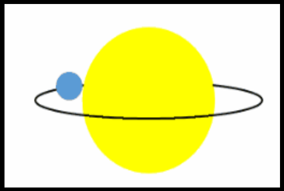


Amateur Astronomer Participation in the TESS Exoplanet Mission

Dennis M. Conti
Chair, AAVSO Exoplanet Section
Member, TESS Follow-up Observing Program

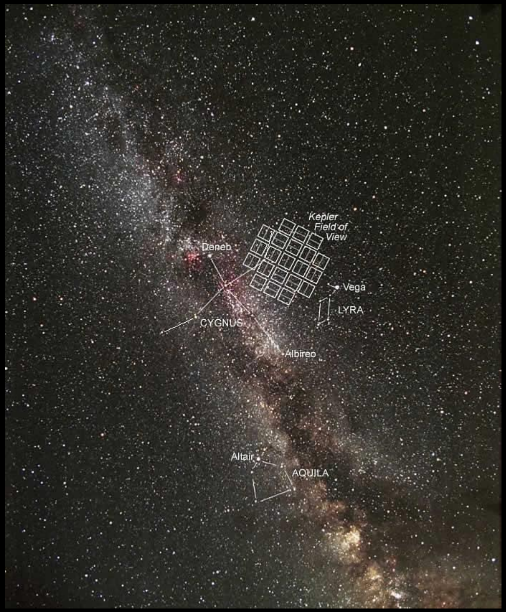
TESS:
Transiting Exoplanet Survey Satellite

↓

The next generation of exoplanet discovery space telescopes

TESS Predecessors

Kepler



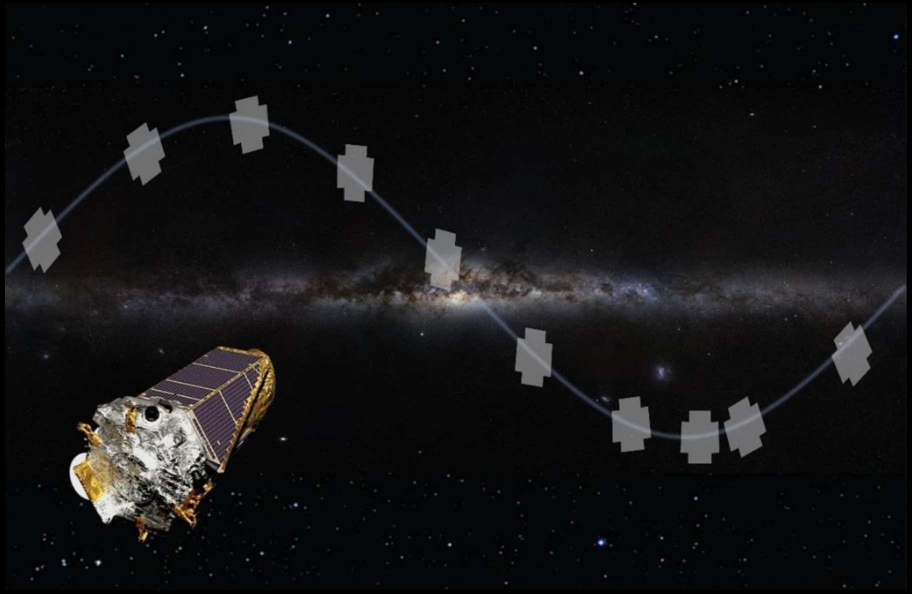
Courtesy : NASA

FOV: Small area in Cygnus

Targets: Earth-size planets around Sun-like stars

Status: Completed

K2



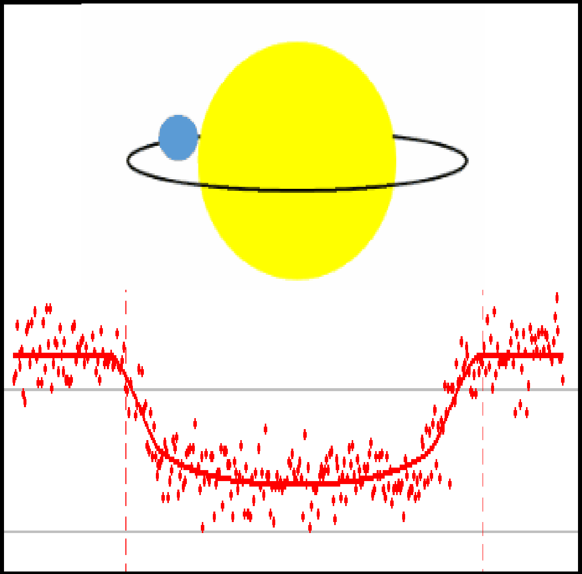
Courtesy : NASA

FOV: Ecliptic plane

Targets: Various

Status: Near end-of-life

All Use the Transiting Method



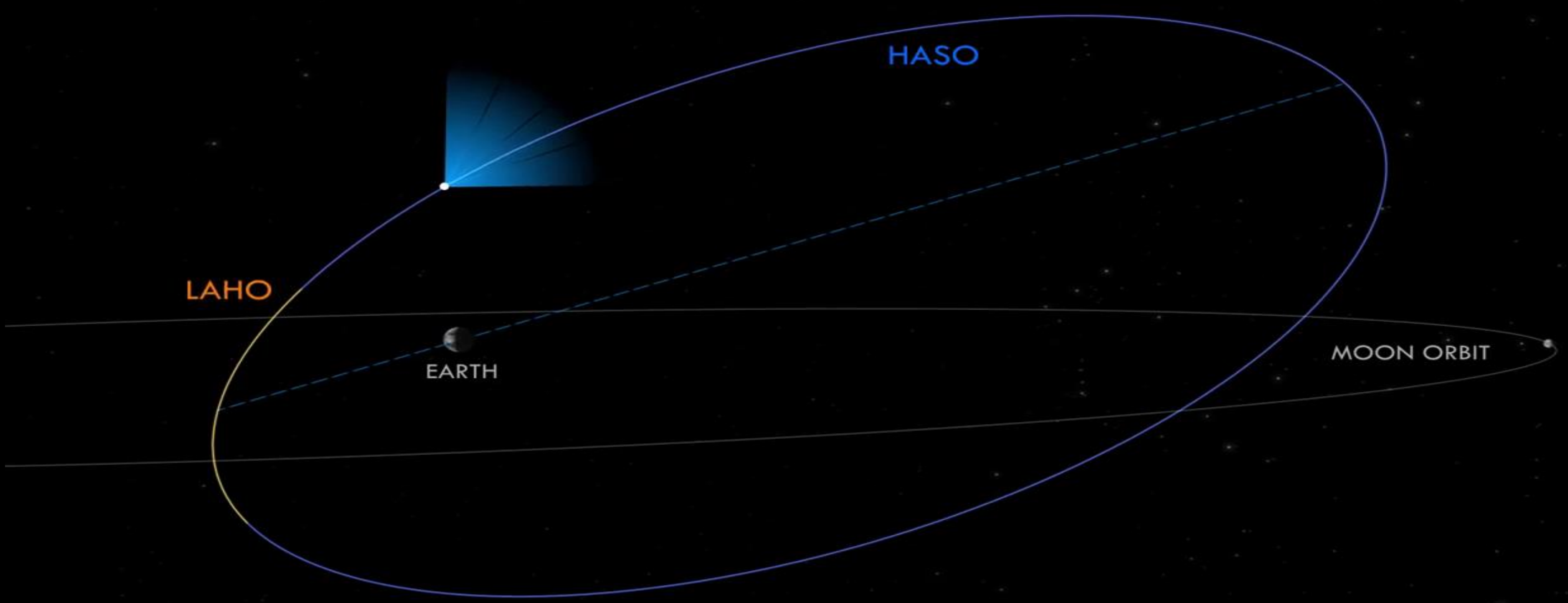
The TESS Mission

- Targets: near-by, bright stars
- Key science objective:
  "Measure the masses of 50 small (less than 4 Earth radii) transiting planets"
  - mass coupled with radius measurements from photometry, can give us average density
  - density will help us identify rocky planets
- TESS has been called a "finder scope" for JWST (James Webb Space Telescope)
- Amateur participation will be an important part of the TESS pipeline

Other Mission Facts

- Image downloads will occur 2 months after checkout
- TESS will cover 85% of the sky – an area 350 times that of Kepler
- TESS will observe into the near-infrared

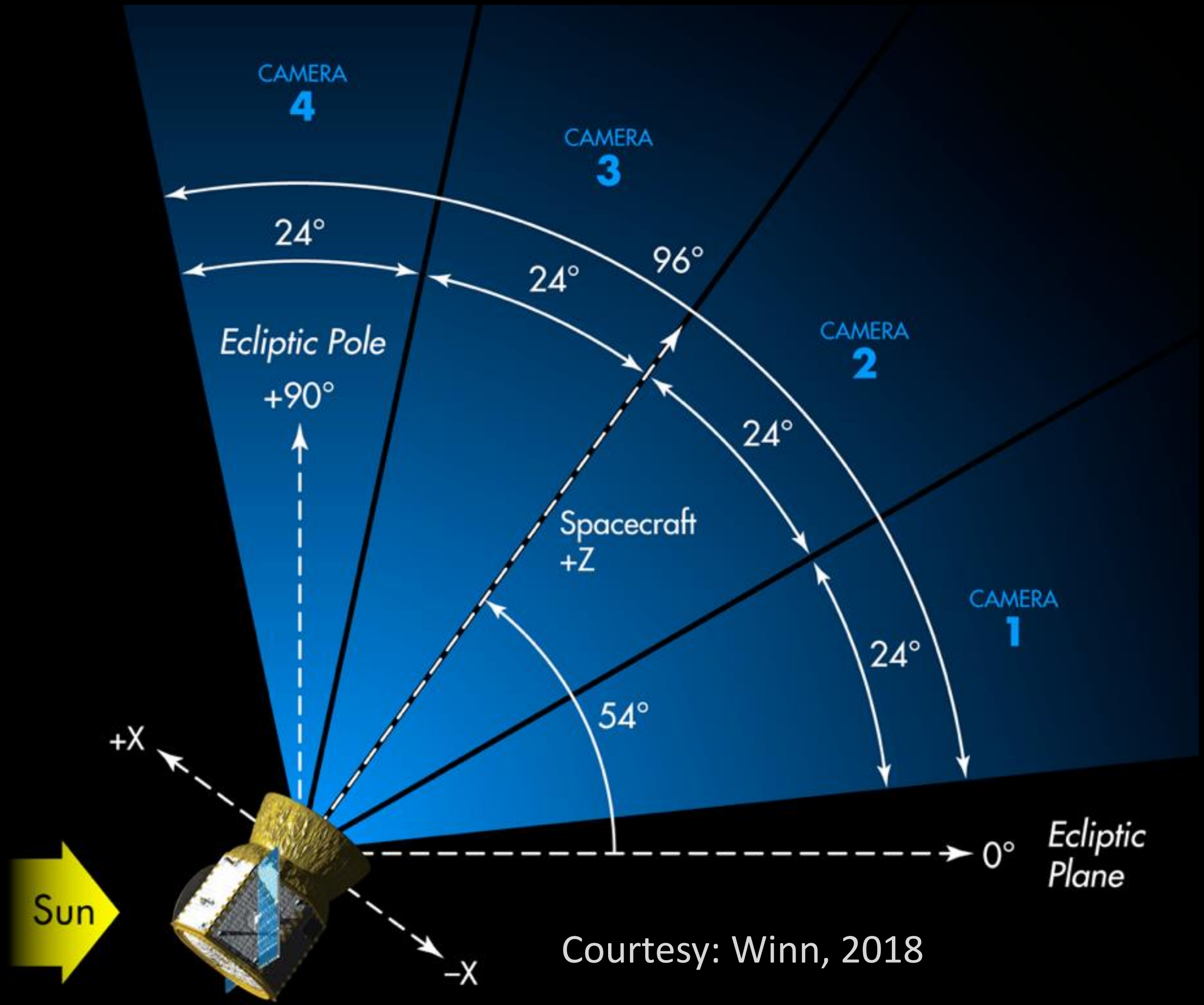
TESS' Unique Orbit



Courtesy: Michael Richmond

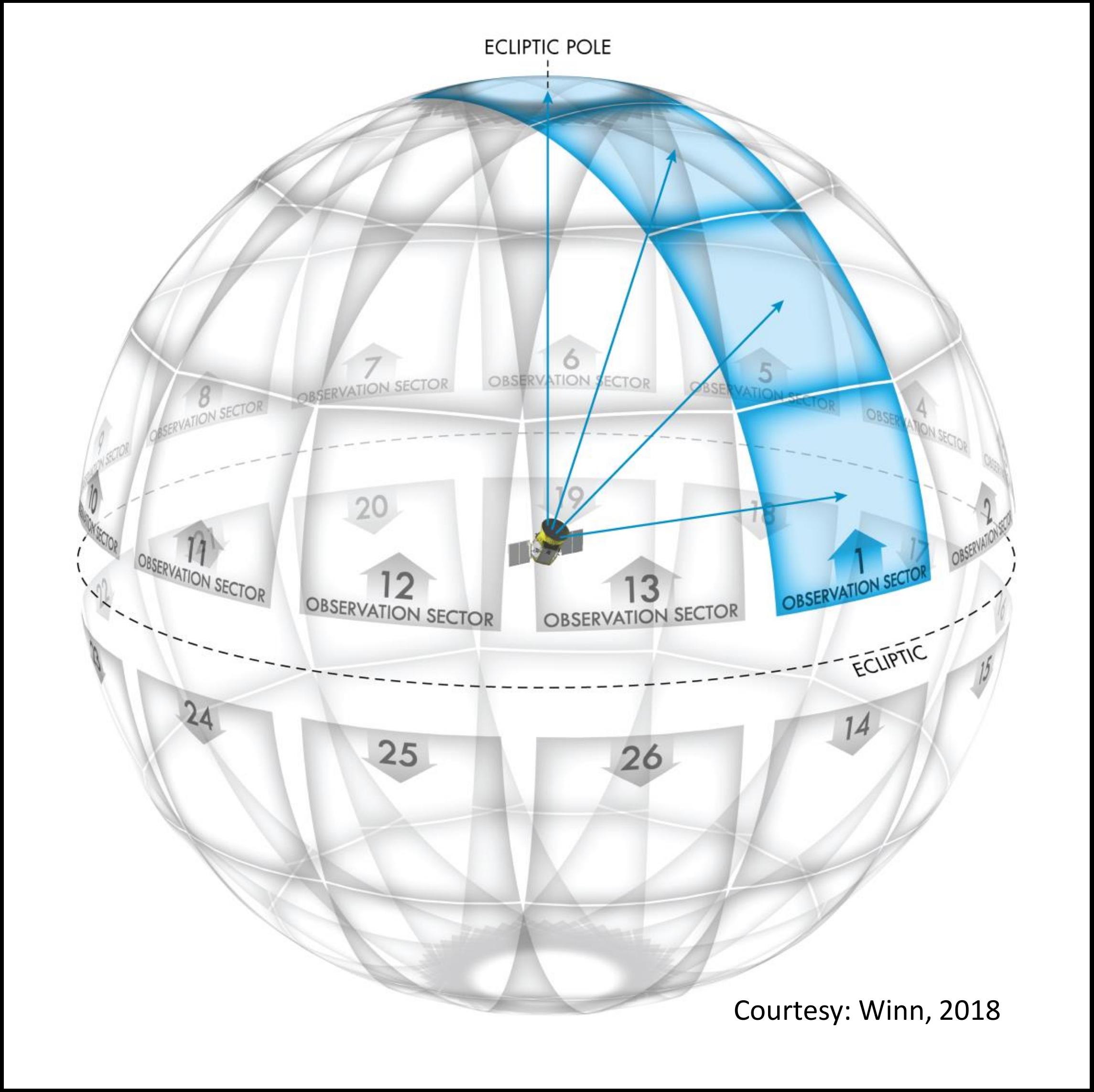
Note: Orbit is stable for a century!

TESS Orientation



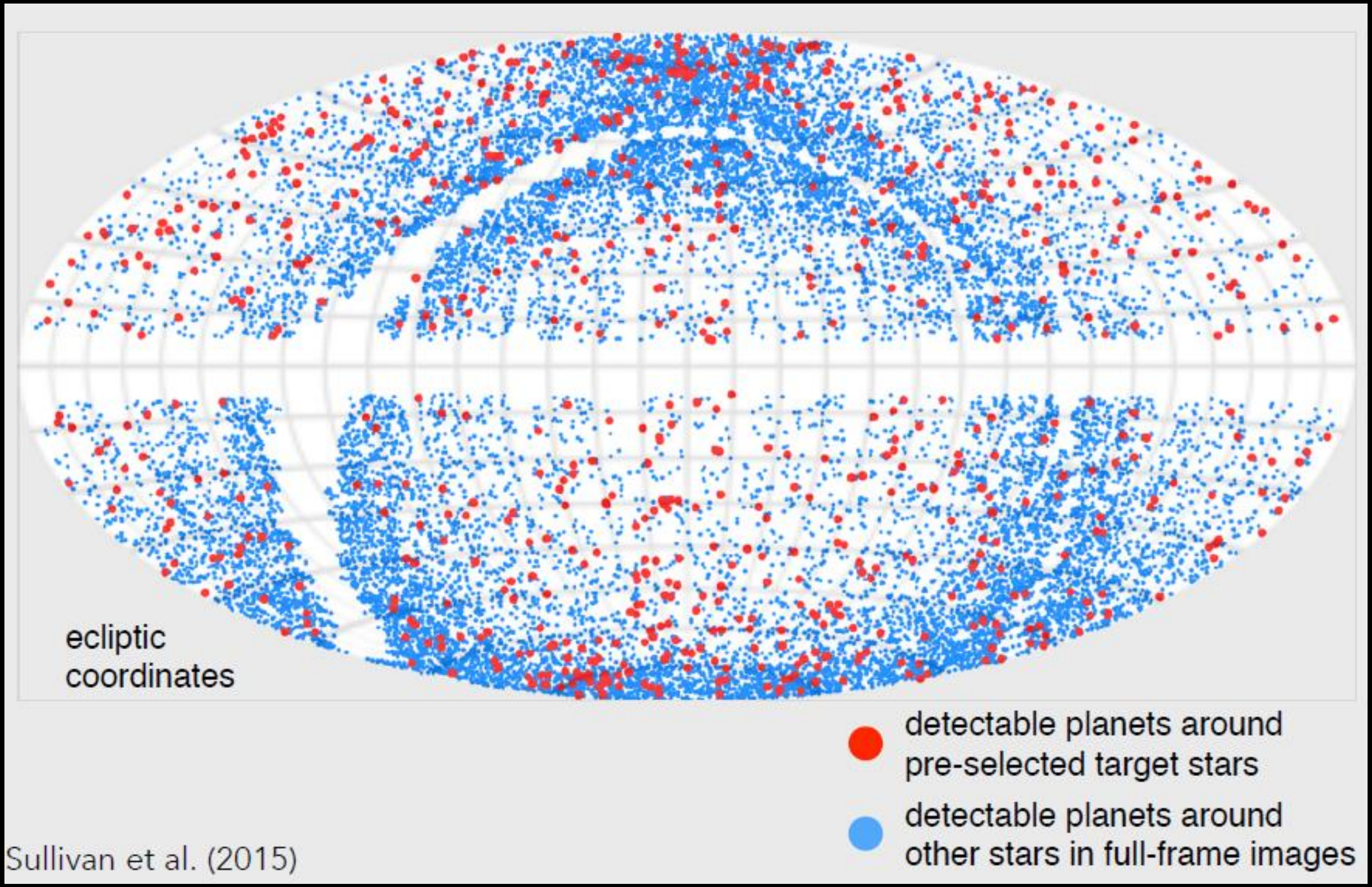
Courtesy: Winn, 2018

TESS All-Sky Survey



Each region gets 27 days of coverage

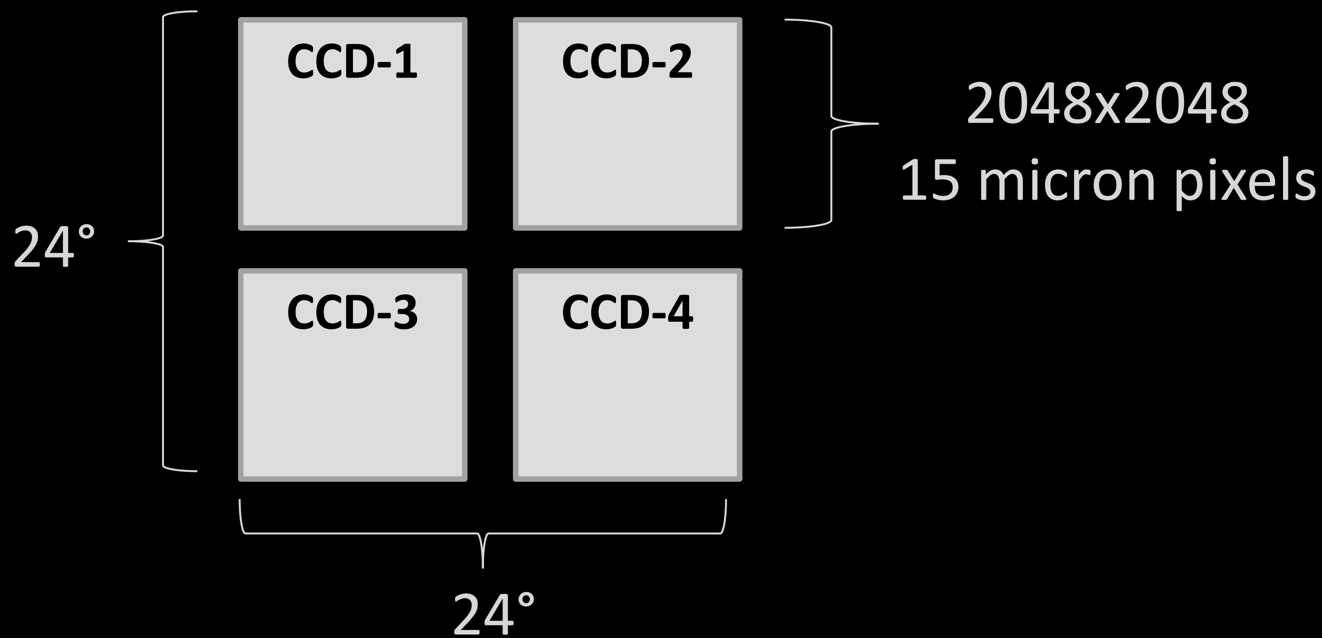
Simulated TESS Planet Detections



TESS Operation

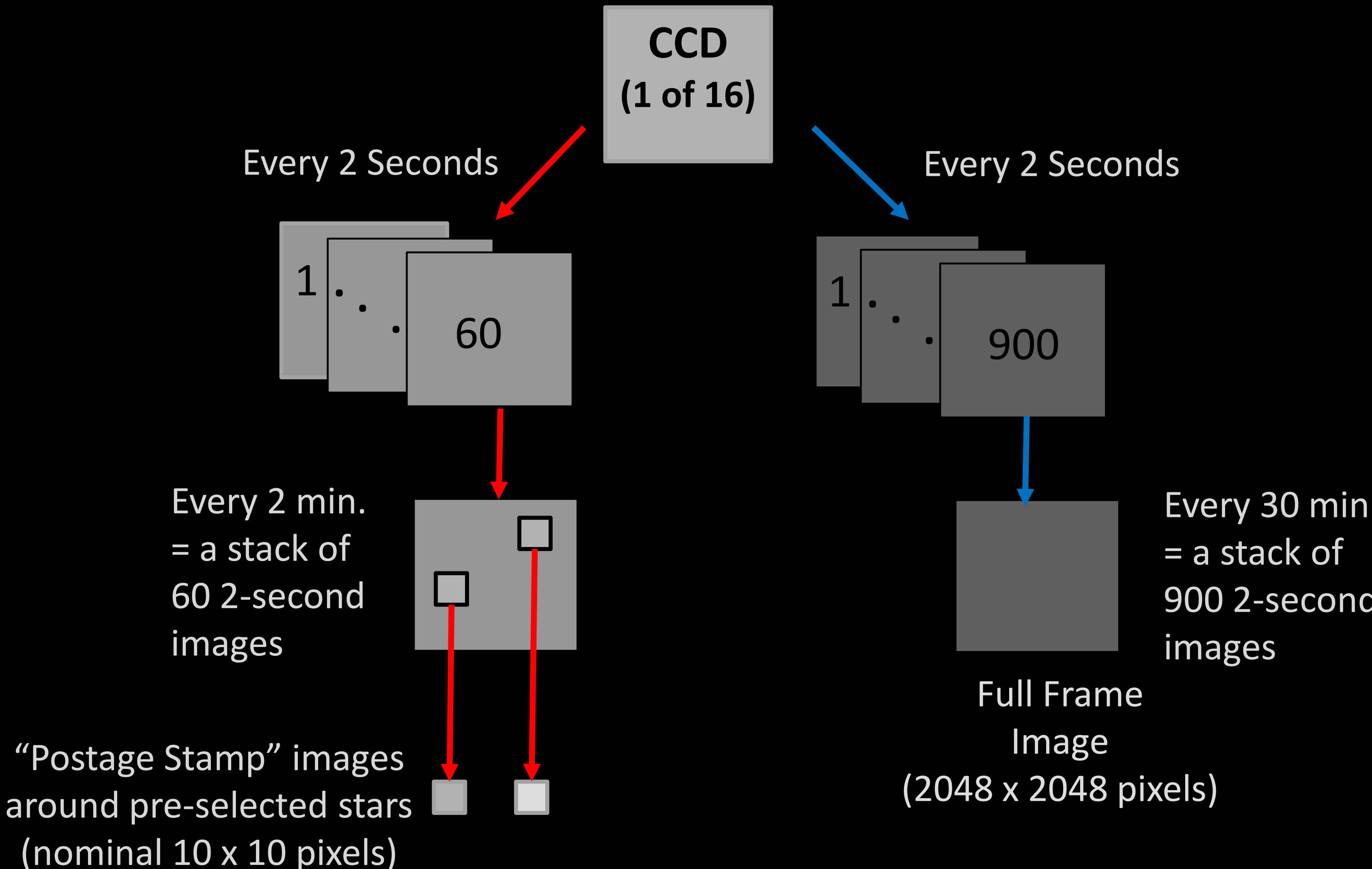
- Data downloads occur when TESS is near Earth in its orbit, in order to reduce download times
- Two 13.7 day orbits per sector
  - so each sector is viewed for at least 27 days
- Ecliptic poles are viewed for 300 days due to overlapping sectors
- Northern ecliptic imaging to begin mid-2019 (a portion of Southern ecliptic in mid-2018)
- Targets:
  - Overall stars: 470 million
  - Pre-selected stars: approx. 200,000

TESS Camera
(1 of 4)

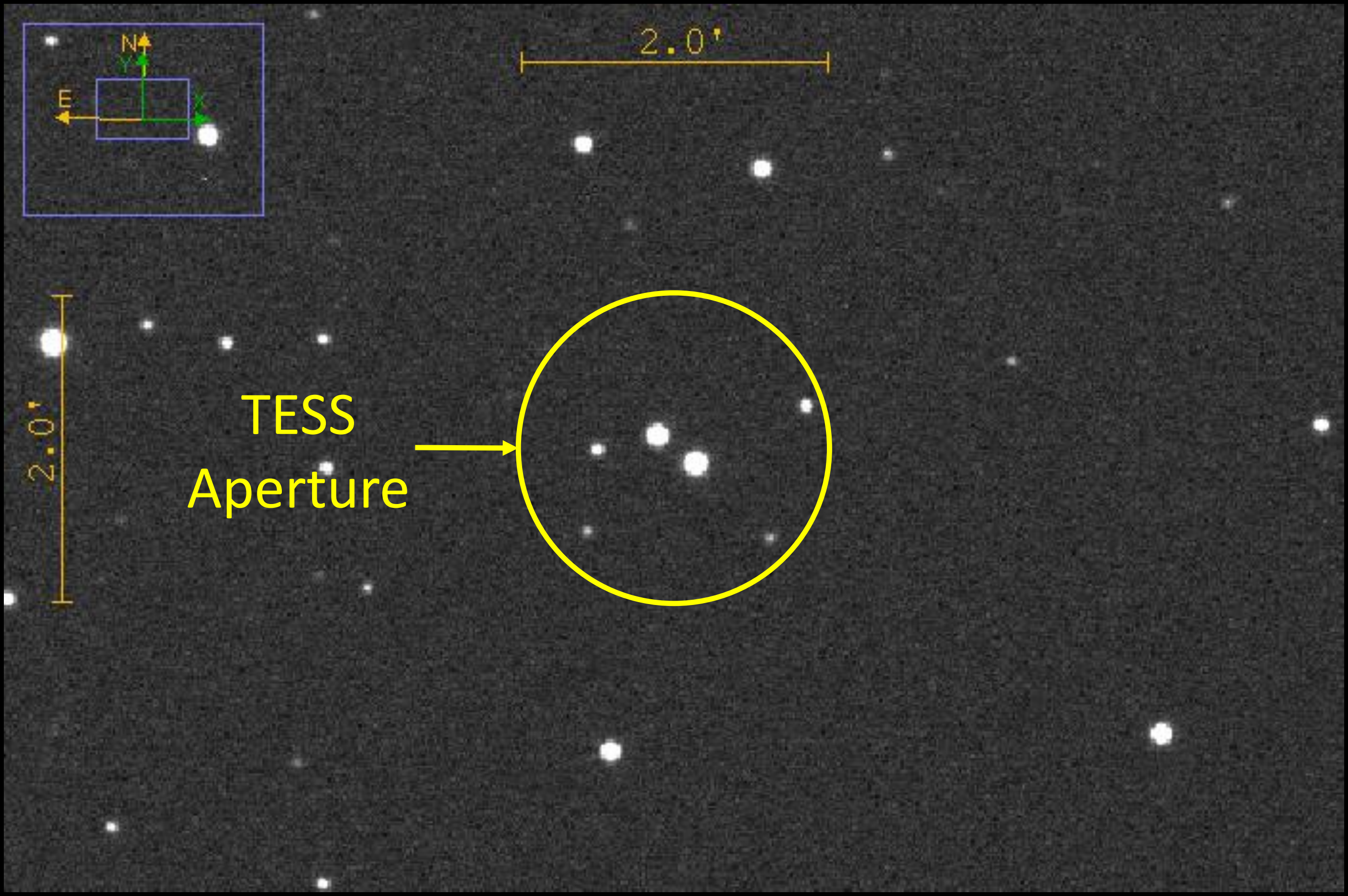


Each camera has a 4” aperture and f/1.4 lens
->image scale of 21”/pixel

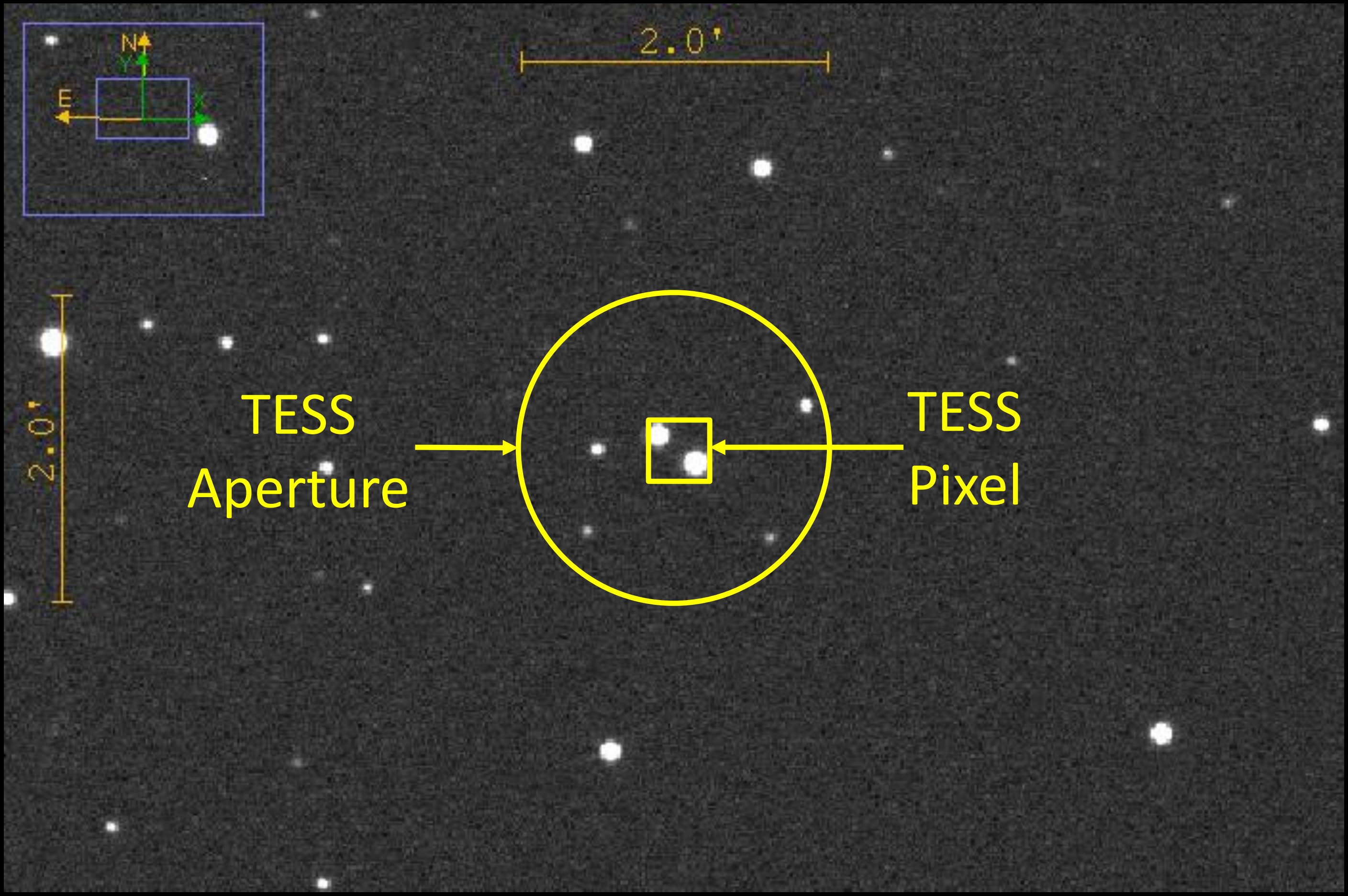
TESS Images


CCD
(1 of 16)
Every 2 Seconds
1
60
Every 2 Seconds
1
900
Every 2 min.
= a stack of
60 2-second
images
Every 30 min.
= a stack of
900 2-second
images
“Postage Stamp” images
around pre-selected stars
(nominal 10 x 10 pixels)
Full Frame
Image
(2048 x 2048 pixels)

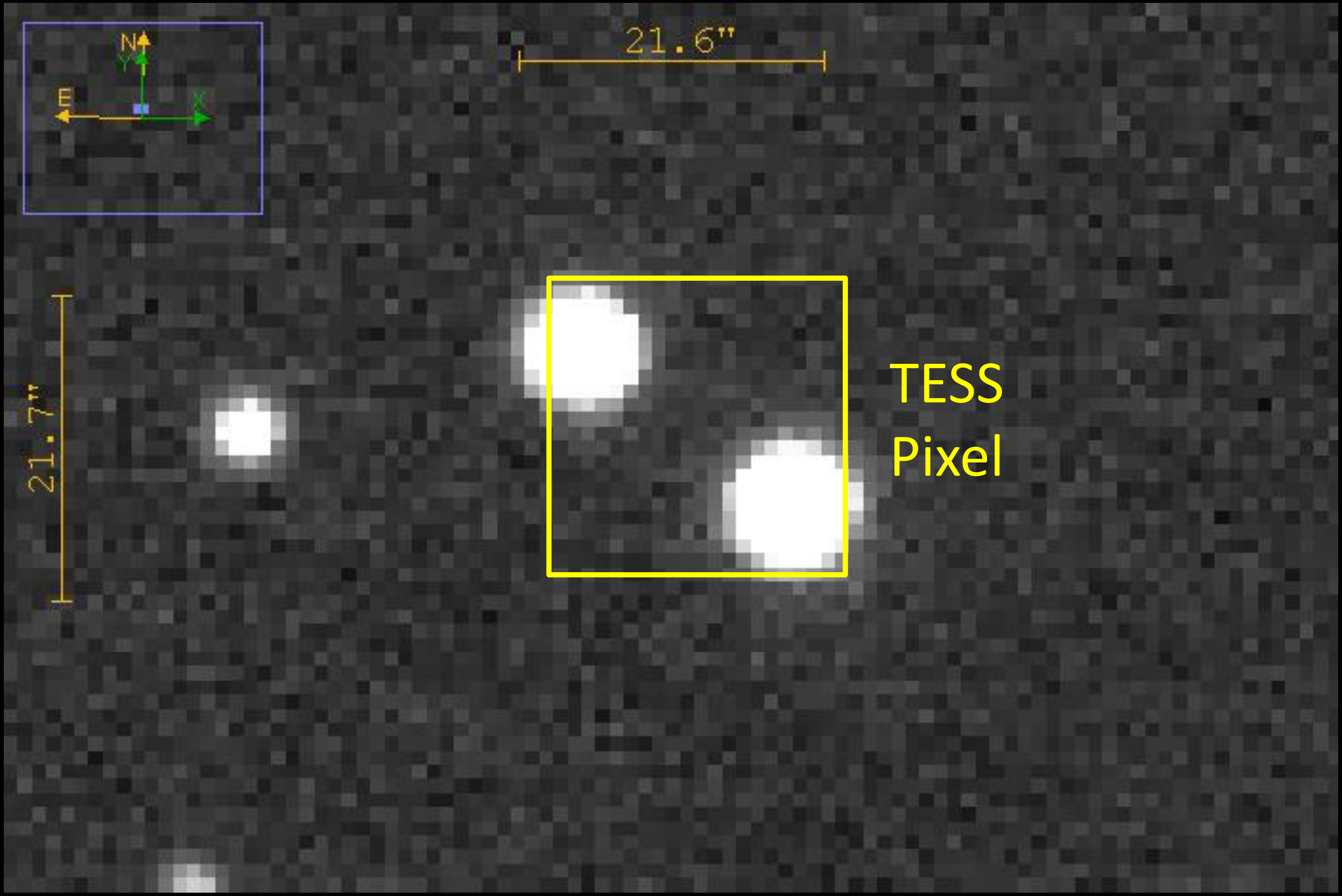
Typical TESS Photometric Aperture: nominal 1 arc-minute radius



TESS Pixel:
21 arc-seconds



TESS Pixel



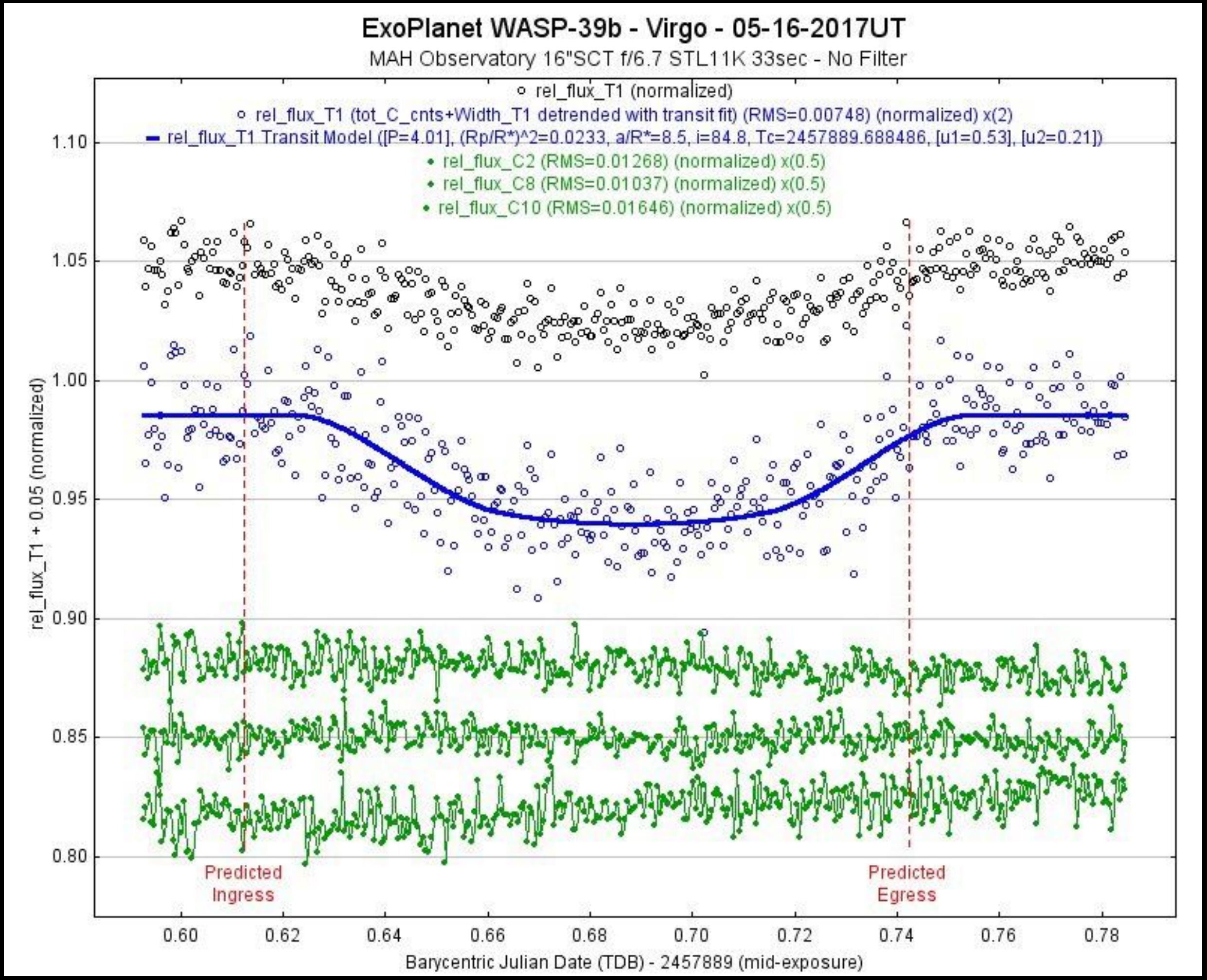
The Challenge

- Due to size of TESS pixels and photometric apertures, the light from multiple stars may be blended together
- Thus, periodic dips in light can be caused by either a true exoplanet transit or various types of false positives
- Initial vetting is first done by computer, then by voting of science team members
- Remaining vetting is done by ground-based, follow-up observations

Ground-based Observation Objectives

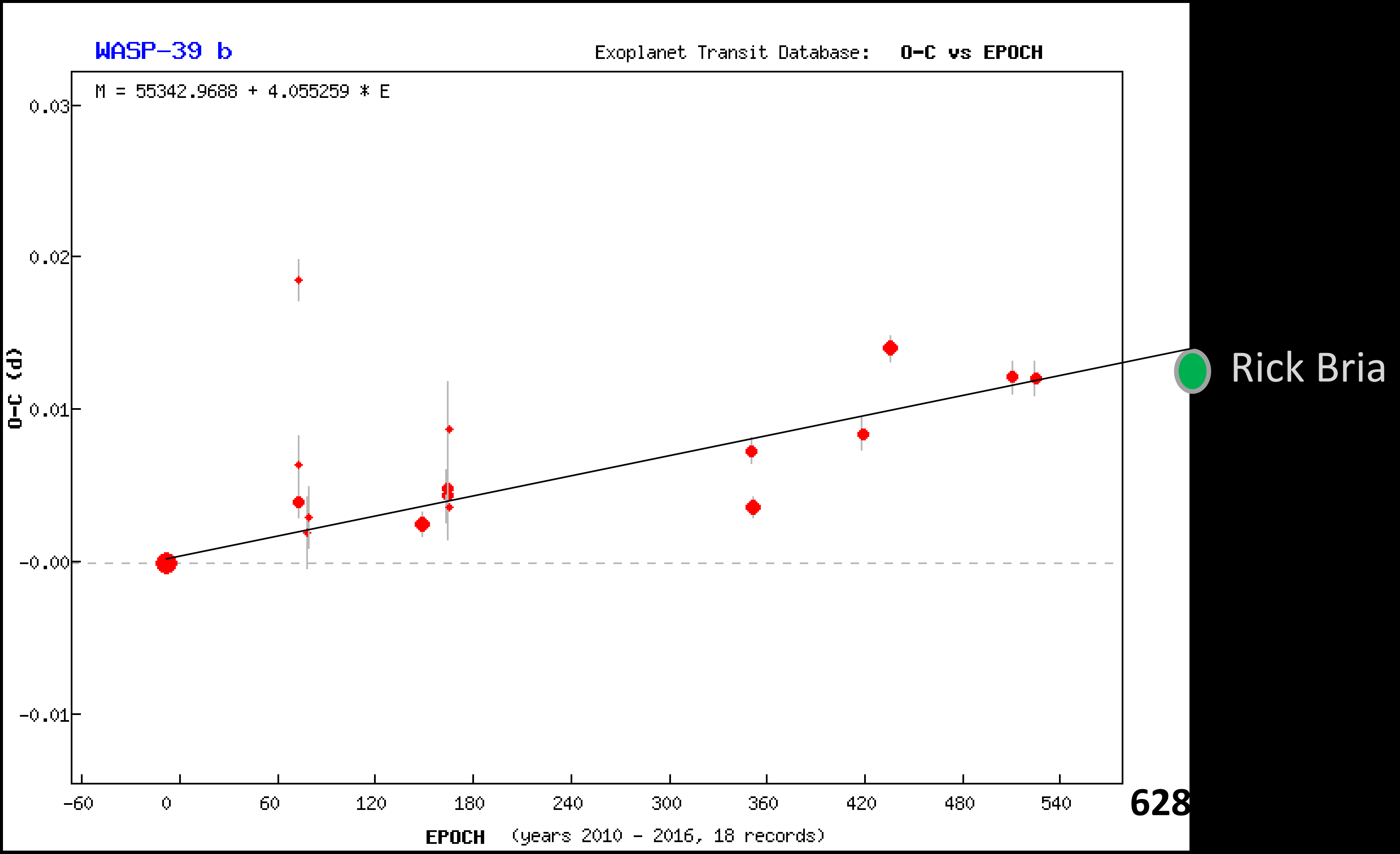
- Determine the source and cause of two or more periodic dips; could be due to:
  - False alarms (e.g., systematics or noise)
  - False positives
  - True exoplanet transits
- Obtain more accurate planet radii measurements
- Obtain transit time variation (TTV) measurements

TTV Example: WASP-39b



Courtesy: Rick Bria

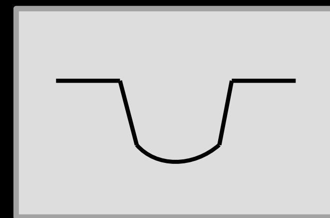
Observed – Computed: WASP-39b



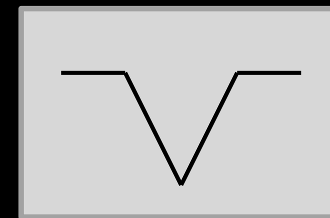
Courtesy: ETD

Photometric Factors Used in Detecting False Positives

- Shape (“morphology”) of light curve

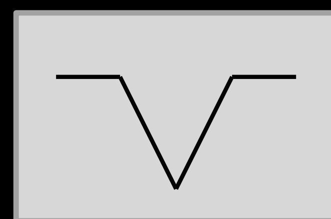


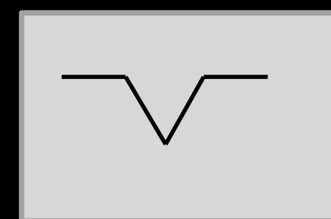
vs.



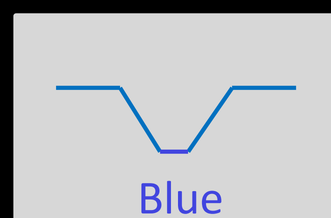
Bucket-shaped V-shaped

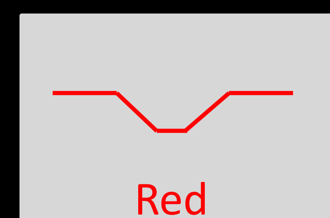
- Alternating (“odd-even”) V-shapes at different depths or not evenly spaced



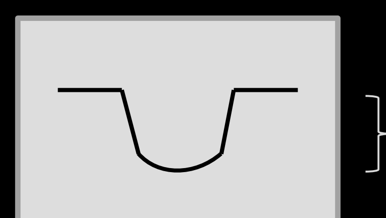


- Depth variations (> 5 mmag) in different passbands





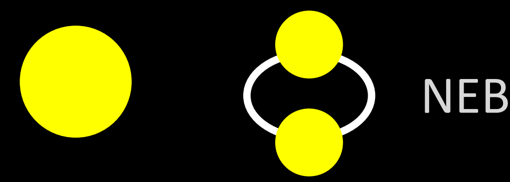
- Depths indicating a non-planetary transiting body (> 2.5 Jupiter radii)



$=(R_p/R_*)^2$

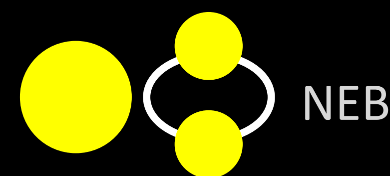
False Positive Scenarios and Detection Factors

The target star has a near-by eclipsing binary (NEB)*

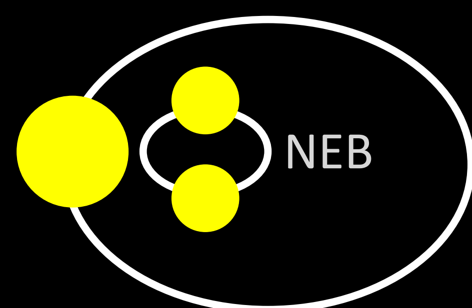


V-shape curve of a near-by star has odd-even depth changes

The NEB and target can't be spatially distinguished*



Hierarchical triple: the target star and NEB are orbiting each other

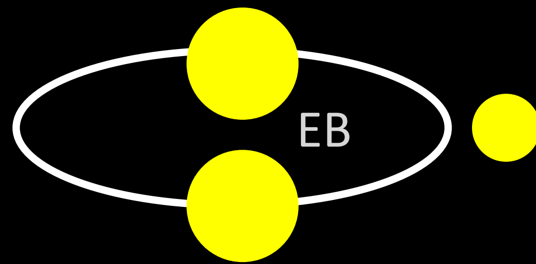


Depth varies in different bandpasses

* Note: could be chance alignments

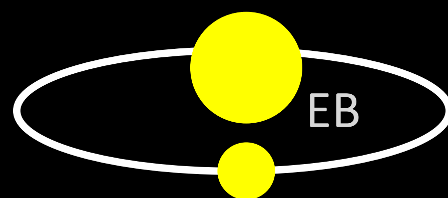
False Positive Scenarios and Detection Factors (cont'd)

Target star is an eclipsing binary (EB) with blending from a neighbor



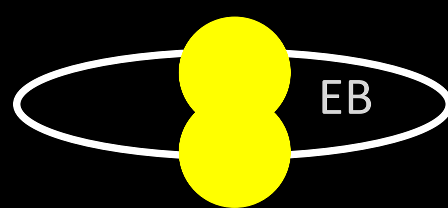
A V-shaped curve (if spatially resolvable from neighbor)

Secondary star in an EB is small enough to mimic a planet transit



Depth and radius of target may imply a non-planetary transit

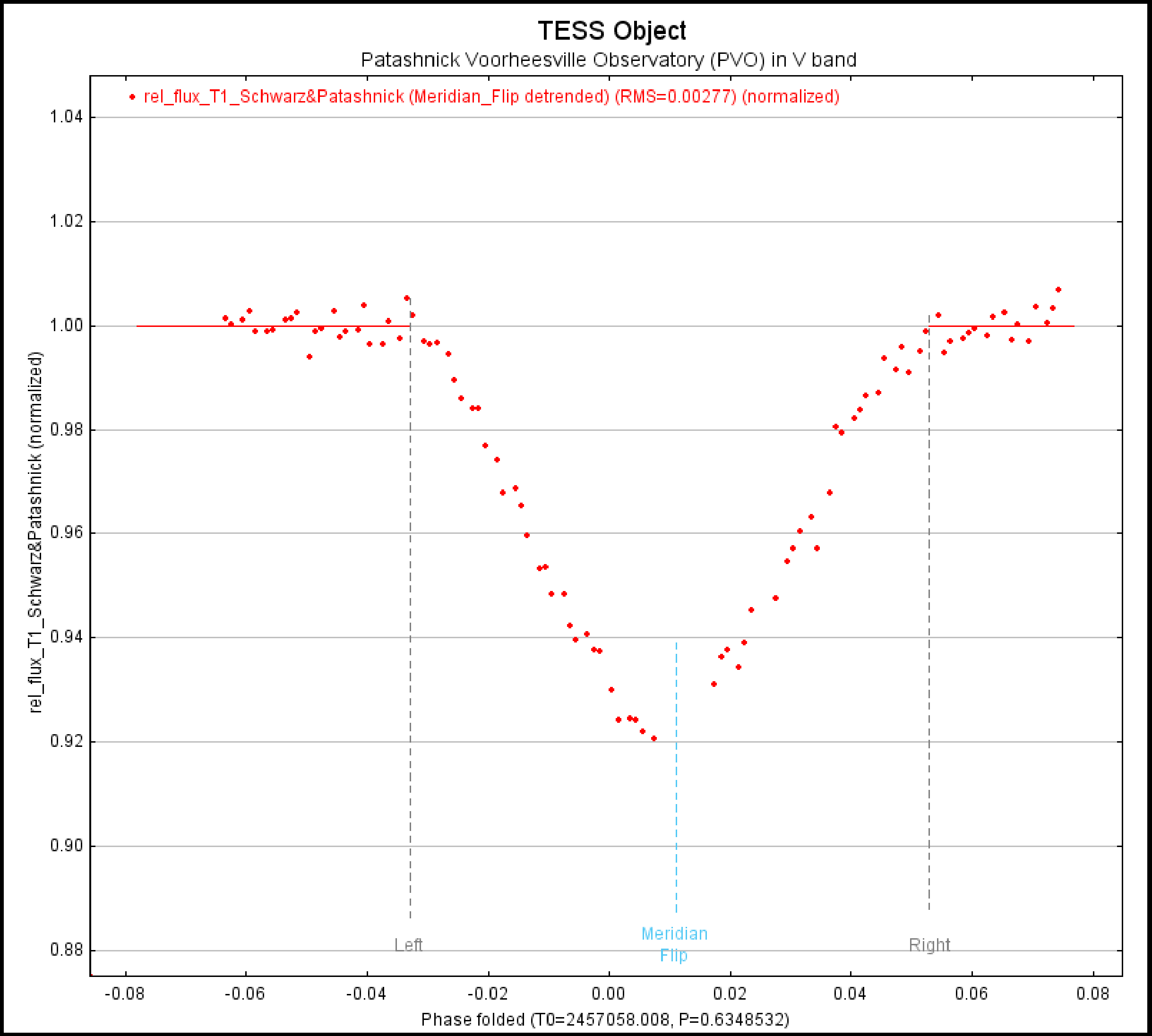
Secondary star in an EB "grazes" the primary star



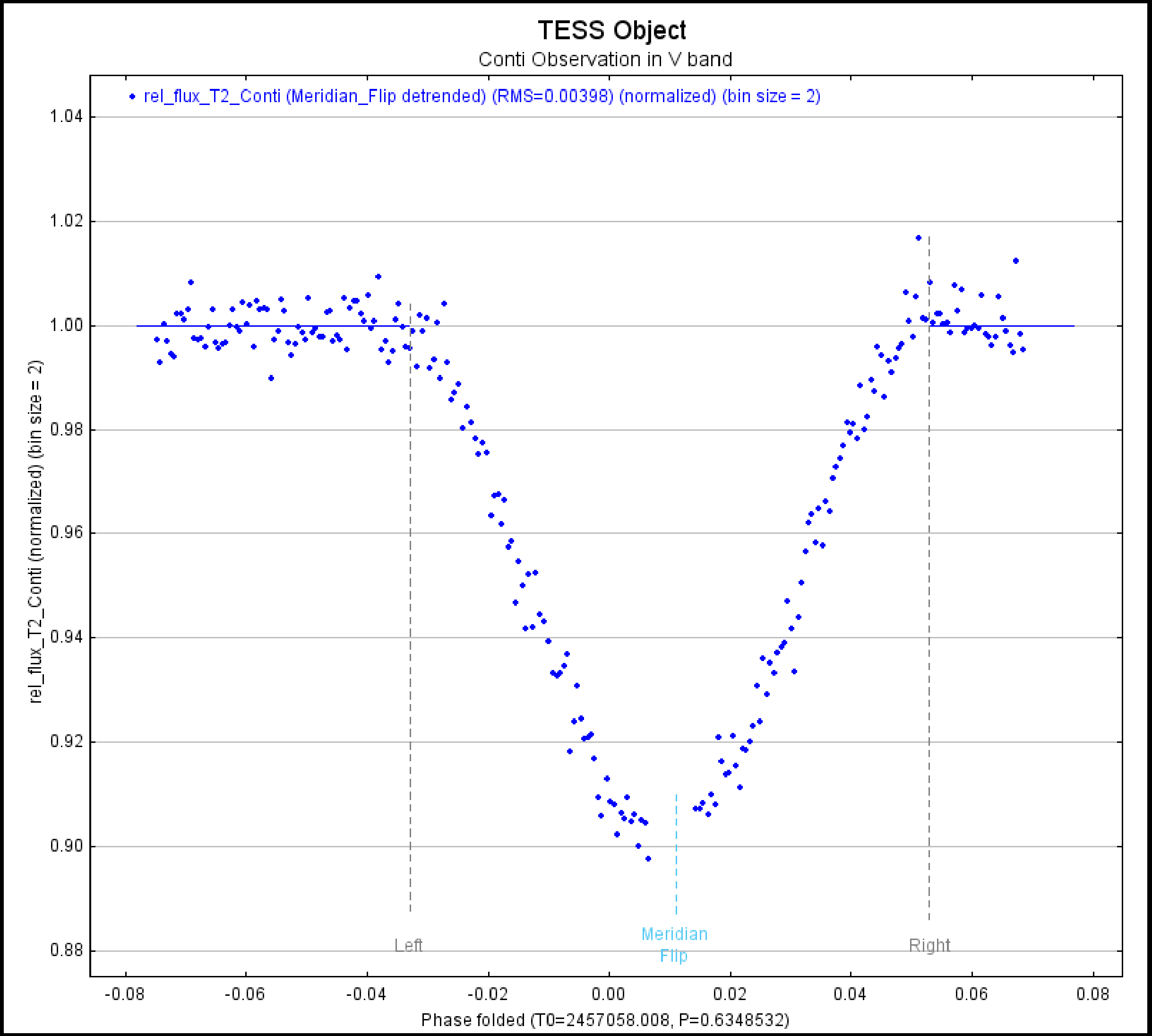
Typically a V-shaped curve

Example: Detection of a NEB

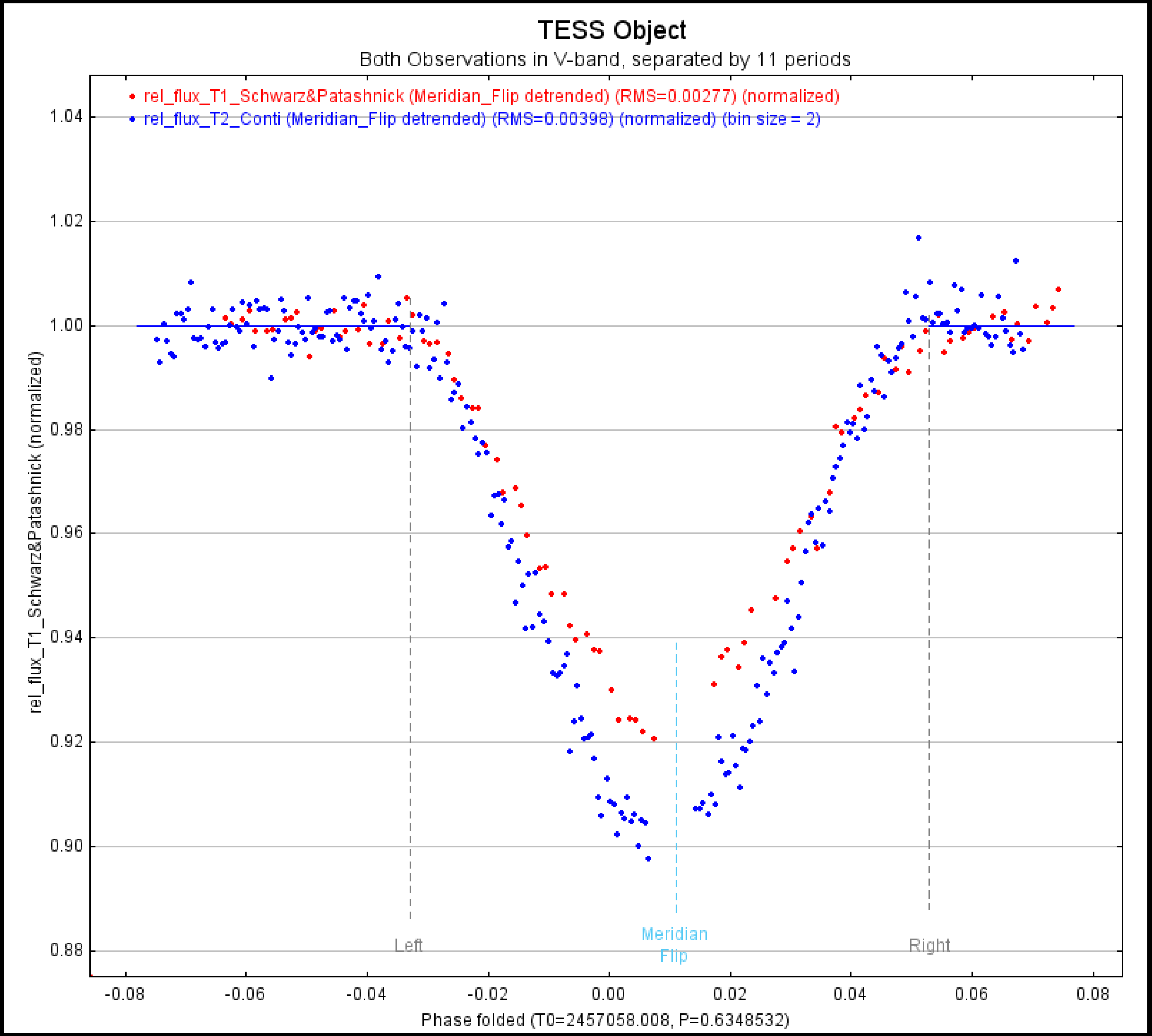
Observation 1



Observation 2
(11 eclipses later)



Phase Folded Observations



Overall TESS Pipeline

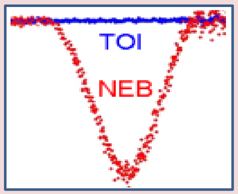
TESS Objects of Interest (TOIs)

False positive screening, blend & stellar characterization

Seeing-Limited Phot.

(SG1)

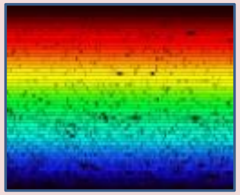
ID nearby EBs, measure photometric blending



Recon Spectroscopy

(SG2)

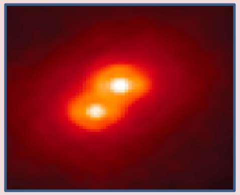
Stellar parameters, ID blended spectra



High-Res Imaging

(SG3)

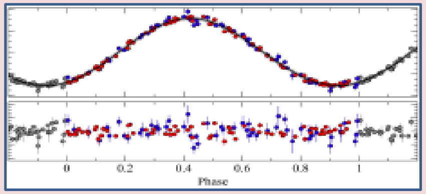
Resolve close companions, characterize multiplicity



Planetary confirmation and characterization

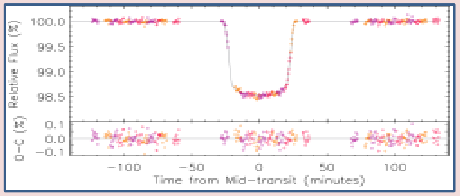
Precise RV Work (SG4)

Derive planetary orbits and masses



Space-Based Photometry (SG5)

Improved light curve, ephemeris, meas. TTVs



Courtesy: Collins, 2018

Amateur Astronomer Participation

- Help distinguish false positives: TESS Follow-up Observing Program (TFOP) Seeing Limited Subgroup
- Help refine the ephemerides after planets are confirmed: observation uploads to ExoFOP-TESS
- Products required from observer:
  - Sample FOV and a plate solved image
  - Comparison stars used
  - Light curve
  - Measurement and plot configuration files used

Online Tools

- TESS Transit Finder – helps observers find suitable targets for a given location during a given time period
- TESS Observations Coordinator – notifies other observers of intent to observe a particular target at a certain time and in a certain wavelength
- ExoFOP-TESS – submission of observation summaries and data products

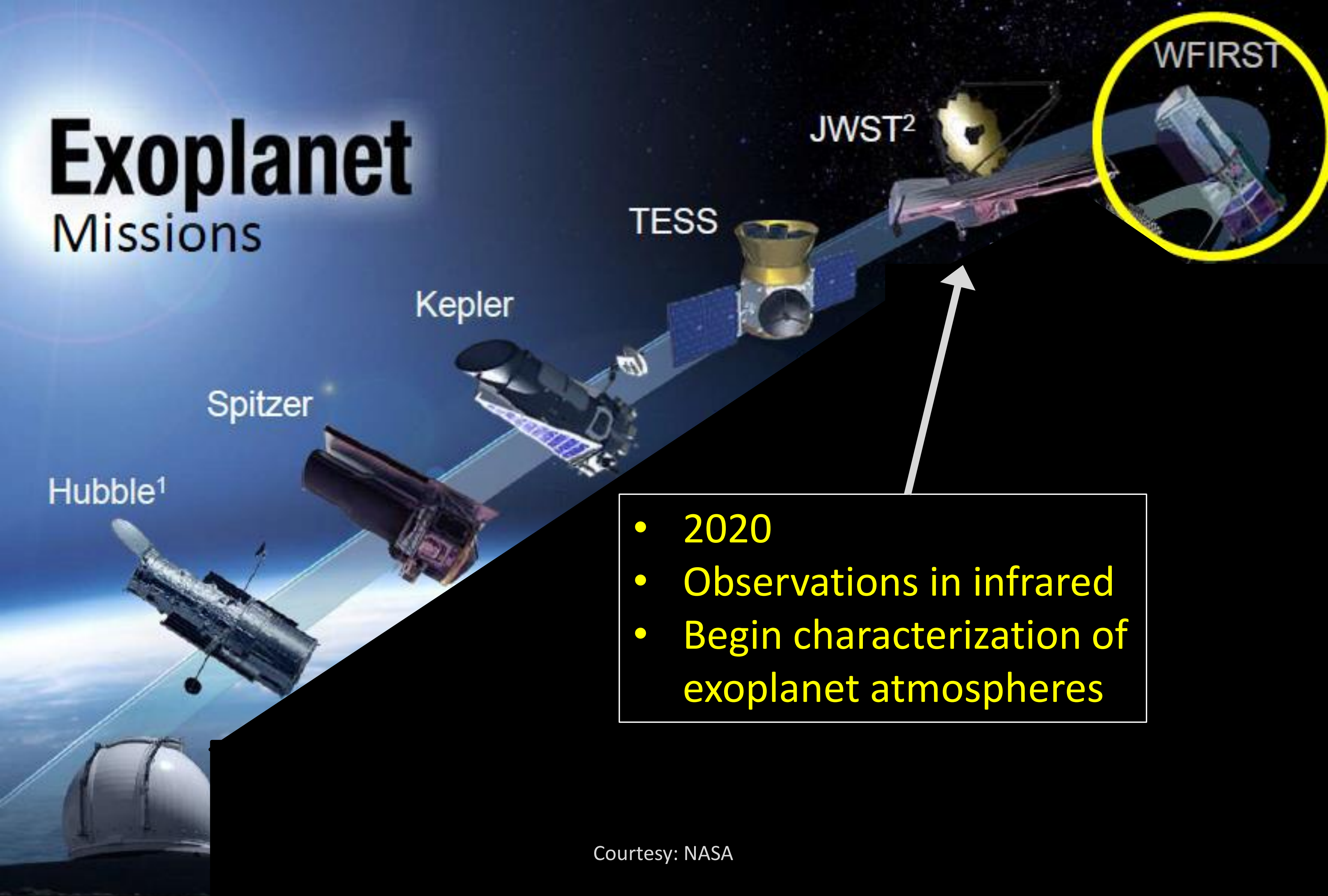
Training Resources

- AAVSO Exoplanet Observing Course – an online, four week course:
  - exoplanet observing best practices
  - use of AstroImageJ for image calibration, differential photometry, and exoplanet transit modeling
- Documentation: "A Practical Guide to Exoplanet Observing" (http://astrodennis.com)

Best Practices

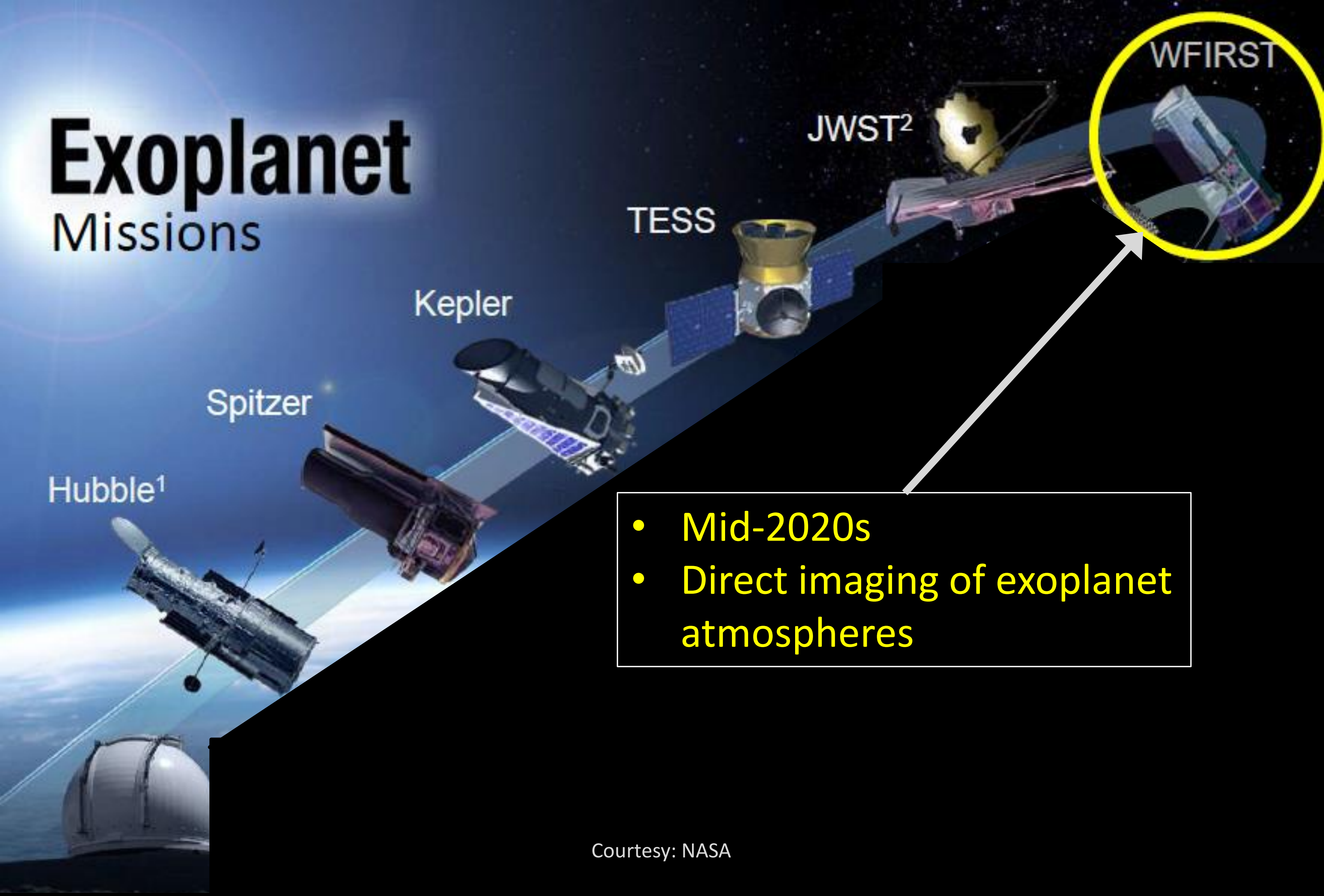
- Image for at least 30 minutes pre-ingress and post-egress
- Use autoguiding to achieve minimal image shift over a 4-6 hour observation window
  - Preferably, guide on the science image
- Use a precise timing source
- Use BJD_{TDB} as timebase
- Handle meridian flips efficiently
- Maximize SNR of target without reaching non-linearity or saturation

Future NASA Exoplanet Missions



- 2020
- Observations in infrared
- Begin characterization of exoplanet atmospheres

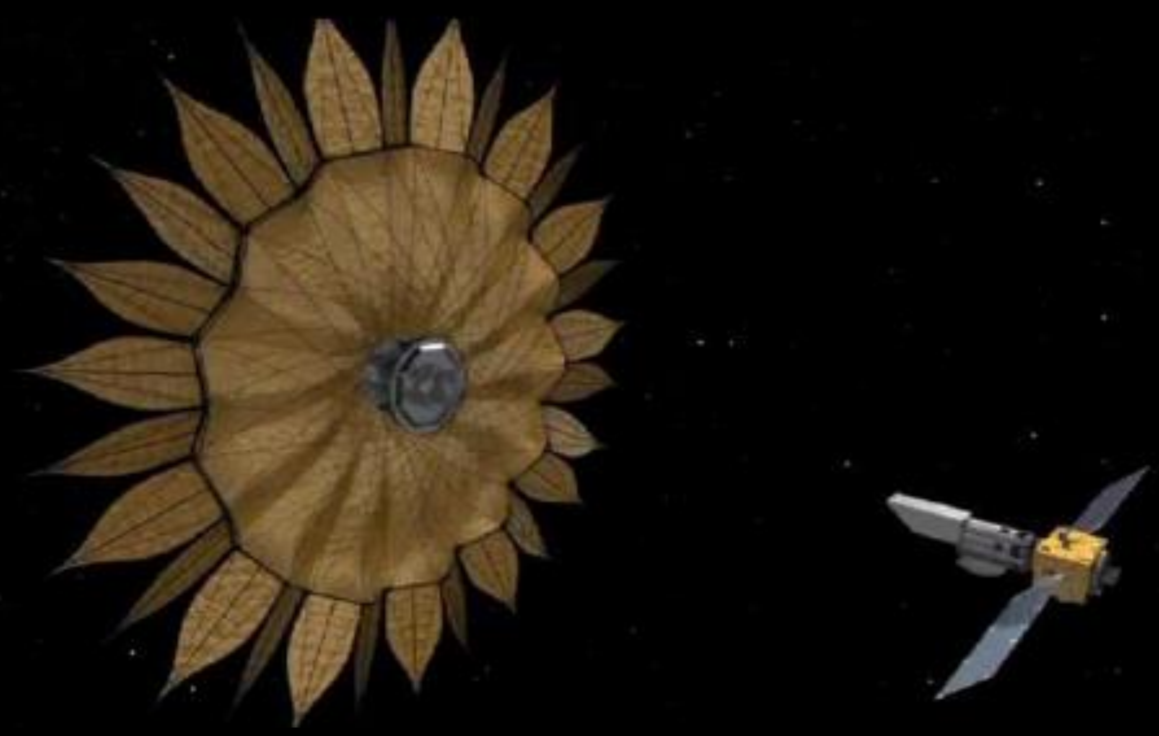
Courtesy: NASA



- Mid-2020s
- Direct imaging of exoplanet atmospheres

Courtesy: NASA

Starshade Technology



Courtesy: NASA

Summary

- Amateur astronomers have already proven their value in supporting existing exoplanet surveys and missions
- The TESS mission provides amateurs with the opportunity to participate in the next frontier of exoplanet discovery
- Opportunities for co-authorship of scientific papers provide an additional benefit
- Amateurs with astro-imaging experience already have the basic complement of equipment and techniques
- Training opportunities, software and documentation are available to enhance one's exoplanet observing skills

Contact Information

Email: dennis@astrodennis.com

Website: http://astrodennis.com