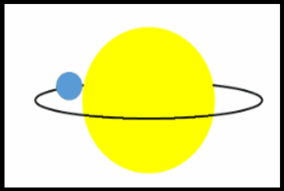

Looking for Zebras When There Are Only Horses

by

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Member, TESS Follow-up Working Group

AAVSO Annual 2017 Meeting

“When you hear hoofbeats, think of horses not zebras”

- Coined in the late 1940s by Dr. Theodore Woodward, professor at the University of Maryland School of Medicine
- Still used today to remind medical students to look for the more “common” diagnosis rather than the “exotic”
- In our search for astrophysical events, such as exoplanet transits, it is easy for us to think that we are looking at a zebra, when in fact it is just a horse

Why is this important?

- In the era of TESS, follow-up, ground-based observations will be needed to help identify (astrophysical-based) false positives
    - Example: to distinguish whether a perceived transit is due to an exoplanet vs. an eclipsing binary

- <u>But first</u>, it is important to understand any non-astrophysical sources that may cause a horse to look like a zebra

How Horses Can Mask As Zebras (or Vice Versa!)

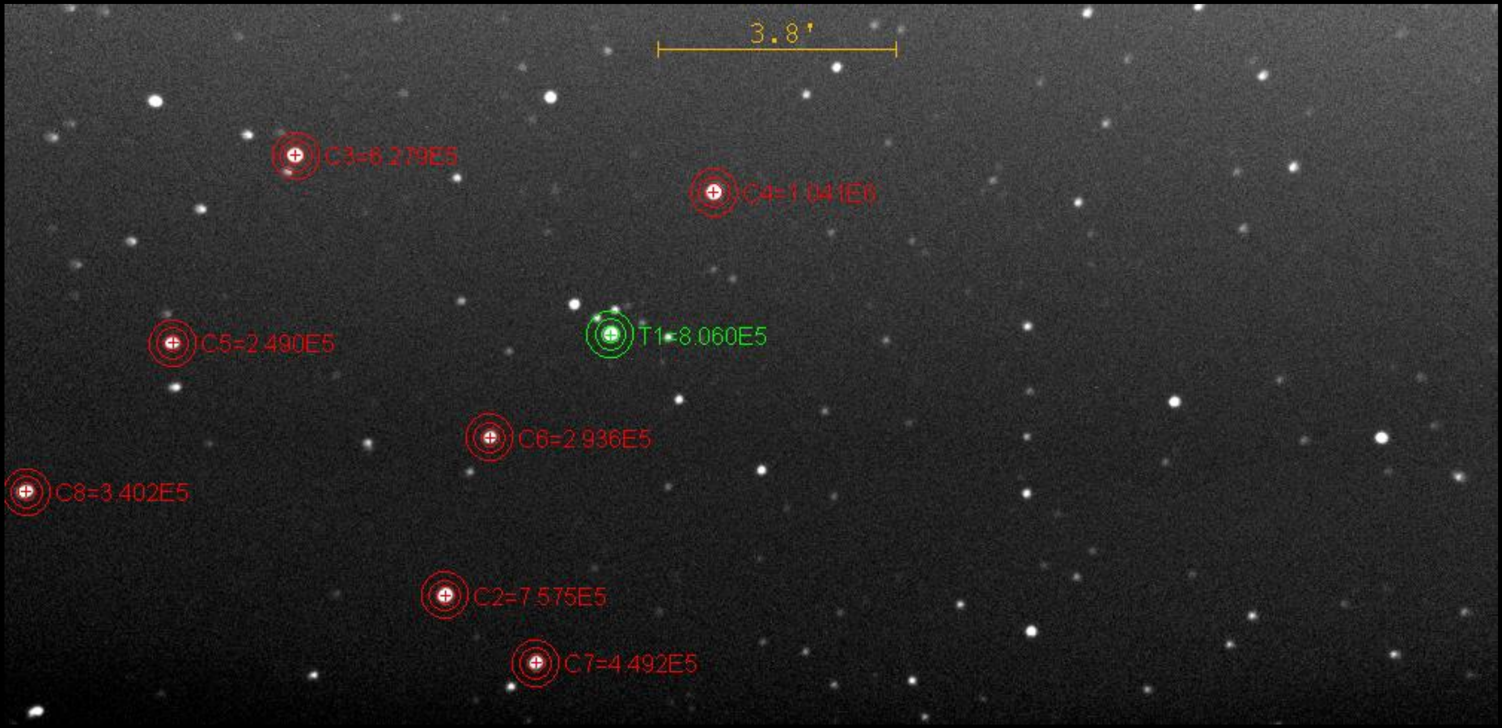
- External effects (atmospheric extinction, light pollution)
- Operational errors (polar misalignment)
- Instrumentation effects (inadequate autoguiding)
- Processing effects introduced during calibration, differential photometry, and transit modeling phases

Some Real Life Examples

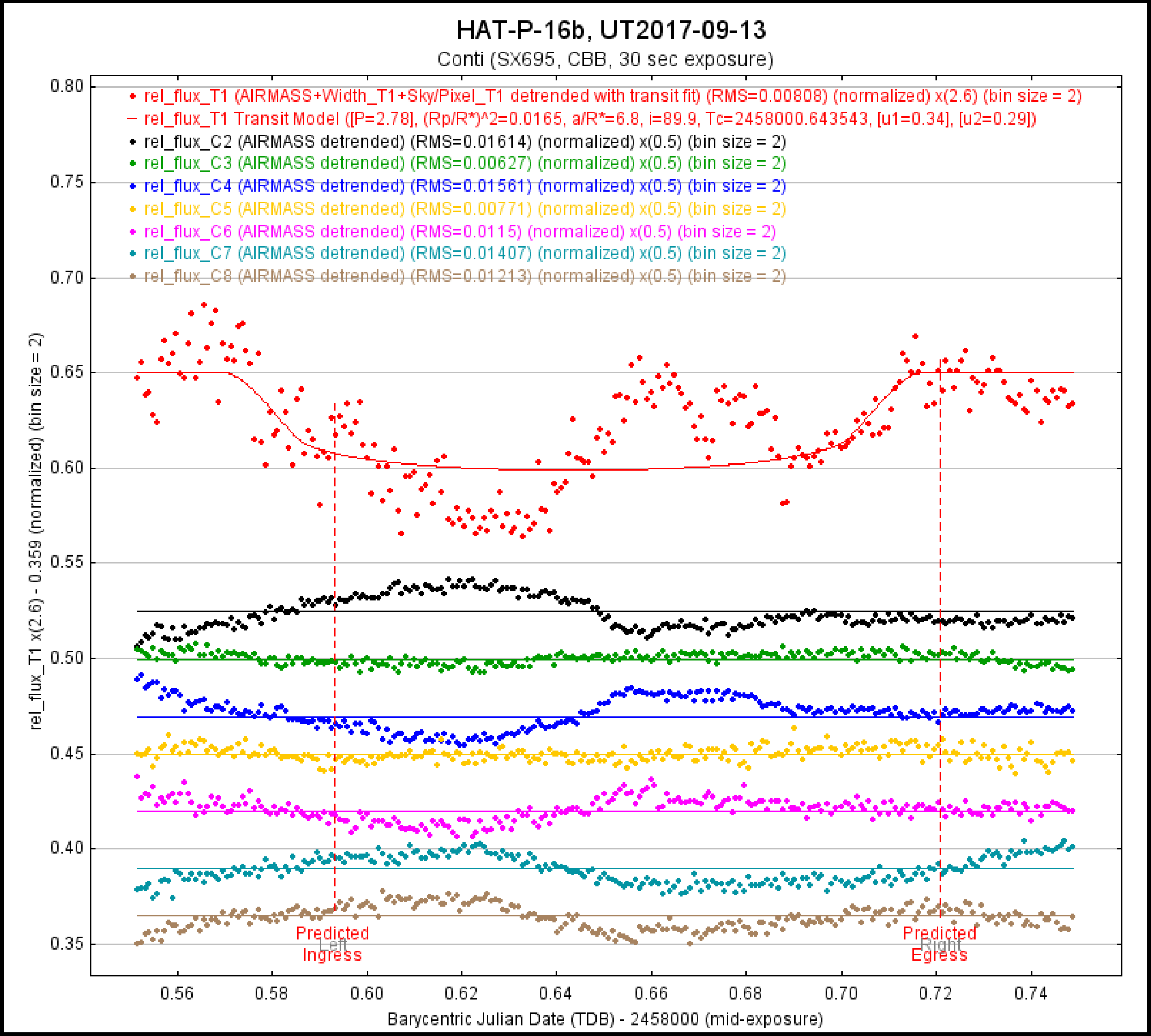
- The “Pokémon” star
- A variable star in the ensemble of comp stars
- The lights from a nearby high-rise
- The light dome of a nearby urban center

Dissecting an Exoplanet Observation: A Zebra or a Horse?

Target and Initial Comp Star Selection



Initial Fit: It Clearly Looks Like a Horse!



Exoplanet Model Fit

Comparison Stars: C2-C8

So Let's Perform a Dissection

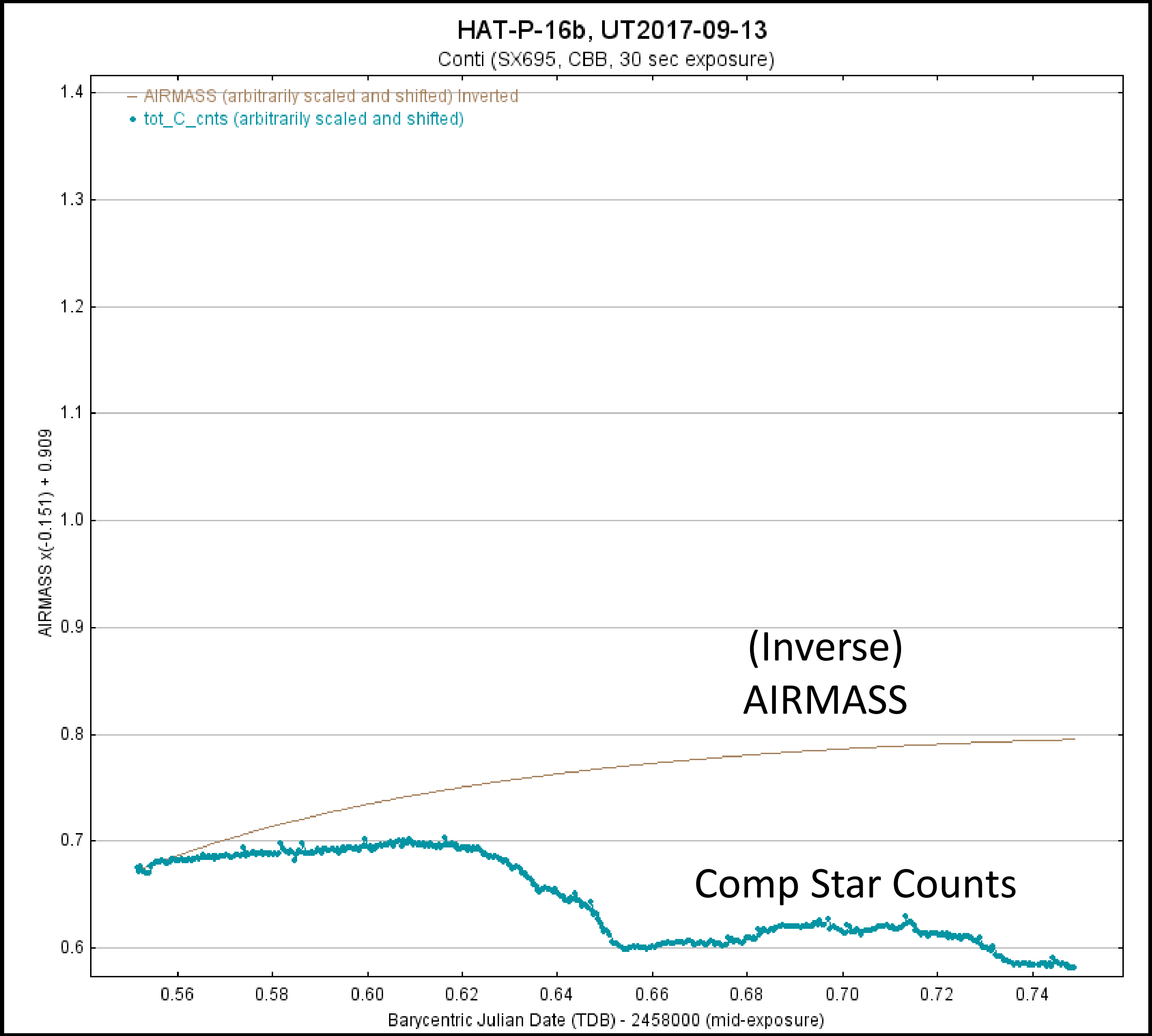
Source Counts from aperture

Sky Background Counts from annulus

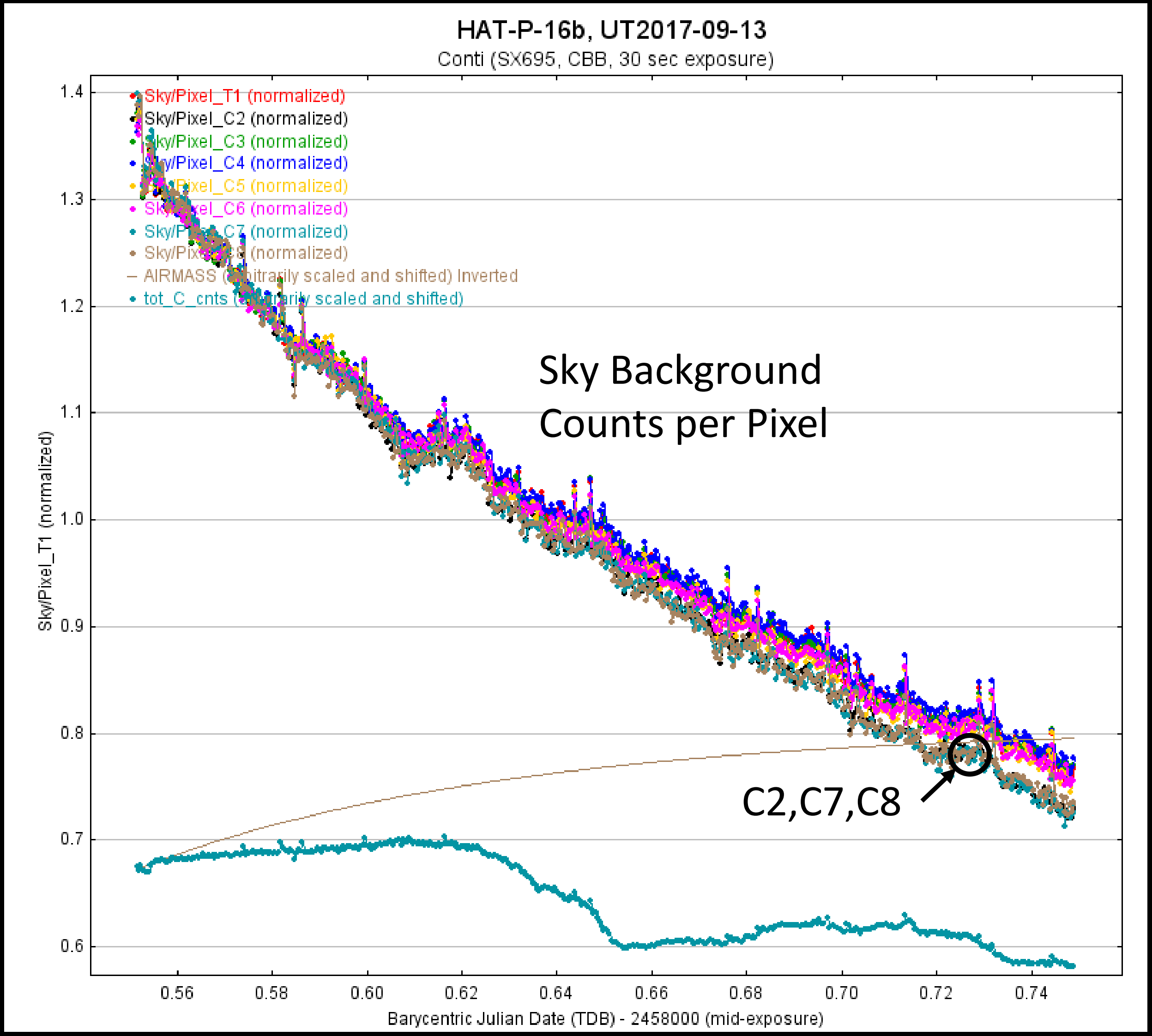
Source Counts - Sky Background

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

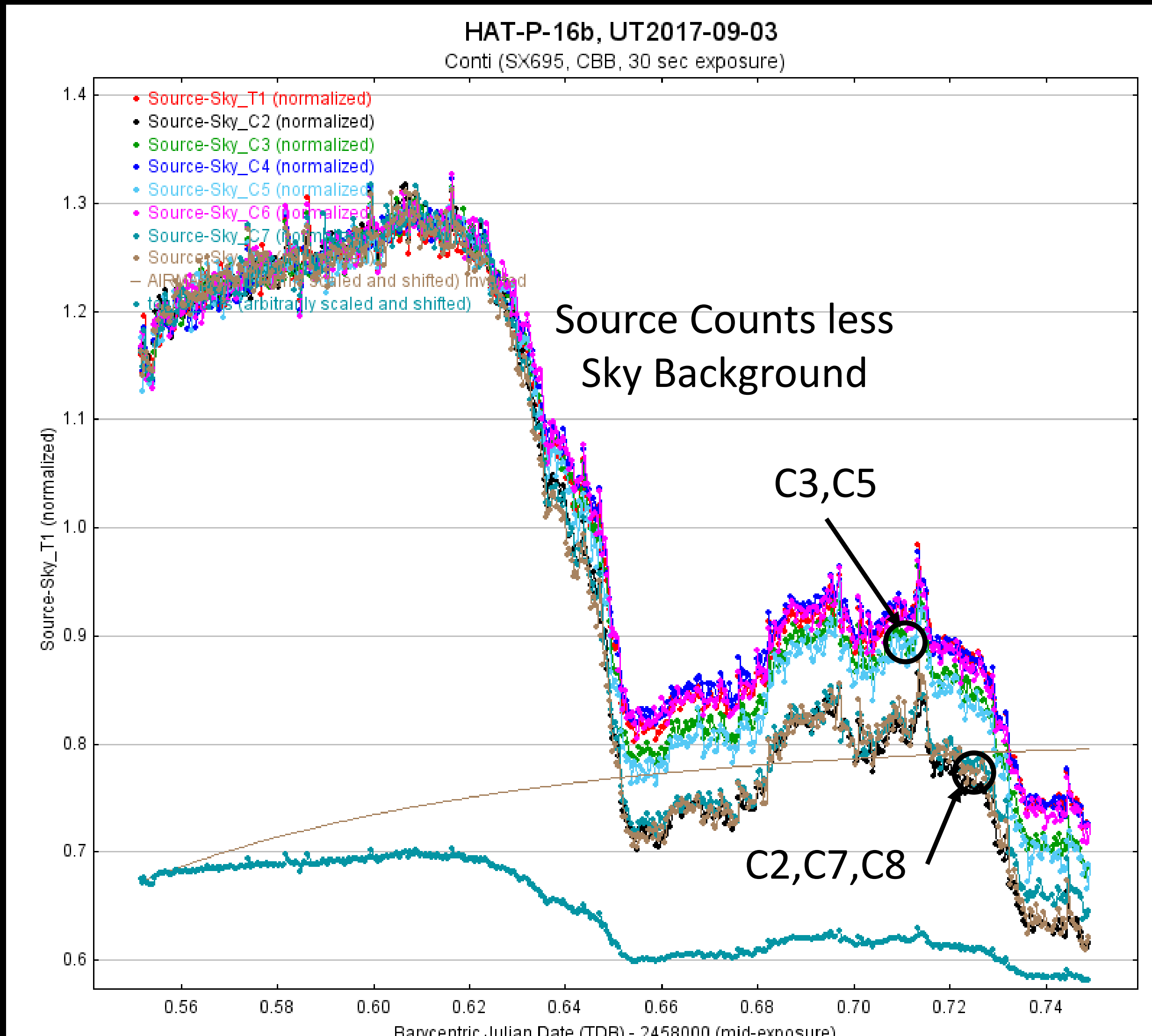
Transparency Conditions



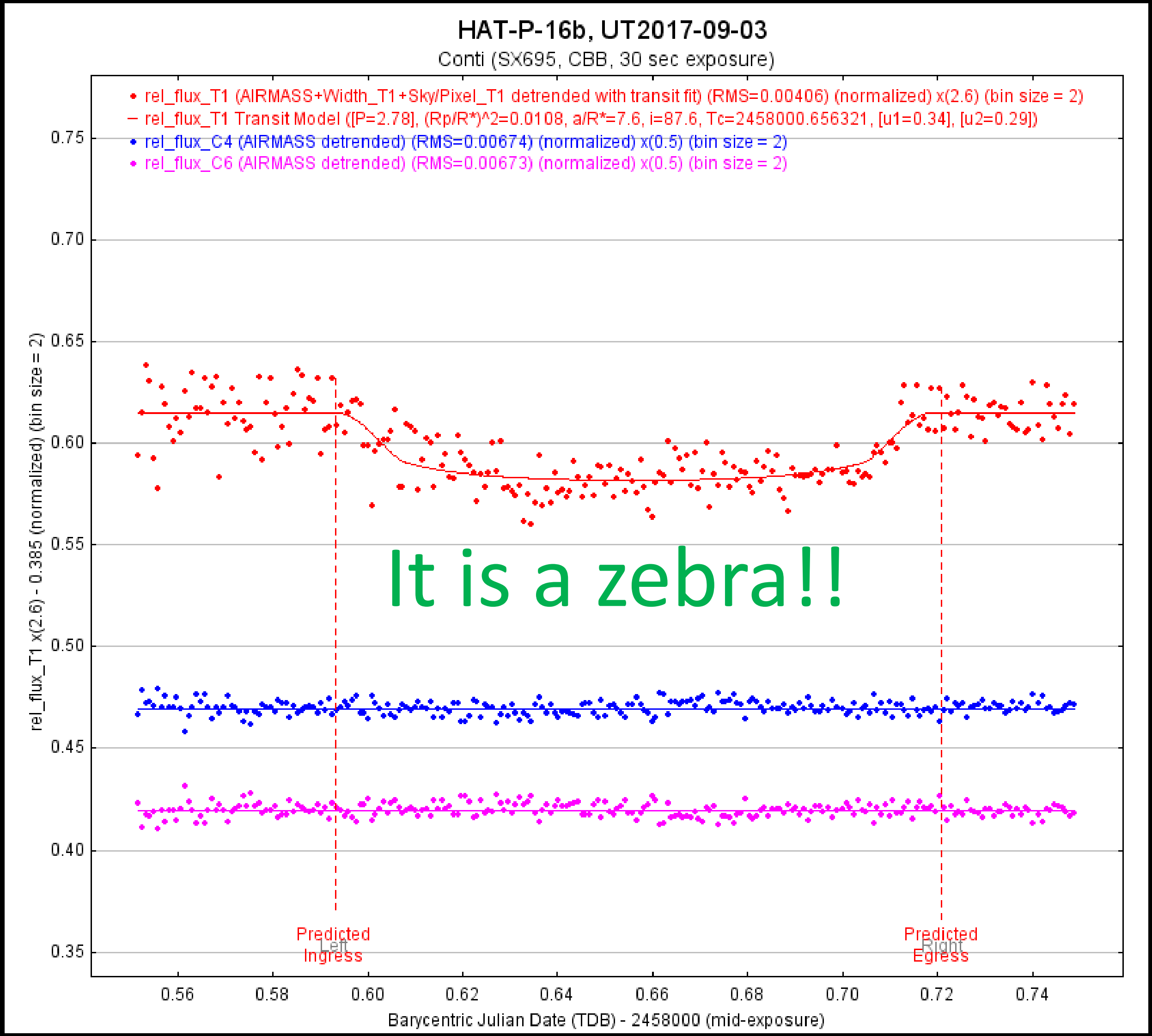
Changes in Background Sky



Detection of Differences in Stellar Type



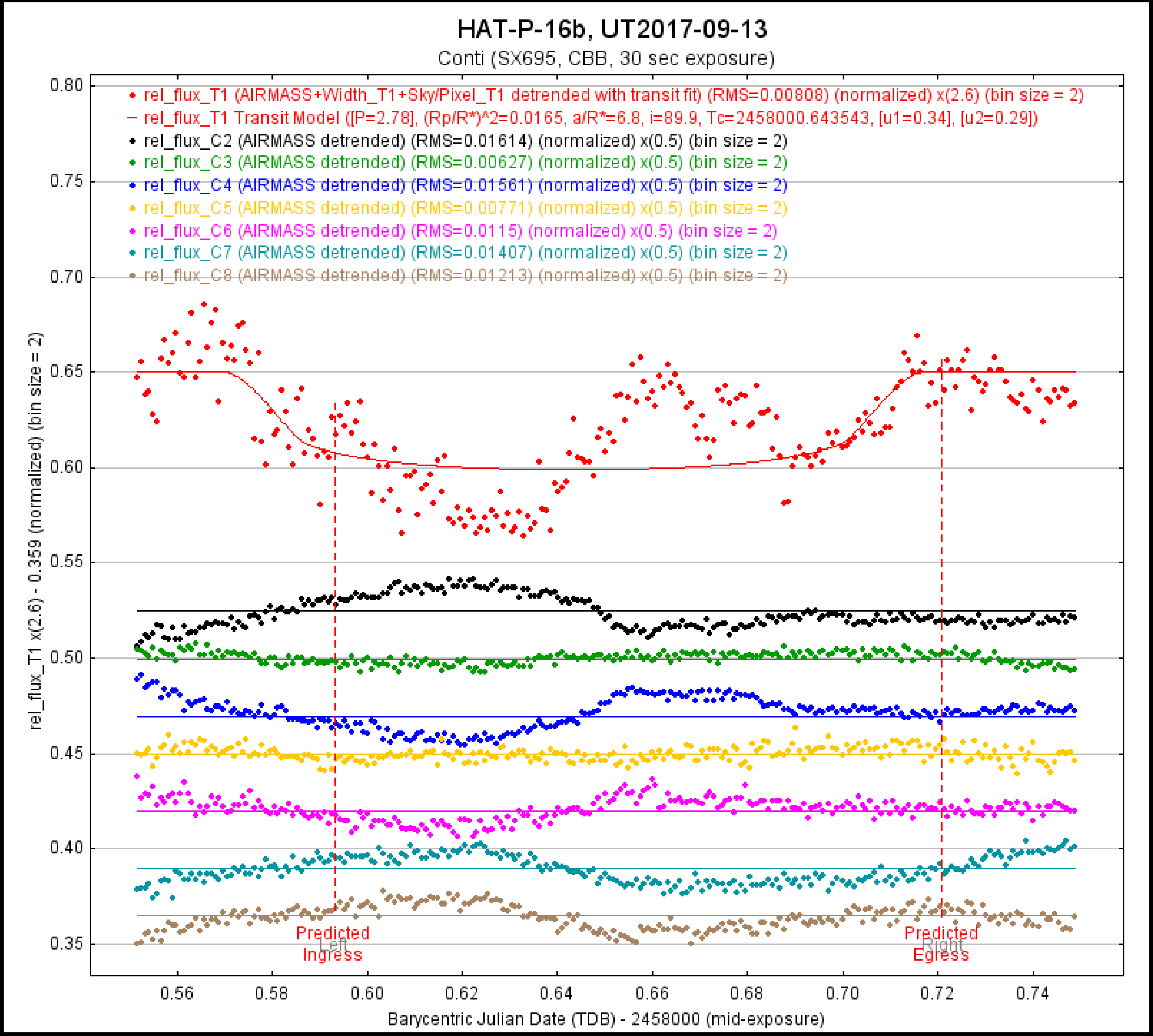
After Deselection of Problematic Comp Stars



Exoplanet Model Fit

Comparison Stars: C4, C6

Initial Fit



Exoplanet Model Fit

Comparison Stars: C2-C8

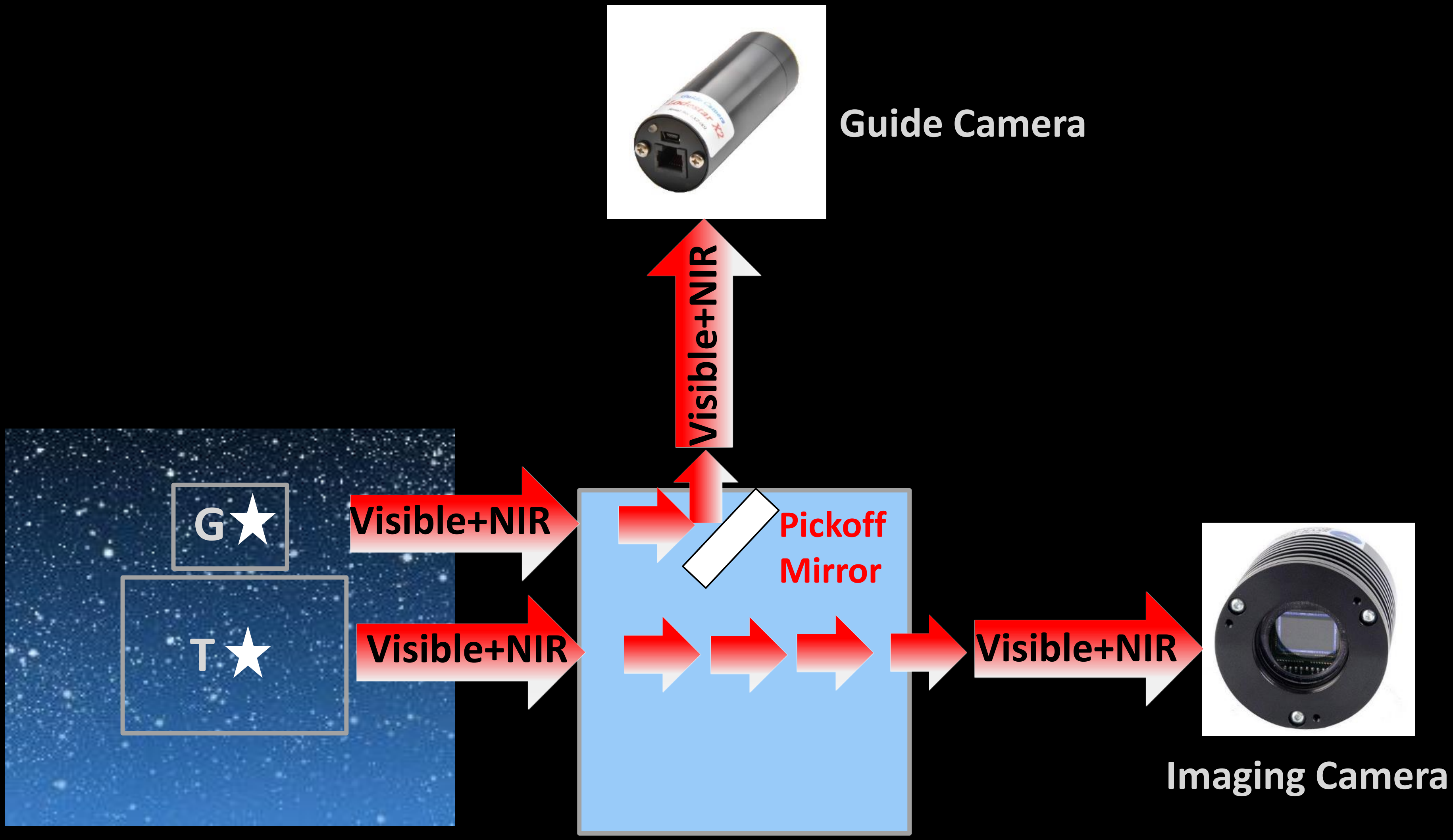
Preparing for TESS

- Seeing limited, follow-up observations will be part of the pipeline to help identify false positives

- The large number of TESS candidate targets will require a larger number of qualified observers

- High precision photometry and multi-wavelength measurements will be desirable for false positive detection

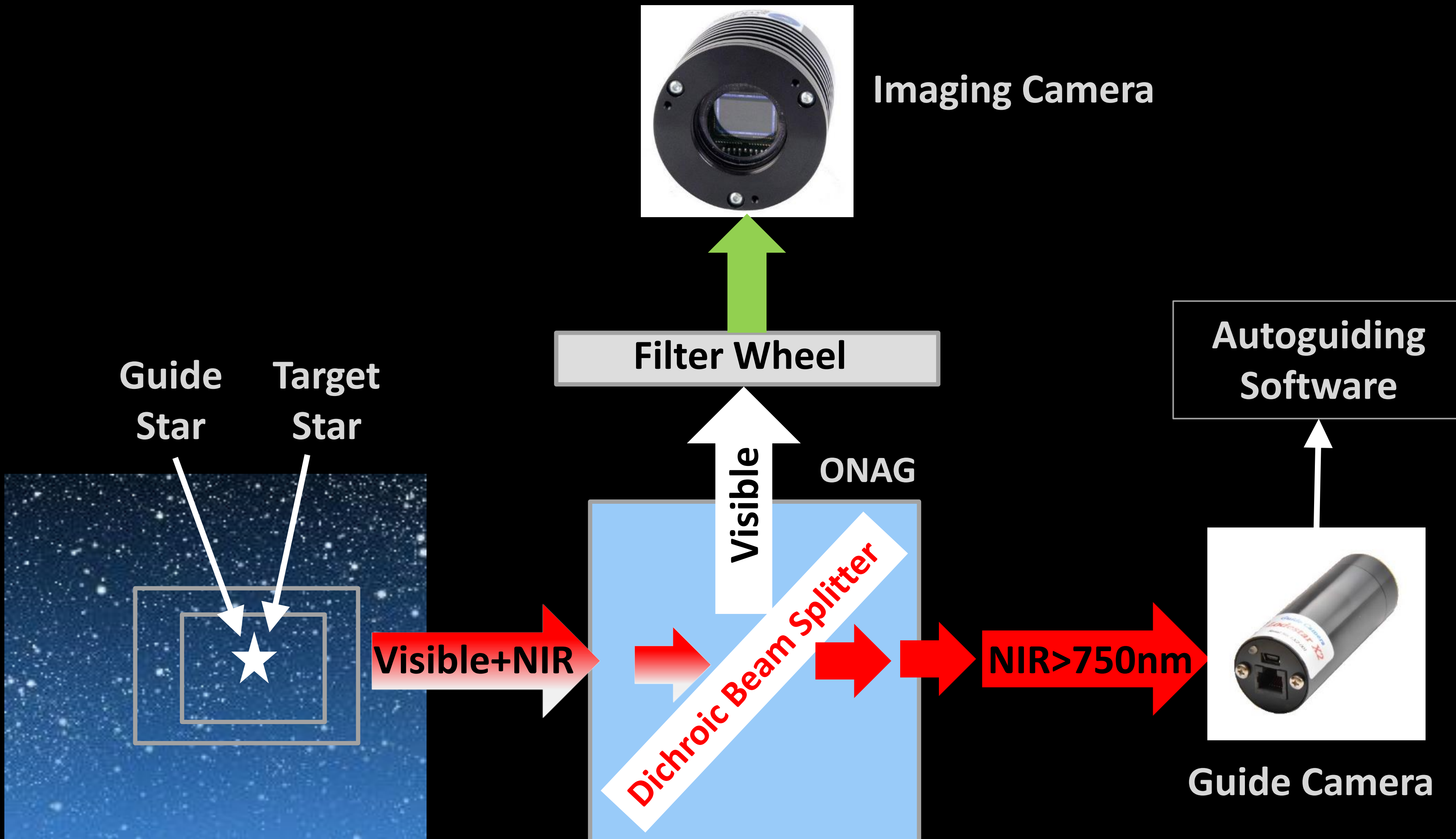
Traditional Off-Axis Guiding



High Precision Autoguiding Techniques

- Goal: minimize movement of target and comp stars during a multi-hour observing session
- Active optics correct for rapid gear errors
- Traditional auto-guiding uses an off-axis guider - field rotation still an issue
- 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



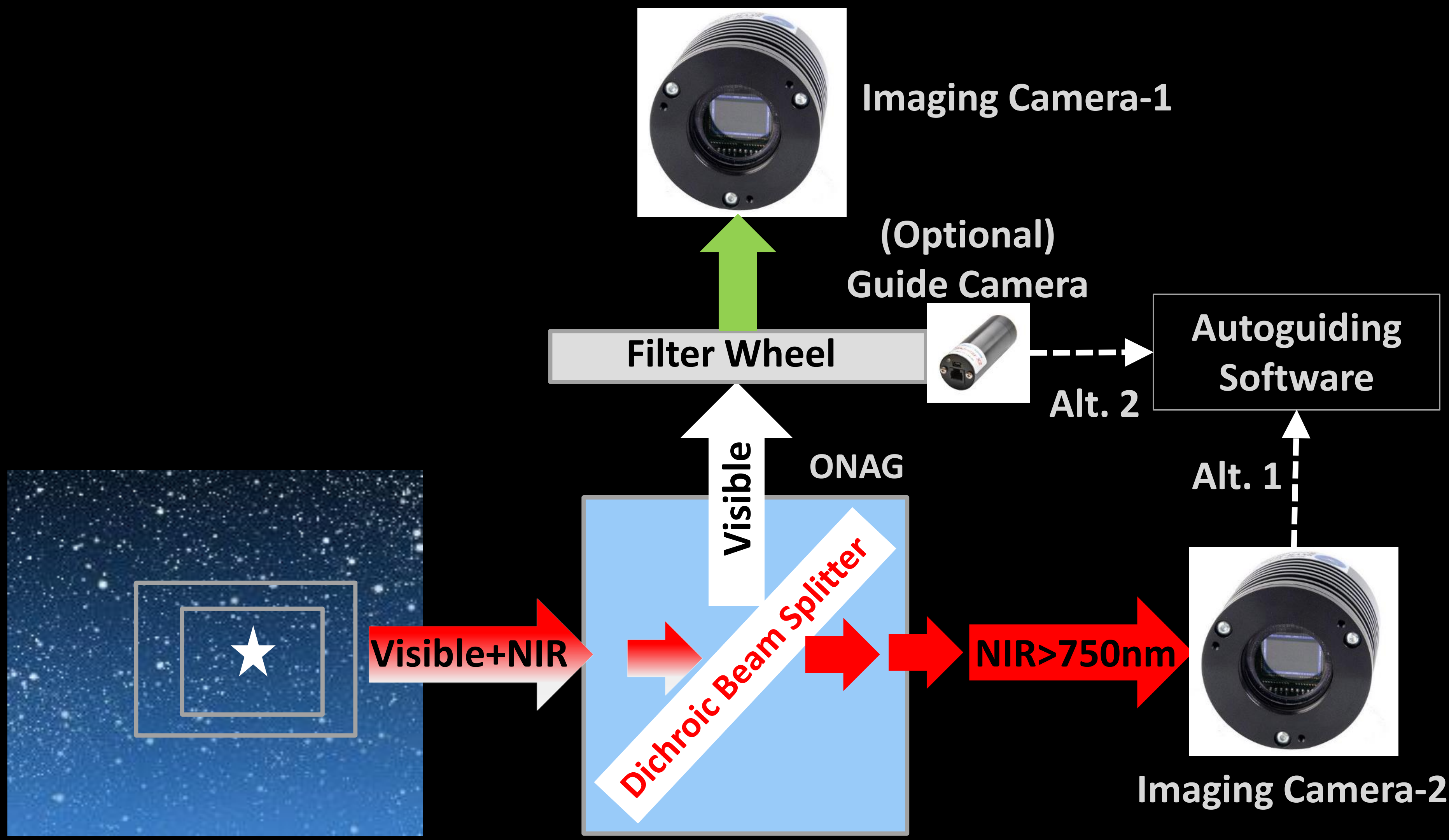
Innovations Foresight, LLC

Simultaneous, Multi-band Measurements

- 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 <u>simultaneous</u> measurements in NIR and in one or more visible bands
  - Advantages: maximizes cadence in each band, reduces systematics
  - Supports autoguiding as well!

Using ONAG for Dual-band Measurements



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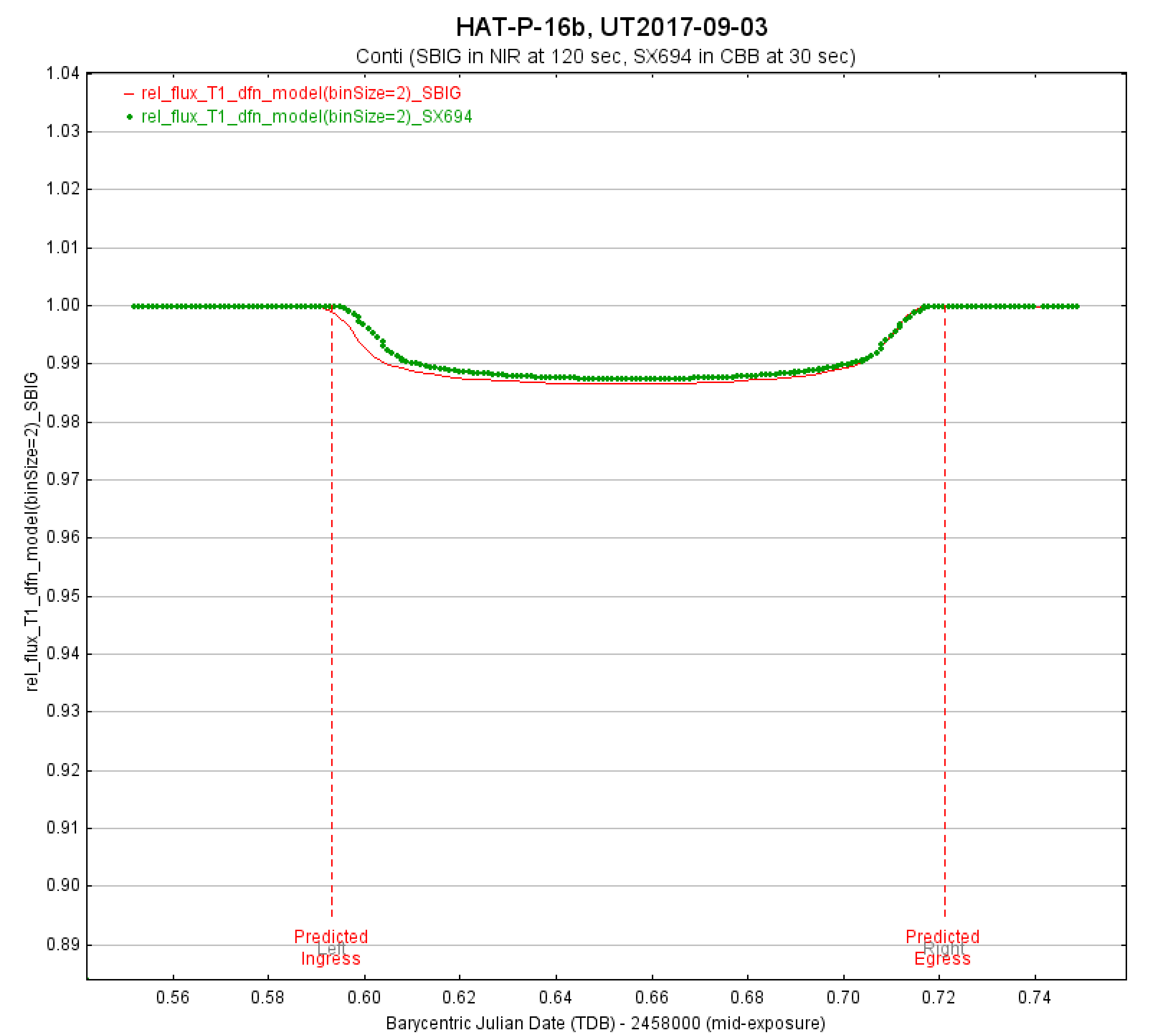
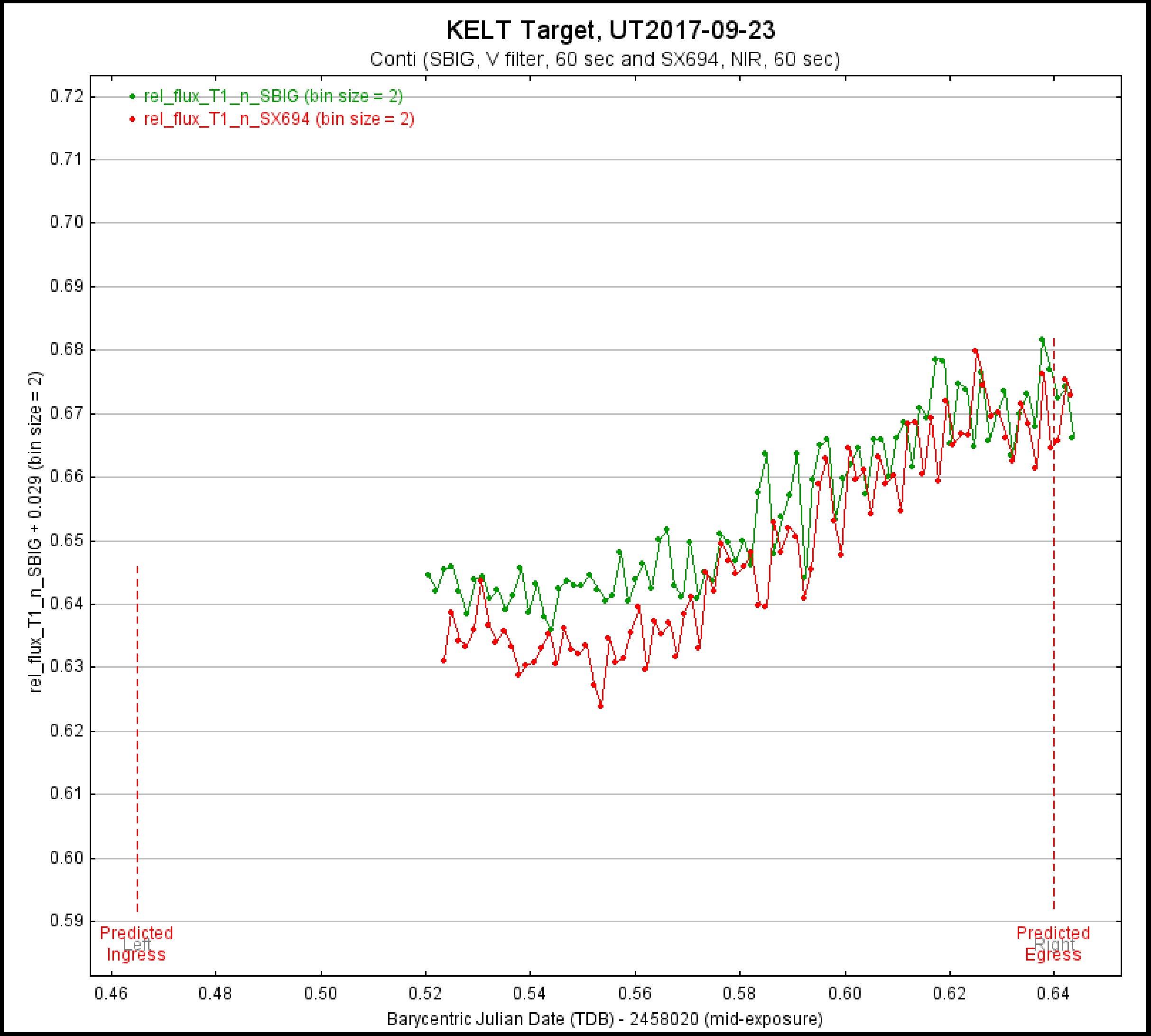
Dual Bandwidth Measurements During an Exoplanet Transit



Dual Bandwidth Measurements During an Eclipsing Binary Transit



Aids to Help Diagnose Horses vs. Zebras

- Documentation of best practices and use of AstroImageJ: “A Practical Guide to Exoplanet Observing” (www.astrodennis.com)
  - 1,916 unique visiting users from 68 countries
  - 466 downloads of the Guide

- Training: AAVSO online course on Exoplanet Observing
  - 80 participants to-date

- Tools:
  - Sample Datasets (Conti)
  - Observation worksheet with hot links (Conti)
  - AstroImageJ (Collins)
  - Speckle Toolbox (Rowe)

- Improved techniques for:
  - higher precision autoguiding
  - simultaneous, dual-band measurement

Summary

- Understand what's behind the results
- Pursue the reasons for any perceived anomalies
- Eliminate any effects due to outliers
- Understand why outliers are happening

However, don't be afraid to stick your neck out like a giraffe since that horse may very well be a zebra!

Addendum

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!