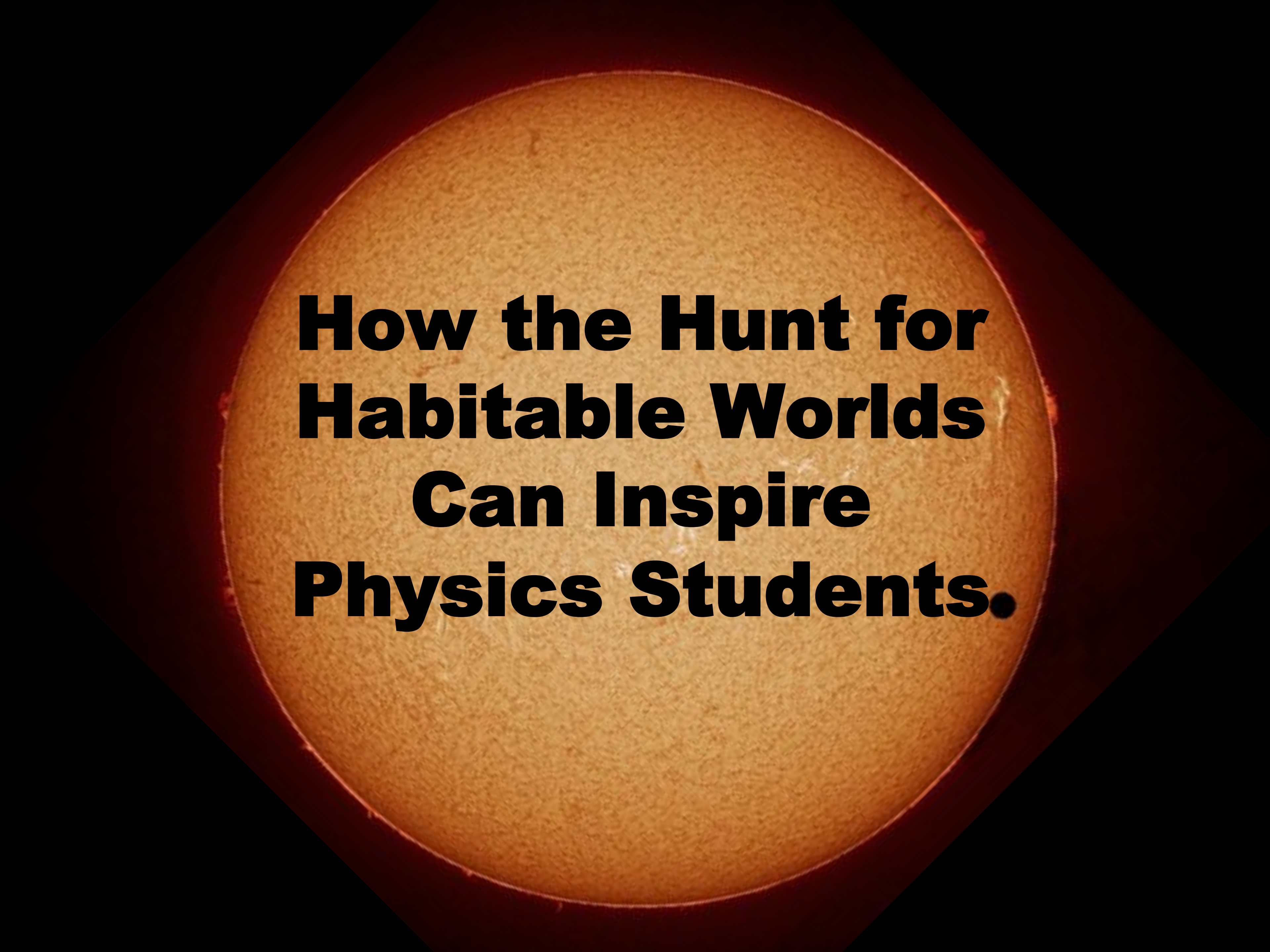
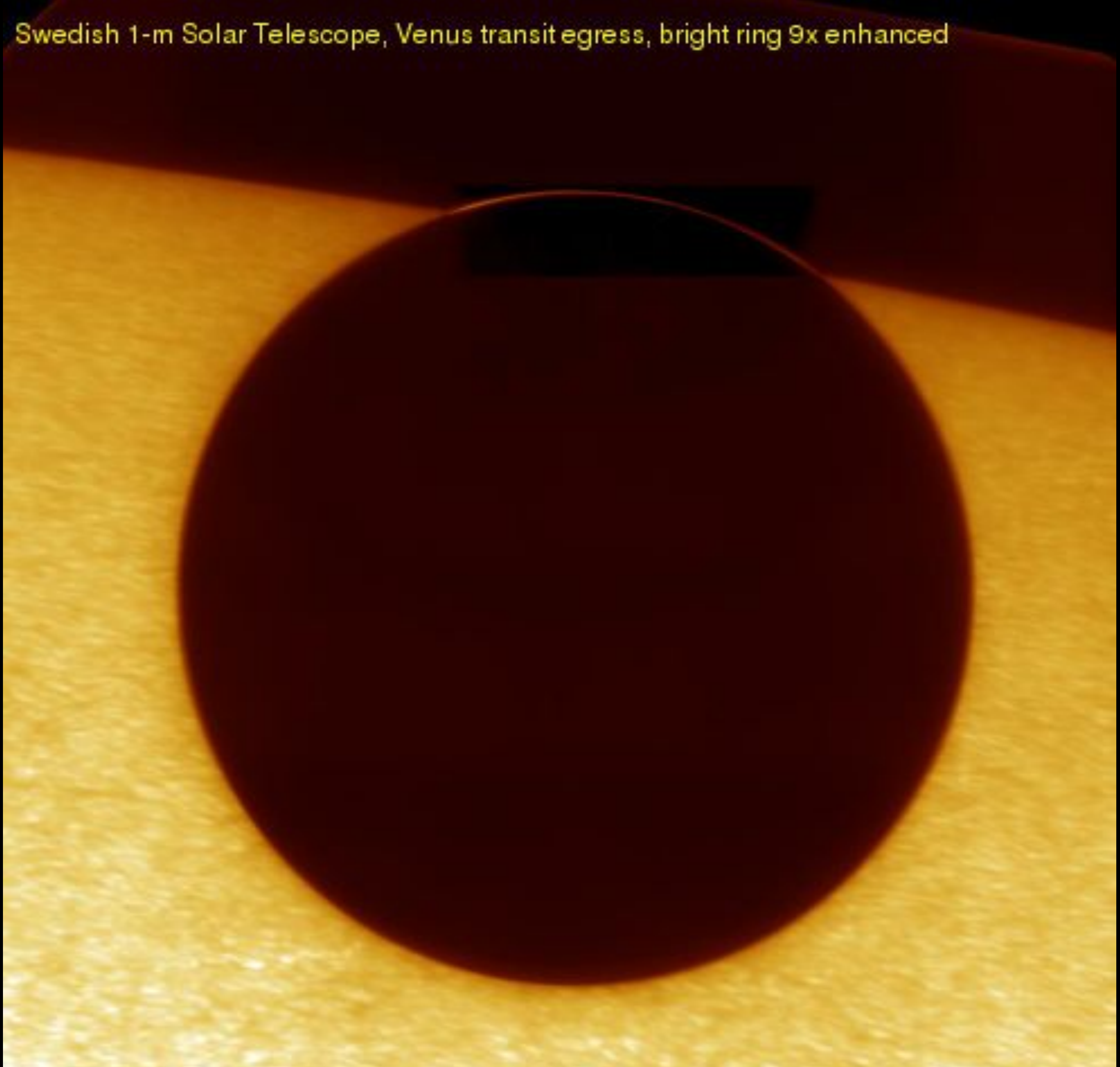
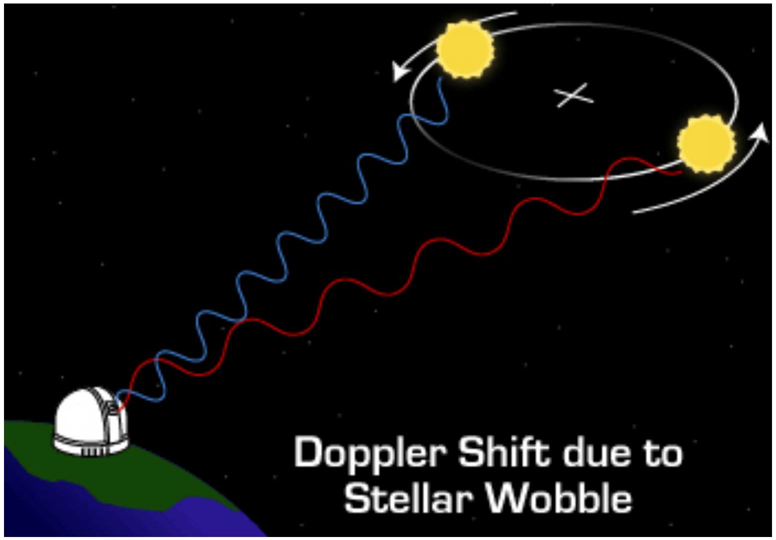

How the Hunt for
Habitable Worlds
Can Inspire
Physics Students.


Swedish 1-m Solar Telescope, Venus transit egress, bright ring 9x enhanced

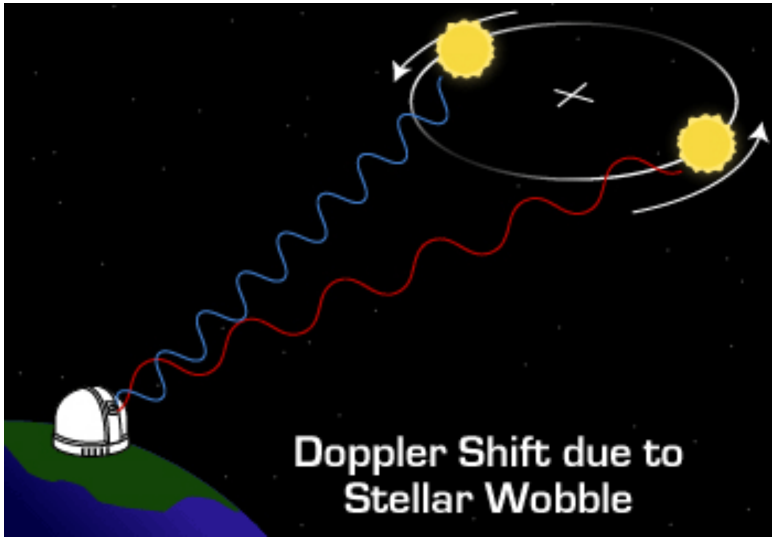
Astronomers have developed two clever *(but indirect)* methods to find exoplanets

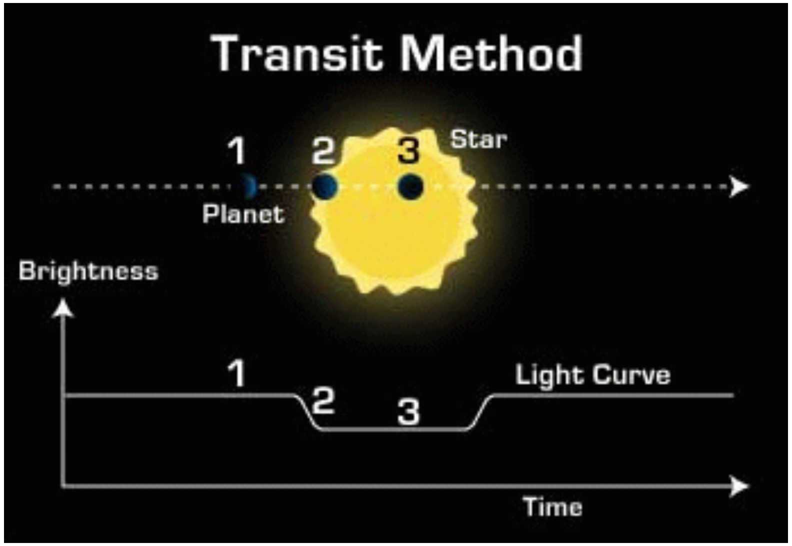


Doppler Method

Determine Planet Mass

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





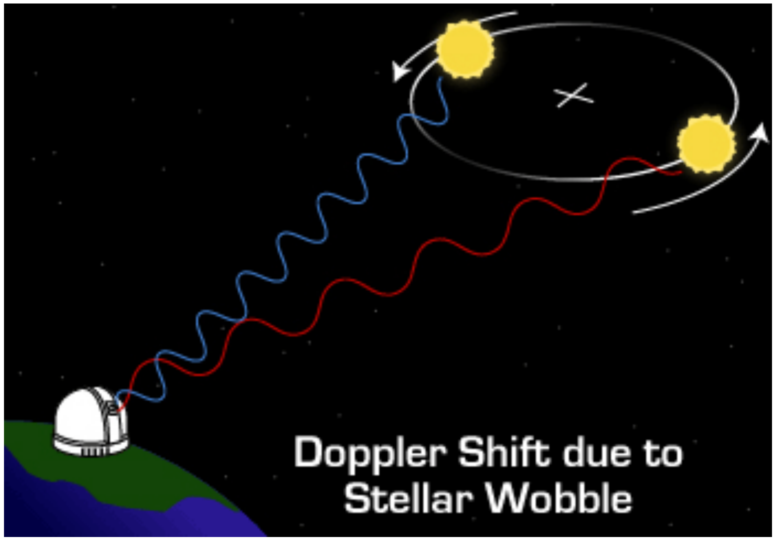
Doppler Method

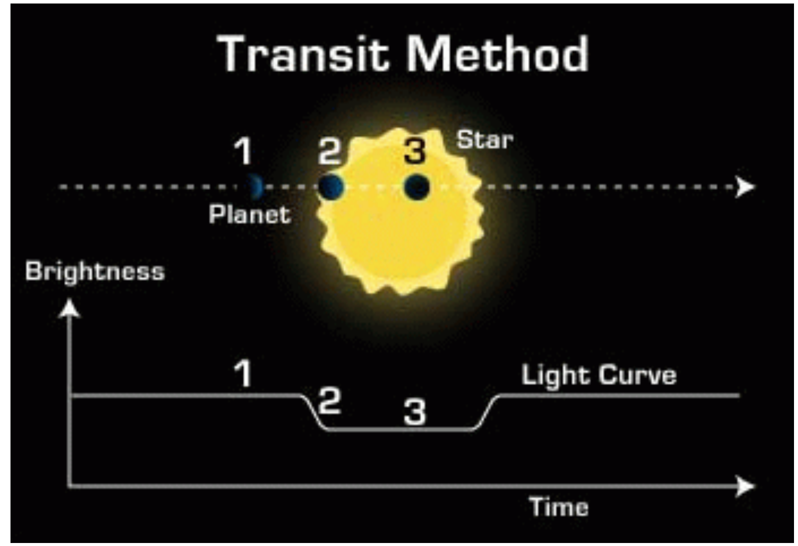
Determine Planet Mass

Transit Method

Determine Planet Diameter

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





Doppler Method

Determine Planet Mass

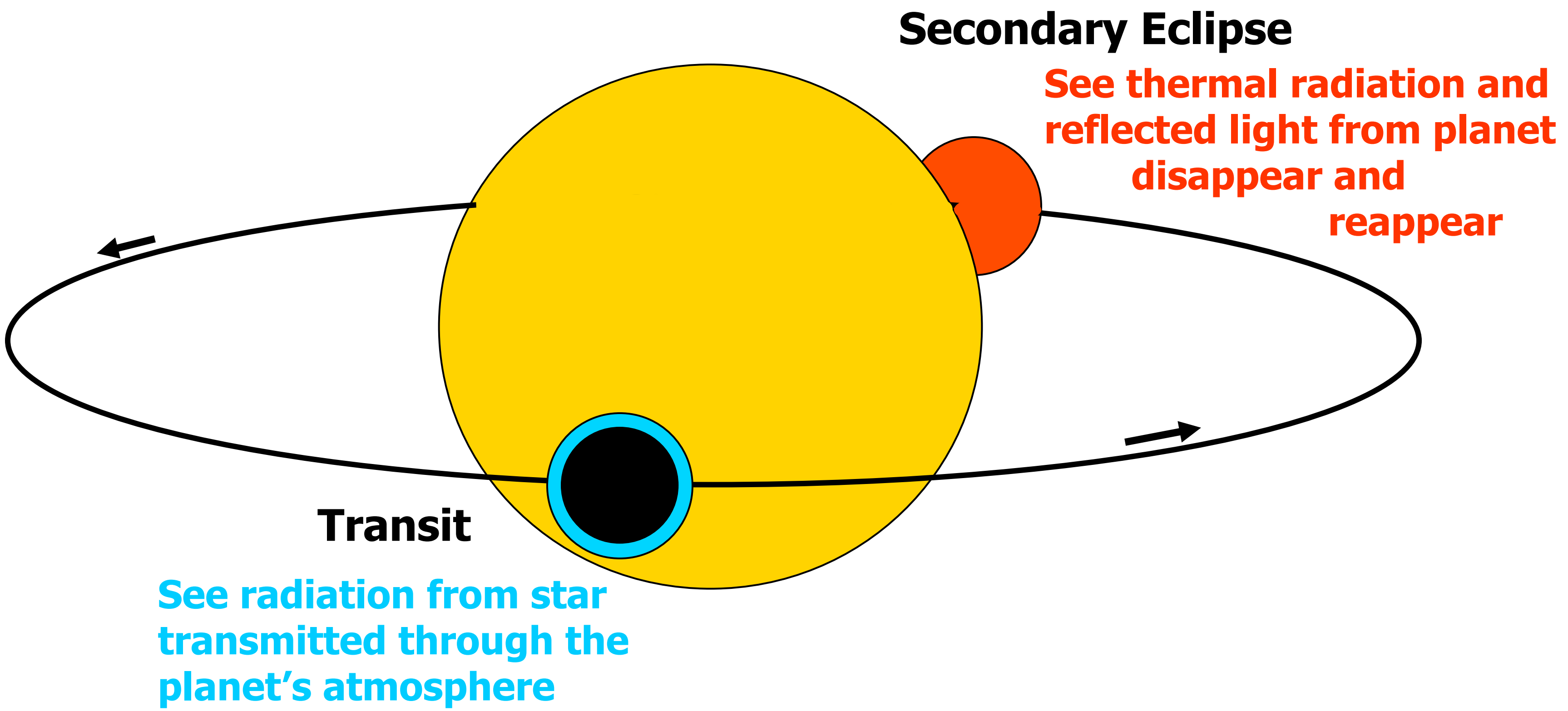
Transit Method

Determine Planet Diameter

Calculate Planet Density and Infer Composition:

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

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



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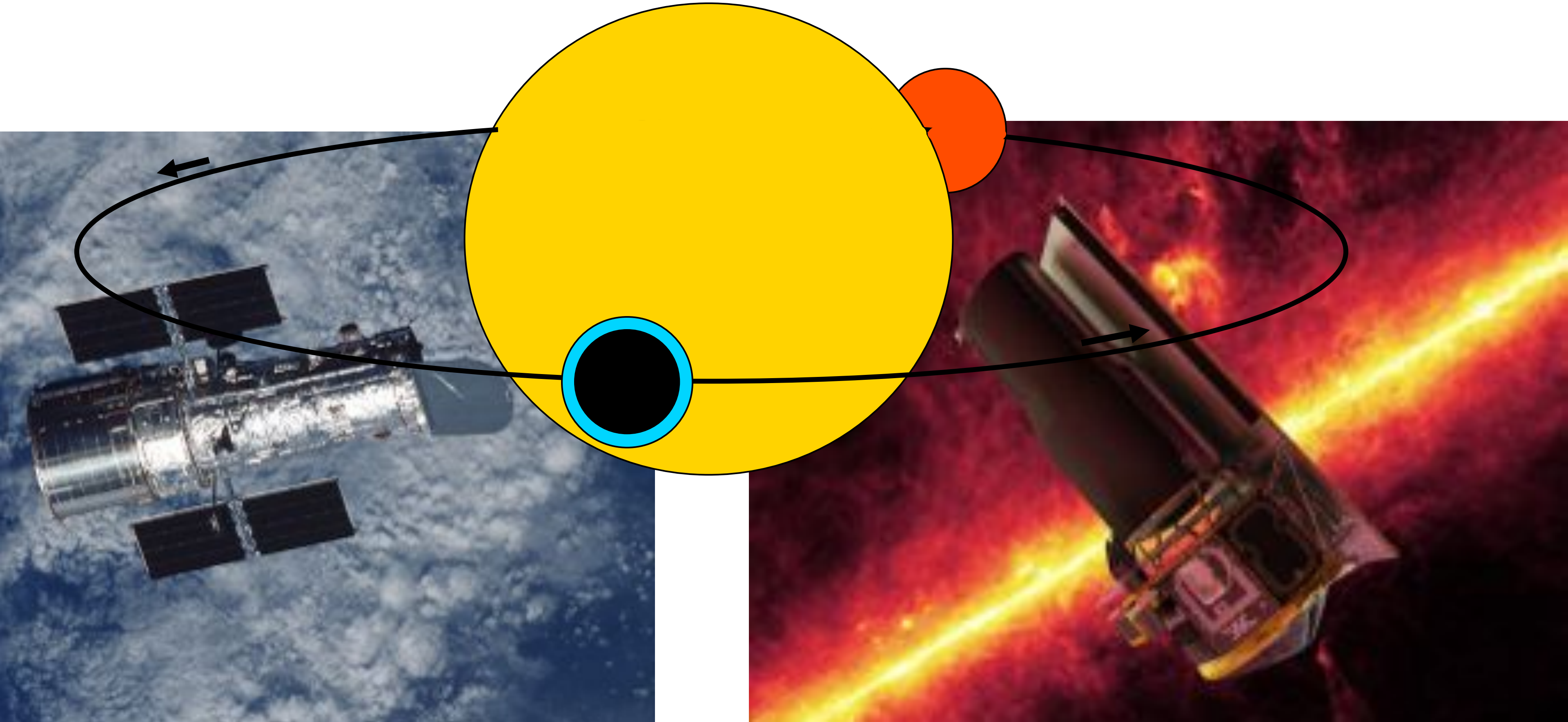
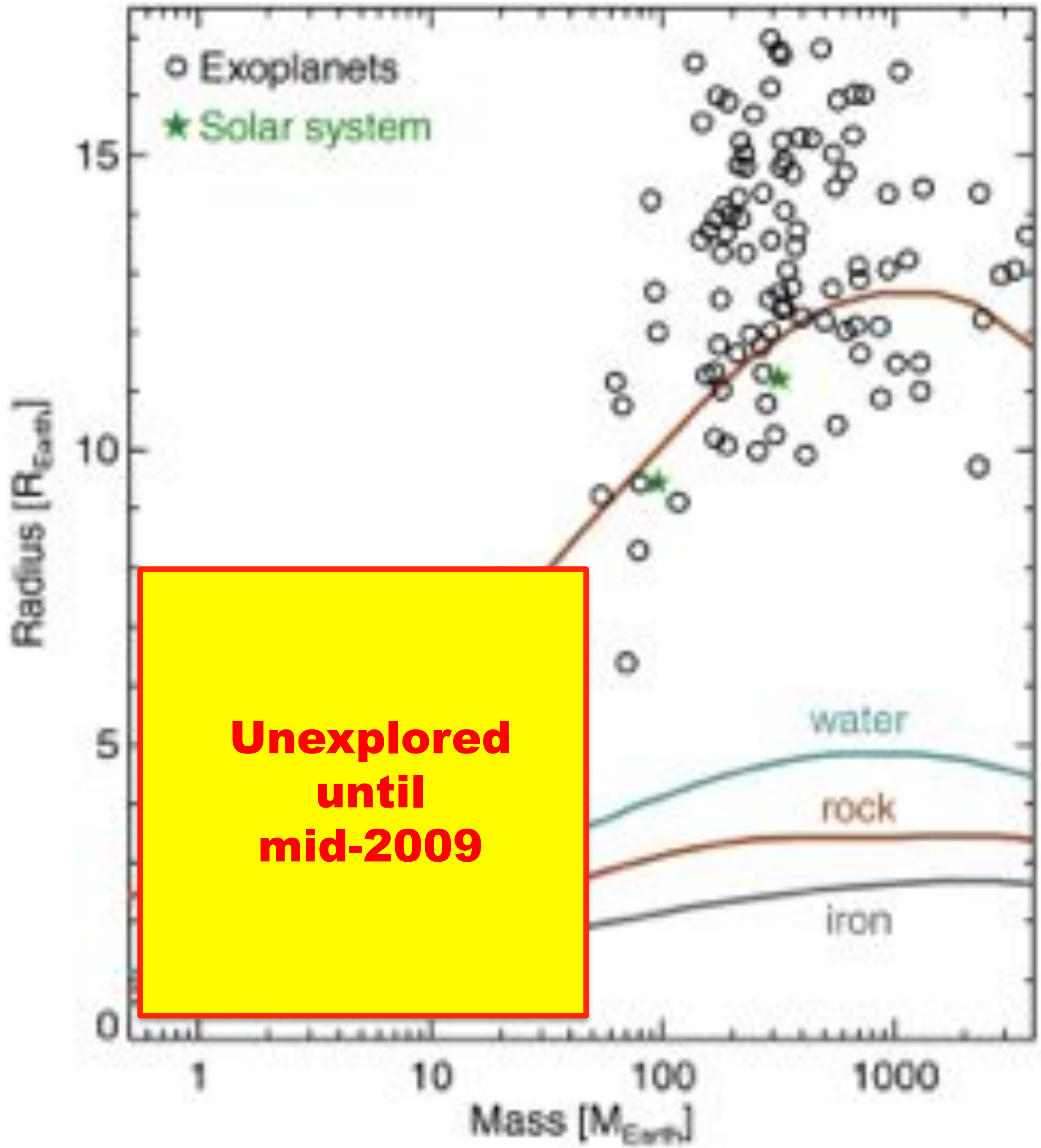


Exoplanet

Mass-Radius

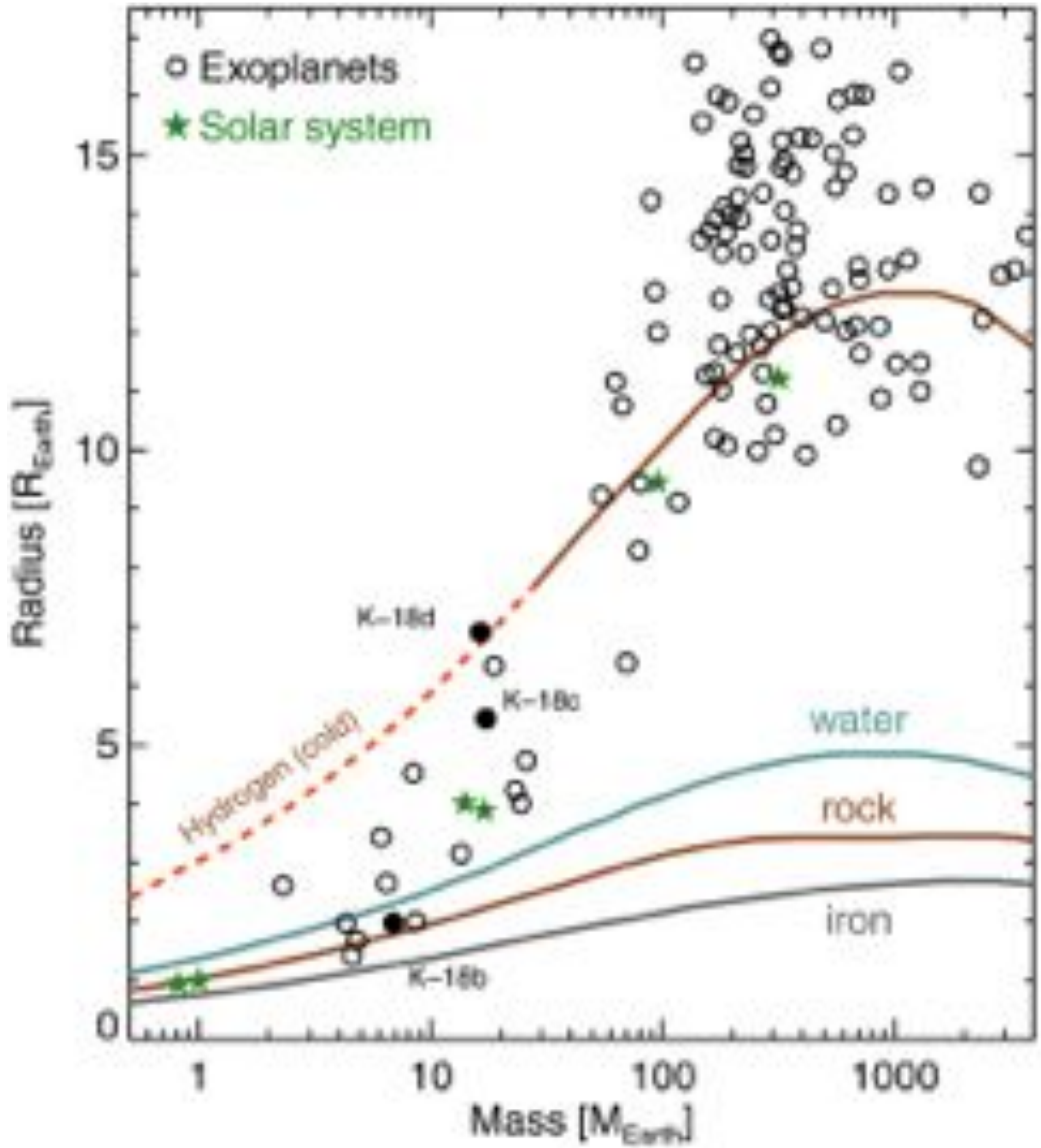
Diagram



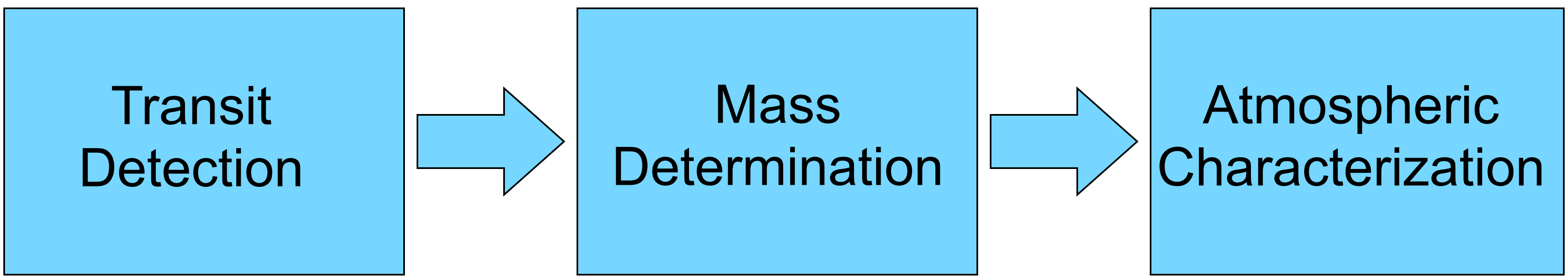
Exoplanet

Mass-Radius

Diagram



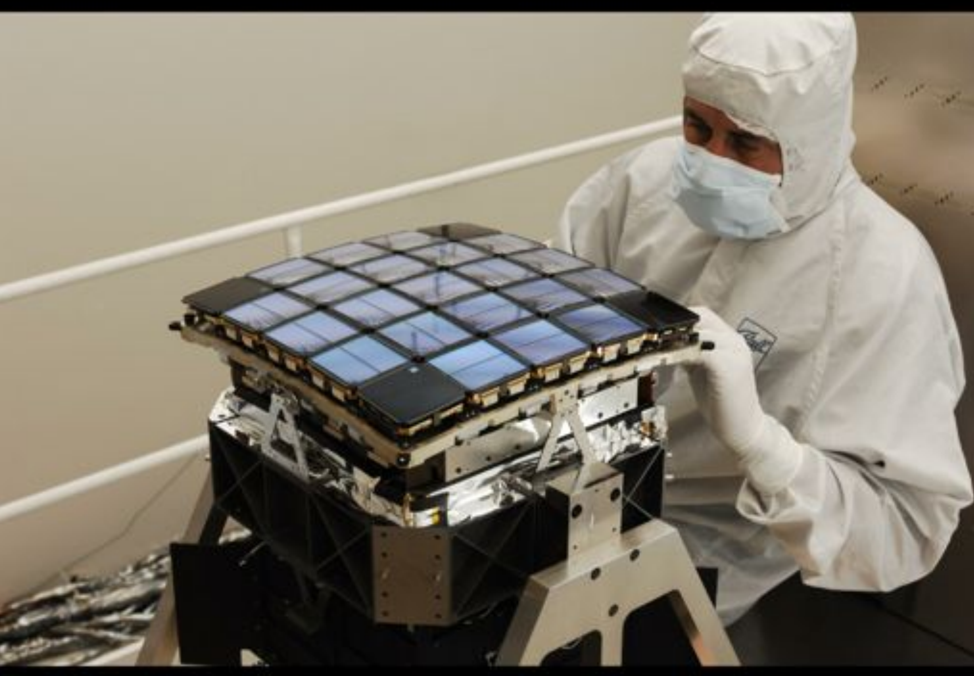
A Brief History of Progress in Comparative Exoplanetology



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

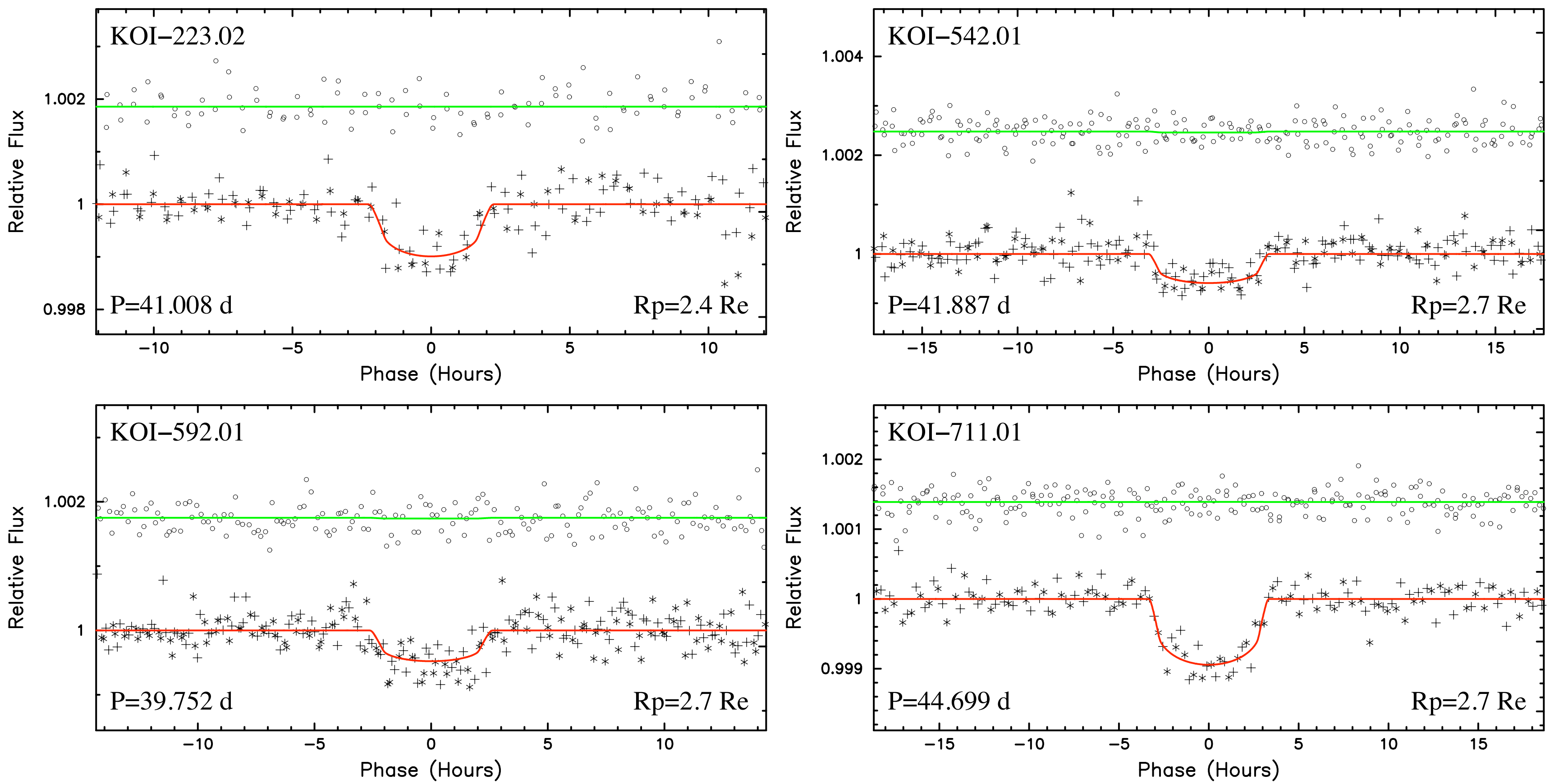
If life requires liquid water, then the planets must be at just the right distance from the star.

We call this the Habitable Zone.

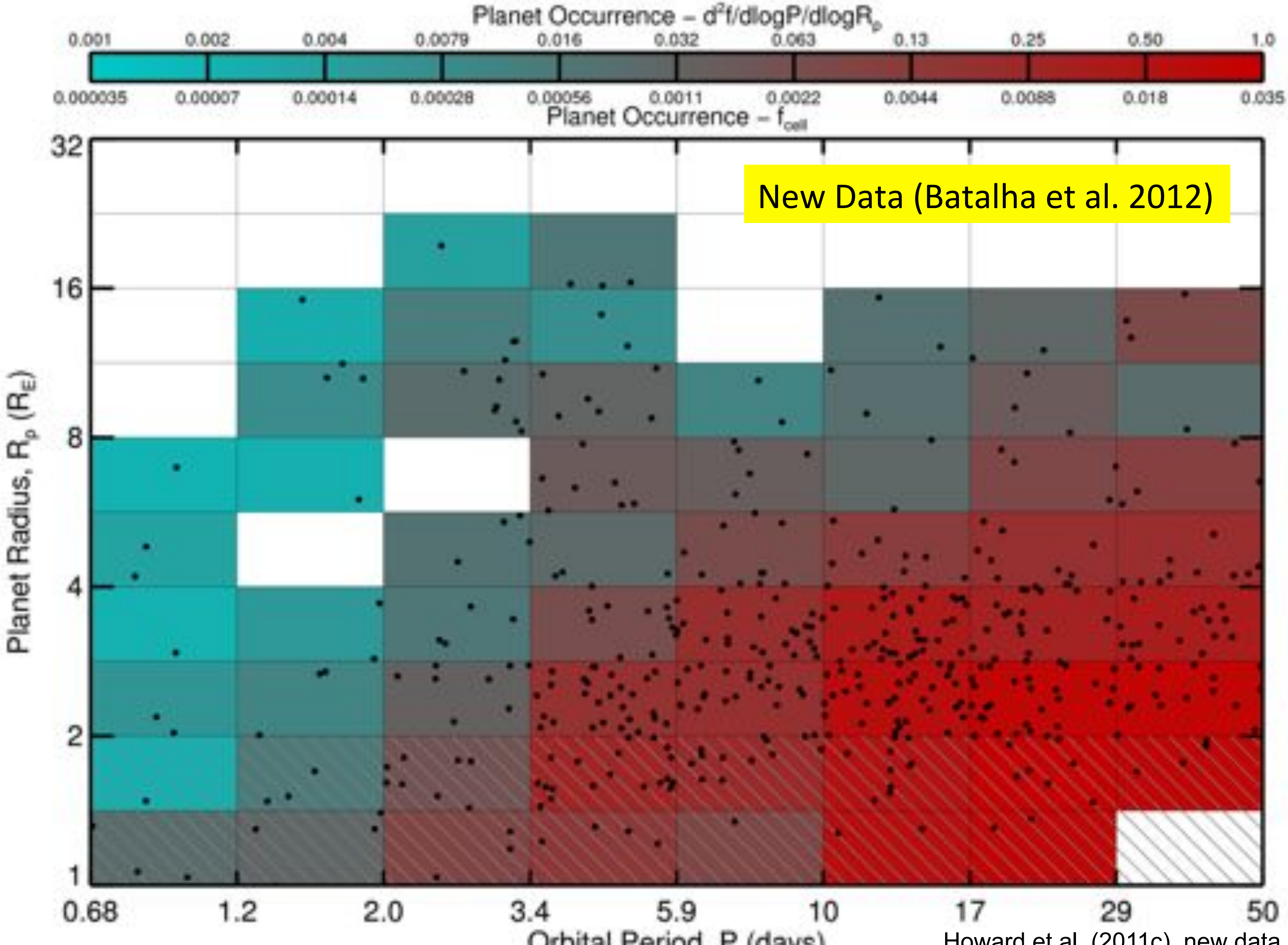


Kepler Mission gathering photometry since May 2009

Some Representative Transit Candidates from the Kepler Data Releases

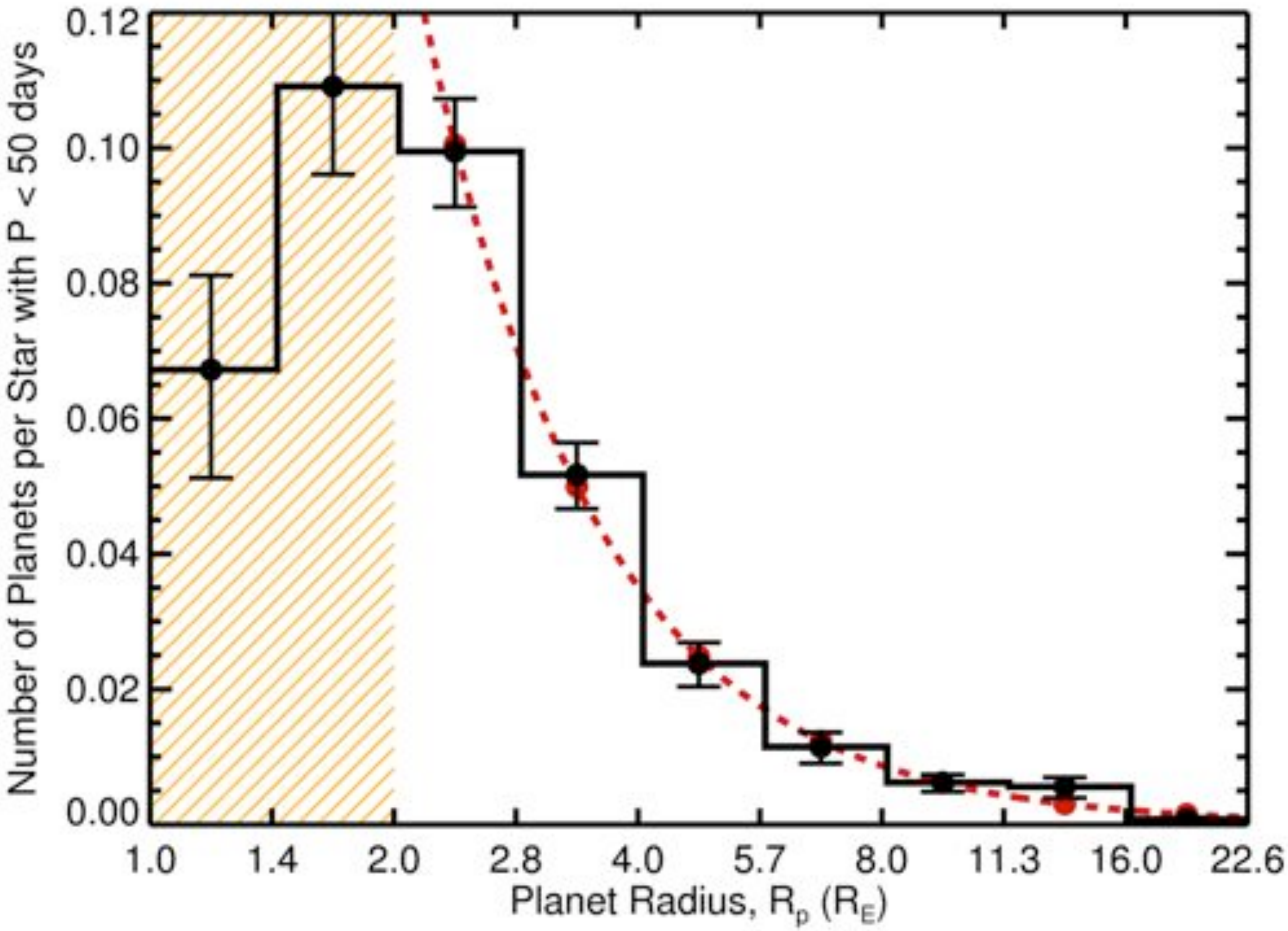


A. Howard and the Kepler Team (2011)



Howard et al. (2011c), new data

Planet Radius Distribution



<u>Power law:</u>

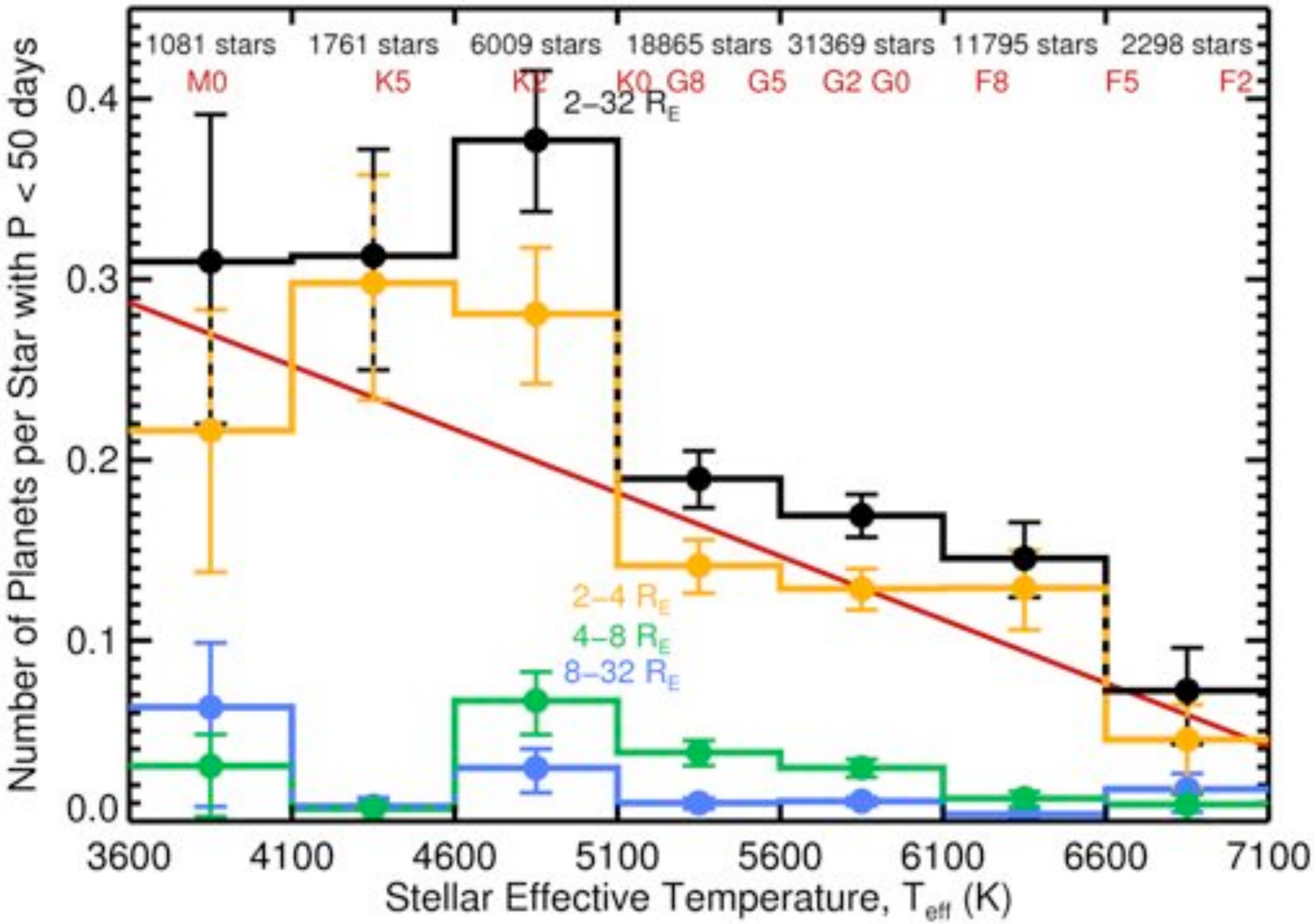
$dN/d\log R = kR^{\alpha}$

$k = 3.8 \pm 0.3$

$\alpha = -2.01 \pm 0.09$

Batalha et al. (2012)

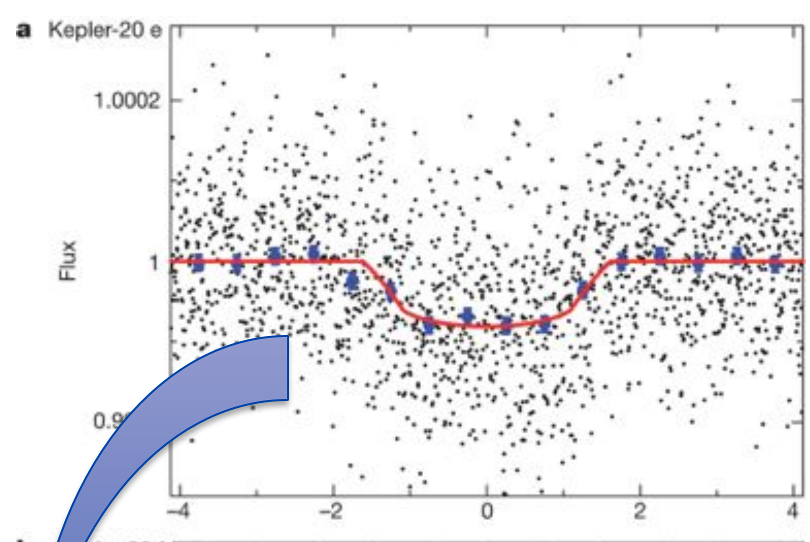
Planet Occurrence vs. Stellar Temperature

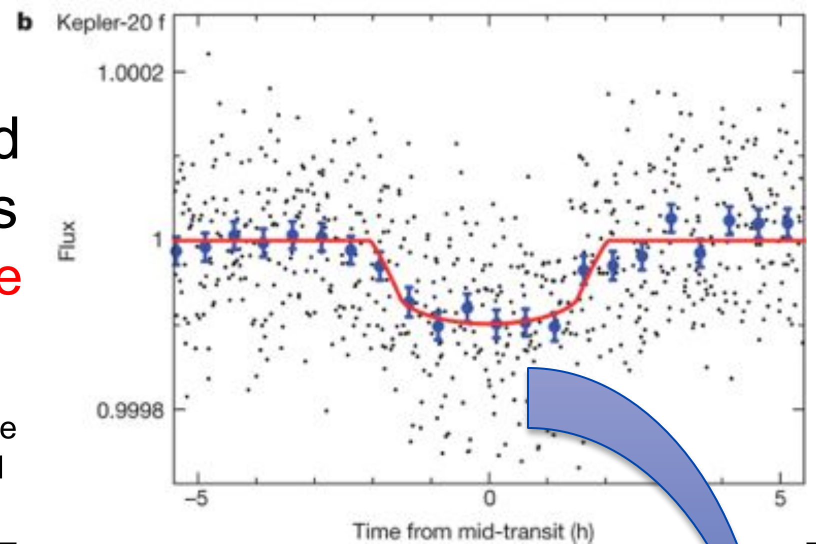


Batalha et al. (2012)

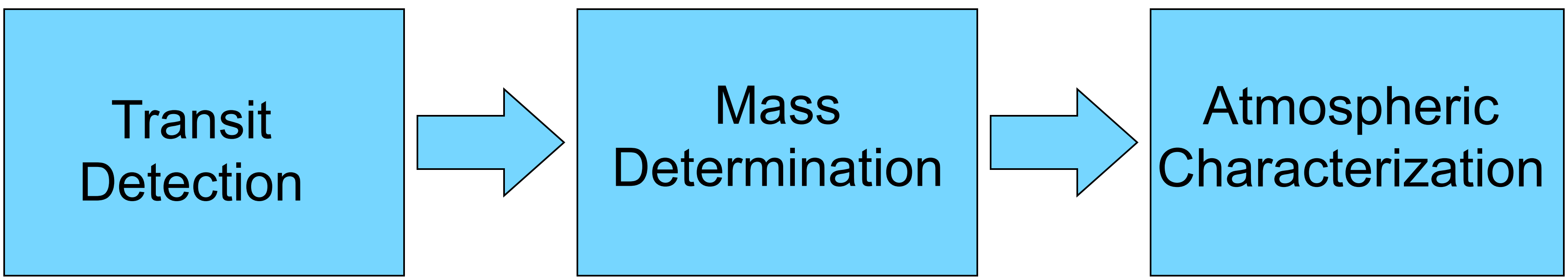
The First Earth-sized Exoplanets (but they are too hot)

Fressin,et al. Nature 20 December 2011





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



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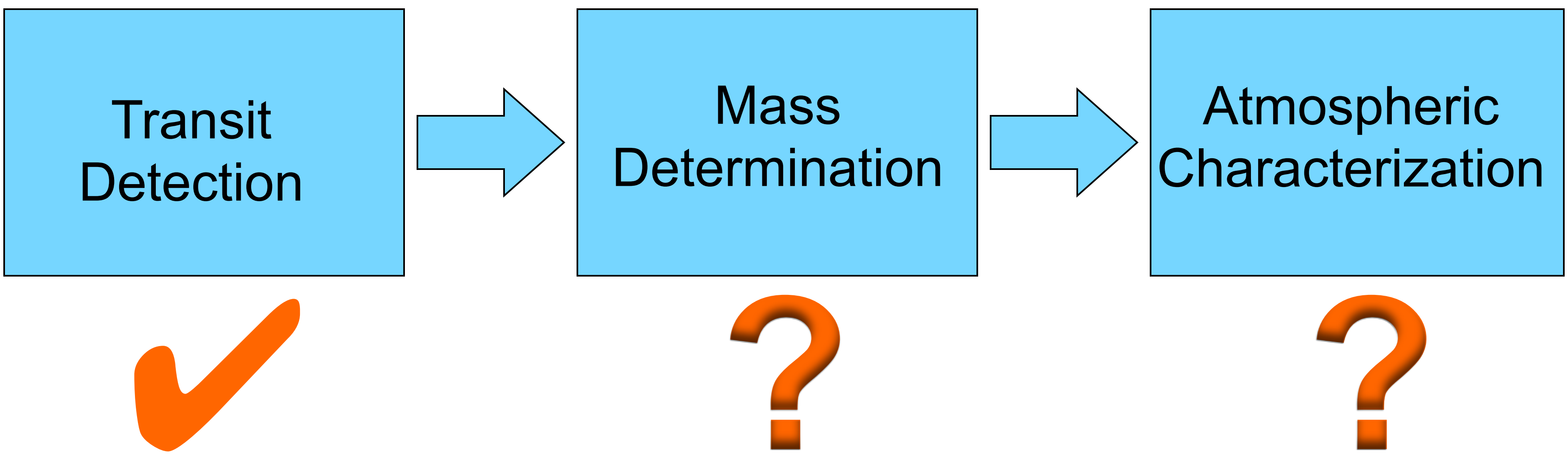
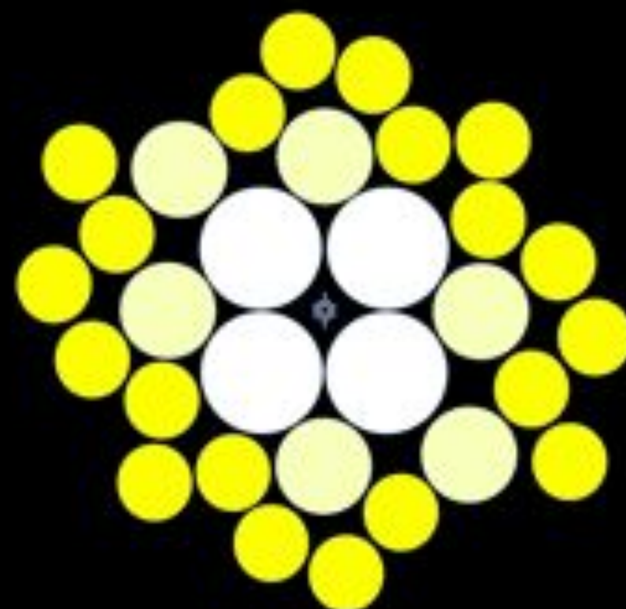
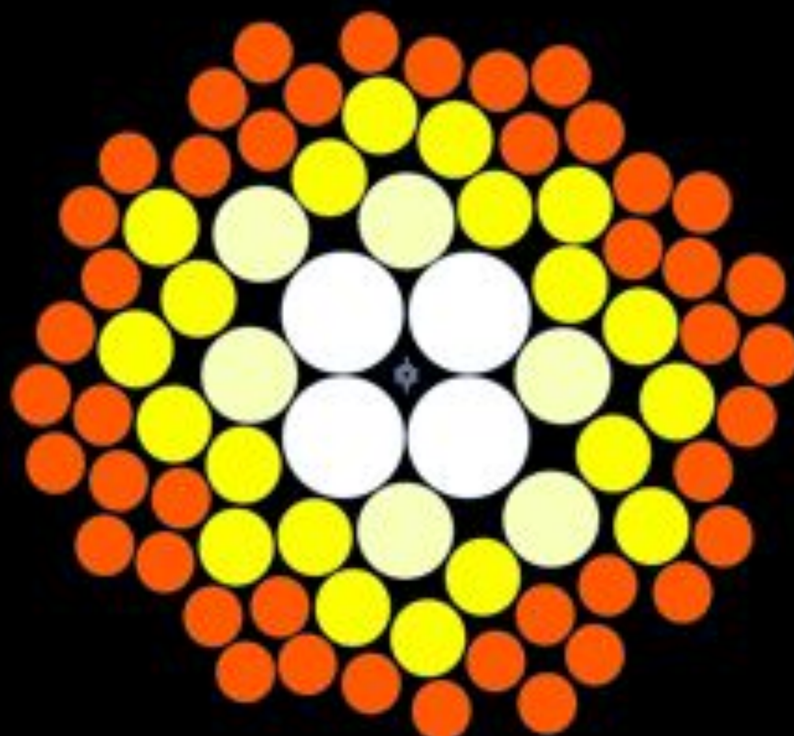
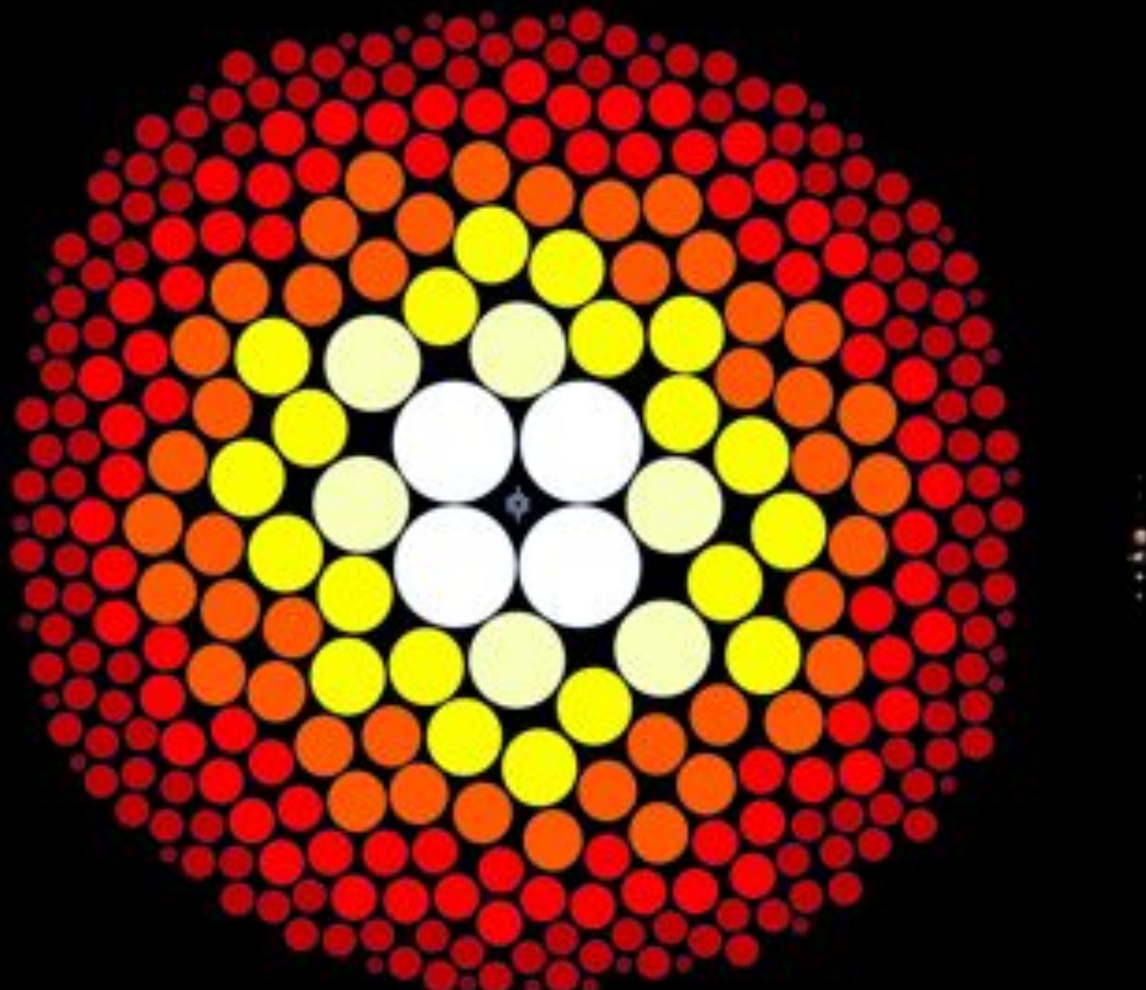




wd	20
O	0
B	0
A	4
F	6
G	20



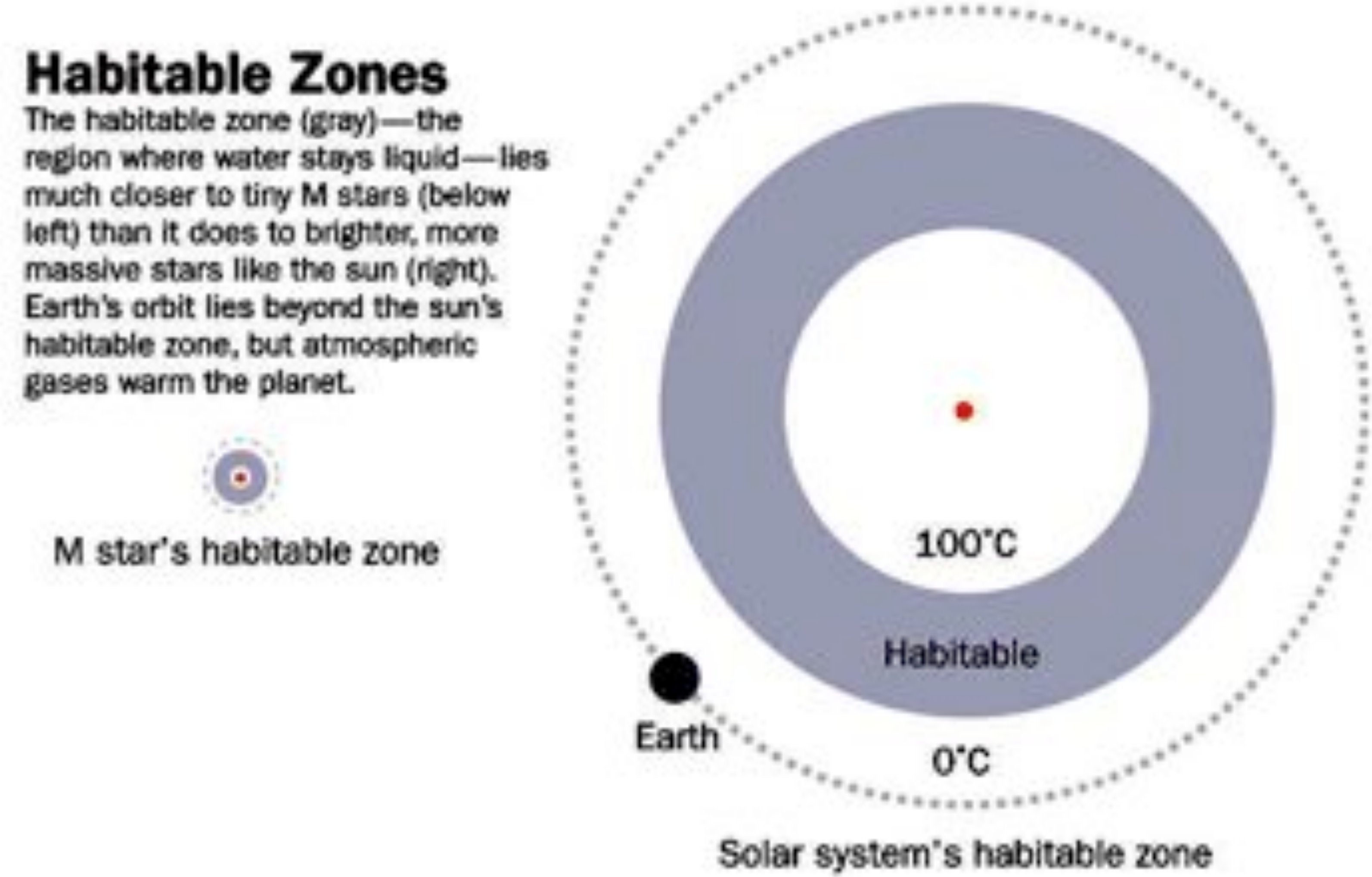
wd	20
O	0
B	0
A	4
F	6
G	20
K	44



wd	20
O	0
B	0
A	4
F	6
G	20
K	44
M	246

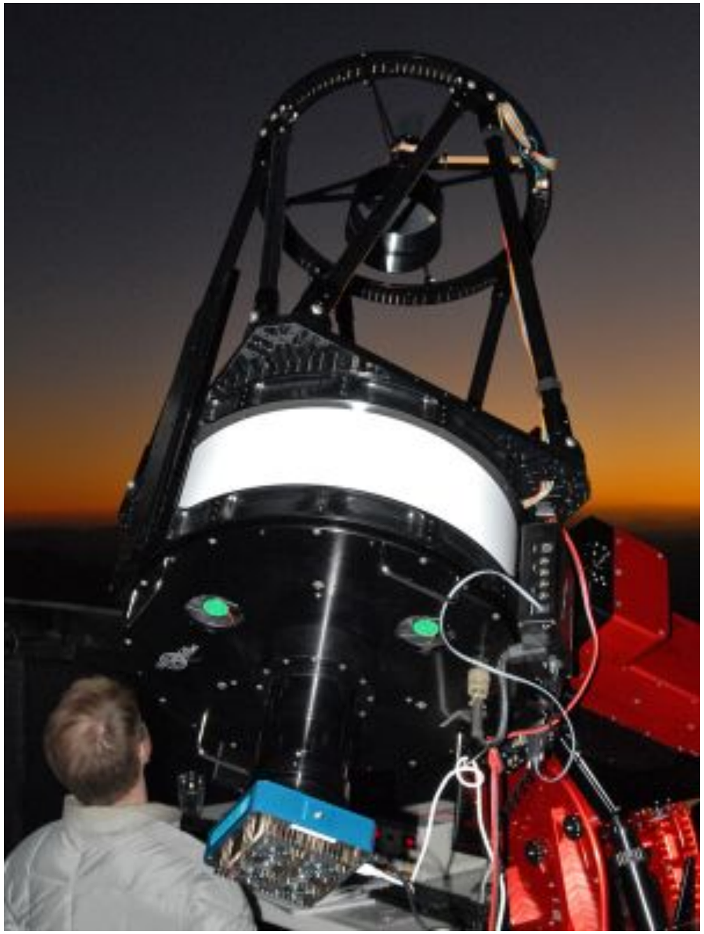
Data from RECONS, image courtesy Todd Henry

The Small Star Opportunity



The MEarth Project

Nutzman & Charbonneau 2008; Irwin et al. 2008



Using 8 X 40cm telescopes, we are surveying the 2000 nearest low-mass stars for planets as small as 2 R_{Earth} orbiting within the habitable zone.

MEarth is different: Monitor stars sequentially & detect transits in progress

We moved into an existing building on Mt Hopkins, Arizona September 2008

Expanding to southern hemisphere (Chile) in 2012

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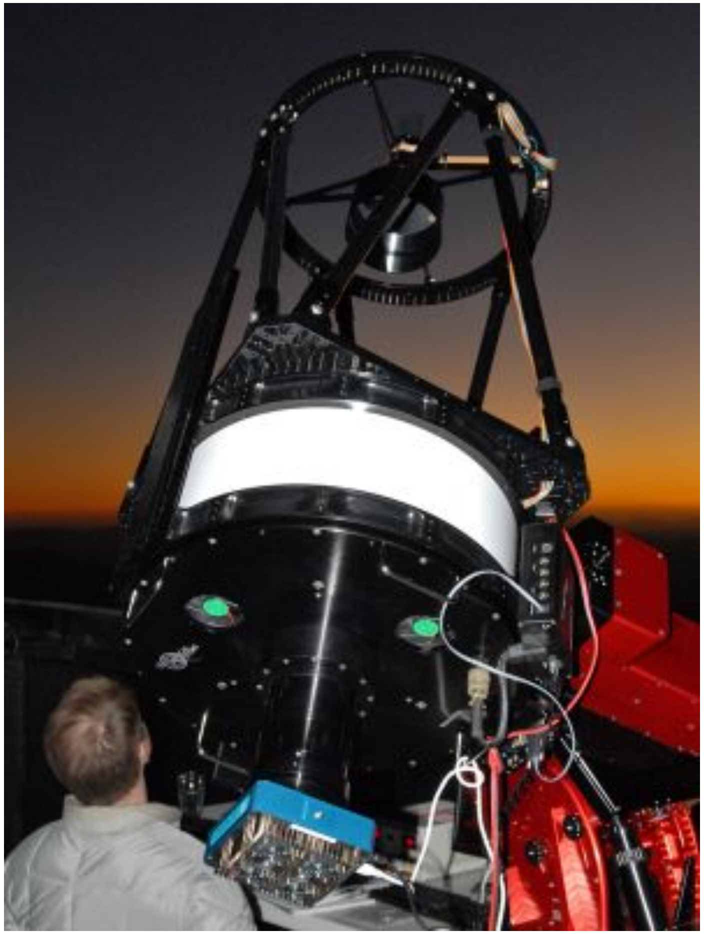

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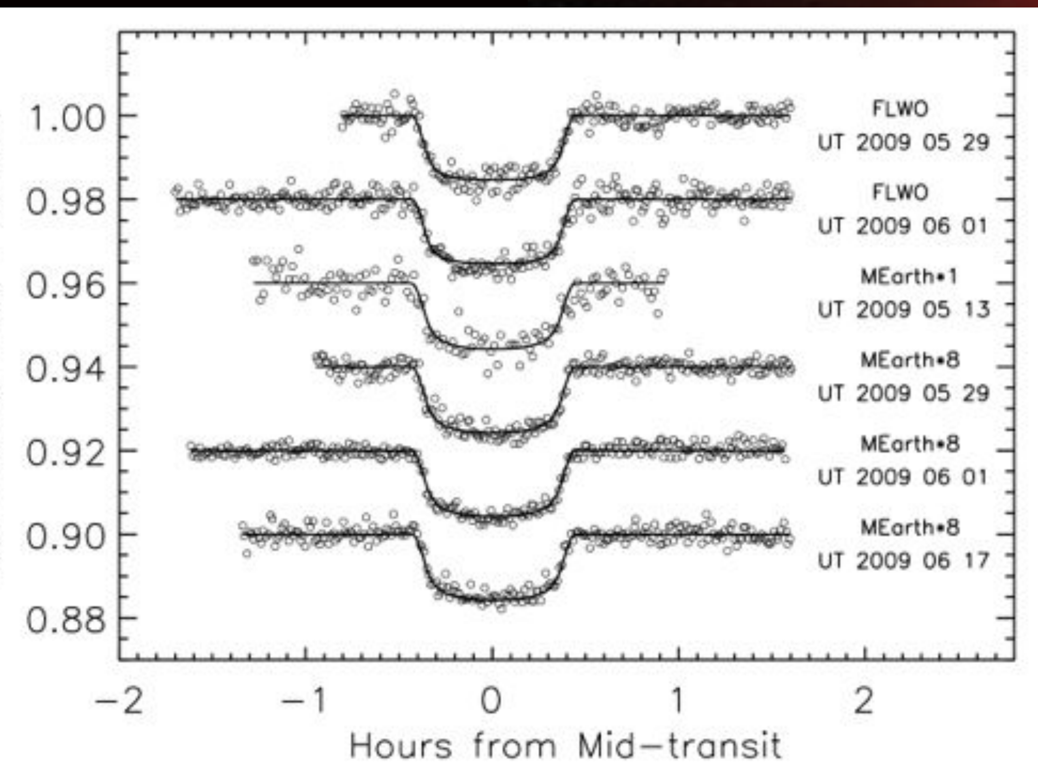
MEarth Project, Whipple Observatory, AZ

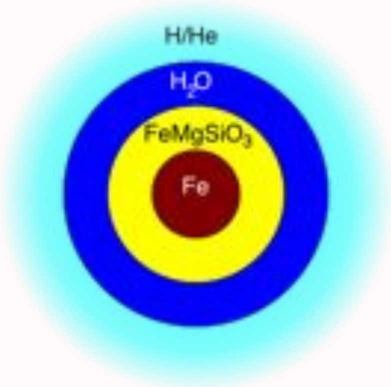
MEarth Discovers the First Nearby Super-Earth



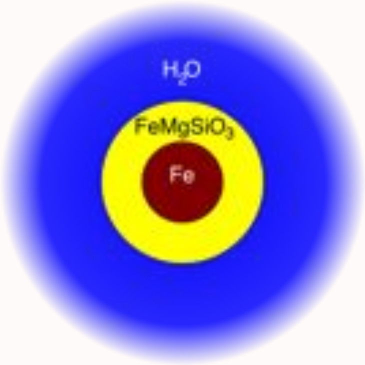
Two Scenarios for GJ 1214b

Rogers and Seager (2010)

Mini Neptune



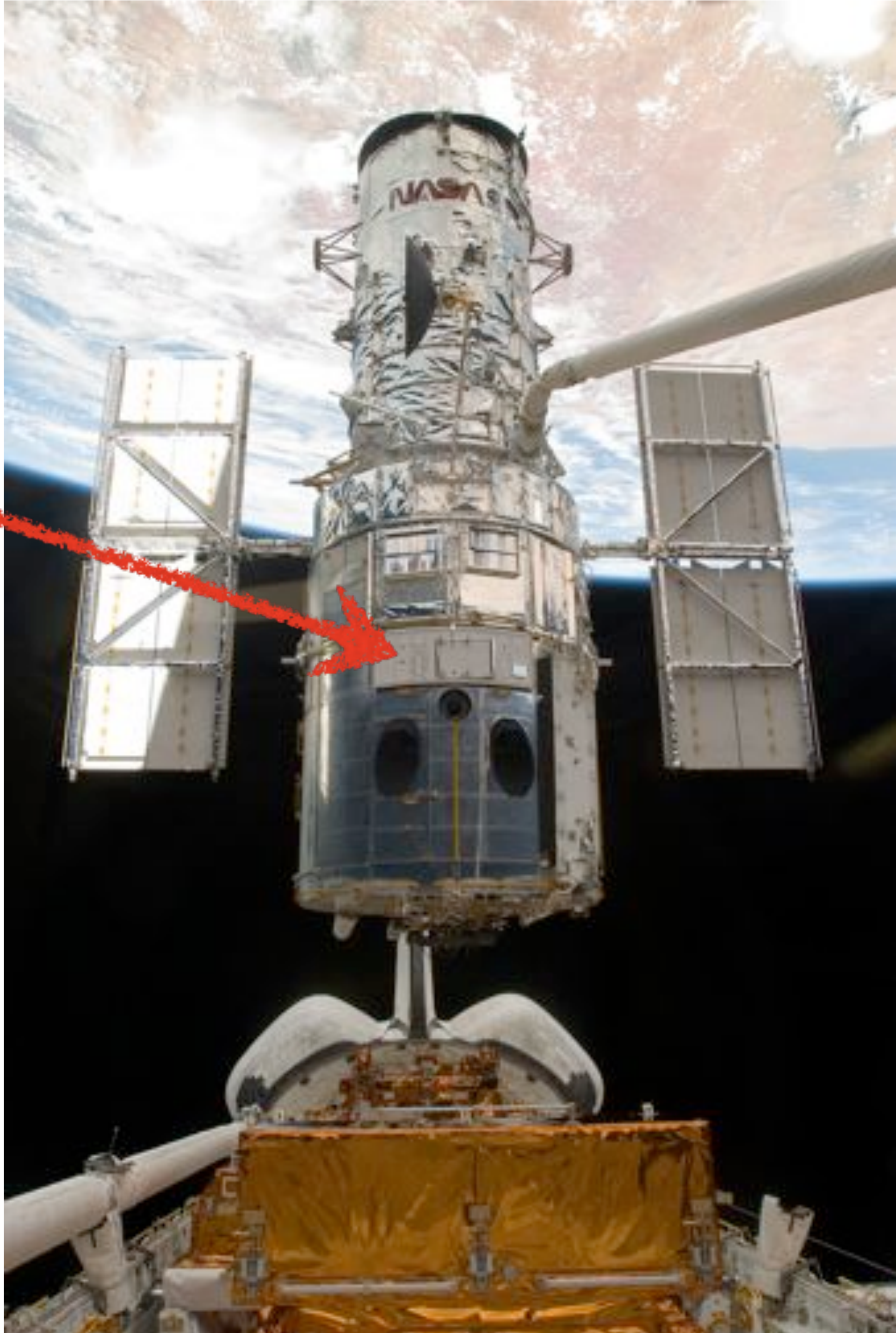
Water World



Next Step:

Use the transmission spectroscopy
to determine
atmospheric scale height and abundances.

Hubble
Wide Field
Camera 3
(WFC3)



three transits

of

GJ1214b

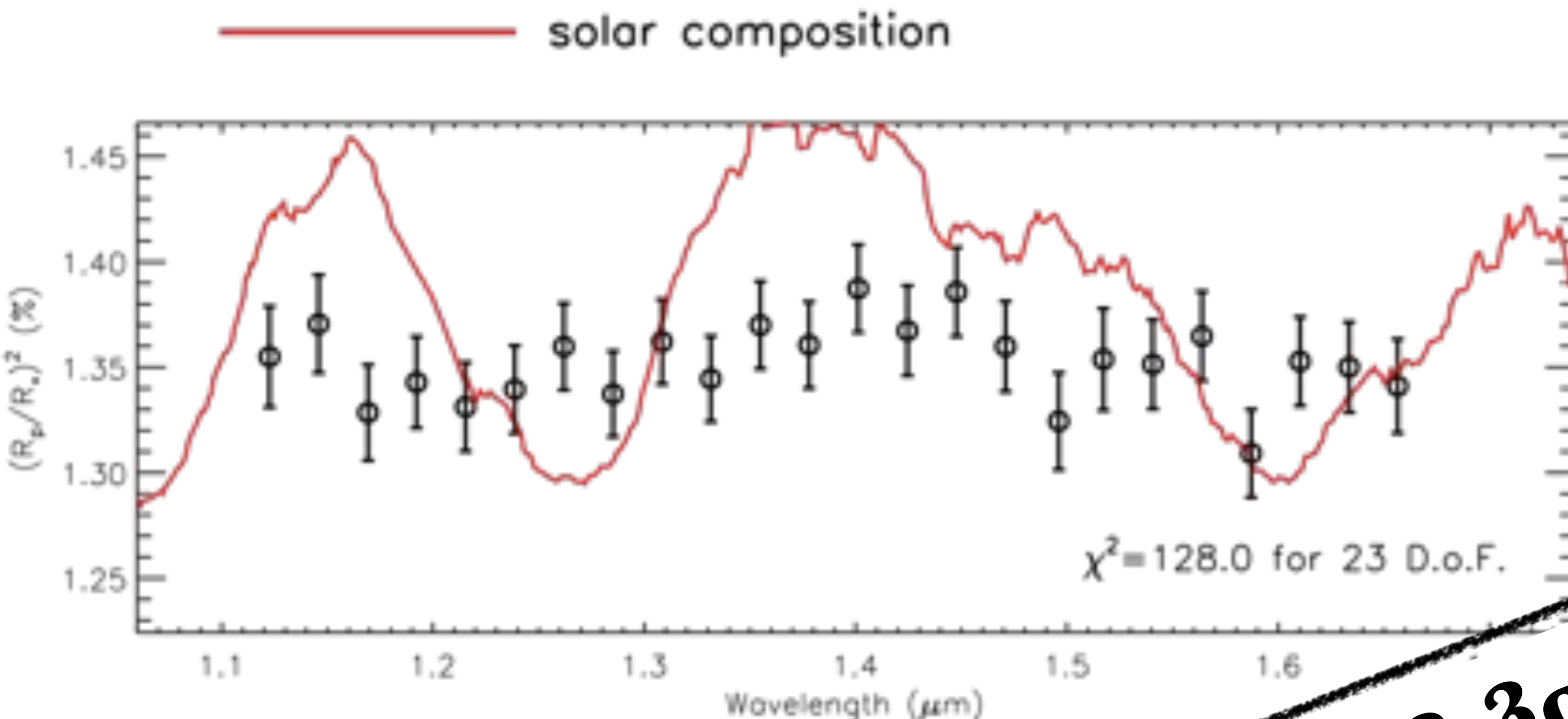
with

1.1-1.7μm

grism spectroscopy

**(WFC3/IR G141;
P.I. = Z. Berta)**

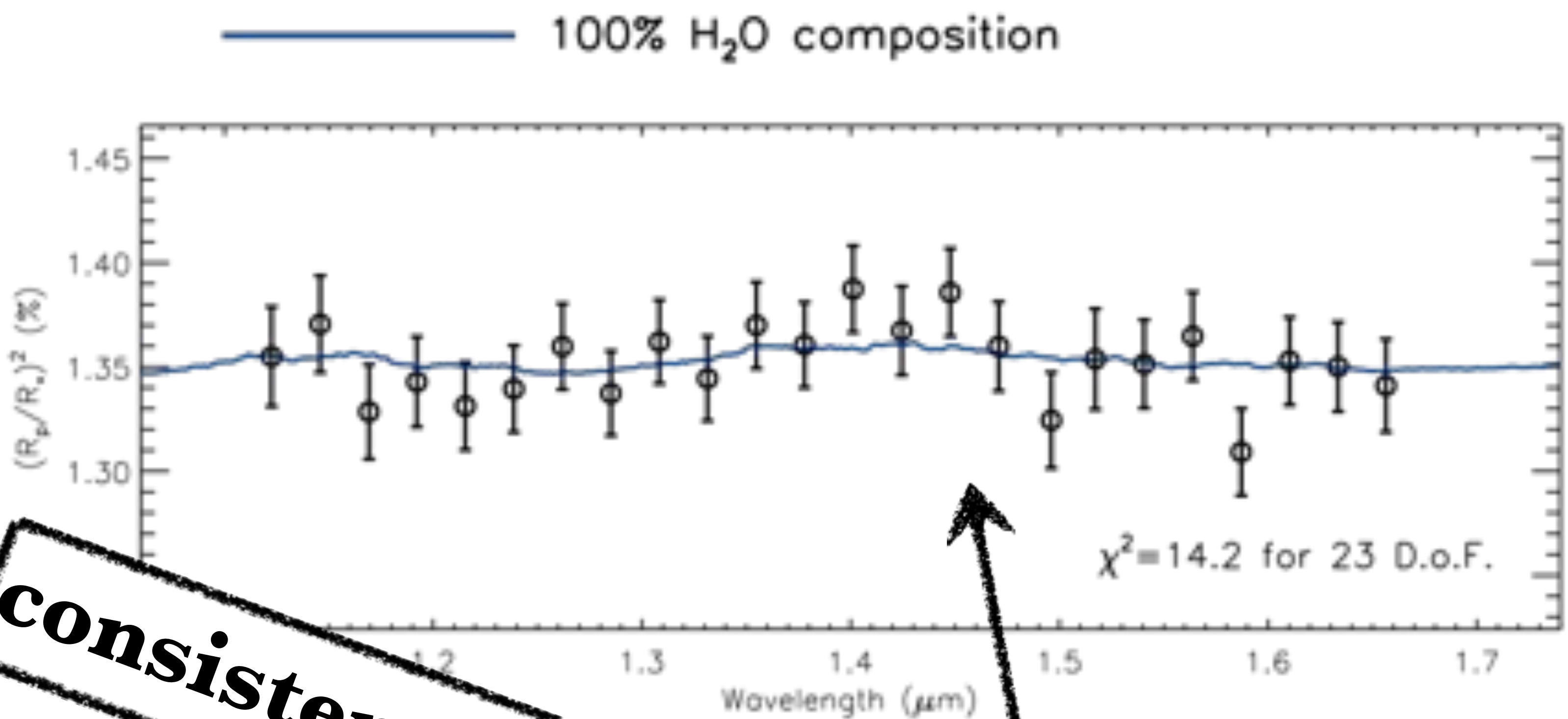
modeling GJ1214b's WFC3 **transmission spectrum**



ruled out at 8.3σ

models from
Miller-Ricci (Kempton)
& Fortney (2010)

modeling GJ1214b's WFC3 **transmission spectrum**

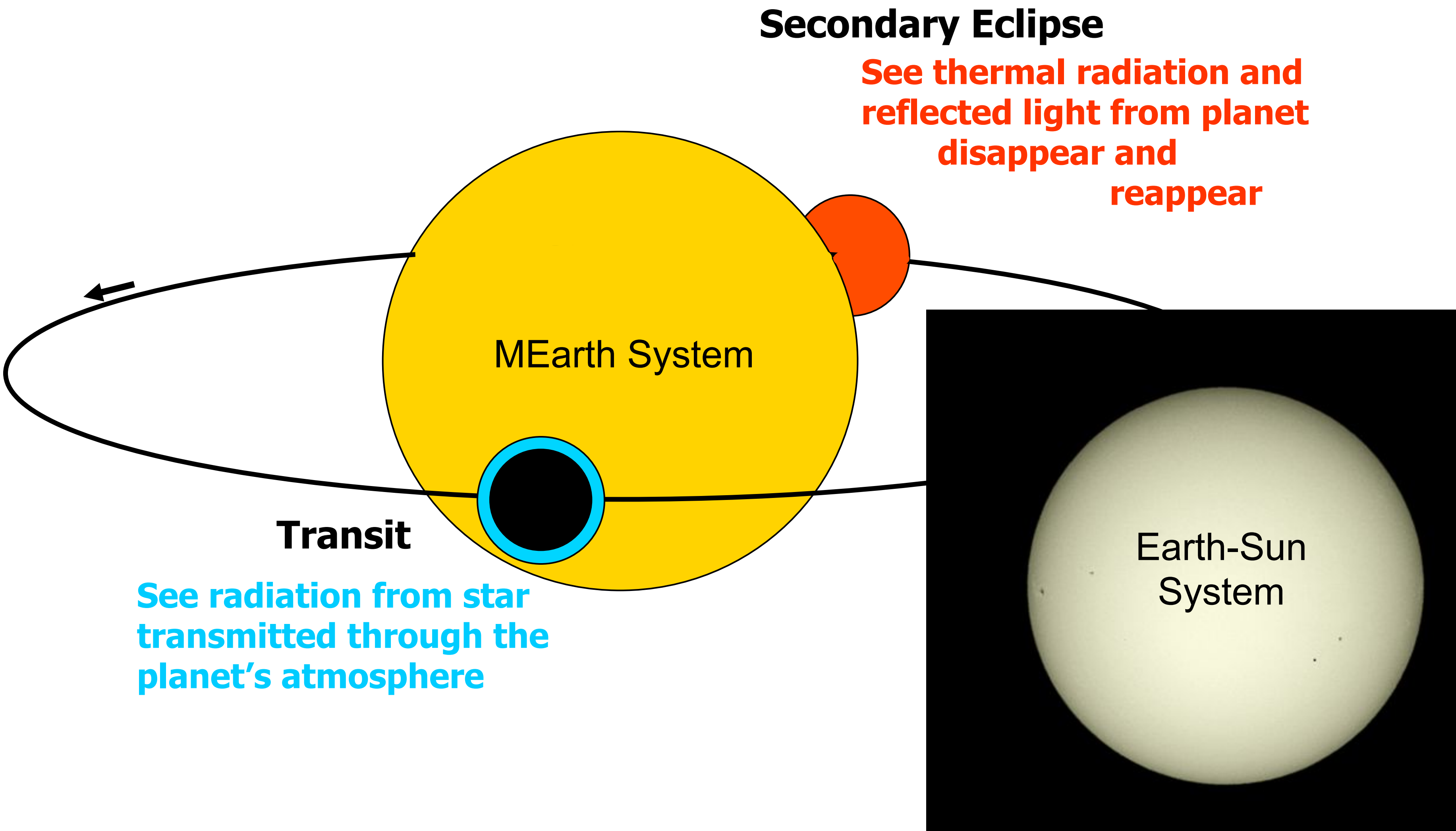


consistent!

water fractions above 20% (70% by mass) are good fits to the WFC3 spectrum

models from
Miller-Ricci (Kempton) & Fortney (2010)

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



Some Ideas for Using Exoplanets to Engage Students in Physics

Are We Alone?

This is arguably the greatest question in all of science.
It is a physics question.

Specific Learning Objectives

- Equations of Motion and Newtonian Gravity
  - Concepts: Center of mass, gravitational force, Kepler's third law, conservation laws.
  - Supplement transits with RV data and they can calculate planet density and infer composition from fundamental physics.
- Energy Balance and Planet Temperature
  - Concepts: Stefan-Boltzmann law, radiation balance; use period to estimate planet temperature.
  - Discussion of habitability and greenhouse effect.
- Data Analysis and Propagation of Uncertainties
  - Comparison of uncertainty due to statistical error (photon noise) and systematic error (stellar radius estimate) on quantity of interest (exoplanet radius).

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This fall, begin your introductory physics course by telling your students…

1. The first earth-like exoplanet will likely be announced before they graduate,

and,

2. they need to understand physics to understand how that discovery was made,

then

3. **challenge them to prove for themselves the existence of exoplanets!**

My Objectives

- What I hope to achieve:
  - Inspire you to include an exoplanet lab in an introductory physics course
  - Reassure you that such a lab can be undertaken with a typical college rooftop telescope
  - Supply you with the basic know-how to implement the lab
- What I won't cover:
  - This is not a complete learning exercise
  - I have not identified the major misconceptions that confront this activity
  - I have not studied outcomes of this activity for student learning

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Equipment (& Common Misconceptions)

- **Telescope:**
  - Seeing, read noise, dark current, sky brightness are all irrelevant. I have done this from LA and Boston!
  - Smaller is better.
  - Tracking vs. guiding.
- **CCD camera:** Without anti-blooming.
- **Filter:** Narrow & red is best. Doesn't need to be a standard bandpass.
- **Computer with Analysis Software:** Maxim DL, CCDSoft, or similar, for extracting time series from images. This is a considerable improvement over IDL/IRAF scripts.
- **Weather:** Ask students to reserve many nights, and issue a go / no-go decision 1-hour before meeting.

Target Selection

Three groups of transiting planet hosts:

- RV-detected Hot Jupiter systems (HD stars)
- Transit-detected Hot Jupiter systems (HAT, TrES, WASP, XO, MEarth, Qatar)
- Kepler- & CoRoT-detected systems (rocky worlds!)

Why?

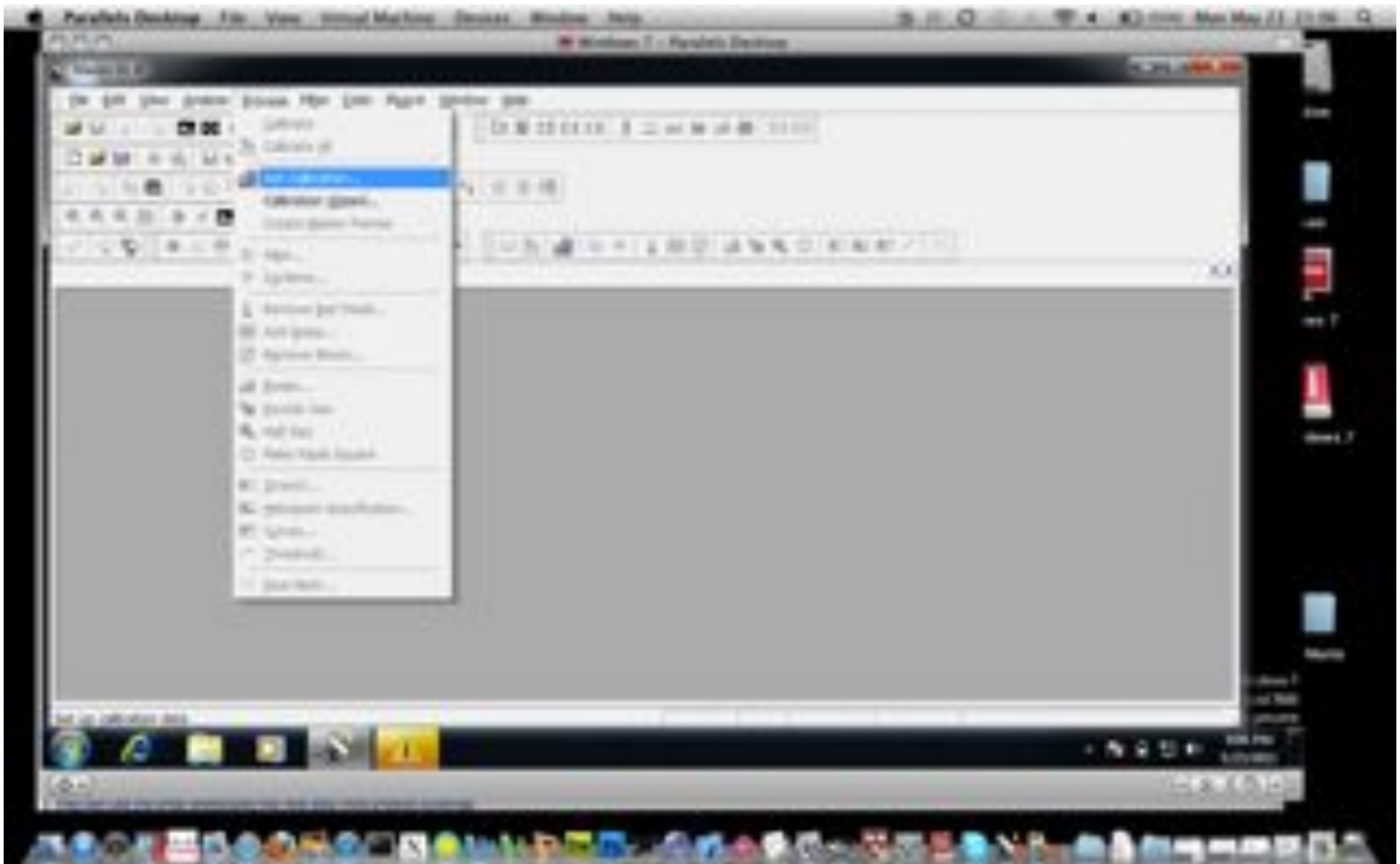
Your field of view will typically be 15’ x 15’ (1024 x 1024 CCD) and you need several calibrators of the same brightness as the target.

There are currently 80 such planets known, guaranteeing several targets on any given night!

Exoplanet Transit Database*:* http://var2.astro.cz/ETD/index.php

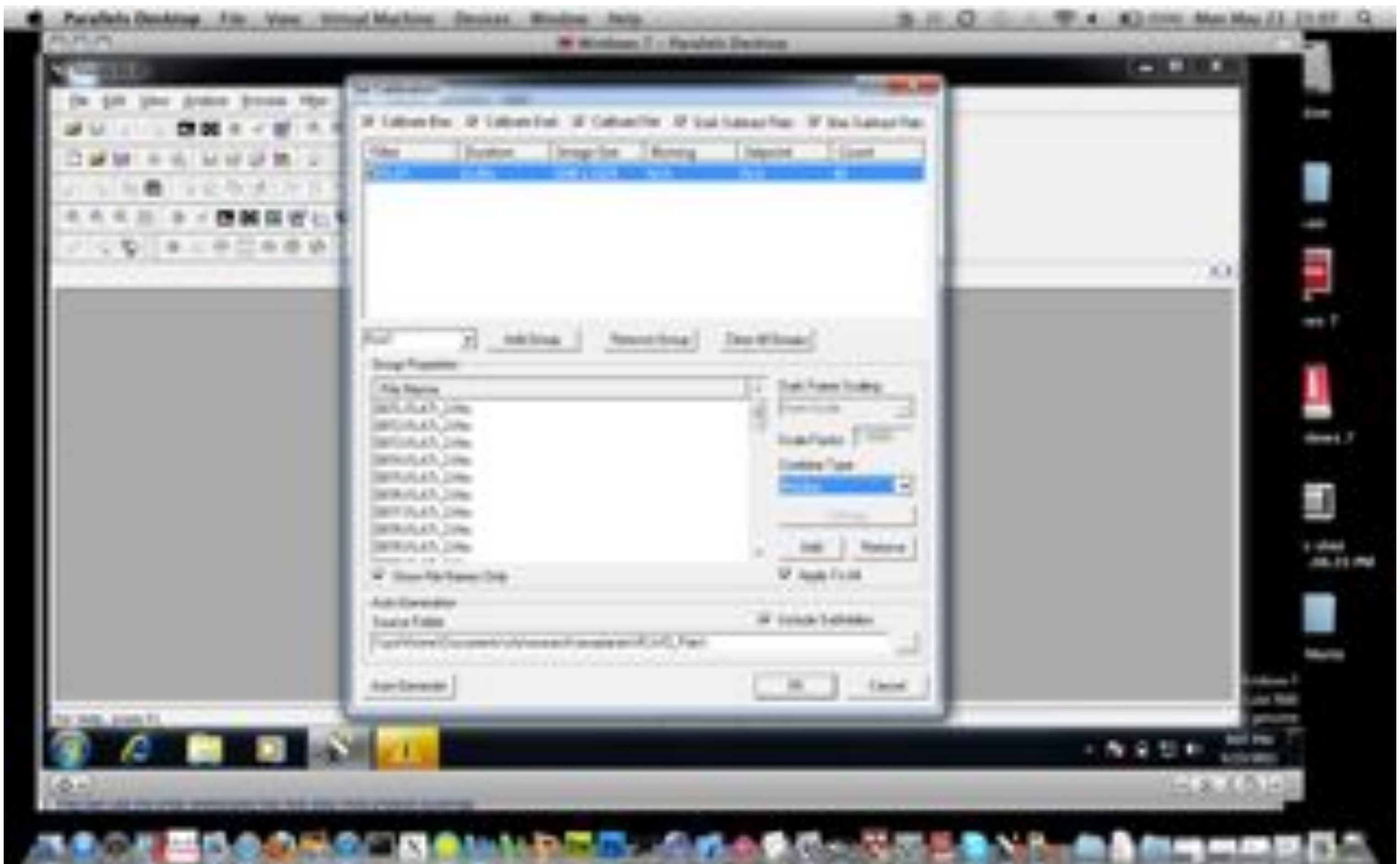
How to Analyze the Data

Step 1: Load all images into Maxim DL.



How to Analyze the Data

Step 2: Click Process --> Set Calibration (this opens a new window) Click Select Files to select flats to be median combined, then hit "OK". Click Process --> Calibrate All.



How to Analyze the Data

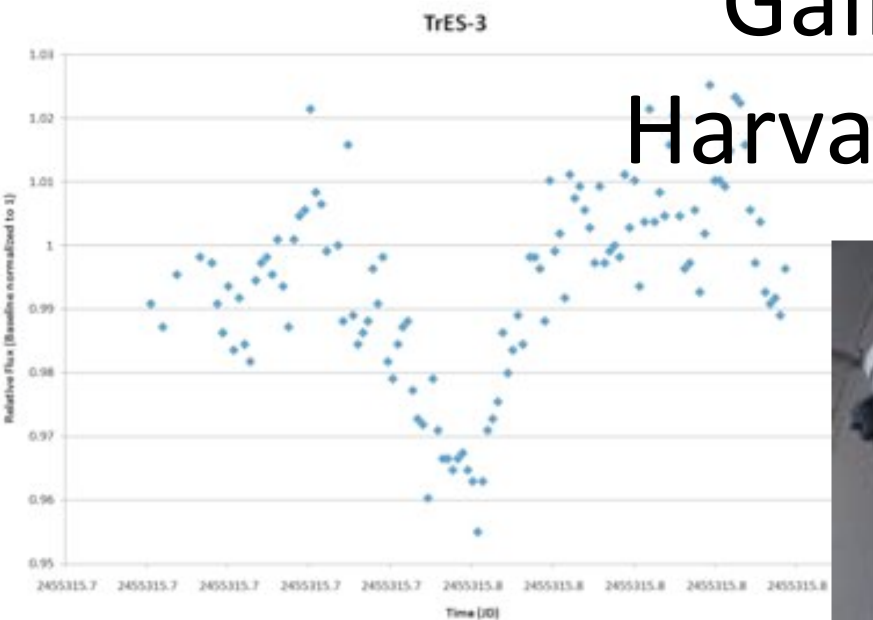
Step 3: Click Analyze --> photometry and adjust the aperture radius and annulus thickness. Check "act on all images", "use star matching" and "snap to centroid”. In photometry window, set 'mouse click tag' to 'New Ref Star’, and click on the calibration star. Type the 'ref mag' of calibration star. Change the 'mouse click tab' to 'new object’ and click on the target star.

How to Analyze the Data

Step 4: Click on the view graph plot (in the photometry window) to display a plot of the light curves. Click on 'save data' to export to an Excel compatible file.

http://iya.cfa.harvard.edu/dev/Other_Worlds_inc/index.php

Gallery of Results from Harvard Clay 16" Telescope



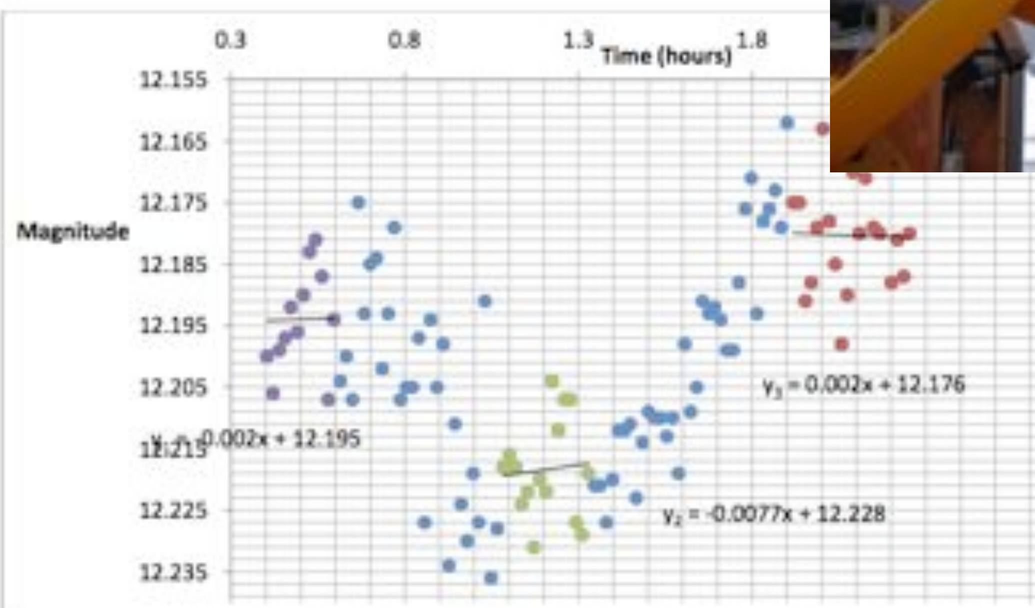
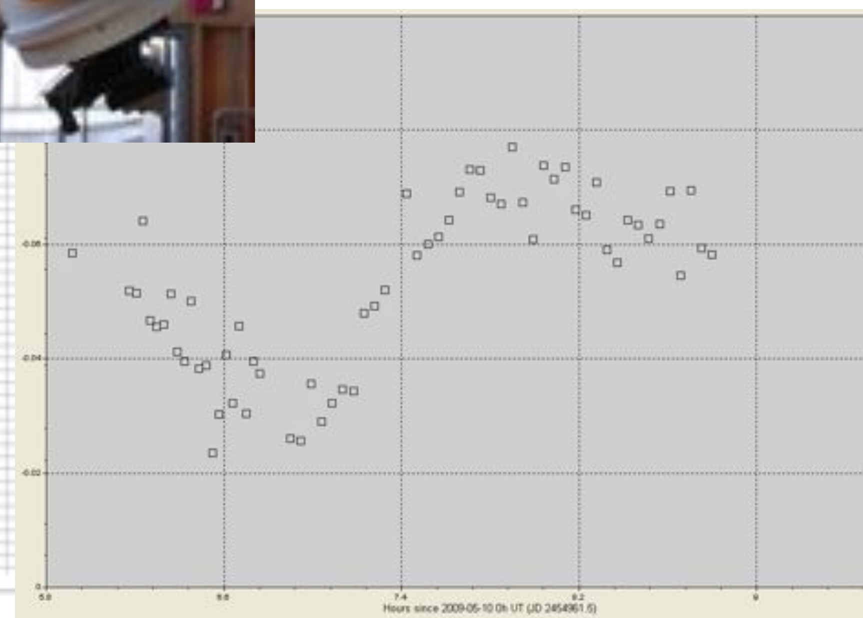


Figure 10



Undergraduate Exoplanet Lab

- I hope I have:
  - Inspired you to include an exoplanet lab in an introductory physics course
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Coming Soon: Transiting Habitable Super-Earths