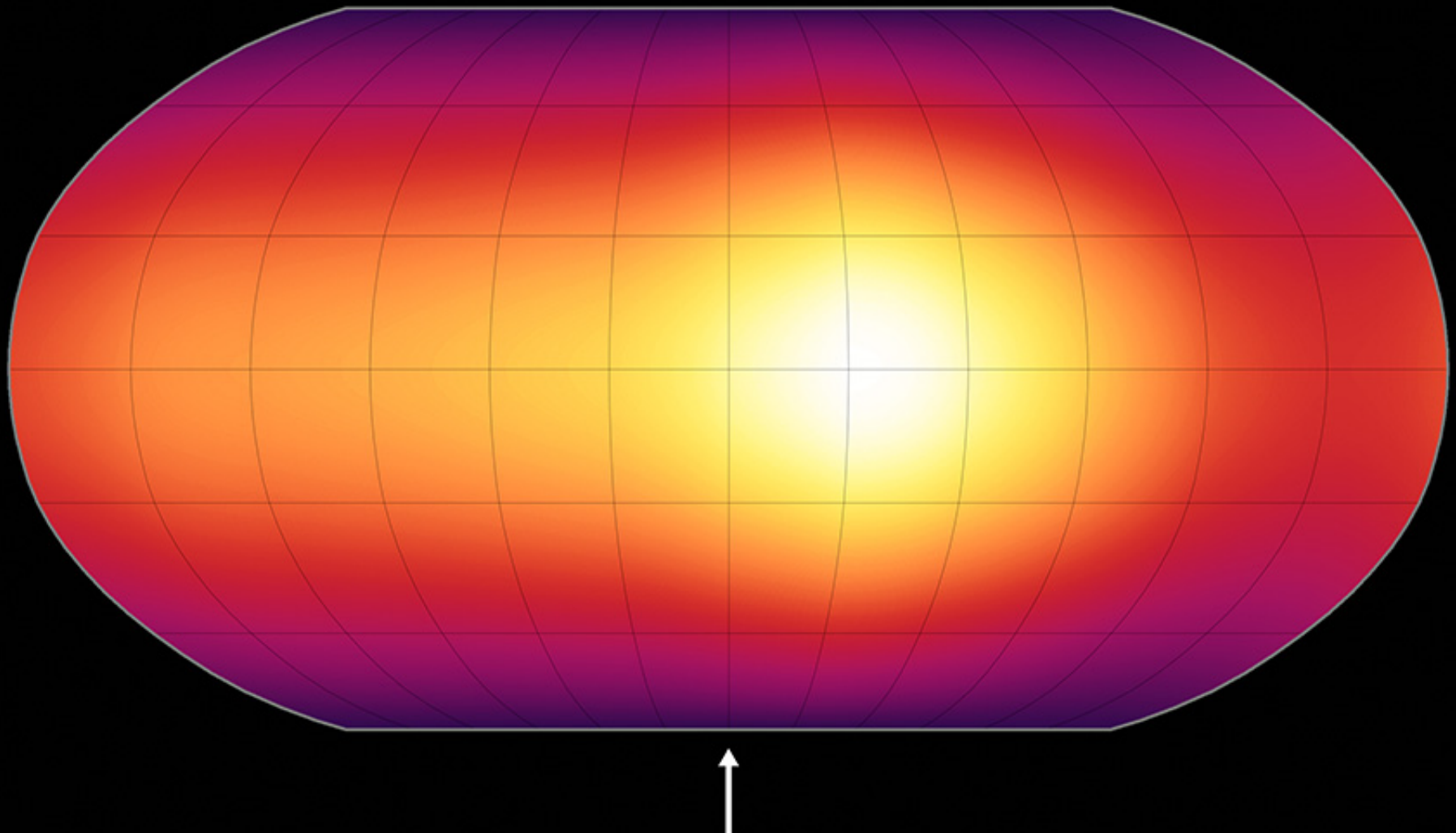
The Direct Study of Exoplanet Atmospheres

David Charbonneau (Harvard-Smithsonian Center for Astrophysics)

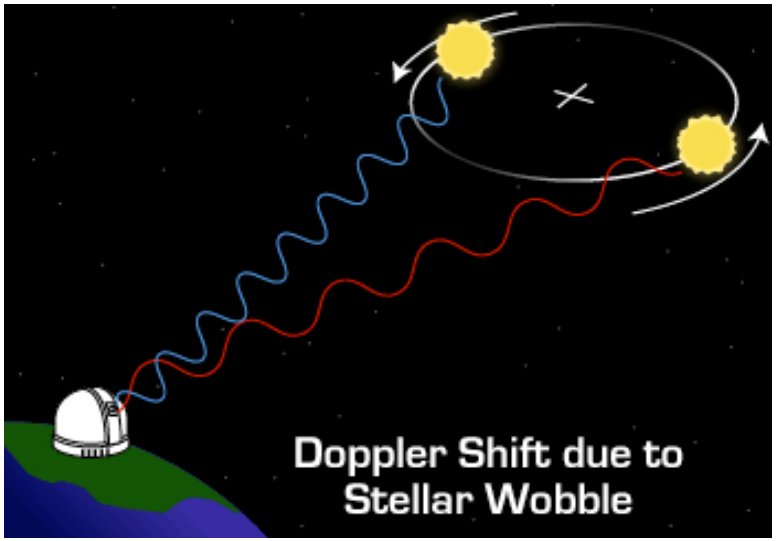
Symposium in Honor of Giovanni Fazio

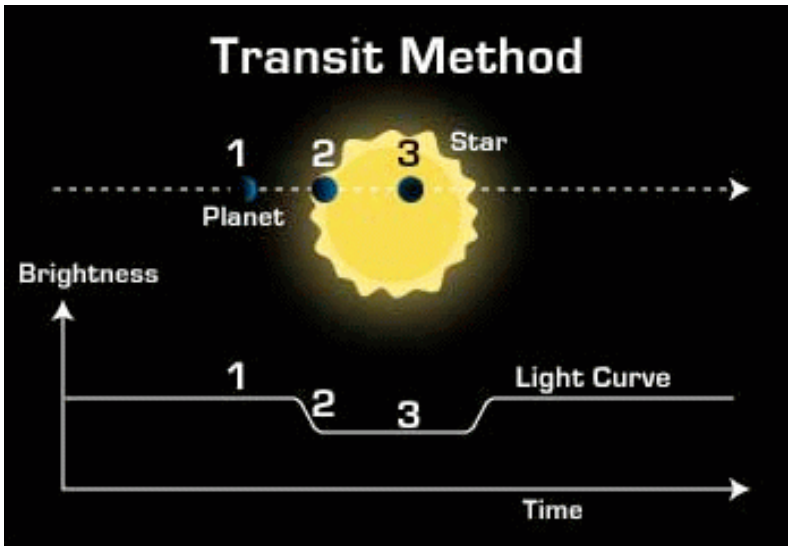
27 May 2008



Statement about the Astronomy & Astrophysics 2010 – 2020 Decadal Survey

Astronomers have developed two clever *(but indirect)* methods to find exoplanets





Doppler Method

Determine Planet Mass

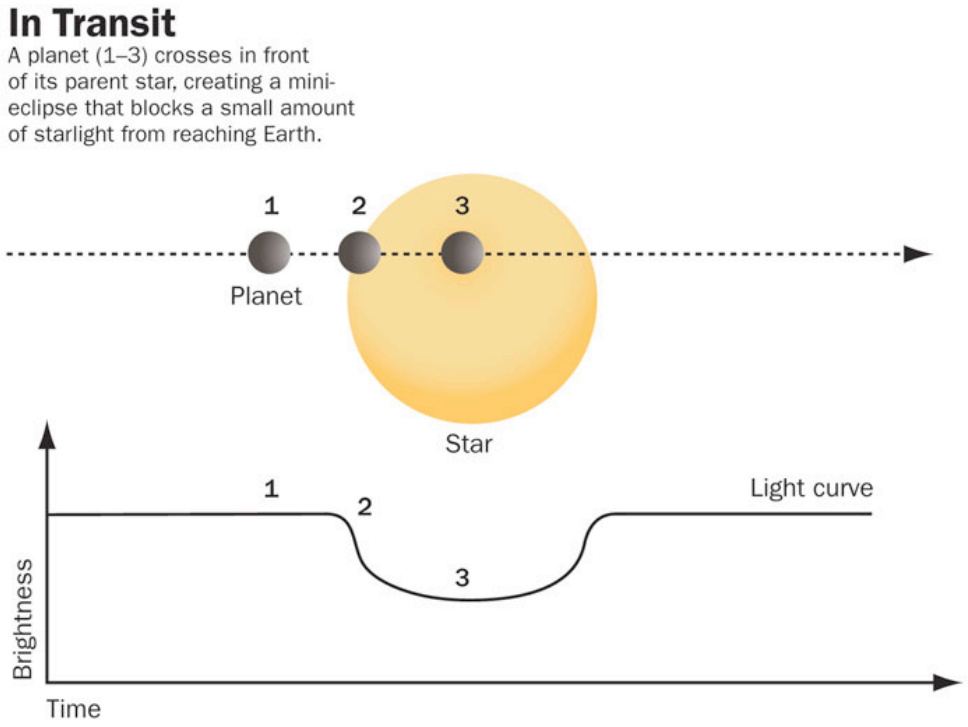
Transit Method

Determine Planet Diameter

Calculate Planet Density and Infer Composition:

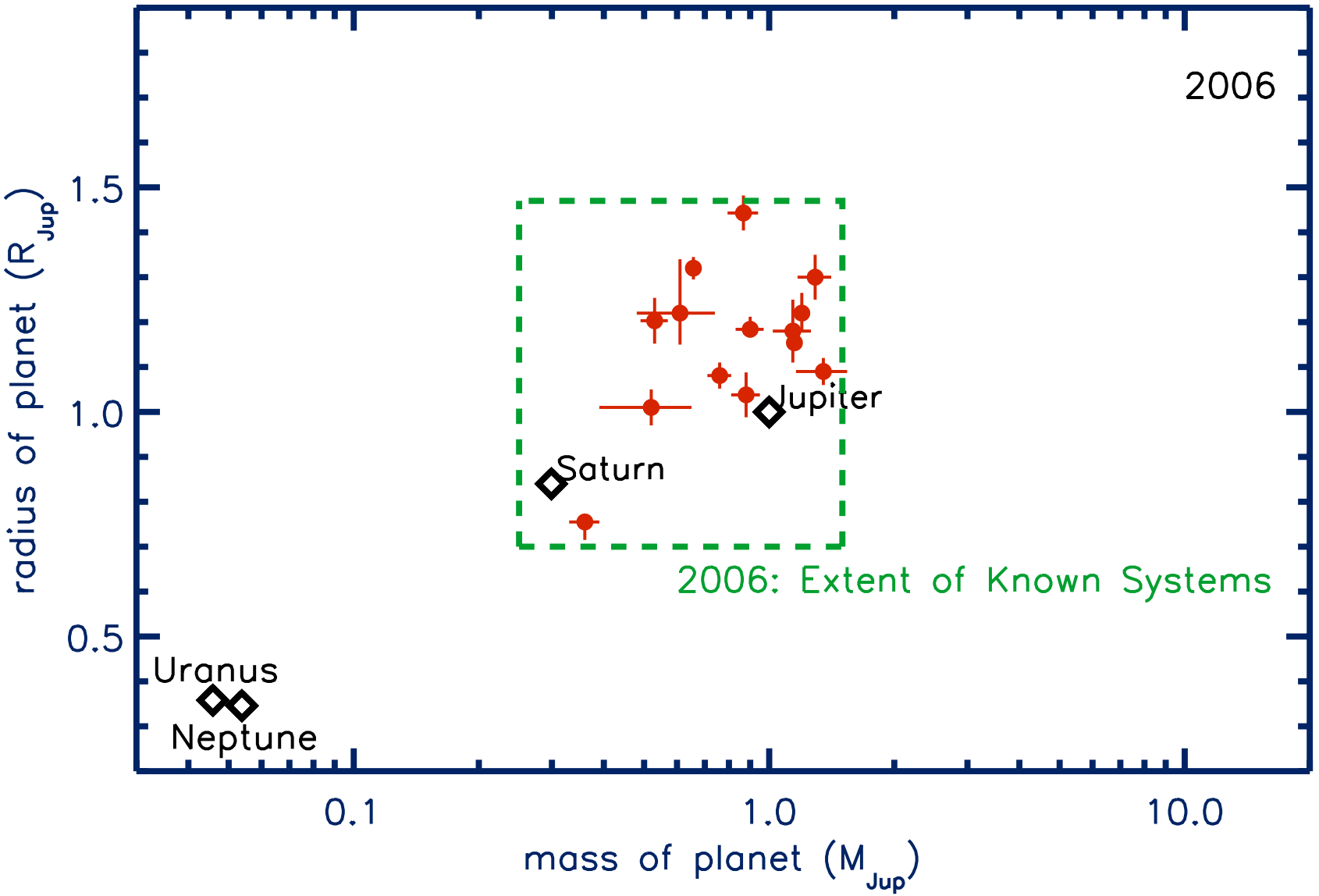
Gas giant (Jupiter), Ice giant (Neptune), or Rocky planet (Earth)

Why All the Fuss About Transiting Exoplanets?

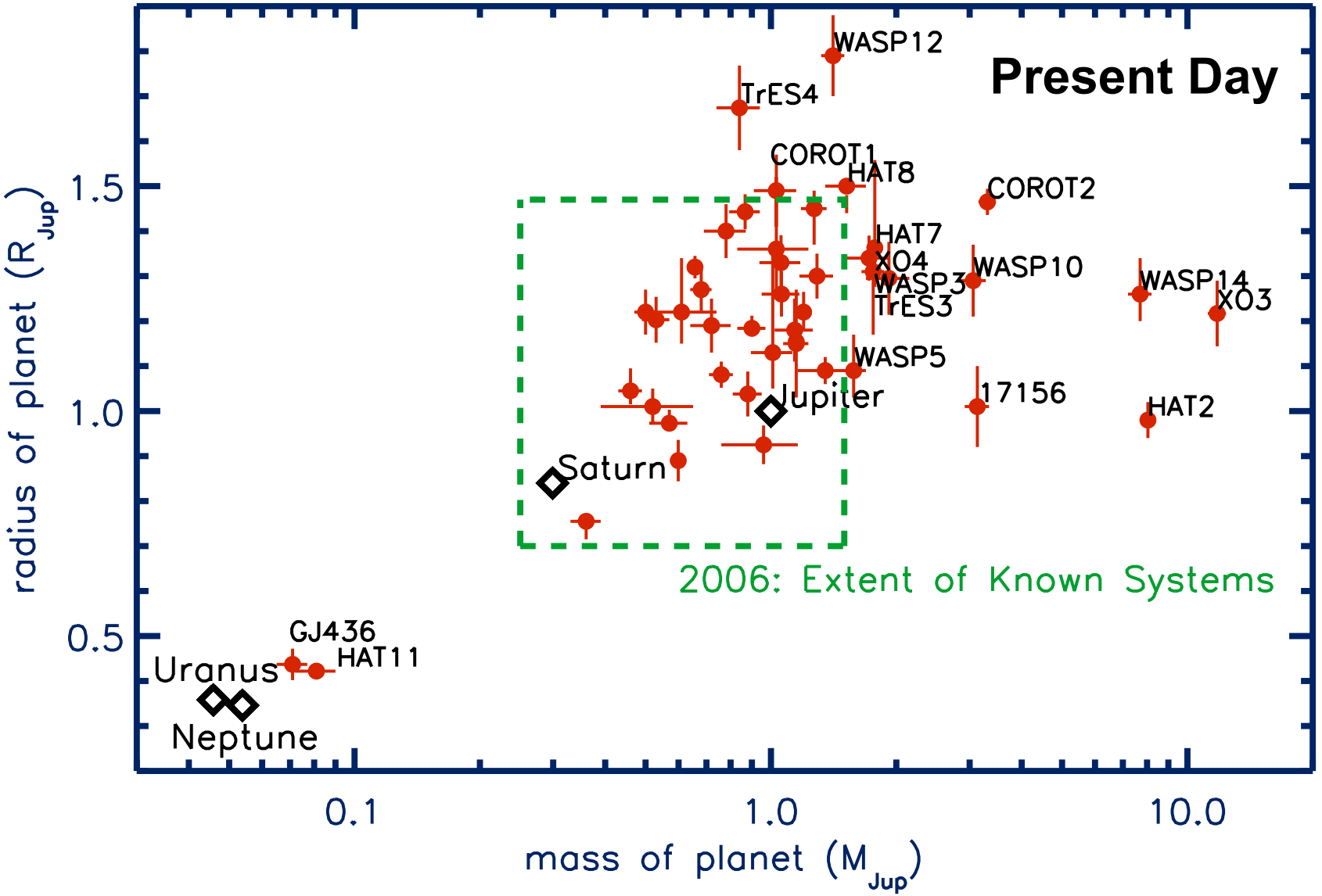


- They permit direct **estimates of the masses and radii**.
- They permit **studies of the exoplanetary atmospheres**.
- They will enable the first **studies of the spectra of potentially habitable worlds** beyond the Solar system.

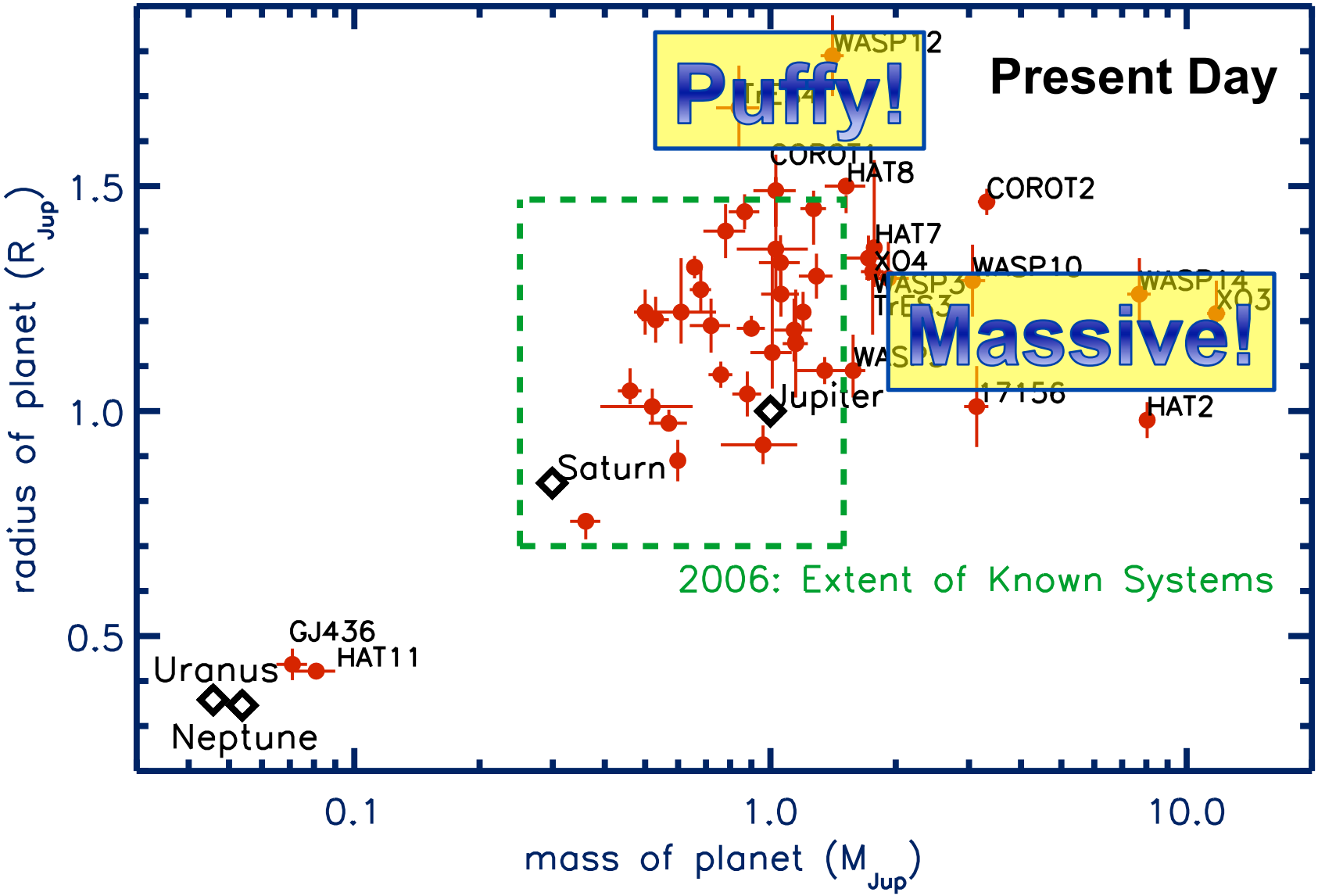
Masses and Sizes



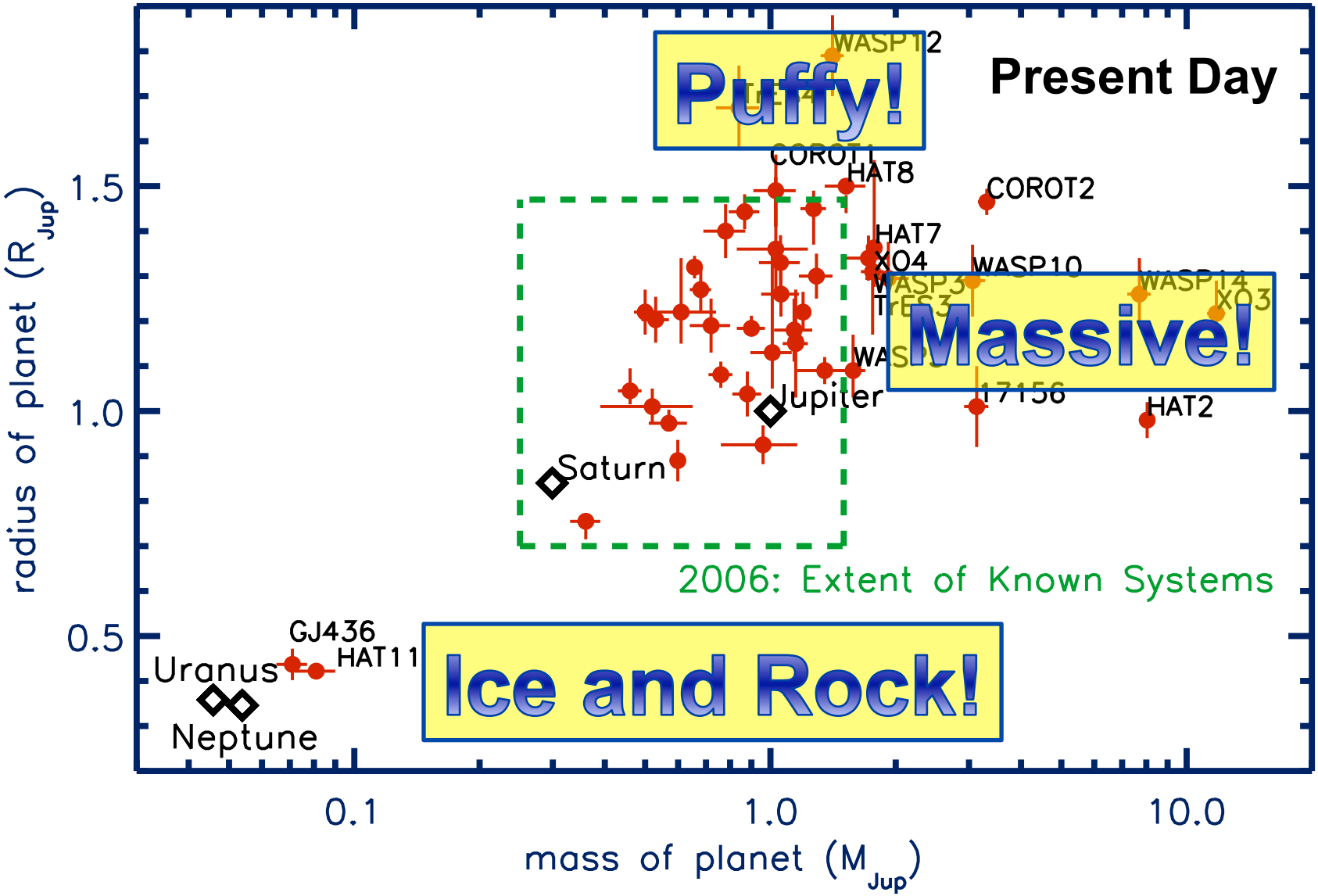
Masses and Sizes



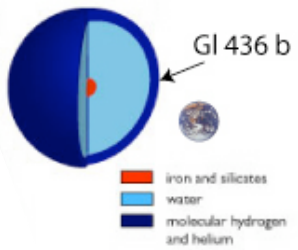
Masses and Sizes

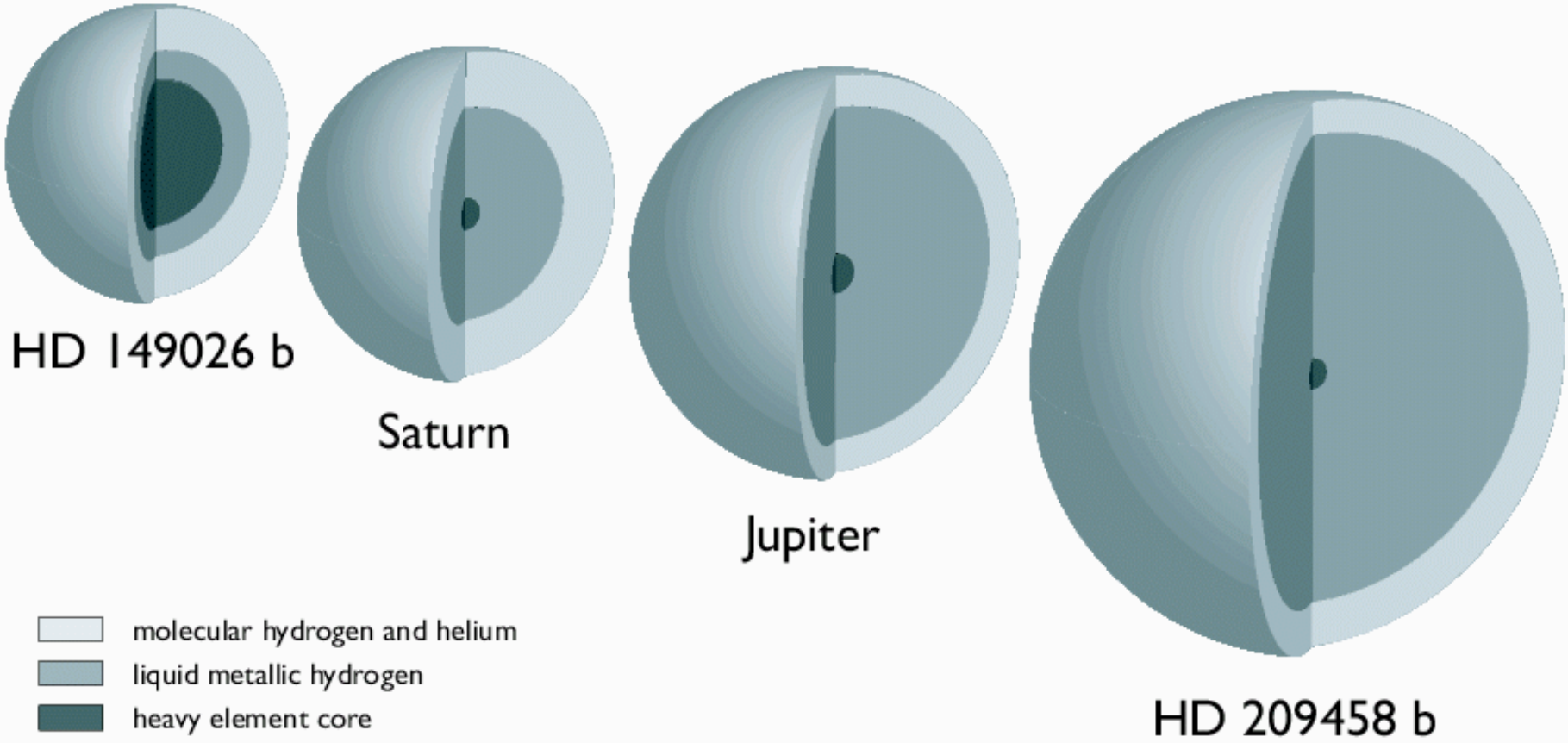


Masses and Sizes



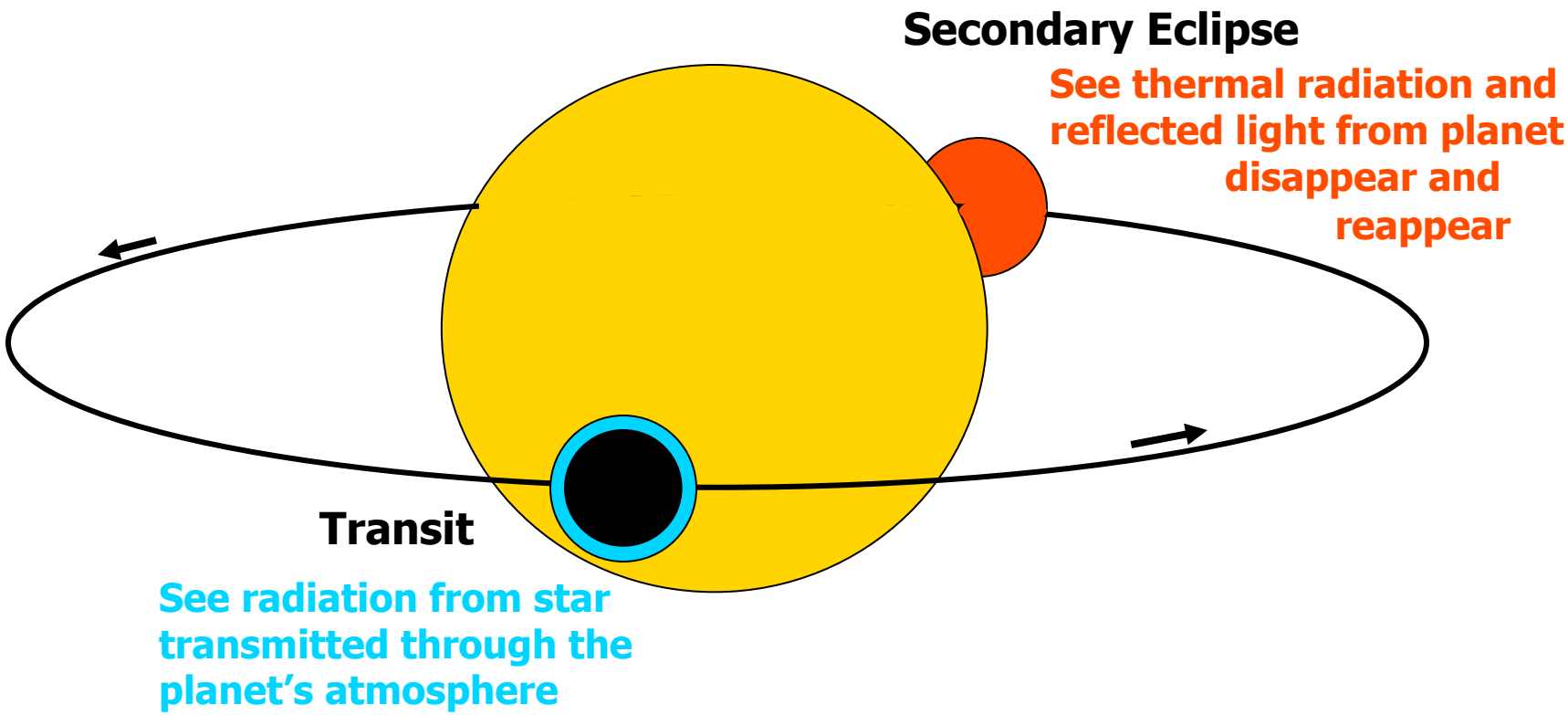
Welcome to the Era of Comparative Exoplanetology



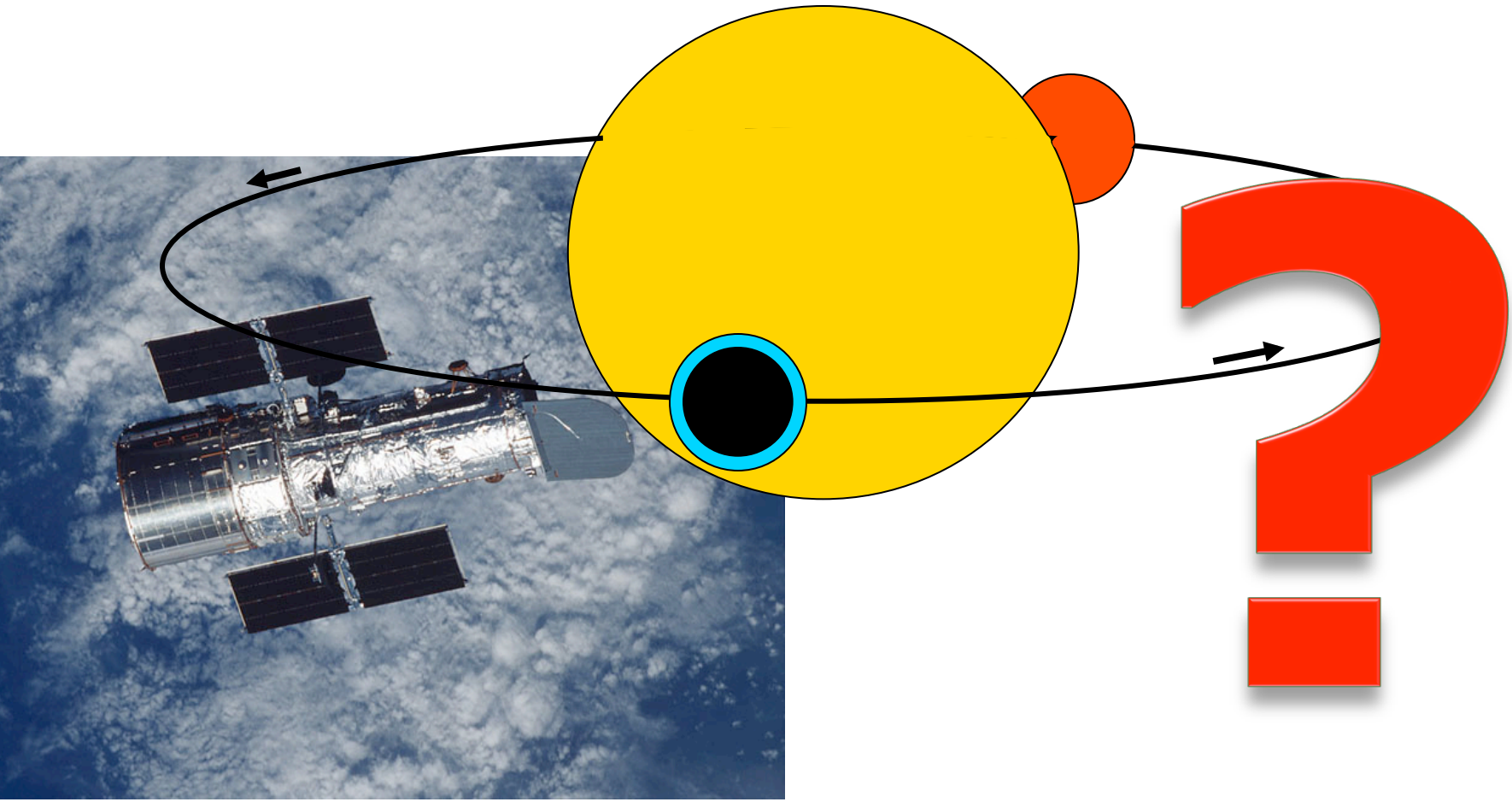


Figures courtesy G. Laughlin

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



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



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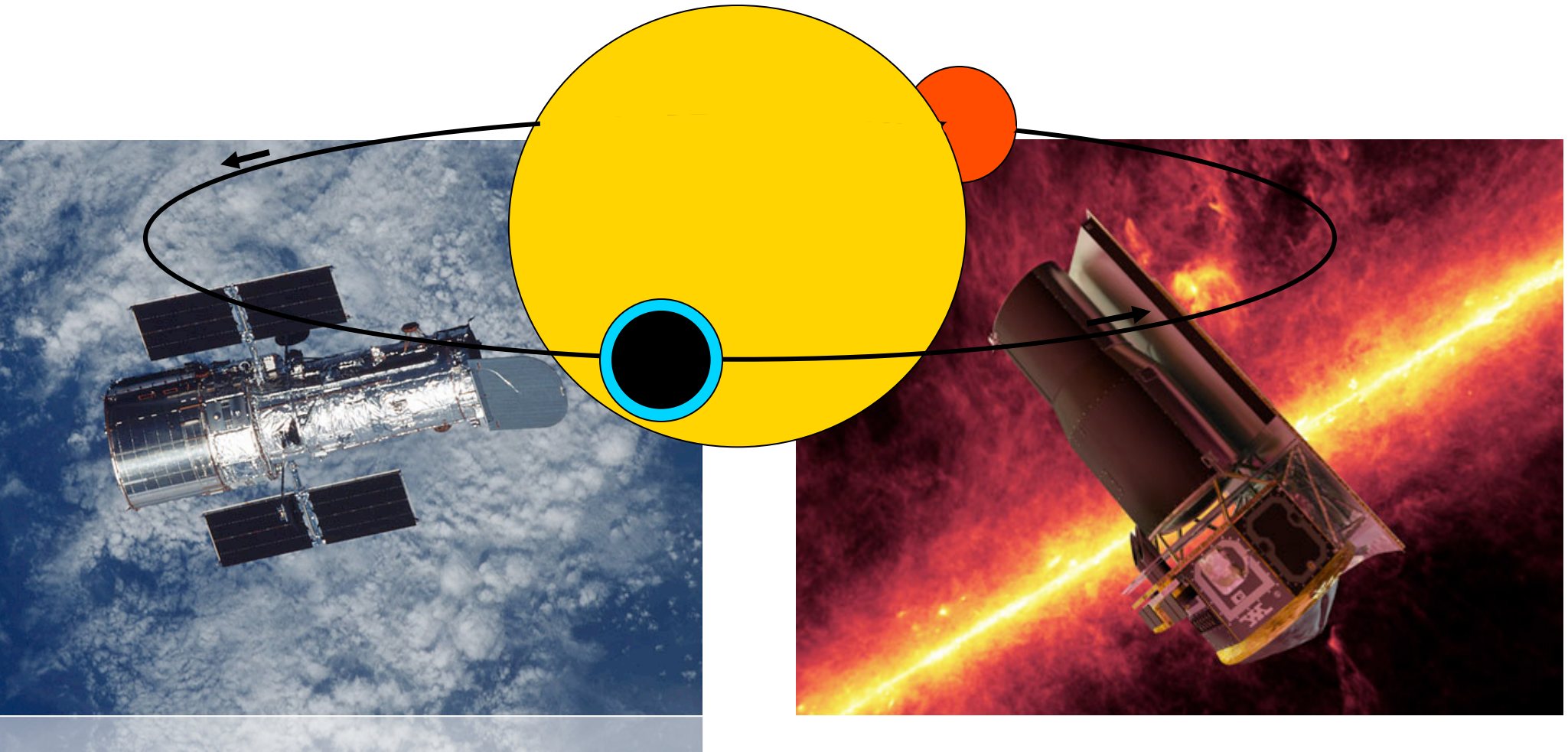

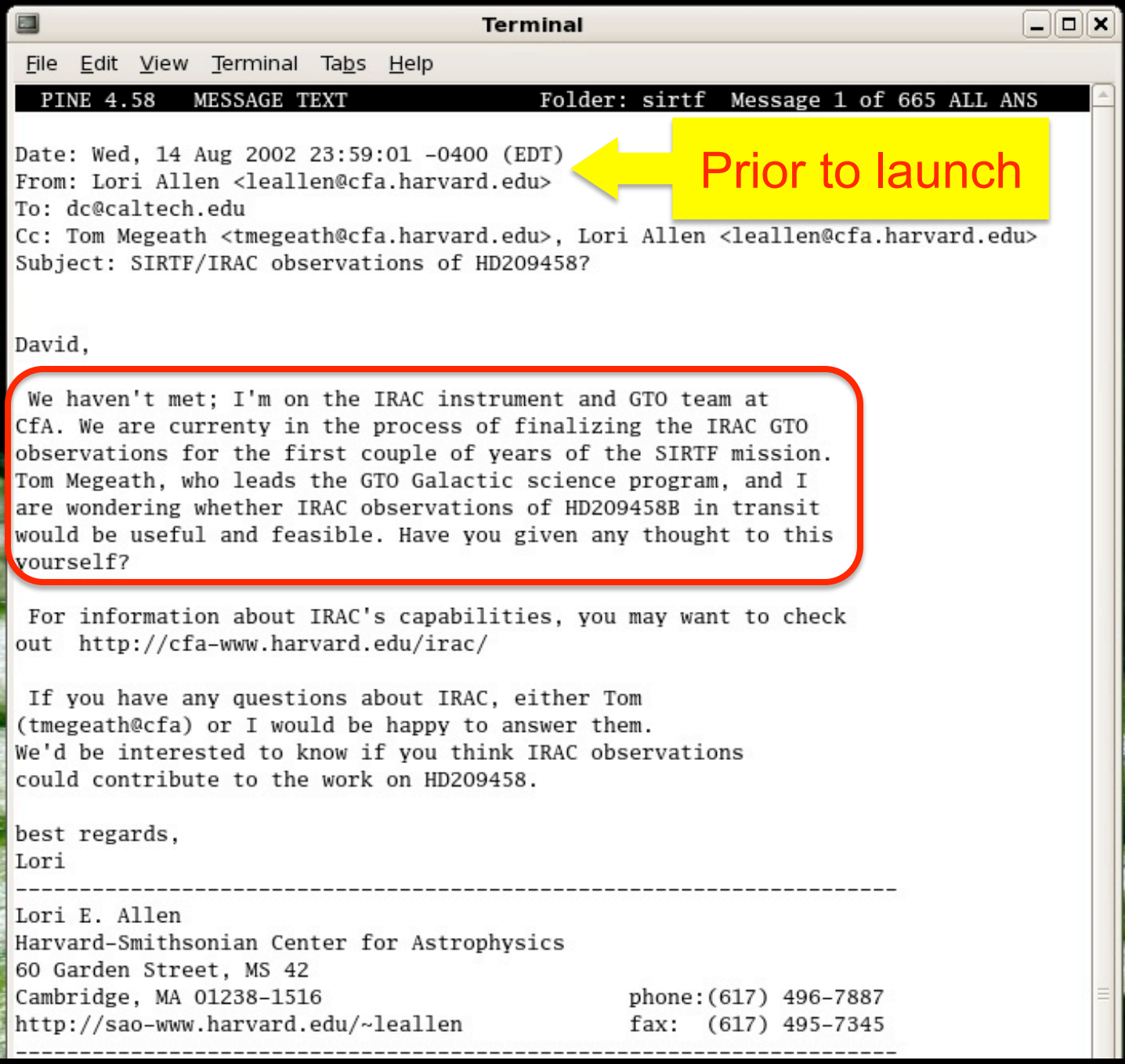
Terminal
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PINE 4.58 MESSAGE TEXT Folder: sirtf Message 1 of 665 ALL ANS
Prior to launch
Date: Wed, 14 Aug 2002 23:59:01 -0400 (EDT)
From: Lori Allen <leallen@cfa.harvard.edu>
To: dc@caltech.edu
Cc: Tom Megeath <tmegeath@cfa.harvard.edu>, Lori Allen <leallen@cfa.harvard.edu>
Subject: SIRTF/IRAC observations of HD209458?
David,
We haven't met; I'm on the IRAC instrument and GTO team at CfA. We are currenty in the process of finalizing the IRAC GTO observations for the first couple of years of the SIRTF mission. Tom Megeath, who leads the GTO Galactic science program, and I are wondering whether IRAC observations of HD209458B in transit would be useful and feasible. Have you given any thought to this yourself?
For information about IRAC's capabilities, you may want to check out http://cfa-www.harvard.edu/irac/
If you have any questions about IRAC, either Tom (tmegeath@cfa) or I would be happy to answer them. We'd be interested to know if you think IRAC observations could contribute to the work on HD209458.
best regards,
Lori
Lori E. Allen
Harvard-Smithsonian Center for Astrophysics
60 Garden Street, MS 42
Cambridge, MA 01238-1516 phone:(617) 496-7887
http://sao-www.harvard.edu/~leallen fax: (617) 495-7345

Date: Thu, 15 Aug 2002 15:41:49 -0700 (PDT)
From: David Charbonneau <dc@astro.caltech.edu>
To: Lori Allen <leallen@cfa.harvard.edu>
Cc: Tom Megeath <tmegeath@cfa.harvard.edu>
Subject: Re: SIRTF/IRAC observations of HD209458?

Hello Lori & Tom,

Thanks for contacting me. Yes indeed I have an idea for
IRAC & HD209458. I had planned on considering this in
more detail when the first AO was released, but please
let me know if you think it would be appropriate for
your GTO (which is certainly preferable from my standpoint).

I don't think observations of the transit would be particularly
interesting, but how about the other side of the coin,
i.e. the secondary eclipse?

(...)

Observing the secondary eclipse in IRAC's four bandpasses would
allow us to measure the eclipse depth as a function of wavelength,
and thus directly estimate the dayside temperature of the planet,
as well as look for any evidence of deviations from blackbody
emission (i.e. constrain the current models). It would also
provide the first direct detection of emitted light from
an extrasolar planet.

(...)

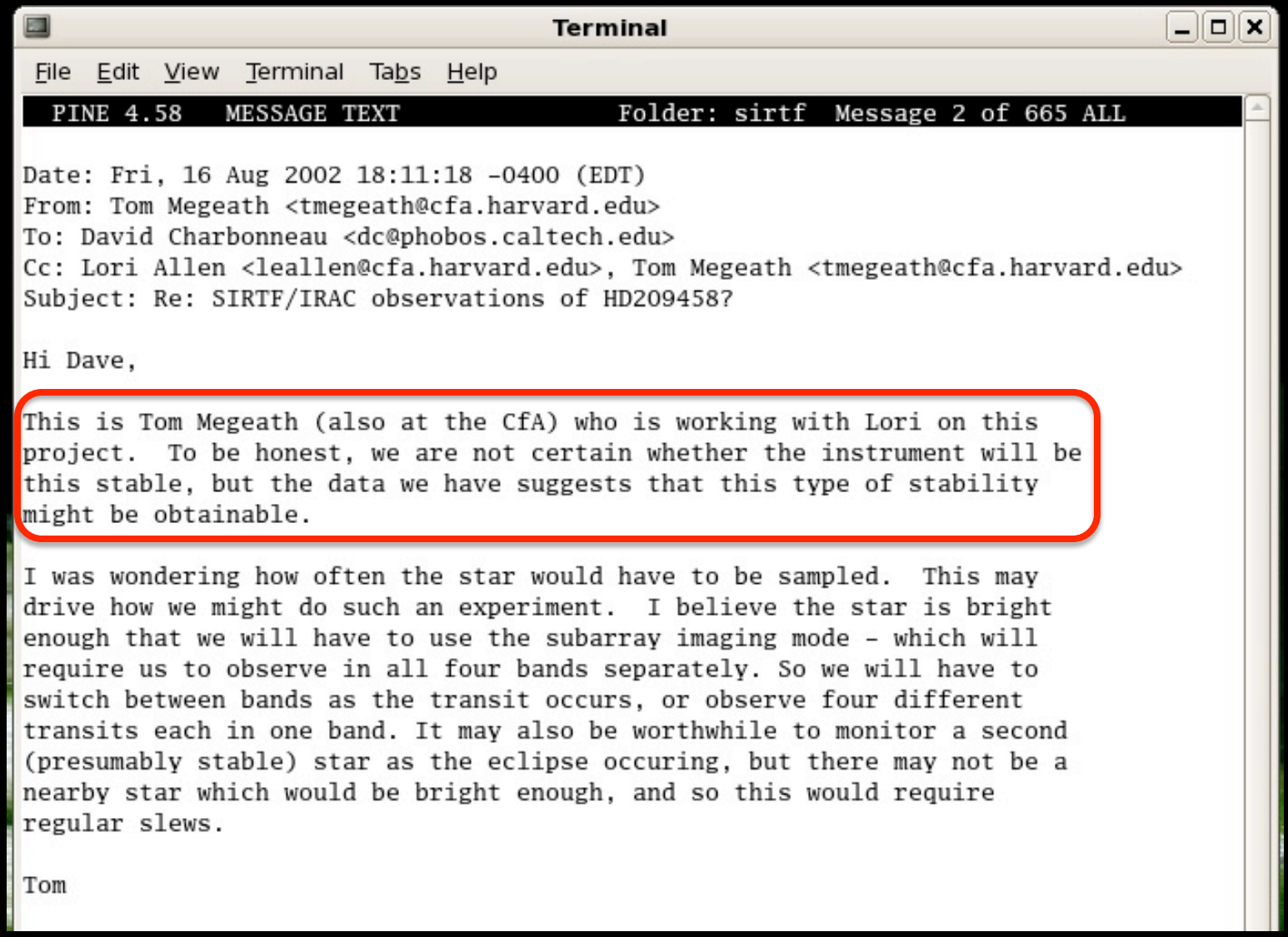
(BTW, I was a grad student at CfA, and only moved out to Caltech
in September 2001. I hope all is well back there!).

Alright, I look forward to your reply!

Dave

California Institute of Technology, 105-24 (Astronomy)
1200 E. California Blvd., Pasadena CA 91125 USA

tel 626 395 4004 fax 626 568 9352
http://www.astro.caltech.edu/~dc


Terminal
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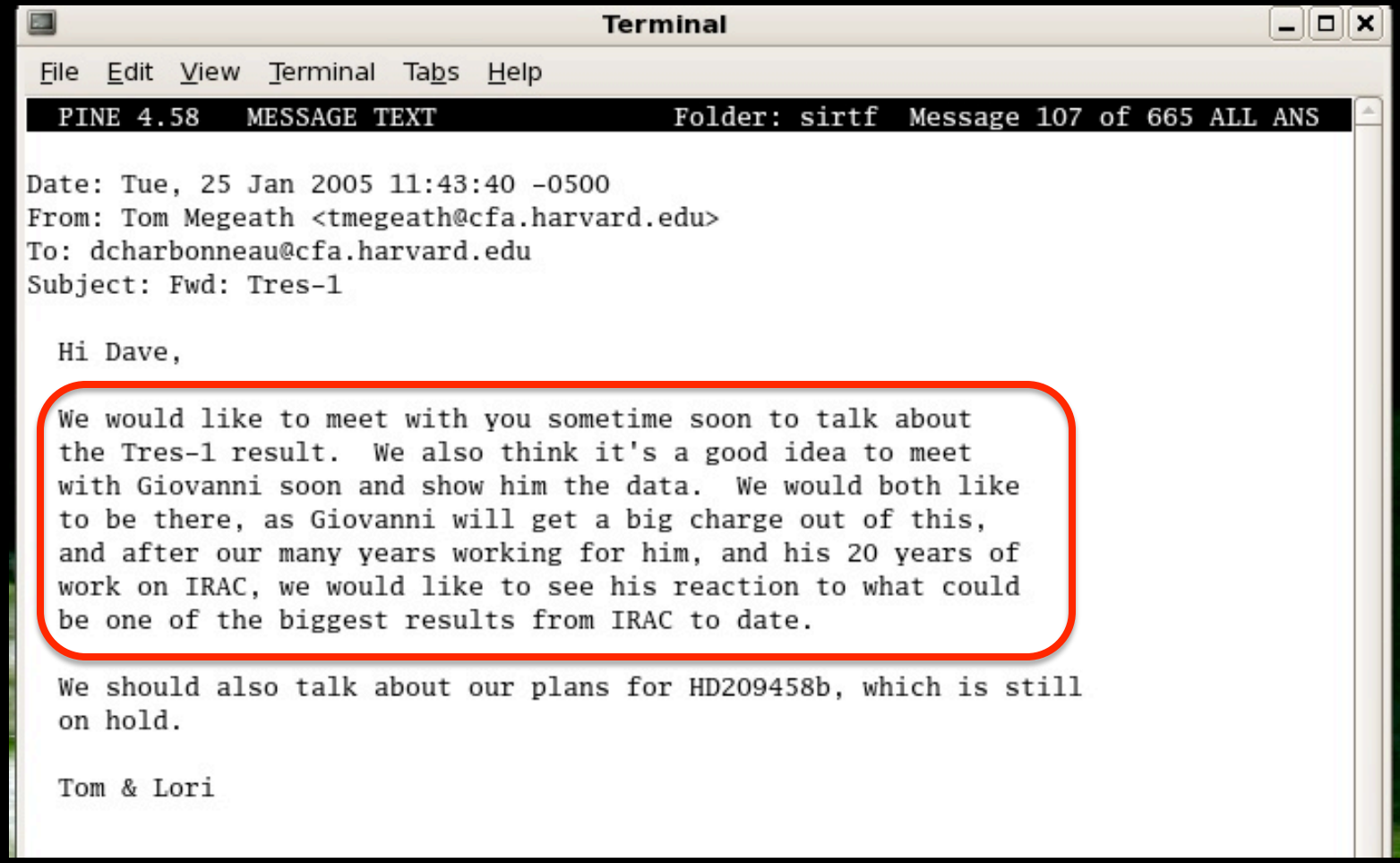
PINE 4.58 MESSAGE TEXT Folder: sirtf Message 2 of 665 ALL
Date: Fri, 16 Aug 2002 18:11:18 -0400 (EDT)
From: Tom Megeath <tmegeath@cfa.harvard.edu>
To: David Charbonneau <dc@phobos.caltech.edu>
Cc: Lori Allen <leallen@cfa.harvard.edu>, Tom Megeath <tmegeath@cfa.harvard.edu>
Subject: Re: SIRTF/IRAC observations of HD209458?
Hi Dave,
This is Tom Megeath (also at the CfA) who is working with Lori on this project. To be honest, we are not certain whether the instrument will be this stable, but the data we have suggests that this type of stability might be obtainable.
I was wondering how often the star would have to be sampled. This may drive how we might do such an experiment. I believe the star is bright enough that we will have to use the subarray imaging mode - which will require us to observe in all four bands separately. So we will have to switch between bands as the transit occurs, or observe four different transits each in one band. It may also be worthwhile to monitor a second (presumably stable) star as the eclipse occuring, but there may not be a nearby star which would be bright enough, and so this would require regular slews.
Tom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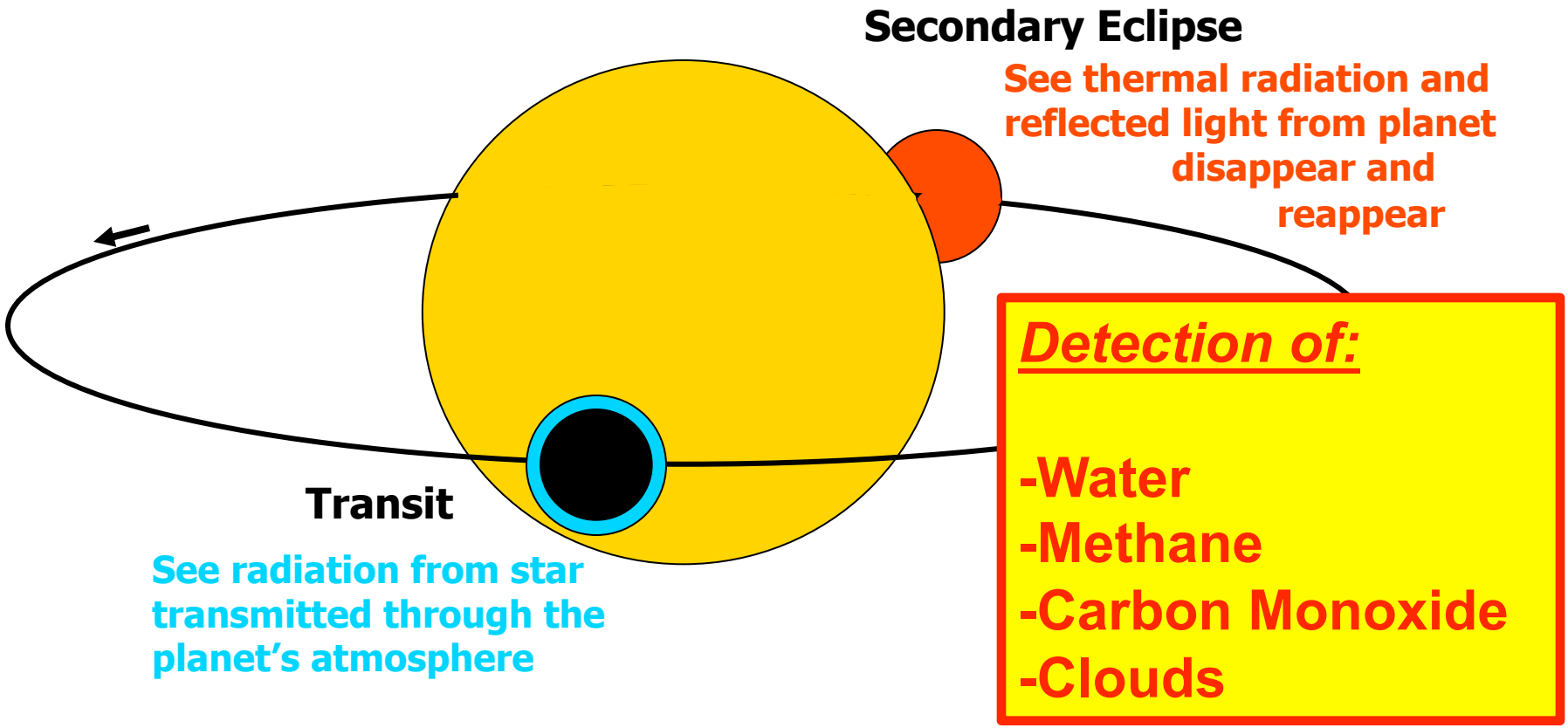
PINE 4.58 MESSAGE TEXT Folder: sirtf Message 107 of 665 ALL ANS
Date: Tue, 25 Jan 2005 11:43:40 -0500
From: Tom Megeath <tmegeath@cfa.harvard.edu>
To: dcharbonneau@cfa.harvard.edu
Subject: Fwd: Tres-1
Hi Dave,
We would like to meet with you sometime soon to talk about the Tres-1 result. We also think it's a good idea to meet with Giovanni soon and show him the data. We would both like to be there, as Giovanni will get a big charge out of this, and after our many years working for him, and his 20 years of work on IRAC, we would like to see his reaction to what could be one of the biggest results from IRAC to date.
We should also talk about our plans for HD209458b, which is still on hold.
Tom & Lori

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



Discovery of Bright Transiting Systems + Amazing Stability of *Spitzer* Space Telescope = Direct Study of Exoplanet Emission

8 BRIGHT systems +
35 moderately bright systems

Cold or Warm: Preeminent for Studies of Exoplanets

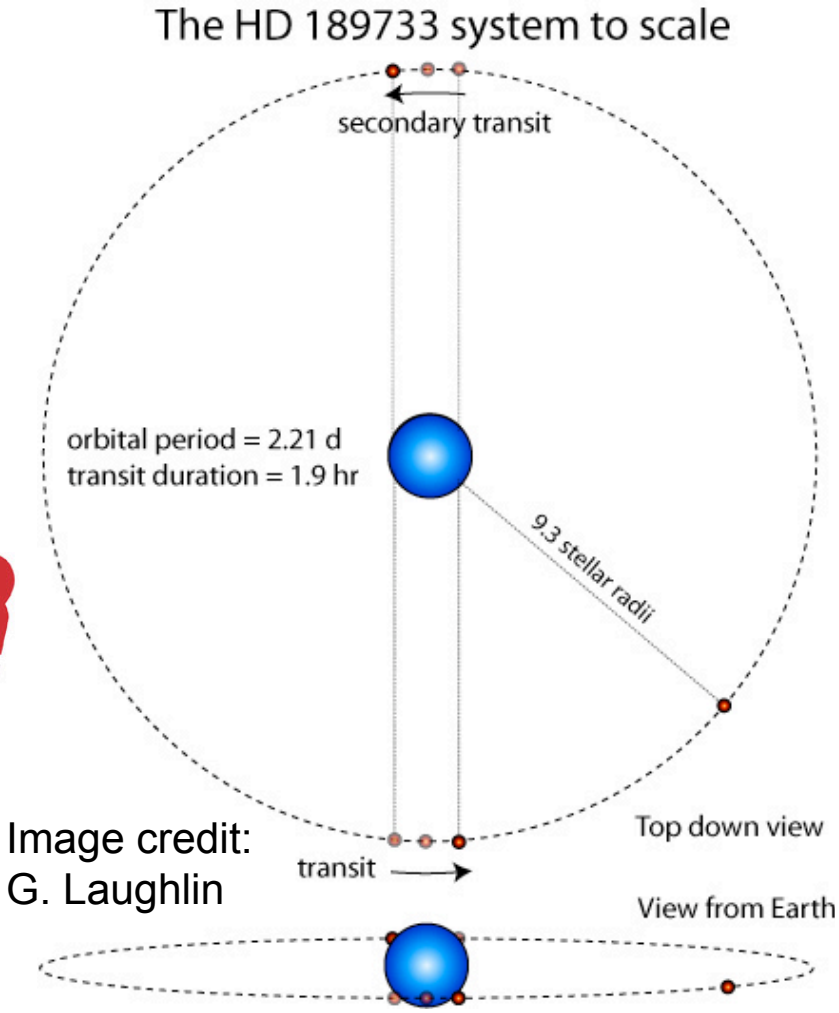
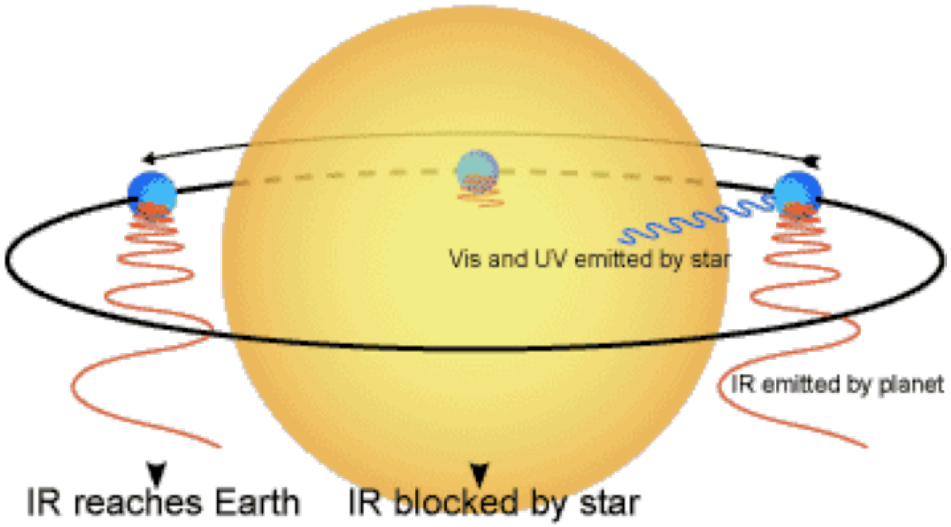
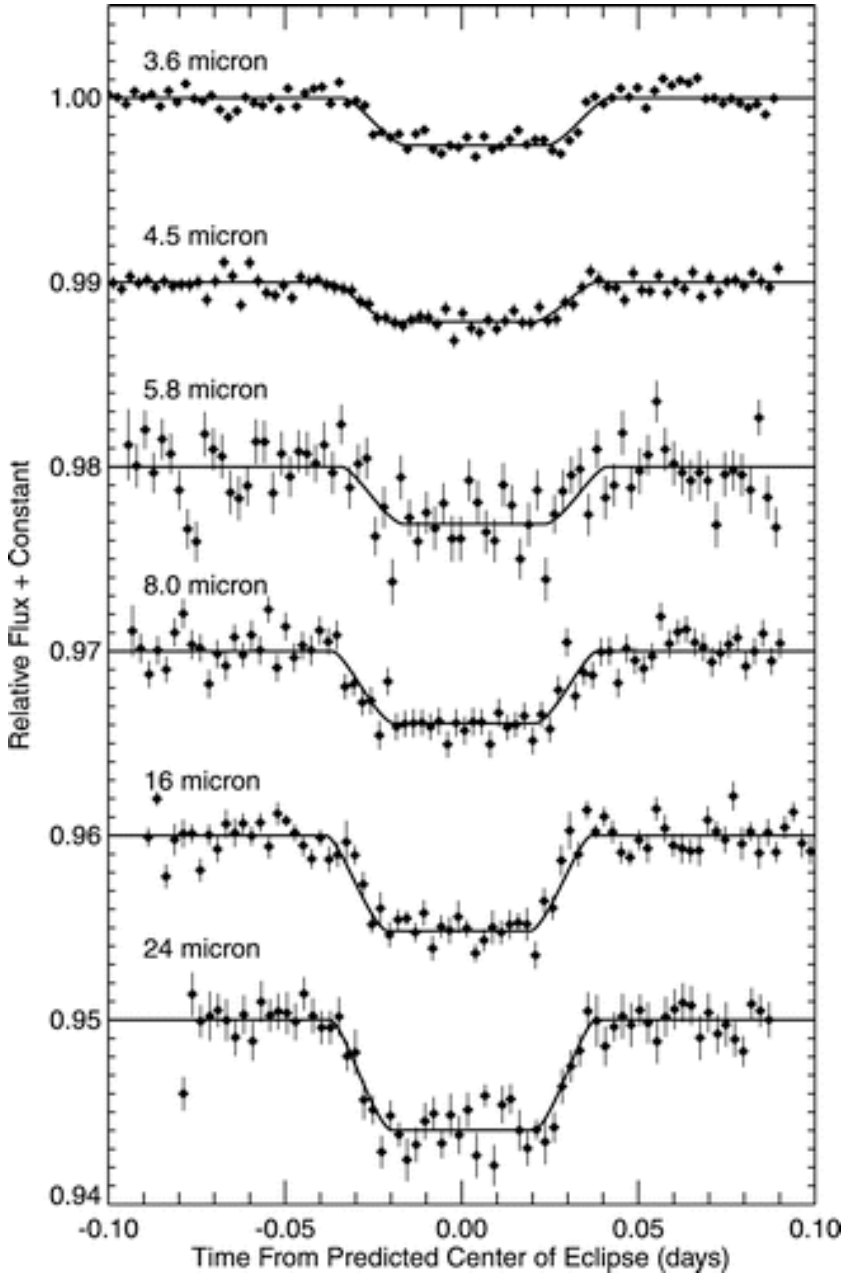


Image credit:
G. Laughlin

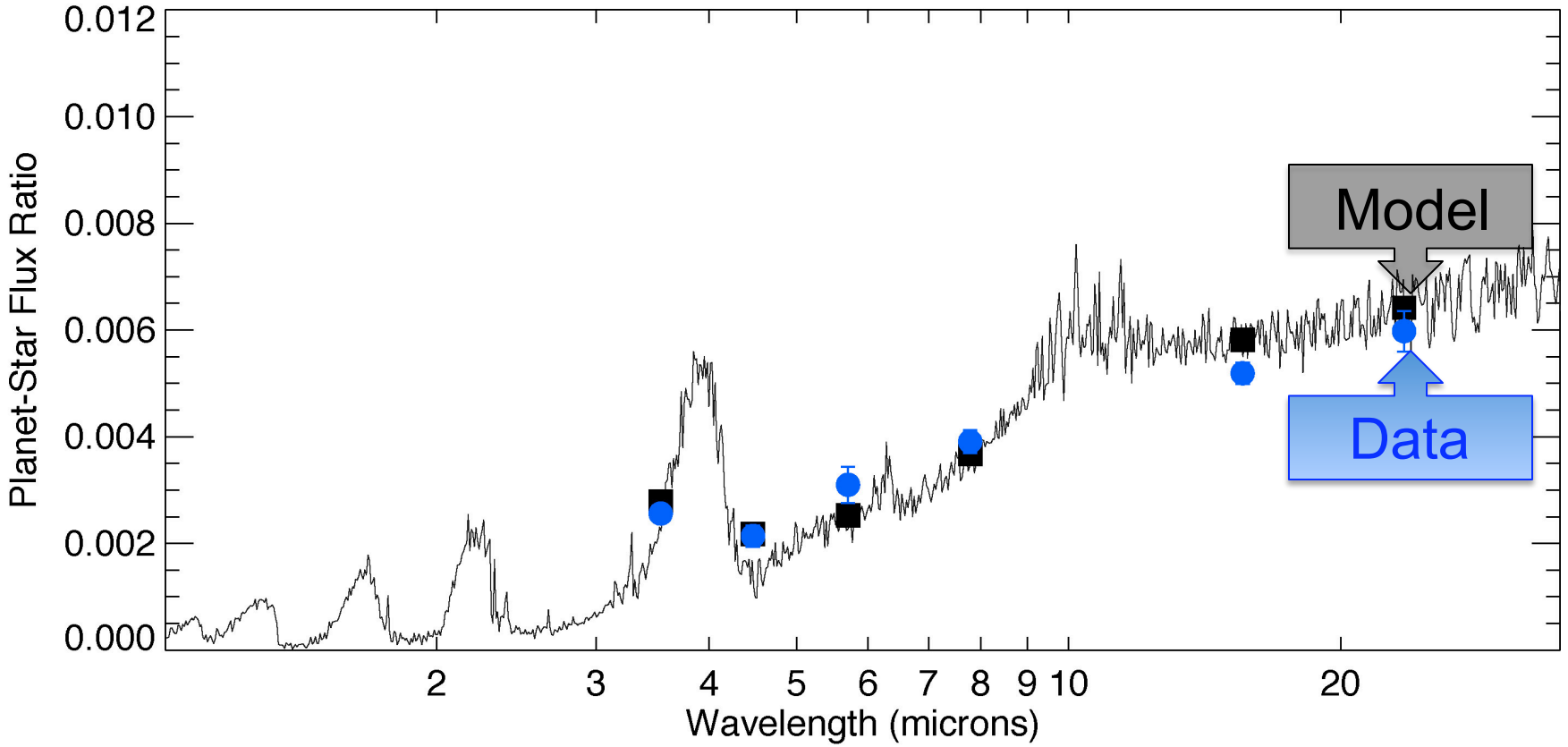
Spitzer Photometry of an Exoplanet Passing ***Behind*** Its Star





Charbonneau, Knutson et al. 2008

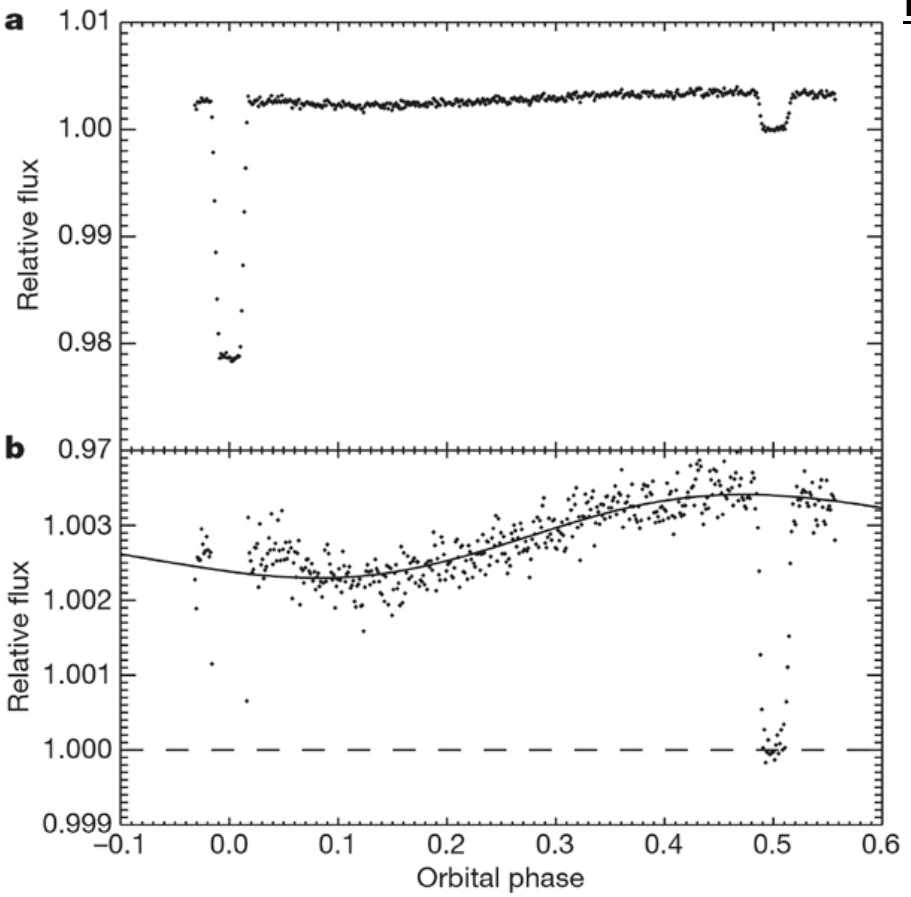
These Observations Permit Us to Study the Temperature and Chemistry of Exoplanet Atmospheres

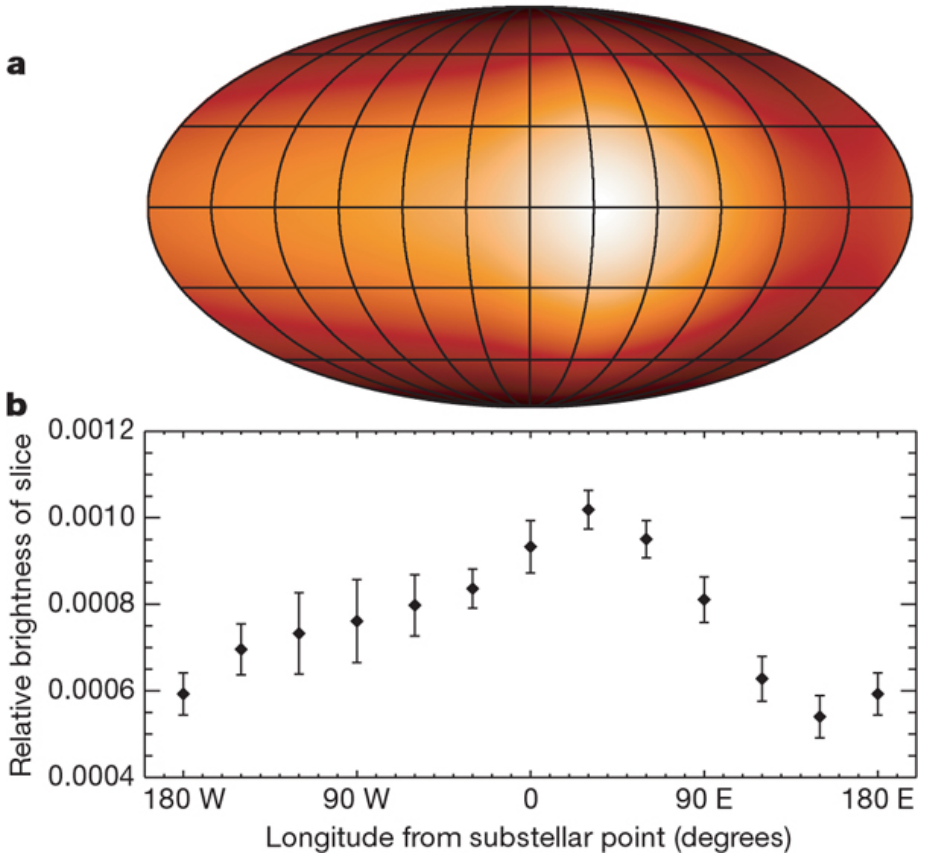


Charbonneau, Knutson et al. (2008)

Mapping the Surface Emission of an Exoplanet

Knutson, Charbonneau, et al. Nature (2007)





Modest day/night temperature difference indicates efficient heat redistribution.

Hottest point on planet lies east of "high noon", indicating winds.

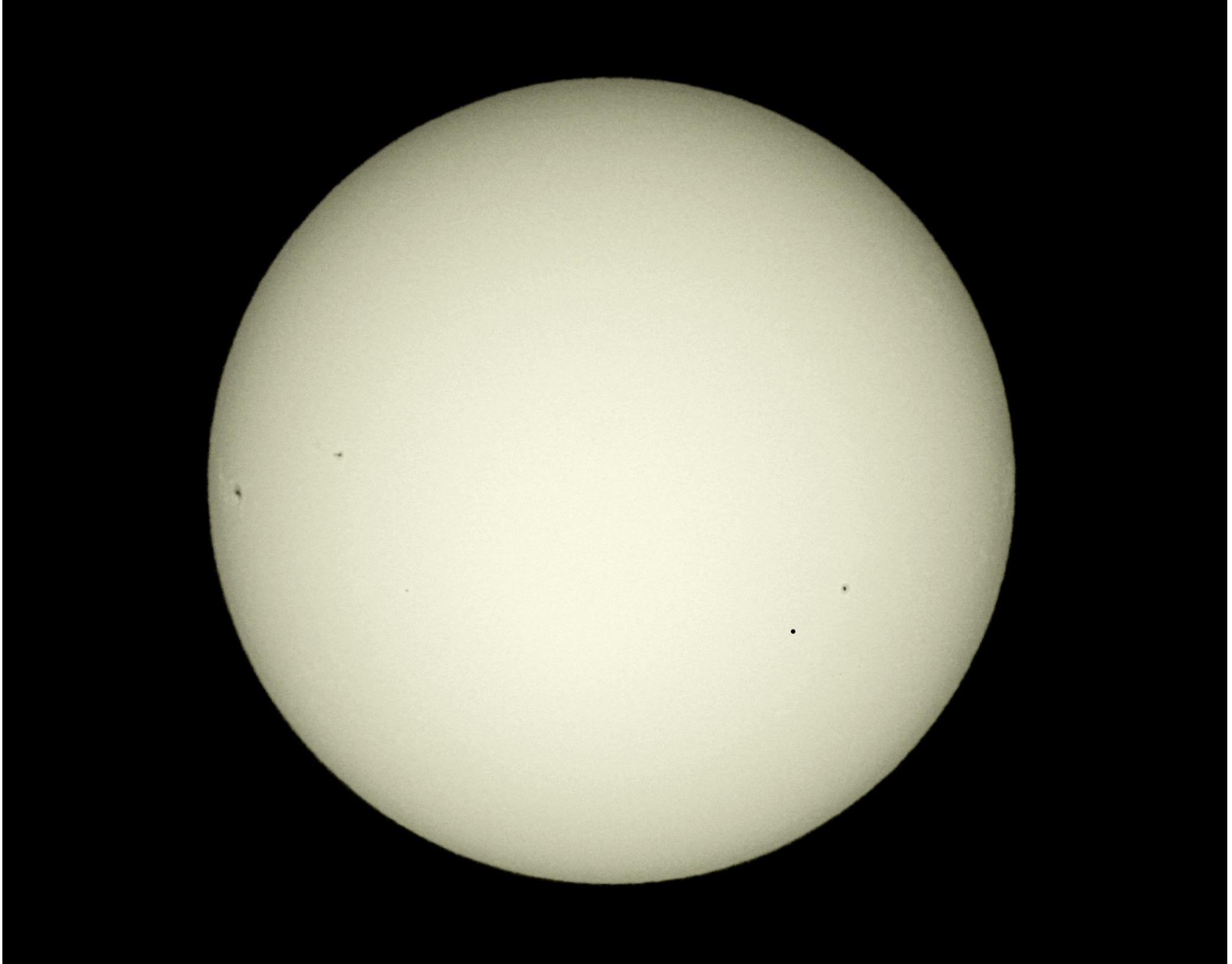
How can we use these techniques
to study the atmosphere
of a habitable exoplanet?

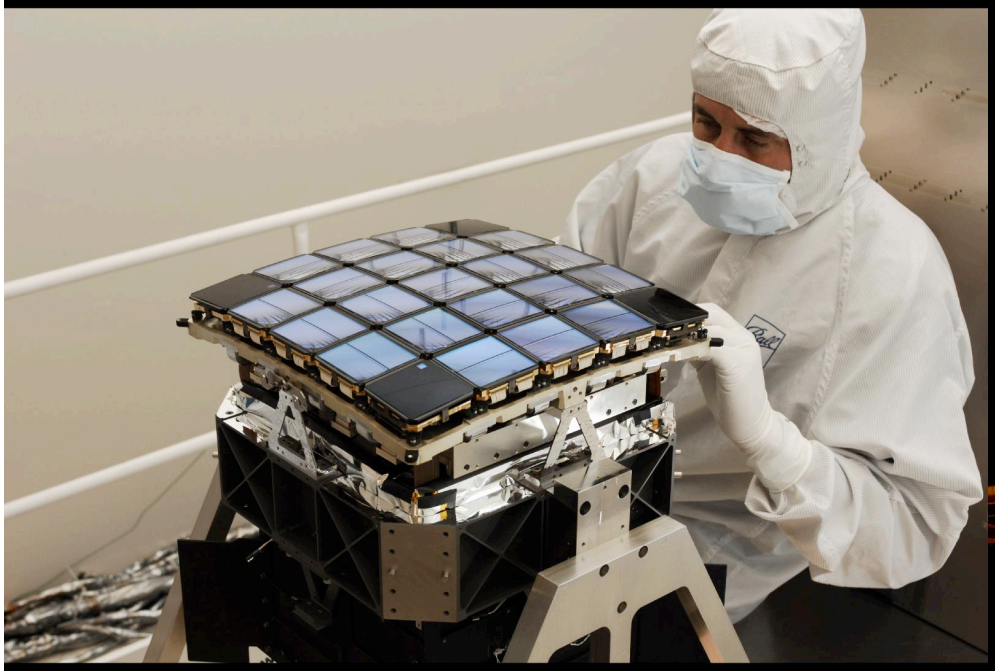
What Are the Prospects for Finding Transiting Terrestrial Planets?

This is what we've observed so far

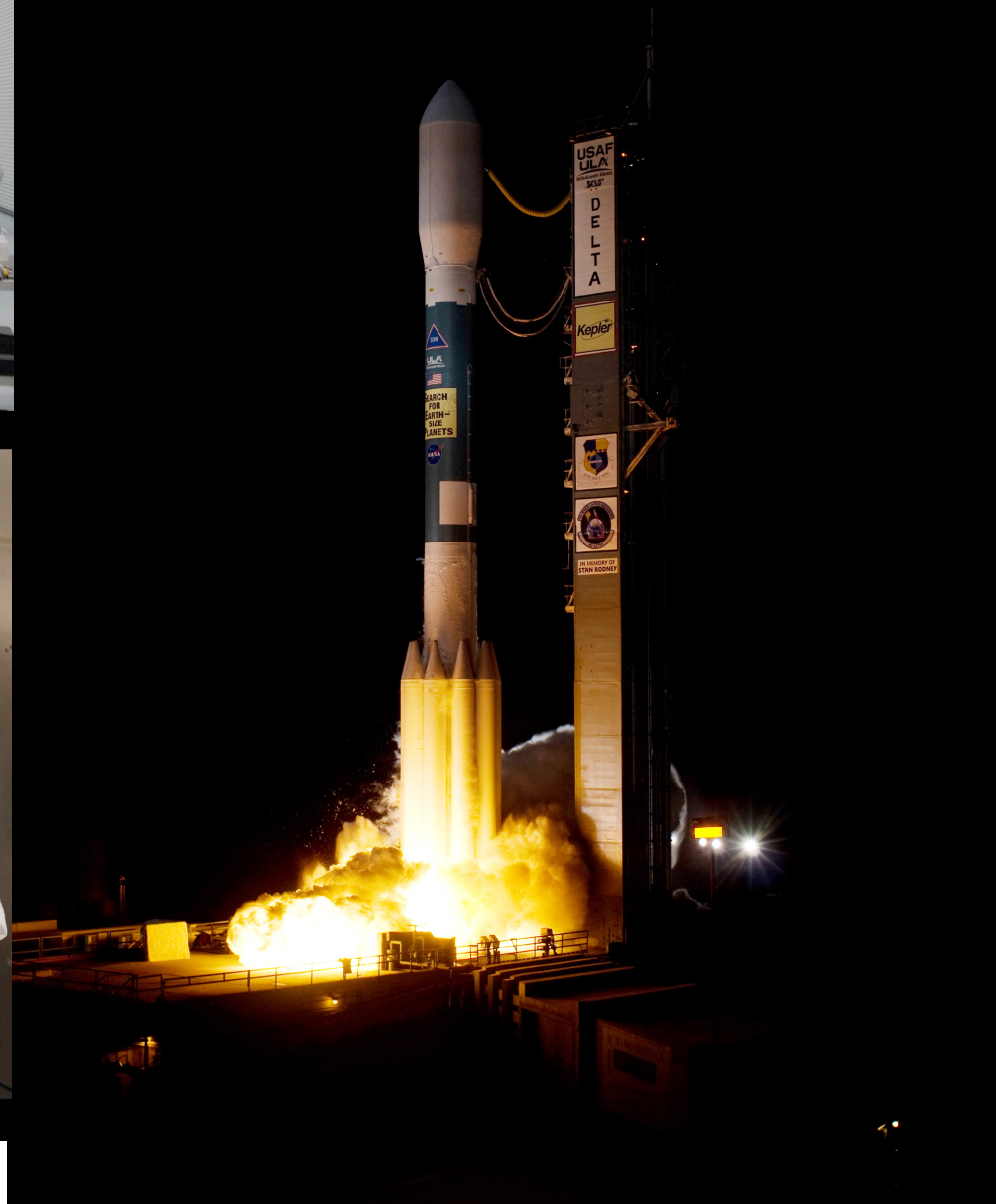
This is what we would like to observe

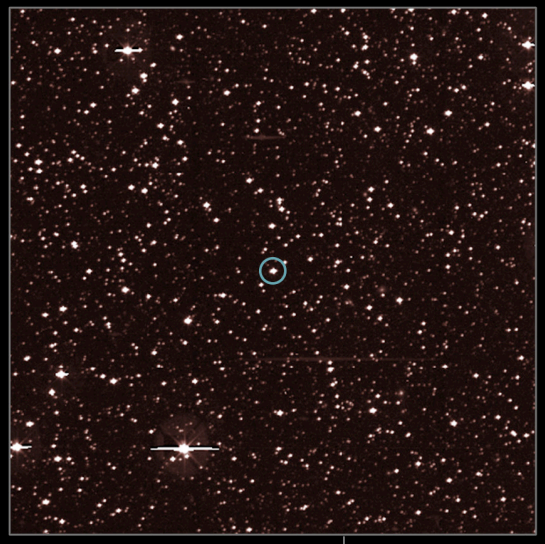
Jupiter's area is 120 times greater than the Earth's, and it has over 300 times the Earth's mass.



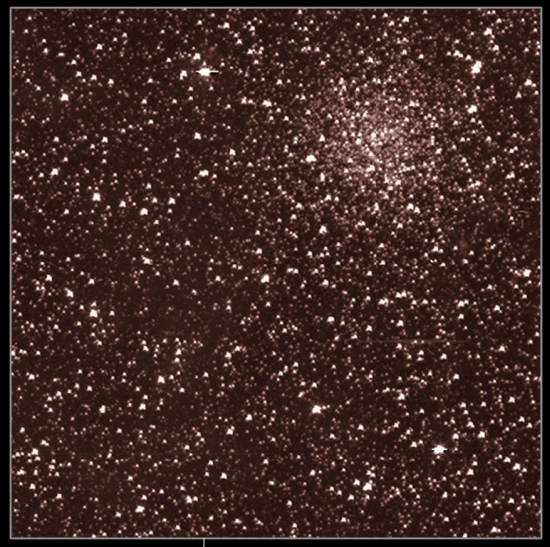


Kepler Mission
Successful Launch
March 6th, 2009

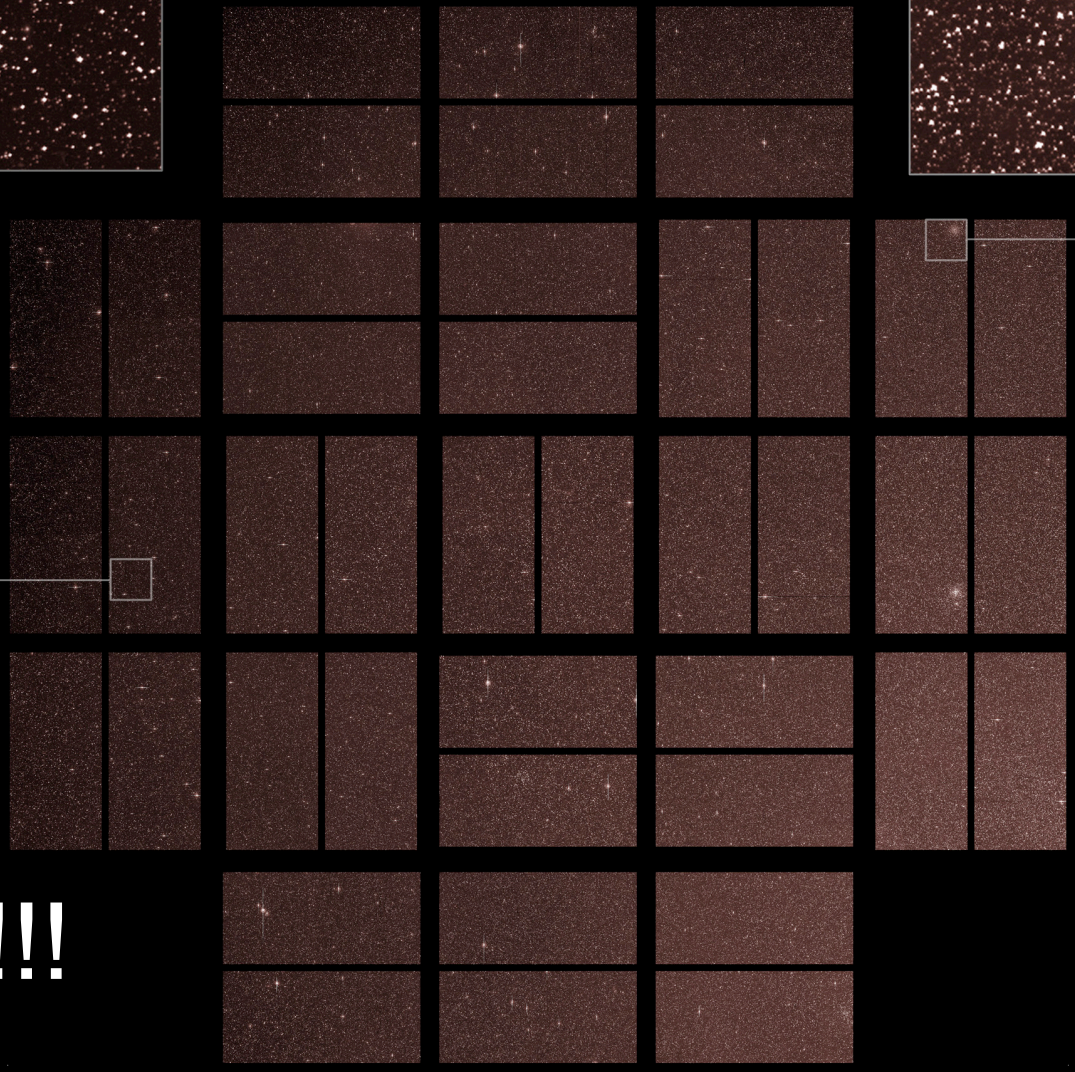




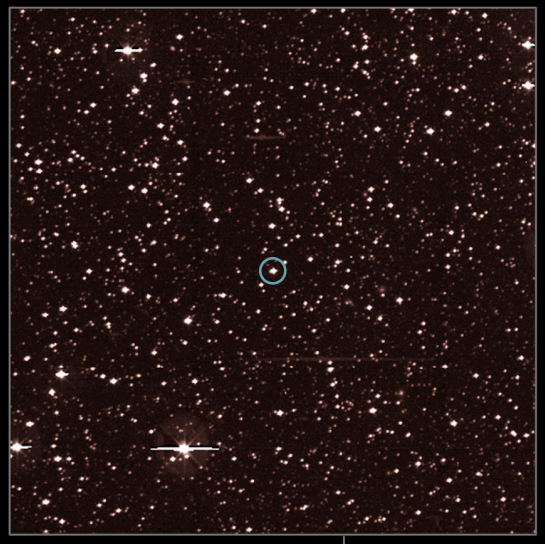
TrES-2



NGC 6791



Kepler First Light Images!!!



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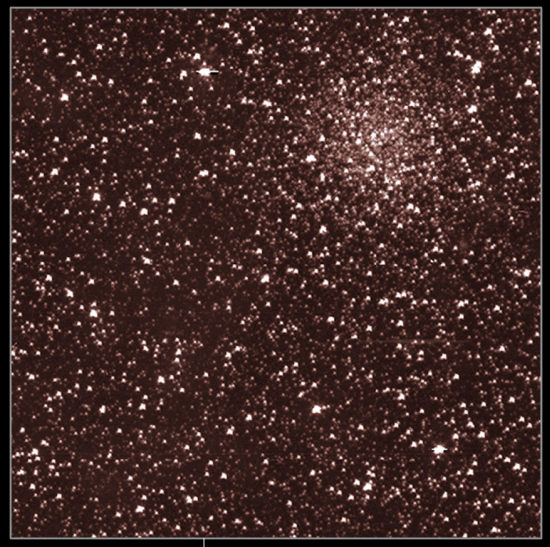


NGC 6791

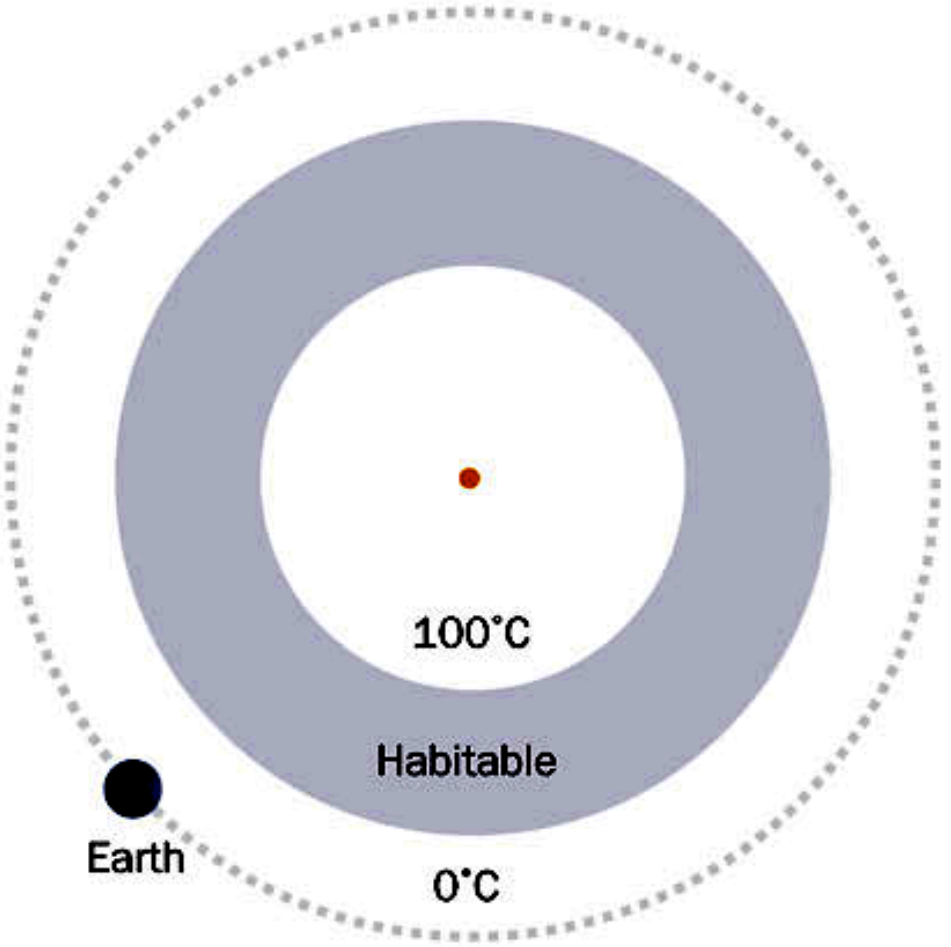
Many Kepler-detected worlds will be studied by Warm Spitzer / IRAC

The Small Star Opportunity

Habitable Zones

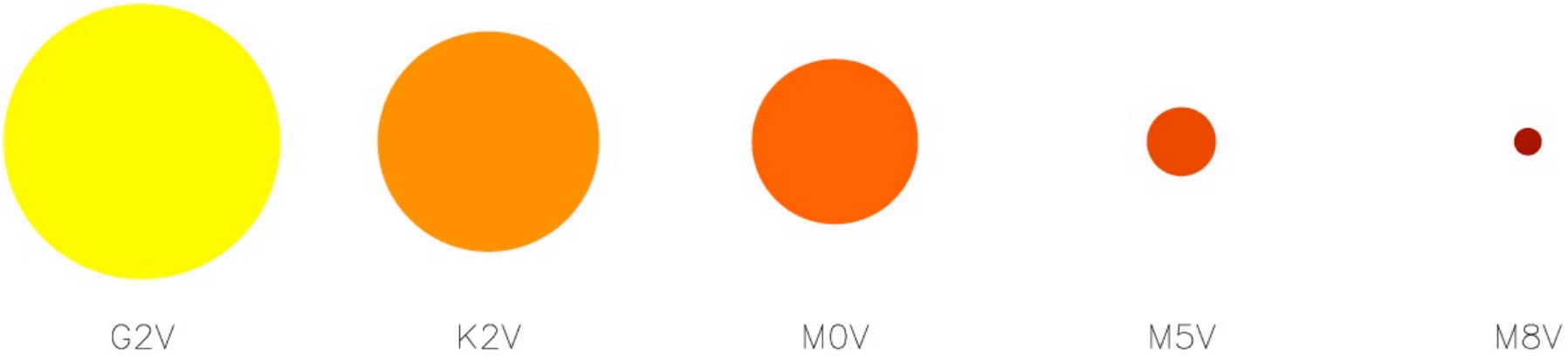
The habitable zone (gray)—the region where water stays liquid—lies much closer to tiny M stars (below left) than it does to brighter, more massive stars like the sun (right). Earth's orbit lies beyond the sun's habitable zone, but atmospheric gases warm the planet.

M star's habitable zone



Solar system's habitable zone

The Small Star Opportunity

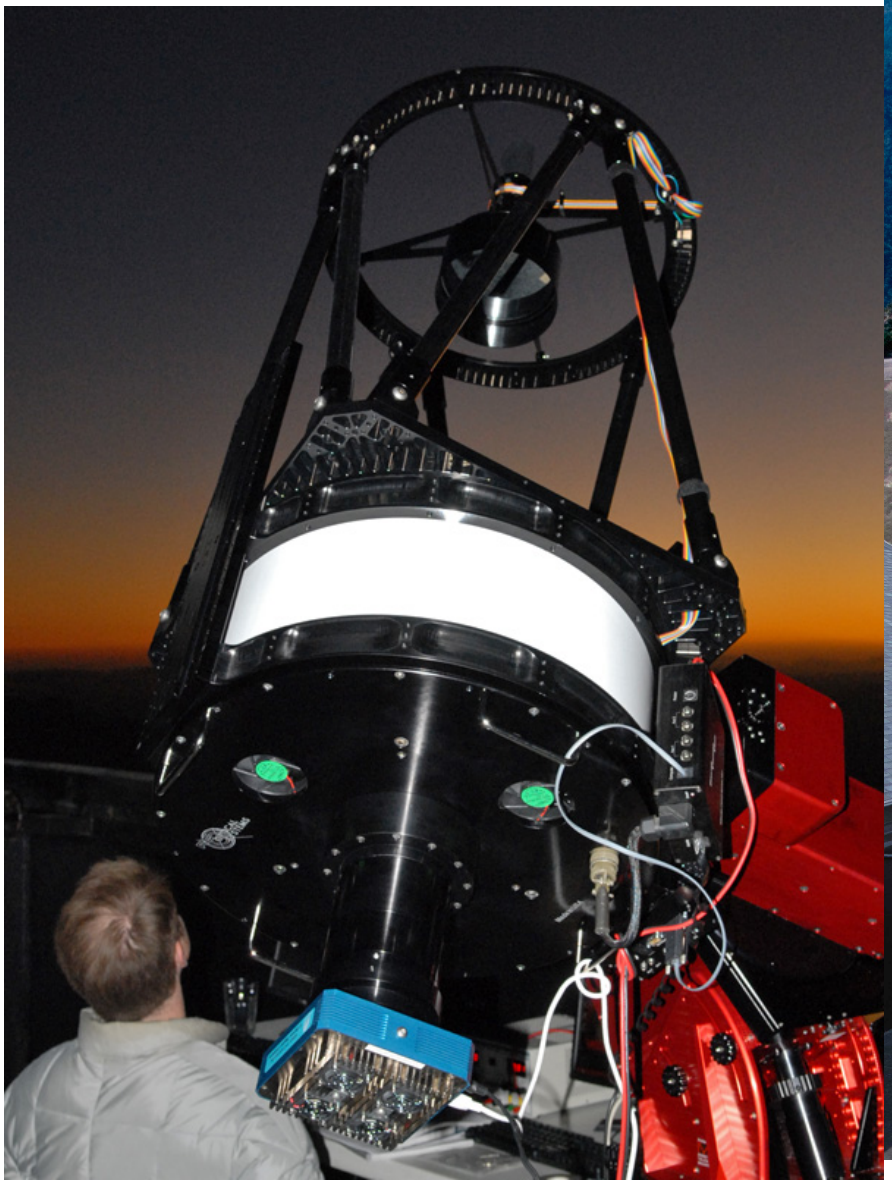


Consider rocky planet in the habitable zone of a low-mass star (known as an M-star):

- ✓ Transits are deeper — *Sun: 0.03%* — *M-star: 0.5%*
- ✓ Transits are more frequent — *Sun: 365 days* — *M-star: 15 days*
- ✓ Transits are more likely — *Sun: 0.5%* — *M-star: 1.6%*

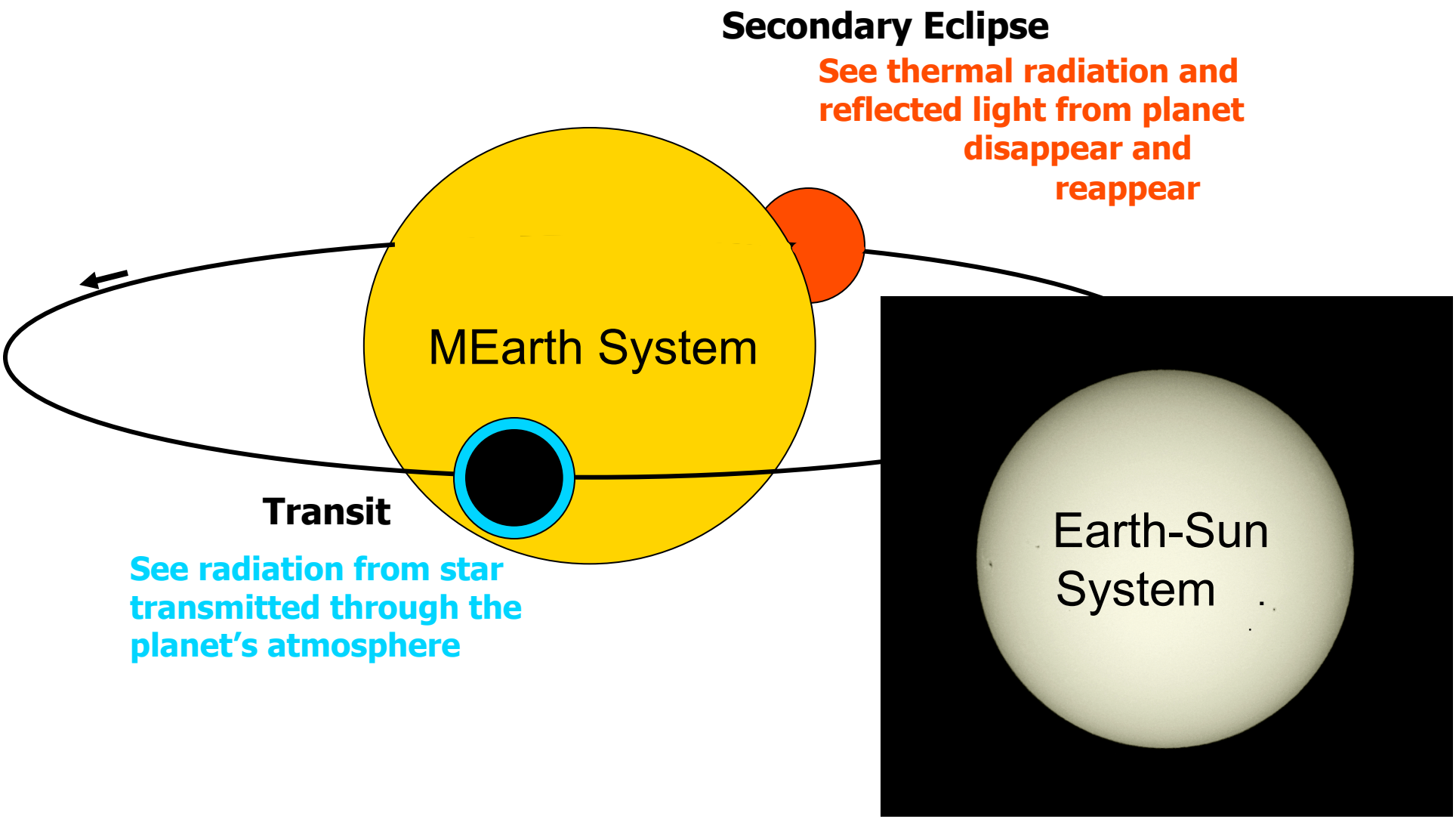
The MEarth Project

with P. Nutzman, J. Irwin, C. Burke, Z. Berta, and E. Falco



MEarth Project, Whipple Observatory, AZ

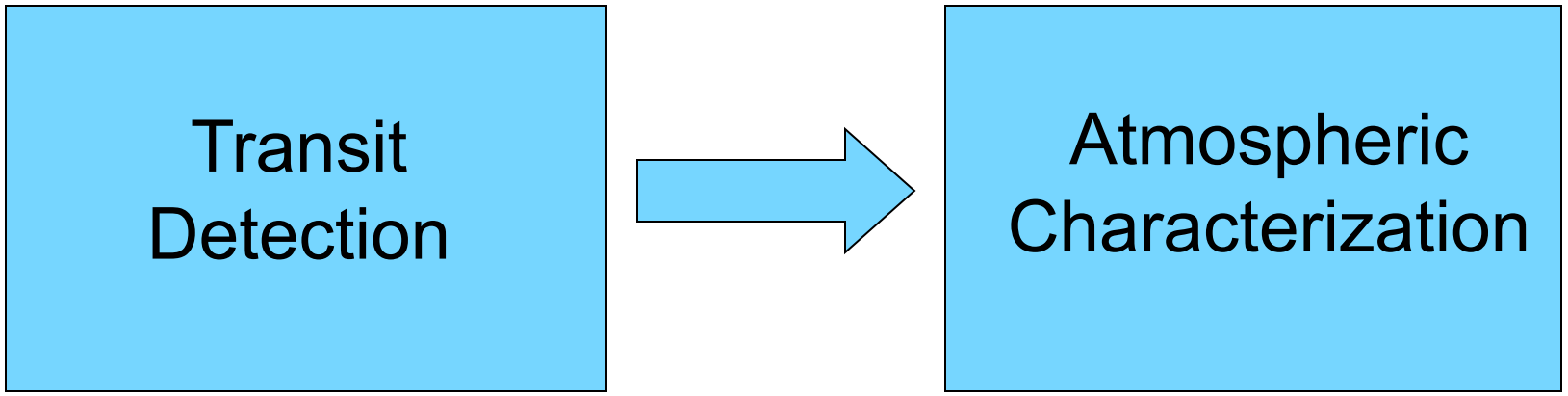
Transit Studies of the Atmospheres Are Facilitated by the Small Size of the Star



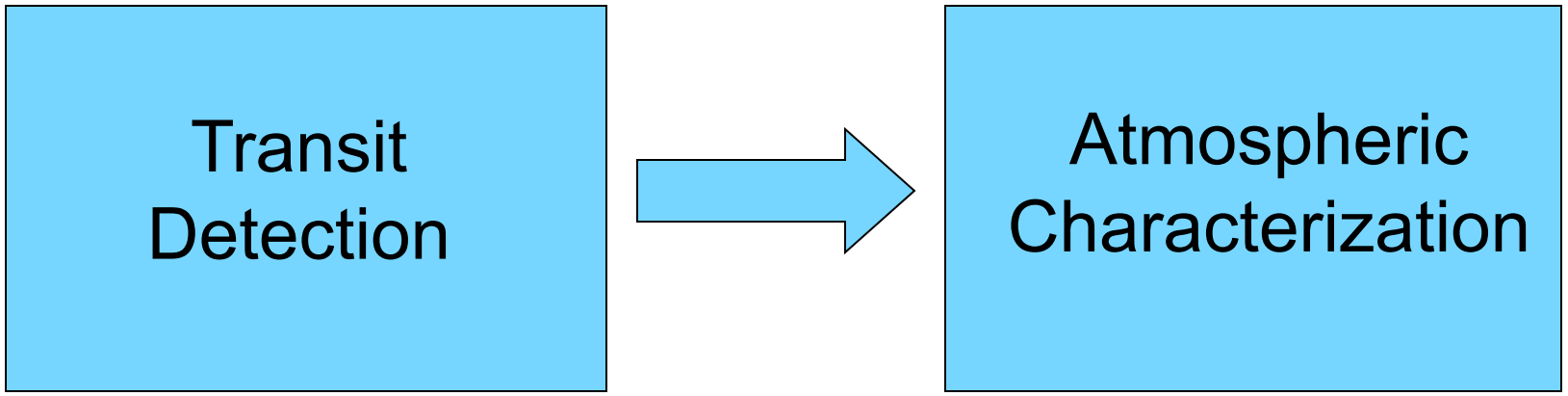
Habitable-Zone Planets Orbiting Low-Mass Stars are Ideal Targets for Atmospheric Studies to Search for **BIOMARKERS**

James Webb Space Telescope is scheduled for launch in 2013.

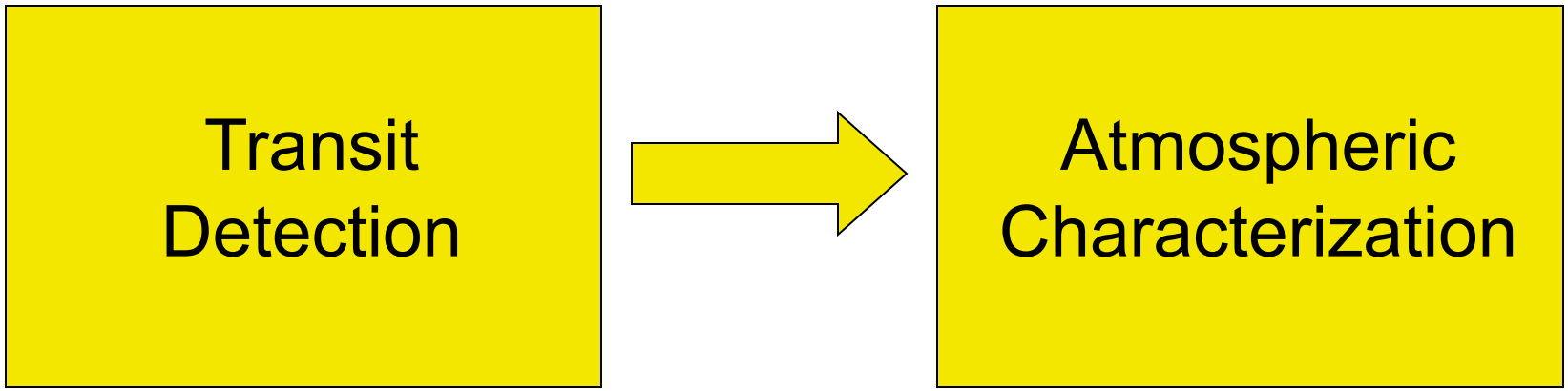
1999 – 2009: Hydrogen + Helium Worlds

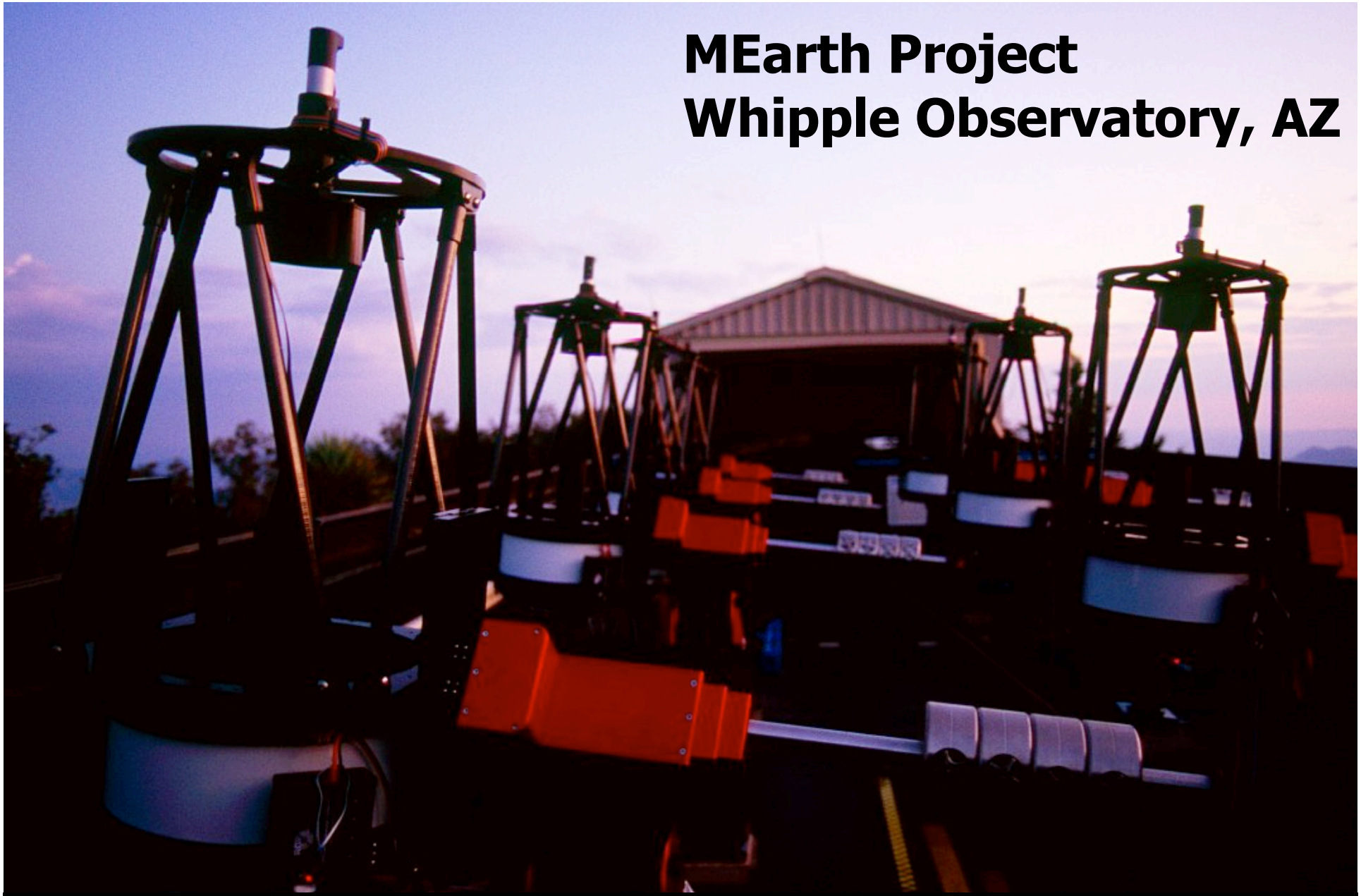


1999 – 2009: Hydrogen + Helium Worlds



Near Future: Rock + Ice Worlds





Coming Soon: SuperEarths Transiting Small Stars