Polarimetry as a tool
(for exoplanet detection and characterization)

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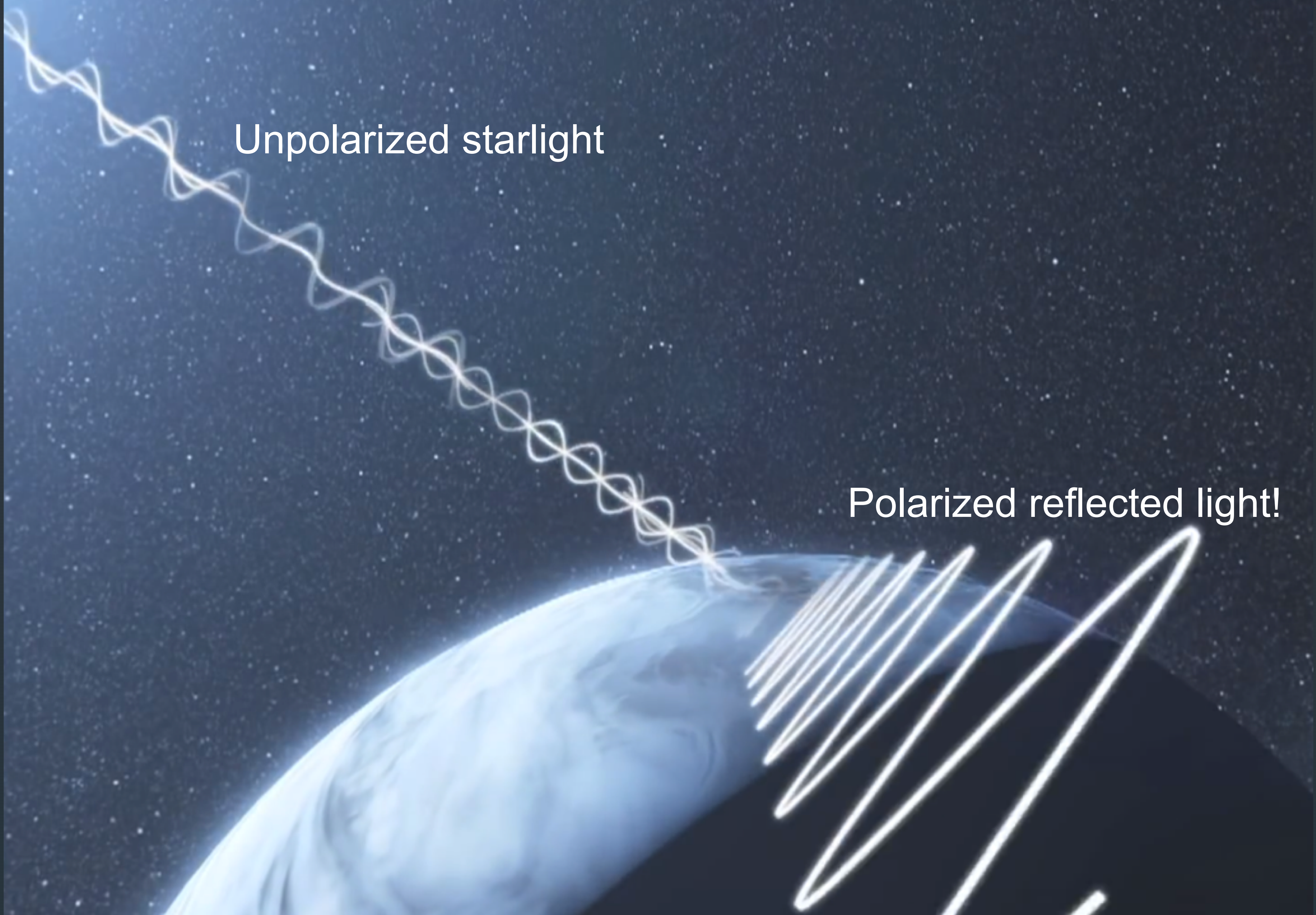
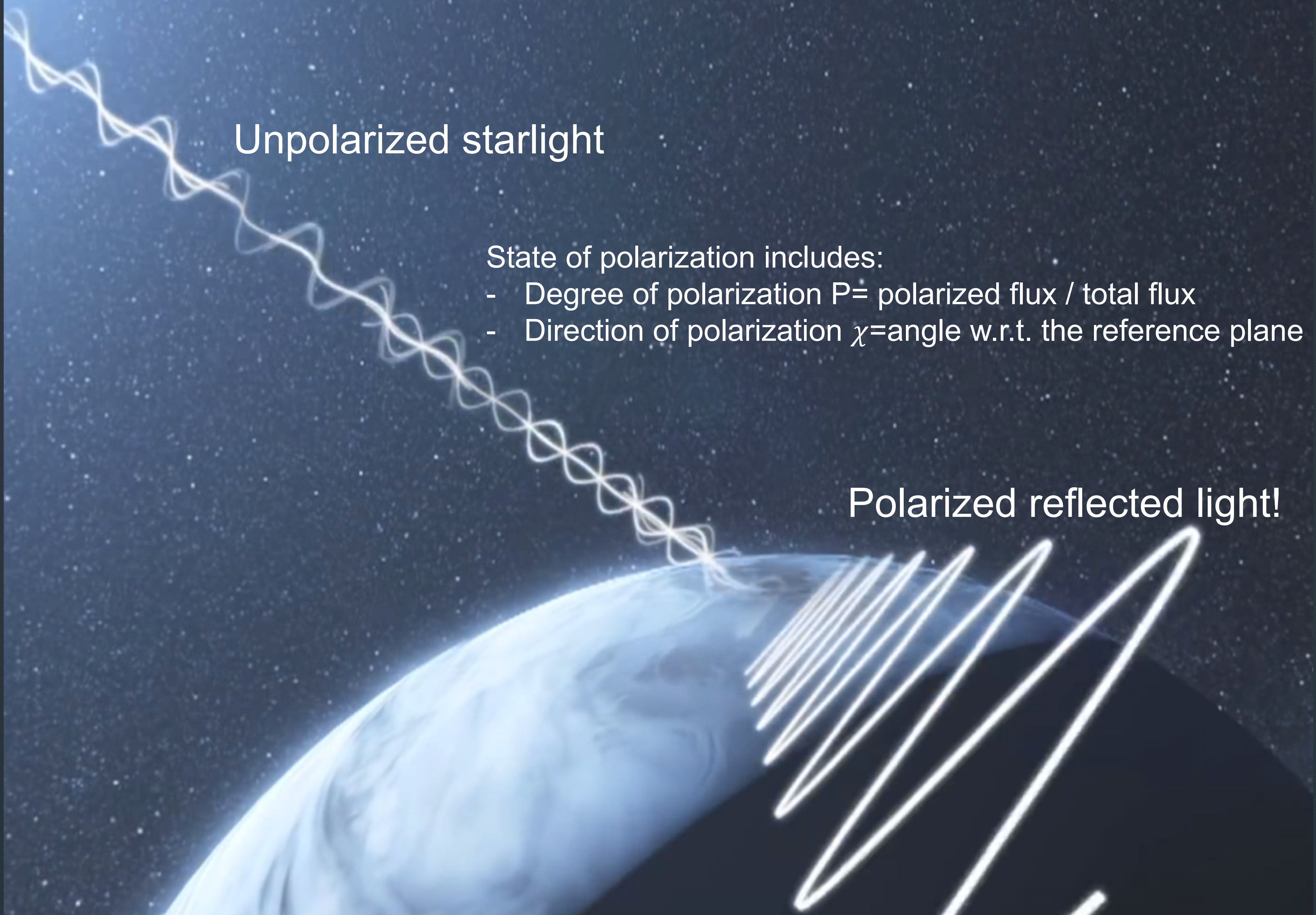
IPAC/Caltech

With contributions from Daphne Stam (TU Delft), Christian Ginski (Leiden University), Ricky Nilsson (Caltech)


Unpolarized starlight
Polarized reflected light!



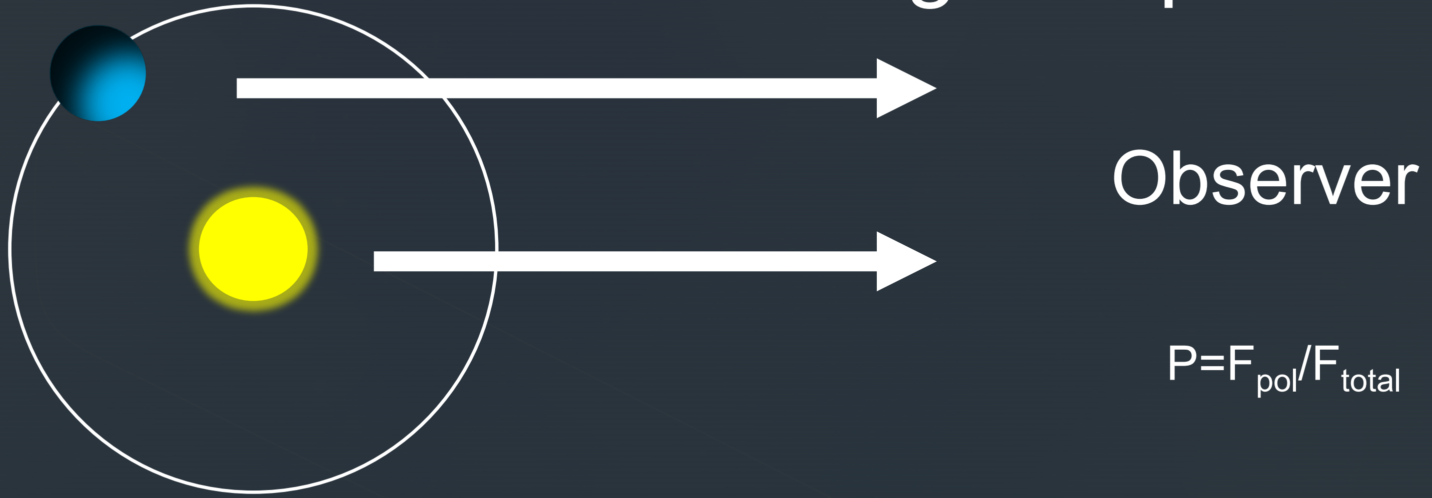
State of polarization includes:

- Degree of polarization P= polarized flux / total flux
- Direction of polarization χ=angle w.r.t. the reference plane

Important uses of Polarimetry

- Detecting exoplanets: polarized signal next to an unpolarized star
- Confirming exoplanet detections: background sources are usually unpolarized
- Characterizing exoplanets: atmospheres and/or planet surfaces
    - Some atmospheric properties cannot be measured with flux alone!

Degree of polarization from reflected starlight dependencies

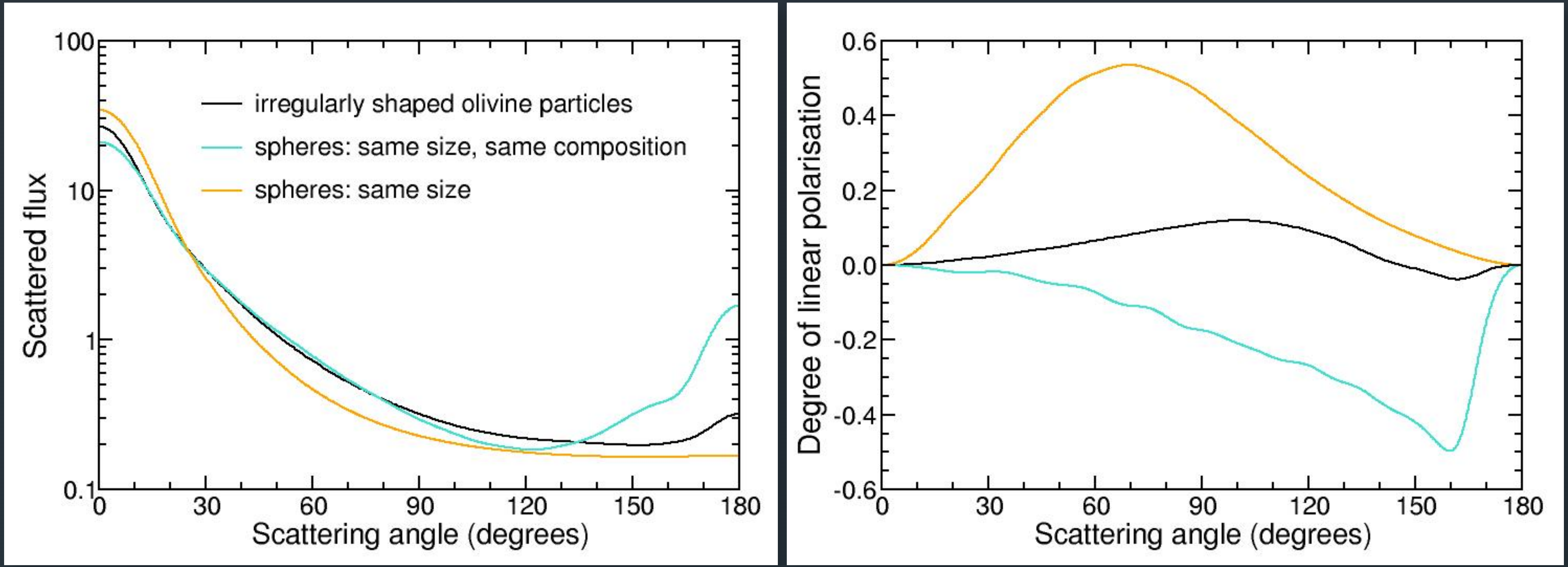


$P = F_{pol}/F_{total}$

- Composition and structure of planet’s atmosphere
  - Scattered by gaseous molecules
  - Scattered by aerosol and/or cloud particles
- Reflection properties of the planets surface
- Wavelength of light
- Illumination and viewing angle
  - Planetary phase angle

Applications of Polarimetry: Particles

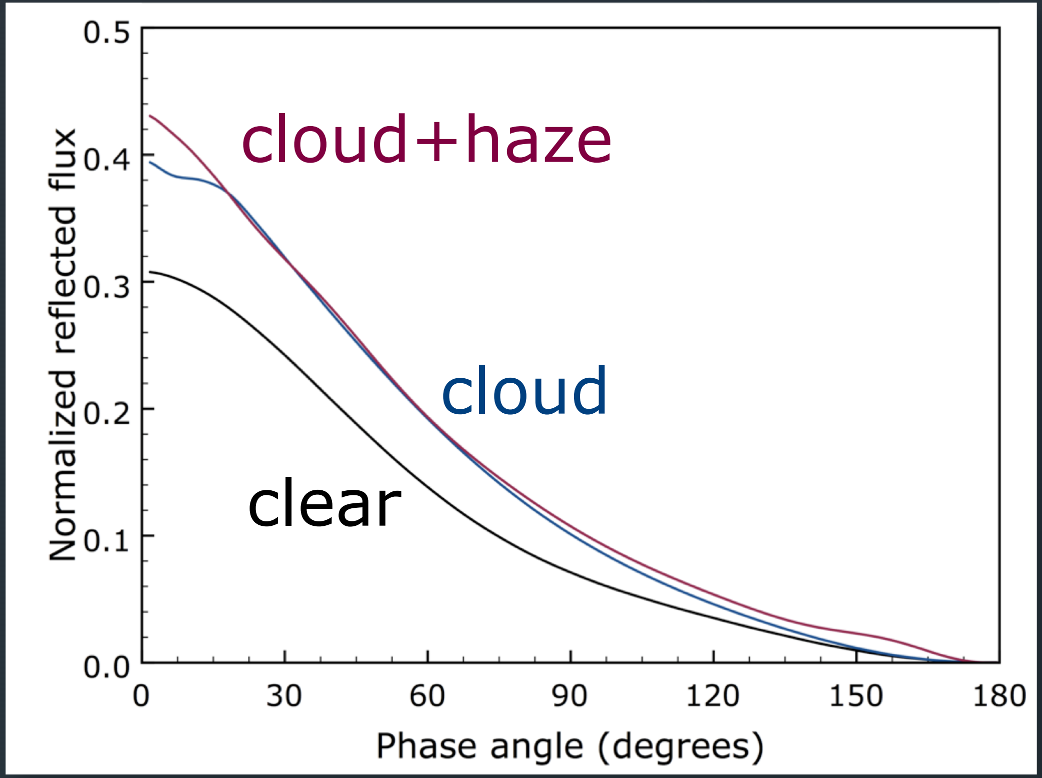
- Polarization of reflected light is very sensitive to the microphysical properties (size, composition, shape) of the scattering particles:

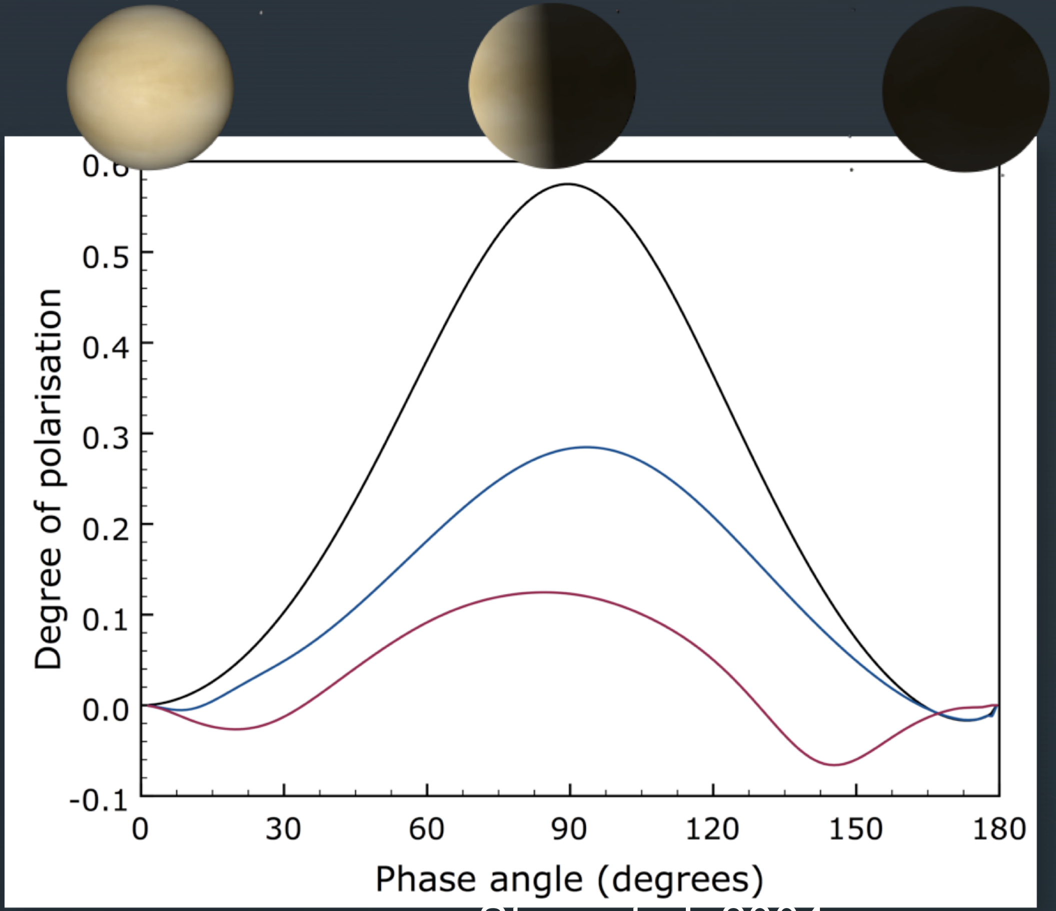


Source: Olga Muñoz

Applications of Polarimetry: atmosphere and surface

- Polarization of reflected light is very sensitive to the composition and structure of a planetary atmosphere and/or surface:





Stam et al. 2004

Polarimetry of reflected light from planets has been around for a long time

- 1929: Bernard Lyot measured the degree of linear polarization as a function of phase-angle of Venus, Mars, Jupiter, and Saturn
- 1957: Kuiper measured infrared polarization of Venus (2 microns)
- 1970s: Measure polarization of reflected light from 0.35 to 0.99 microns to derive size, composition, and altitude of Venus' cloud particles
- 1980s: Confirmed by probes: Pioneer Venus, haze characterization, variability in hazes

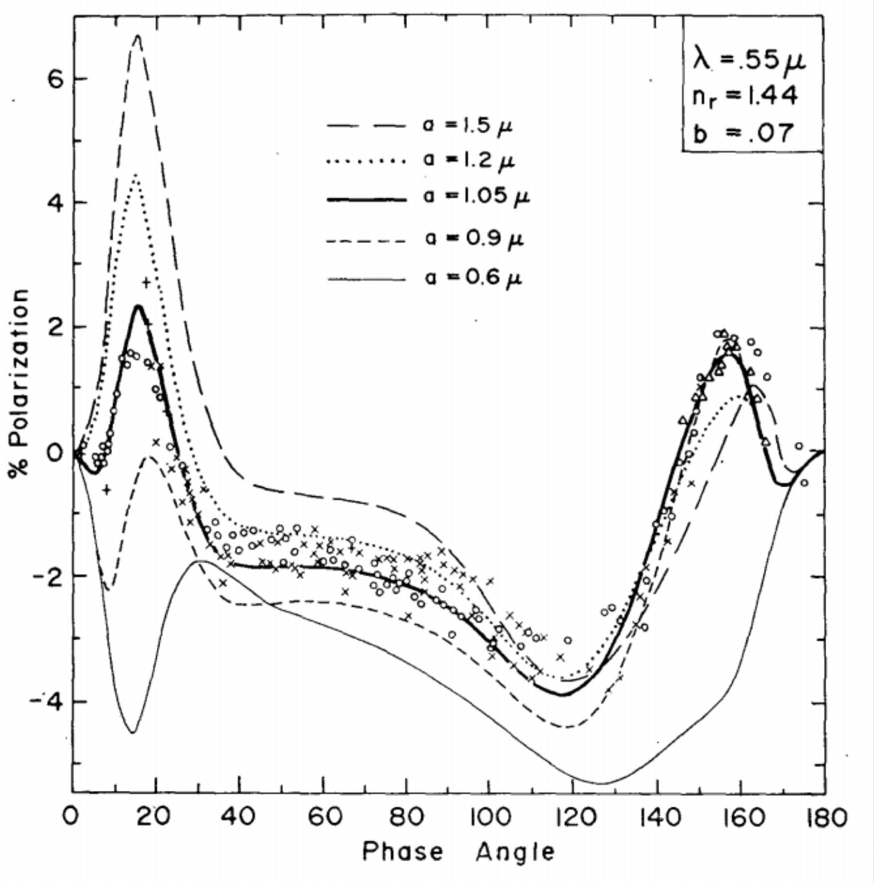


Fig. 4. Observations of the polarization of sunlight reflected by Venus in the visual wavelength region and theoretical computations for $\lambda = 0.55\ \mu m$. The ○'s are wide-band visual observations by Lyot (1929) while the other observations are for an intermediate bandwidth filter centered at $\lambda = 0.55\ \mu m$; the ×'s were obtained by Coffeen and Gehrels (1969), the +'s by Coffeen (cf. Dollfus and Coffeen, 1970), and the Δ's (which refer to the central part of the crescent) by Veverka (1971). The theoretical curves are all for a refractive index 1.44, the size distribution (8) with $b = 0.07$, and a Rayleigh contribution $f_R = 0.045$. The different curves show the influence of the effective radius on the polarization.

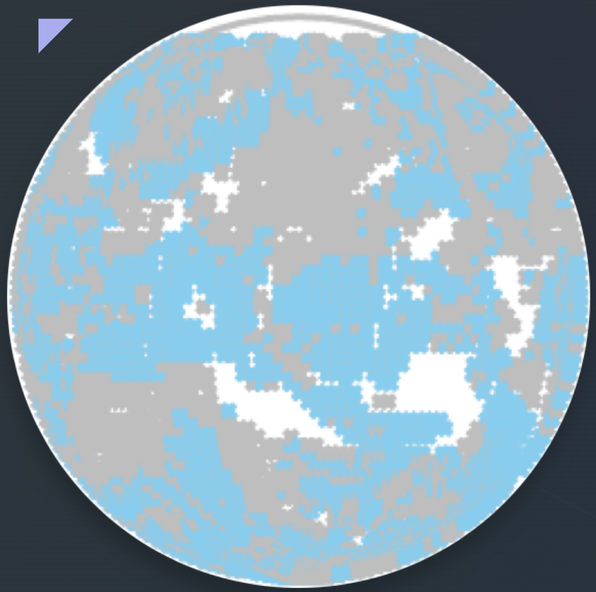
Hansen & Hovenier 1974

Polarization of Earth

- Broadband polarimetric measurements of disk-integrated Earthshine found a (true) linear polarization of about 30-35% at 90º (Dollfus et al. 1957)
- Sterzik et al. 2012 used FORS/VLT to measure linear spectropolarization of Earthshine
  - April: 10-15% cloud-free land vegetation
  - June: Little or absent cloud-free vegetation surfaces
  - Used to infer biosignatures

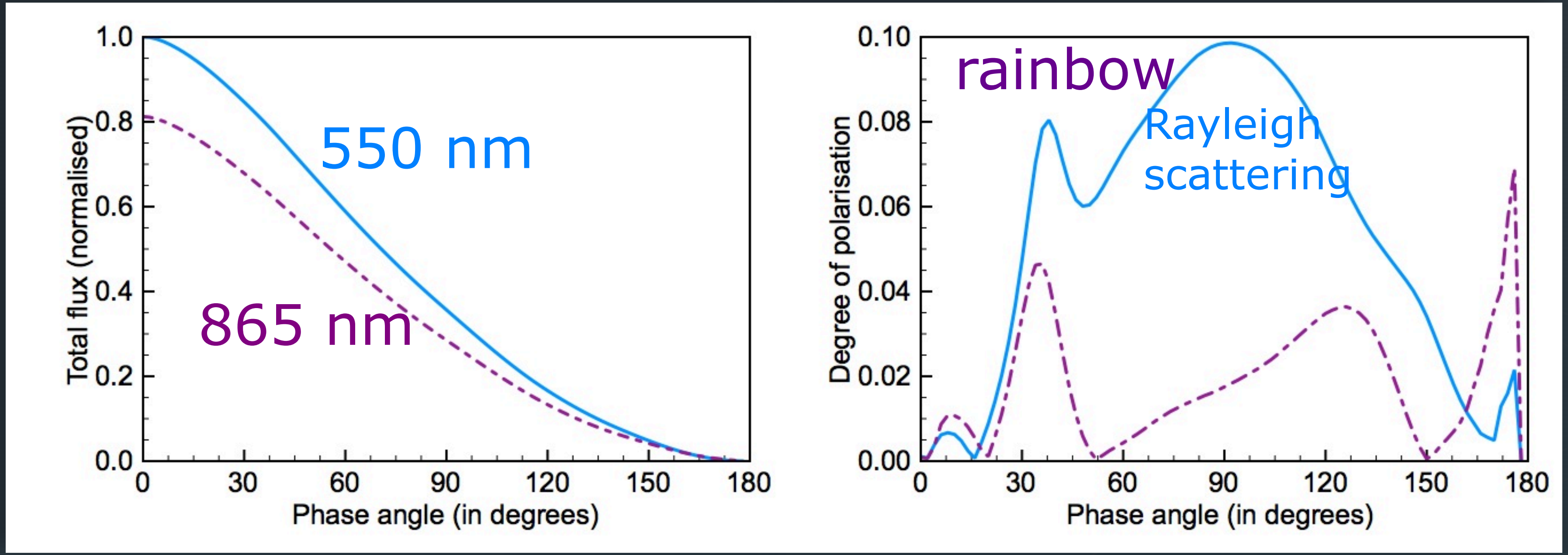
Table 1 | Earth observations

	Observing date	
Observations	25 April 2011, 09:00 UT	10 June 2011, 01:00 UT
View of Earth as seen from the Moon		
Sun–Earth–Moon phase (degrees)	87	102
Ocean fraction in Earthshine (%)	18	46
Vegetation fraction in Earthshine (%)	7	3
Tundra, shrub, ice and desert fraction in Earthshine (%)	3	1
Total cloud fraction in Earthshine (%)	72	50
Cloud fraction $\tau > 6$ (%)	42	27

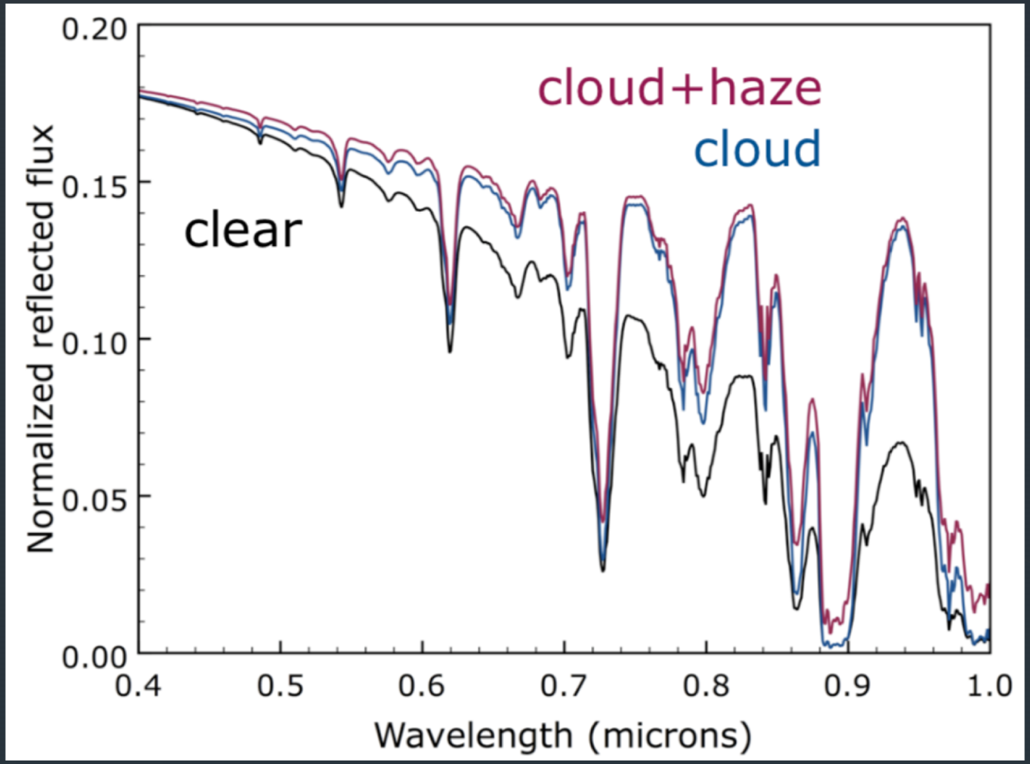


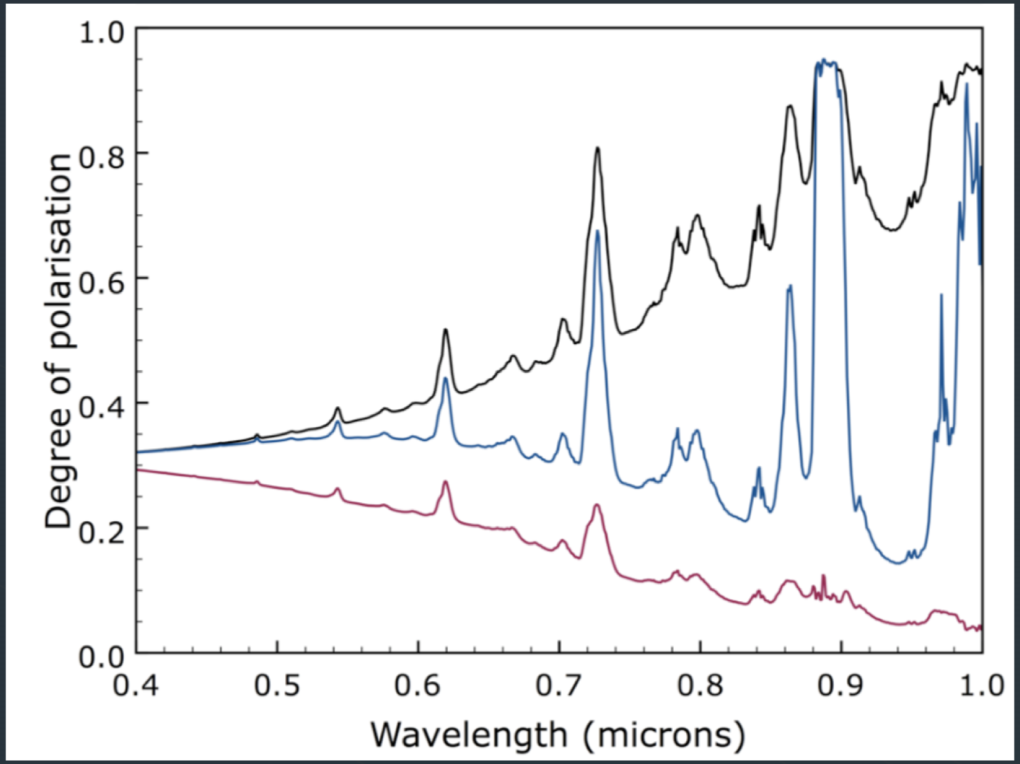
Polarization of Earth

- Karalidi et al. (2010) made a model of earth with realistic cloud coverage from remote-sensing satellite data (MODIS)
  - 64% liquid water clouds, 36% ice clouds, 28% 2 cloud layers



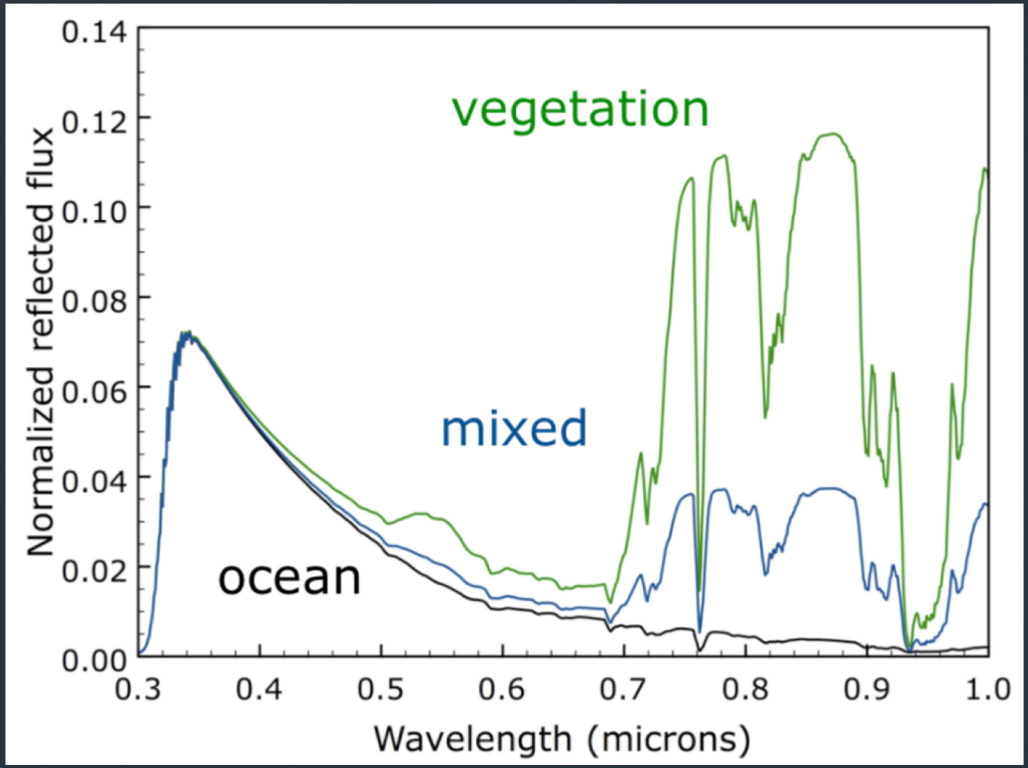
Exoplanets: Simulations of reflected light gaseous planets

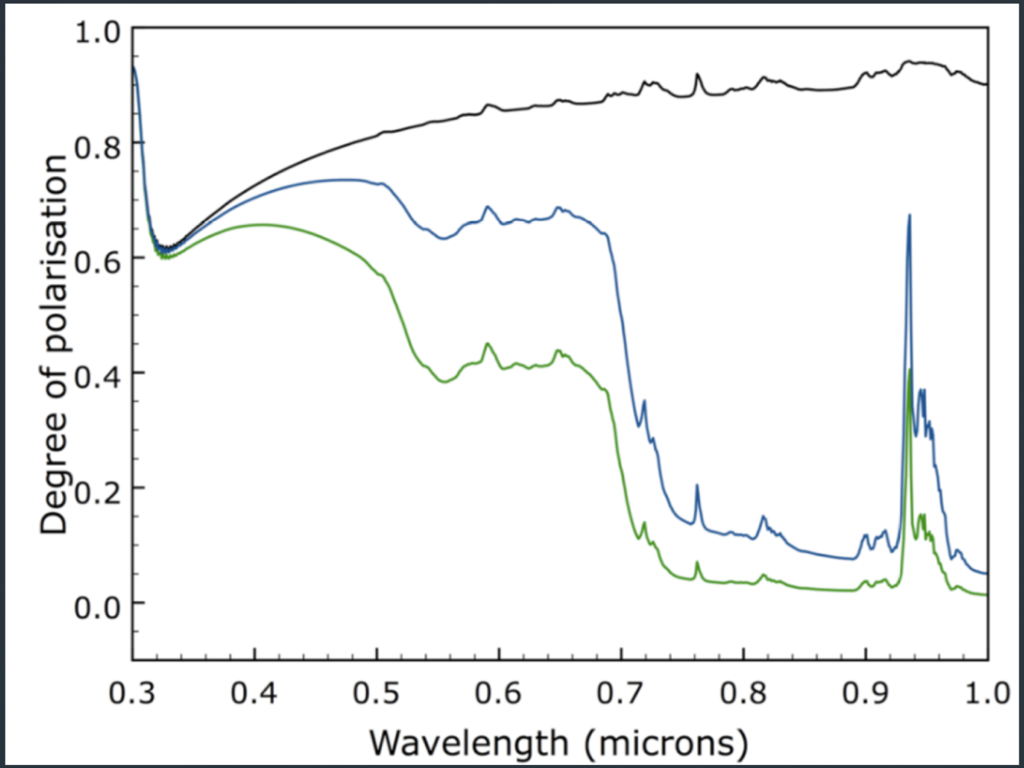




Planetary phase angle 90º
Jupiter-like horizontally homogeneous atmospheres.
Stam et al. 2004

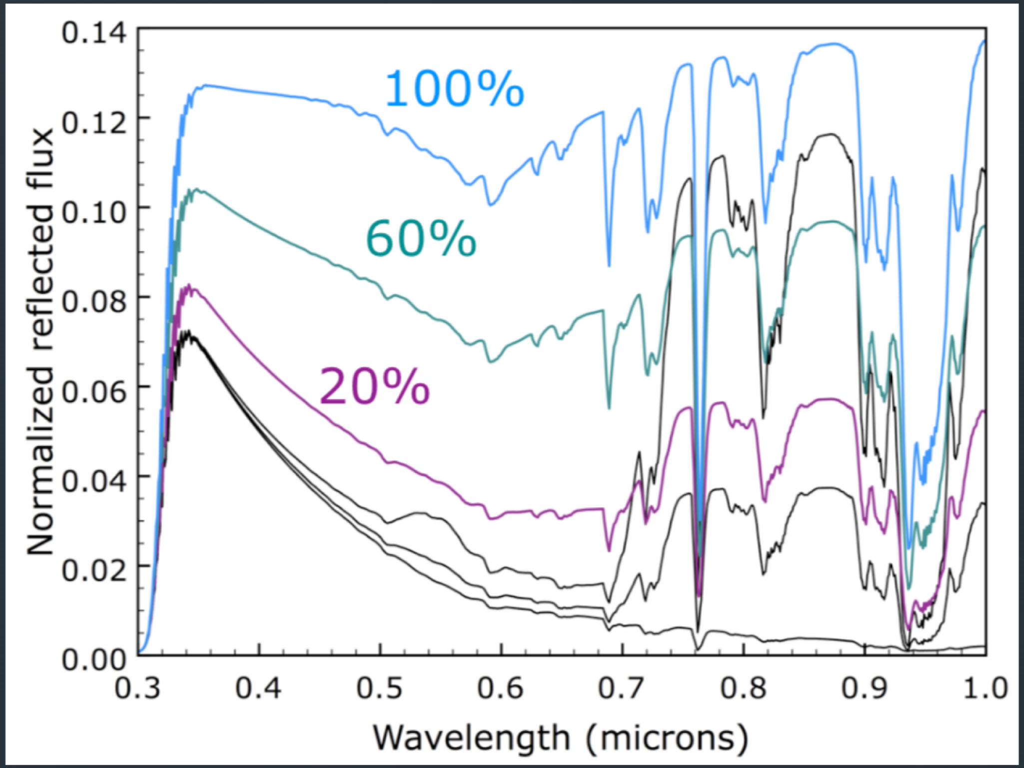
Exoplanets: Simulations of Earth-like Exoplanets (cloud free)

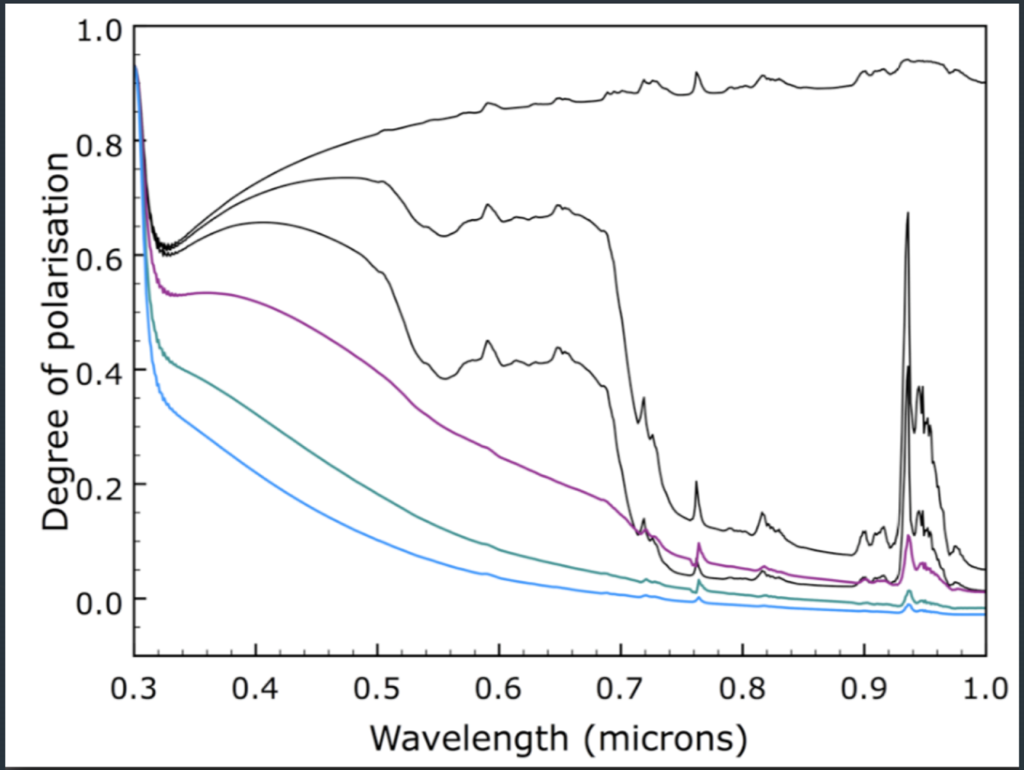




Planetary phase angle 90º
Cloud-free planets with surfaces covered by: 100% vegetation, 100% ocean, 30% veg + 70% ocean.
Stam et al. 2008

Exoplanets: Simulations of Earth-like Exoplanets (with clouds)



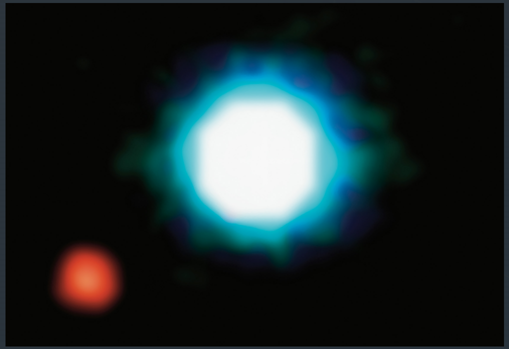


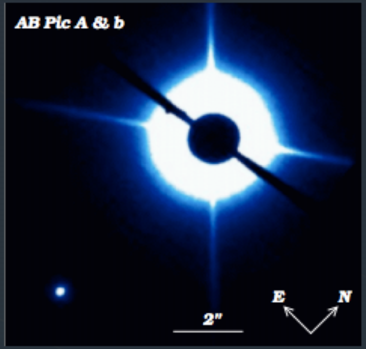
Planetary phase angle 90º
Cloud-free Planets with surfaces covered by: 100% vegetation, 100% ocean, 30% veg + 70% ocean.
Mixed planet with cloud coverage of 20%, 60%, 100%.
Stam et al. 2008

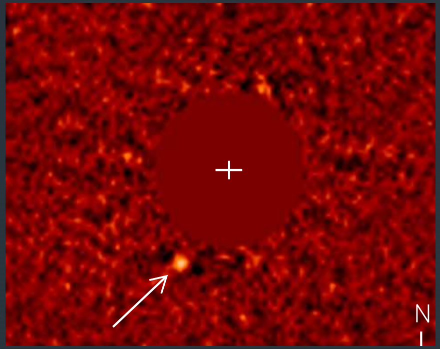
Challenges of polarimetry

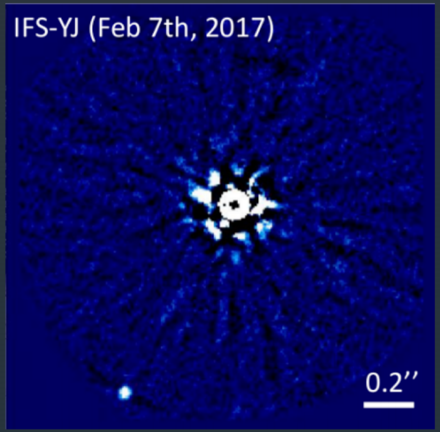
- Other sources of polarimetry
  - Instrumental polarimetry
  - Optics/reflections off mirrors
  - Interstellar clouds
  - Stellar small unresolved disk
- Degree of polarization is very small at small phase angles
- Faint objects are difficult to observe – lose photons
- Lack of calibration sources
- Fitting data can be difficult -- radiative transfer algorithms with polarization are complicated and time-consuming
- Reflected light vs thermal …

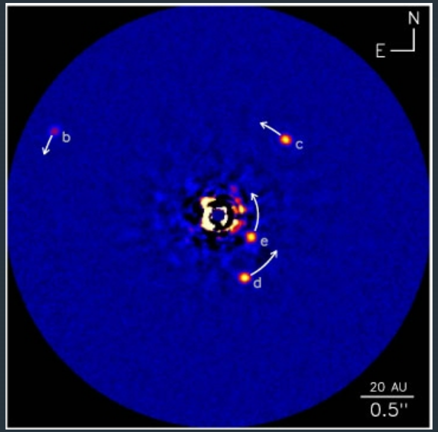
Current imaged planets are self-luminous

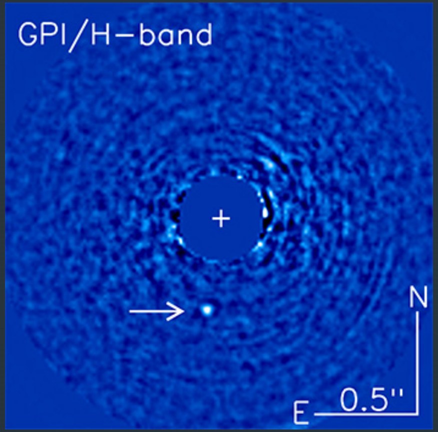


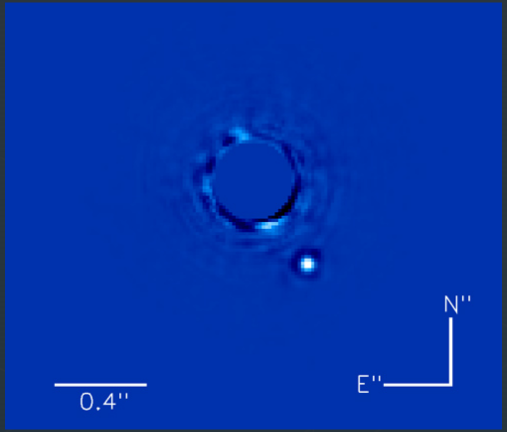




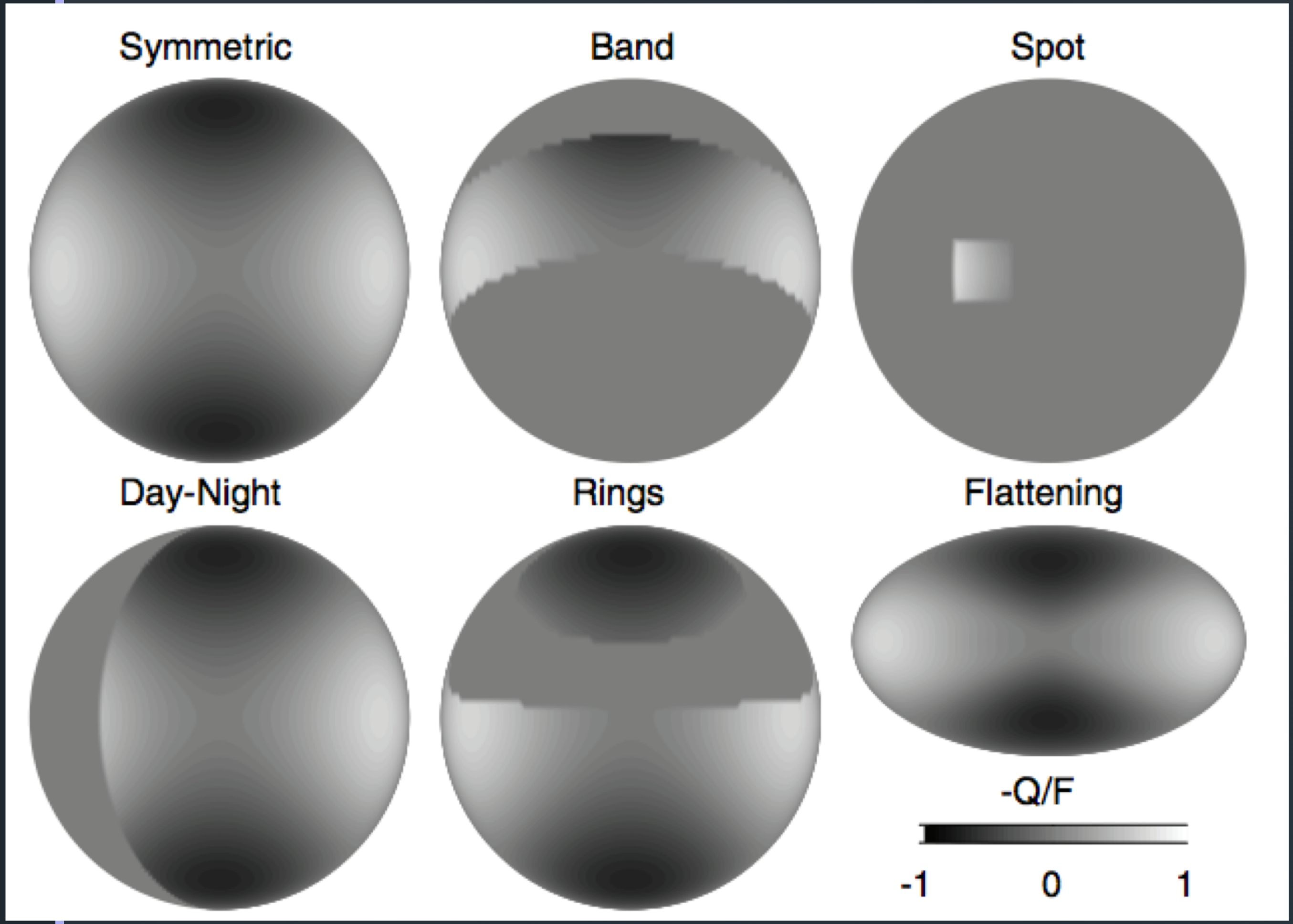








Thermal polarization signal



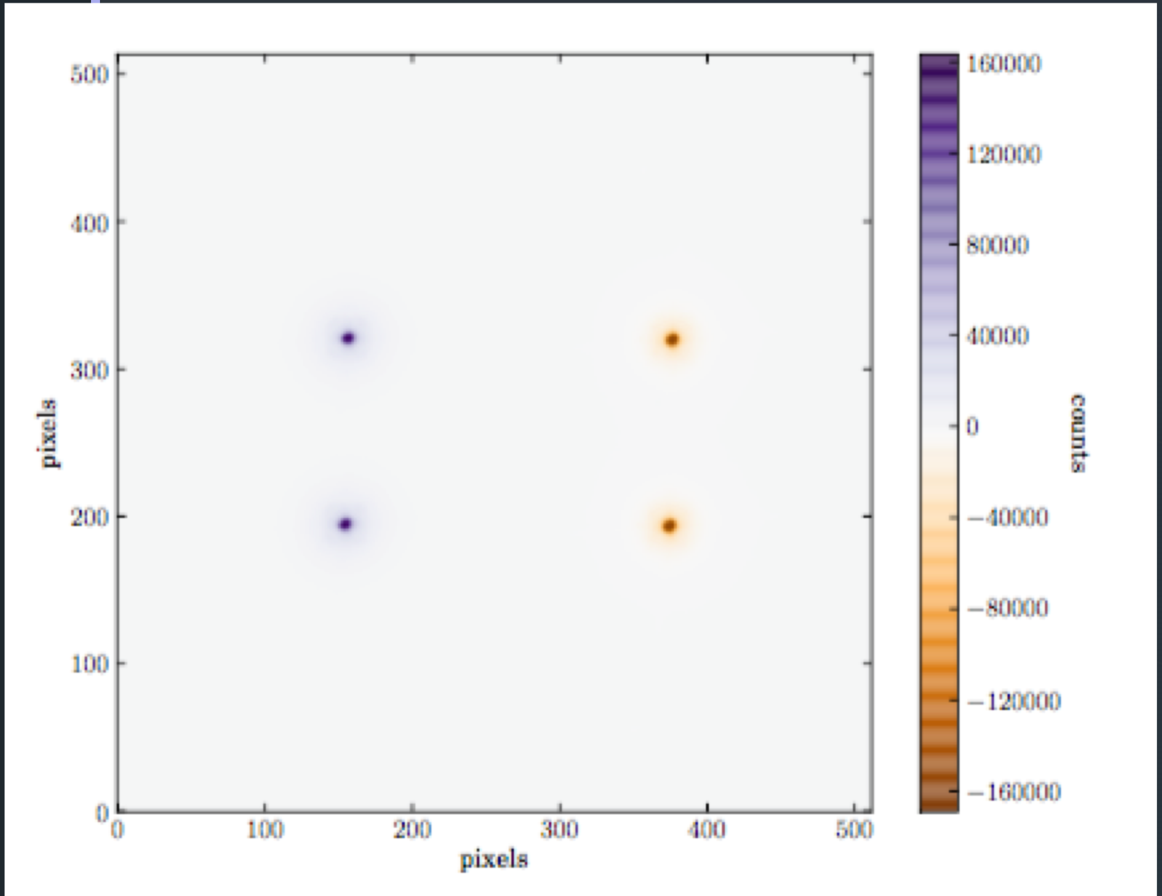
De Kok et al. 2011
(see also Stolker et al. 2017)

- Challenges:
  - Net thermal polarization signal requires asymmetry (otherwise polarized thermal signal will cancel out)
  - Banded and oblate planet will give very similar polarization signal
- Infrared polarized signal confirms presence of scattering particles
- Variability in polarization will reveal moving clouds, hot spots, planet spin axis

Current thermal polarization from the ground

- Exoplanets -- non-detections
  - HR 8799 P<1%, PZ Tel B P<0.1%. Van Holstein et al. (2017)
- Brown dwarfs:
  - Typically P≤1%
  - Only 3 published near-IR polarimetric T-dwarf: all null results/upper limits
  - Unfavorable viewing angle or cloudless?
- Debris disks
- Protoplanetary disks

Post-processing with polarimetry



Example: HR 8799 with NACO/VLT
Dither pattern and rotate half-wave plate (+22.5º)
De Juan Ovelar 2013

- Dual-beam polarimetric imaging
  - Split beam into orthogonally polarized beams
- Opposing preferences to sky rotation
  - Pupil-stabilized allows sky rotation, but not fixed polarization direction
- Polarimetric angular differential imaging (PADI)

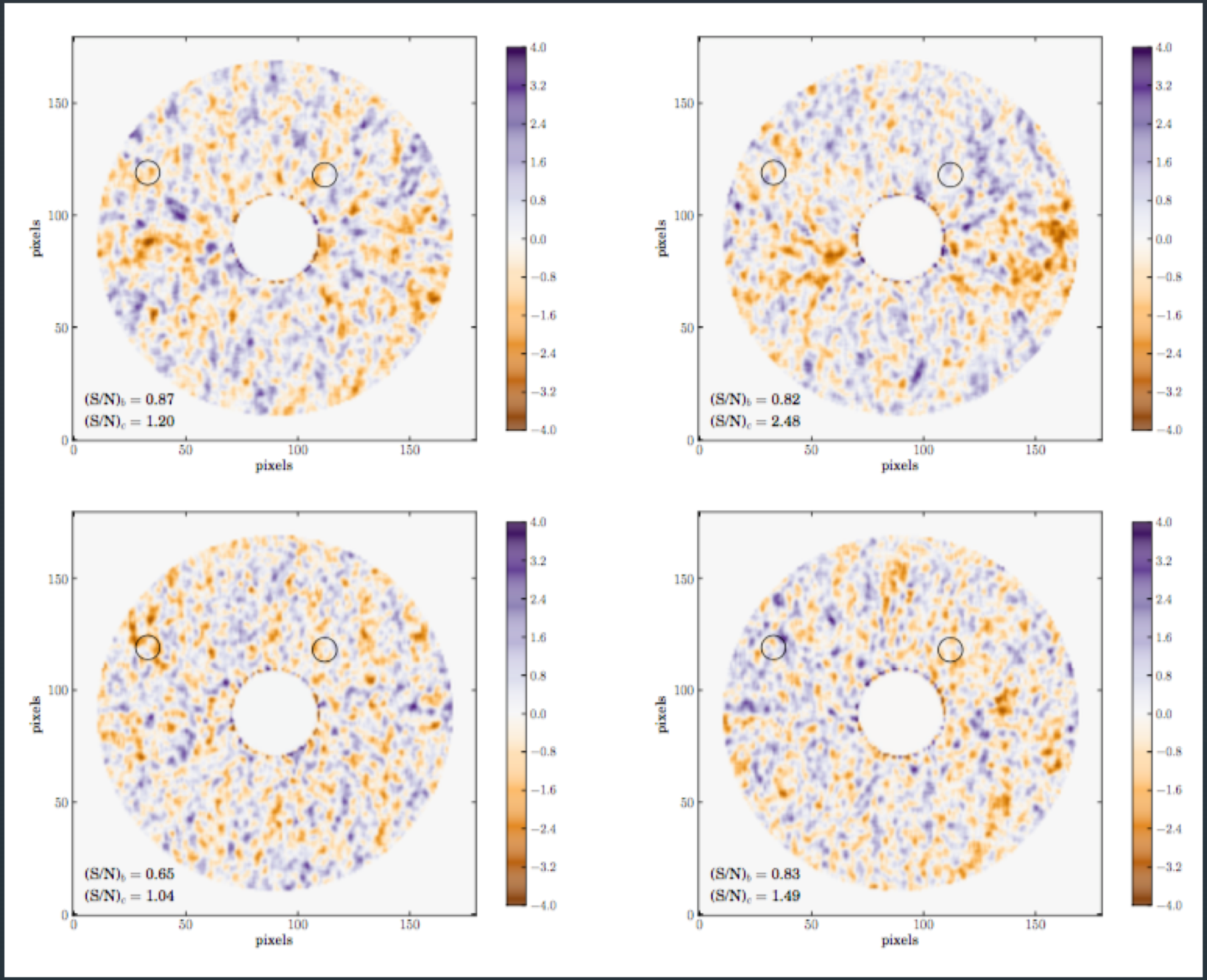
Stokes parameters

TABLE 2.1: FIRST LEFT AND RIGHT DITHERED POLARIMETRIC BLOCKS

θ_{HWP} (°)	I_{UL}	-	I_{LL}	=	Beam subtr.	I_{UR}	-	I_{LR}	=	Beam subtr.
0	$I+Q'$	-	$I-Q'$	=	$Q'_{1,1}$	$I+Q'$	-	$I-Q'$	=	$Q'_{1,5}$
22.5	$I+U'$	-	$I-U'$	=	$U'_{1,1}$	$I+U'$	-	$I-U'$	=	$U'_{1,5}$
45	$I-Q'$	-	$I+Q'$	=	$Q'_{2,1}$	$I-Q'$	-	$I+Q'$	=	$Q'_{2,5}$
67.5	$I-U'$	-	$I+U'$	=	$U'_{2,1}$	$I-U'$	-	$I+U'$	=	$U'_{2,5}$
90	$I+Q'$	-	$I-Q'$	=	$Q'_{1,2}$	$I+Q'$	-	$I-Q'$	=	$Q'_{1,6}$
112.5	$I+U'$	-	$I-U'$	=	$U'_{1,2}$	$I+U'$	-	$I-U'$	=	$U'_{1,6}$
135	$I-Q'$	-	$I+Q'$	=	$Q'_{2,2}$	$I-Q'$	-	$I+Q'$	=	$Q'_{2,6}$
157.5	$I-U'$	-	$I+U'$	=	$U'_{2,2}$	$I-U'$	-	$I+U'$	=	$U'_{2,6}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$				
337.5	$I-U'$	-	$I+U'$	=	$U'_{2,4}$	$I-U'$	-	$I+U'$	=	$U'_{2,8}$

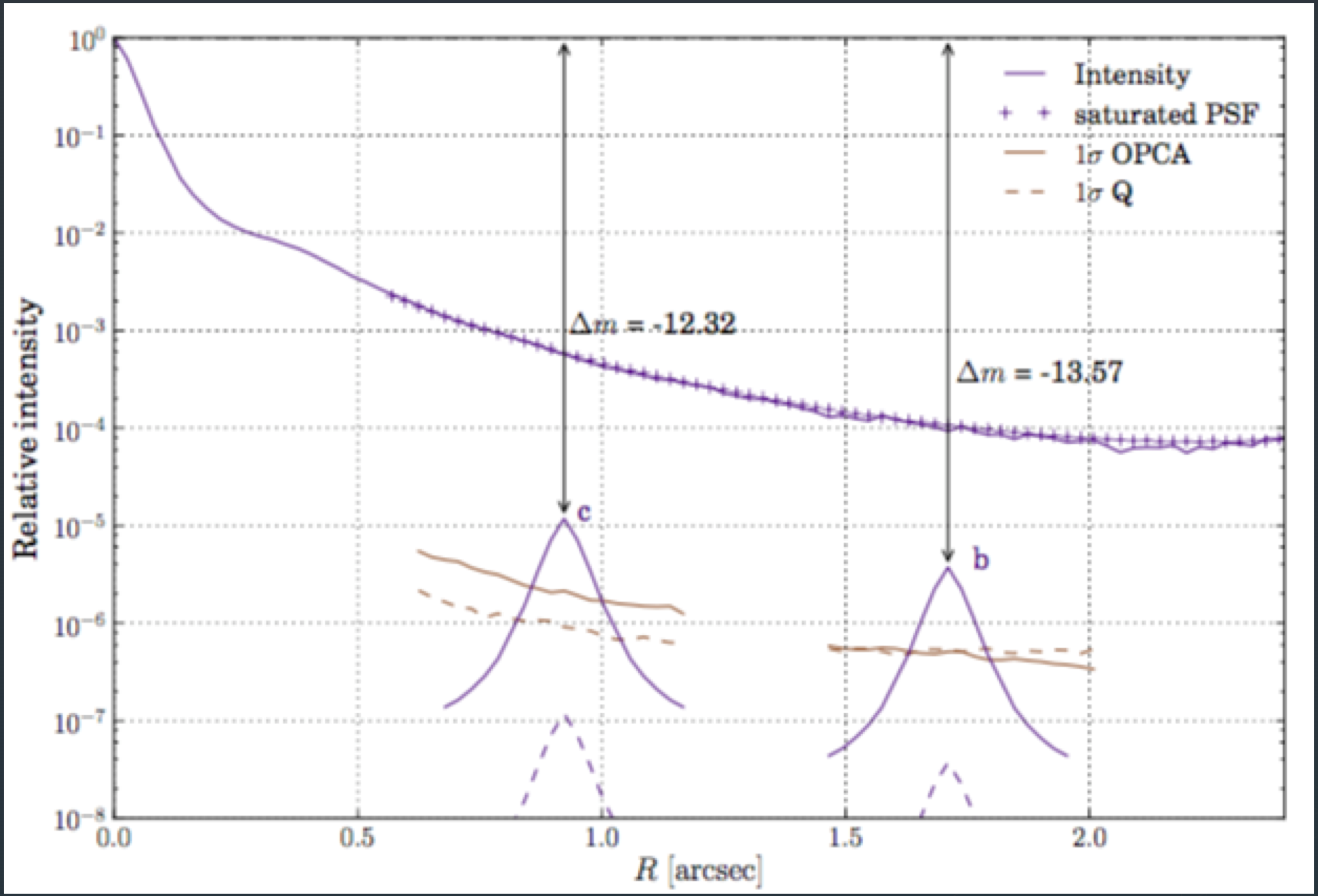
De Juan Ovelar 2013

Results from HR 8799 planet search with NACO



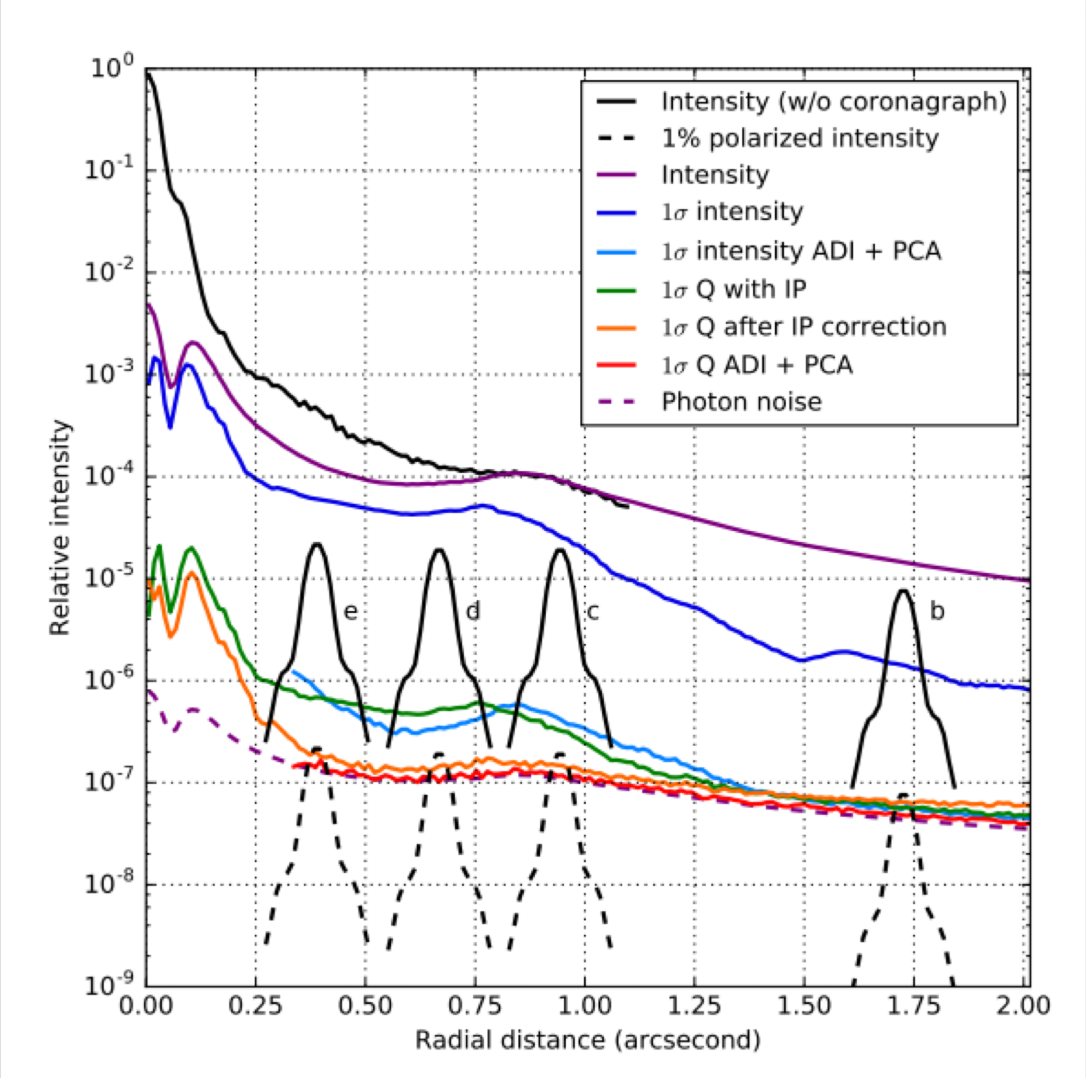
- Polarization limits of [H, Ks]:
  - HR 8799 b [14.8, 11.2]%
  - HR 8799 c [4.7, 5.9]%
- PADI increases contrast by up to 1 magnitude

De Juan Ovelar 2013



De Juan Ovelar 2013

Results from HR 8799 planet search with SPHERE

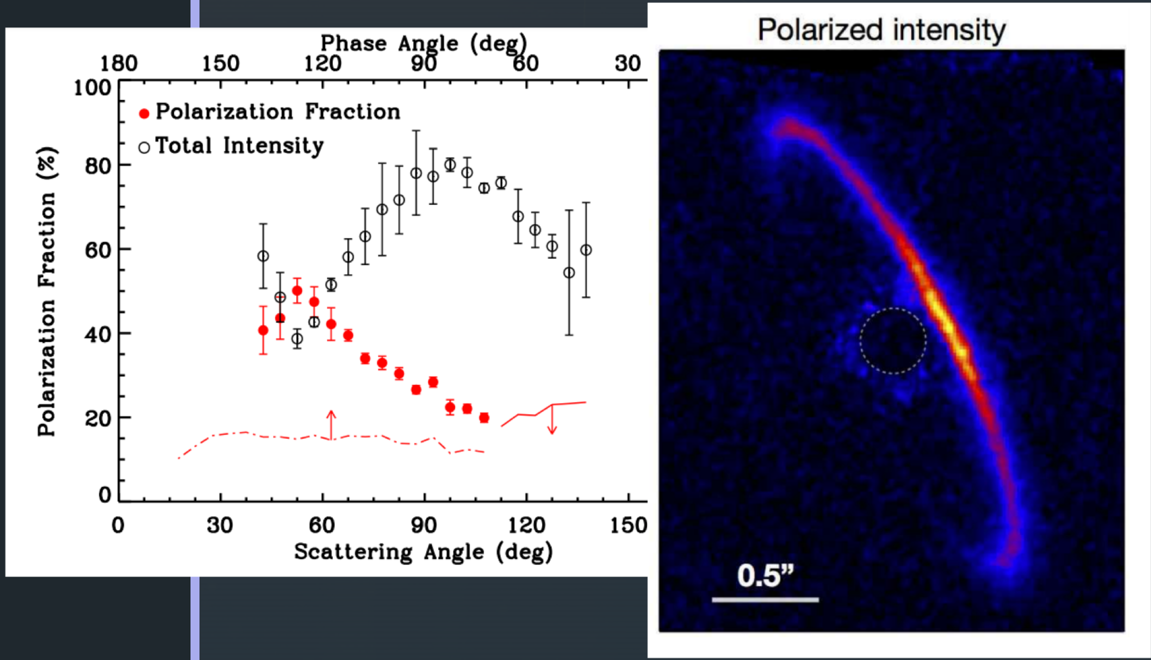


Van Holstein et al. 2017

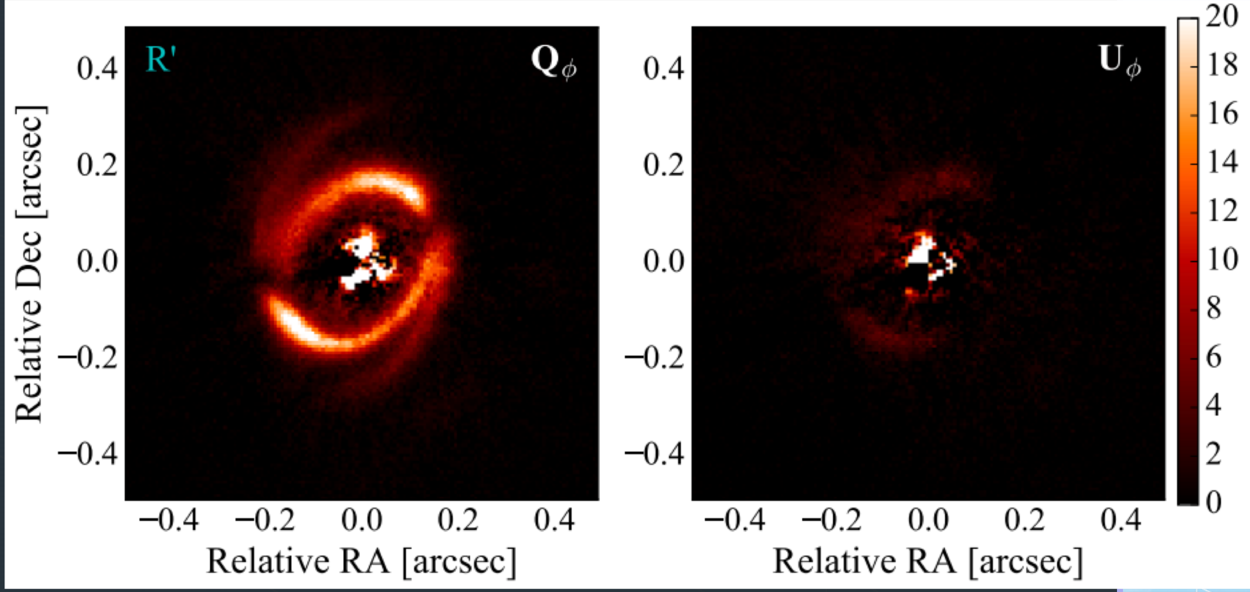
- Van Holstein et al. 2017
- Describe instrument and telescope polarization with absolute polarimetric accuracy of 0.1%
- Polarization limits of 1% for all four planets

Available instruments

- GPI/Gemini (H+K band)
- ZIMPOL/SPHERE/VLT (500-900 nm)
- IRDIS/SPHERE/VLT (Y,J,H,K)



Perrin et al. 2014

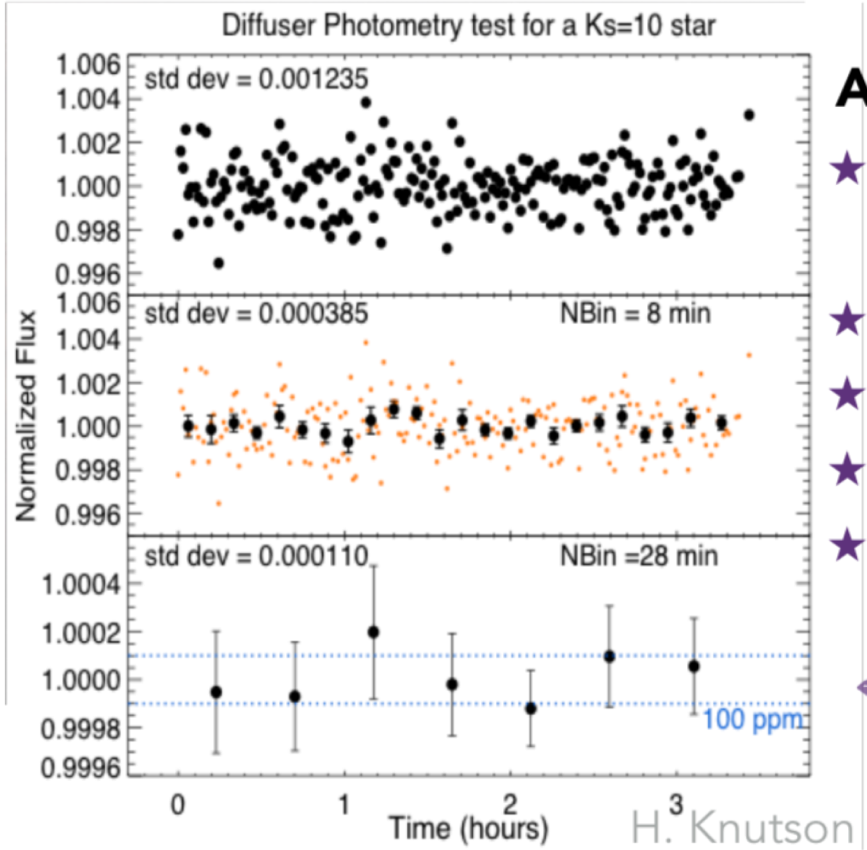


Benisty et al. 2017

- WIRC-POL/Palomar (NIR spectropolarimeter)

WIRC-POL at Palomar

200-inch Hale telescope and WIRC upgrade

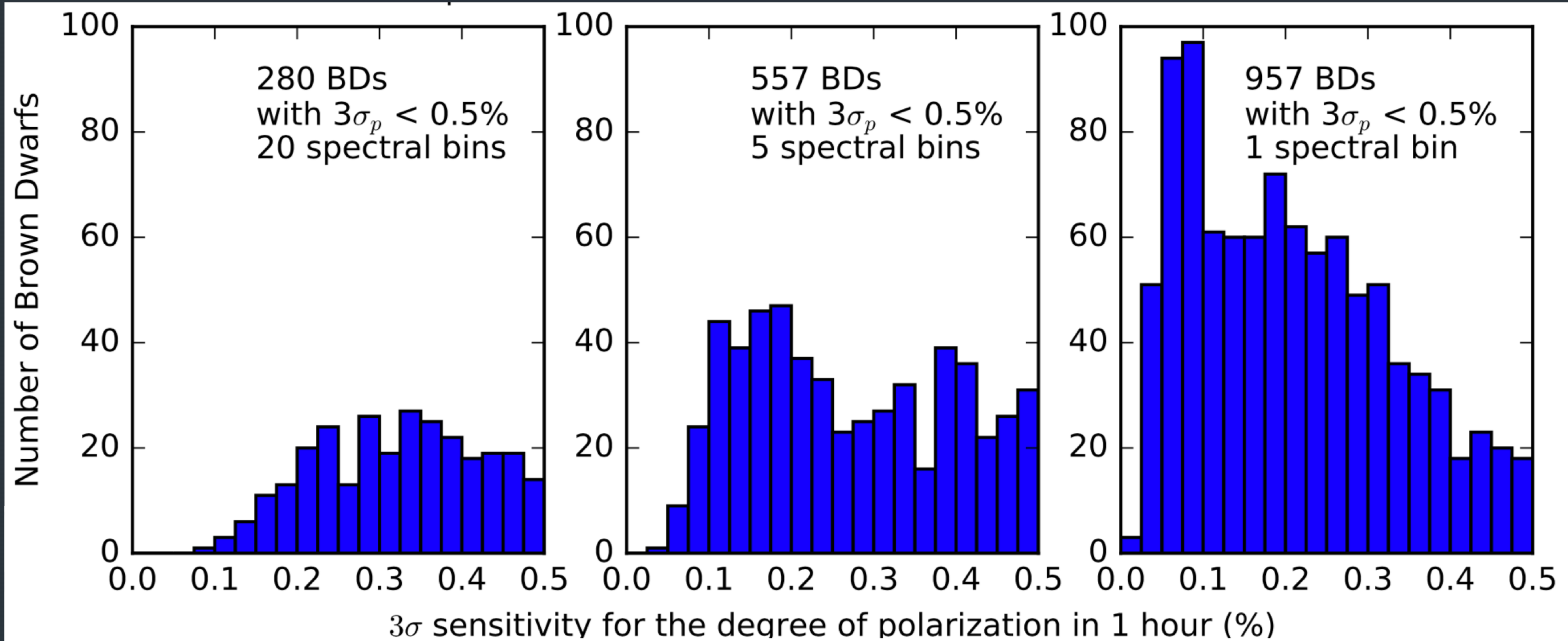


A unique telescope at Palomar Observatory

★ Largest equatorial mounted telescope in the world
★ Extremely stable tracking
★ No differential motion of optics
★ Low and stable instrument polarization
★ 100 ppm precision demonstrated with WIRC (Wide-field InfraRed Camera) at prime focus

Source: Ricky Nilsson

WIRC-POL Survey

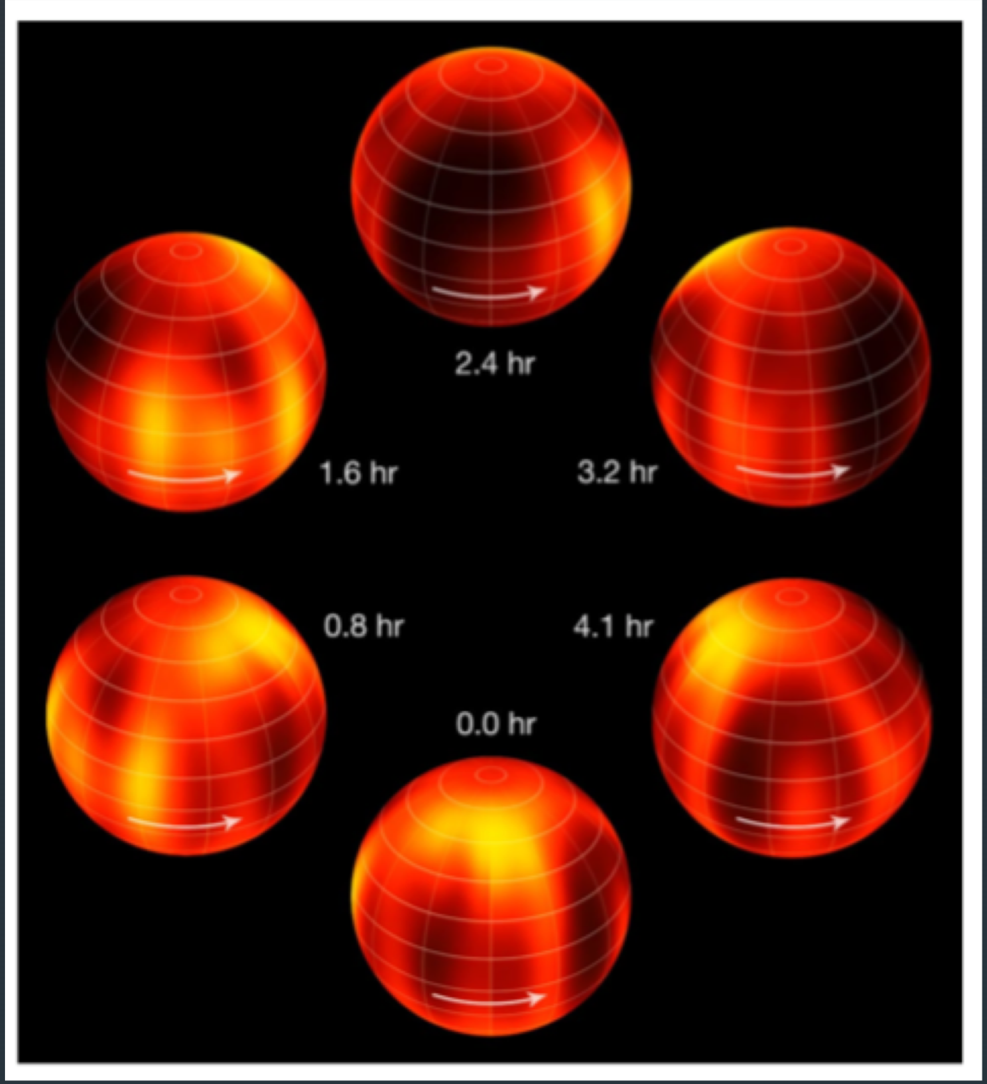


Key science: Spectro-polarimetry of brown dwarfs

- ★ Spectro-polarimetric library of ~1000 brown dwarfs across MLTY spectral types
- ★ Baseline survey at J and H (R~120-150)
- ★ Follow up any >3σ signature for SP variability

Source: Ricky Nilsson

WIRC-POL Survey



- Luhman 16B (Crossfield et al. 2014) and other brown dwarfs in L/T transition show signs of patchy clouds
- Polarization signal above 1% or variability on timescale of rotation period -> clouds!

Conclusions

- Polarization is a powerful tool for exoplanet detection, confirmation, and characterization
- Reflected light polarization can reveal some atmospheric properties which cannot be measured with flux alone!
- Thermal polarization signal from brown dwarfs and exoplanets is expected to be very small <1%
- Other sources of polarization remain a challenge, in particular for low flux sources

Sources:
De Kok et al. 2011
De Juan Ovelar 2013 PhD thesis
Hansen & Hovenier 1974
Jensen-Clem et al. 2016
Lyot 1929
Millar-Blanchaer et al. 2016
Stam et al. 2004
Stam et al. 2008
Stolker et al. 2017
Van Holstein et al. 2017