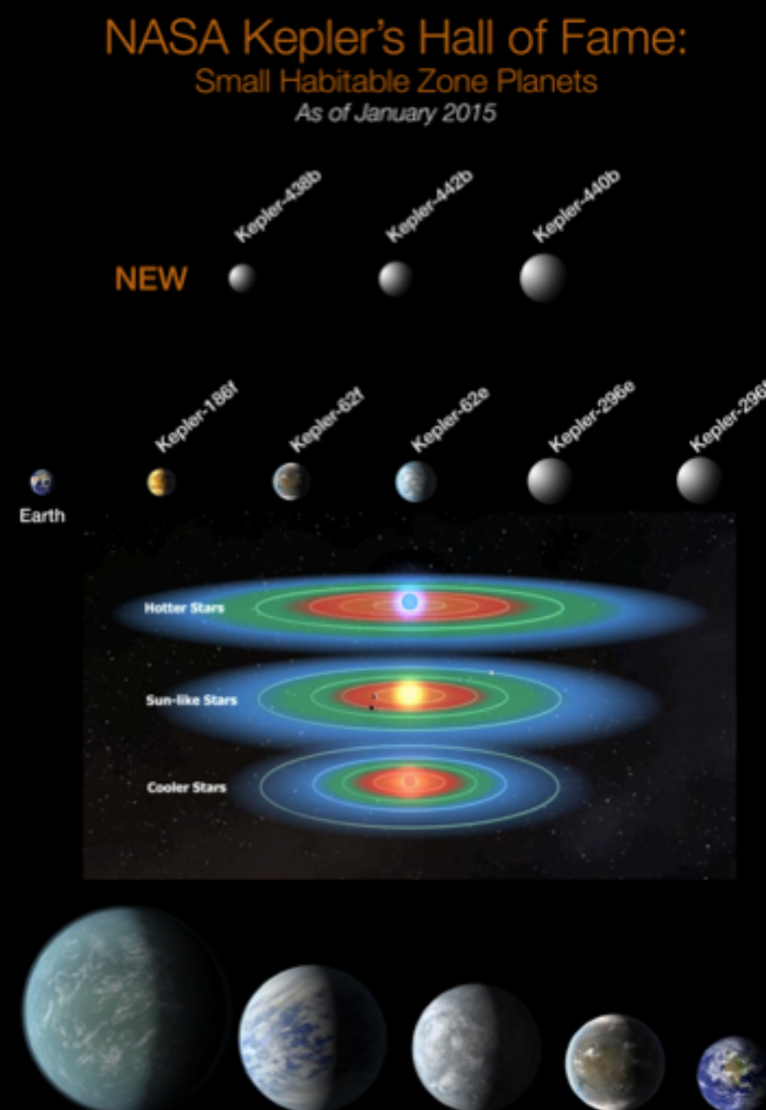
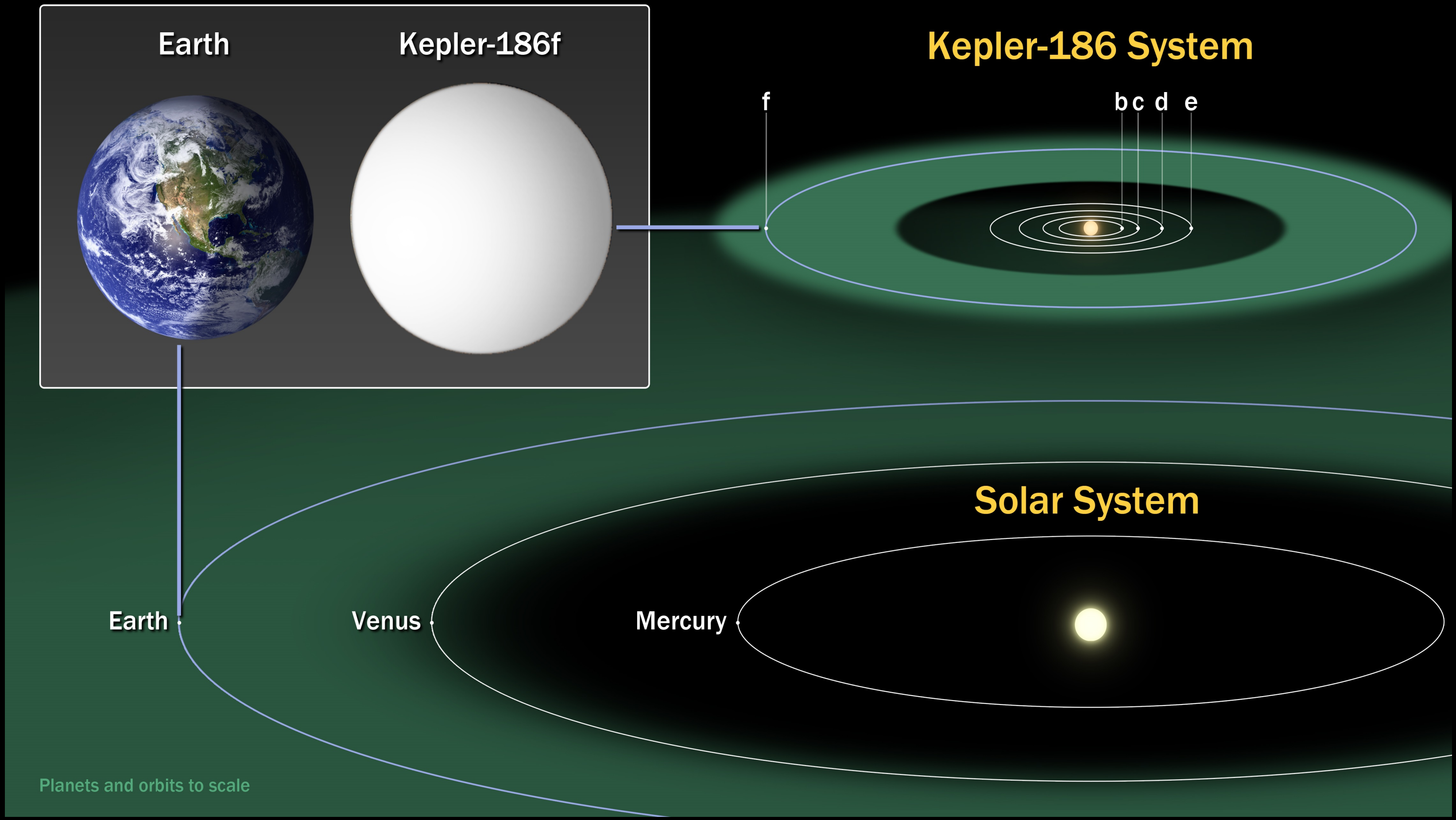
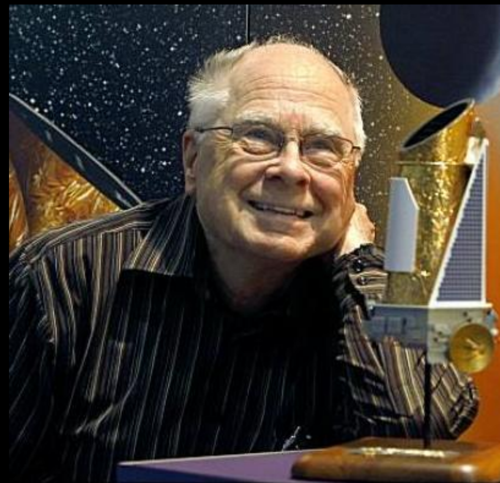
Validation and Compilation of Kepler Habitable Zone Candidates

Nader Haghighipour, Stephen Kane, Ravi Kopparapu





Kepler's core objective is to detect and characterize extrasolar planets, with special emphasis on the occurrence rate of Earth-sized planets in the HZ



Kepler HZ Working Group

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Dimitar Sasselov
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The Habitable Zone Working Group (HZWG) was created to properly vet and characterize the number of Kepler exoplanet candidates whose orbital locations and physical sizes make them prime candidates for habitability.

- Maintain a list of Kepler candidates whose orbits completely or partially enter the HZ of their host stars

- Obtain confirmation data and/or improve stellar classification to better characterize the limits of the HZ

- Perform detailed climate models where applicable for suitable candidates including (for example) the effects of water vapor, CO_2, clouds, albedo, and tides.

- Serve as a resource to people working on planet confirmation papers to provide HZ information for those systems.

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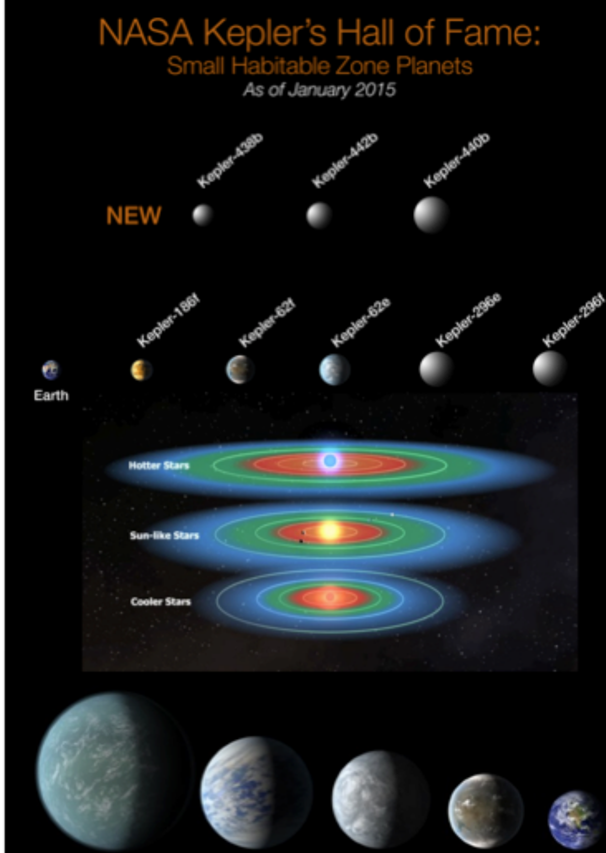


Looking for habitable planets around different types of stars (Frank Selsis)

Habitable zone (Ravi Kppparapu)

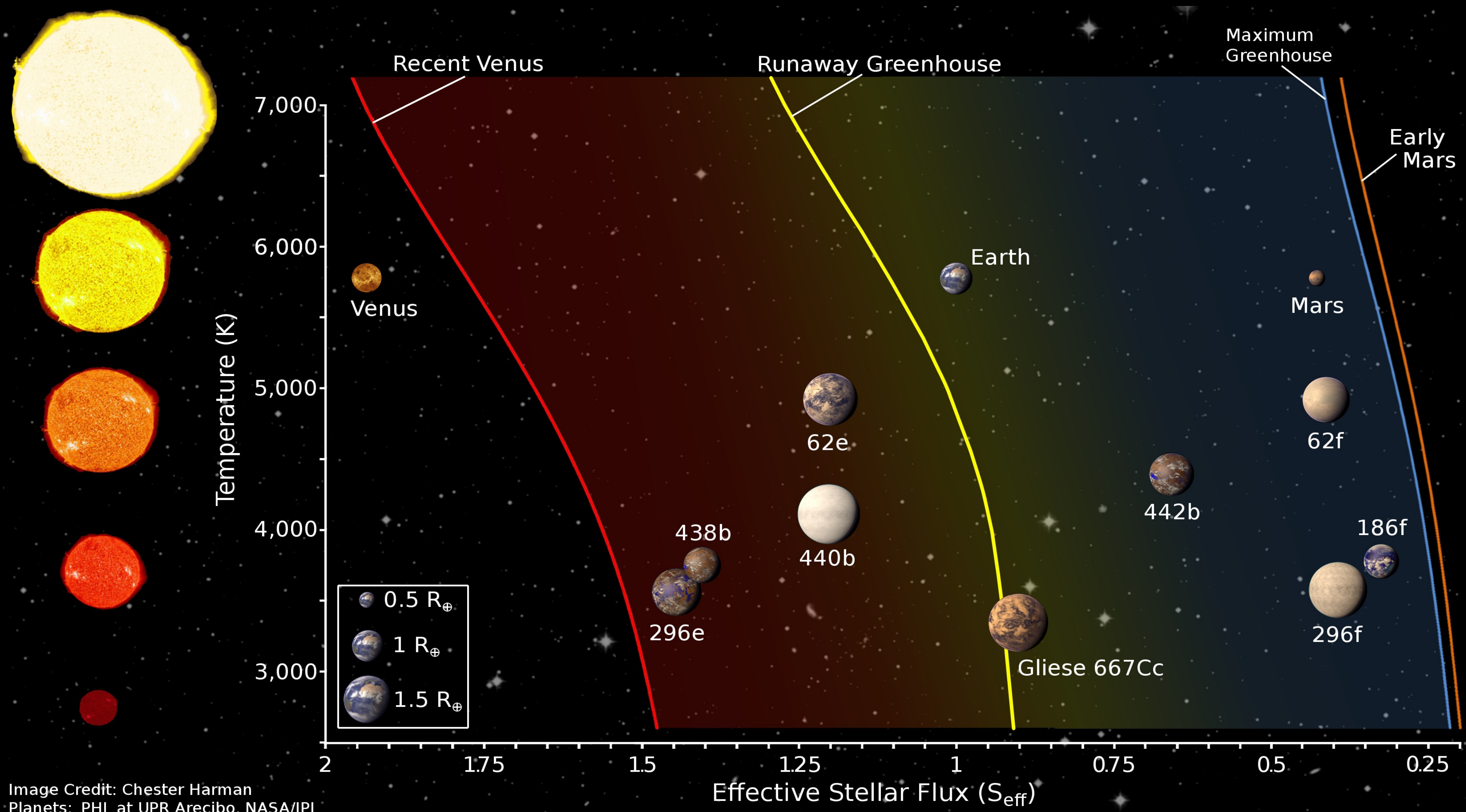
Follow-up confirmation (David Ciardi)

Validation processes (Guillermo Torres)

Habitable Zones

Estimates and Applications

Ravi Kopparapu (Penn State, Kepler HZWG)



(Kopparapu et al 2013, 2014)

Observational Habitable Zone

Region around a star where a terrestrial size/mass planet with a CO_2-H_2O-N_2 atmosphere can sustain liquid water on its surface.

It is a subset of a larger definition of “The” habitable zone where life can arise (irrespective of detectability)

Which HZ to Use?

What is the purpose?

- To calculate occurrence?

or

- to follow-up HZ planets for atmospheric characterization?

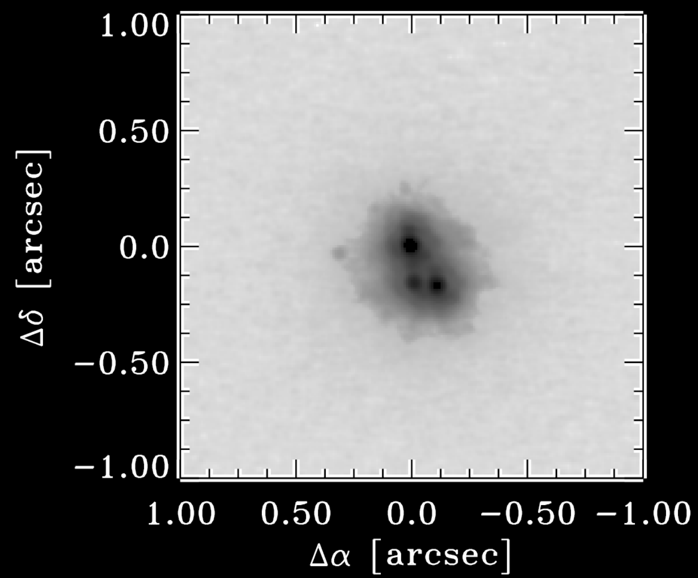
TO CALCULATE OCCURRENCE RATES

Conservative estimates of the HZs (runaway greenhouse for the inner edge, maximum greenhouse for the outer edge)

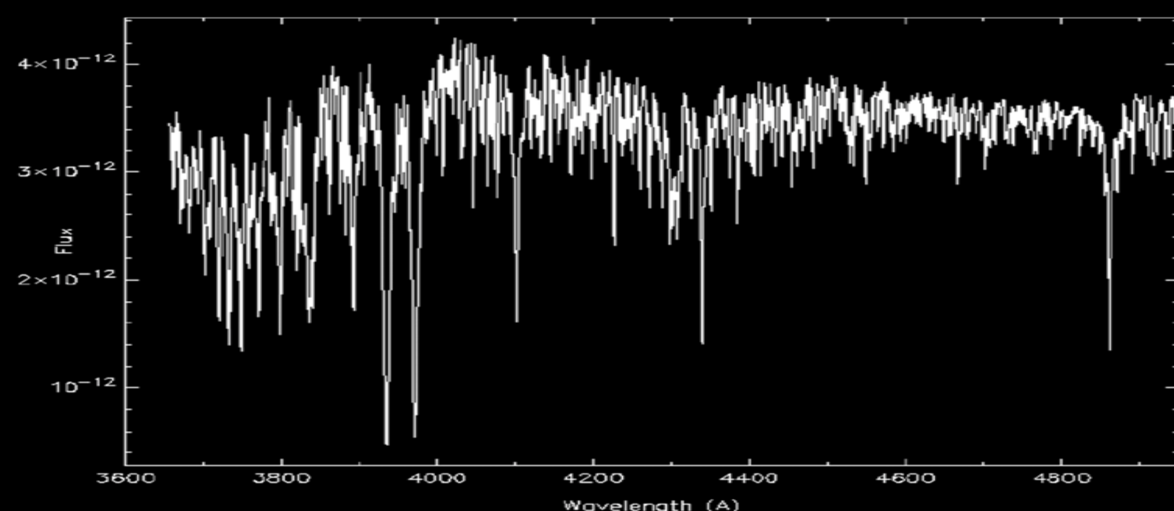
This provides a conservative estimate of “eta_Earth”,

This conservative “eta_Earth” estimate can then be used to determine the size of future direct imaging telescope.

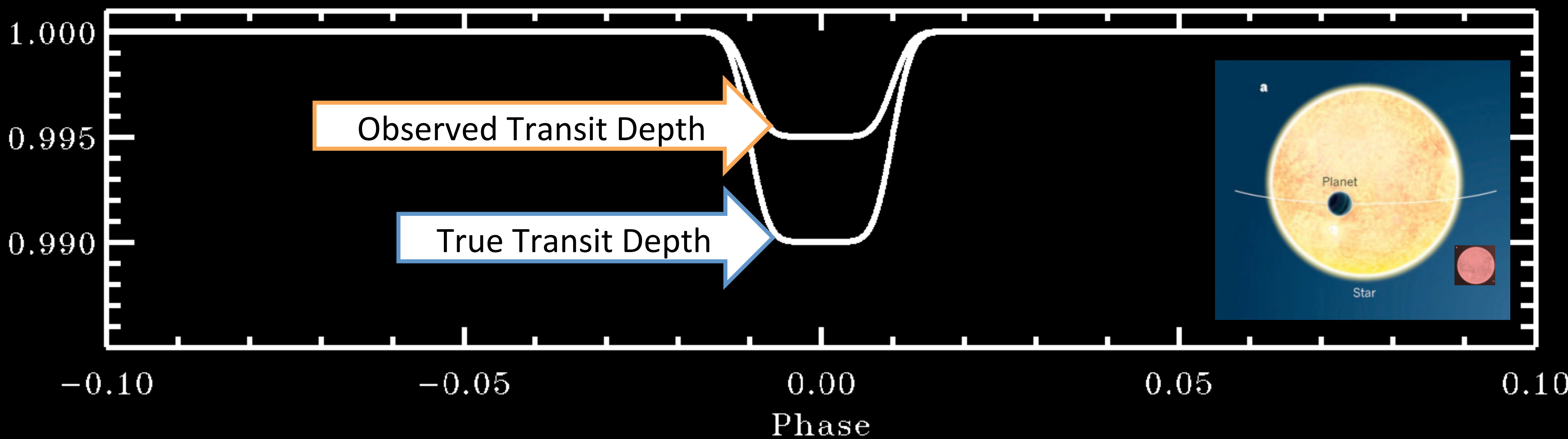
The Need for Follow-Up Observations in the Quest for Habitable Planets



David R. Ciardi
(*NExScI/Caltech*)

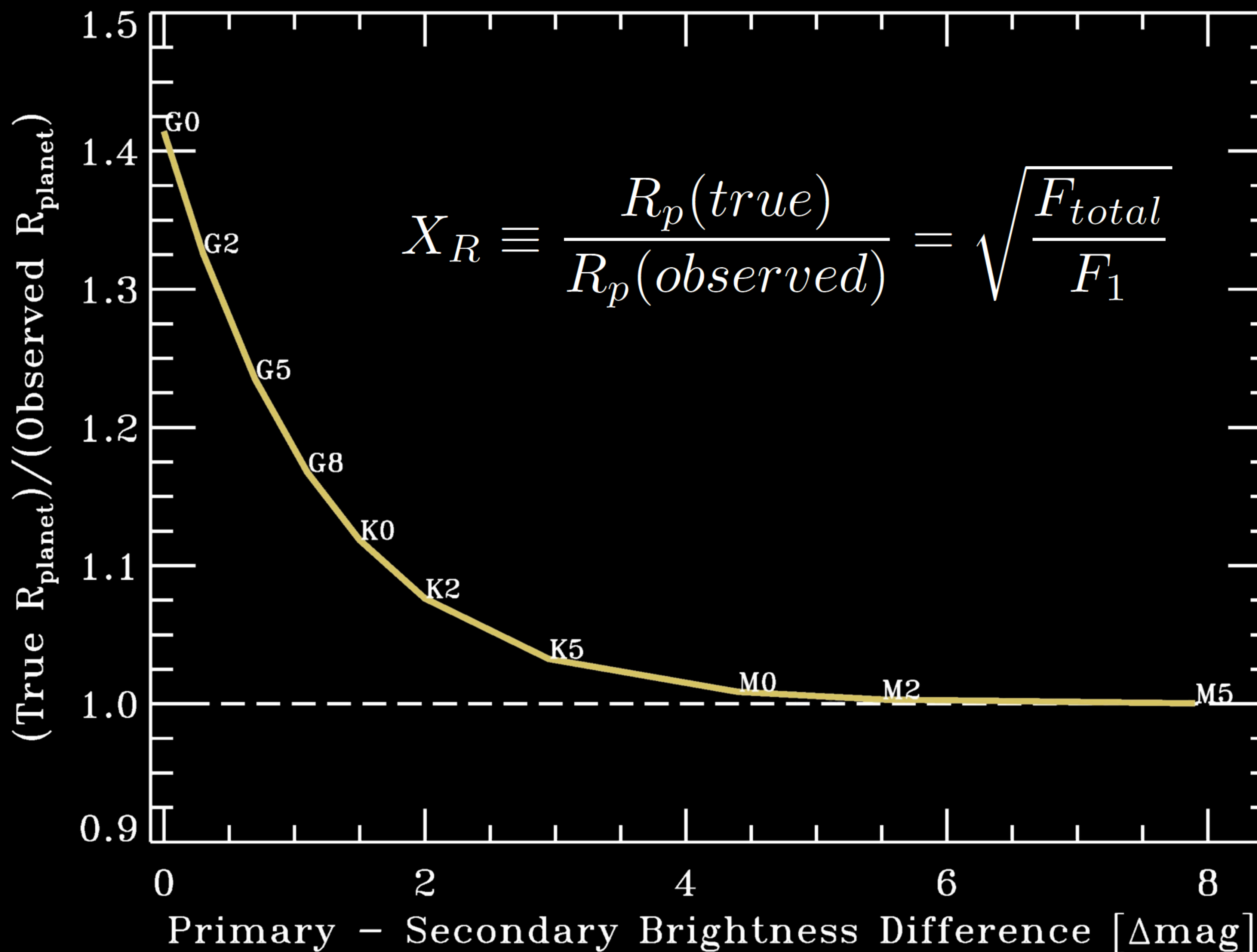


Blended Stars Can Dilute the Transit Depth



$$\delta_o = \left(\frac{F_t}{F_{total}}\right)\left(\frac{R_p}{R_{t\star}}\right)^2$$

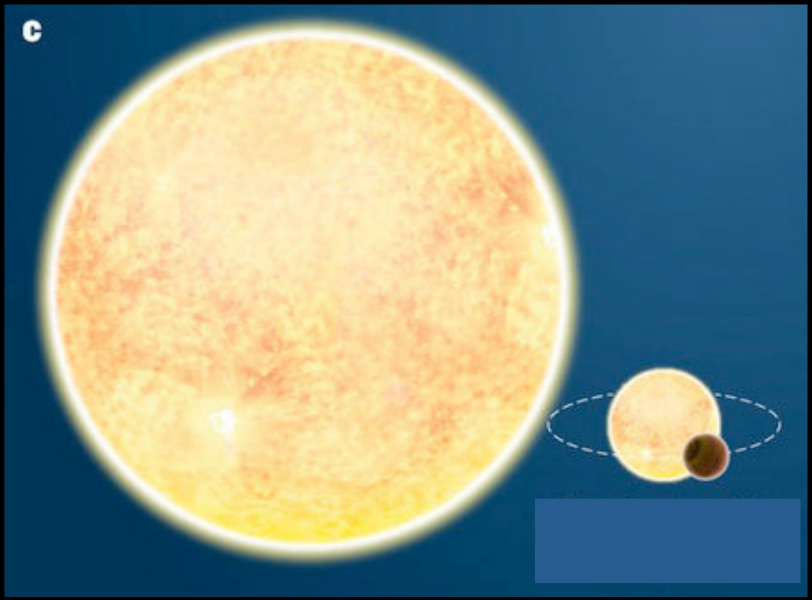
Underestimate R_p From Binary Blends



(Horch et al. 2014, Ciardi et al. 2015)

What if the planet orbits the secondary?

Need to take into account the photometric blending **AND** the radius of the secondary star



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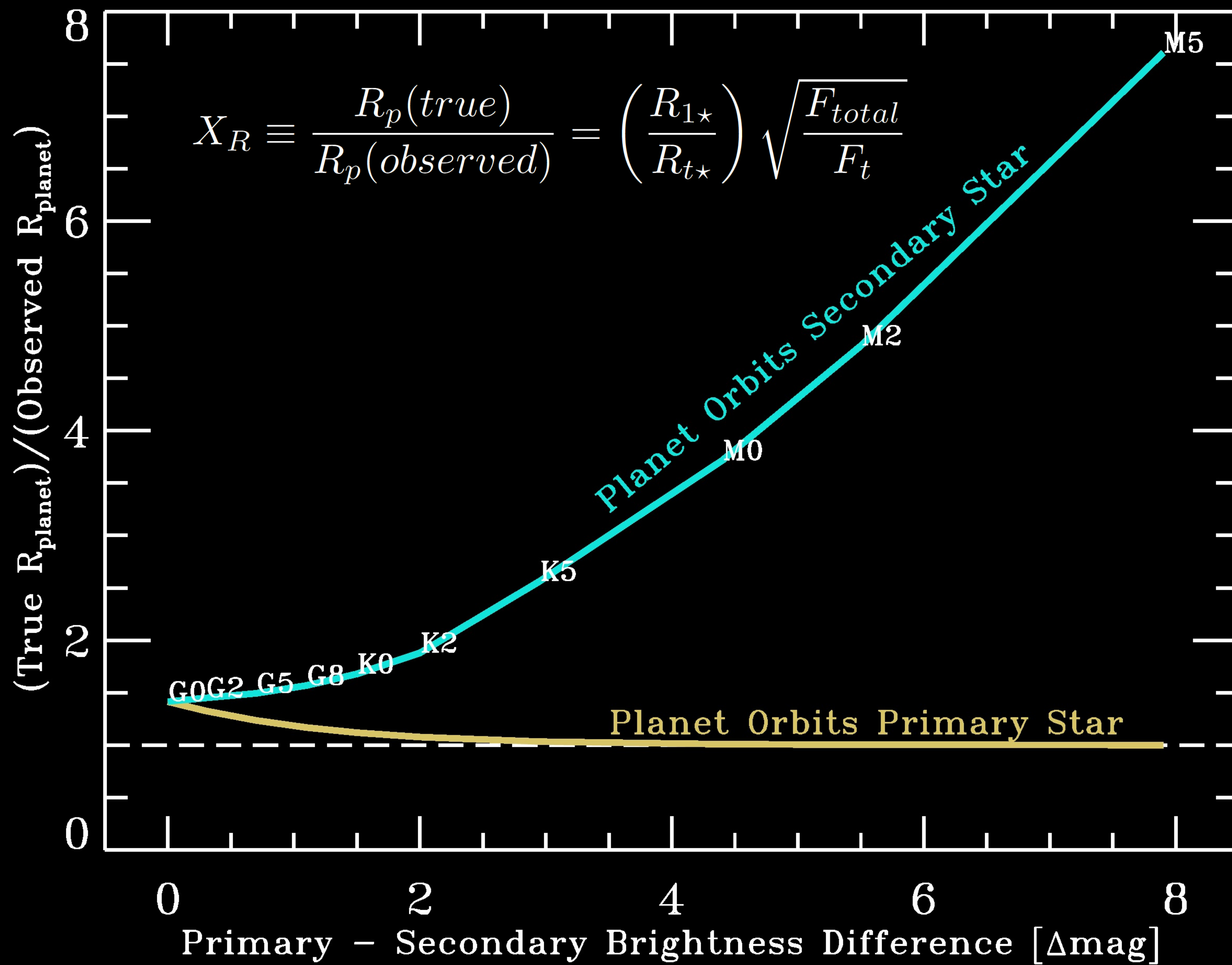
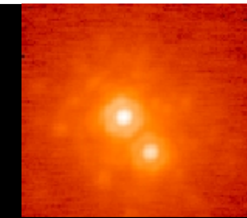
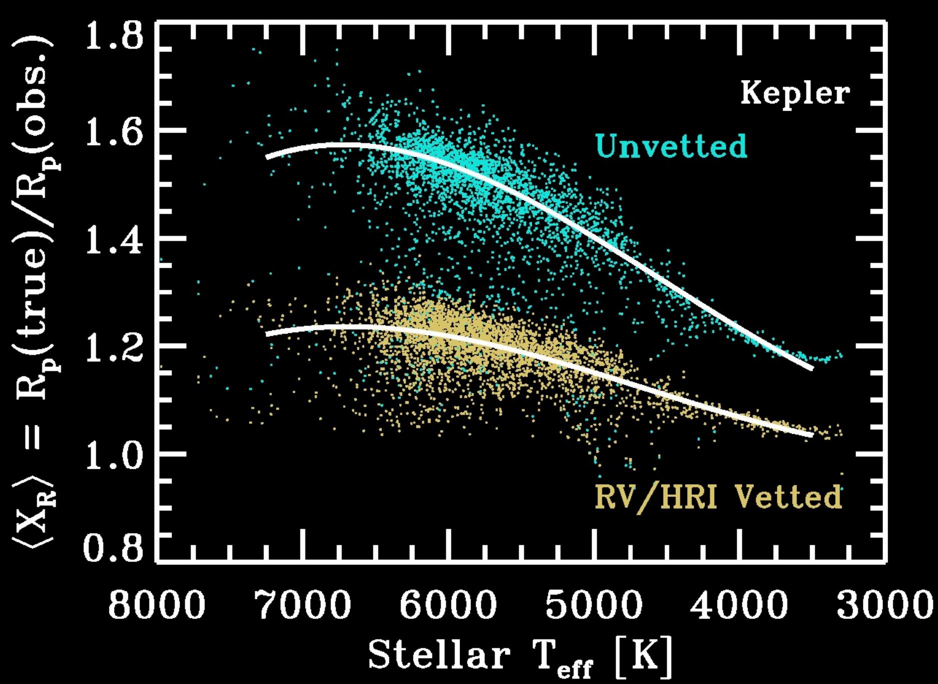


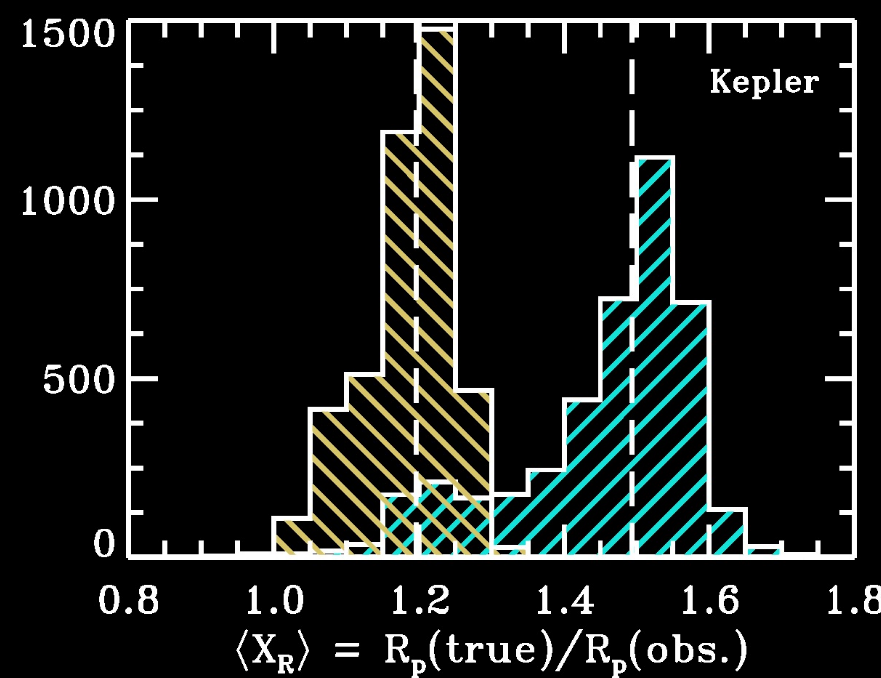
(Horch et al. 2014, Ciardi et al. 2015)

Need for follow-up observation



- KOI list assumes all stars are singles
- KOI radii may be underestimated, on average, by 1.5x but may be as much as >10x if planet orbits low-mass companion star
- Must look carefully at any one HZ candidate and understand the stellar companions that may have been missed in the follow-up observations
- Strong implications for occurrence rate estimates from KOI list

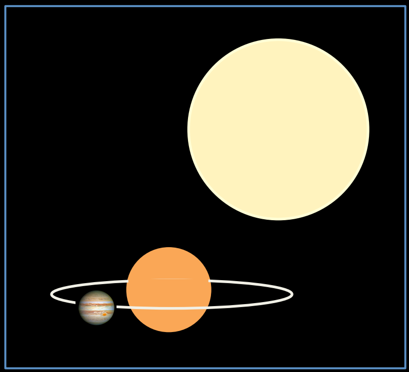




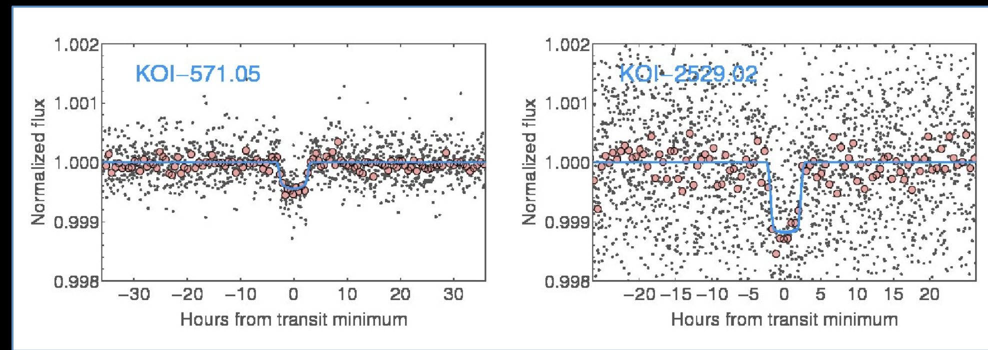
Statistical Validation of HZ Planets Techniques and Challenges

Willie Torres (*Harvard-Smithsonian Center for Astrophysics*)

- Most common types of false positives (blends)
  - Background/foreground eclipsing binaries
  - Physically associated eclipsing binaries
  - Unseen background/foreground stars with a (larger) transiting planet
  - Physically associated star with a transiting planet



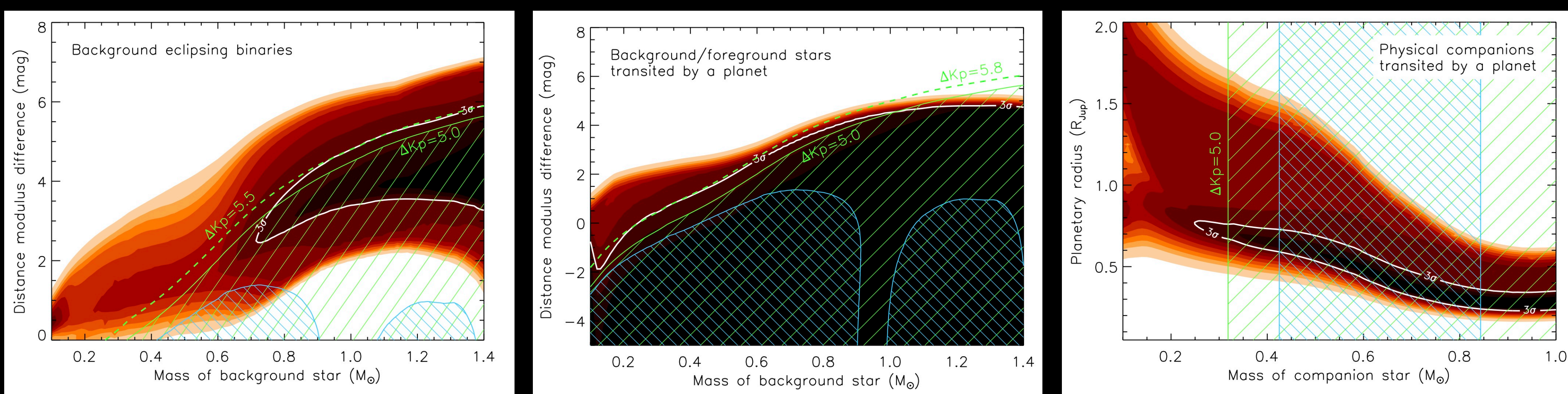
- Information used to rule out or quantify blends
  - Shape of the transit curve (depth, overall duration, slope of ingress/egress)



  - Known frequencies of eclipsing binaries and planets around other stars
  - Number density of stars in the vicinity of the target
  - Follow-up observations: high-resolution imaging, spectroscopy (optical, NIR), colors, flux centroid motion
- Stellar characterization
  - M dwarfs are more difficult (T_{eff}, log g, [Fe/H])
  - Close stellar companions complicate matters

BLENDER Validations

- Simulate large numbers of blends of different types spanning entire parameter space
- Rule out as many as possible using the transit shape information, flux centroid motion analysis, and follow-up observations



Results

Blend Frequencies, Planet Priors, Odds Ratios, and Significance Level of the Validation for Our Targets

Candidate	HTP	BP	BEB	PL	Odds Ratio	Significance	PL_{comp}	$\mathcal{P}$[targ]
KOI-0571.05	1.15×10^{-6}	1.32×10^{-7}	6.60×10^{-8}	2.15×10^{-3}	1595	99.94%	...	...
KOI-1422.04	7.75×10^{-7}	4.74×10^{-8}	1.28×10^{-8}	3.19×10^{-4}	382	99.74%	5.94×10^{-4}	78.4%
KOI-1422.05	4.49×10^{-7}	4.84×10^{-8}	1.29×10^{-8}	4.63×10^{-4}	907	99.89%	7.25×10^{-5}	86.5%
KOI-2529.02	3.24×10^{-6}	2.17×10^{-9}	5.55×10^{-9}	1.31×10^{-3}	403	99.75%	5.61×10^{-6}	99.6%
KOI-3255.01	4.29×10^{-7}	4.79×10^{-11}	...	4.91×10^{-4}	1144	99.91%	4.39×10^{-4}	52.8%
KOI-3284.01	6.71×10^{-7}	1.10×10^{-9}	9.27×10^{-10}	1.57×10^{-3}	2333	99.96%	8.02×10^{-4}	66.2%
KOI-4005.01	3.71×10^{-7}	...	...	6.61×10^{-4}	1782	99.94%	...	...
KOI-4087.01	1.34×10^{-7}	...	...	1.32×10^{-4}	985	99.90%	...	...
KOI-4427.01	2.23×10^{-6}	1.07×10^{-9}	1.39×10^{-10}	2.62×10^{-4}	117	99.16%	...	...
KOI-4622.01	9.98×10^{-8}	3.82×10^{-10}	6.68×10^{-12}	2.08×10^{-3}	20761	99.99%	...	...
KOI-4742.01	1.37×10^{-6}	4.89×10^{-10}	5.45×10^{-12}	1.26×10^{-3}	919	99.89%	...	...
KOI-4745.01	1.53×10^{-6}	1.41×10^{-9}	9.19×10^{-12}	2.85×10^{-3}	1861	99.95%	...	...

Notes. For several of the candidates the blend frequencies for the BP and/or BEB scenarios are negligible and are not listed. For the four targets with close companions PL_{comp} is the planet prior assuming the planet transits the close companion, and $\mathcal{P}$[targ] the probability that the planet transits the target rather than the companion.

Planet probability (“prior”)

Background/foreground eclipsing binaries

Background/foreground stars transited by a planet

Physically associated stars transited by a planet (dominant contribution)

False Positives and Validation

- Validation of small HZ planet candidates can be challenging, and typically requires using all of the information at our disposal to be successful
  - Detailed shape of the transit signal
  - Constraints from follow-up observations
  - Known statistics of eclipsing binaries and of planets (from *Kepler*, or Doppler surveys if necessary)
- Physical companion stars transited by a (larger) planet must be considered as a viable false positive scenario, and such blends tend to dominate over other types of false positives

Kepler HZWG: Current Update

Assembling the best HZ candidates from the latest sample of KOIs using a variety of criteria (e.g., the conservative vs optimistic HZ, larger vs smaller than $2R_E$ planet radius to takes into account stellar uncertainties in the KOI sample). The $\sim 1.6R_E$ criteria will be used after follow-up data have been applied to the stellar properties.

Follow-up data are being systematically used to vet the candidates. False-alarm statistics is also being used. This will enable us to examine the most interesting cases using Willie Torres' blender algorithm.

The final product is a paper and tables of candidates that will be presented to the community for further study. Feedback will be requested from the community as to what additional information we can provide to aid in climate models and/or follow-up observations.