MULTIPLICITY OF TESS EXOPLANET STARS: HIGH-RESOLUTION SPECKLE IMAGING OF EXOPLANET HOST STARS

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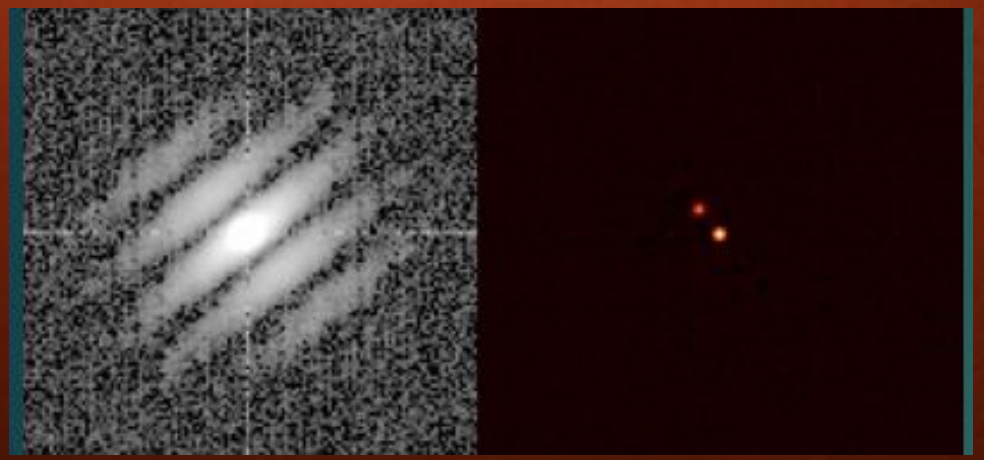

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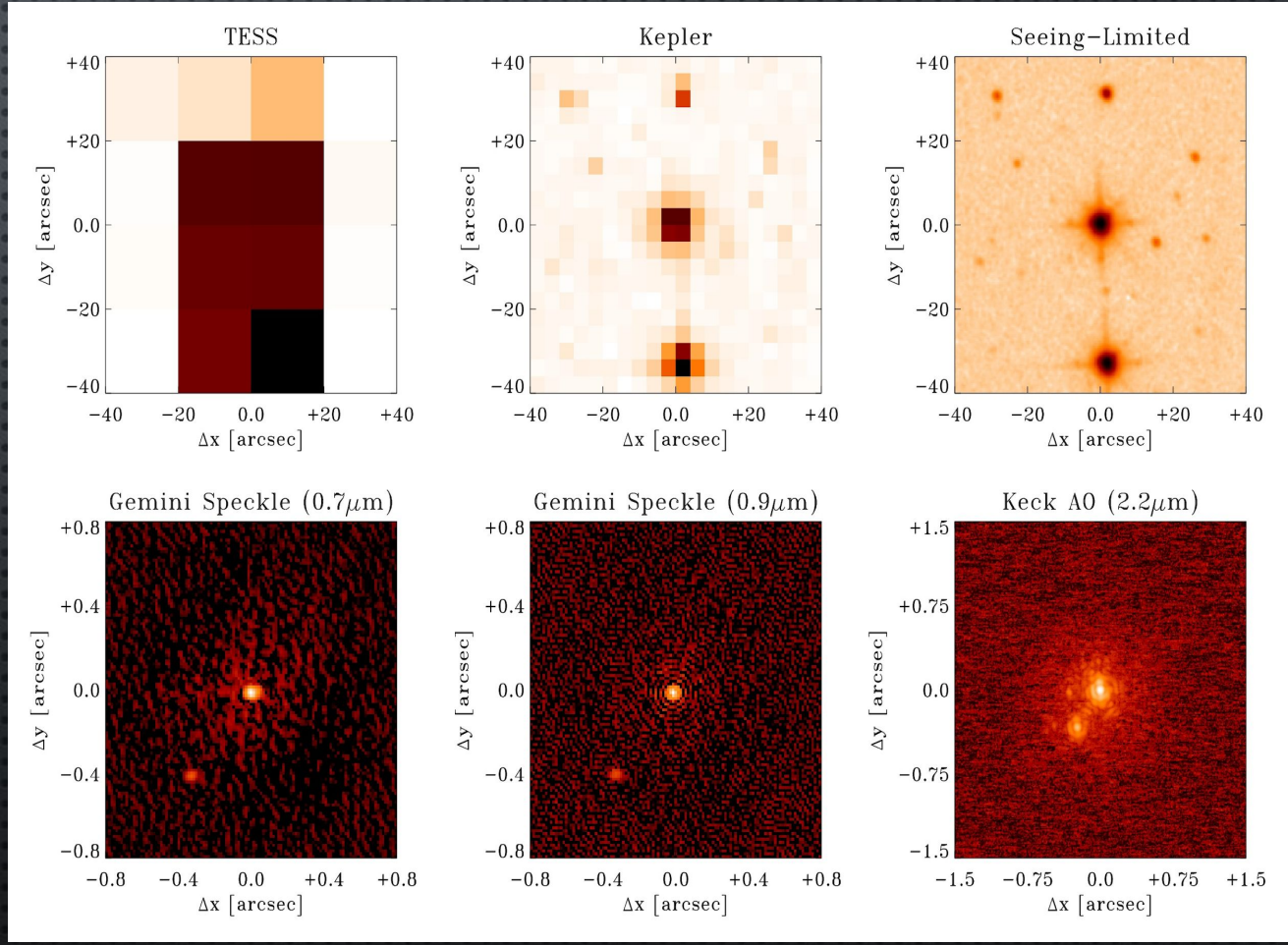
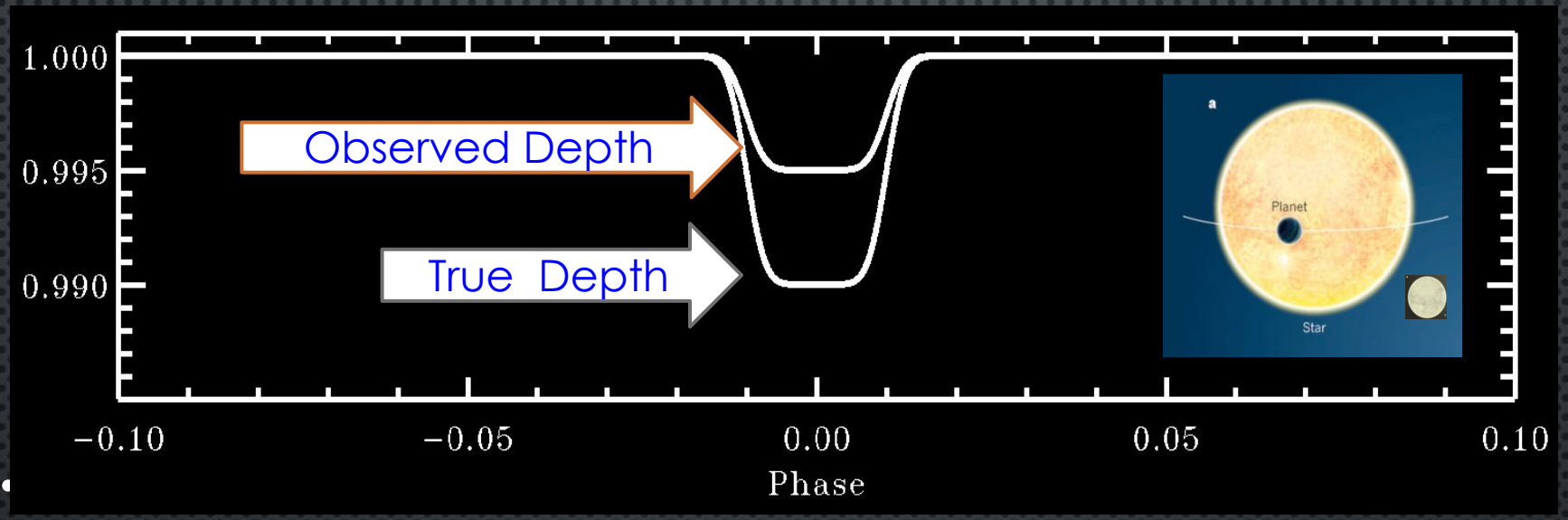
EXAMPLE: KEPLER-1002

- Kepler list assumes star is a single star
  - $R_P = 1.4\ R_{EARTH}$
  - Boundary of rocky and non-rocky planets
  - In gap of planet distribution found by Fulton et al.
- Really a Binary – If planet orbits primary star
  - $R_P = 1.8\ R_{EARTH}$
  - Non-rocky super-earth/mini-Neptune and no longer in planet distribution gap
- If planet orbits secondary star
  - $R_P = 3.5\ R_{EARTH}$
  - Neptune-like planet



ACCURATE PLANET RADII FROM TRANSITS …



- Proper accounting of Blending by Companion Stars
- Assessment of which star the planet might orbit

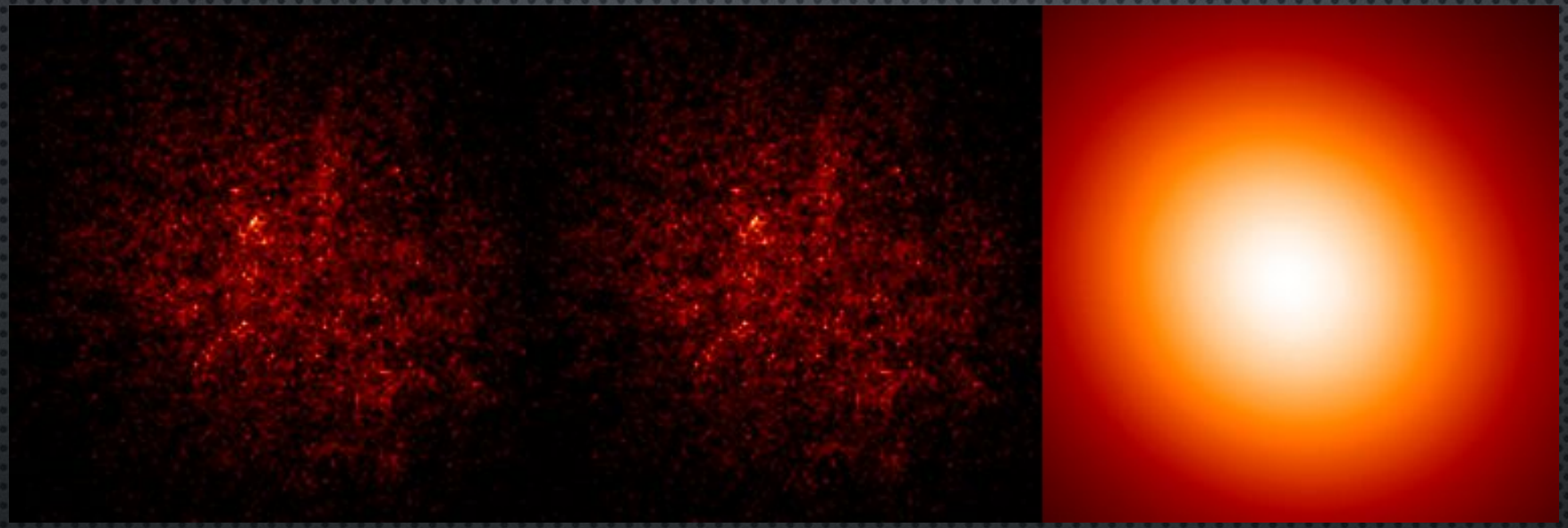
$$\delta_o \equiv \left(\frac{F_t}{F_{total}}\right)\left(\frac{R_p}{R_{t\star}}\right)^2$$

If you know nothing about the multiplicity of a star and assume it is a single star, then the planet radii are statistically underestimated by a factor of X_R=1.5

WHY DO WE NEED TO DETECT CLOSE (BOUND) COMPANIONS?

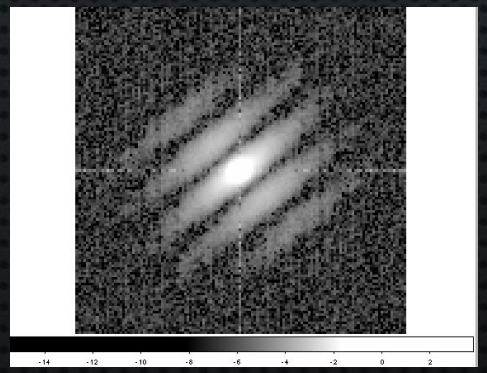
~46% of exoplanets are hosted by binary/multiple star systems	Exoplanet Validation and Characterization
Essentially only way to validate small/long period planets	Planet radii corrections proper mean density (~R^3)
If in a multiple star system - planets always are larger, less dense than assumed	Lead to correct exoplanet and stellar fundamental properties
Occurrence rate studies – exoplanet statistics	Characterize Exoplanet / Host stars formation, dynamics, evolution
Identify planet detection and characterization biases	Habitable Zone, radius gap (in or out – which star does the planet orbit?)
Resolve RV discovery "trends"	Define orbital planes – Astrometry (planet vs. companion)
(Future) space mission best targets - spectra & imaging	Help resolve microlensing systems to determine accurate masses
Find faint companions within ~5" using real-image co-adds	Other high resolution / high time cadence observations

SPECKLE IMAGE RECONSTRUCTION: HOW DOES IT WORK? WE USE FOURIER TRANSFORMS TECHNIQUES



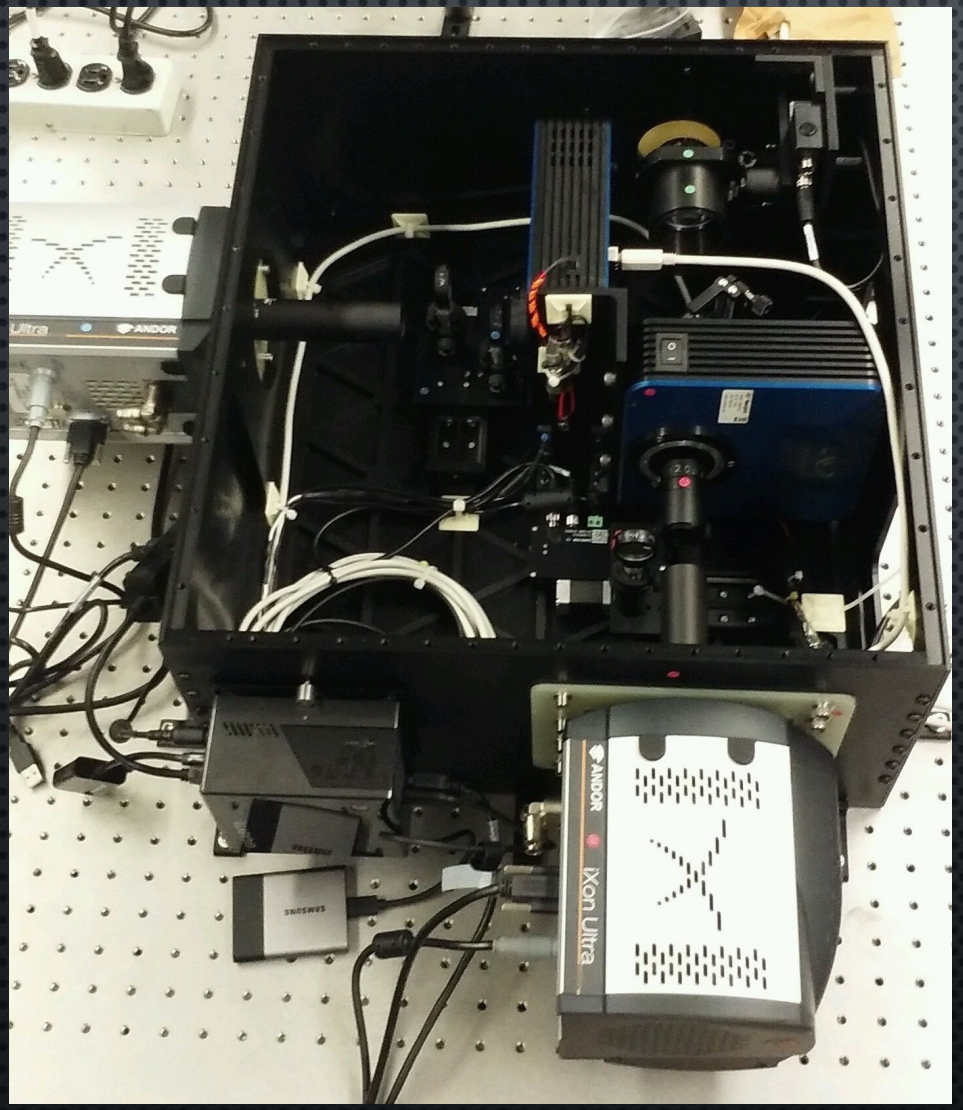
Speckles | Integrated Image | Reconstructed Image

1 arcsec

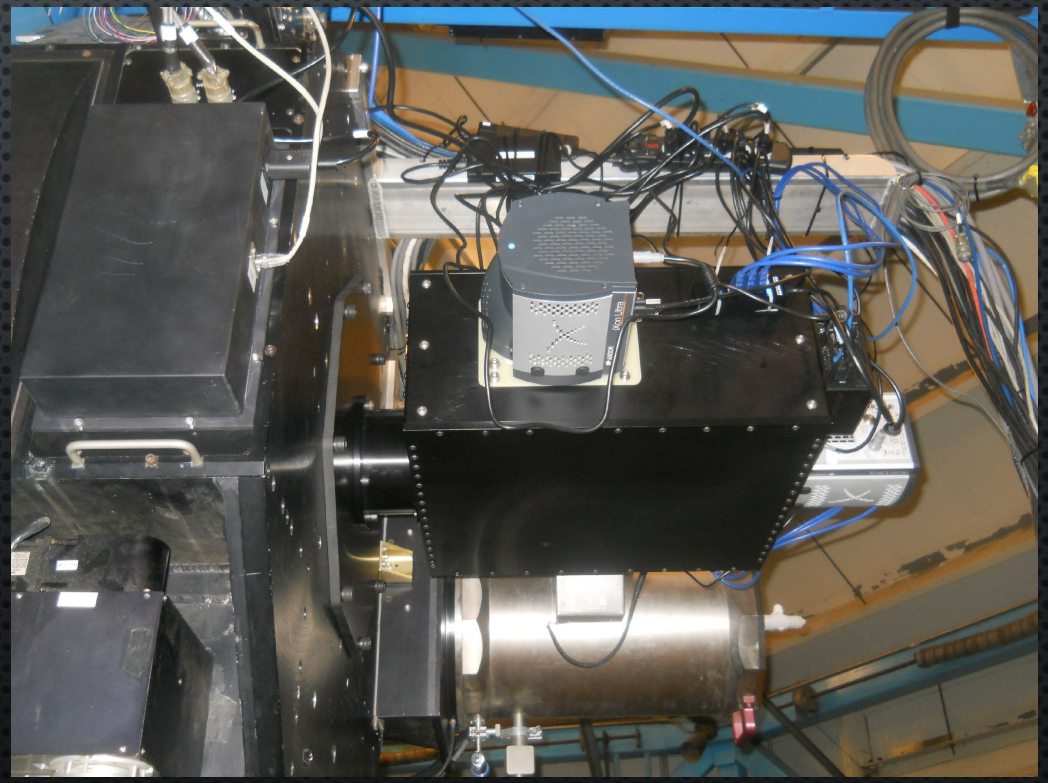


Co-added power spectra reveal fringe pattern for double (multiple) stars yielding Separation, Position Angle, and Delta Magnitude

NASA FUNDED SPECKLE INSTRUMENTS



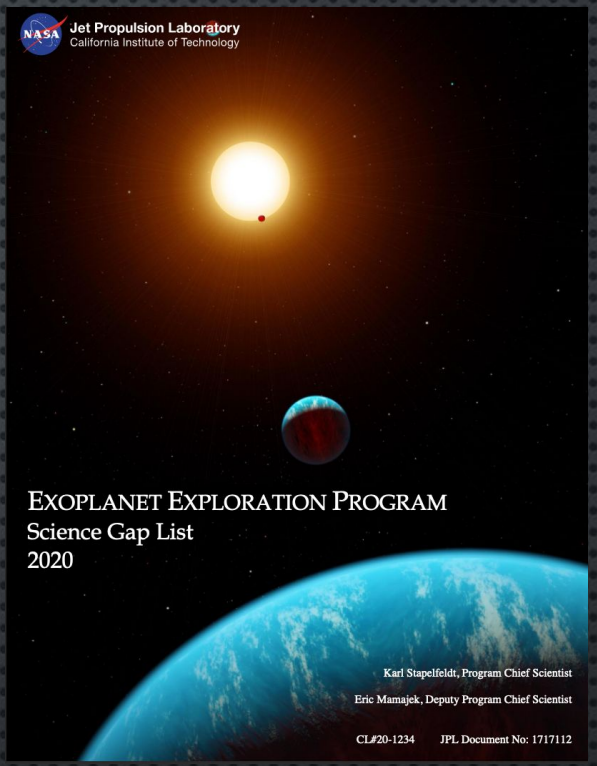
- NESSI at WIYN available to community starting in 2017,
- ‘Alopeke/Zorro at Gemini-N/S available to community starting in 2018
- Both obtain simultaneous two-color images



SURVEYING EXOPLANET HOST STARS: A COMMUNITY SERVICE PROGRAM

- FY22 will be this community program's 13th year of operation
  - Kepler -> K2 -> TESS, GB and RV searches, other exoplanet programs
- Provide high-resolution imaging for TESS TOI's and other exoplanet candidates
- We support the community with open data access and fully reduced data products hosted at the NASA exoplanet Archive (NExScI - EXOFOP)
- The program uses 3 NASA funded instruments at WIYN and Gemini Telescopes
- Speckle imaging is available ~100 nights/year
  - Community Targets are collected and ranked by TESS project, list at NExScI
  - Our program Takes requests from community for modest number of targets
  - Community can write NOIRLab "open skies" Proposals to use the instruments

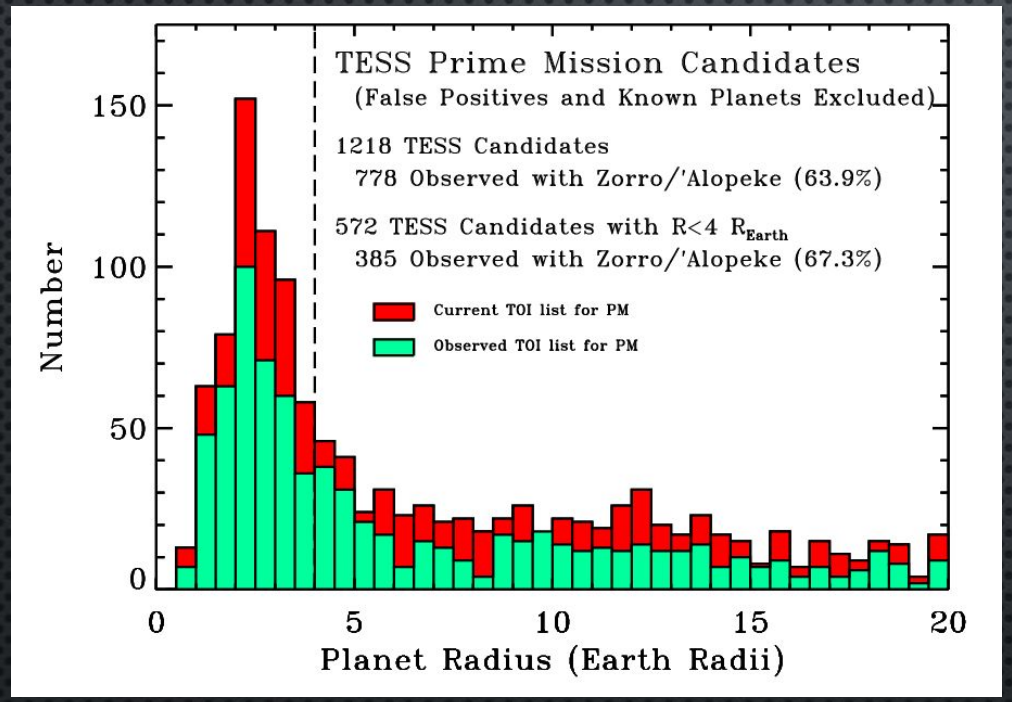
HIGH-RESOLUTION SPECKLE IMAGING: EXOPLANET SCIENCE GAPS DIRECTLY ADDRESSED AND ENABLED (EXEP SG LIST 2020)

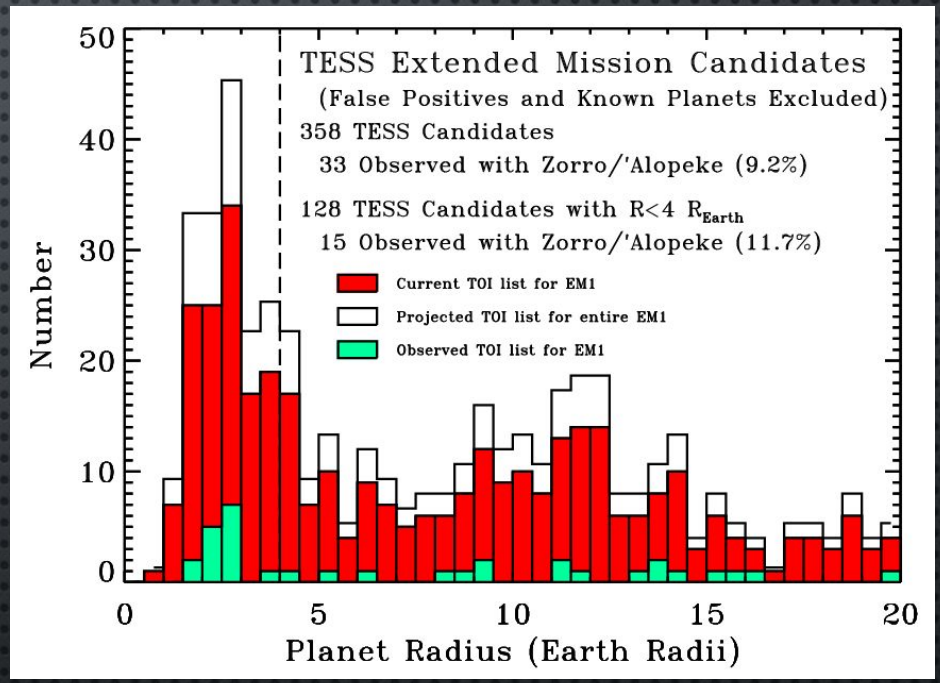


- **SCIENCE GAP 12 - MEASUREMENTS OF ACCURATE TRANSITING PLANET RADII**
- **SCIENCE GAP 07 - PROPERTIES OF KNOWN EXOPLANET HOST STARS**
- **SCIENCE GAP 10 - PRECURSOR OBSERVATIONS OF DIRECT IMAGING TARGETS**
- **SCIENCE GAP 04 - PLANETARY SYSTEM ARCHITECTURES: OCCURRENCE RATES FOR EXOPLANETS OF ALL SIZES**
- **SCIENCE GAP 05 - OCCURRENCE RATES AND UNCERTAINTIES FOR TEMPERATE ROCKY PLANETS (ETA-EARTH)**

- ENABLING FOR SG-01, SG-02, SG-03, SG-06

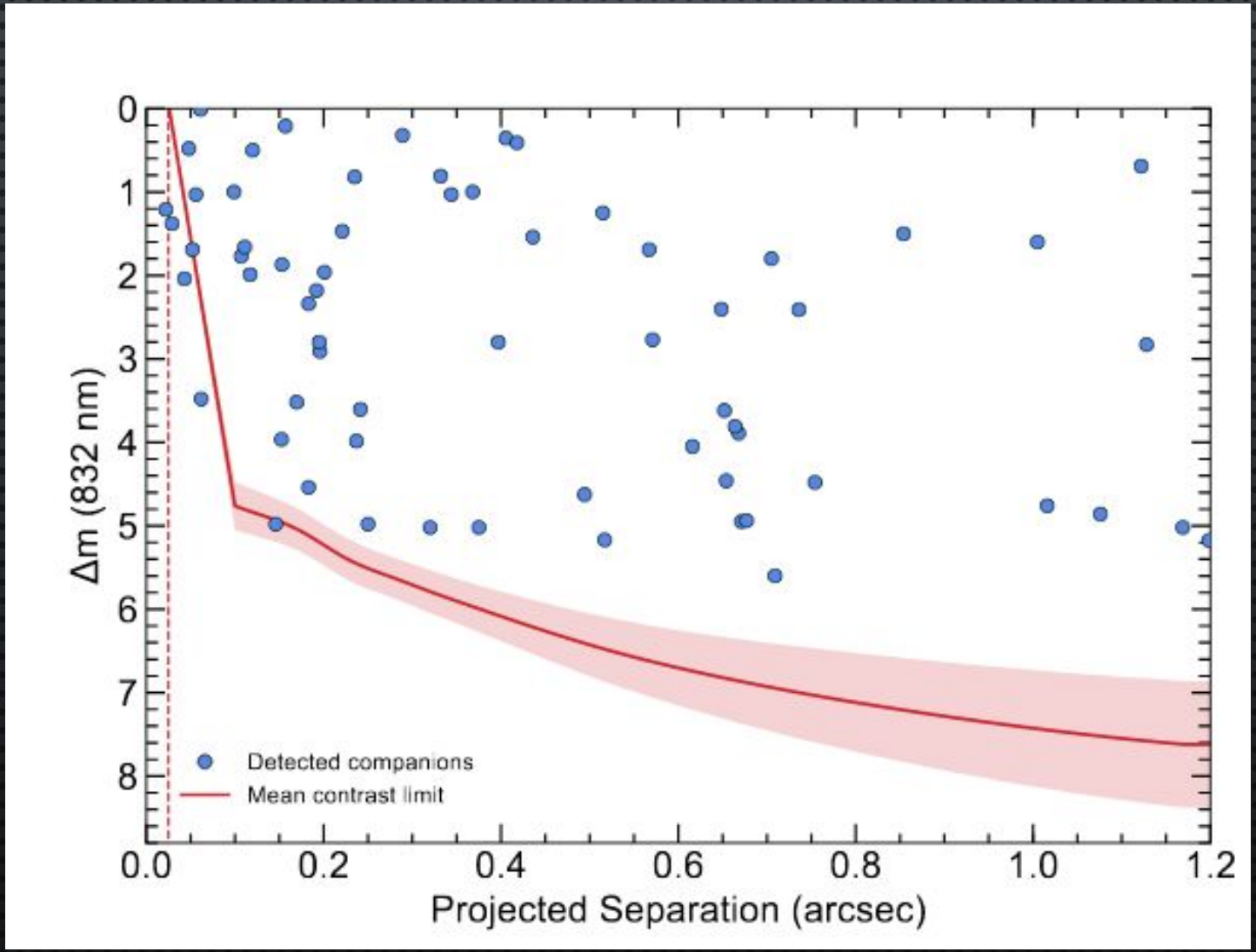
TESS TOIS OBSERVATIONAL PROGRESS



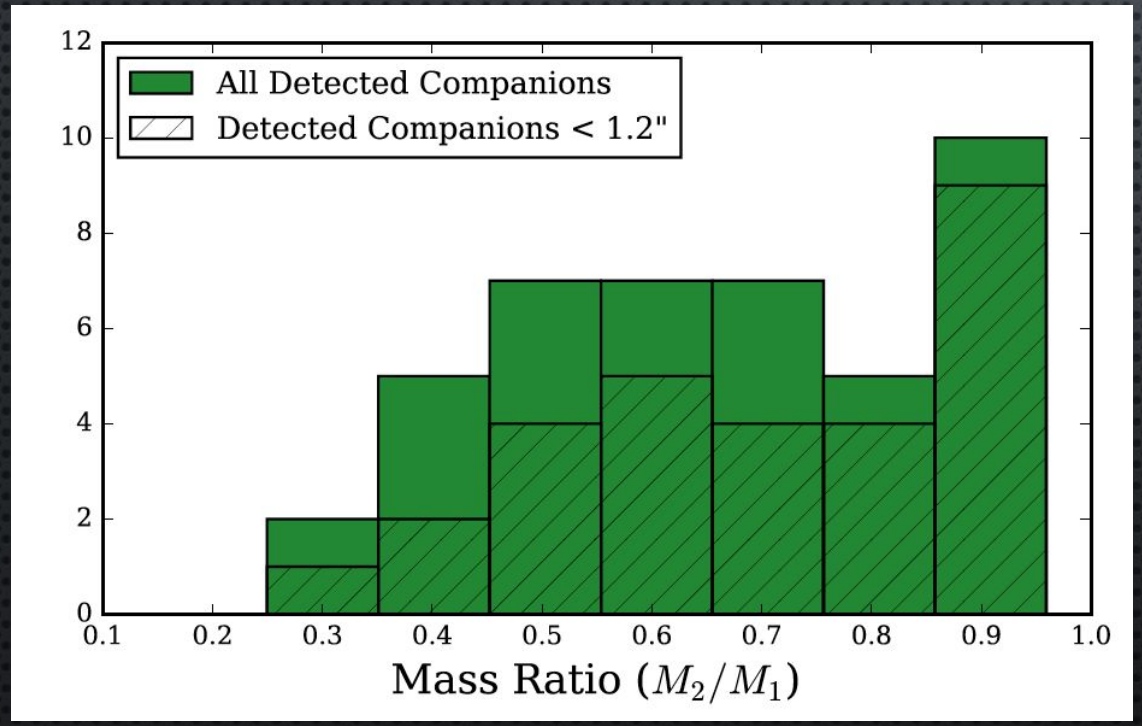


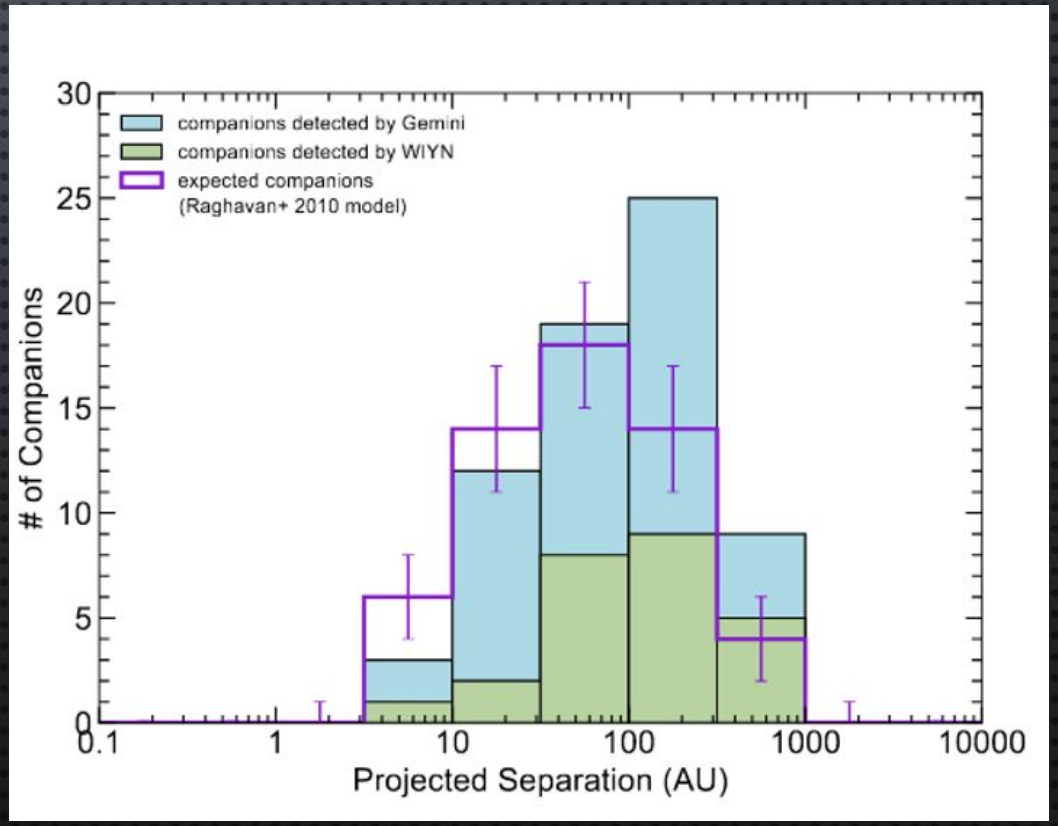
ALL of our speckle images, and final data products are available to the community at EXOFOP with no exclusive use period. (Raw data archived as well)

EXOPLANET HOST BINARIES:
MEAN DETECTION AND CONTRAST LIMITS: 20 MAS TO 1.2 ARCSEC

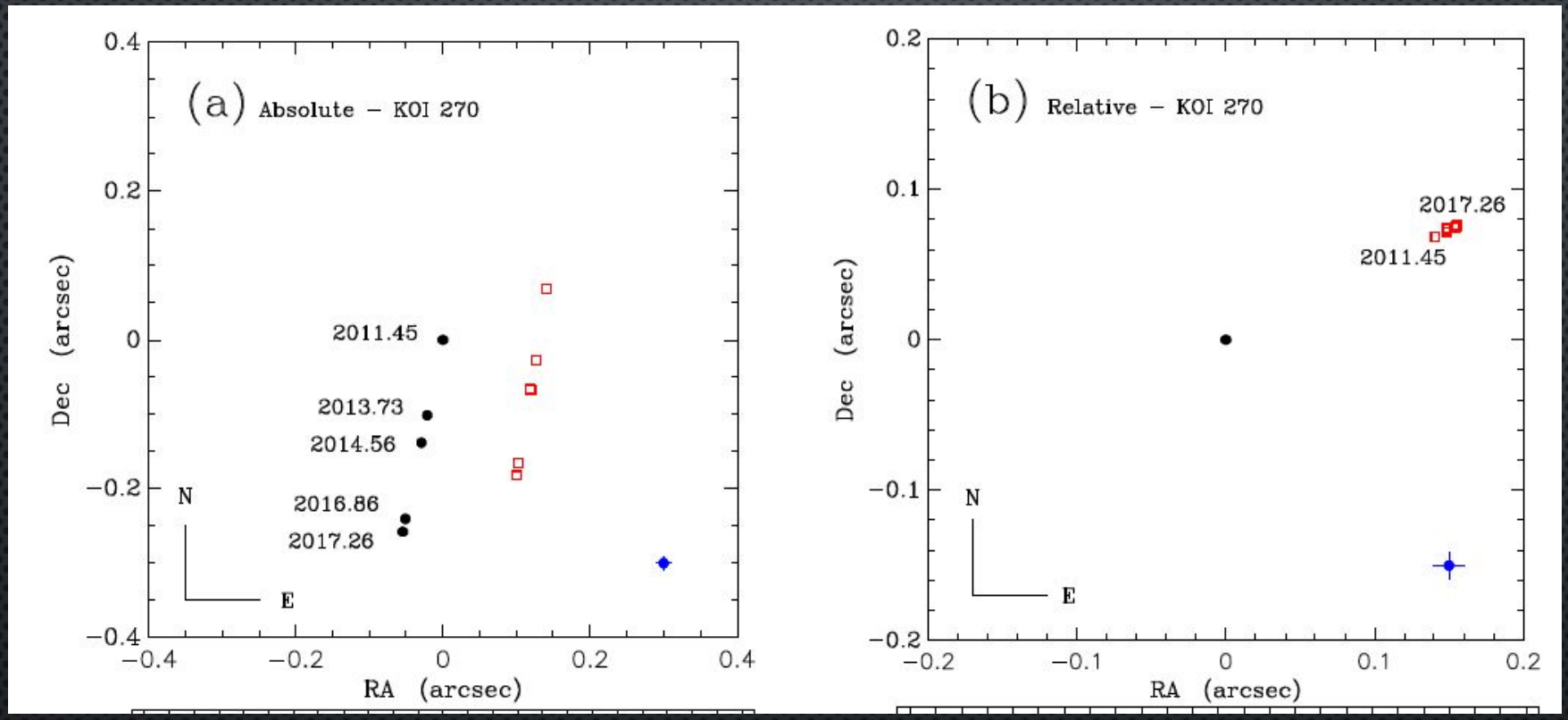


EXOPLANET BINARY HOST STARS: MASS RATIO SIMILAR TO FIELD STARS, ORBITAL PERIOD DISTRIBUTION WIDER





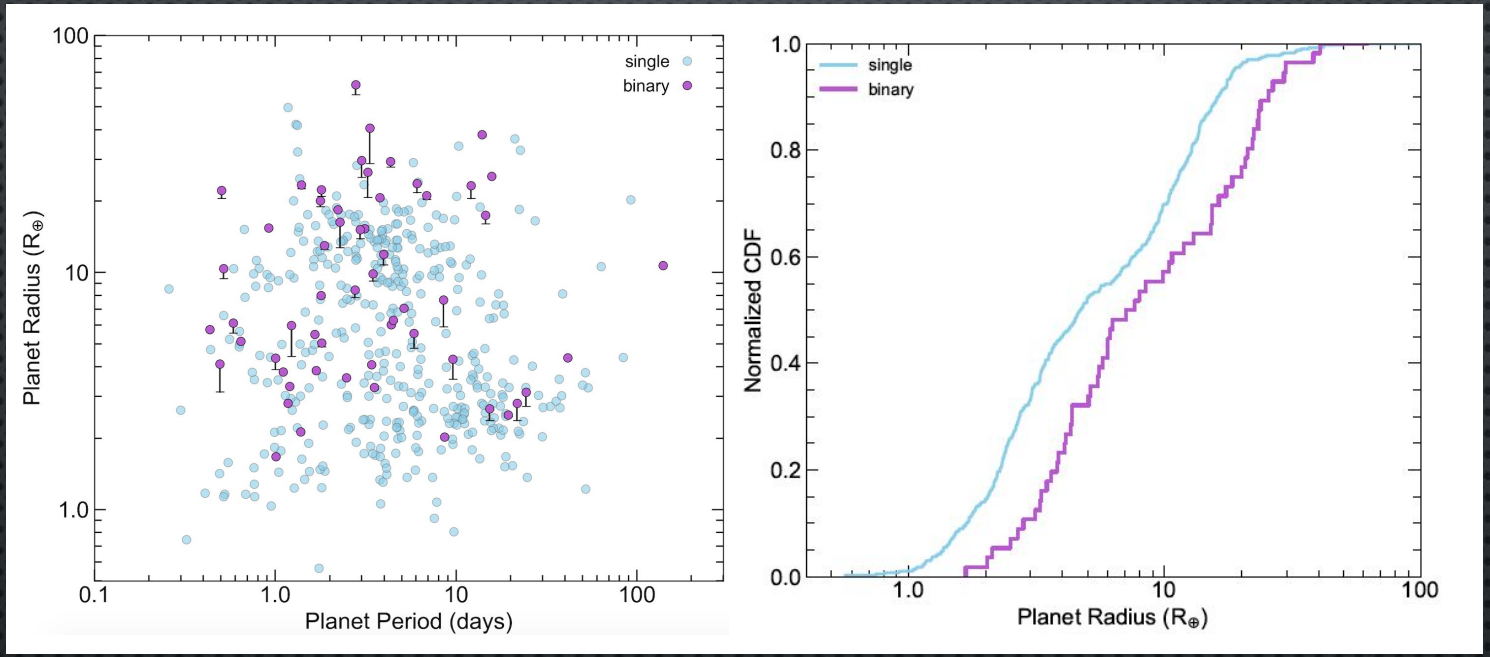
BINARY EXOPLANET HOST STAR ASTROMETRY



Absolute and Relative Astrometry of Exoplanet Host Star Binary Orbits – Note companion orbital plane looks to be in the exoplanet transit plane. Decades for Kepler, a few years for TESS

Understanding binary host stars provides robust tests for exoplanet (and binary star) formation, dynamics, and evolution.

Earth-Size Exoplanet Detection and Occurrence Rate: Large observational bias found for small exoplanet detections

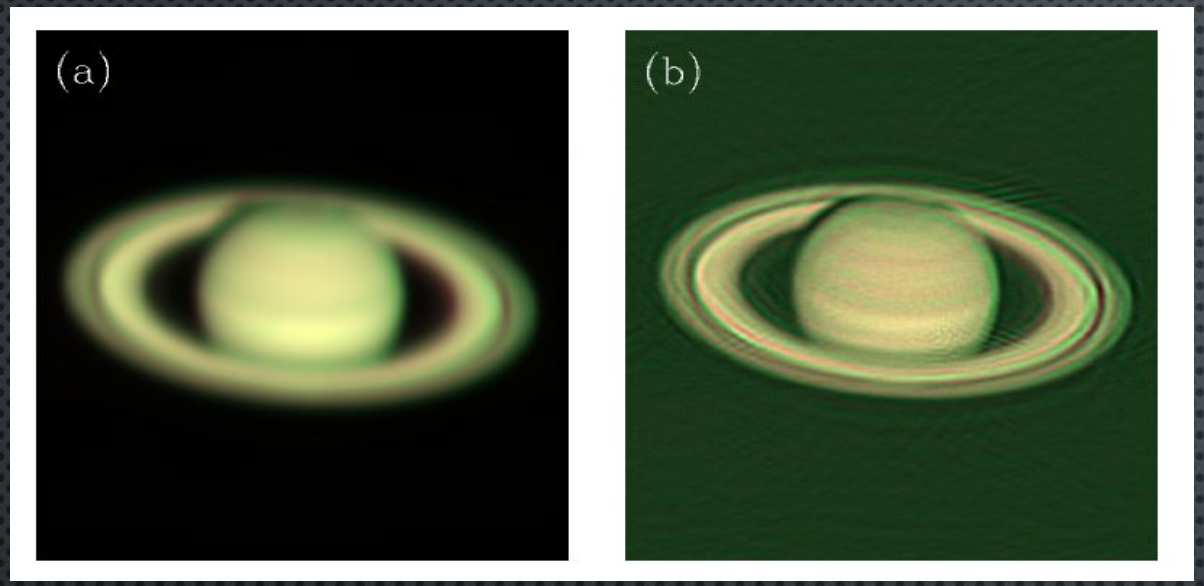


Left: Exoplanet radii separated into single and close binary host stars as discovered in our work.
Note that even prior to radius correction, there is an observational bias against finding small planets in binary hosts.

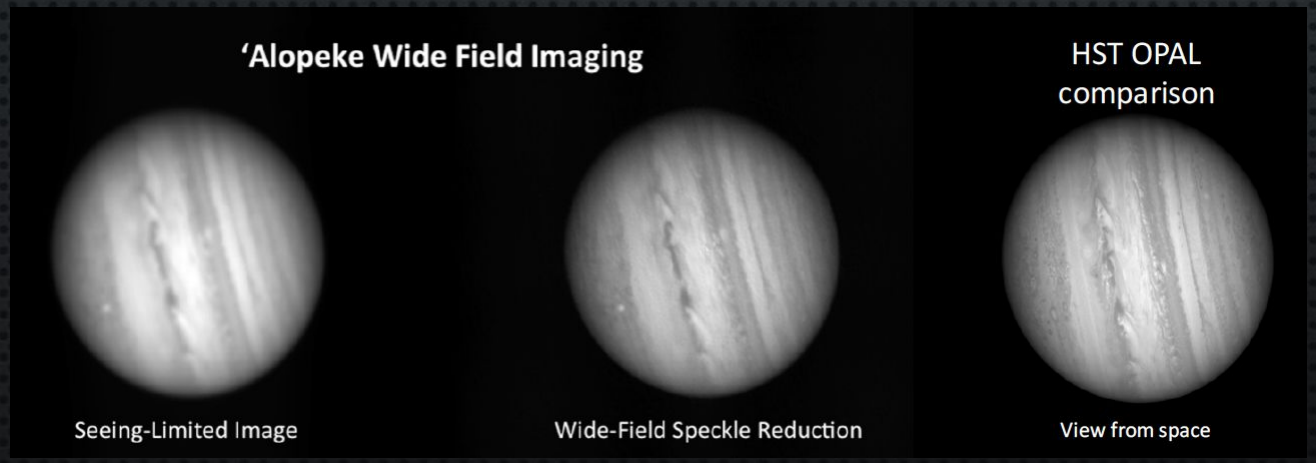
Right: Cumulative density function showing undetected small (<~2 R_e) exoplanets which reside in binaries.

Lester, Matson, Howell, et al. (2021) AJ in press.

"WIDE-FIELD" TARGET INITIAL TESTS: SEEING LIMITED TO SHARPER IMAGES



Saturn and Jupiter rival HST resolution



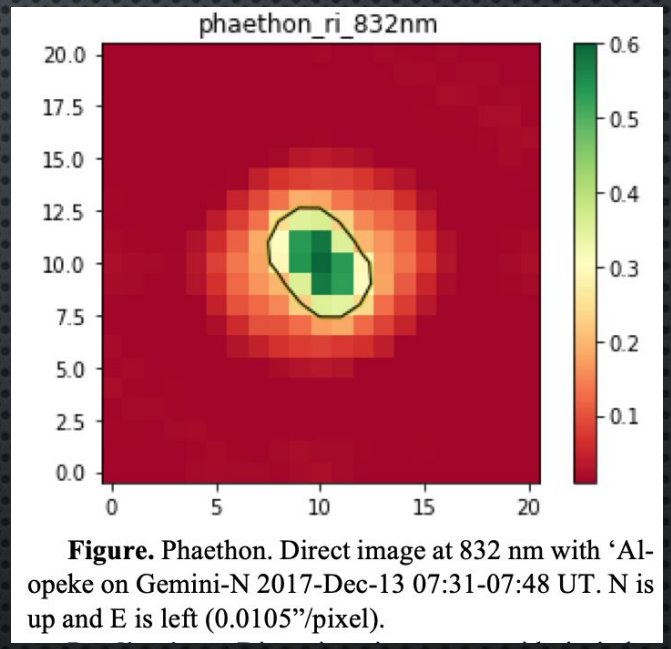
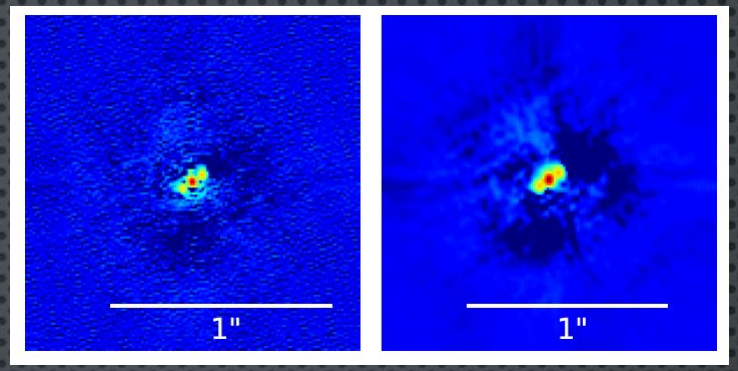
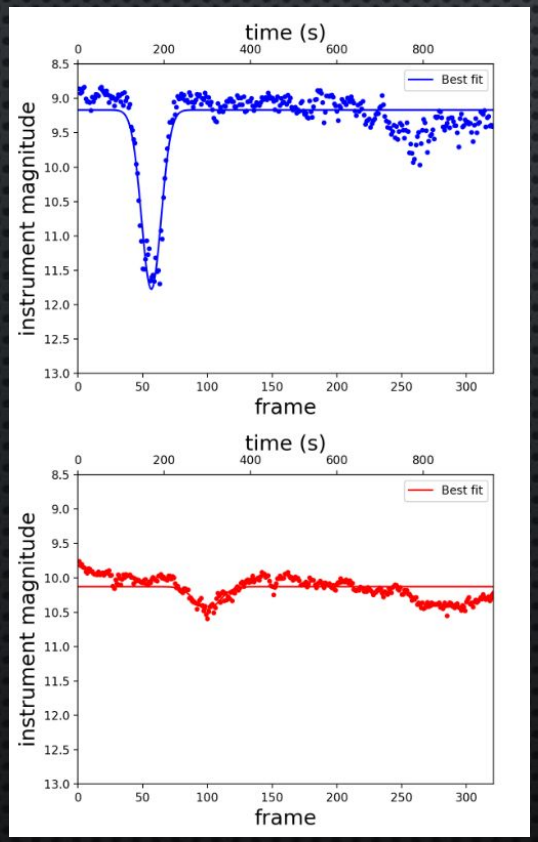


Figure. Phaethon. Direct image at 832 nm with 'Alopeke on Gemini-N 2017-Dec-13 07:31-07:48 UT. N is up and E is left (0.0105"/pixel).

Asteroid Phaethon reveals elongated shape

MICROLENS TARGET IMAGING: DETECTED LENS AND SOURCE KOJIMA_1LB: SEP = 0.058", PA = 301, DELTA = 3.71.





Simultaneous blue+red high-speed light curves of an eclipsing pair of white dwarfs

Nova V906 Car imaged at 832 nm, 978 days after its explosion. The shell is fully resolved with a radius of 90 mas

Summary

- Detecting unresolved stellar companions is of critical value to many aspects of Exoplanet Science
- Speckle interferometry on 4 to 8–m telescopes is not "your Mother's speckle imaging" – reaches diffraction limit, obtains contrasts of 5-10 magnitudes, sources as faint as 18th magnitude
- Community exoplanet program and open use of the instruments allows Equitable access to data and products
- All raw and fully reduced data available with no exclusive use period at NASA Exoplanet Archive
- Instruments offer additional science value to NASA community

NASA HIGH-RESOLUTION IMAGING: SOME RECENT RESULTS

We directly work with ~30 community PI/groups and 20 additional stand-alone PIs.

Contributed to over 80 exoplanet papers (2020-present)

- Scott, N., et al. – Speckle interferometric Instruments for Gemini, in press, Astronomy and Space Science/Astronomical Instrumentation, in press
- Lester, K., et al. – TESS host stars high-resolution imaging with Gemini, in press AJ,

  Note: Press release 28 June
- 2021FrASS...8...10H; The NASA High-Resolution Speckle Interferometric Imaging Program: Validation and Characterization of Exoplanets and Their Stellar Hosts, Howell, S. B., et al.
- 2021 AJ....161..164H; WIYN TESS host star observations – 2018-2019, submitted Oct 2020, Howell, S. B., et al.
- AJ 2021, 161,21; Identifying Bound Stellar Companions to Kepler Exoplanet Host Stars Using Speckle Imaging, Colton, Horch, Howell, et al.
- 2020 ApJ...898...47F; Exoplanet Host Stars Fit as Single Stars: Effects on the Stellar Parameters, Furlan, E. & Howell, S. B.
- 2020 FrASS...7...10; The Grand Challenges of Exoplanets, Howell, Steve B.
- 2019 AJ....157..211; Detecting Unresolved Binaries in TESS Data with Speckle Imaging, Matson, Rachel A.; Howell, Steve B.; Ciardi, David R.
- 2019 AJ....158..113; High-resolution Imaging Transit Photometry of Kepler-13AB, Howell, Steve B.; Scott, Nicholas J. Matson, Rachel A. *and 2 more*