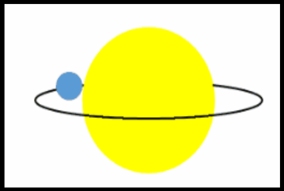
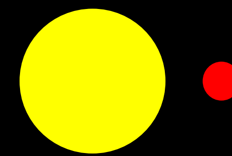


Fundamentals of Exoplanet Observing

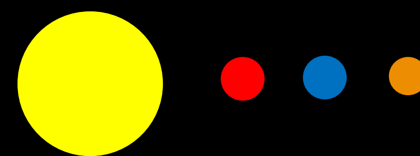
Dennis M. Conti
Chair, AAVSO Exoplanet Section

The Strange World of Exoplanets

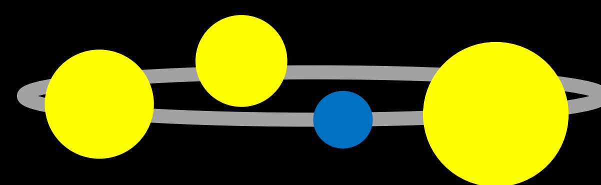
- Most exoplanets we have discovered are close-in, large planets: “Hot Jupiters”



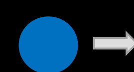
- Some stars have multiple planets



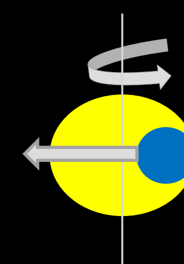
- Some planets orbit multiple stars



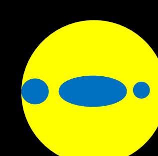
- Some “planets” are free-floating



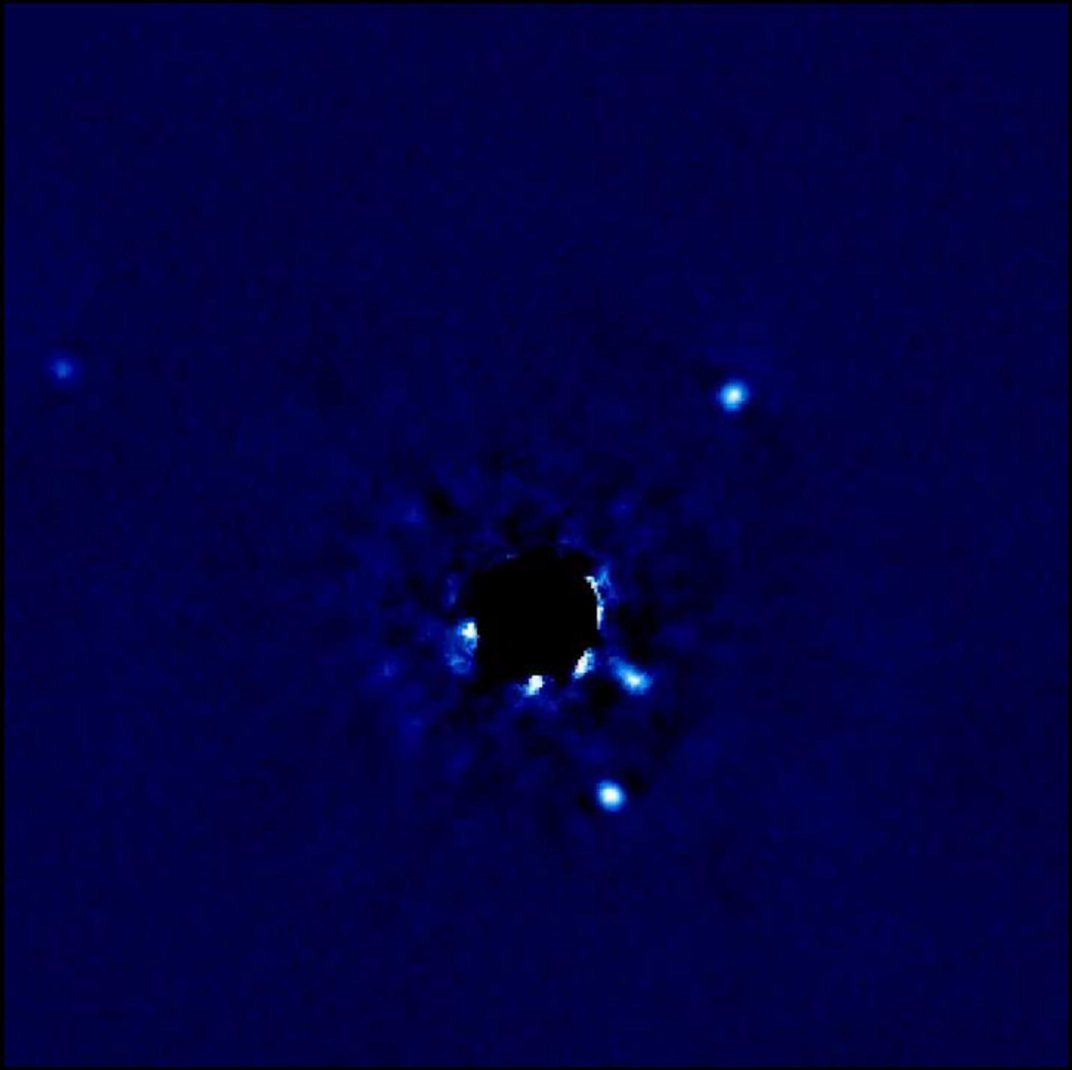
- Some planets’ orbits are opposite from their star’s rotation



- Some planetesimals are disintegrating around their host star

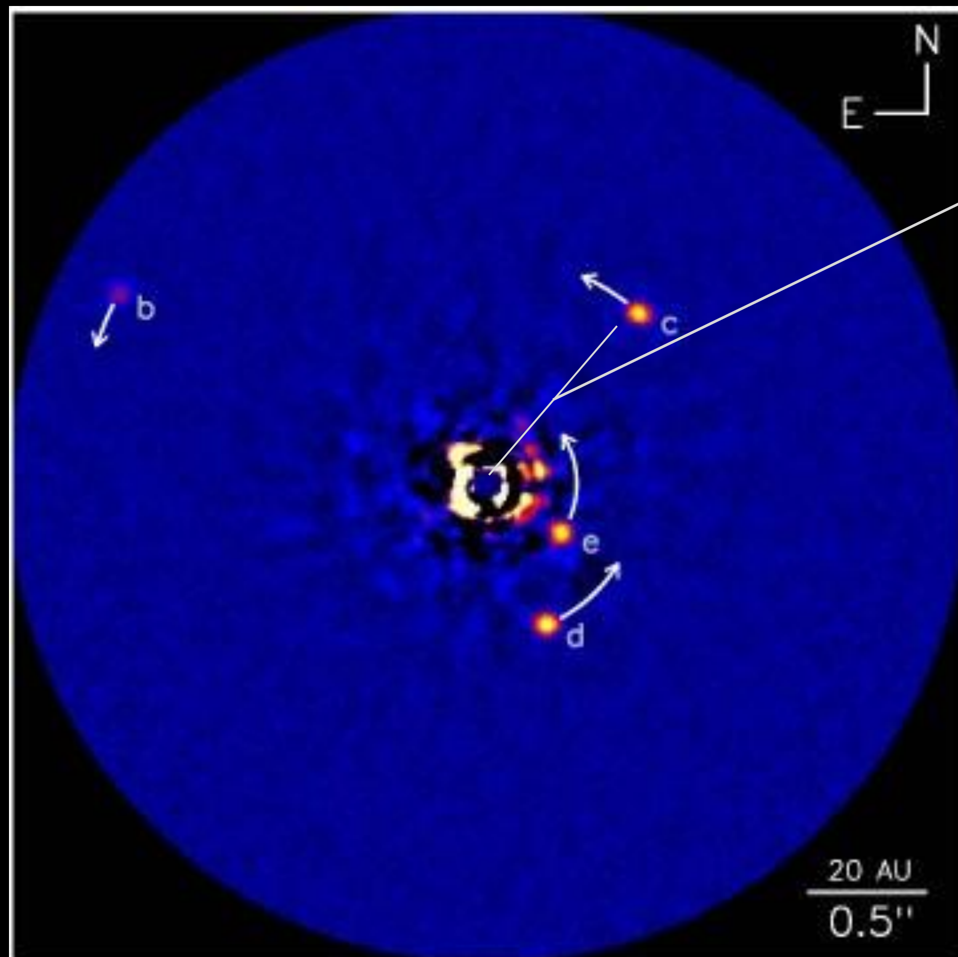


Multi-Planet Example: HR 8799

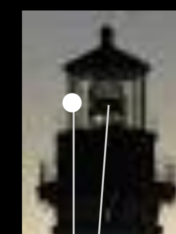


Courtesy: Michael Tabb

The Challenge



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

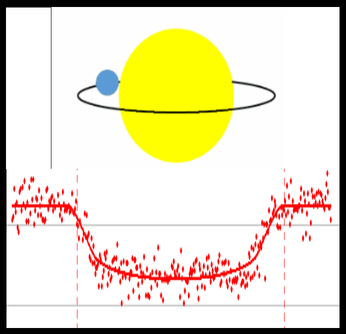


1 mile

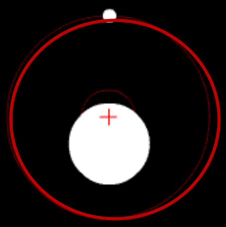
Courtesy: Keck Observatory

Exoplanet Detection Methods

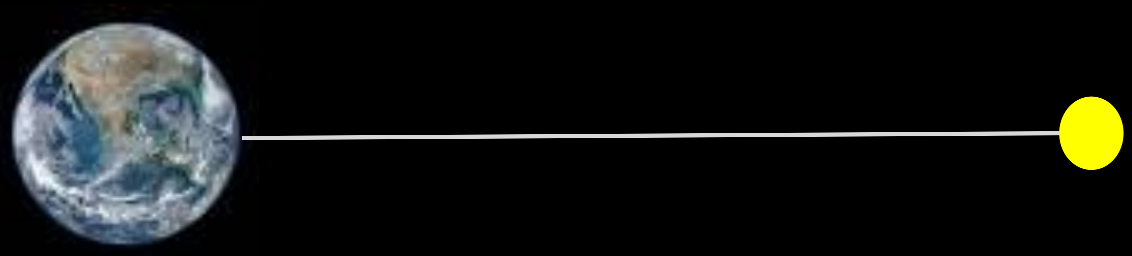
- Transit Method:
  - the dominant method used by amateur astronomers



- Radial Velocity Method



- Microlensing



Exoplanet Detection Methods

- Transit Method:
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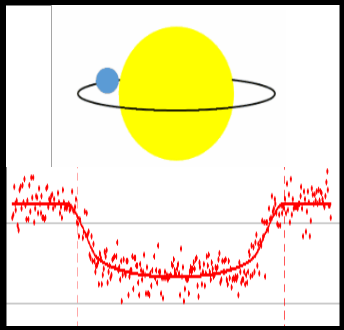
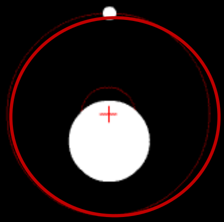


- Radial Velocity Method

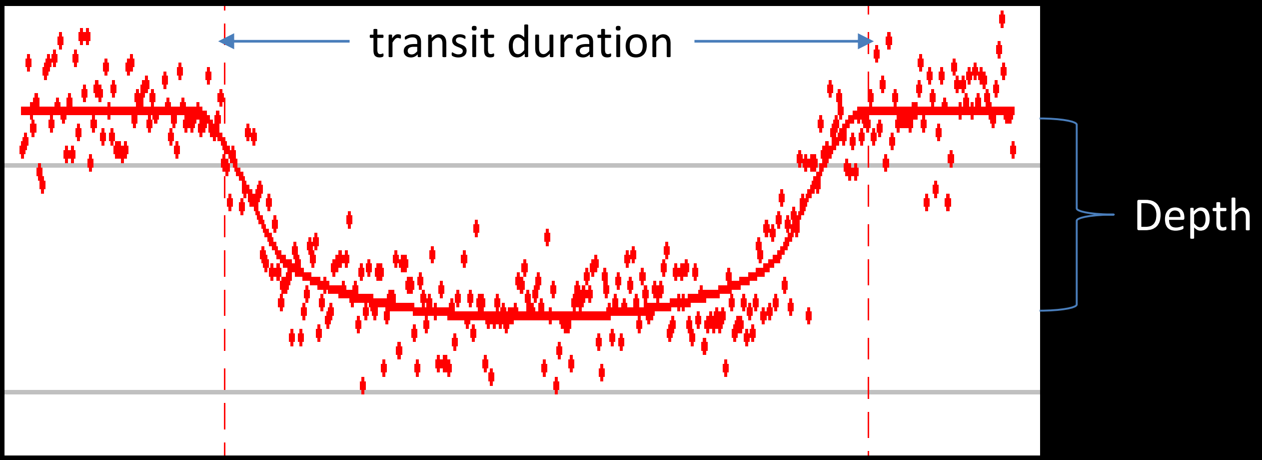


- Microlensing

- Pulsations of Host Star

- Direct Imaging

The Transit Light Curve:
A Relative Measure of the Target Star's Brightness



We can learn a lot just from the light curve!

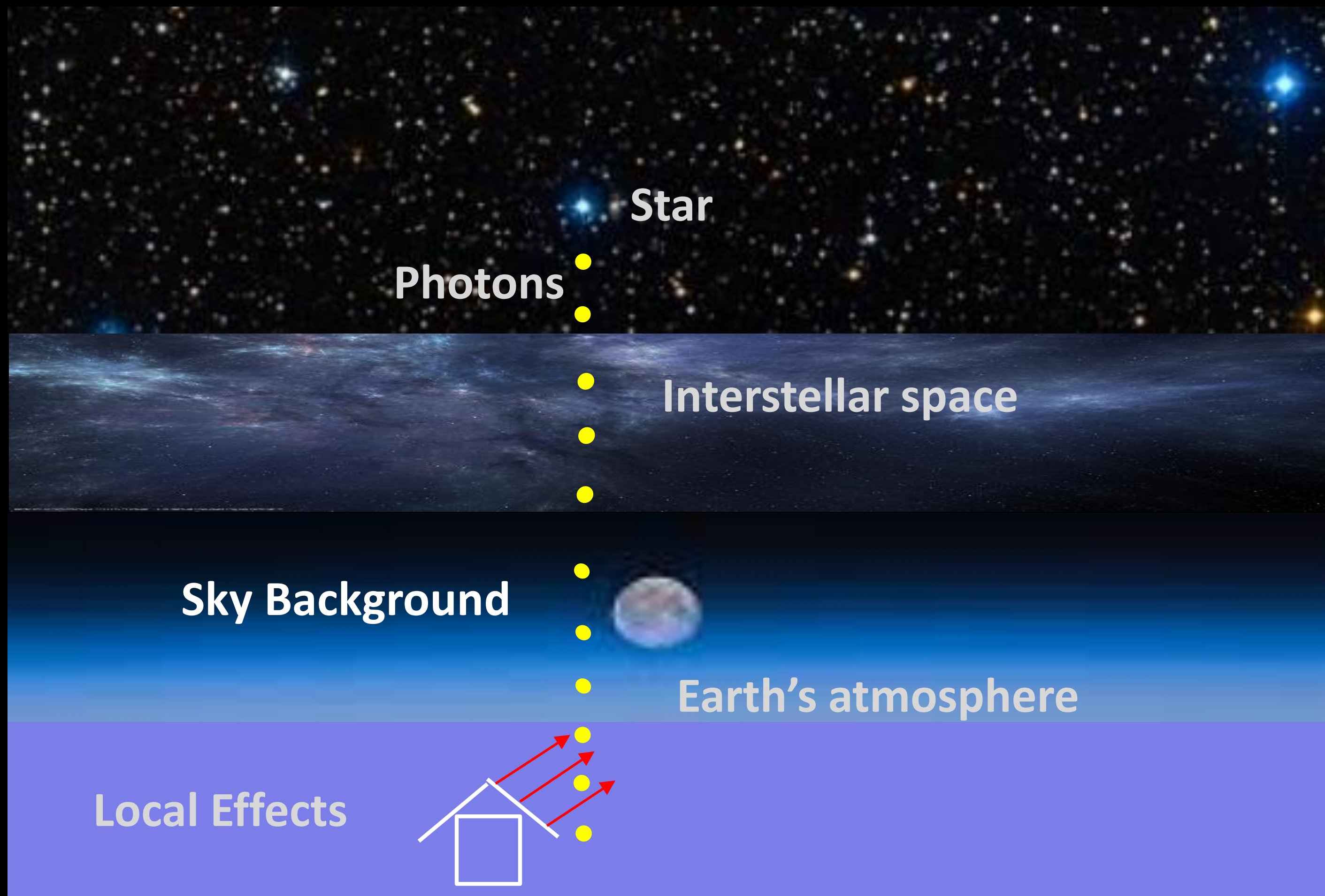
- How big the planet is (its radius)
- How far it is from its host star (the size of its orbit)
- How inclined is its orbit from our line-of-sight
- Whether it is truly a planet or another star

It's All About Counting Photons!

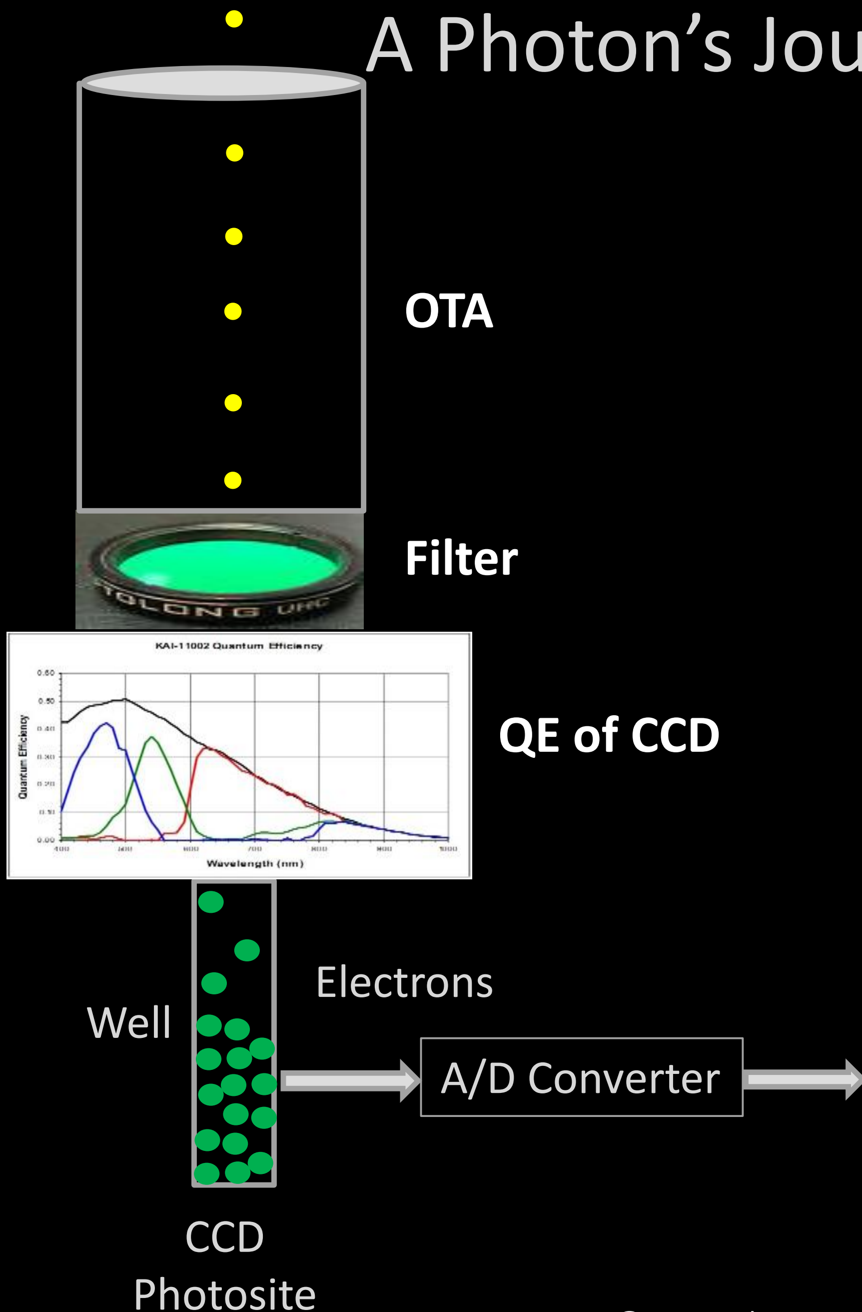
… and doing it accurately and precisely

… and maximizing <u>Signal</u> and reducing <u>Noise</u>

Follow the Photon!



A Photon's Journey (cont'd)



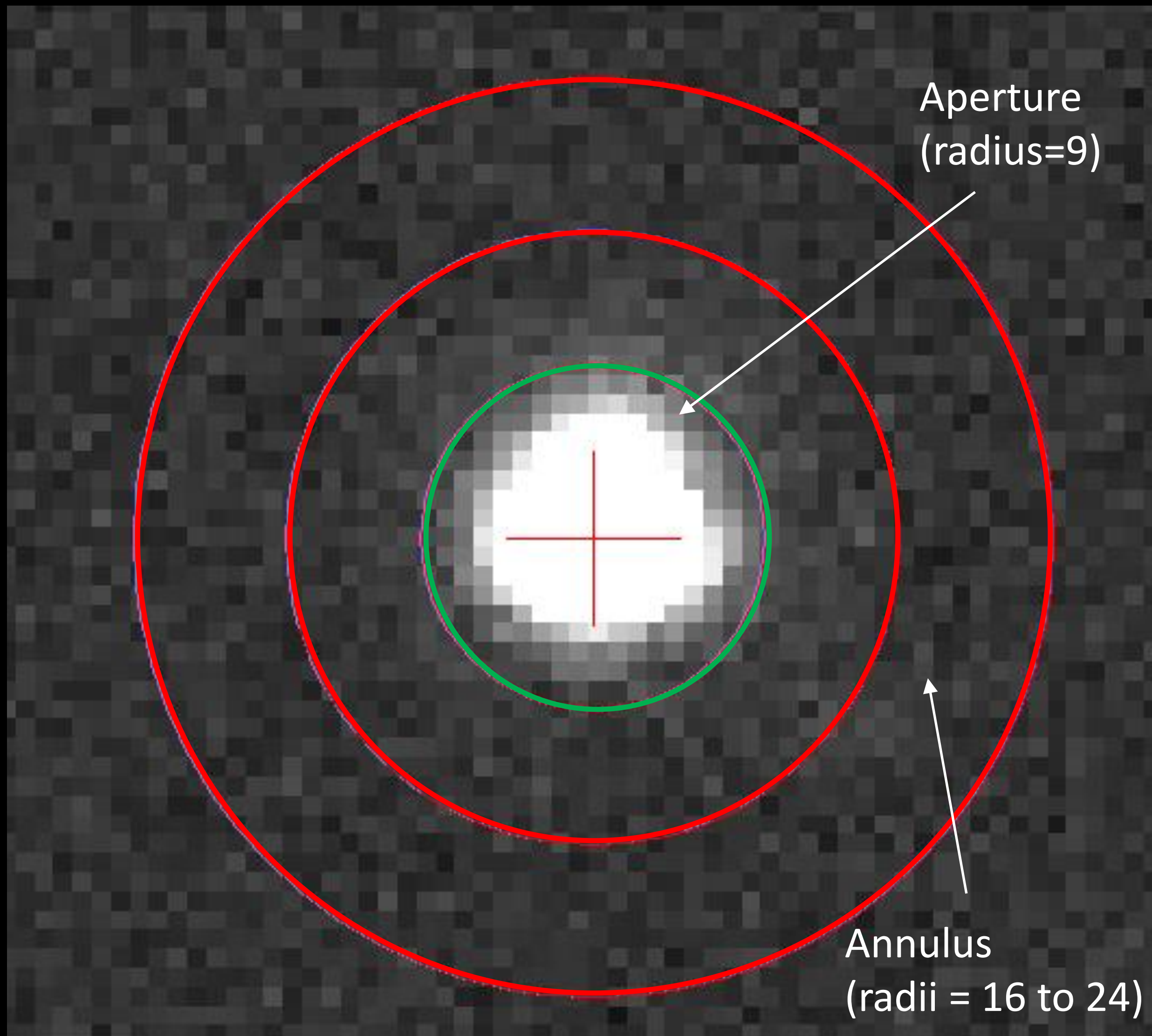
ADUs per Pixel

Pos	330	331	332	333	334	335	336	337	338	339	340	341	342
589	386	496	494	695	932	1170	1310	1198	1121	771	630	455	362
590	450	622	748	1052	1397	1916	1961	1815	1344	1069	883	590	466
591	494	687	936	1665	2356	3118	3425	2755	1967	1434	978	705	575
592	626	892	1461	2487	4470	5530	5689	4639	3051	2028	1251	672	610
593	768	1164	2195	4307	6910	9001	10074	7753	5251	2890	1713	1066	625
594	825	1538	3221	6535	10583	15120	15572	12125	7578	3886	2273	1346	748
595	930	1760	3530	7445	12876	18911	19476	15213	9978	5272	2919	1532	913
596	870	1521	3102	6141	11995	17968	18835	14734	9907	5523	2828	1696	958
597	664	1194	1898	4182	7531	10983	11624	10406	6526	3652	2275	1287	958
598	614	854	1179	1837	3298	4250	4765	4593	3258	1918	1346	881	589
599	409	452	732	1229	1471	1613	1678	1722	1385	1152	754	688	535
600	408	577	537	670	757	878	954	814	787	534	622	447	415
601	295	335	415	451	524	578	524	582	500	399	466	345	406

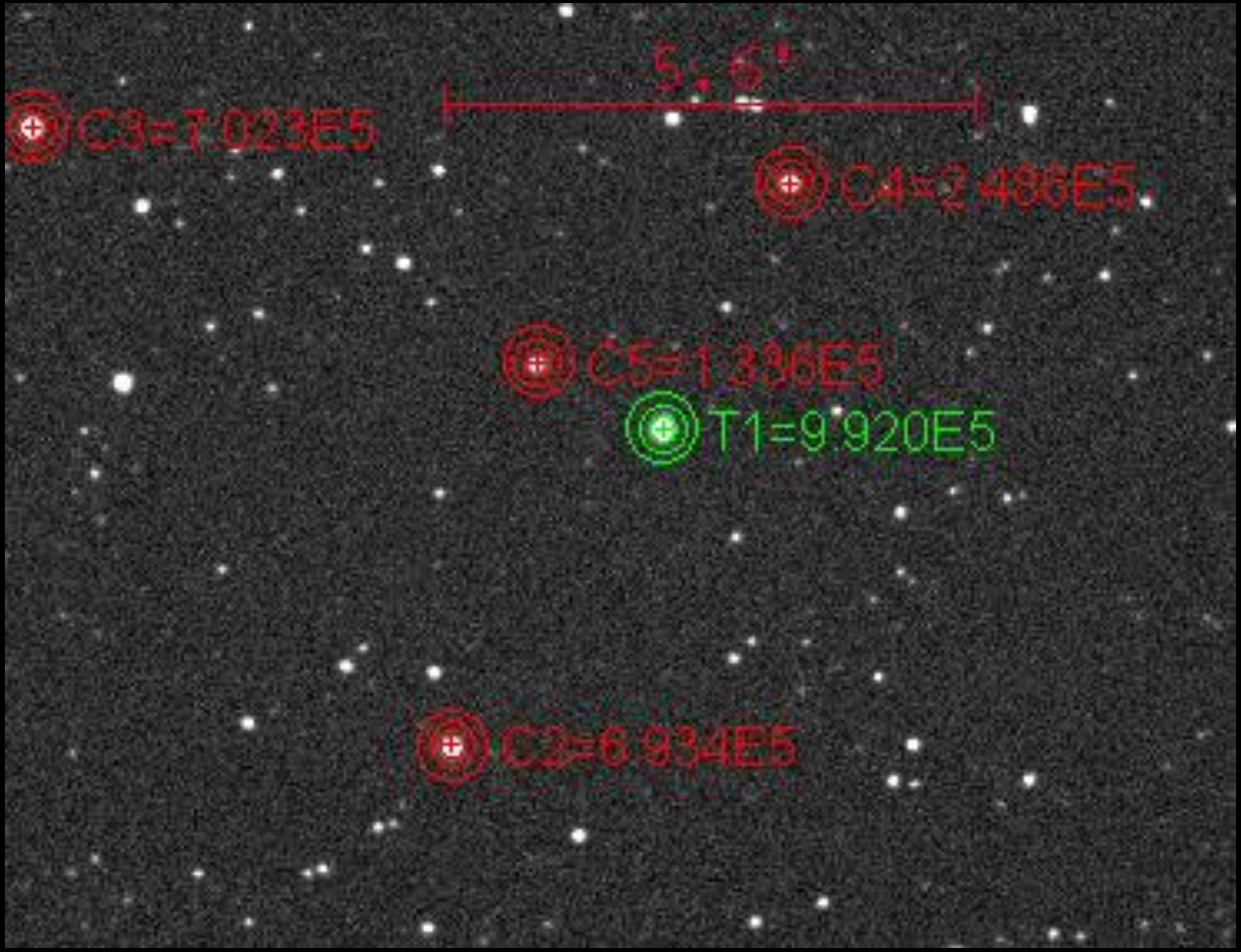
Measuring Change in a Star Brightness

- Take images that contain the Target star and some number of Comparison stars in the same field-of-view
- Use Aperture Photometry to get the "adjusted brightness" of each individual star
- Use Differential Photometry to compare the "adjusted brightness" of the target star RELATIVE to the sum of that of the comparison stars

Aperture Photometry



Differential Photometry

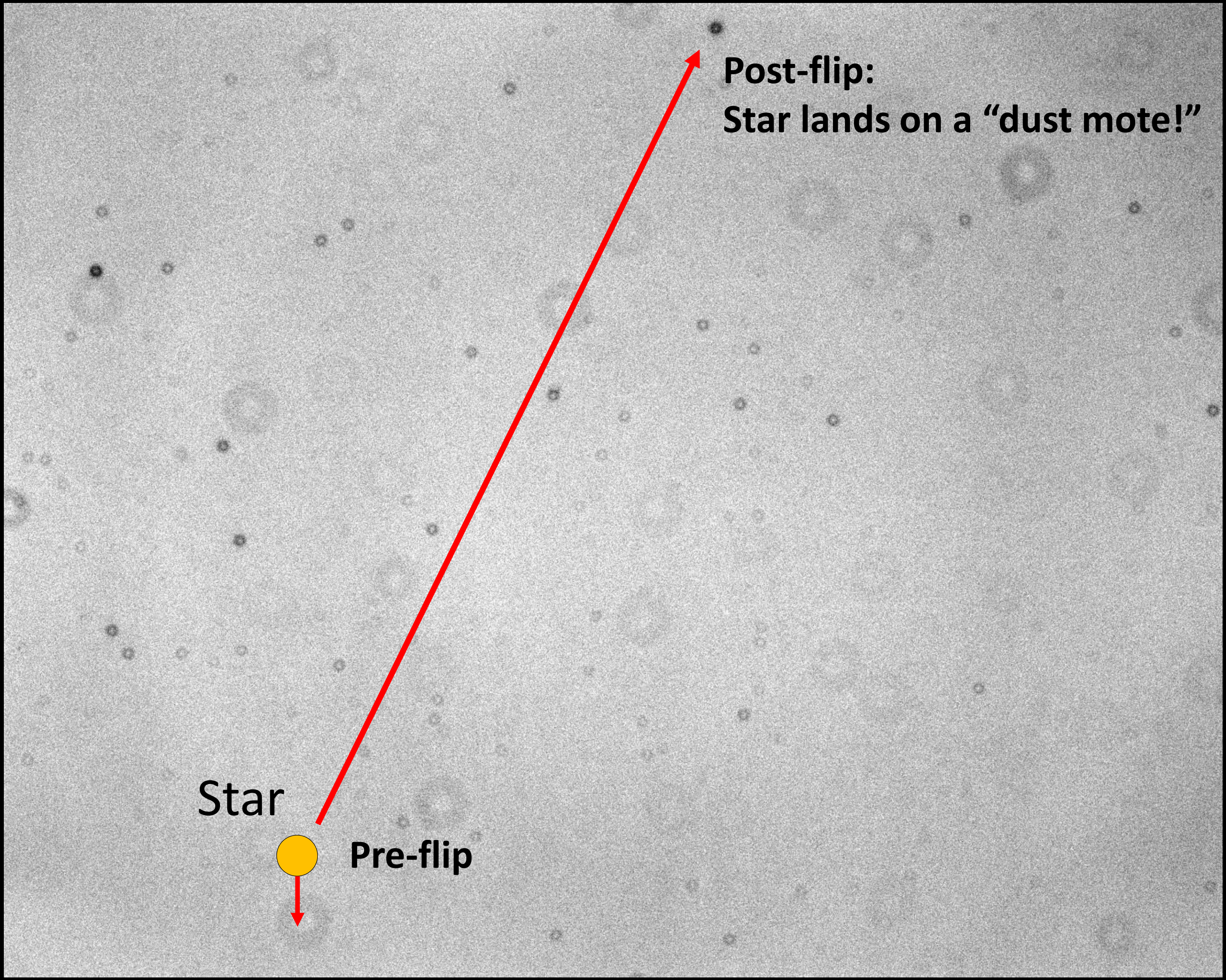


Sources of Signal and Noise

- Signals:
  - Detected photons: photons that translate to ADU counts
  - Dark current: an unwanted signal that is a function of exposure time
  - Bias: a constant offset to ADU count
  - Affects of dust motes

- Noise:
  - Shot noise – uncertainty in photon counts
  - Dark current noise – uncertainty in dark current
  - Readout noise – uncertainty in read noise

The Importance of Uniform Flats and Guiding!



Minimizing Star Movement

Goal: minimize movement in RA and DEC
over the entire (4-6 hour) session

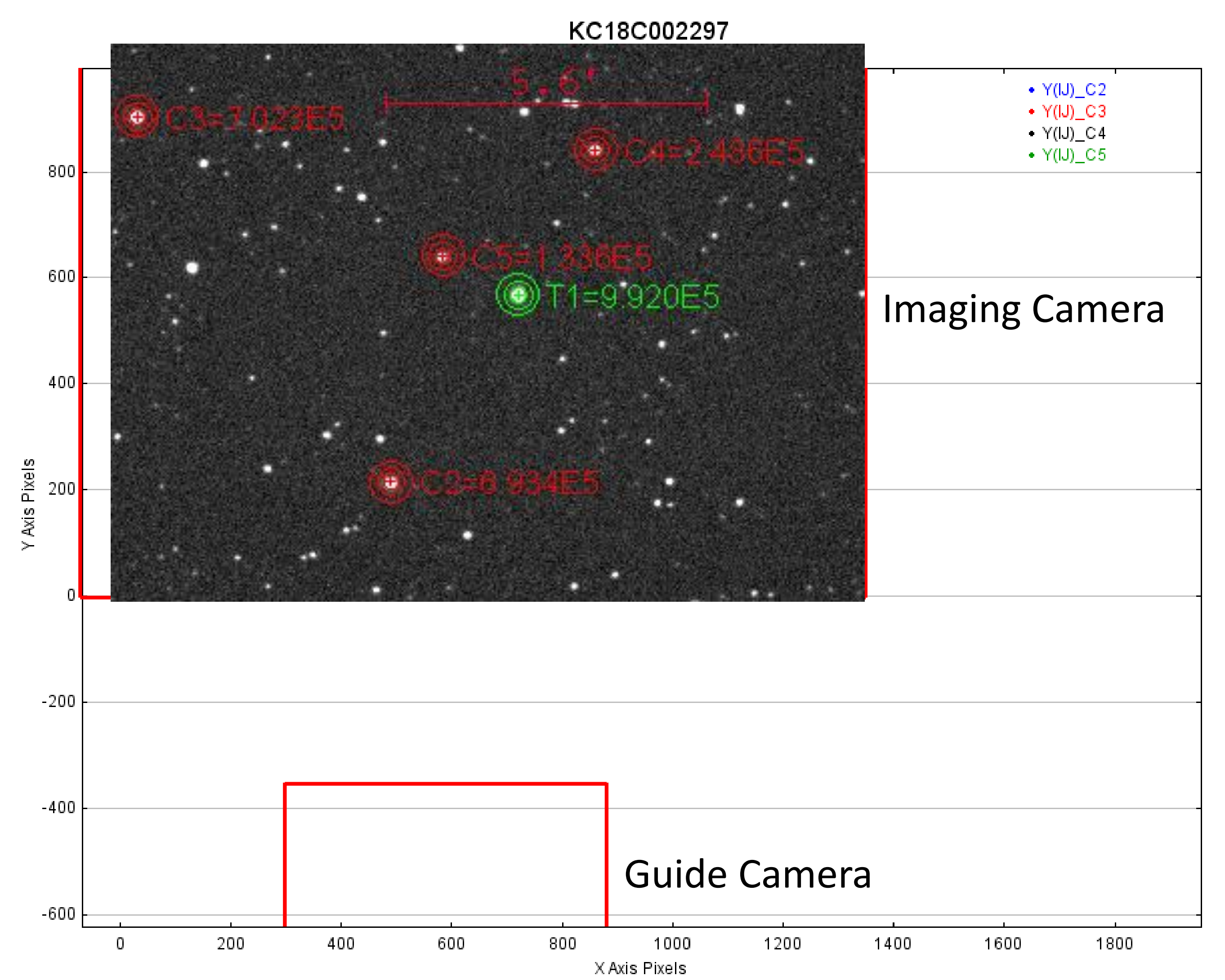
- Amount of pixel movement (field rotation) is a function of:
  - polar alignment error
  - overall integration time
  - distance from guide star to target
  - focal length
  - declination of target
- Minimize periodic error
- Have a well-balanced mount
- Consider aligning with refracted pole vs. true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

Autoguiding

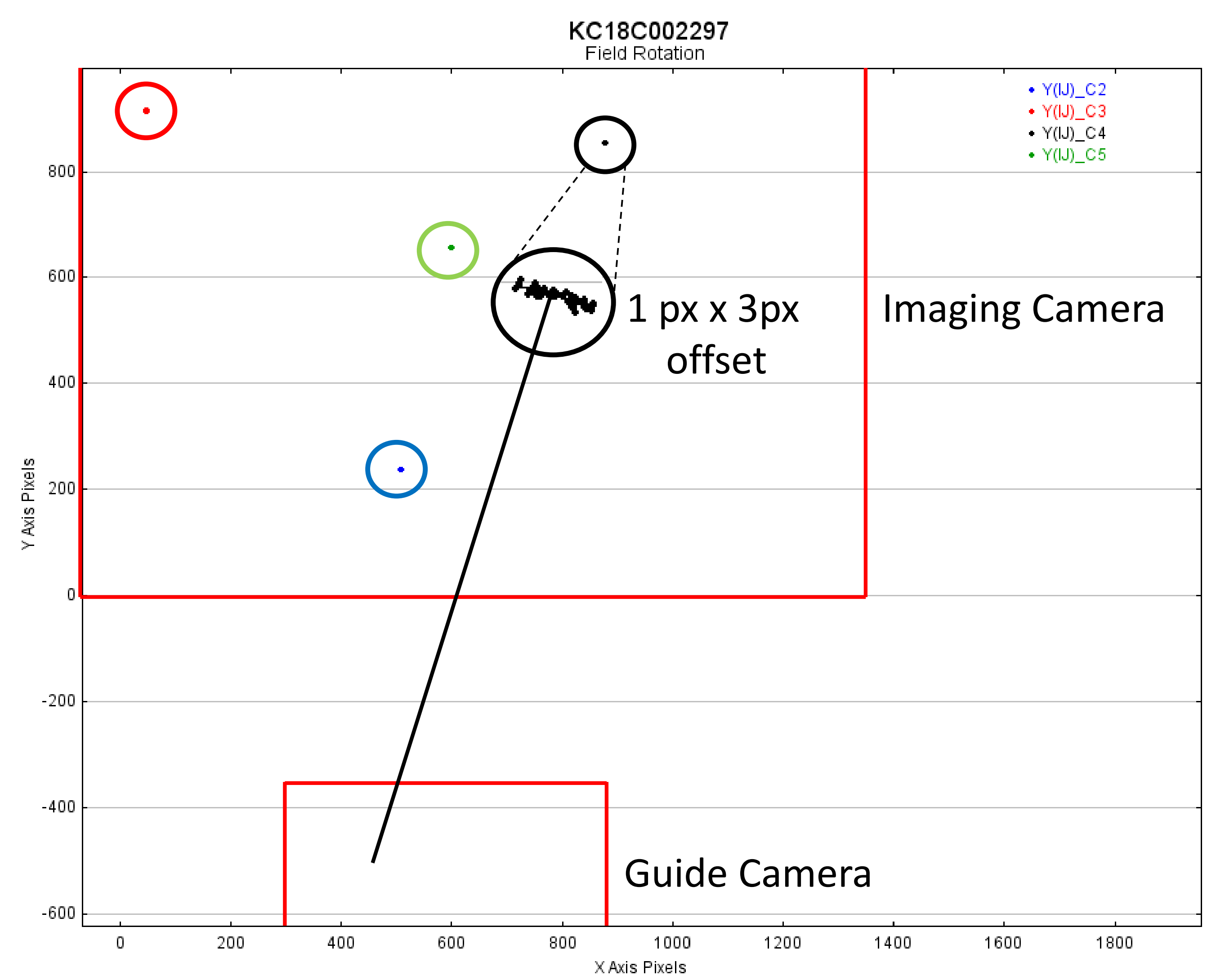
- Approaches:
  - Use a guide scope
  - Off-axis guiding
  - On-camera guide chip
  - On-axis guider

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

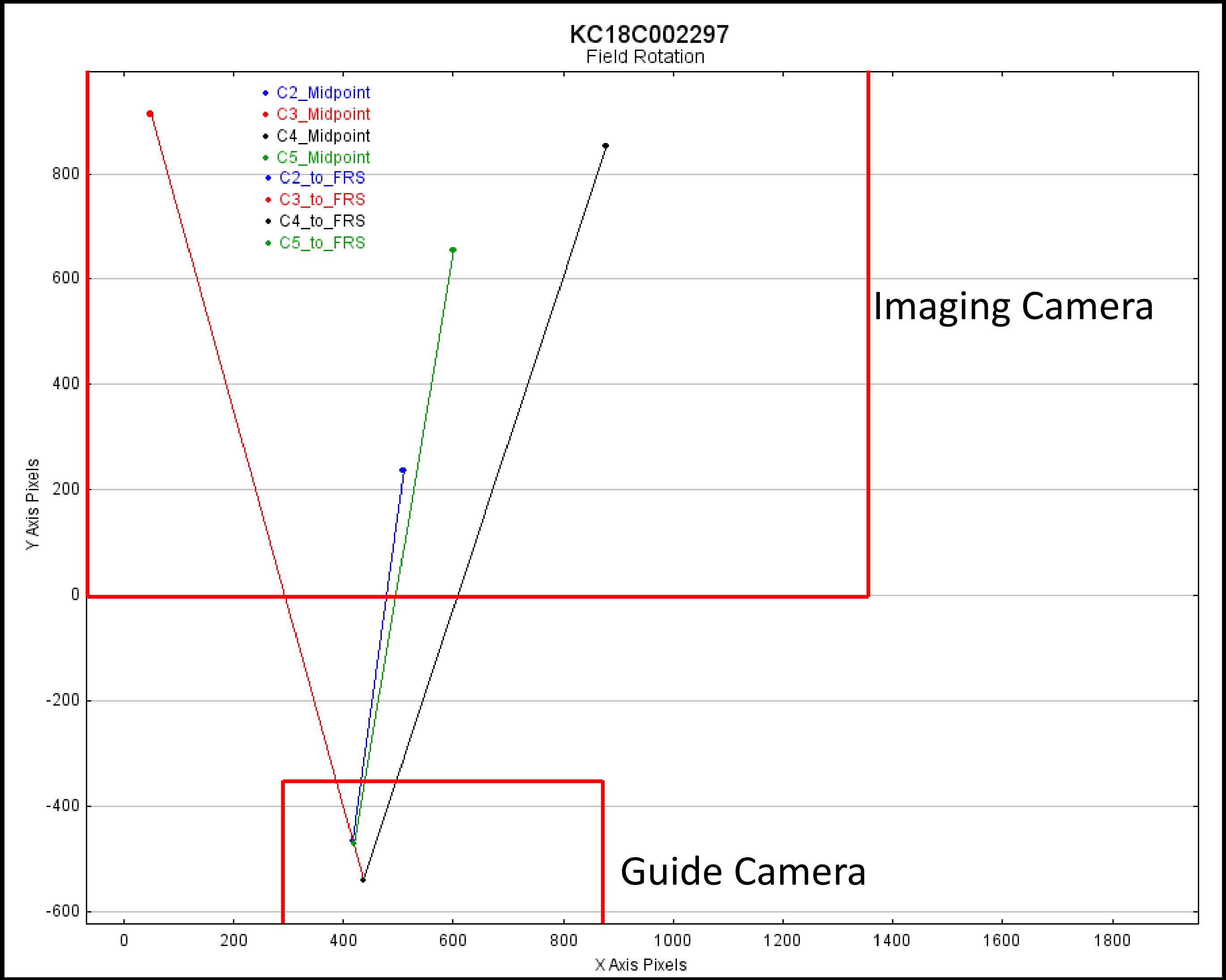
Field Rotation Example for: 1.5 hour session, .009° polar misalignment



Field Rotation Example for:
1.5 hour session, .009° polar misalignment



Detecting Source of Field Rotation



Field Rotation
(even with autoguiding!)

- Increases with:
  - polar misalignment
  - distance from star to guide star
  - declination
  - observation time

- Even if target star is used as the guide star, surrounding Comp stars could have field rotation

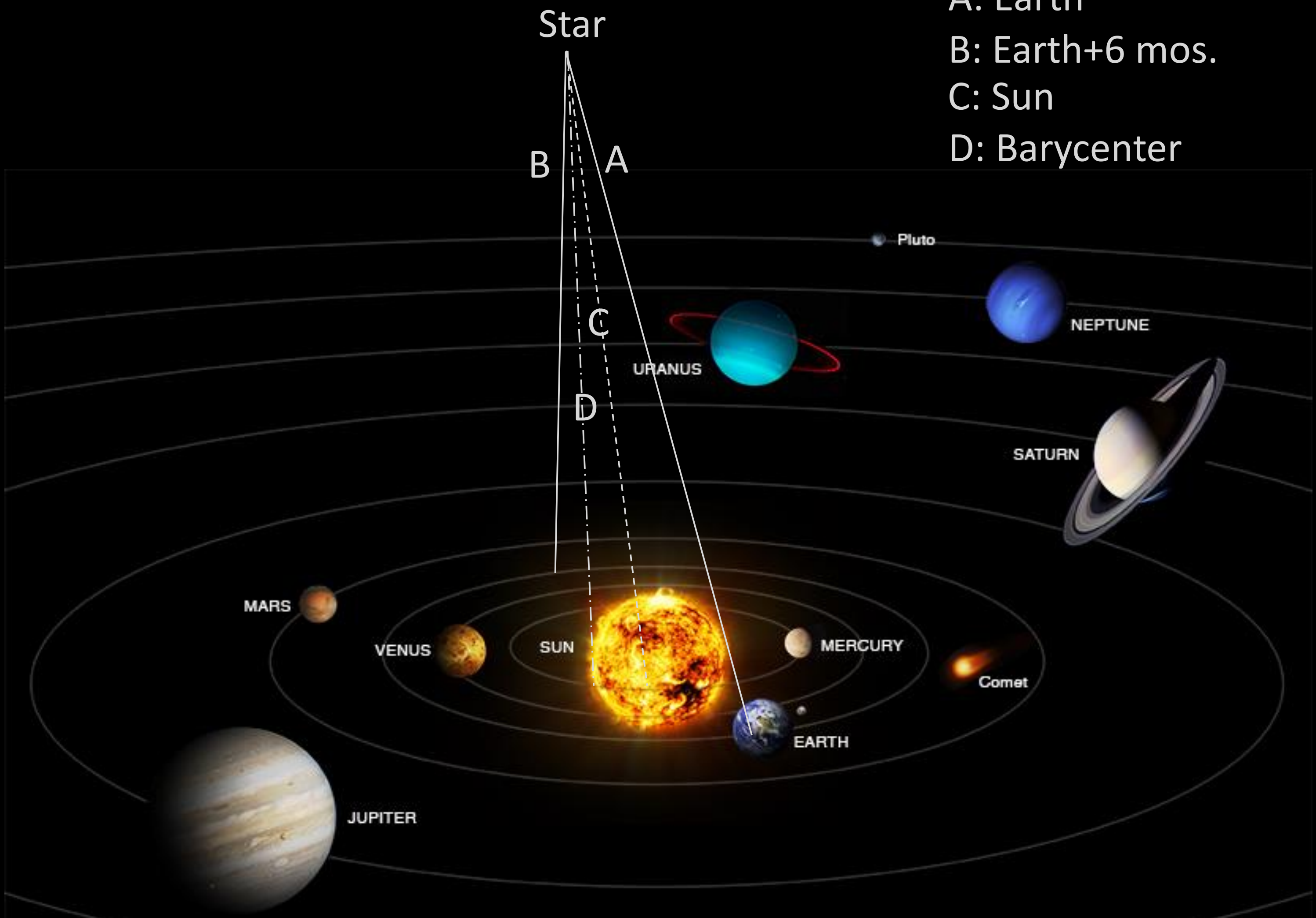
- Summary:
  - Minimize polar misalignment
  - Place target star as close as possible to guide star
  - Choose comp stars near target star

It is important to…

- …know in what time base are the predicted transit times
- ..use the appropriate time base for exoplanet transit results

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 Suffern, NY: 16:00 on April 6, 2017
- UTC time at Greenwich, England: 20:00 on April 6, 2017
- JD_{UTC} (above in Julian Date form): 2457850.33333

↓ -1.47min.

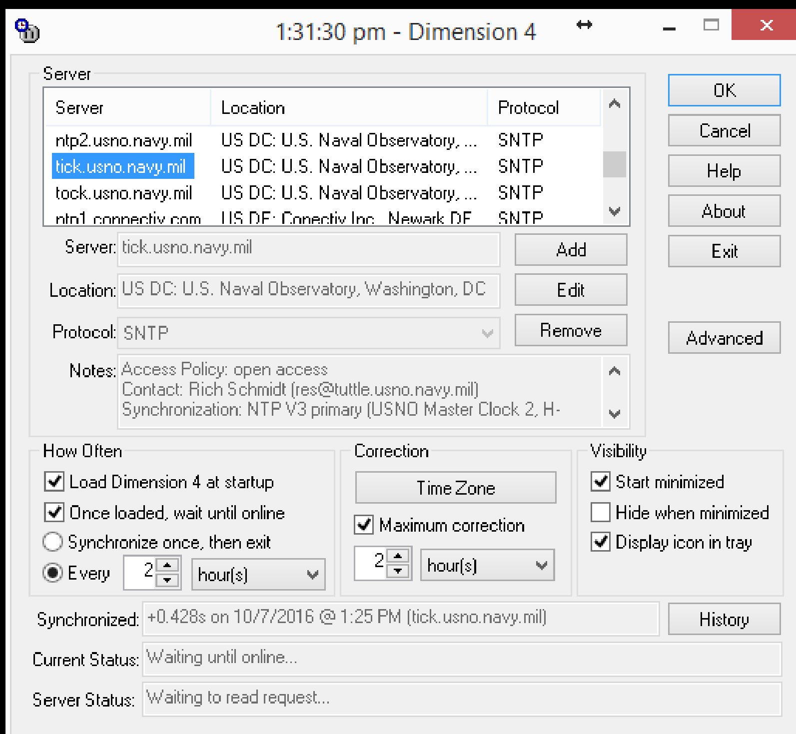
- HJD_{UTC} (Heliocentric Julian Date, UTC) for WASP-12 ($06^h\ 30^m\ 33^s$, +29° 40′ 20″) 2457850.33231

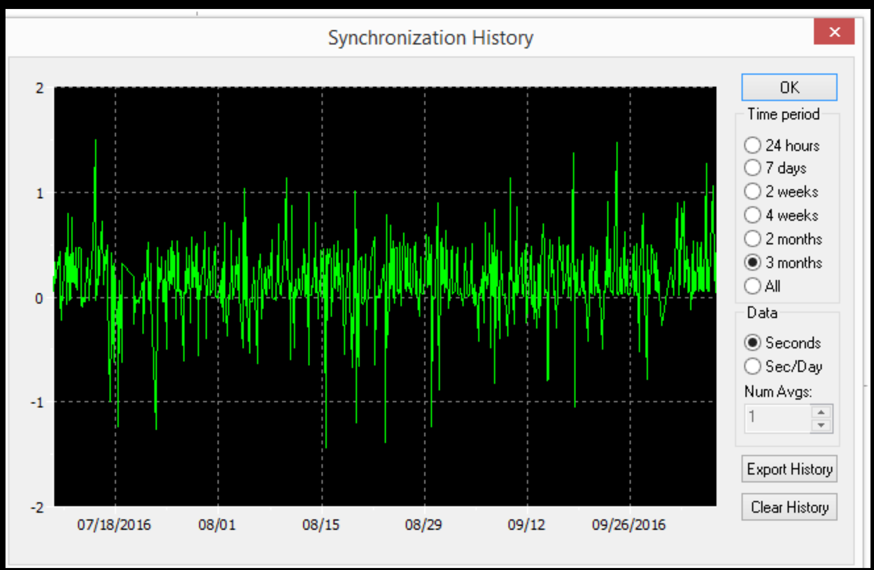
↓ +1.17 min.

- BJD_{TDB} (Barycentric Julian Date, Barycentric Dynamical Time) for WASP-12 and Suffern (41.1° N, 74.1° W, 95m alt.) 2457850.33312

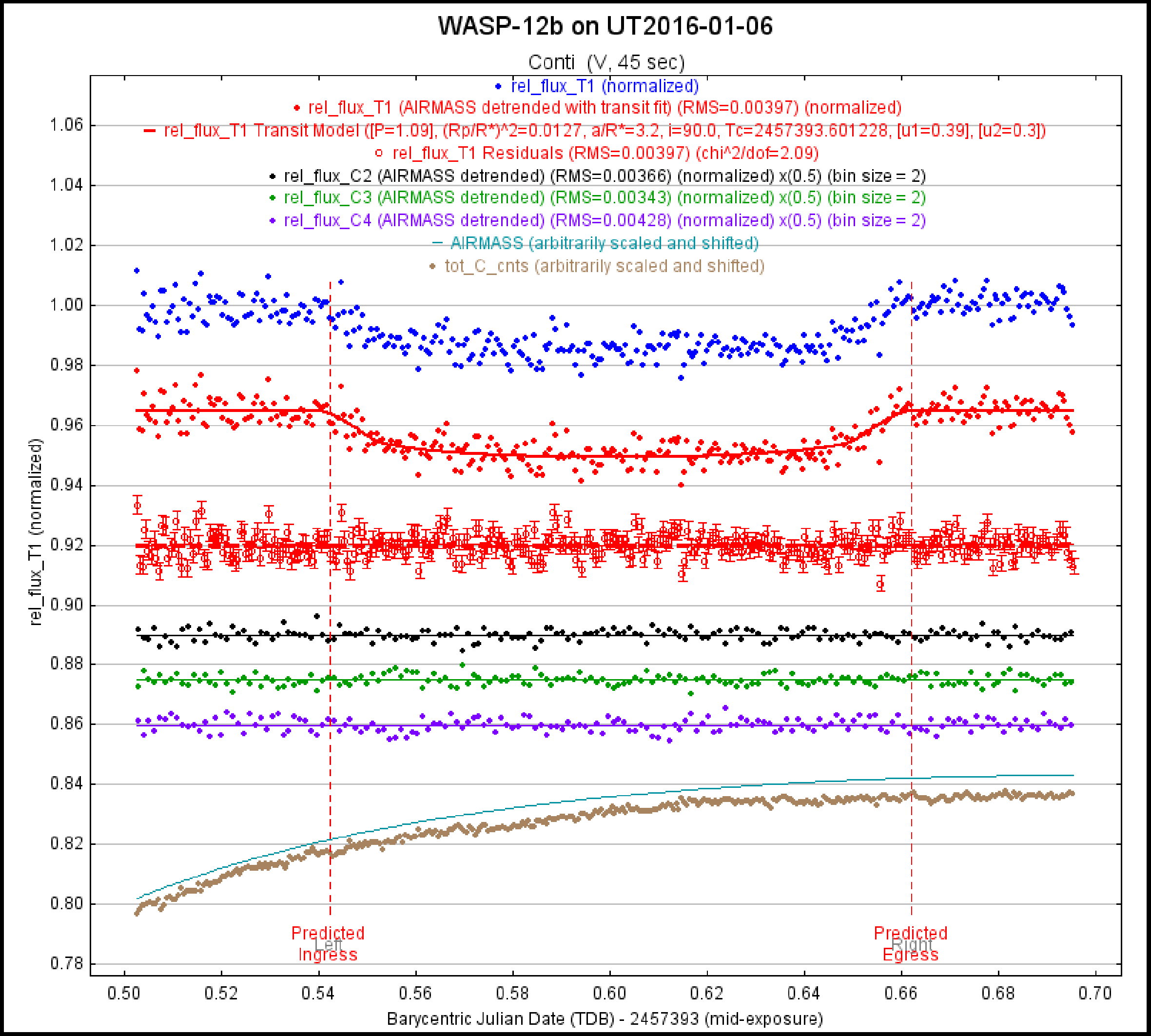
Accurately Record Time of Capture

- Periodically update image capture computer clock to synchronize it with atomic clock
- Popular freeware to do this: Dimension 4

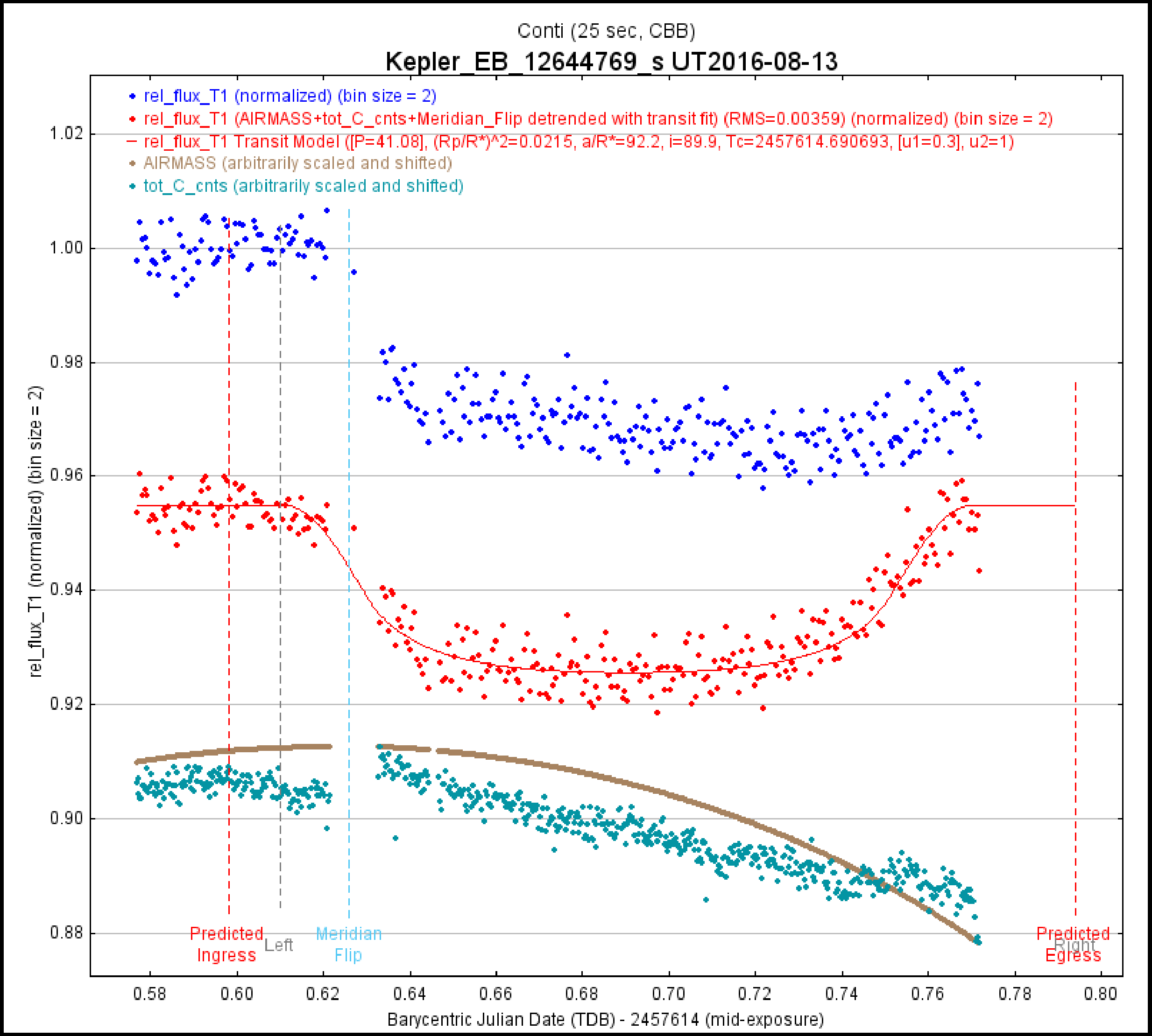


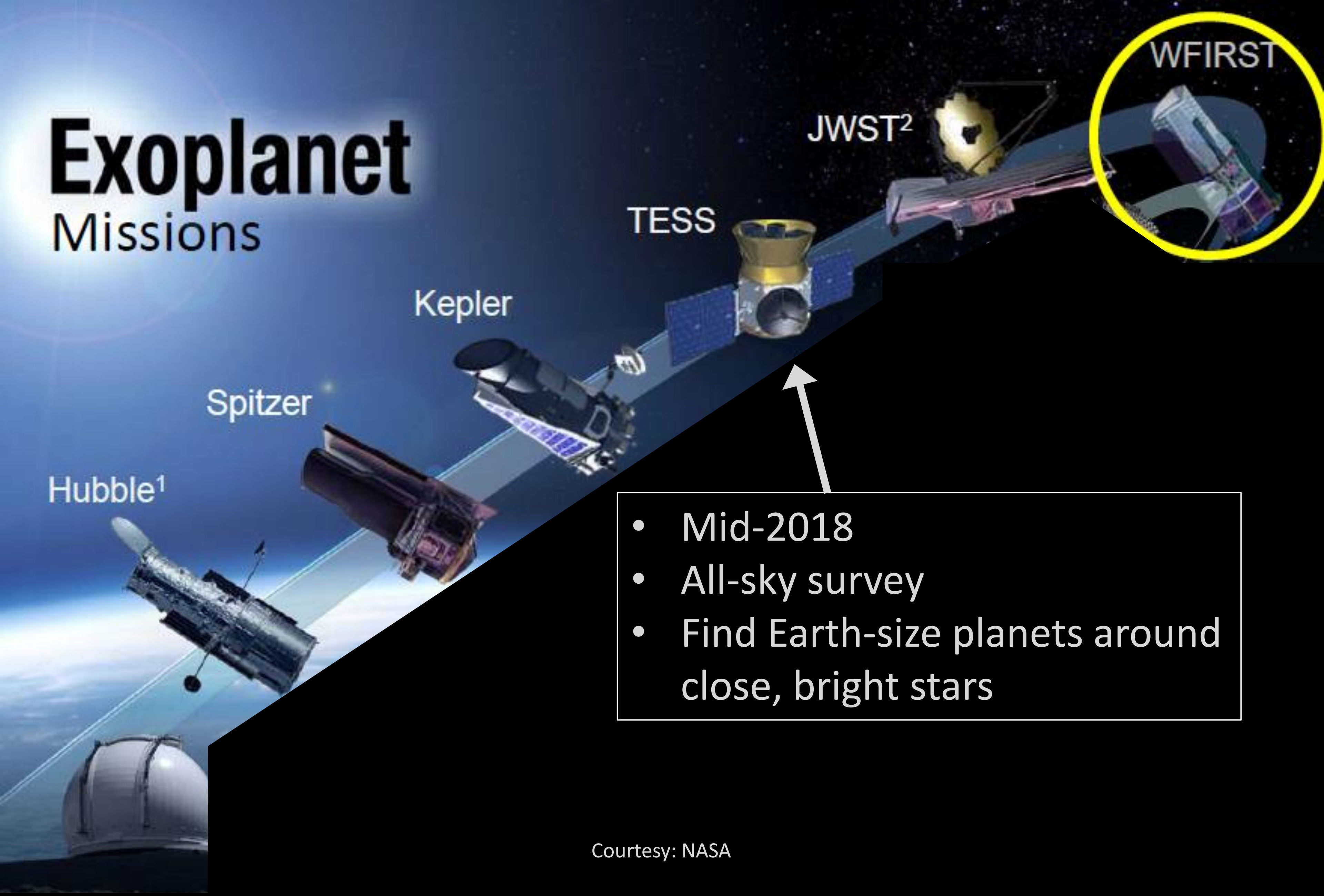


The Result:
A Well-Fitted Exoplanet Light Curve



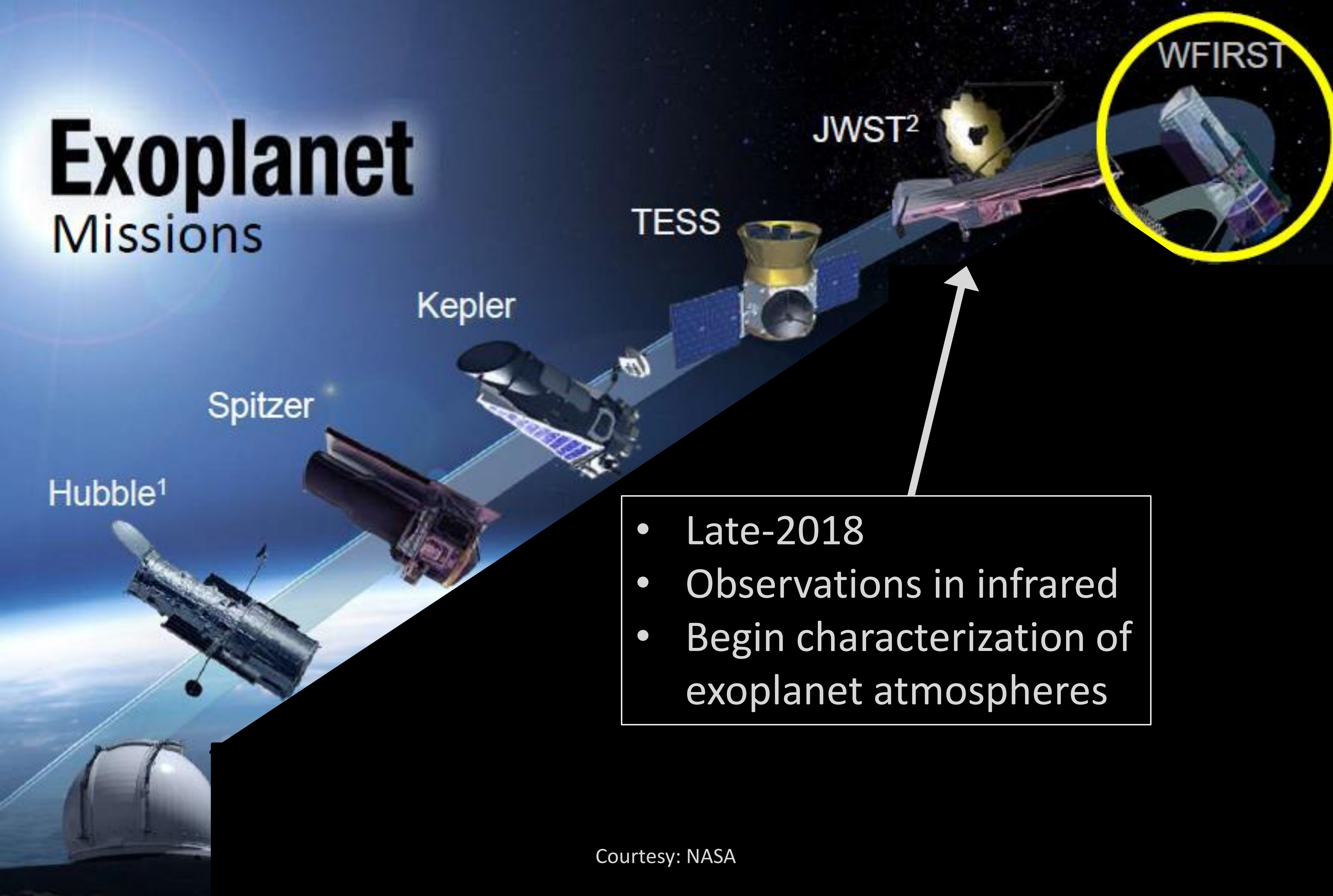
An Eclipsing Binary Light Curve





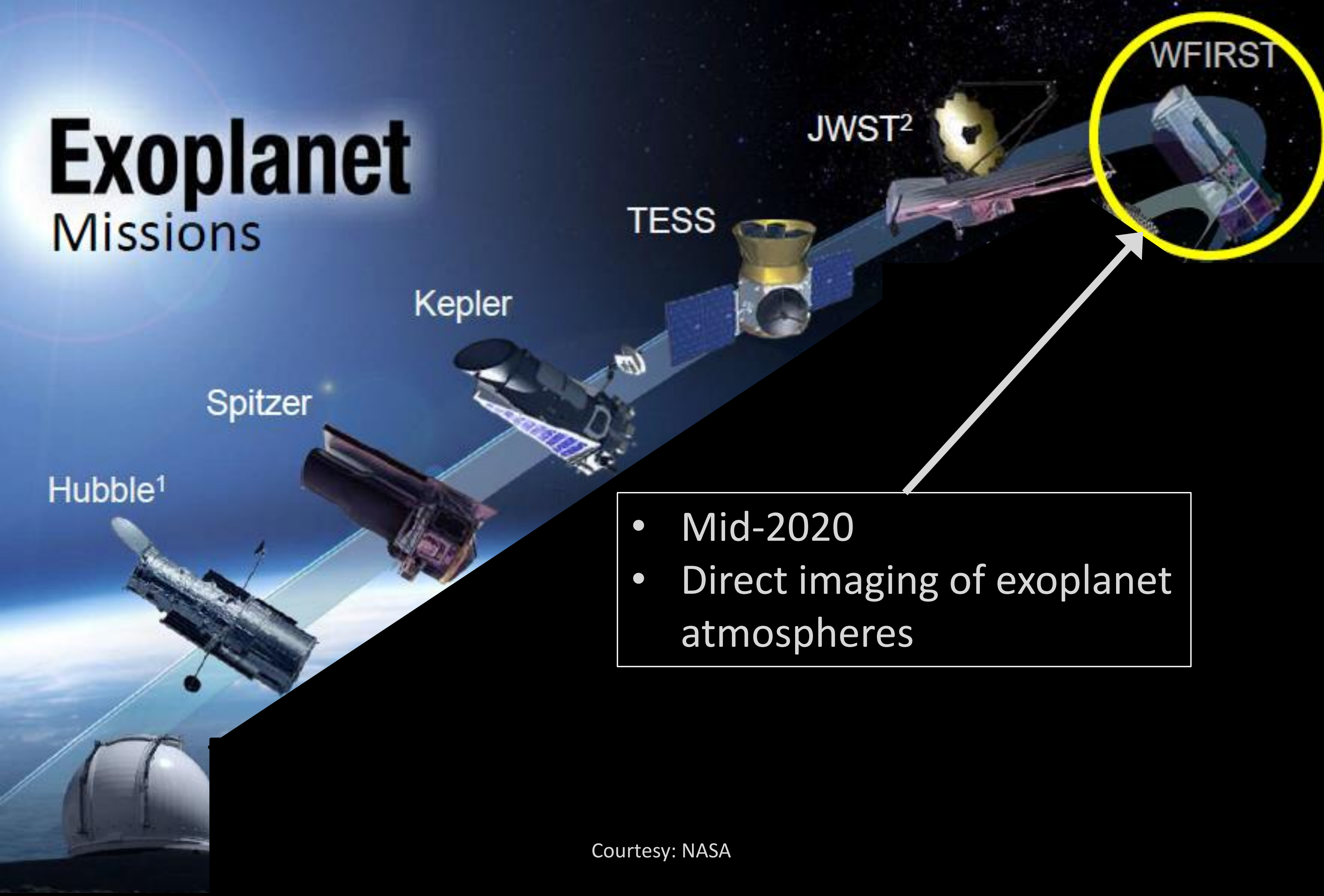
- Mid-2018
- All-sky survey
- Find Earth-size planets around close, bright stars

Courtesy: NASA



- Late-2018
- Observations in infrared
- Begin characterization of exoplanet atmospheres

Courtesy: NASA



- Mid-2020
- Direct imaging of exoplanet atmospheres

Courtesy: NASA

Opportunities for Contributions To Exoplanet Research

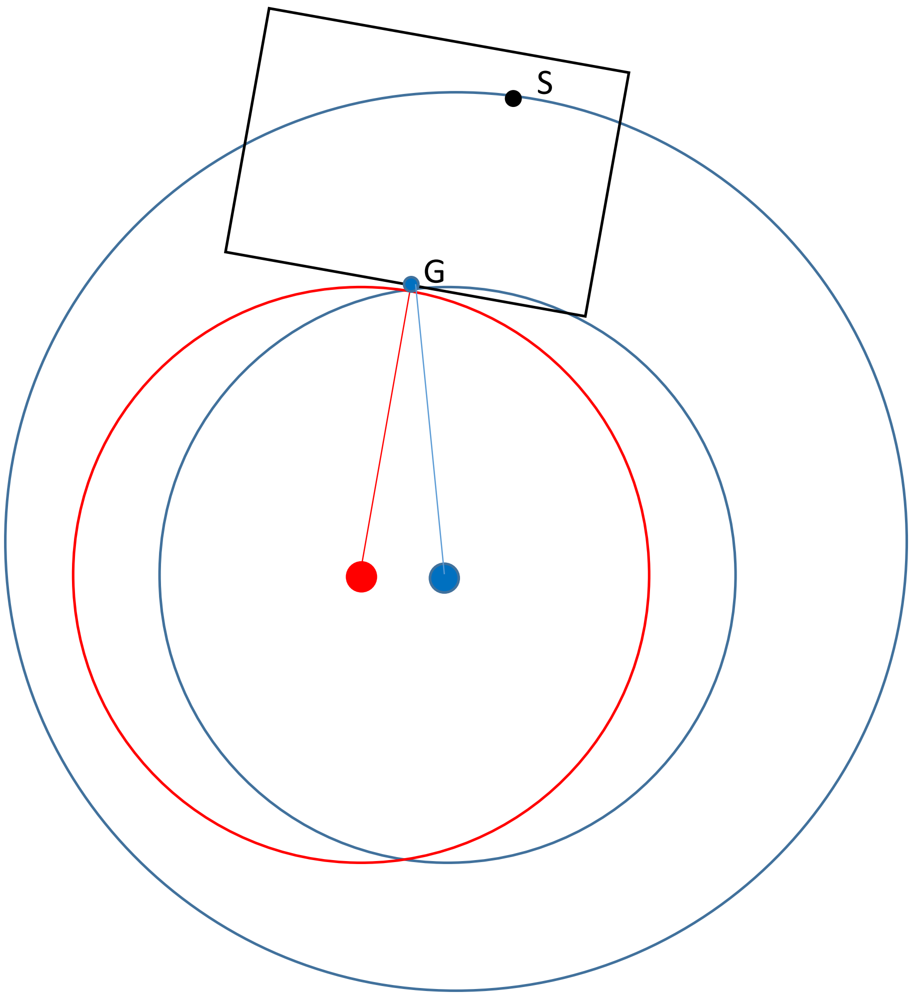
- Confirm new exoplanets – the KELT program
- Refine information about known exoplanets – the Hubble collaboration
- Help determine Transit Timing Variations – the ETD project
- Conduct follow-up, ground-based observations for TESS

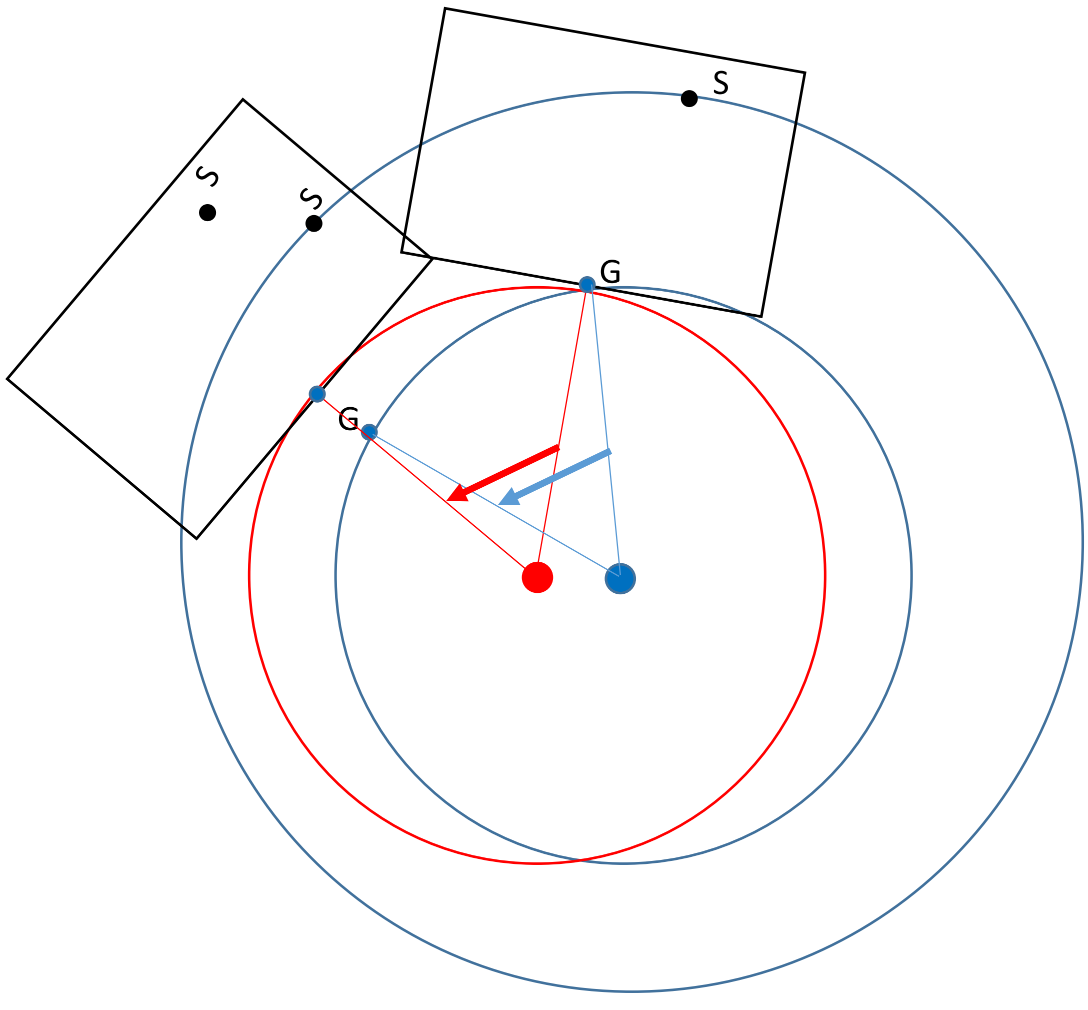
Summary

- Amateur astronomers are able to conduct exoplanet transit observations with amazing accuracy
- Their contribution to exoplanet research continues to be of value to professional astronomers
- The need for such observations in the near future will continue to grow

Resources

1. A Practical Guide to Exoplanet Observing, Dennis M. Conti, http://astrodennis.com
2. Exoplanet Observing for Amateurs, Second Edition (Plus), Bruce L. Gary
3. The Exoplanet Handbook, Michael Perryman
4. The Handbook of Astronomical Image Processing, Richard Berry and James Burnell (comes with AIP4WIN photometry software)
5. The AAVSO Guide to CCD Photometry
6. The AAVSO CCD Observing Manual


S
G


S
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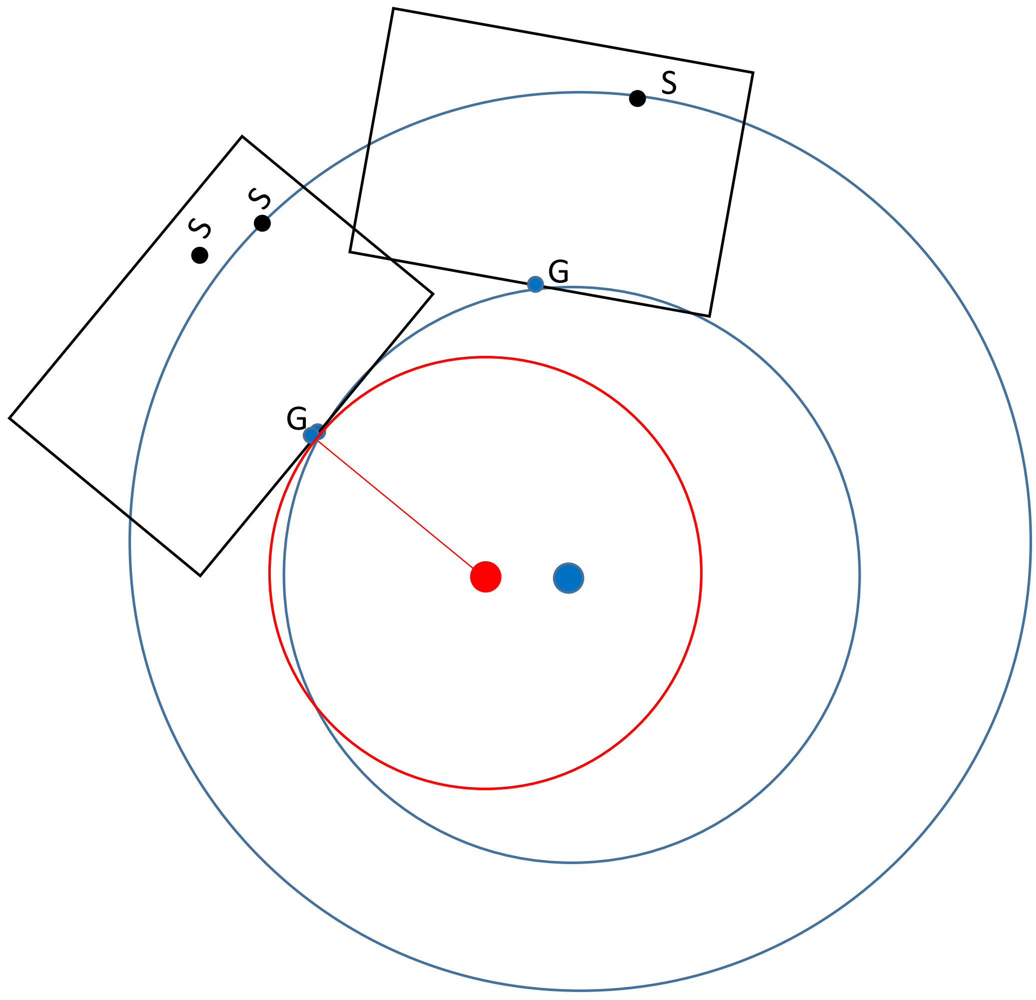

S
S
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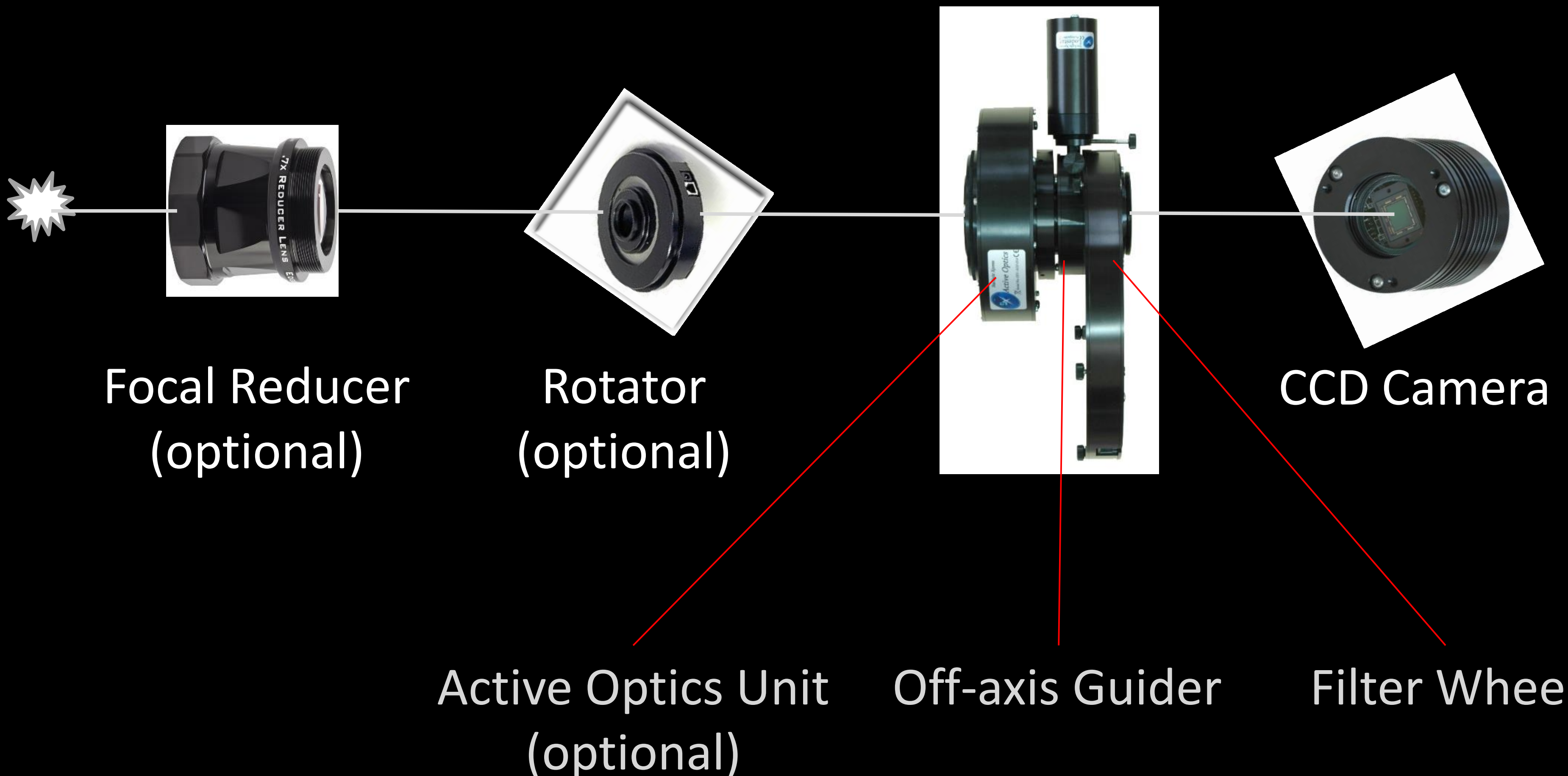
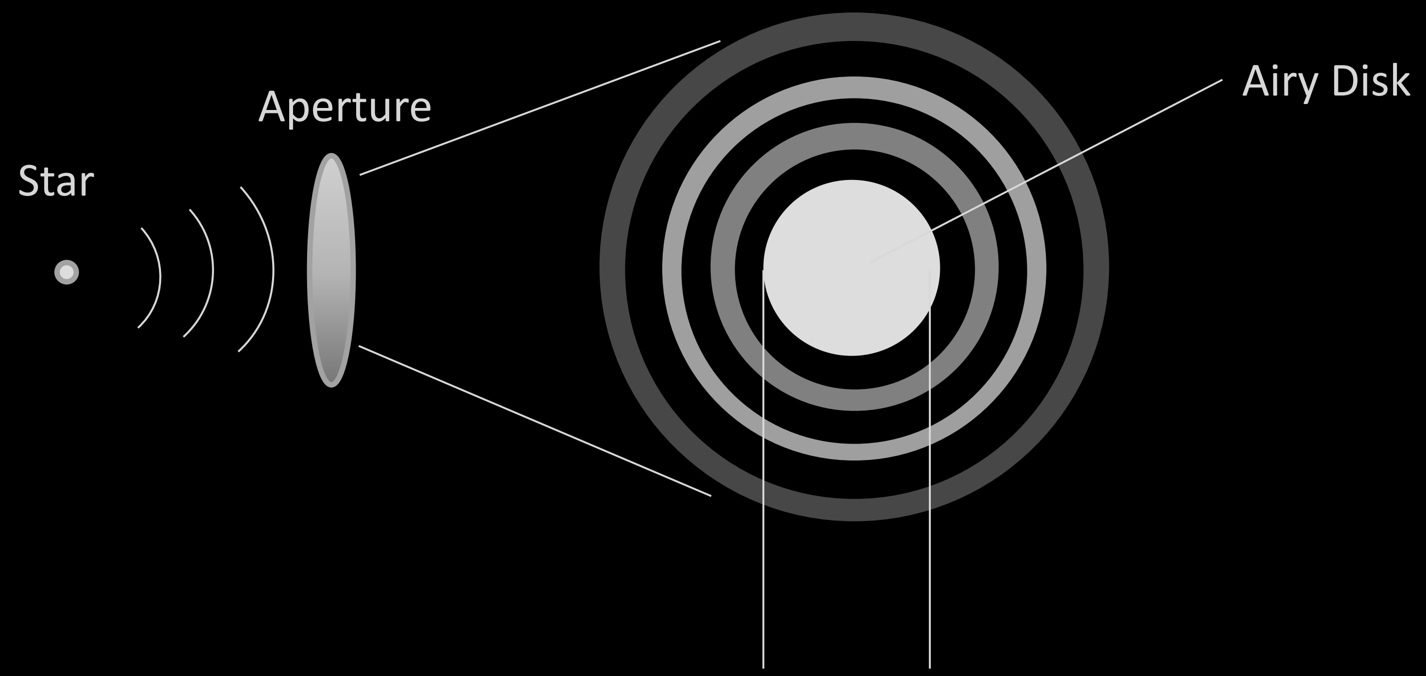
G

Addendum

Imaging Chain



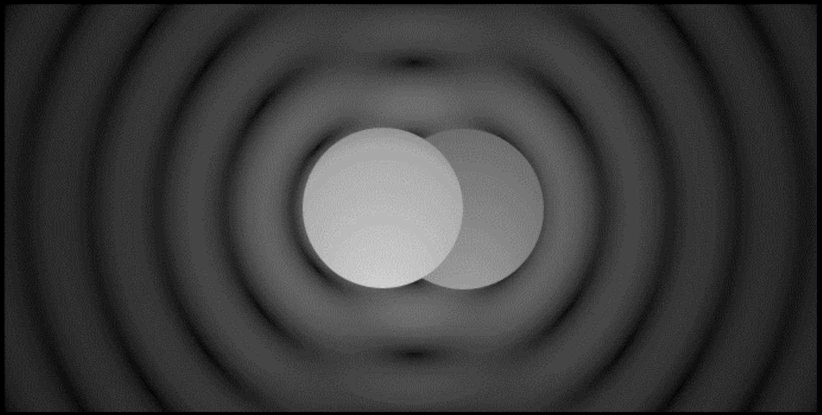
Point Spread Function (PSF)



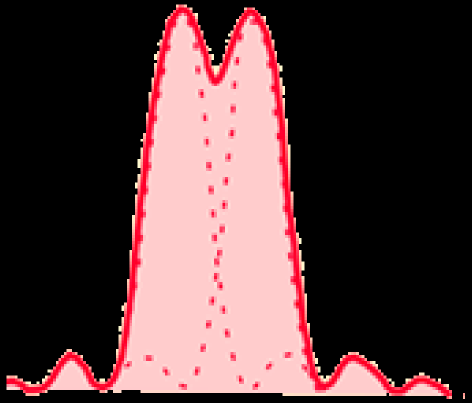
2.44*wavelength/aperture diameter (in radians)

For an 11” scope at 656 nm = 1.2 arcseconds

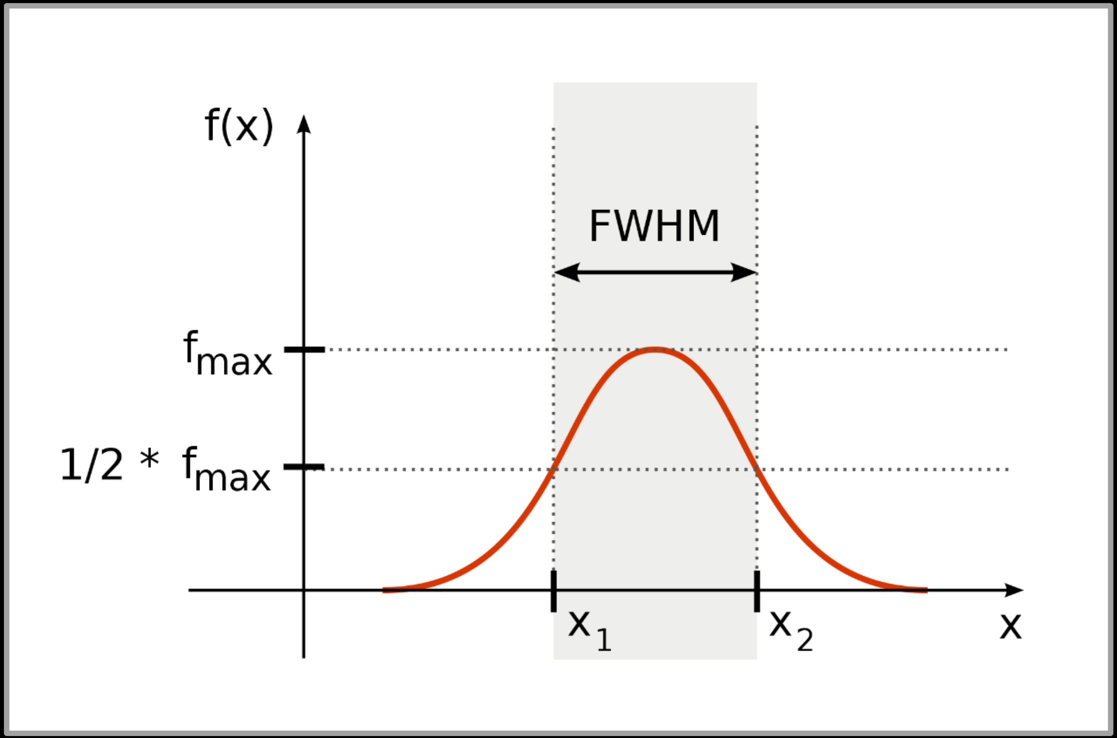
Resolution: Raleigh Criterion



By Spencer Bliven - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=31456019



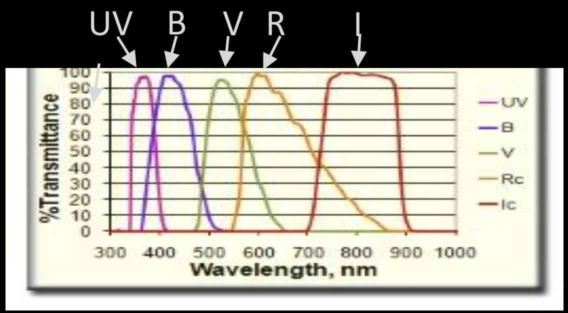
Full Width at Half Maximum (FWHM)



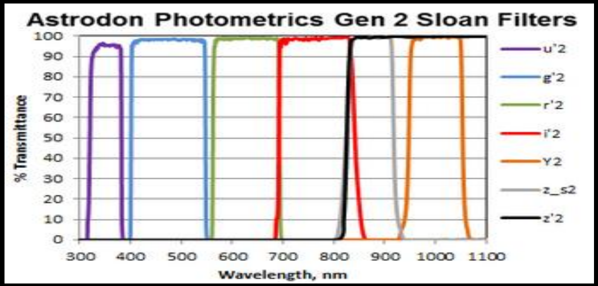
- Used as a measure of "seeing"

Bandpass Filters

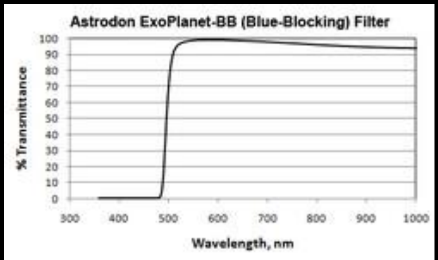
- Standard photometric filters (preferred for exoplanet work):
  - Johnson-Cousins:



  - Sloan Digital Sky Survey (SDSS):

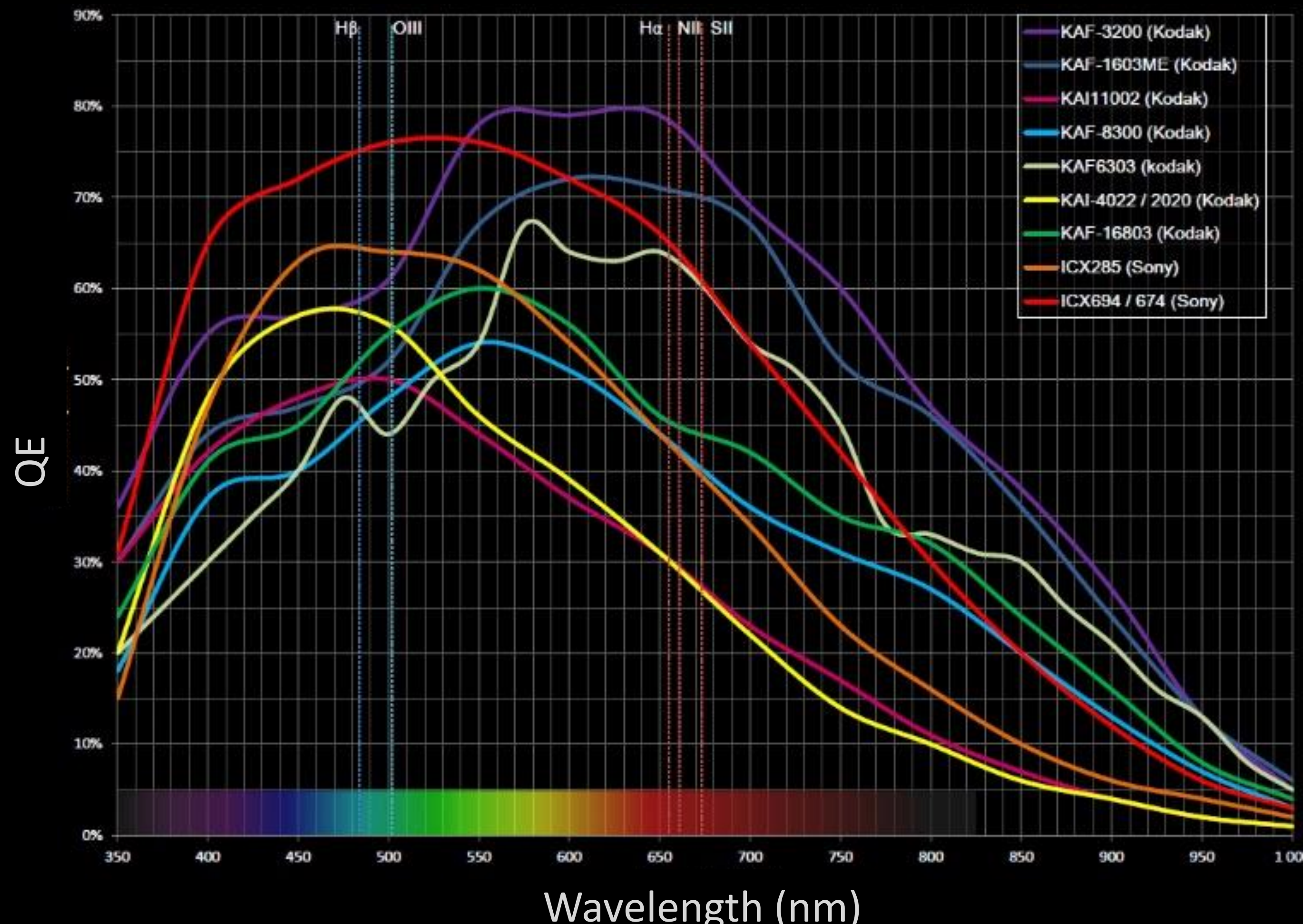


  - "Exoplanet" Filter:
    (Clear Blue Blocking)



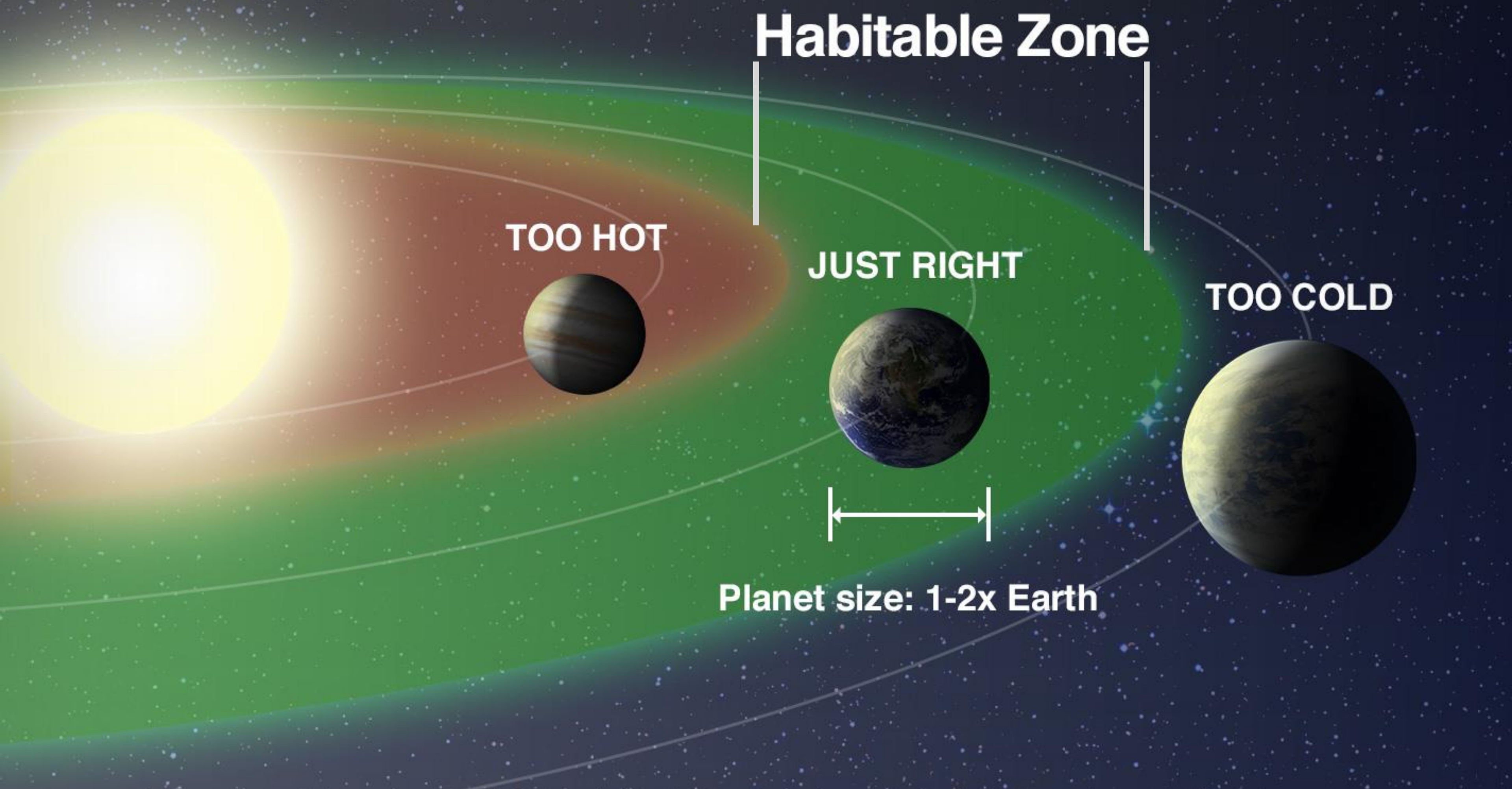
Courtesy: Astrodon

Quantum Efficiency (QE) of a CCD Detector



By Philippe Bernhard

The Kepler spacecraft has now confirmed that Earth-size planets exist in the habitable zone!



Courtesy: NASA

By the Numbers
(as of 03/07/17)

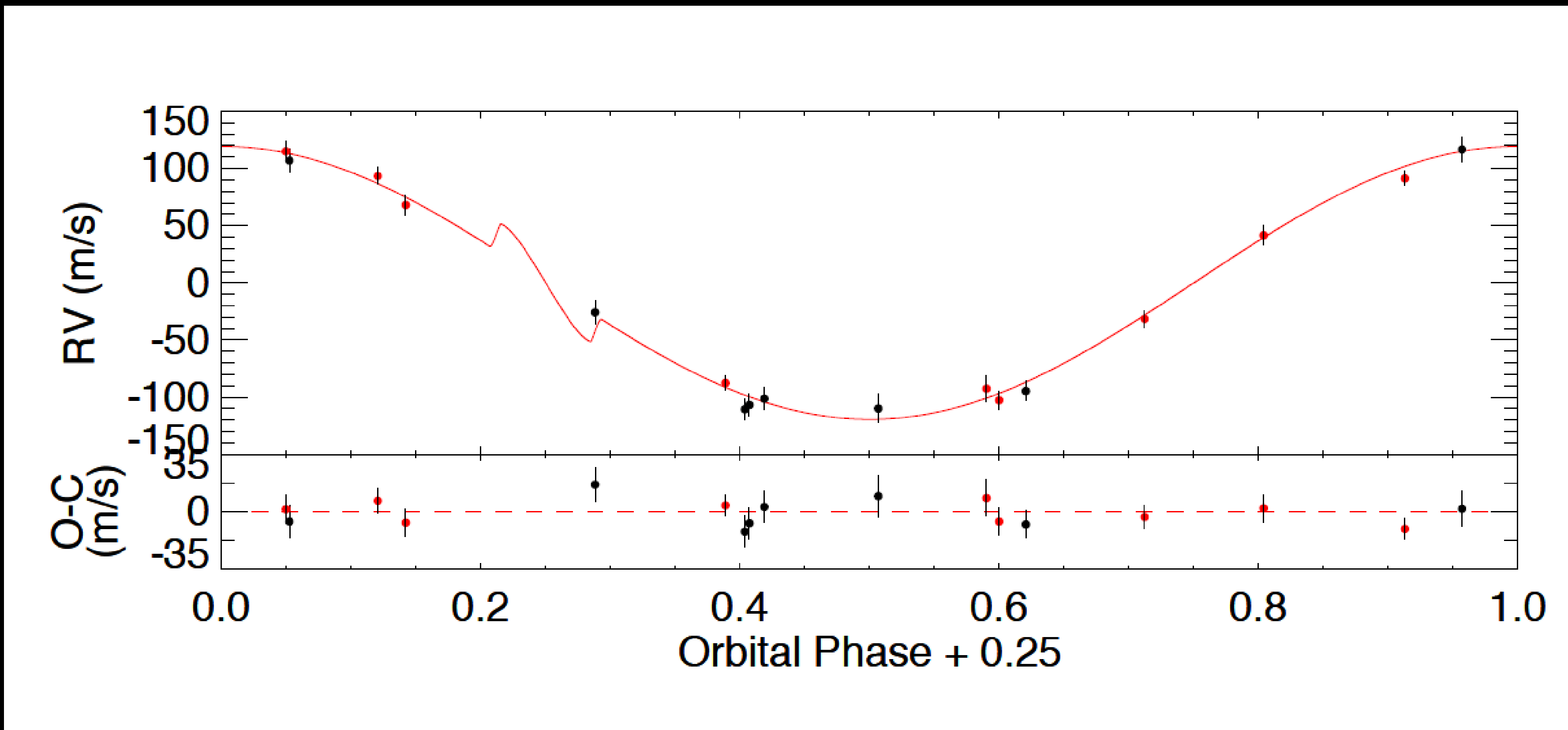
- 3,458 confirmed exoplanets
- 2,416 unconfirmed candidates
- 297 candidates in the habitable zone

What is Driving Us?

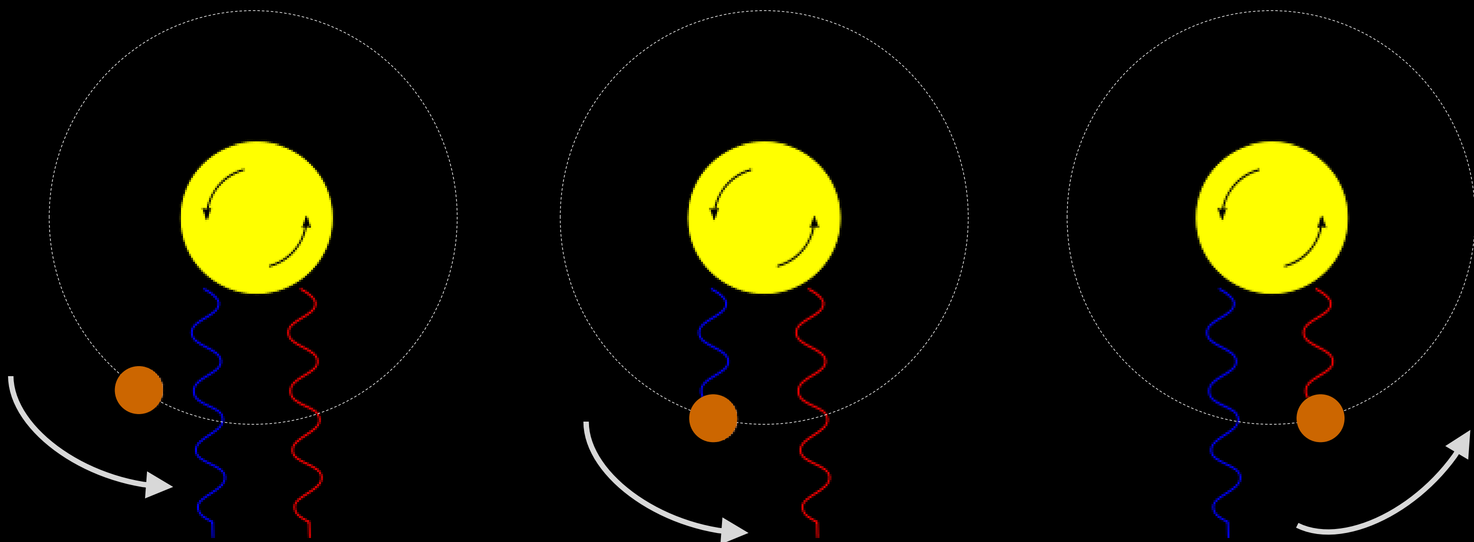
- How do planets form?
- How was our solar system formed?

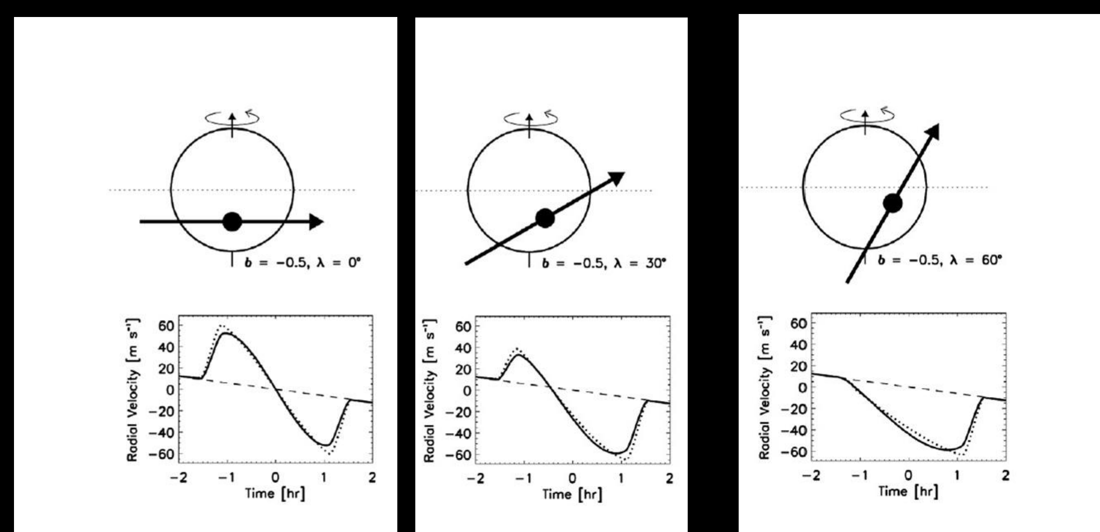
The ultimate goal:
detect biomarkers in the atmosphere of planets in the habitable zone

Radial Velocity Method



The Rossiter-McLaughlin Effect

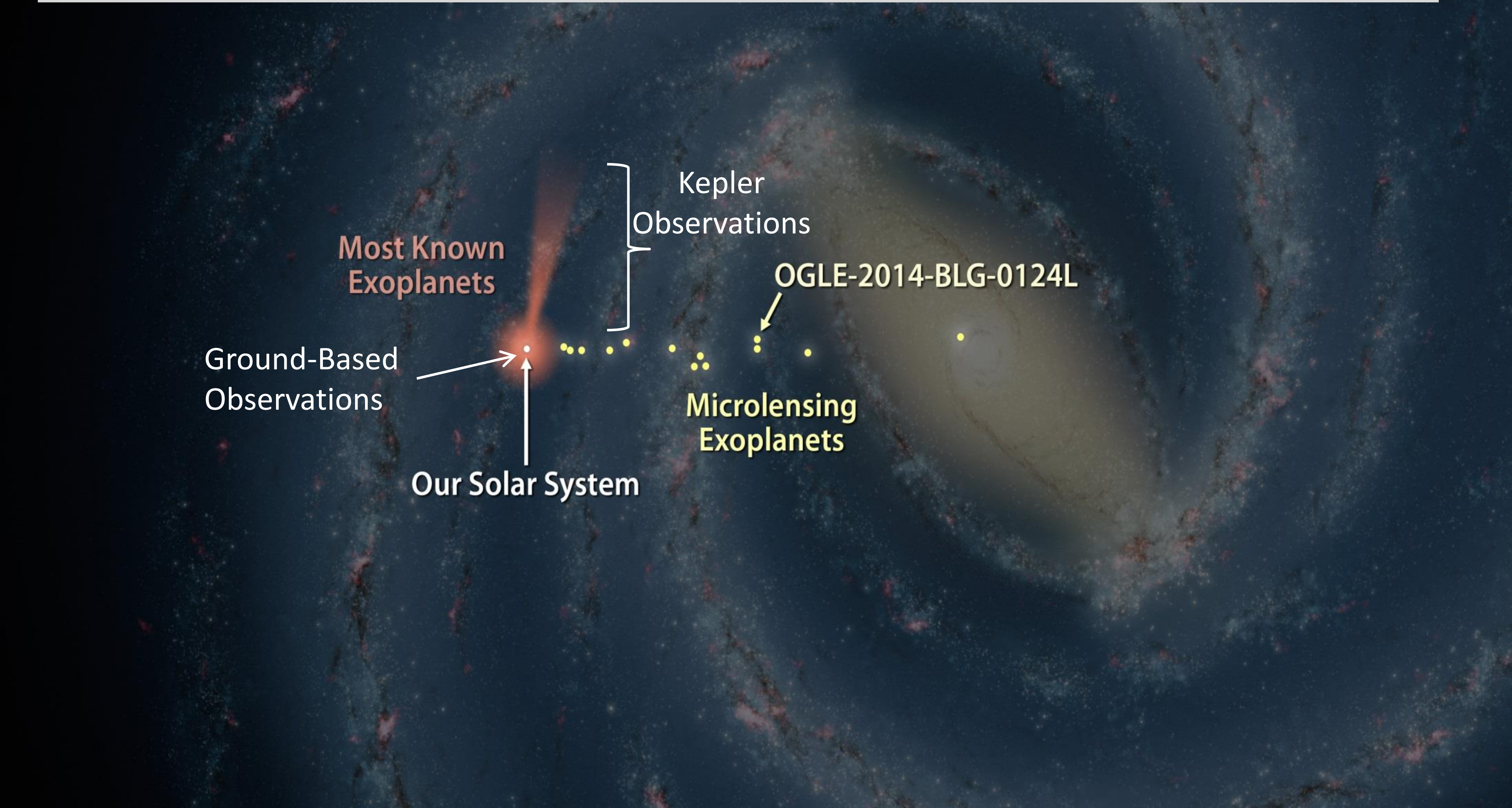




Exoplanet Information

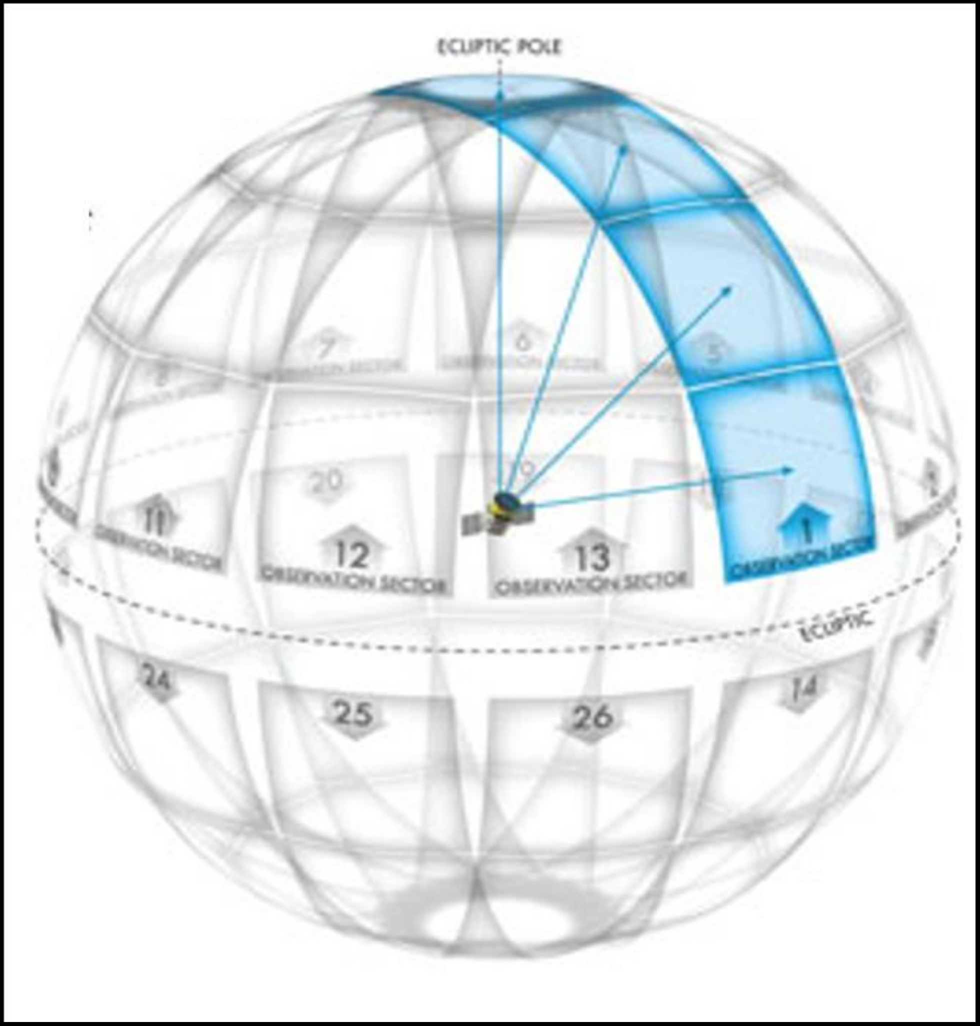
- NASA Exoplanet Archive: http://exoplanetarchive.ipac.caltech.edu/cgi-bin/TransitView/nph-visibletbls?dataset=transits
- Exoplanet Transit Database (ETD) Website): http://var2.astro.cz/ETD/predictions.php
- Exoplanets.org Website: http://exoplanets.org

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

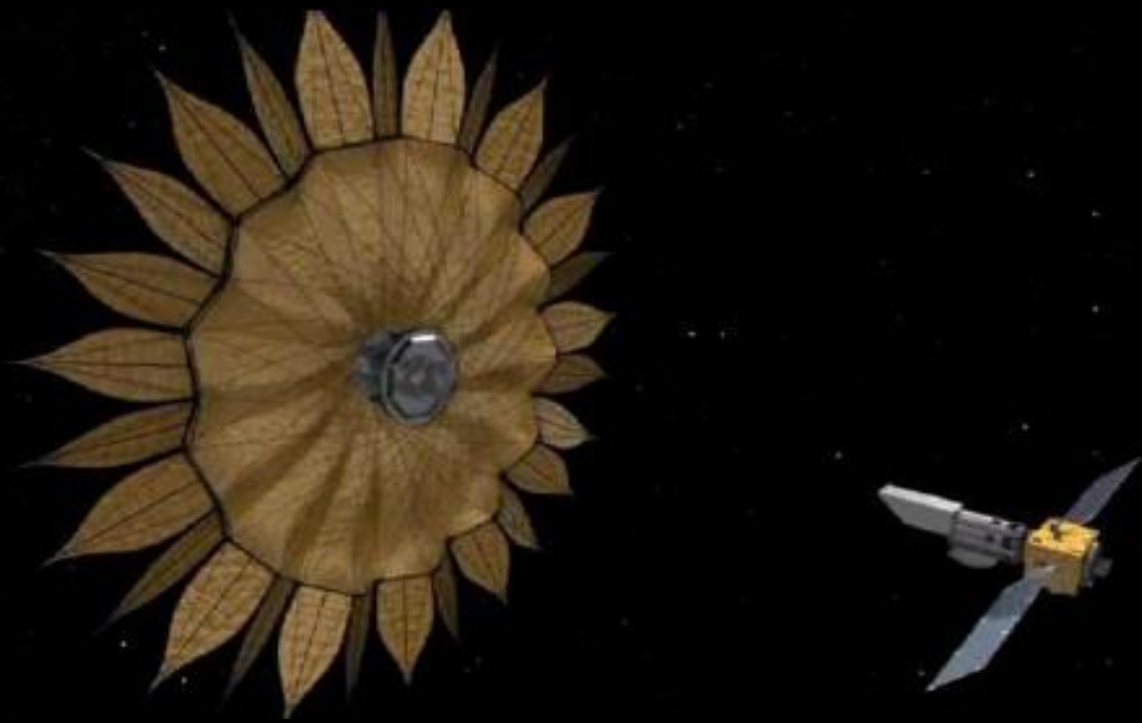


Courtesy NASA/JPL-Caltech

TESS Survey


ECLIPTIC POLE
20
11
OBSERVATION SECTOR
12
OBSERVATION SECTOR
13
OBSERVATION SECTOR
1
OBSERVATION SECTOR
ECLIPTIC
24
25
26
14

Starshade Technology



Courtesy: NASA