Spectropolarimetry of exoplanets

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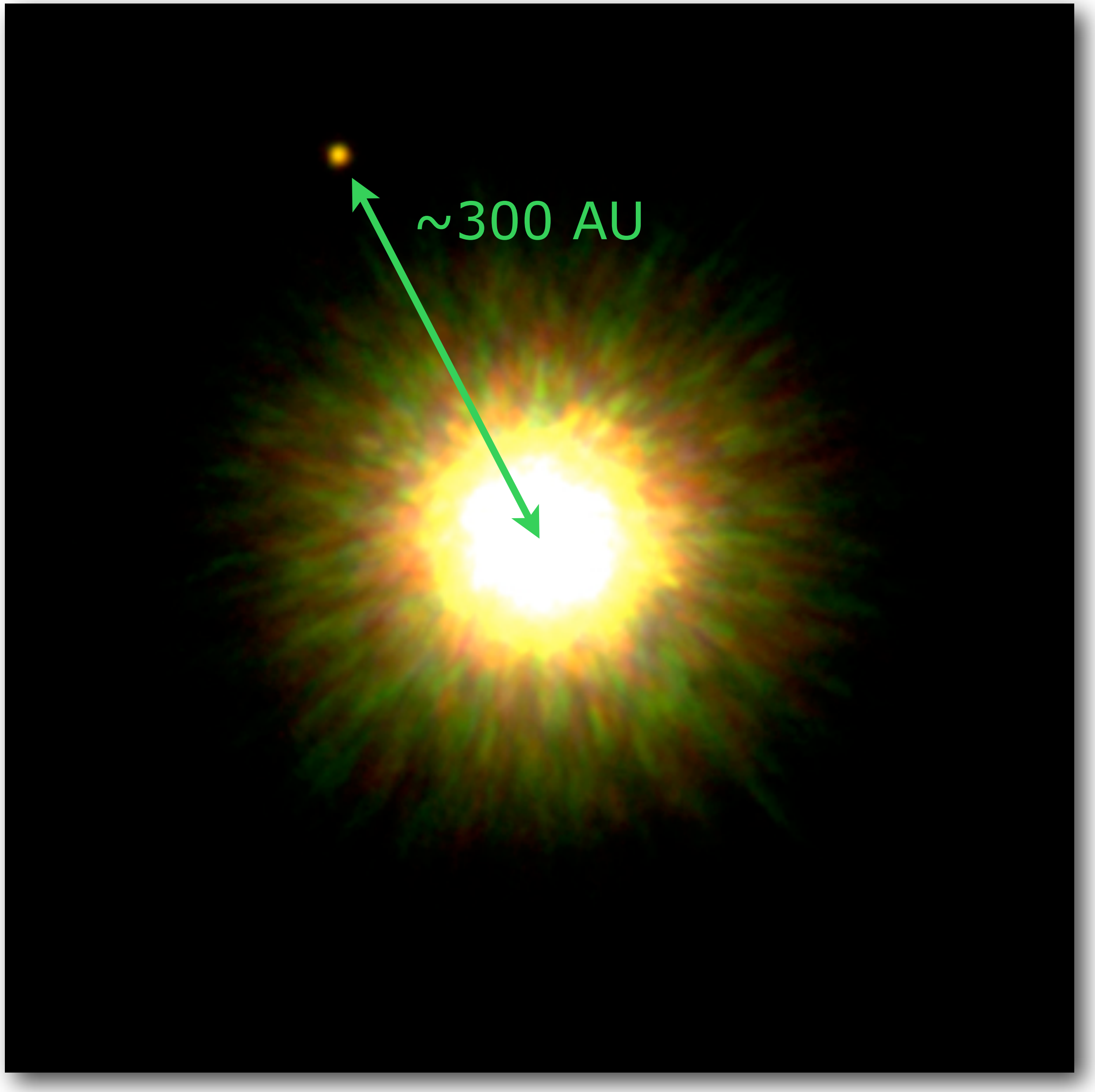
Directly detecting exoplanets

A sharp picture of a gaseous exoplanet around a solar-type star using Gemini North (an 8-m, ground-based telescope with adaptive optics):



(Lafrenière et al., 2008):

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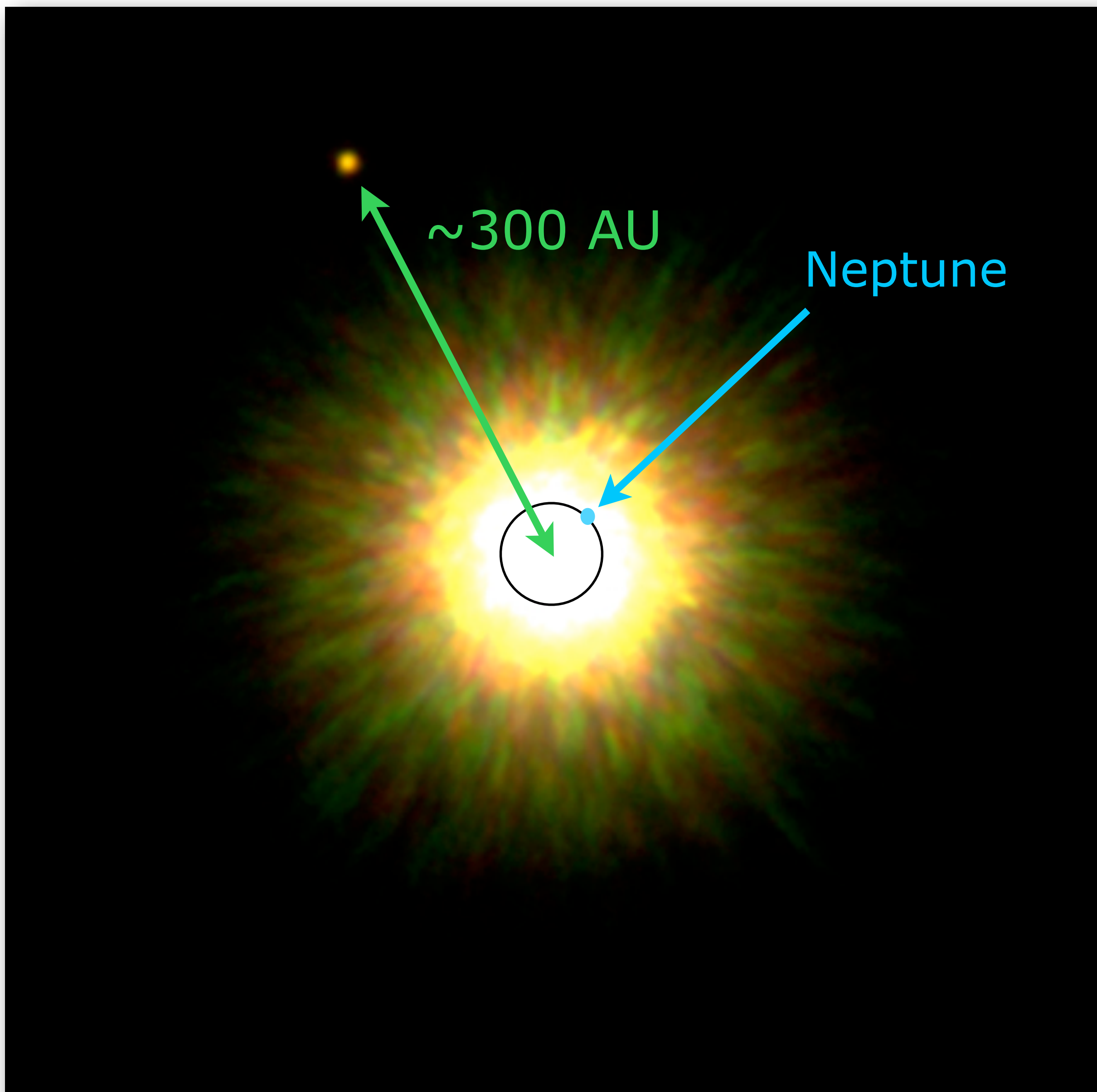

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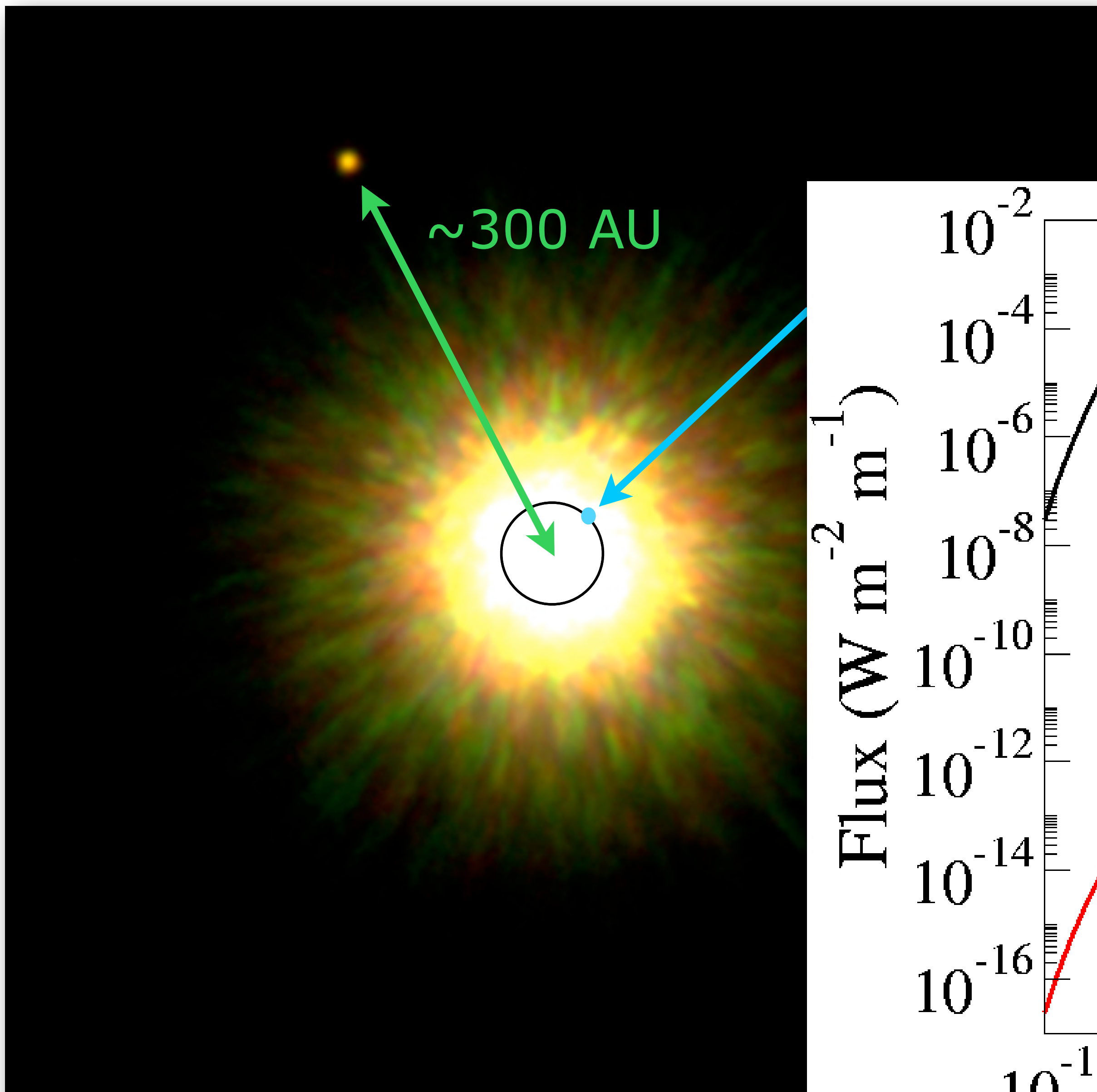

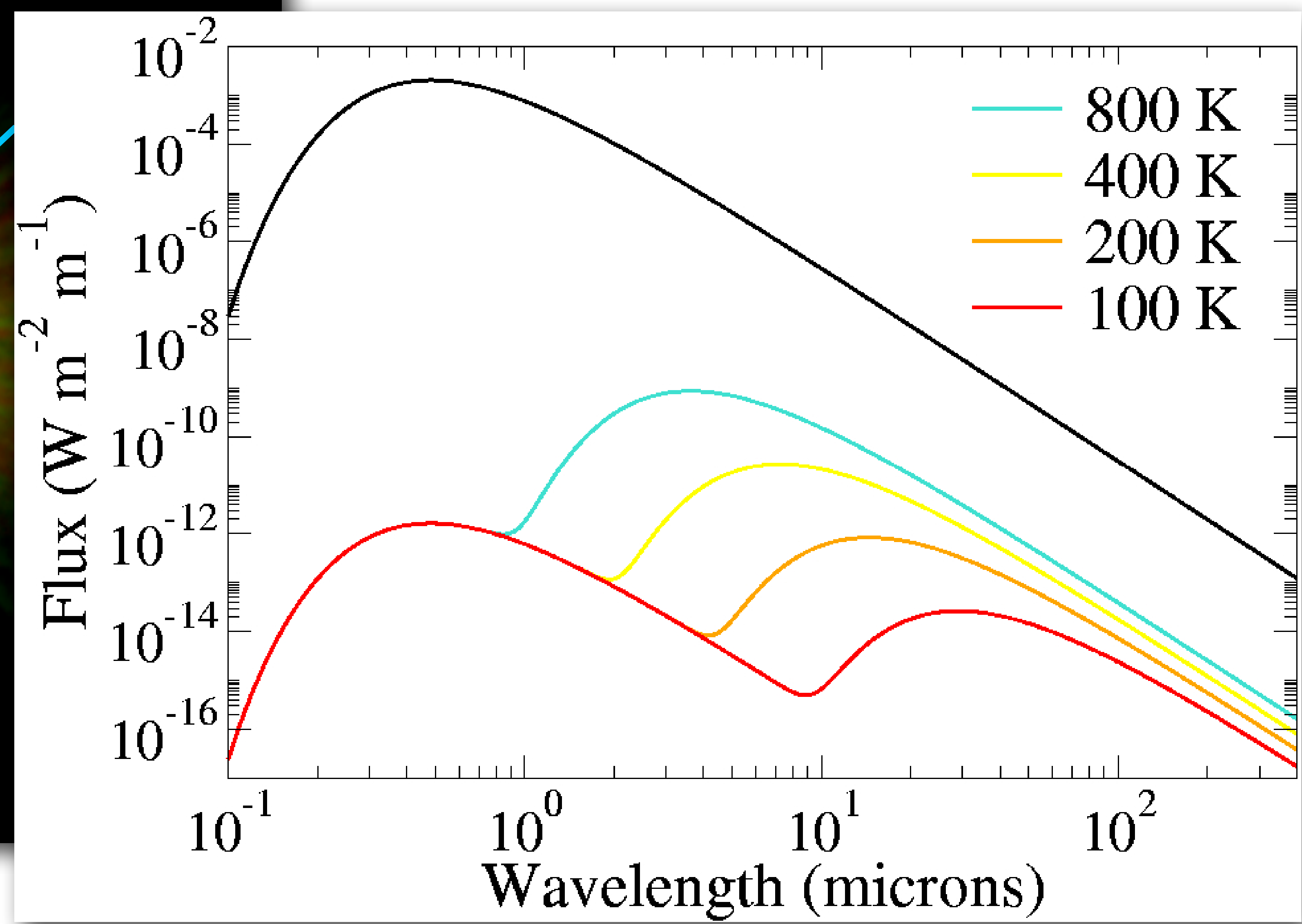

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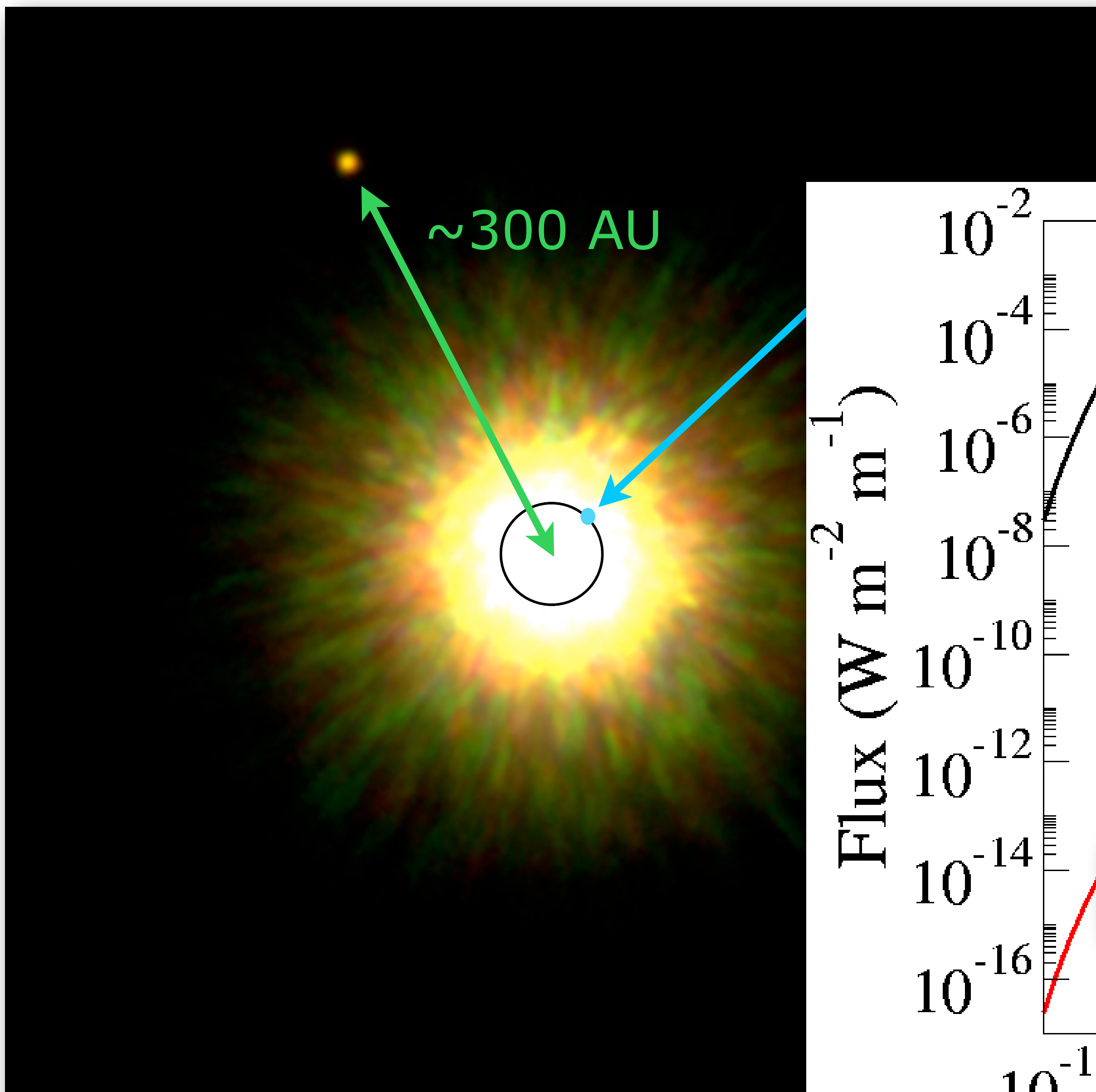

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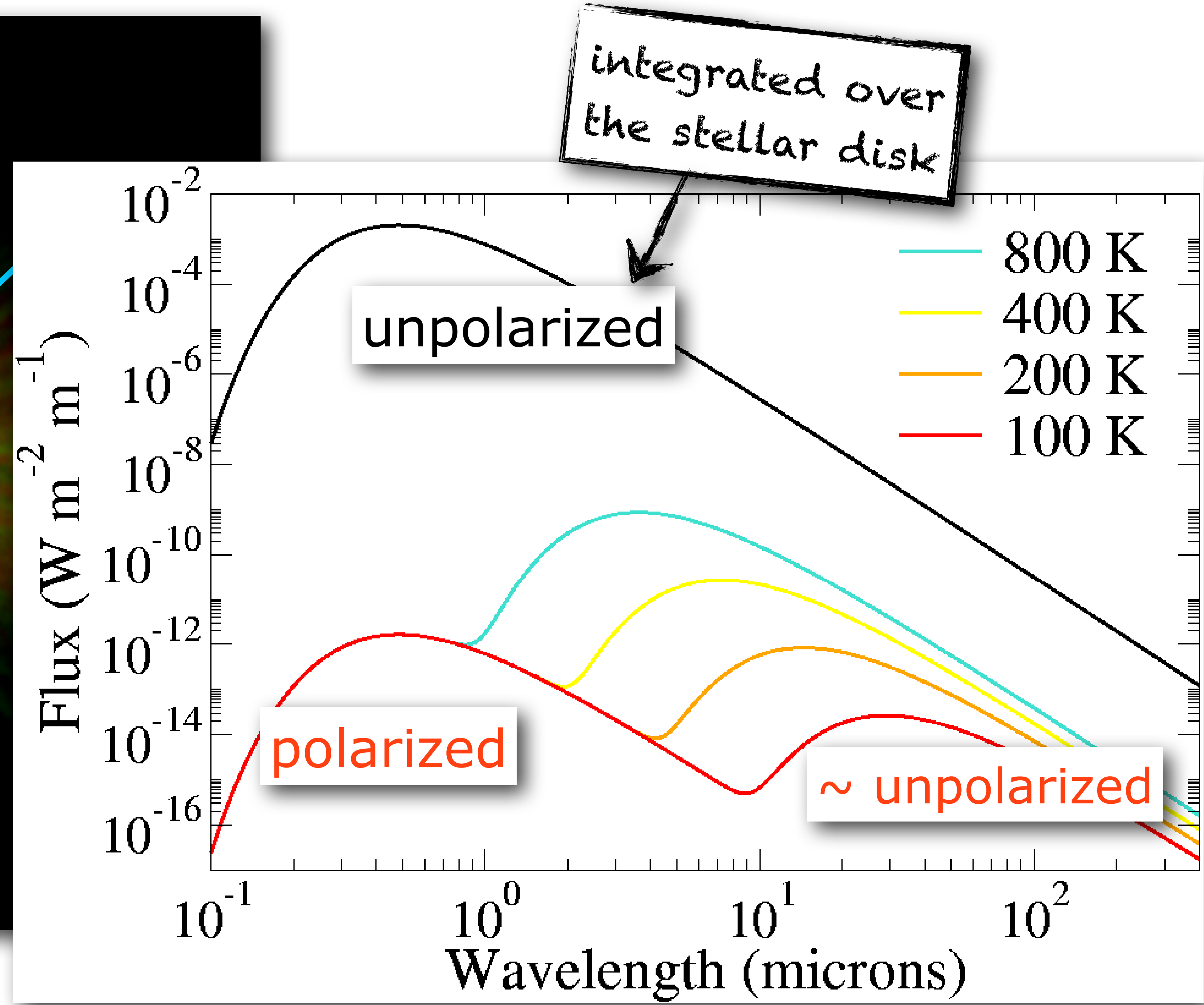
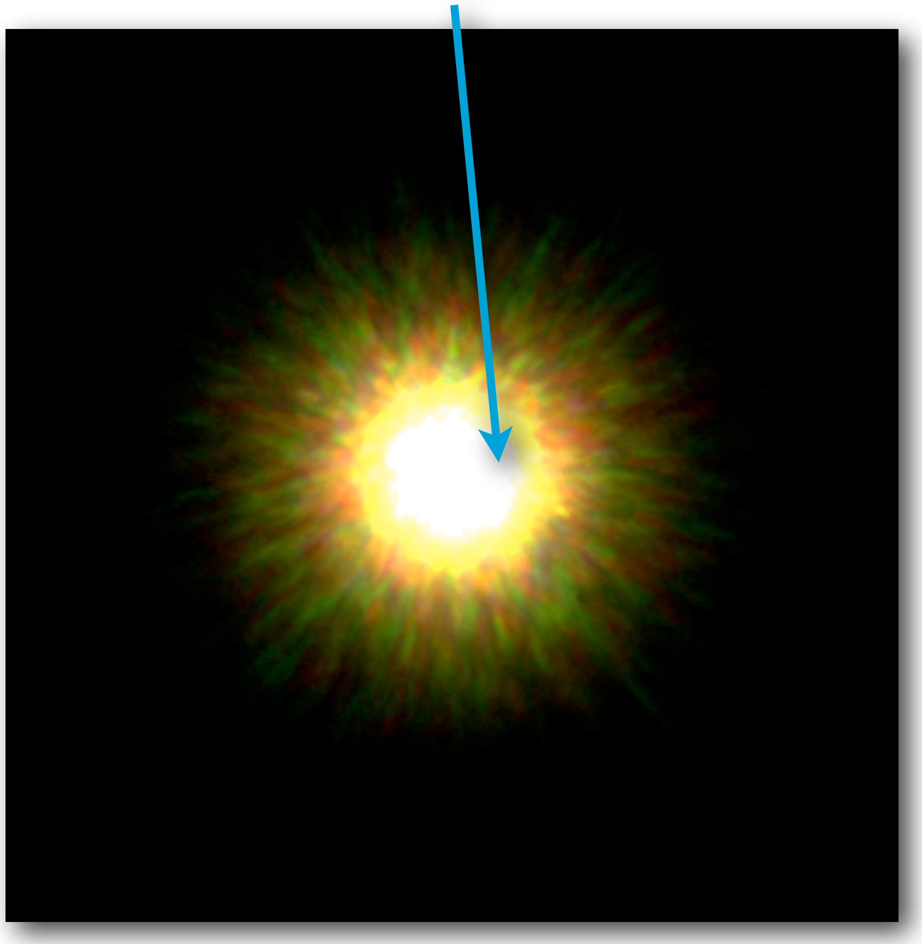


The unpolarized stellar background flux

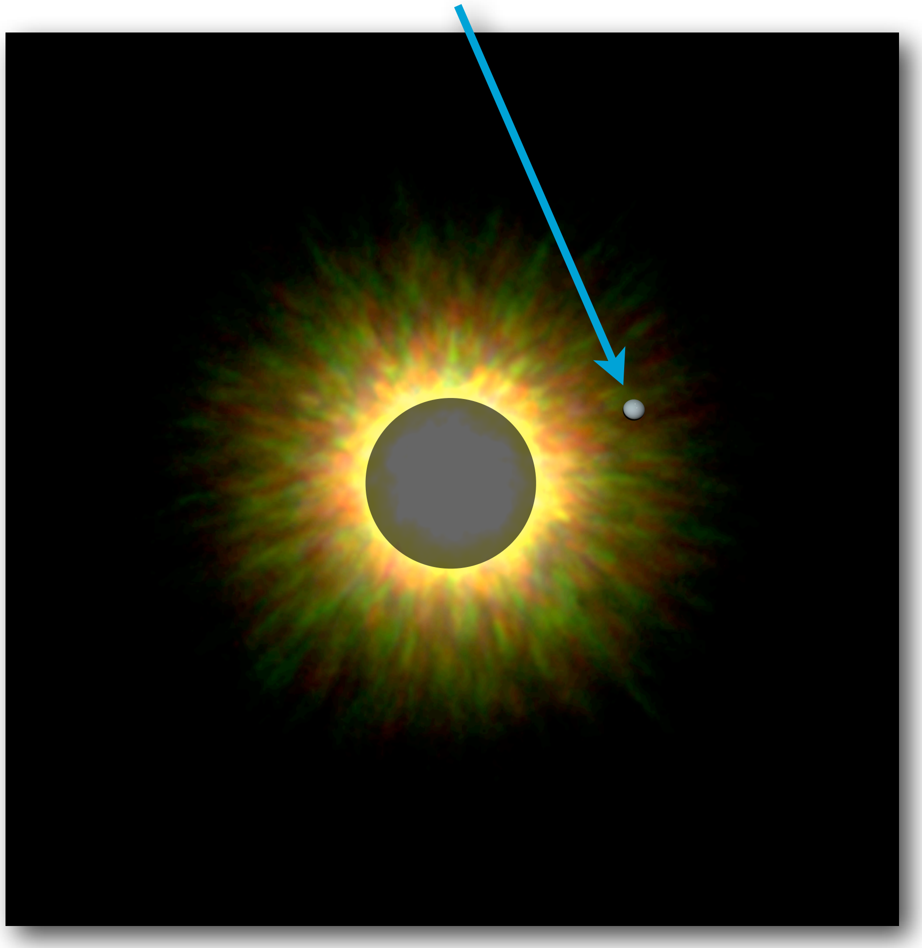
The relative strength of an exoplanet's polarization signal depends strongly on the background flux due to e.g. the parent star:

Close-in planets



Instrument example:
PlanetPol (Jim Hough)

Resolved planets



Instrument examples:
SPHERE/VLT, GPI/Gemini, EPICS/ELT

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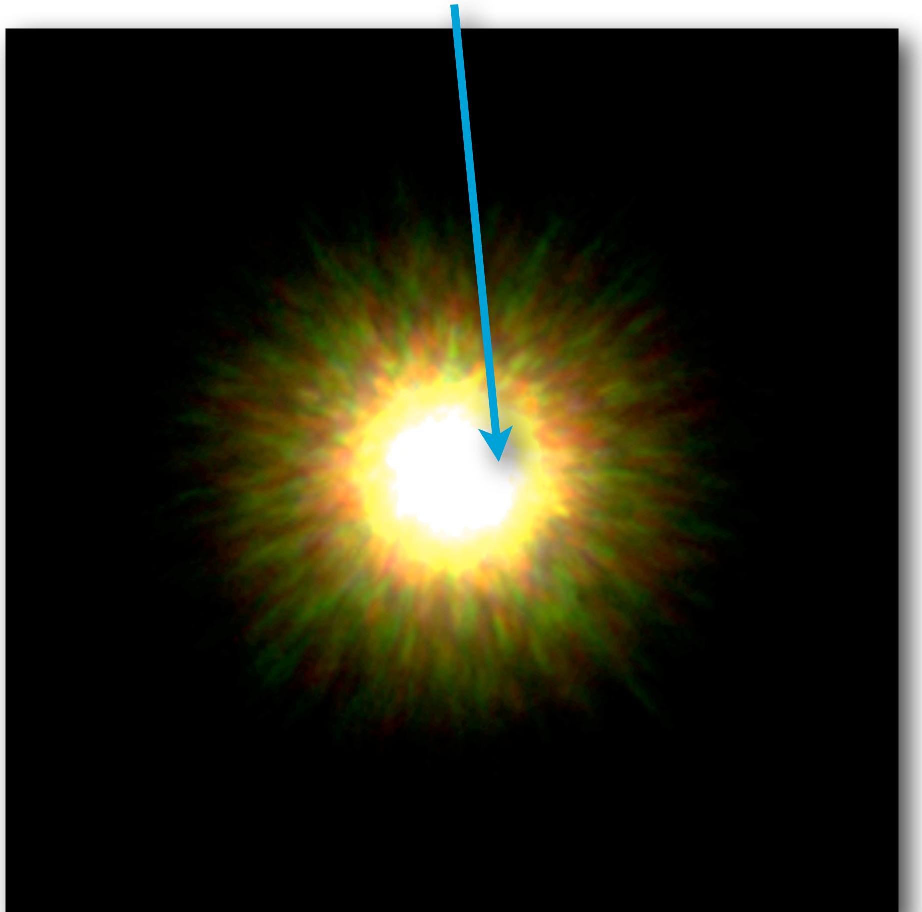

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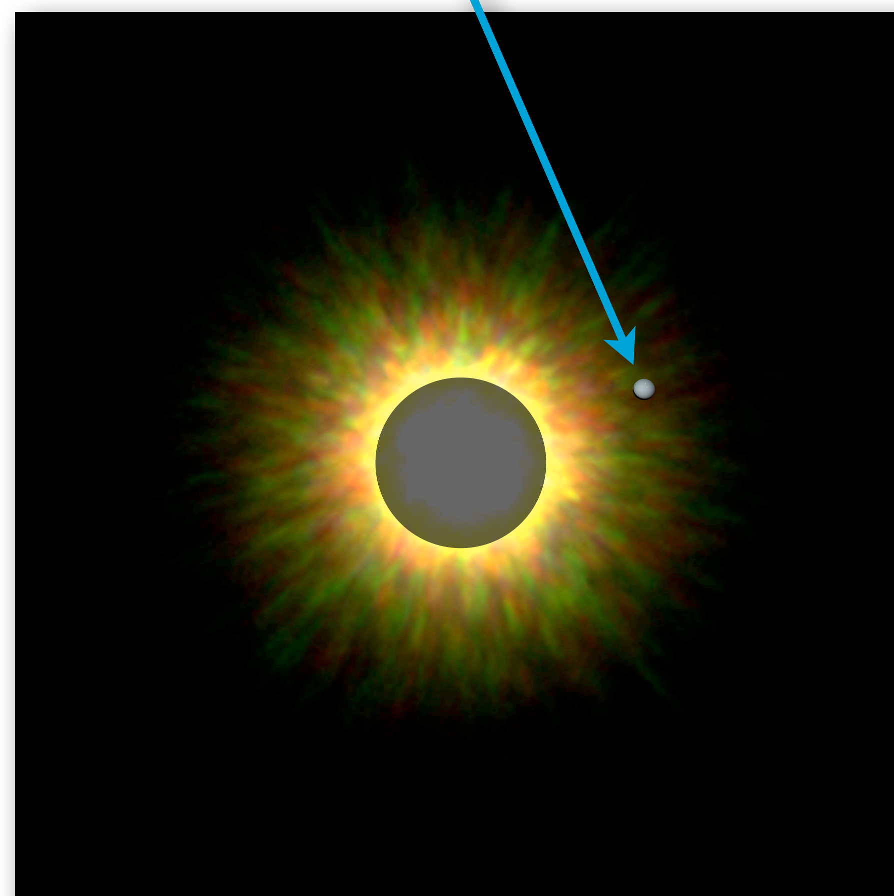

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In the following, we ignore background starlight, exo-zodiacal light ...

Why is reflected starlight polarized?

Starlight that is reflected by (exo)planets gets polarized upon:

- scattering by gas molecules in the atmosphere
- scattering by atmospheric aerosol and/or cloud particles
- reflection by the surface (if there is any)

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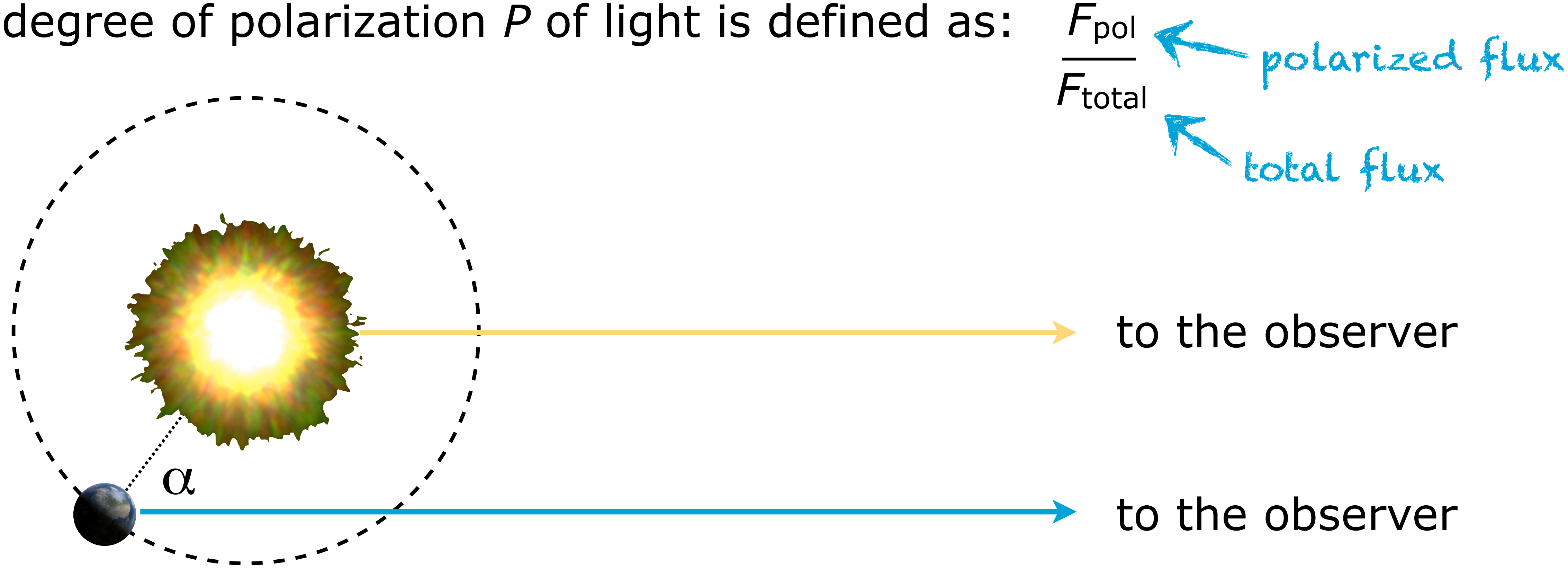
Polarimetry can be used for:
- detecting exoplanets: finding a polarized signal near an unpolarized star
- confirming detections: background sources are usually unpolarized
- characterizing exoplanetary atmospheres and/or surfaces

Polarimetry for exoplanet characterization

The degree of polarization *P* of light is defined as: $\frac{F_{\text{pol}}}{F_{\text{total}}}$



The degree of polarization *P* of reflected starlight depends on*:

- The composition and structure of the planet's atmosphere
- The reflection properties of the planet's surface
- The wavelength λ of the light
- The planetary phase angle α

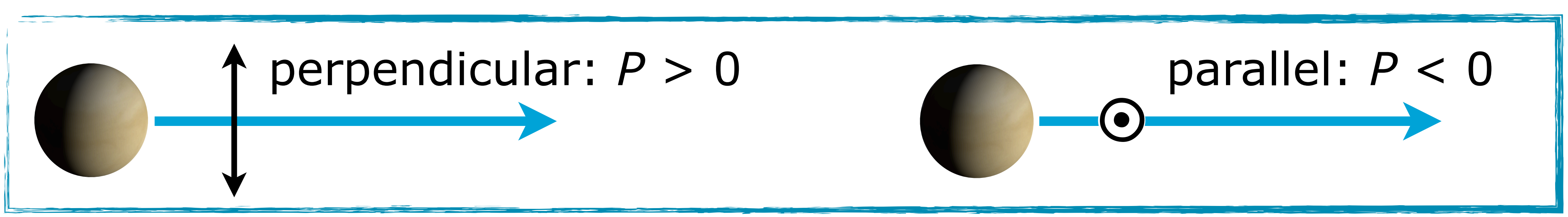
* *P* does not depend on: planet's size, distance to the star, distance to the observer!

Reference planes and negative polarization

The reference plane for the polarization is the **planetary scattering plane** (through star, planet, and observer):

If a planet is mirror-symmetric with respect to the reference plane:

- the reflected starlight is linearly polarized, not circularly
- the direction of polarization is perpendicular or parallel to the plane!



A Solar System example: polarization of Venus

The degree of linear polarization *P* of sunlight reflected by Venus as function of the phase angle α, for two different wavelengths λ:

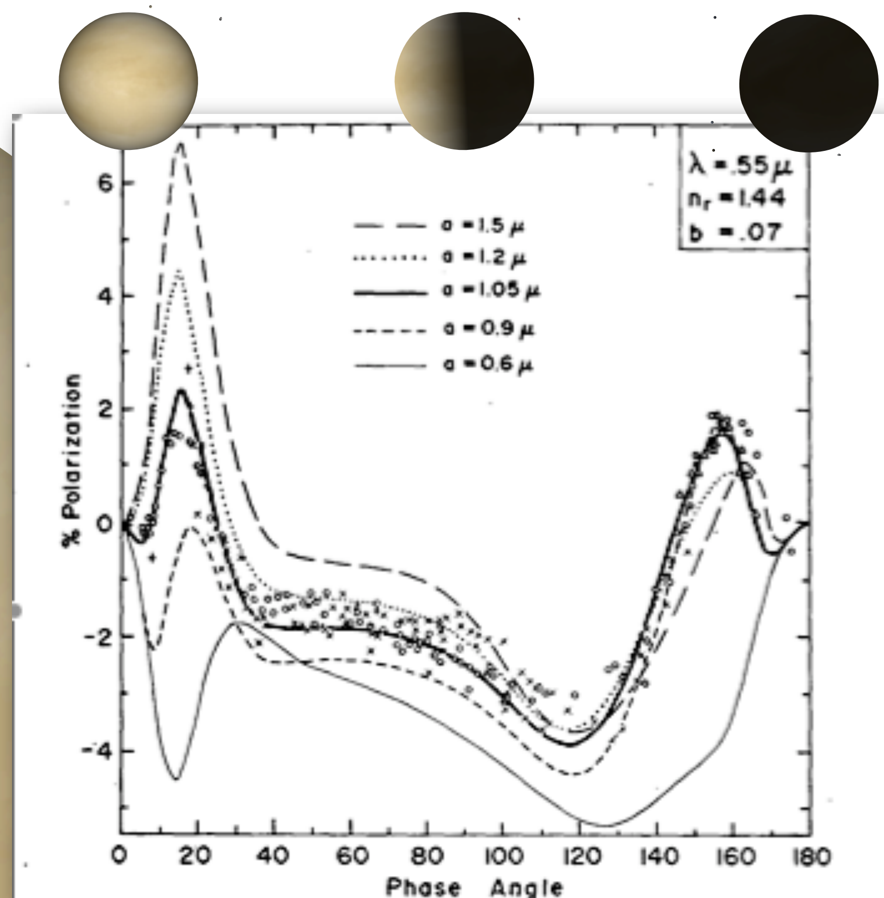


FIG. 4. Observations of the polarization of sunlight reflected by Venus in the visual wavelength region and theoretical computations for λ = 0.55 μm. The ○'s are wide-band visual observations by Lyot (1929) while the other observations are for an intermediate bandwidth filter centered at λ = 0.55 μm; 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.

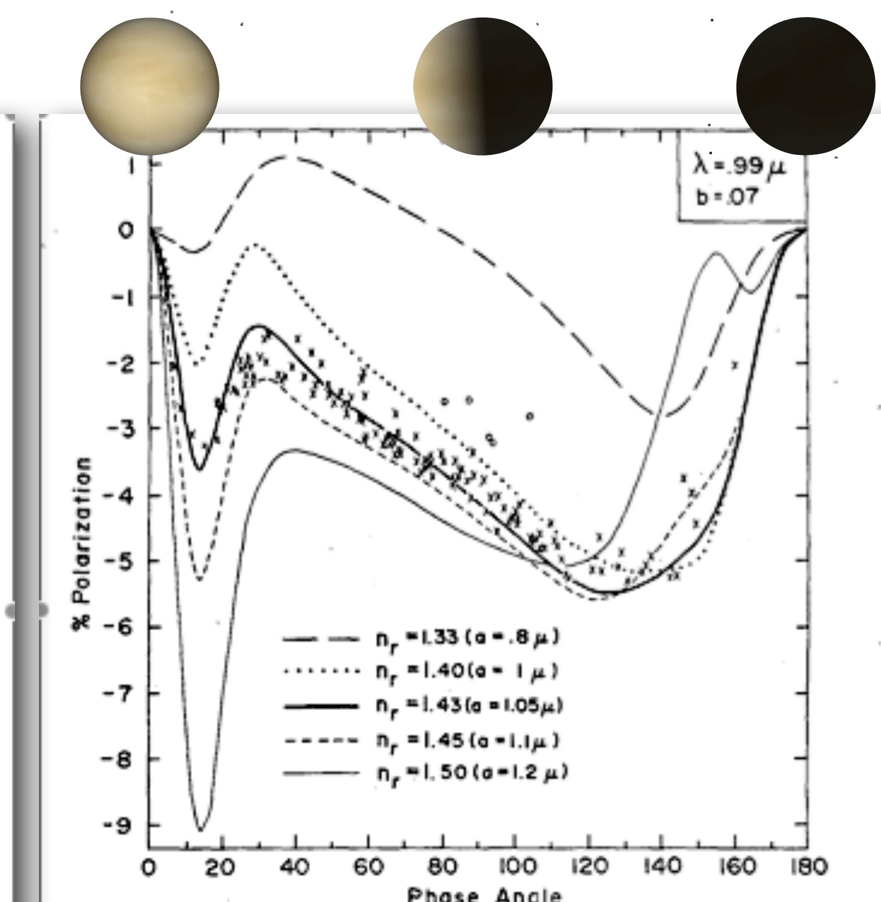


FIG. 7. Observations and theoretical computations of the polarization of sunlight reflected by Venus at λ = 0.99 μm. The observations were made with an intermediate bandwidth filter, the ×'s being obtained by Coffeen and Gehrels (1969) in 1959–67 and by Coffeen (cf. Dollfus and Coffeen, 1970) from 1967 to March 1969, and the ○'s being obtained by Coffeen (cf. Dollfus and Coffeen, 1970) in May–July, 1969. The theoretical curves are for spherical particles having the size distribution (8) with $b = 0.07$. The different theoretical curves are for various refractive indices, the effective particle radius being selected in each case to yield closest agreement with the observations for all wavelengths.

Hansen & Hovenier [1974] used ground-based polarimetry to derive the size, composition (H_2SO_4), and altitude of Venus' cloud particles

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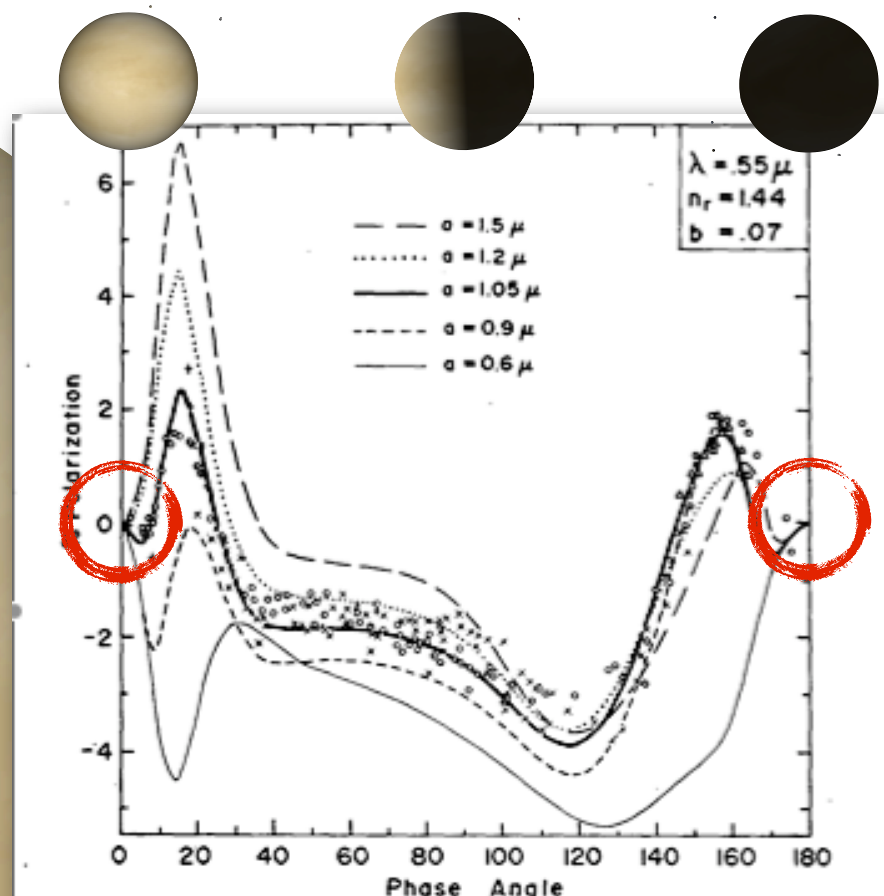

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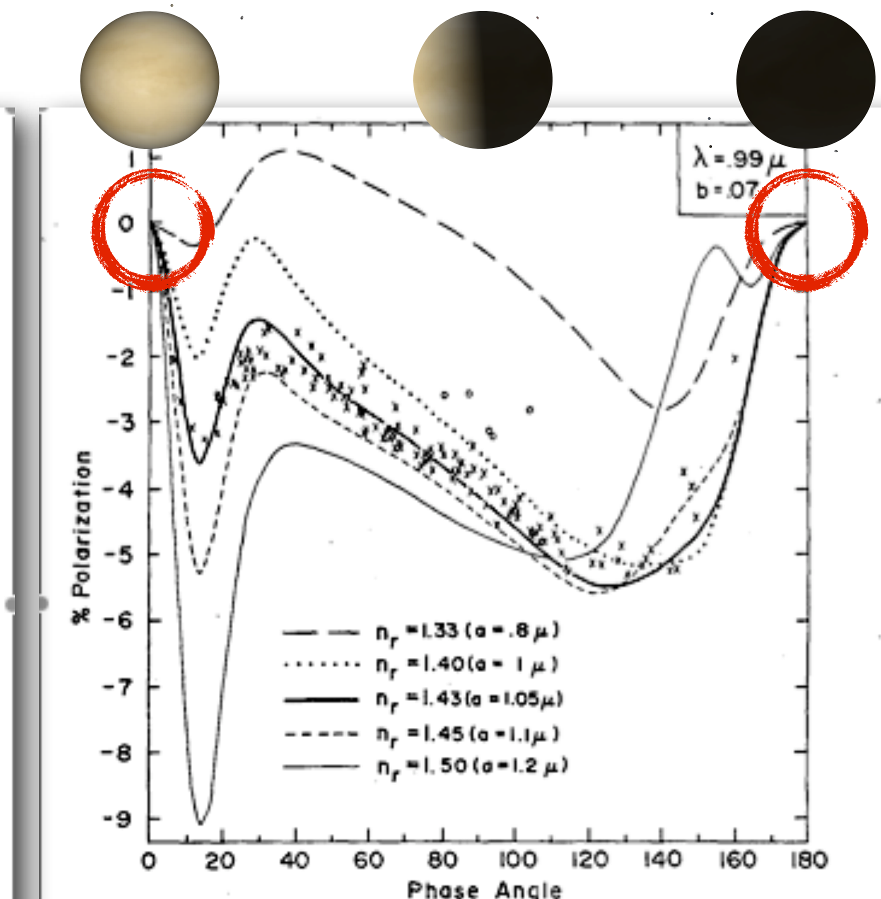

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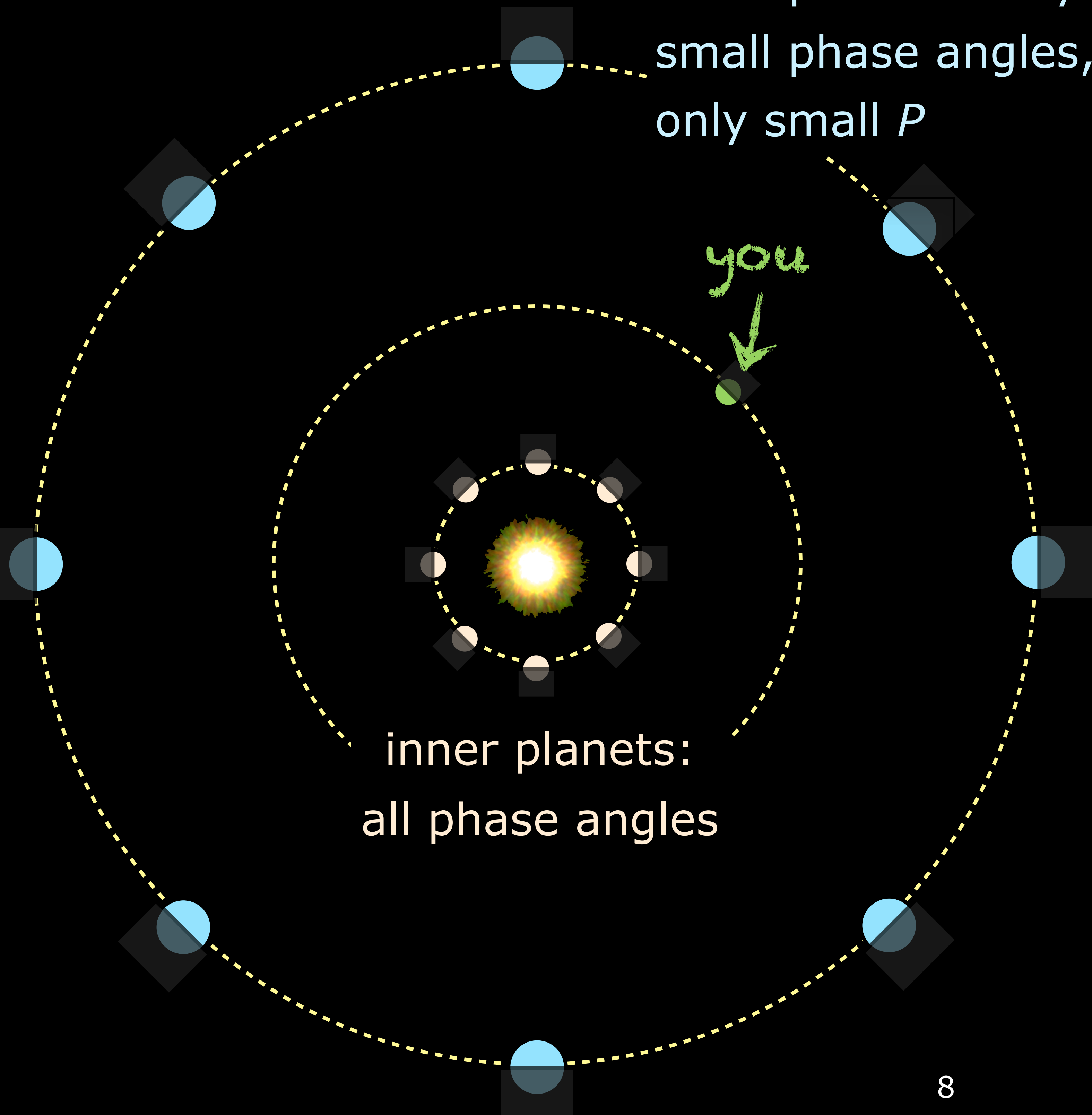
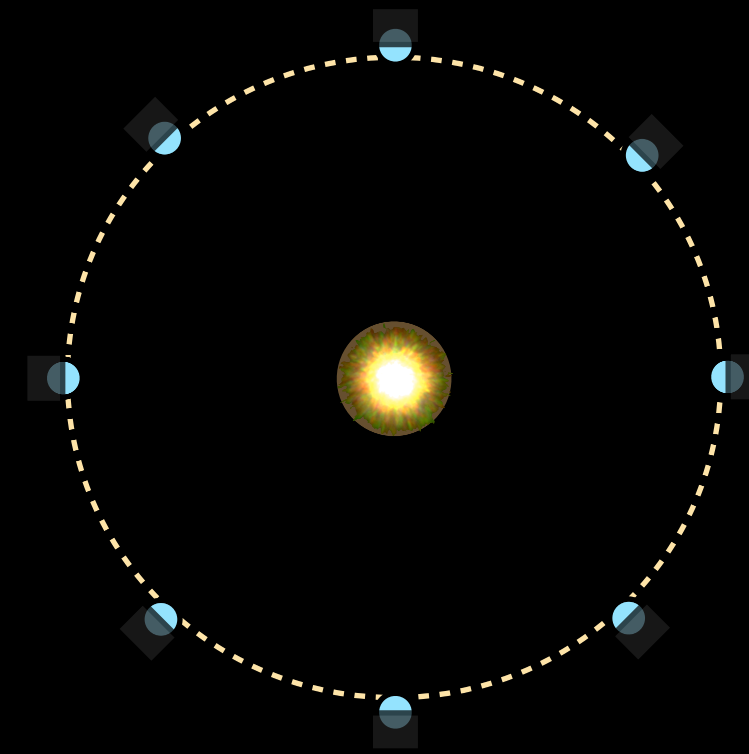
At small and large phase angles, *P*=0 because of symmetry!

Phase angle coverage





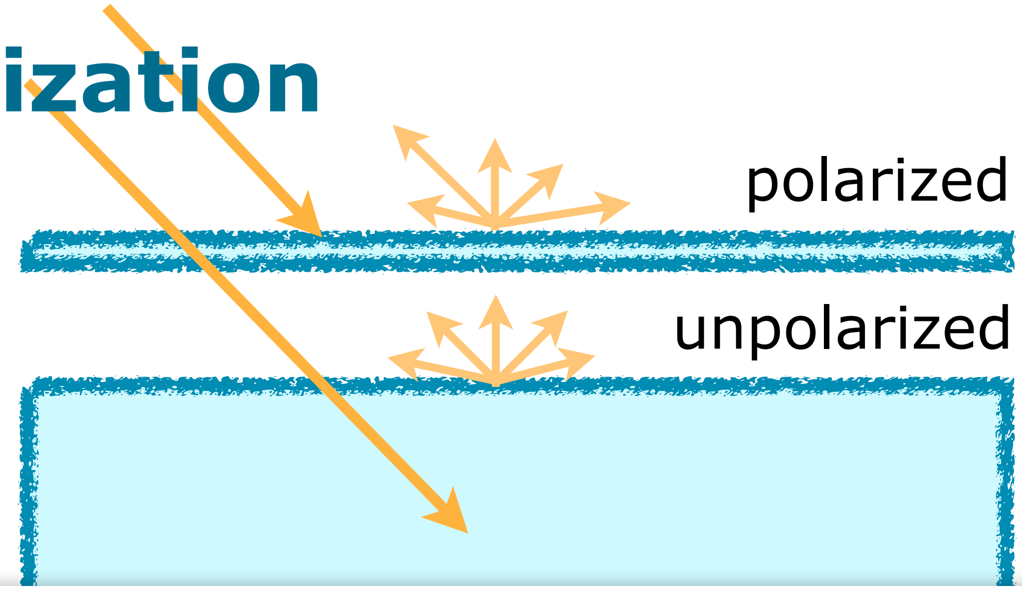
The phase angle range at which an exoplanet can be observed depends on the inclination angle i of its orbit:

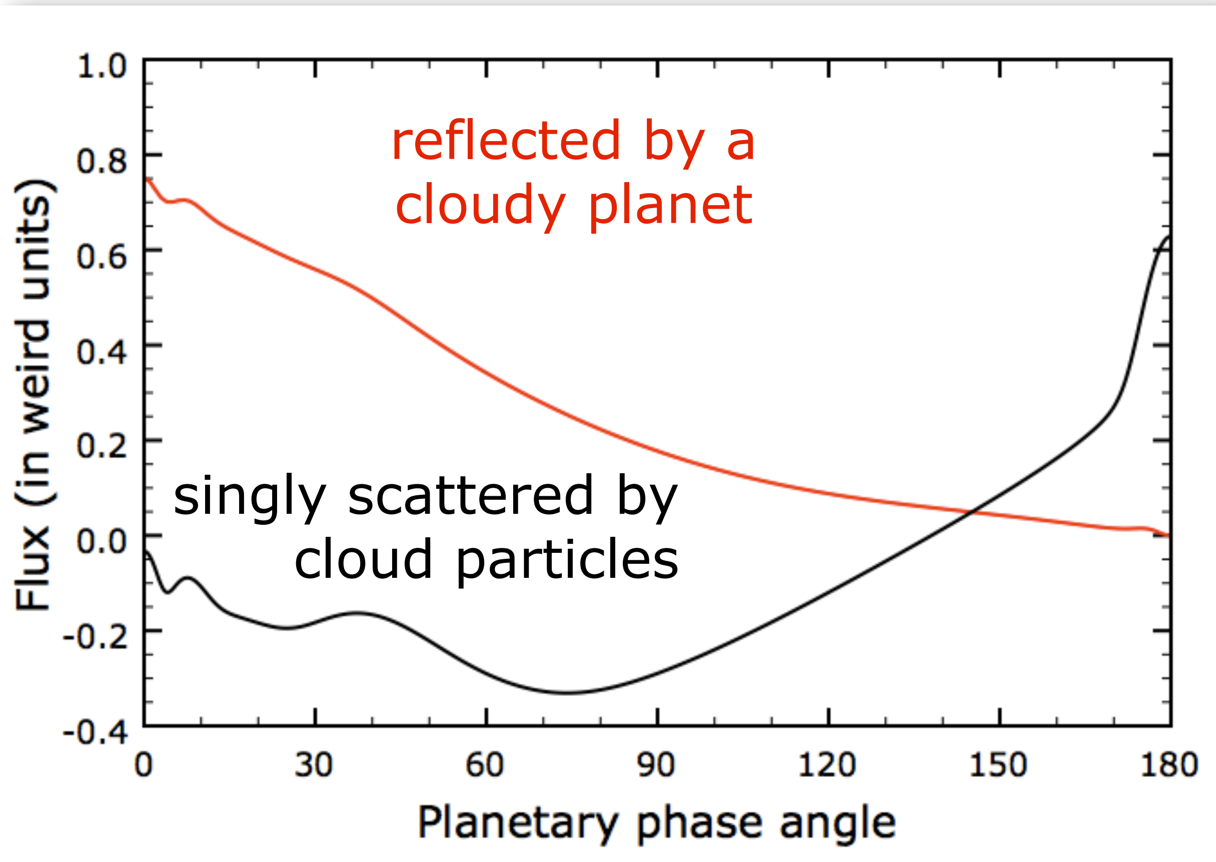
$$90^\circ - i \;\leq\; \alpha \;\leq\; 90^\circ + i$$

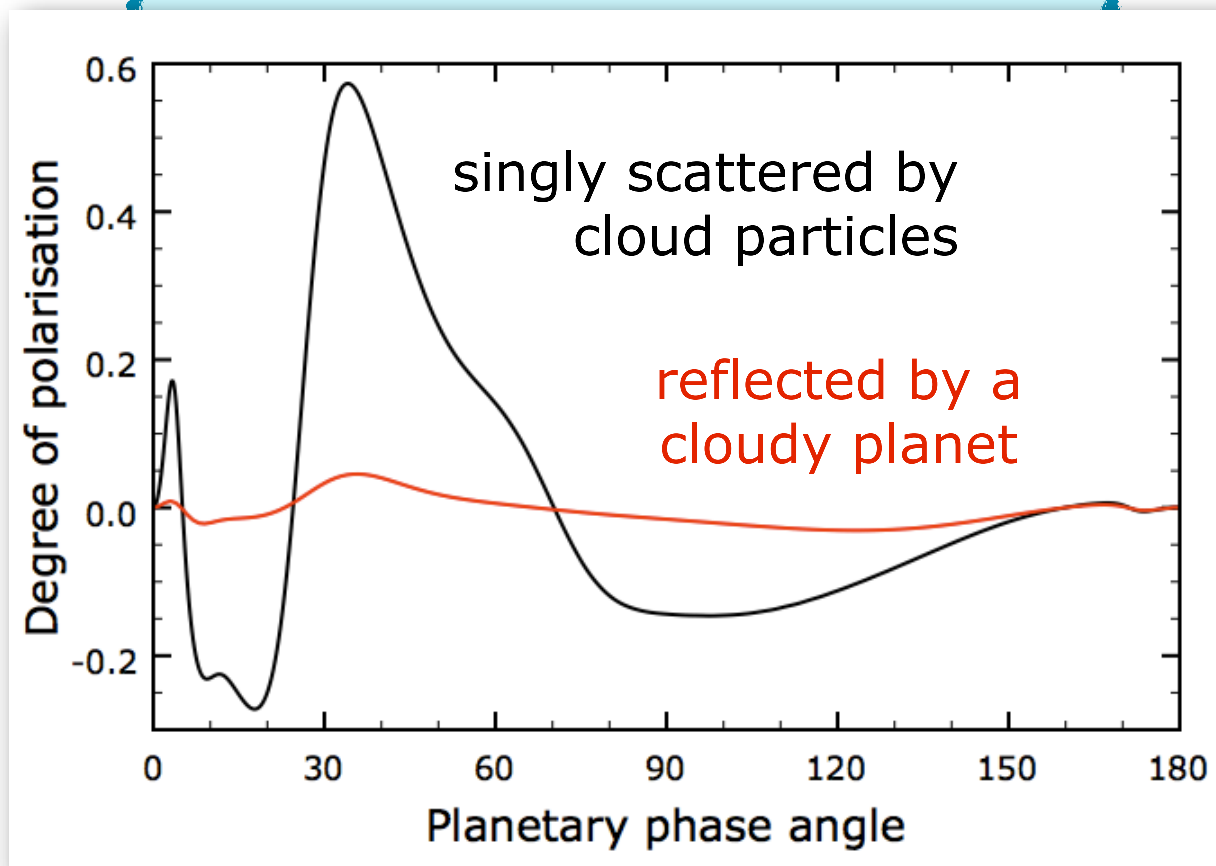
$i=0^\circ$ for a face-on orbit
$i=90^\circ$ for an edge-on orbit

Information content of polarization

Angular features of the single scattering polarization phase function of particles are preserved upon multiple scattering:







Comparison: light singly scattered by liquid water cloud droplets and light reflected by a fully cloudy planet with a cloud optical thickness of 100. Spherical liquid water cloud droplets, with r_{eff}=2.0 μm, n_r=1.3 and n_i=0.00001.

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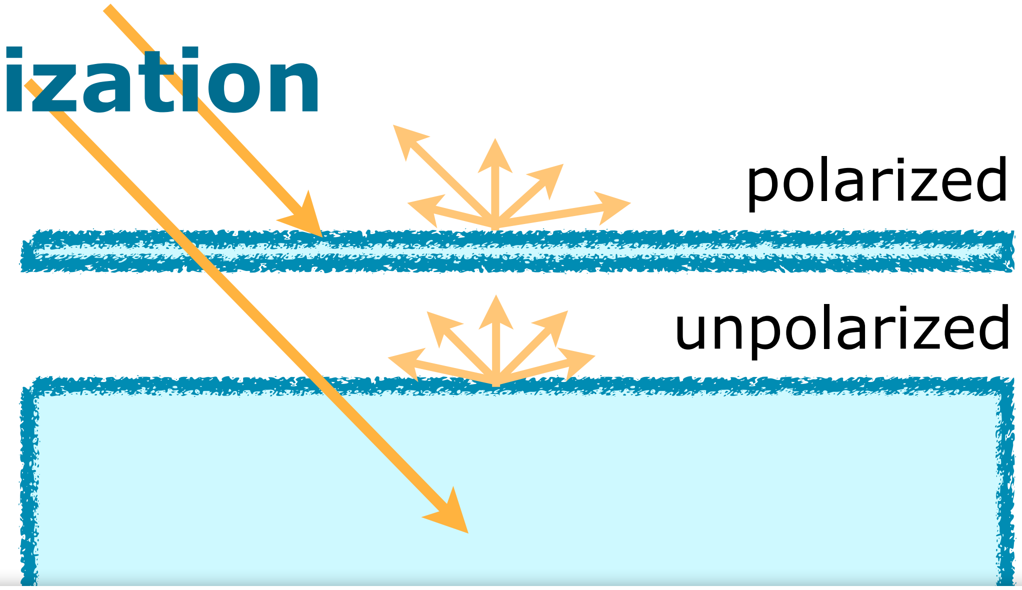
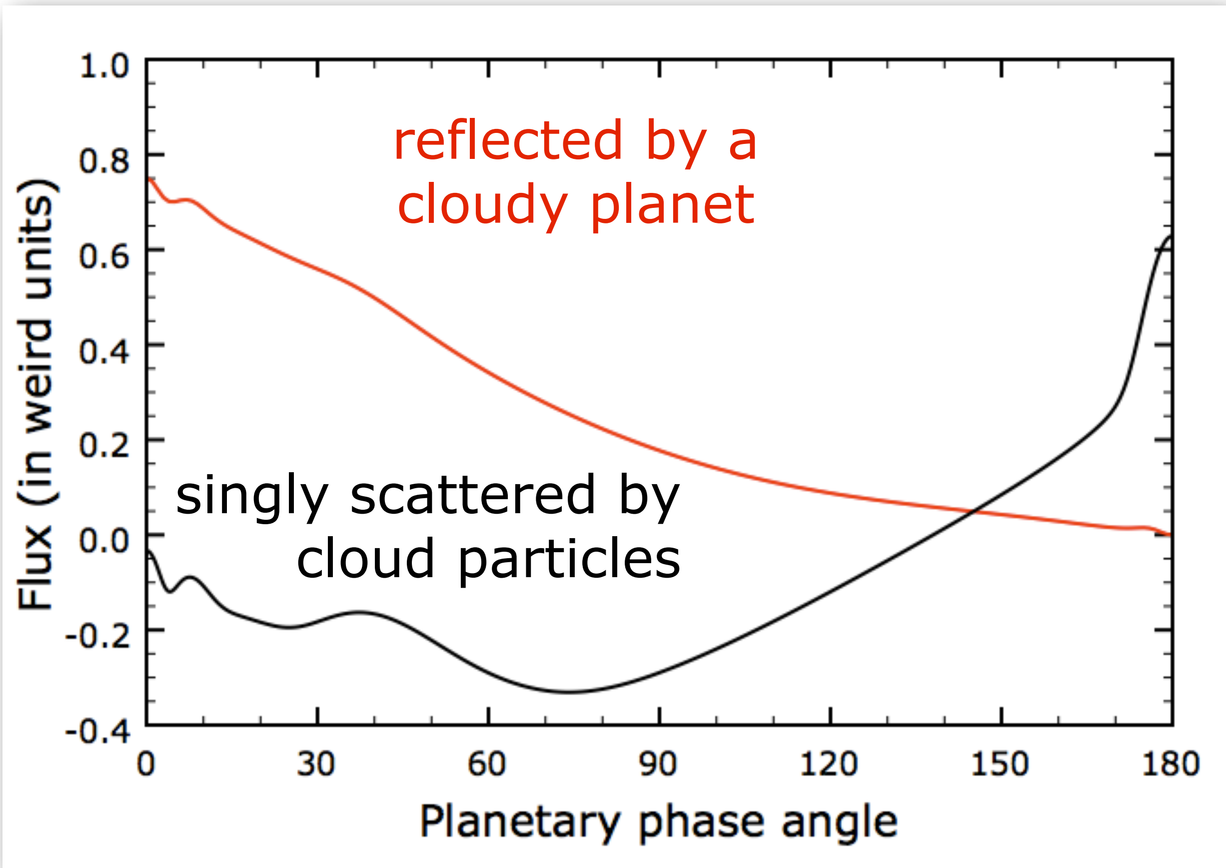
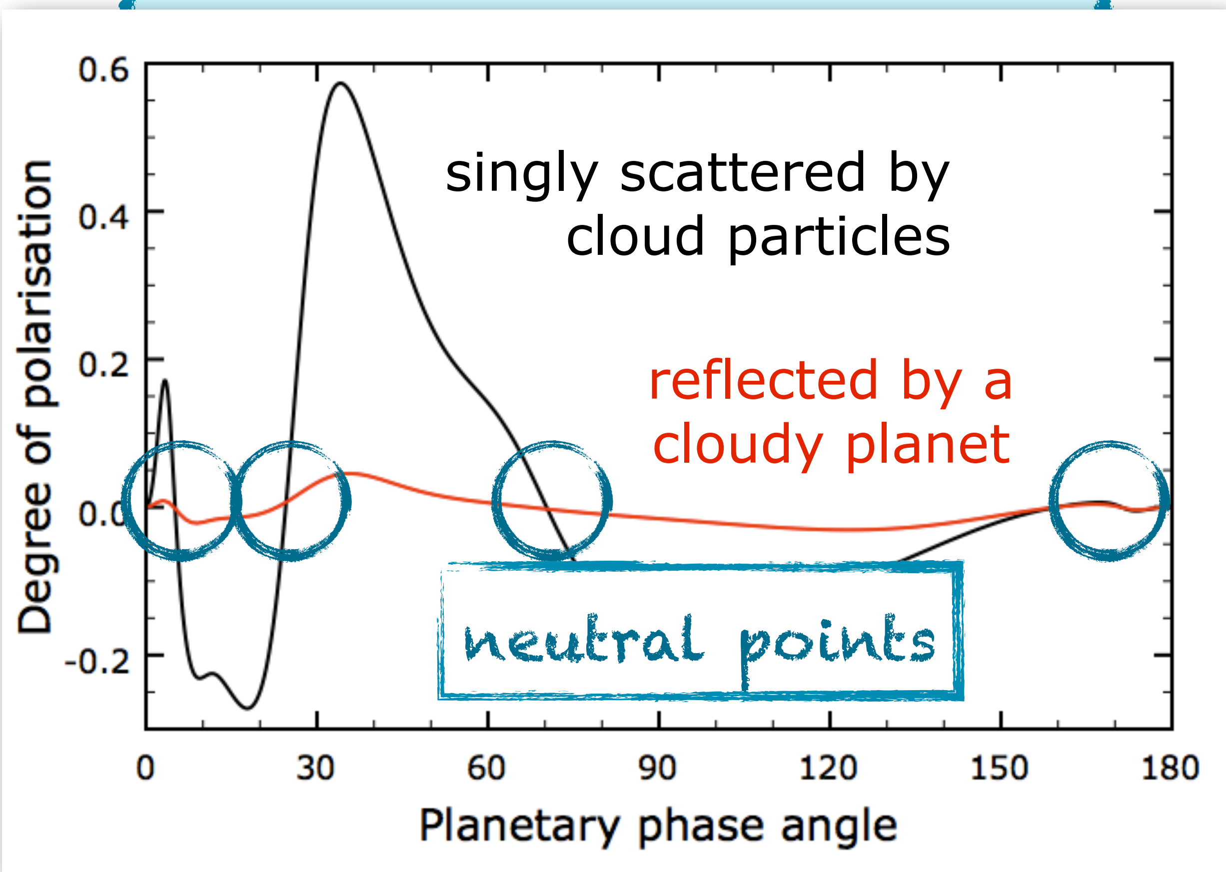




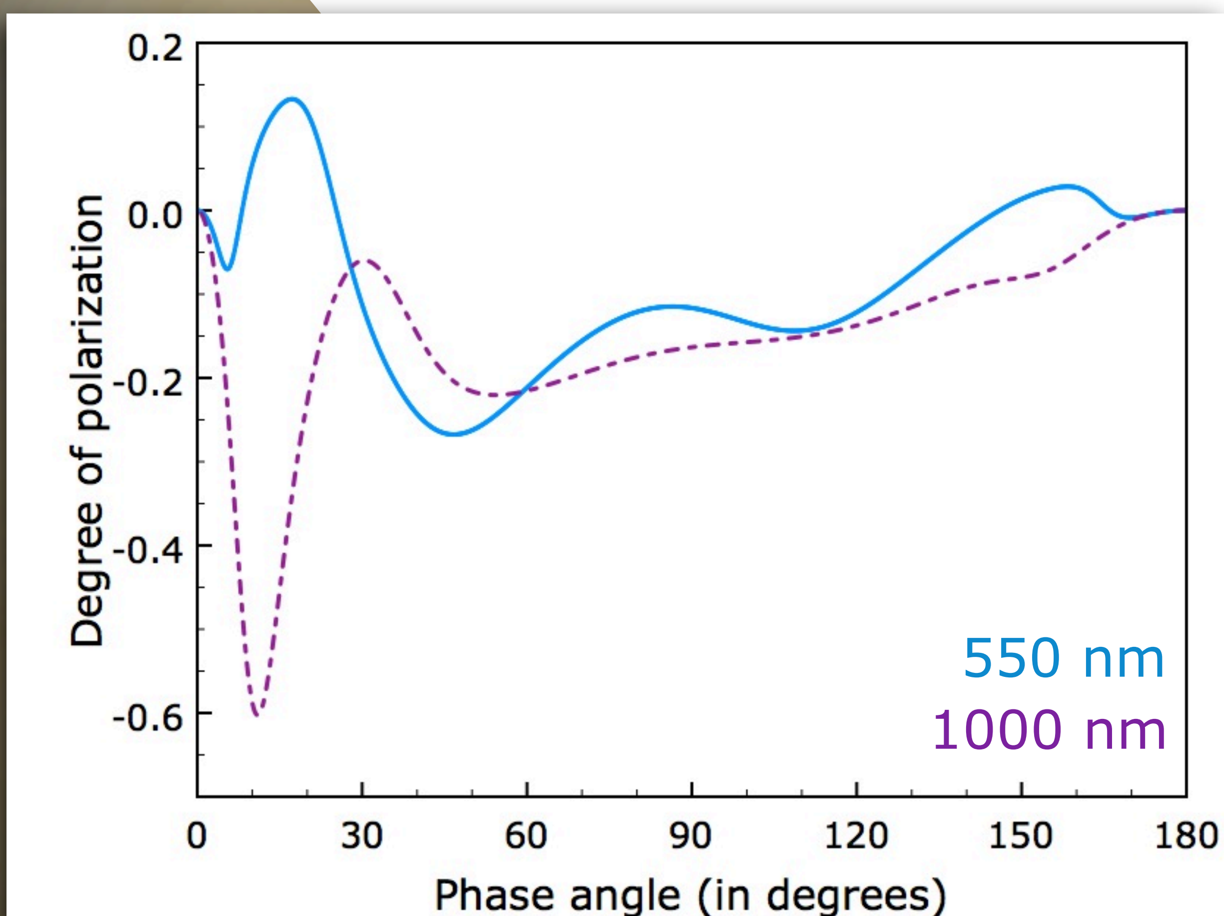


Comparison: light singly scattered by liquid water cloud droplets and light reflected by a fully cloudy planet with a cloud optical thickness of 100. Spherical liquid water cloud droplets, with r_{eff}=2.0 μm, n_r=1.3 and n_i=0.00001.

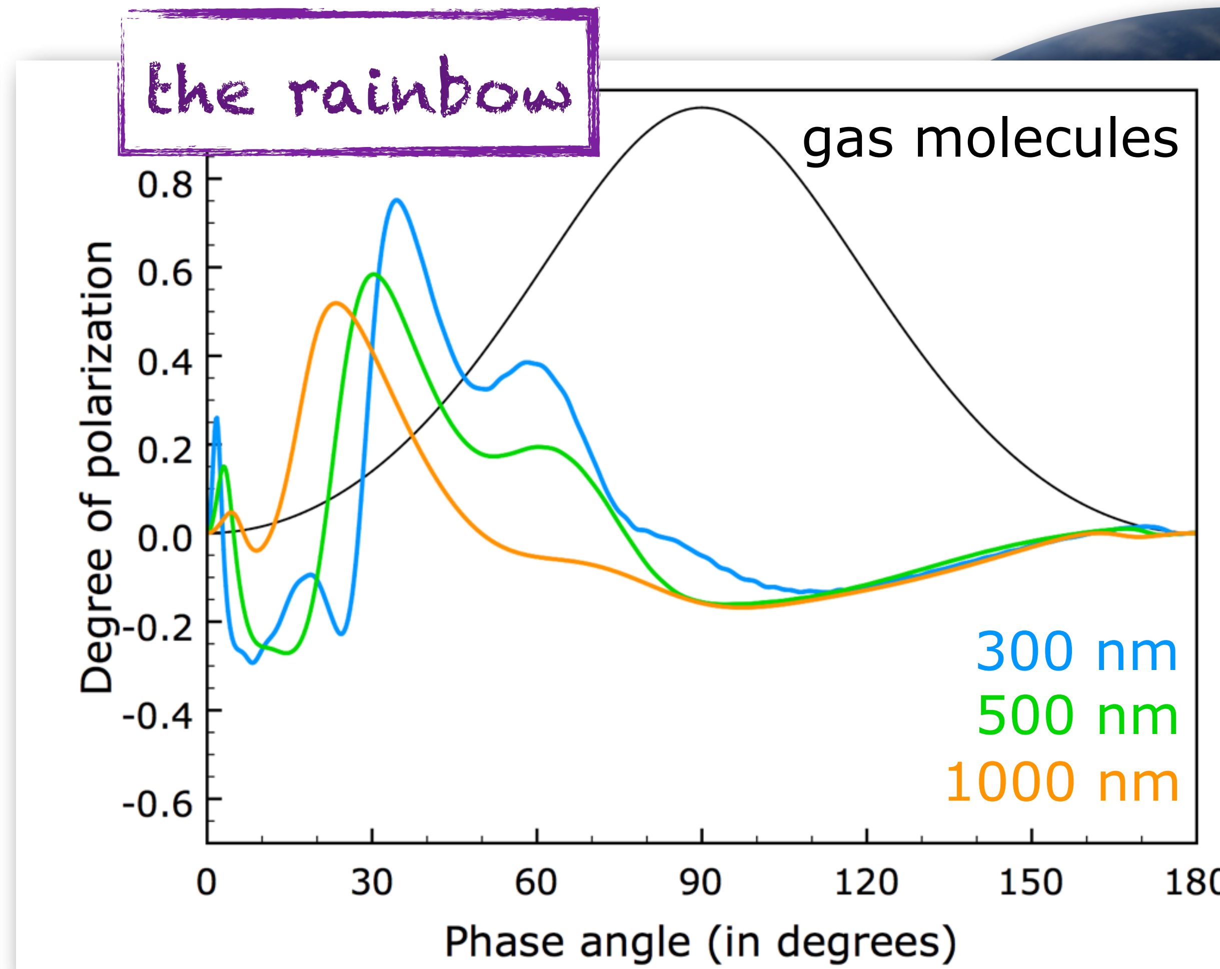
Single scattering by cloud particles

The single scattering polarization phase function of particles depends strongly on their microphysical properties (size, shape, composition):

H_2SO_4 cloud droplets

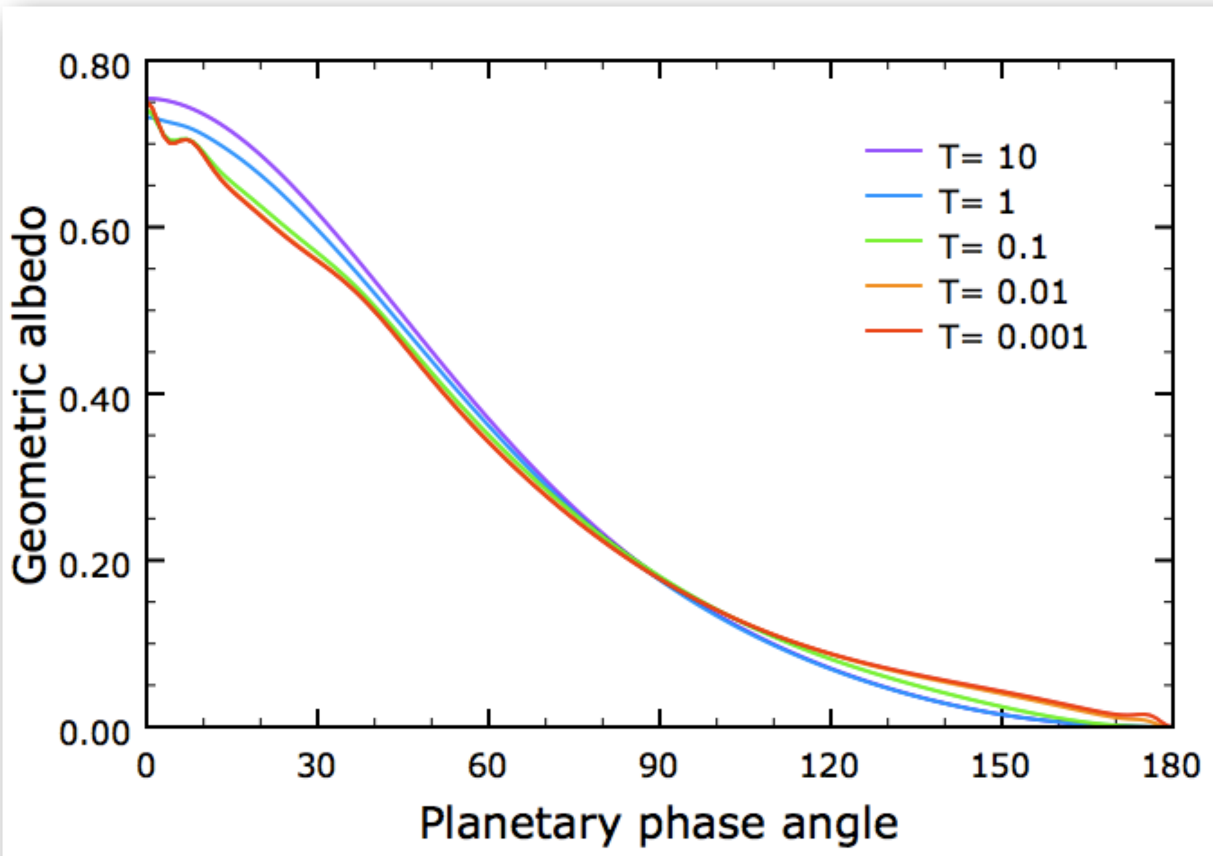


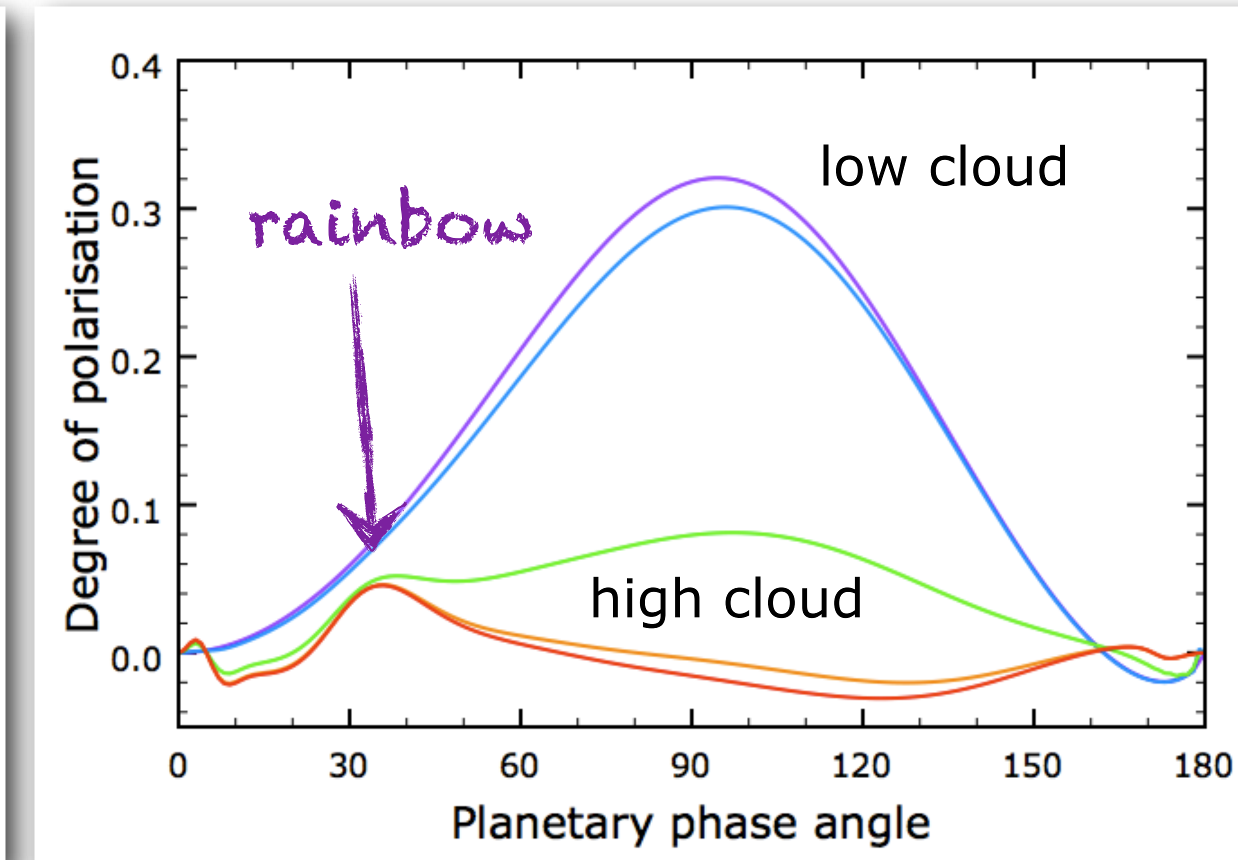
H_2O cloud droplets



Flux and polarization of cloudy exo-Earths

The flux and polarization of starlight reflected by an Earth-like model exoplanet with a **liquid water cloud** below a gas layer as functions of α:

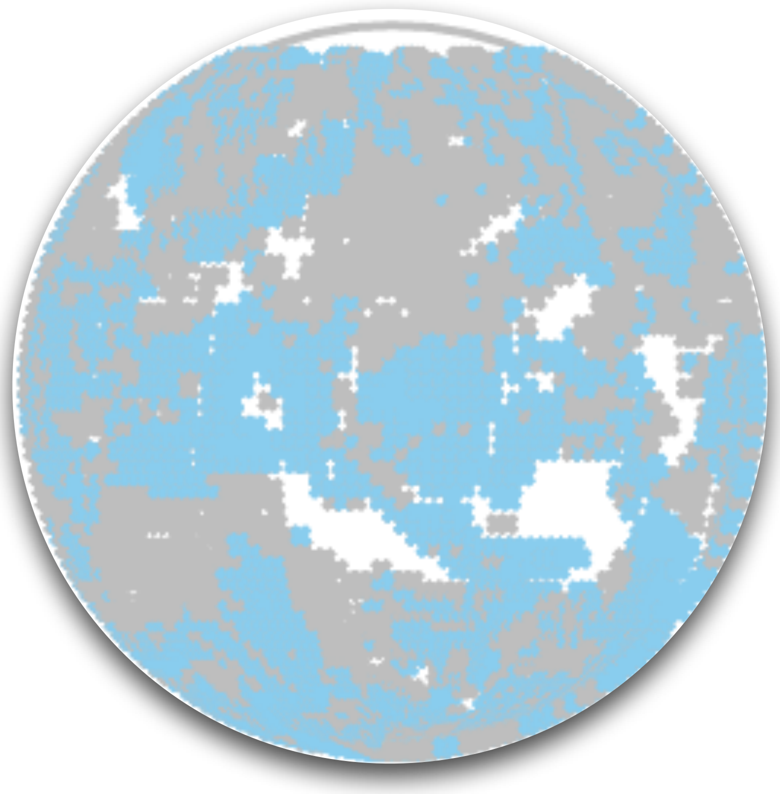




A gas layer, overlaying a cloud with optical thickness 100.
Spherical cloud droplets, with r_{eff}=2.0 μm, n_r=1.3 and n_i=0.00001.
The cloud top altitude/optical thickness τ of the gas layer is varied.

Signals of a realistically cloud covered exo-Earth

Using cloud parameter data from an Earth remote-sensing satellite, an Earth-like model planet with a realistic cloud coverage was made:



Earth's clouds on 25 April 2011 from MODIS data (NASA). The planet is covered by ~63% liquid water clouds (grey), and ~36% ice clouds (white). About 28% of the planet is covered by 2 cloud layers.

(Karalidi, Stam & Hovenier, 2012)

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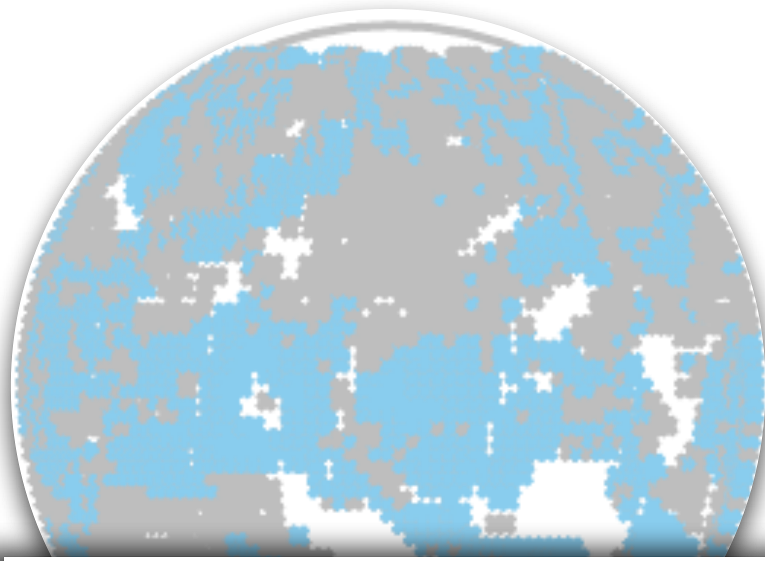

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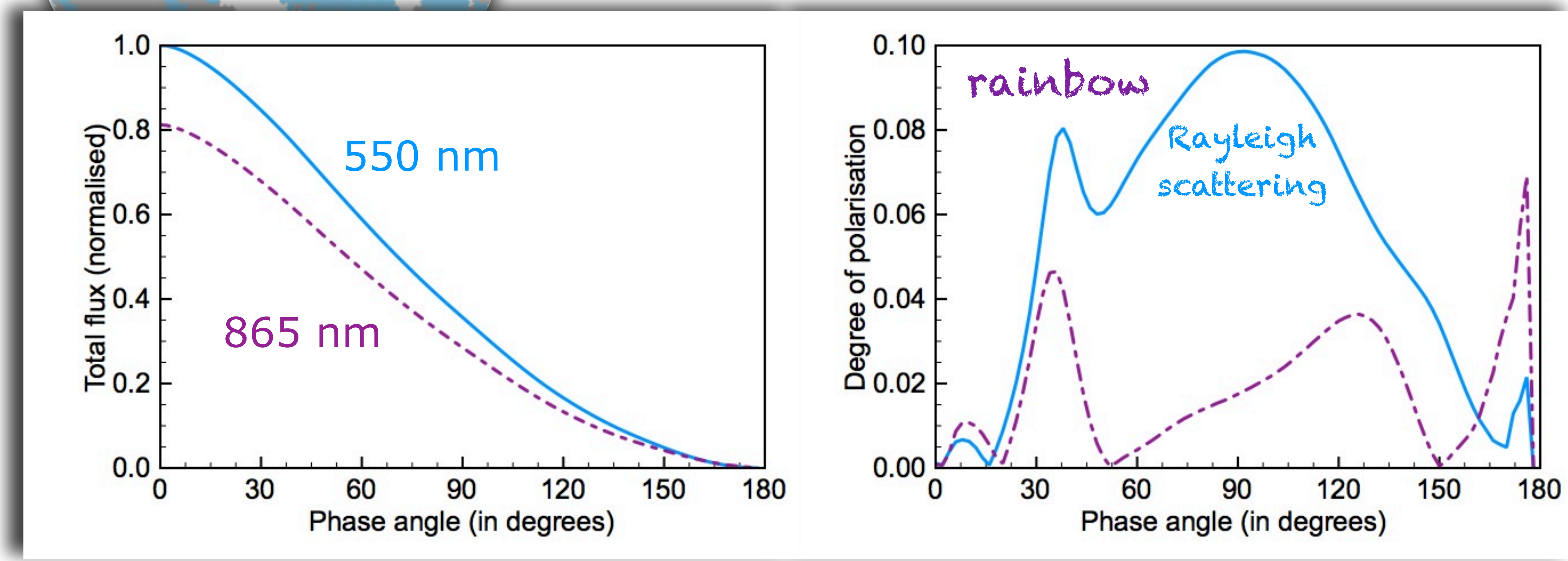

A spectropolarimeter for exoplanet research

LOUPE: The Lunar Observatory for Unresolved Polarimetry of Earth

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From the moon, we can monitor the whole Earth:

- during its daily rotation
- at phase angles from 0° to 180°
- throughout the seasons
- outside the Earth's atmosphere

This cannot be done from:

- Low Earth Orbit satellites
- geostationary satellites
- Earth-shine observations
- non-dedicated missions (e.g. Galileo, Venus Express, ...)

Summary

- Polarimetry appears to be a strong tool for the detection and confirmation of exoplanets
- Polarimetry can help to characterize exoplanetary atmospheres and surfaces because it is very sensitive to their composition and structure, while the reflected flux is far less sensitive
- We will get so few photons from exoplanets, we should retrieve all the information they carry with them
- Our own Earth can be used a test-bed for retrieval methods, for example by measuring the flux and polarization of the Earth from the moon with LOUPE