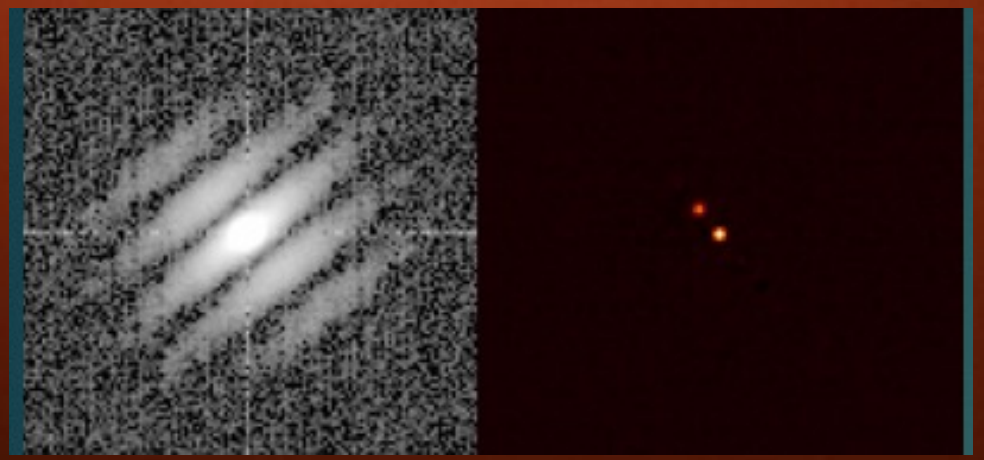
THE CONSEQUENCES OF BINARY EXOPLANET HOST STARS

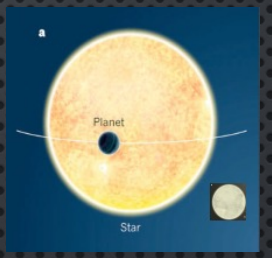
STEVE B. HOWELL
NASA AMES RESEARCH CENTER

DAVID CIARDI, ELISE FURLAN, CRYSTAL GNILKA,
KATIE LESTER, RACHEL MATSON



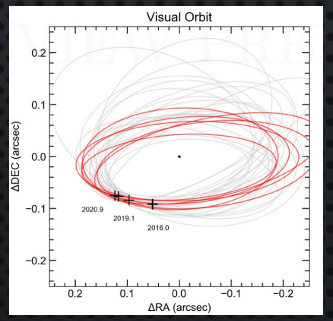
PLATO Mission Conference 2021
11-15 Oct. 2021

OUTLINE



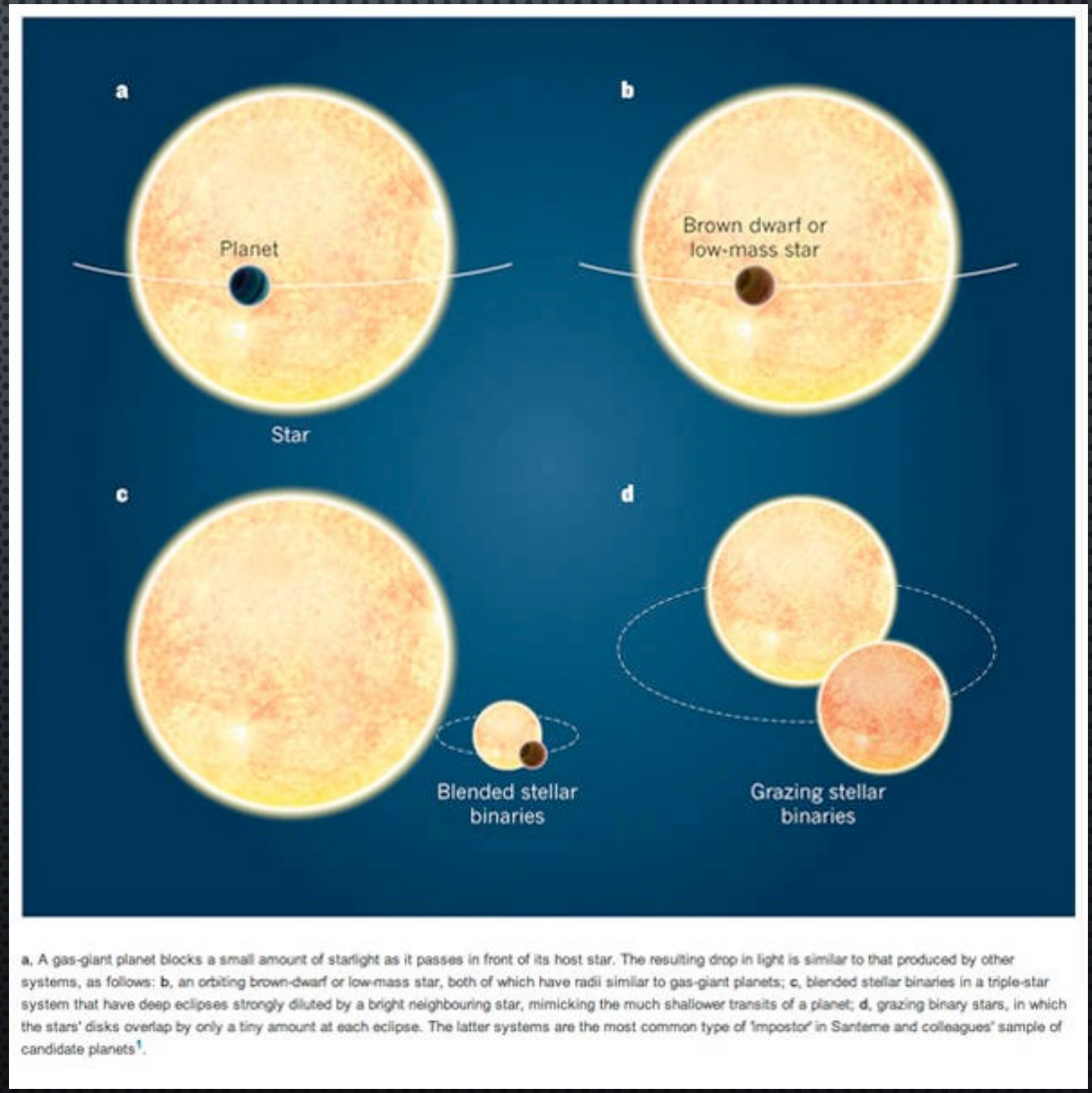
- REASONS TO SEARCH FOR AND IDENTIFY NEARBY (BOUND OR LOS) STELLAR COMPANIONS
- CONSEQUENCES OF ASSUMING SINGLE EXOPLANET HOST STARS
- HIGH-RESOLUTION IMAGING OF EXOPLANET HOST STARS (OPTICAL + IR/AO)

  - SPECKLE IMAGING DISCUSSED IN THIS TALK
  - SPECKLE & IR/AO DISCUSSED IN D. CIARDI'S TALK, FRIDAY (15 OCT) @ 15:15
- RECENT SCIENTIFIC FINDINGS FOR EXOPLANET HOST STARS AND THEIR PLANETS
- THE OPEN COMMUNITY HIGH-RESOLUTION IMAGING PROGRAM
- SUMMARY



Exoplanet Validation & Characterization

- True planet
- Low-mass Companion
- Eclipsing Binary
- Background Eclipsing Binary
- Correct Planet Properties



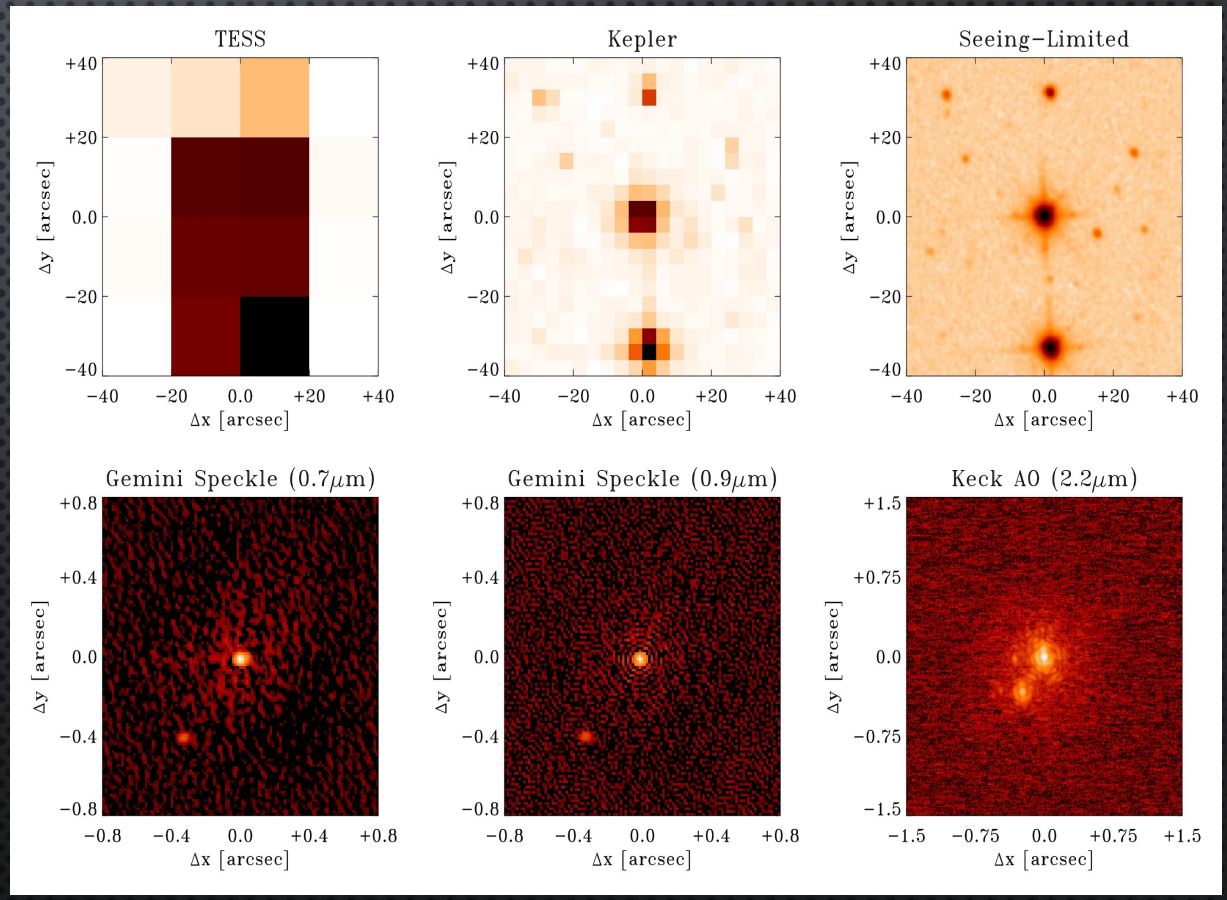
a, A gas-giant planet blocks a small amount of starlight as it passes in front of its host star. The resulting drop in light is similar to that produced by other systems, as follows: b, an orbiting brown-dwarf or low-mass star, both of which have radii similar to gas-giant planets; c, blended stellar binaries in a triple-star system that have deep eclipses strongly diluted by a bright neighbouring star, mimicking the much shallower transits of a planet; d, grazing binary stars, in which the stars' disks overlap by only a tiny amount at each eclipse. The latter systems are the most common type of 'impostor' in Santerne and colleagues' sample of candidate planets[1].

REASONS TO DETECT CLOSE (BOUND) COMPANIONS?

~46% of exoplanets are hosted by binary/multiple star systems (FGK) and about 25% for M stars.	Exoplanet Validation and Characterization
Essentially only way to validate small/long period planets (e.g., Earths in habitable zone)	Planet radii corrections → proper mean density (~R^3) Rocky planet or not?
If in a multiple star system - planets are larger & less dense than assumed	Lead to correct exoplanet and stellar fundamental properties – composite image/spectra both cause incorrect properties of star and planet
Occurrence rate studies – exoplanet statistics Small (<2 R_e) planets are not detected in binary systems	Characterize Exoplanet / Host star 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" - Additional planets or stellar companion?	Define orbital planes – orbital solutions (planets and companion)
(Future) space mission best targets - spectra & imaging (e.g., PLATO, ROMAN, ARIEL)	Help resolve microlensing systems to determine accurate masses
Find faint companions within ~2-4" using real-images	Obtain knowledge of binary star properties.

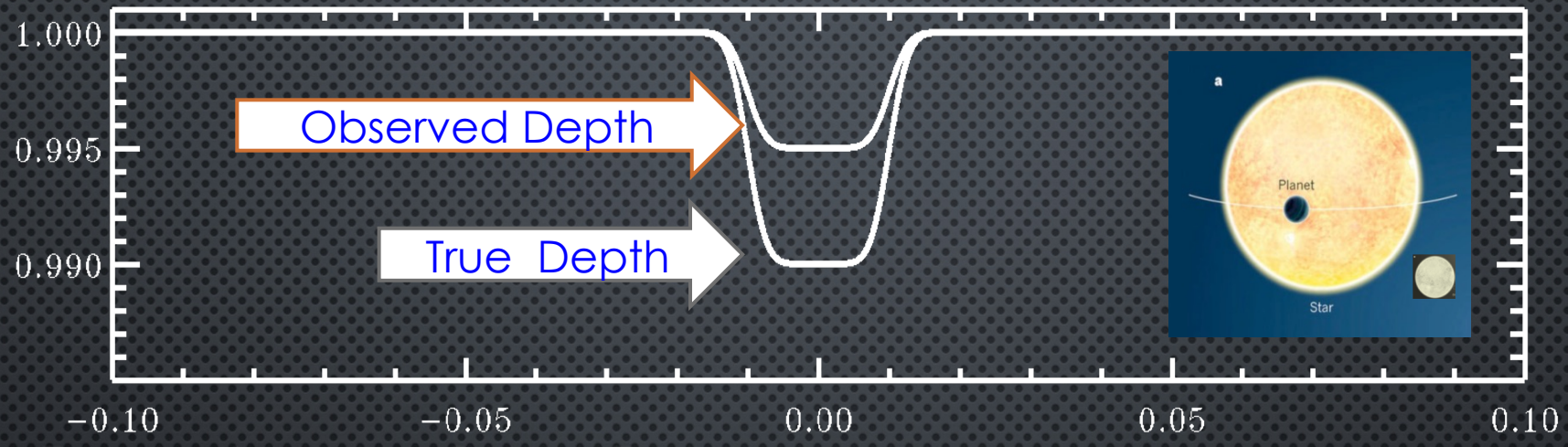
EXAMPLE: KEPLER-1002

- KEPLER LIST ASSUMES STAR IS A SINGLE STAR
  - $R_P = 1.4\ R_{EARTH}$
  - BOUNDARY OF ROCKY / 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



Note scale change between top/bottom rows.
Figure adapted from Ciardi et al., 2015

ACCURATE PLANET RADII FROM TRANSITS …

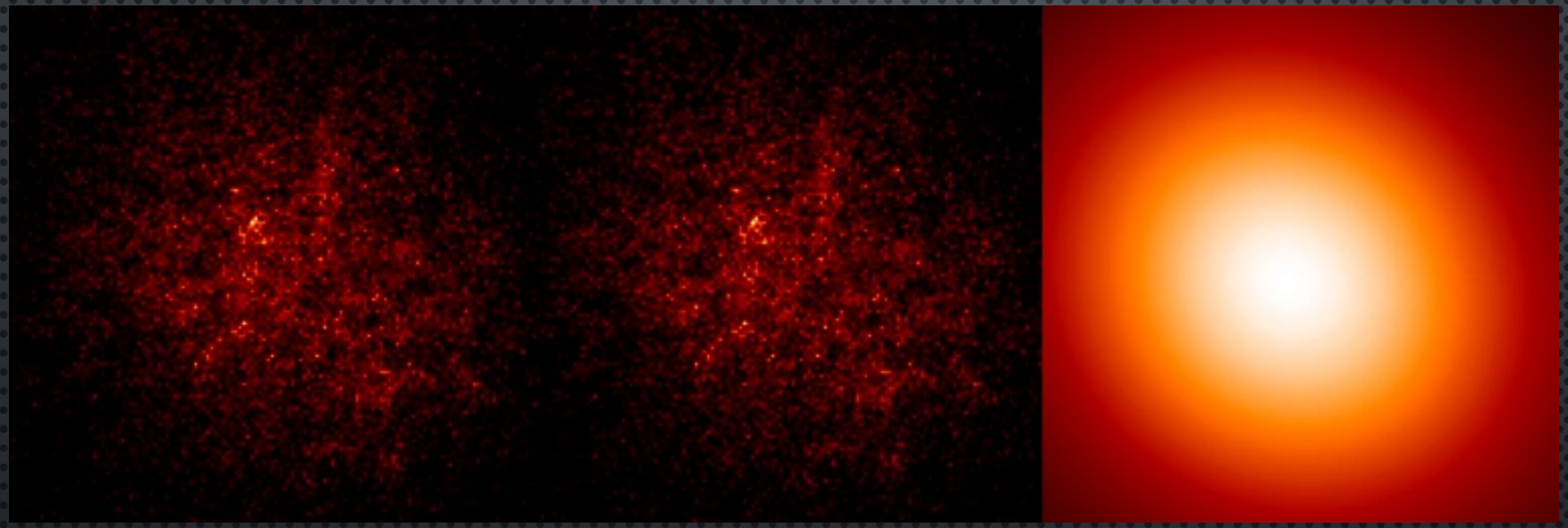


- REQUIRE ACCURATE STELLAR RADII
- PROPER ACCOUNTING OF BLENDING BY COMPANION STARS
- ASSESSMENT OF WHICH STAR THE PLANET MIGHT ORBIT

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

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 See Ciardi et al., 2015.

SPECKLE INTERFEROMETRY: OPTICAL BANDPASS "AO" DONE IN SOFTWARE



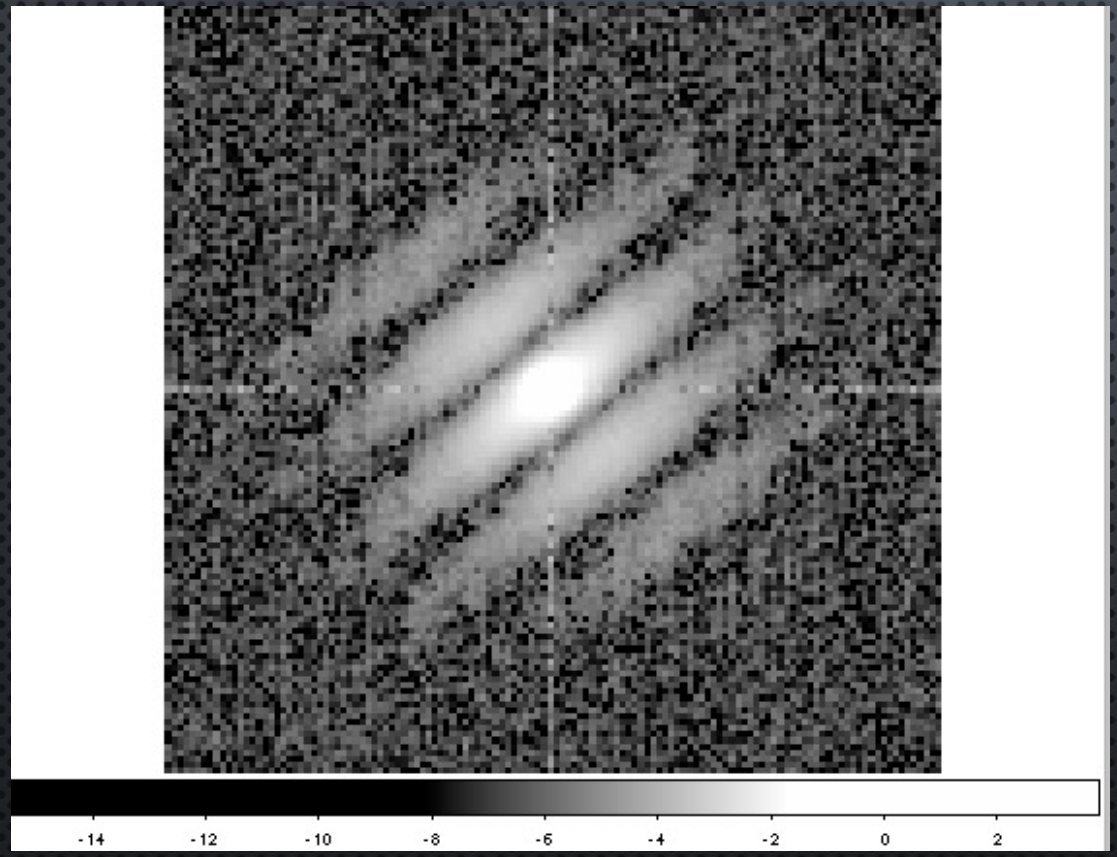
Speckles | Integrated Image | Reconstructed Image

1 arcsec

Fast exposures freeze atmospheric distortion, Fourier data analysis allows detection and property determination for close companions.

Reach diffraction limited imaging using ground-based telescopes. Provides highest resolution imaging for any single telescope.

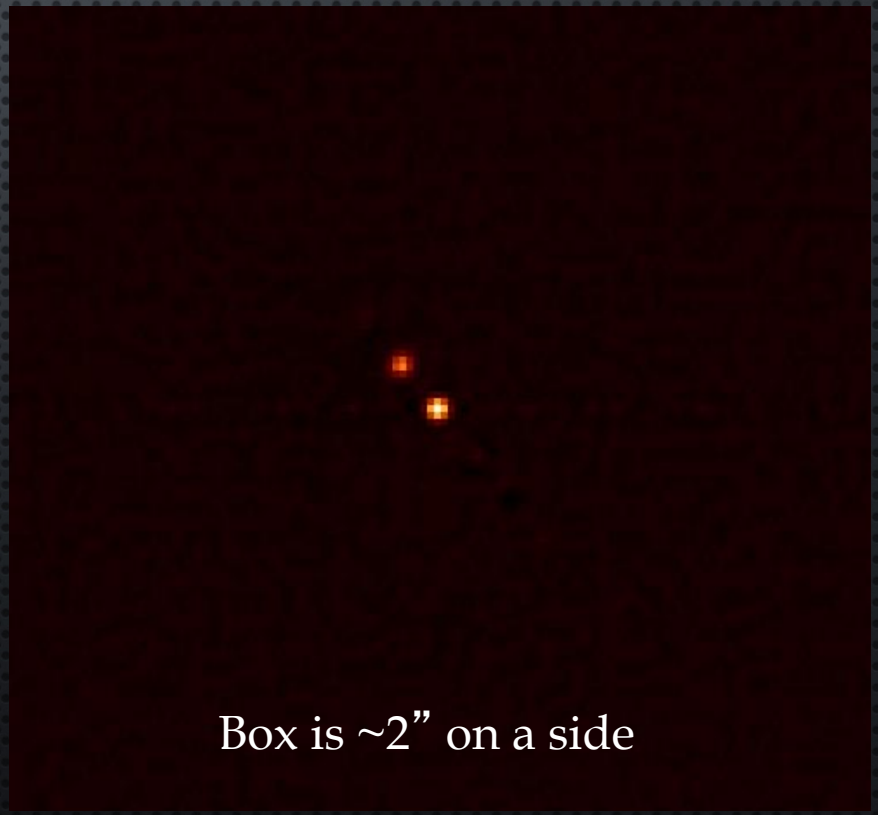
FOURIER SPACE POWER SPECTRA REVEAL POINT SOURCE PROPERTIES



Final power spectrum reveal fringe pattern for double (multiple) stars yielding Separation, Position Angle, and Delta Magnitude

Example Exoplanet Host Star
Discovered to be a binary

R~11.6, a=0.16”, dm=0.85



Box is ~2” on a side

SPECKLE INTERFEROMETRIC INSTRUMENTS AT GEMINI

SIMULTANEOUS TWO-COLOR IMAGING; PUBLICLY AVAILABLE

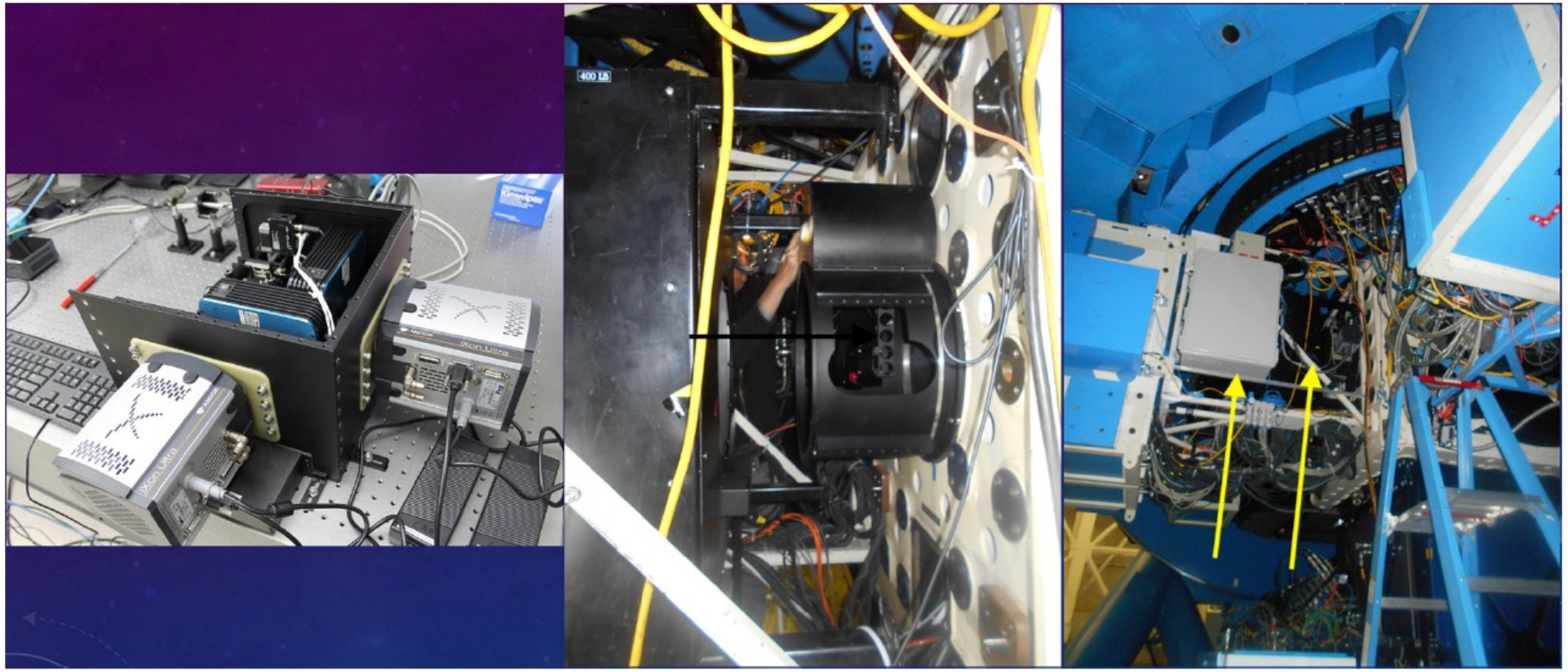
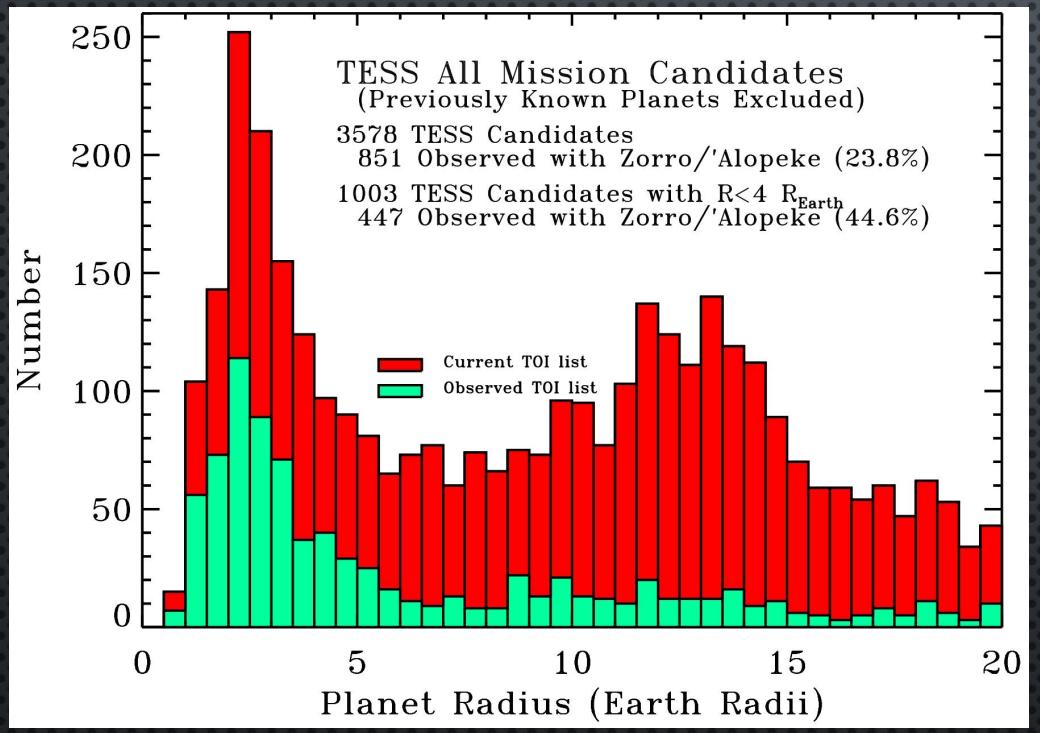
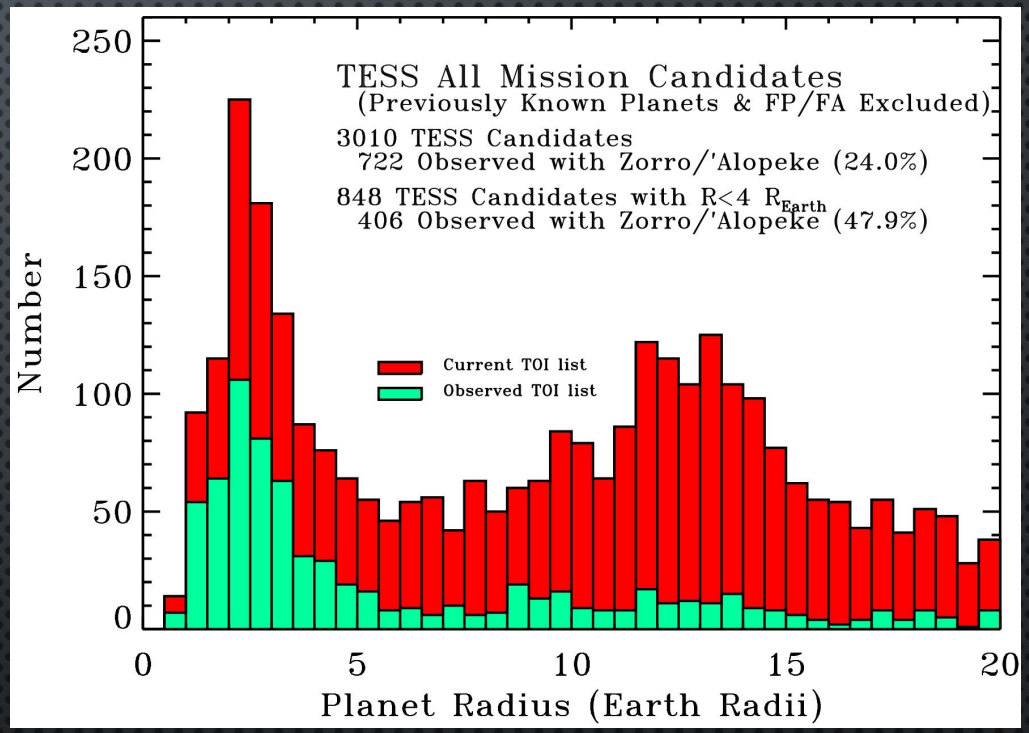


FIGURE 5 | (Left) One of the two identical speckle imagers under construction at the NASA Ames Research Center. The two grey boxes extending out of the black box are the two Andor EMCCD cameras. **(Middle)** A close-up view of the instrument mounted on Gemini at the GCAL port and **(Right)** a view of the instrument (black box) with the associated power supply, electronics, and computer unit (white box). See yellow arrows.

See Howell, et al., 2021, FrASS, 8, 10 and Scott, et al., 2021, FrASS, 8, 138

TESS TOI SPECKLE IMAGING PROGRESS (AS OF 8 OCT 2021)

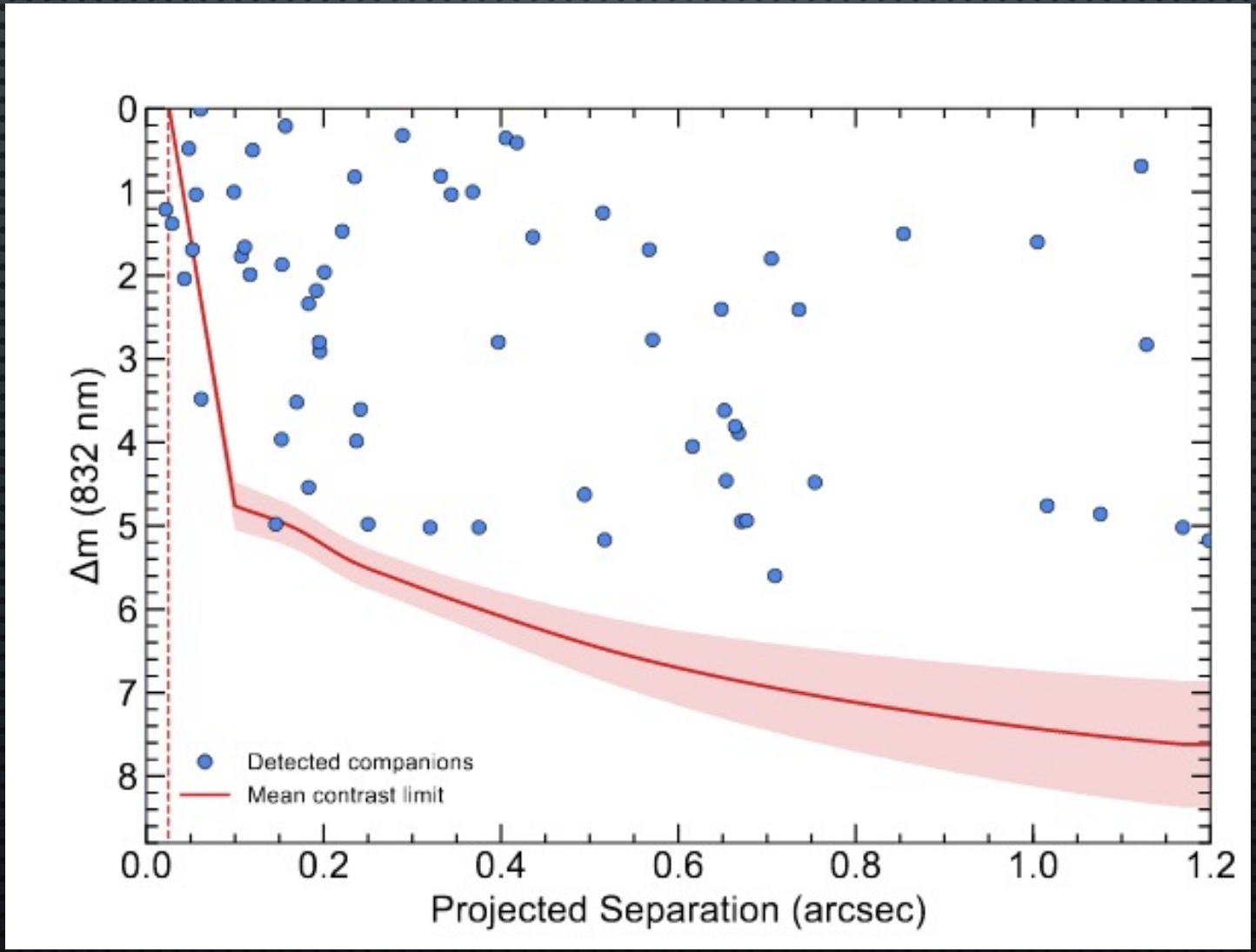




ALL of our high-resolution images, and final data products are available to the community at EXOFOP with no exclusive use period.
(Raw data archived as well)

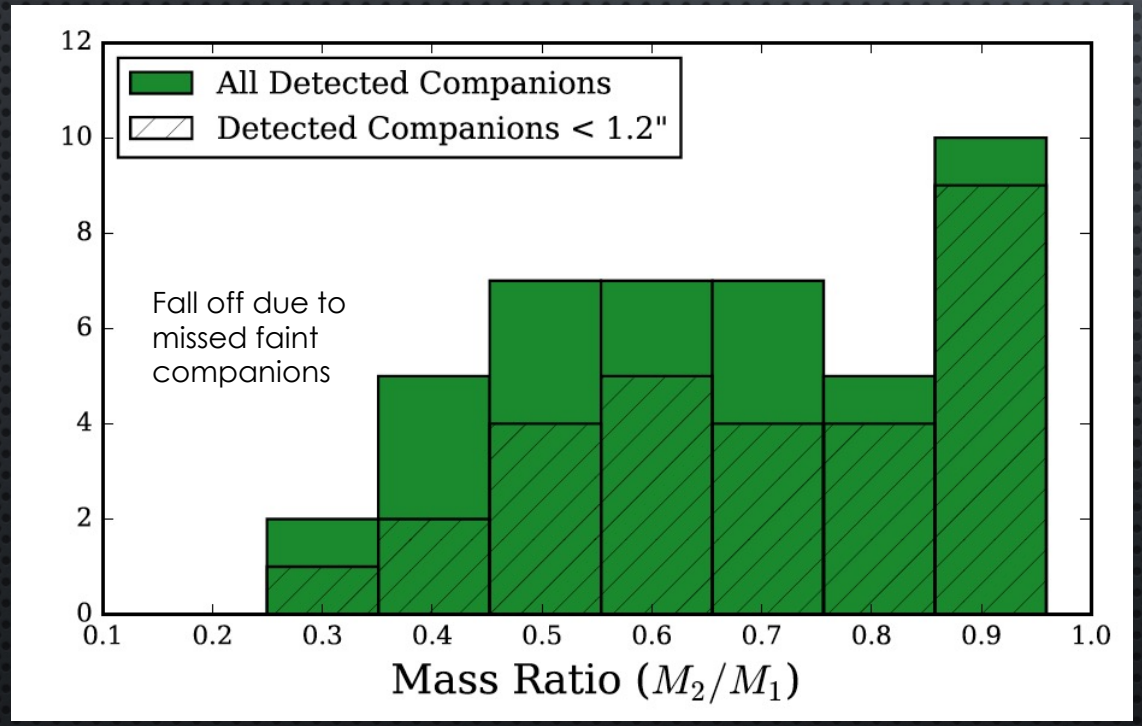
EXOPLANET HOST BINARIES: SPECKLE IMAGING AT GEMINI 8-M

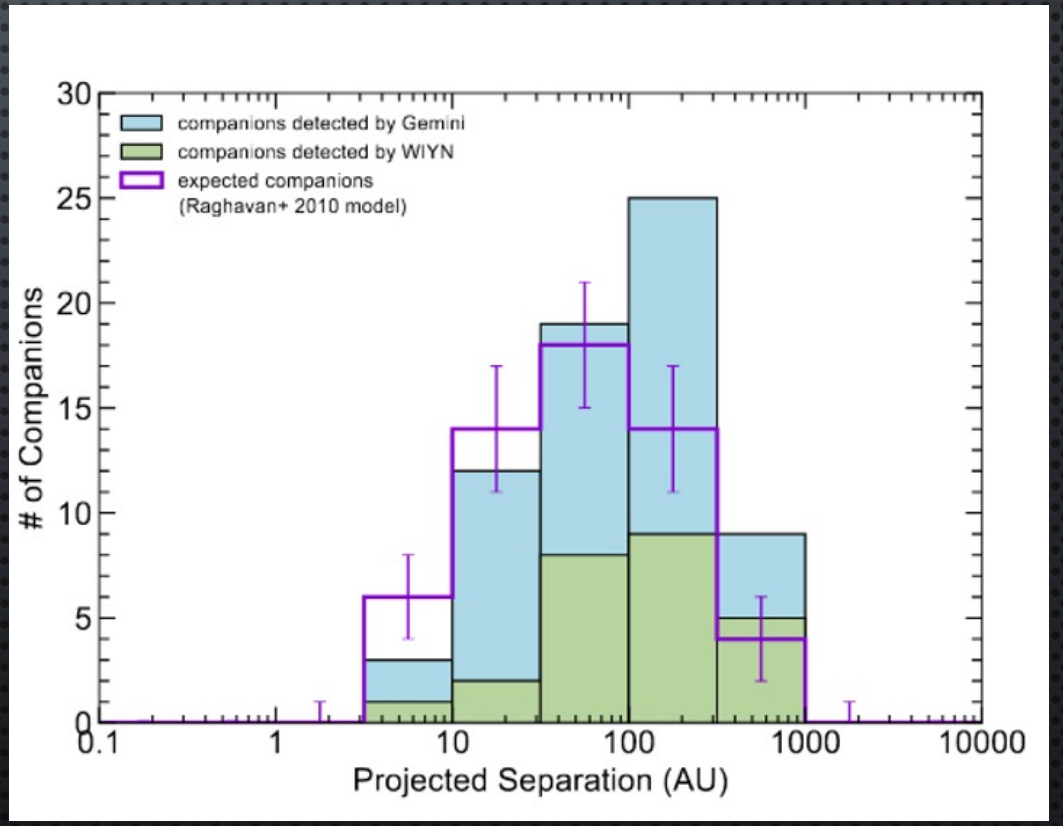
MEAN DETECTION AND CONTRAST LIMITS: ~20 MAS TO 1.2 ARCSEC



From:
Lester et al., 2021

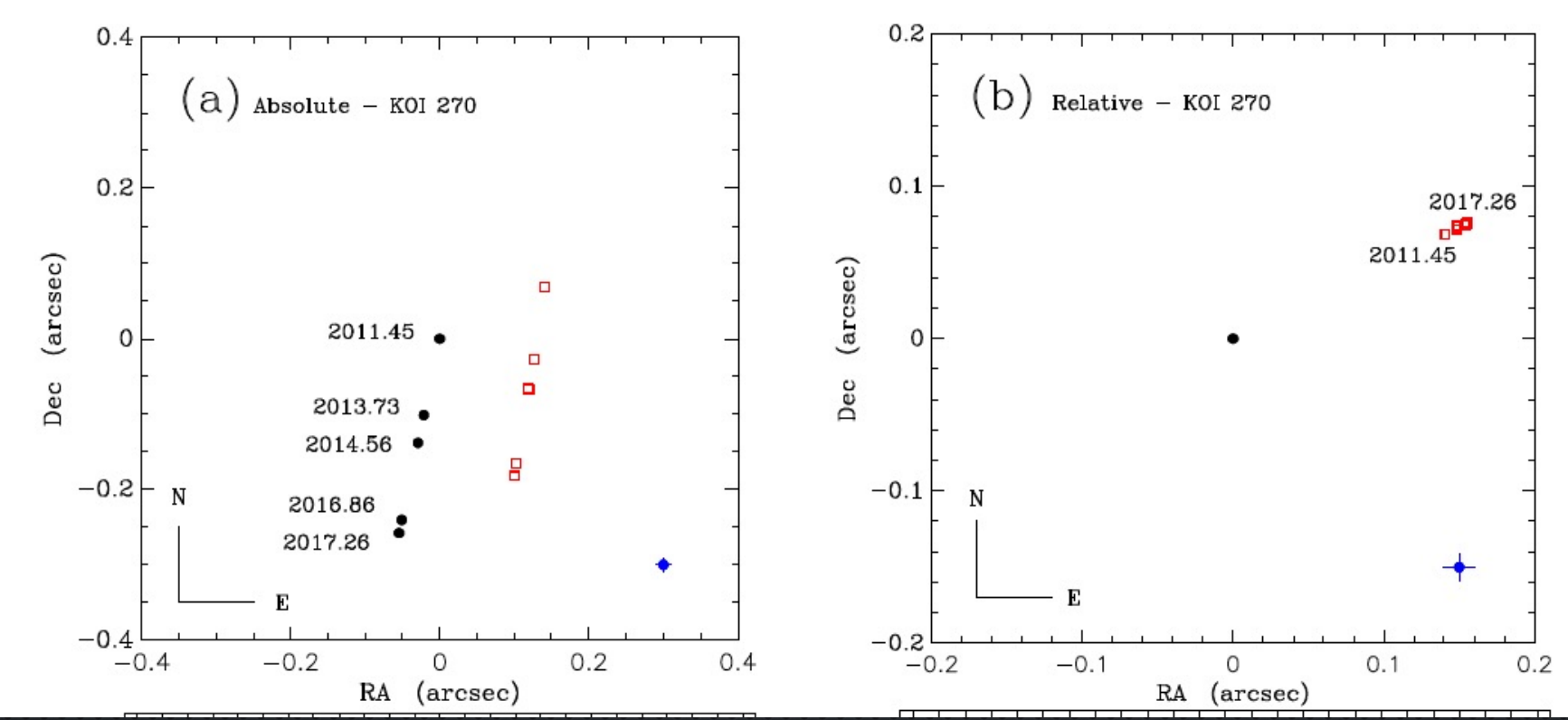
EXOPLANET BINARY HOST STARS:
MASS RATIO SIMILAR TO FIELD STARS, ORBITAL PERIOD DISTRIBUTION WIDER





See Howell et al., 2021; Lester et al., 2021

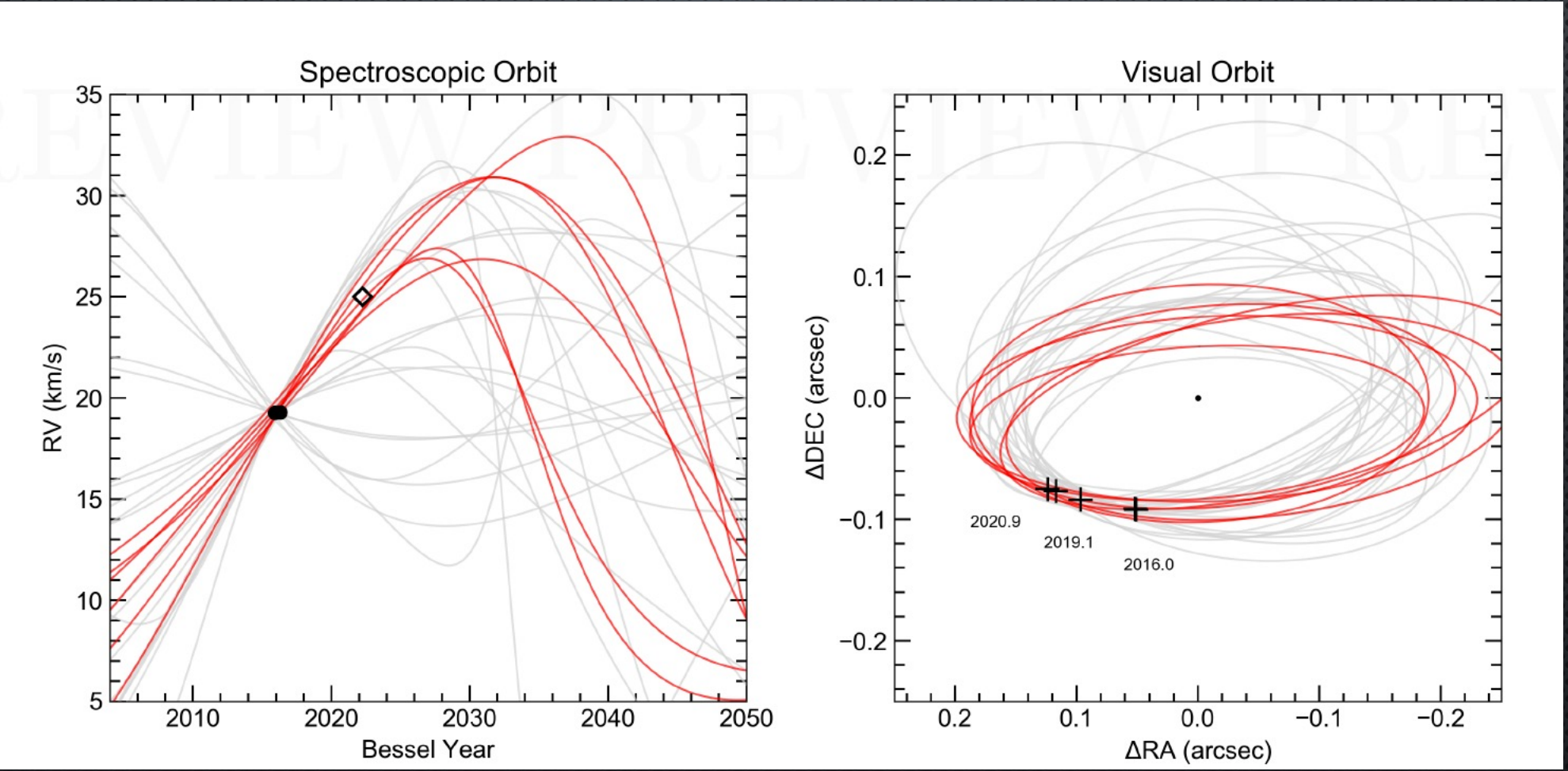
EXOPLANET HOST STAR ASTROMETRY - KEPLER



Absolute and Relative Astrometry of Typical Kepler Binary Host star – Kepler 449. This system hosts two exoplanets and the stellar pair is 43 au apart, with an orbital period near 270 years. Six years of speckle imaging reveals CPM behavior and possible plane crossing orbit. Will require decades for good potential orbital solution.

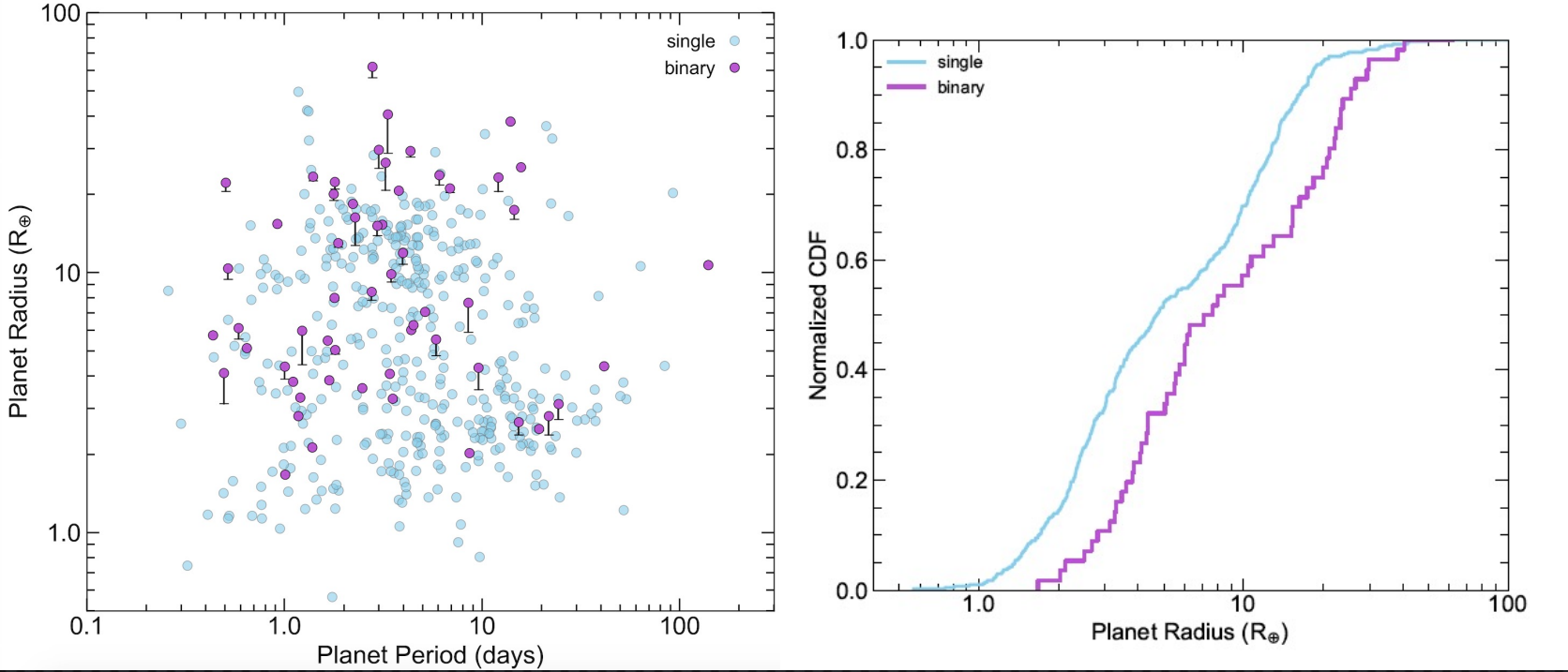
See Colton et al., 2020

TESS FULL ORBITAL SOLUTIONS



The brighter stars and closer distances allow good orbital solutions for many binary stars within a few years. Left: Radial velocity curves and possible spectroscopic orbits.
Right: Speckle imaging astrometric points and possible orbits. Red orbits are combined solutions.

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. Also see David Ciardi's talk, Friday (15 Oct) @ 15:15

SURVEYING EXOPLANET HOST STARS: A COMMUNITY SERVICE PROGRAM

- 2022 WILL BE THIS COMMUNITY PROGRAM'S 14TH YEAR OF OPERATION
  - KEPLER -> K2 -> TESS → PLATO, ROMAN, ARIEL + OTHER EXOPLANET PROGRAMS
- PROVIDE HIGH-RESOLUTION IMAGING, HIGH-SPEED PHOTOMETRY, A VARIETY OF FILTERS AND OBSERVING MODES, PROPOSAL AND OBSERVING SUPPORT.
- WE SUPPORT THE COMMUNITY WITH OPEN DATA ACCESS AND FULLY REDUCED DATA PRODUCTS HOSTED AT THE NASA EXOPLANET ARCHIVE (NEXSCI - EXOFOP)
- THE PROGRAM USES 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

SUMMARY

- Detecting unresolved stellar companions is of critical value to many aspects of exoplanet science
  - host star binary properties, planet and stellar properties, formation and evolution of exoplanetary systems
- Exoplanet host stars
  - Binary fraction seems similar to "field" stars
  - Binary hosts are more widely separated then "field" binaries
  - Exoplanet occurrence rate seems similar to single hosts – BUT …
  - Small (<2 R_E) planets are not detected in binary star systems
- Speckle interferometry on 4 to 8–m telescopes is not "your Mother's speckle imaging" – reaches diffraction limit (~20 mas), obtains contrasts of 6-10 magnitudes, sources as faint as 19TH 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 open science and value added to world-wide community & all Exoplanet missions

Contact: steve.b.howell@nasa.gov