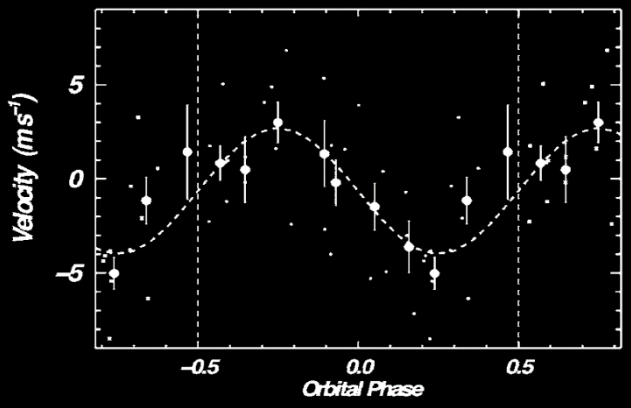
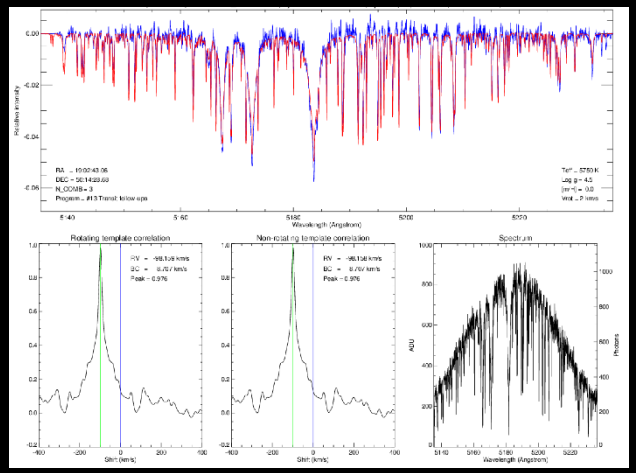
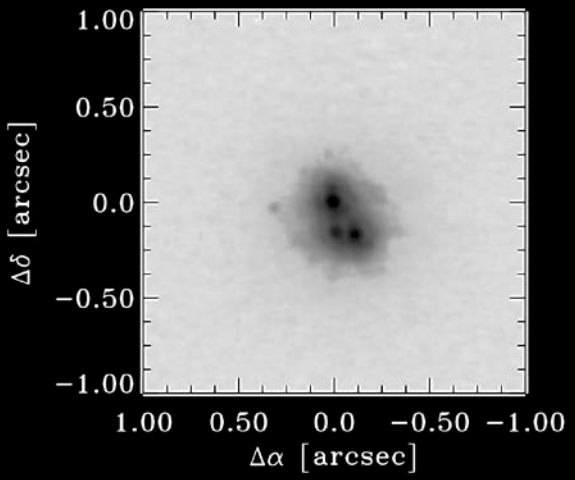
Lessons Learned from the Kepler/K2 Follow-Up Observation Programs: *Leading to TESS … and now PLATO*







David R. Ciardi
Caltech-NASA Exoplanet Science Institute
07 Sep 2017

A Tale of Two Follow-Up Programs

- Kepler
  - Project produced light curves and planetary candidates
  - Small, dedicated project funded follow-up program
  - Community contributions
- K2
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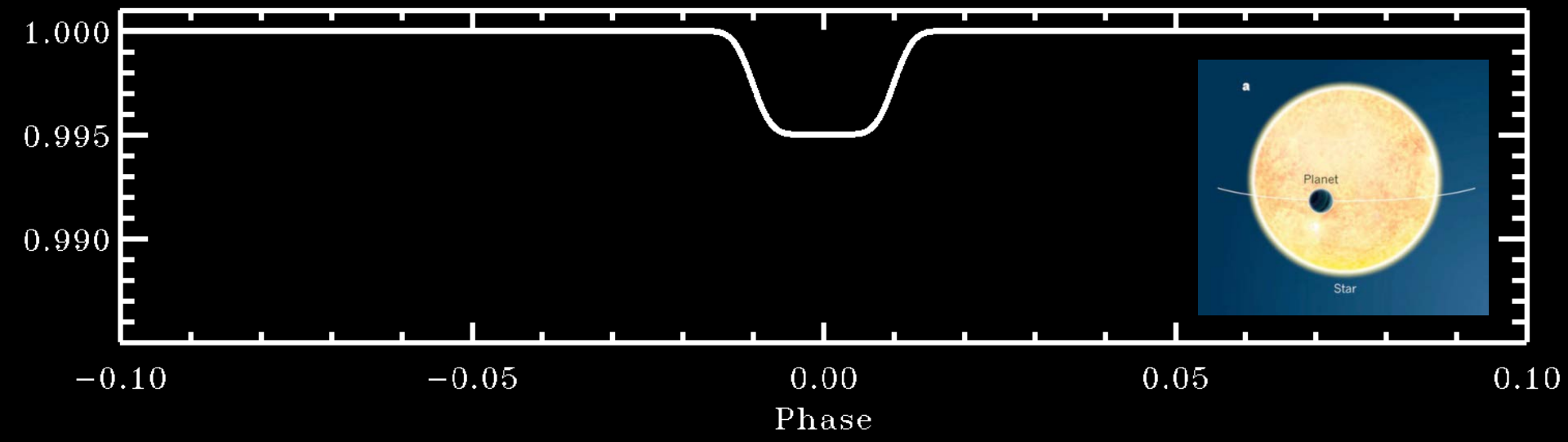
  - No funded project follow-up program
  - Only community driven observations

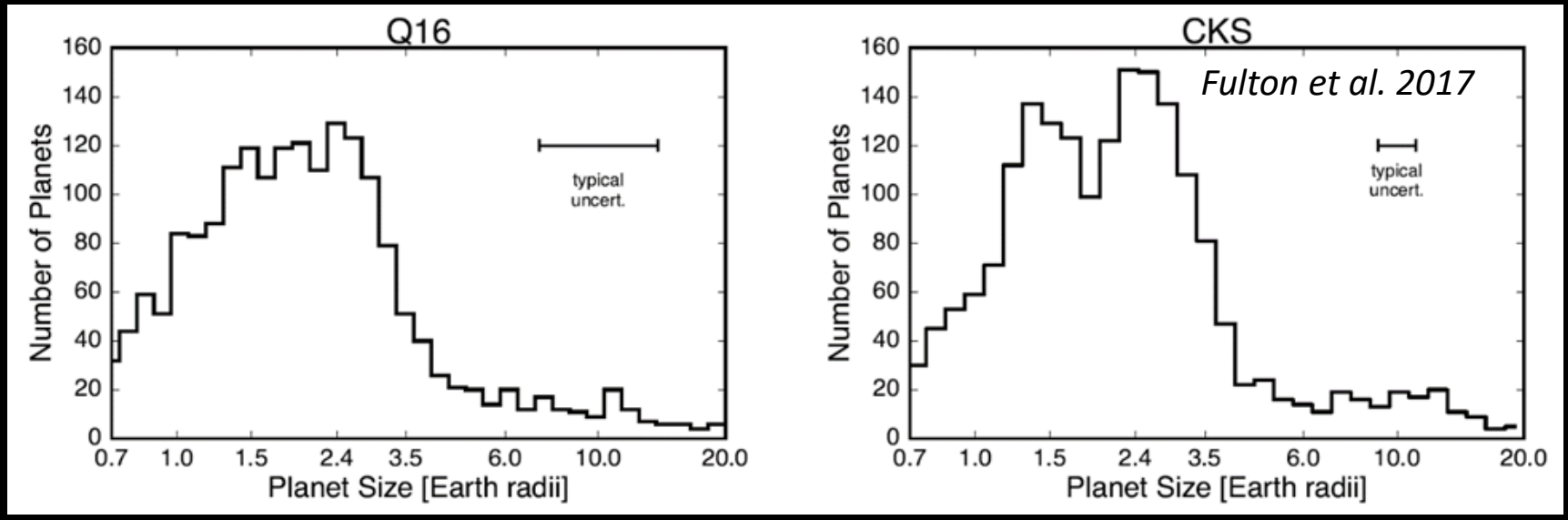
Transits: The Need for Follow-Up



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

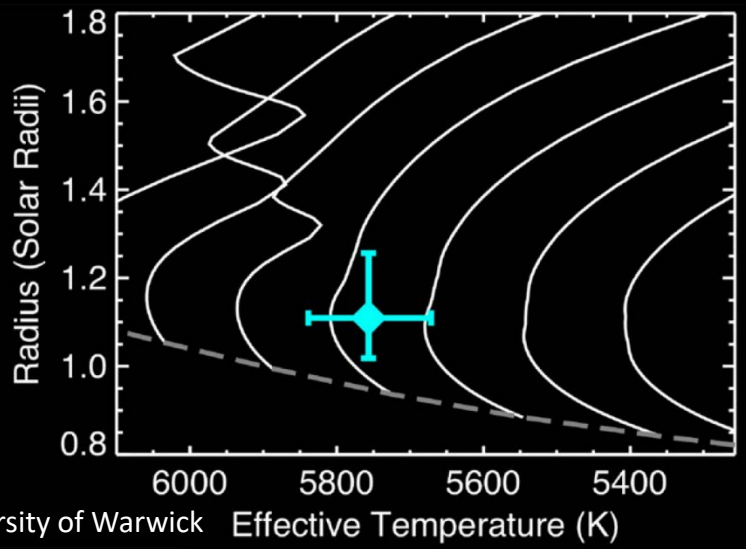
Importance of Good Stellar RadII

- Gap in planet distribution hidden in original distribution

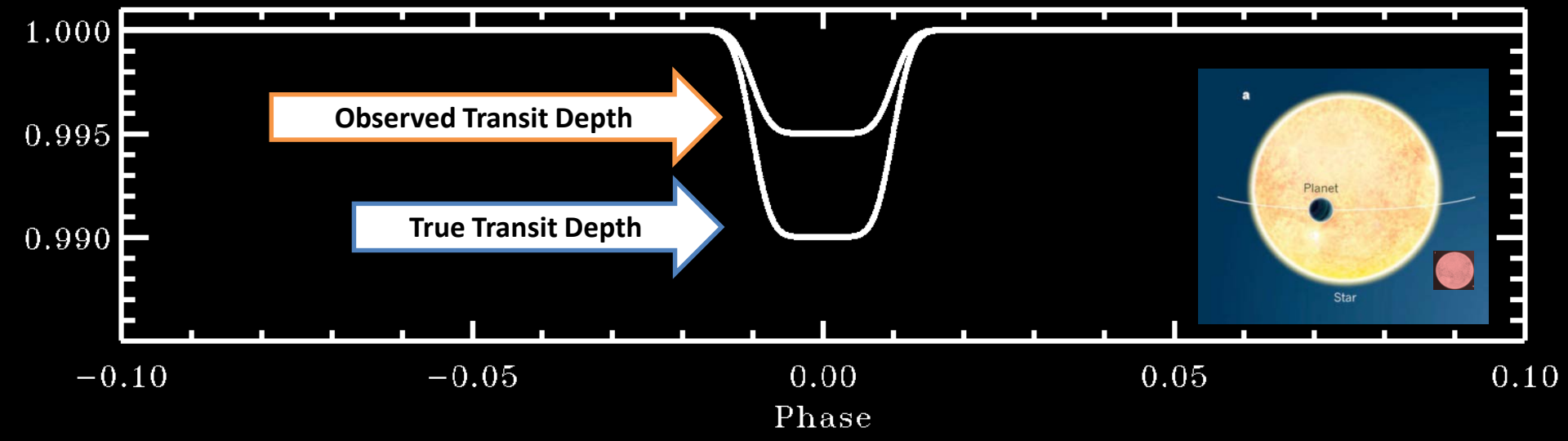


Jenkins et al. 2015

- Kepler 452b
  - Original KOI Parameters
    - $R_* = 0.75\ R_{sun}$
    - $R_p = 1.1\ R_{earth}$
  - After Keck
    - $R_* = 1.1\ R_{sun}$
    - $R_p = 1.6\ R_{earth}$

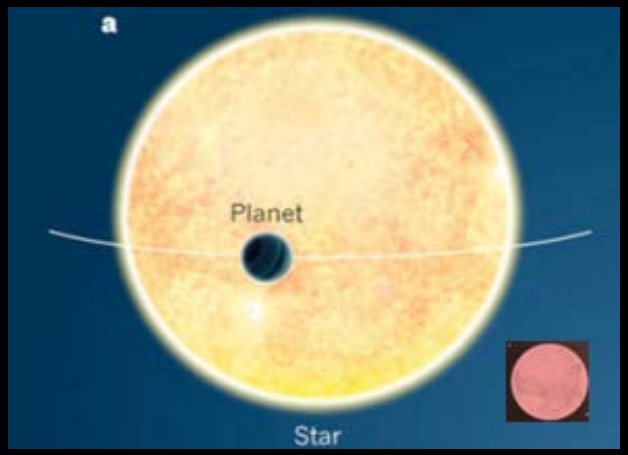


But, It's More Complicated …

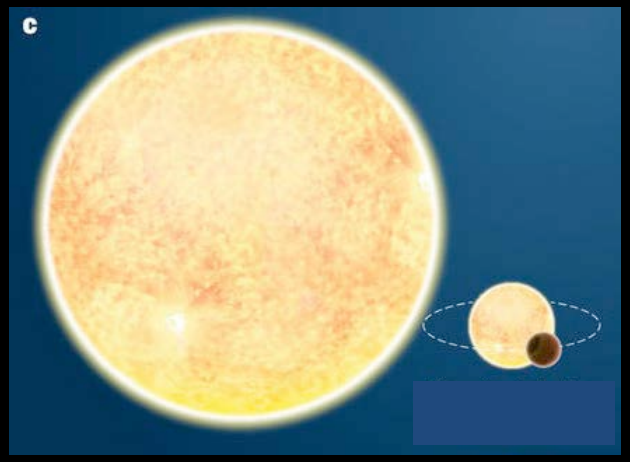


$$\delta_o = \left(\frac{F_t}{F_{total}}\right)\left(\frac{R_p}{R_{t\star}}\right)^2$$

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



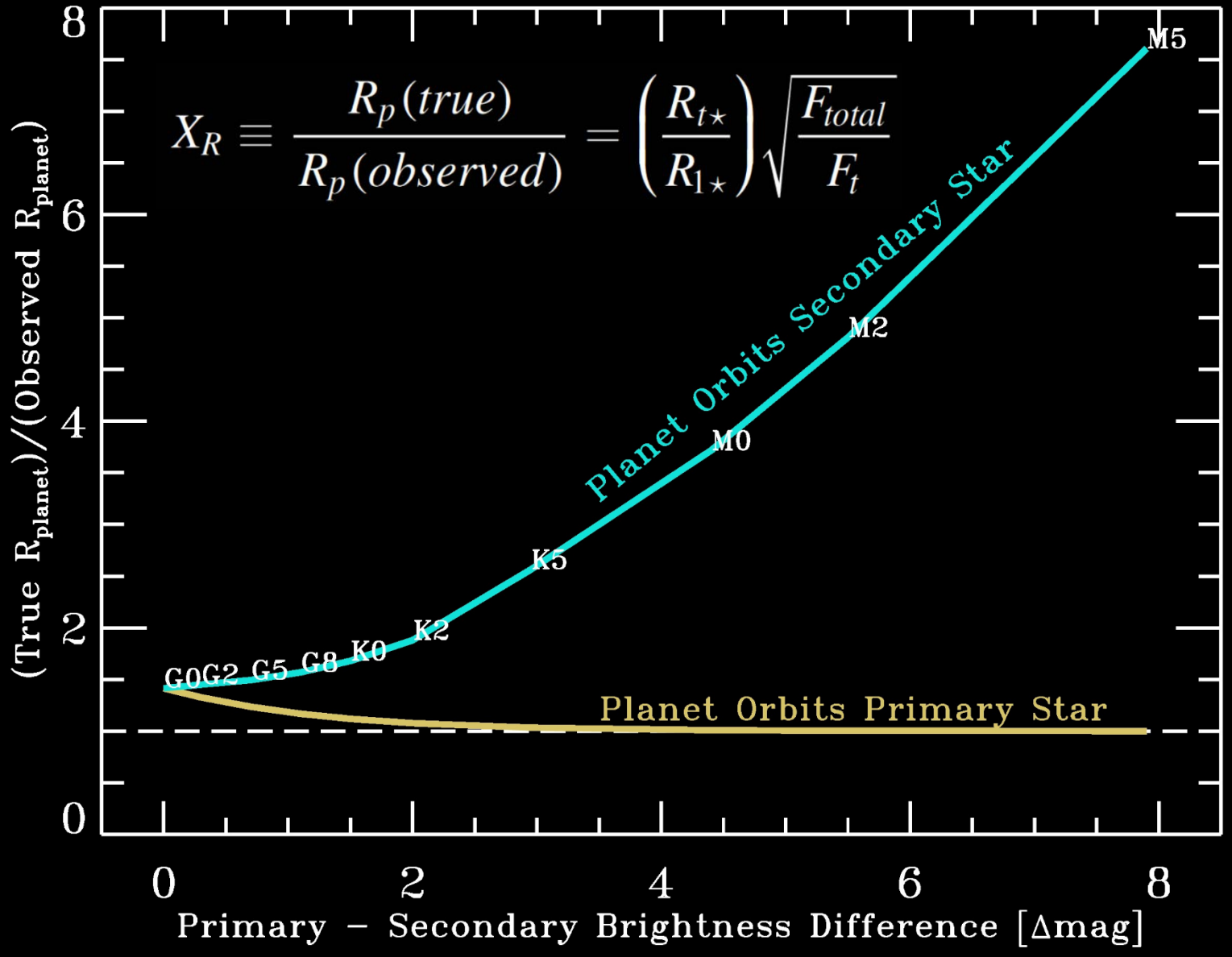
or



What if the planet orbits the companion?

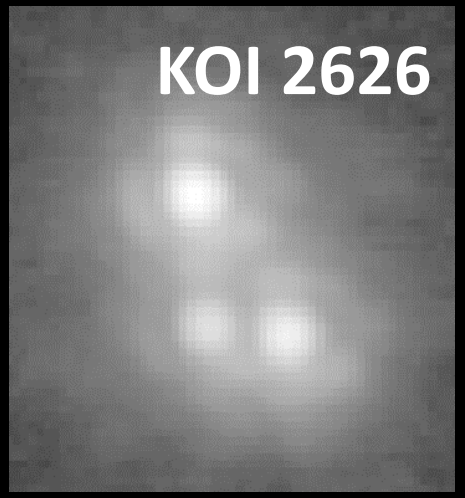
$$\delta_o = \left(\frac{F_t}{F_{total}}\right)\left(\frac{R_p}{R_{t\star}}\right)^2$$

What if the planet orbits the secondary?



KOI2626 – From HZ Earth-sized Planet to Not

- Single stars assumed in the KOI list
- Need follow-up to determine if there are stellar companions
- If there is a stellar companion, which star does the planet orbit?
- If there no stellar companion is detected, what fraction of companions were missed?

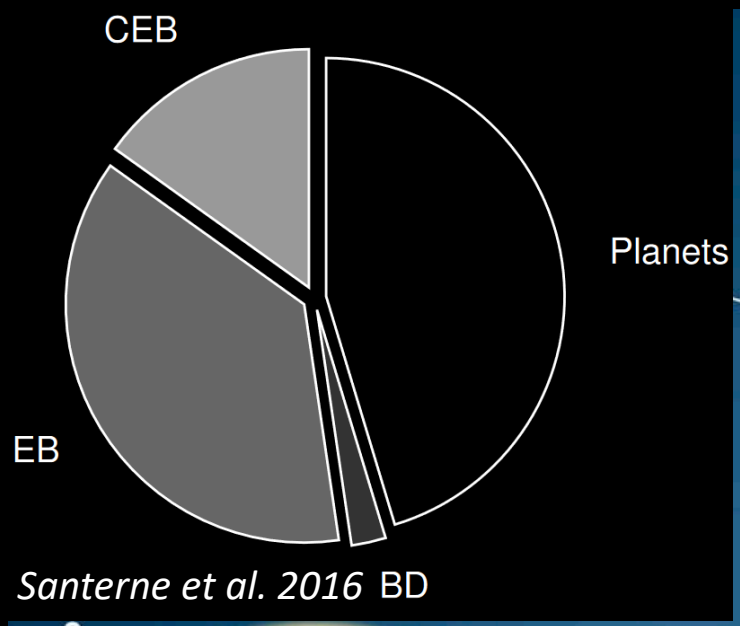


Cartier et al. 2015

	Stellar Temperature and Radius	Planet Radius	Equilibrium Temperature
KOI List: Single Star	3480 K 0.35 R_{Sun}	1.12+/-0.16 Re	229 K (0.7 S_0)
Component A	3650 K 0.48 R_{sun}	2.04+/-0.33 Re	265 K (1.17 S_0)
Component B	3520 K 0.42 R_{sun}	2.37+/-0.44 Re	244 K (0.84 S_0)
Component C	3400 K 0.32 R_{Sun}	2.58+/-0.62 Re	217 K (0.52 S_0)

And False Positives Make it Even More Complicated

Giant planet false positive rate ~50%



Santerne et al. 2016

Kepler Follow-Up Observation Program

- At first …
  - Find the planets
  - Vet and characterize the planets
  - Spectroscopy, 2-point RV at quadrature, High resolution imaging
  - Publish the discovery papers
- And then …
  - It became apparent that there were thousands of planets – it was like nothing the community had ever seen before!
  - Concentrated on systems with small planets
  - Shifted our efforts to systematically vet and characterize the stellar hosts
  - Abandoned the 2-point RV at quadrature
  - Made all follow-up data available to the public on exofop website (exofop.ipac.caltech.edu)

- Dedicated Kepler-funded program from 2009 to 2015
- 5 small groups within the funded FOP
- 11 different telescopes: over >3000 nights collectively among the team

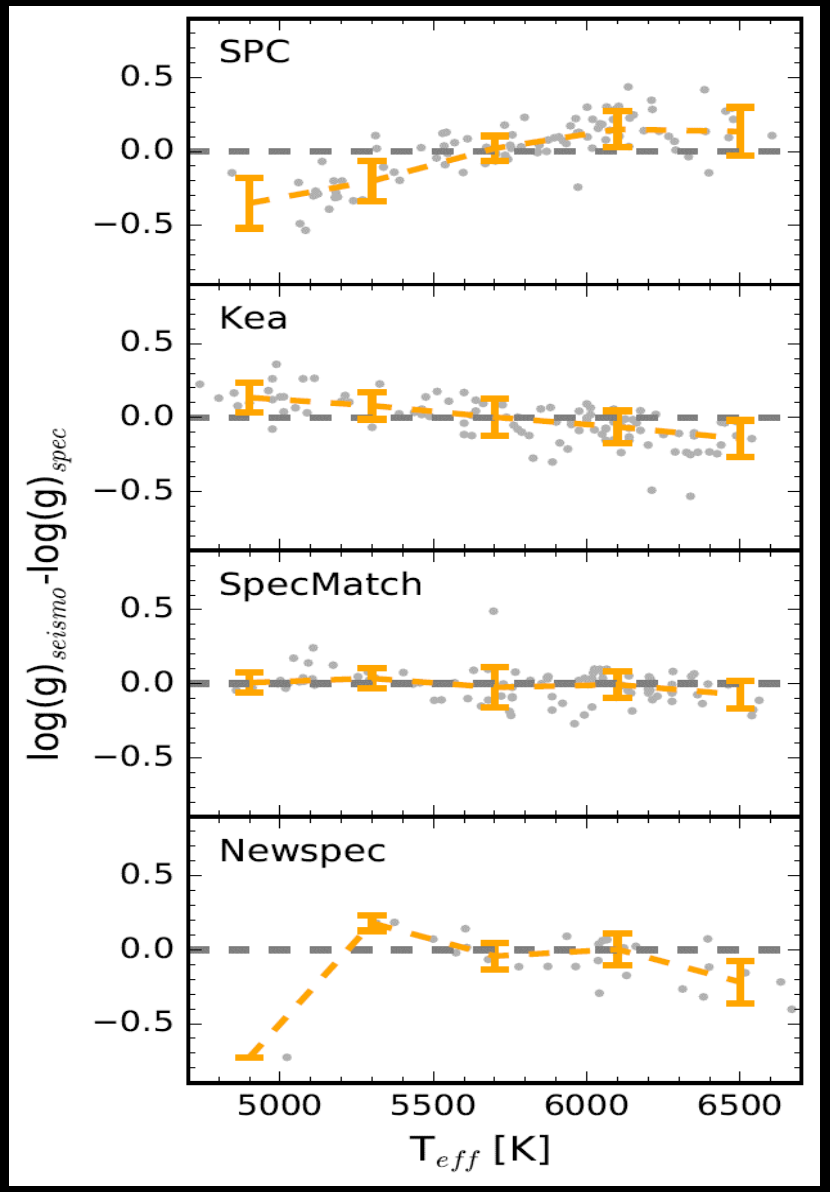
And Plenty Of Community contributions

- Unfunded Community Members who just did stuff (too many to list!)
  - Spectroscopy
  - Radial velocity
  - Imaging
  - Astereoseismology
  - TTVs
  - Etc …
- Groups contributed their data to the effort and often worked with the funded team
- This was all enabled because the candidates were made available to the public!

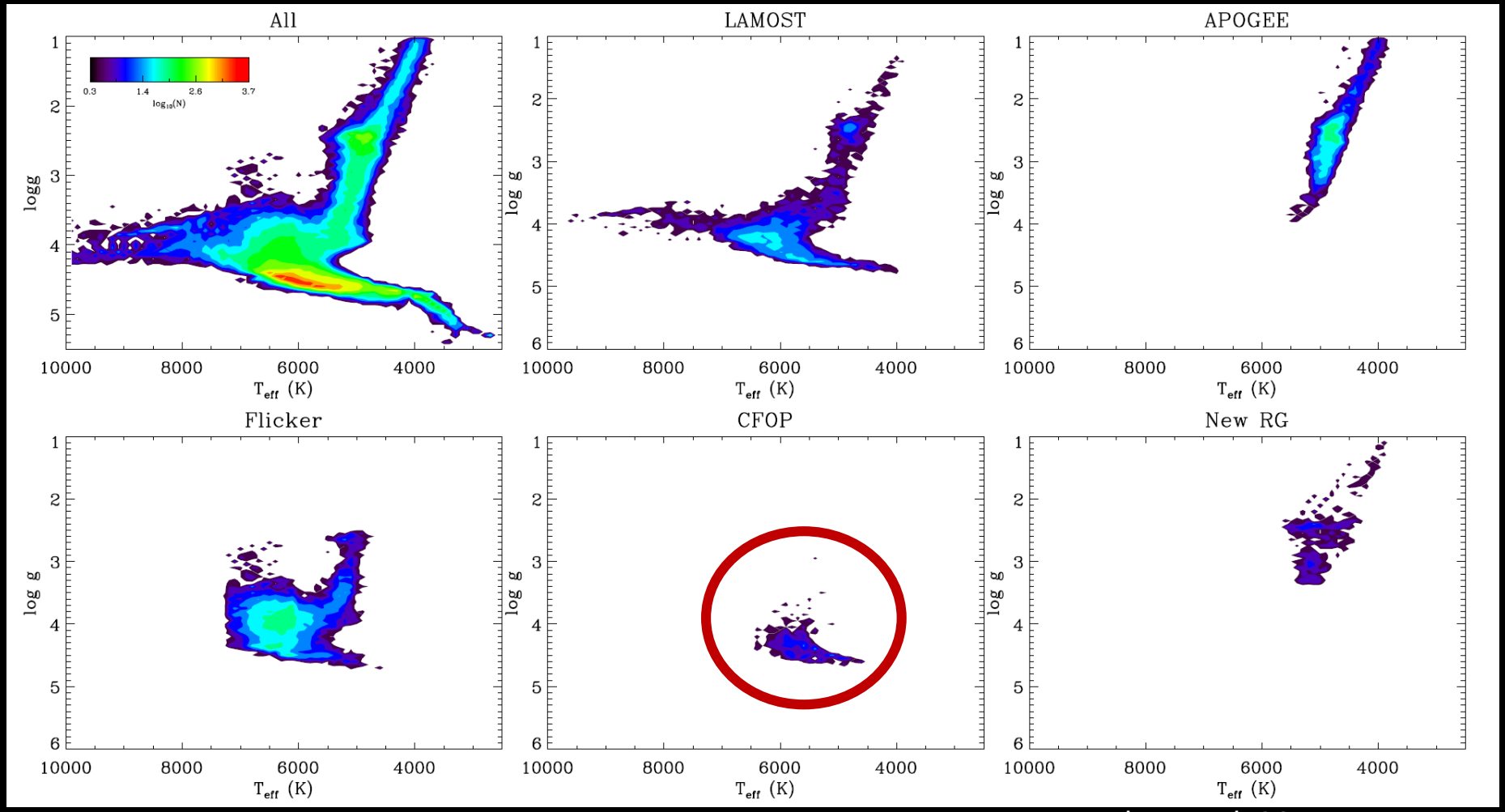
FOP: Spectroscopy

Furlan, Ciardi, et al. in prep

- Made a concerted effort to observe as many of the KOIs as possible in a uniform manner
- ~60% of the KOIs were observed
- 615 common set of “standards” with parameters from seismology to connect the different facilities
  - Characterized differences and limitations of different datasets
- What is truth ?



We still needed the Community

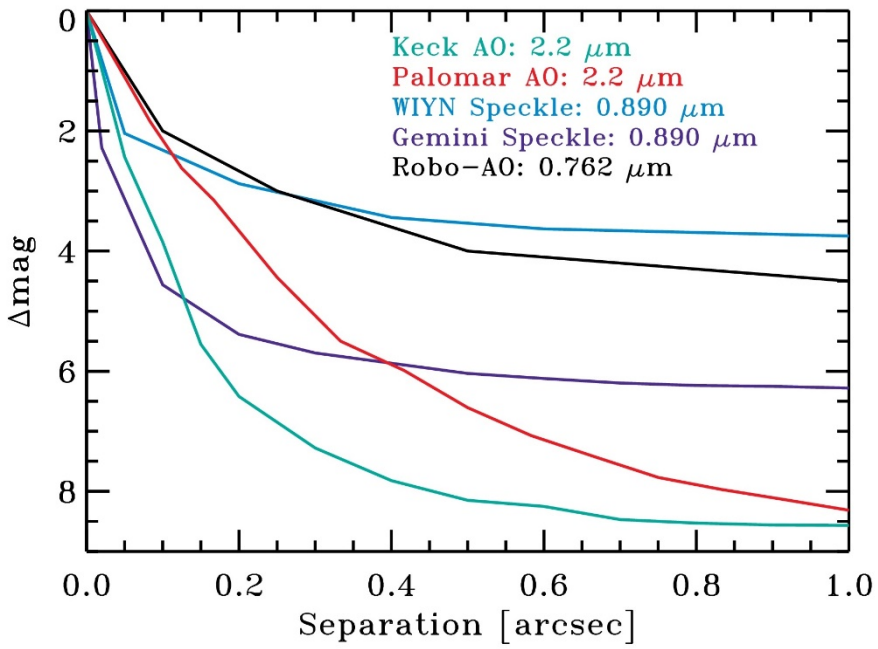


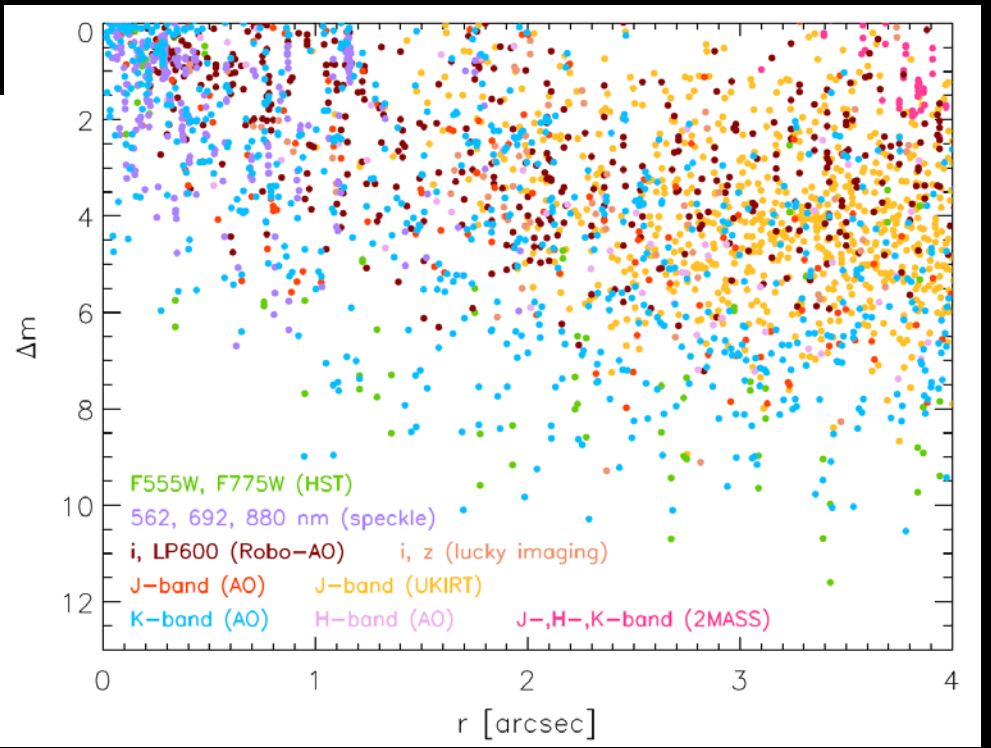
Mathur et al. 2017

FOP: Imaging

- Made a concerted effort to observe as many of the KOIs as possible in a uniform manner
- ~90% of the KOIs were observed
- Combined different techniques and wavelengths (e.g., NIR AO, Optical AO, Optical Speckle, Optical Lucky Imaging)
- Direct contributions from outside non-funded community members

Furlan, Ciardi, et al. 2017





Some Important Lessons from the Kepler Follow-Up Program (IMHO)

- Allowing public access to the KOIs enabled the community to contribute so that "all" of the KOIs could be observed
- There is no strict order to the observations since we get time on telescopes when we get it
  - Imaging and spectroscopy are equally important
  - Precision radial velocities are the exception
- Take time to understand how to combine data from different telescopes/instruments: a common set of observations are crucial
- Data collection is not enough! Reduce, analyze, and share data!!!
- More observations are better as long as the observations are not exactly duplicating (don't do same star with same facility)
- Lots of communication
  - Meetings (virtual and real) !!!
  - Everyone knew what was going on so everyone understood the priorities
  - Web environment to share data/results (exofop.ipac.caltech.edu)
- Never underestimate the ability of nature to trick you

A Tale of Two Follow-Up Programs

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  - Only community driven planet finding and follow-up observations

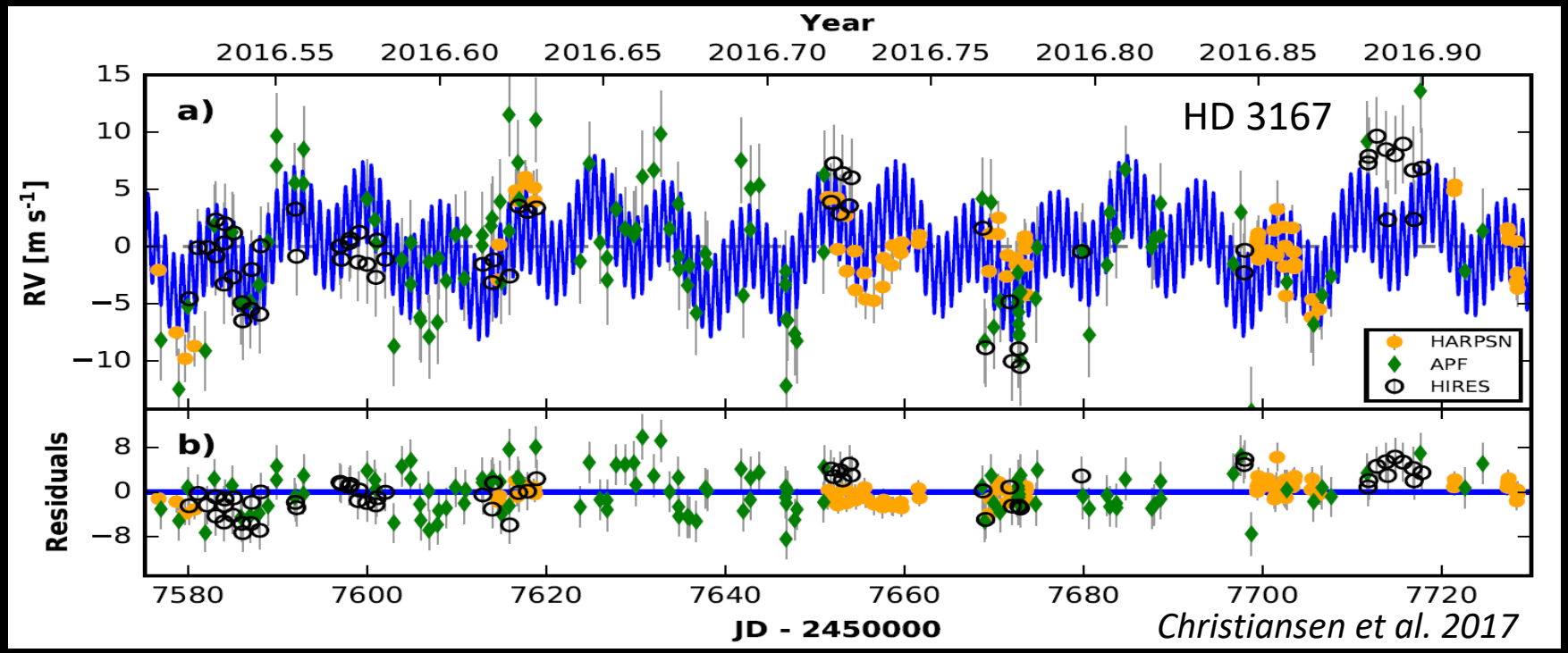
K2: The Wild West …

- Unlike Kepler mission, there were no project light curves and no planetary candidates for K2
- There is no funded or coordinated follow-up program organized by NASA or the project
- Community self-organized into loose collaborations with some overlap – and much competition!

K2: The Wild West …

- After the first year, competitive groups started to merge and work together
- Groups began to share data on the exofop website
- There is still much overlap and lack of communication between competitive groups … and duplication of resources
- But it is getting better …

K2: The Wild West …



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- Groups began to share data on the exofop website
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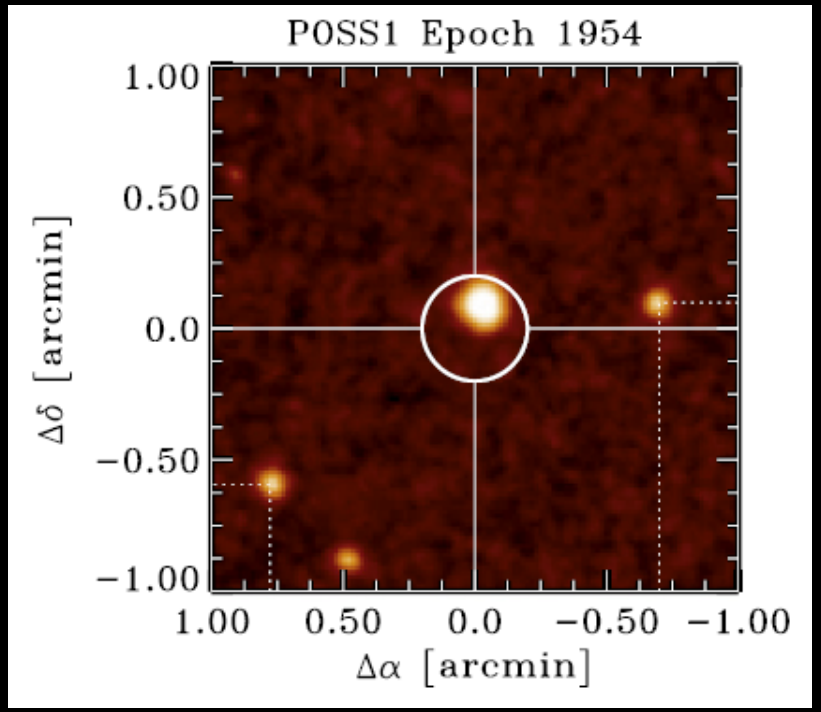
- But it is getting better …

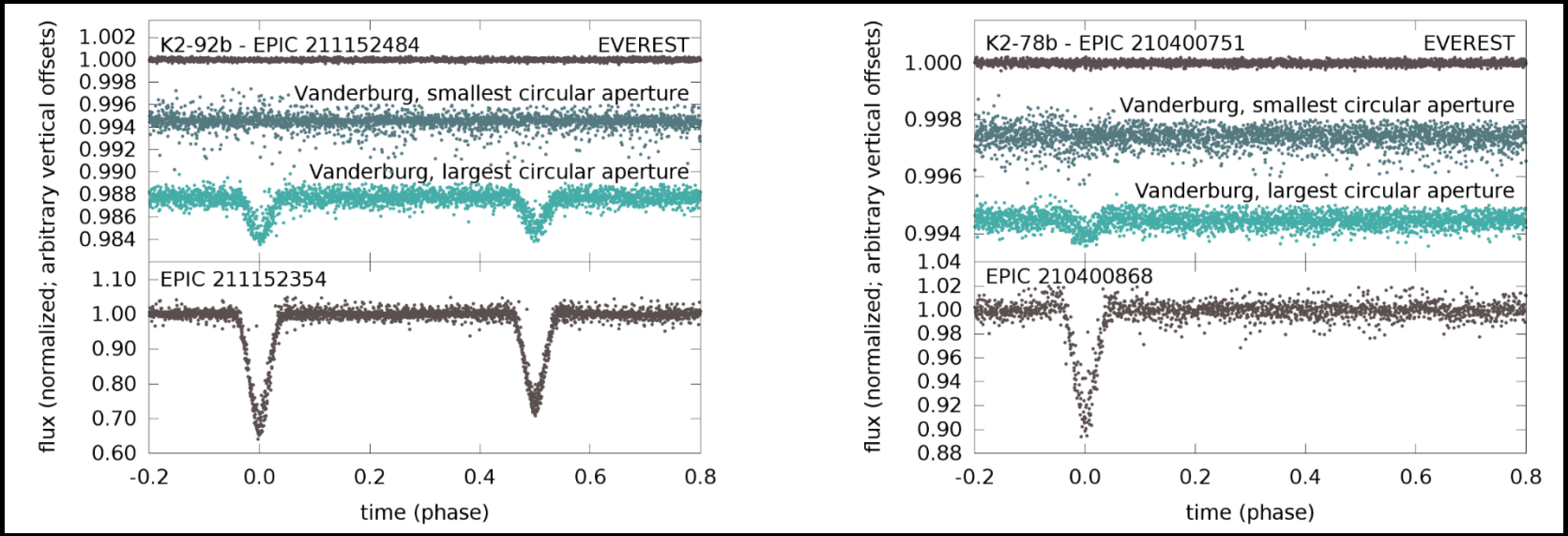
K2's Brighter Stars

- Enables small telescope observations
  - Seeing-limited images and (on-off) time-series (remember CoRoT!!)
  - Spectroscopy on a larger number of telescopes
- Stars are typically closer – significant proper motion to search for companions and background stars
- Seismology
- Gaia!!! (soon)

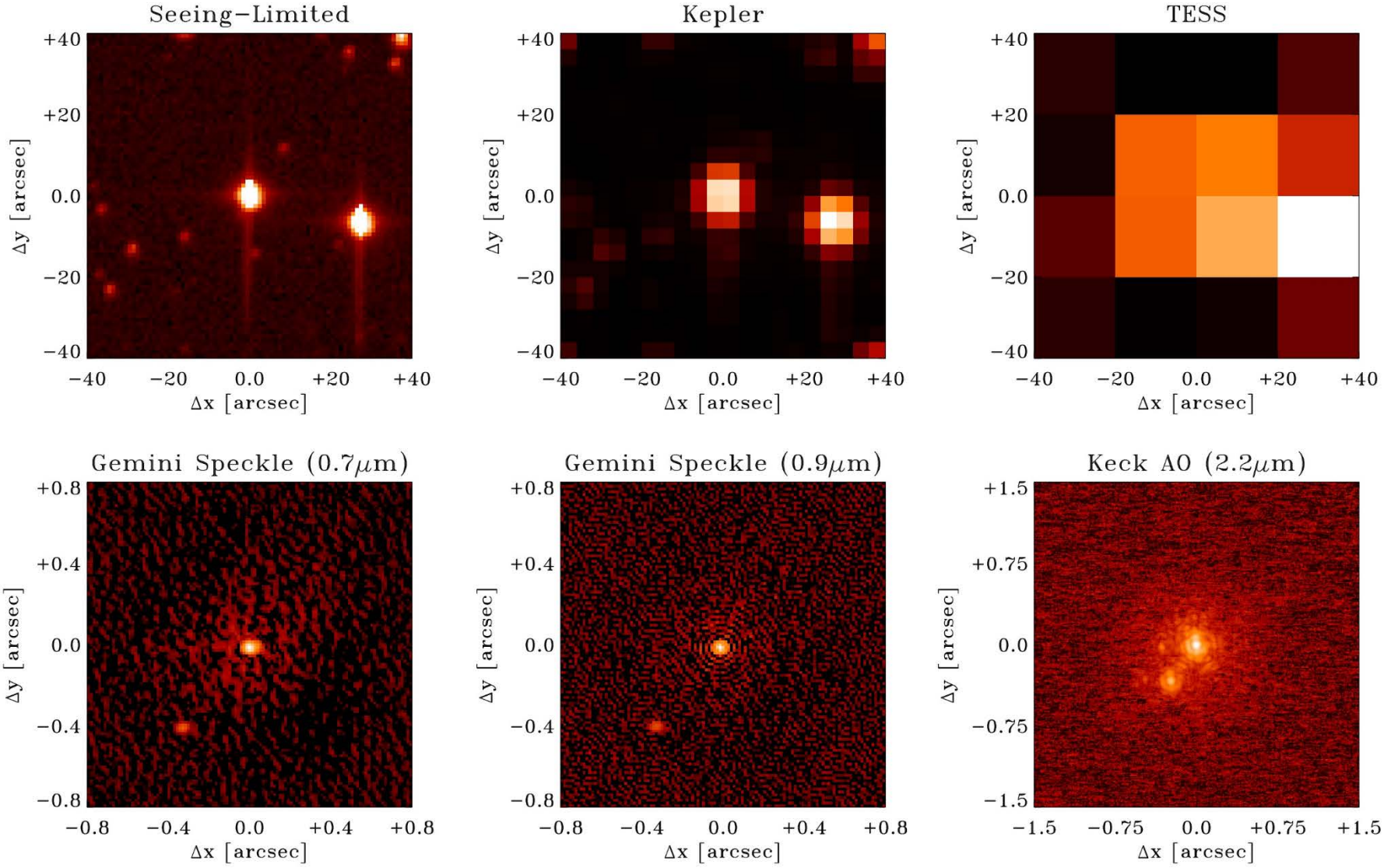


However, sometimes …

- … no matter how careful you think you are, you can still be wrong (J. Cabrera's talk yesterday)
- Bring all your resources to bear!!!



Cabrera et al. 2017

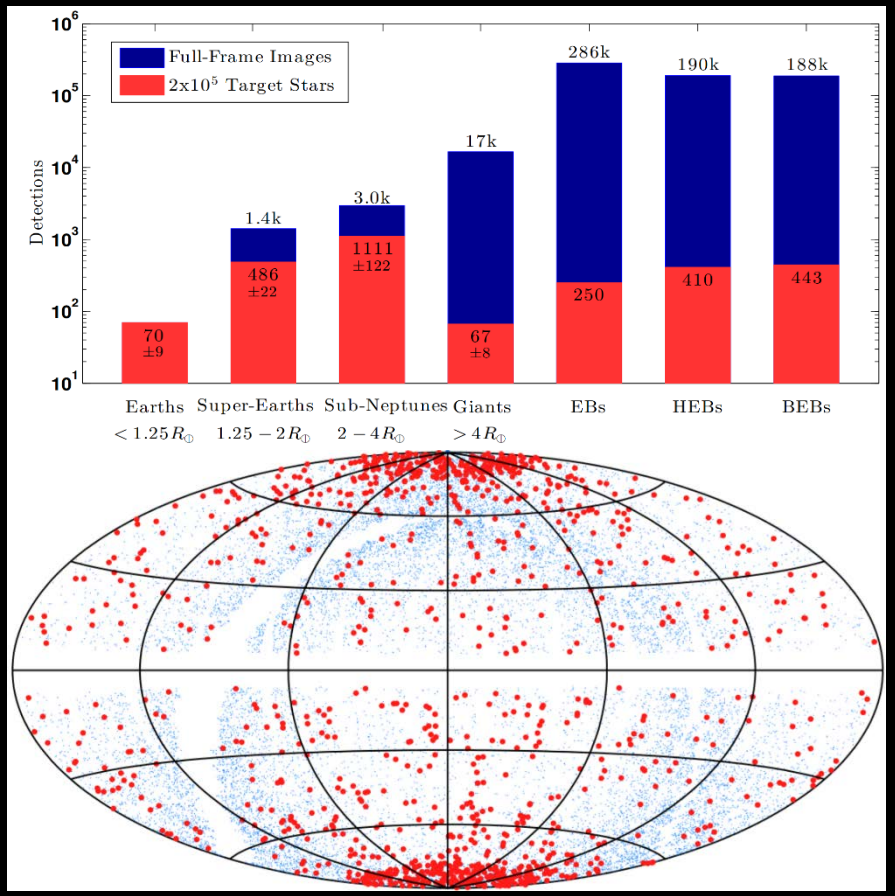

Seeing−Limited
Kepler
TESS
Gemini Speckle (0.7μm)
Gemini Speckle (0.9μm)
Keck AO (2.2μm)
Δx [arcsec]
Δy [arcsec]
+40
+20
0.0
−20
−40
+0.8
+0.4
−0.4
−0.8
+1.5
+0.75
−0.75
−1.5

Some Important Lessons from the K2 Follow-Up Program (IMHO)

- Lessons from Kepler Follow-Up Program apply
- Groups are much more protective of their programs when the teams have to produce their own light curves and planetary candidates
  - Leads to over-subscription and inefficient use of limited telescope resources – especially high resolution imaging and high precision radial velocity
- Within the groups, highly organized
- But … competitive groups are willing to collaborate
- Don’t forget: Never underestimate the ability of nature to trick you

An Eye Toward TESS … and PLATO

- Targets all over the sky!
- Orders of magnitude more targets than Kepler and K2
- More candidate observations needed than telescope resources available
- Bigger pixels really matter
  - Seeing-limited imaging and time series coupled with Spectroscopy, Gaia, and High Resolution Imaging is extremely important



Know Thy Star – Know Thy Planet Conference

Assessing the Impact of Stellar Characterization on Our Understanding of Exoplanets

October 9-12, 2017, Pasadena, CA

Invited Speakers Include

Martin Asplund (ANU)
Heather Cegla (University of Geneva)
David Ciardi (Caltech/IPAC)
Courtney Dressing (UC Berkeley)
Elliott Horch (Southern Connecticut State University)
Daniel Huber (University of Hawaii)
Paul Kalas (UC Berkeley)
Heather Knutson (Caltech)
Phil Muirhead (Boston University)
Ilaria Pascucci (University of Arizona)
Josh Pepper (Lehigh University)
Erik Petigura (Caltech)
Alessandro Sozzetti (INAF-Torino)
Rachel Street (Las Cumbres Observatory)
Sharon Wang (Carnegie Institution of Washington)
Angie Wolfgang (Penn State University)

Scientific Organizing Committee

Chas Beichman (Caltech/IPAC-NExScI)
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Dave Latham (CfA)
Eric Mamajek (JPL)
Savita Mathur (SSI)
Dave Soderblom (STScI)

http://nexsci.caltech.edu/conferences/2017/knowthystar

Agenda is filled; Registration is Still Open