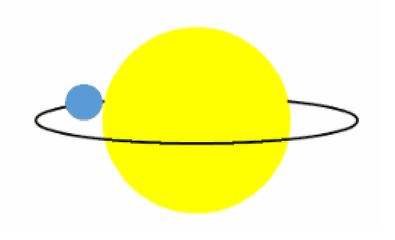
Exoplanet Observing by Amateur Astronomers

May 22, 2016



by

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The Night Sky

Q: Which stars host one or more planets?

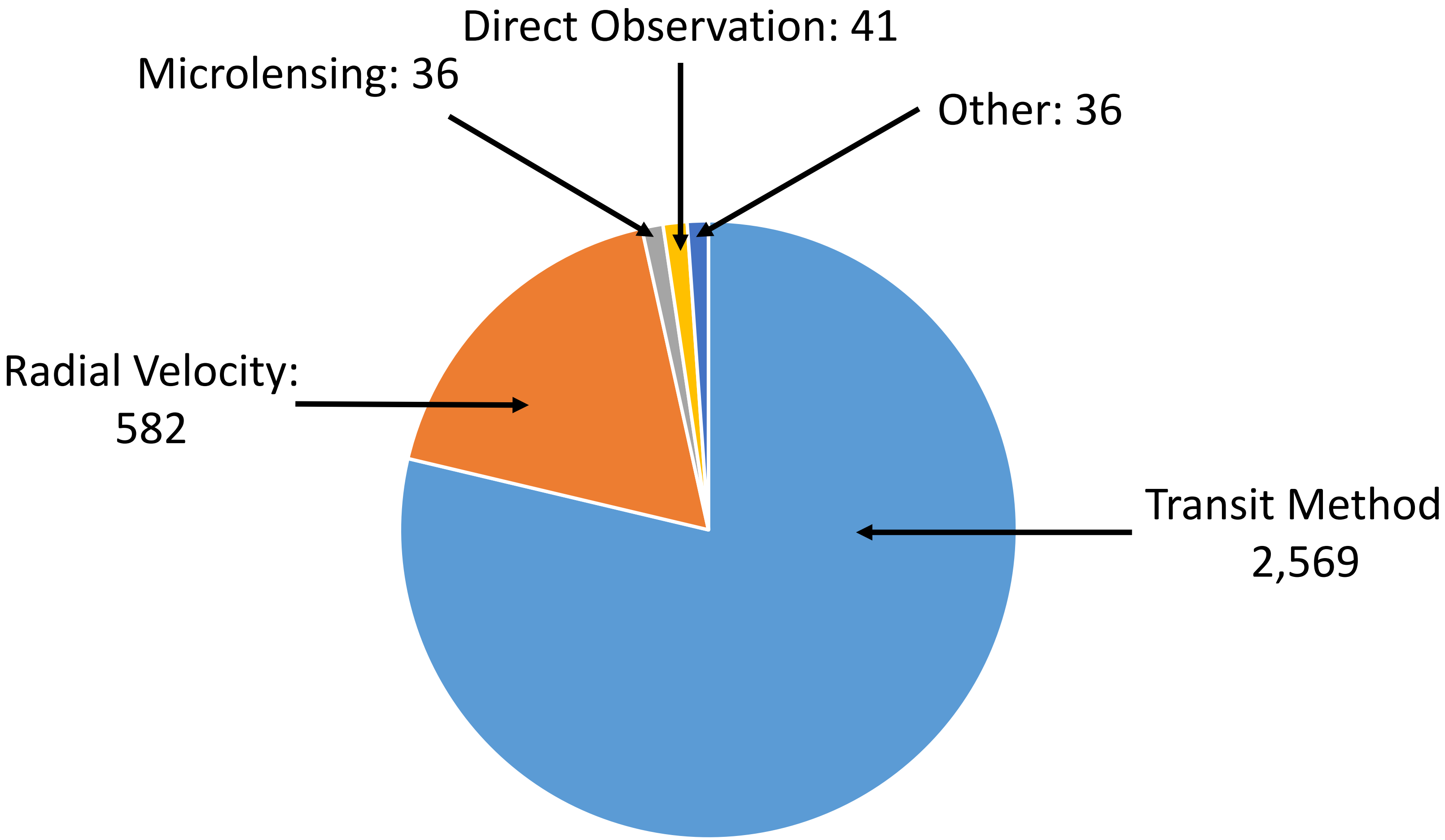
A: Most of them!

…and one in five are believed to host an Earth-sized planet that could support life!

Background

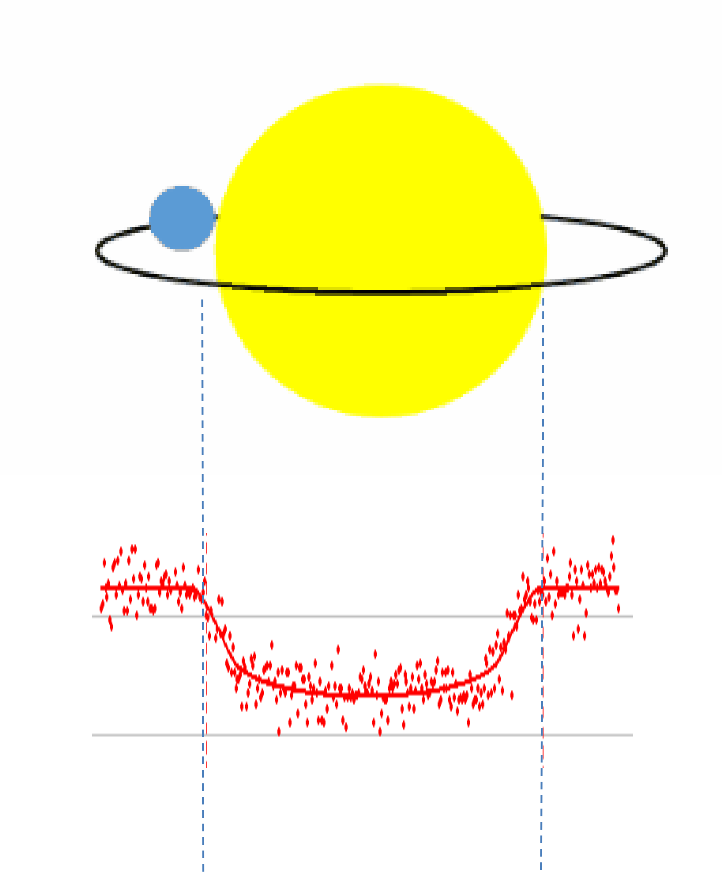
- Exoplanet (Extrasolar Planet) – a planet orbiting a distant "host star"
- First exoplanet was discovered in 1992
- Both space-based (e.g., Kepler) and ground based observatories have been used to detect exoplanets

Detection Methods: 3,264 Confirmed Exoplanets



The Transit Method

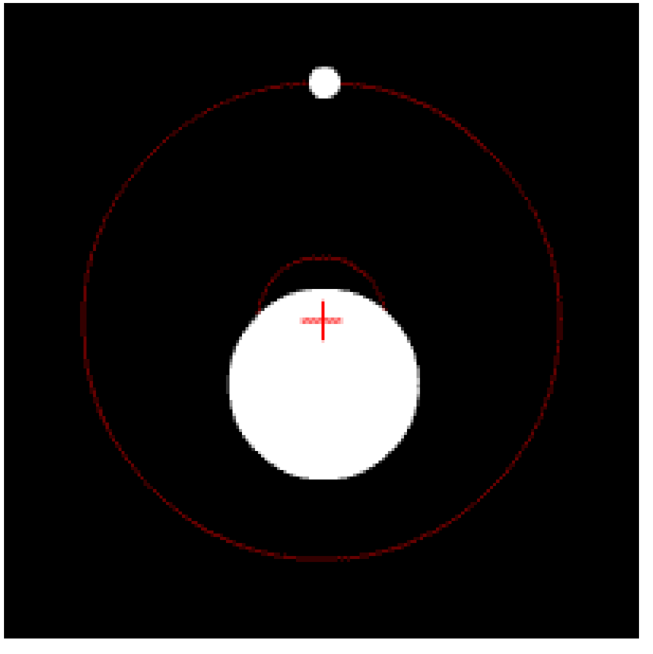
- Measures dip and length of light curve



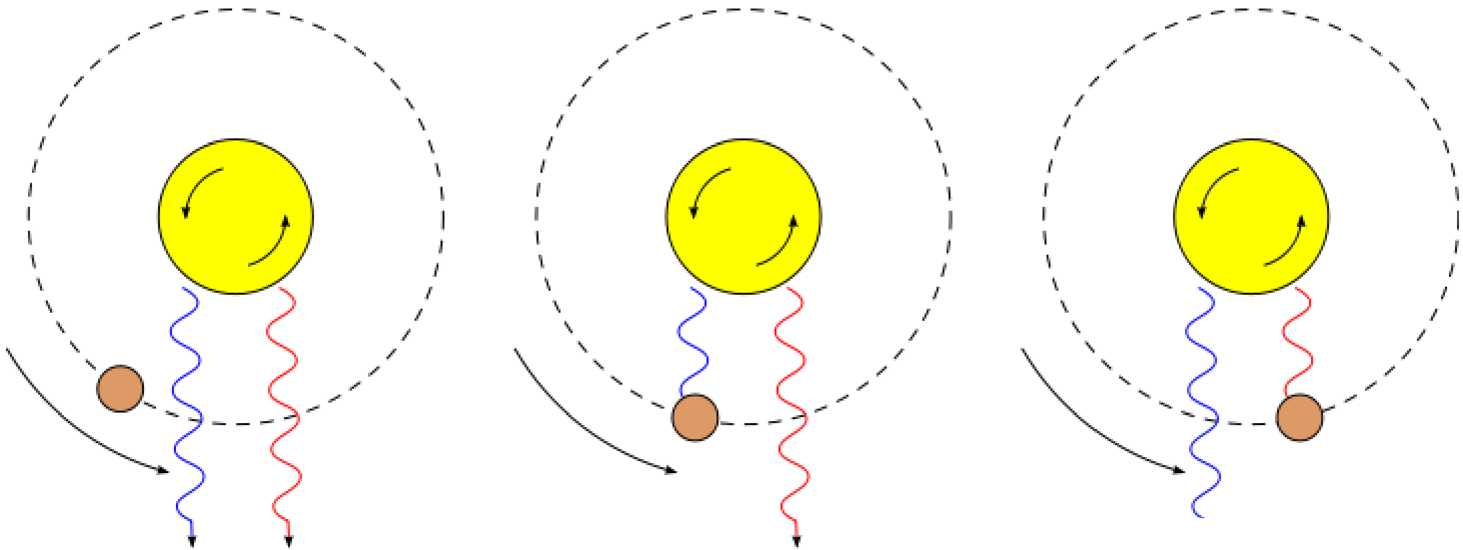
The Radial Velocity Method

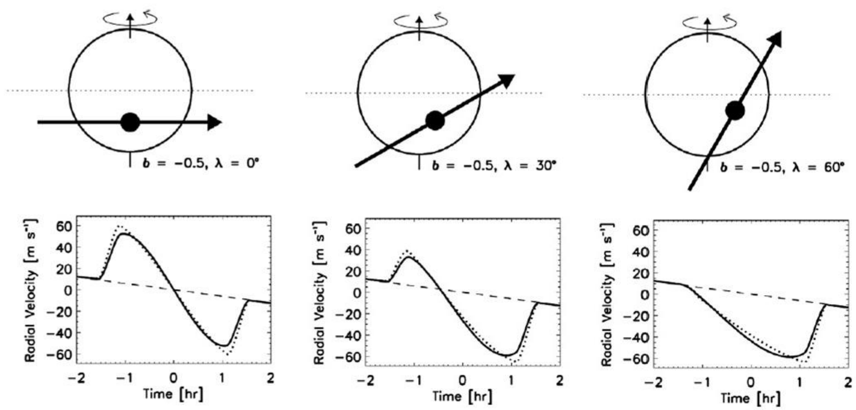
- Measures the Doppler shift of the host star's spectrum as an orbiting planet causes it to wobble around their common center of gravity ("orbital reflex motion")

- Can even be used to determine the orientation and direction of the planet's orbit (the Rossiter McLaughlin Effect)



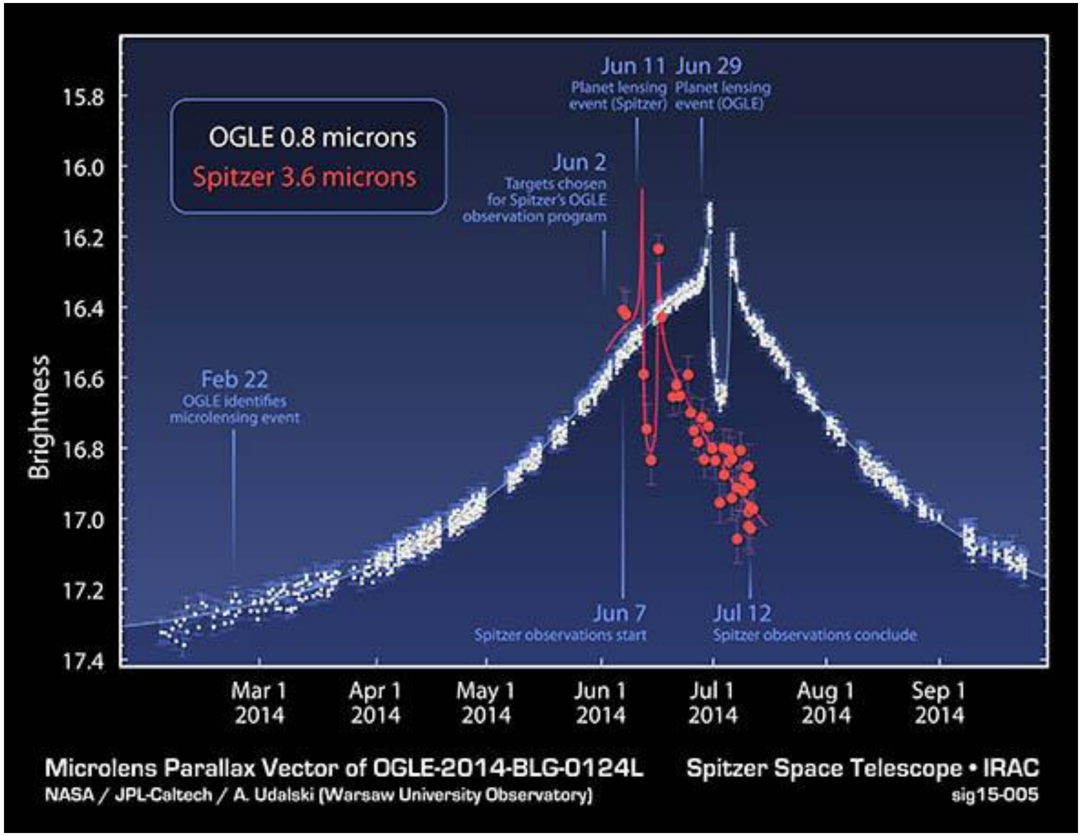
The Rossiter-McLaughlin Effect





The Microlensing Method

- Measures the change in magnification of a background star as a planet orbits the foreground "lensing" star



Direct Imaging

- The "Holy Grail" of methods to determine habitable planets (see October 2015 *S&T* article)

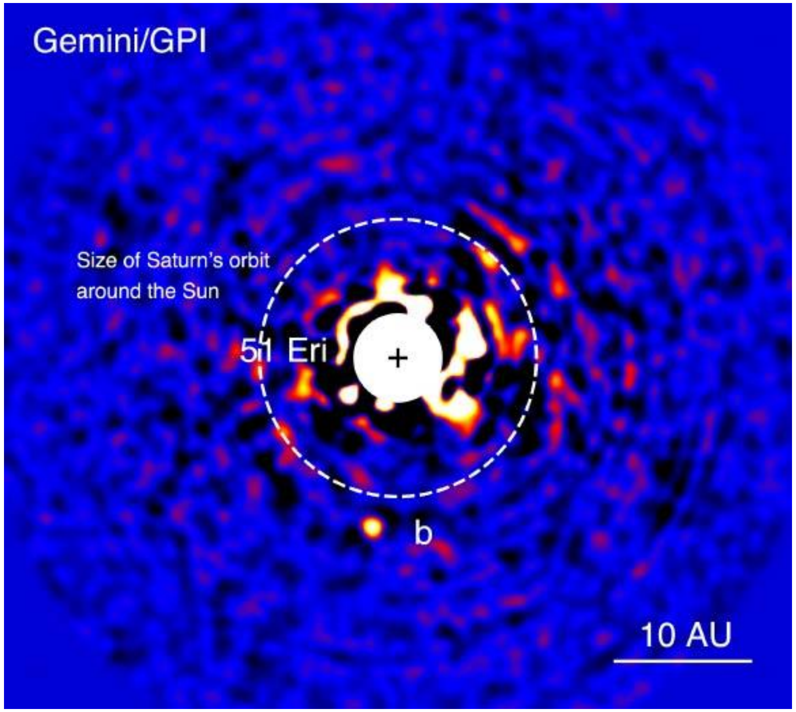
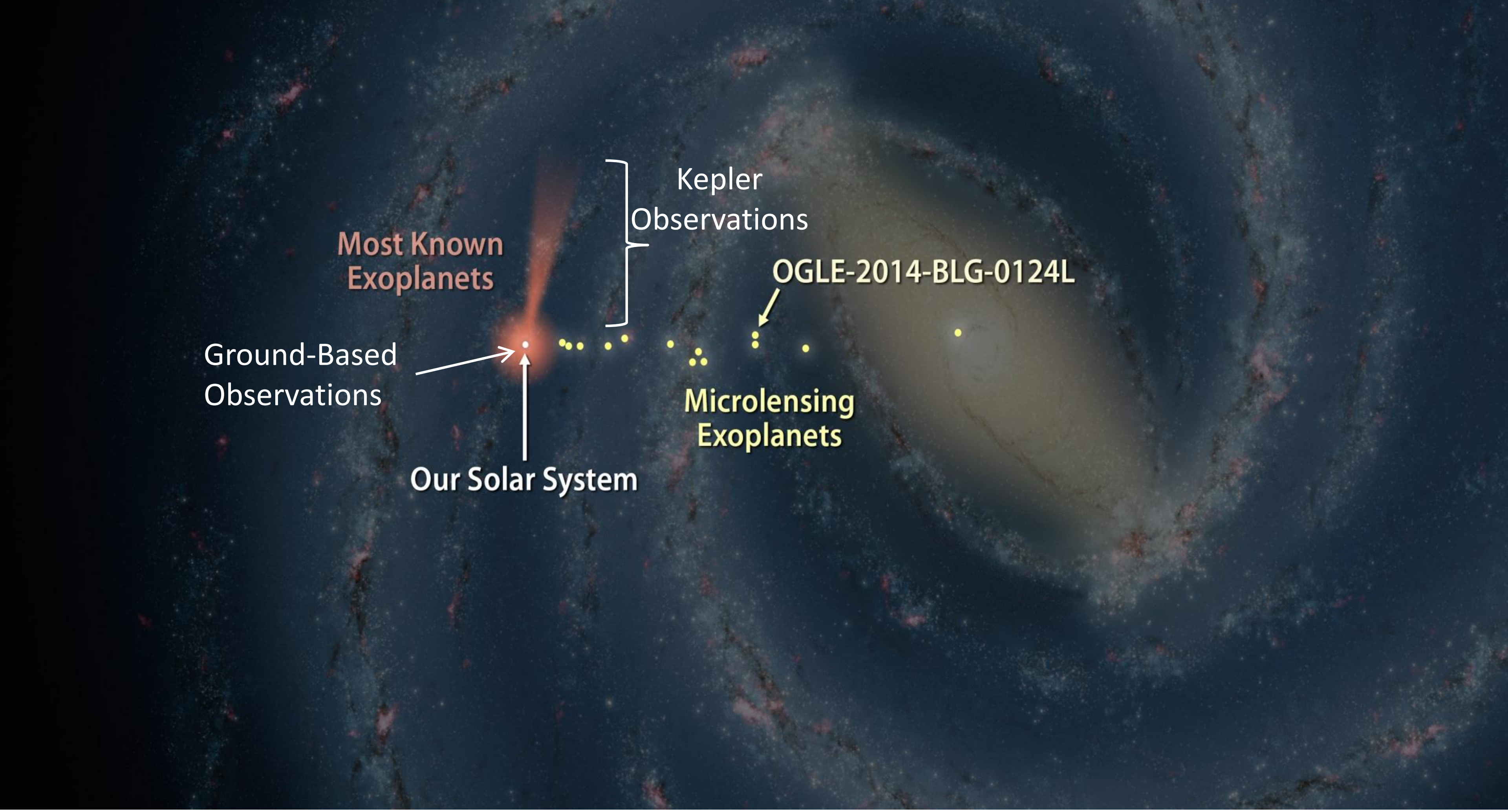
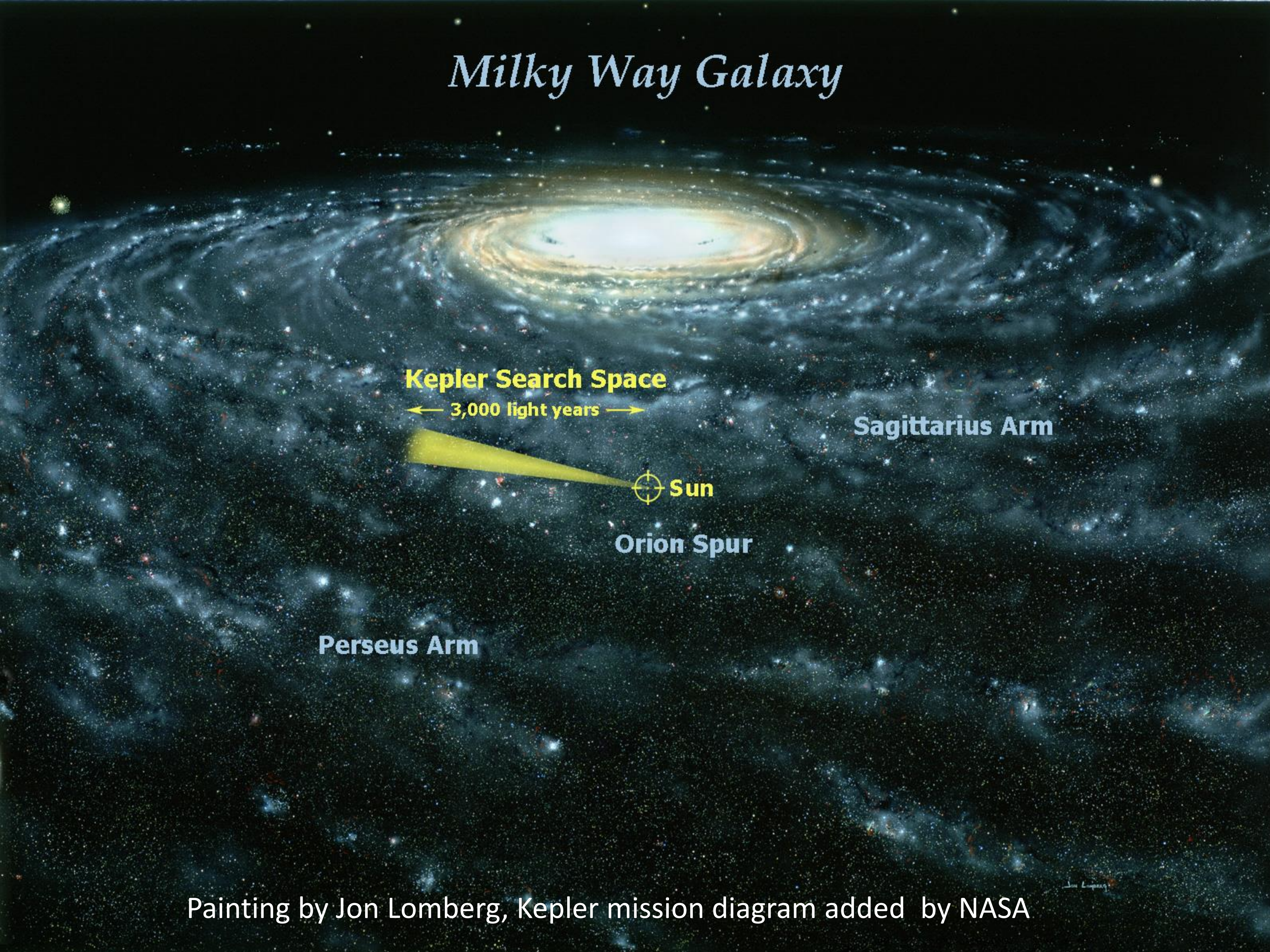


Image credit: J. Rameau, University of Montreal / C. Marois, Herzberg Institute of Astrophysics.

Until now, we are mostly looking in our immediate neighborhood!

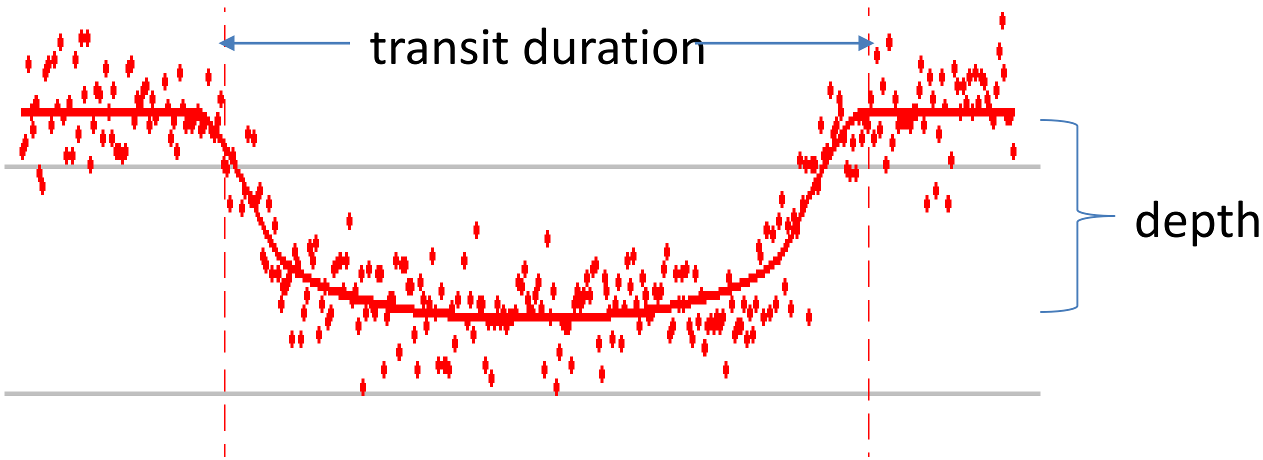


Courtesy NASA/JPL-Caltech



Painting by Jon Lomberg, Kepler mission diagram added by NASA

What can we learn from the Light Curve?



- Exoplanet radius
- Exoplanet orbital radius
- Exoplanet orbit inclination to our line-of-sight

Assumes knowledge of host star’s radius and exoplanet’s orbital period

Creating the Light Curve

- Differential Photometry is used to calculate the relative change in flux between the Host star and one or more comparison star

- The flux of the Host and comparison stars are first adjusted for background sky noise (due to light pollution, sky glow, moon light, etc.)

- A data point on the light curve = the relative change in flux of the Host star

- A best fit of the model of a transit is made based on these data points

Suspected Star Spot

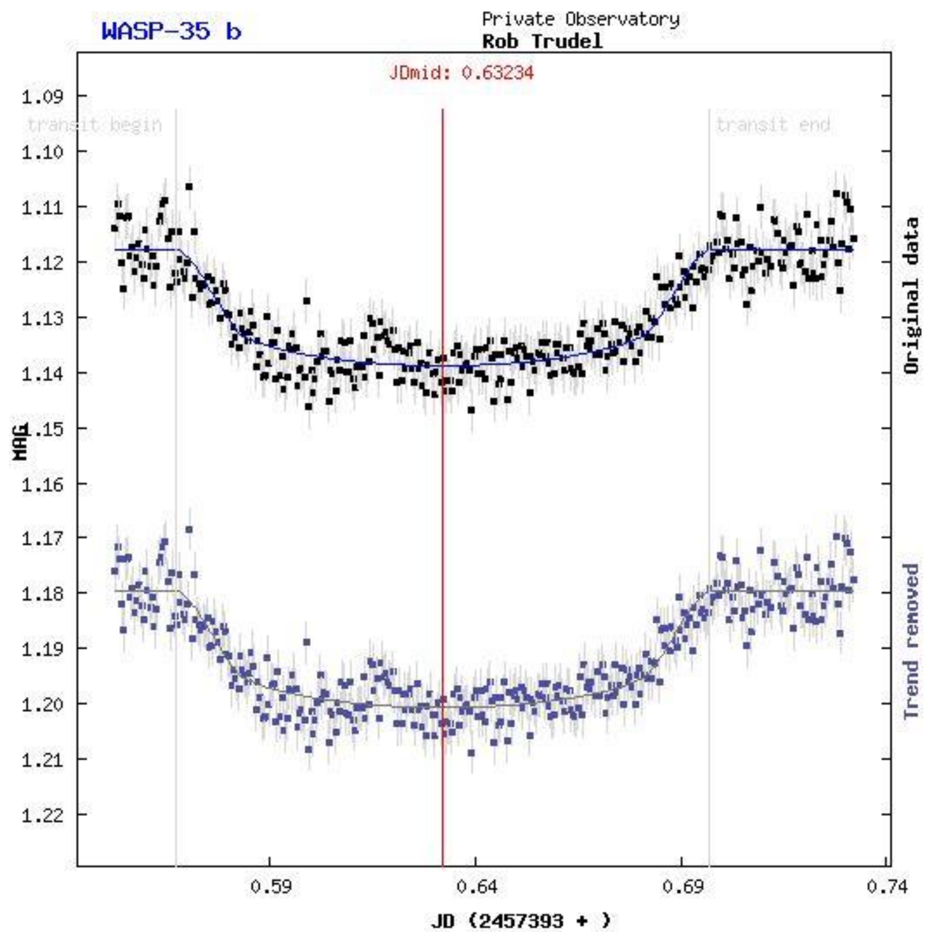


Image Courtesy of Robert Trudel

Amateur Astronomers Can Detect Exoplanets!

…using the transit method to determine a light curve

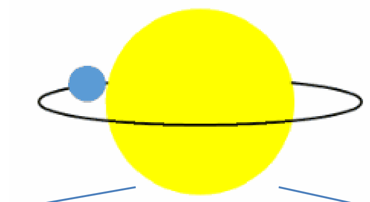
…using the same equipment used for deep sky imaging

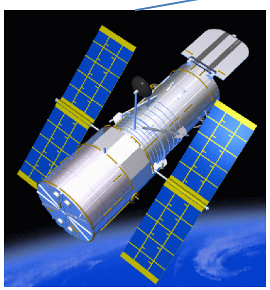
…even in light polluted skies

…with >90% accuracy

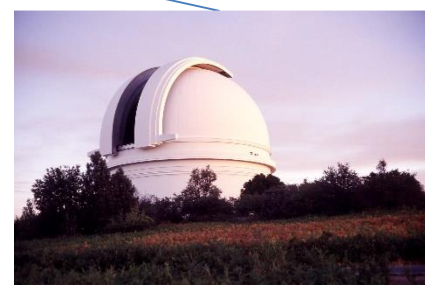
…and their observations are providing valuable science data!

Exoplanet
Pro/Am Collaborations





Space-based Observatories



Ground-based Observatories

Amateur Astronomers

Current Collaborations

- Confirmation of exoplanet candidates
  - KELT Follow-up Project

- Refinement of ephemeris of confirmed exoplanets
  - Hubble Study of Exoplanet Atmospheres

- Study of anomalous activity
  - Characterization of orbiting “planetesimals”
  - Example: WD-1145+017b – a suspected disintegrating asteroid orbiting a white dwarf

Hubble Exoplanet Pro/Am Project

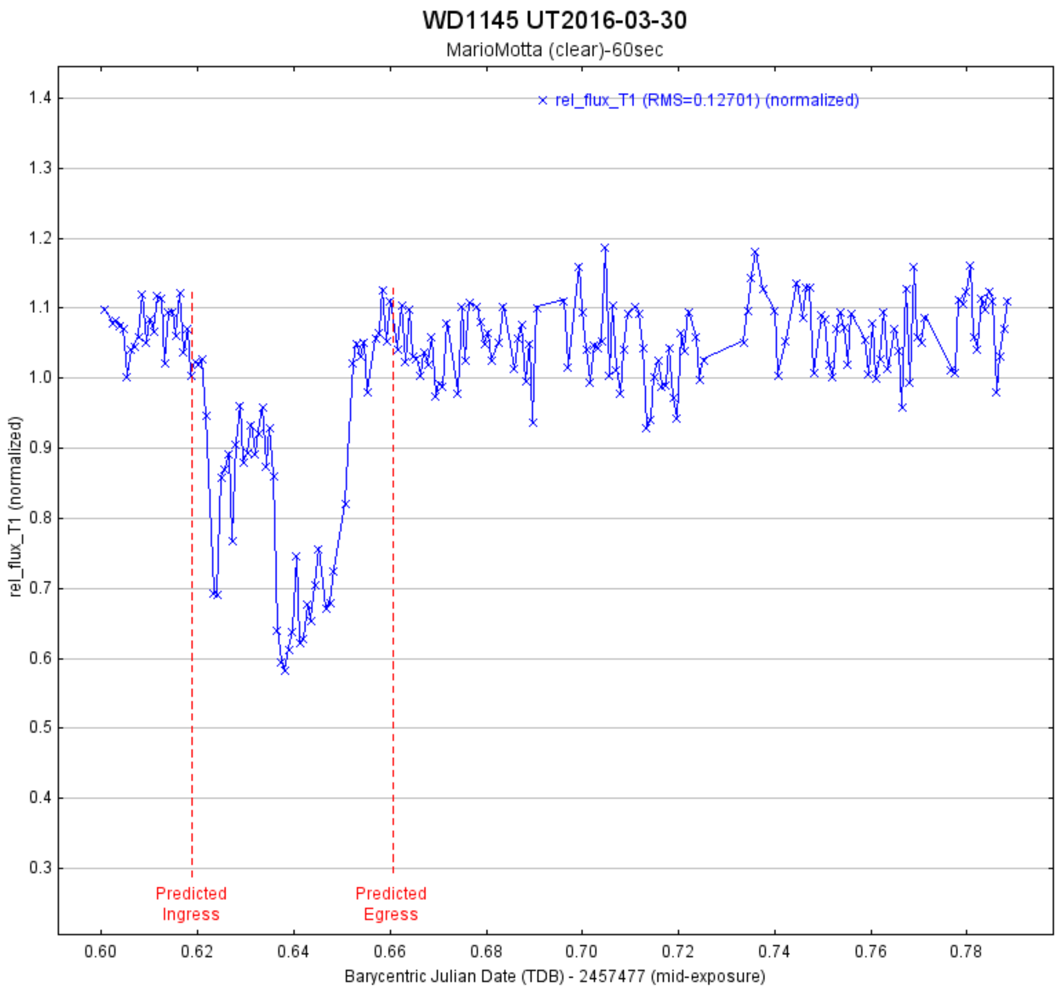
- An approved Hubble Space Telescope (HST) survey of 15 exoplanets is taking place throughout 2016
- The survey's purpose is to obtain key science data regarding the atmosphere of these 15 exoplanets prior to the James Webb Space Telescope (JWST)
- The project's Principal Investigator is noted planetary scientist Dr. Drake Deming
- Approach:
  - Hubble's Wide Field Camera 3 is using spatial scanning and a grating prism (grism) to obtain spectroscopy measurements in the 1.4 micron band
  - Each exoplanet is being visited one or more times

Hubble Pro/Am Collaboration

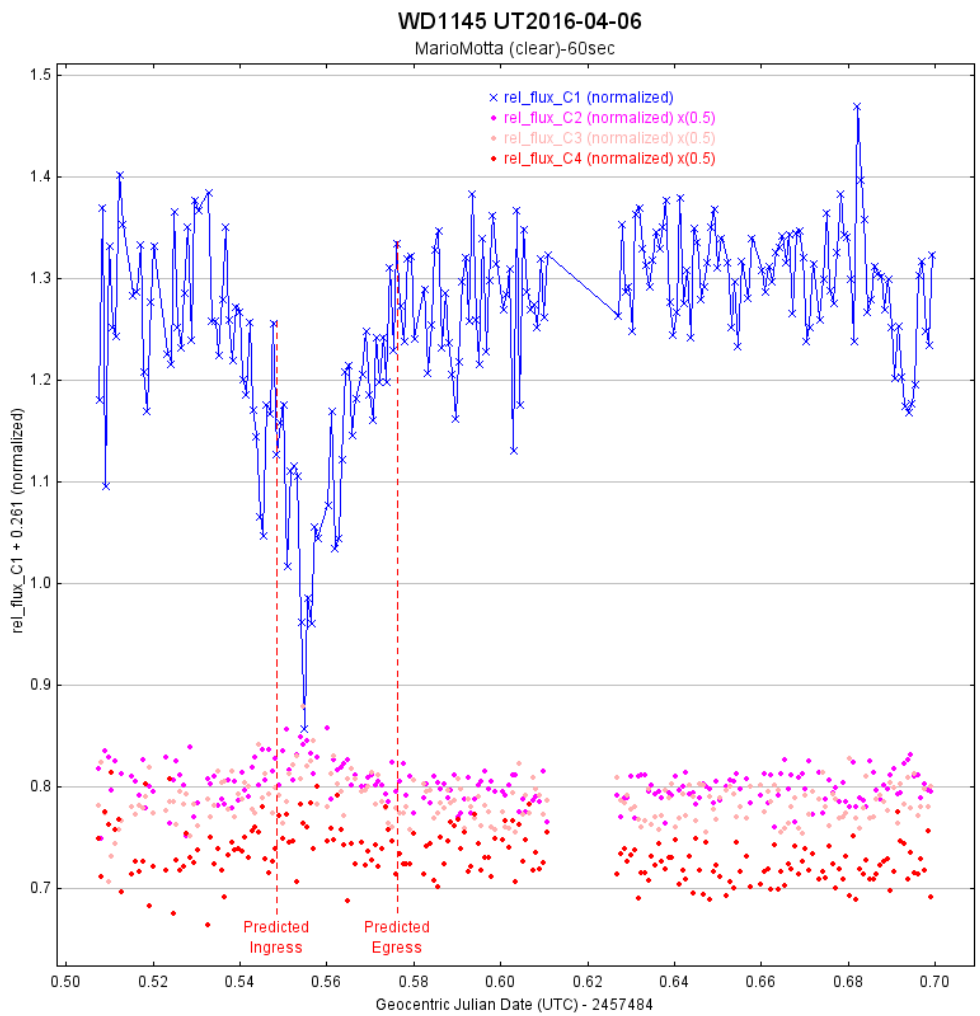
- Objectives:
  - provide refined ephemeris of the target exoplanets to the HST team
  - determine any unusual activity such as star spots or flares on the target planet's host star
  - develop a framework and a world-wide network of advanced amateur astronomers for other such collaborations
- Status:
  - observations have been made of 9 of the 15 exoplanet targets
  - follow-up observations will be made of these and the remaining 6 targets through the end of 2016

Location of Participating Observation Sites

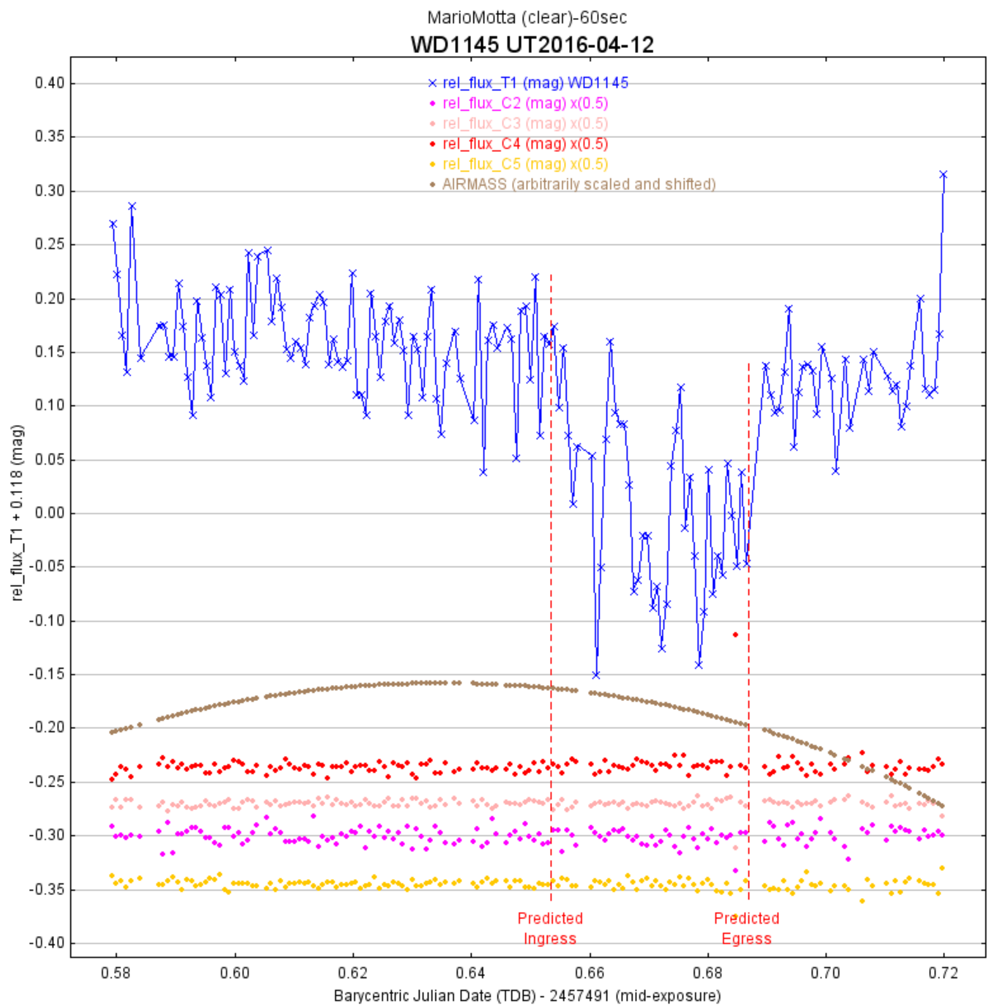
Detection of Other "Exo-Objects" (e.g., Disintegrating Planetesimals) by Amateur Astronomers!



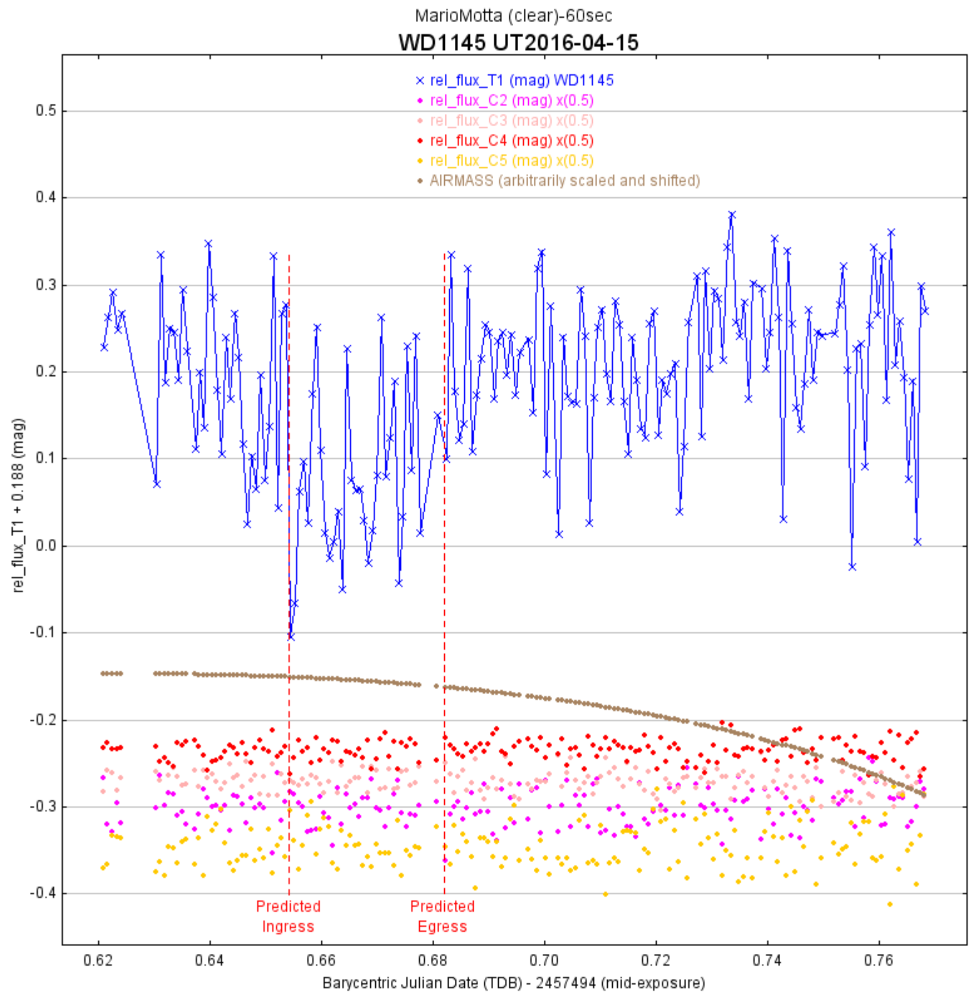
Courtesy of Mario Motta



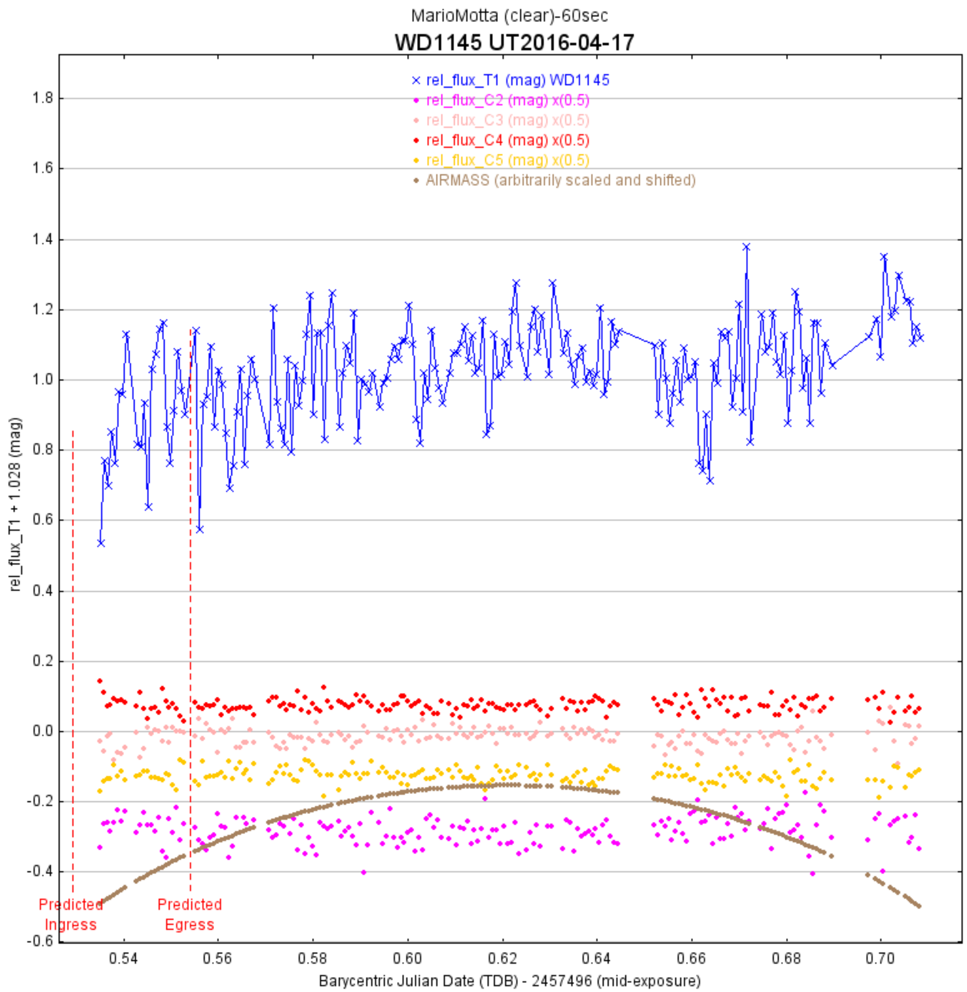
Courtesy of Mario Motta



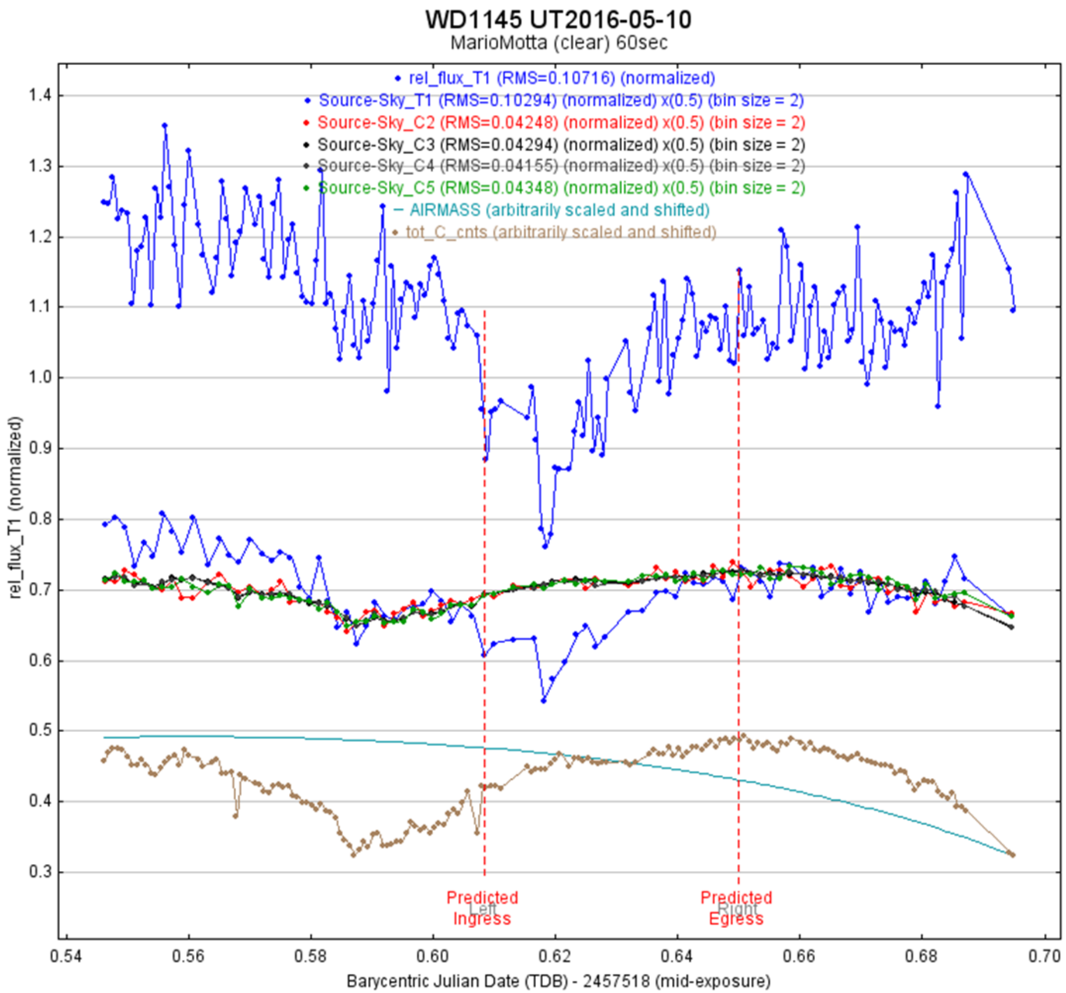
Courtesy of Mario Motta



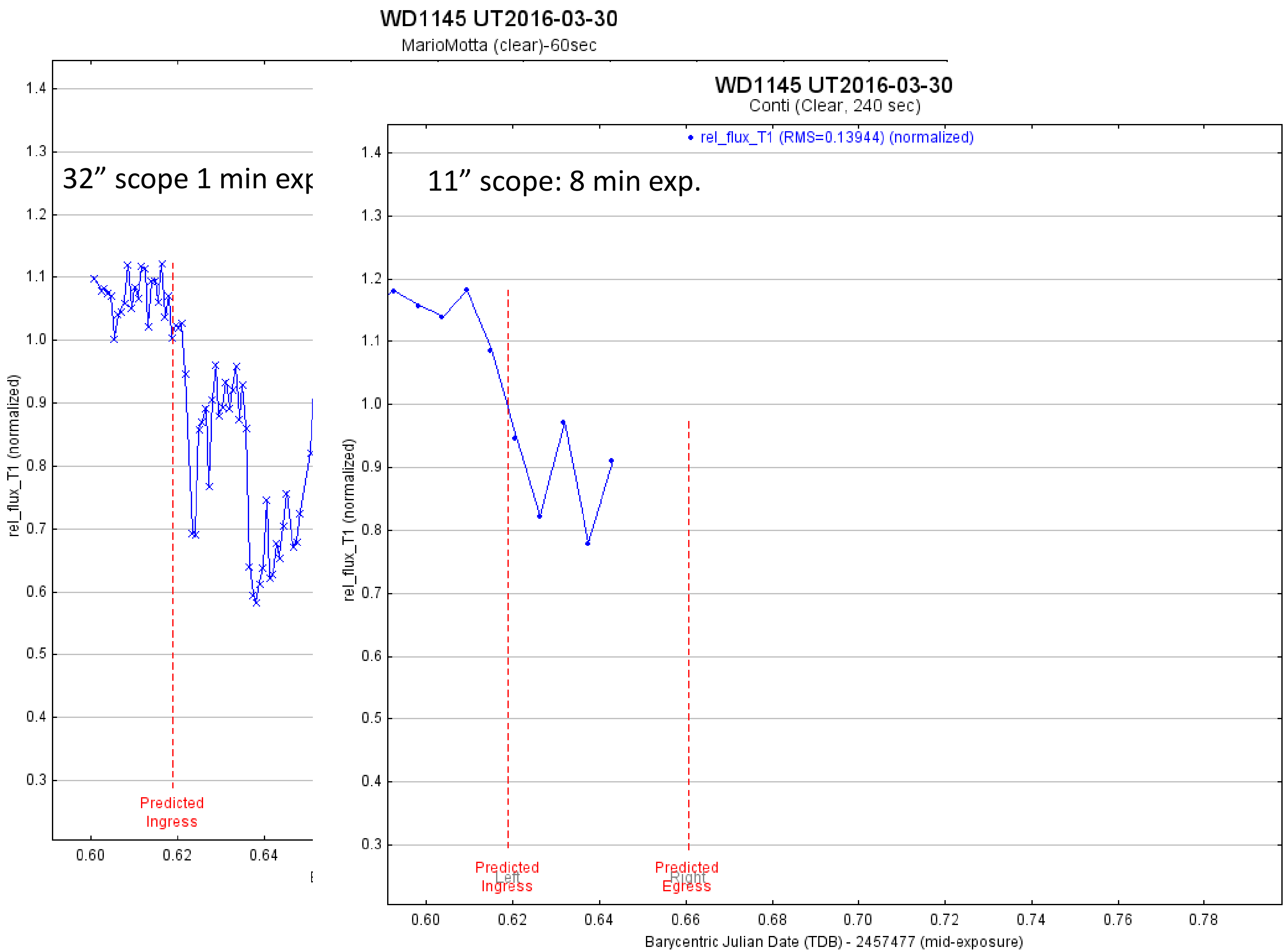
Courtesy of Mario Motta



Courtesy of Mario Motta



Courtesy of Mario Motta


WD1145 UT2016-03-30
MarioMotta (clear)-60sec
32” scope 1 min exp
rel_flux_T1 (normalized)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Predicted
Ingress
0.60
0.62
0.64
WD1145 UT2016-03-30
Conti (Clear, 240 sec)
rel_flux_T1 (RMS=0.13944) (normalized)
11” scope: 8 min exp.
rel_flux_T1 (normalized)
Predicted
Ingress
Left
Predicted
Egress
Right
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
0.78
Barycentric Julian Date (TDB) - 2457477 (mid-exposure)

The Future

Courtesy NASA

Summary

- Detection by amateur astronomers of exoplanets is possible, even in light-polluted areas
- Detection of other "exo-objects" also has now been demonstrated
- If properly coordinated, amateur astronomers can and are providing valuable information to professional exoplanet investigators
- Exoplanet detection is challenging, but extremely rewarding

The thrill of seeing a light curve develop of a transiting distant planet can be as satisfying as seeing the result of a pretty deep-sky picture!

Resources

1. A Practical Guide to Exoplanet Observing, Dennis M. Conti, http://astrodennis.com.

2. AstroImageJ, Karen Collins, http://www.astro.louisville.edu/software/astroimagej/.

3. Exoplanet Observing for Amateurs, Second Edition (Plus), Bruce L. Gary

4. The Exoplanet Handbook, Michael Perryman

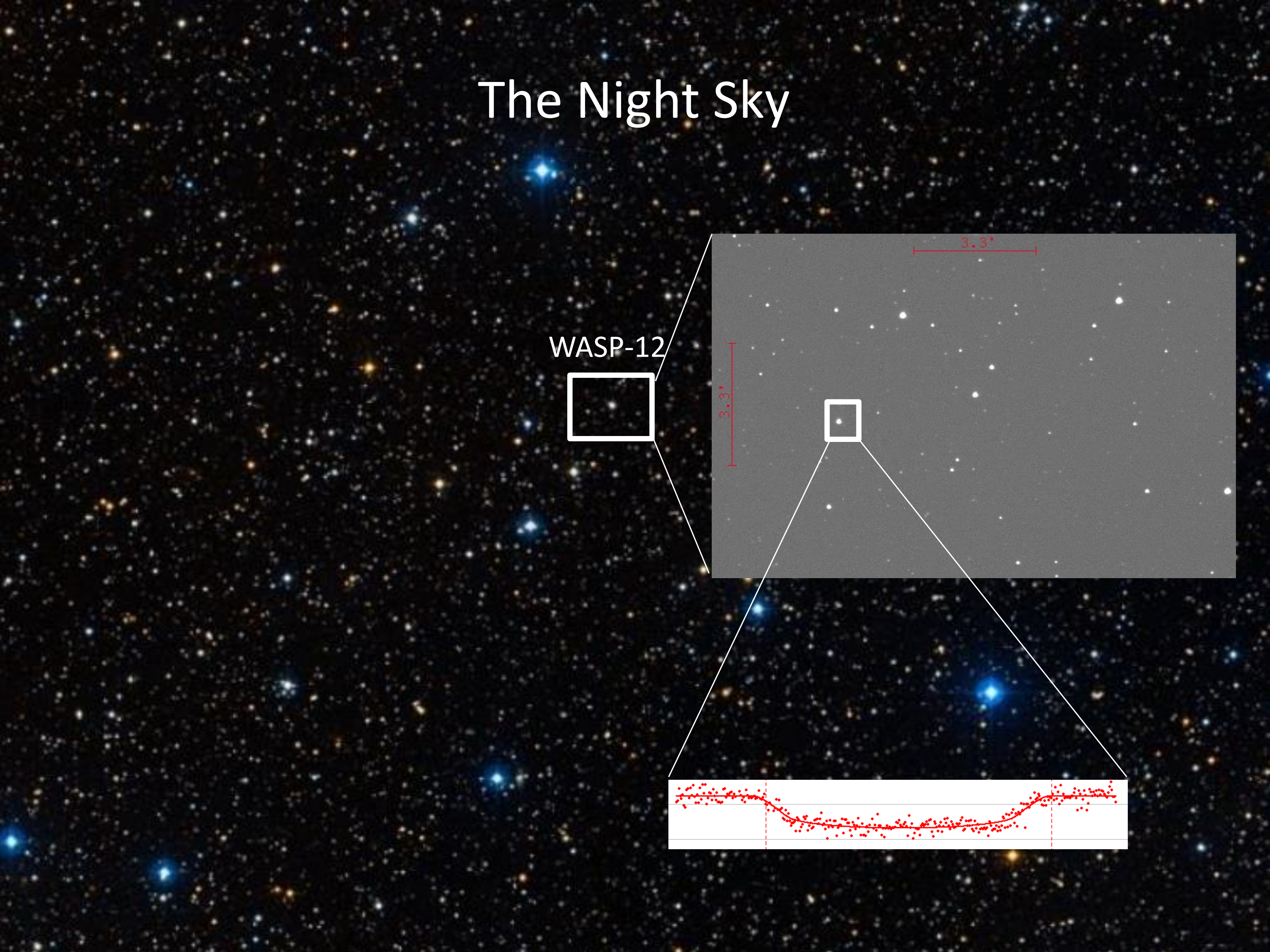
5. The Handbook of Astronomical Image Processing, Richard Berry and James Burnell (comes with AIP4WIN photometry software)

6. The AAVSO Guide to CCD Photometry, Version 1.1, 2014

7. The AAVSO CCD Observing Manual, 2011

Case Study

The Night Sky



Case Study: Detection of WASP-12b

Date/Time: January 5-6, 2016

Site: Suburban Annapolis, MD

Image scale= 0.63 arc-sec/pixel

FOV=14x11 arc-min.

Filter: V

Exposures: 337@45 seconds each

Observatory Setup
Location: Suburban Annapolis, MD

Four Phases to Exoplanet Observing

- Preparation Phase
- Image Capture Phase
- Calibration Phase
- Post-Processing and Modelling Phase

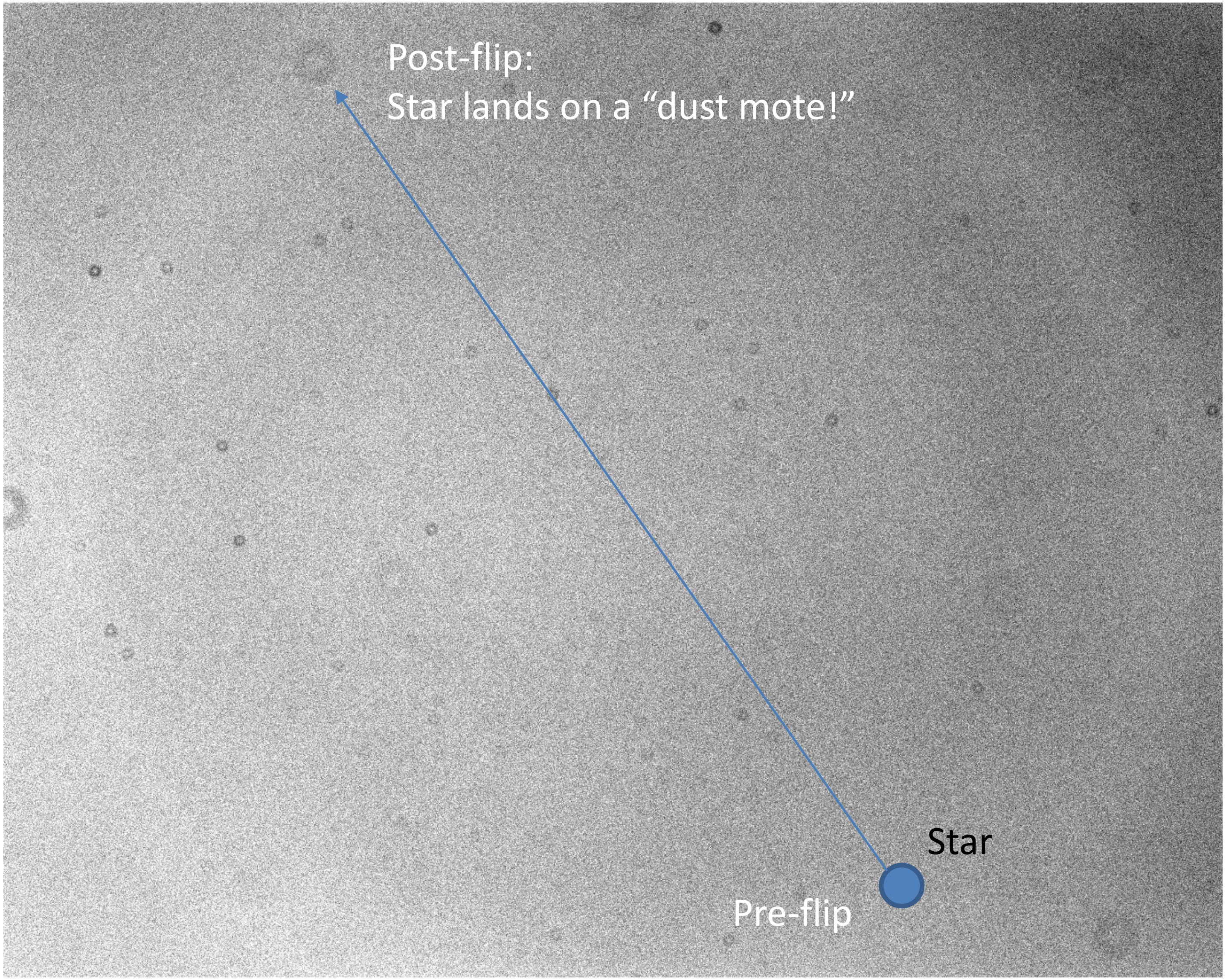
Preparation Phase

- Collect preliminary information
- Select an exoplanet target
- Predict potential meridian flips for GEMs
- Choose appropriate exposure times: important that host and comparison stars do not reach saturation during imaging session!
- Setup file directories
- Acclimate CCD camera to appropriate temperature
- Generate flat files if twilight flats are used
- Setup autoguiding system
- Synchronize image capture computer to USNO atomic clock

Image Capture Phase

- Begin imaging session 1 hour before predicted ingress time and end 1 hour after egress time
- Handle a meridian flip as expeditiously as possible
- After capturing raw images, capture darks and biases, as well as flats if an electroluminescence panel is used

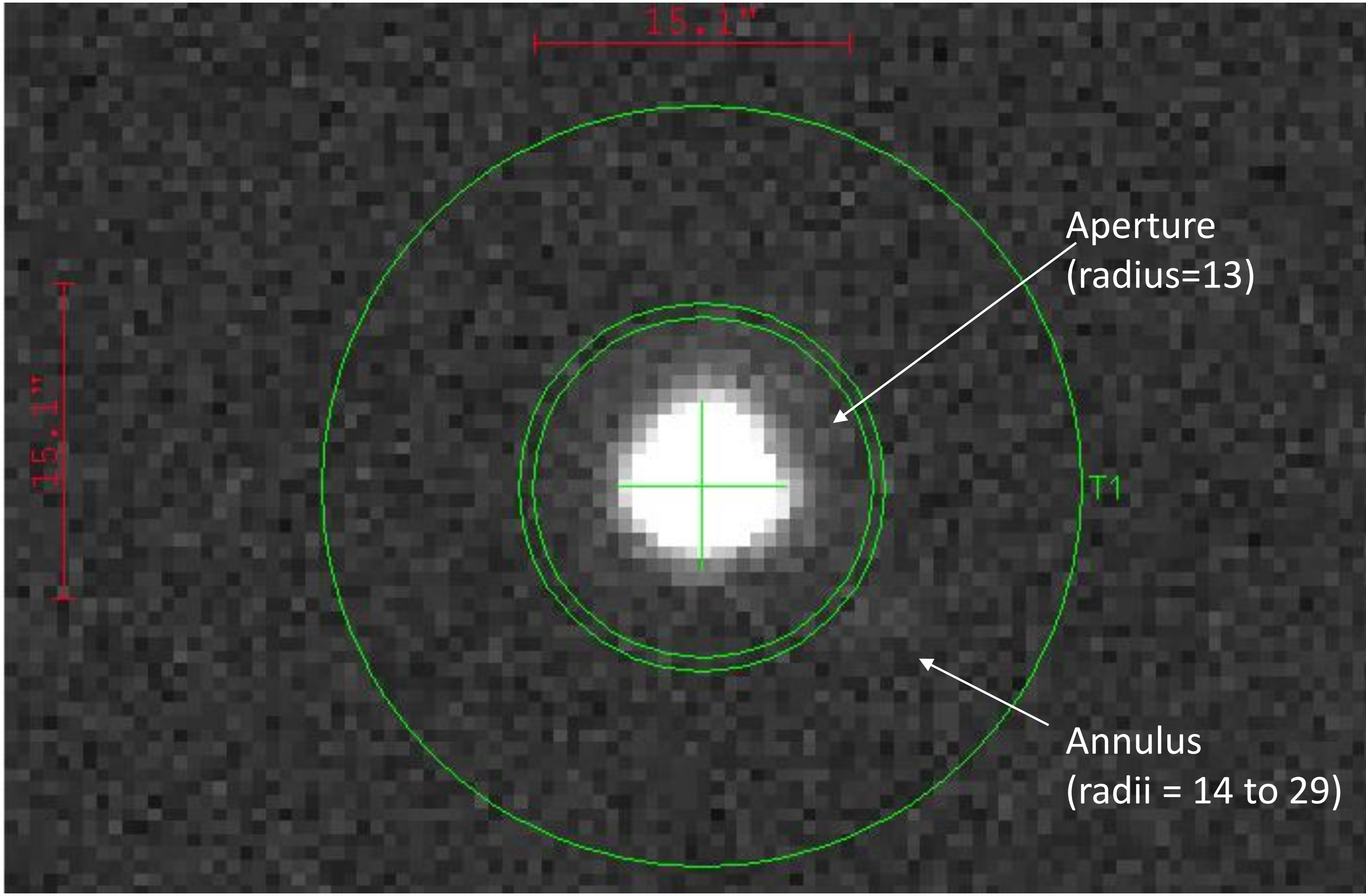
The Importance of Uniform Flats



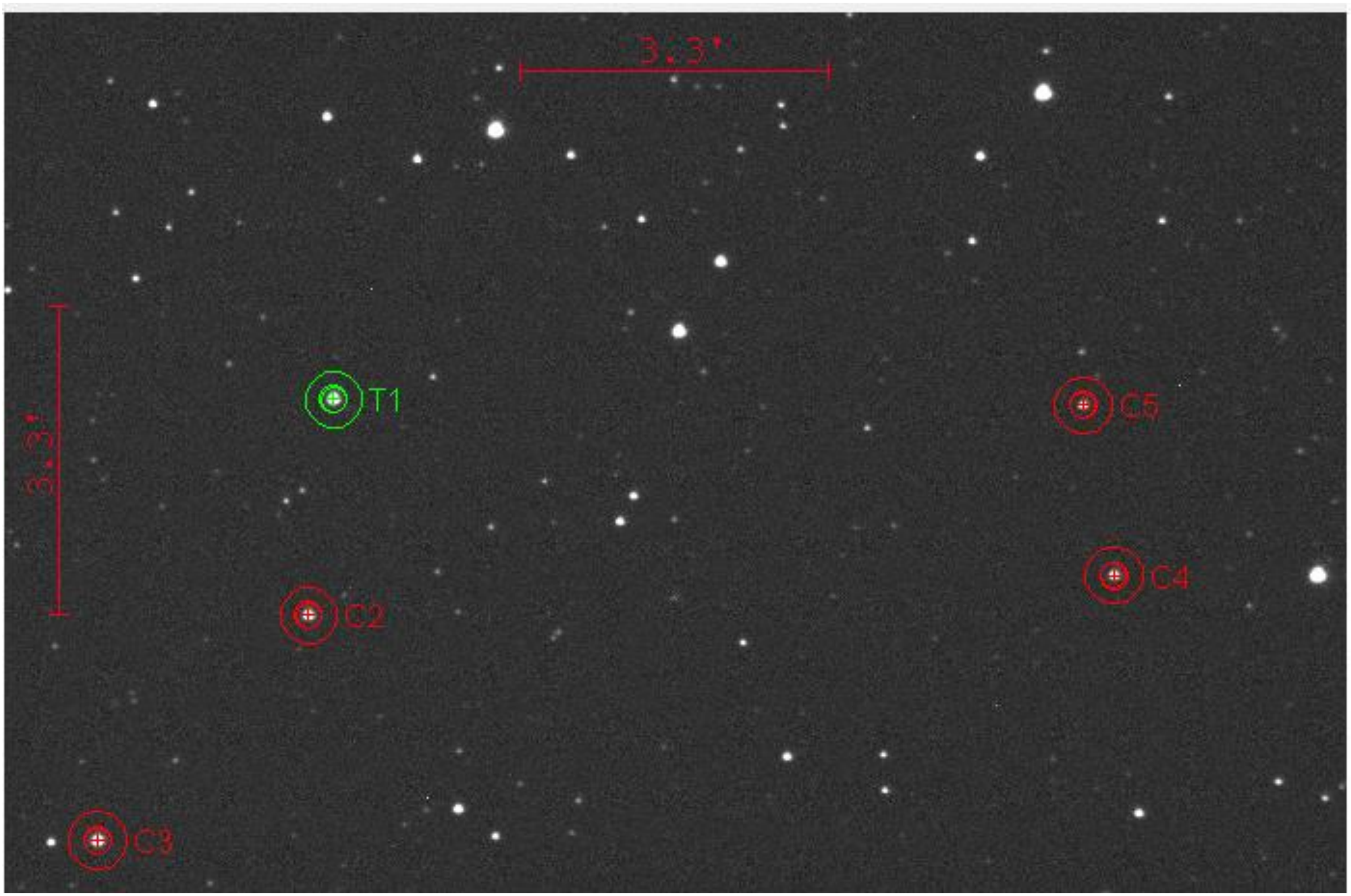
Post-Processing and Modelling

- Use AstroImageJ freeware to conduct this last phase
- Calibrate raw images using bias, darks, flats
- Update FITS headers of calibrated files with AIRMASS and BJD_{TDB} times (Barycentric Julian Date/Barycentric Dynamical Time)
- Conduct differential photometry on calibrated files

The Key Tools of Differential Photometry: the Aperture and Annulus



Selection of Comparison Stars around WASP-12



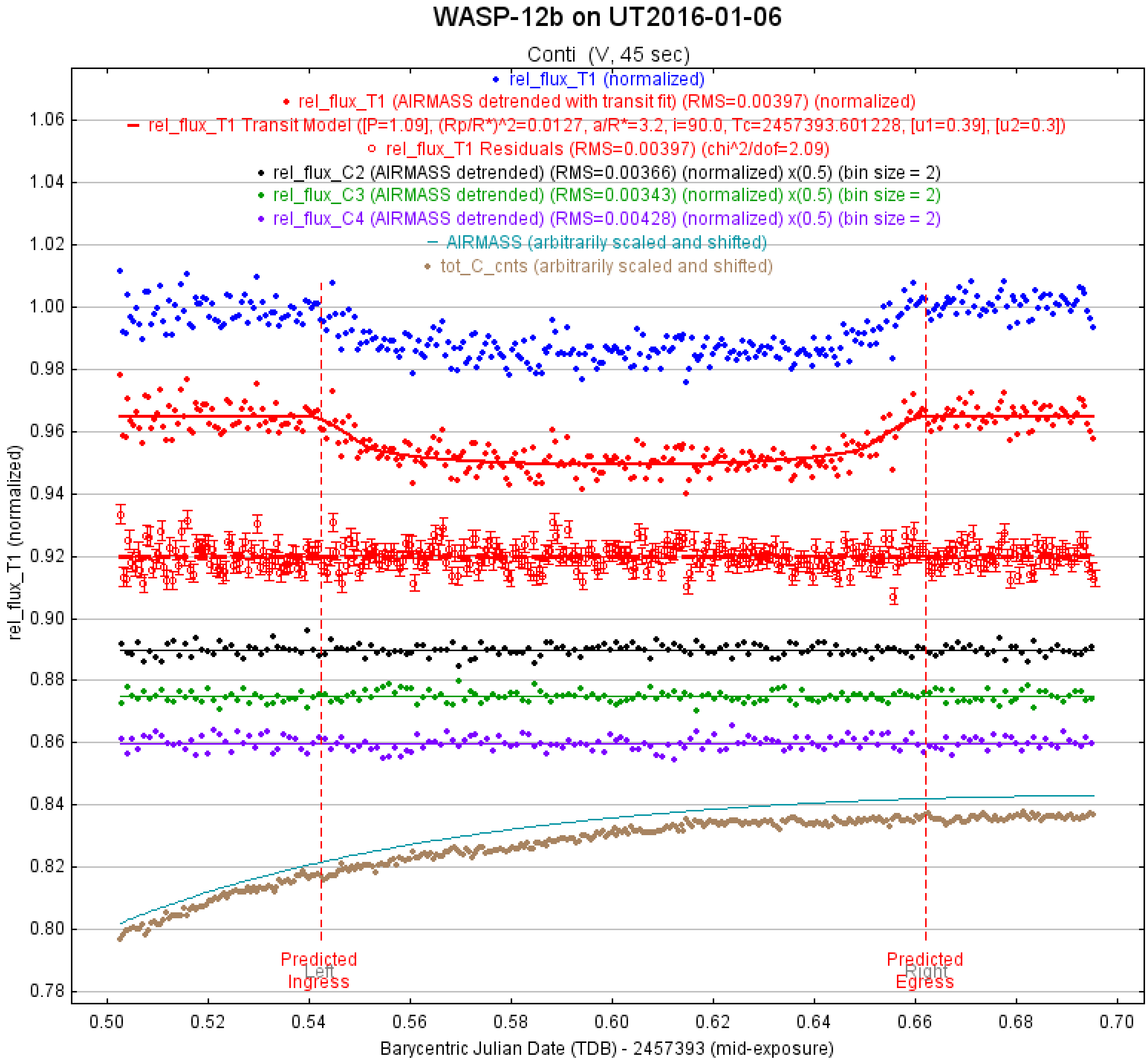
Conduct Model Fit

- Enter into AstroImageJ:
  - Orbital period
  - Predicted ingress/egress times
  - Limb darkening coefficients
  - Optionally, mass of Host star

- Add appropriate detrend parameters

- Select and adjust placement of light curve plots

- Deselect any comparison stars that are not linear


WASP-12b on UT2016-01-06
Conti (V, 45 sec)
rel_flux_T1 (normalized)
rel_flux_T1 (AIRMASS detrended with transit fit) (RMS=0.00397) (normalized)
rel_flux_T1 Transit Model ([P=1.09], (Rp/R*)^2=0.0127, a/R*=3.2, i=90.0, Tc=2457393.601228, [u1=0.39], [u2=0.3])
rel_flux_T1 Residuals (RMS=0.00397) (chi^2/dof=2.09)
rel_flux_C2 (AIRMASS detrended) (RMS=0.00366) (normalized) x(0.5) (bin size = 2)
rel_flux_C3 (AIRMASS detrended) (RMS=0.00343) (normalized) x(0.5) (bin size = 2)
rel_flux_C4 (AIRMASS detrended) (RMS=0.00428) (normalized) x(0.5) (bin size = 2)
AIRMASS (arbitrarily scaled and shifted)
tot_C_cnts (arbitrarily scaled and shifted)
rel_flux_T1 (normalized)
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
Predicted Left Ingress
Predicted Right Egress
0.50
0.52
0.54
0.56
0.58
0.60
0.62
0.64
0.66
0.68
0.70
Barycentric Julian Date (TDB) - 2457393 (mid-exposure)

rel_flux_T1

User Specified Parameters (not fitted)

Orbital Parameters

Period (days)	Cir	Ecc	ω (deg)
1.09142245	☑	0.0	0.0

Host Star Parameters (enter one)

Sp.T.	Teff (K)	J-K	R* (Rsun)	M* (Msun)	ρ* (cgs)
A5V	7761	0.108	1.630	1.860	0.612

Transit Parameters

☑ Enable Transit Fit ☑ Auto Update Priors [Extract Prior Center Values From Light Curve, Orbit, and Fit Markers]

Parameter	Best Fit	Lock	Prior Center	Use	Prior Width	Cust	StepSize
Baseline Flux (Raw)	0.559914002	☐	0.55974614	☐	0.111949228	☐	0.1
$(R_p / R_*)^2$	0.012724416	☐	0.014289873	☐	0.007144937	☐	0.014289873
a / R_*	3.216520358	☐	3.311238013	☐	1.9	☐	1.0
T_C	2457393.601228008	☐	2457393.602271072	☐	0.015	☐	0.01
Inclination (deg)	89.979982568	☐	82.5	☐	15.0	☐	1.0
Quad LD u1	0.390560810	☑	0.39056081	☐	1.0	☐	0.1
Quad LD u2	0.302699200	☑	0.3026992	☐	1.0	☐	0.1

	b	t14 (d)	t14 (hms)	t23 (d)	tau (d)	ρ* (cgs)	(e)SpT	Rp (Rjup)
Calculated from model	0.001	0.122729	02:56:44	0.097083	0.012823	0.5280	A5V	1.79

Detrend Parameters

Use	Parameter	Best Fit	Lock	Prior Center	Use	Prior Width	Cust	StepSize
☑	AIRMASS	-0.001602964152	☐	-0.008	☐	1.0	☐	0.1
☐	Meridian_Flip		☐	0.0	☐	1.0	☐	0.1
☐	Width_T1		☐	0.0	☐	1.0	☐	0.1
☐	Sky/Pixel_T1		☐	0.0	☐	1.0	☐	0.1
☐	X(FITS)_T1		☐	0.0	☐	1.0	☐	0.1
☐	Y(FITS)_T1		☐	0.0	☐	1.0	☐	0.1
☐	tot_C_cnts		☐	0.0	☐	1.0	☐	0.1
☐	BJD_TDB		☐	0.0	☐	1.0	☐	0.1

Fit Statistics

	RMS (norm)	chi²/dof	BIC	dof	chi²
Fit Statistics	0.003969	2.089682	758.0445	330	689.5950

Plot Settings

☑ Show Model — ☑ Show in legend — Line Color: red — Line Width: 2

☑ Show Residuals — ☑ Show in legend, ☑ Show Error — Line Color: red — Line Width: 2 — Symbol: circle — Symbol Color: red — Shift: -0.045

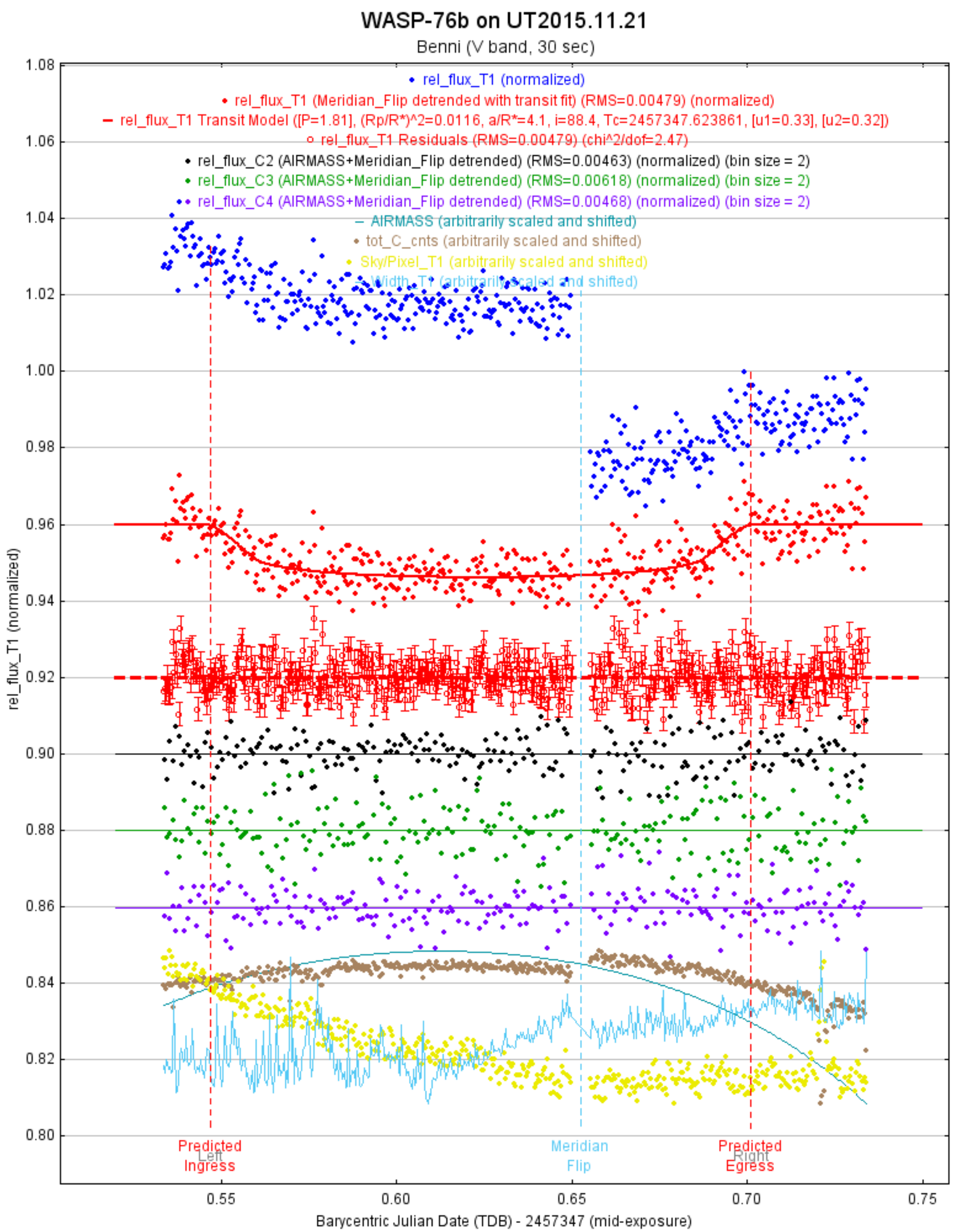
Fit Control

	Fit Update Options	Fit Tolerance	Max Allowed Steps	Steps Taken
Fit Control	☑ Auto Update Fit [Update Fit Now]	1.0E-8	20,000	774

Accuracy of Model Fit Results for the Case Study

Parameter	Model Fit	Published	Accuracy
Transit depth	0.0127	0.0138	92.0%
Transit duration	176.7 min.	175.7 min	99.4%
Orbit radius	0.024 au	0.023 au	95.7%
Orbit inclination	90 °	82.5 °	90.9%
Planet radius	1.79_{Jup}	1.79_{Jup}	100%

Light Curve with Effects of Meridian Flip Detrended



Exoplanet Observing vs. Deep Sky Imaging

- Where Exoplanet Observing is more stringent:
  - Calibration (with darks, flats) a necessity
  - Consideration for atmospheric extinction
  - Accurate polar alignment and guiding
  - Appropriate image scale (i.e., arc-seconds/pixel)
  - Choice of filter
  - Necessity to stay within CCD linearity (to avoid saturation of Host Star)
  - Choice of aperture and annulus radii

- Where Exoplanet Observing is less stringent:
  - Less sensitive to light pollution, moon light, and scintillation
  - In some cases, out-of-focus stars may be desirable

Science Contributions from Amateur Exoplanet Observations

- Can help confirm candidate planets (e.g., there are currently 3,704 unconfirmed Kepler candidates)

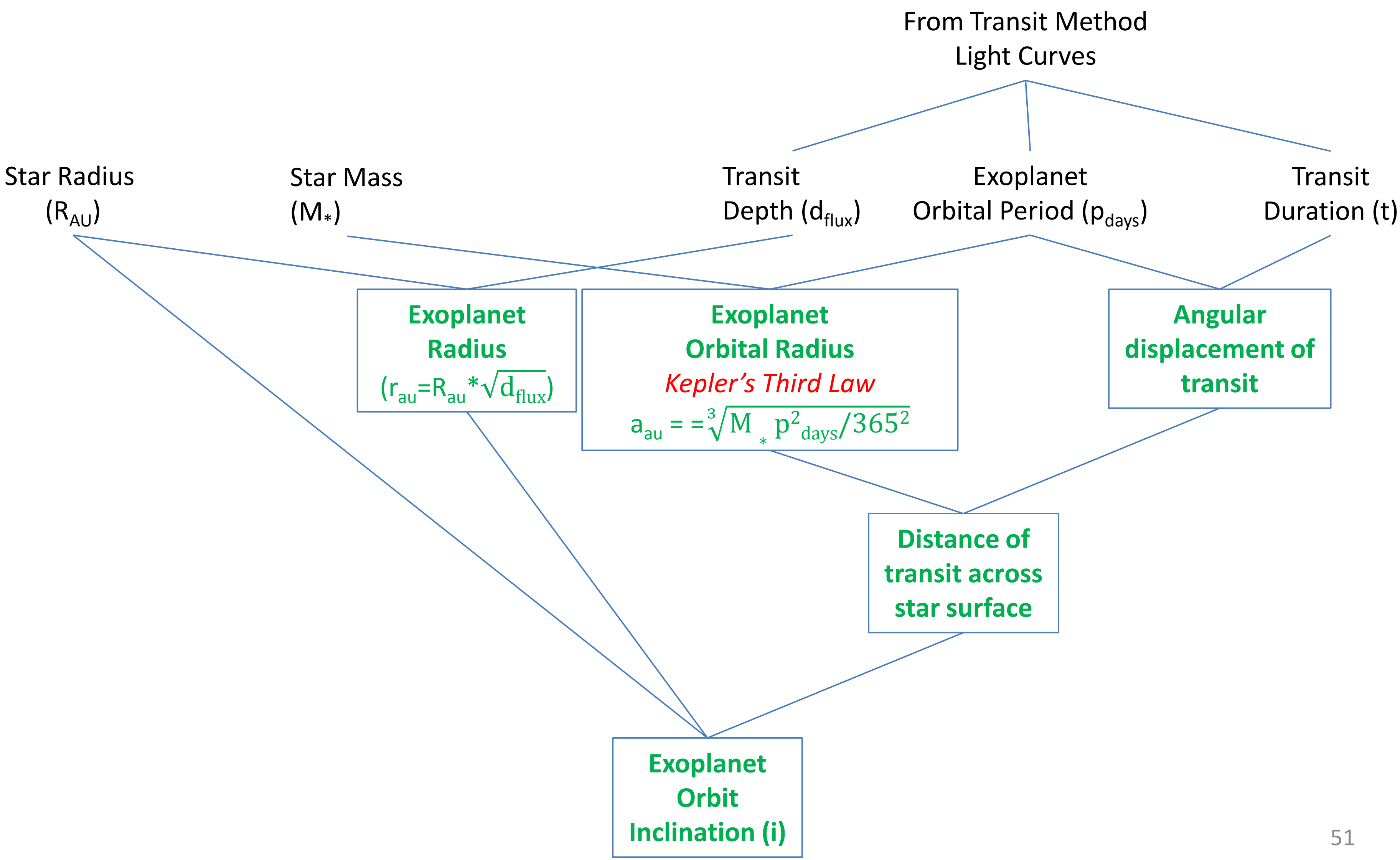
- Can refine transit times and depths of confirmed planets

- Can help determine Transit Time Variations that could indicate multi-planetary systems

- Can detect occurrences of host star events (e.g., "star spots")

- Can collaborate with professional astronomers on specific exoplanet studies

Derivation of Exoplanet Properties Using Transit Method



Derivation of Additional Exoplanet Properties Using Radial Velocity Method