

# Direct Detection of Exoplanets with Polarimetry

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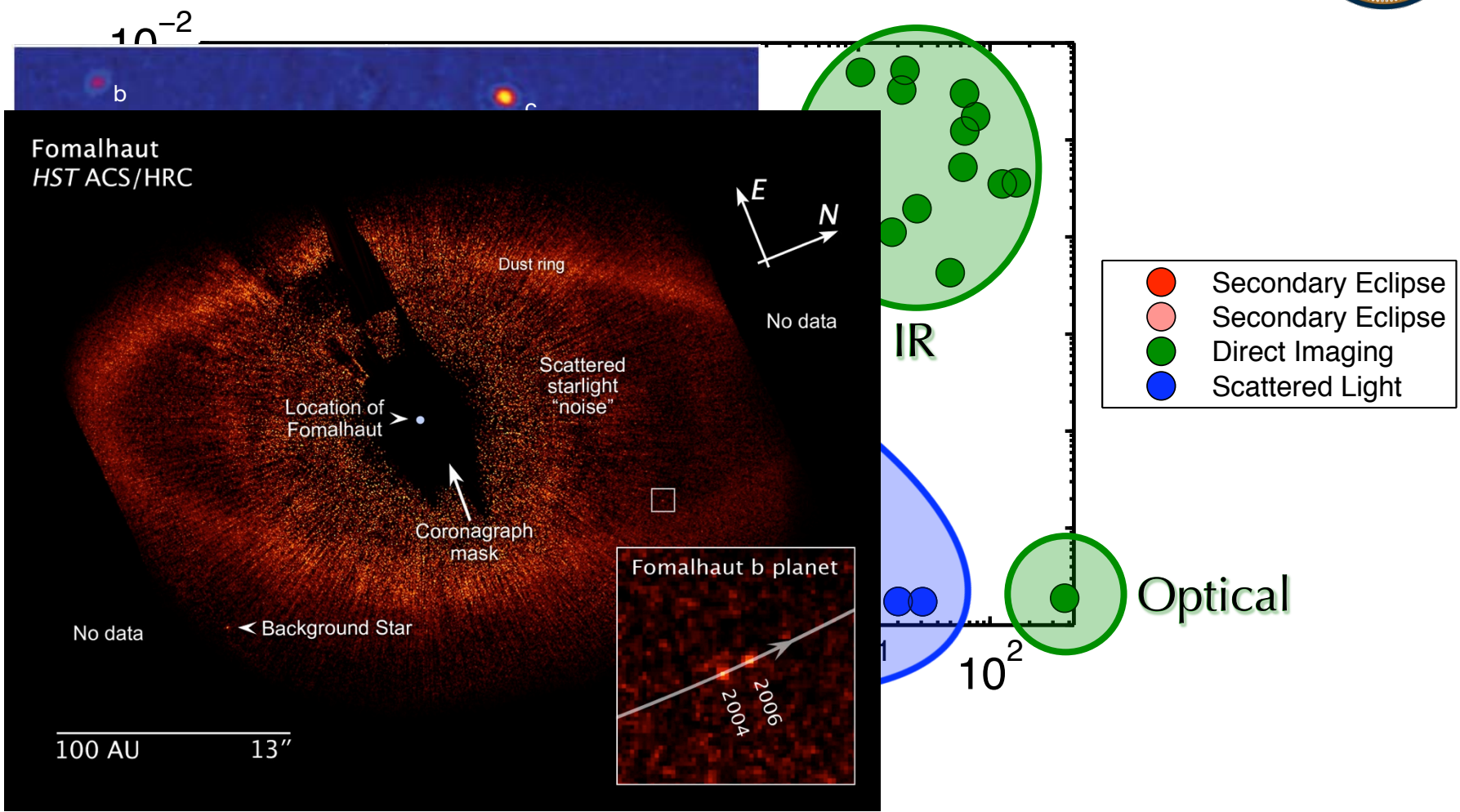
Sagan Fellow, UC Santa Cruz

Sagan Symposium: Nov. 9, 2012



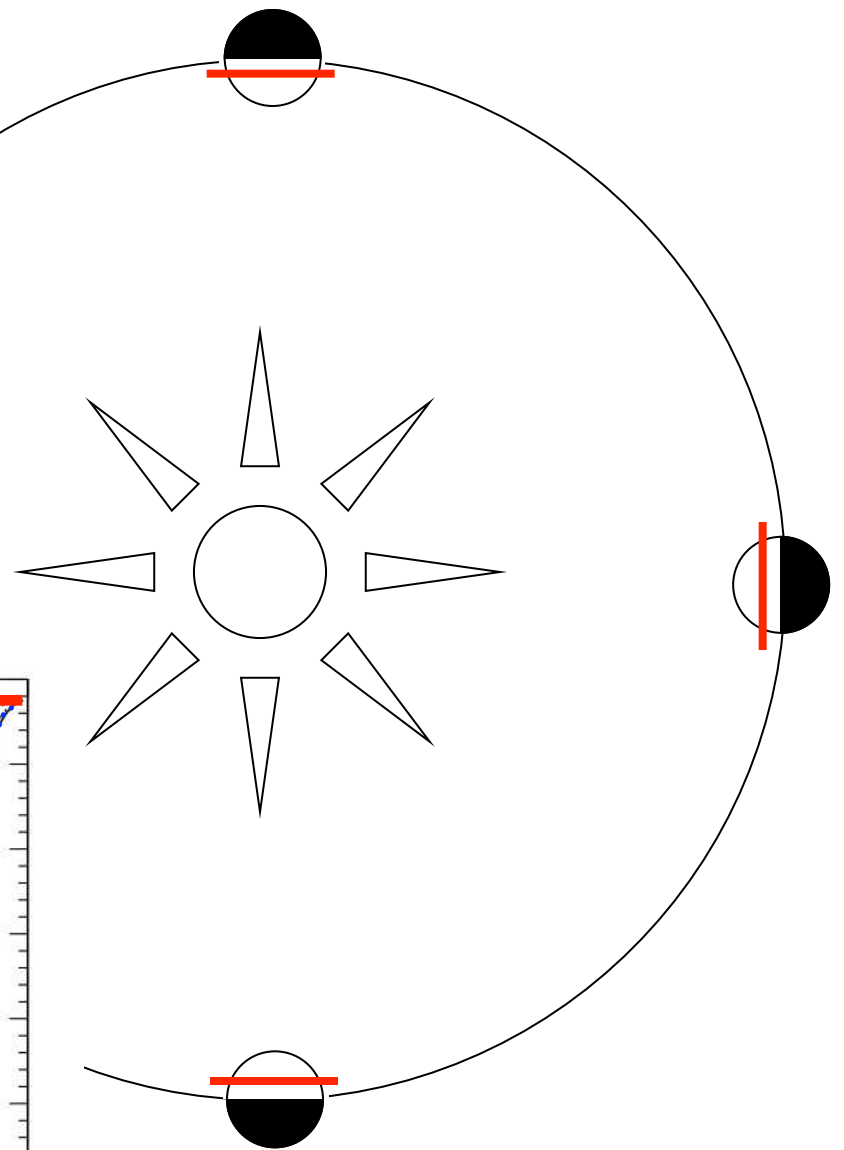
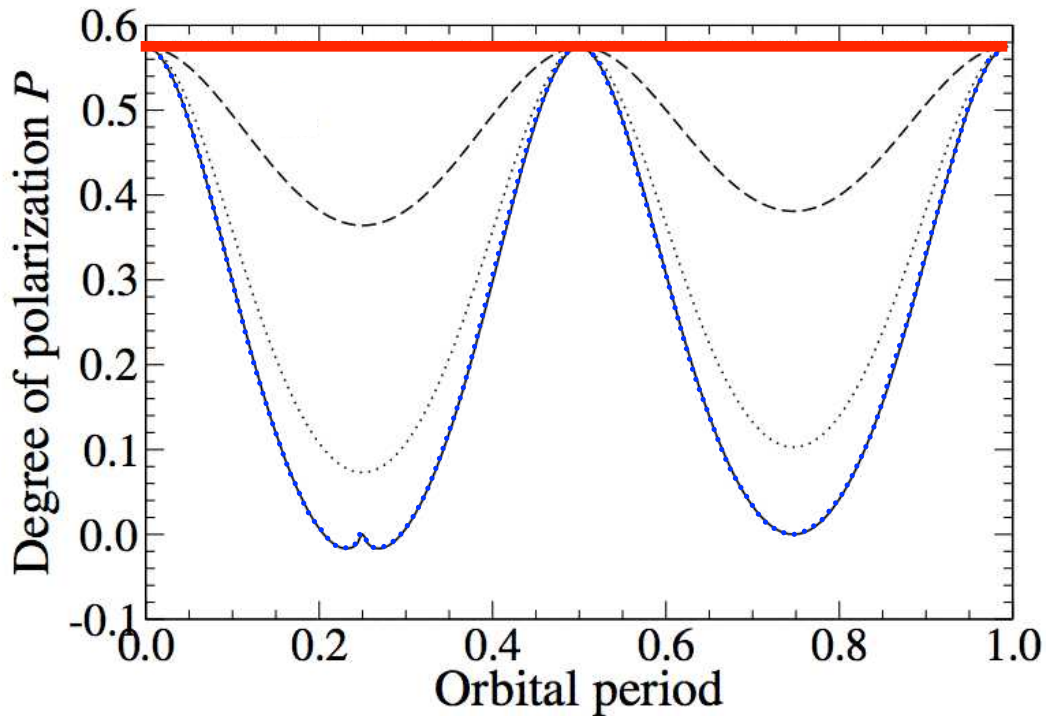


# Exoplanet Contrast



# Inclination from Polarimetry

Face-on



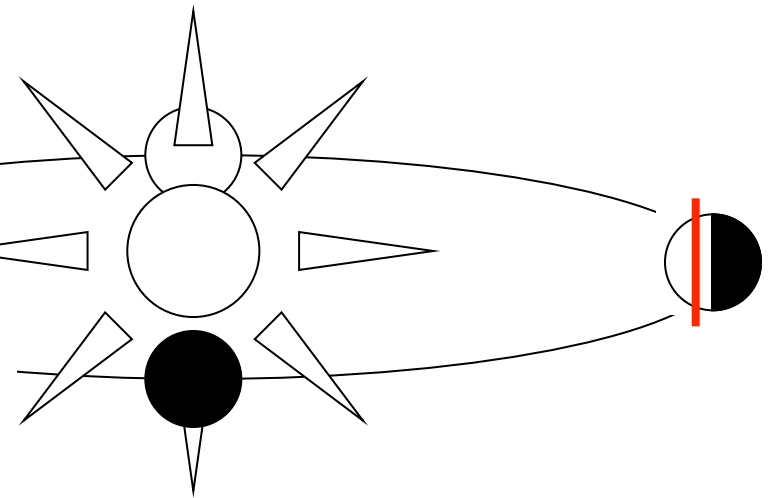
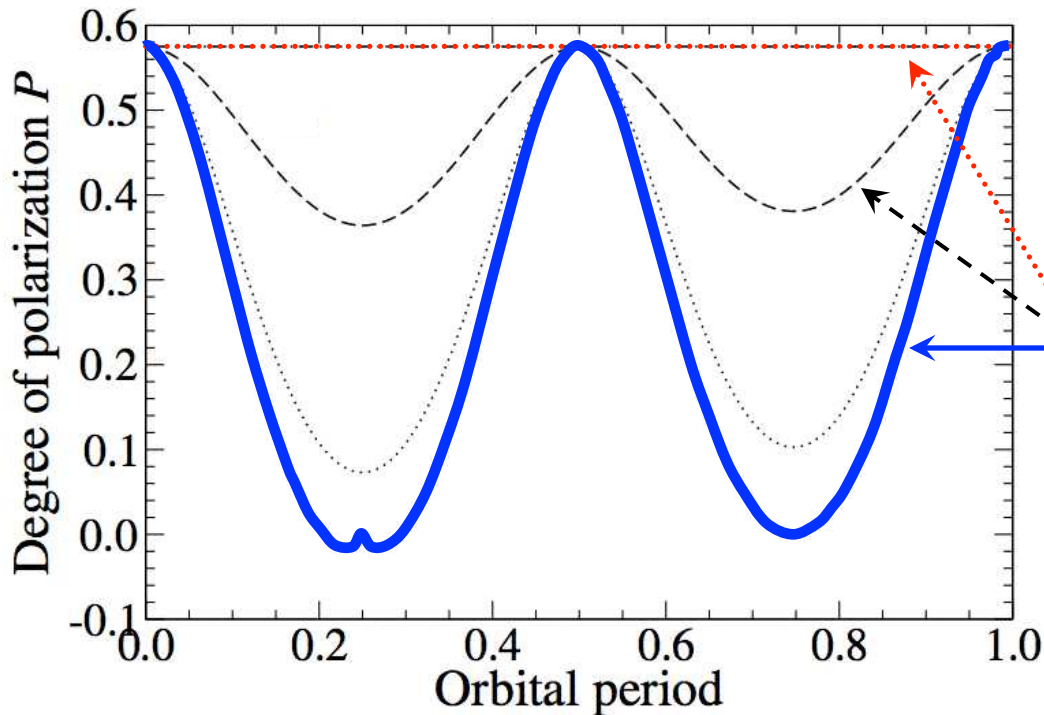
Stam et al. 2004



# Inclination from Polarimetry

$< 10^{-5}$  precision  
( $> 10^{10}$  photons)

Edge-on



Minimum  $P \Rightarrow$  Inclination

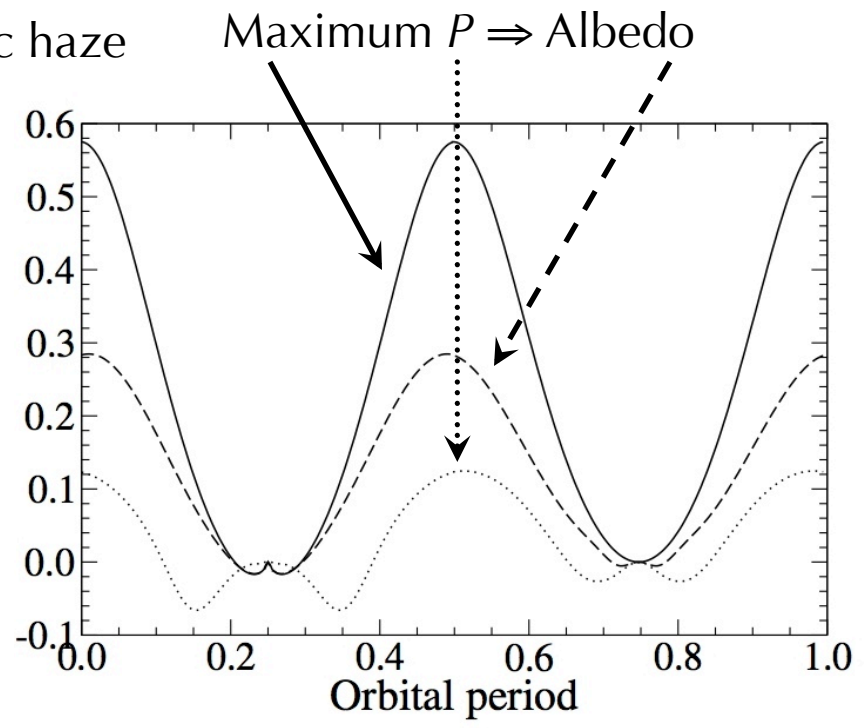
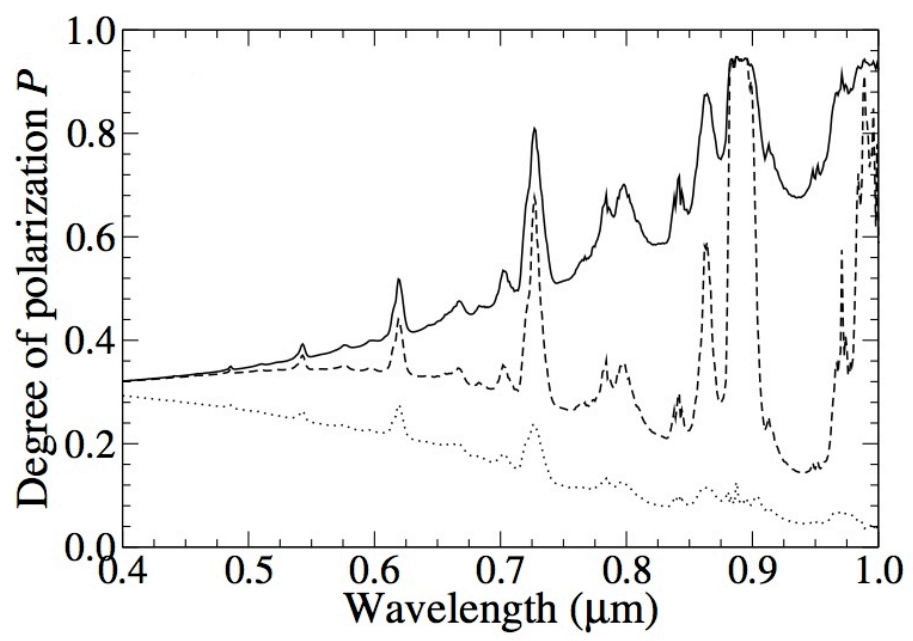
Stam et al. 2004





# Atmospheric Structure

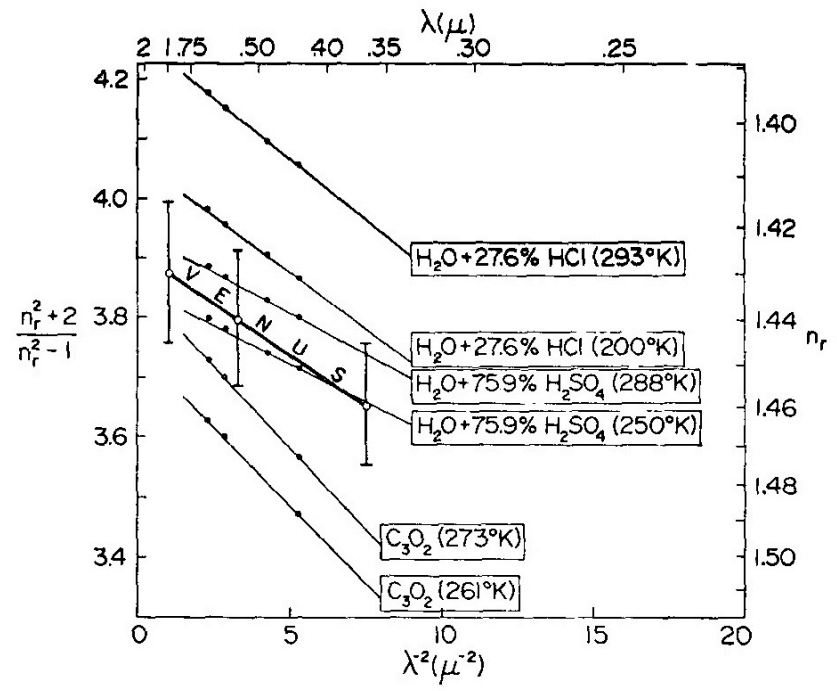
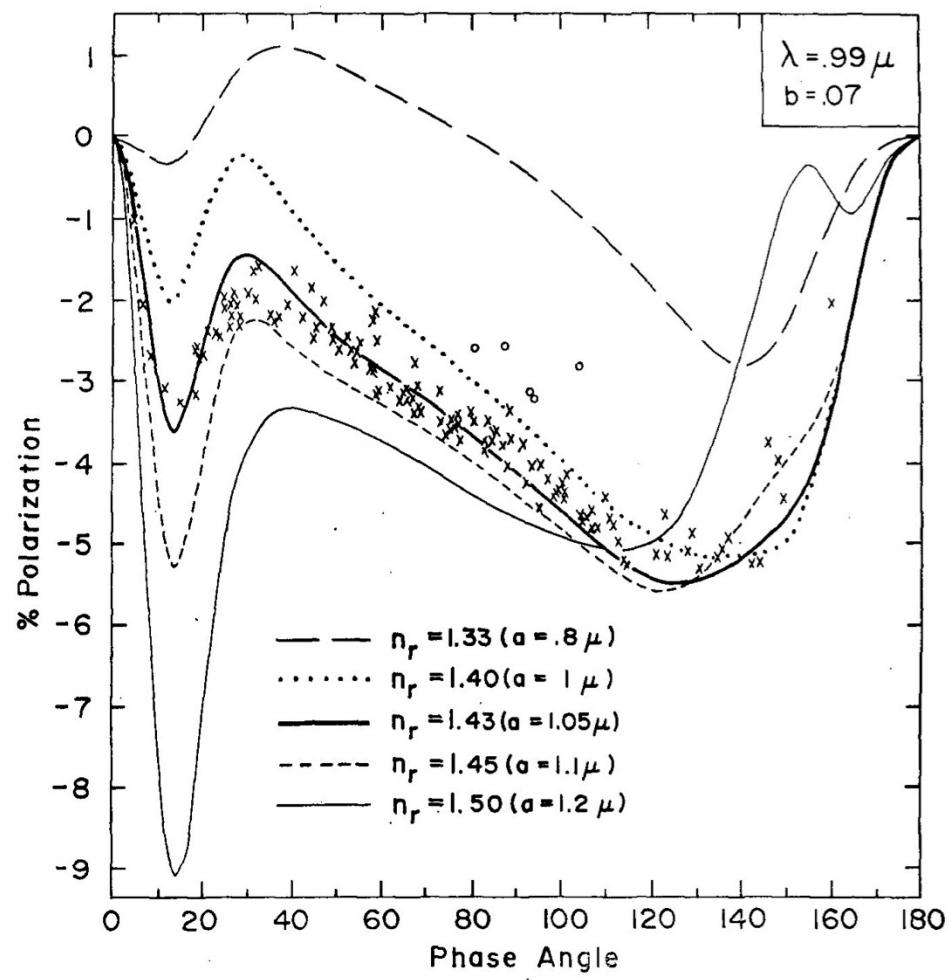
- Clear
- - - Tropospheric cloud
- ..... Tropospheric cloud + stratospheric haze



Stam et al. 2004



# Sulfuric Acid in Venus

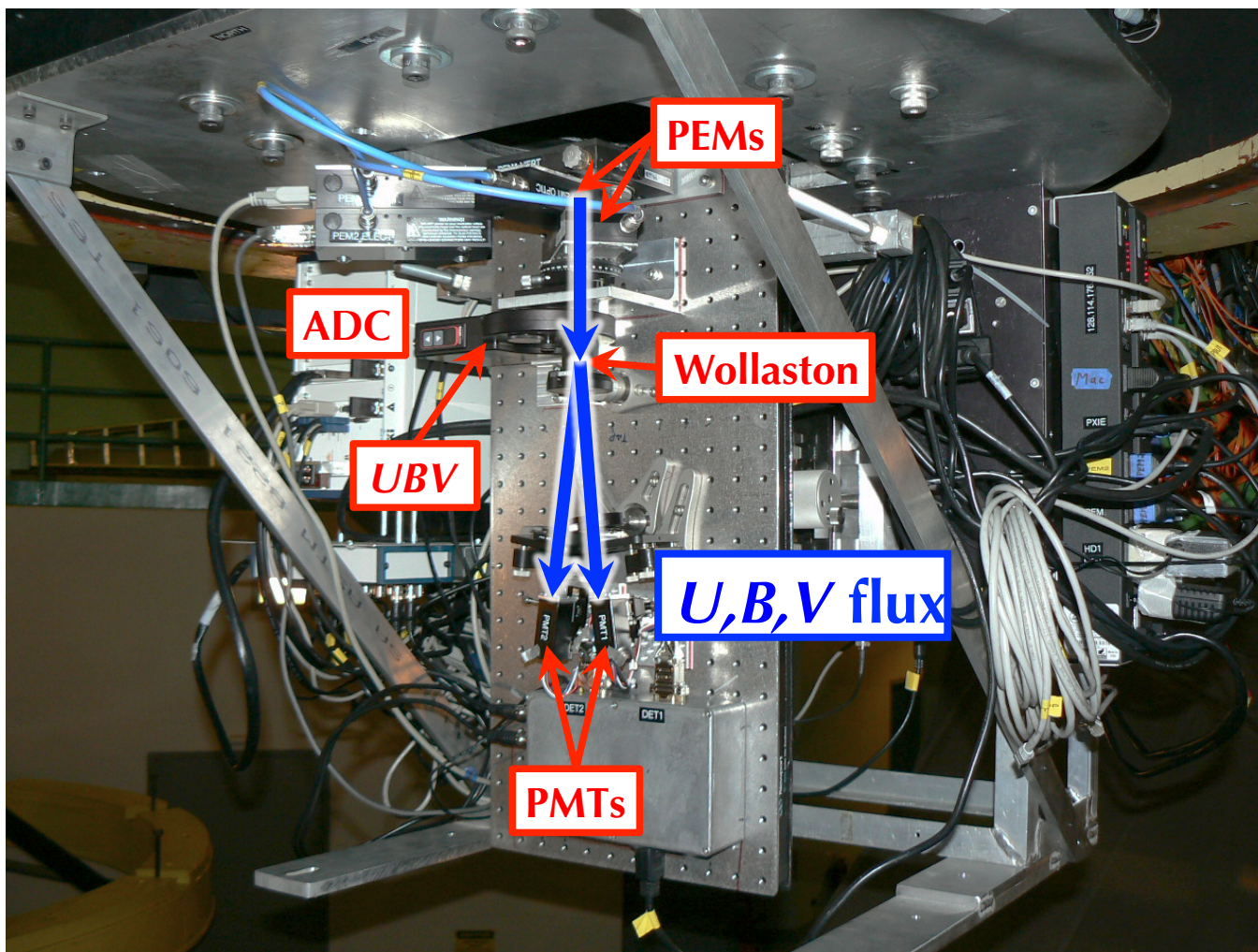


Coffeen & Gehrels 1969  
 Hansen & Hovenier 1974



# POLISH2

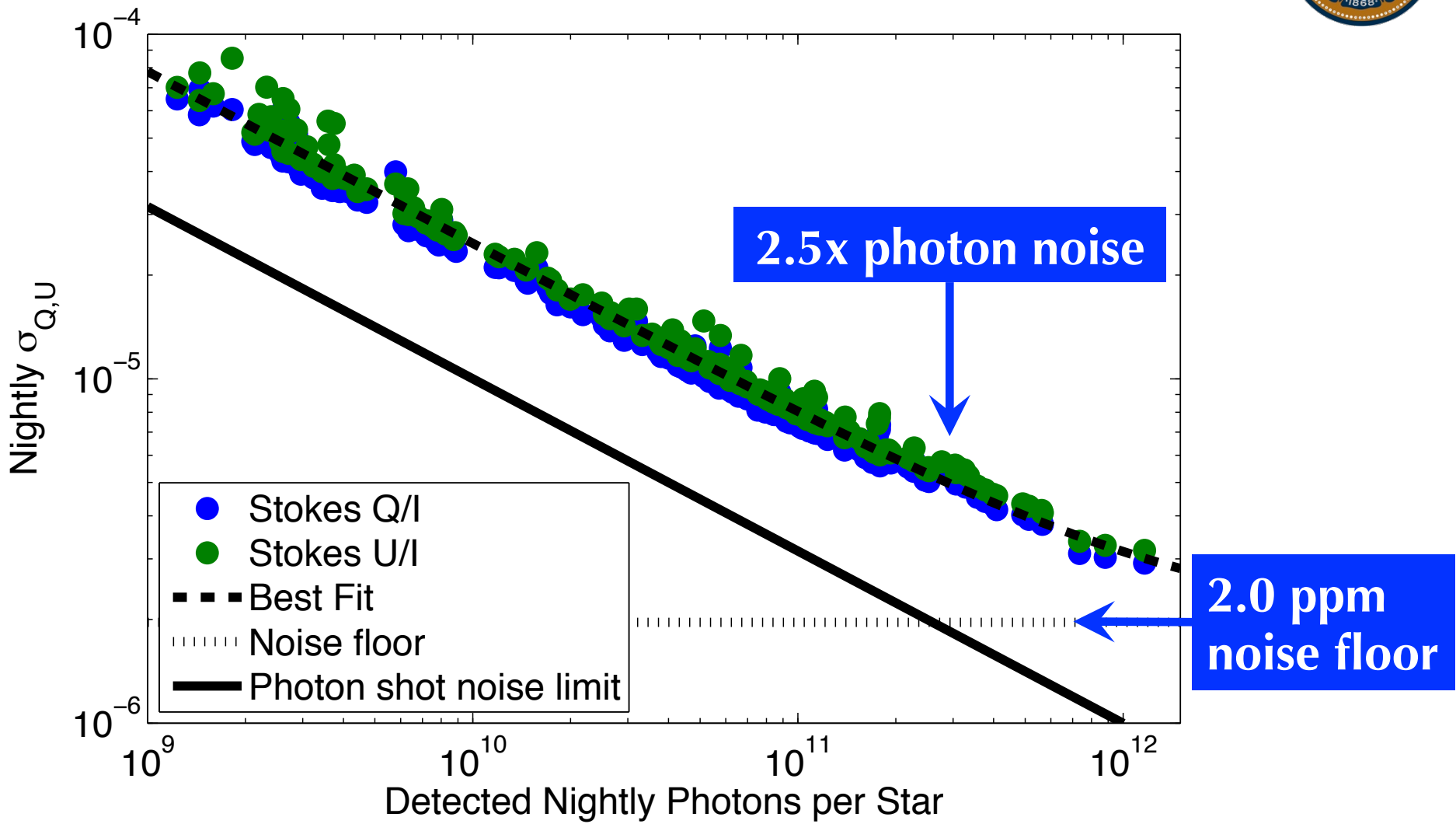
Wiktorowicz & Matthews, 2008, PASP, 120, 1282





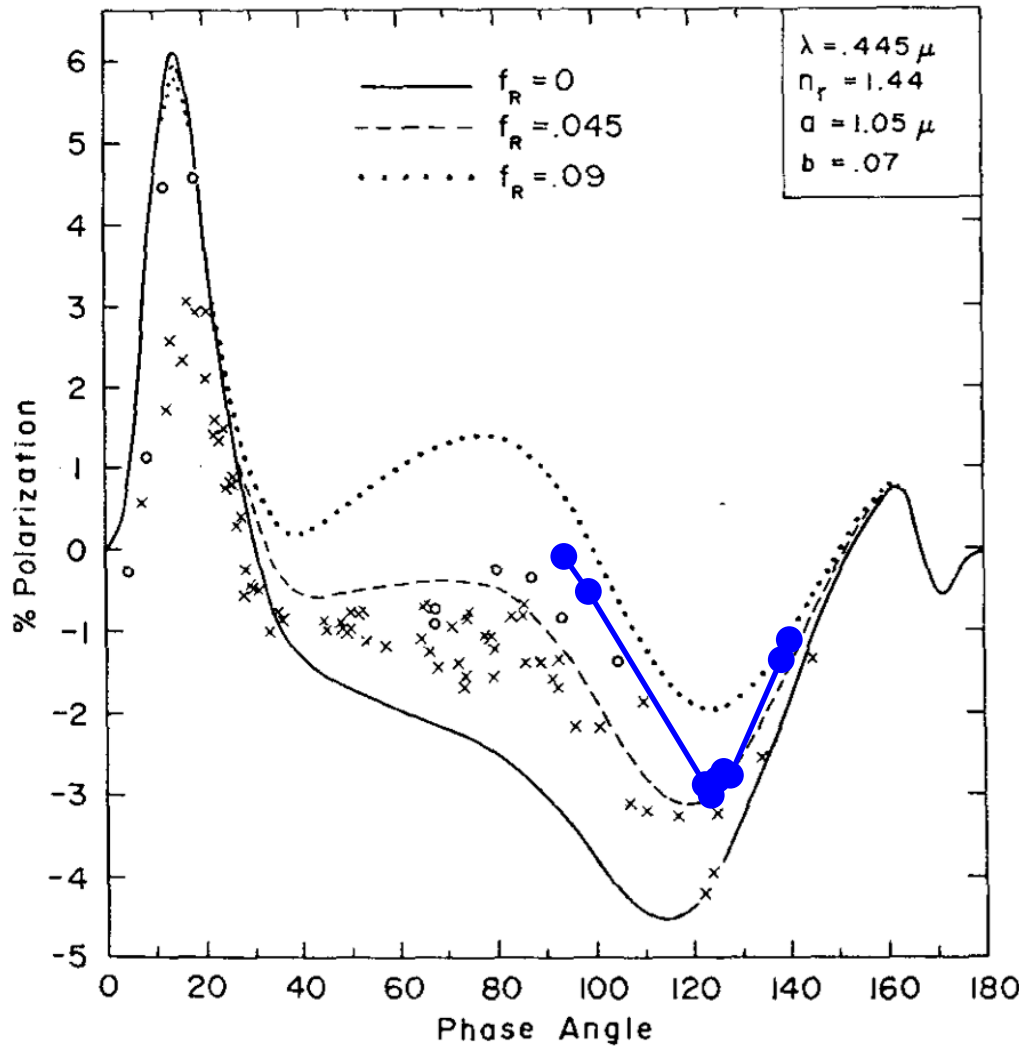


# POLISH2 Performance





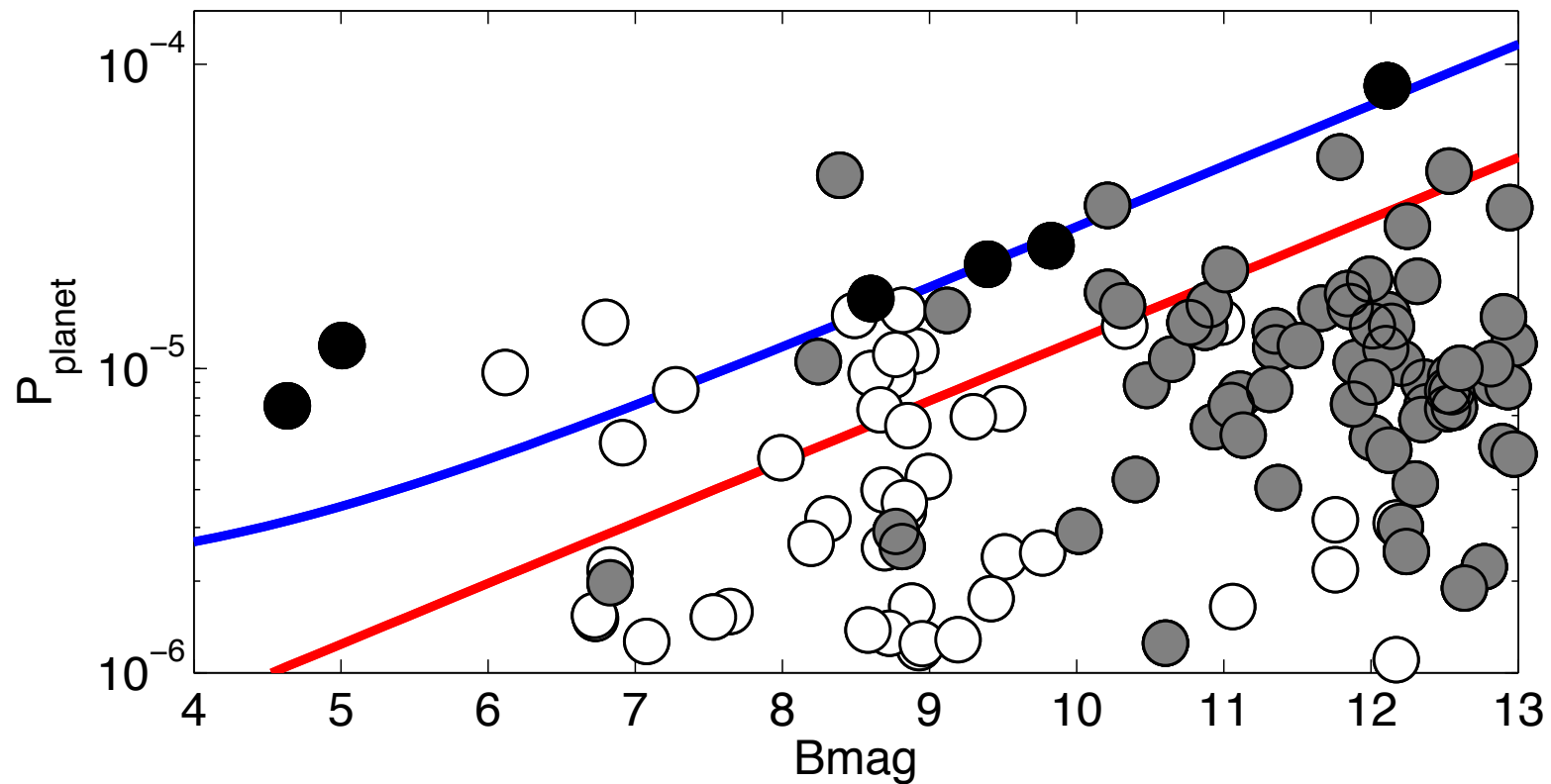
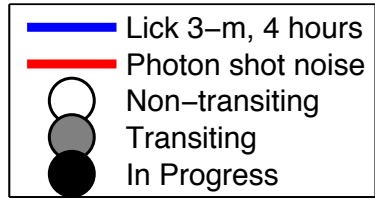
# Venus, *B* Band



Coffeen & Gehrels 1969  
 Hansen & Hovenier 1974



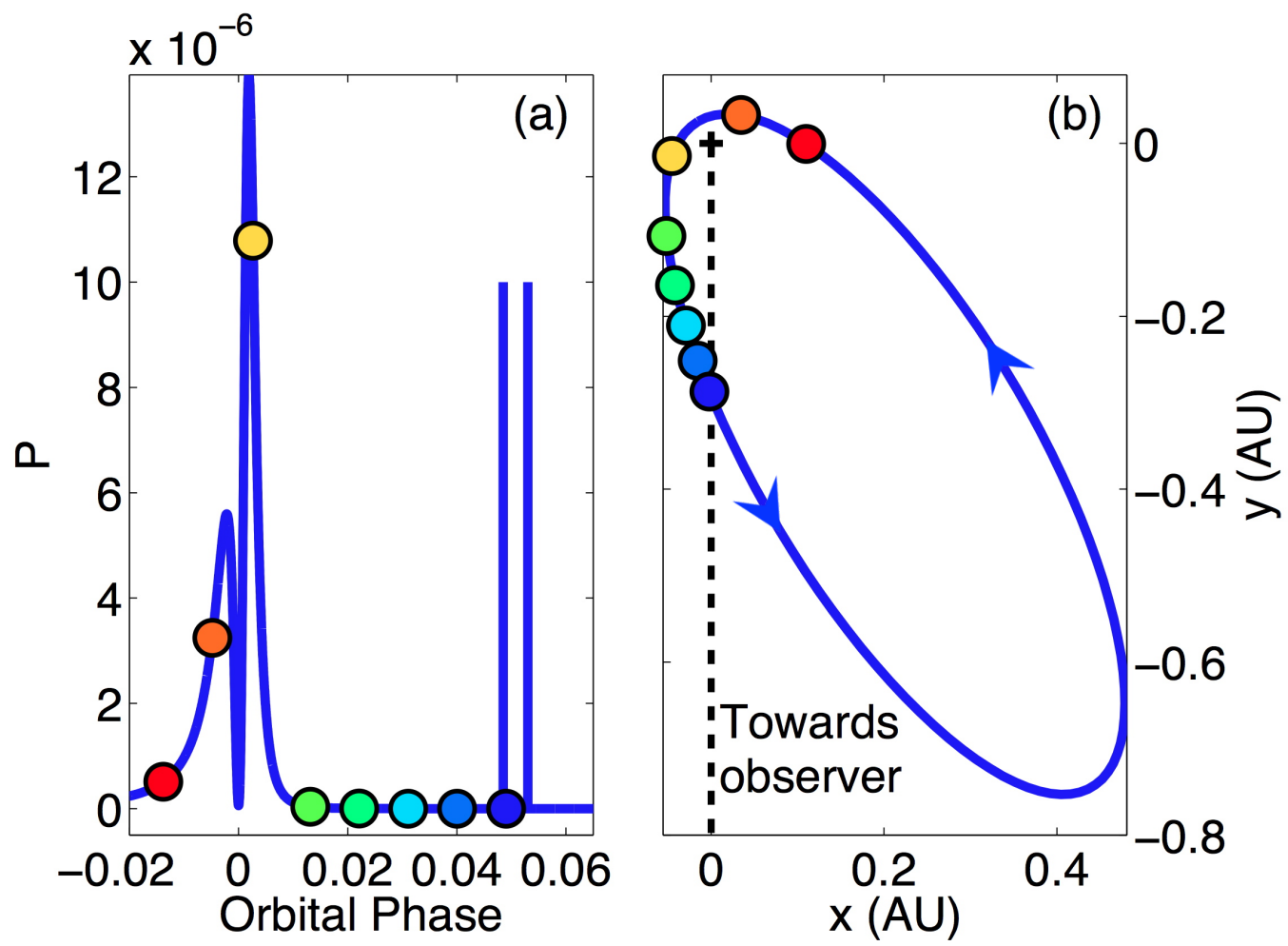
# Exoplanet Detectability





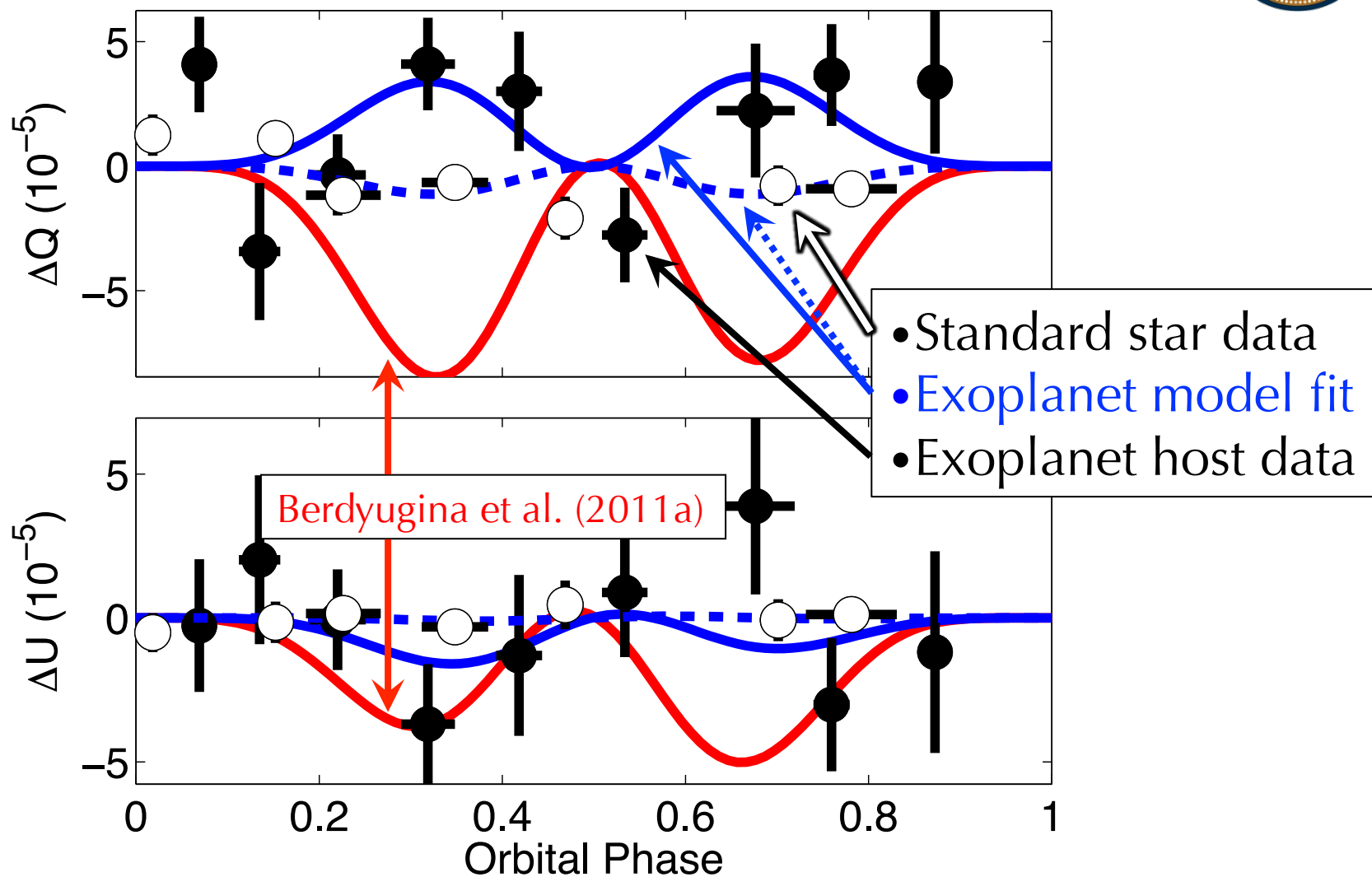


# Eccentric Exoplanets



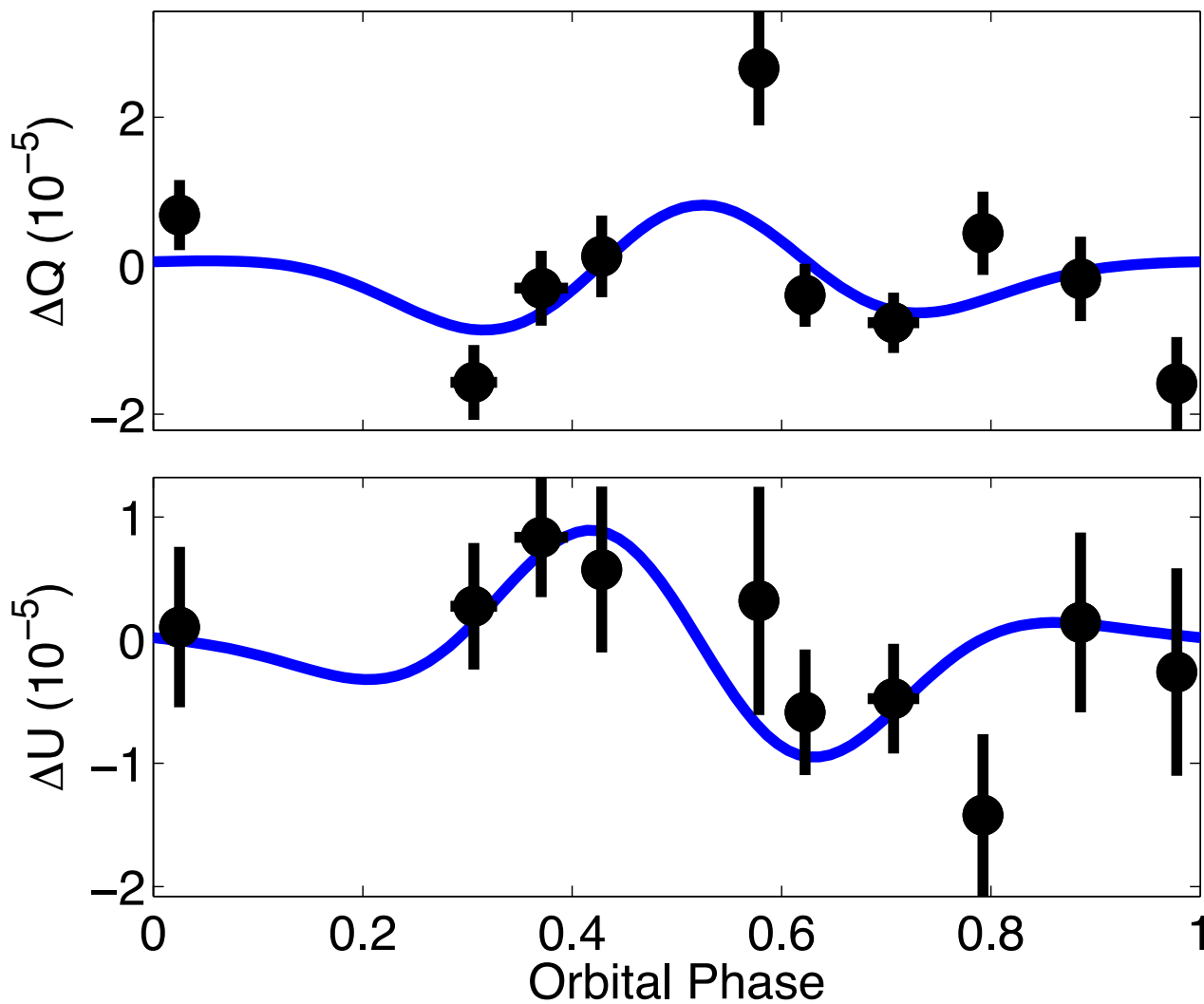


# Transiting Hot Jupiter





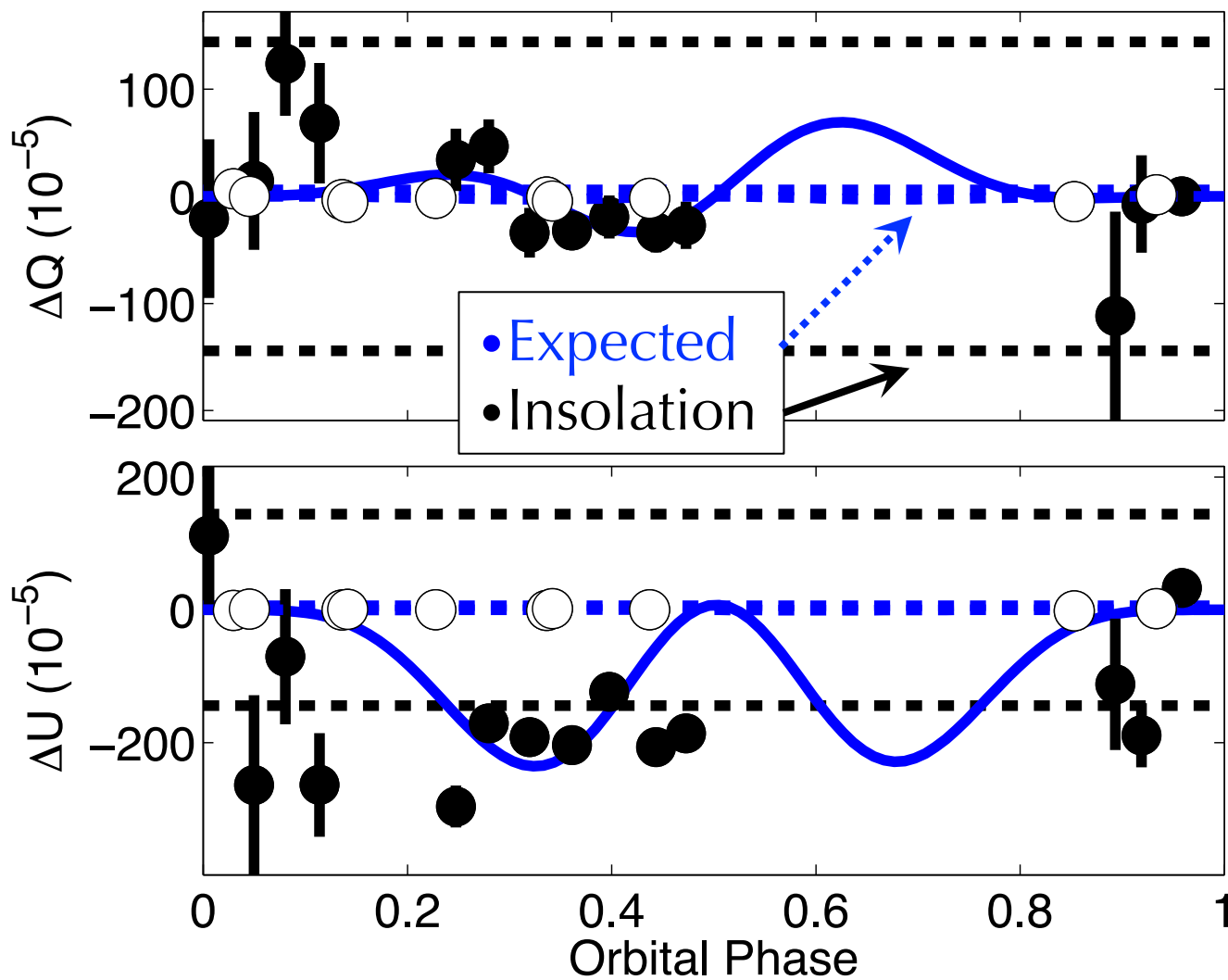
# Non-Transiting HJ







# Non-Spherical HJ





# Conclusions

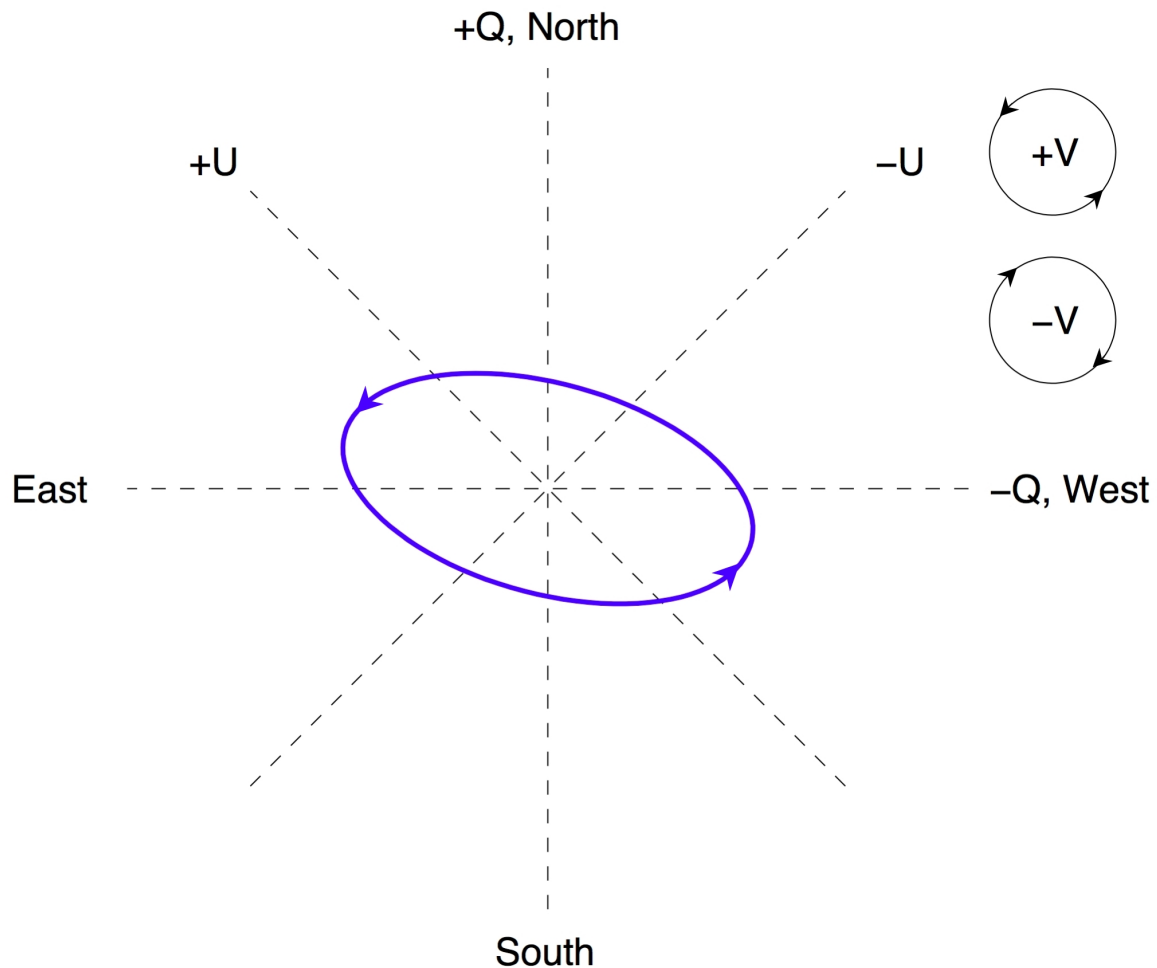
- Scattered light from exoplanets is polarized, allows direct detection regardless of inclination
- Albedo, inclination, and scattering properties (cloud structure, composition) may be probed
- Upgraded POLISH2 may directly detect up to a dozen exoplanets at the Lick 3-m
- Survey: 1) hot Jupiters, 2) eccentric Jovians, 3) extended/tidally distorted Jovians, and 4) a super-Earth
- 3 potential exoplanet detections
- Systematics important at the  $10^{-5}$  level and are being mitigated



polish2



# Polarimetry





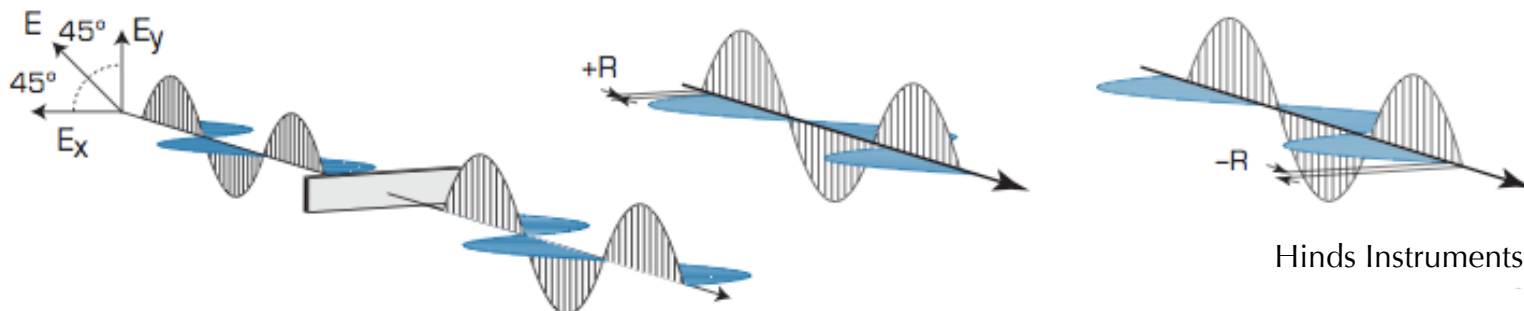
# Planetary Polarization

- Light scattered by atmospheres is linearly polarized
  - H<sub>2</sub> Rayleigh scattering
  - Aerosol, cloud particle Mie scattering
- Two polarization cycles per orbit
- Change in polarization *vector*  $\Rightarrow$  inclination, albedo, atmospheric composition

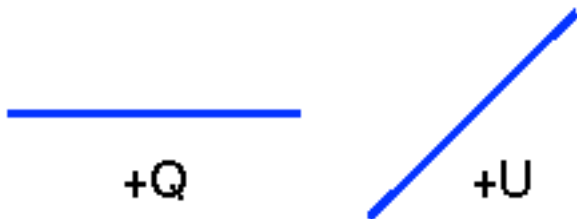




# Photoelastic Modulator

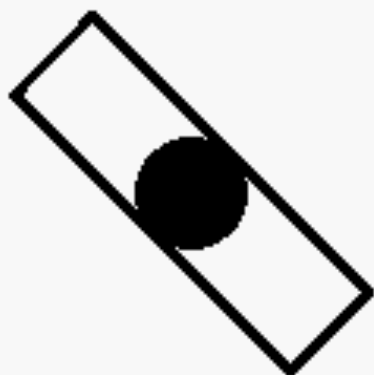


$t = 0 \mu s$

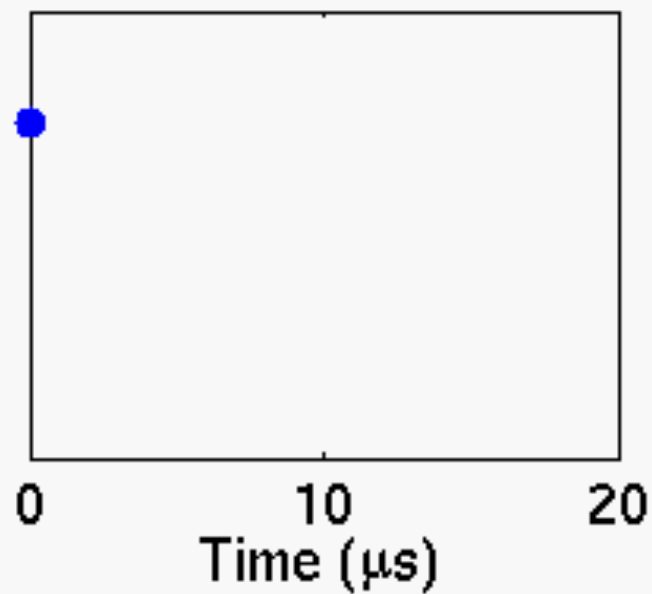
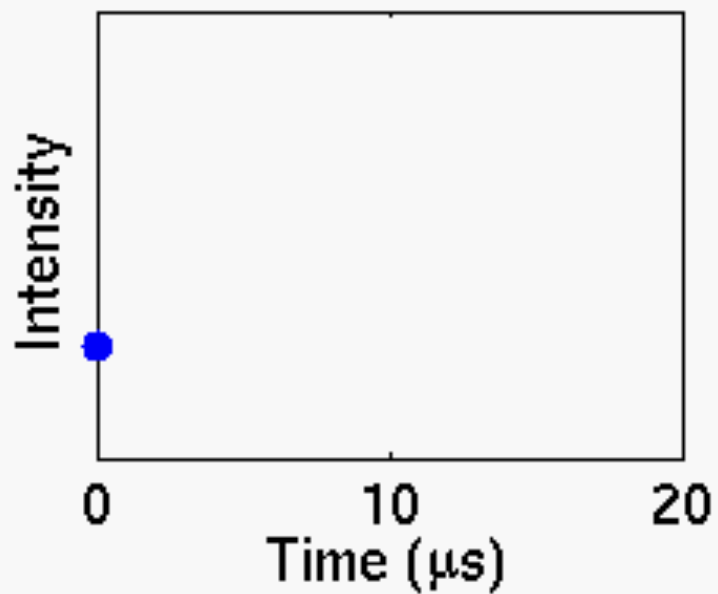
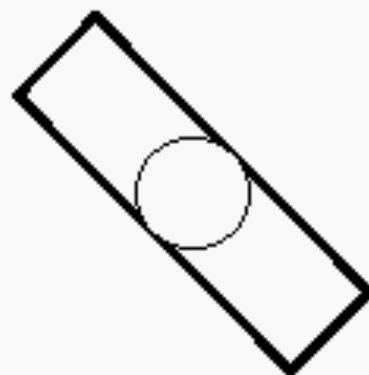


- Birefringence: horizontal E field lags/leads vertical
- Non-birefringent material stressed  $\Rightarrow$  birefringence

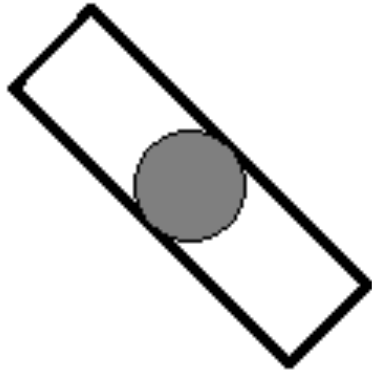
Left Beam



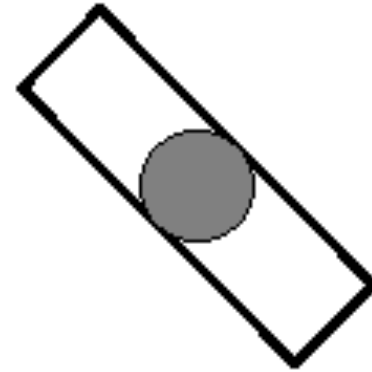
Right Beam



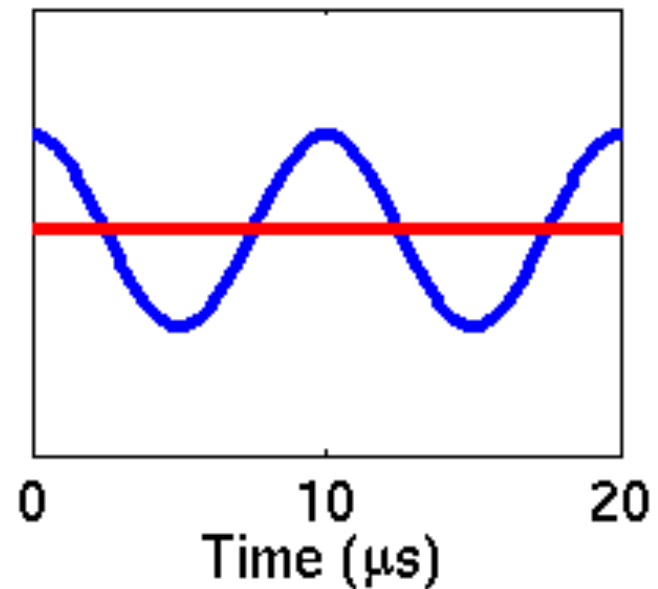
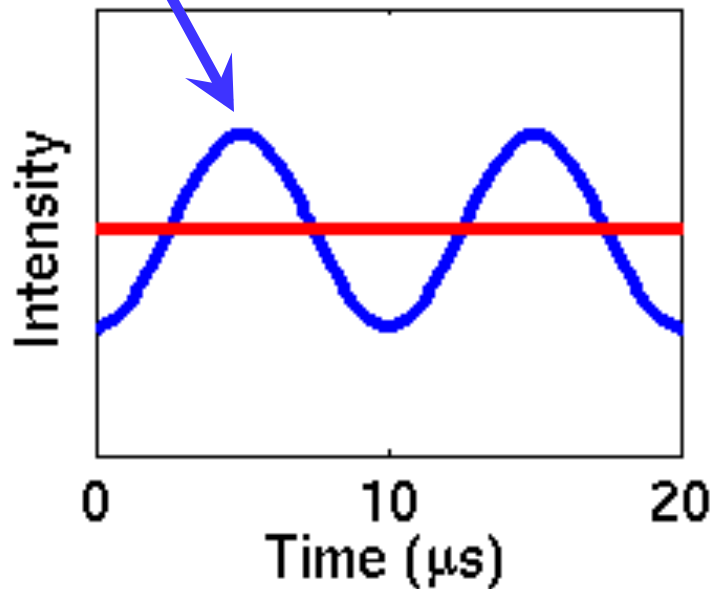
Left Beam



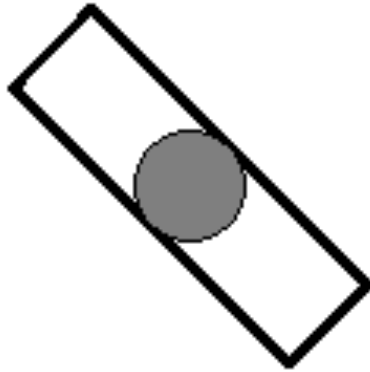
Right Beam



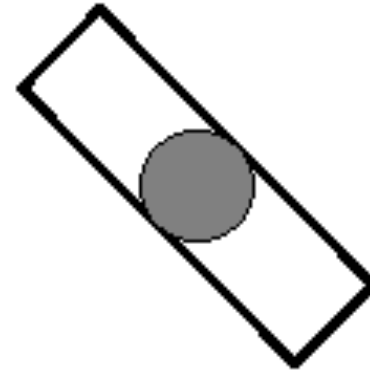
Nearly sinusoidal:  $50 + 150 \text{ kHz} + \dots + (2n-1)f = \text{Stokes } V/I$   
 $100 + 200 \text{ kHz} + \dots + (2n)f = \text{Stokes } Q/I, U/I$



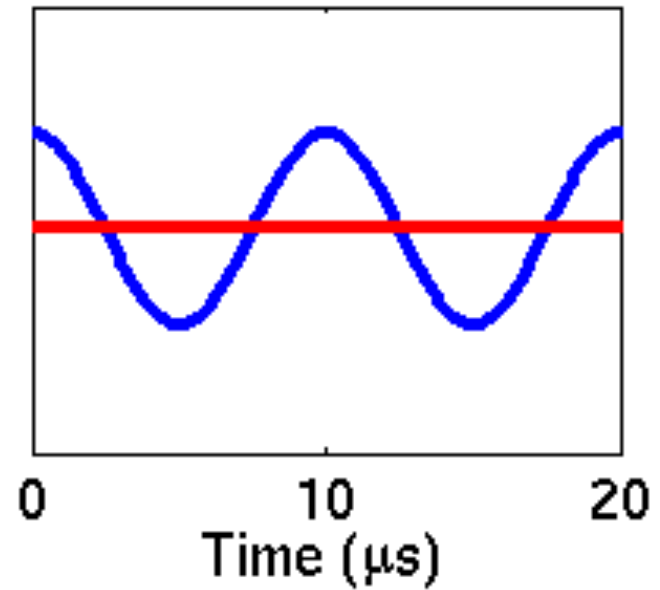
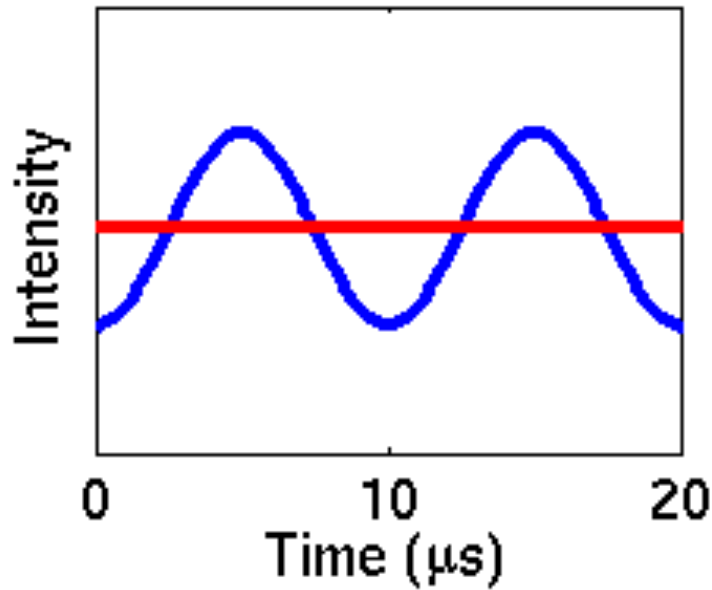
Left Beam



Right Beam

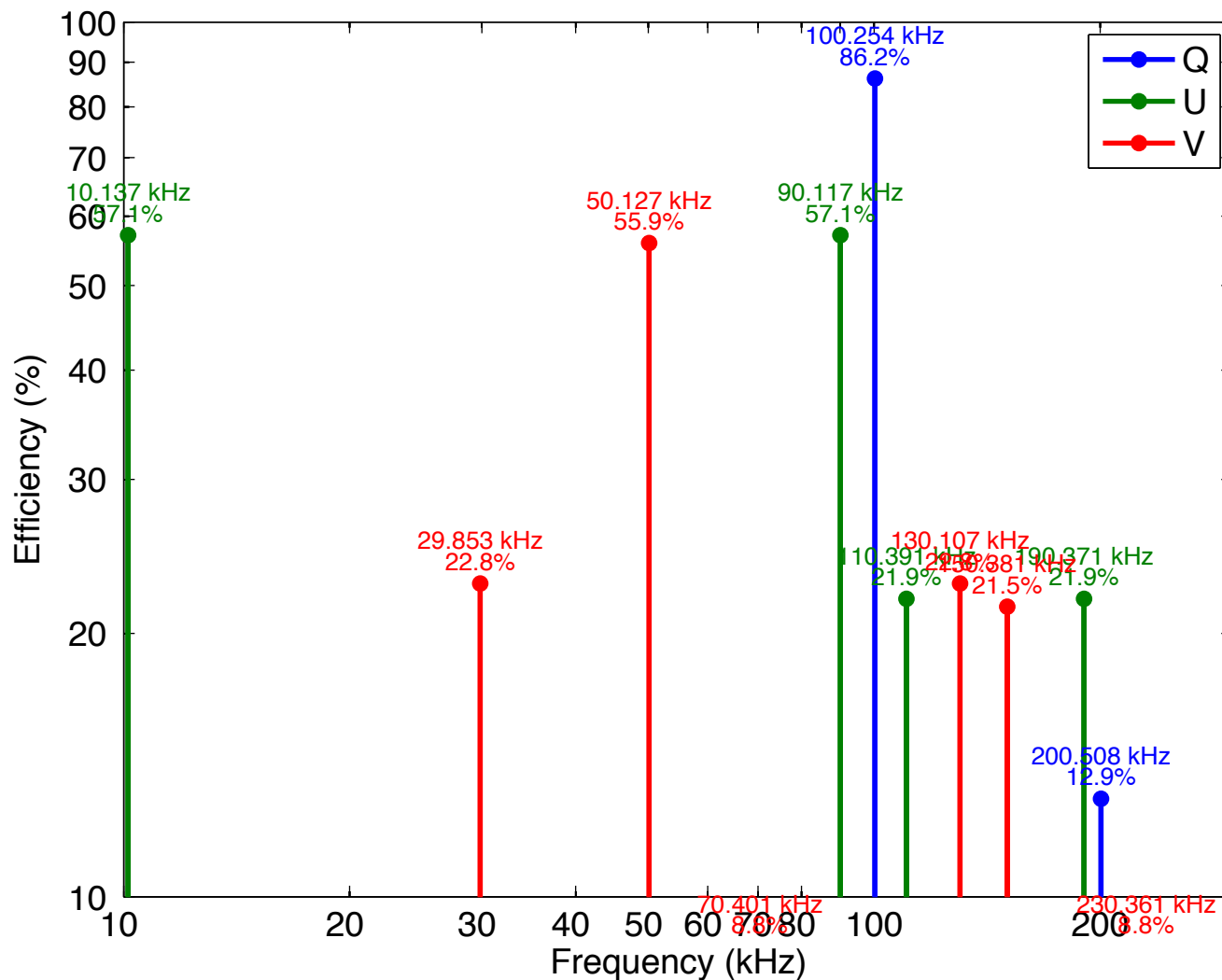


$$P \propto \frac{AC}{DC}$$





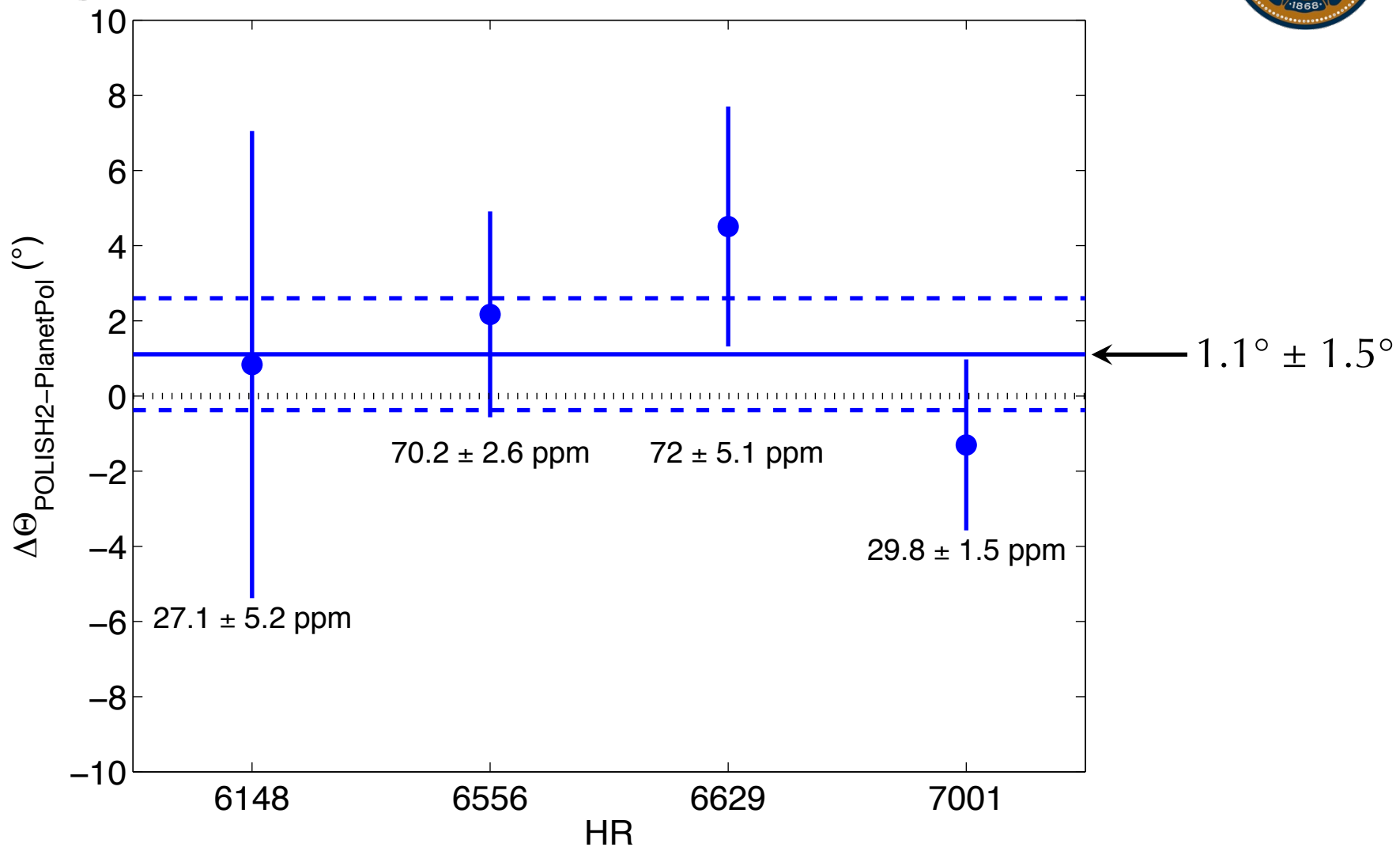
# Signal Frequencies





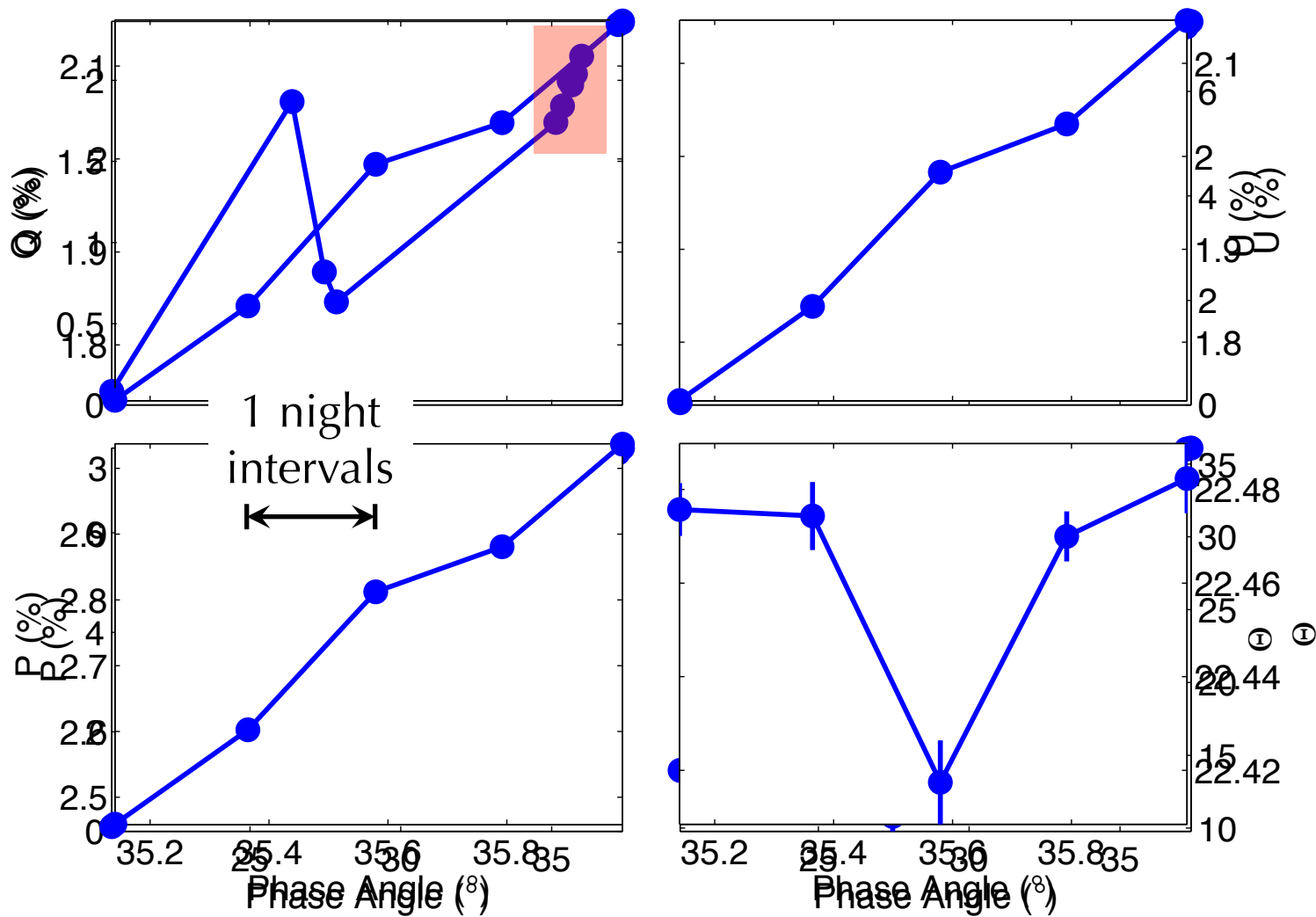


# POLISH2 Validation



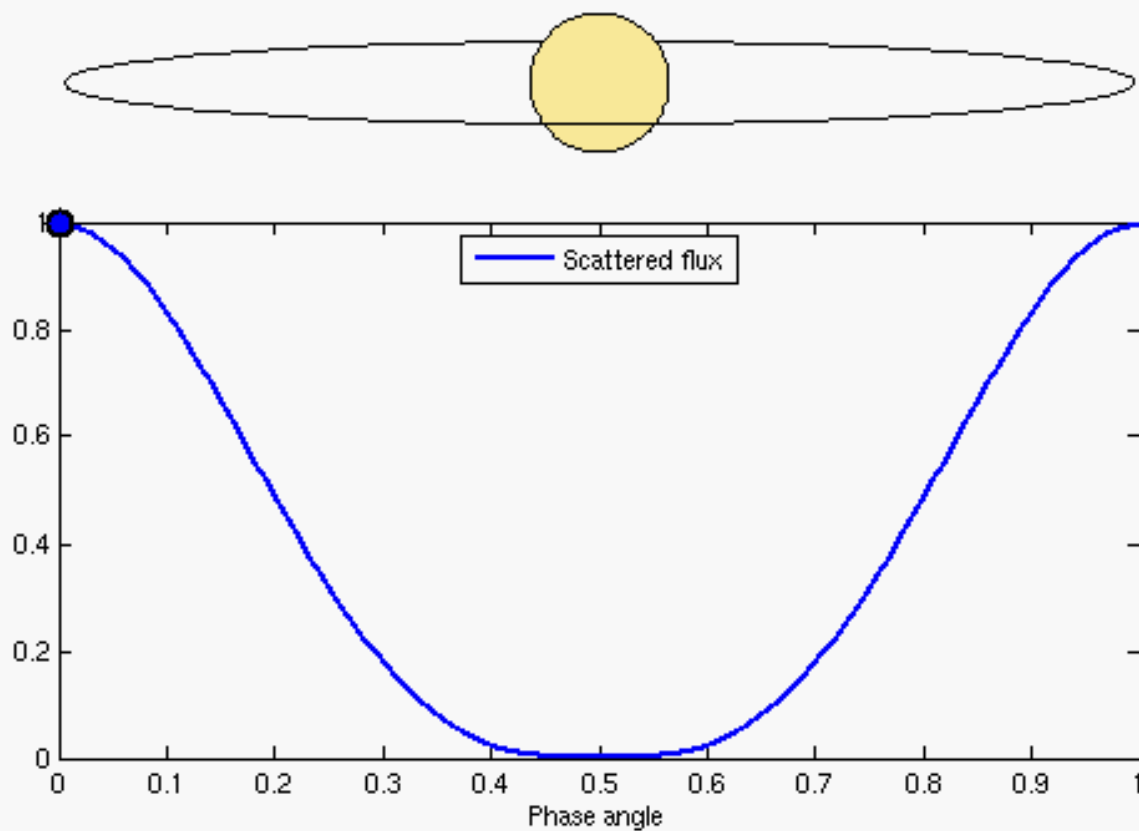


# Mars, *B* Band



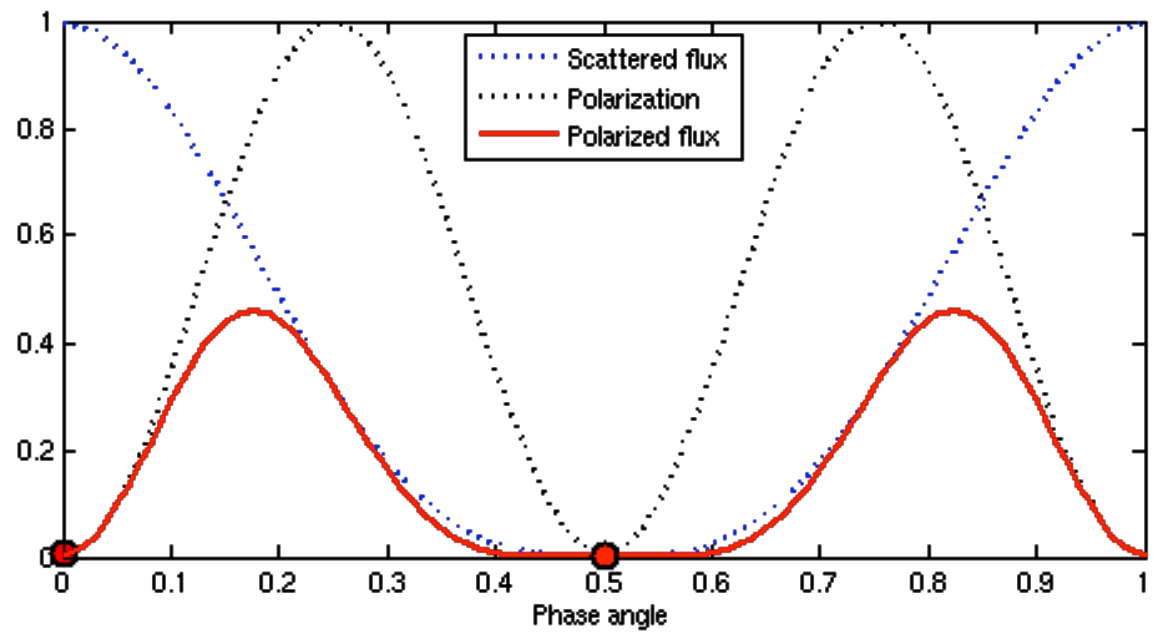
polish<sub>2</sub>

# Scattering Model



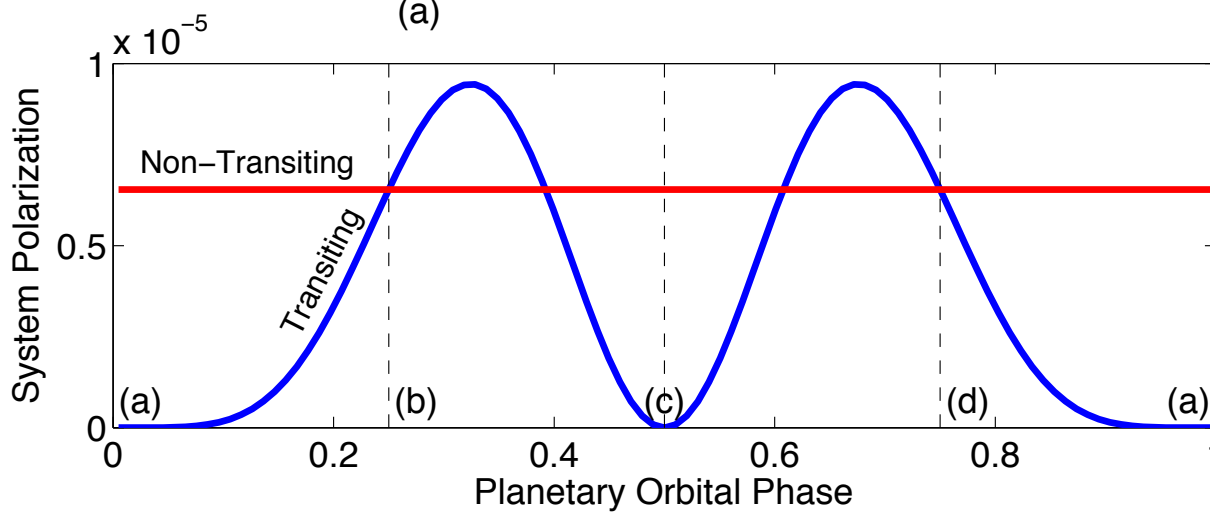
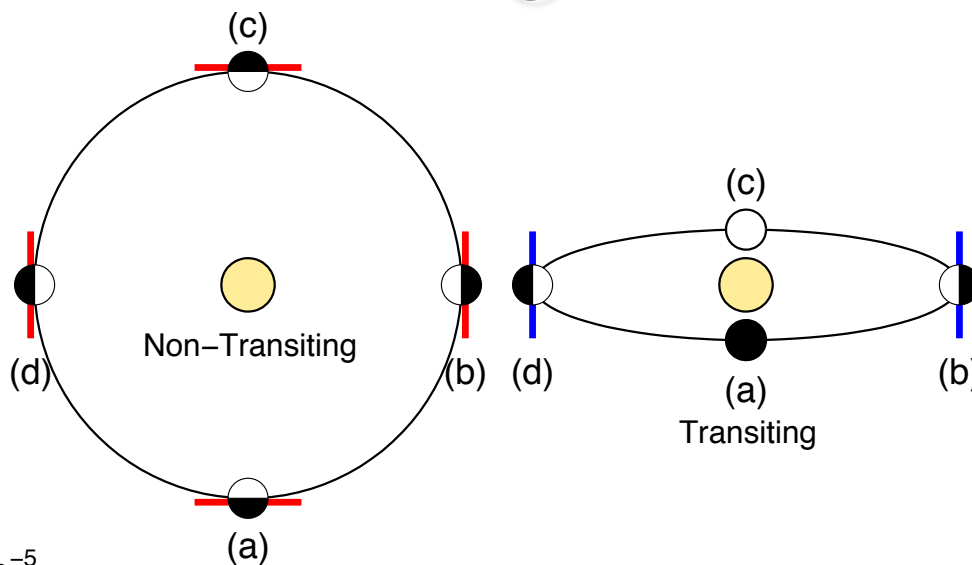


# Scattering Model





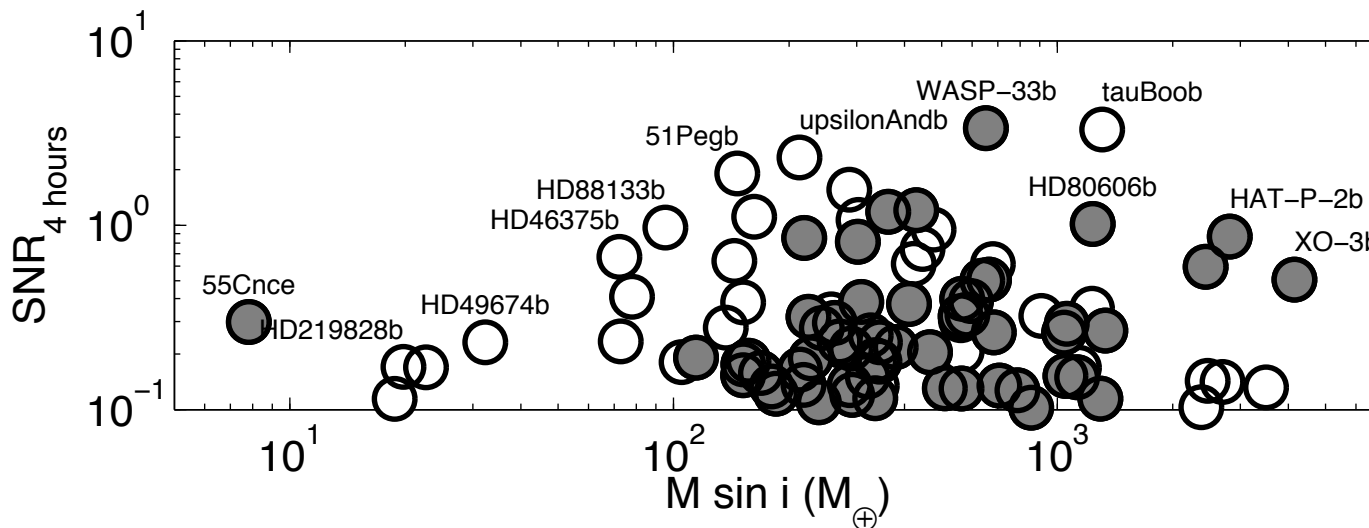
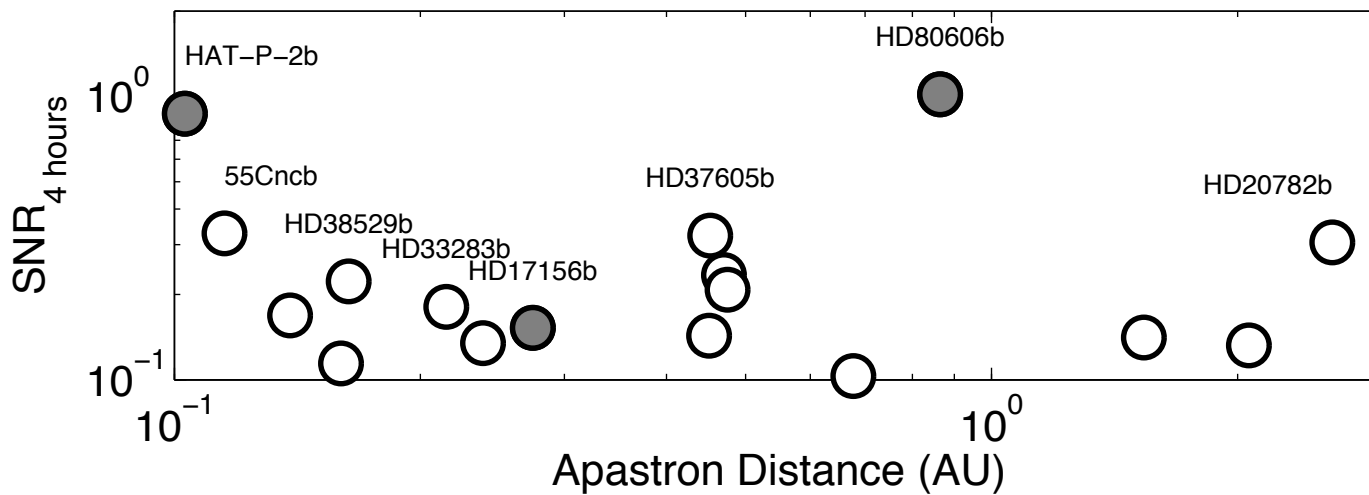
# Scattering Model







# Exoplanet SNR

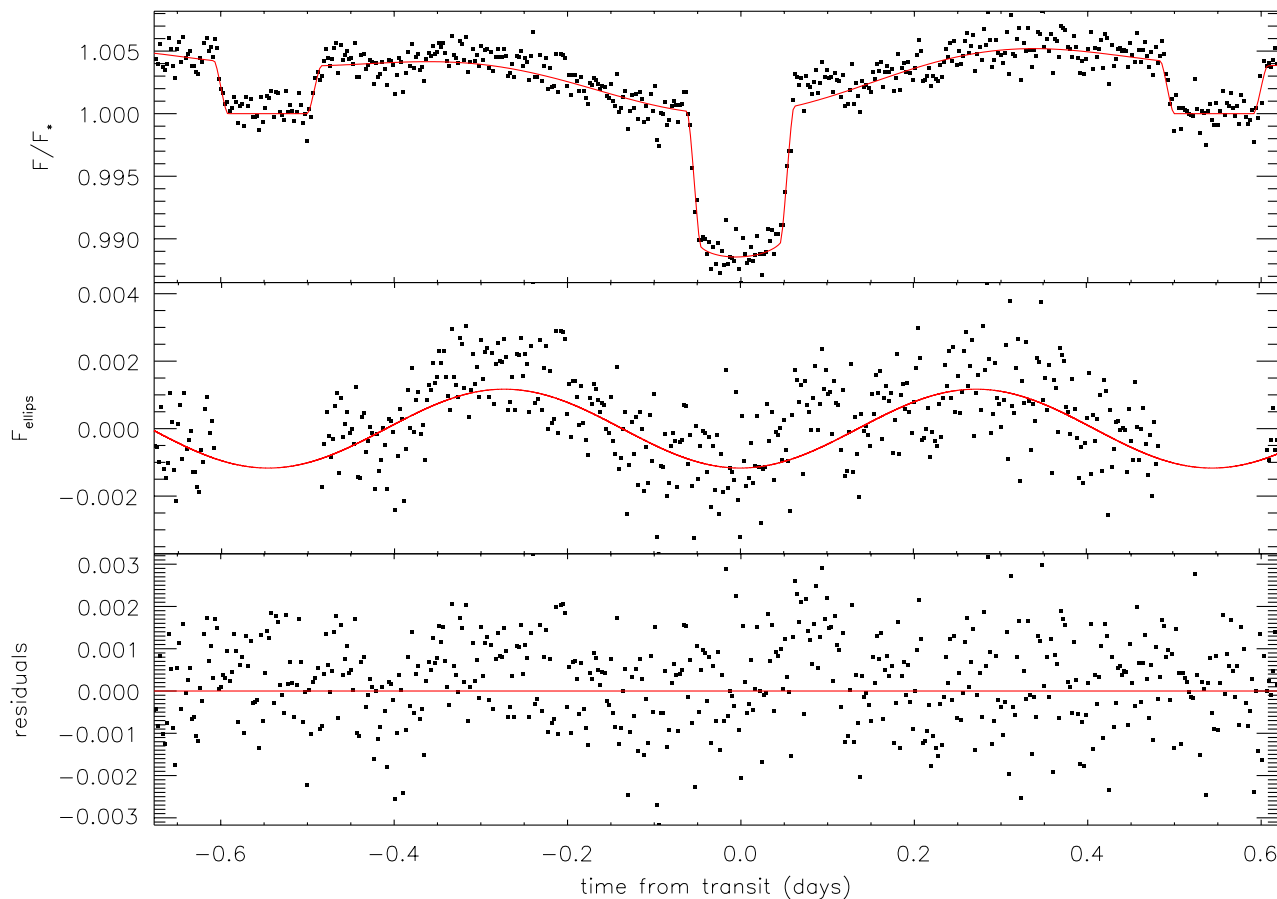




# Tidally Distorted Planets

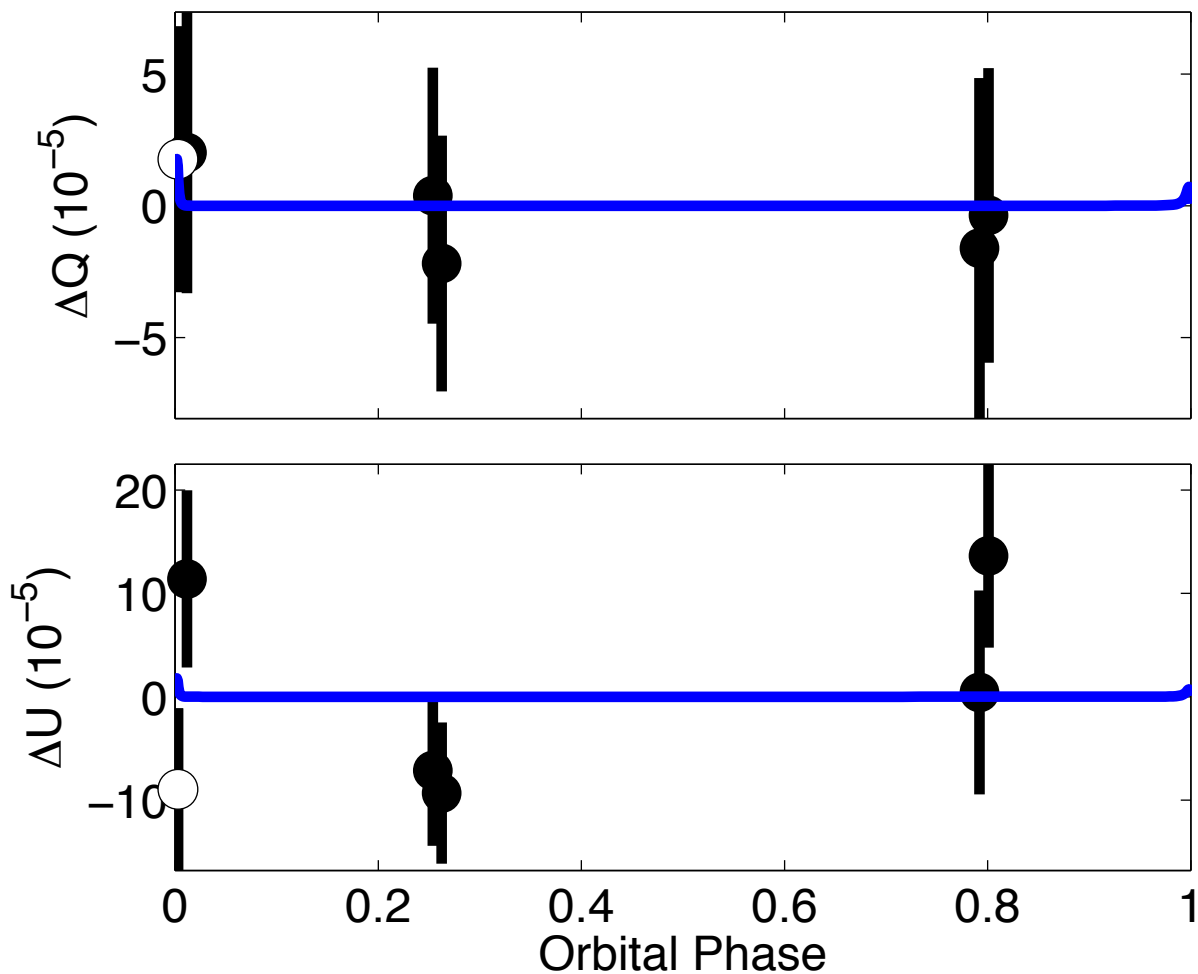
THE ASTROPHYSICAL JOURNAL, 747:82 (17pp), 2012 March 1

COWAN ET AL.



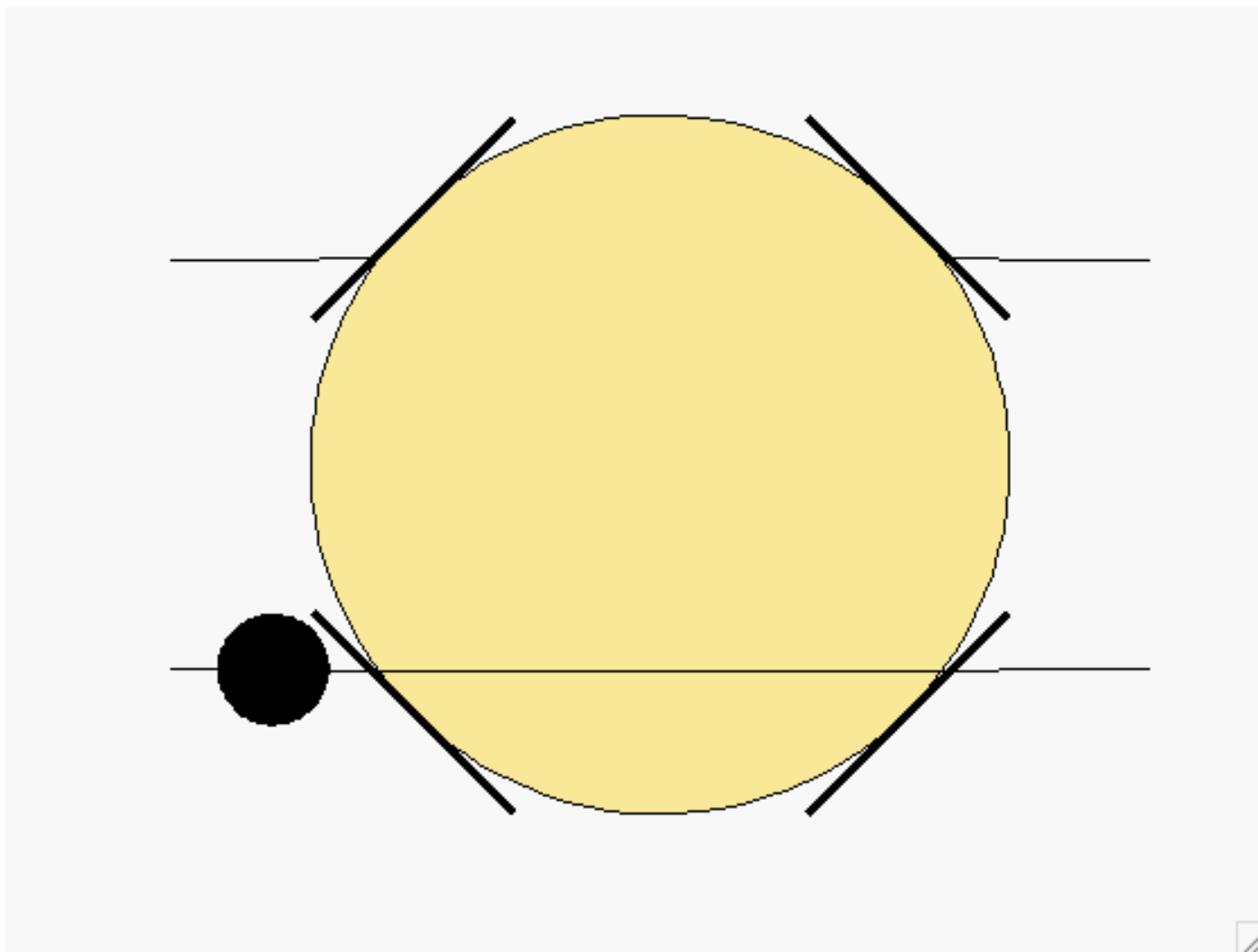


# Eccentric Jovian





# Polarized Transit





# Polarized Transit

