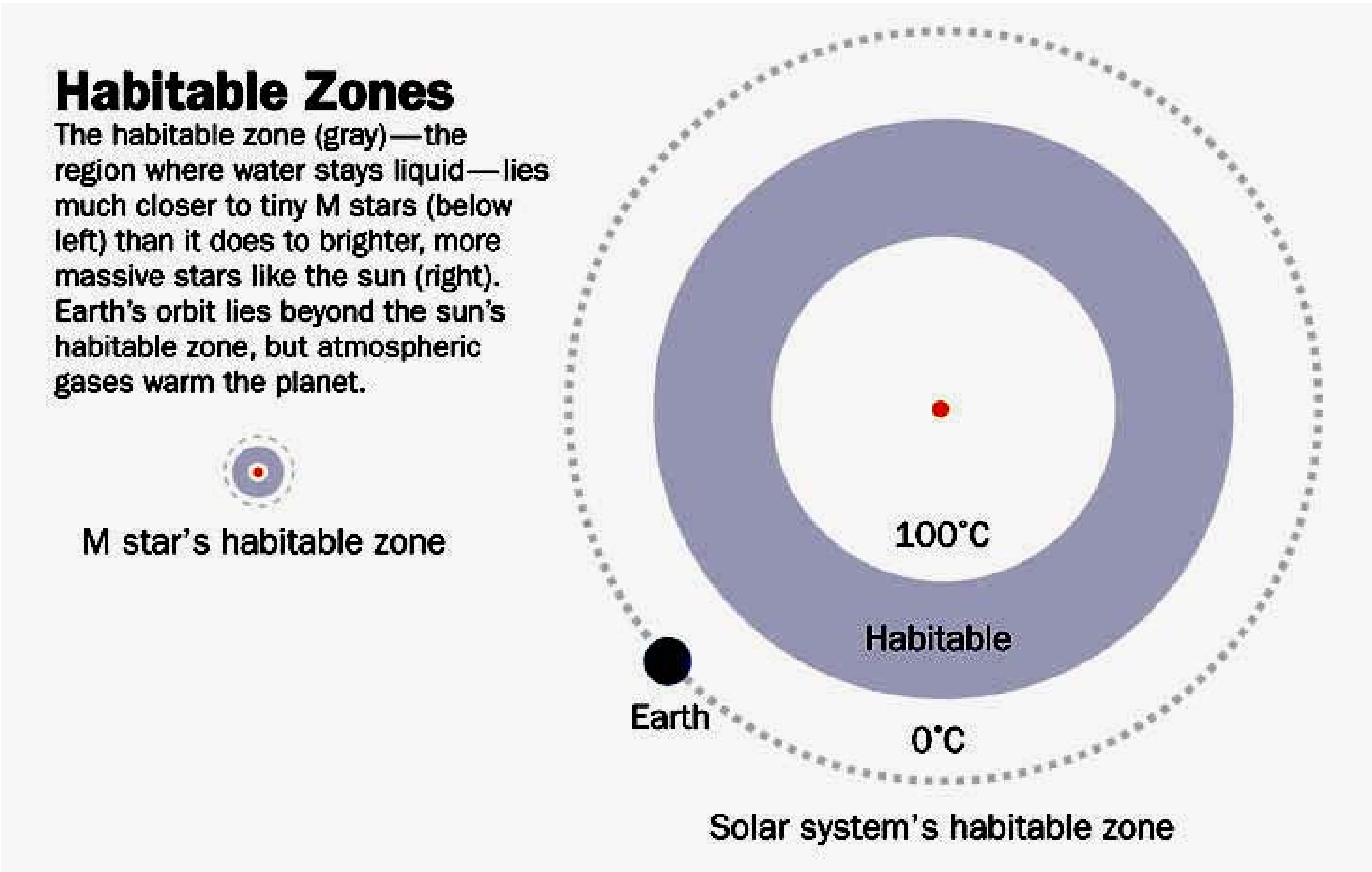
Power spectra of *Kepler*photometry of three solar-like stars (grey) over 200 – 8000 μHz.

Perhaps Kepler can yield independent estimates of stellar density, and by inference age, radius and mass for planet-host stars?

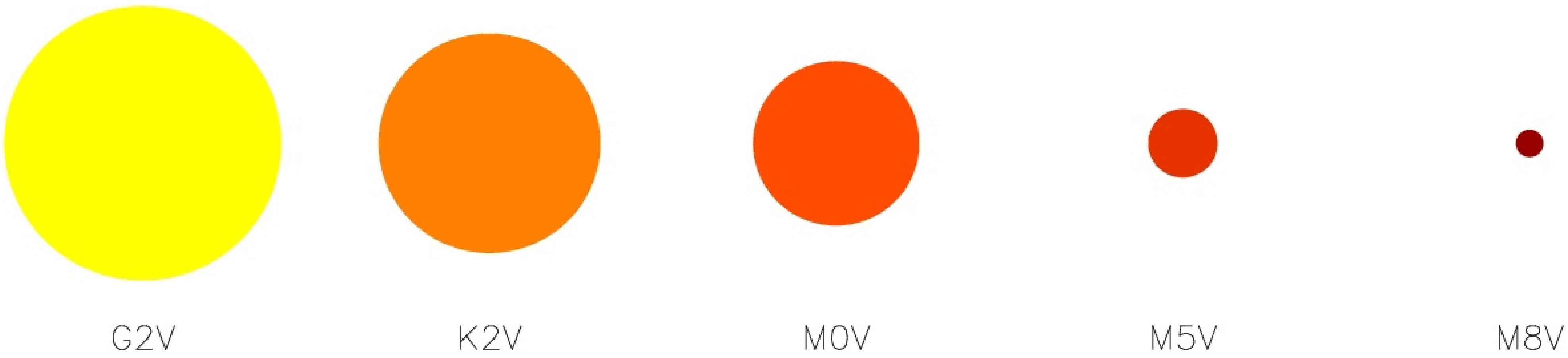
A Brief Look Ahead at the Path Ahead for Kepler-Detected Worlds



Plan #3: The Small Star Opportunity

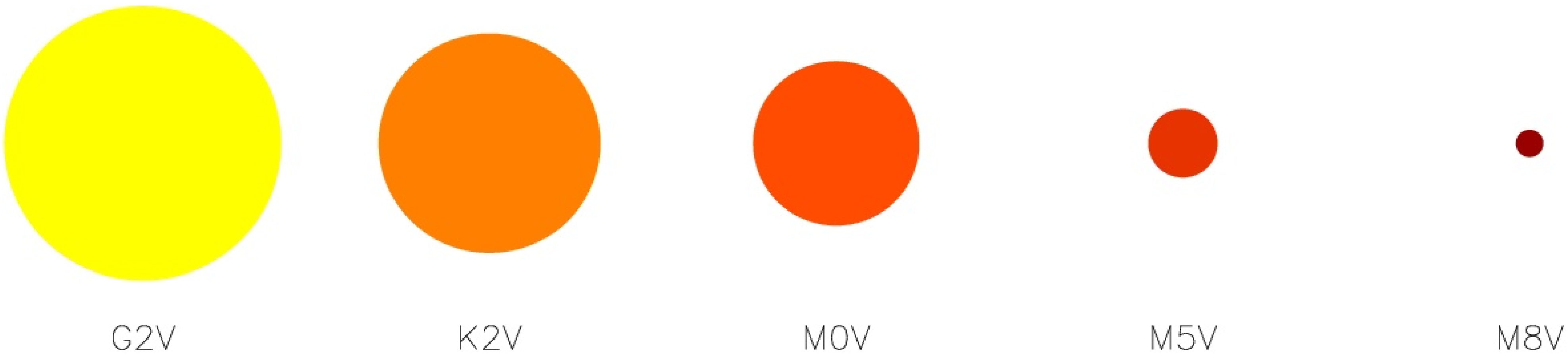


The Small Star Opportunity



Consider a 7-M_{Earth} 2-R_{Earth} habitable zone planet:

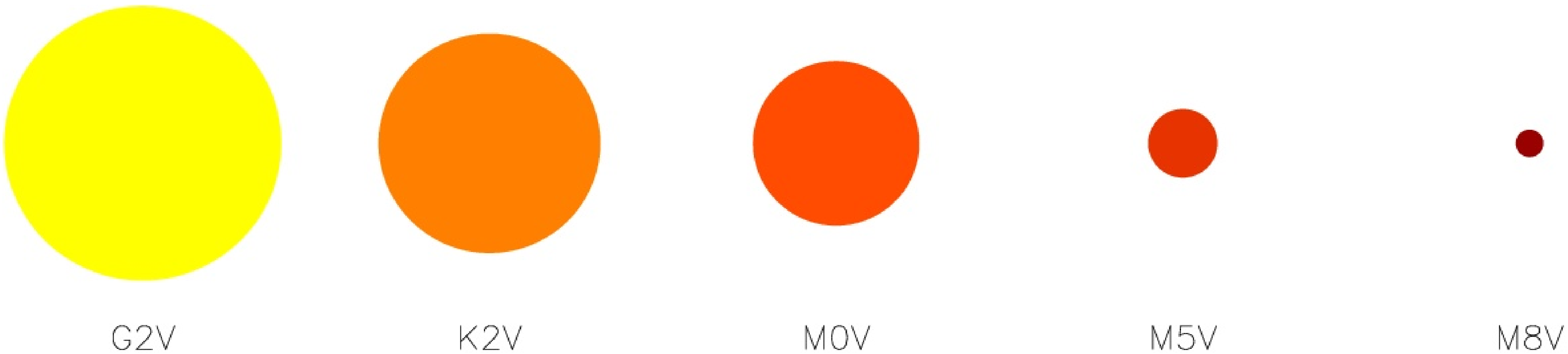
The Small Star Opportunity



Consider a 7-M_{Earth} 2-R_{Earth} habitable zone planet:

✓ Transits are deeper *Sun: 0.03%* *M5V: 0.5%*

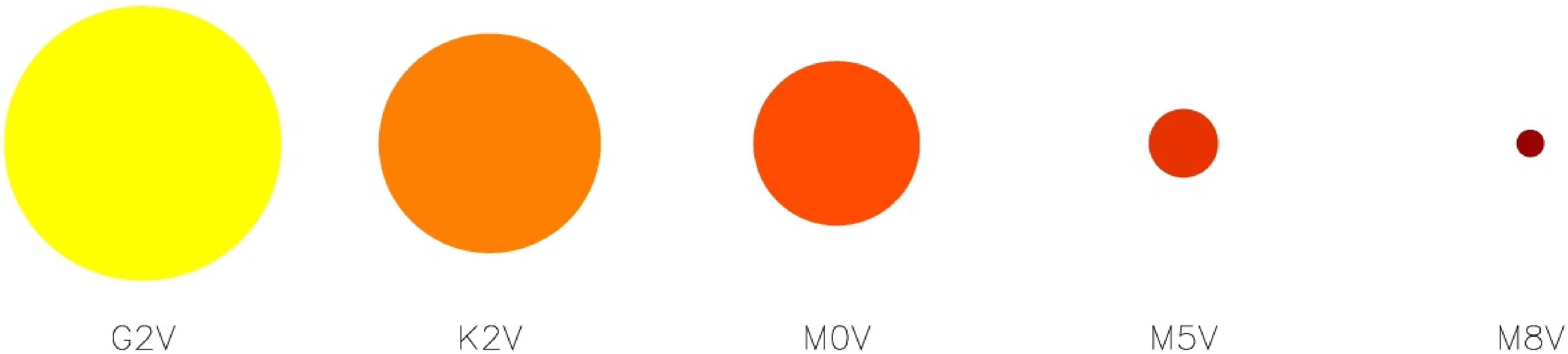
The Small Star Opportunity



Consider a 7-M_{Earth} 2-R_{Earth} habitable zone planet:

✓ Transits are deeper *Sun: 0.03%* *M5V: 0.5%*
✓ Transits are more frequent *Sun: 365 days* *M5V: 15 days*

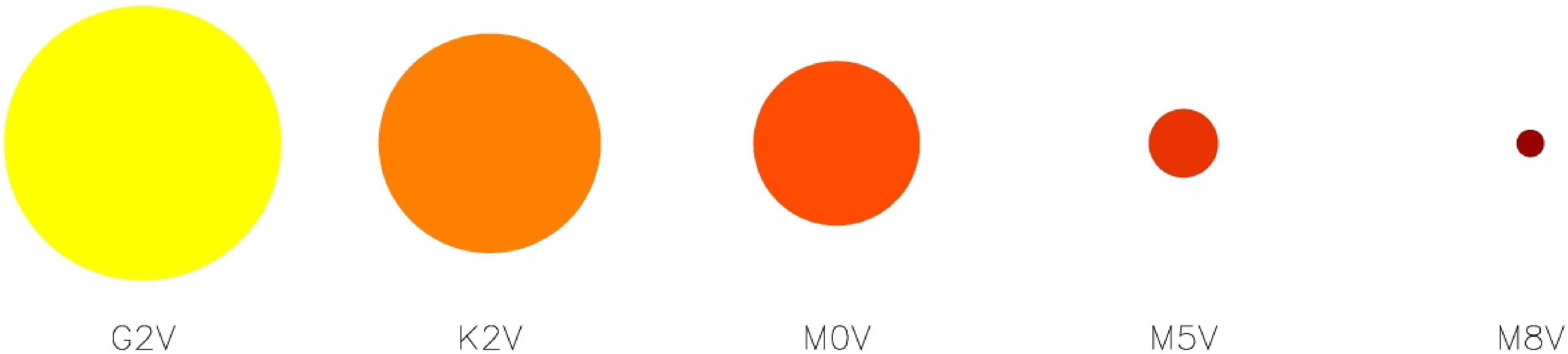
The Small Star Opportunity



Consider a 7-M_{Earth} 2-R_{Earth} habitable zone planet:

✓ Transits are deeper	*Sun: 0.03%*	*M5V: 0.5%*
✓ Transits are more frequent	*Sun: 365 days*	*M5V: 15 days*
✓ Transits are more likely	*Sun: 0.5%*	*M5V: 1.6%*

The Small Star Opportunity



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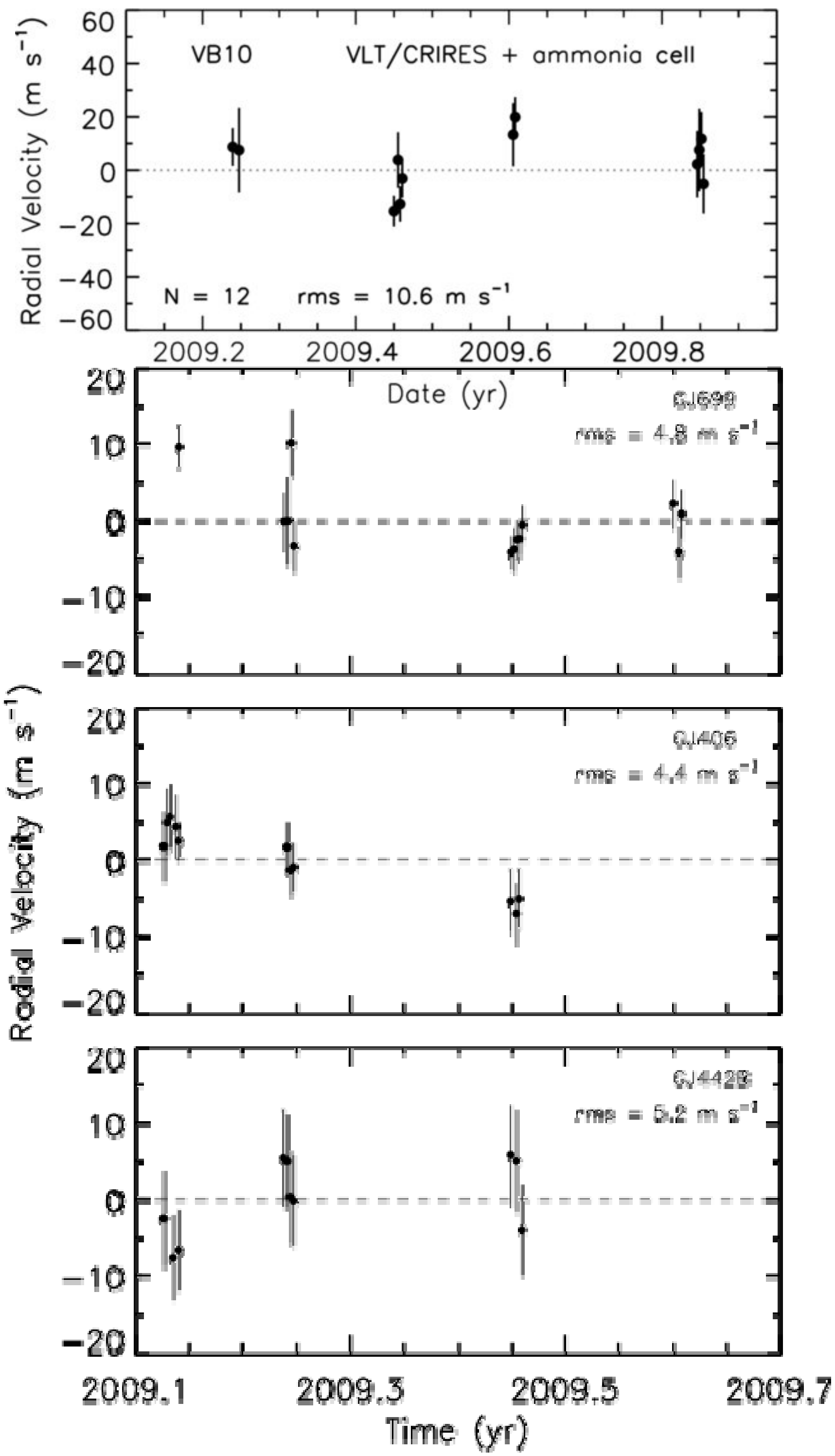
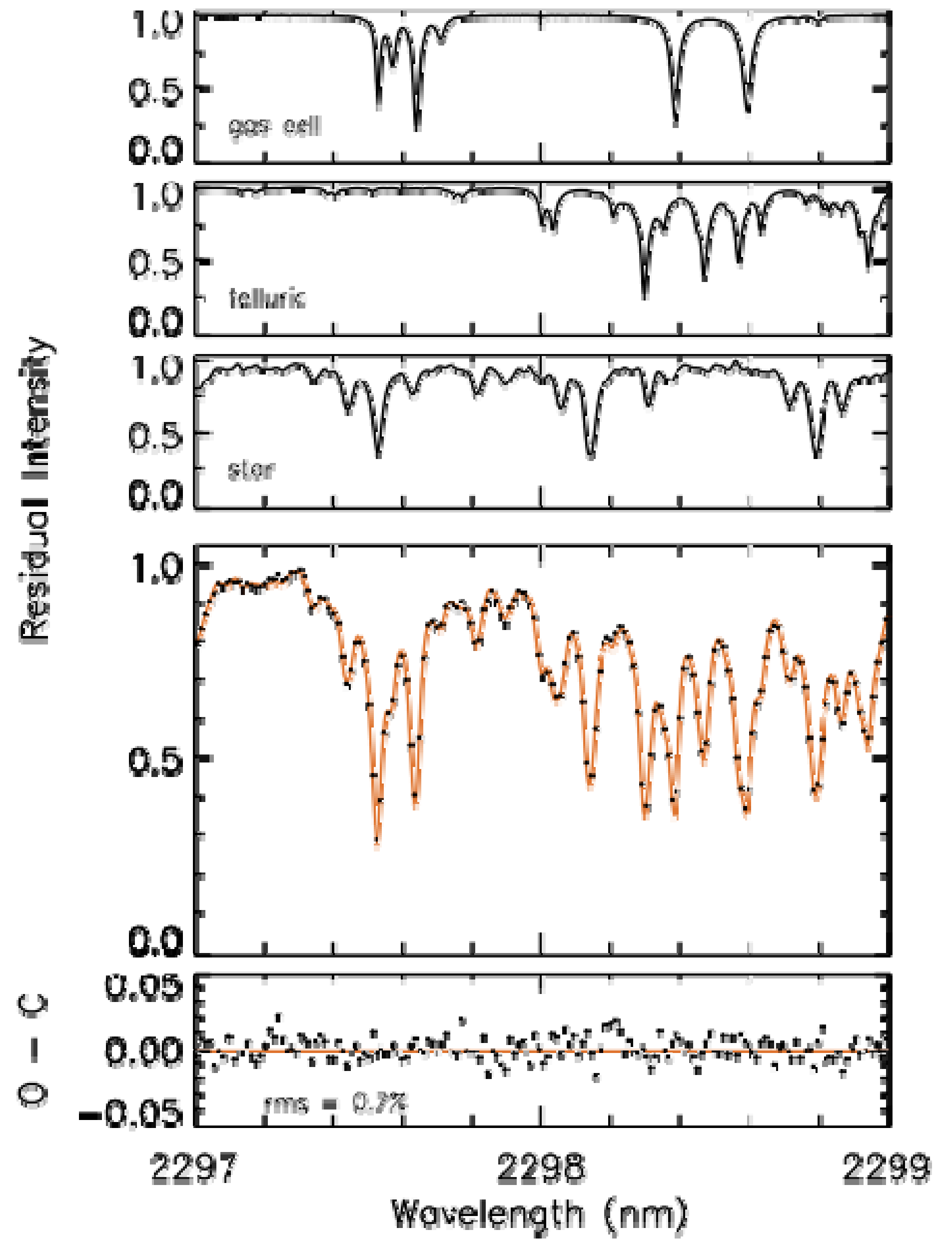
✓ Transits are more frequent	*Sun: 365 days*	*M5V: 15 days*
✓ Transits are more likely	*Sun: 0.5%*	*M5V: 1.6%*
✓ Greater Doppler Wobble	*Sun: 1.3 m/s*	*M5V: 10 m/s*

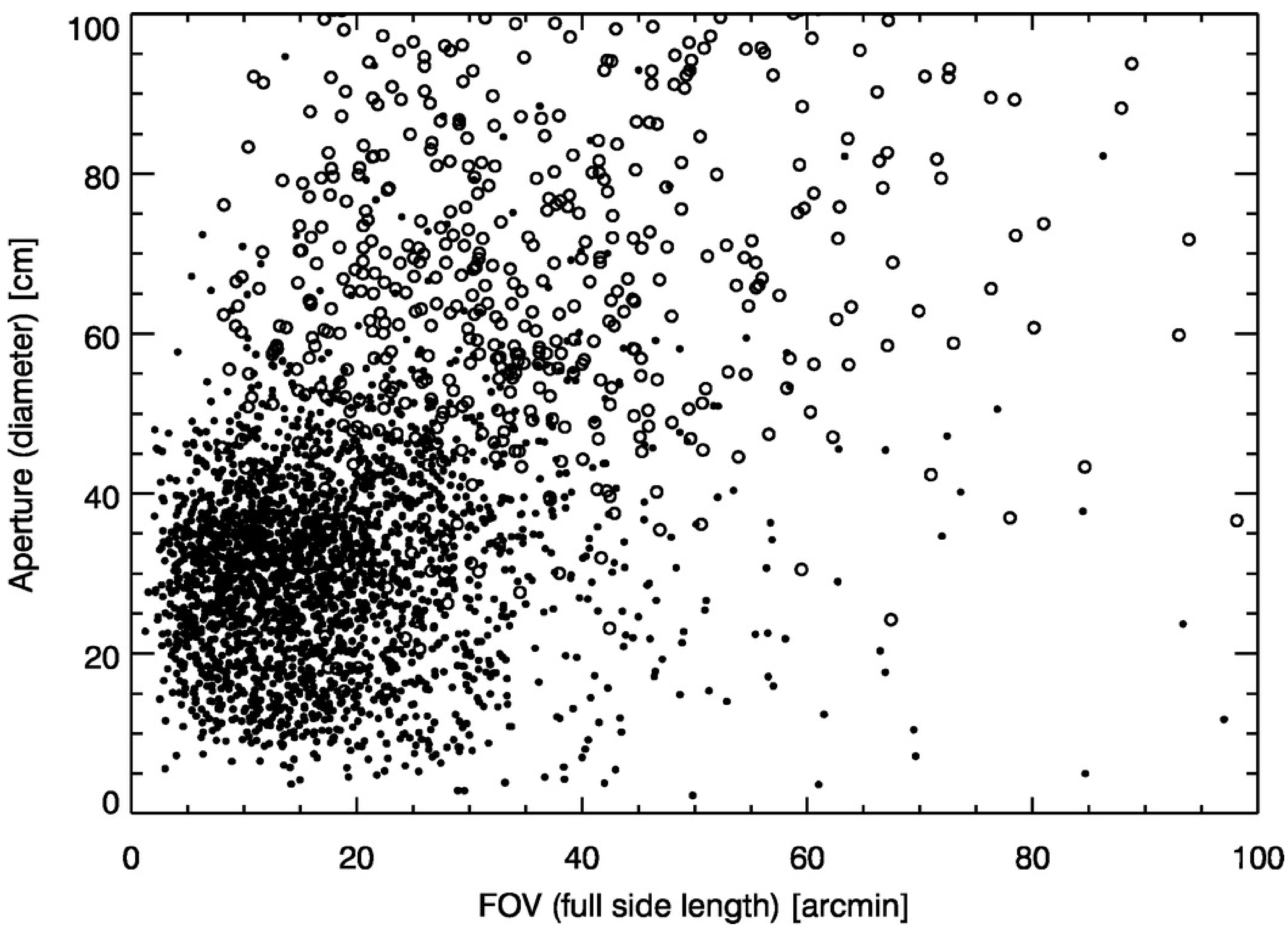
Precise RVs in the Infrared

Bean et al. 2009





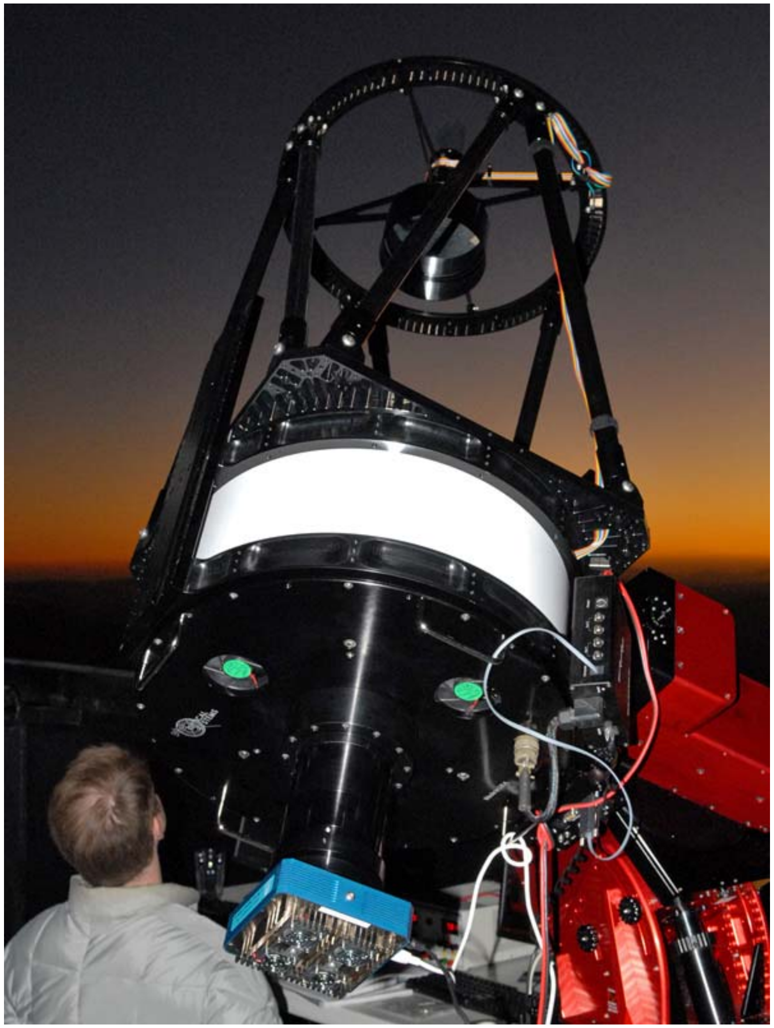
Survey Design



Nutzman& Charbonneau 2008

<u>Goal:</u> Survey 2000 M-dwarfs for habitable zone 2 R_{Earth} planets

- Survey can be completed in 3 years with 8 X 40cm telescopes
- If occurrence is 100%, expected yield is 26 detections



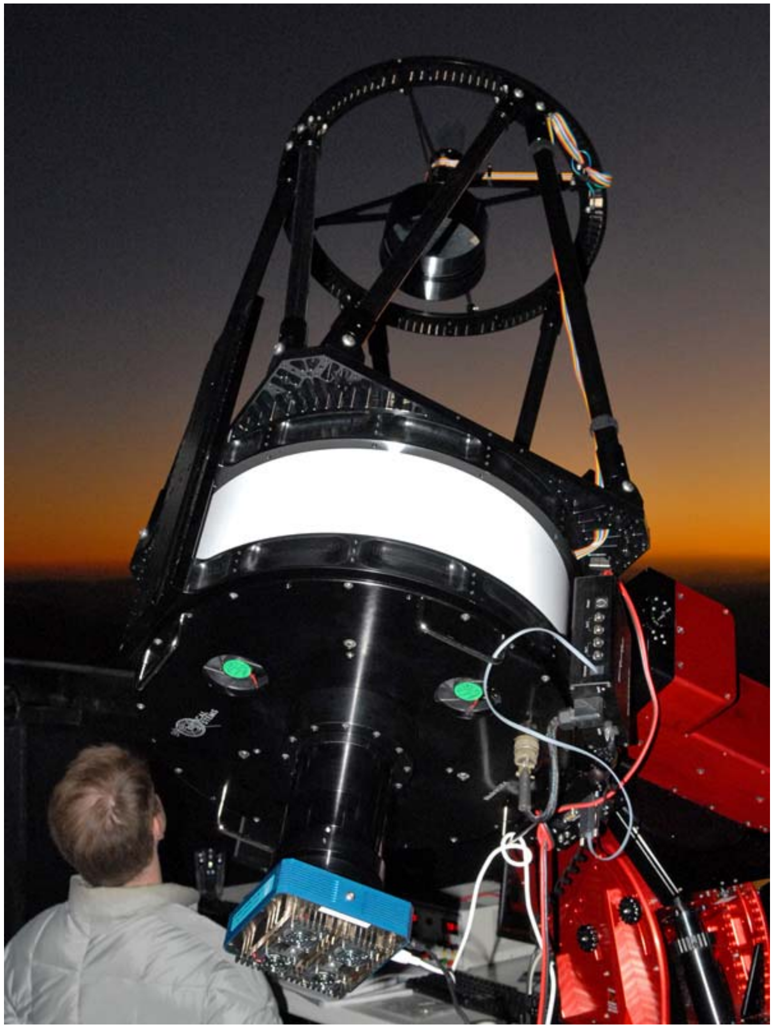
The MEarth Project

Berta, Burke, Irwin, Nutzman, Weiss & Charbonneau

- Using 8 X 16-inch telescopes, we are surveying the 2000 nearest low-mass stars for planets as small as 2 R_{Earth} orbiting within the habitable zone.
- We monitor stars *sequentially* and plan to detect transits *in progress*.
- We moved into an existing building on Mt Hopkins, Arizona.
- ***All 8 telescopes now operational*** (as of 28 September 2008)

The MEarth Project

Berta, Burke, Irwin, Nutzman, Weiss & Charbonneau



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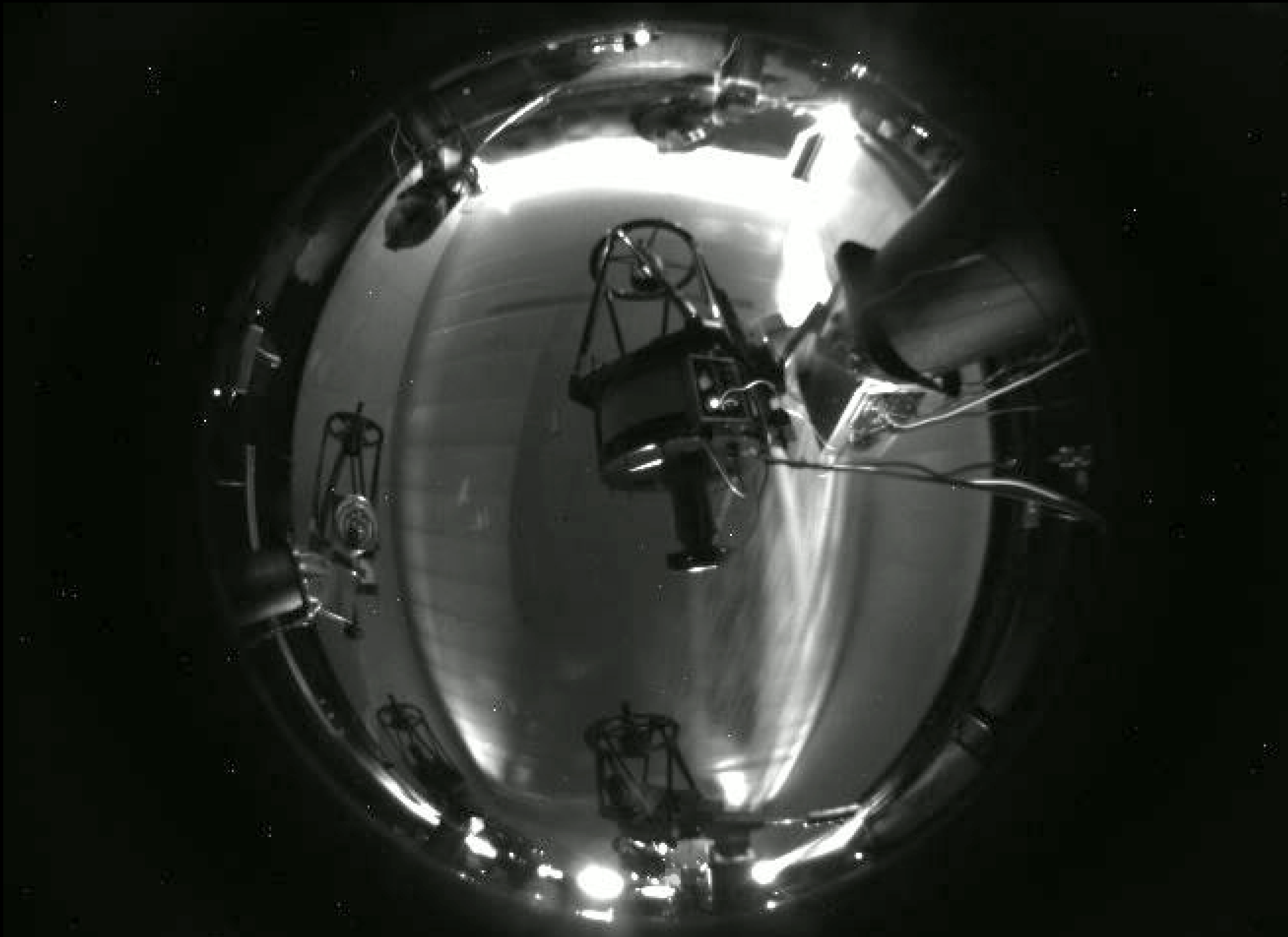
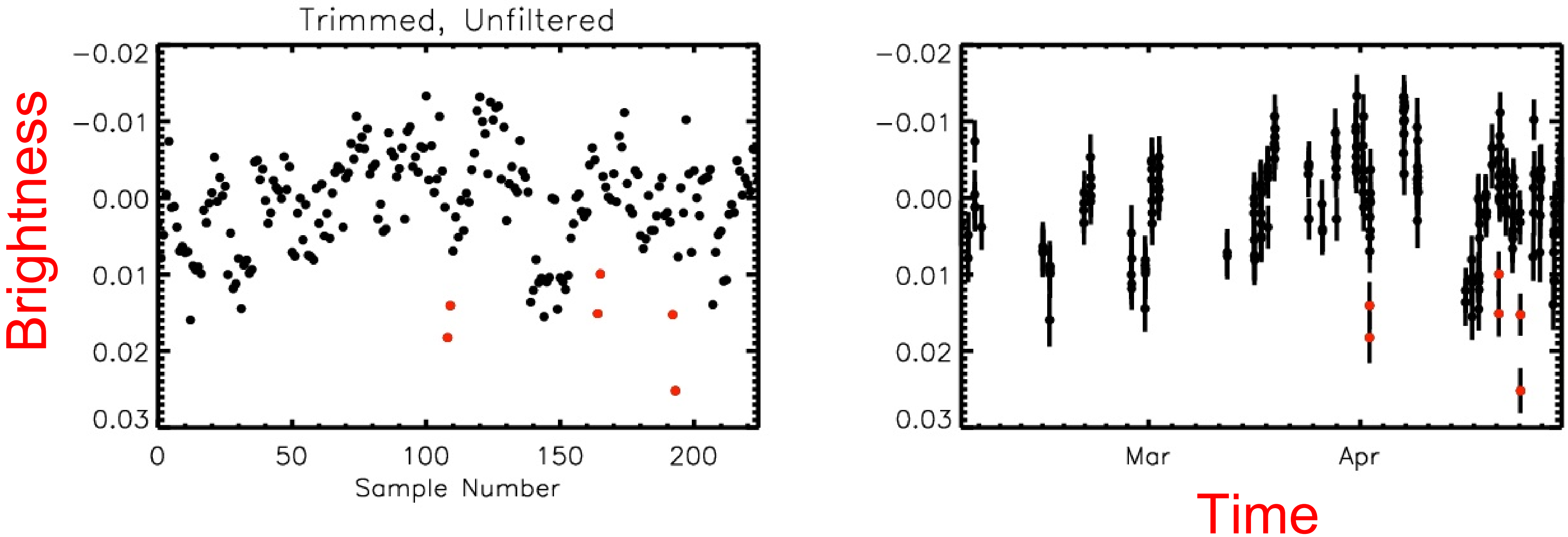
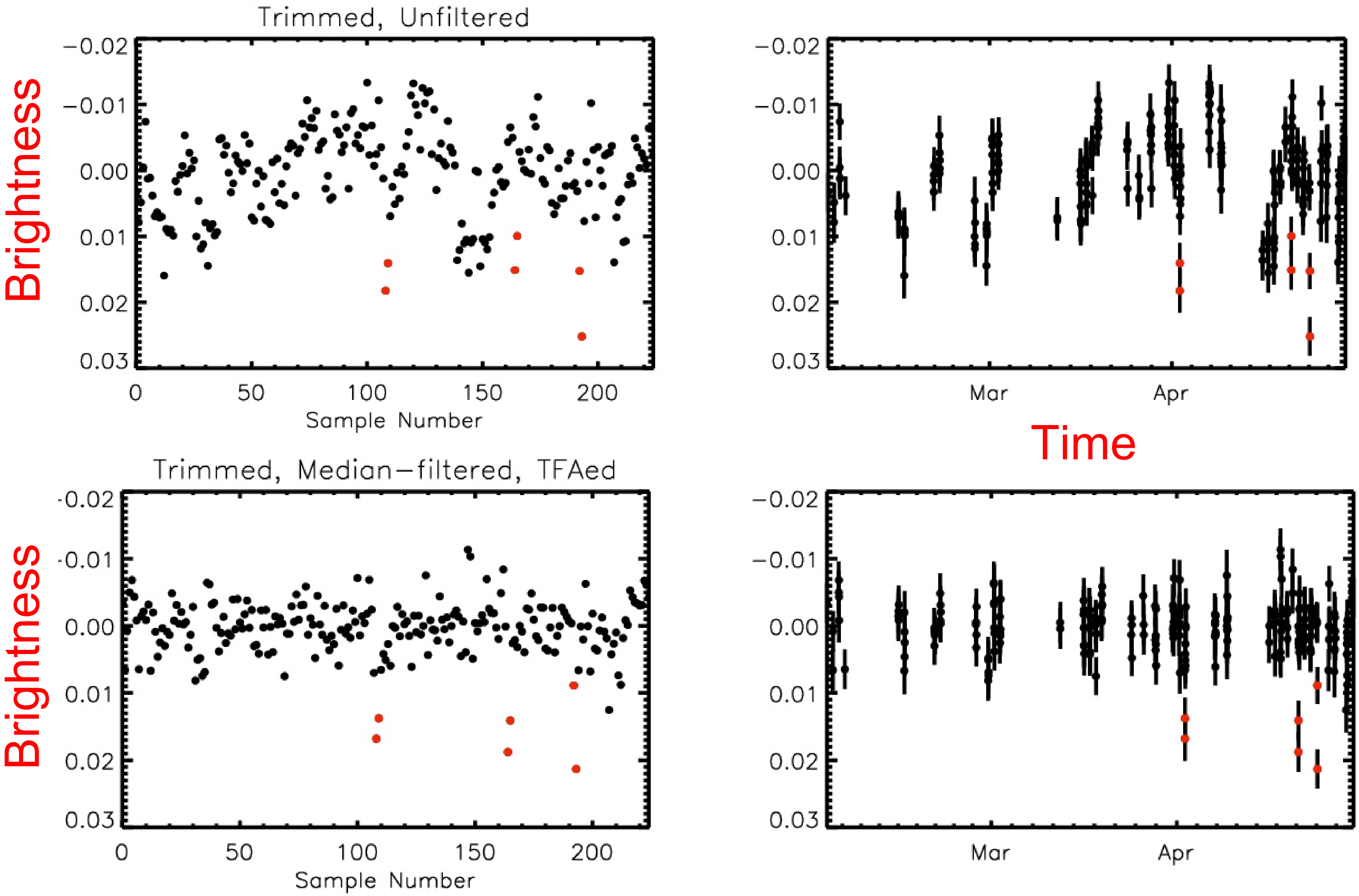


MEarth Project, Whipple Observatory, AZ

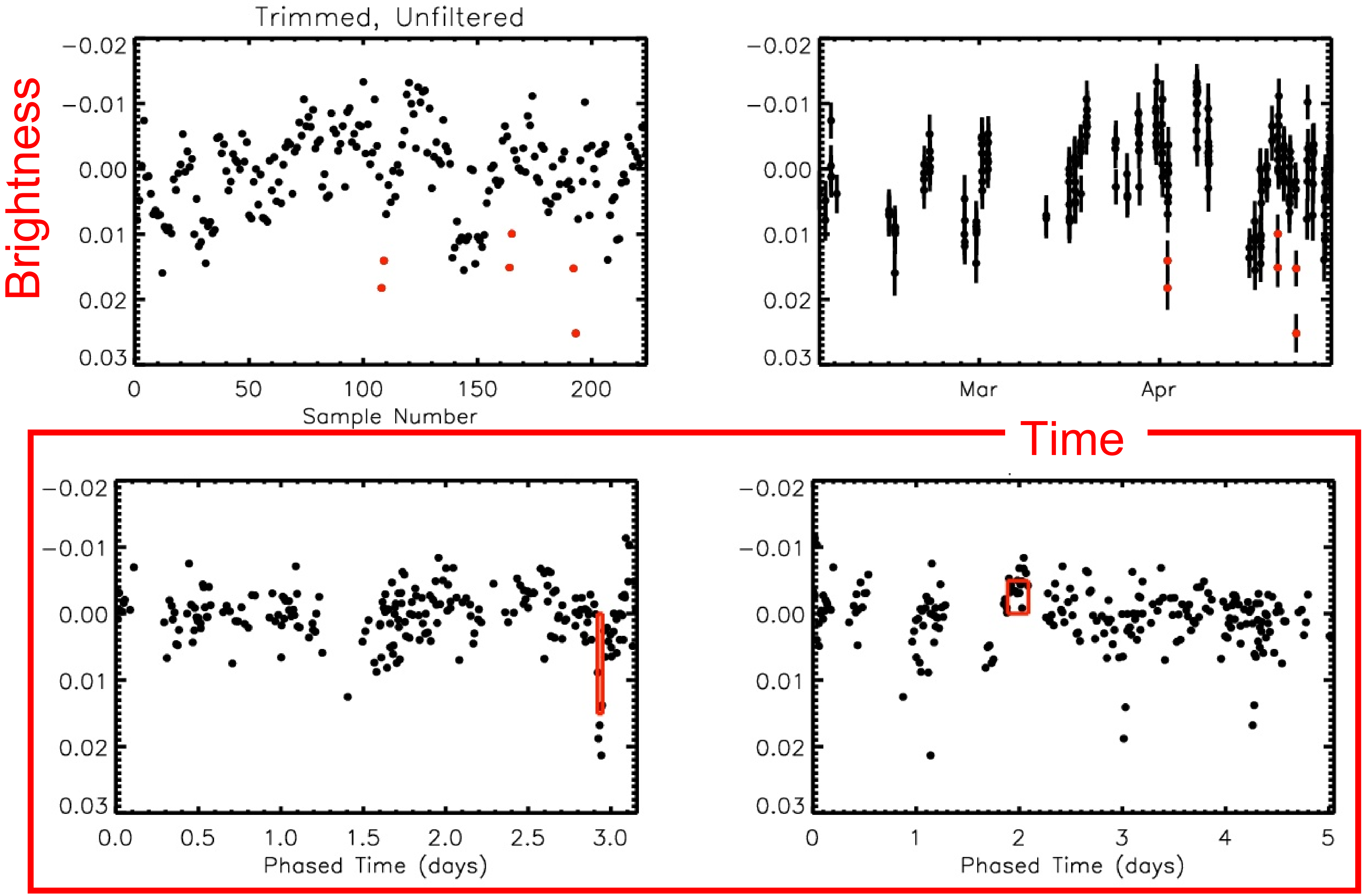
MEarth: The Challenge of Spotted Stars



MEarth: The Challenge of Spotted Stars

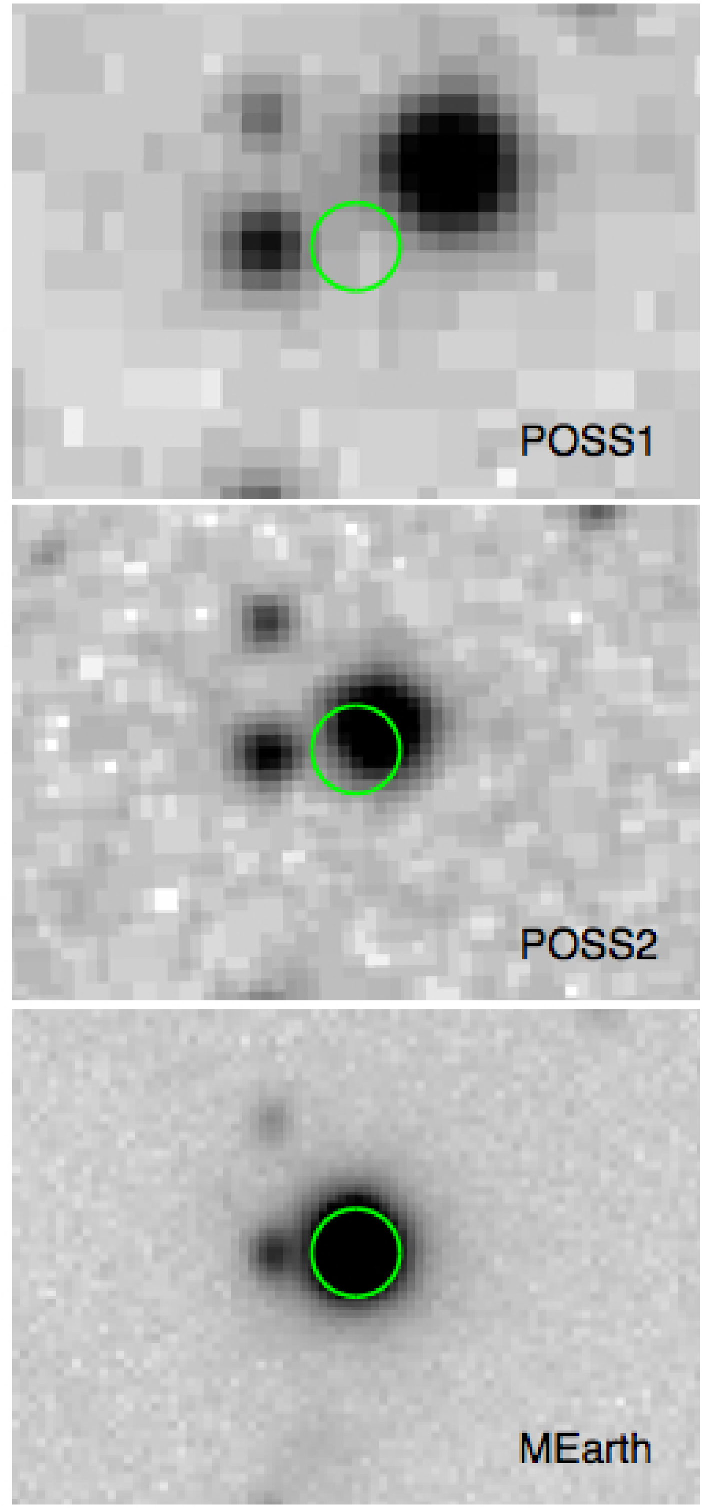


MEarth: The Challenge of Spotted Stars

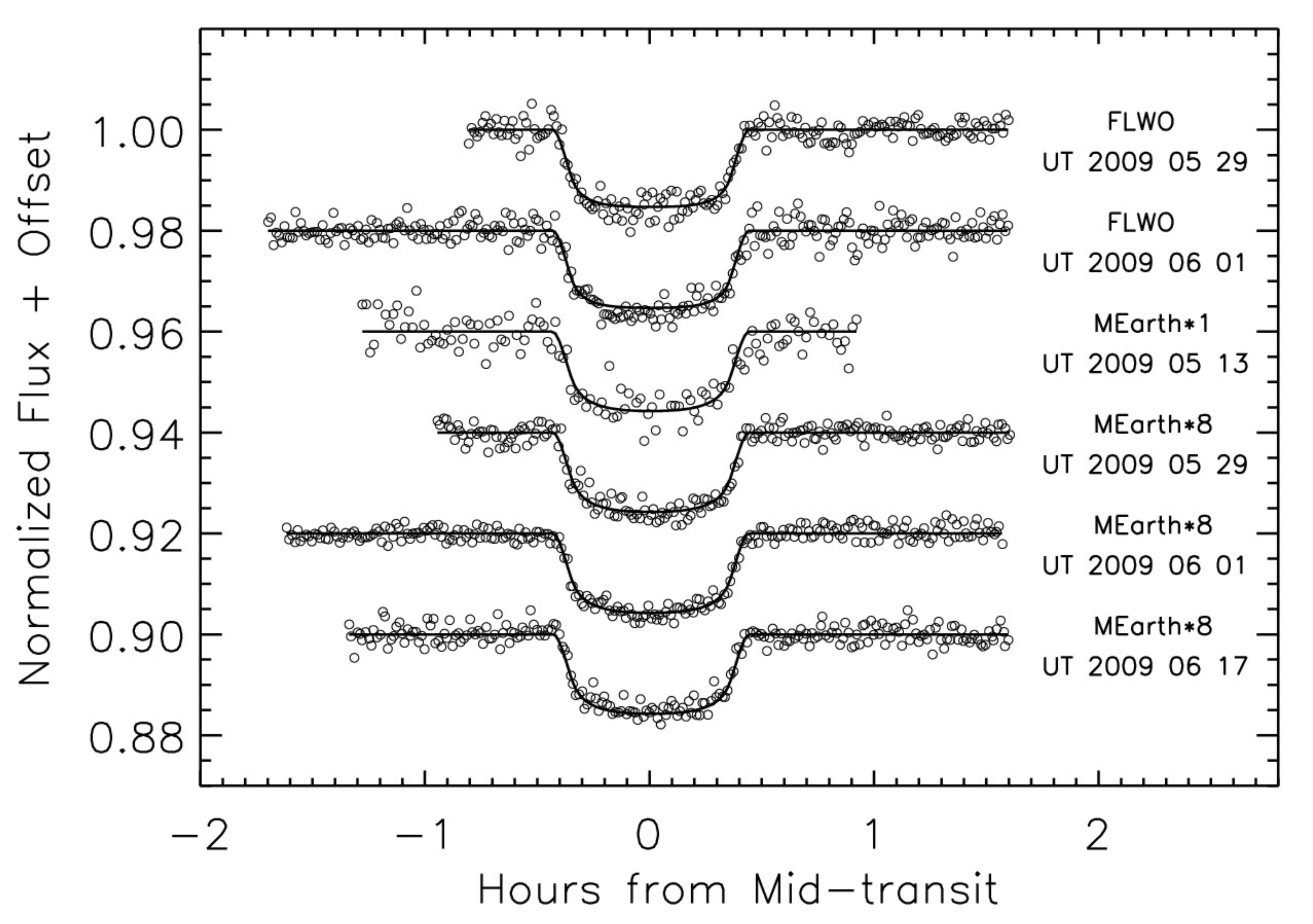


MEarth: Freedom from False Positives

+ high proper-motion eliminates physically-unassociated blends
+ short ingress relative to orbital period eliminates bound triples

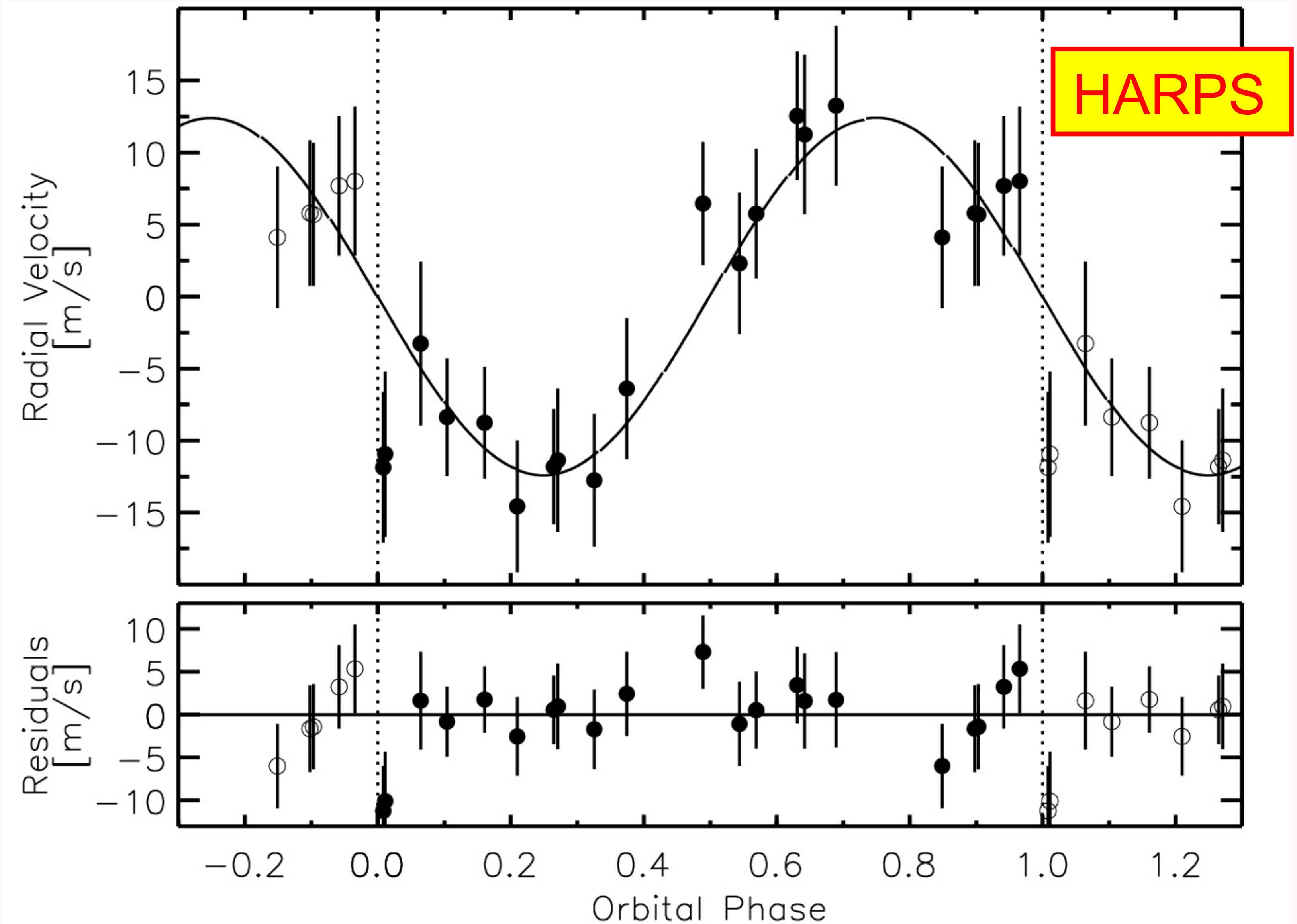


A Nearby Transiting Super-Earth: GJ1214b



Charbonneau et al. Nature 17 Dec 2009

A Nearby Transiting Super-Earth: GJ1214b

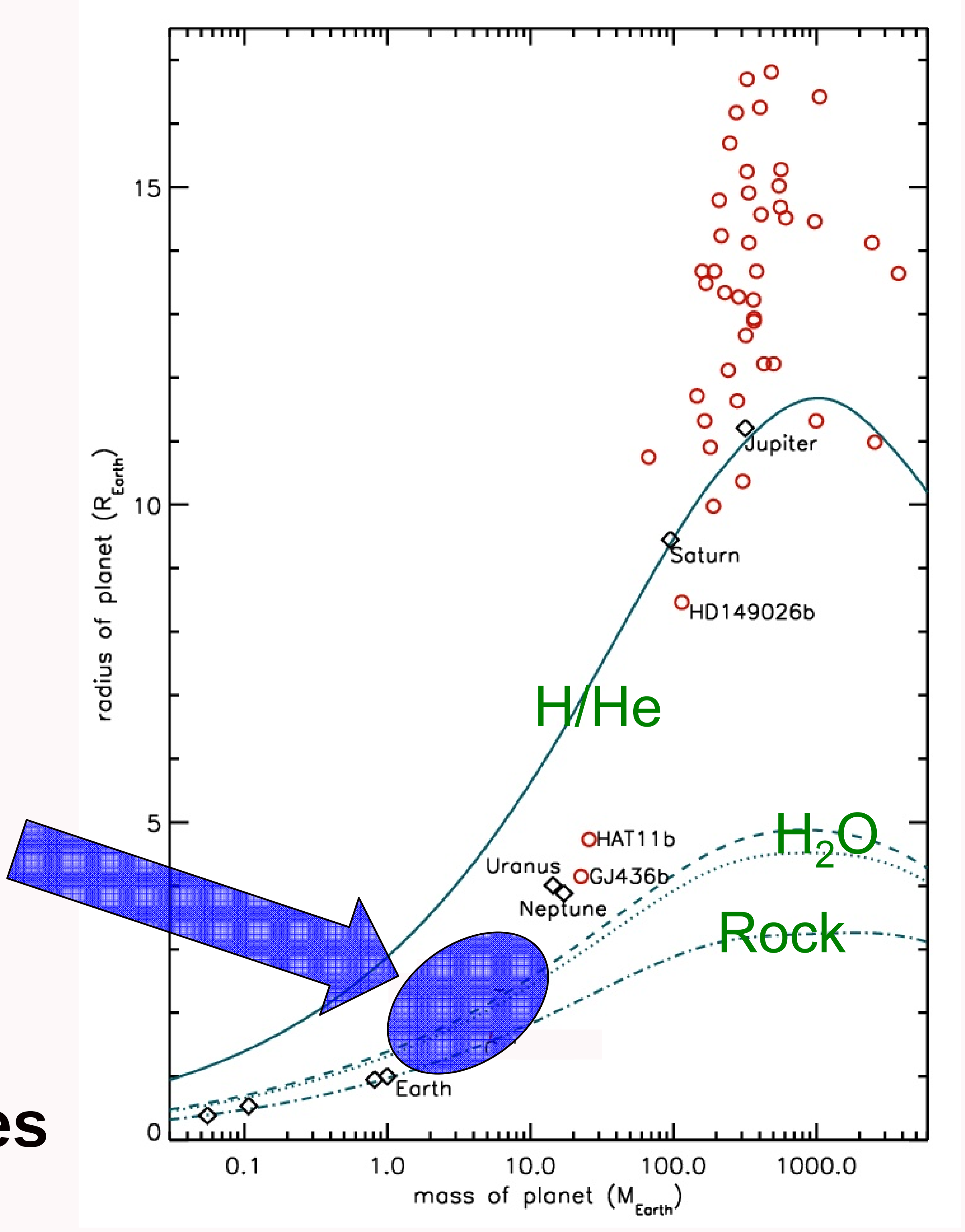


Charbonneau et al. Nature 17 Dec 2009

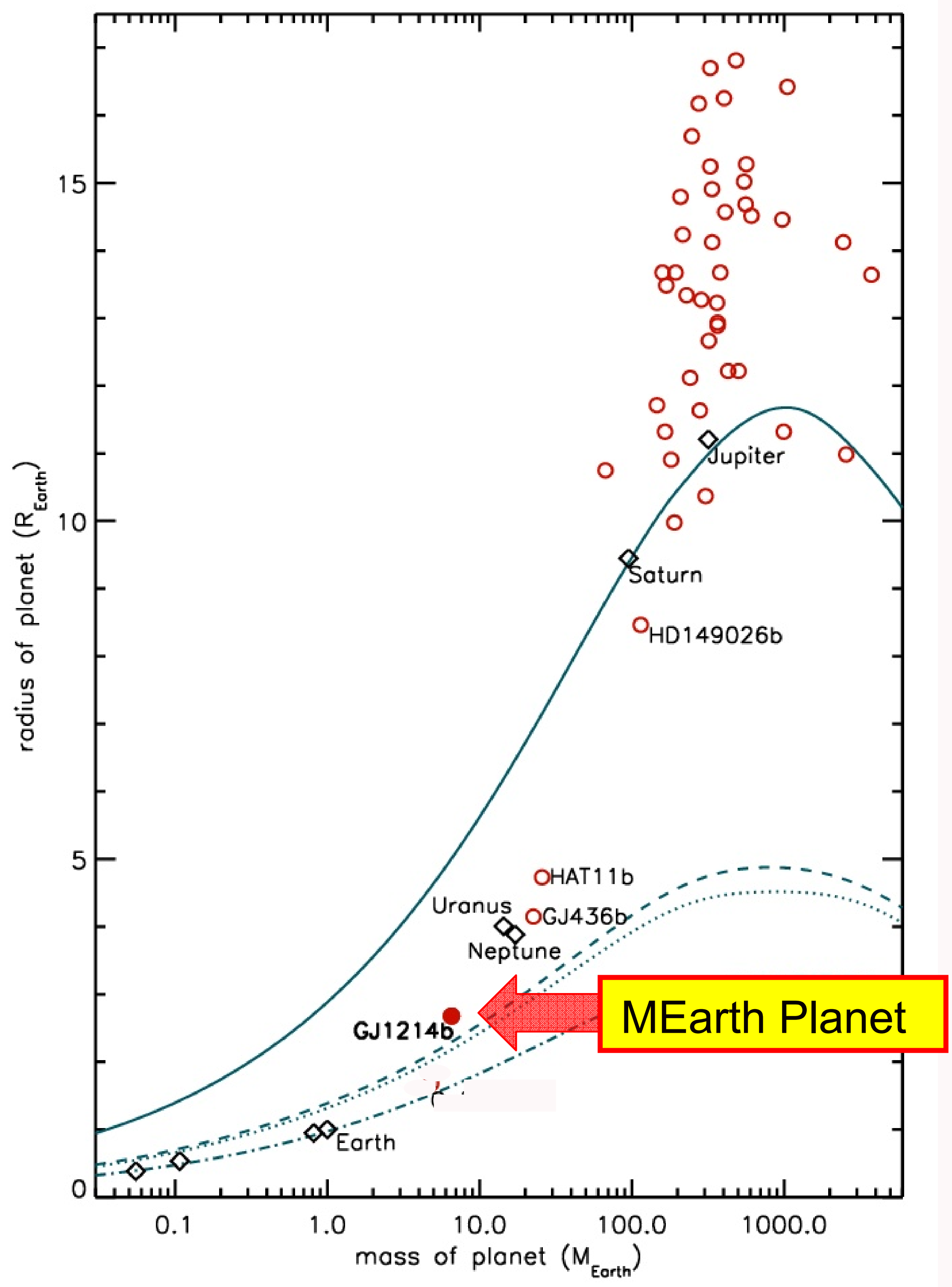
A Diversity of Worlds

Super-Earths

Mass range:
2 – 10 Earth masses



The Era of the Super-Earths is Upon Us!



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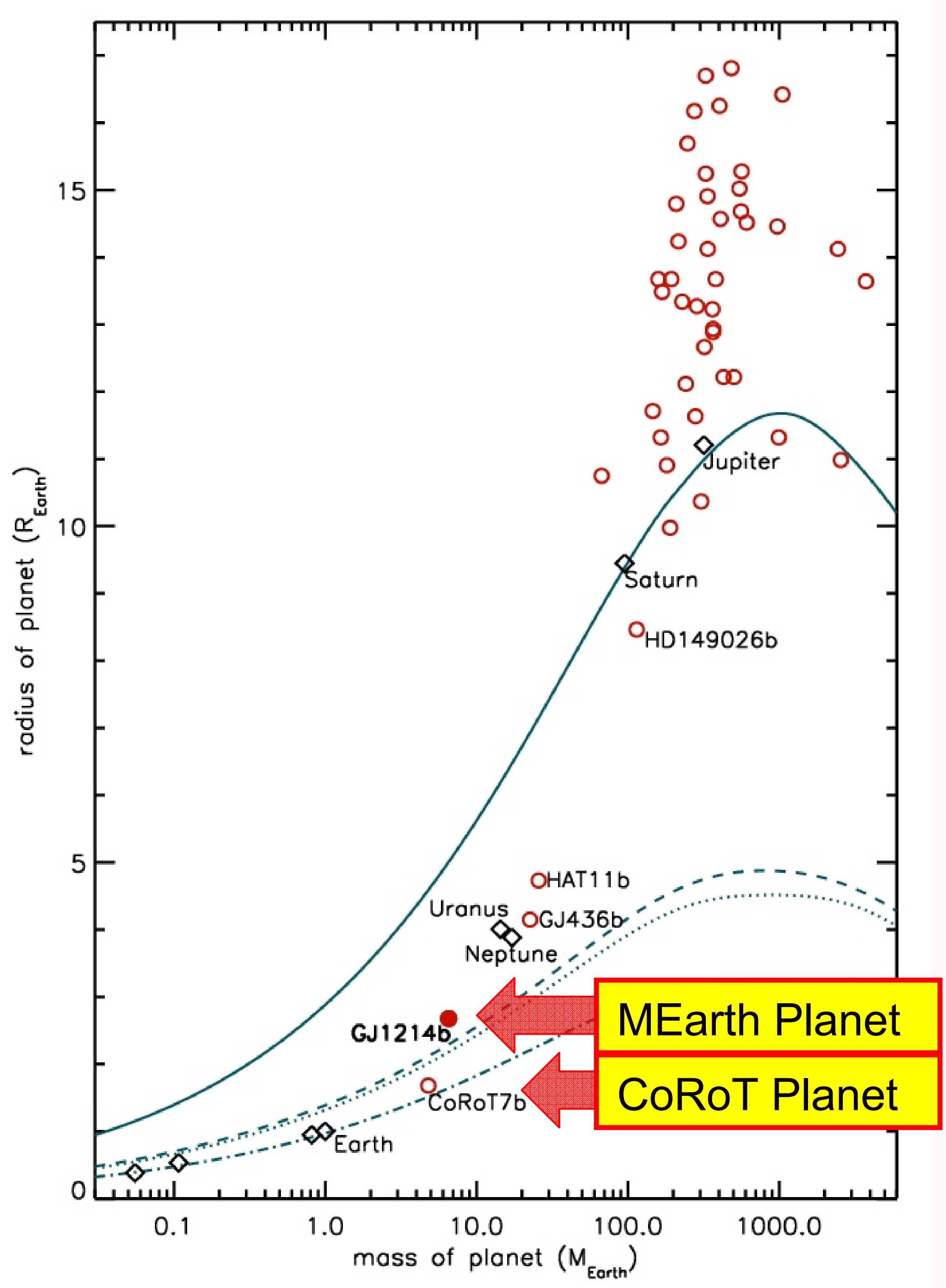

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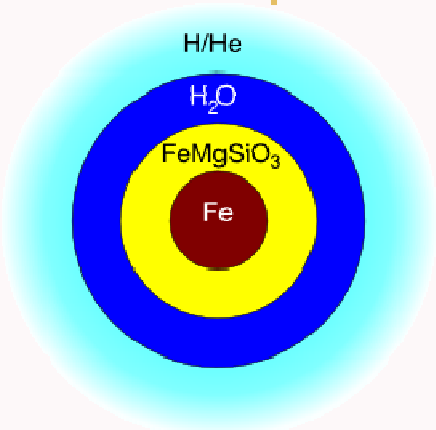
Three Scenarios for GJ 1214b

Rogers and Seager 2009 arXiv:0912.3234

Mini Neptune



Gas layer is primordial dominated by H/He from nebula.

Requires 10^{-4} to 6.8% H/He by mass (greater than Venus, but less than Neptune).

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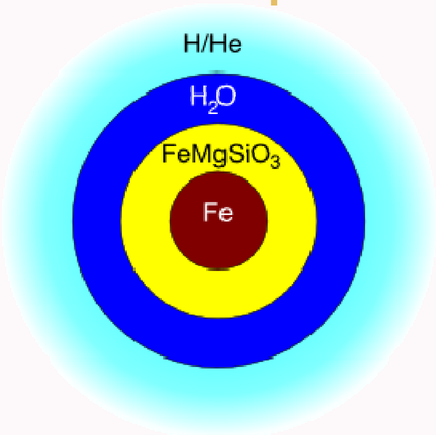

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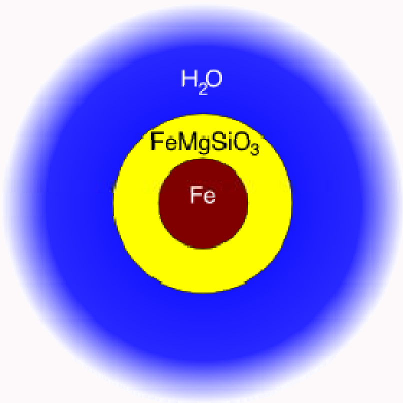
Water Planet



Planet was not sufficiently massive to accrete H/He envelope. Envelope is vapor from sublimated ices.

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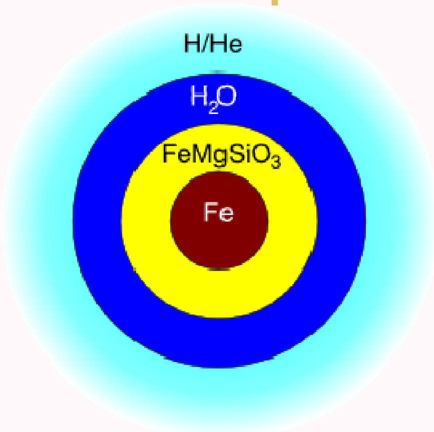

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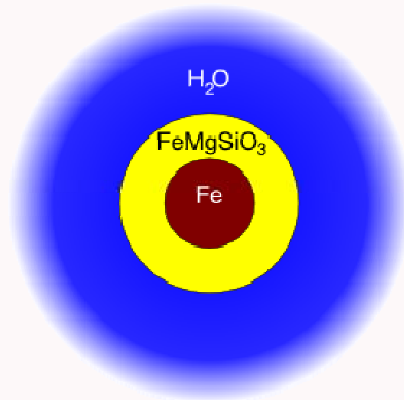

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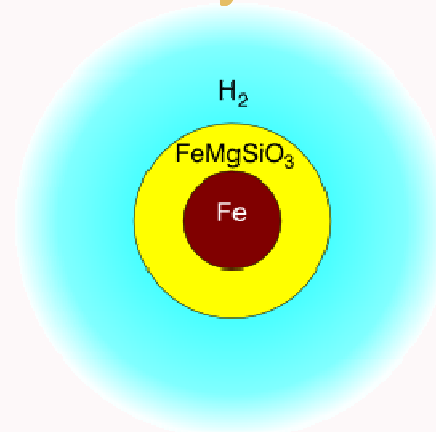
Rocky Heart

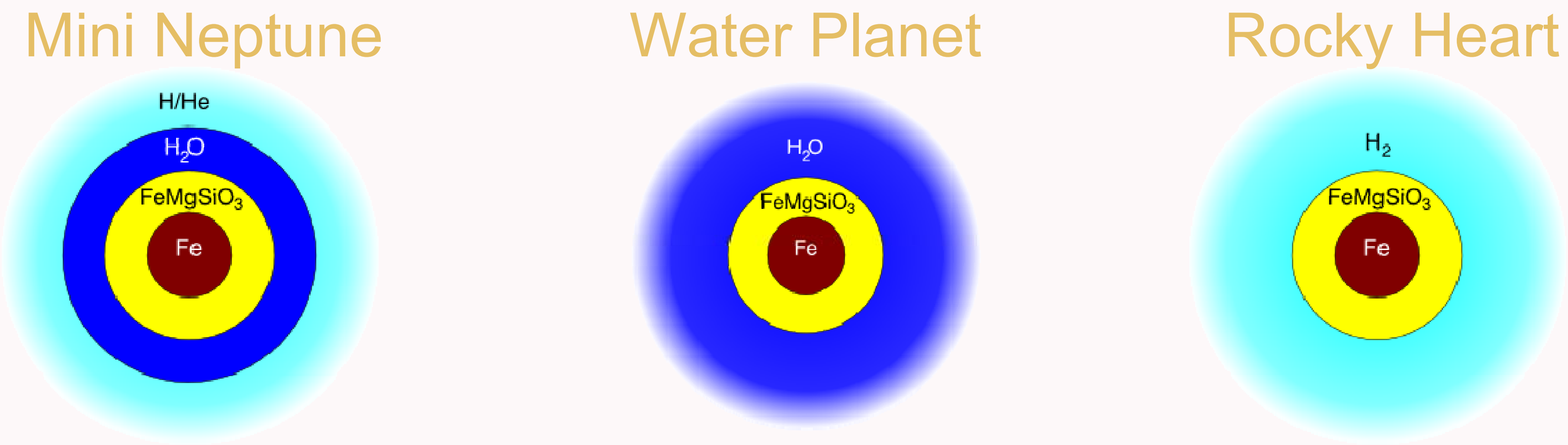


Outgassed atmosphere must be hydrogen rich but would lack He.

Based on chondrites, fraction of H available may be insufficient given likely escape.

Three Scenarios for GJ 1214b

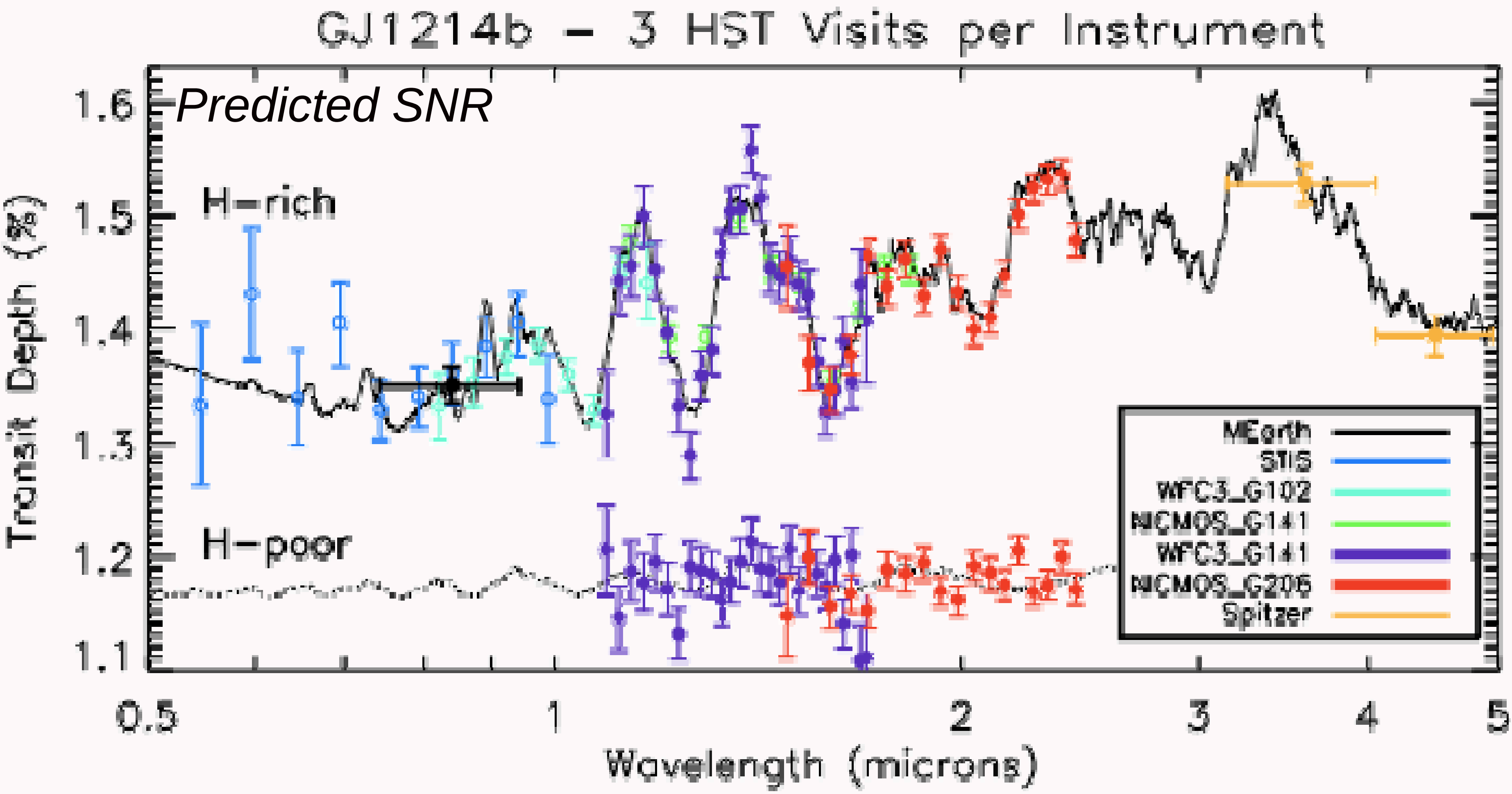
Rogers and Seager 2009 arXiv:0912.3234



Next Step: Use the Miller-Ricci Method to determine atmospheric scale height and abundances.

Byproduct of HST spectroscopy would be photometric sensitivity to Ganyemede-sized moons (because star is small)

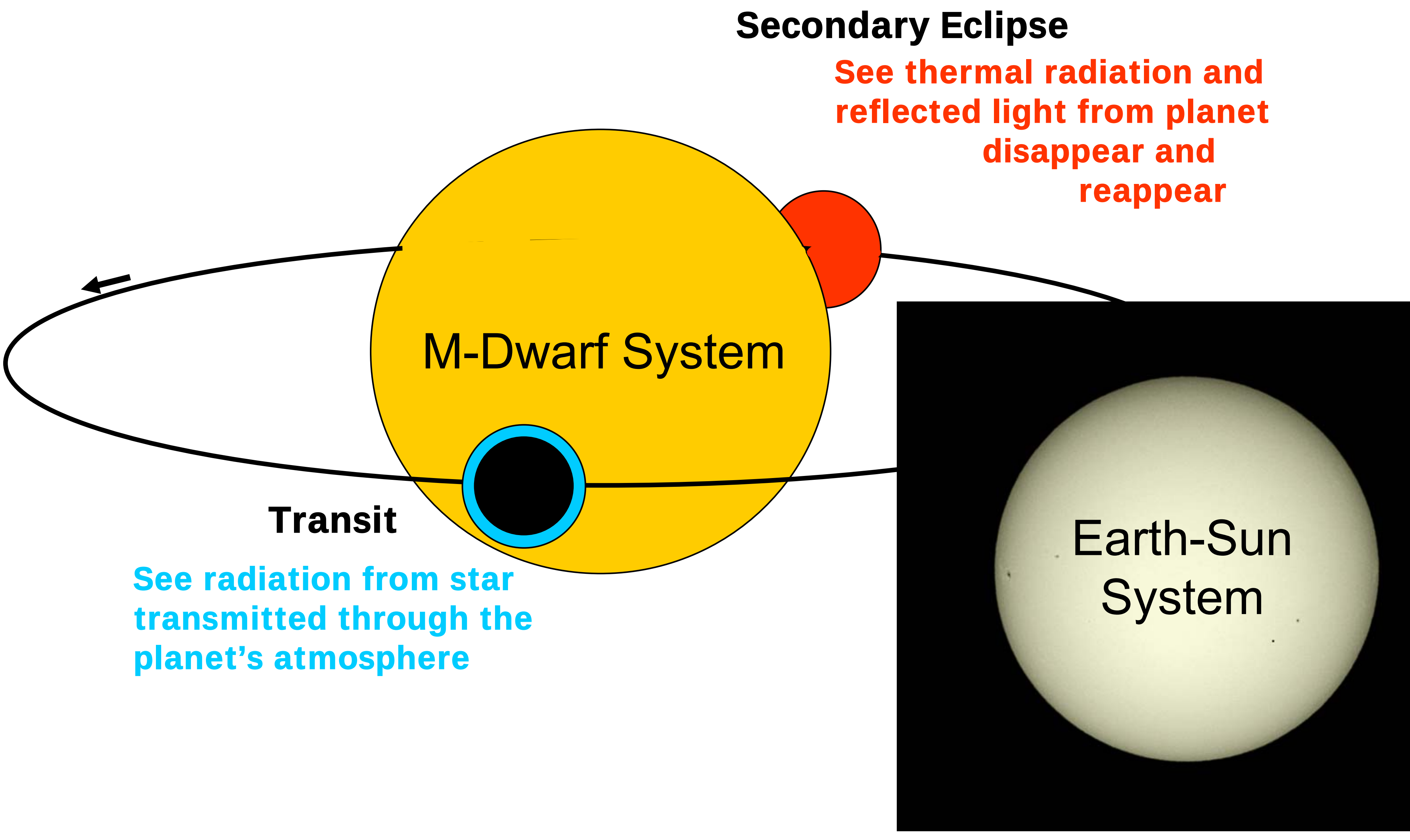
Super-Earth Atmospheres Already Accessible to HST



Secondary Science:
Ganymede-sized Moons!

Figure By Zach Berta

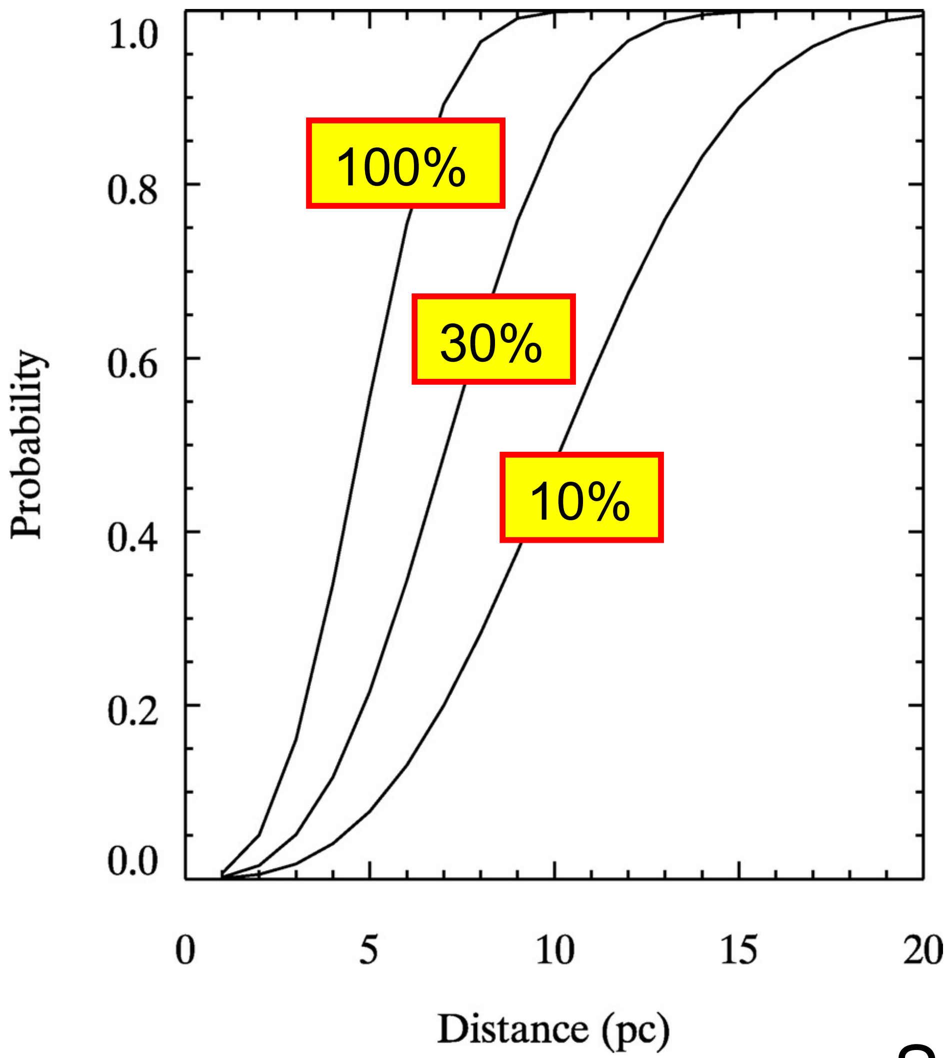
Transit Studies of the Atmospheres Are Facilitated by the Small Size of the Star

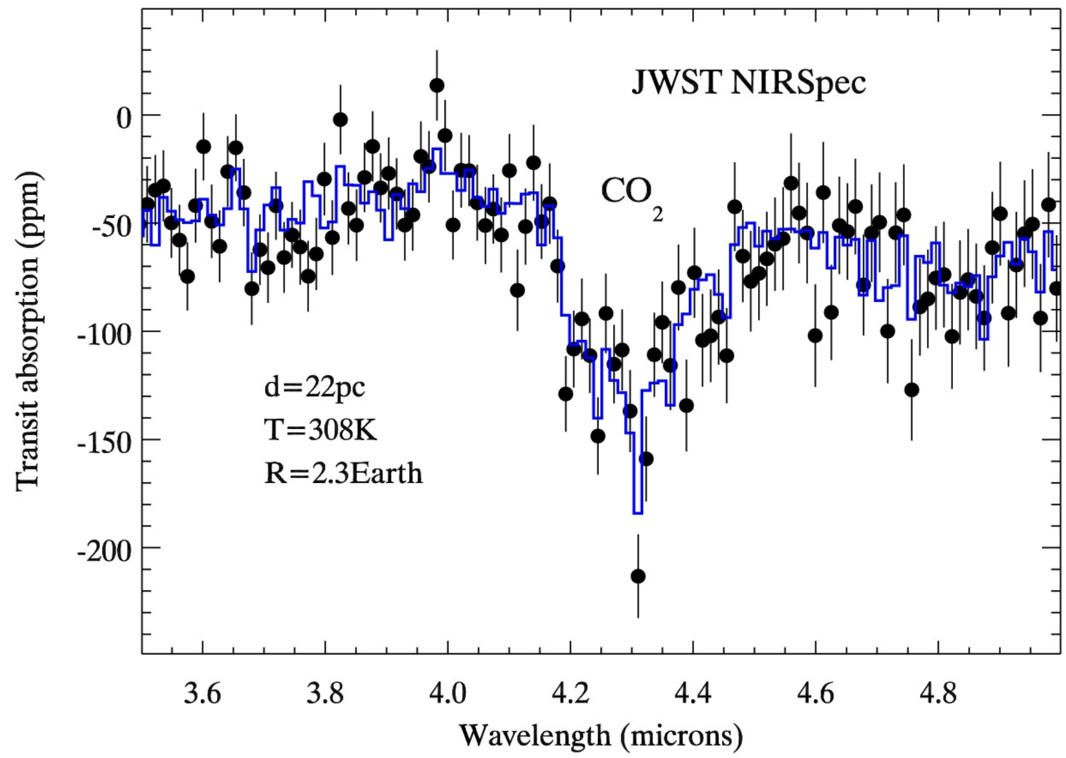


Habitable-Zone Planets Orbiting Low-Mass Stars are Ideal Targets for Atmospheric Studies to Search for **BIOMARKERS**

James Webb Space Telescope is scheduled for launch in 2014.

Planning for JWST Studies of Habitable Super-Earths





See Deming et al. (2009) for details

A Brief Look at the Path Ahead for Habitable Planets of Small Stars

Ground Based

Ground Based

Space Based

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