

Status of Exoplanet Polarimetry

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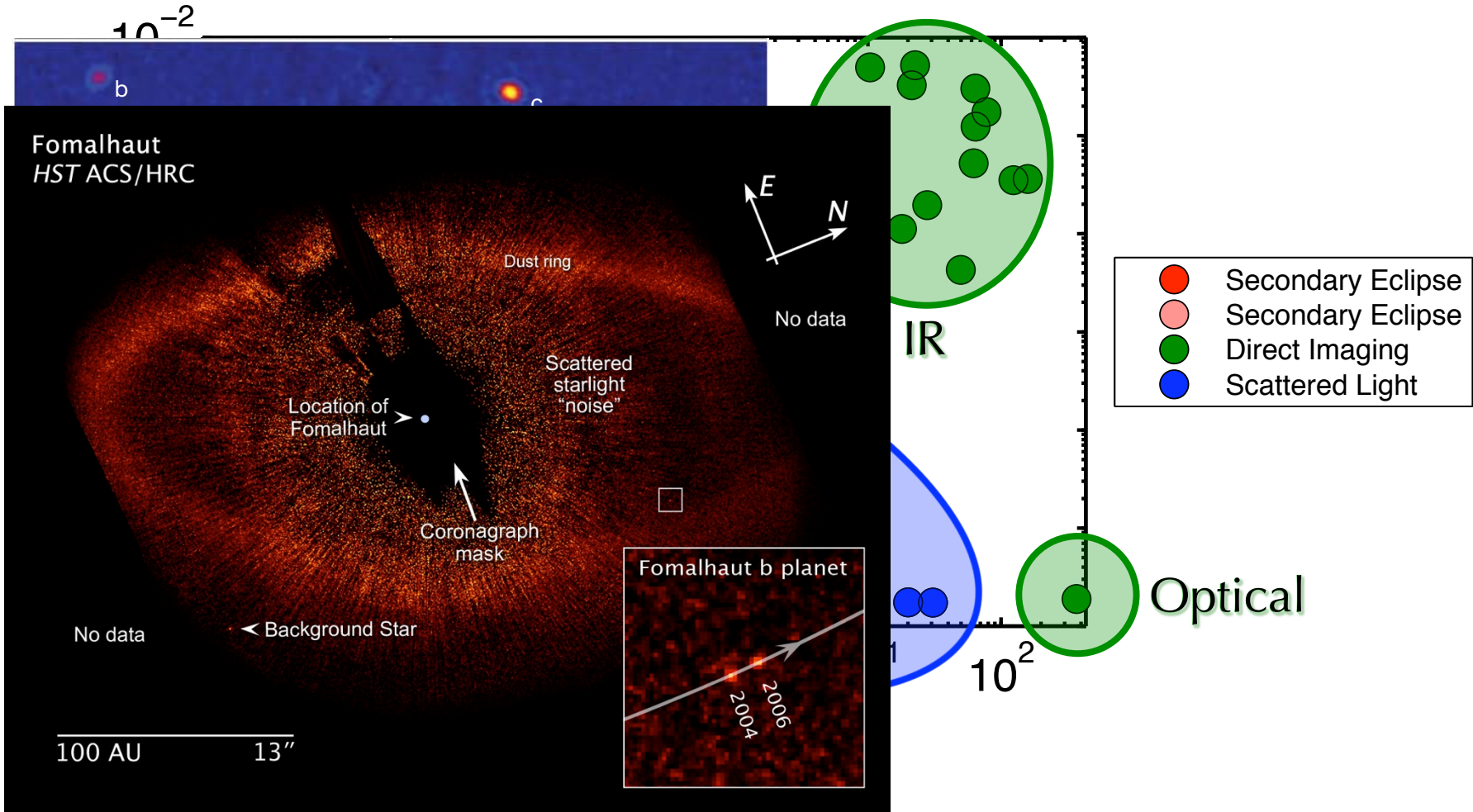
May 29, 2014

Astropol 2014: Grenoble, France



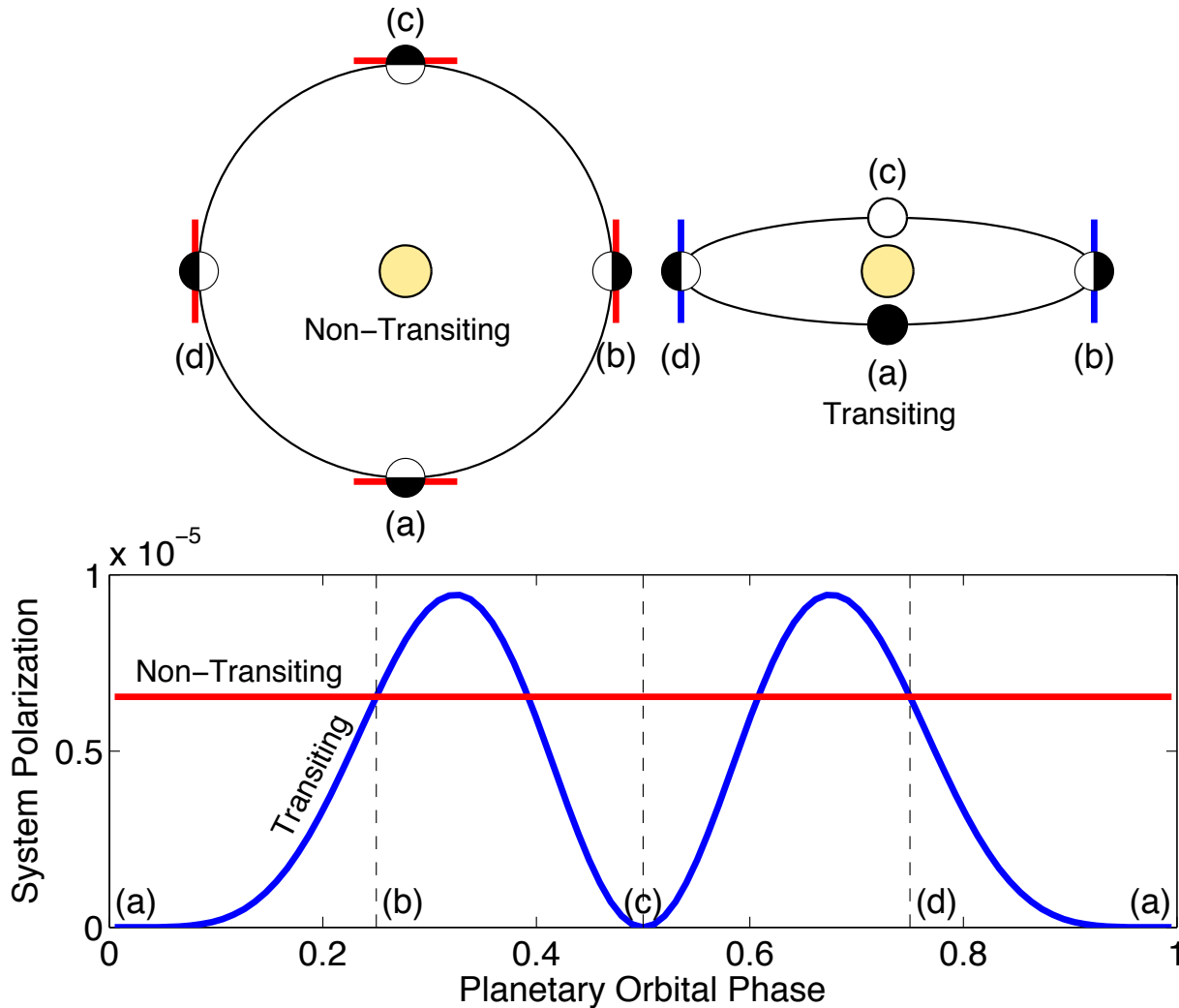
Exoplanet Contrast Ratios

Spatially Resolved vs. Unresolved



Spatially Unresolved Planets

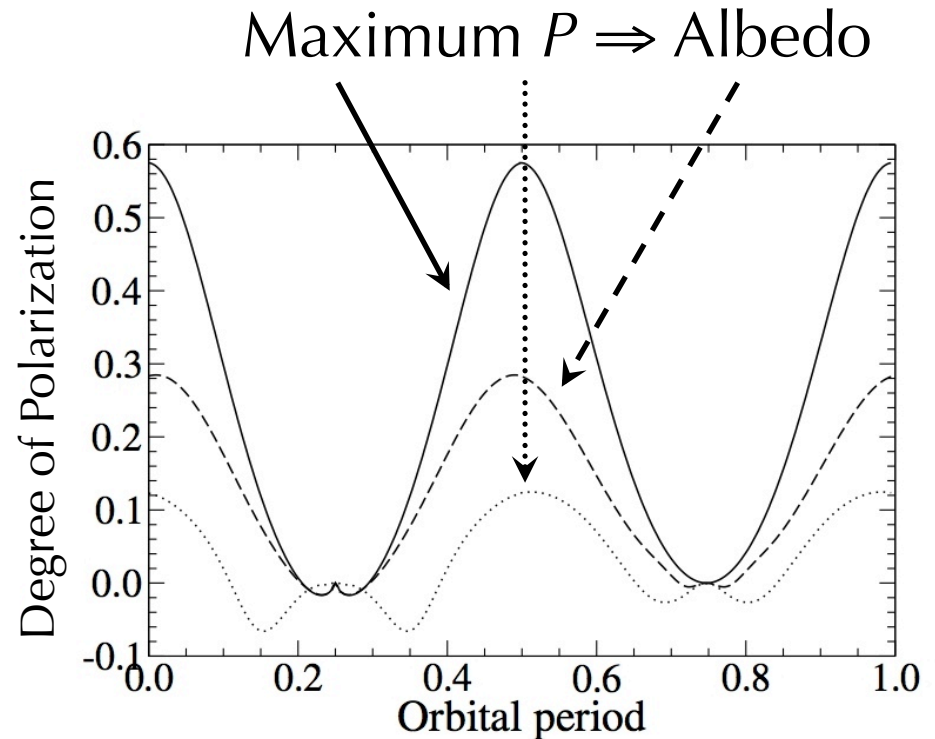
Orbital Inclination from Scattered Light



Spatially Unresolved Planets

Albedo, Clouds, & Hazes from Scattered Light

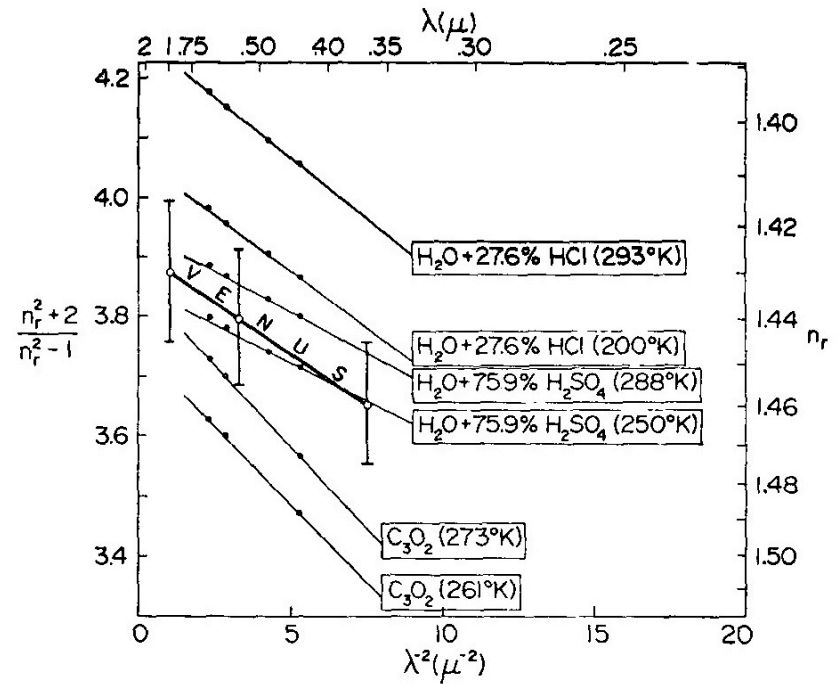
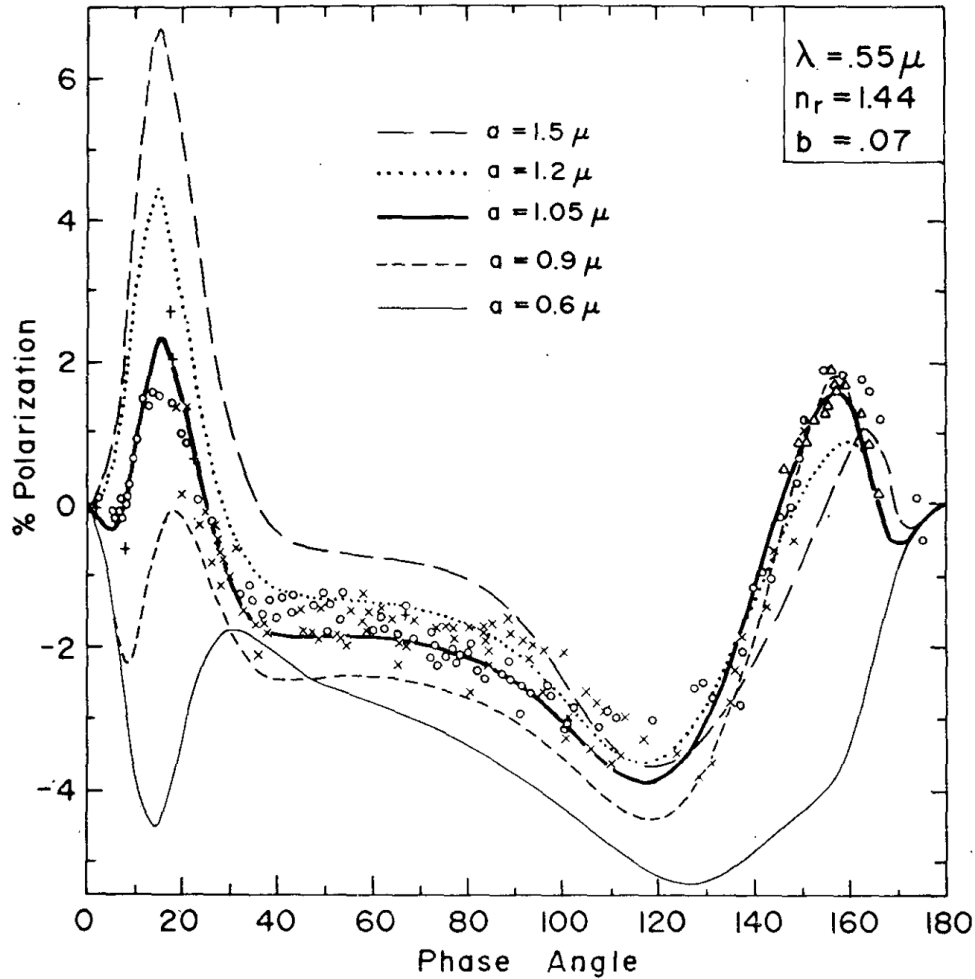
- Clear
- - - Tropospheric cloud
- Cloud + stratospheric haze



Stam et al. 2004

Solar System Heritage

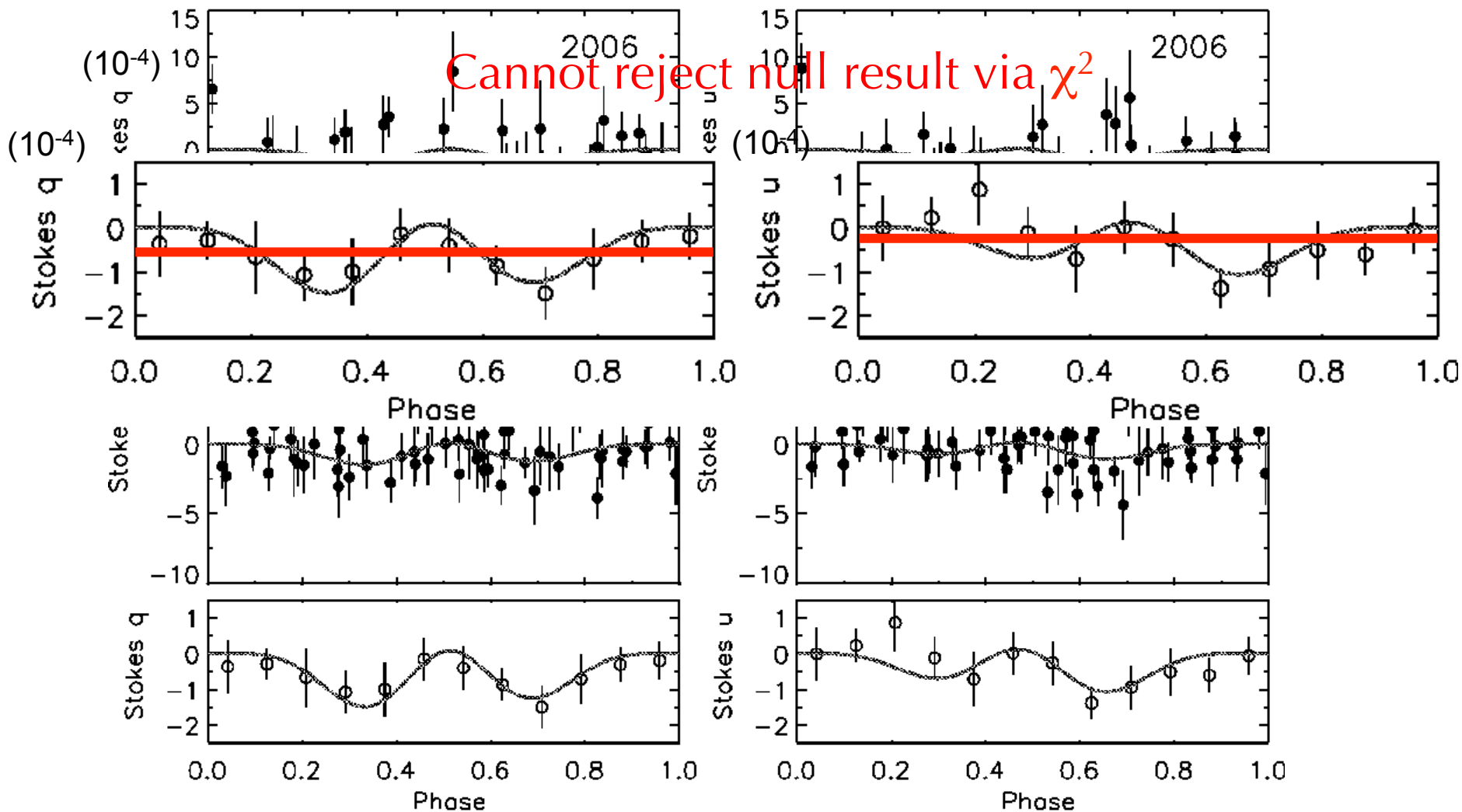
Cloud Composition: Sulfuric Acid in Venus



Coffeen & Gehrels 1969
 Hansen & Hovenier 1974

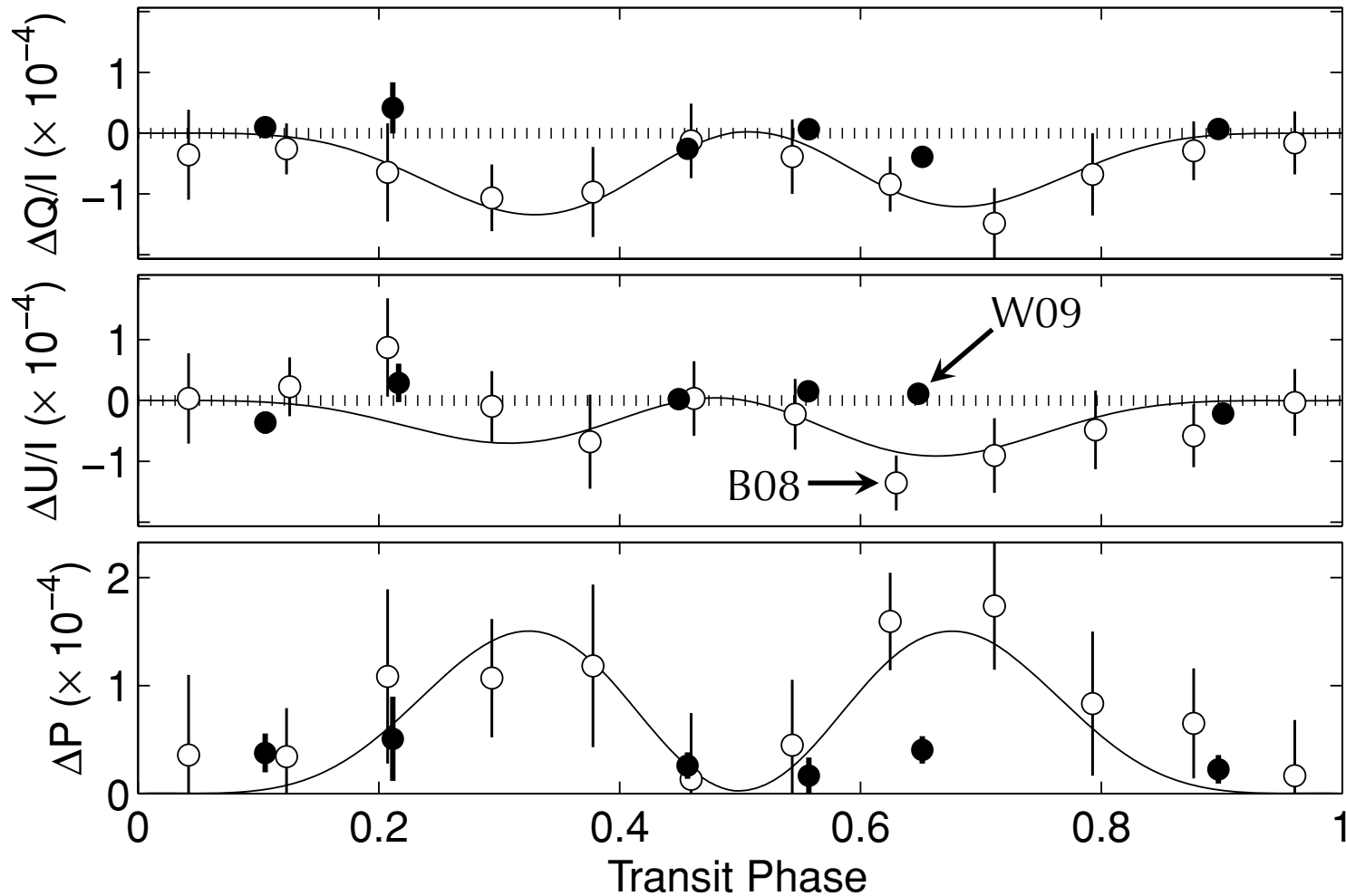
Spatially Unresolved Planets

HD 189733b (Berdyugina et al. 2008: KVA 0.6-m, ~100 nights)



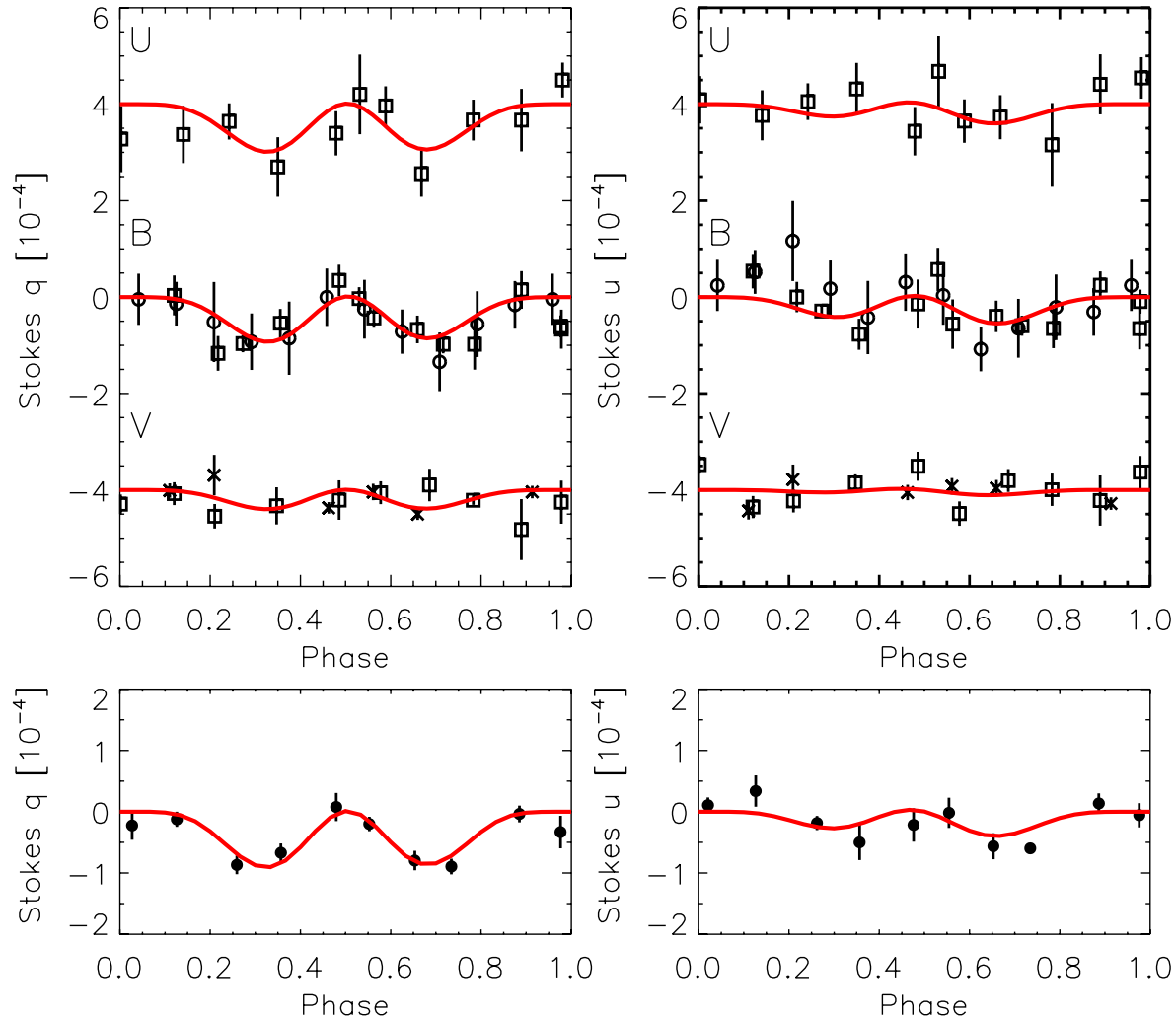
Spatially Unresolved Planets

HD 189733b (Wiktorowicz 2009: Palomar 5-m, 6 nights)



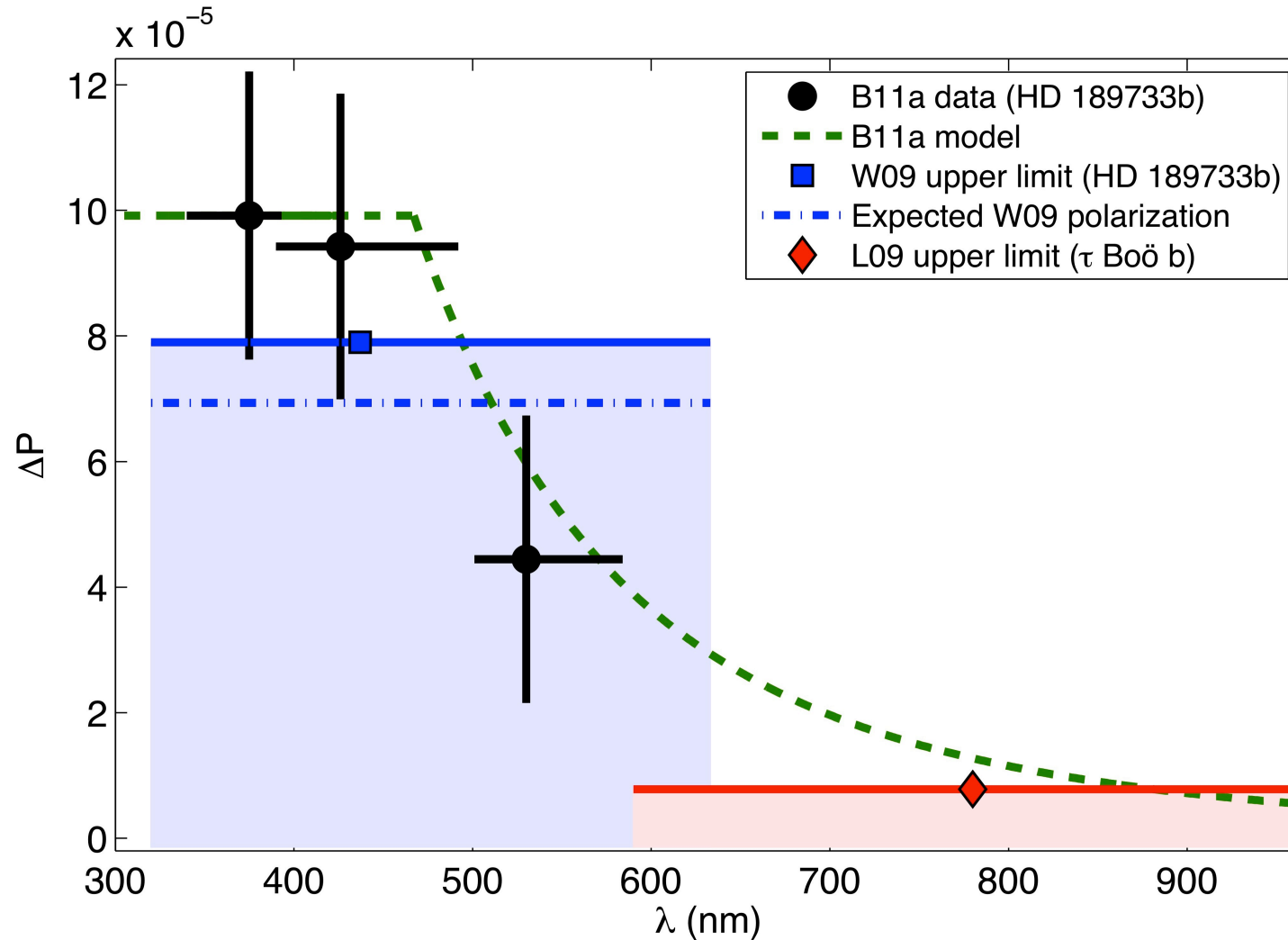
Spatially Unresolved Planets

HD 189733b (Berdyugina et al. 2011a: NOT 2.5-m, 9 nights)



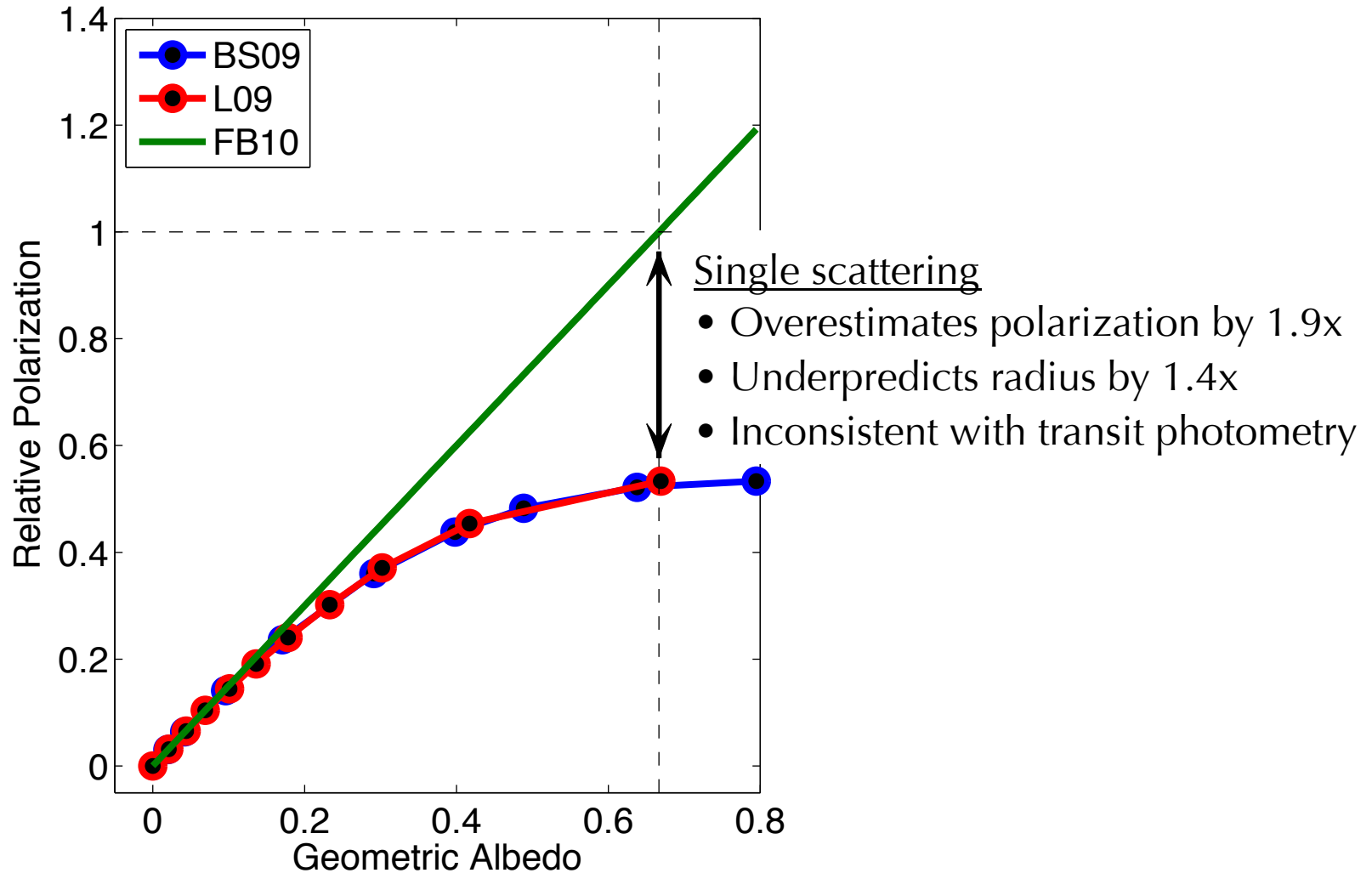
Spatially Unresolved Planets

HD 189733b (Berdyugina et al. 2011a; Wiktorowicz 2009) & τ Boö b (Lucas et al. 2009)



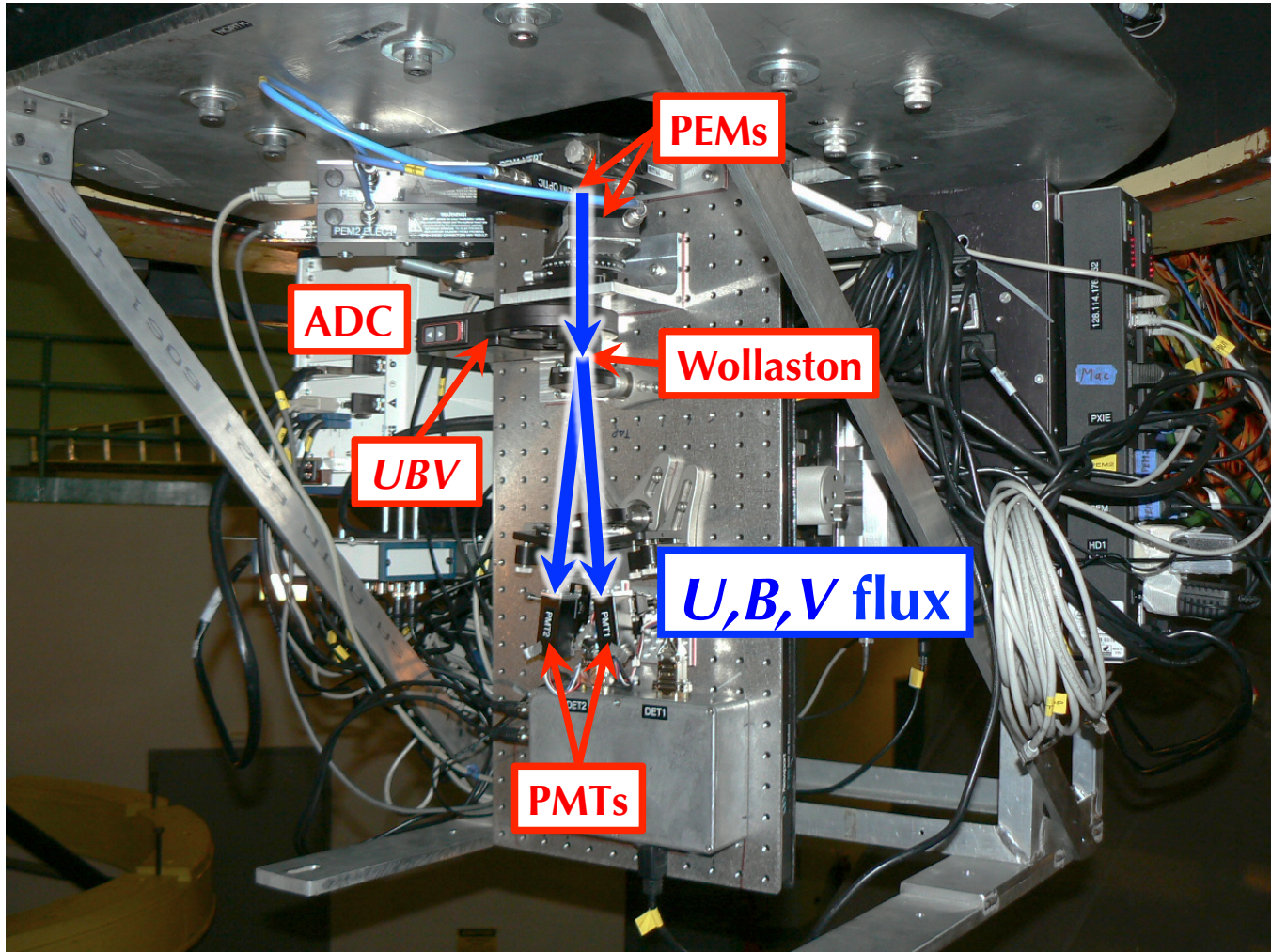
Spatially Unresolved Planets

Single (Fluri & Berdyugina 2010) vs. Multiple Scattering (Buenzli & Schmid 2009; Lucas et al. 2009)

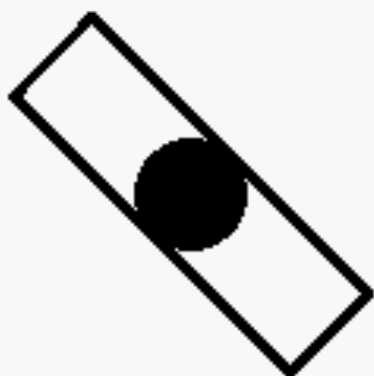


POLISH2

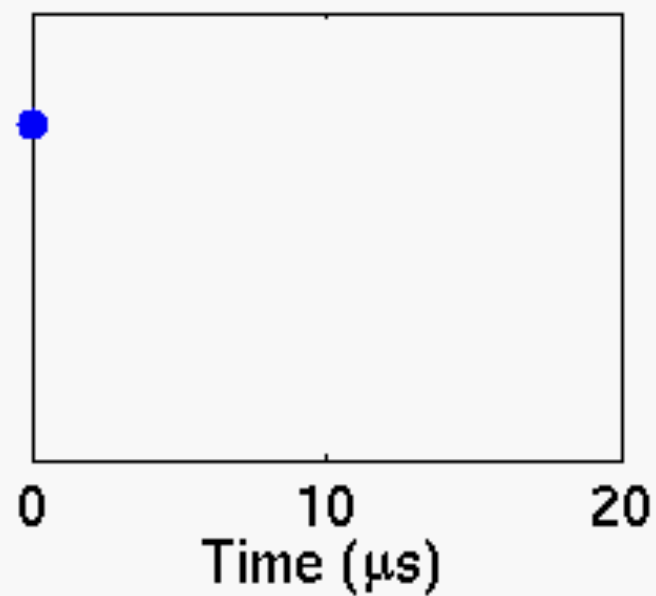
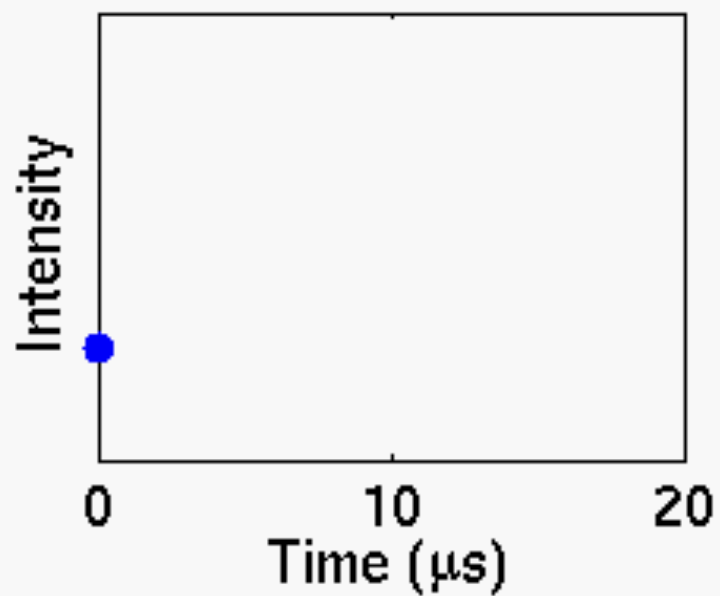
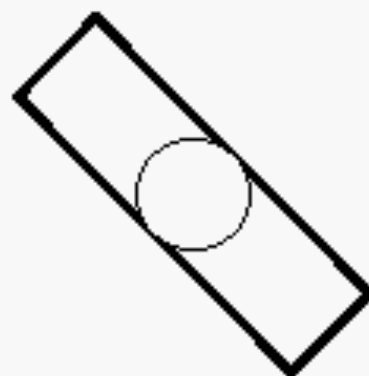
Commissioned April 2011 (~100 nights at each of Lick 3-m and 1-m)



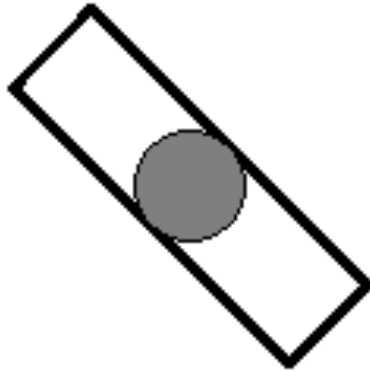
Left Beam



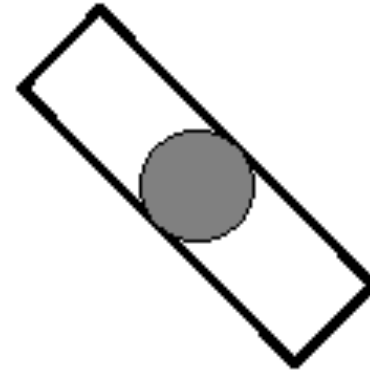
Right Beam



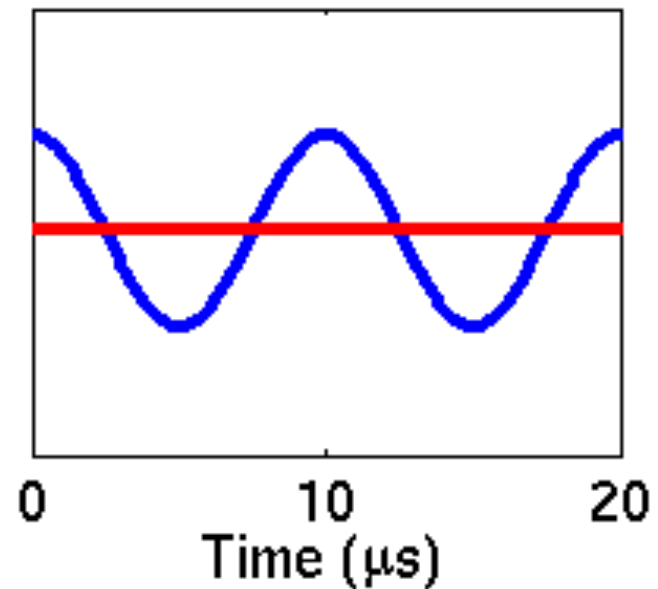
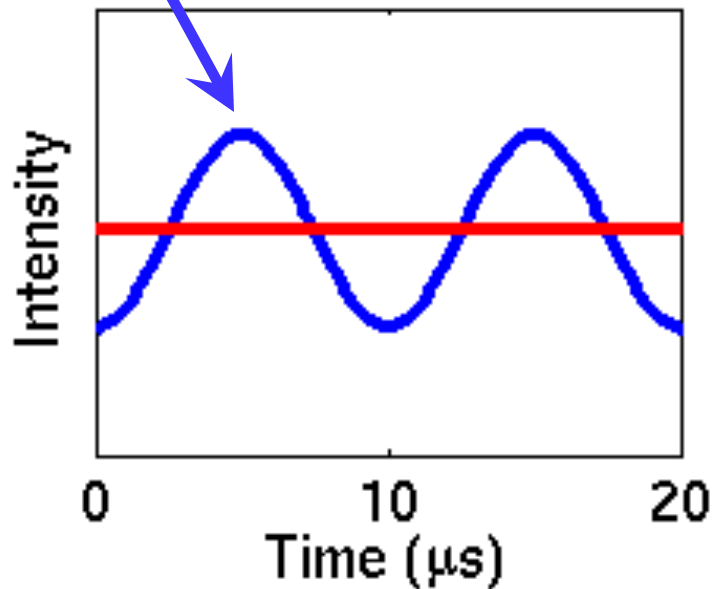
Left Beam



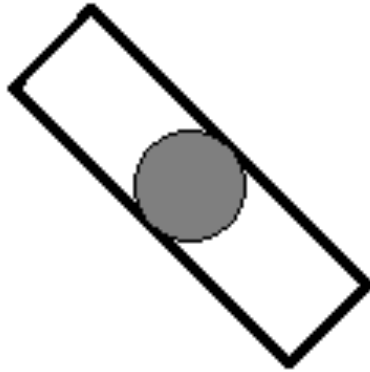
Right Beam



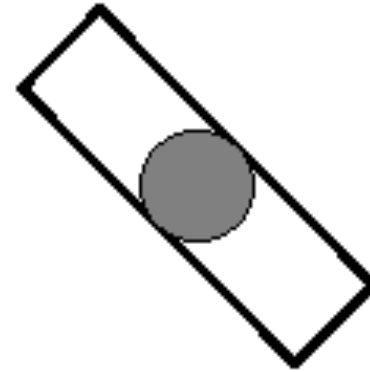
Nearly sinusoidal: $50 + 150 \text{ kHz} + \dots + (2n-1)f = \text{Stokes } V/I$
 $100 + 200 \text{ kHz} + \dots + (2n)f = \text{Stokes } Q/I, U/I$



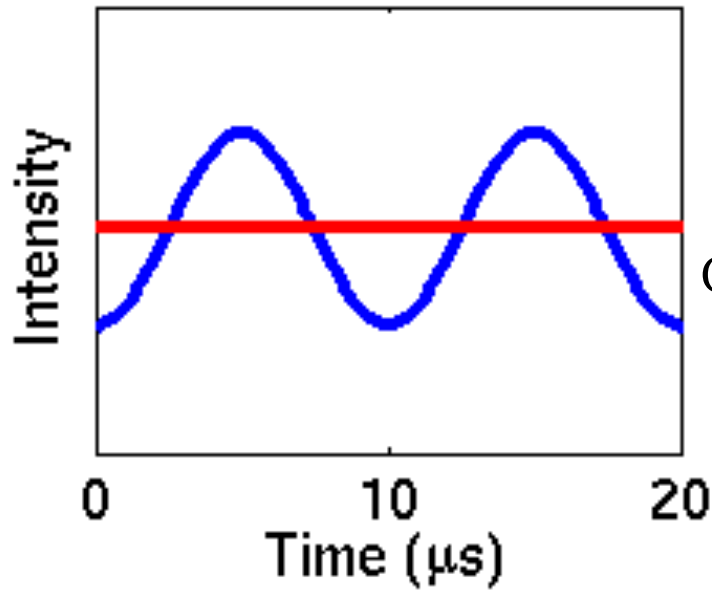
Left Beam





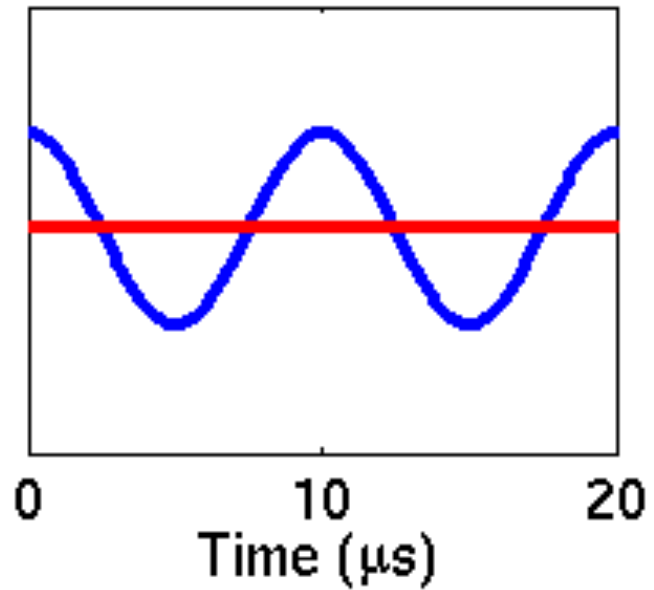
Right Beam



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

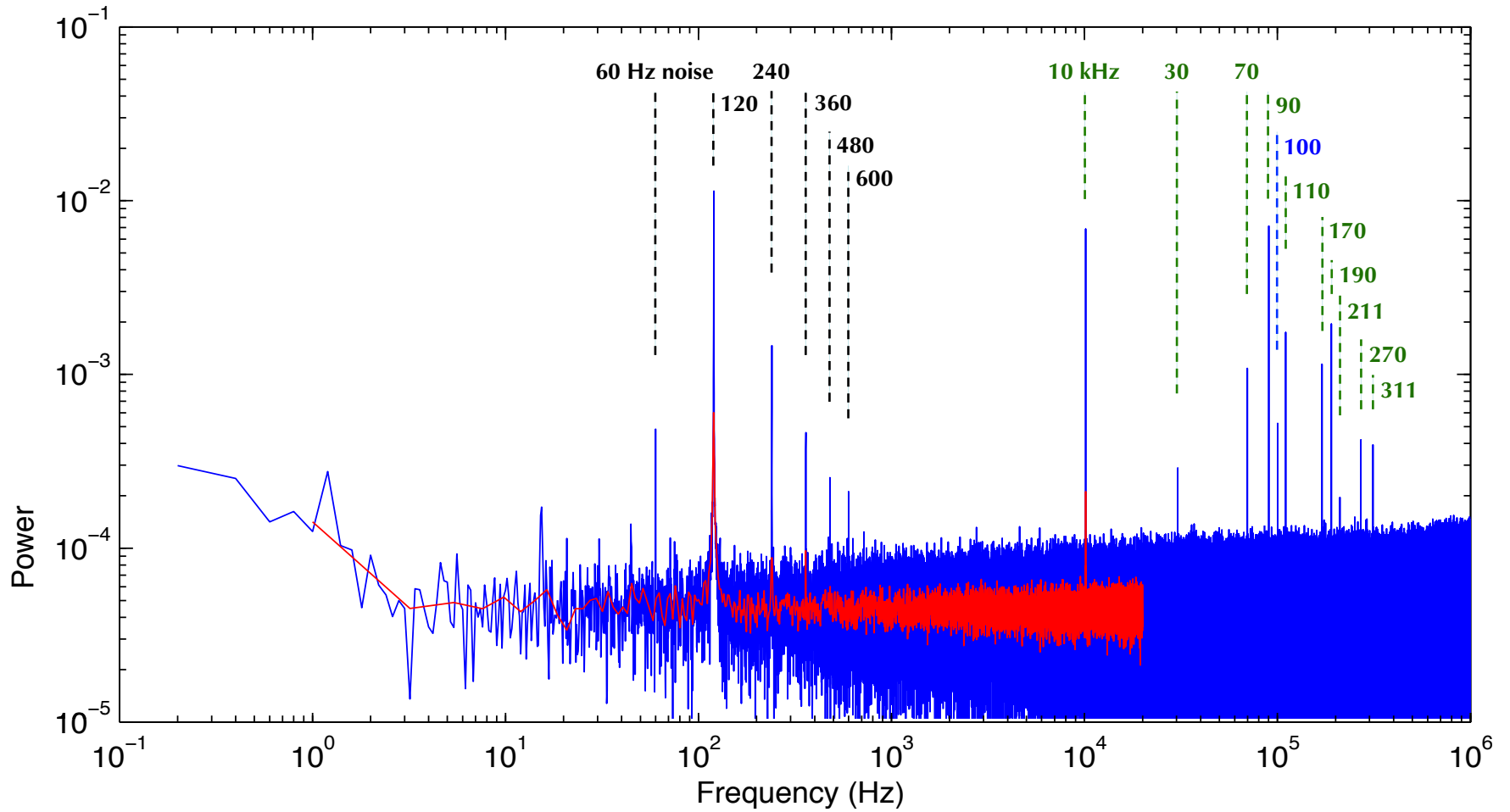


Q  



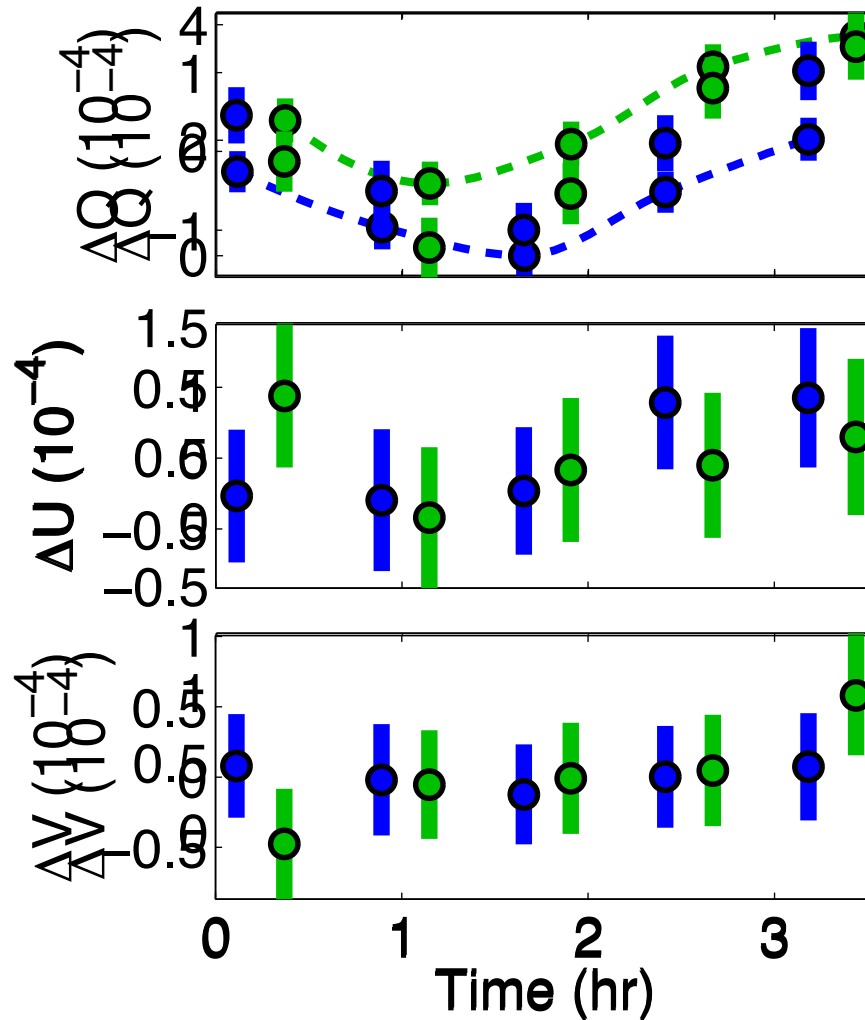
POLISH2

Modulation Frequencies



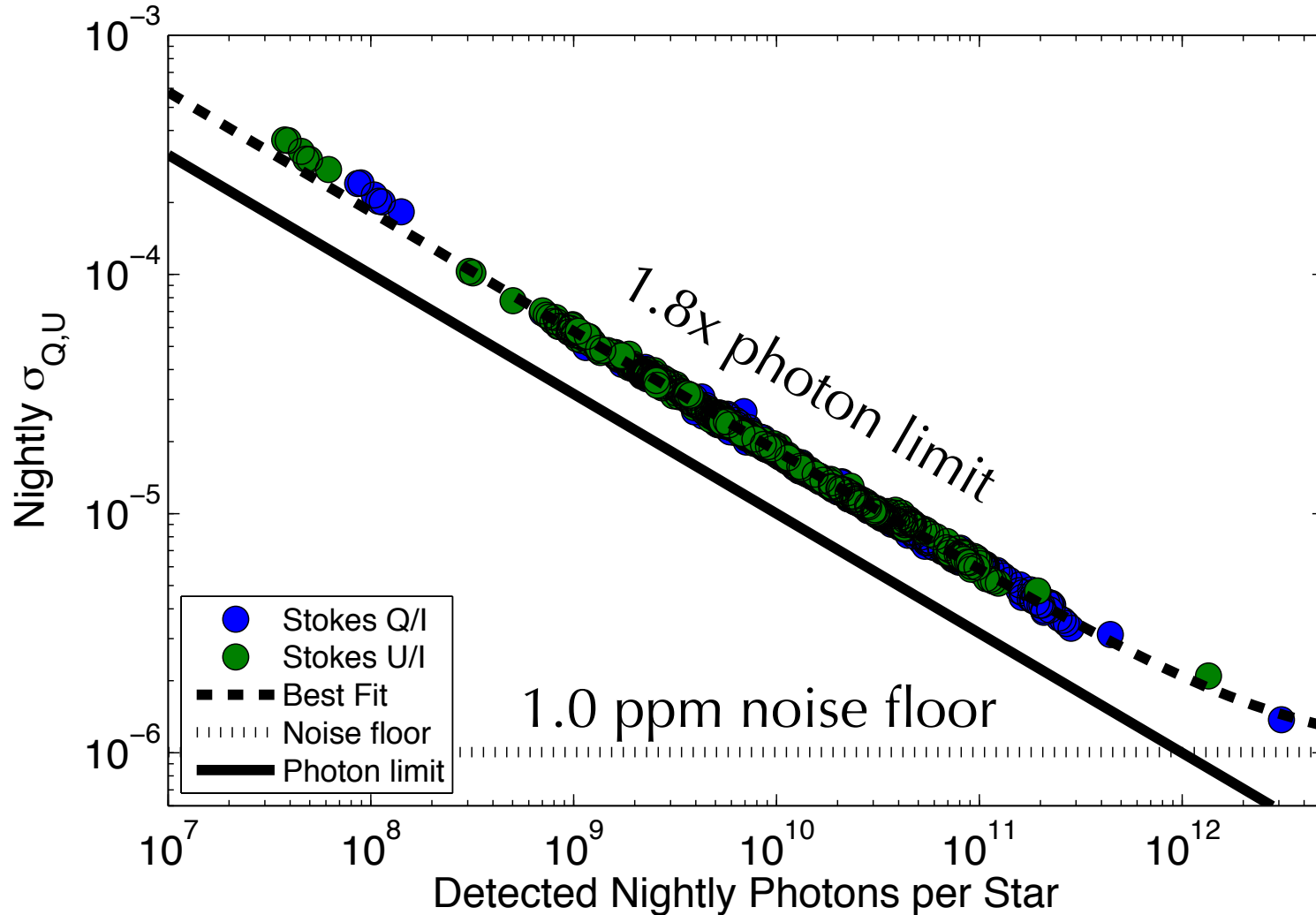
POLISH2

Vesta Observations (Known $\sim 0.01\%$ Variable)



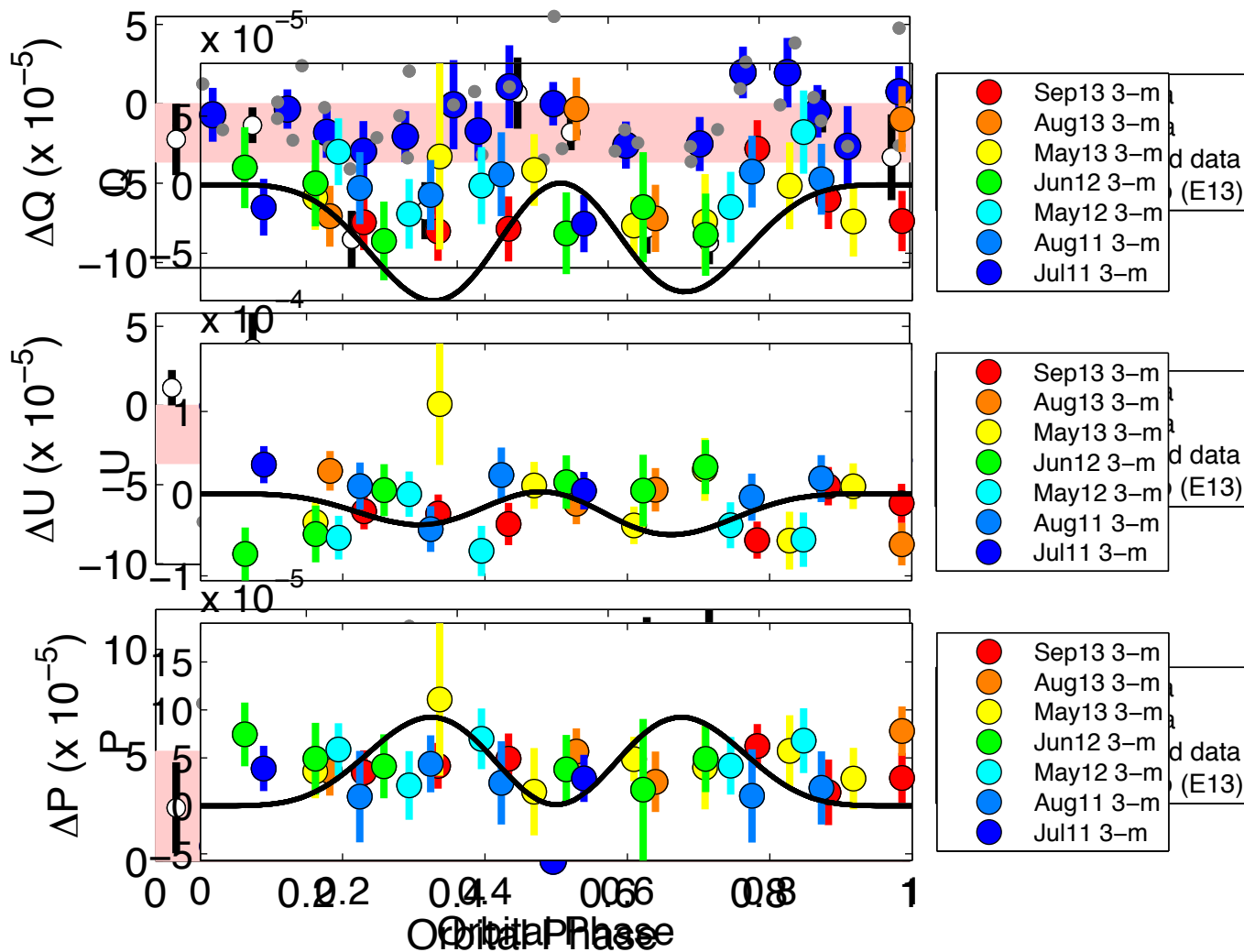
Systematic Effects

Sensitivity: Photon Noise



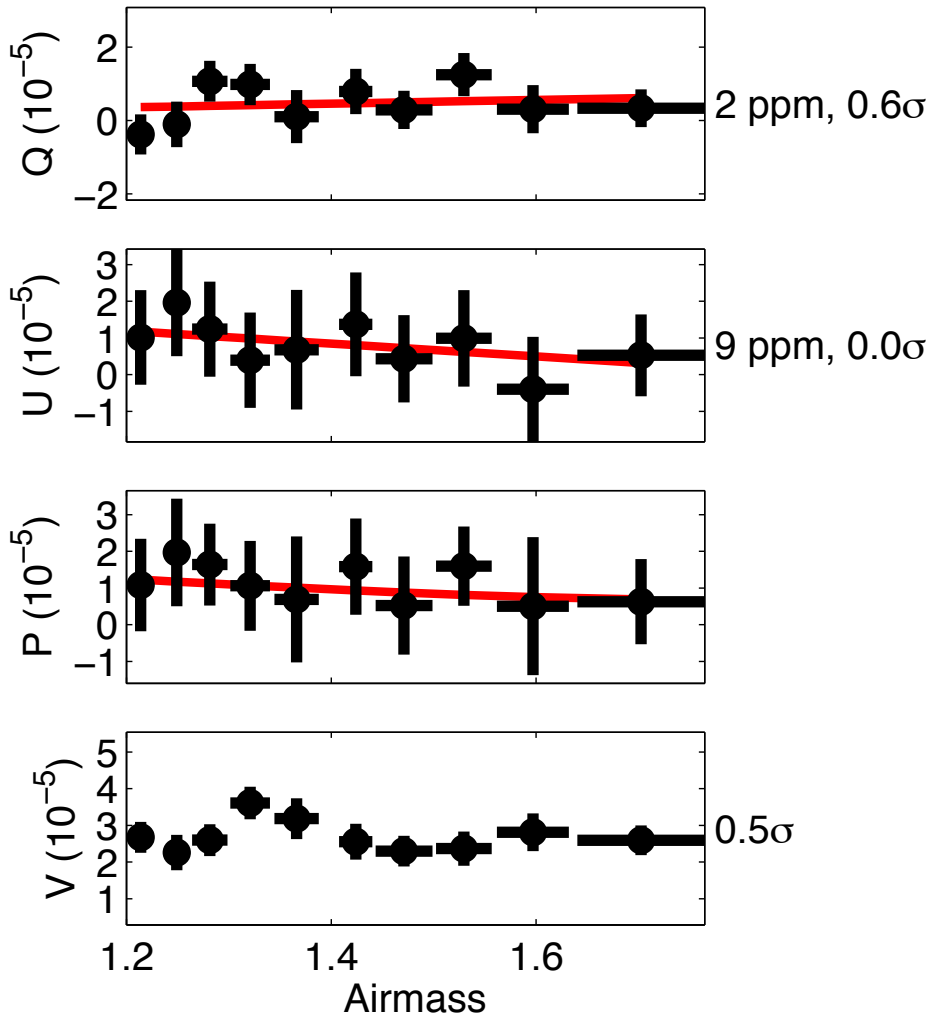
Spatially Unresolved Planets

HD 189733b (Wiktorowicz et al., in prep.: Lick 3-m, 35+ nights)



Systematic Effects

Accuracy: Airmass/Sky/Flexure via “Unpolarized” Star HR 4295



- Airmass, sky polarization, flexure insignificant for weakly polarized stars

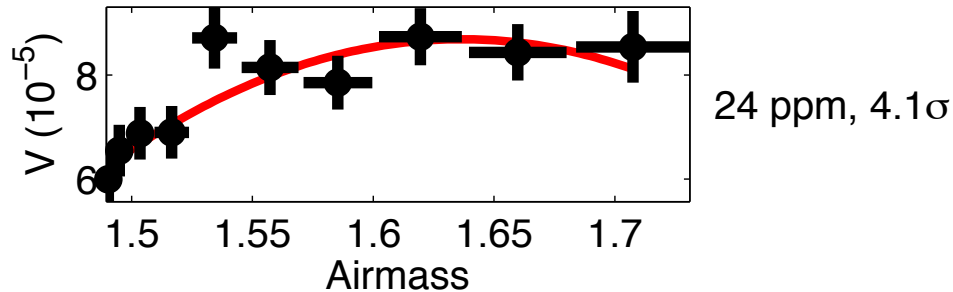
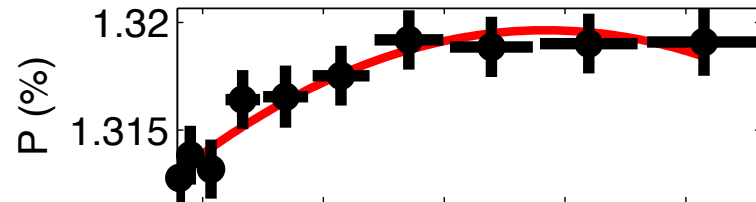
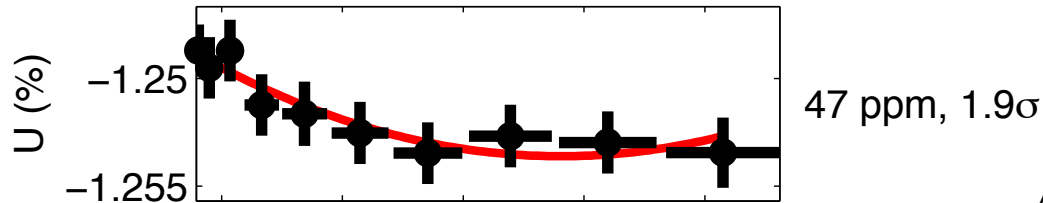
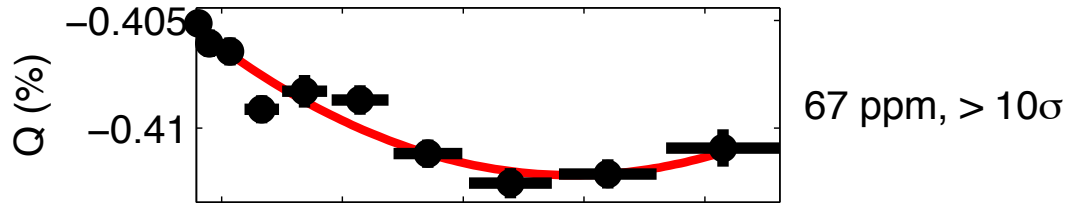
$$\frac{Q_{\text{star}}}{I_{\text{star}}} = \frac{Q_{\text{star+sky}} - Q_{\text{sky}}}{I_{\text{star+sky}} - I_{\text{sky}}}$$

$$\frac{Q_{\text{star}}}{I_{\text{star}}} \neq \frac{Q_{\text{star+sky}}}{I_{\text{star+sky}}} - \frac{Q_{\text{sky}}}{I_{\text{sky}}}$$

- $> 10^{12}$ sky photons not needed for ppm accuracy on star!

Systematic Effects

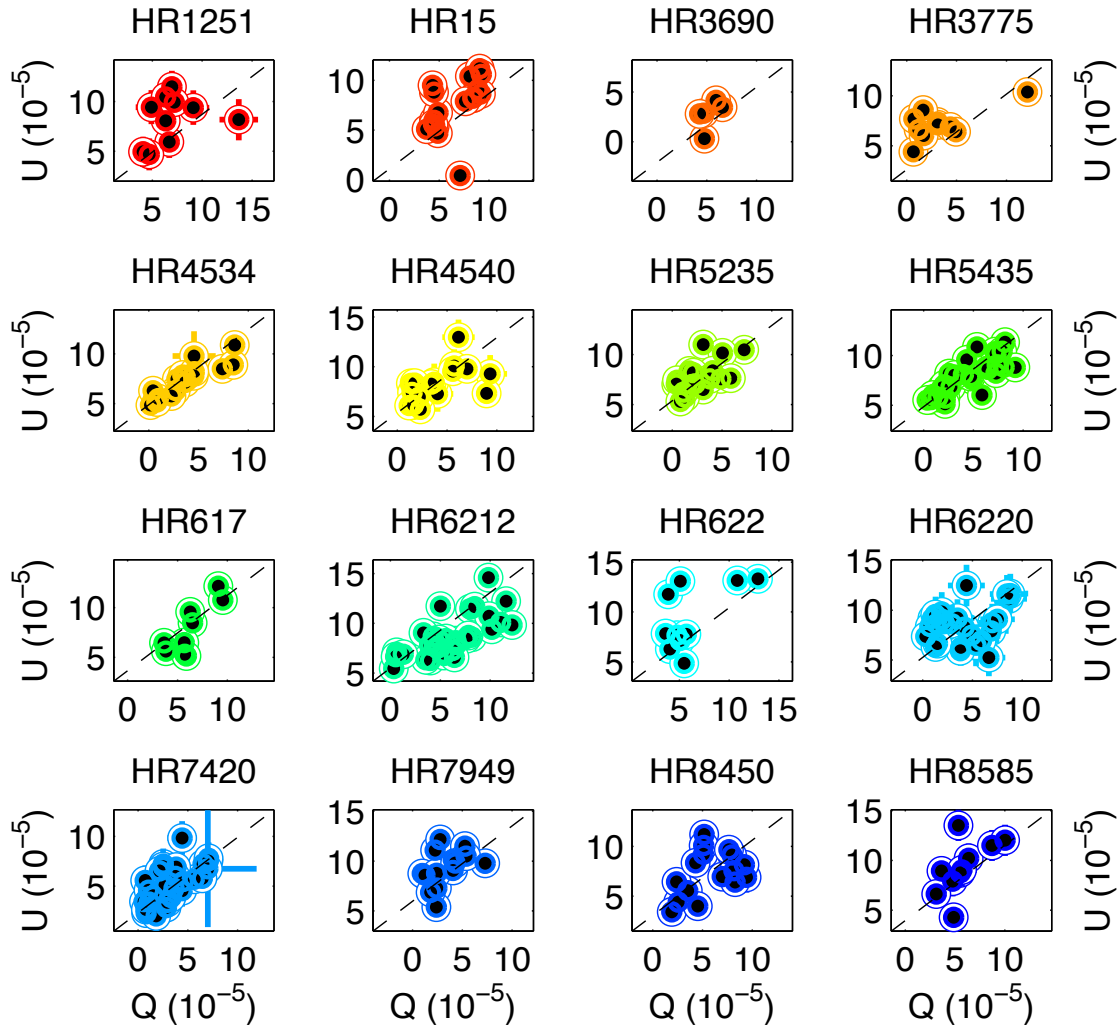
Accuracy: Airmass/Flexure (?) via Polarized Star ζ Oph



Airmass, flexure significant
for strongly polarized stars
($\approx P / 200$ effect)

Systematic Effects

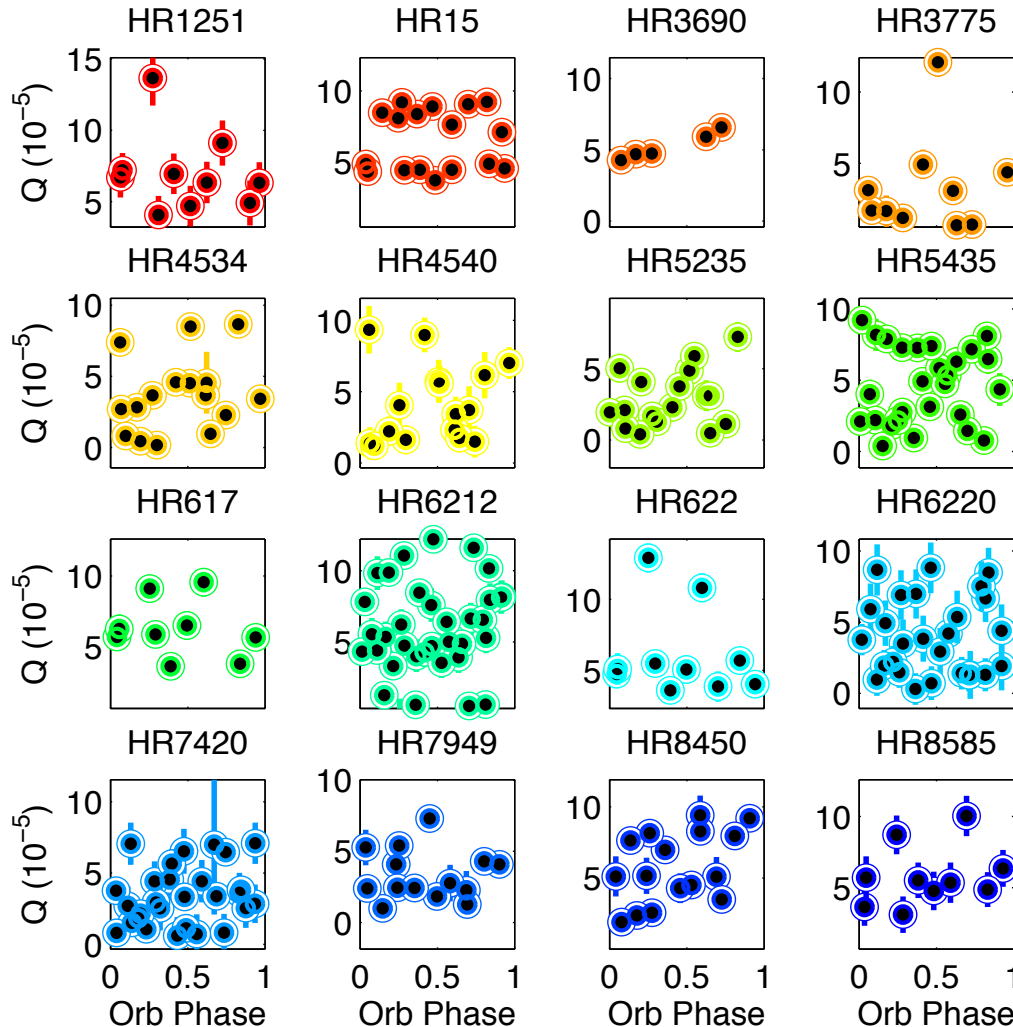
Accuracy: Telescope Polarization via “Unpolarized” Stars



- Amplitudes $\approx 10^{-4}$
- Q, U correlated

Systematic Effects

Accuracy: Telescope Polarization via “Unpolarized” Stars

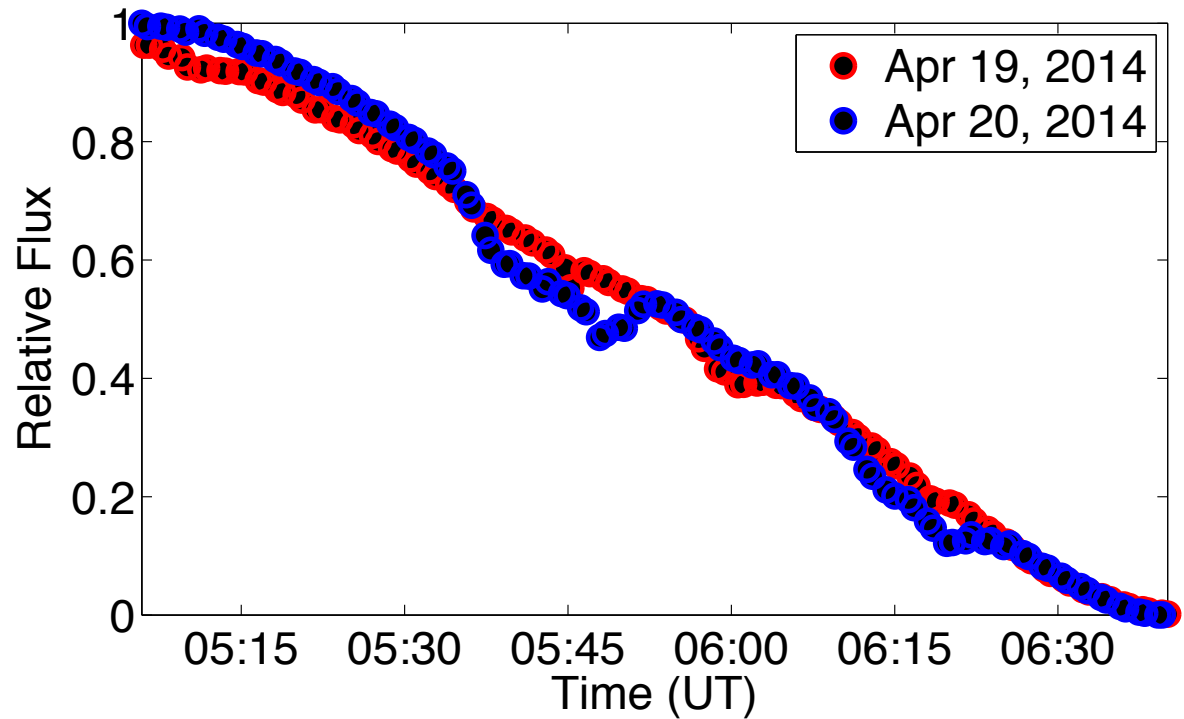
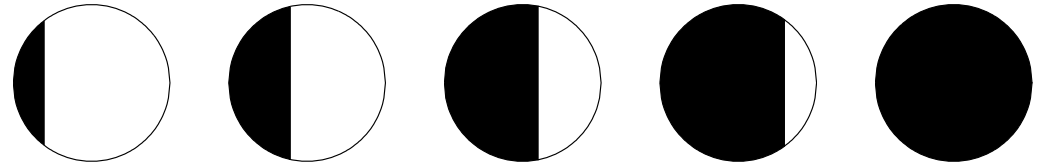


- Q , orbital phase usually uncorrelated, but not always!
- Same calibrators must be observed nightly or else bias introduced
- **Bad hypothesis:** Can we see modulation in known exoplanet system?
- **Good hypothesis:** If unknown which star harbored exoplanet, could we identify it?

Systematic Effects

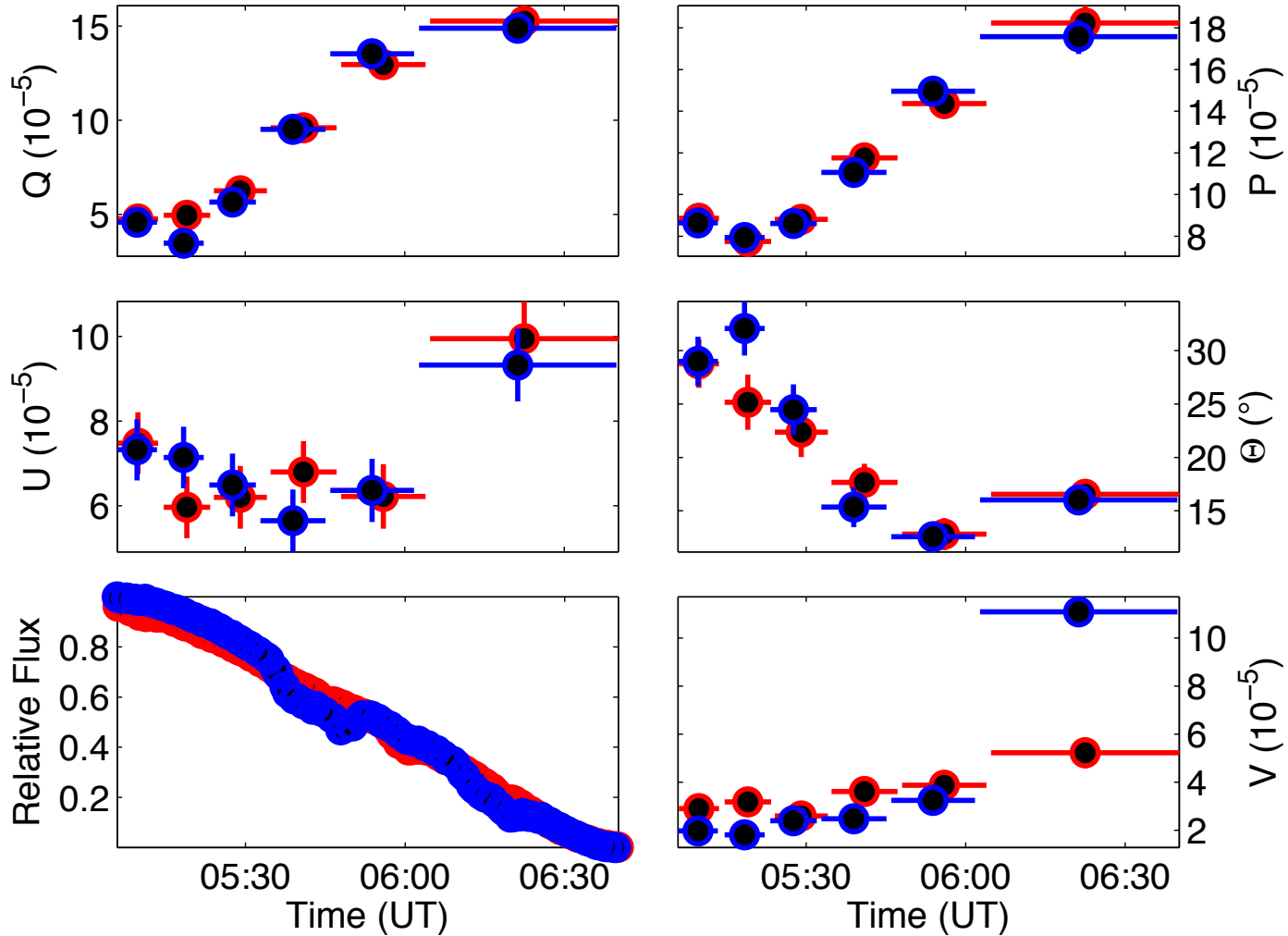
Accuracy: Telescope Polarization Mapping

- Halt dome motion, allow dome to occult mirror while tracking star
- Maps polarization across mirror
- Repeat next night to observe changes



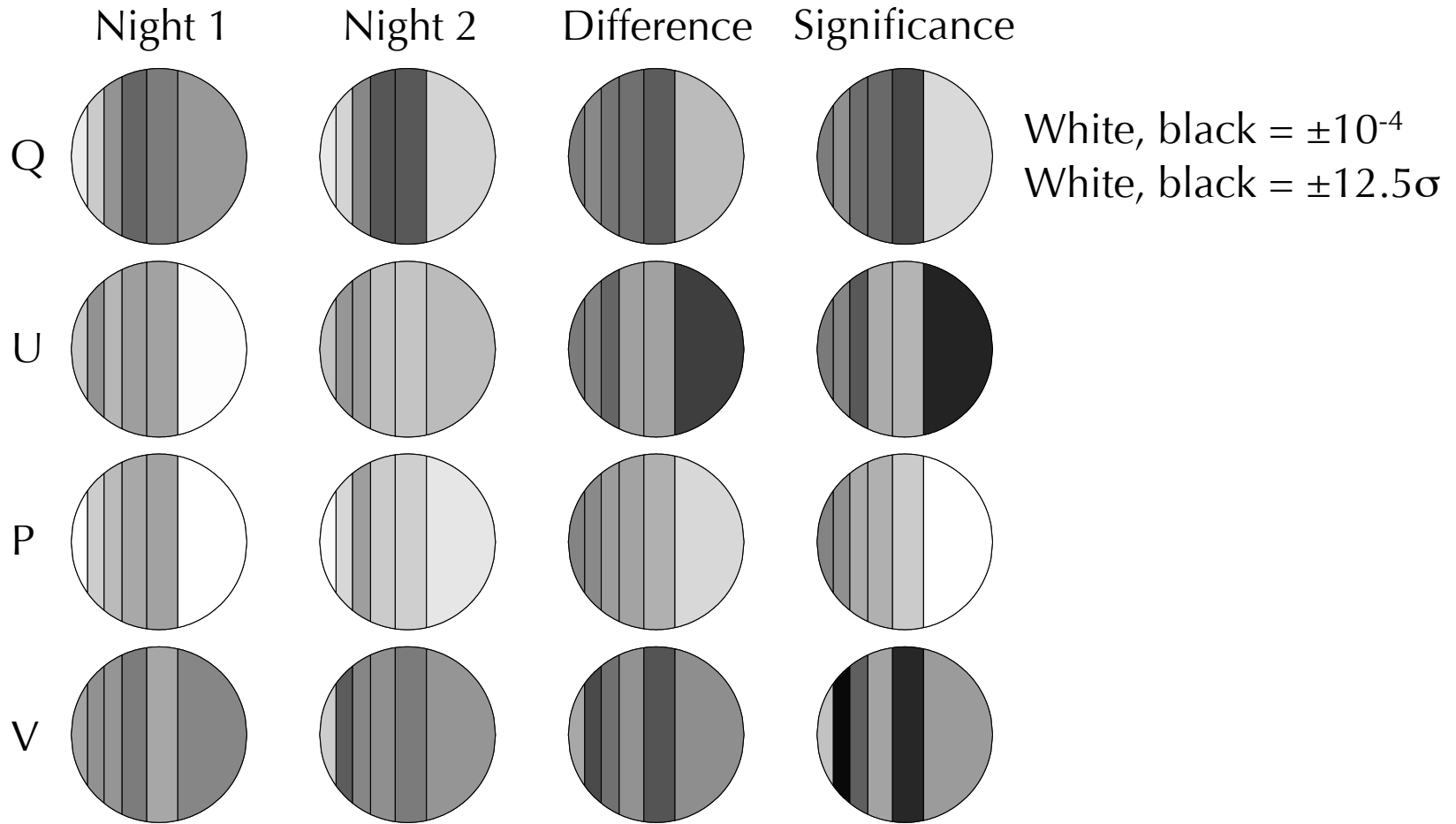
Systematic Effects

Accuracy: Telescope Polarization Mapping



Systematic Effects

Accuracy: Telescope Polarization Mapping



Conclusion

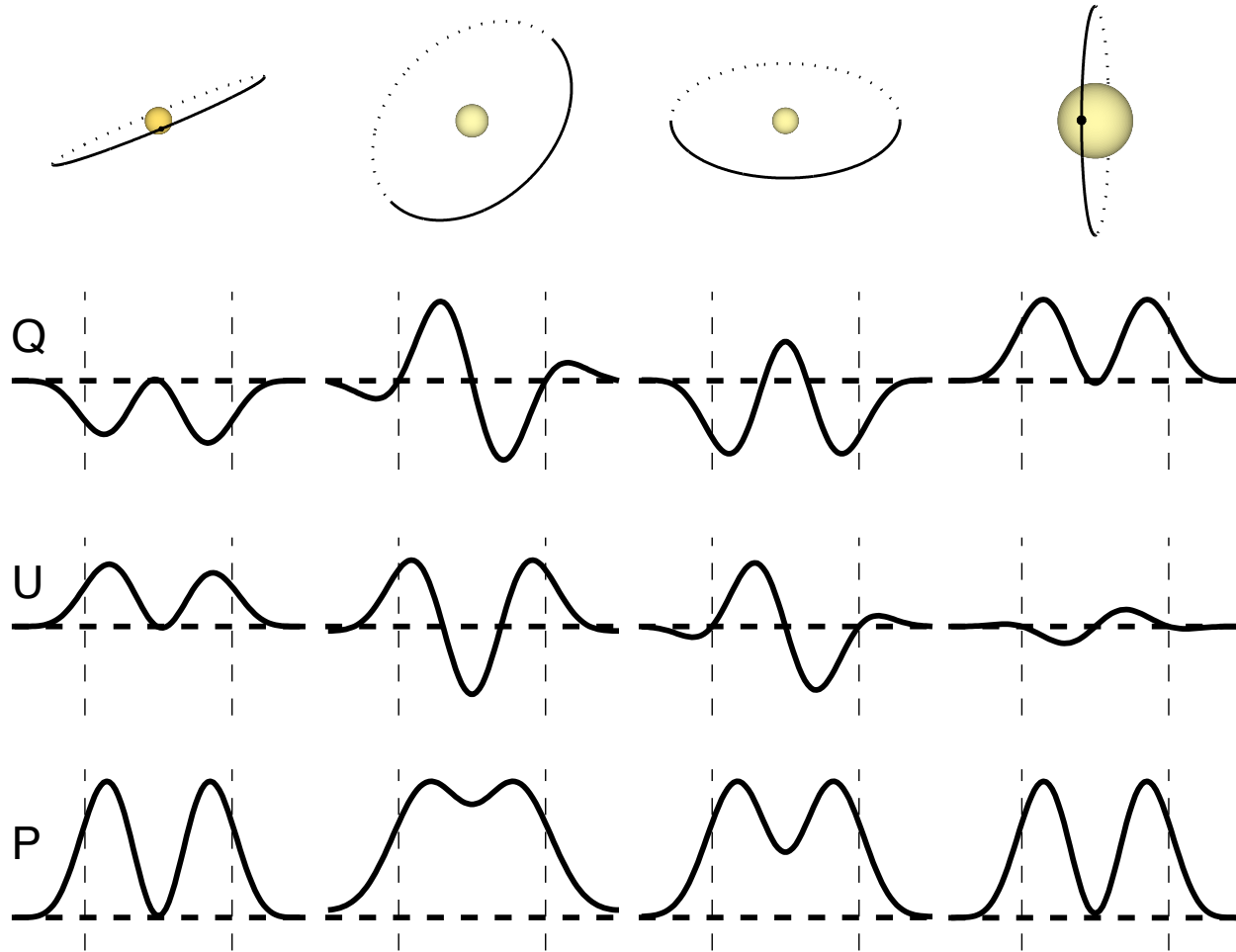
- Scattered light from exoplanets will be polarized
 - Orbital inclination (resolve $M \sin i$)
 - Presence or lack of clouds
 - Composition of clouds if exist
- Burden of proof is on observer: must show that modulation **requires** exoplanet, as opposed to “is not inconsistent with” exoplanet
 - Observe successive occultations for variability from all other sources
- HD 189733b polarized, scattered light detection: **falsified**
- Systematic effects severe even on equatorial telescope
 - Strongly polarized star: airmass/flexure significant
 - “Unpolarized” star: **airmass/flexure insignificant, sky well calibrated**
 - “Unpolarized” stars show variability, assumption that always uncorrelated with exoplanet period **falsified**
 - Map telescope polarization by occulting mirror with dome
 - Statistically significant **spatial and temporal variations in telescope polarization**



polish2

Spatially Unresolved Planets

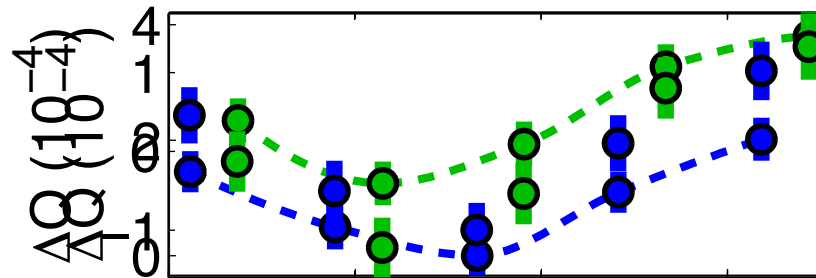
Longitude of Ascending Node from Scattered Light



POLISH2

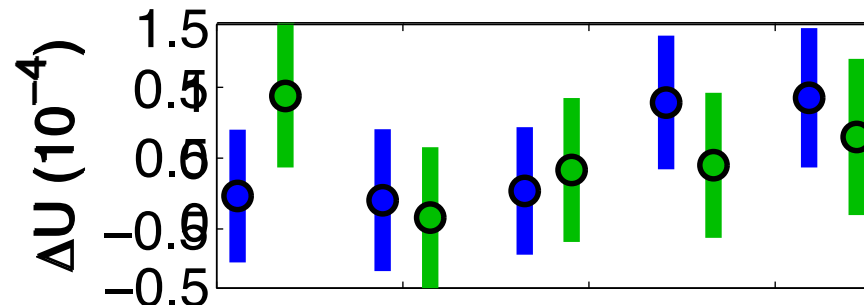
Vesta Observations (Known $\sim 0.01\%$ Variable)

$$Q_{B \text{ band}} = 0.2868(16)\%$$
$$Q_{V \text{ band}} = 0.3015(17)\%$$



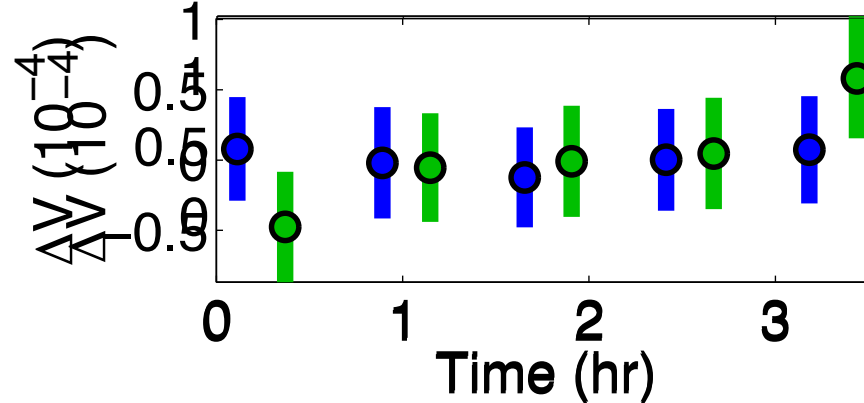
$$\text{Error } Q_{B \text{ band}} = 0.0036\%$$
$$\text{Error } Q_{V \text{ band}} = 0.0039\%$$

$$U_{B \text{ band}} = 0.0356(21)\%$$
$$U_{V \text{ band}} = 0.0386(23)\%$$



$$\text{Error } U_{B \text{ band}} = 0.0047\%$$
$$\text{Error } U_{V \text{ band}} = 0.0051\%$$

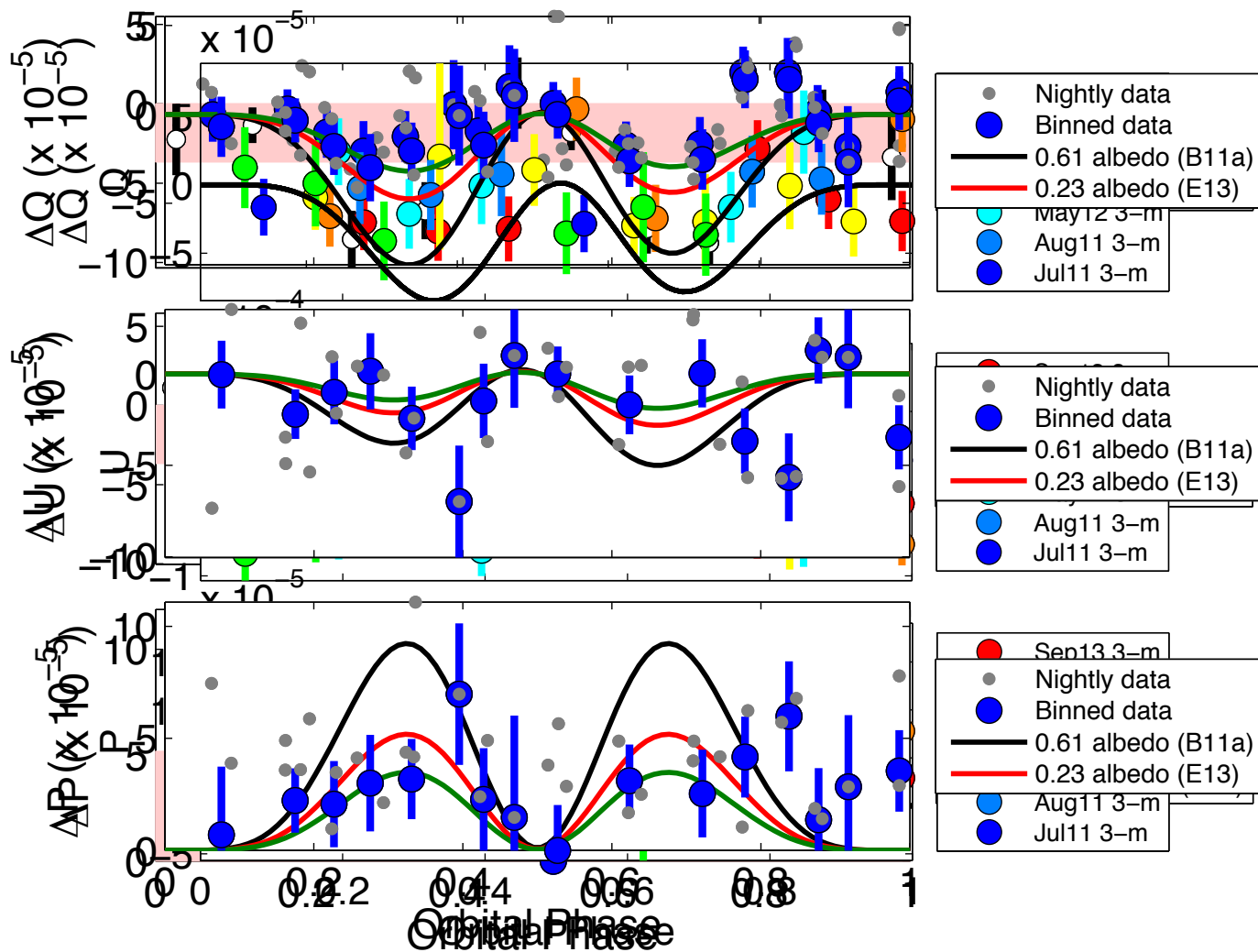
$$V_{B \text{ band}} = 0.0197(17)\%$$
$$V_{V \text{ band}} = 0.0226(18)\%$$



$$\text{Error } V_{B \text{ band}} = 0.0037\%$$
$$\text{Error } V_{V \text{ band}} = 0.0040\%$$

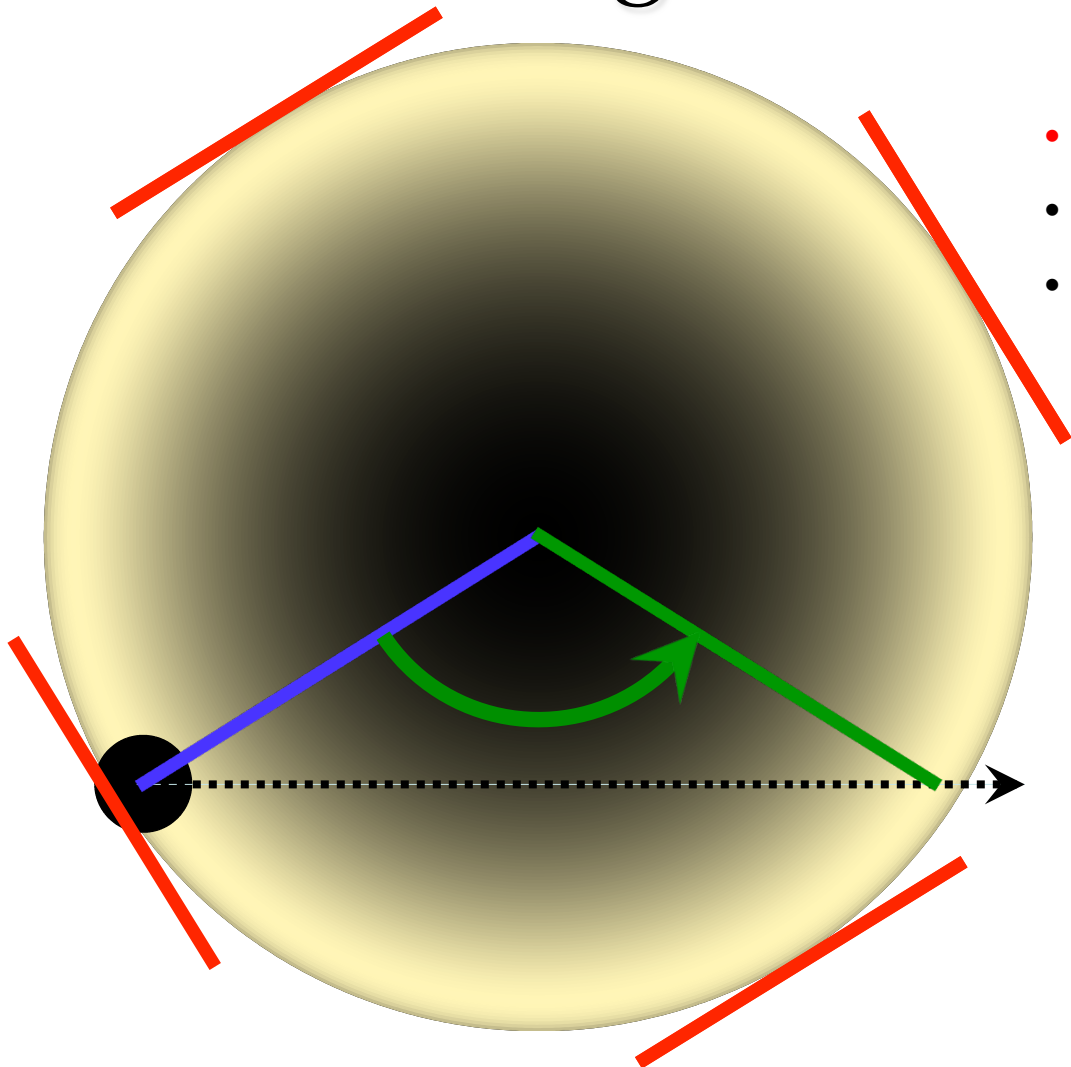
Spatially Unresolved Planets

HD 189733b (Wiktorowicz et al., in prep.: Lick 3-m, 35+ nights)





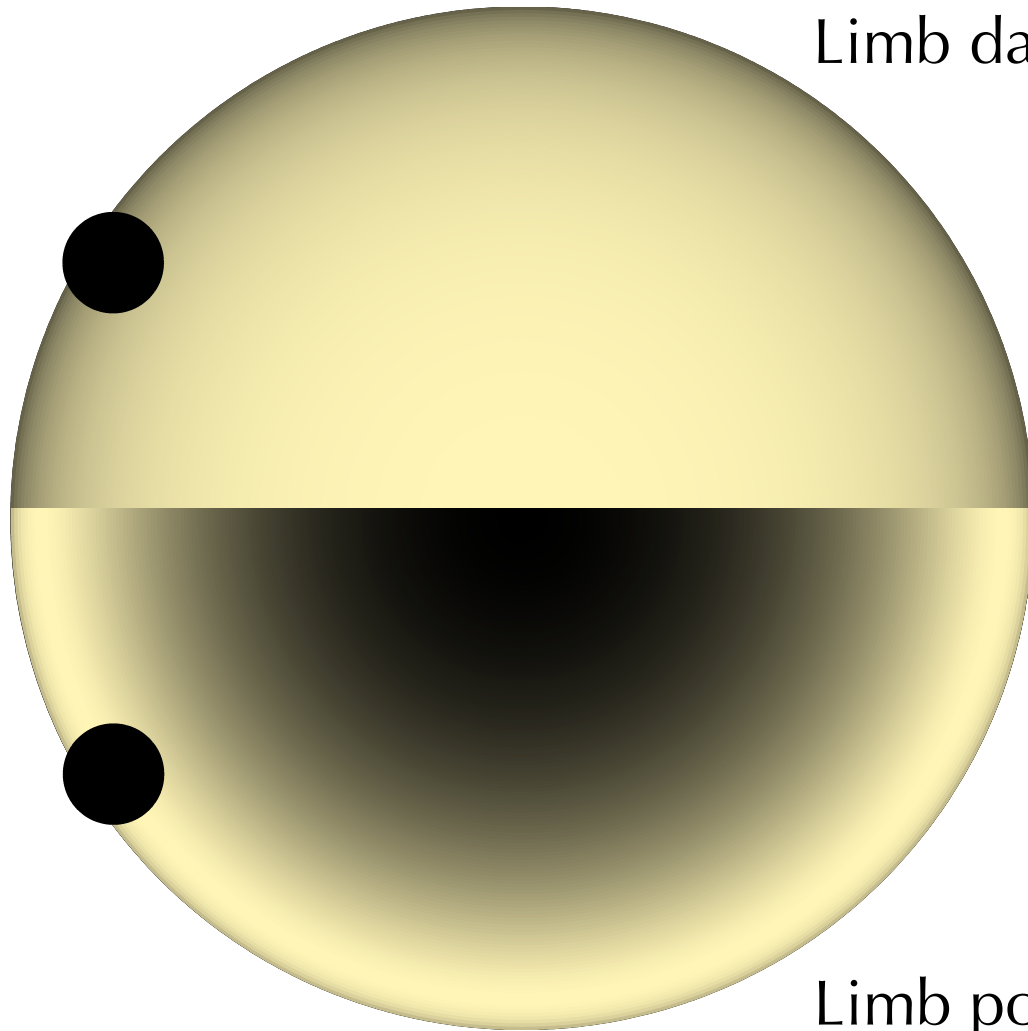
Ingress Polarization



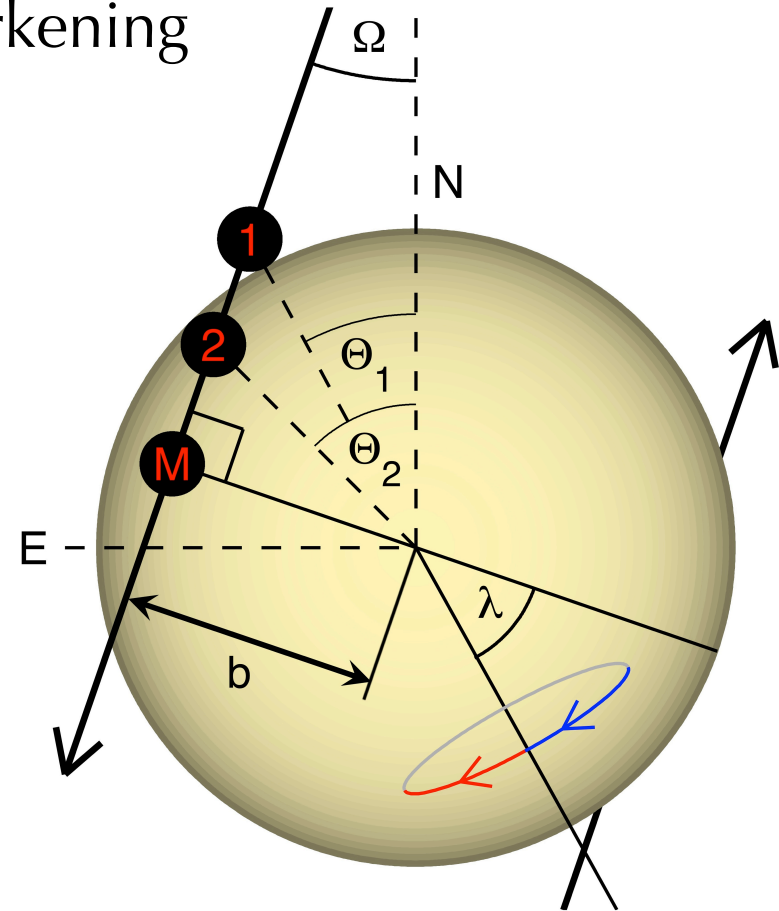
- **Limb polarized tangent to limb**
 - Integrated stellar polarization = 0
 - Limb occultation at ingress:
 - Asymmetry
 - Polarization spike
 - **Polarization PA parallel to line joining stellar / planet centers**
 - **PA rotates during transit**
- CW for "Northern" Hem. transit
 CCW for "Southern" Hem. transit

Spatially Unresolved Planets

Transit Polarimetry (Nagirner 1962; Carciofi & Magalhães 2005)



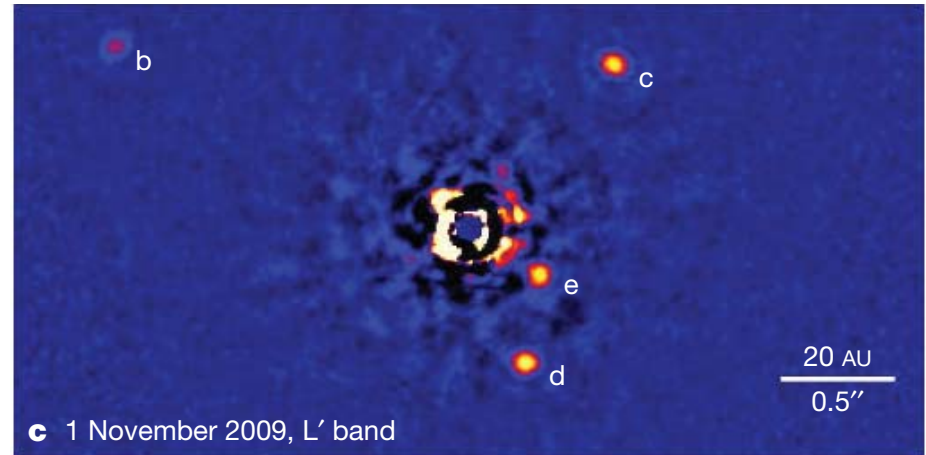
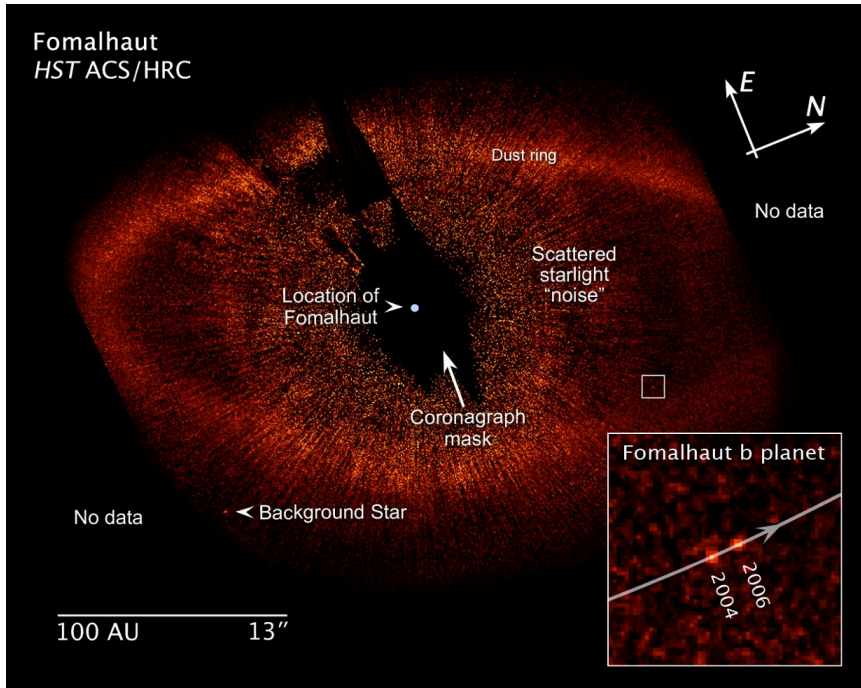
Limb darkening



Limb polarization

Spatially Resolved Planets

Last But Not Least



Thermal Emission: Most rapid rotators

GPI
SPHERE IRDIS

Scattered Light: Closest stars
SPHERE ZIMPOL