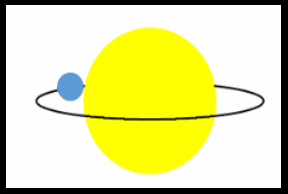


The Fundamentals of Exoplanet Observing

Dennis M. Conti
dennis@astrodennis.com
www.astrodennis.com

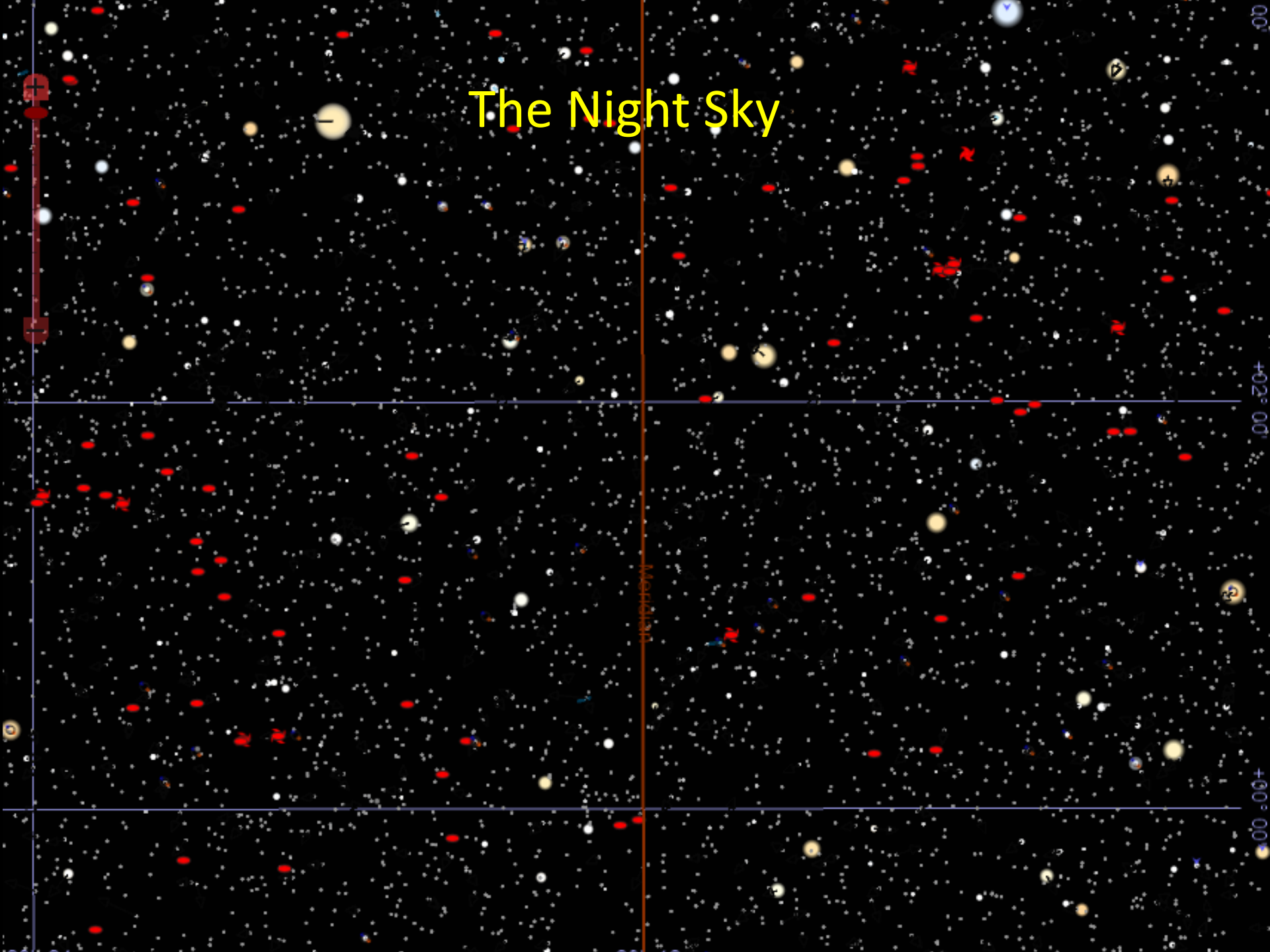
Chair, AAVSO Exoplanet Section

The AAVSO
(American Association of Variable Star Observers)

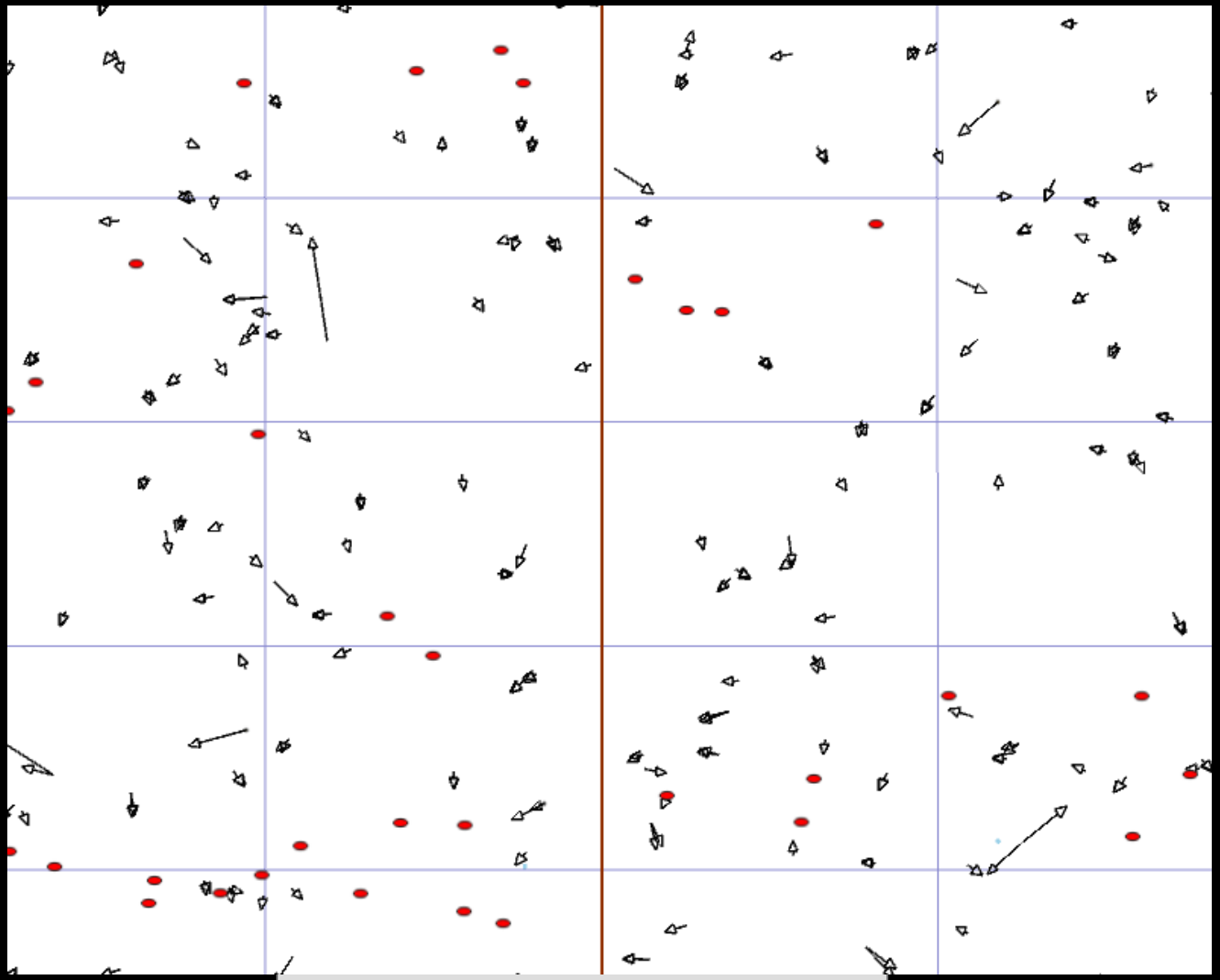
- Founded in 1911:
  - traditional focus: observing and archiving data on variable stars
  - users: professional astronomers and research scientists
  - foster and support pro/am collaborations

- In 2015, established an Exoplanet Section

- Section's purpose: help observers conduct research-grade, exoplanet observations


The Night Sky

The Sky is a Very Active Place!!



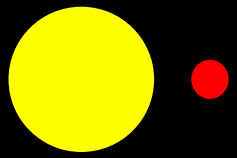
Proper Motion of Stars
for the Next 1,000 Years

Some Interesting Facts

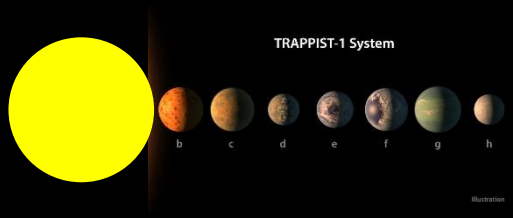
- There are as many planets as there are stars
- Planets are diverse in mass, density, and composition
- Some planets are tidally locked to their parent star
- 1 out of 6 planets might have a massive exomoon
- More than 50% of stars have one or more companion stars
- Planets in multi-star systems are quite common
- Some binary stars eclipsing each other can look like a planet transiting a host star

The Strange World of Exoplanets

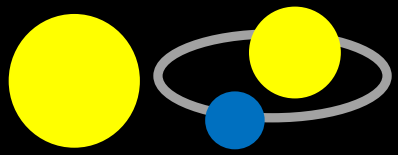
- Most exoplanets we have discovered are close-in, large planets: “Hot Jupiters”



- Some stars have multiple planets

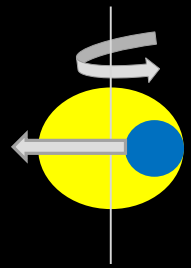


- Some planets orbit a star in a multiple star system

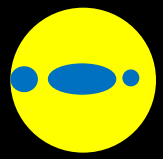


- Some “planets” are free-floating

- Some planets’ orbits are opposite from their star’s rotation

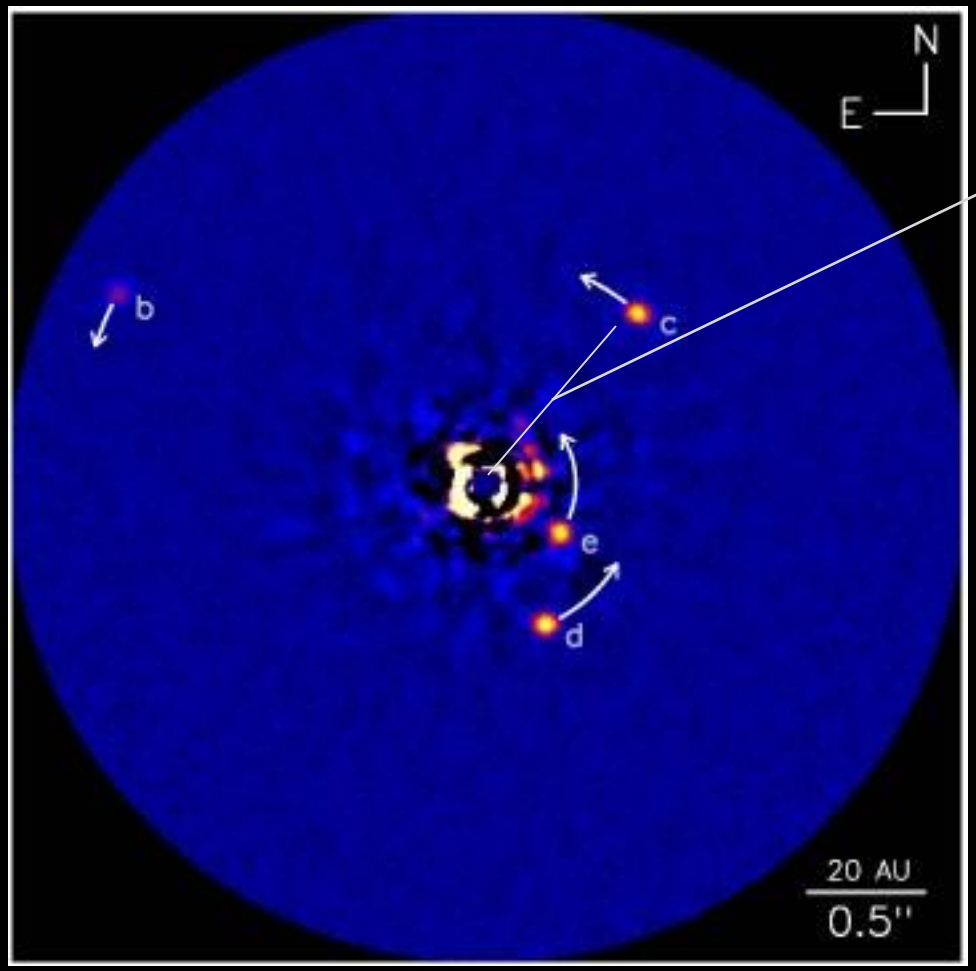


- Some planetesimals are disintegrating around their host star



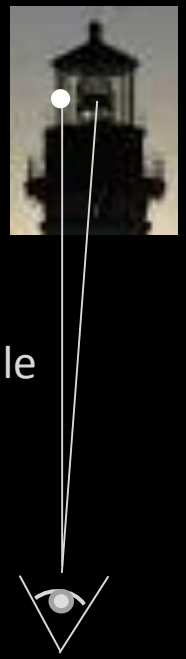
The Challenge

HR 8799



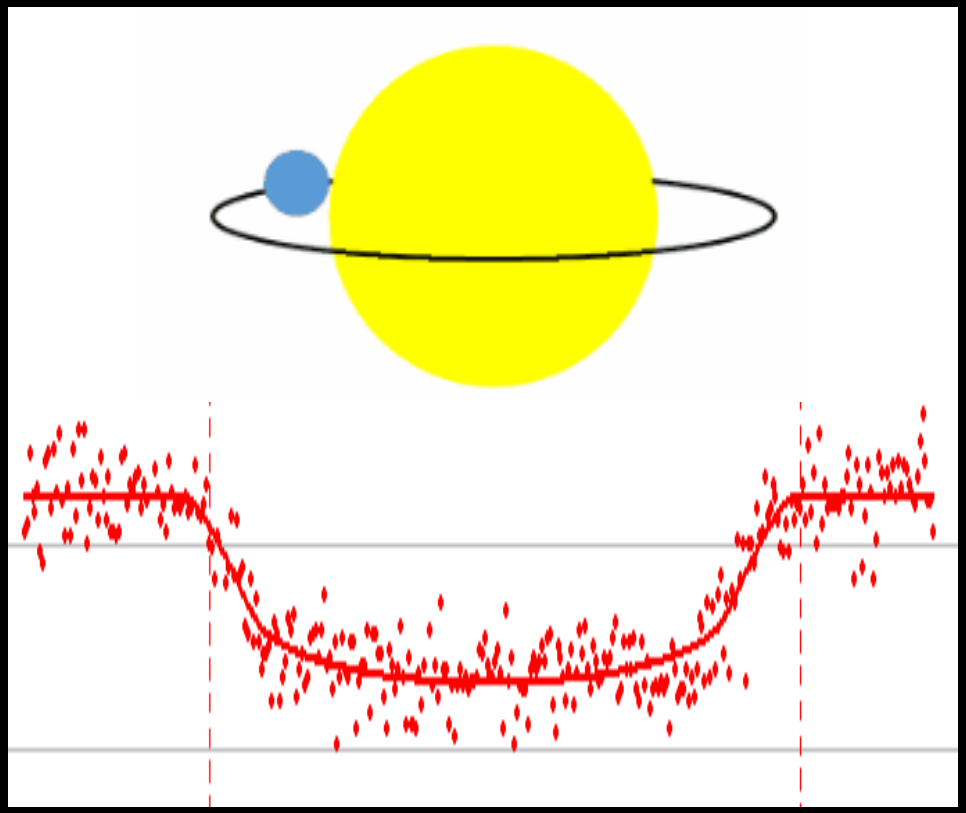
Courtesy: Keck Observatory

Equivalent to seeing the reflected light of a baseball that is ¼" from a lighthouse 1 mile away:

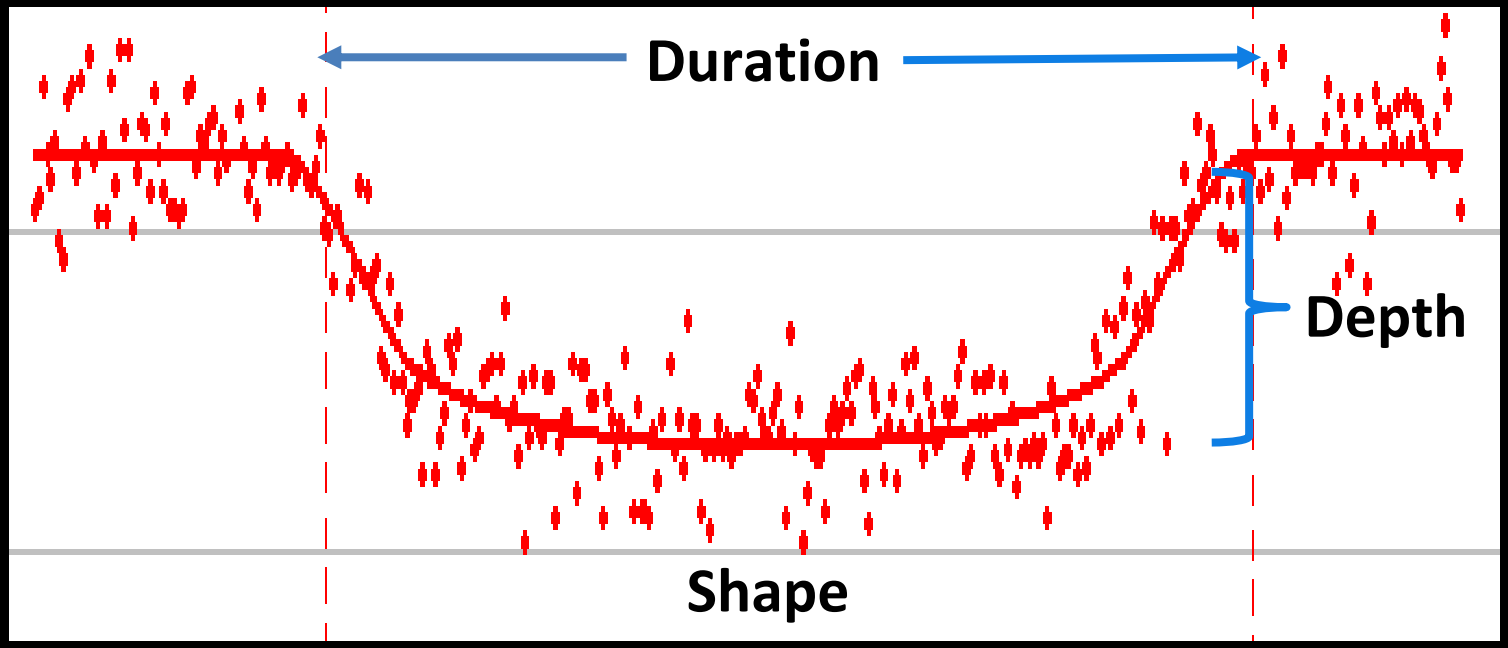


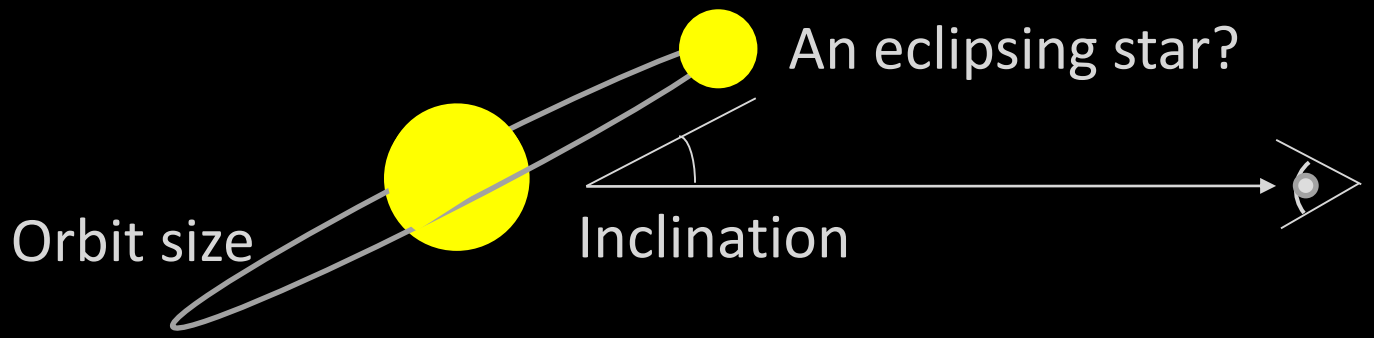
1 mile

The Transit Method: The Dominant Method Used by Amateur Astronomers



We can learn a lot from the light curve!

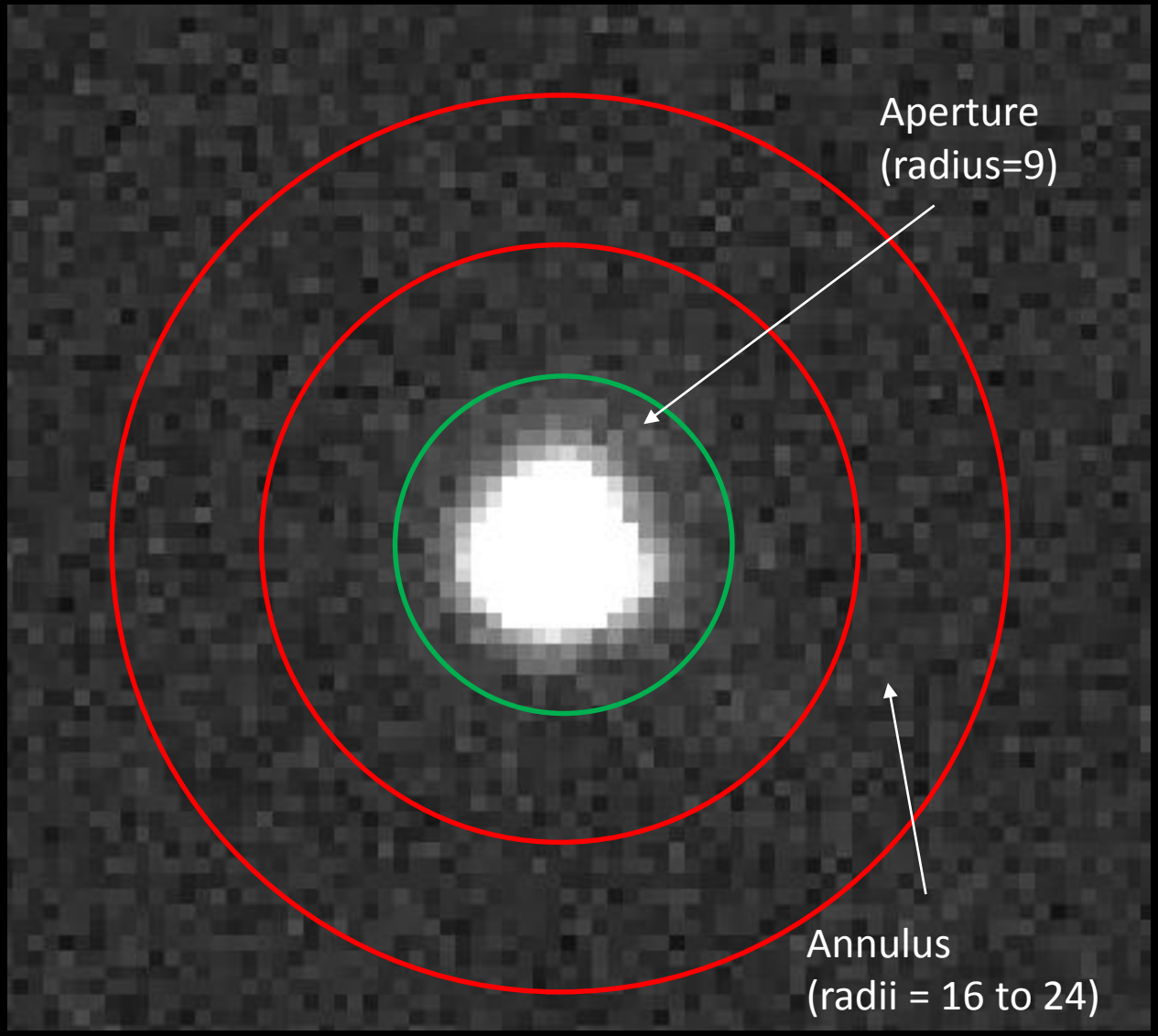




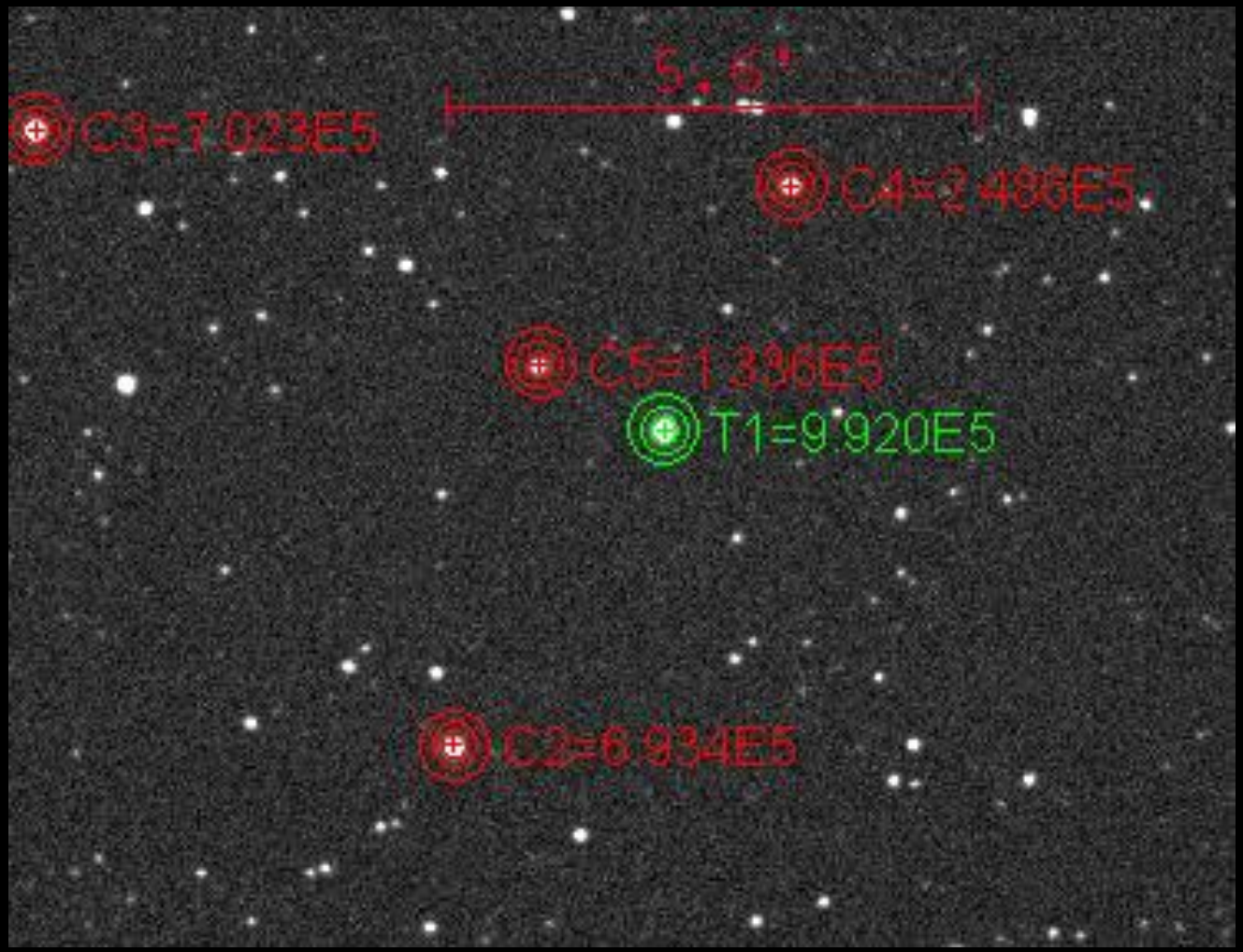
Capturing Data for the Light Curve

- Images of a star field containing the parent star are taken over a 4-6 hour period
- For each image, the brightness (flux) of the target star and several comparison stars are measured
- The relative change in flux between the target star and all the comparison stars is computed
- Why not just measure the brightness of the parent star?
  - Light pollution, a passing cloud, atmospheric turbulence, etc. could cause an artificial change in the star's flux
  - However, these should affect all other comparison stars in the same way
  - Any relative change should then be due to something particular to the target star

Aperture Photometry



Differential Photometry



Getting a Measure of a Star's Flux

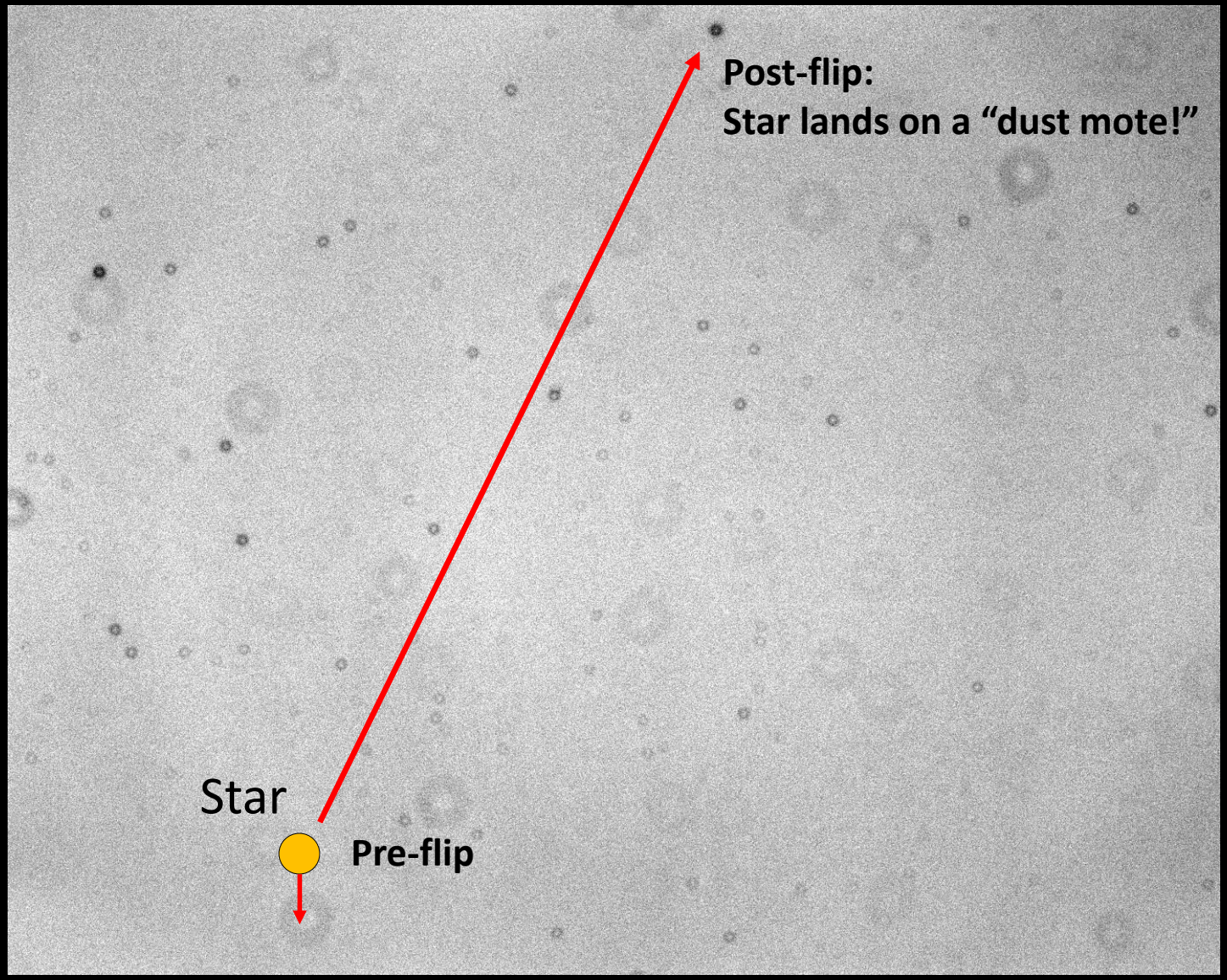
Source Counts from aperture

Sky Background Counts from annulus

Source Counts - Sky Background

$$\text{Relative flux of Target} = \frac{\text{Target's Source Counts - Sky Background}}{\text{Sum of Comp Stars' Source Counts - Sky Background}}$$

The Importance of Uniform Flats and Guiding!



Goal:
Minimize image movement over the entire (4-6 hour) session

- Amount of movement (field rotation) is a function of:
  - polar alignment error
  - overall integration time
  - distance from guide star to target
  - focal length
  - declination of target
- Minimize periodic error
- Have a well-balanced mount
- Autoguiding is essential!

Autoguiding

- Approaches:
  - Use a guide scope
  - Off-axis guiding
  - On-axis guider

- Minimize the distance from guide star to target and comp stars

Traditional Off-Axis Guiding

Guide Camera

Visible+NIR

G★

T★

Visible+NIR

Visible+NIR

Pickoff Mirror

Visible+NIR

Imaging Camera

On-Axis Guiding Techniques

- Use science image as source of guide star - useful when guide corrections times can be = or > science image exposure times

- Use an on-axis guider (ONAG)

On-Axis Guiding

Imaging Camera

Filter Wheel

Autoguiding Software

Guide Star

Target Star

Visible

ONAG

Visible+NIR

Dichroic Beam Splitter

NIR>750nm

Guide Camera

Innovations Foresight, LLC

Simultaneous, Multi-band Measurements

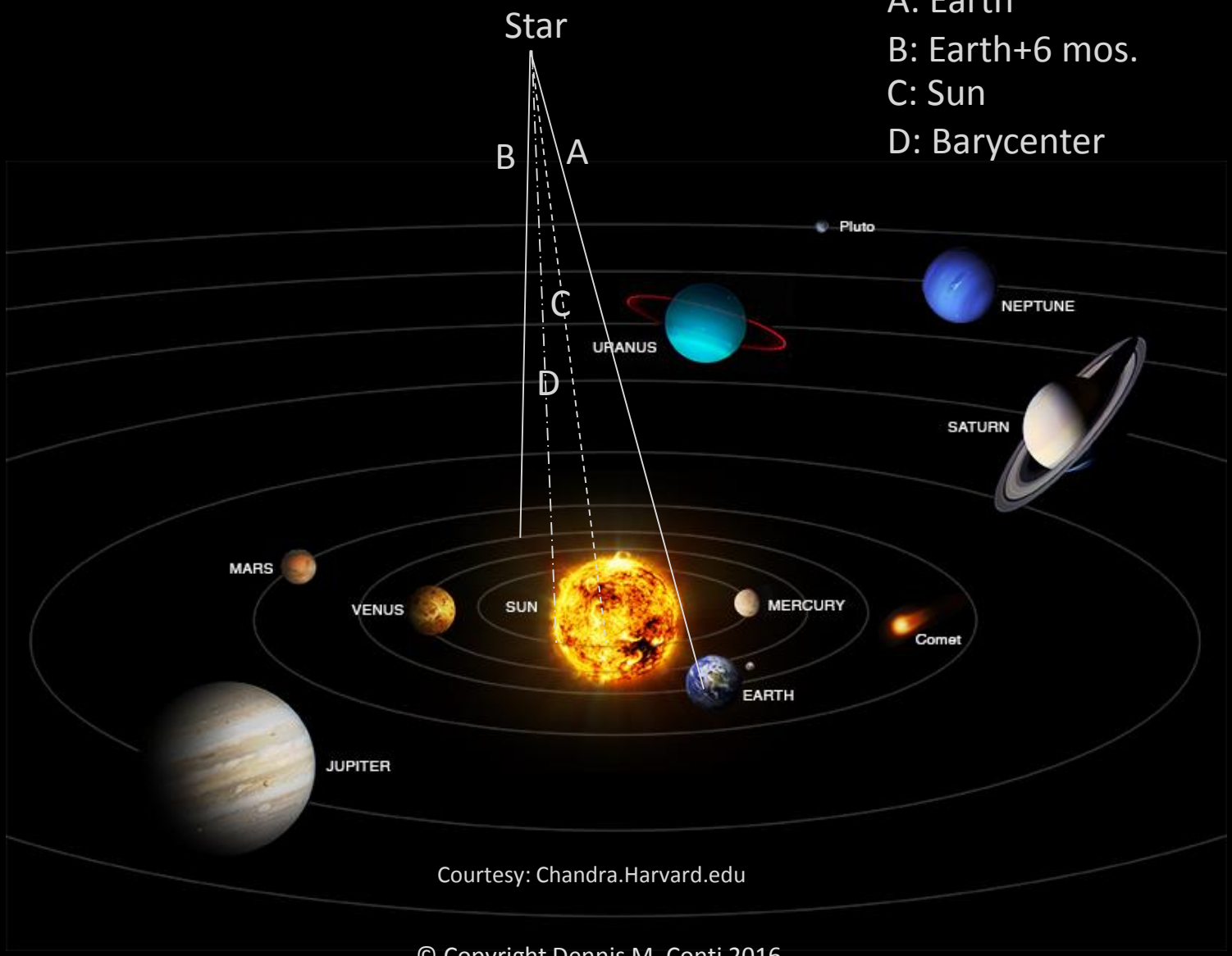
- Useful in detecting false positives (example, an eclipsing binary vs. a true exoplanet transit)

- Traditional approach: use a single camera with alternating filters
  - Disadvantages: reduces cadence in each band, potential introduction of systematics

- A new approach: repurpose the ONAG to allow for simultaneous measurements in near-infrared (NIR) and in one or more visible bands
  - Advantages: maximizes cadence in each band, reduces systematics
  - Supports autoguiding as well!

Reference Locations

A: Earth
B: Earth+6 mos.
C: Sun
D: Barycenter



Courtesy: Chandra.Harvard.edu

What time is it?

Time base = reference location and time standard (clock)

- Local time at San Diego, CA: 13:00 on October 29, 2016
- UTC time at Greenwich, England: 20:00 on October 29, 2016
- JD_{UTC} (above in Julian Date form): 2457691.33333

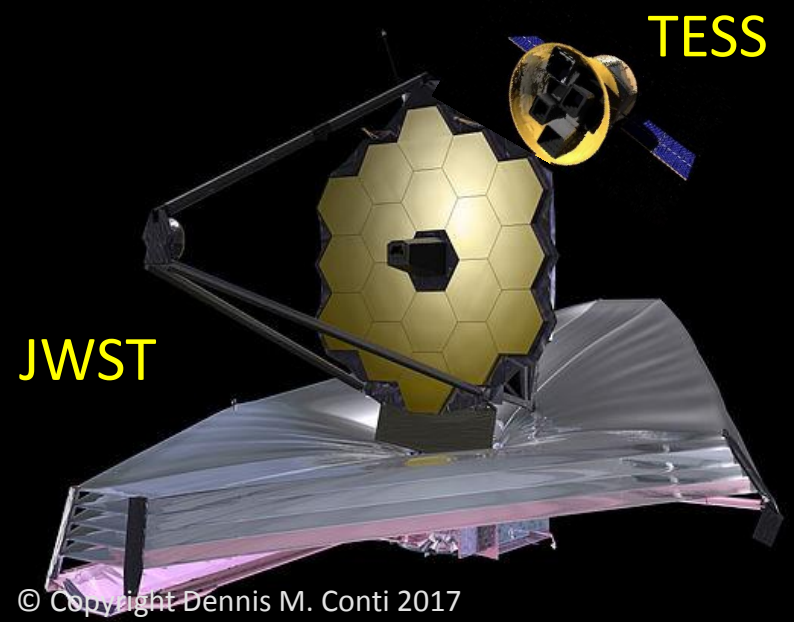
  ↓ +6.4 min.
- HJD_{UTC} (Heliocentric Julian Date, UTC) for target at (00h 01m 26.92s, 39°23’01.7”): 2457691.33780

  ↓ +1.1 min.
- BJD_{TDB} (Barycentric Julian Date, Barycentric Dynamical Time) for and 32:36:48N, 116:19:55W, 1131m alt.: 2457691.33858

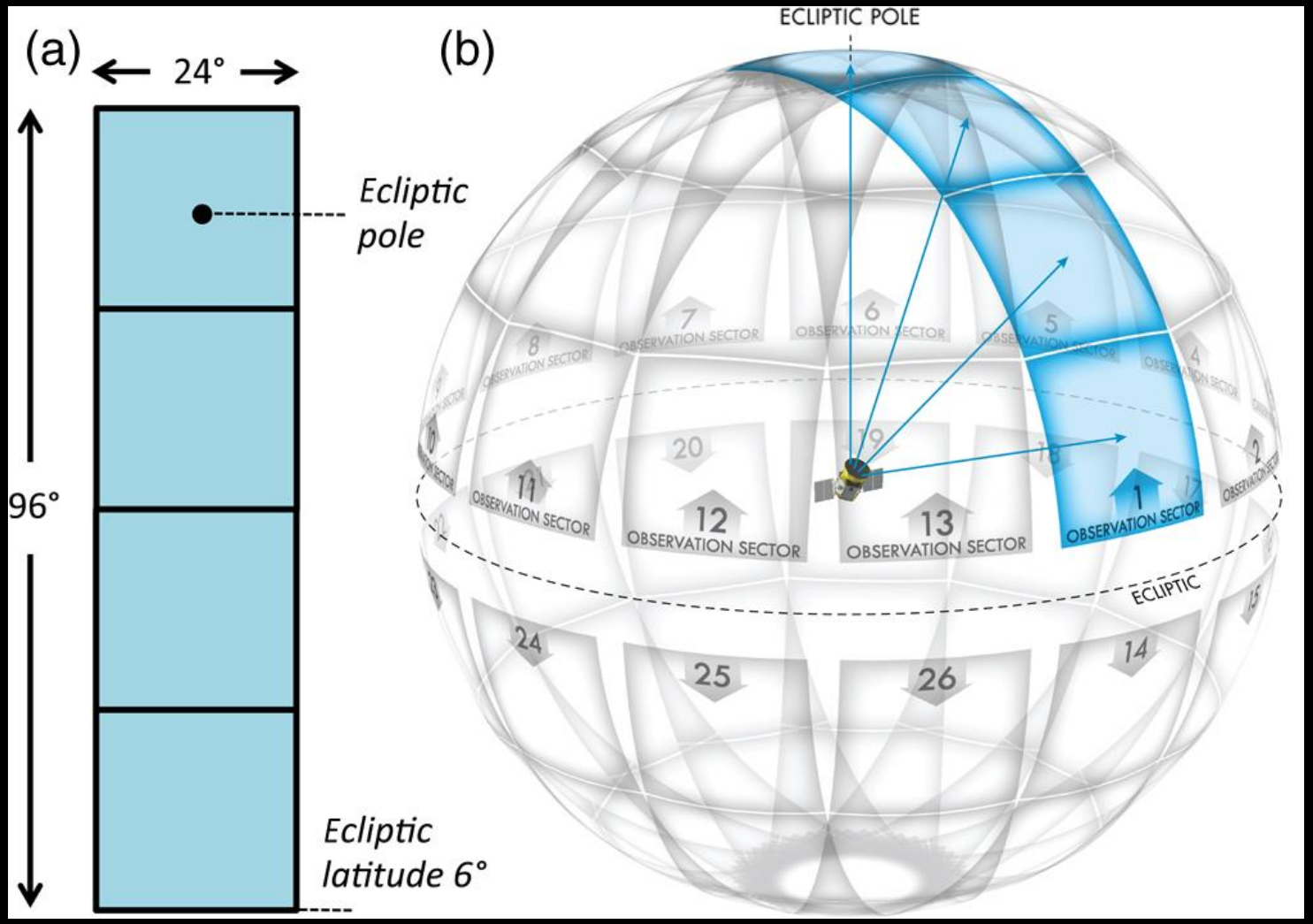
Upcoming TESS Pro/Am Opportunity

TESS: Transiting Exoplanet Survey Satellite

- All-sky survey of near-by, bright stars
- Science objective: measure masses of 50 planets whose size is less than 4 Earth radii
- Think of TESS as a “finder scope” for the James Webb Space Telescope (JWST):



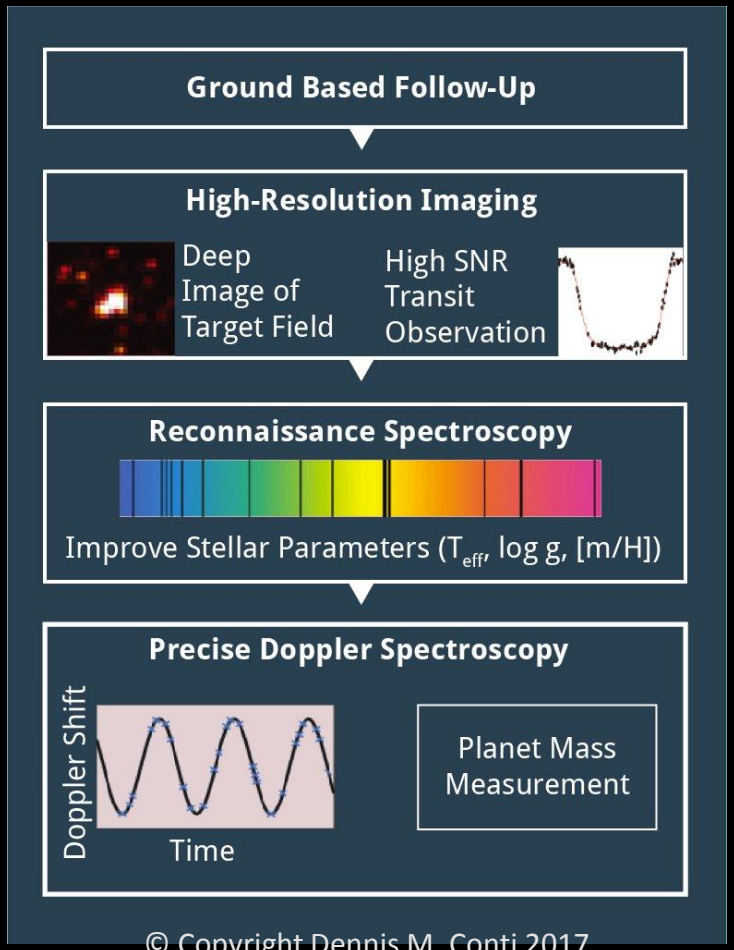
TESS: Transiting Exoplanet Survey Satellite



Scheduled launch: March, 2018

Amateur Astronomer Participation in TESS

- Ground-based observations will be part of the pipeline to help identify false positives



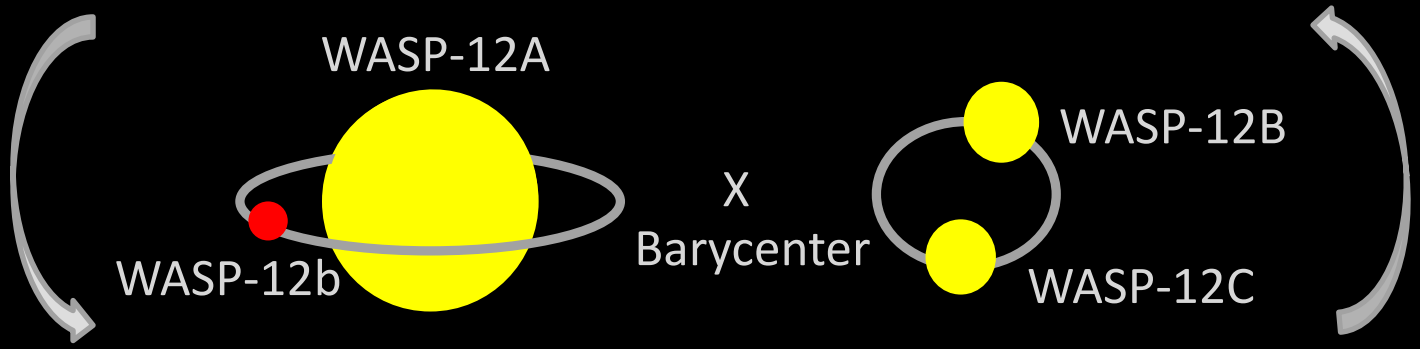
Aids to Help Amateur Astronomers Achieve Higher Precision Exoplanet Observations

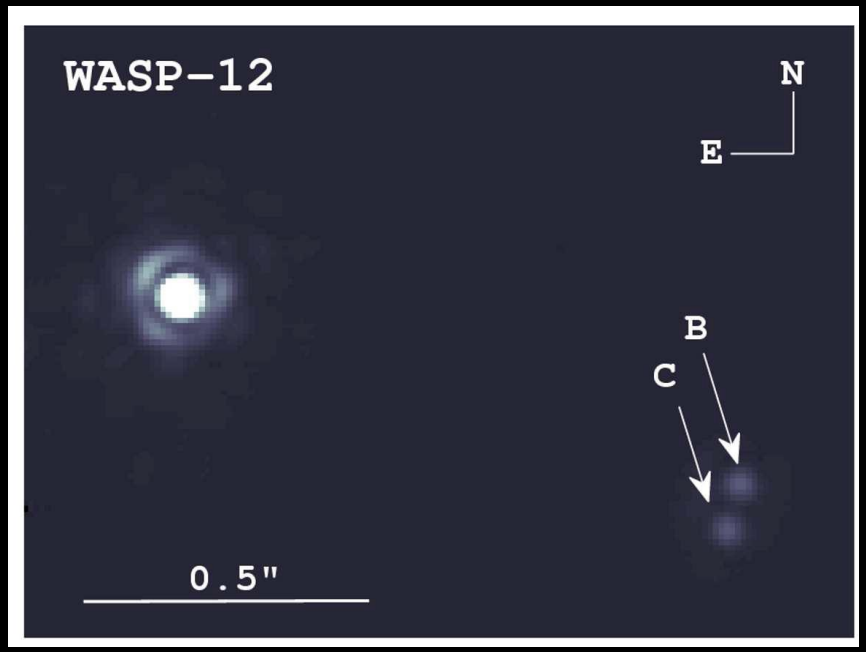
- "A Practical Guide to Exoplanet Observing" (www.astrodennis.com)
  - 1,916 unique visiting users from 68 countries
- Training: AAVSO online course on Exoplanet Observing
  - 80 participants to-date
- Tools available:
  - Sample Images
  - Observation worksheet with hot links
  - AstroImageJ for exoplanet processing
- Improved techniques developed for:
  - higher precision autoguiding
  - simultaneous, multi-band measurement

Exoplanet Observing Using AstroImageJ

Sample Target: WASP-12b

- Part of a hierarchical triple system:





KECK AO image,
Courtesy: Bechter, et al., 2015

WASP-12b Description

- Planet radius = 1.9 Jupiter radii
- Orbital axis/radius of Parent star = 3.08
- Inclination = 83 degrees

Addendum

Using ONAG for Dual-band Measurements

Imaging Camera-1

(Optional)
Guide Camera

Filter Wheel

Alt. 2

Autoguiding Software

Visible

ONAG

Alt. 1

Visible+NIR

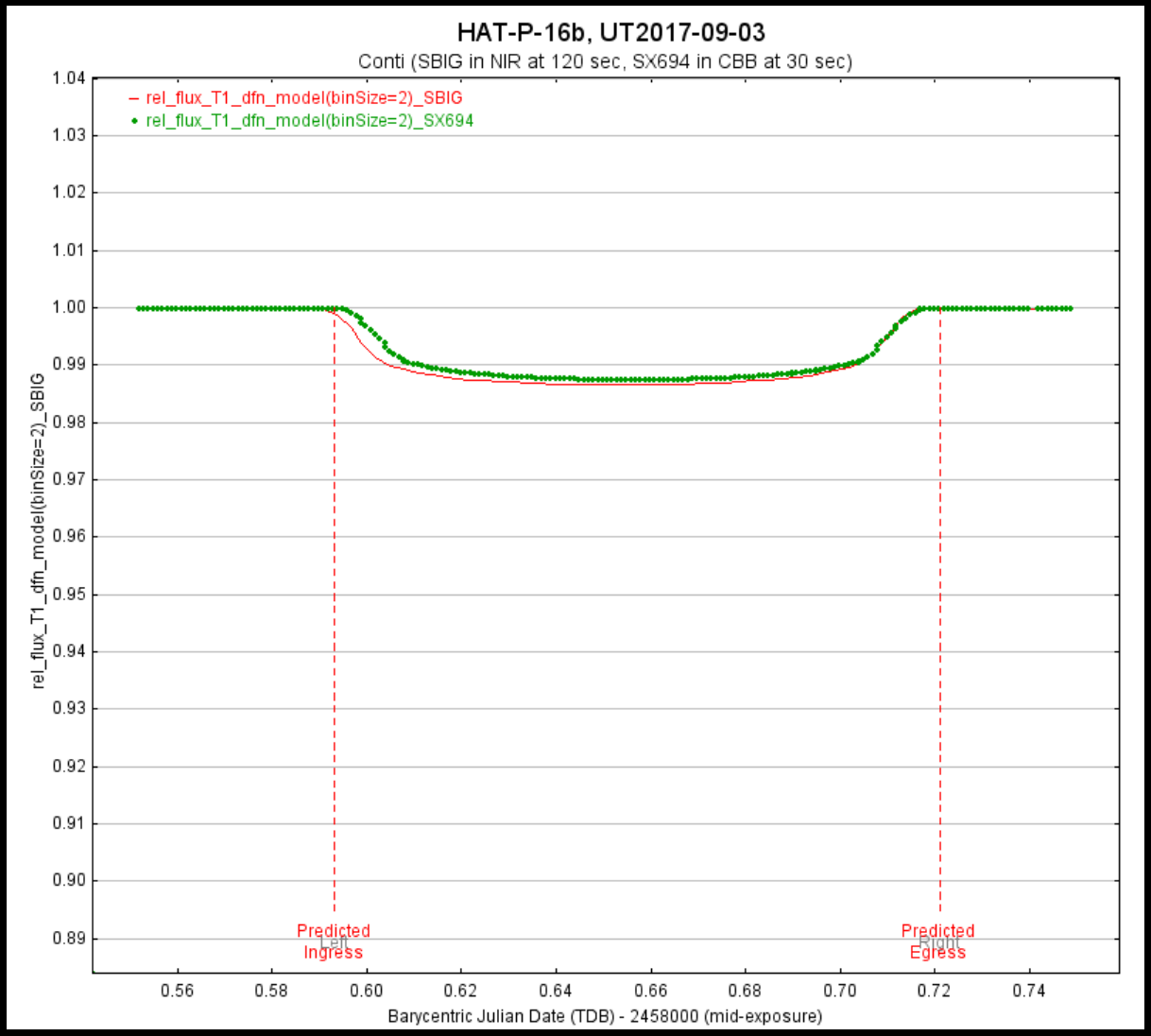
Dichroic Beam Splitter

NIR>750nm

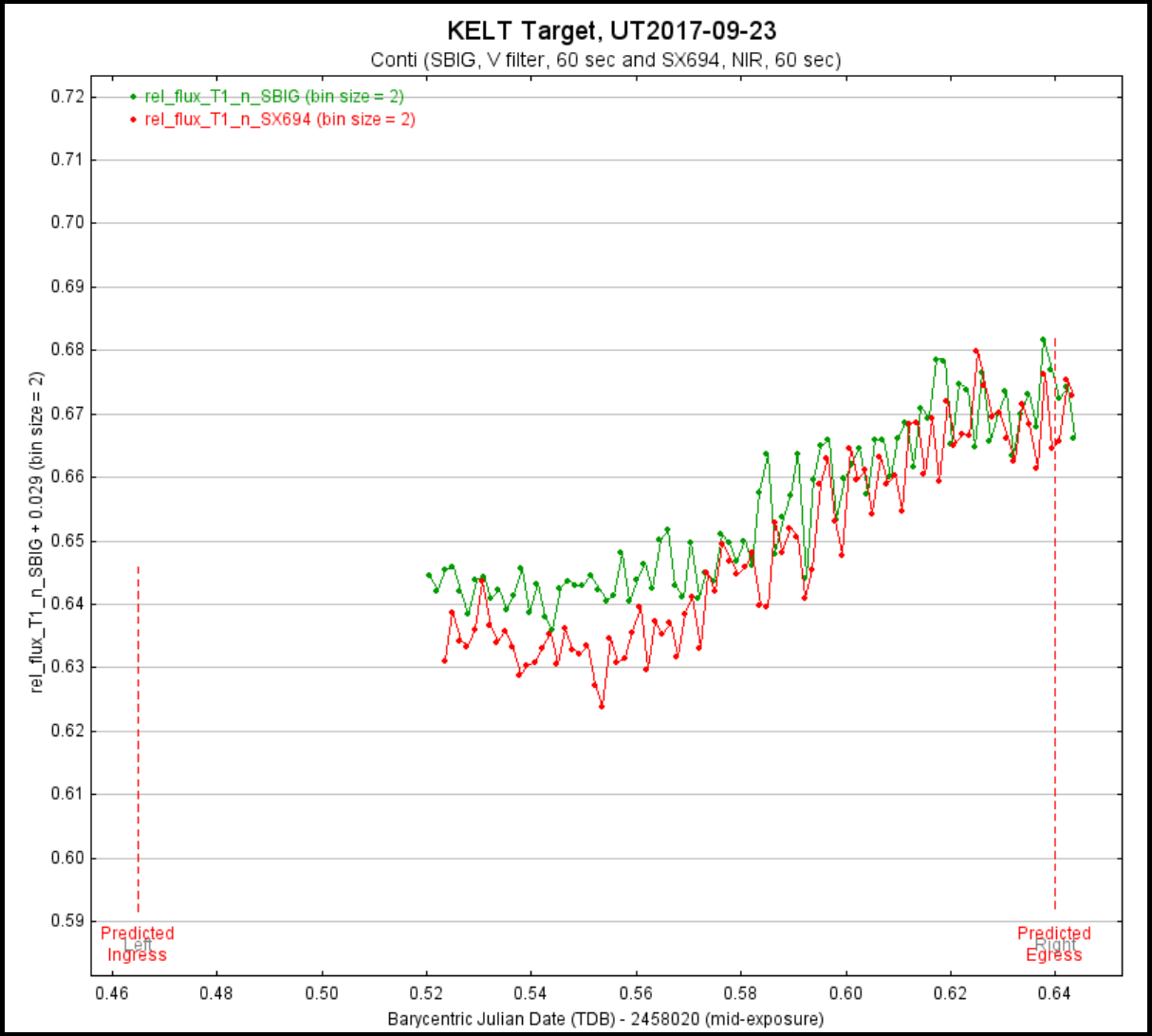
Imaging Camera-2

Innovations Foresight, LLC

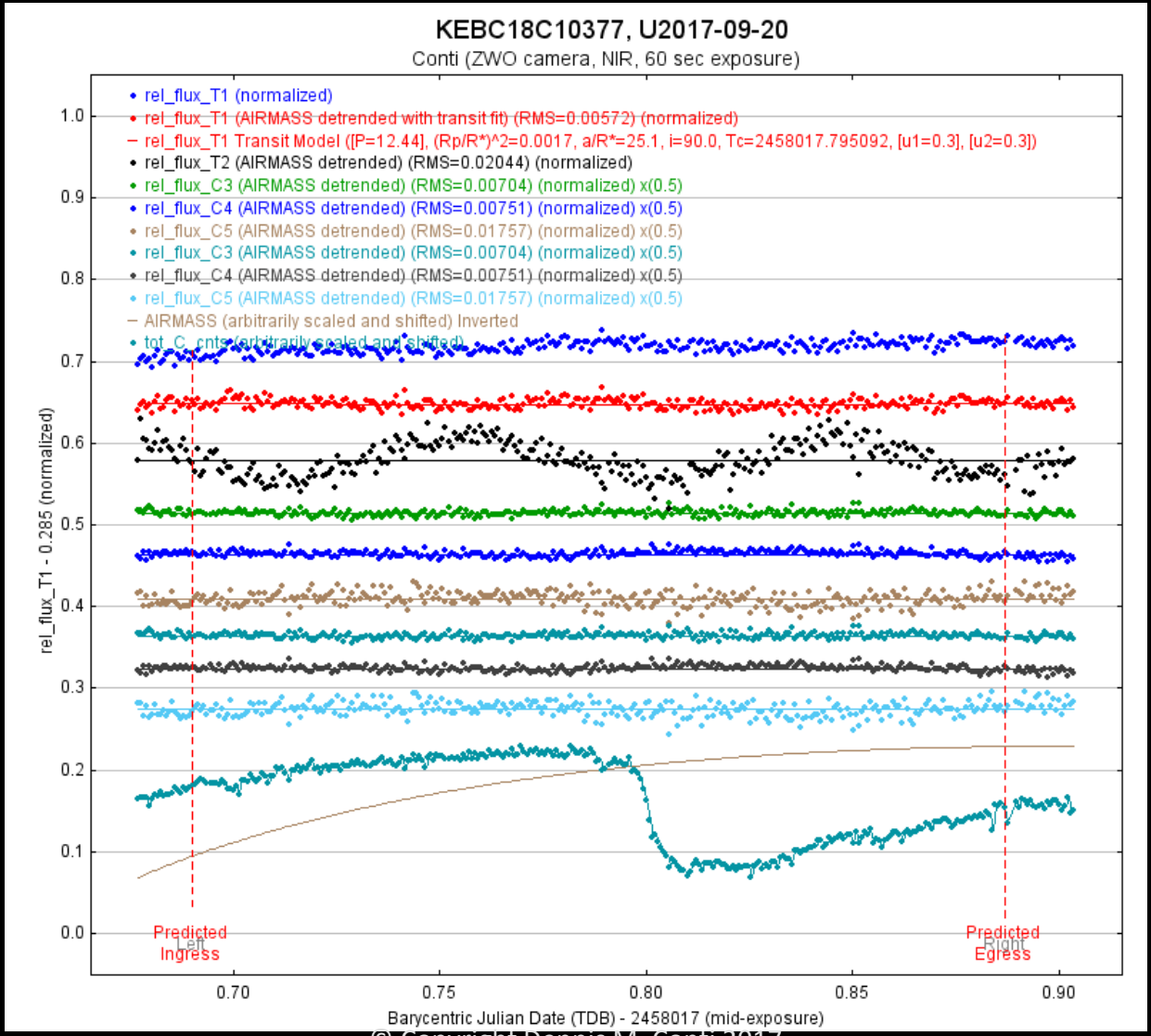
Dual Bandwidth Measurements During an Exoplanet Transit



Dual Bandwidth Measurements During an Eclipsing Binary Transit



Observation with a CMOS Camera



Precision Comparison: Off-Axis vs. On-Axis Guiding

- Conditions:
  - target: HIP 94083
  - location: +76.8° declination, 41° altitude
  - exposures: 548 at 5 seconds for 1 hour
  - polar alignment: excellent
- Results:

	Off-Axis	On-Axis
– Date	6/10/17	6/8/17
– Seeing	2.6”	3.1”
– Tracking error (in RA)	0.41”	0.46”
– Max. deviation:		
at center of FOV	6.3 pixels	1.8 pixels
at edge of FOV	8.1 pixels	3.2 pixels

Under worse seeing conditions, On-Axis Guiding provided a 71% improvement over traditional Off-Axis Guiding!