

# Calibration and analysis of the telluric O<sub>2</sub>-bands

a spectropolarimetric approach for aerosol and cloud analysis



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Daphne Stam, TU Delft

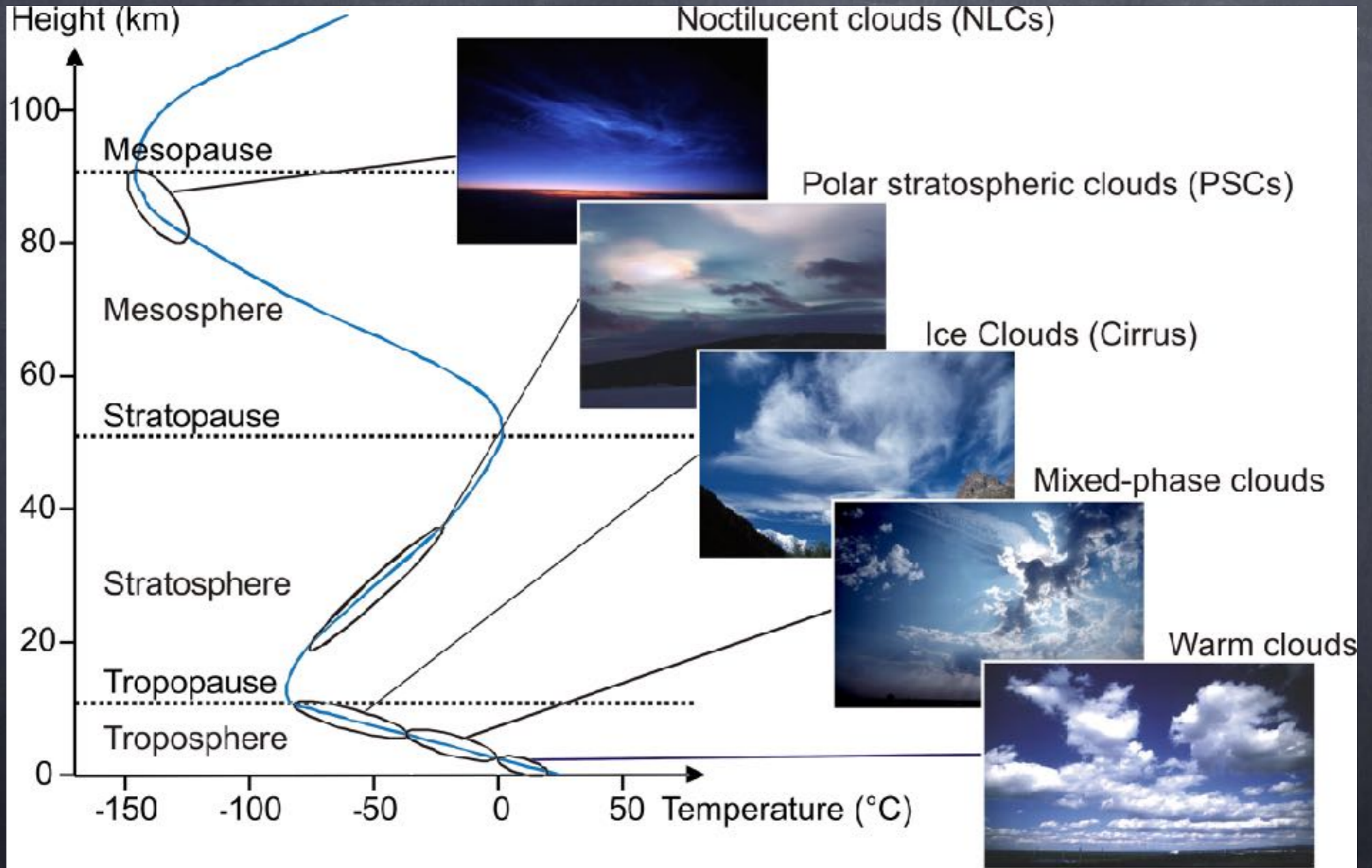
# Observatory/Astronomy relevance

:

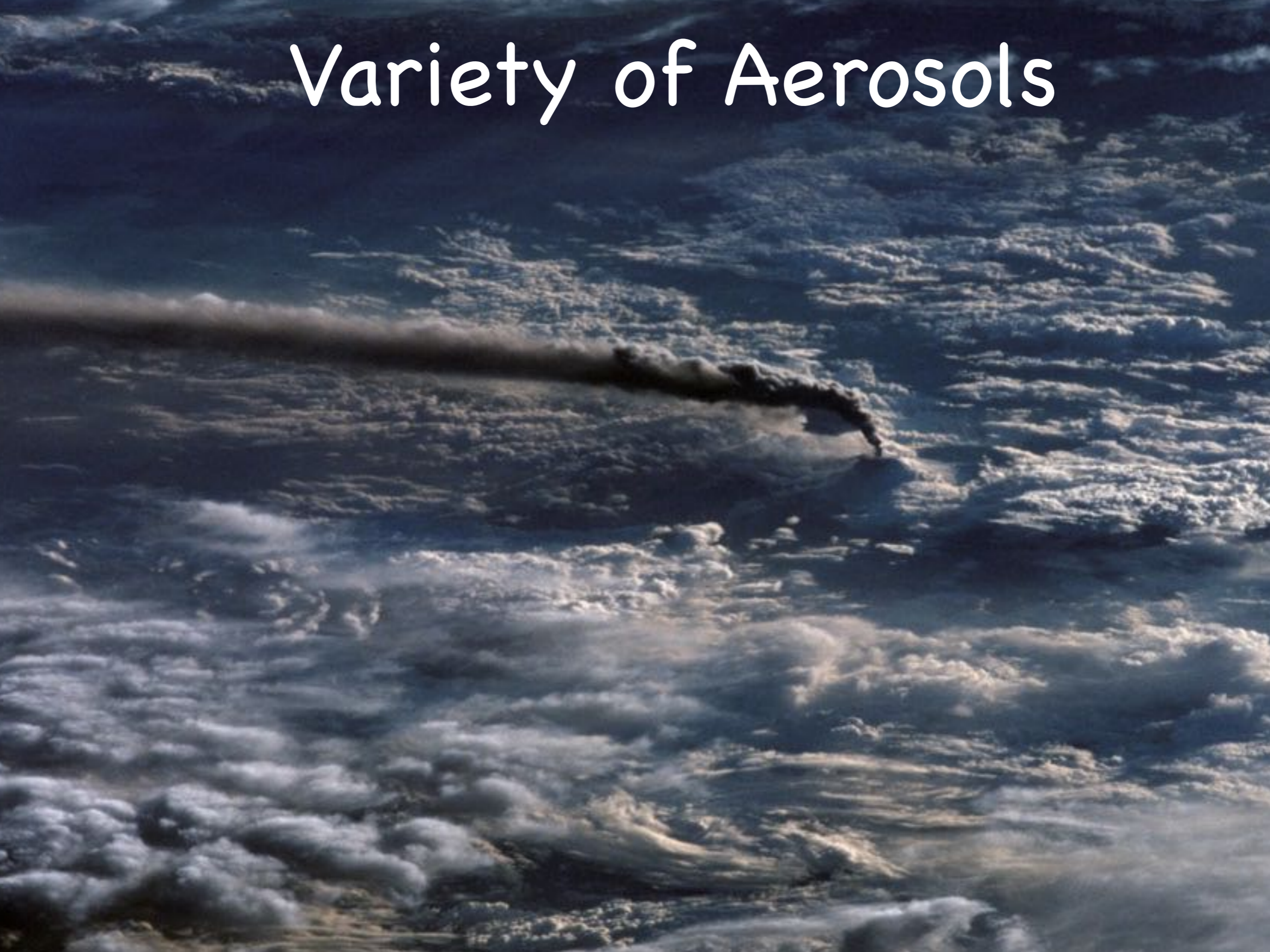
beyond atmosphere classification (transparency/seeing/PWV)

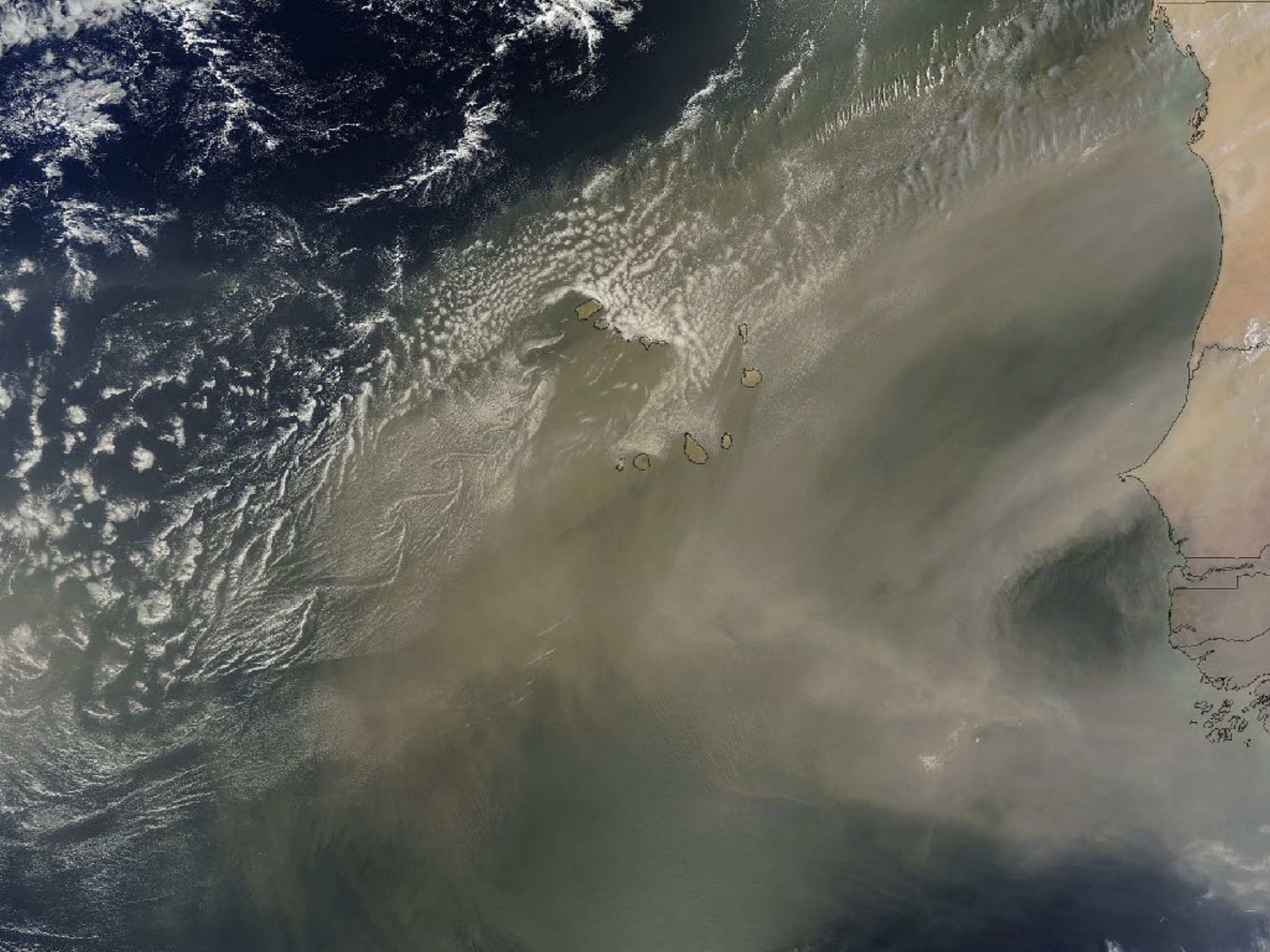
- telluric calibration (molecfit)
- forecasting (wind, turbulence, IQ, -> meteorology)
- predictive scheduling
- exo-Earth atmosphere characterisation

# Earth Cloud Systems

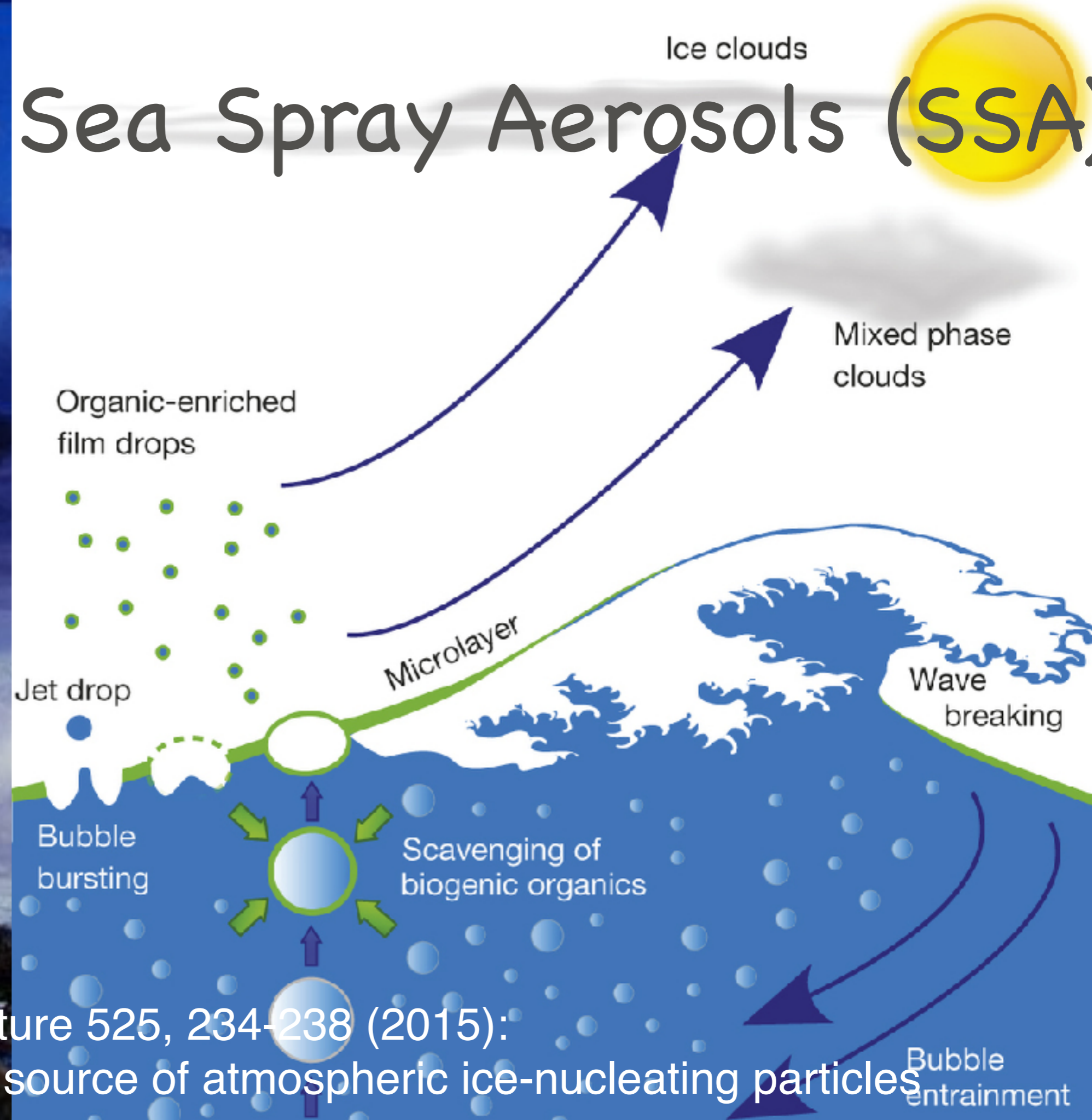


# Variety of Aerosols





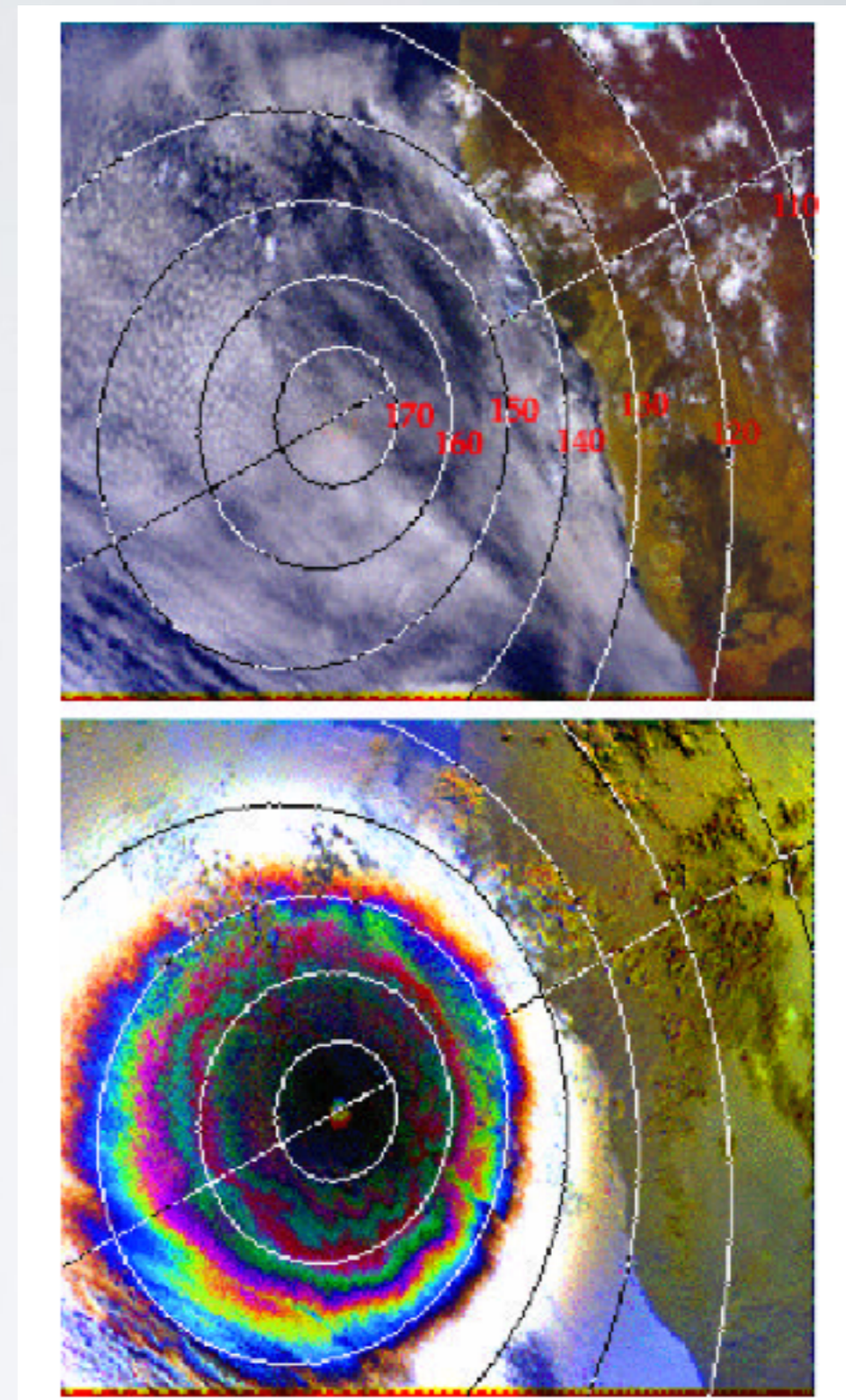
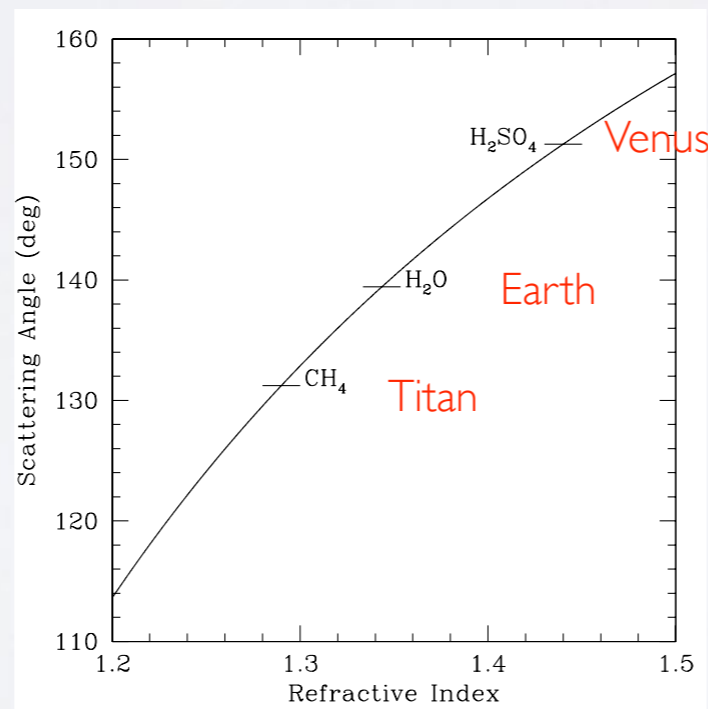
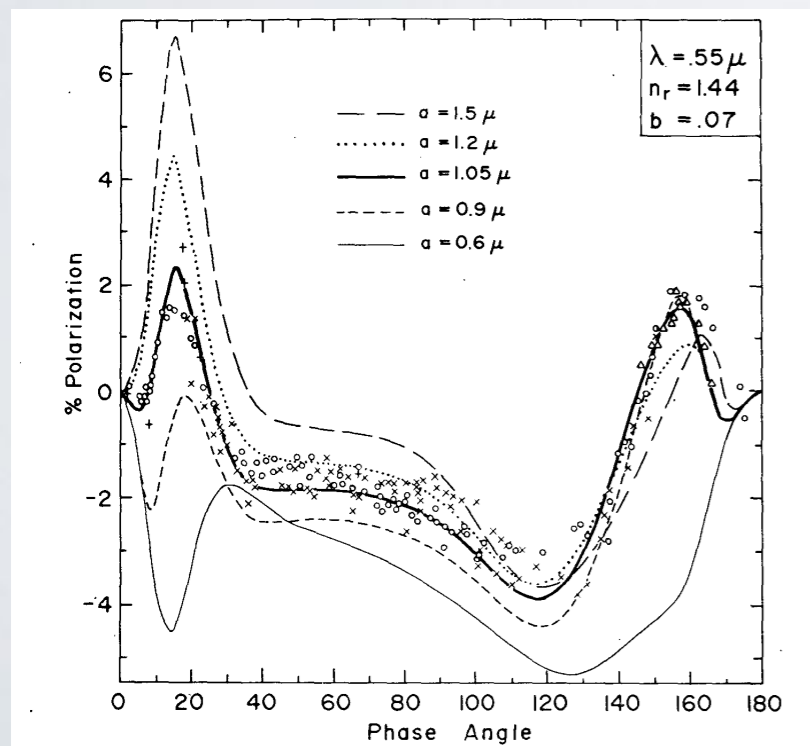
# Sea Spray Aerosols (SSA)



T. Wilson et al. Nature 525, 234-238 (2015):  
A Marine biogenic source of atmospheric ice-nucleating particles

# Polarimetric Signatures of Planet Earth

## rainbow polarization



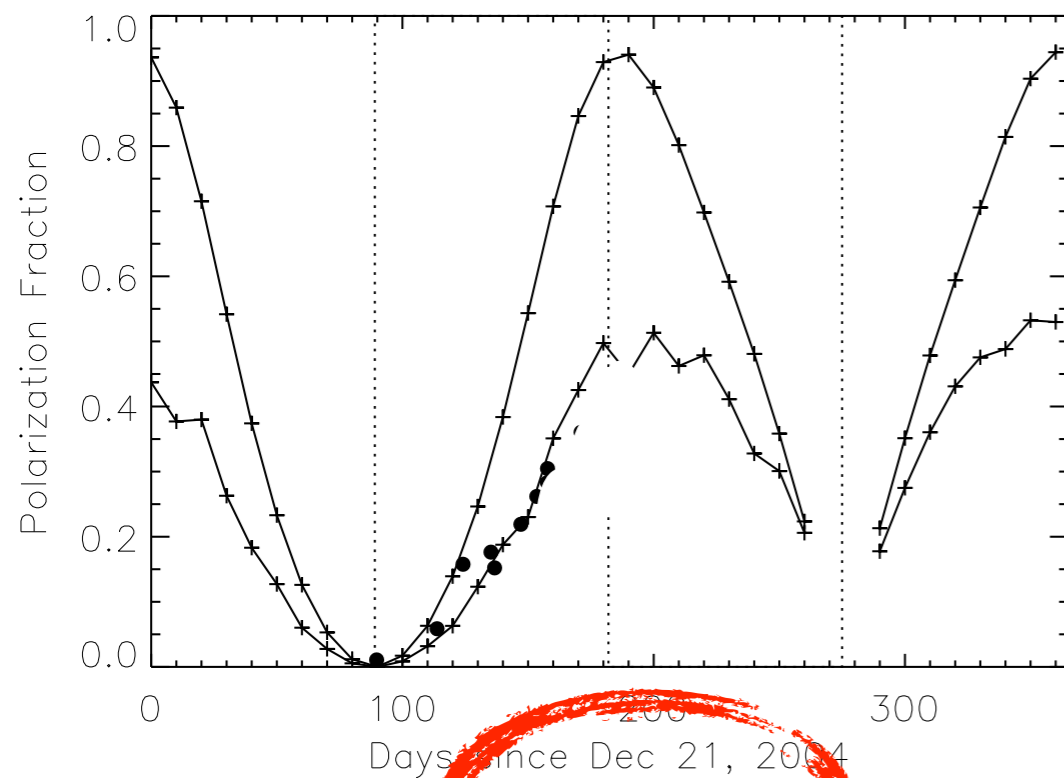
Hansen, J. E. & Hovenier, J. W. Interpretation of the polarization of Venus. *Journal of Atmospheric Science* **31**, 1137–1160 (1974).

Bréon, F. M. & Goloub, P. Cloud droplet effective radius from spaceborne polarization measurements. *Geophysical research letters* **25**, 1879–1882 (1998).

Bailey, J. Rainbows, Polarization, and the Search for Habitable Planets. *Astrobiology* **7**, 320–332 (2007).

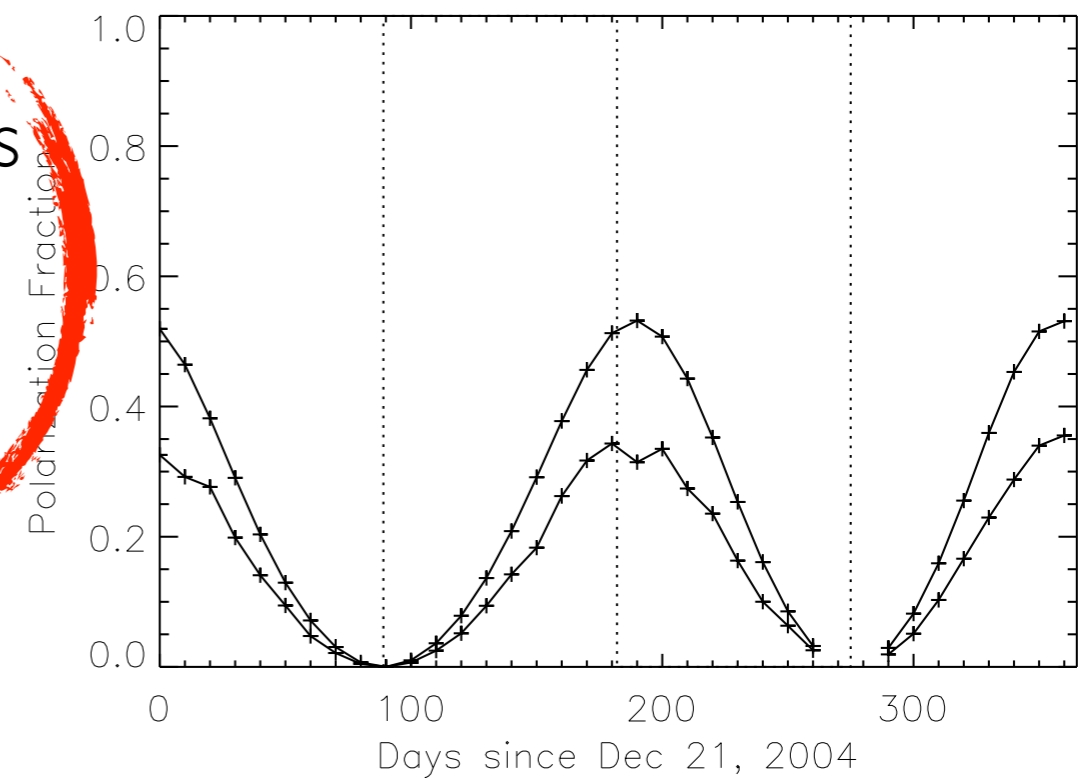
# Polarimetric Signatures of Planet Earth

pure ocean surface



Phase Angle

pure land surface



Phase Angle

no clouds

clouds

McCullough, P. R. Models of Polarized Light from Oceans and Atmospheres of Earth-like Extrasolar Planets. *arXiv astro-ph*, (2006).

Williams, D. M. & Gaidos, E. Detecting the glint of starlight on the oceans of distant planets. *Icarus* **195**, 927–937 (2008).

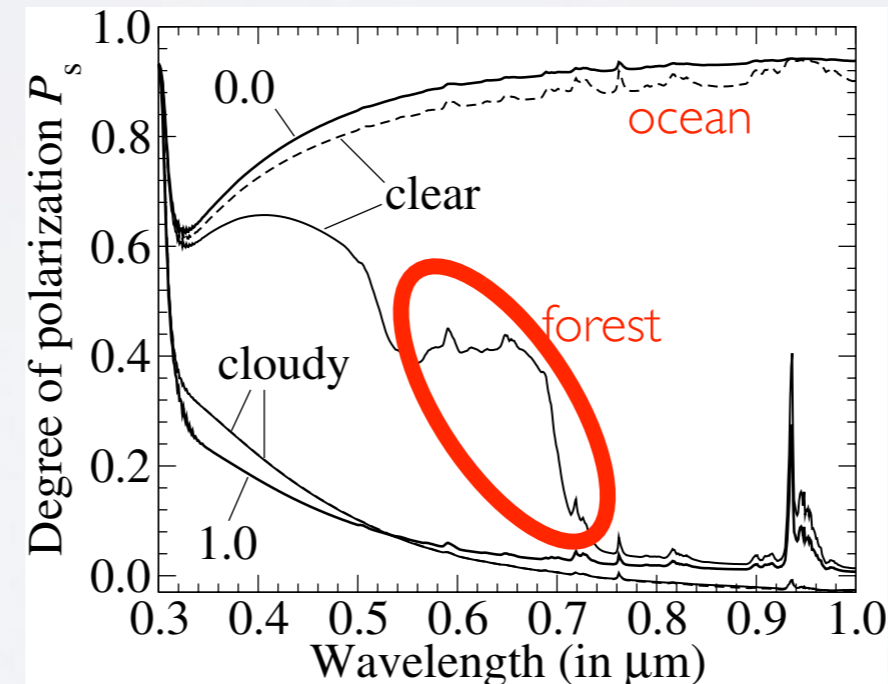
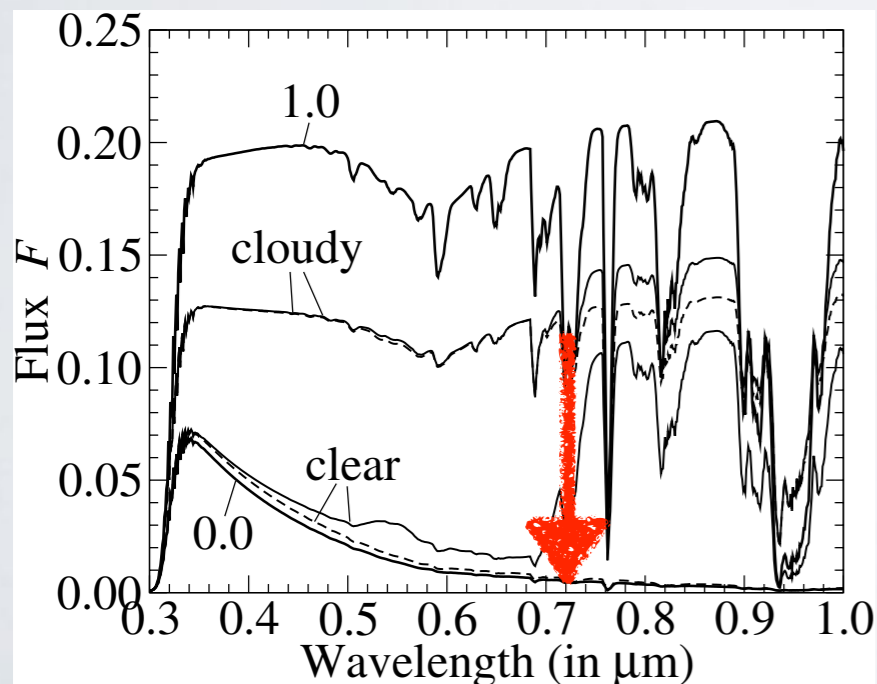
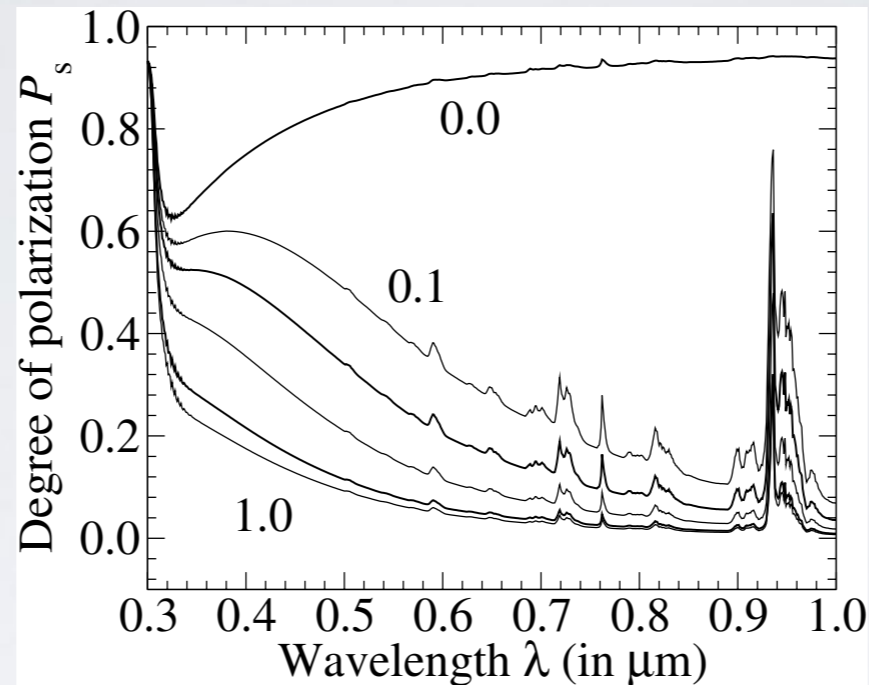
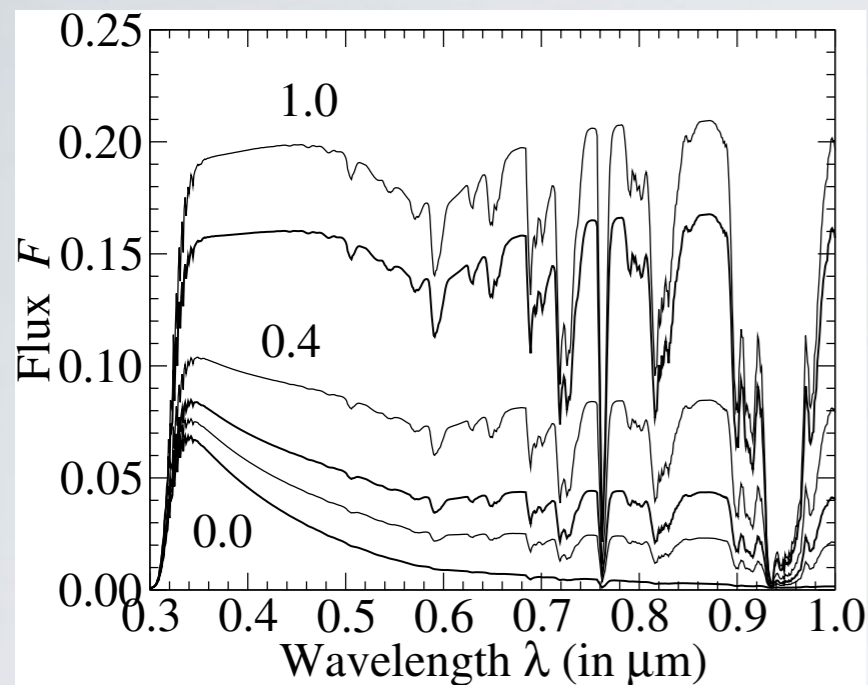
# Modelling Earth's Polarization

VRT calc. include

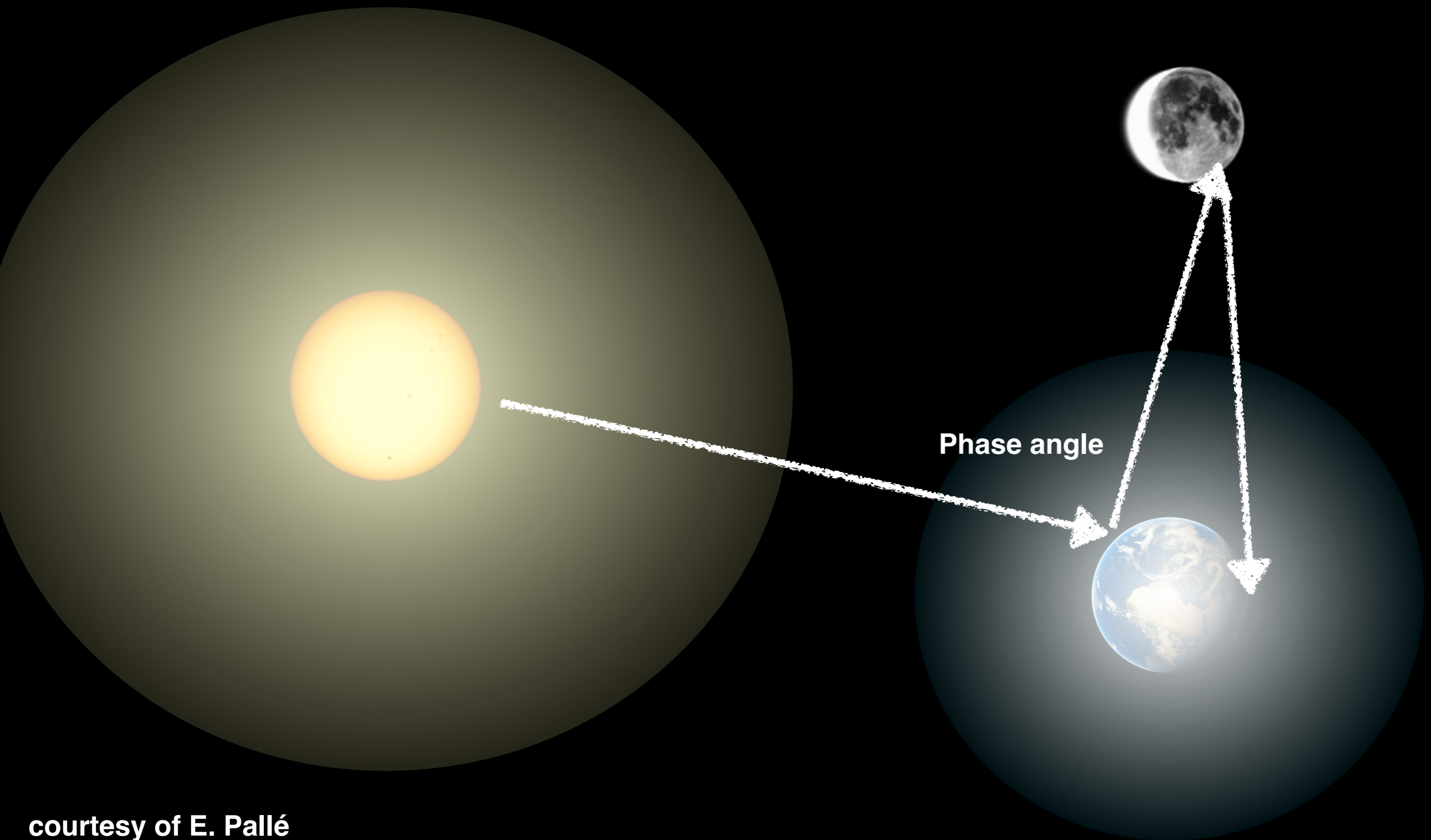
atmosphere  
geometry  
surfaces

missing

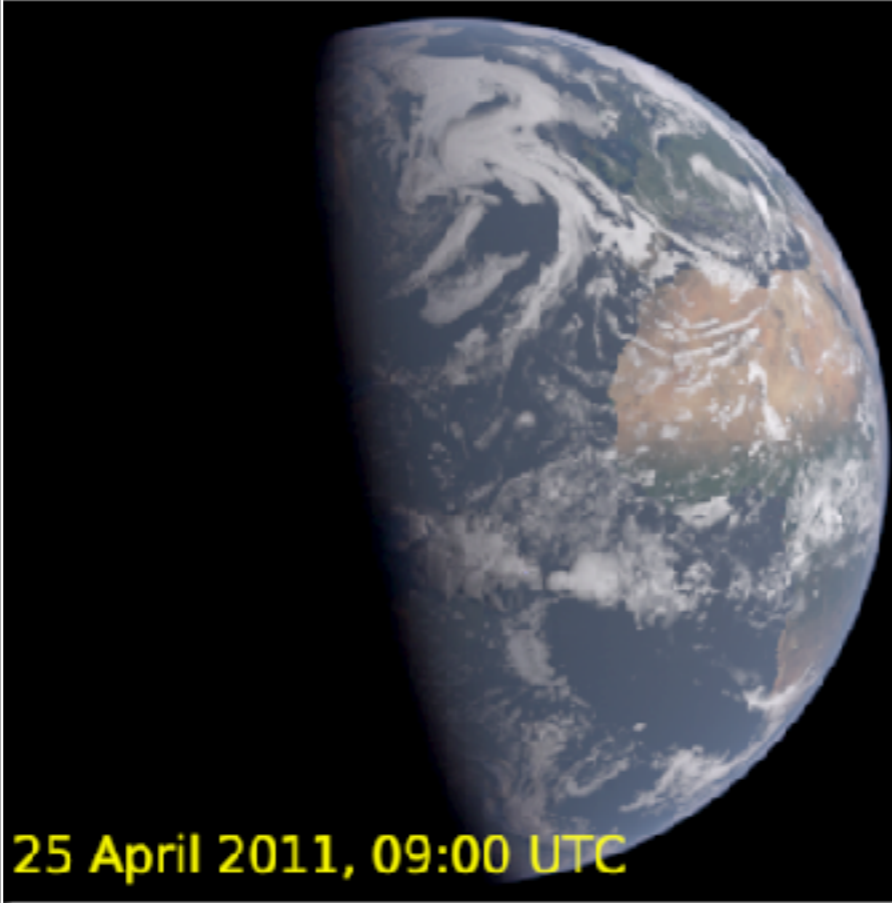

inhomogenities  
realistic clouds  
aerosols/haze  
realistic surfaces



# Earthshine



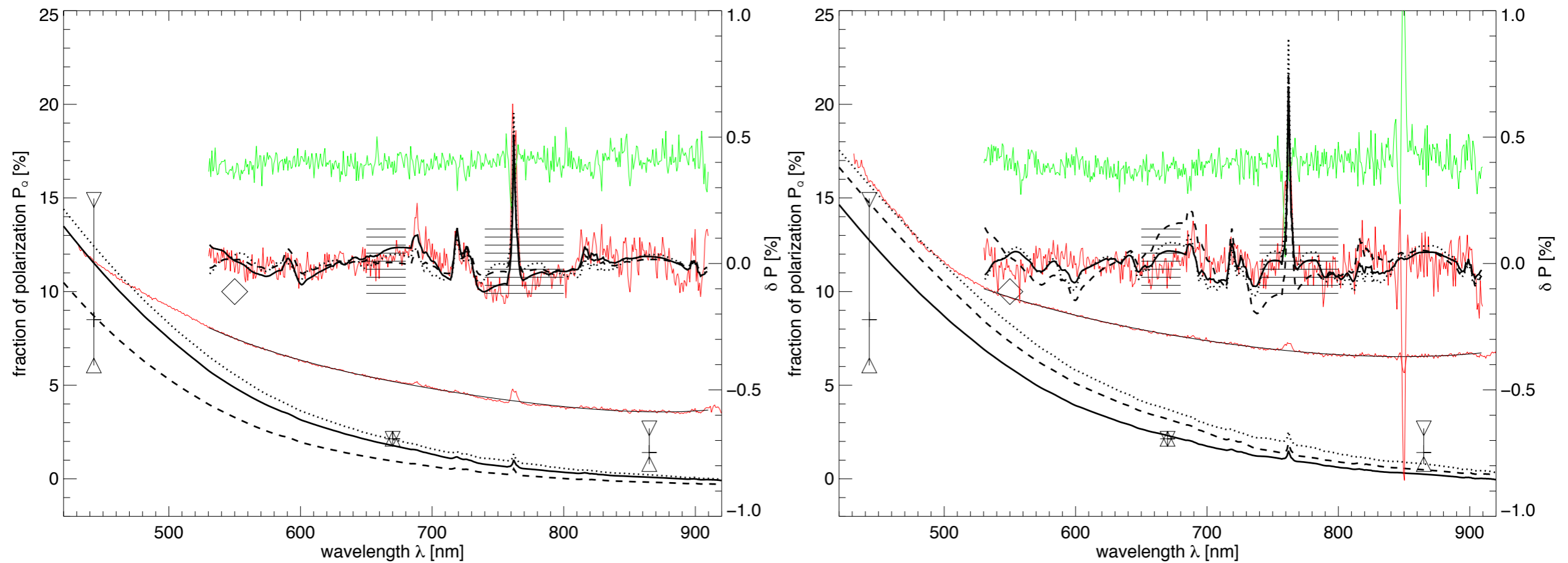
# Spectropolarimetry of ES:

Observing Date	25-Apr-2011:UT09	10-Jun-2011:UT01
View of Earth as seen from the Moon	 25 April 2011, 09:00 UTC	 10 June 2011, 01:00 UTC
Sun-Earth-Moon phase	87 deg	102 deg
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 $\tau > 6$	40%	27%

# line vers. continuum

25-Apr-2011:UT09

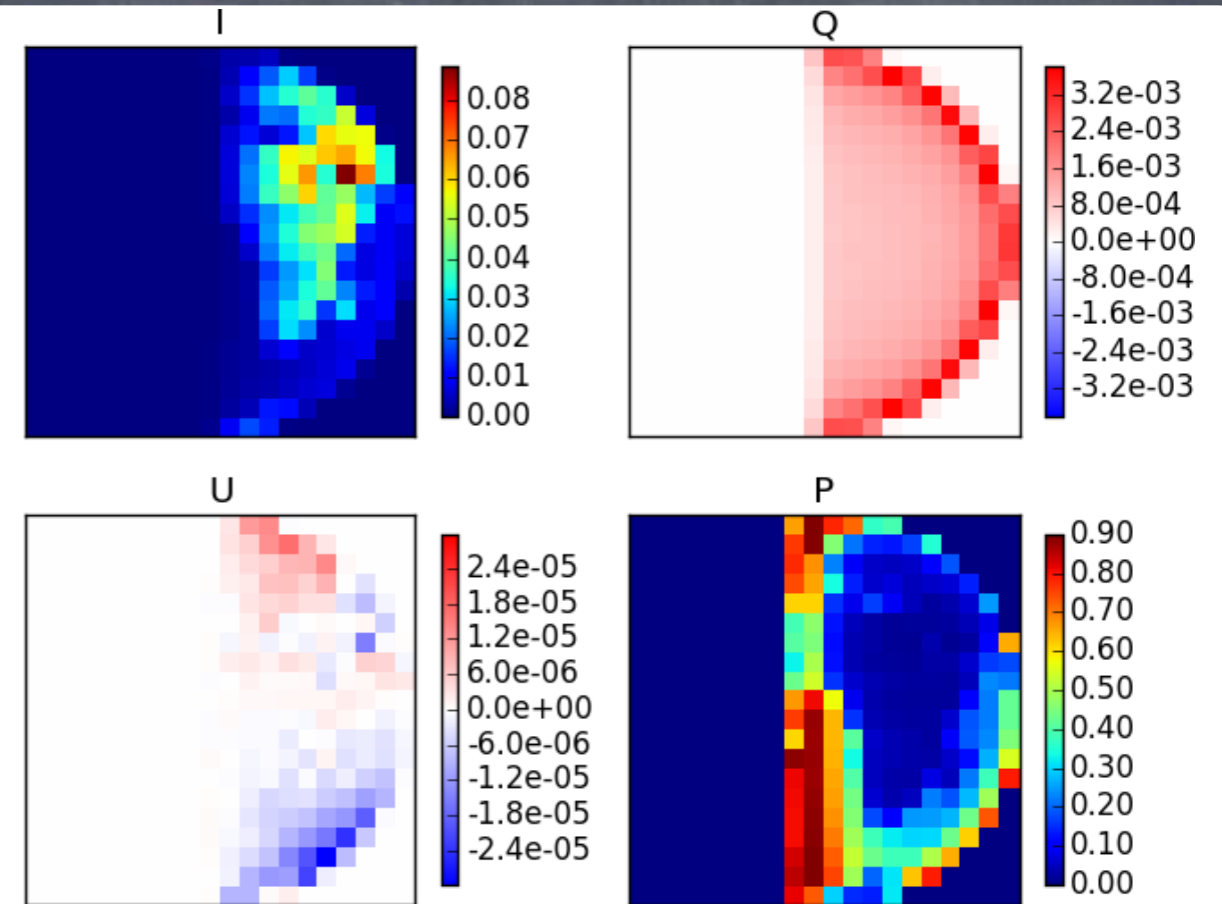
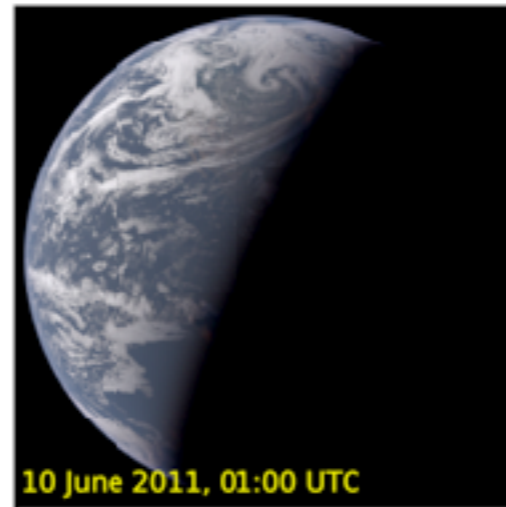
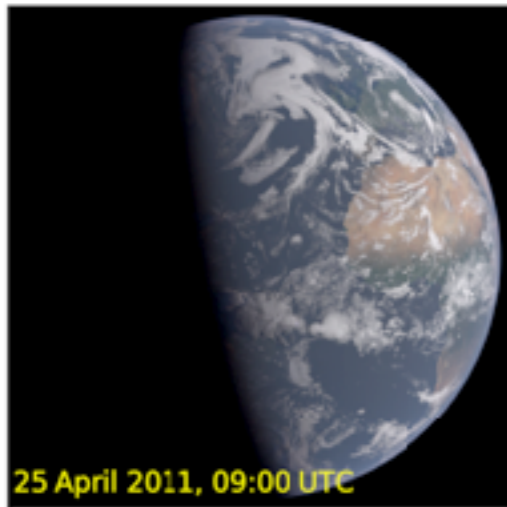
10-Jun-2011:UT01



D. Stams model spectra (3nm resolution) agree qualitatively with the measurements (1nm): O2A strength, water, NDVI.

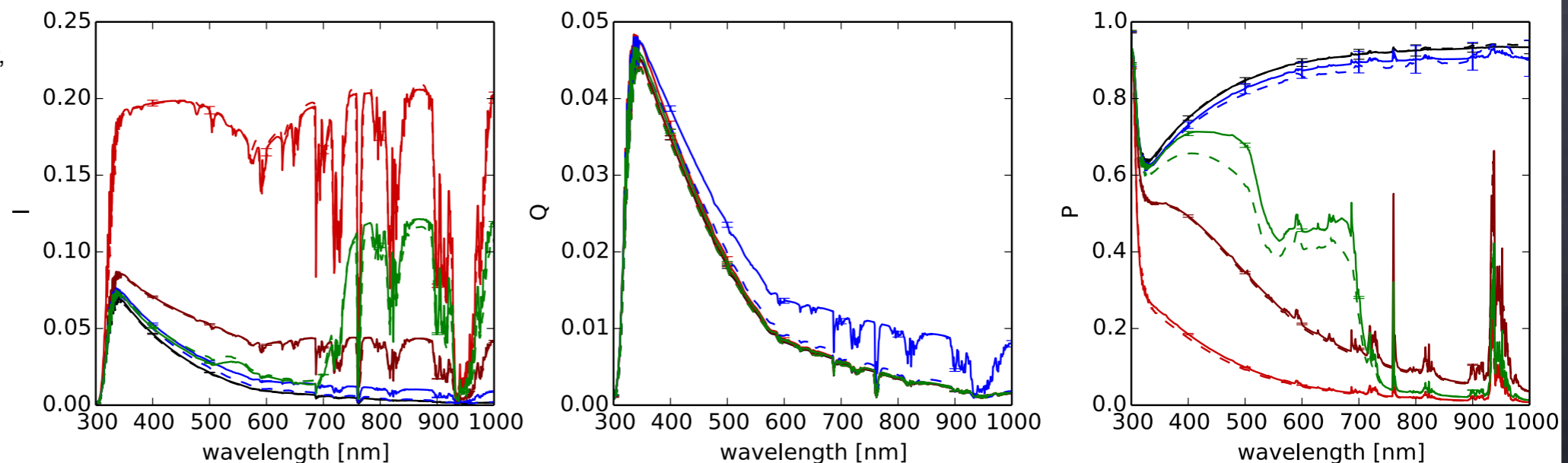
# MYSTIC 3D-vec. rad. transfer

w/ **C. Emde** (Monte Carlo code for the pHYSically correct Tracing of photons In Cloudy atmospheres)








Emde, C., Buras, R., Mayer, B. & Blumthaler, M. The impact of aerosols on polarized sky radiance: **model development, validation, and applications**. *Atmos. Chem. Phys.* 10, 383–396–396 (2010).

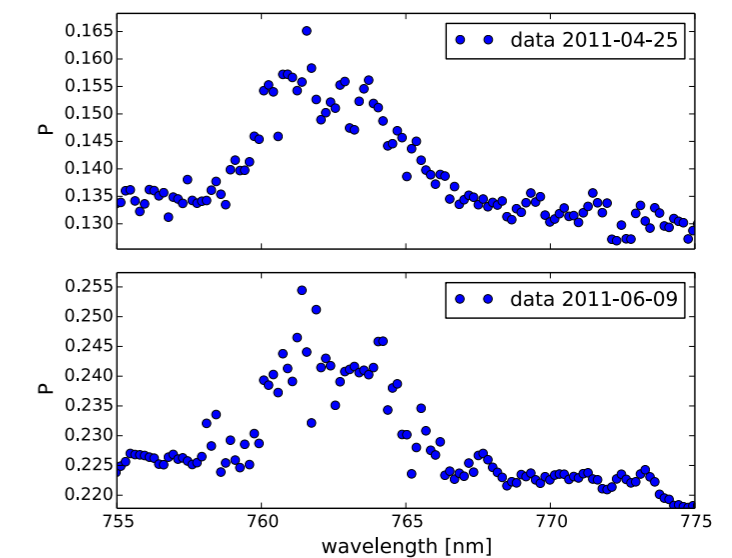
Emde, C., Buras, R. & Mayer, B. An efficient method to compute **high spectral resolution** polarized solar radiances using the **Monte Carlo** approach. *Journal of Quantitative Spectroscopy and Radiative Transfer* 112, 1622–1631 (2011).



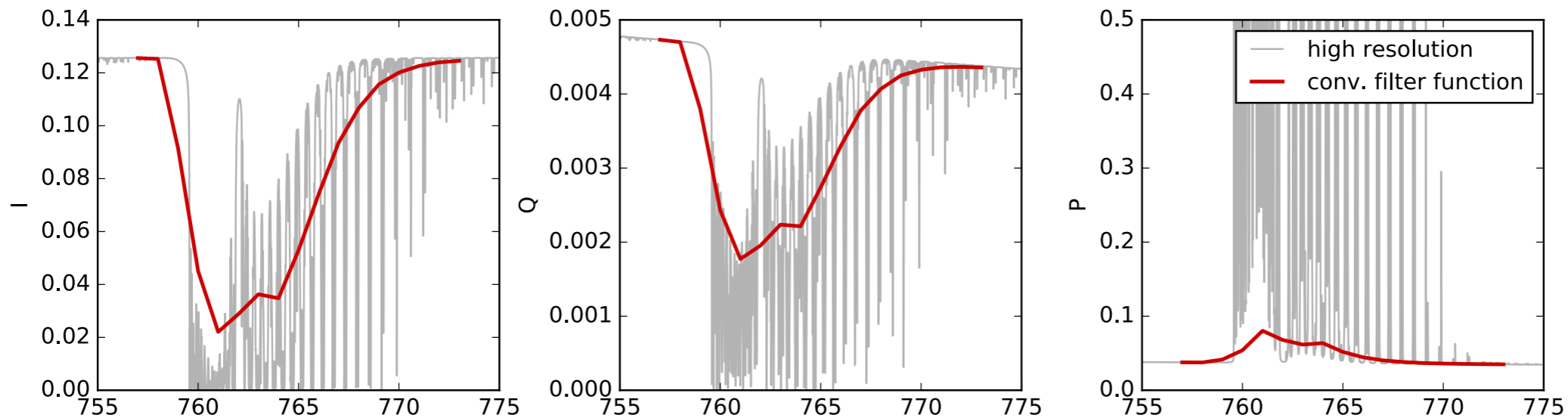
surface type:

 Lambert 0.0	 Lambert 0.2	 Lambert 1.0	 Ocean / Fresnel	 Gras / Forest
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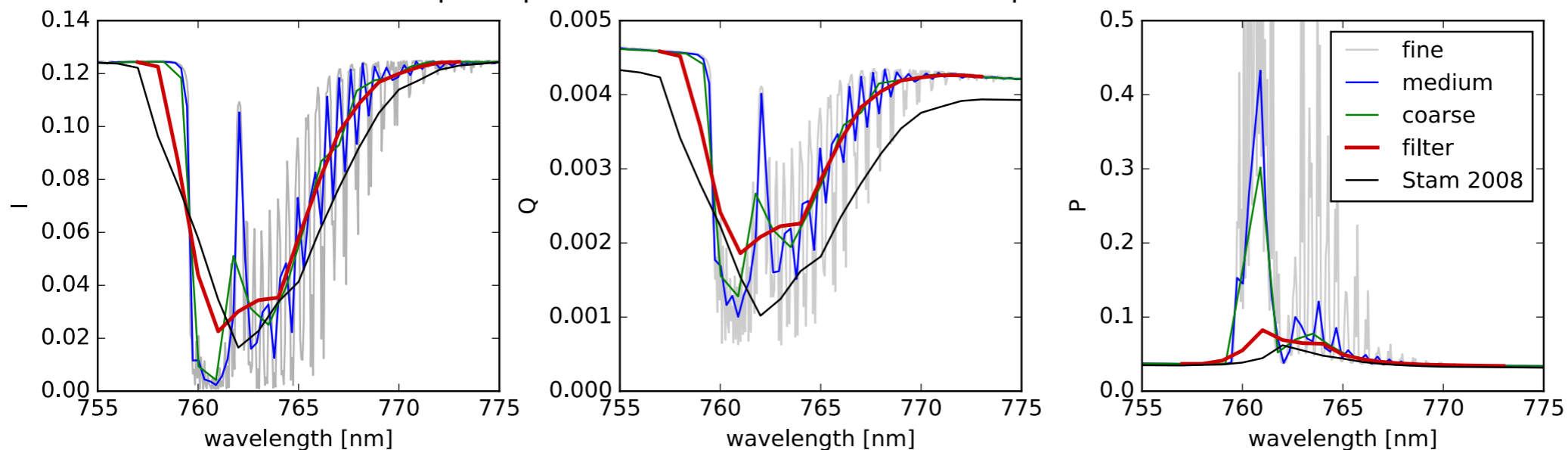
# We'd like high spectral resolution



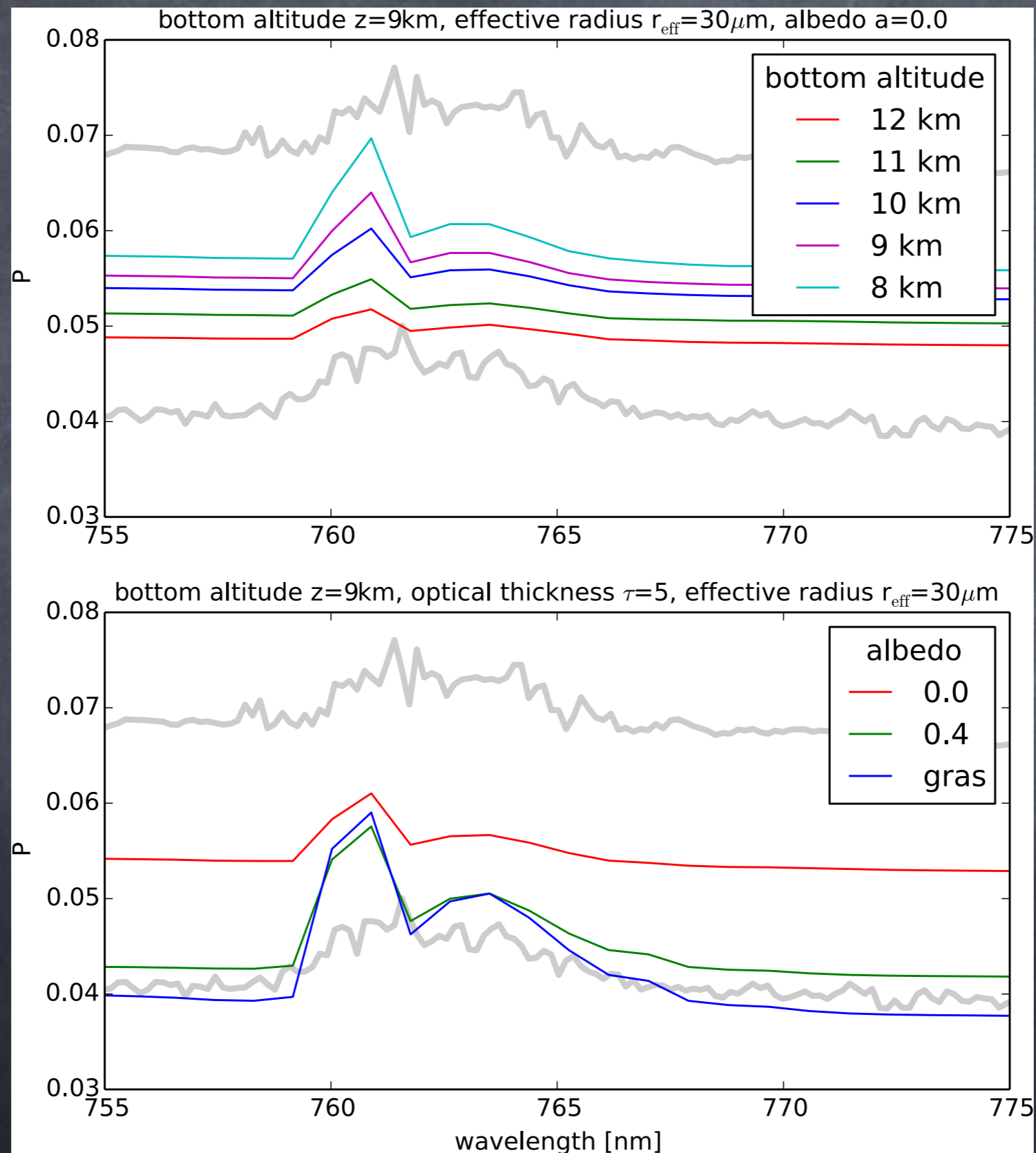
accurate simulation with instrument filter function (FWHM~3nm)



absorption parameterization with different spectral resolutions

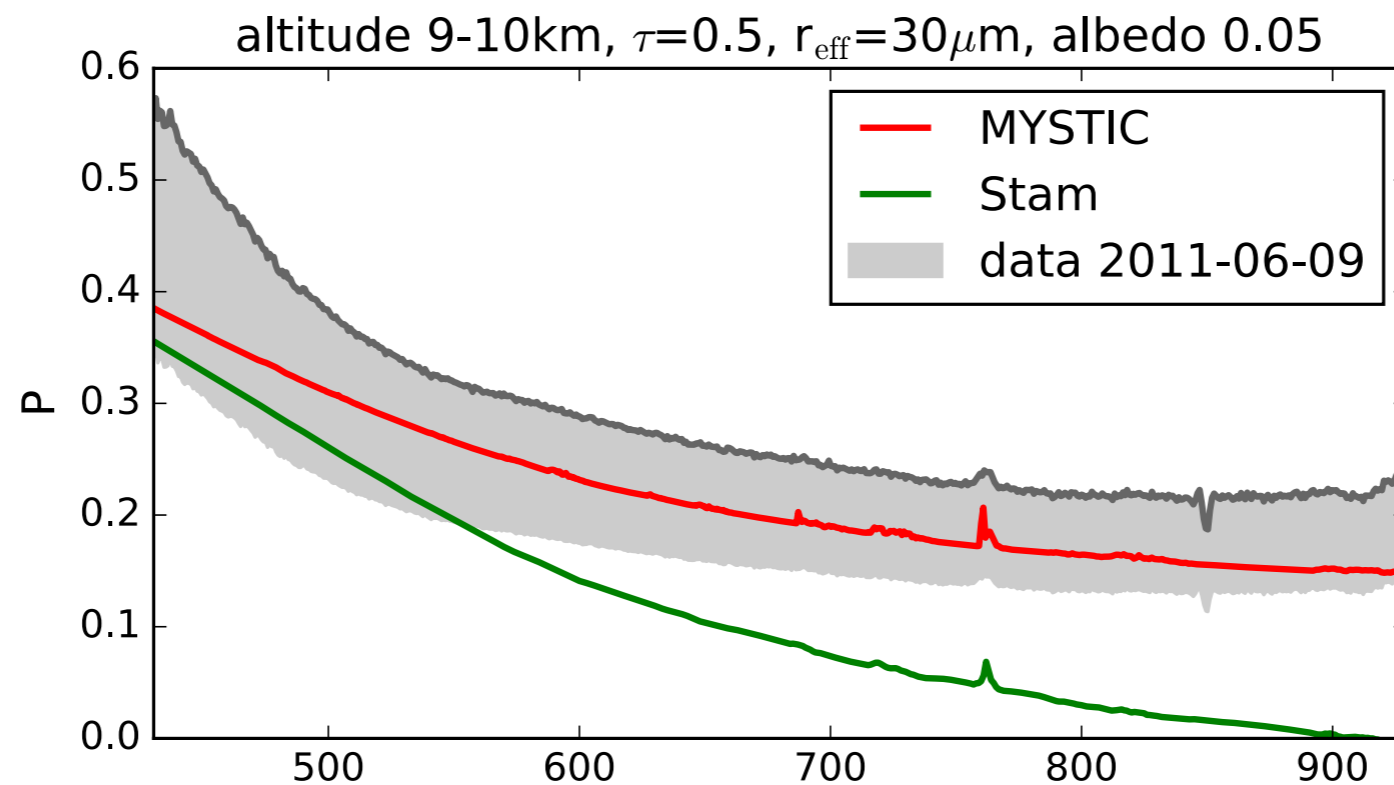
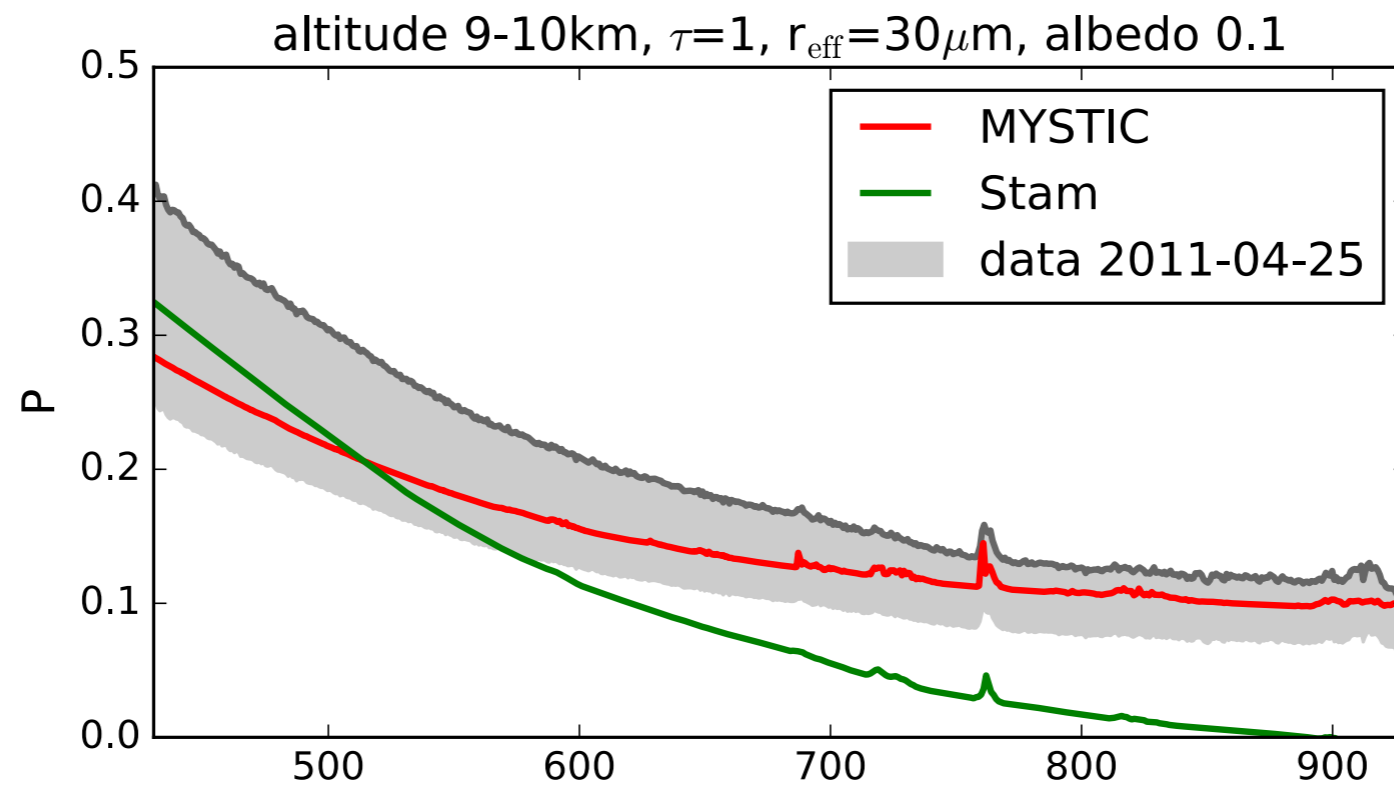


# Sensitivity of high altitude clouds

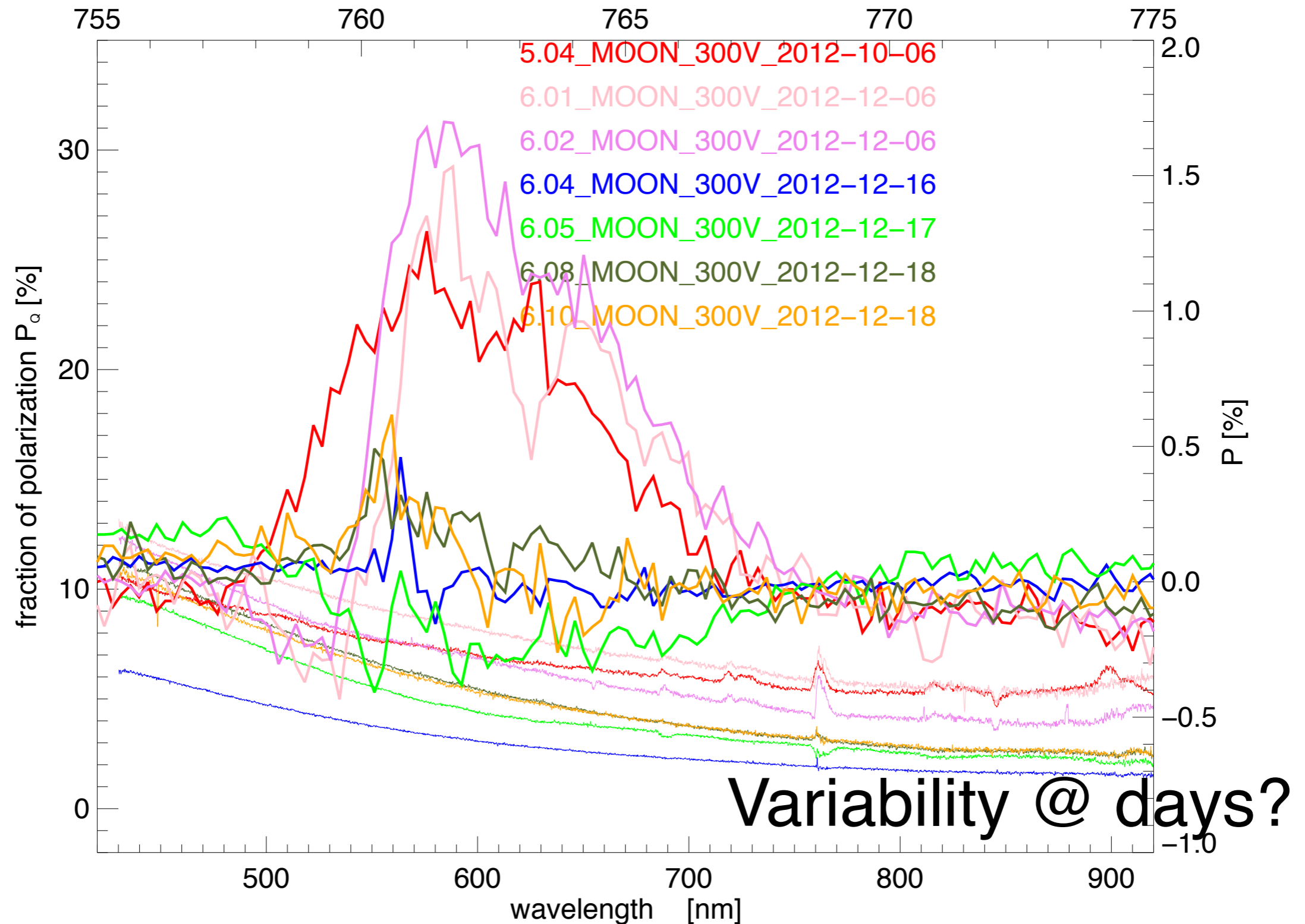


Emde, C., Buras, R., Sterzik, M.. & Bagnulo, S. Influence of aerosols, water and ice clouds on polarisation spectra of Earthshine. *A&A ref.* (2017).

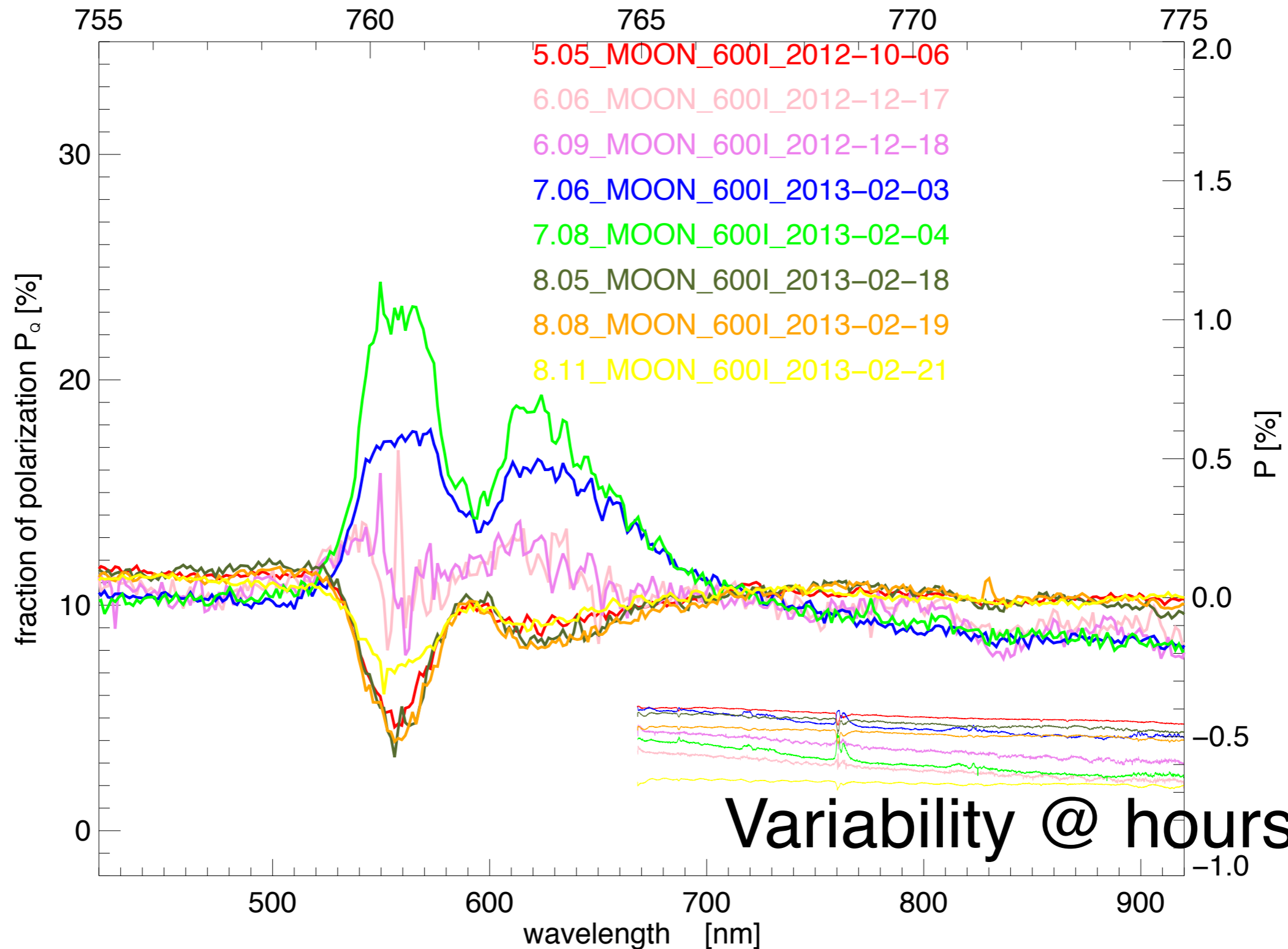
# ES modelling vers.2



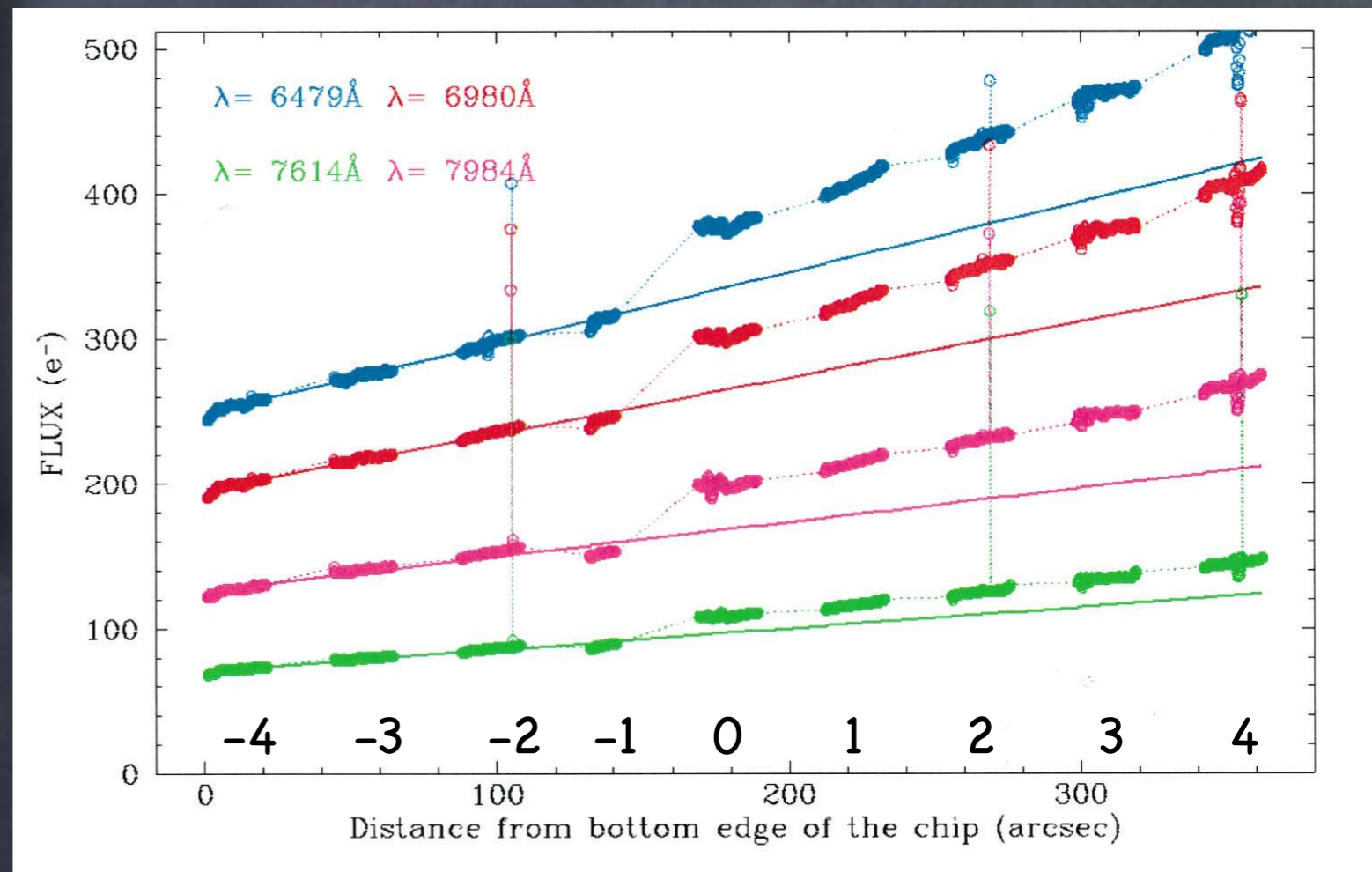
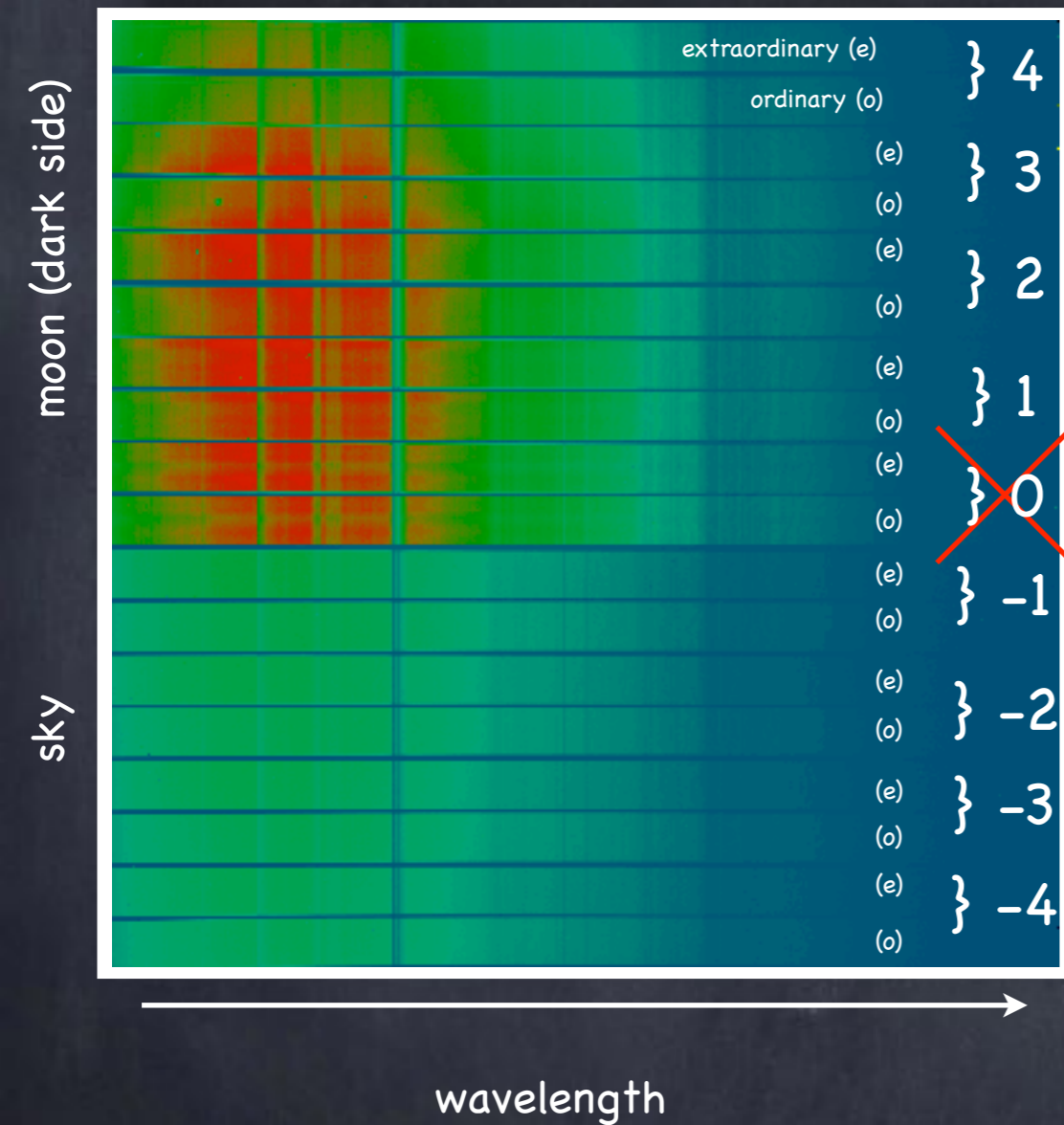
# Earthshine O2-A observed



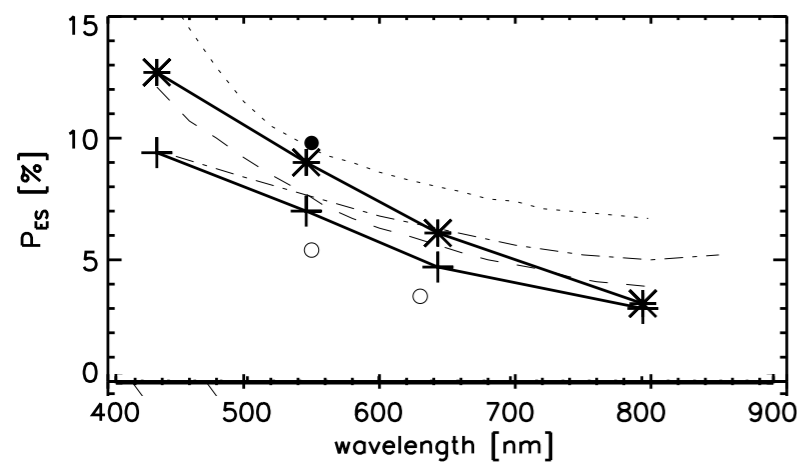
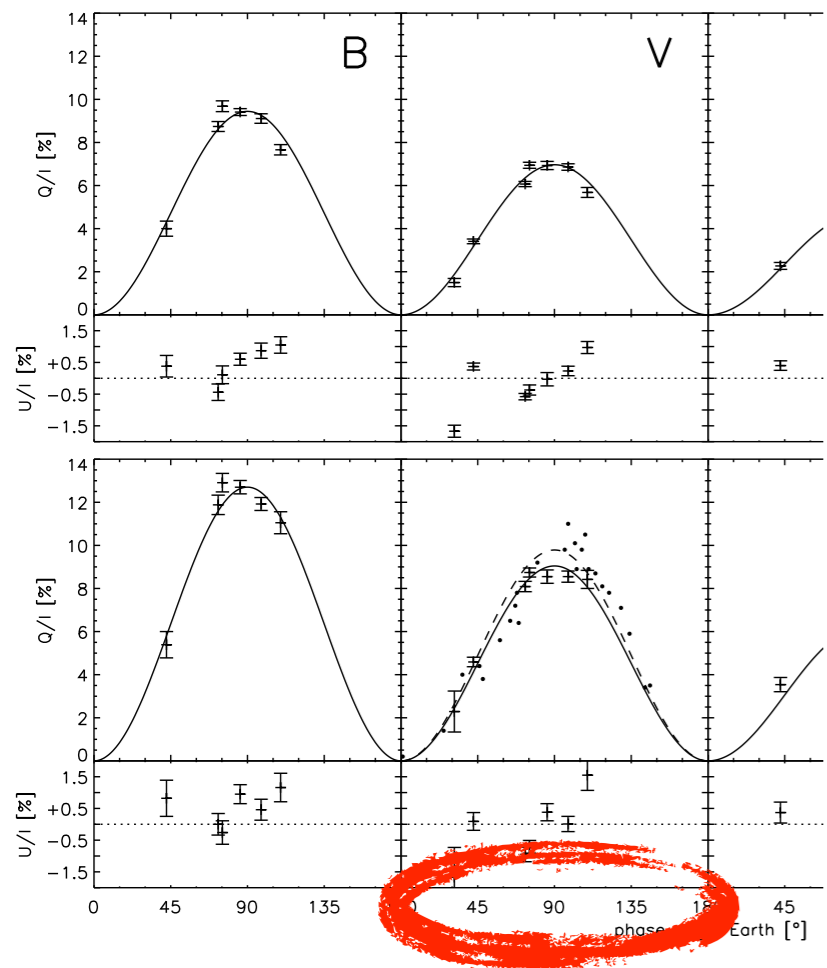
# Earthshine O2-A observed



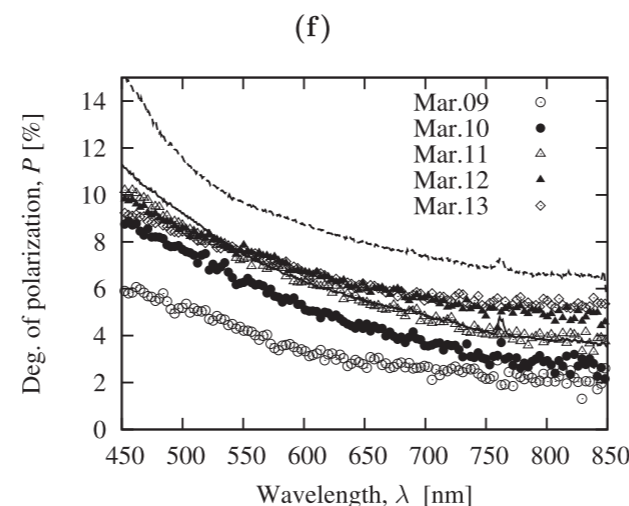
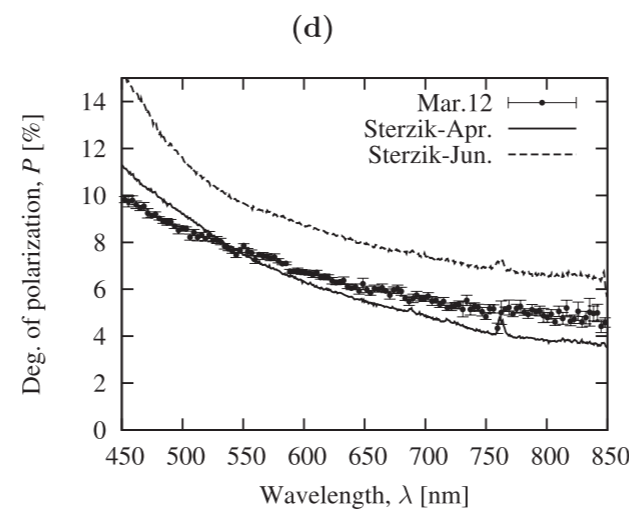
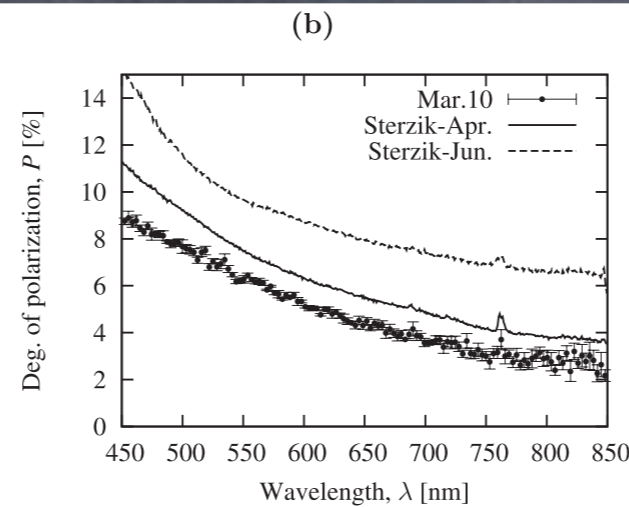
# Signal and Background around the Lunar Limb



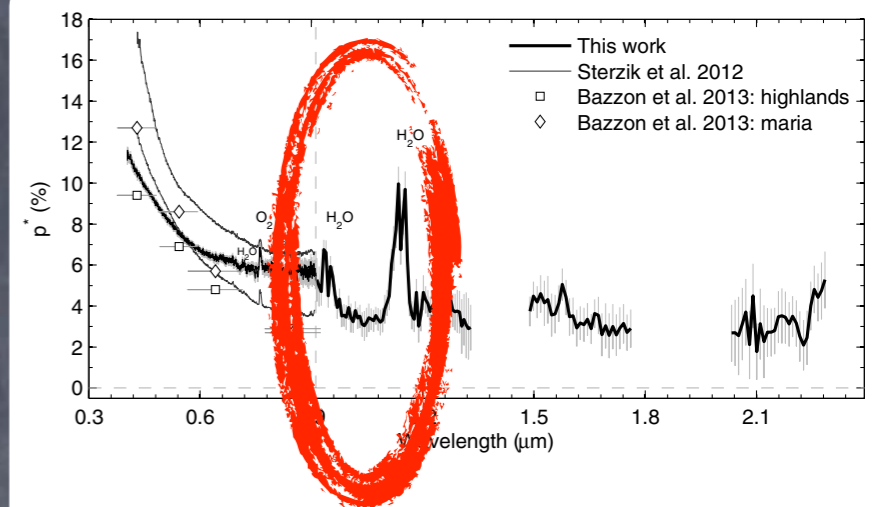
# More (Spectro-)Polarimetry of ES



Bazzon, A., Schmid, H. M. & Gisler, D. Measurement of the earthshine polarization in the B, V, R, and I band as **function of phase**. *arXiv astro-ph.EP*, (2013).



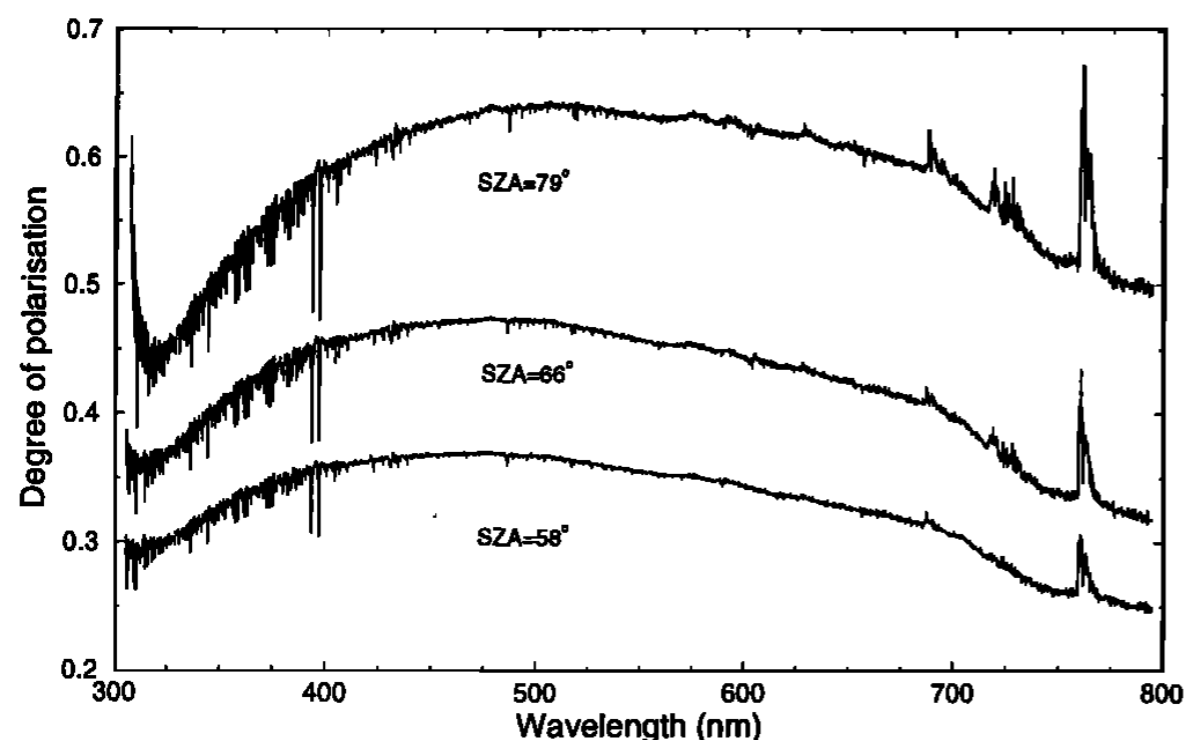
Takahashi, J. *et al.* **Phase Variation** of Earthshine Polarization Spectra. *Publications of the Astronomical Society of Japan* **65**, 38 (2013).



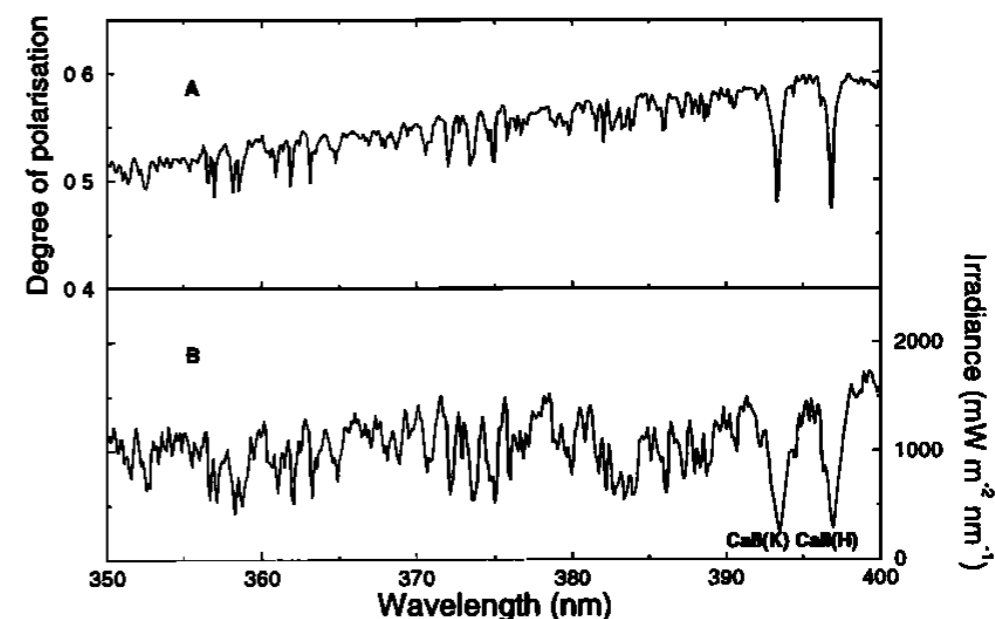
Miles-Páez, P. A., Pallé, E. & Zapatero Osorio, M. R. Simultaneous optical and **near-infrared** linear spectropolarimetry of the earthshine. *A&A* **562**, L5 (2014).

# Spectral fine-structure in the polarisation of skylight

I. Aben<sup>1</sup>, F. Helderman<sup>1</sup>, D.M. Stam<sup>2,3,4</sup>, and P. Stammes<sup>3</sup>

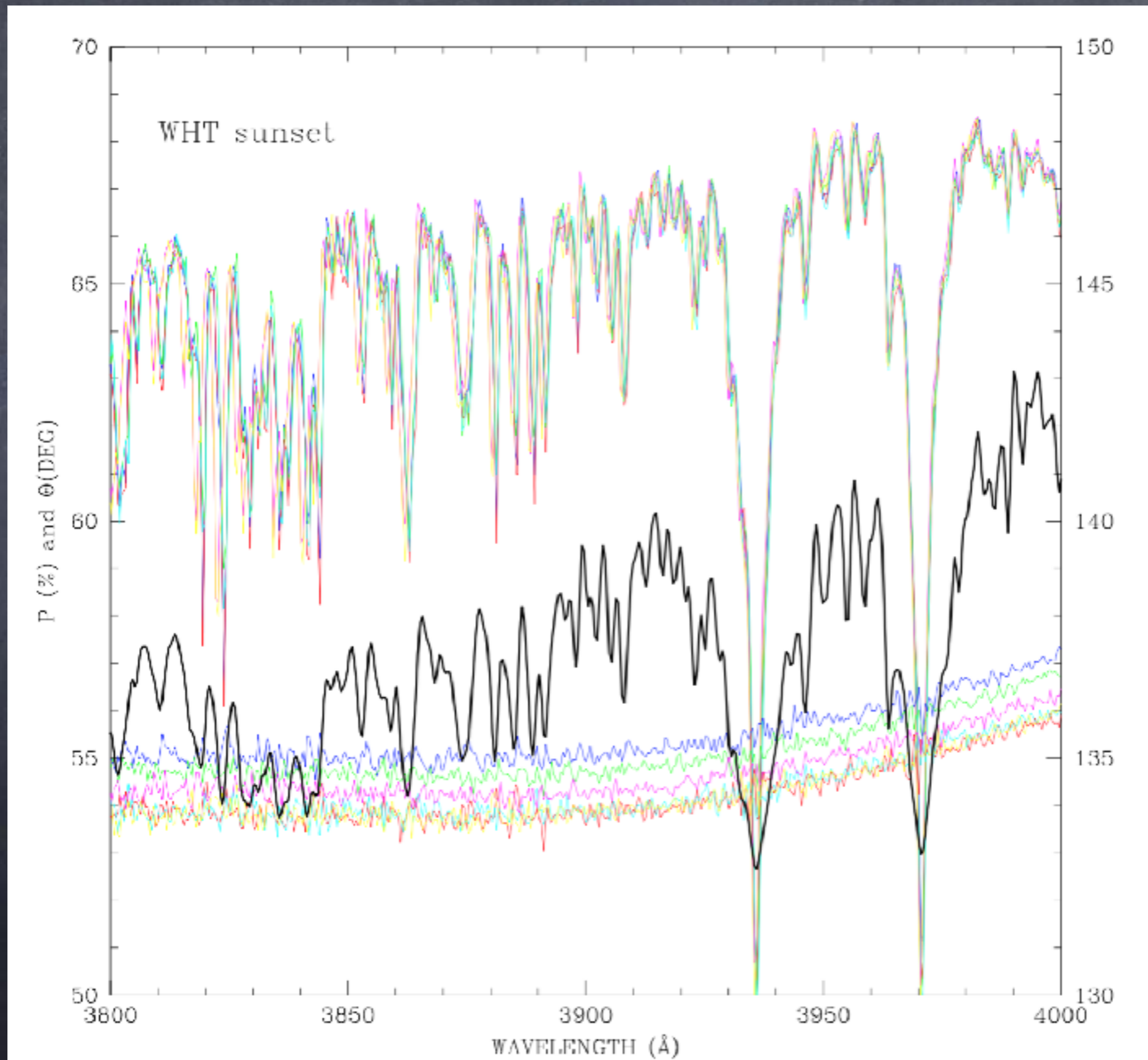


**Figure 1.** The degree of linear polarisation of the cloud-free zenith sky as a function of wavelength from 305 to 794 nm, for three values of the solar zenith angle (SZA), as measured at SRON, Utrecht, The Netherlands (52.1°N, 5.2°E) on the morning of April, 7, 1997. Superimposed on the broad-band continuum, spectral fine-structure in the polarisation is observed.



**Figure 3.** The UV part of the zenith sky polarisation spectrum for SZA = 79° is shown in more detail (top). The spectral fine-structure in the measured polarisation coincides closely with the Fraunhofer lines in the extra-terrestrial solar irradiance spectrum (bottom). The latter has been measured on April, 7, 1997, by GOME on ERS-2. Even the smallest spectral features in the polarisation coincide with Fraunhofer lines, which demonstrates the precision ( $\sim 10^{-3}$ ) of the measurements.

# Spectropolarimetry of our Sky



# Polarization of skylight in the O<sub>2</sub>A band: effects of aerosol properties

Eyk Boesche,<sup>1,\*</sup> Piet Stammes,<sup>2,4</sup> Réne Preusker,<sup>1</sup> Ralf Bennartz,<sup>3,5</sup>  
Wouter Knap,<sup>2</sup> and Juergen Fischer<sup>1</sup>

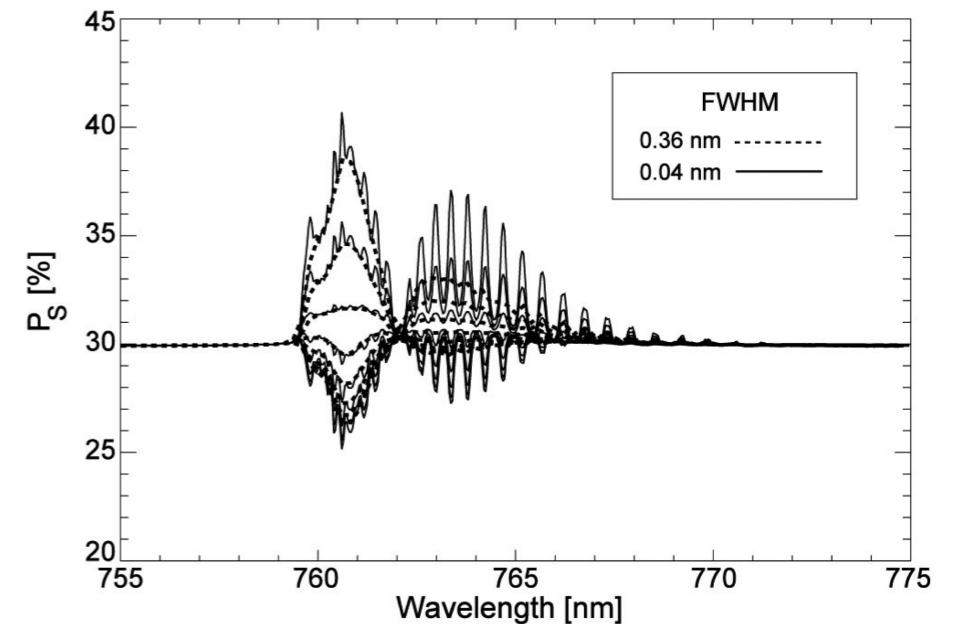
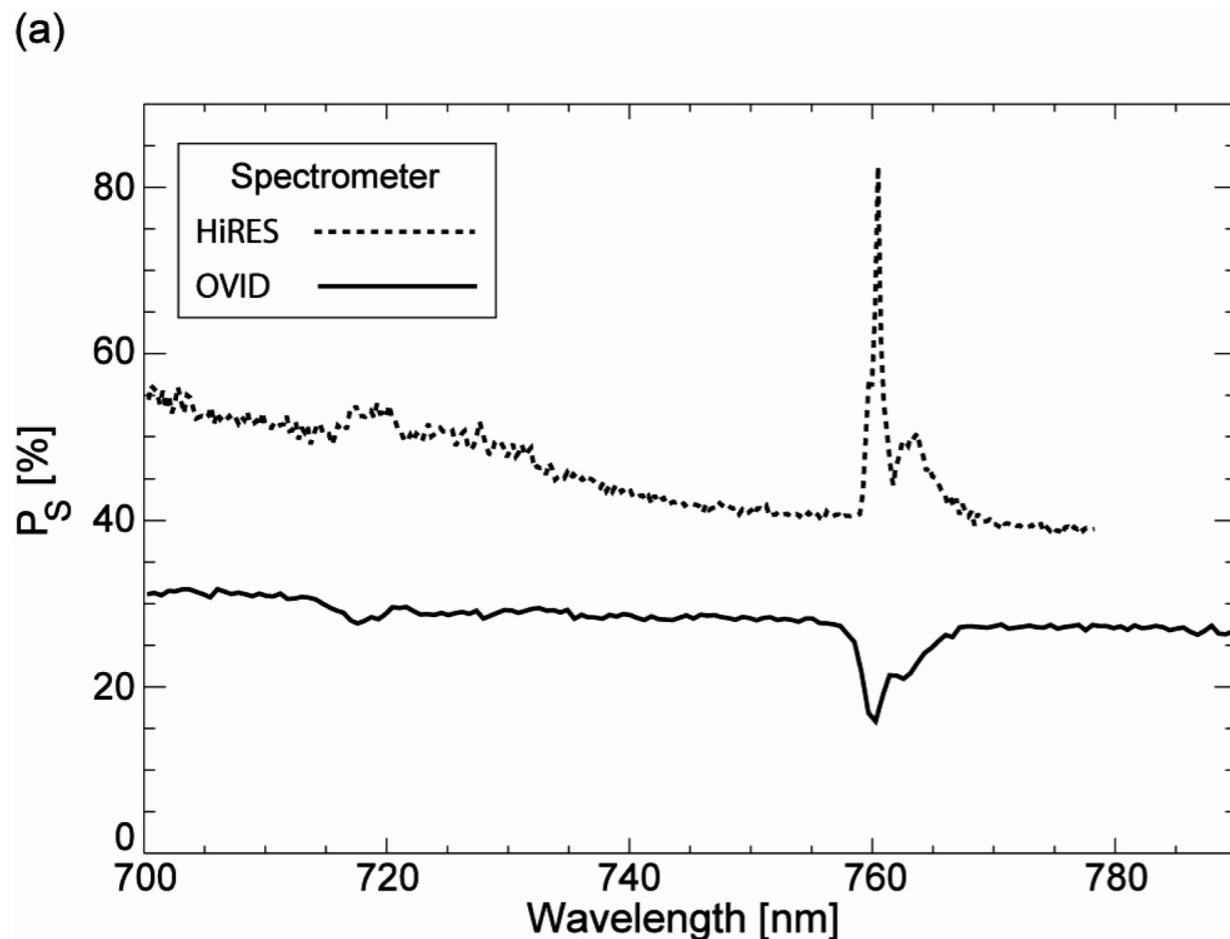
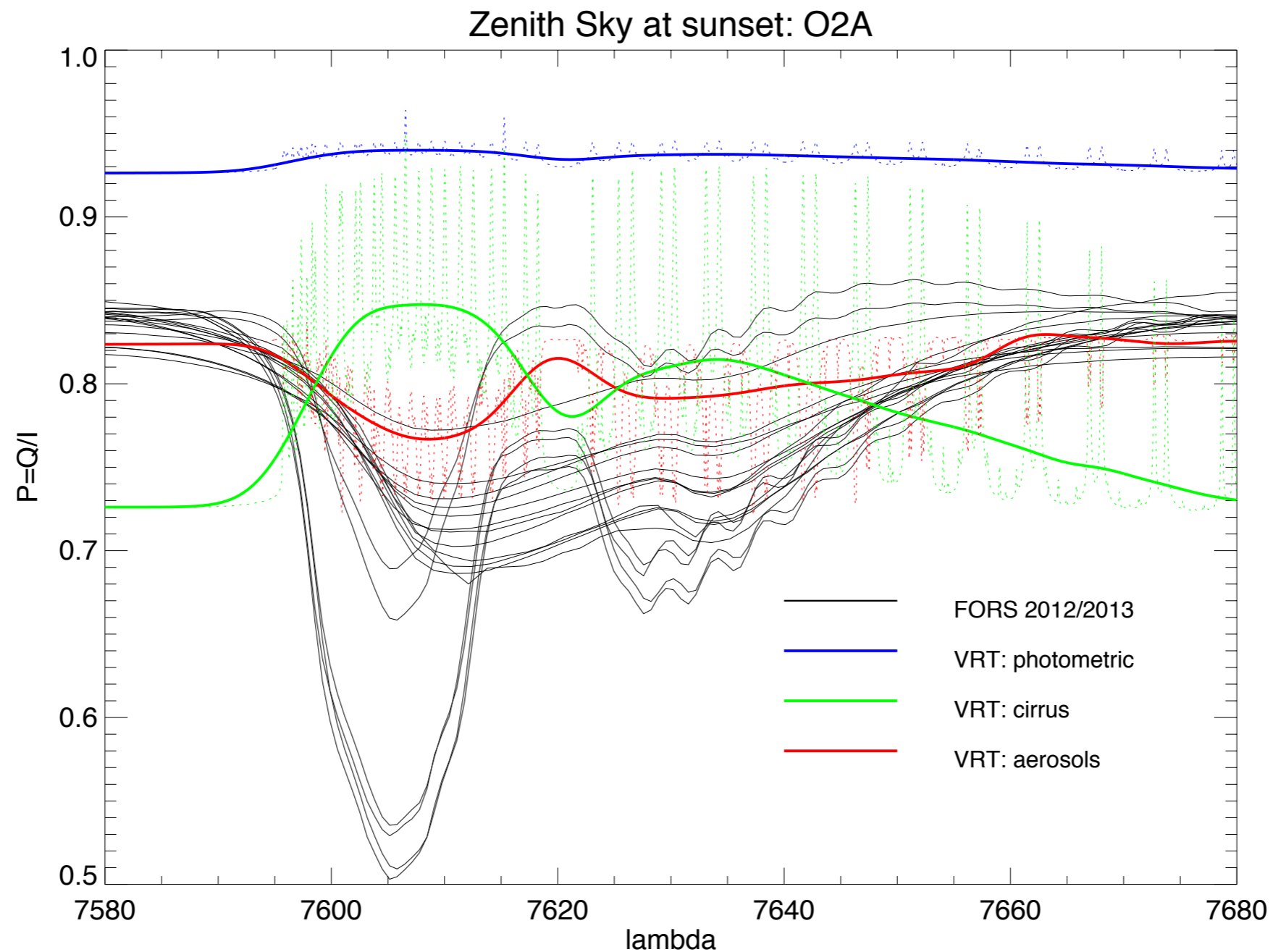
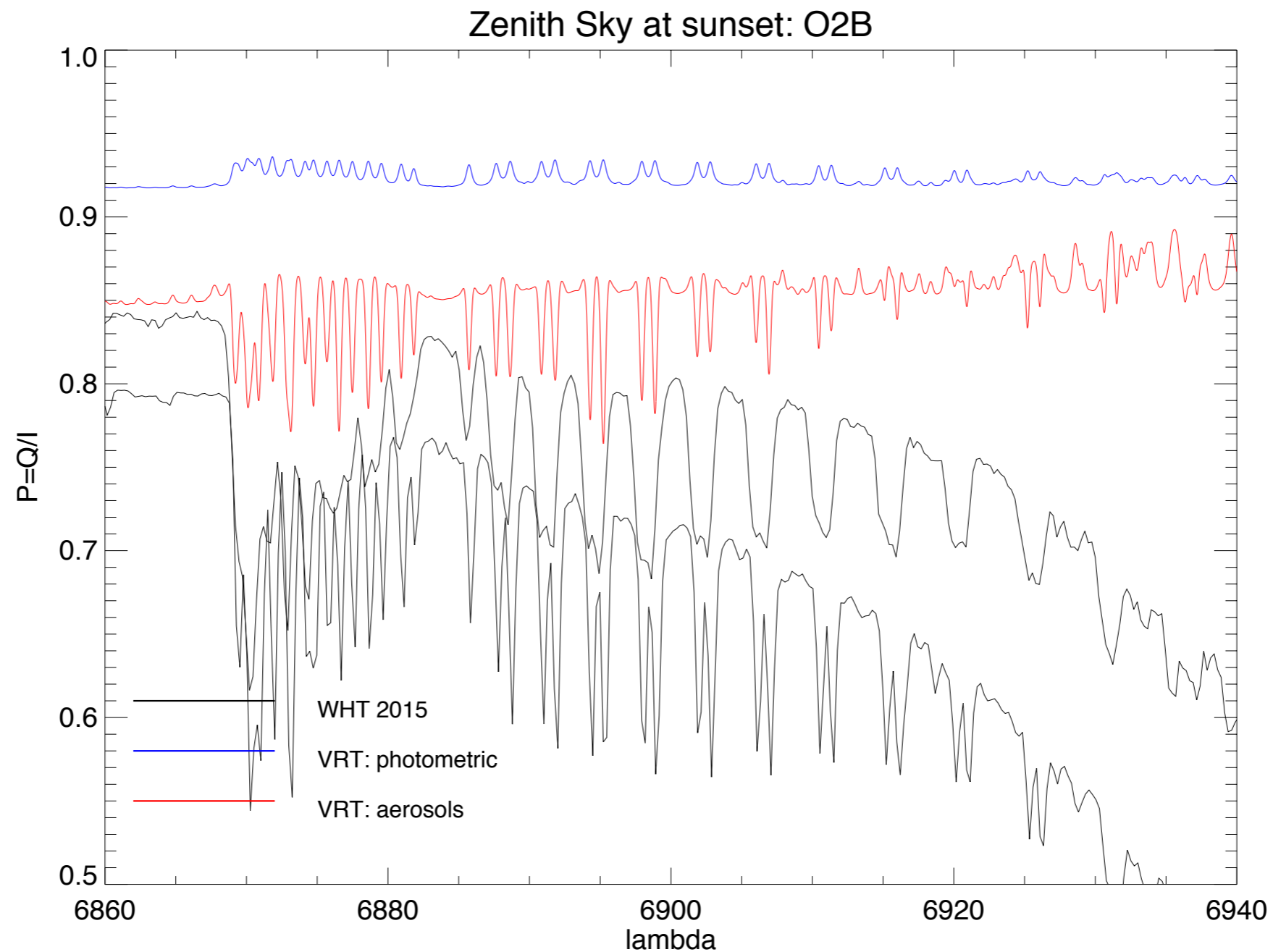


Fig. 11. Degree of linear polarization of zenith skylight as a function of wavelength at a solar zenith angle of  $\theta_0 = 65^\circ$  for two different spectral response functions and different altitudes of the elevated scattering layer. The boundary layer comprises Aerosol<sub>1</sub> and optical thickness of  $\tau_{BL} = 0.048$  and the elevated layer comprises scatterer  $C_1$  with  $\tau_{EL} = 0.100$ . The elevated layer is shifted through the atmosphere from 2 to 16 km in steps of two kilometers, resulting in a decrease of  $P_b$  with increasing altitude of the elevated layer.

# Spectropolarimetry of our Sky



# Spectropolarimetry of our Sky



# Proposal: SpecPols of Zenith Sky

- use FORS2pol and HARPSpol @ high spectral resolution
- monitoring of sunset sky-flats
- retrieve aerosol and cirrus content, composition, and height distribution with VRT model
- timescale of variability (stability)
- correlate with extinction
- correlate with local (mining) and global (volcano) effects
- validate retrieval code for the local (zenith) patch
- apply to Earthshine skybackground/global retrieval