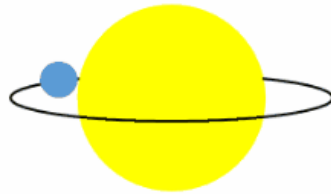


# Exoplanet Observations by Amateur Astronomers



by  
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Chairman, AAVSO Exoplanet Section  
email: [dennis@astrodennis.com](mailto:dennis@astrodennis.com)

# The Night Sky

Q: Which stars host one or more planets?

A: Most of them!

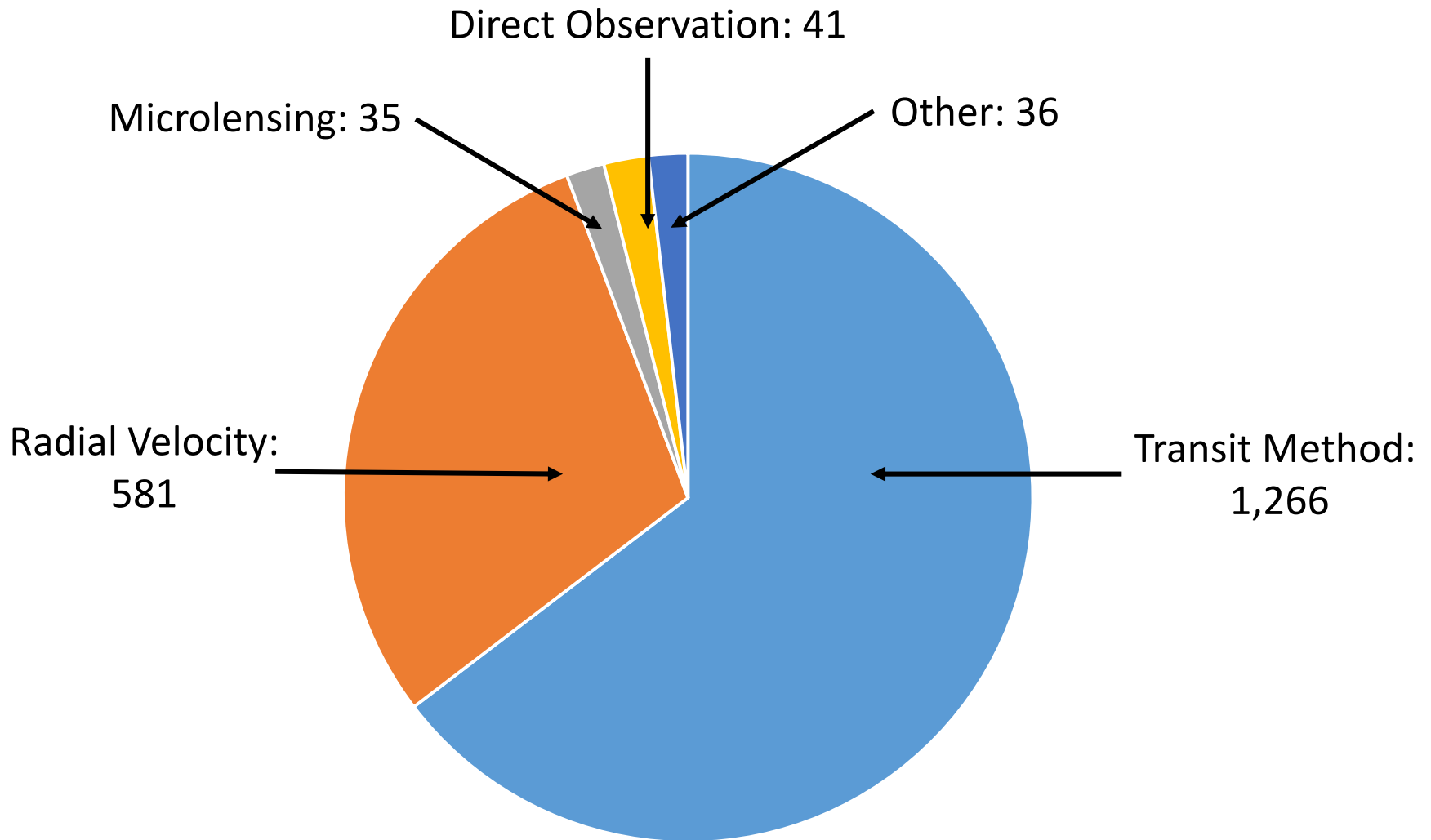
...and one in five are believed to host an  
Earth-sized planet that could support life!



# Background

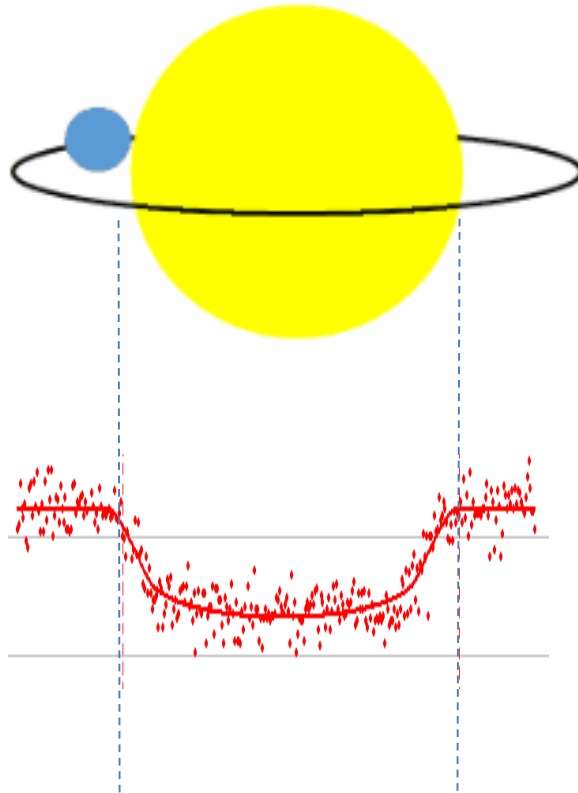
- Exoplanet (Extrasolar Planet) – a planet orbiting a distant “host star”
- First exoplanet was discovered in 1992
- Both space-based (e.g., Kepler) and ground based observatories have been used to detect exoplanets

# Detection Methods: 1,959 Confirmed Exoplanets



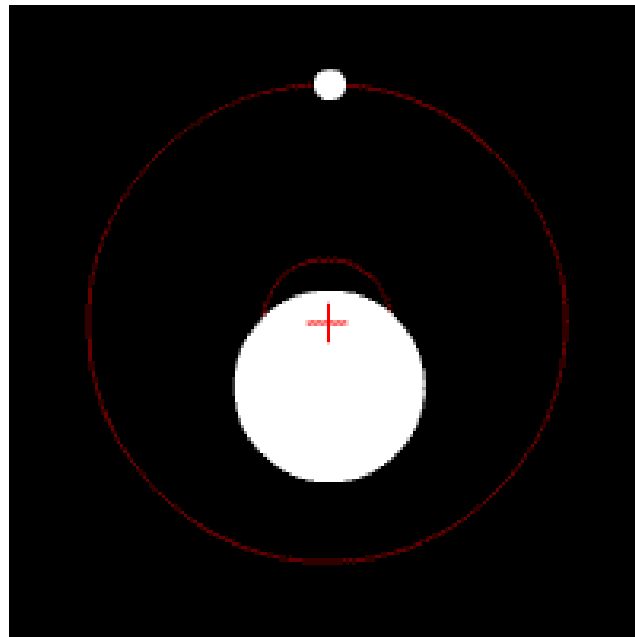
# The Transit Method

- Measures dip and length of light curve

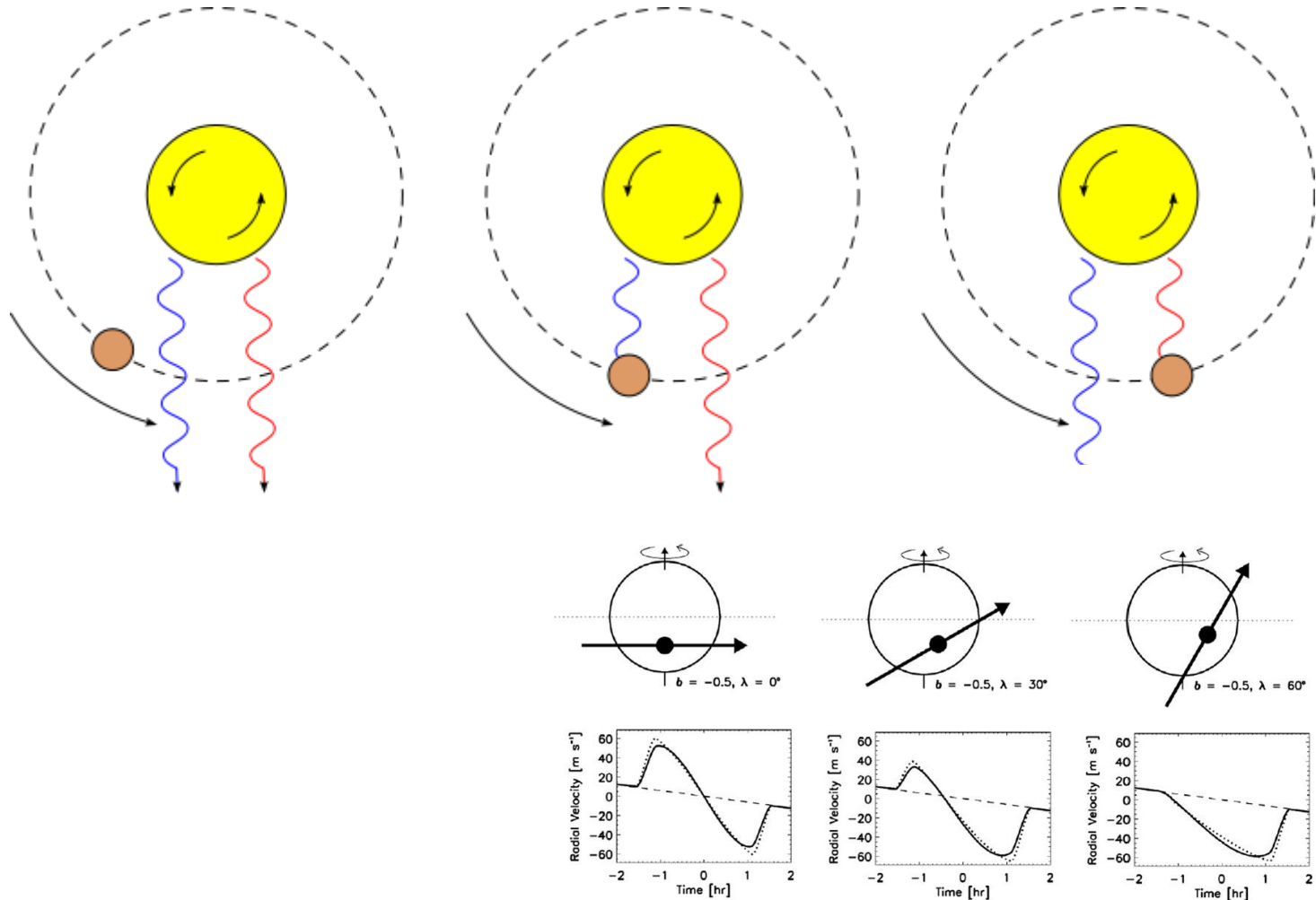


# The Radial Velocity Method

- 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)

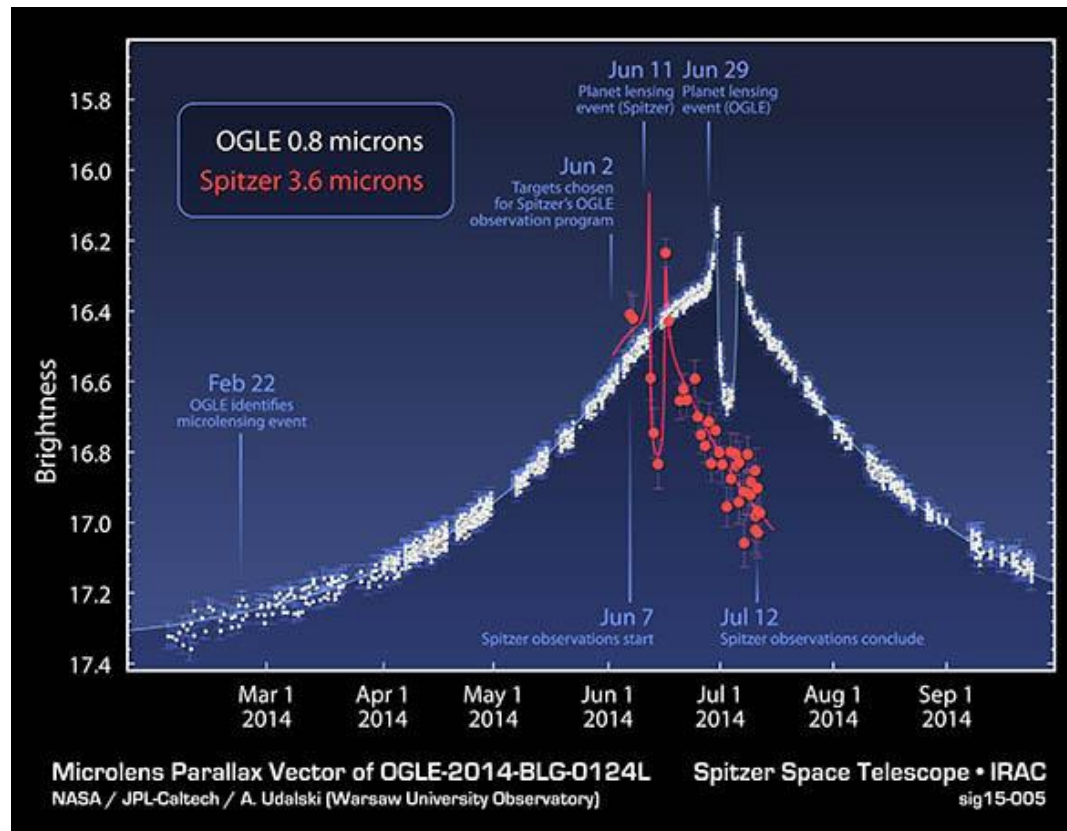


# The Rossiter-McLaughlin Effect



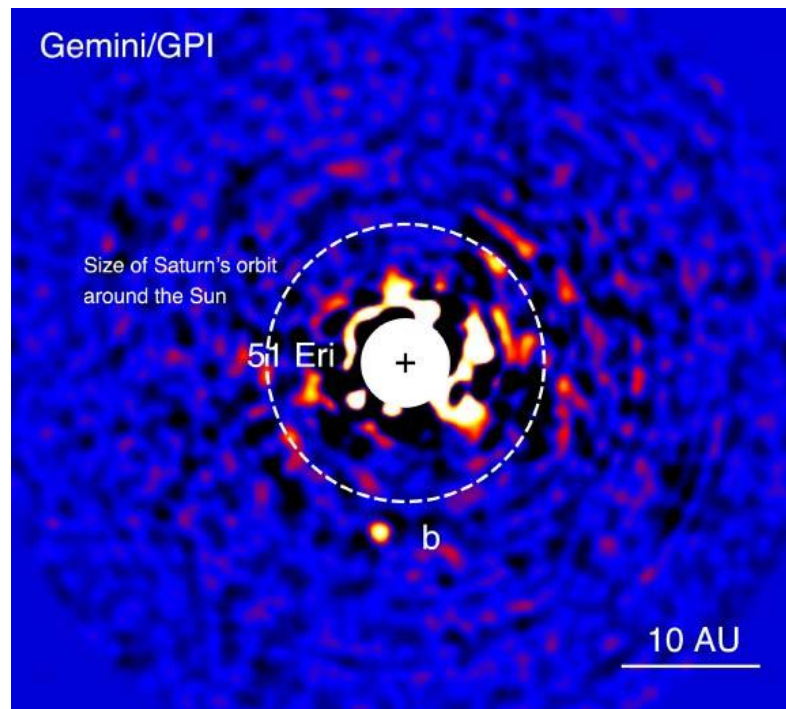
# The Microlensing Method

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

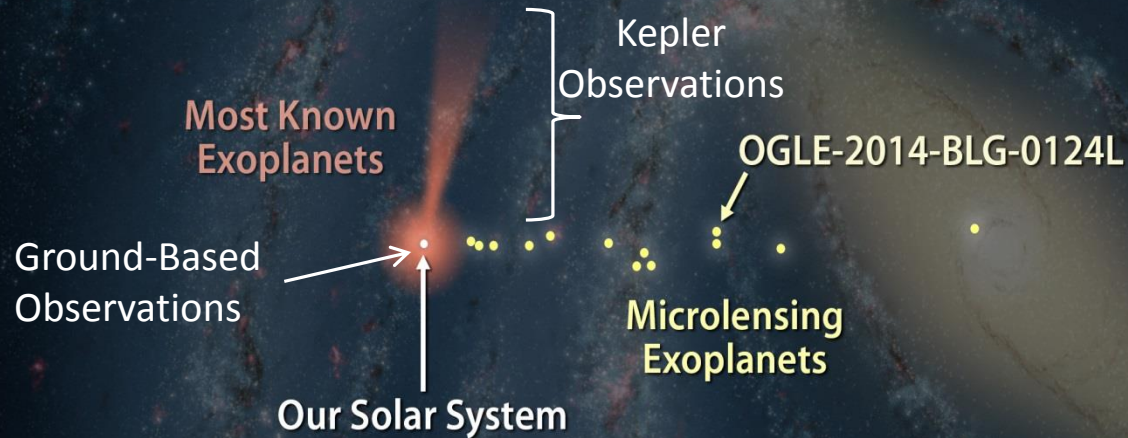


# Direct Imaging

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

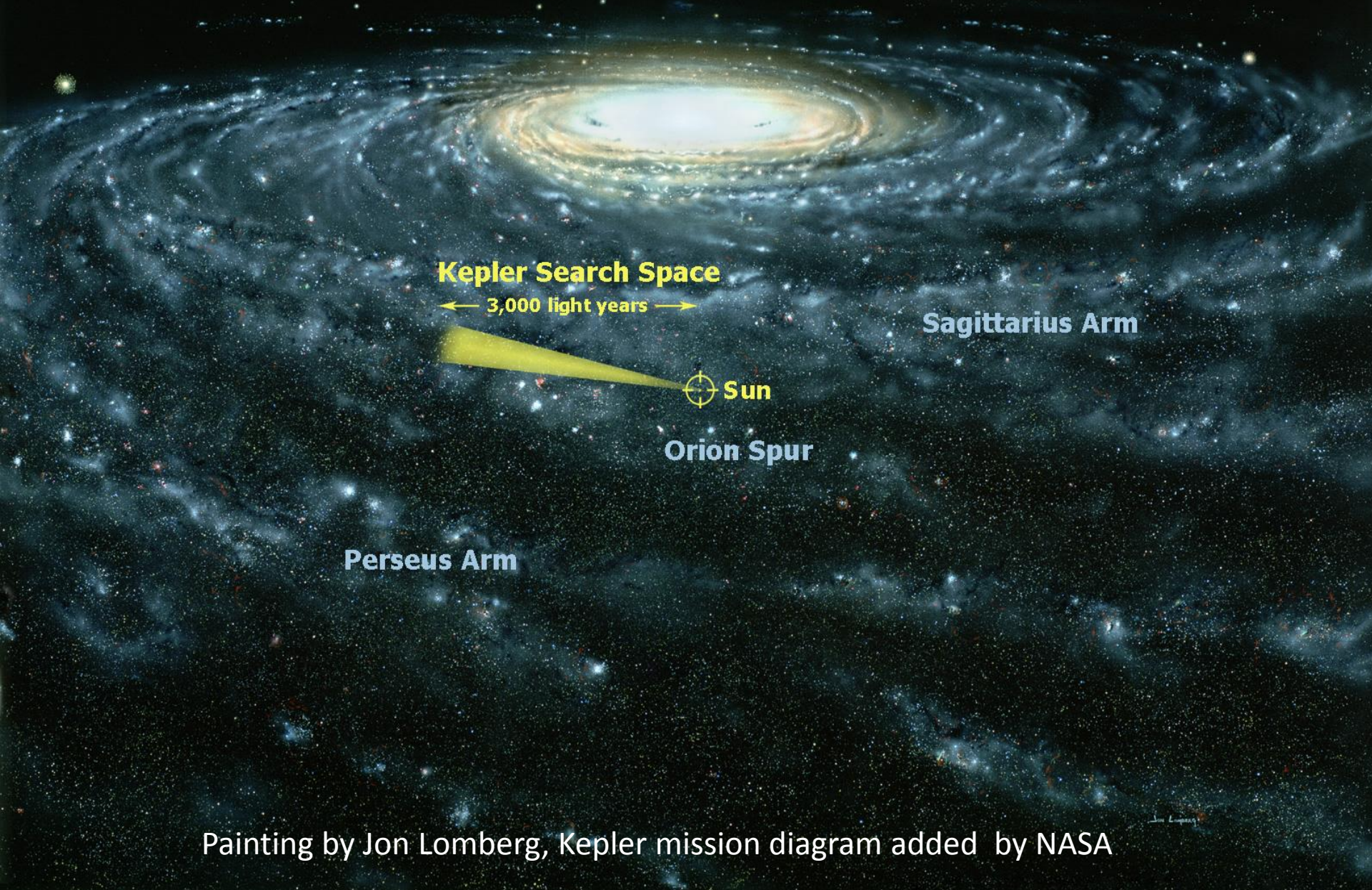


Until now, we are mostly looking in our immediate neighborhood!



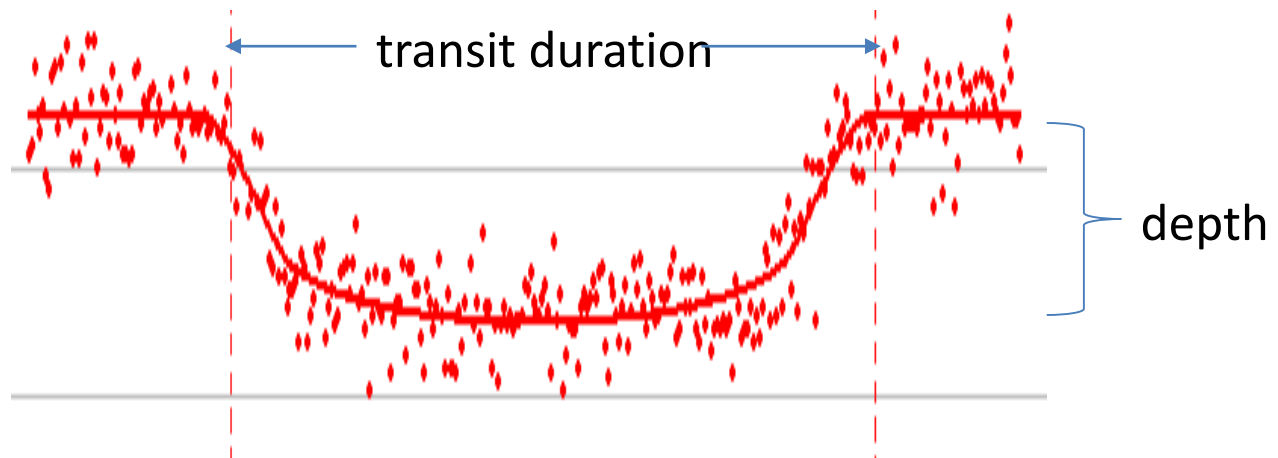
Courtesy NASA/JPL-Caltech

# *Milky Way Galaxy*



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

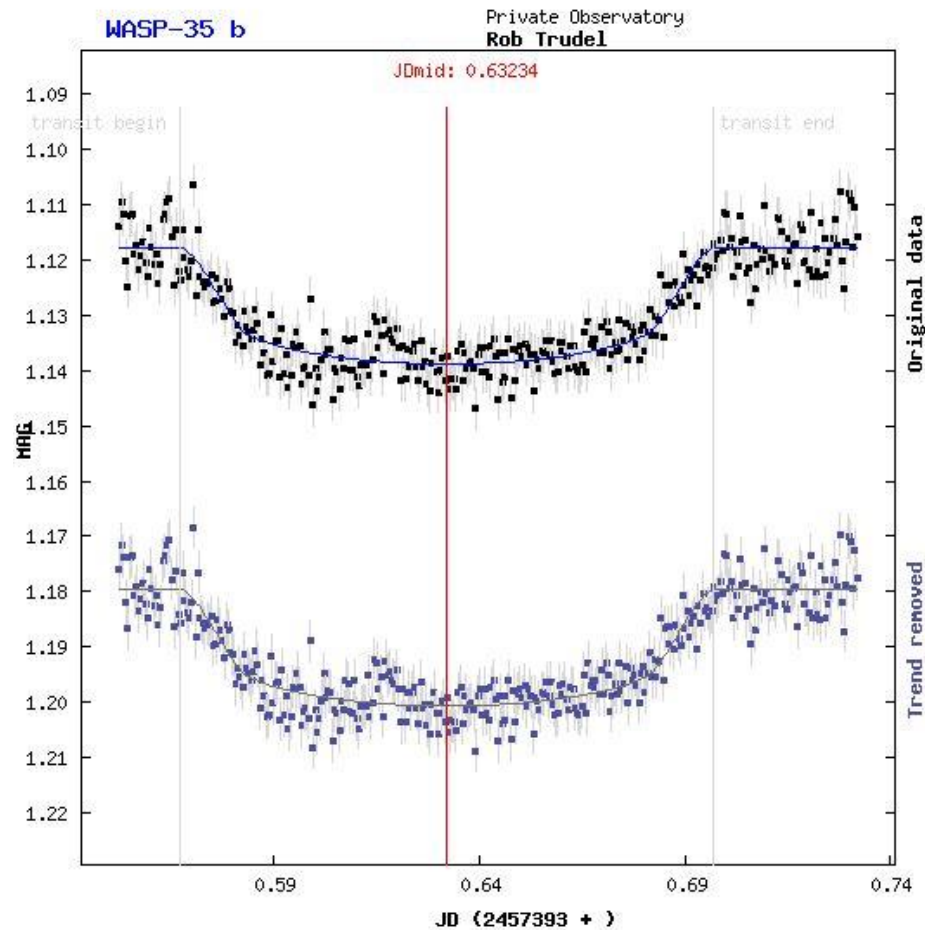


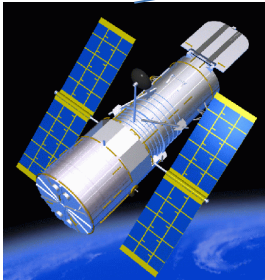
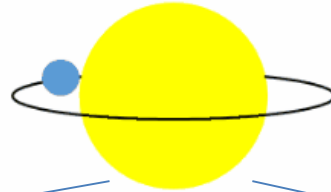
Image Courtesy of Robert Trudel

# Amateur Astronomers Can Detect Exoplanets!

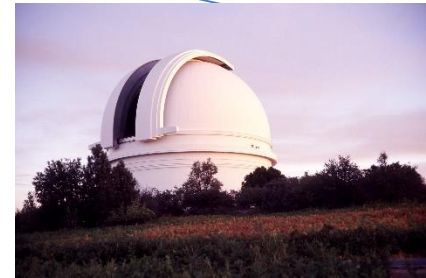


- ...using the transit method to determine a light curve
- ...using the same equipment used for deep sky imaging
- ...even in light polluted skies
- ...with >90% accuracy
- ...and their observations are providing valuable science data!

# 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

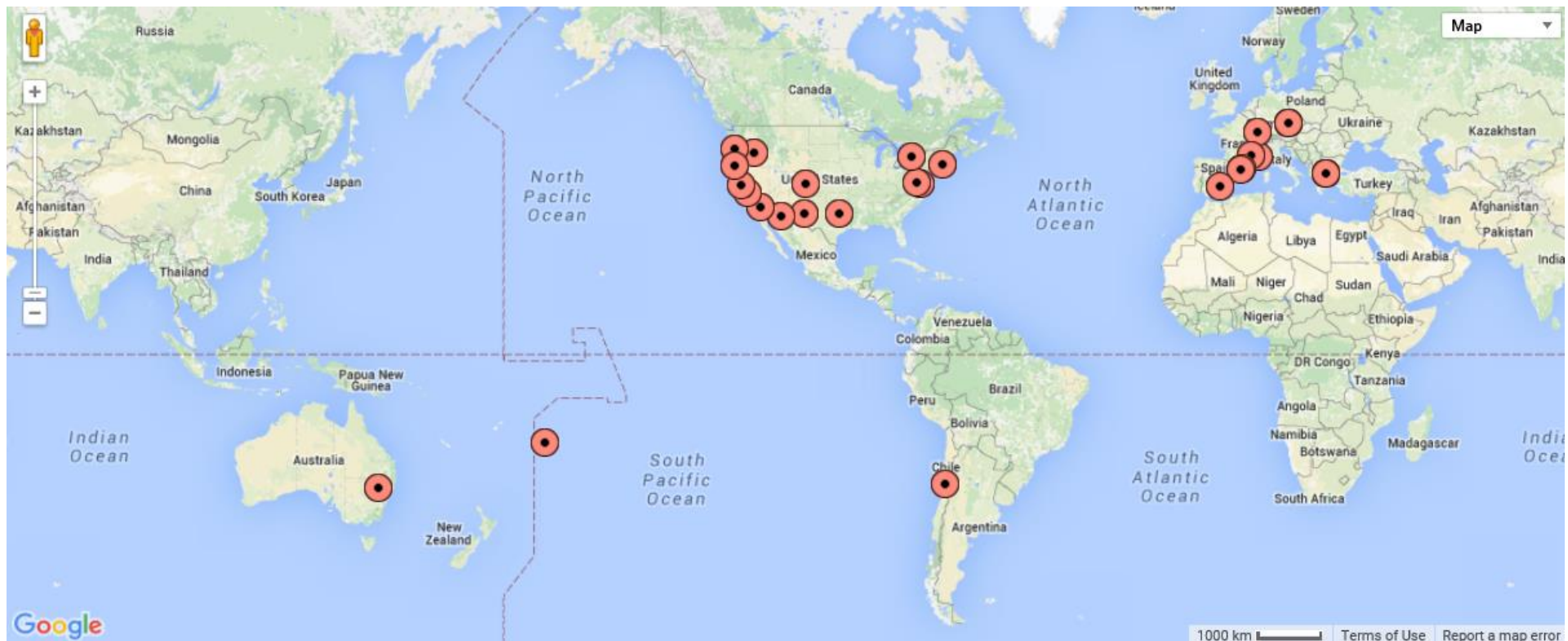
# Hubble Exoplanet Pro/Am Project

- 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



Late Breaking News:

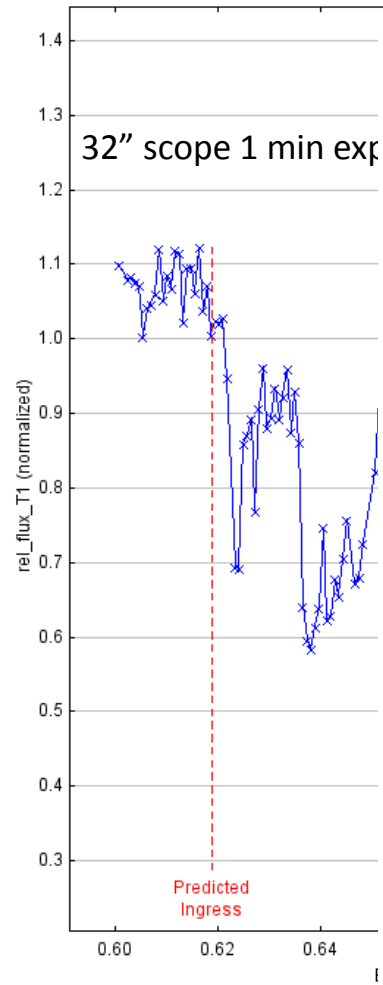
Detection of Planetesimals  
by Amateur Astronomers!

# WD 1145+017

- A white dwarf suspected of being transited by one or several asteroids with dust emission
- First detected by Kepler's K2 mission showing varying periods, depths, and shapes of light curves
- Recent observations successfully made by a handful of amateur astronomers with apertures as small as 11" scopes

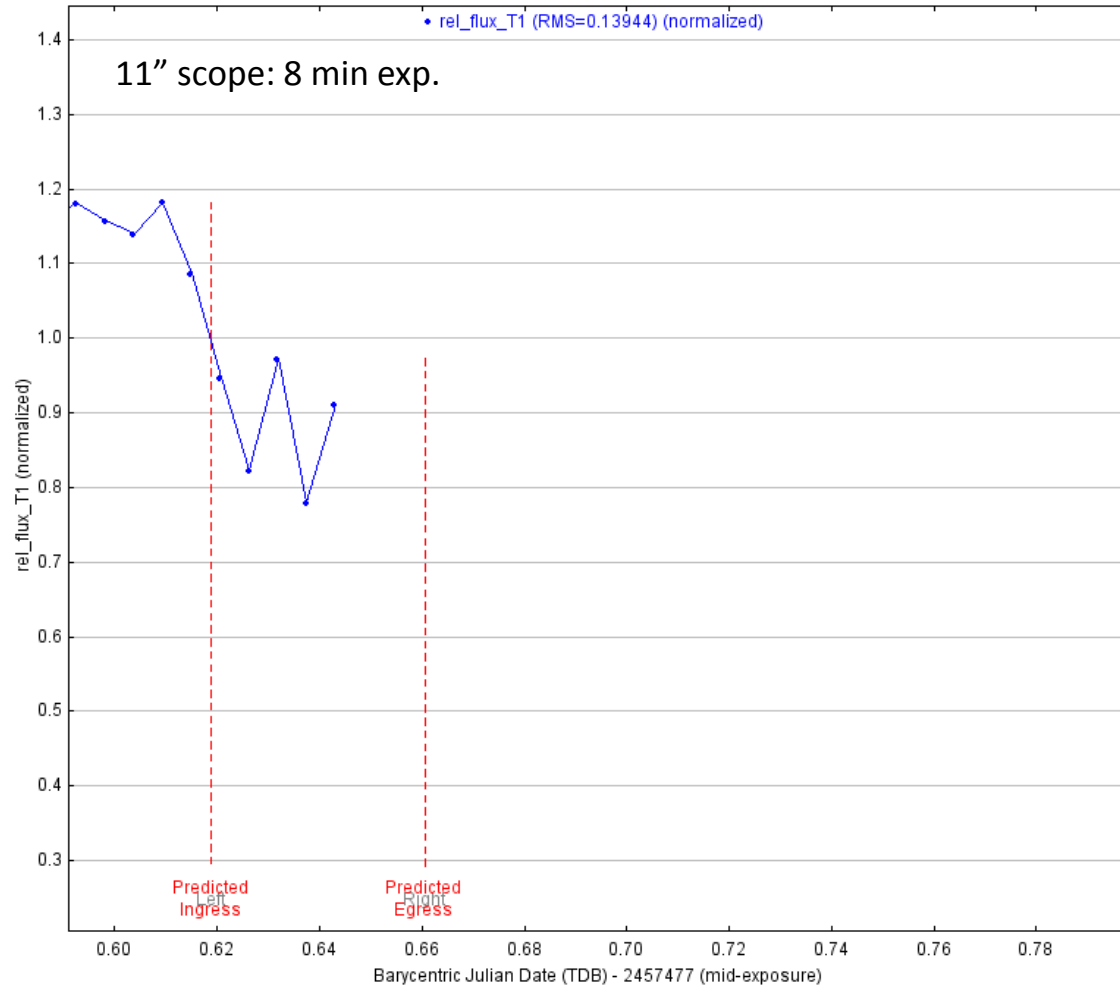
# WD1145 UT2016-03-30

MarioMotta (clear)-60sec



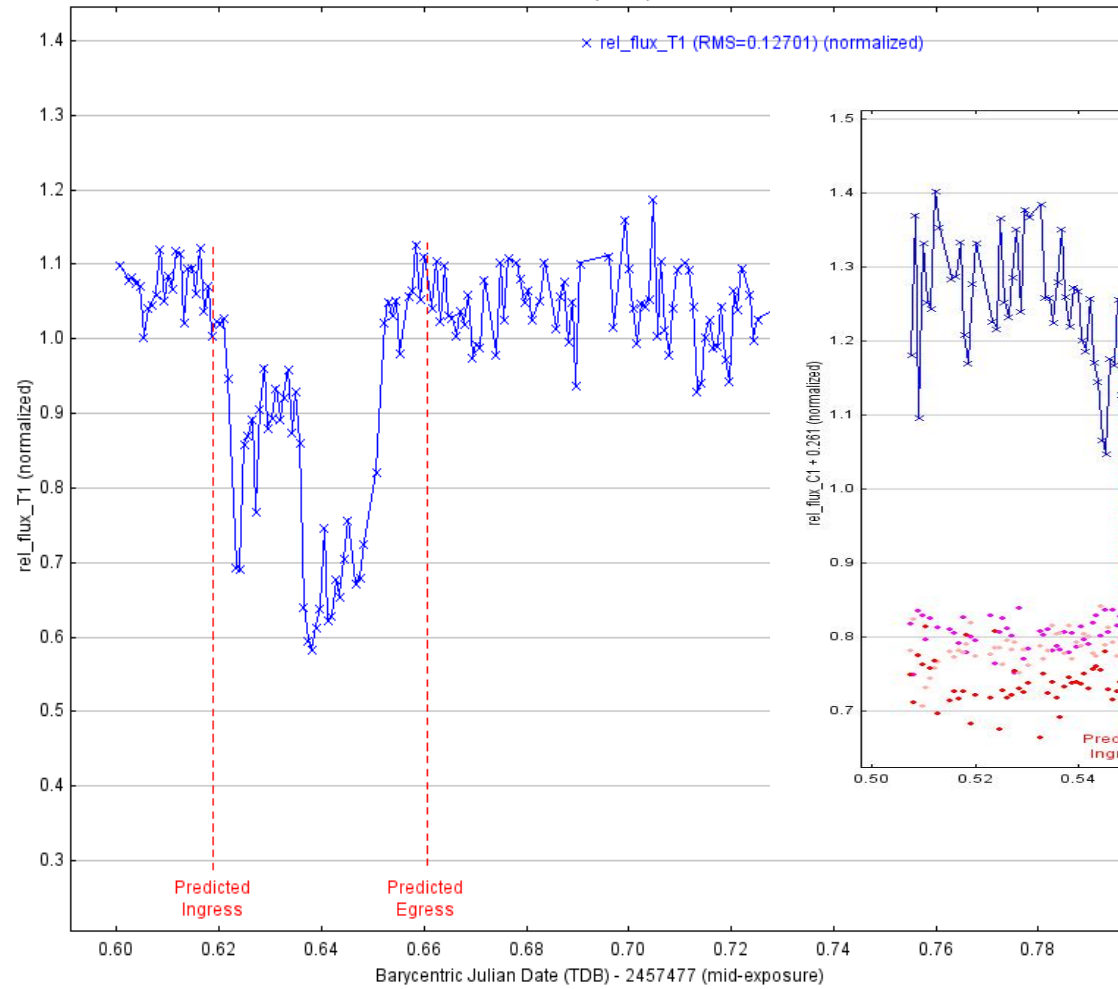
# WD1145 UT2016-03-30

Conti (Clear, 240 sec)



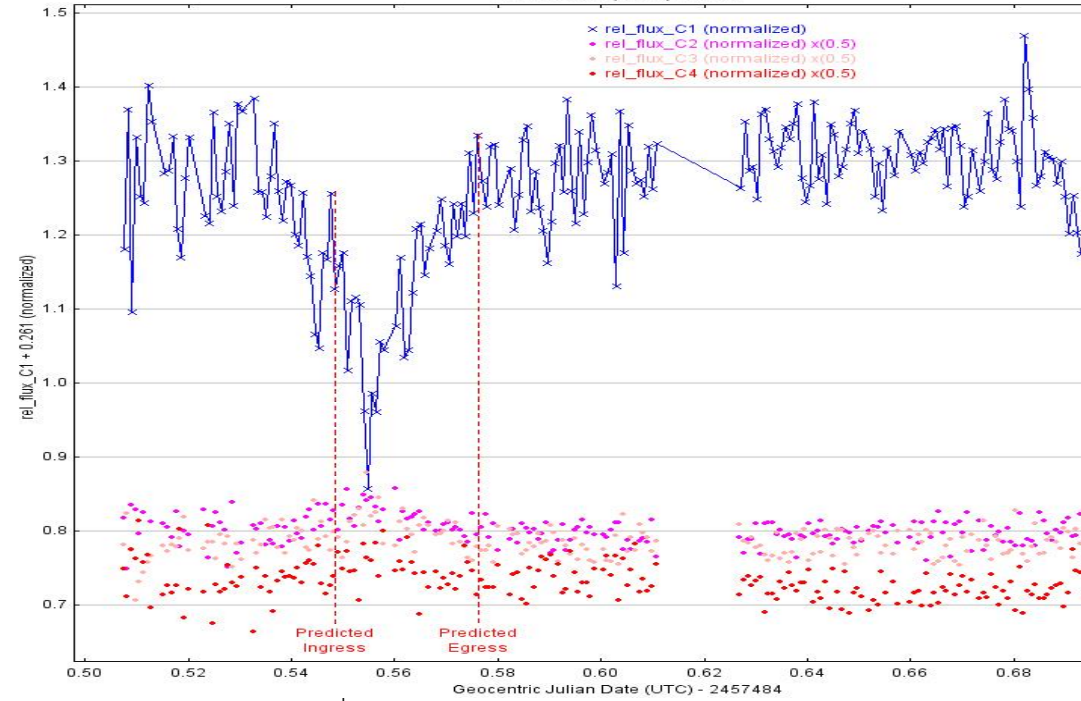
# WD1145 UT2016-03-30

MarioMotta (clear)-60sec



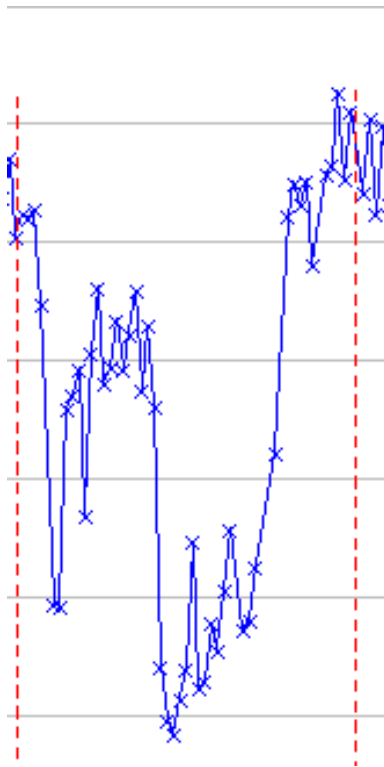
# WD1145 UT2016-04-06

MarioMotta (clear)-60sec

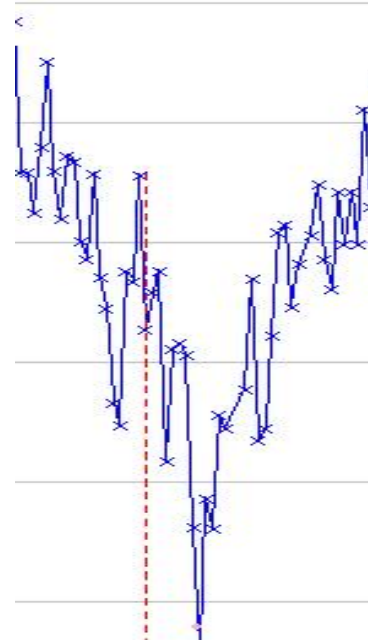


Images courtesy of Mario Motta:  
WD 1145+017

2016-03-30



2016-04-06



# The Future

# Exoplanet Missions



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!*

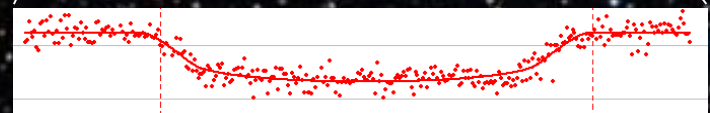
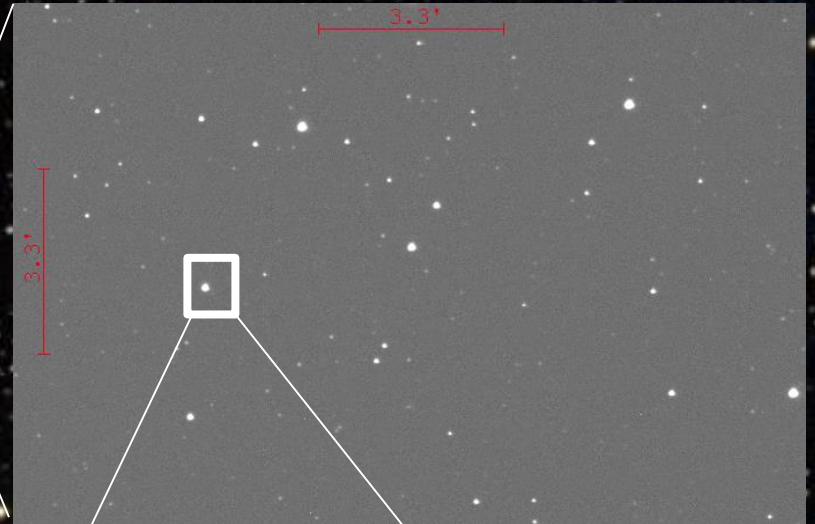
# Resources

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

WASP-12



# 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

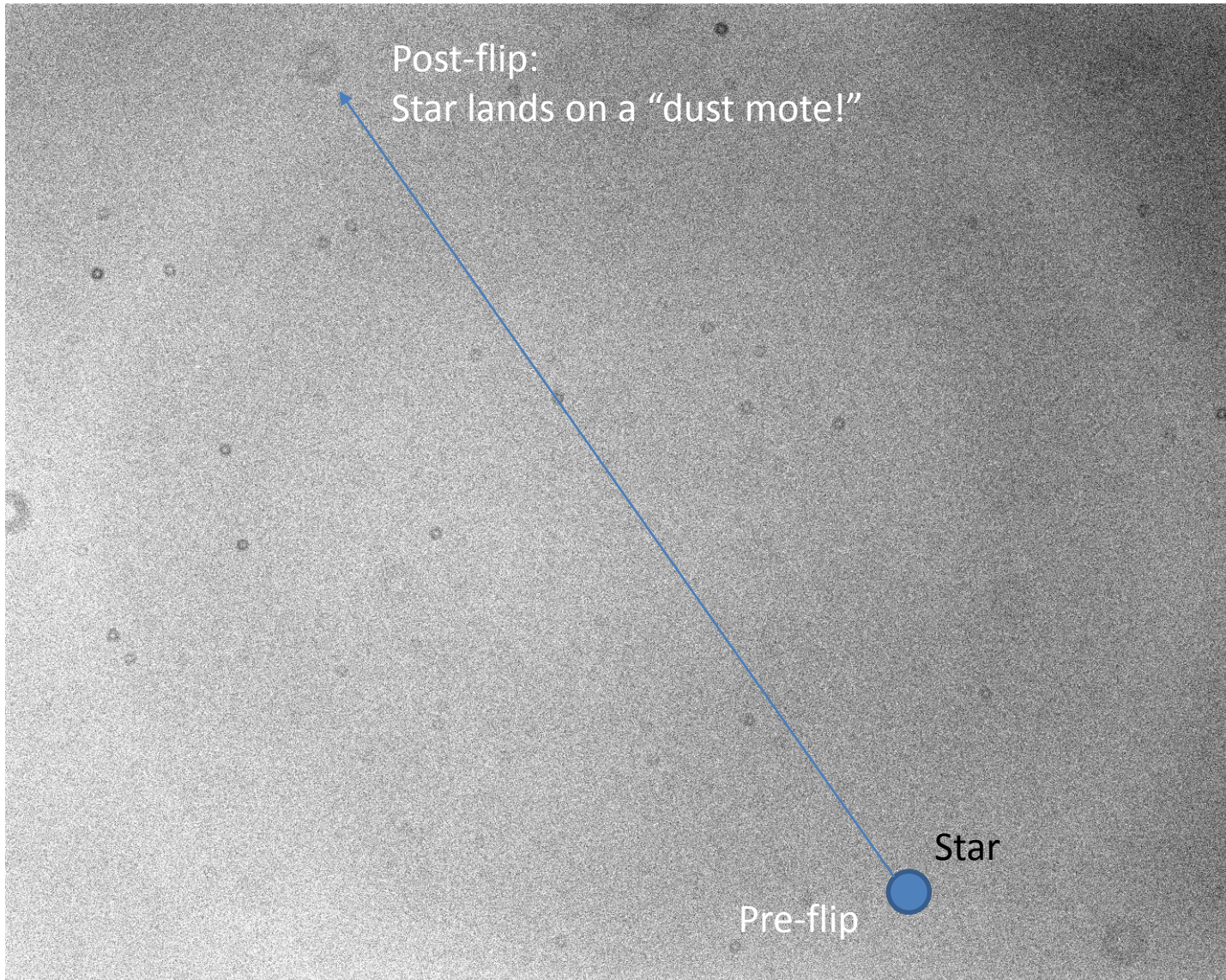
# Preparation Phase

- 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

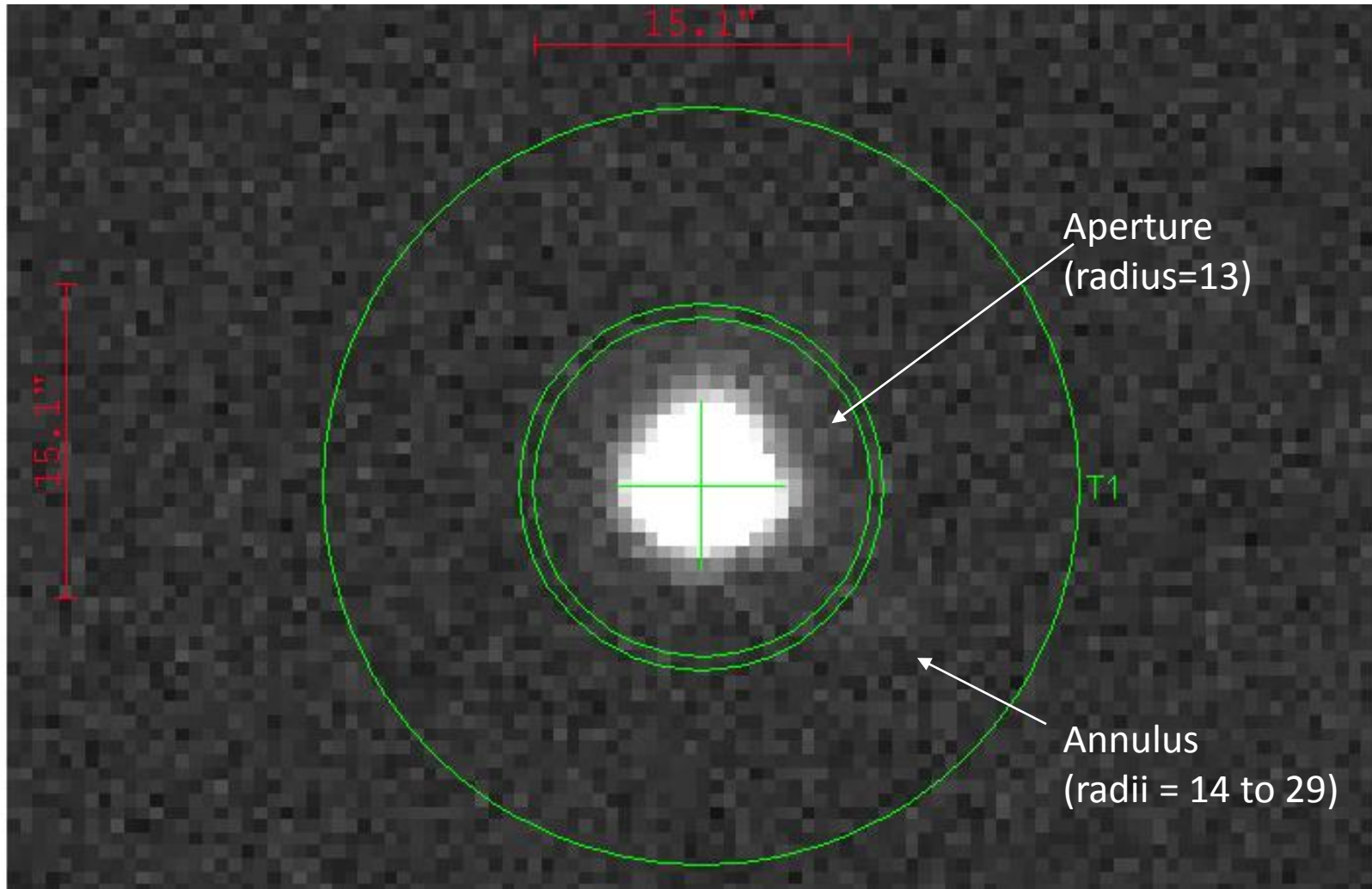
# The Importance of Uniform Flats



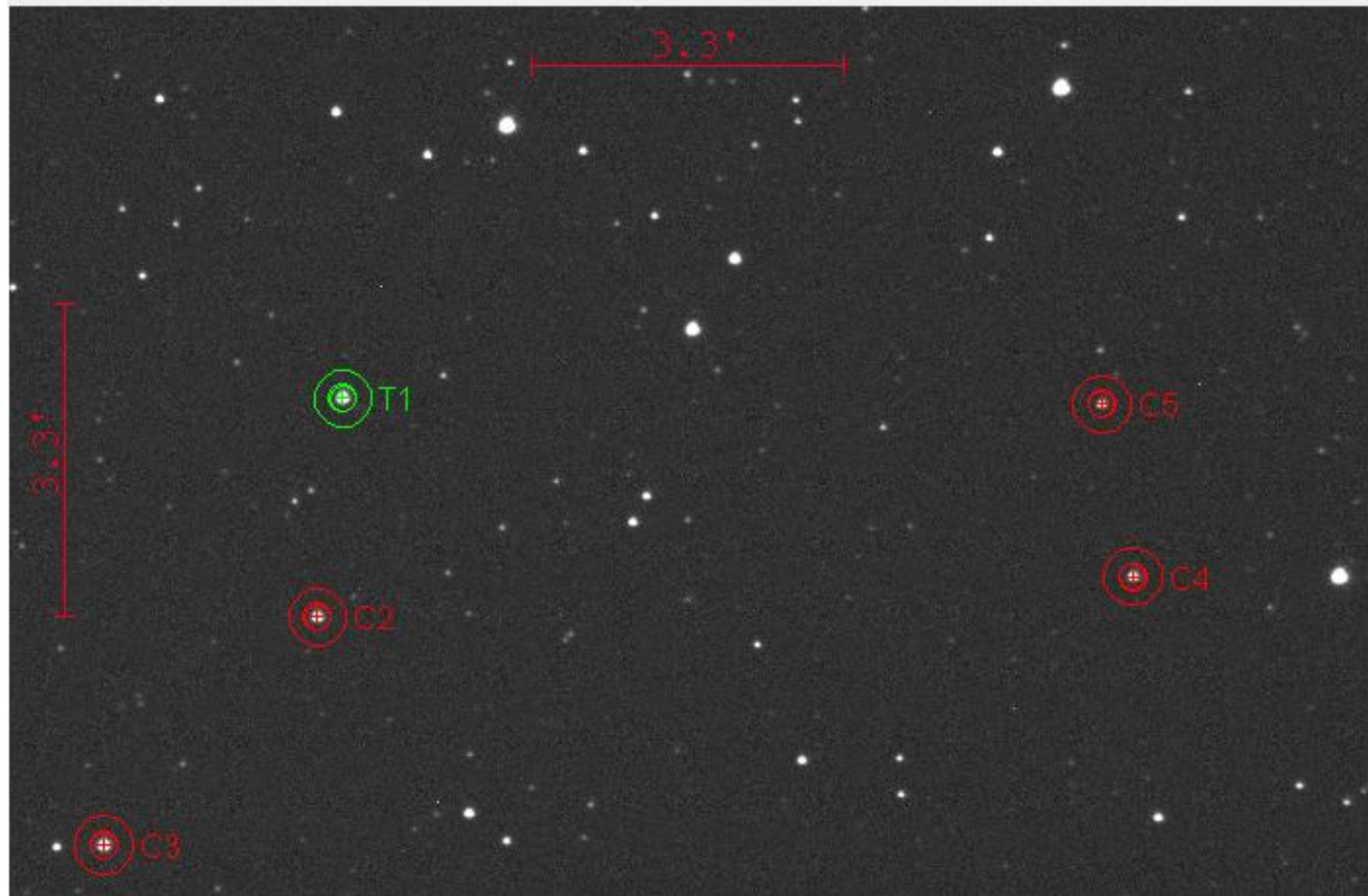
# Post-Processing and Modelling

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

# The Key Tools of Differential Photometry: the Aperture and Annulus



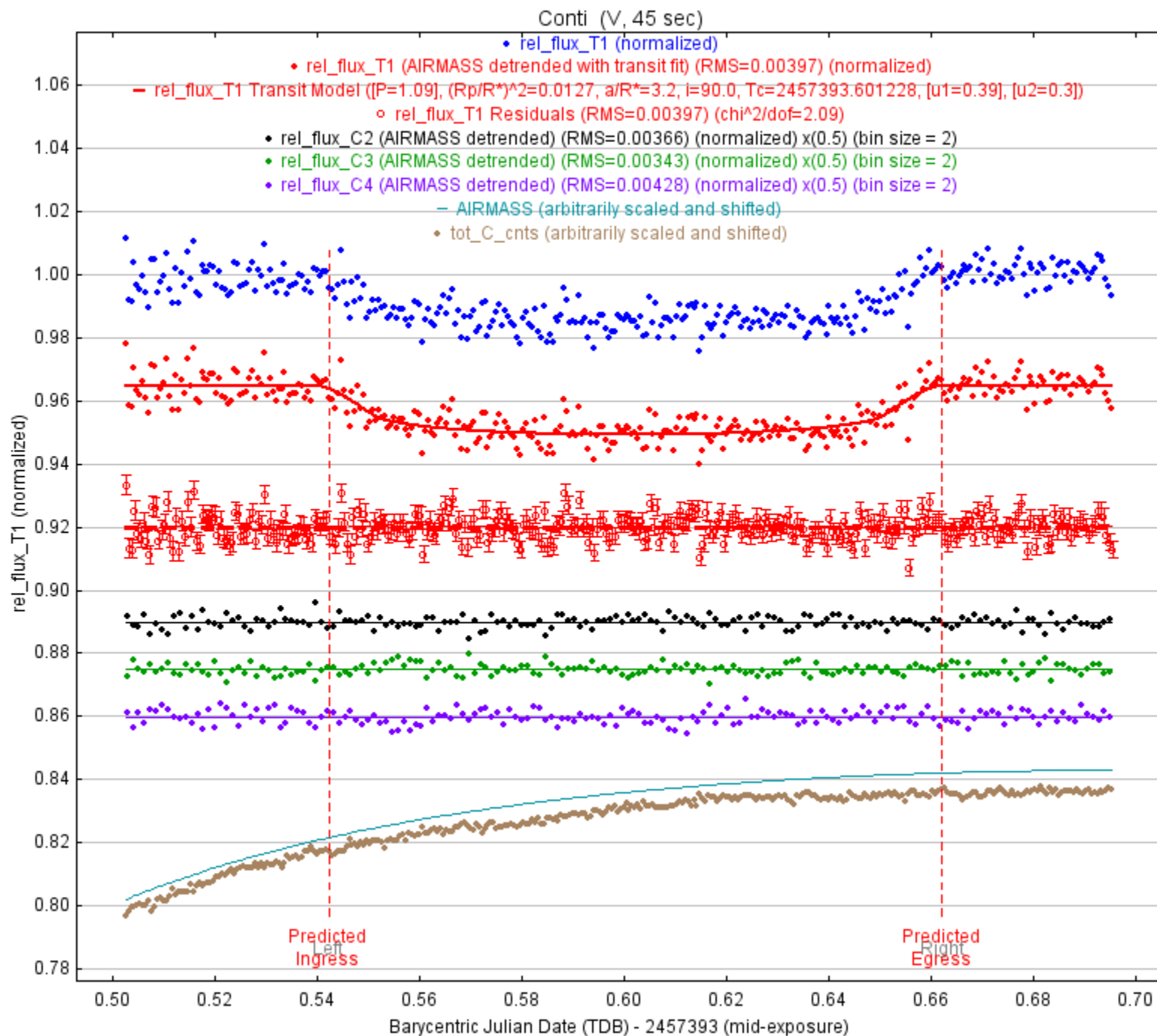
# Selection of Comparison Stars around WASP-12



# Conduct Model Fit

- Enter into AstrolmageJ:
  - 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



## User Specified Parameters (not fitted)

Orbital Parameters			Host Parameters (enter one)						
Period (days)	Cir	Ecc	$\omega$ (deg)	Sp.T.	Teff (K)	J-K	R* (Rsun)	M* (Msun)	p* (cgs)
1.09142245	<input checked="" type="checkbox"/>	0.0	0.0	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	<input type="checkbox"/>	0.55974614	<input type="checkbox"/>	0.111949228	<input type="checkbox"/>	0.1	
$(R_p / R_*)^2$	0.012724416	<input type="checkbox"/>	0.014289873	<input type="checkbox"/>	0.007144937	<input type="checkbox"/>	0.014289873	
$a / R_*$	3.216520358	<input type="checkbox"/>	3.311238013	<input type="checkbox"/>	1.9	<input type="checkbox"/>	1.0	
$T_C$	2457393.601228008	<input type="checkbox"/>	2457393.602271072	<input type="checkbox"/>	0.015	<input type="checkbox"/>	0.01	
Inclination (deg)	89.979982568	<input type="checkbox"/>	82.5	<input type="checkbox"/>	15.0	<input type="checkbox"/>	1.0	
Quad LD u1	0.390560810	<input checked="" type="checkbox"/>	0.39056081	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1	
Quad LD u2	0.302699200	<input checked="" type="checkbox"/>	0.3026992	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1	
Calculated from model	b	t14 (d)	t14 (hms)	t23 (d)	tau (d)	p* (cgs)	(e)SpT	Rp (Rjup)
	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
<input checked="" type="checkbox"/>	AIRMASS	-0.001602964152	<input type="checkbox"/>	-0.008	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1
<input type="checkbox"/>	Meridian_Flip		<input type="checkbox"/>	0.0	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1
<input type="checkbox"/>	Width_T1		<input type="checkbox"/>	0.0	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1
<input type="checkbox"/>	Sky/Pixel_T1		<input type="checkbox"/>	0.0	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1
<input type="checkbox"/>	X(FITS)_T1		<input type="checkbox"/>	0.0	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1
<input type="checkbox"/>	Y(FITS)_T1		<input type="checkbox"/>	0.0	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1
<input type="checkbox"/>	tot_C_cnts		<input type="checkbox"/>	0.0	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1
<input type="checkbox"/>	BJD_TDB		<input type="checkbox"/>	0.0	<input type="checkbox"/>	1.0	<input type="checkbox"/>	0.1

## Fit Statistics

Fit Statistics	RMS (norm)	chi <sup>2</sup> /dof	BIC	dof	chi <sup>2</sup>
	0.003969	2.089682	758.0445	330	689.5950

## Plot Settings

<input checked="" type="checkbox"/> Show Model	<input checked="" type="checkbox"/> Show in legend	Line Color: red	Line Width: 2
<input checked="" type="checkbox"/> Show Residuals	<input checked="" type="checkbox"/> Show in legend	Line Color: red	Line Width: 2
	<input checked="" type="checkbox"/> Show Error	Symbol: circle	Symbol Color: red
		Shift: -0.045	

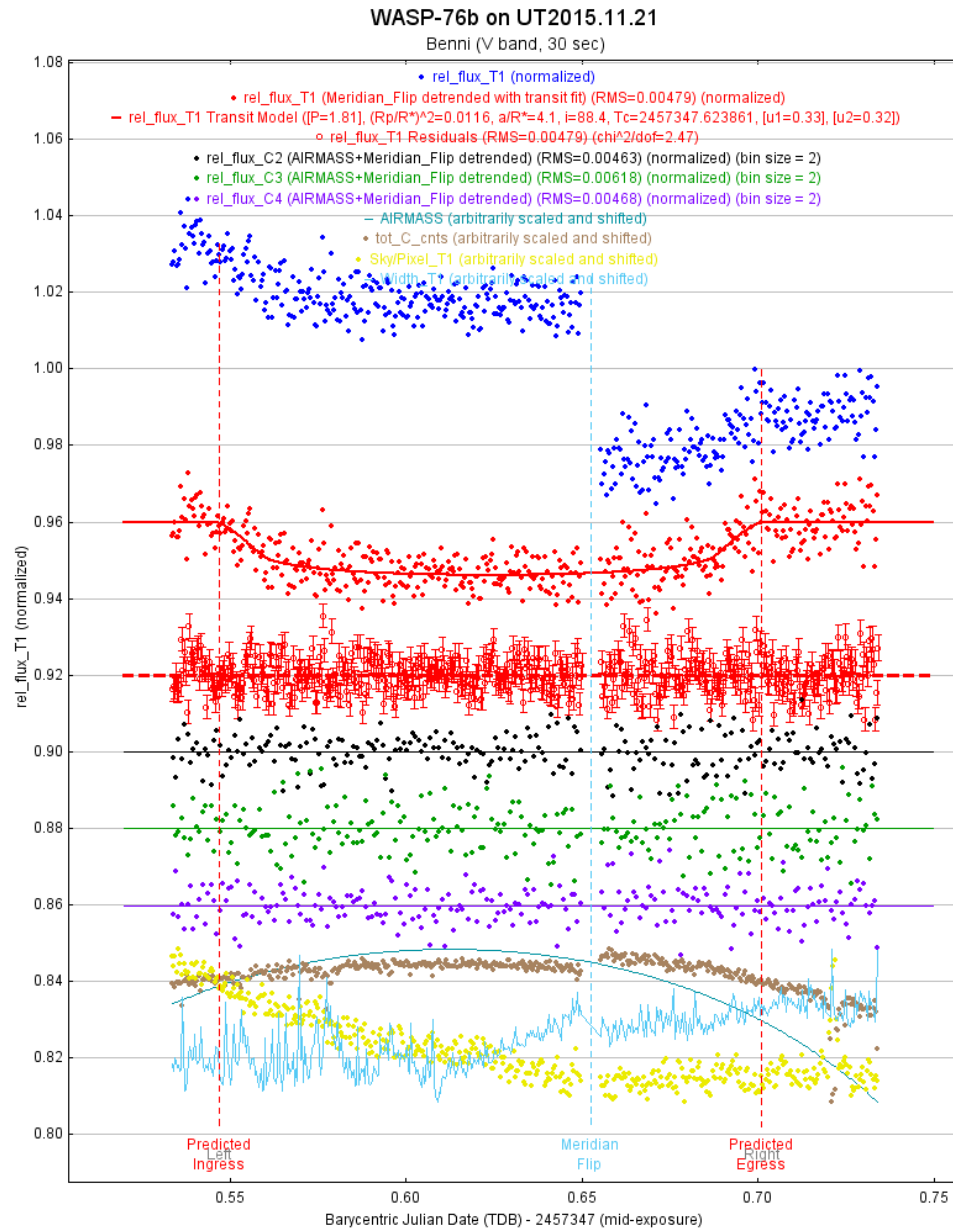
## Fit Control

Fit Control	Fit Update Options	Fit Tolerance	Max Allowed Steps	Steps Taken
	<input checked="" type="checkbox"/> 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 <sub>Jup</sub>	1.79 <sub>Jup</sub>	100%

# Light Curve with Effects of Meridian Flip Detrended



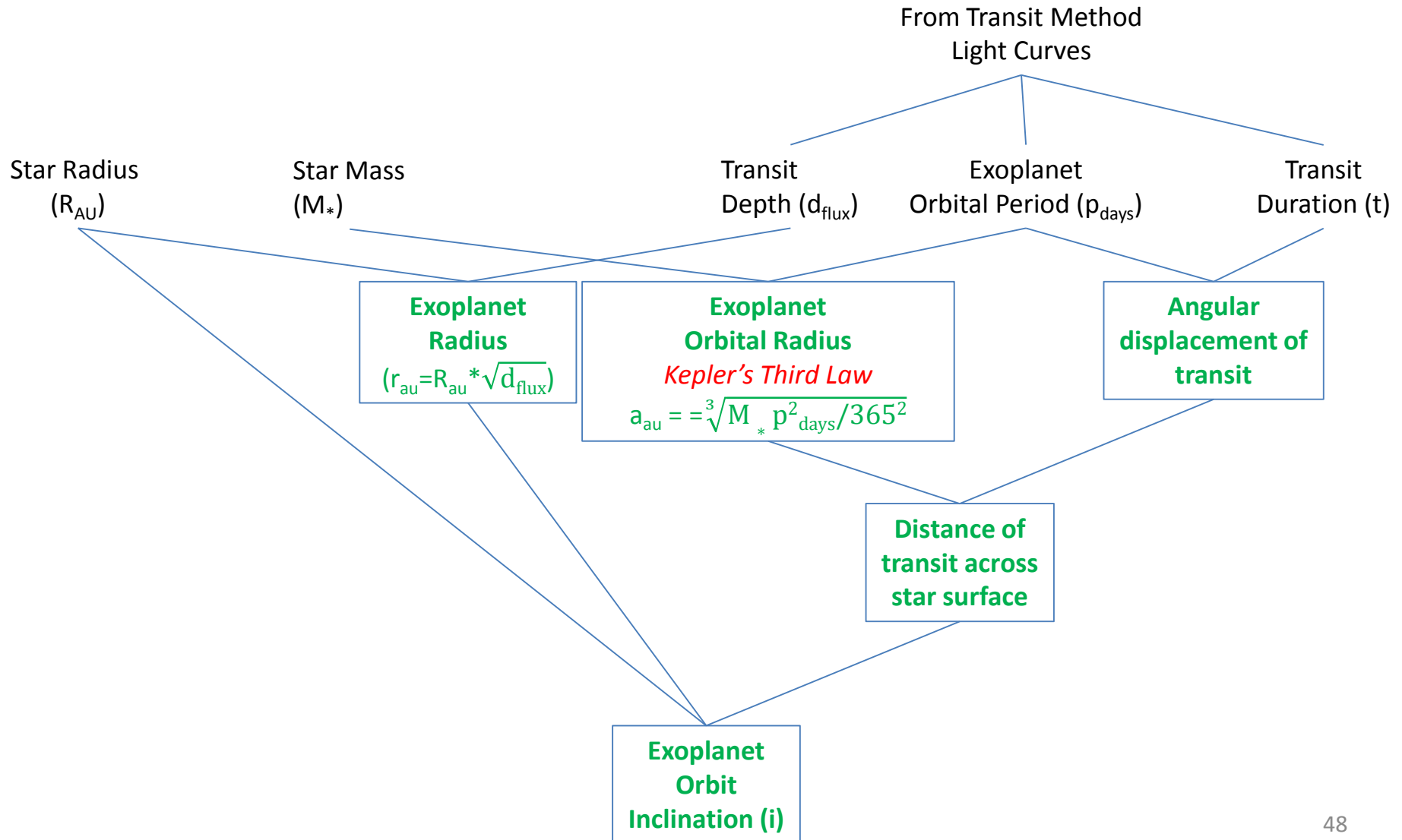
# Exoplanet Observing vs. Deep Sky Imaging

- 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

