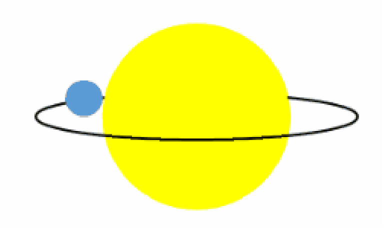
Exoplanet Observing by Amateur Astronomers



by
Dennis M. Conti
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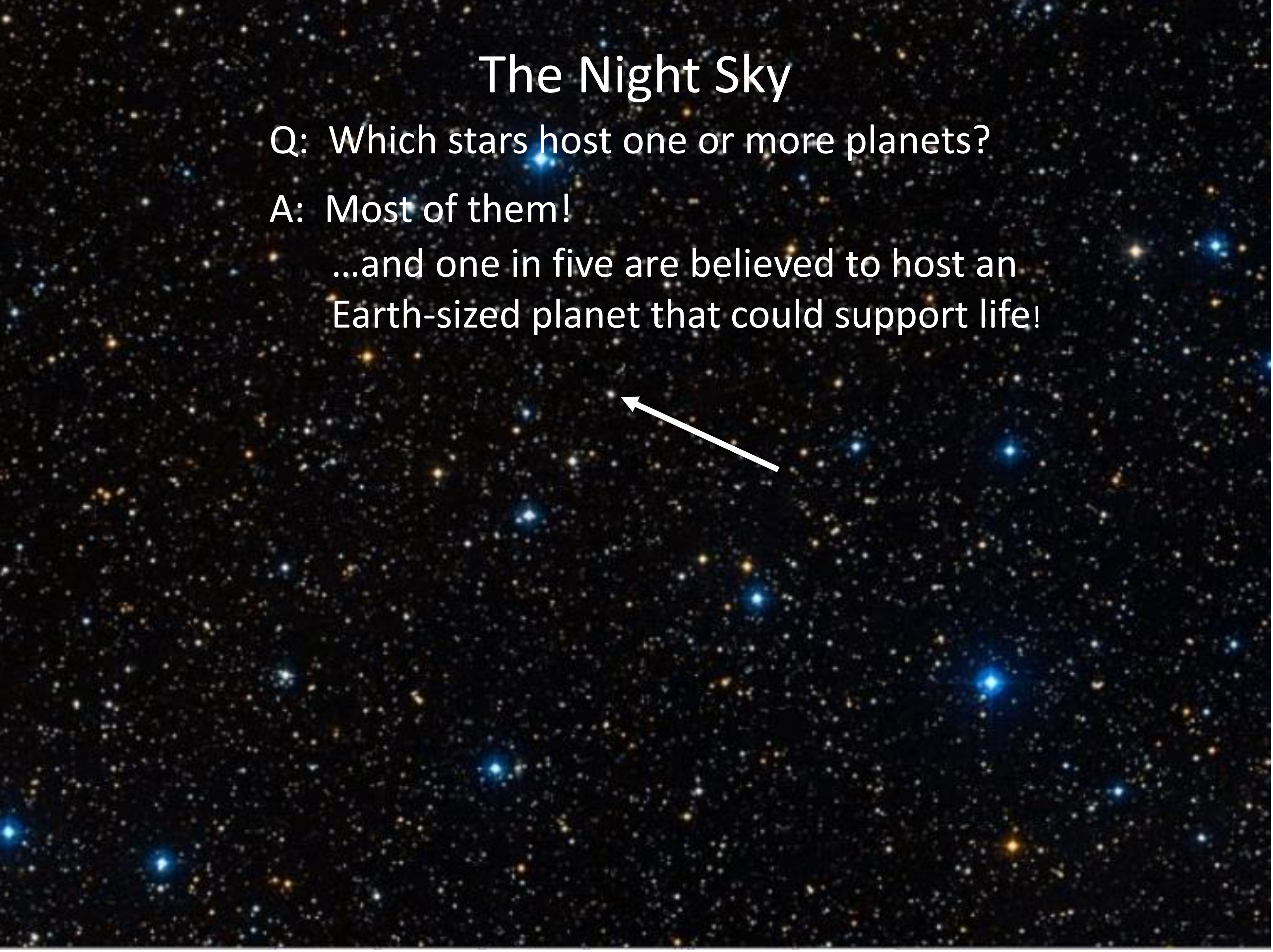
The Night Sky

Q: Which stars host one or more planets?

A: Most of them!

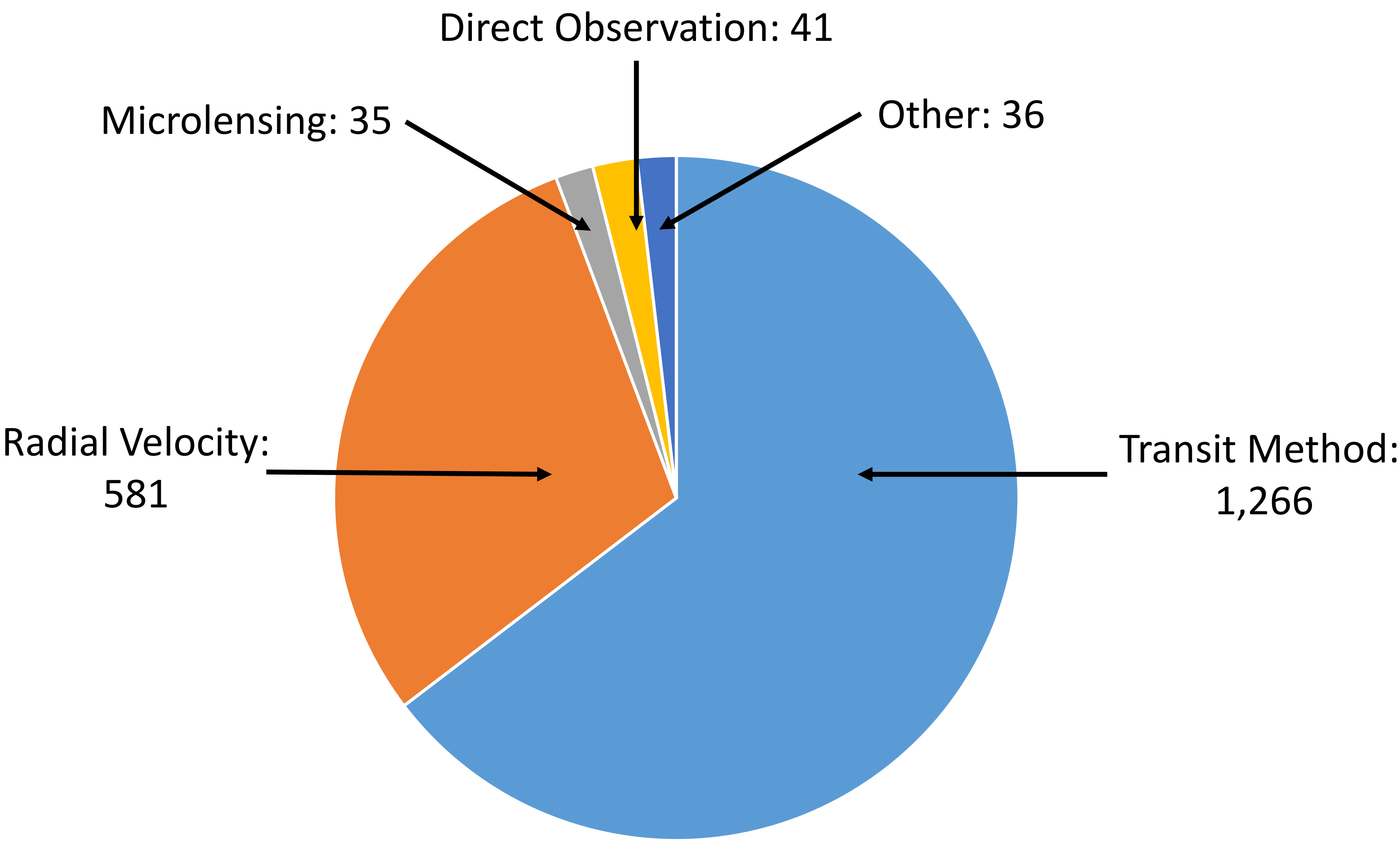
…and one in five are believed to host an Earth-sized planet that could support life!



Background

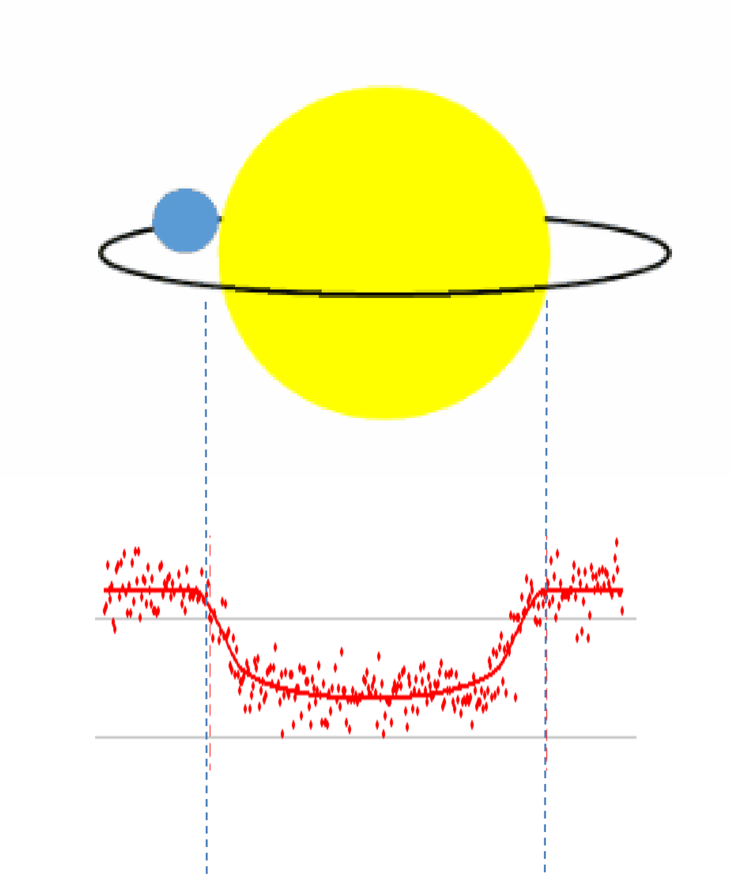
- Exoplanet (Extrasolar Planet) – a planet orbiting a distant "host star"
- First exoplanet was discovered in 1992
- Both space-based (e.g., Kepler) and ground based observatories have been used to detect exoplanets

Detection Methods:
1,959 Confirmed Exoplanets



The Transit Method

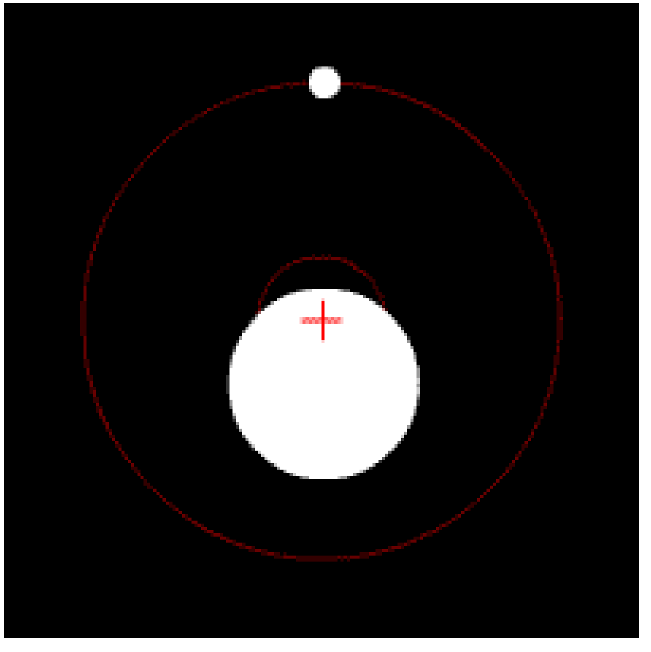
- Measures dip and length of light curve



The Radial Velocity Method

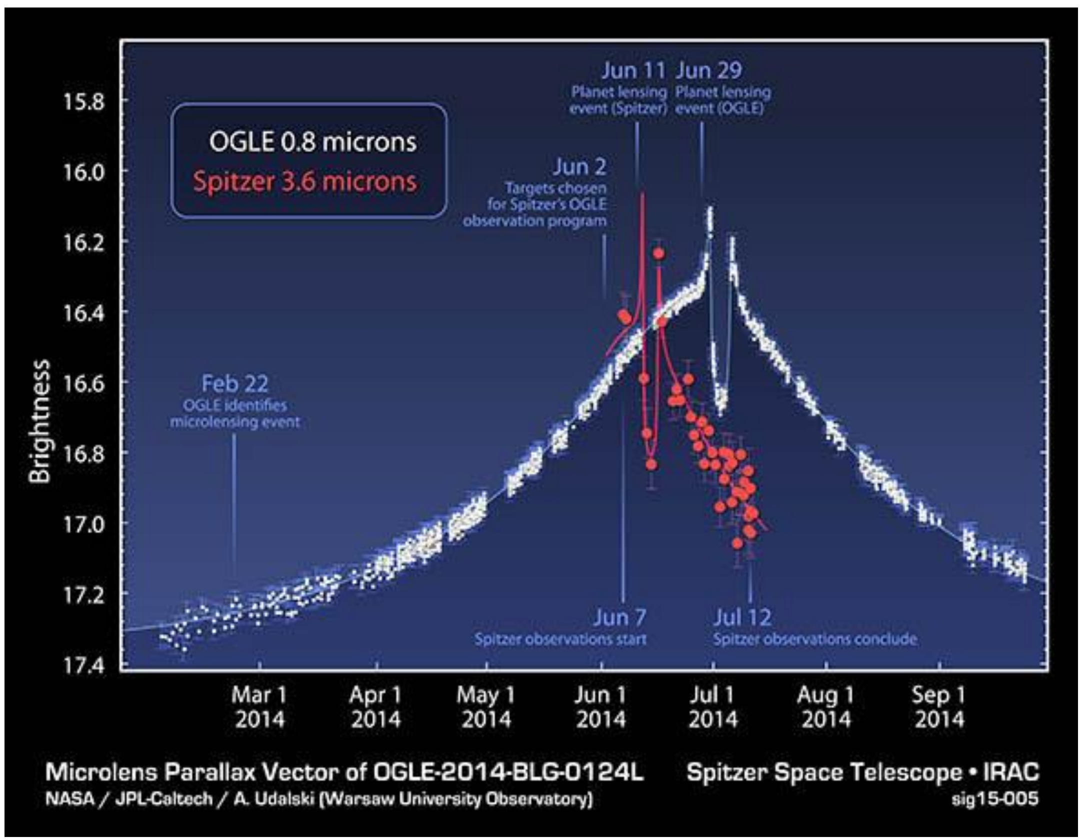
- Measures the Doppler shift of the host star’s spectrum as an orbiting planet causes it to wobble around their common center of gravity (“orbital reflex motion”)

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



The 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)

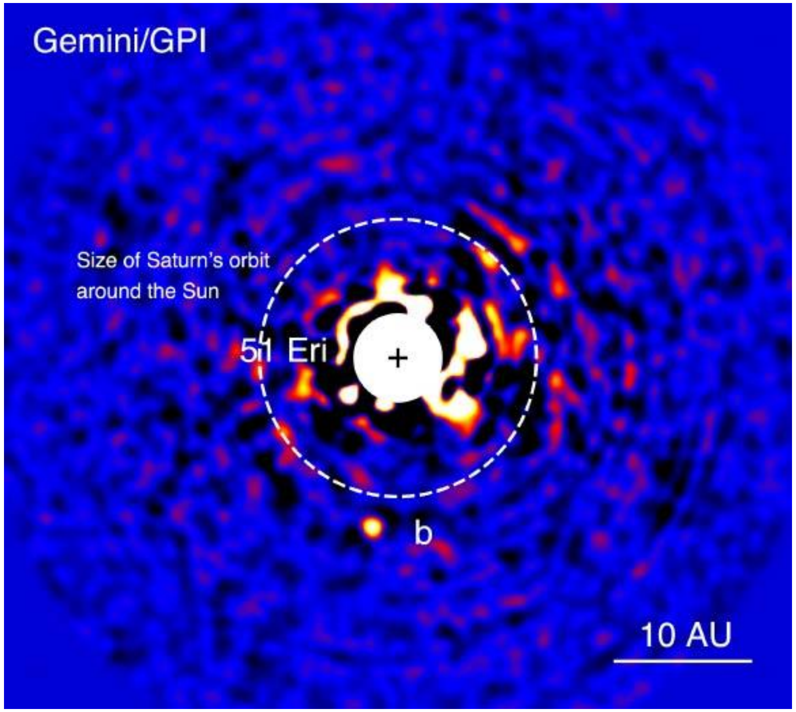
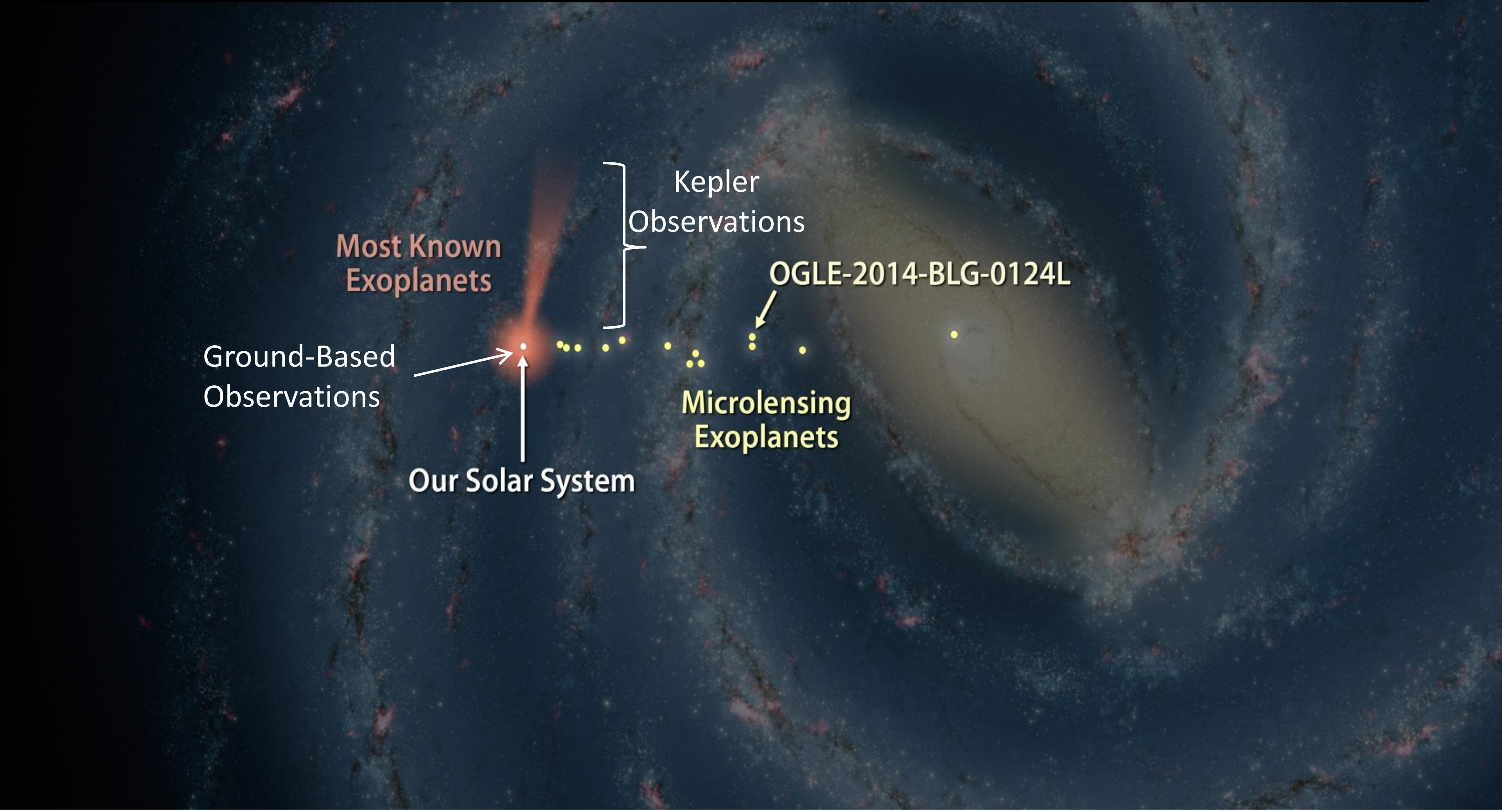
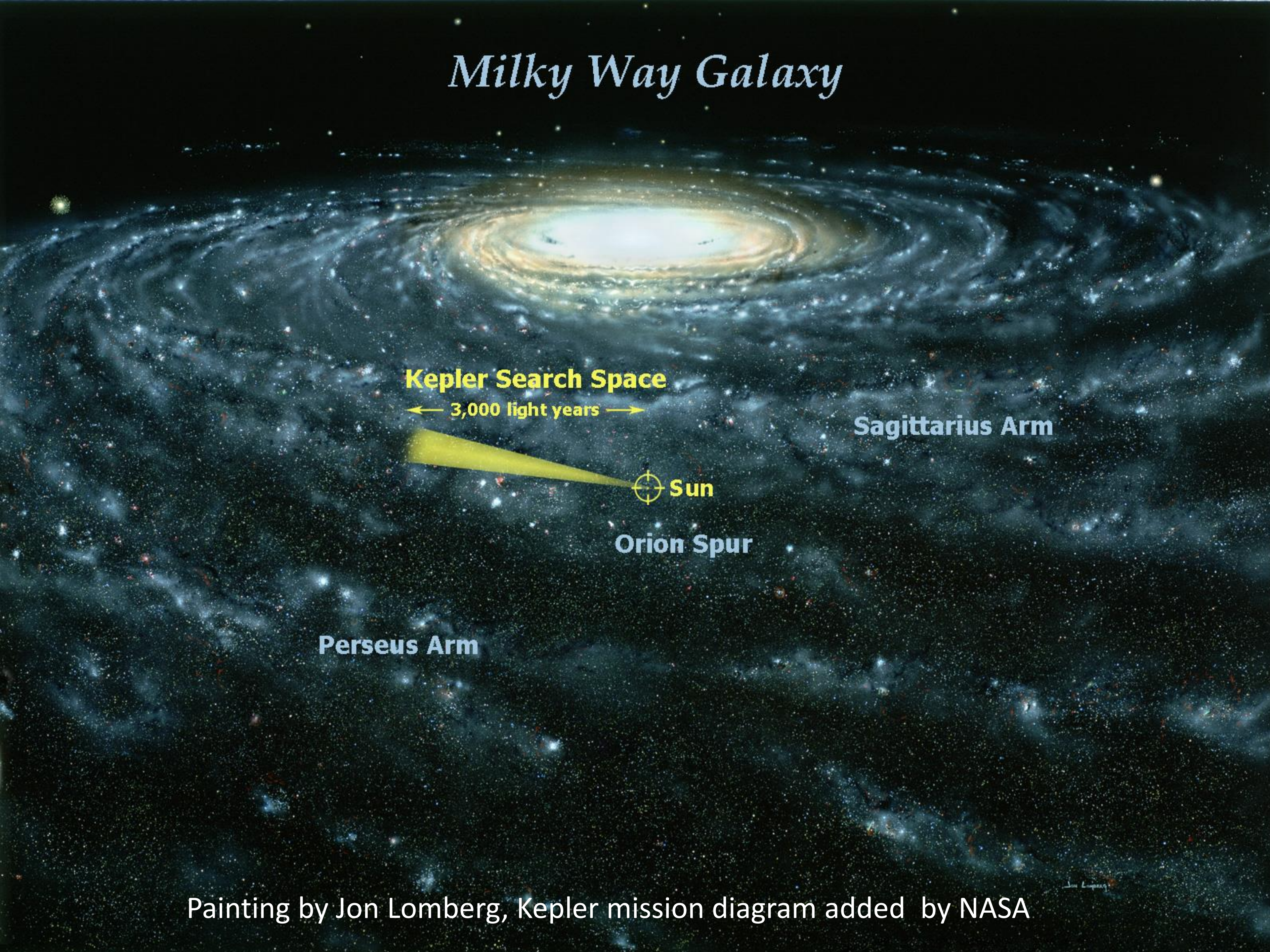


Image credit: J. Rameau, University of Montreal / C. Marois, Herzberg Institute of Astrophysics.

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

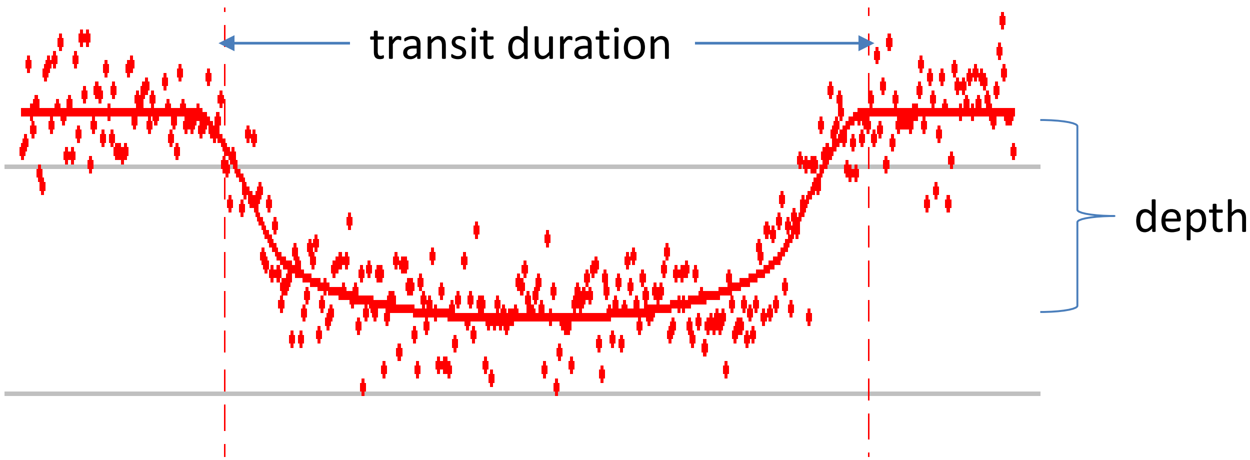


Courtesy NASA/JPL-Caltech



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

Amateur Astronomers Can Detect Exoplanets!

…using the transit method to determine a light curve

…using the same equipment used for deep sky imaging

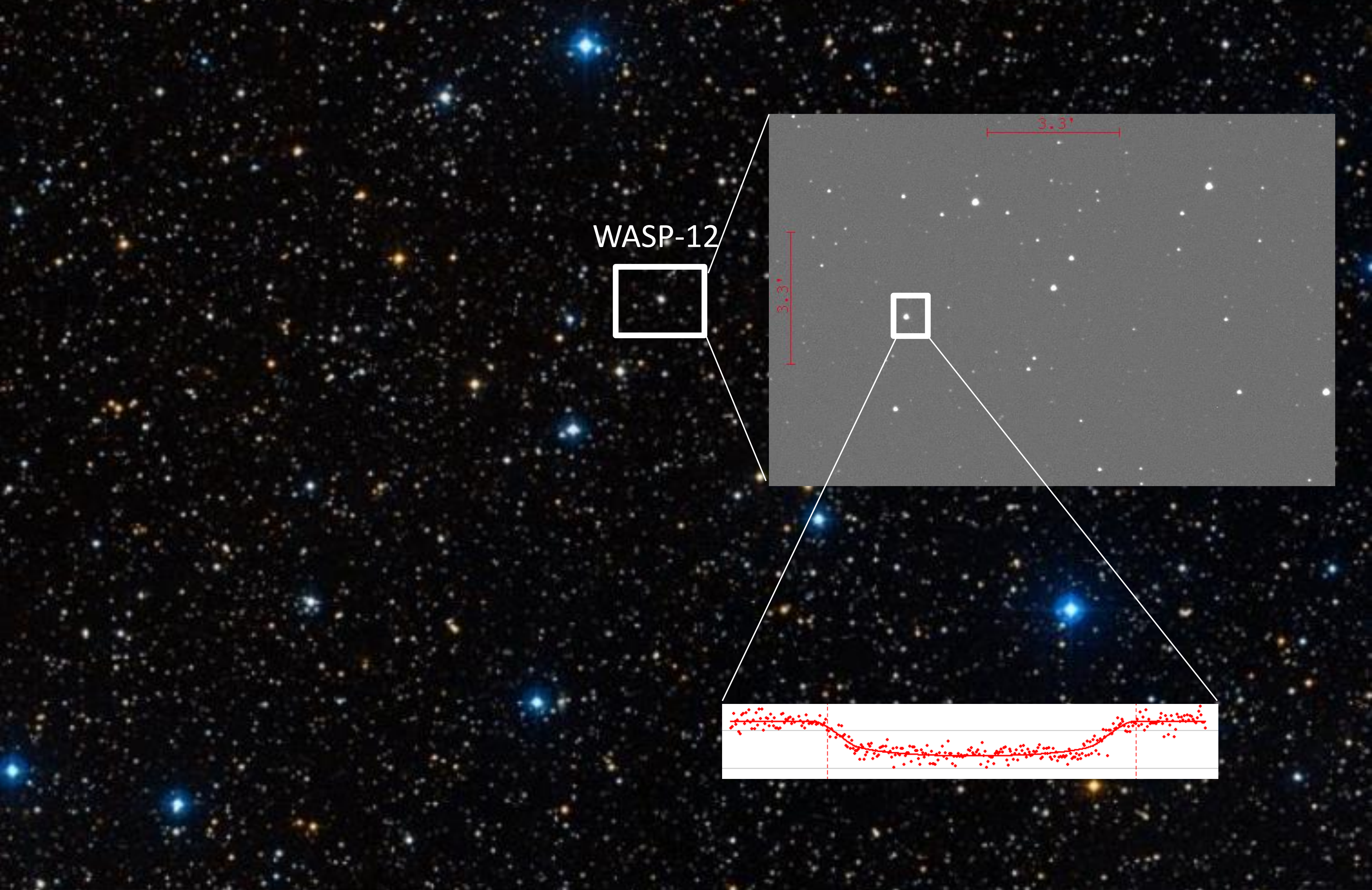
…even in light polluted skies

…with >90% accuracy

…and their observations are providing valuable science data!

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

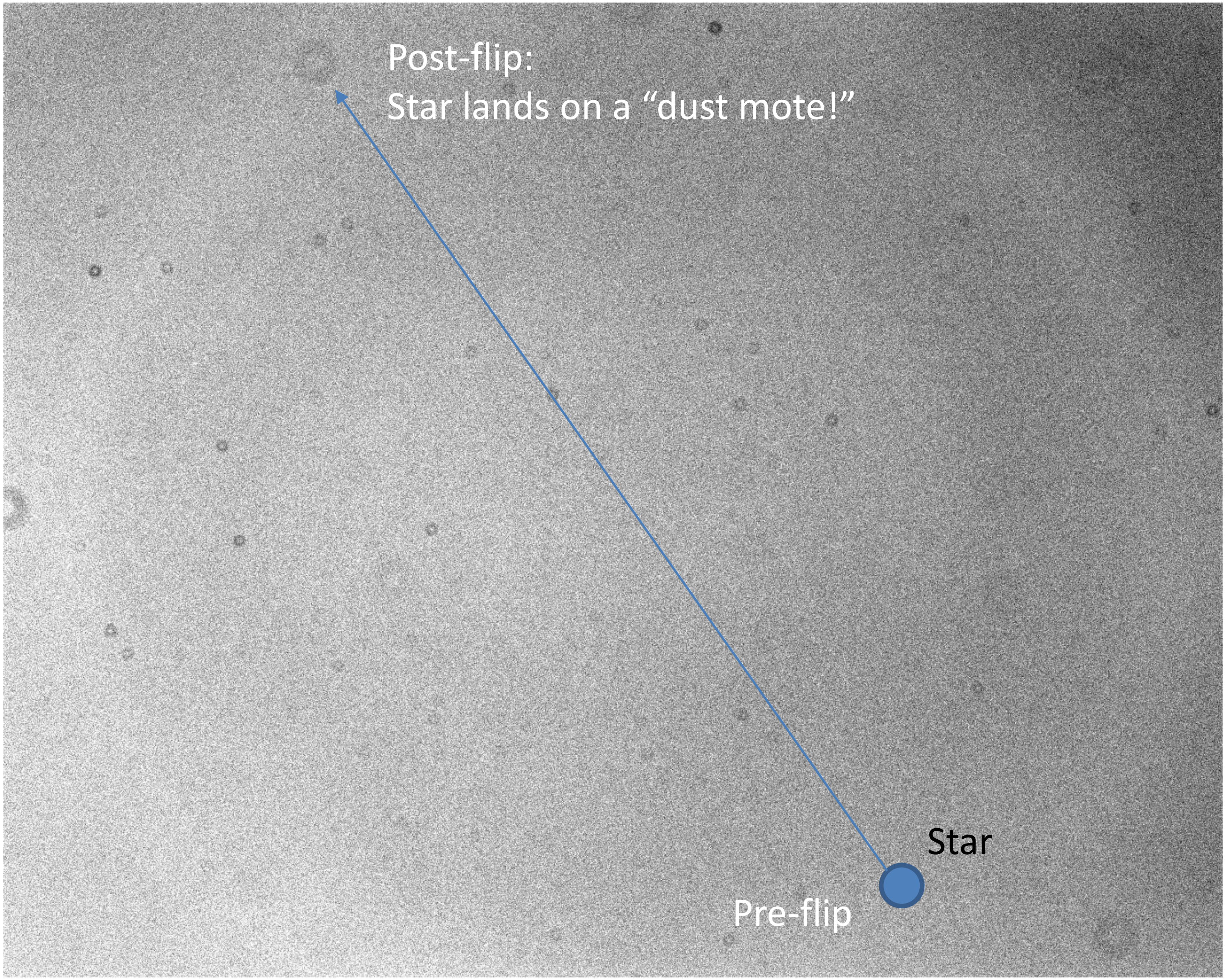
Preparation Phase

- Predict potential meridian flips for GEMs
- Choose appropriate exposure times: important that host and comparison stars do not reach saturation during imaging session!
- Acclimate CCD camera to appropriate temperature
- Generate flat files if twilight flats are used
- 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

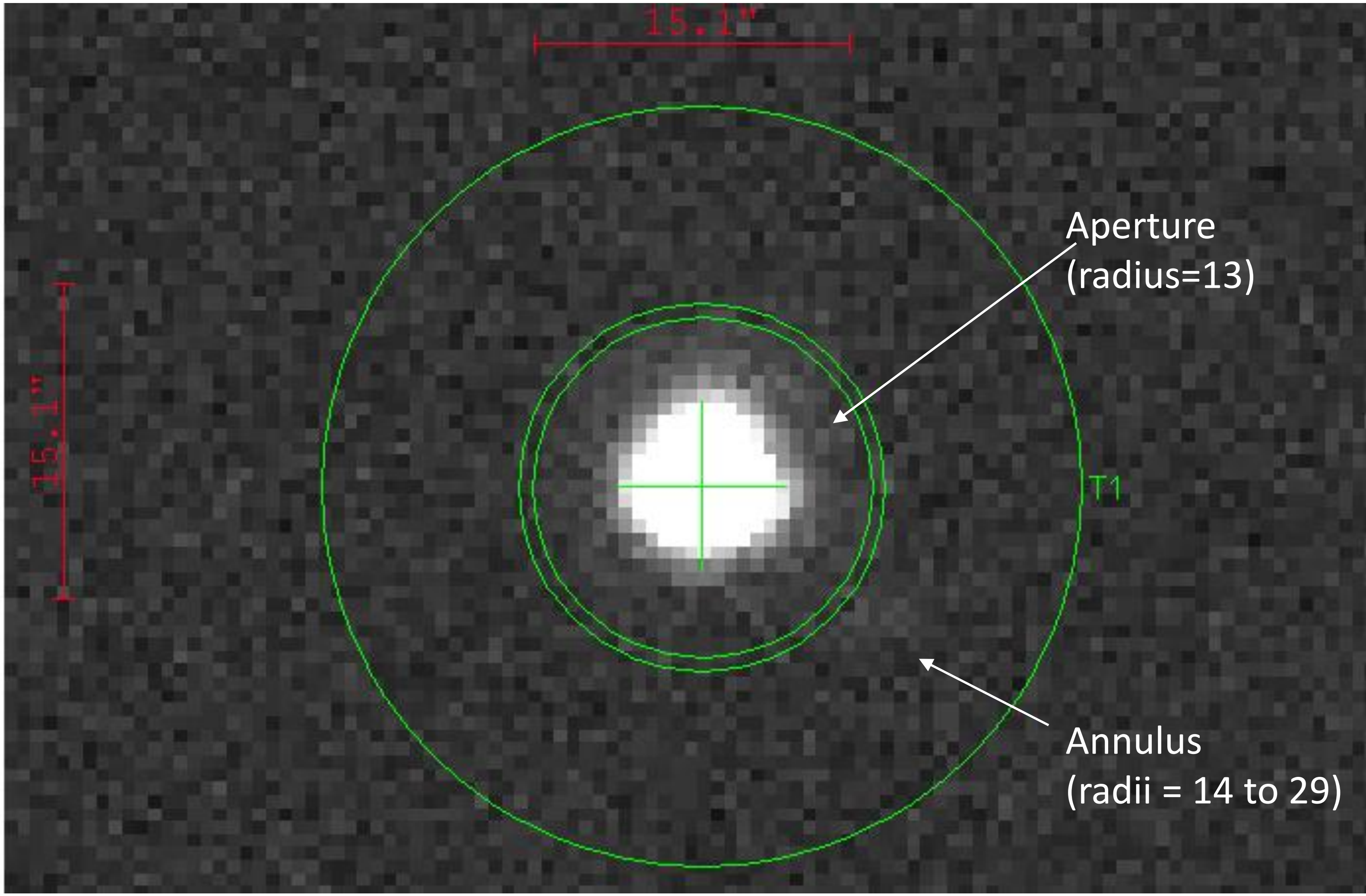
The Importance of Uniform Flats



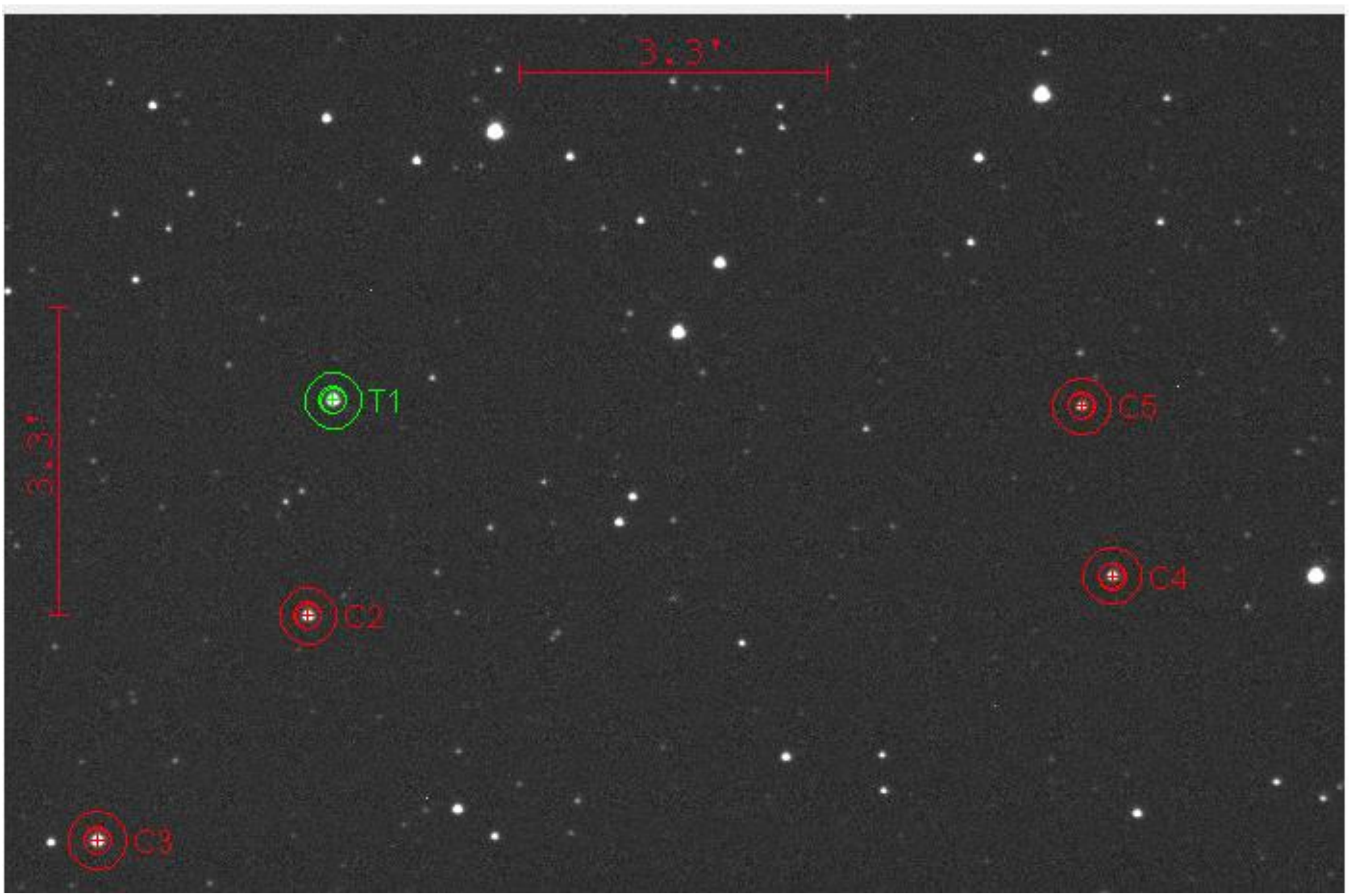
Post-Processing and Modelling

- 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



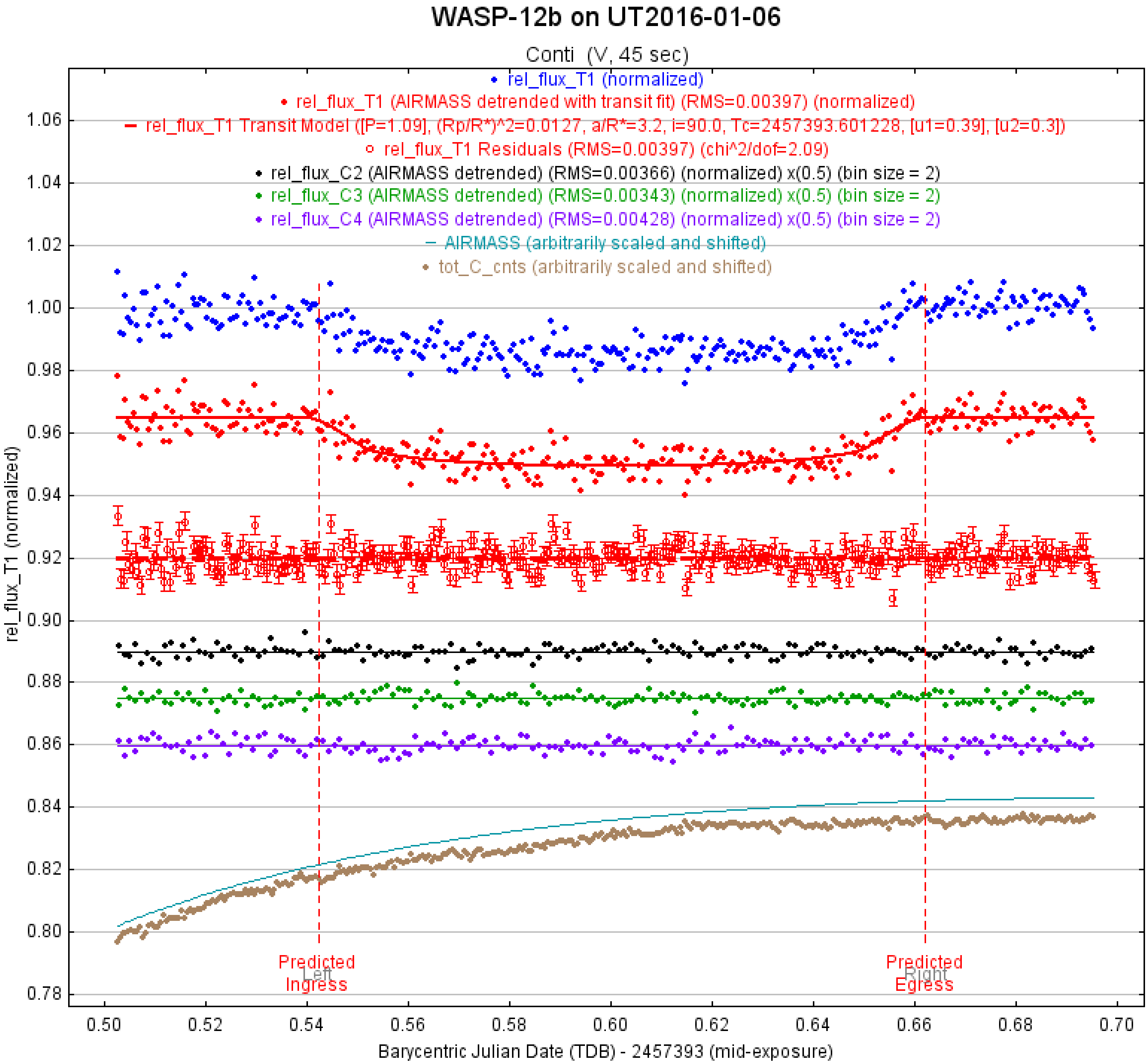
Conduct Model Fit

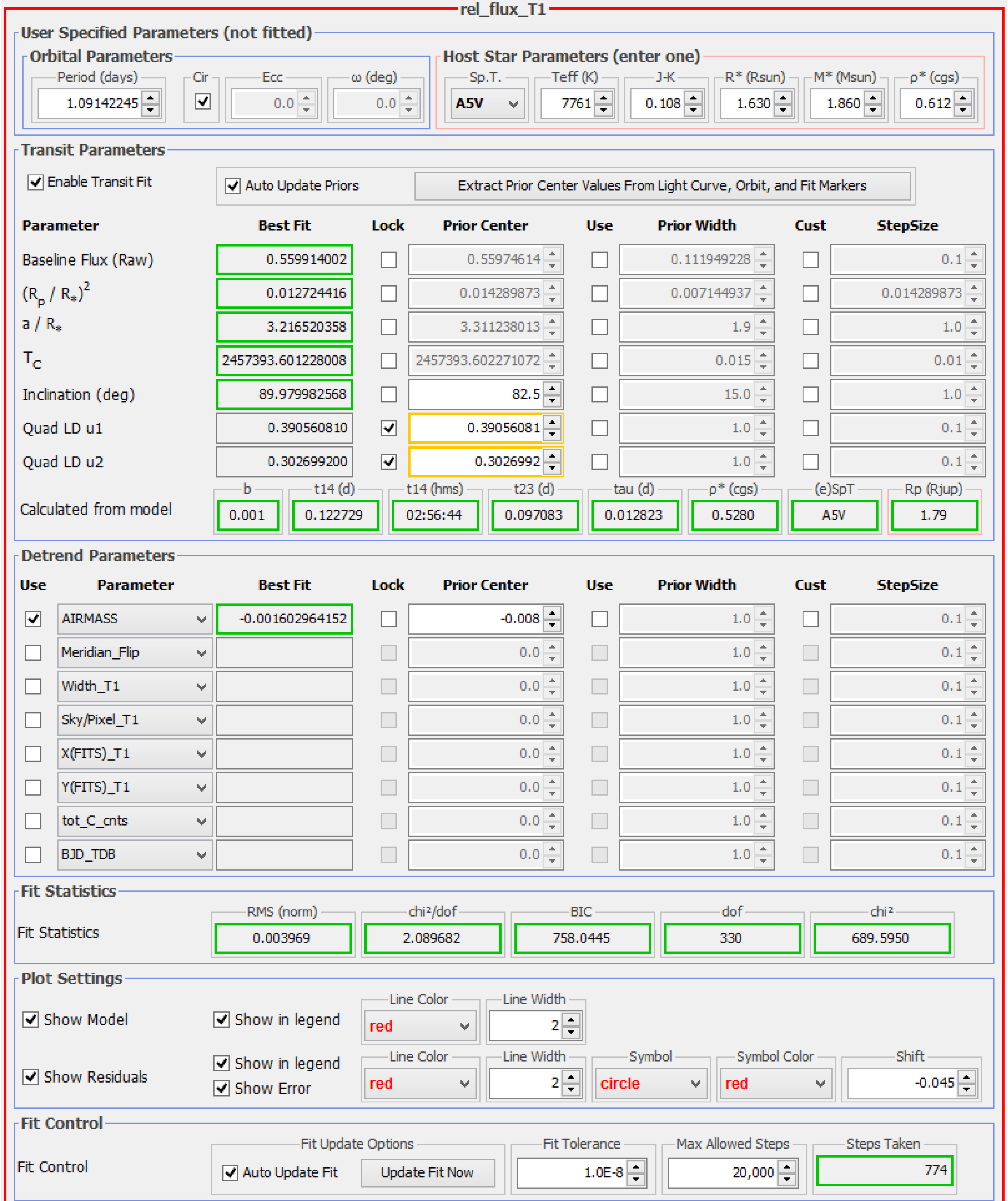
- Enter initial conditions into the modelling program:
  - Orbital period
  - Predicted ingress/egress times
  - Limb darkening coefficients
  - Optionally, mass of Host star

- Add appropriate detrend parameters

- Select and adjust placement of light curve plots

- Deselect any comparison stars that are not linear

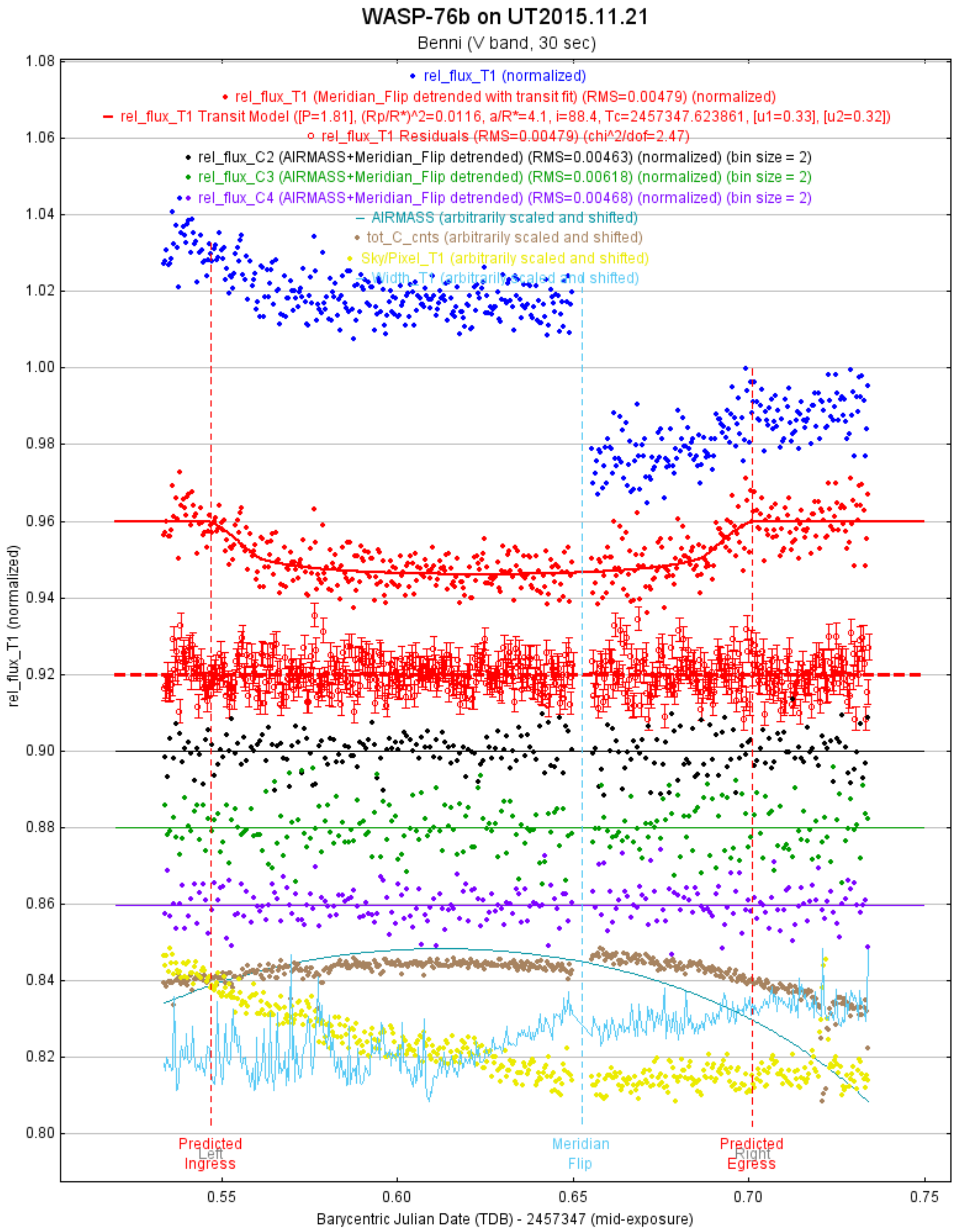

WASP-12b on UT2016-01-06
Conti (V, 45 sec)
rel_flux_T1 (normalized)
rel_flux_T1 (AIRMASS detrended with transit fit) (RMS=0.00397) (normalized)
rel_flux_T1 Transit Model ([P=1.09], (Rp/R*)^2=0.0127, a/R*=3.2, i=90.0, Tc=2457393.601228, [u1=0.39], [u2=0.3])
rel_flux_T1 Residuals (RMS=0.00397) (chi^2/dof=2.09)
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) 1.09142245
Cir
Ecc 0.0
ω (deg) 0.0
Host Star Parameters (enter one)
Sp.T. A5V
Teff (K) 7761
J-K 0.108
R* (Rsun) 1.630
M* (Msun) 1.860
ρ* (cgs) 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
(Rp / R*)2 0.012724416 0.014289873 0.007144937 0.014289873
a / R* 3.216520358 3.311238013 1.9 1.0
TC 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
Calculated from model
b 0.001
t14 (d) 0.122729
t14 (hms) 02:56:44
t23 (d) 0.097083
tau (d) 0.012823
ρ* (cgs) 0.5280
(e)SpT A5V
Rp (Rjup) 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
Fit Statistics
RMS (norm) 0.003969
chi²/dof 2.089682
BIC 758.0445
dof 330
chi² 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 Control
Fit Update Options
Auto Update Fit
Update Fit Now
Fit Tolerance 1.0E-8
Max Allowed Steps 20,000
Steps Taken 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

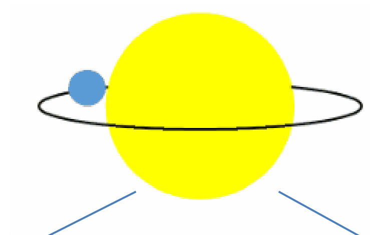
- Where Exoplanet Observing is more stringent:
  - Calibration (with darks, flats) a necessity
  - Consideration for atmospheric extinction
  - Accurate polar alignment and guiding
  - Appropriate image scale (i.e., arc-seconds/pixel)
  - Choice of filter
  - Necessity to stay within CCD linearity (to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

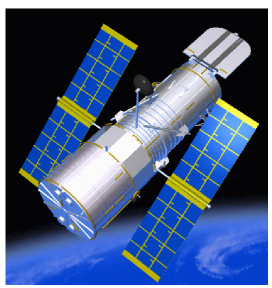
- Where Exoplanet Observing is less stringent:
  - Less sensitive to light pollution, moon light, and scintillation
  - In some cases, out-of-focus stars may be desirable

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

Hubble Exoplanet Pro/Am Collaboration





Hubble Science Team

World-wide Network of Amateur Astronomers

Project Background

- 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 some 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

Amateur Astronomer Collaboration

- The purpose of this collaboration is to:
  1. Help the Hubble science team better refine the ephemeris of the target exoplanets.
  2. Determine any unusual activity such as star spots or flares on the target planet’s host star.
  3. Develop a framework and a world-wide network of advanced amateur astronomers for other such collaborations.

- The ability of amateur astronomers to develop highly accurate light curves of transiting exoplanets is now well-established, especially of “hot Jupiters.”

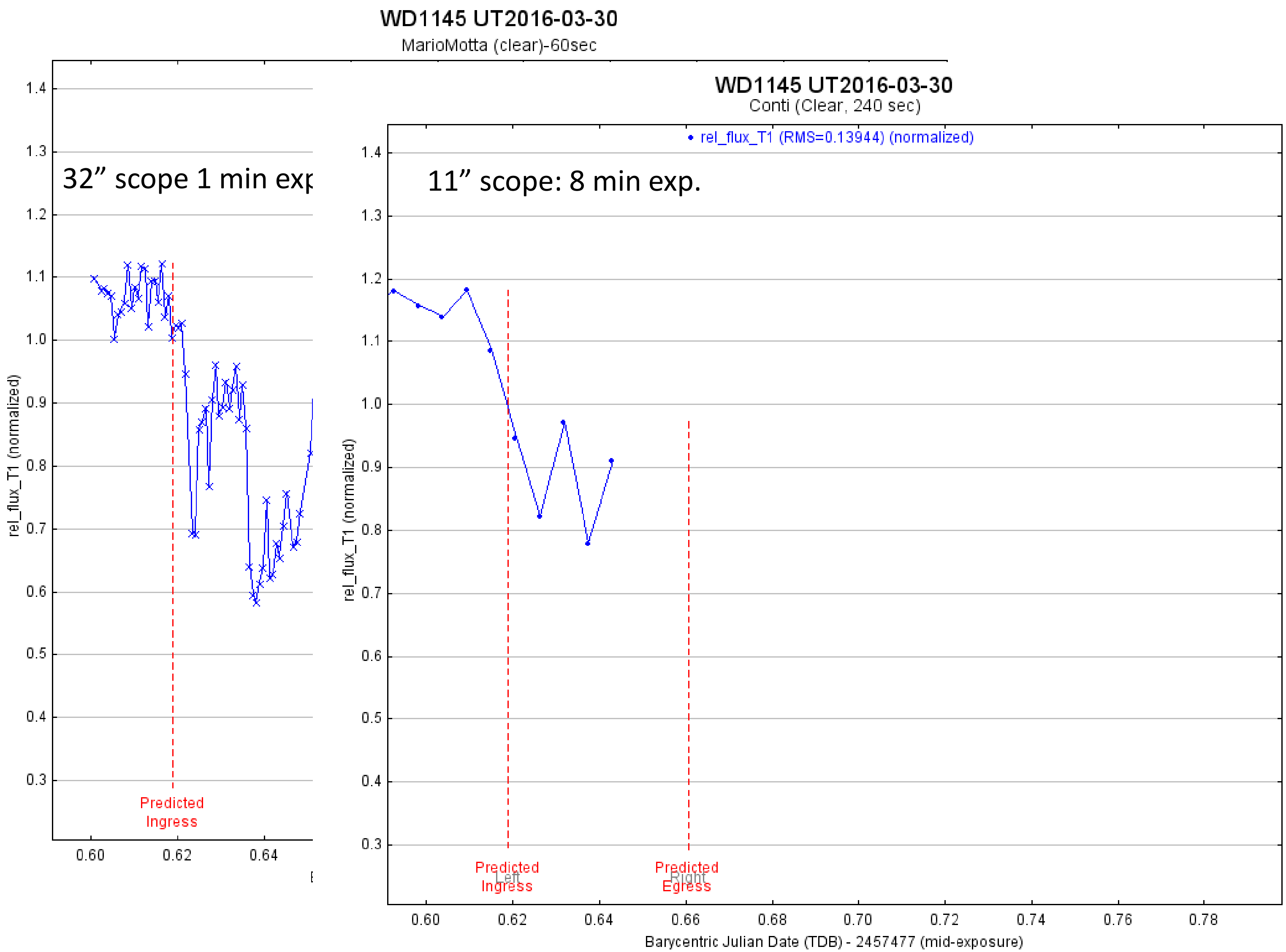
Location of Participating Observation Sites

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
32” scope 1 min exp
rel_flux_T1 (normalized)
Predicted
Ingress
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
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

- Future exoplanet missions will have even a greater need for exoplanet follow-ups by amateur astronomers

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