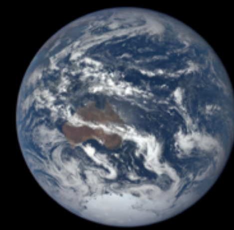
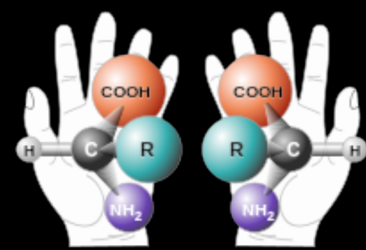
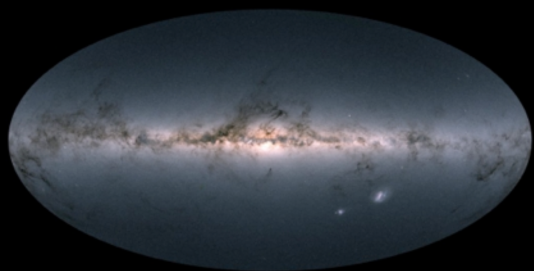
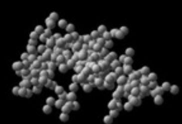


Polarisation by scattering & Biomarkers



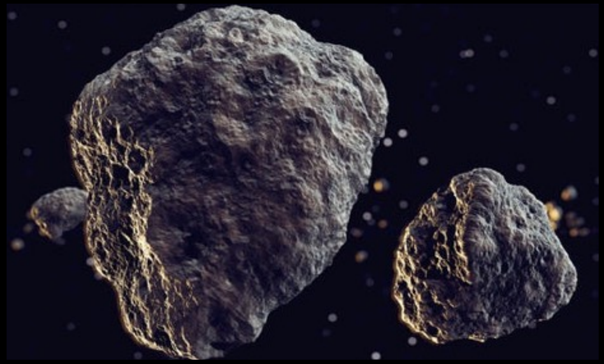


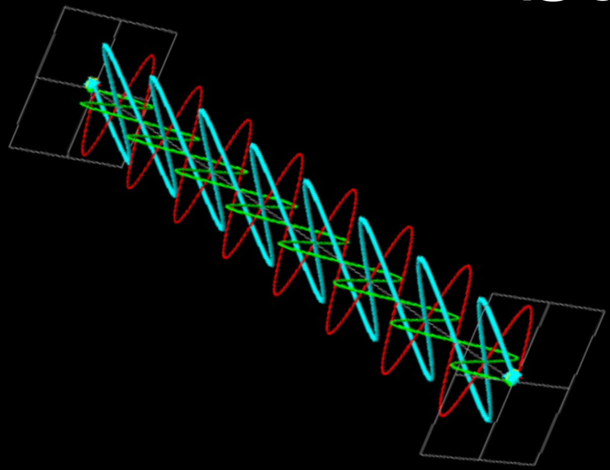


Stefano Bagnulo

Armagh Observatory & Planetarium
Exploring the Cosmos since 1790

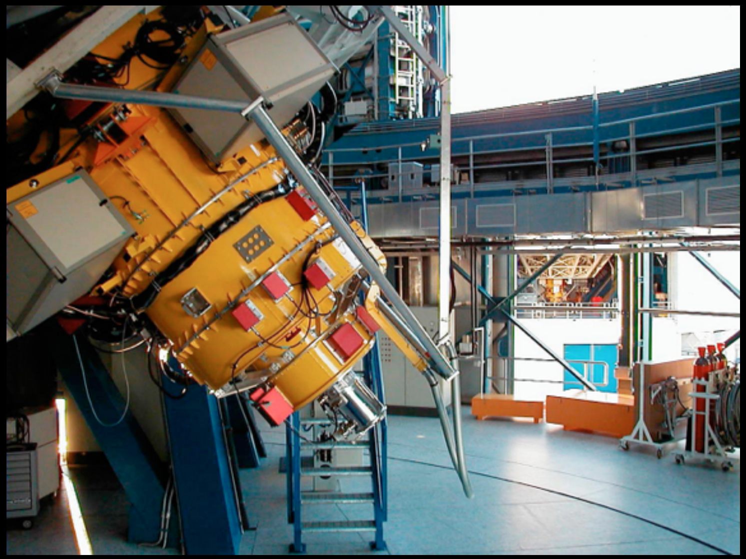
IOP Institute of Physics
Juno Supporter

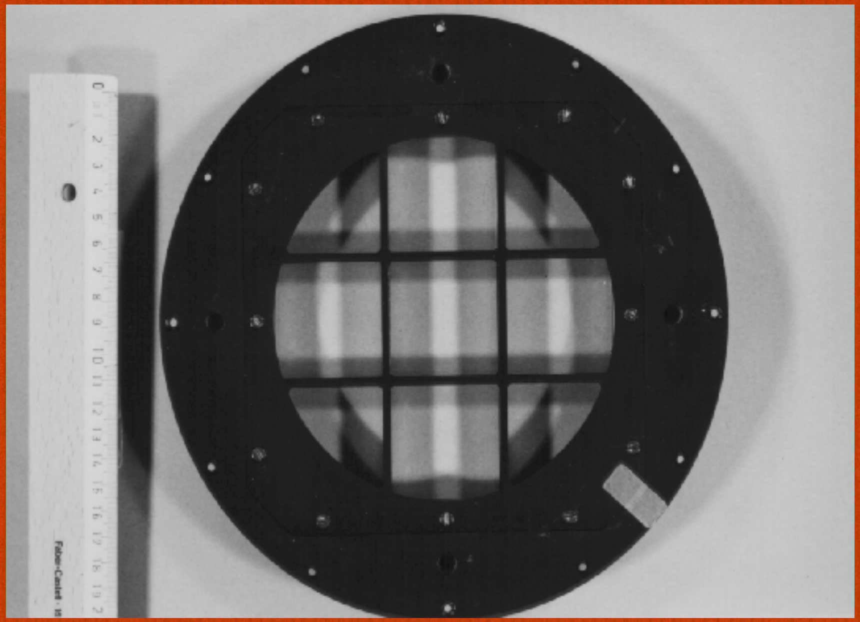


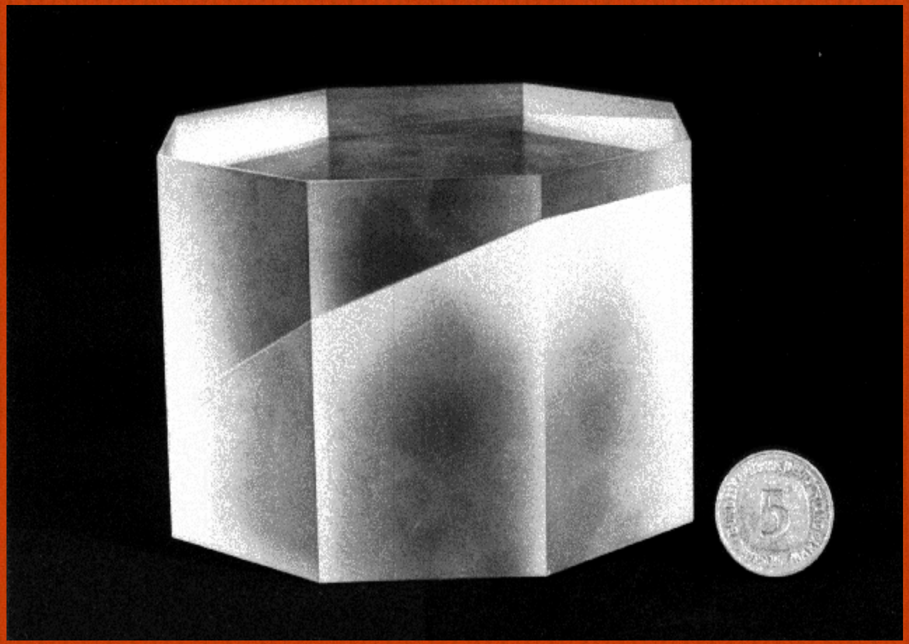


ESO

20th Anniversary of Science Exploration with FORS

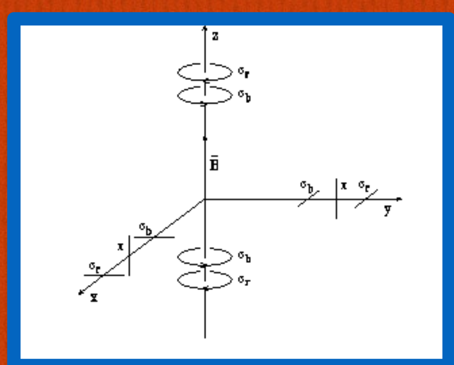


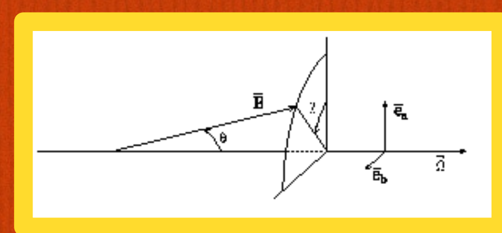


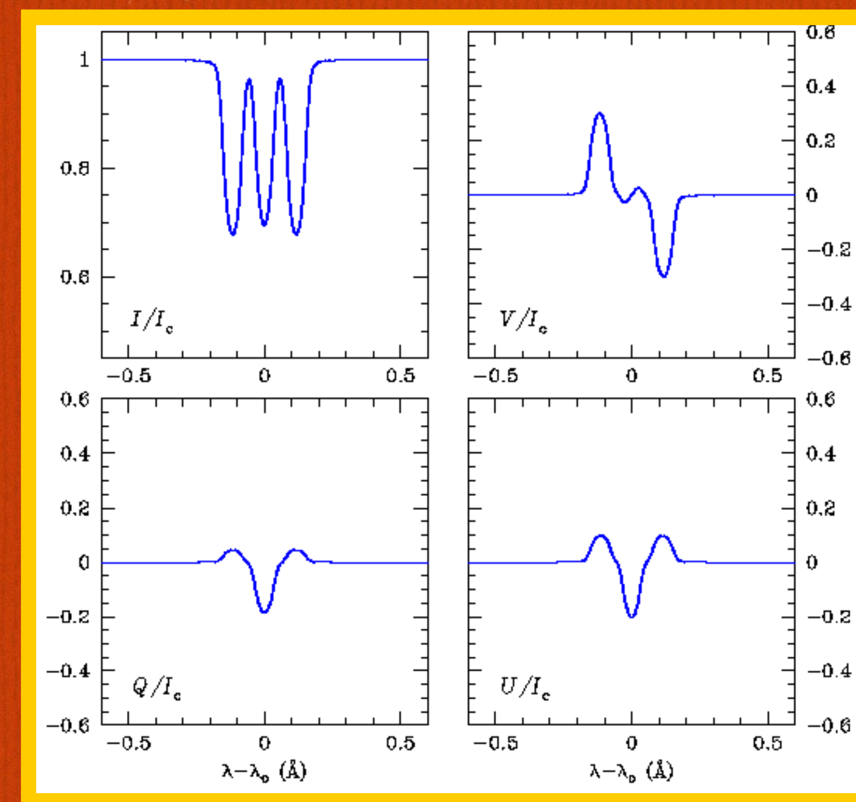

5

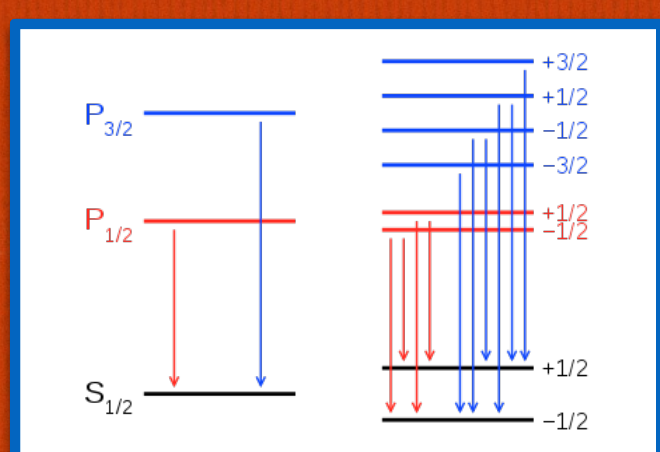
Everything that breaks the symmetry in a radiative source or between the source and the observer produces polarisation

ZEEMAN EFFECT

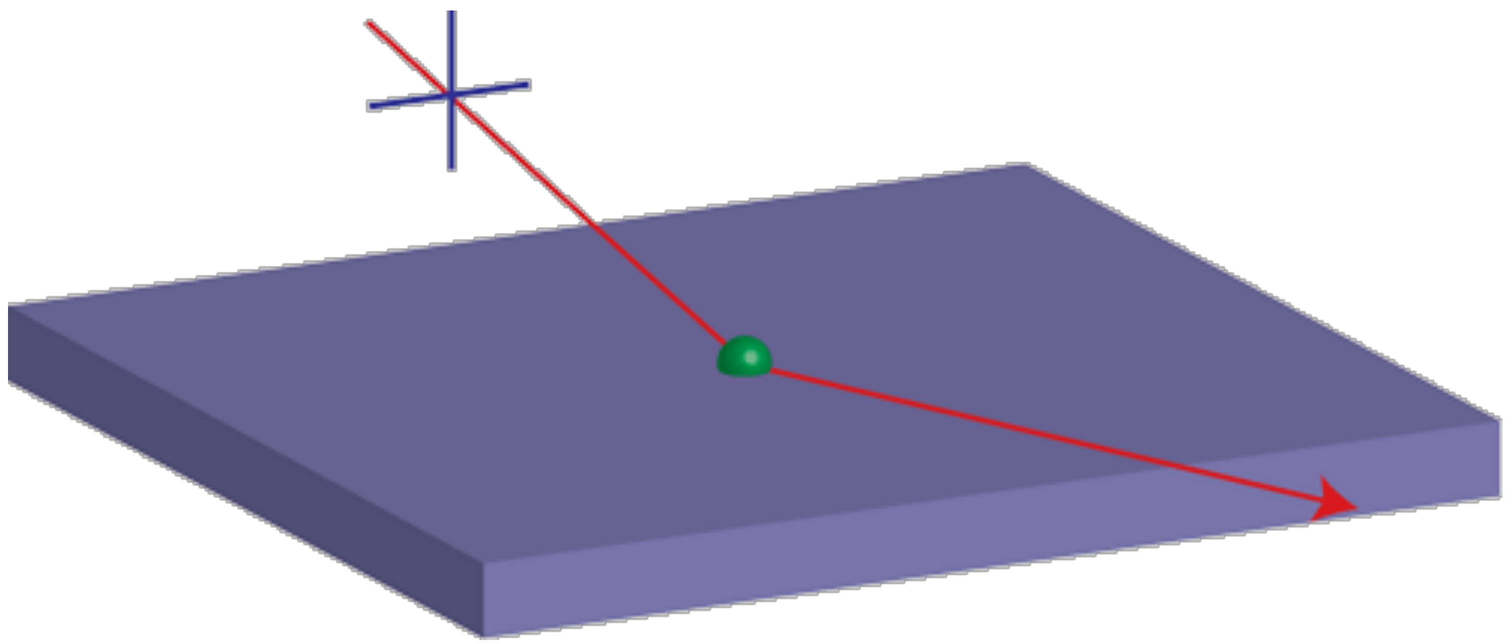








2k hours with FORS1



http://background.uchicago.edu/~whu/intermediate/polarization/polar1.html

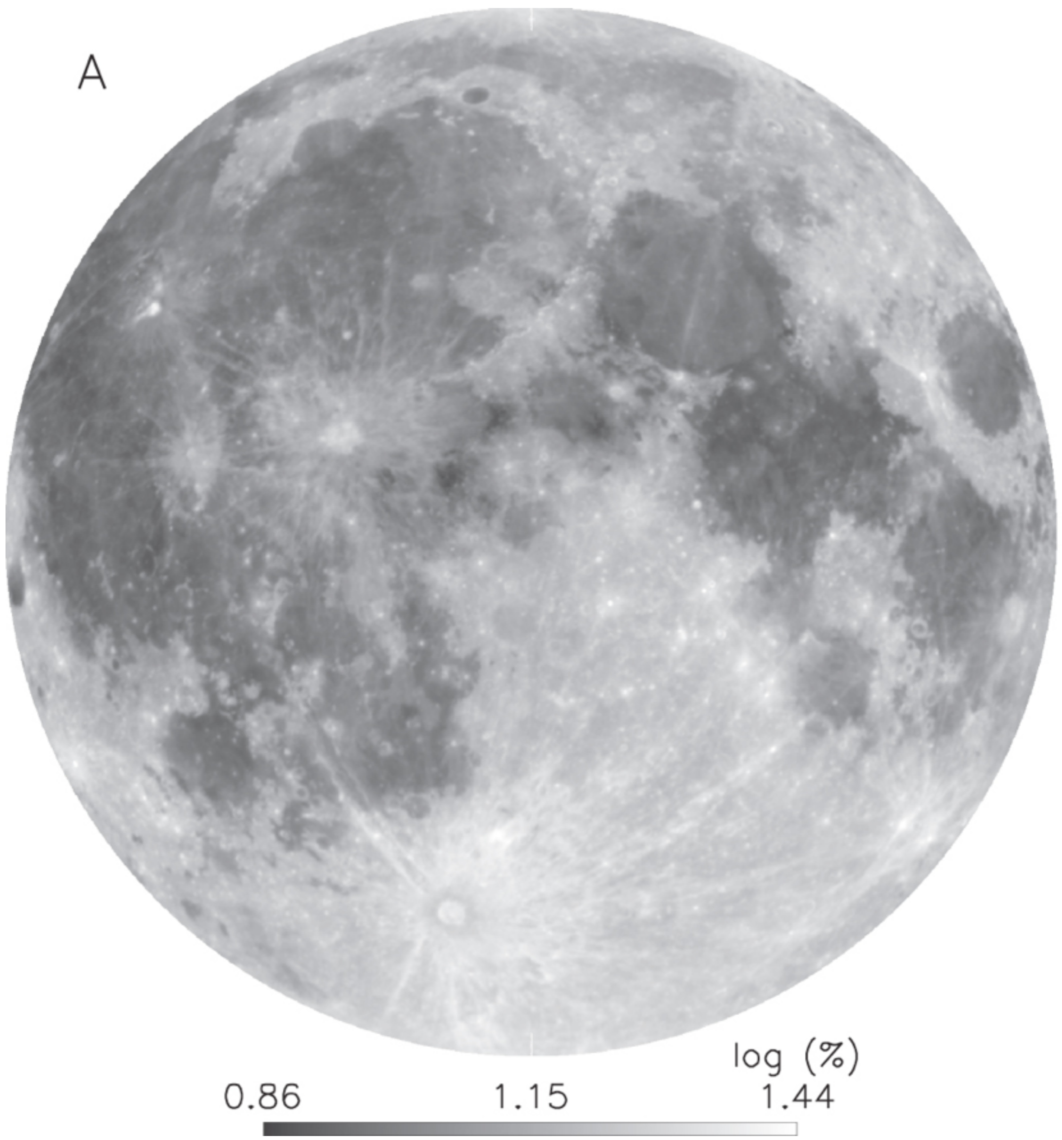
Contrast enhancing technique

Polarimetry may reveal features that, if observed in "natural light", would be washed out by some effect

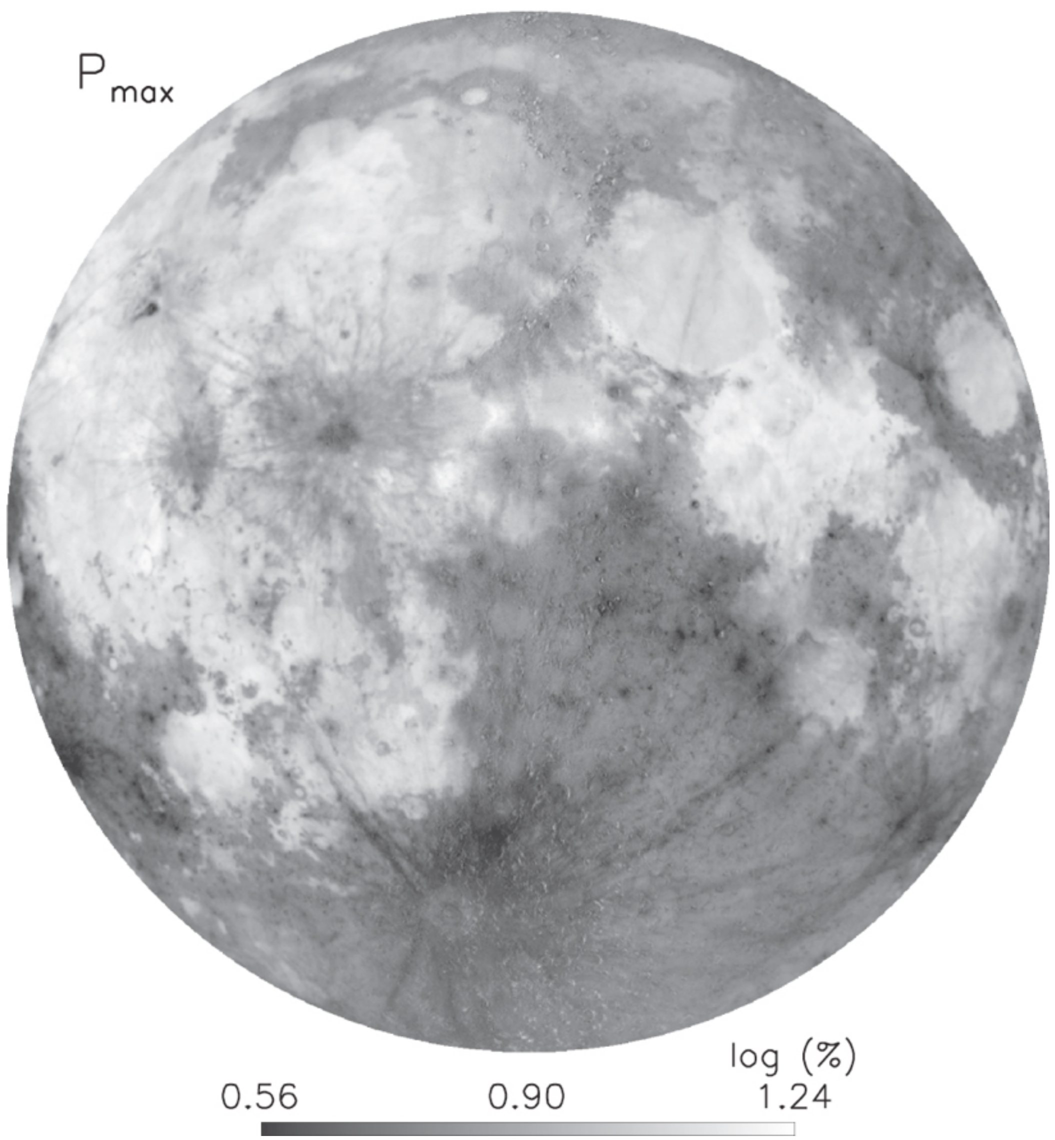
Light emitted by the star is not polarised, while the light reflected by the planet is polarised.
By suppressing the unpolarised light one may be able to see the planets orbiting around the star.

Polarimetry brings information ***in addition*** to intensity rather than ***alternative*** to intensity

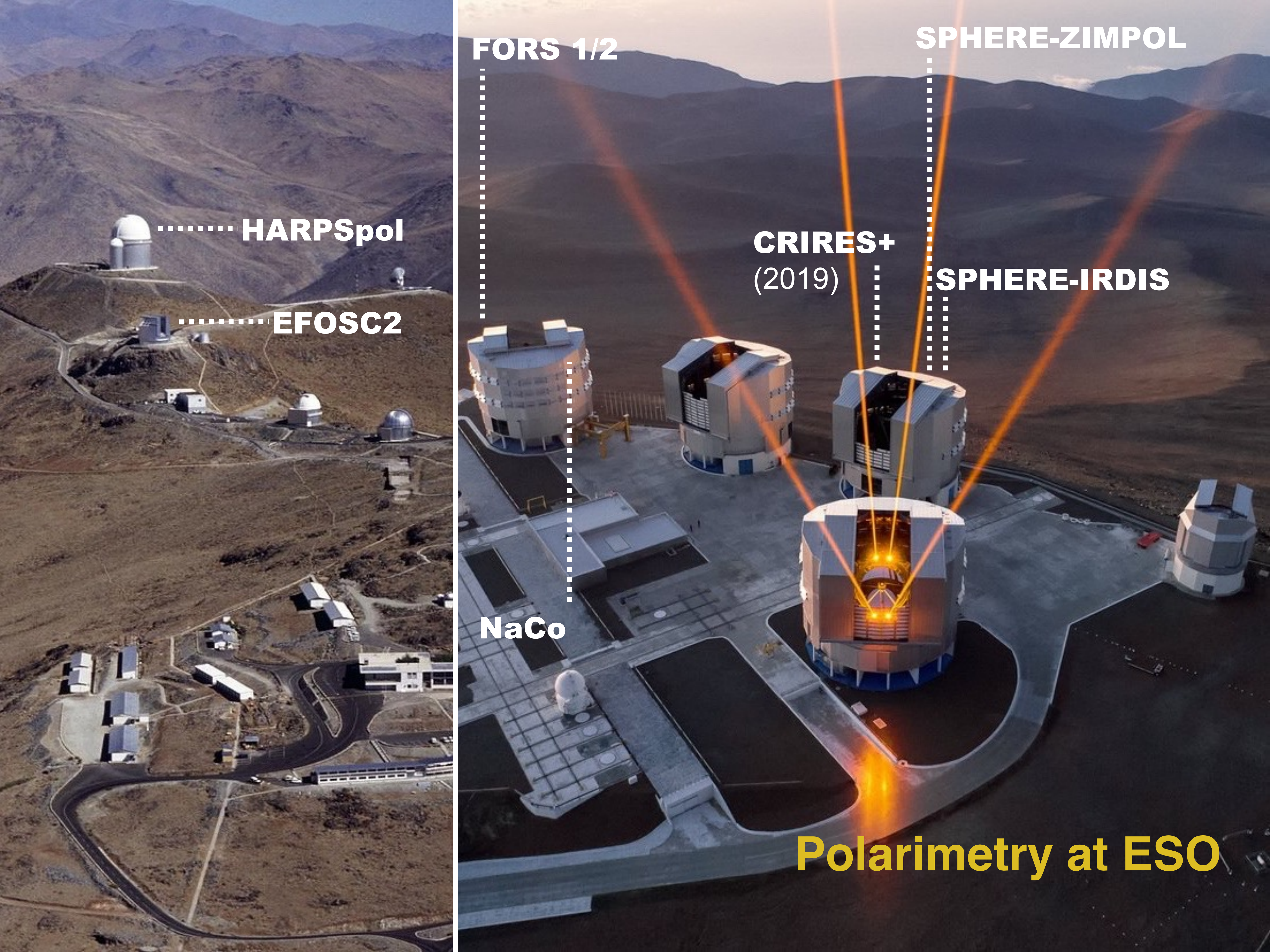
Albedo



Pmax



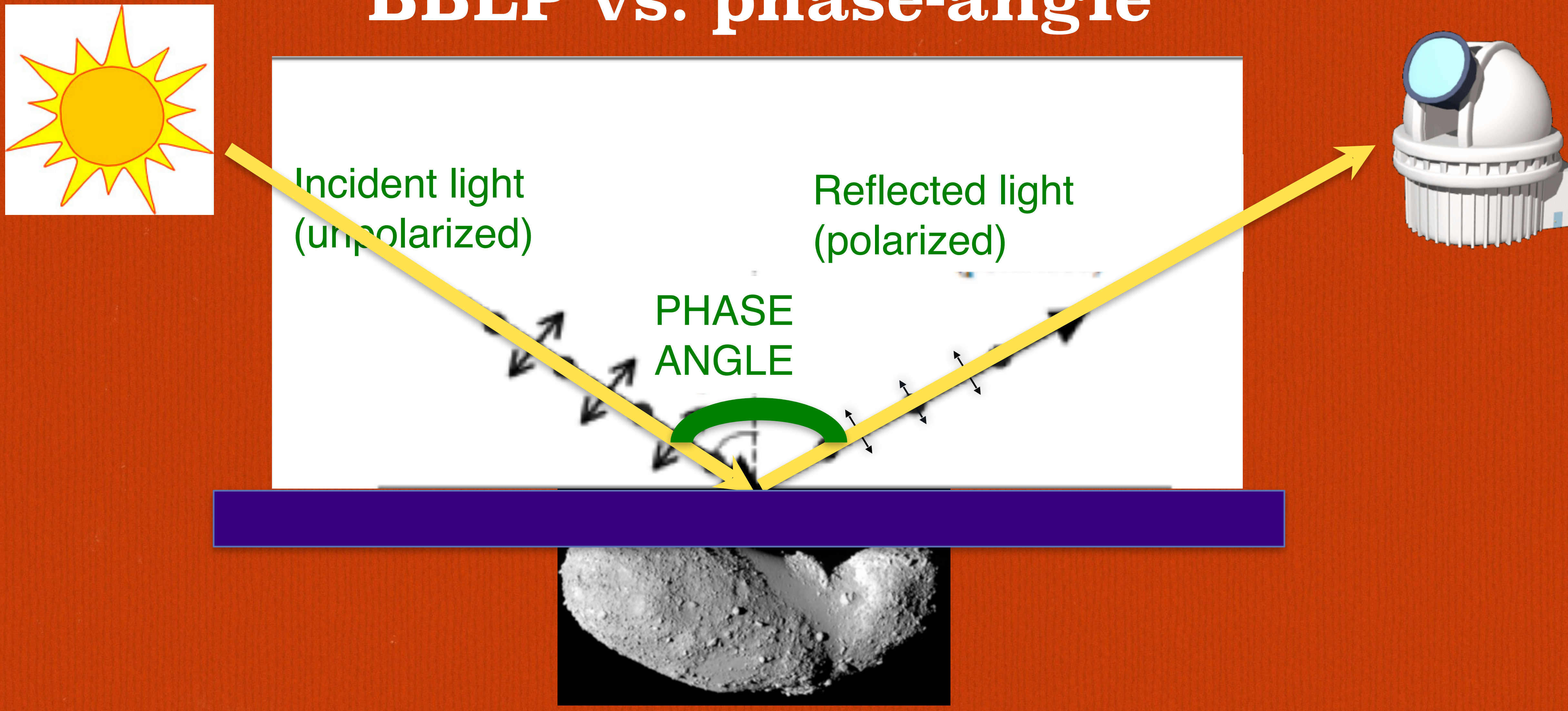
Jeong et al. (2015)


HARPSpol
EFOSC2
FORS 1/2
SPHERE-ZIMPOL
CRIRES+
(2019)
SPHERE-IRDIS
NaCo
Polarimetry at ESO

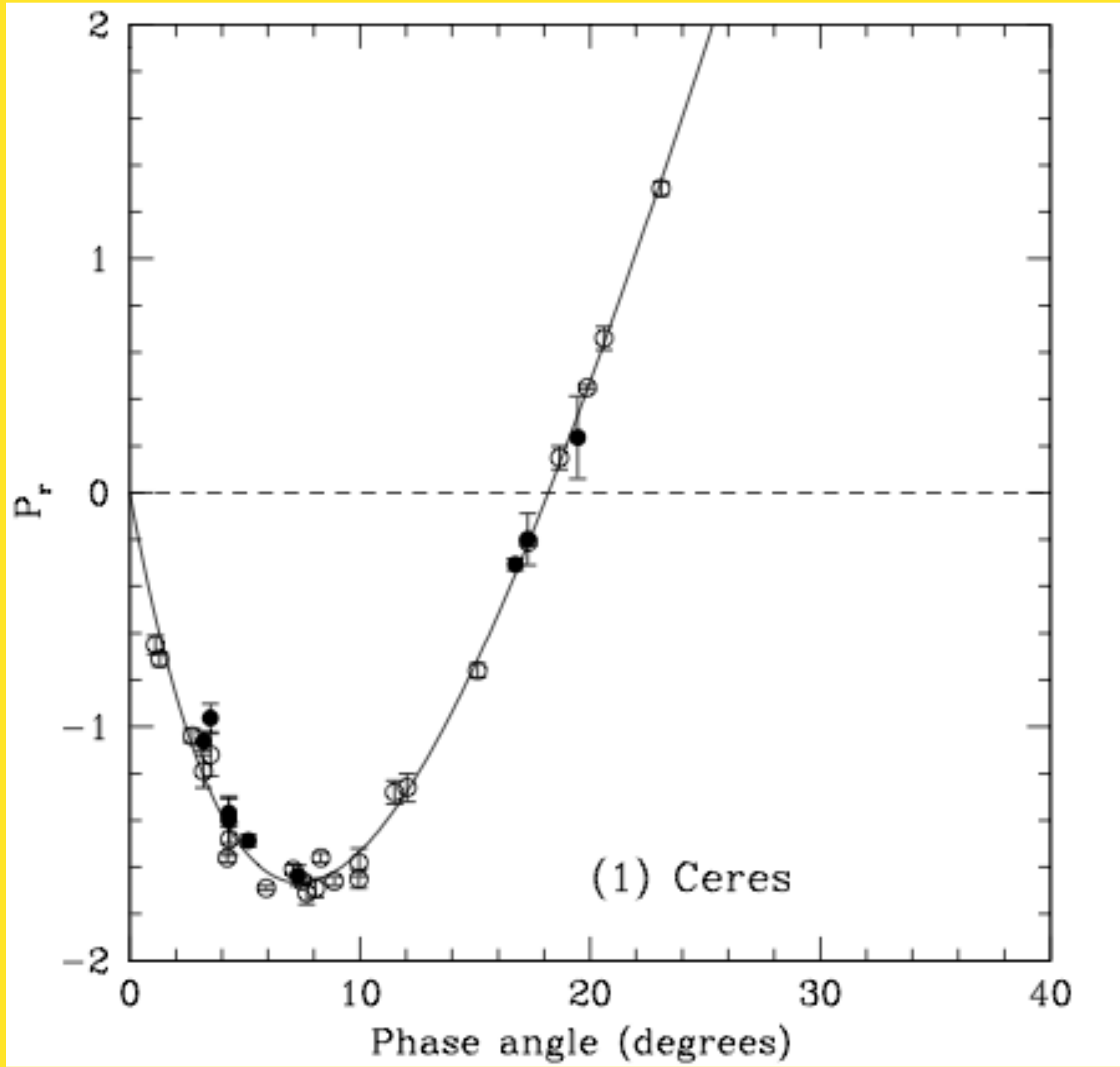
- **Cassegrain mounted** —> no oblique reflections —> no spurious polarisation from the telescope
- **Beam swapping technique** —> (most) instrumental effects cancel out (optical scheme from Appenzeller 1967)
- Multi mode: **Imaging** polarimetry and **spectra-polarimetry**
- Attached at a **large** telescope —> faint objects
- **Service mode** operations —> monitoring programmes

“Traditional” polarimetry of solar system objects

"Traditional" polarimetry of solar system objects: BBLP vs. phase-angle



0º < α < 30º-40º



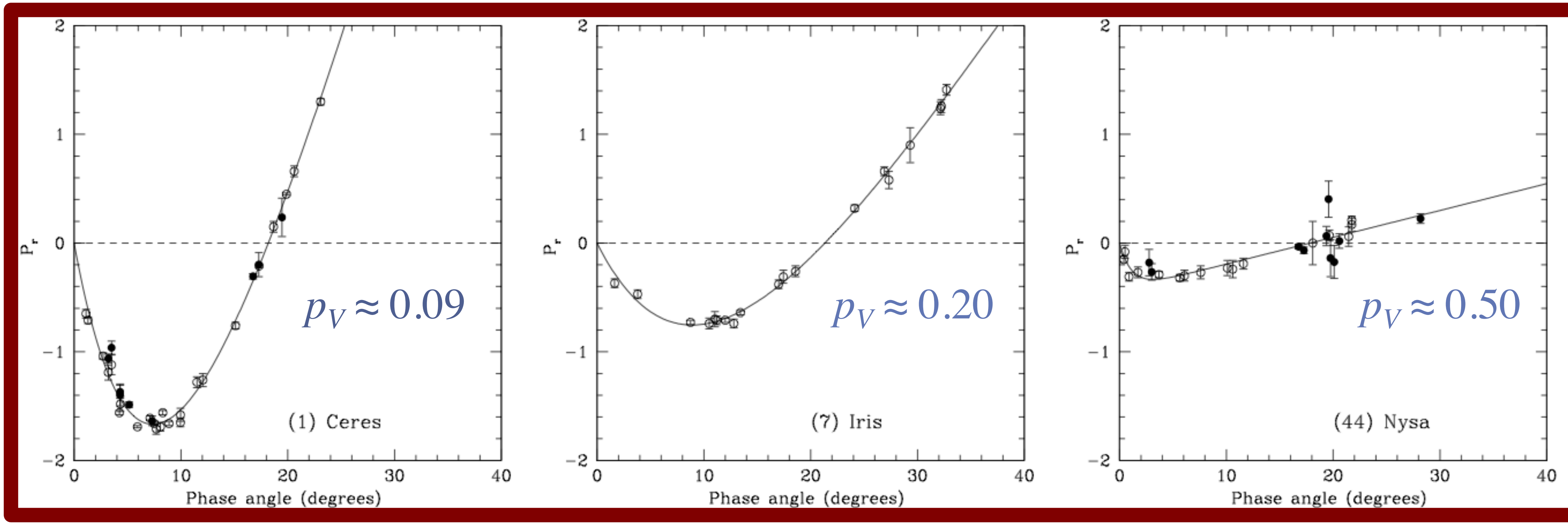
Cellino et al. (2016)

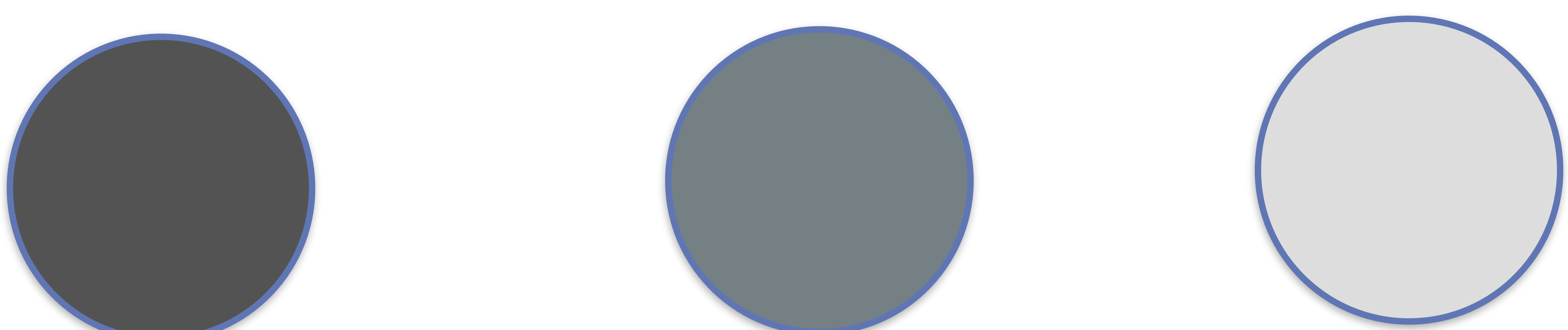
ASTEROIDS POLARIMETRIC CURVES: ALBEDO + SURFACE STRUCTURE & COMPOSITION

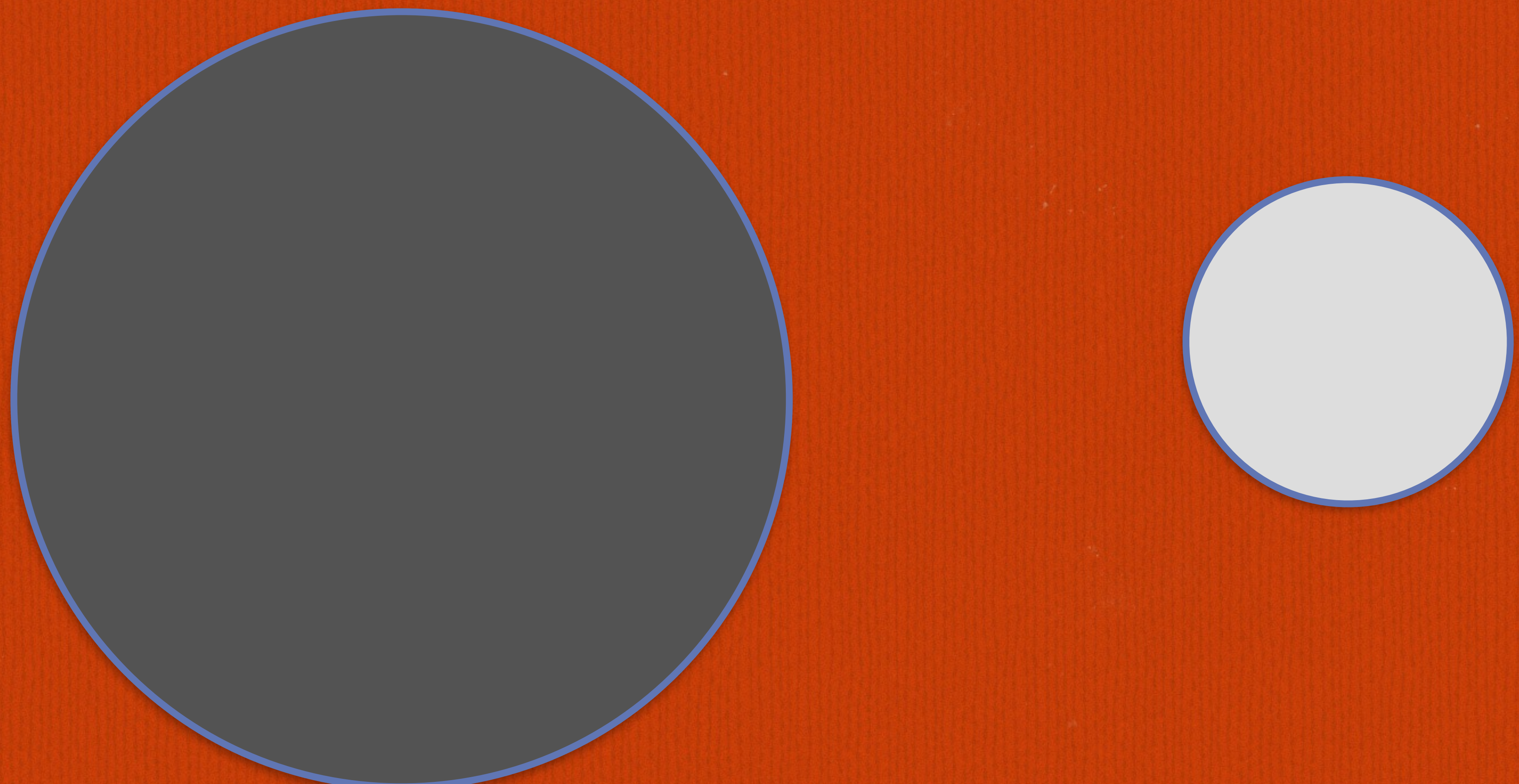
C-type (carbonaceous)
low albedo (0.03 – 0.10)
large amount of carbon

S-type (silicaceous)
albedo ~ 0. 1- 0.2
iron- or magnesium silicates

E-type
albedo : 0.25 – 0.60
(enstatite ($MgSiO_3$) achondrite)

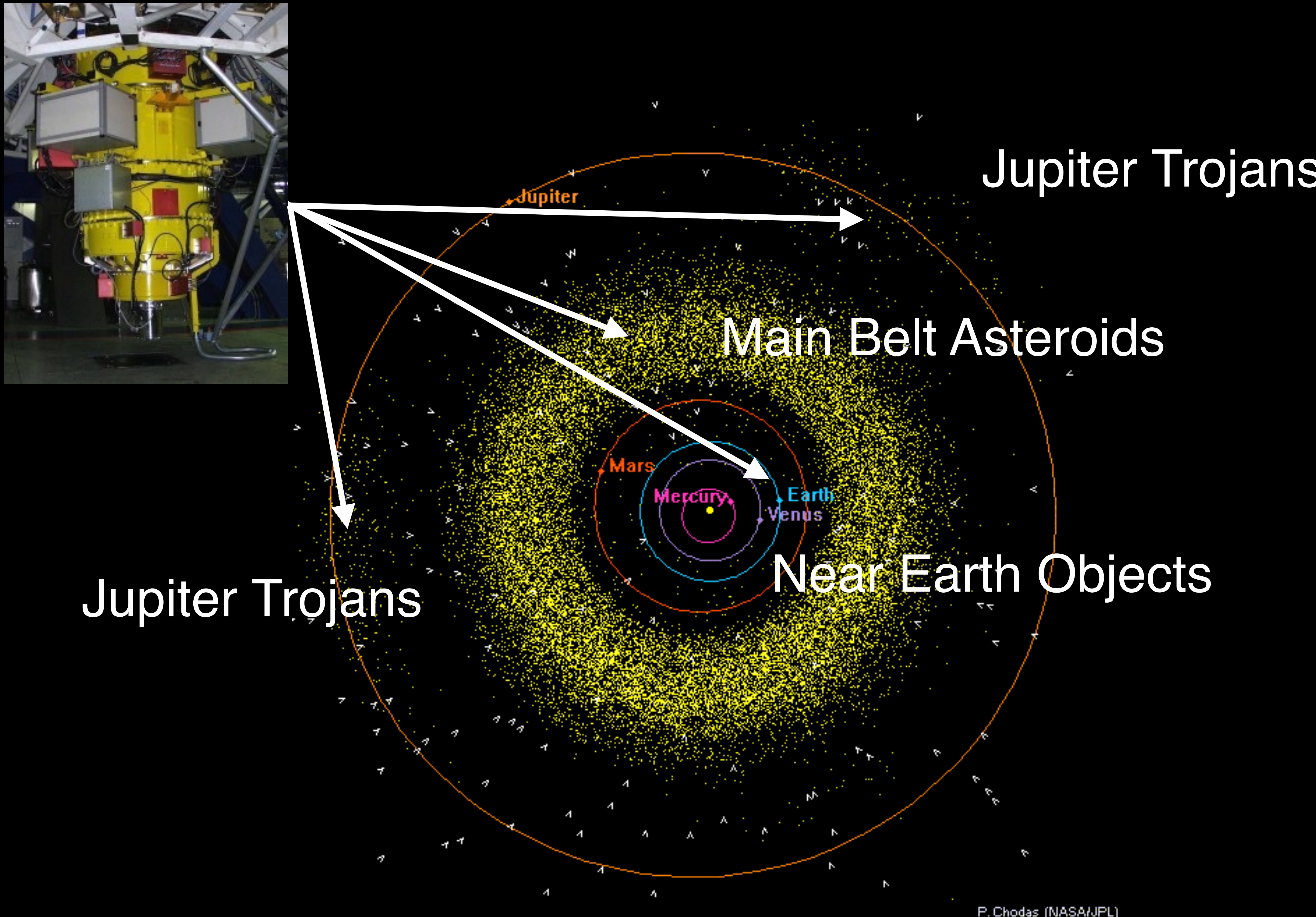


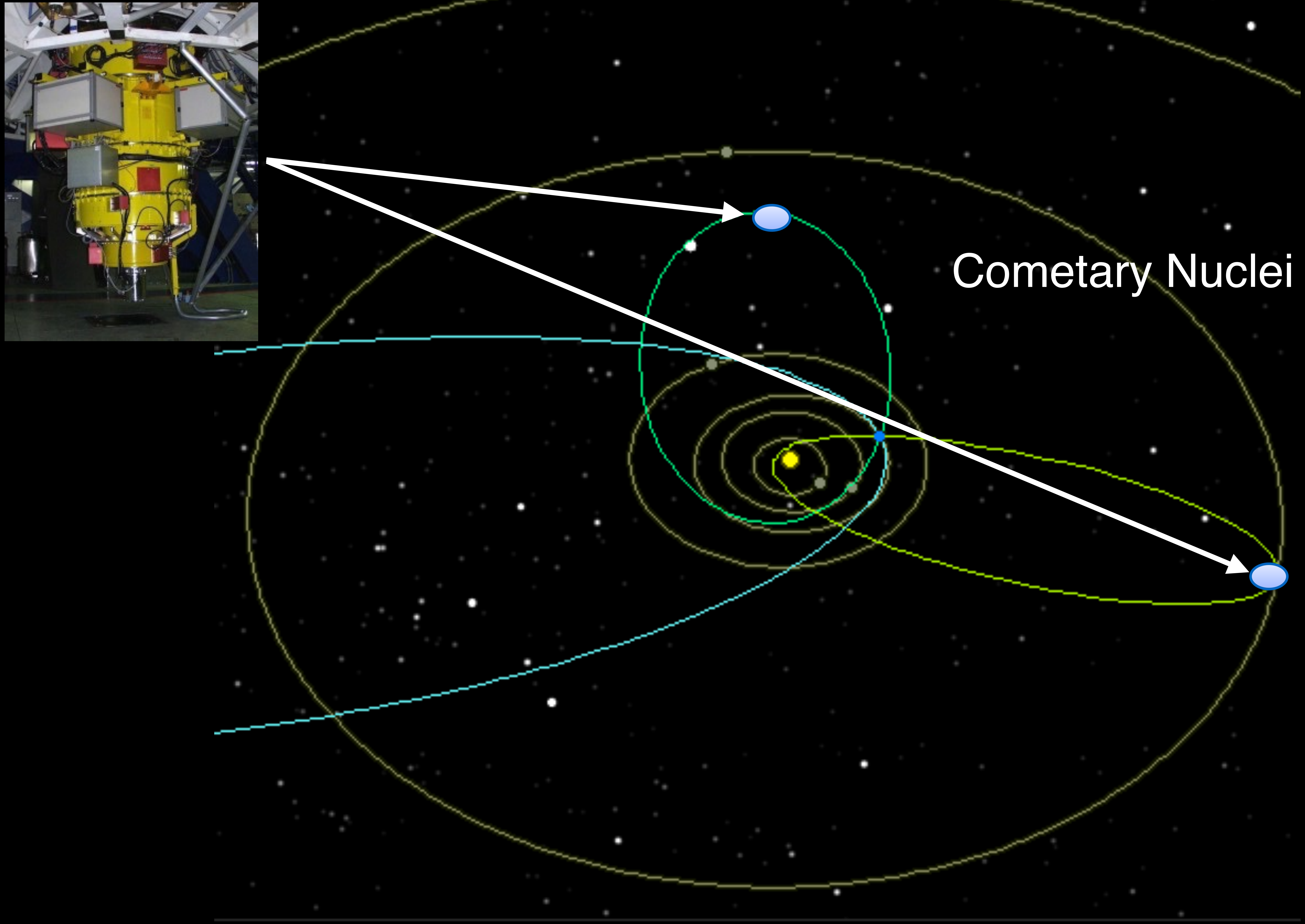


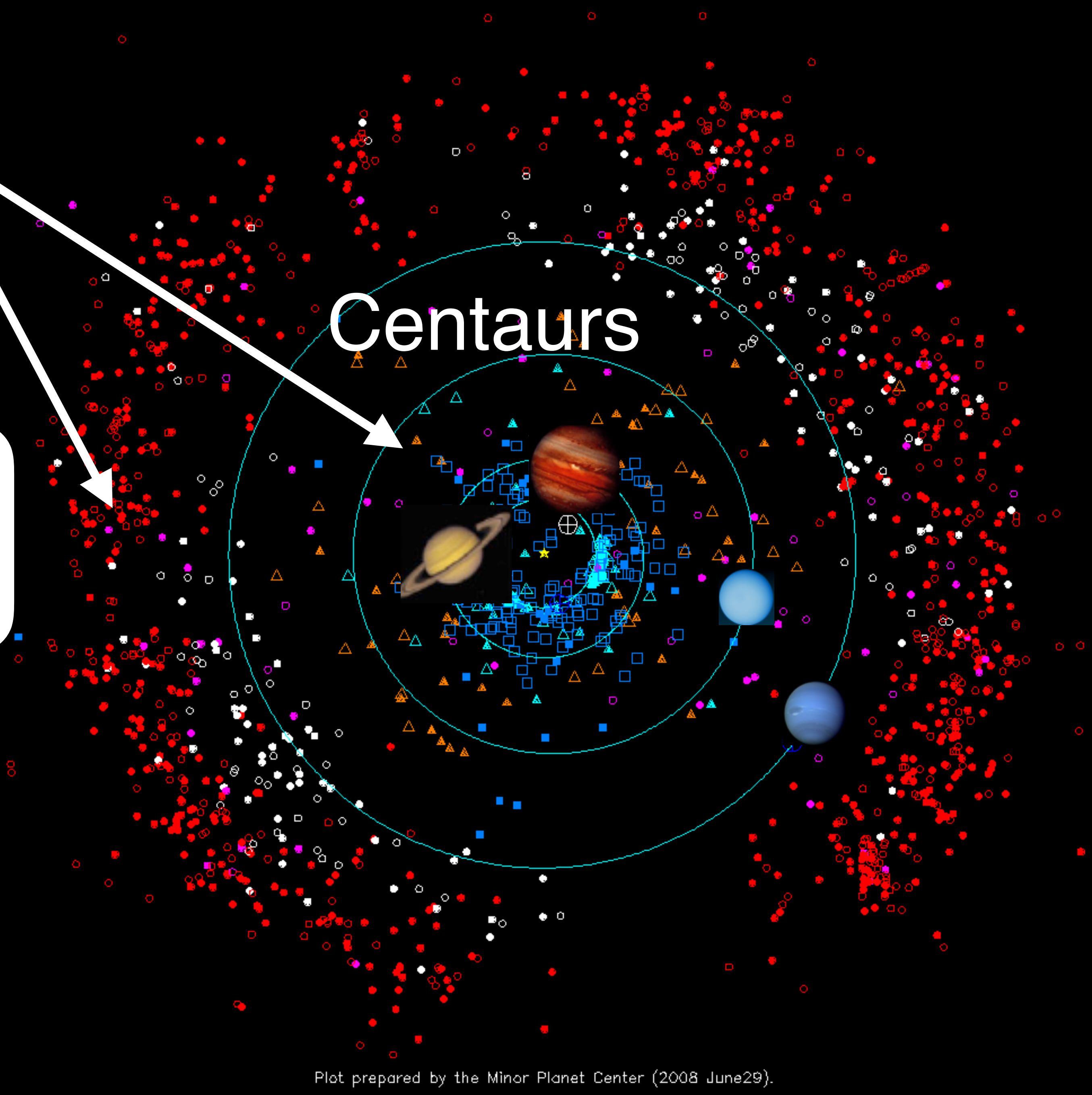


Photometry alone cannot tell us whether a spatially unresolved asteroid is bright and small, or dark and big

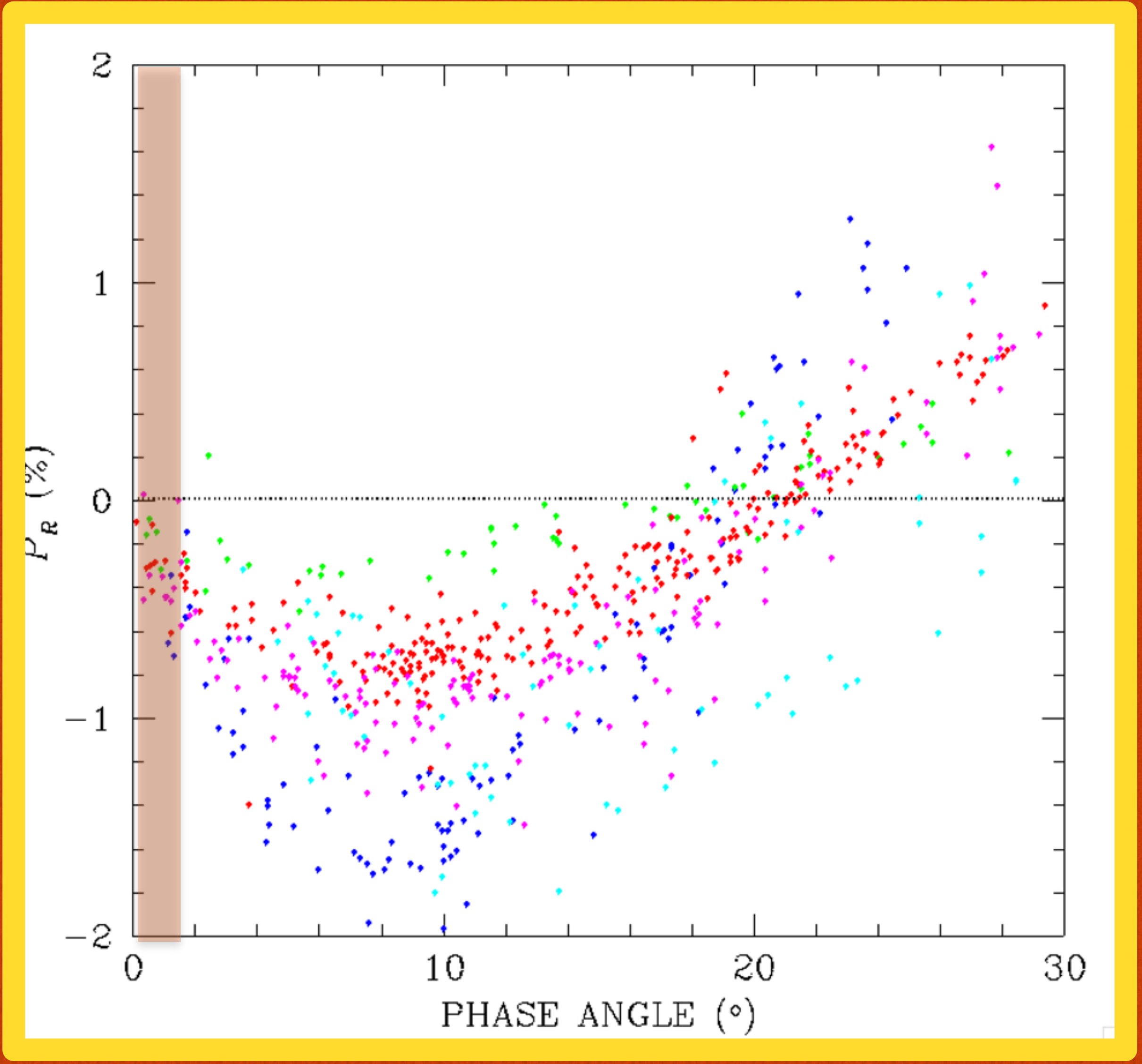
However, polarimetry allows us to measure the albedo, and combined with photometry we can measure also the asteroid size


Jupiter Trojans
Jupiter
Main Belt Asteroids
Mars
Earth
Mercury
Venus
Near Earth Objects
Jupiter Trojans
P. Chodas (NASA/JPL)

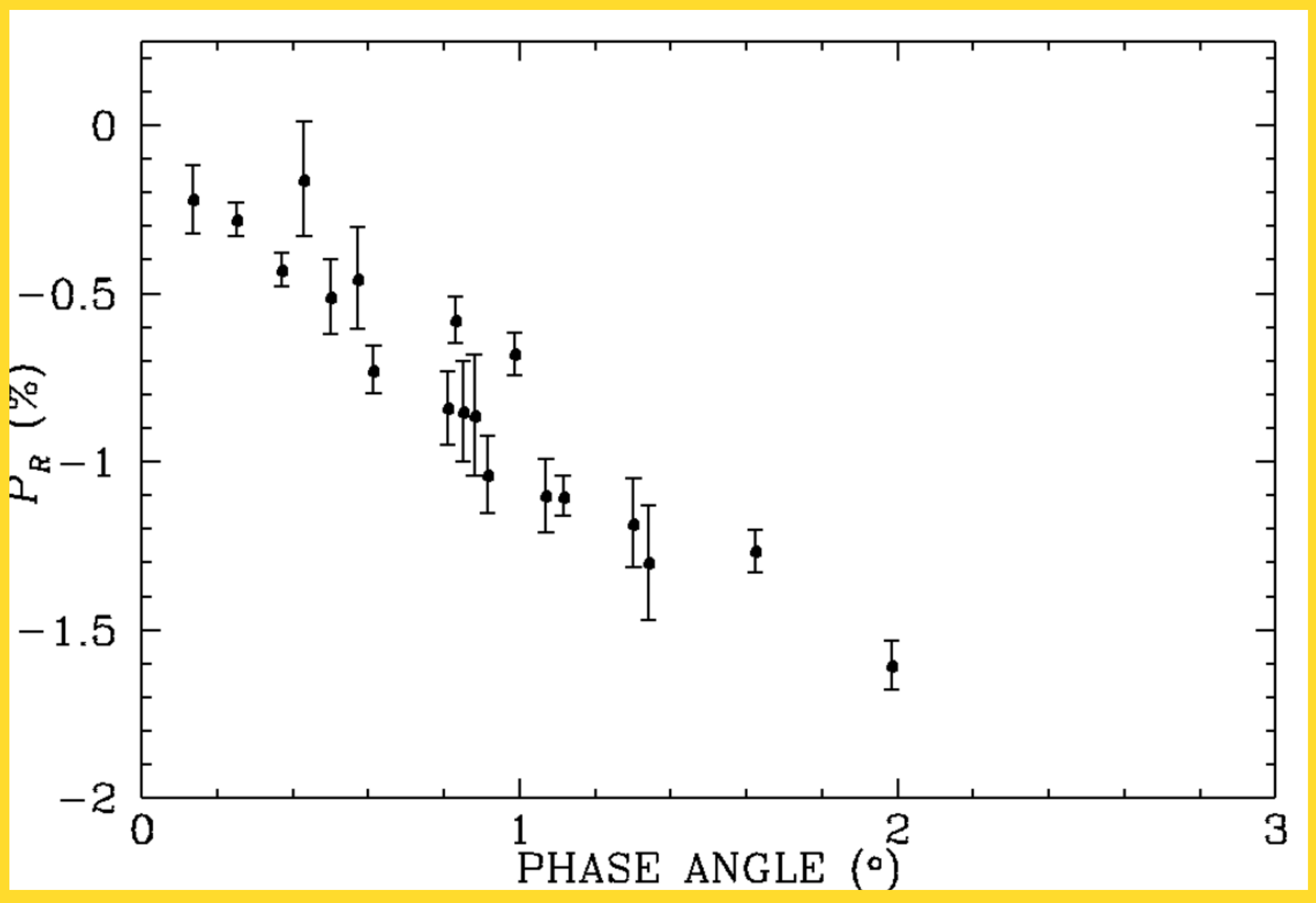

Cometary Nuclei


TNOs
Centaurs
Plot prepared by the Minor Planet Center (2008 June29).

BBLP of Main Belt Asteroids

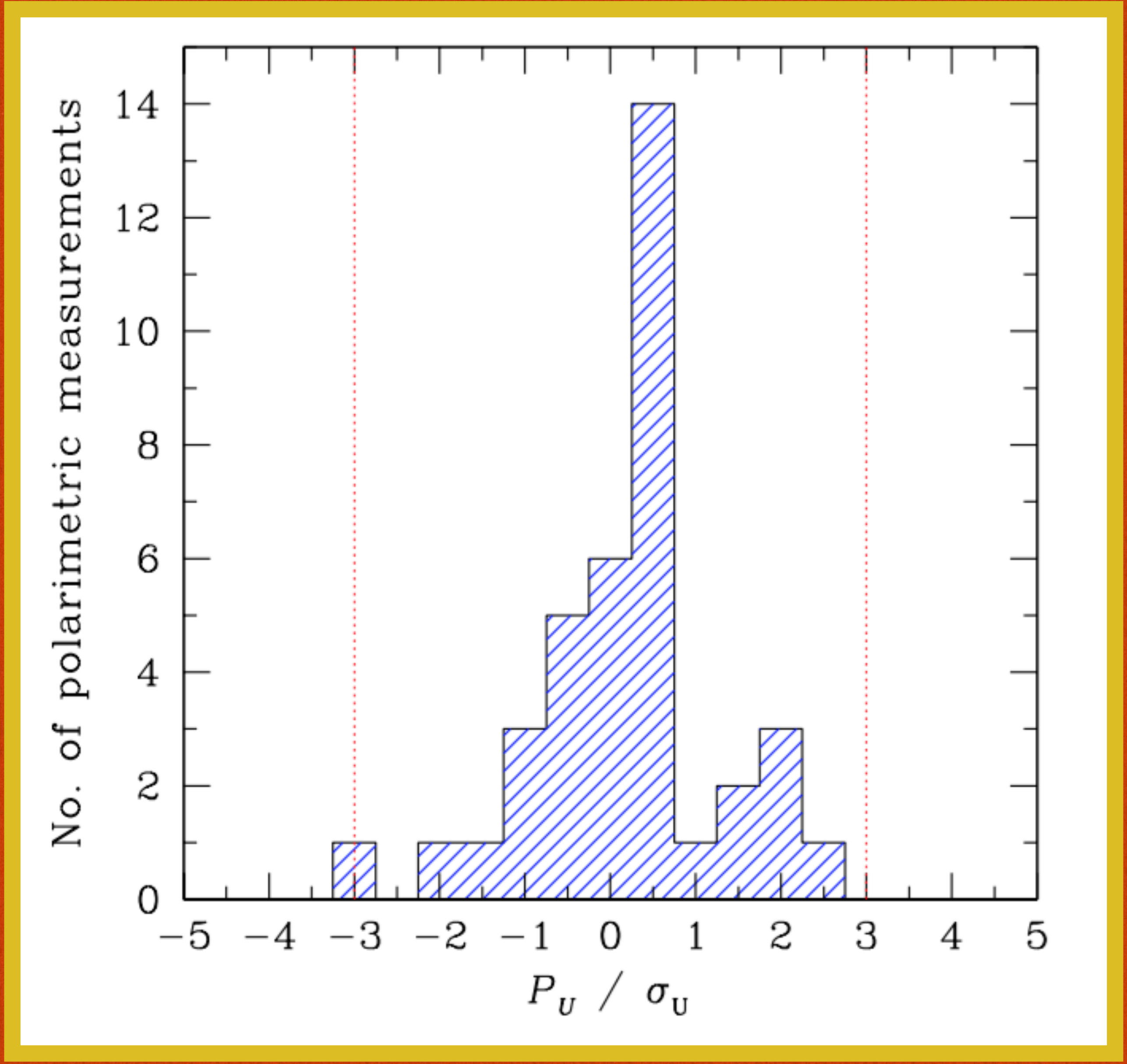


BBLP of TNOs

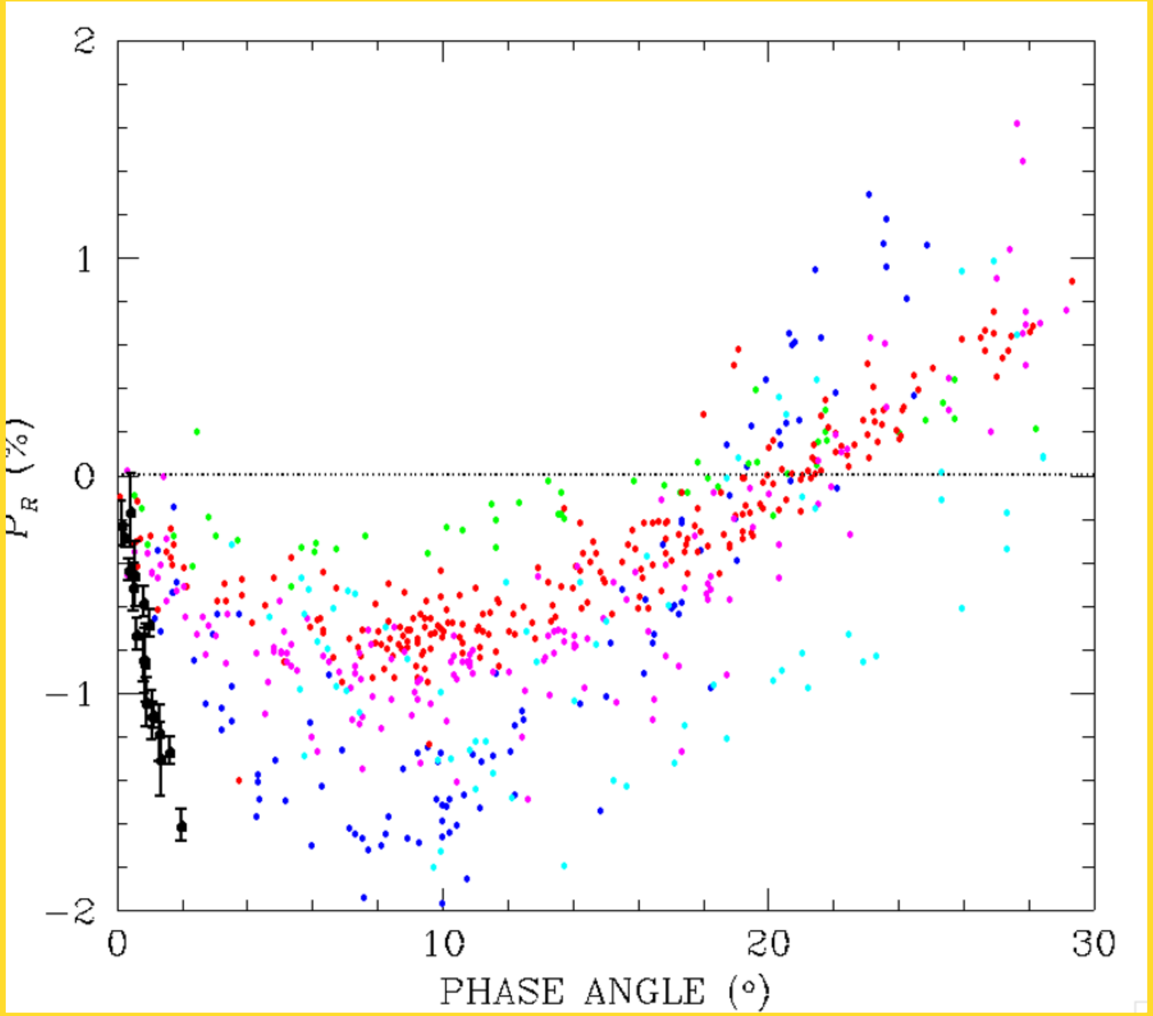


Boehnhardt et al. (2002)
Bagnulo et al (2008)

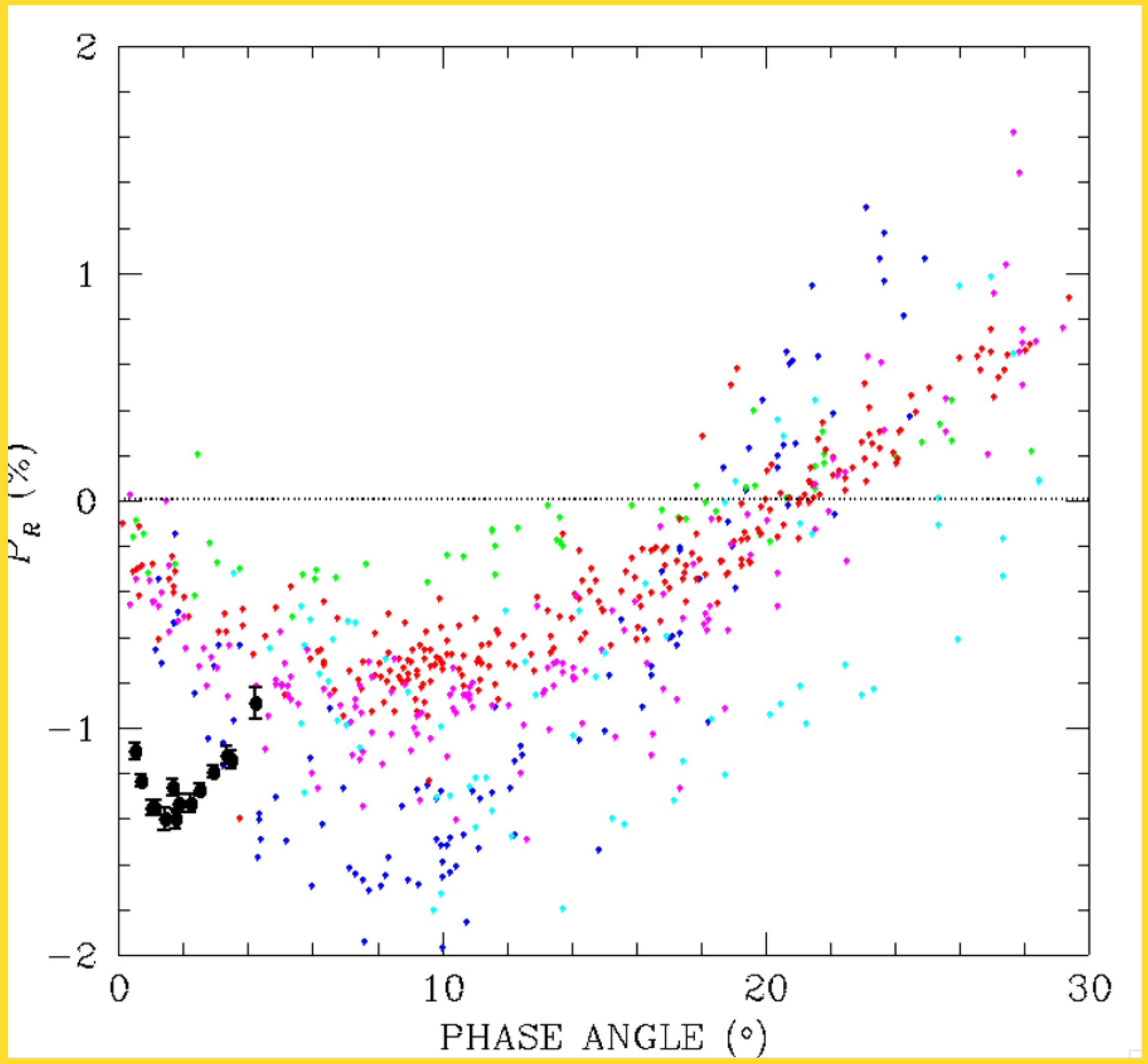
How do we know that measurements are accurate?

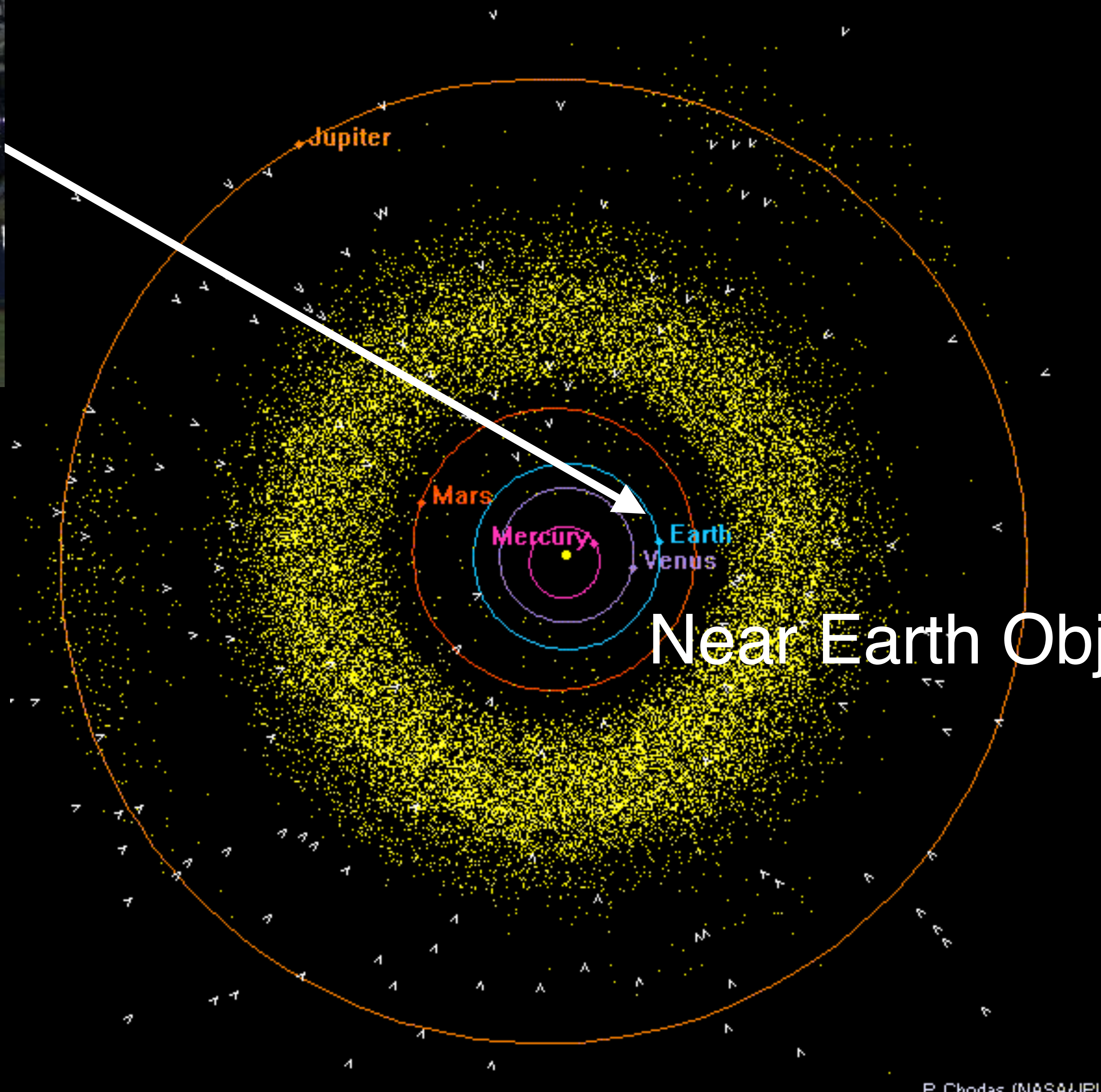


BBLP of TNOs + MB asteroids

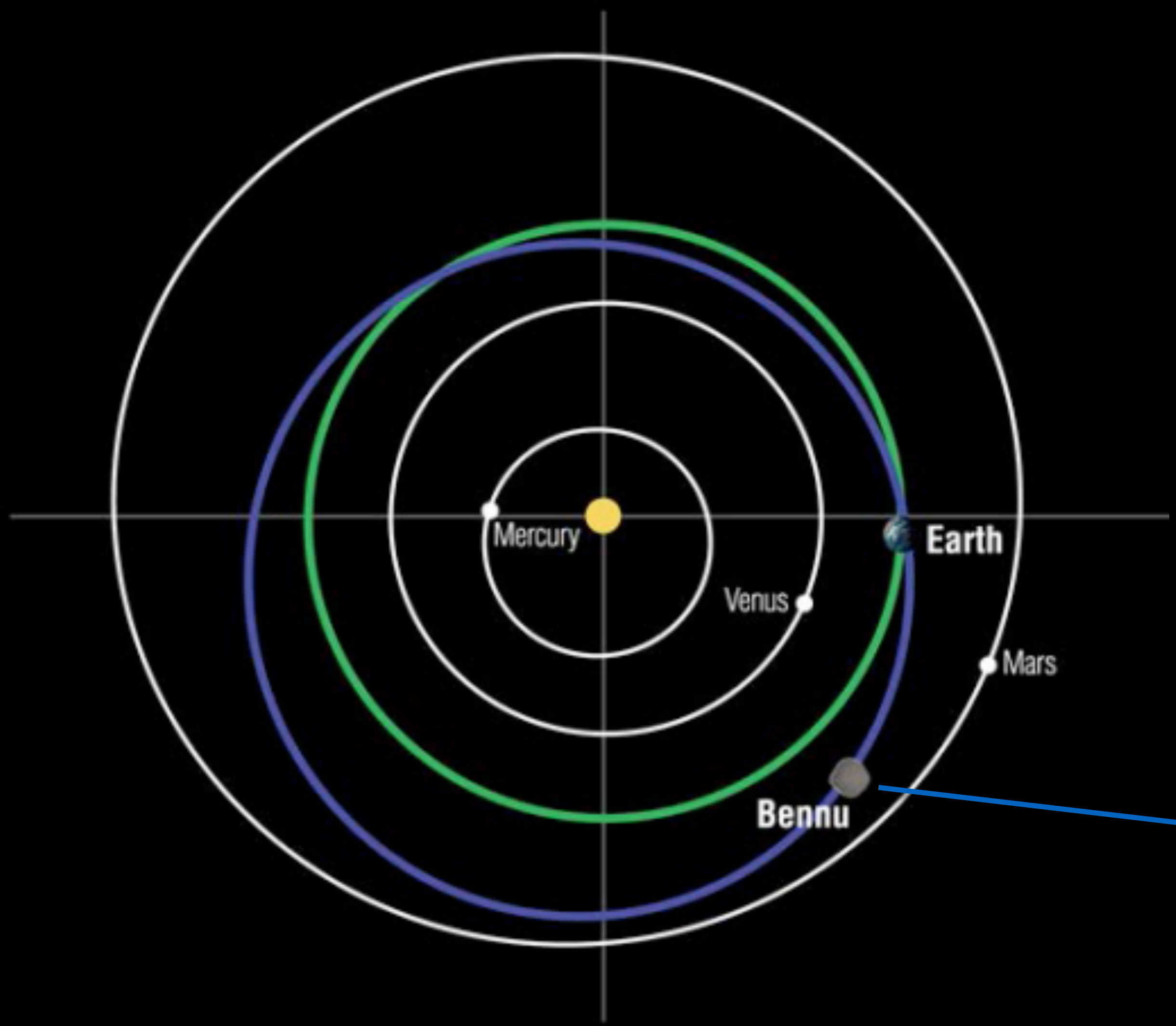


BBLP of Centaur Chiron + MB asteroids





Near Earth Objects


Mercury
Earth
Venus
Mars
Bennu

BENNU

Scientists chose Bennu as the target of the OSIRIS-REx mission because of its composition, size, and proximity to Earth. Bennu is a rare B-type asteroid (primitive and carbon-rich), which is expected to have organic compounds and water-bearing minerals like clays.

BENNU FACTS:

Equatorial Diameter: ~500 m

Polar Diameter: ~510 m

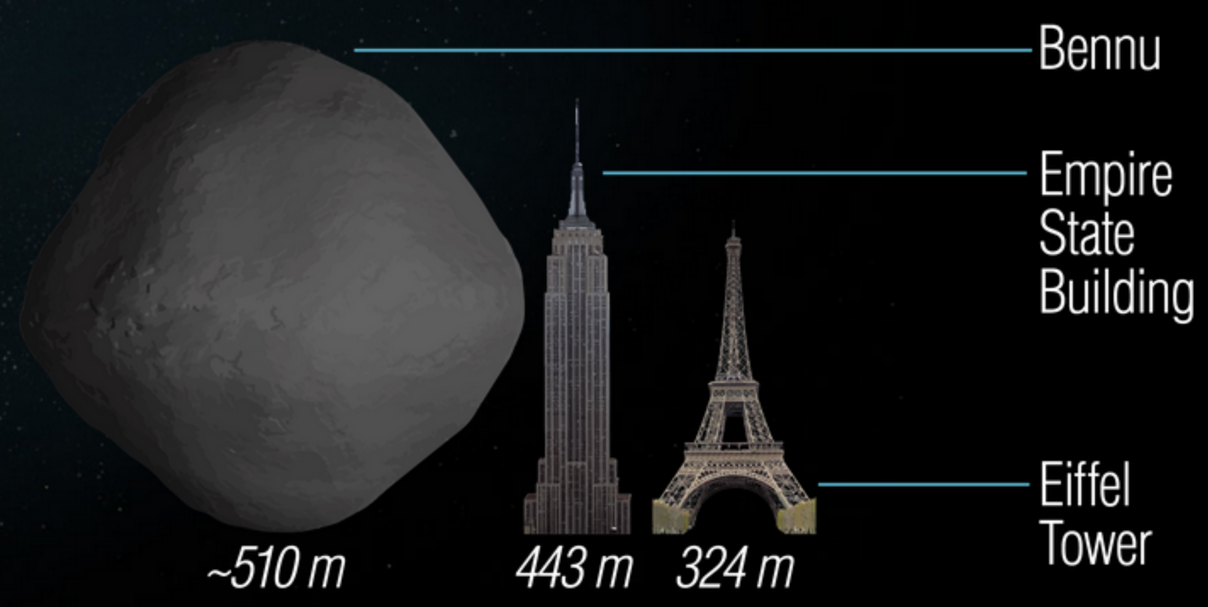
Average Speed: 63,000 mph

Rotation Period: 4.3 hrs

Orbital Period: 1.2 yrs

Orbital Inclination: 6 degrees

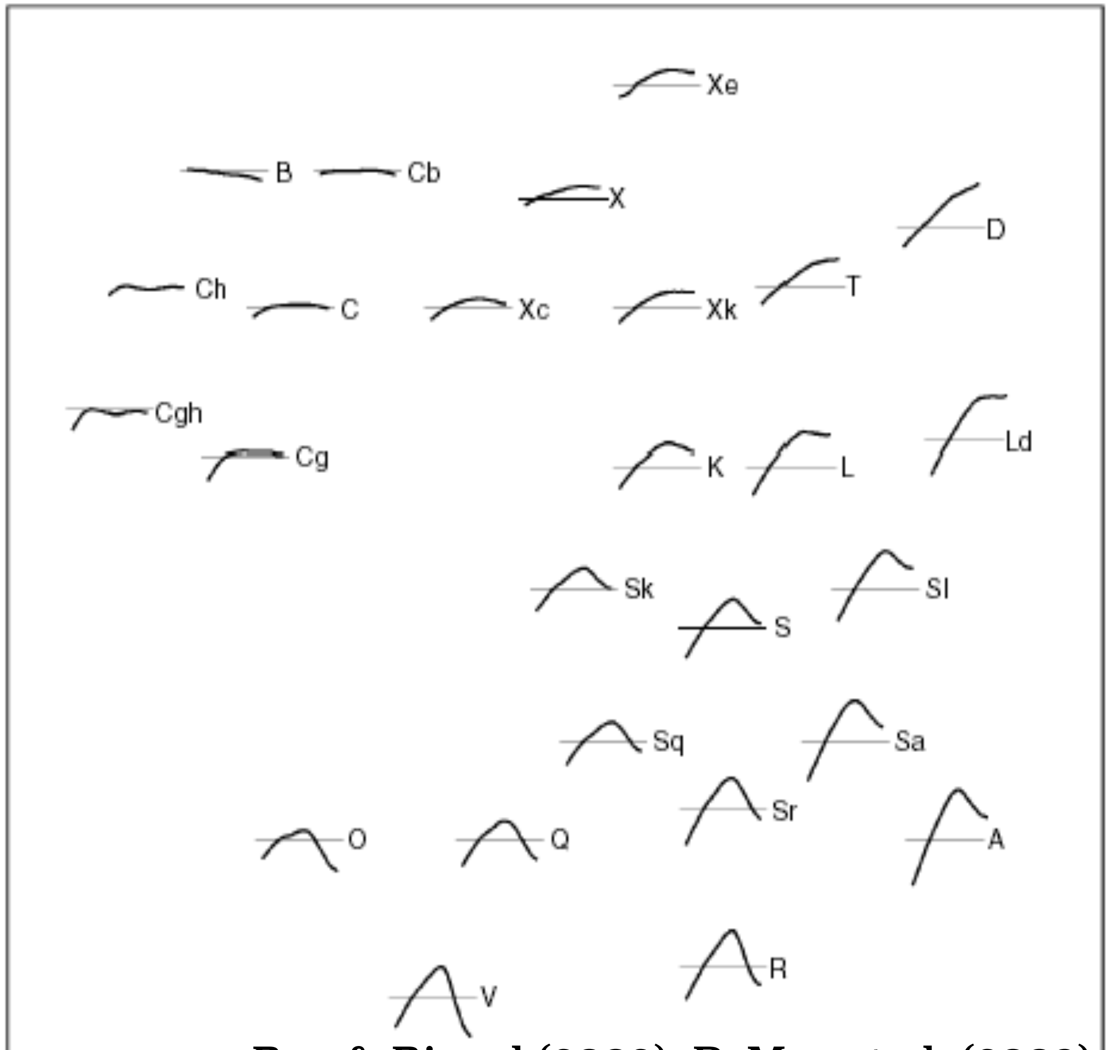
Earth Approach: Bennu comes close to Earth every 6 yrs



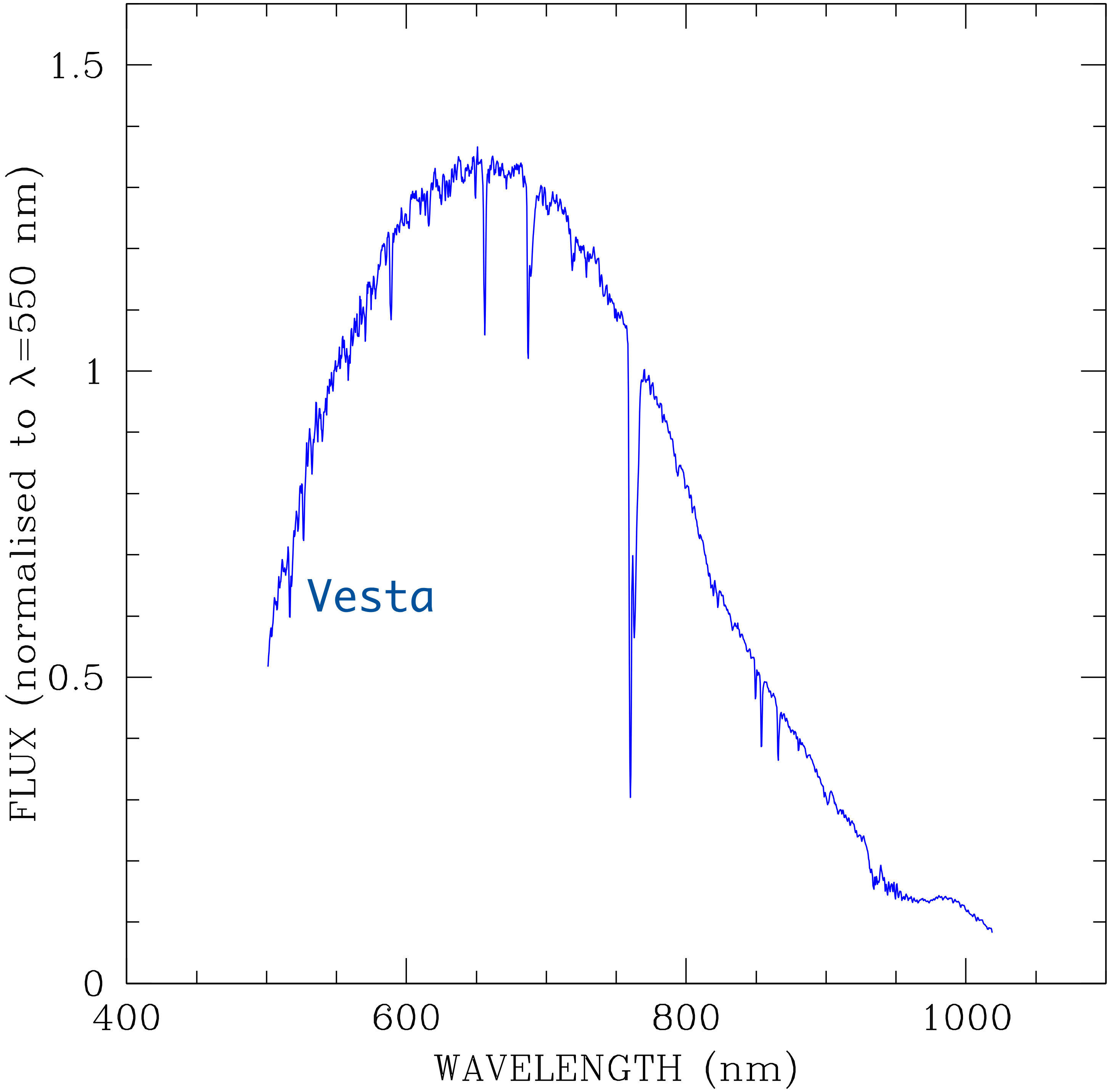
Primitive asteroids have not significantly changed since they formed nearly 4.5 billion years ago. Because of this, we hope to find organic molecules on Bennu like those that may have led to the origin of life on Earth.

[Learn more and watch the story of Bennu's Journey.]

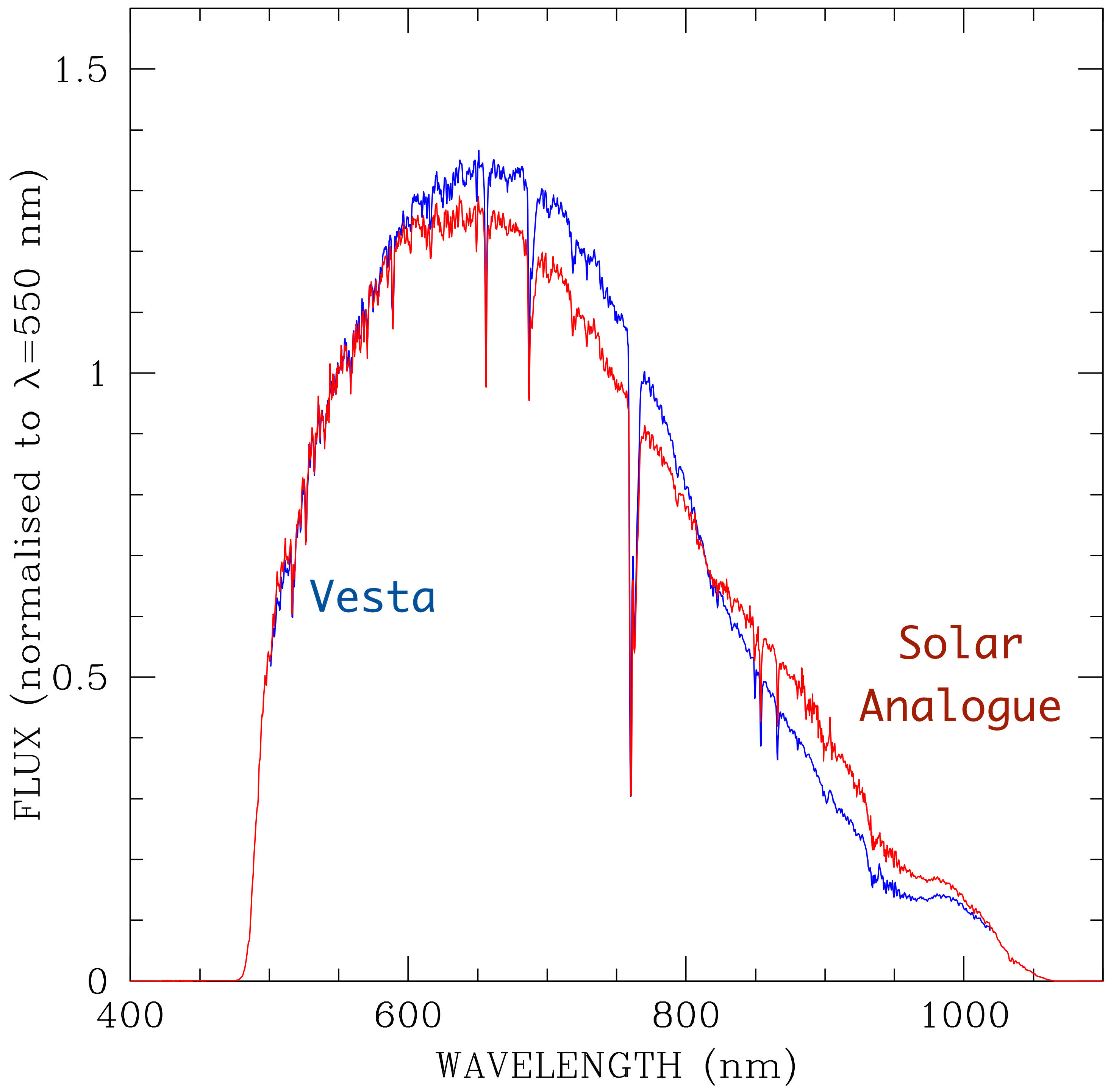
Reflectance spectra of asteroids are classified in taxonomic classes



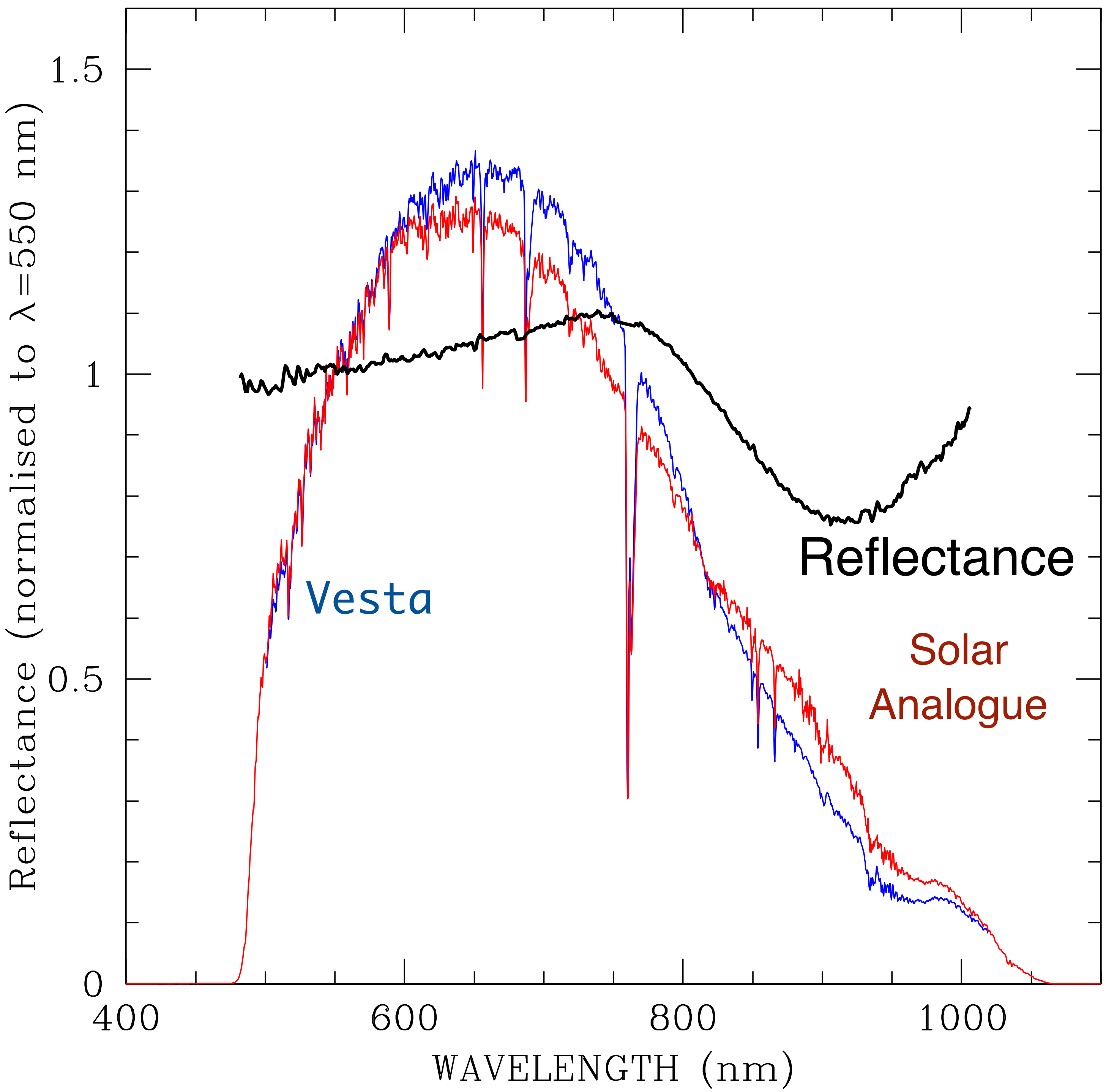
Bus & Binzel (2002), DeMeo et al. (2009)



Vesta
FLUX (normalised to λ=550 nm)
WAVELENGTH (nm)
0
0.5
1
1.5
400
600
800
1000



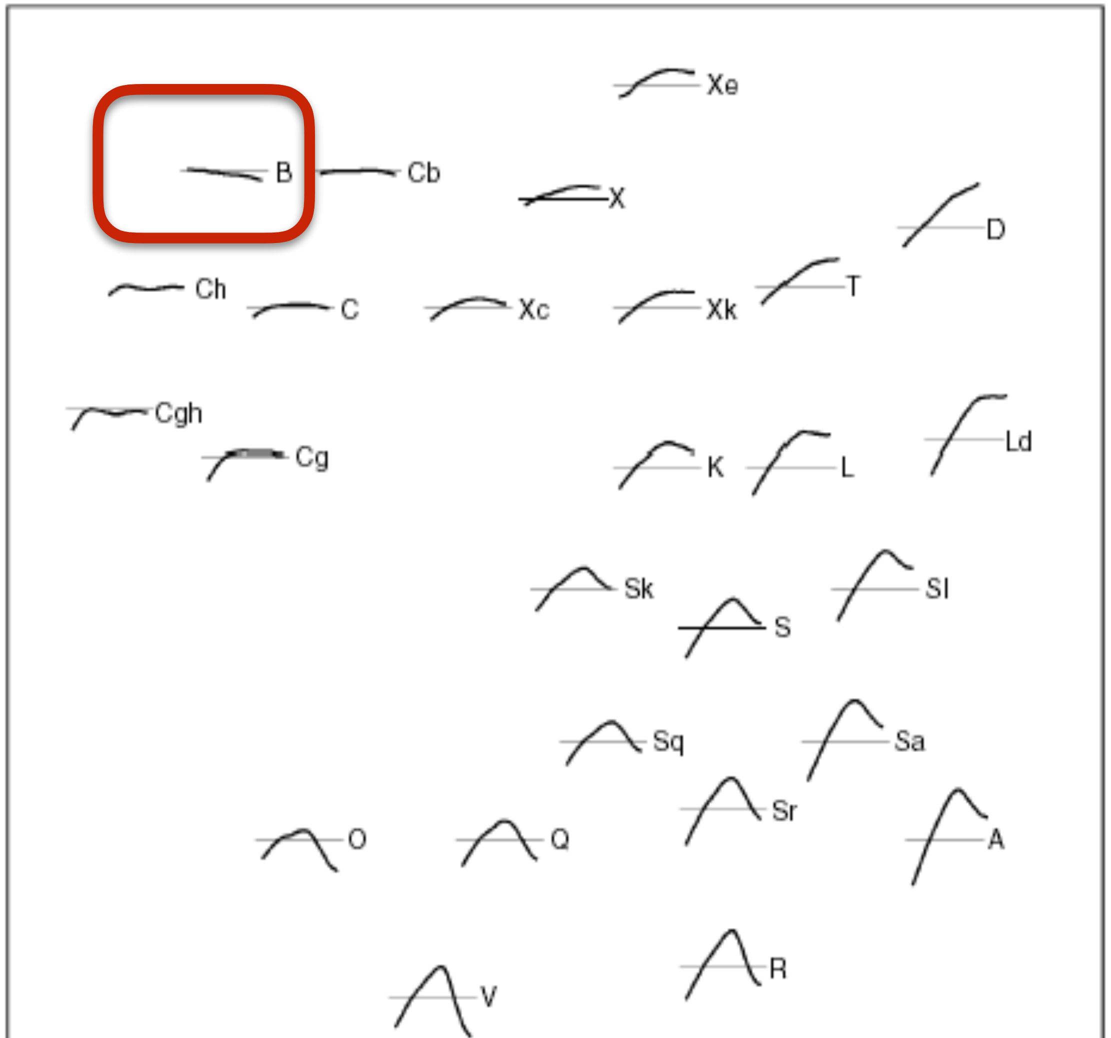
FLUX (normalised to λ=550 nm)
1.5
1
0.5
0
400
600
800
1000
WAVELENGTH (nm)
Vesta
Solar
Analogue



Reflectance (normalised to λ=550 nm)
1.5
1
0.5
0
400
600
800
1000
WAVELENGTH (nm)
Vesta
Reflectance
Solar
Analogue

SMASS classification of reflectance spectra of asteroids

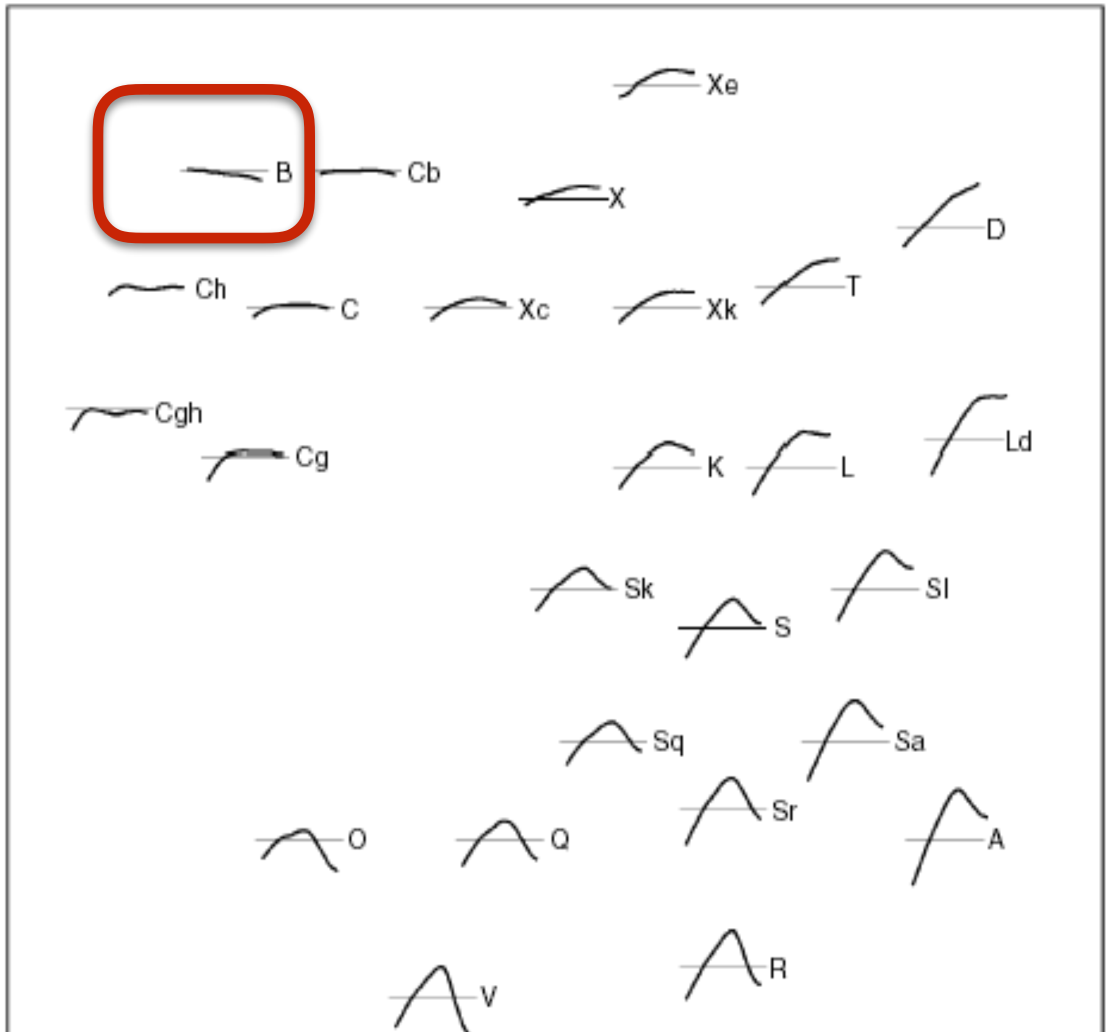
Taxonomic classifications have been rapidly evolving with time



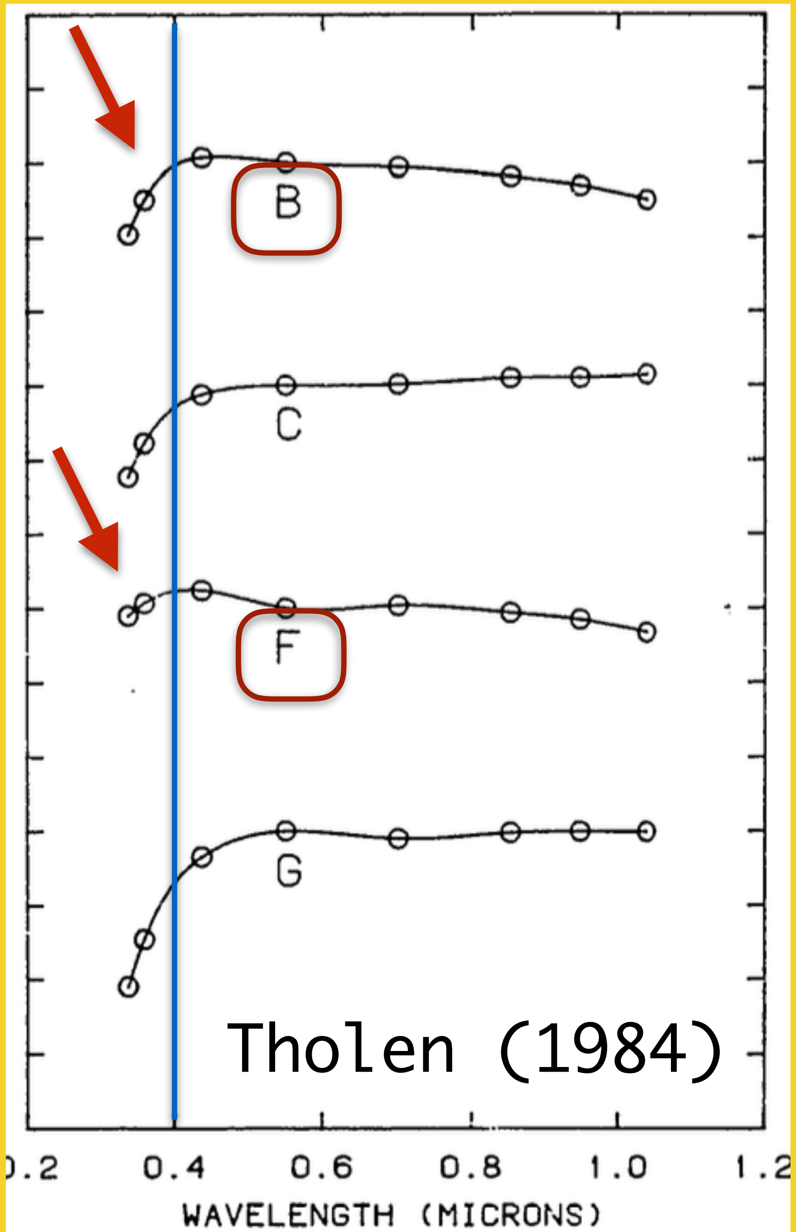
Bus & Binzel (2002), DeMeo et al. (2009)

The modern B class of asteroids has incorporated the older F taxonomic class

F+B ⟶ B

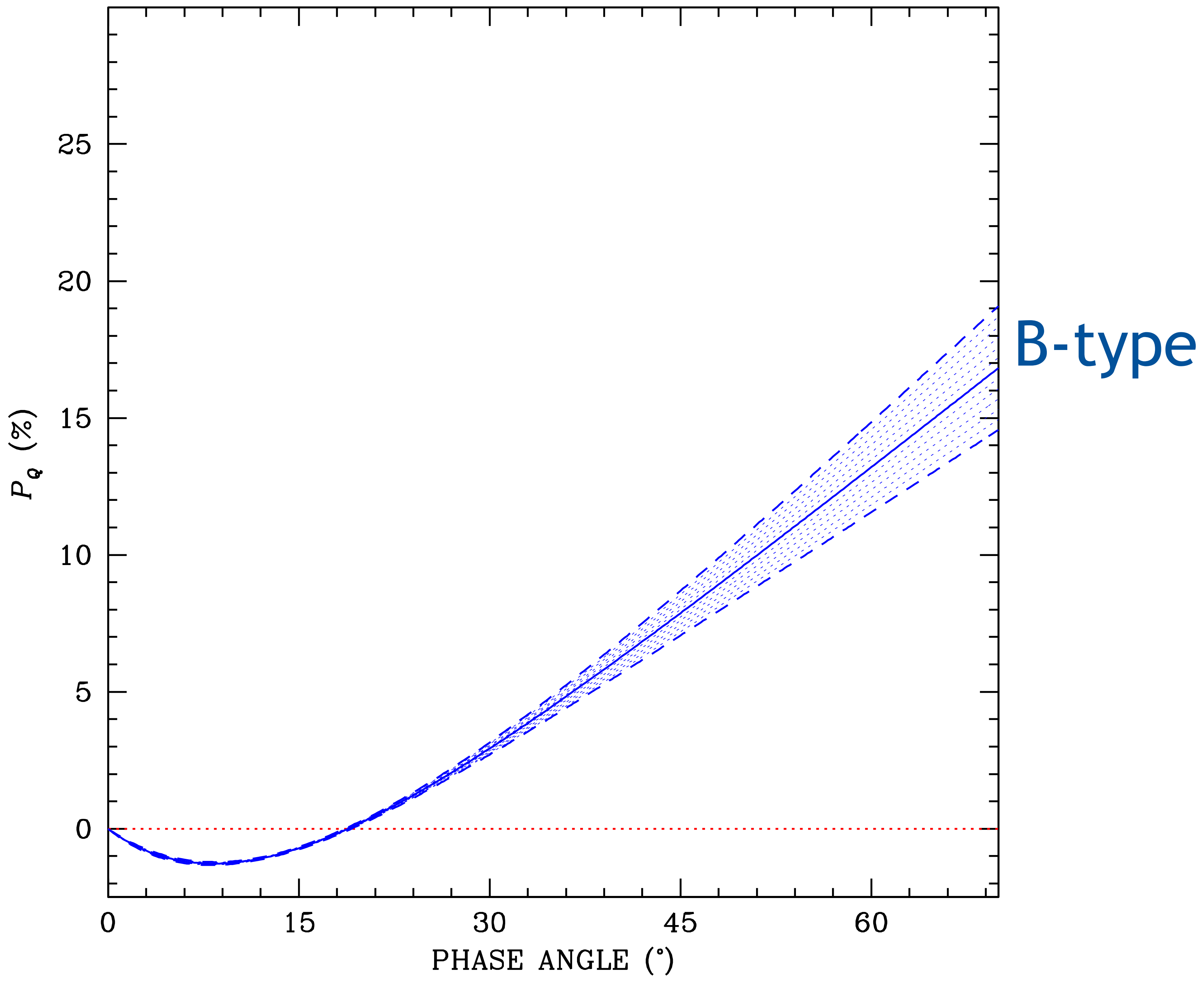


Bus & Binzel (2002), DeMeo et al. (2009)

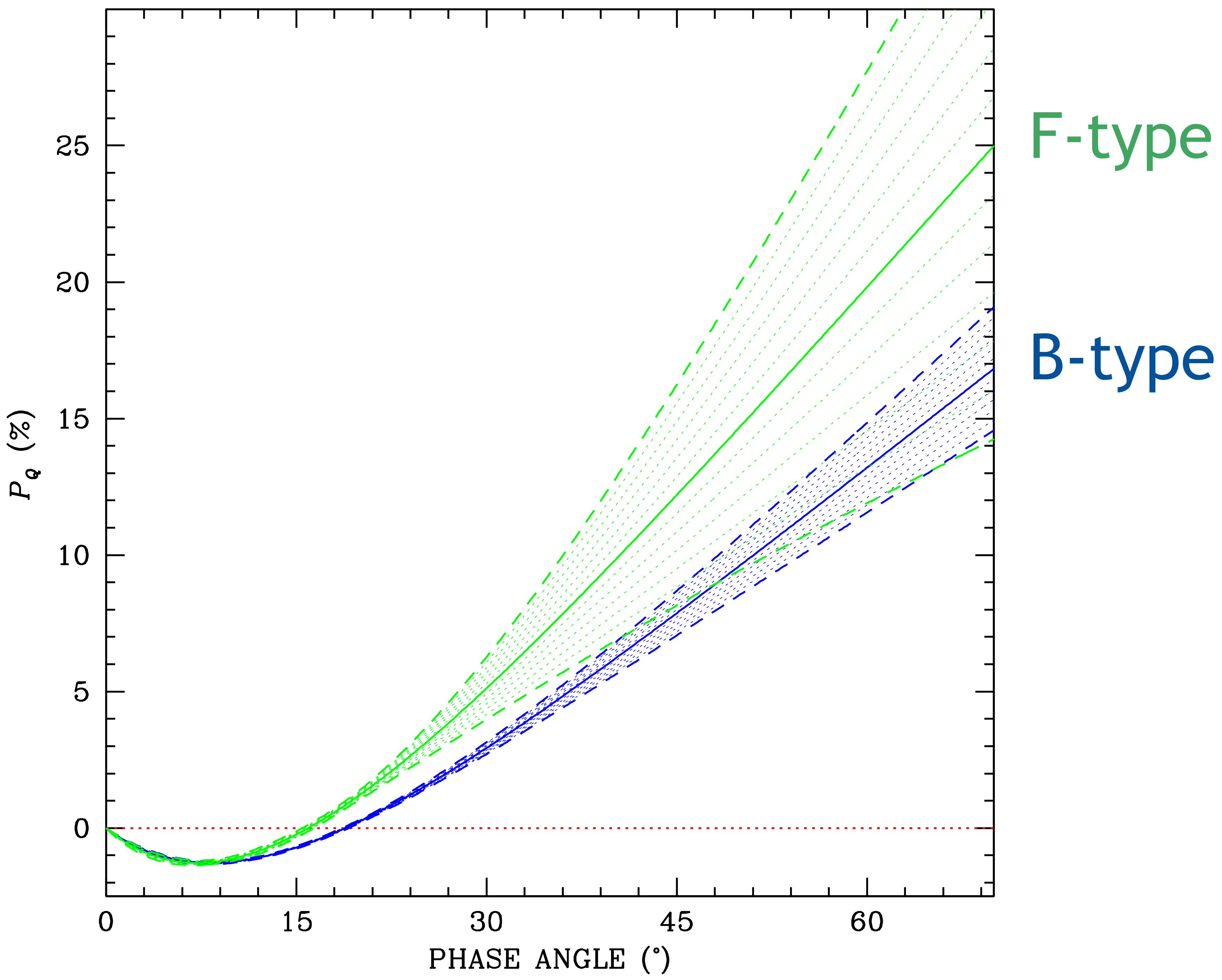


- F-type differ from B-type at λ< 400nm
- F and B not distinguishable with the criteria used in the SMASS classification (where they are grouped together under the B-type umbrella)

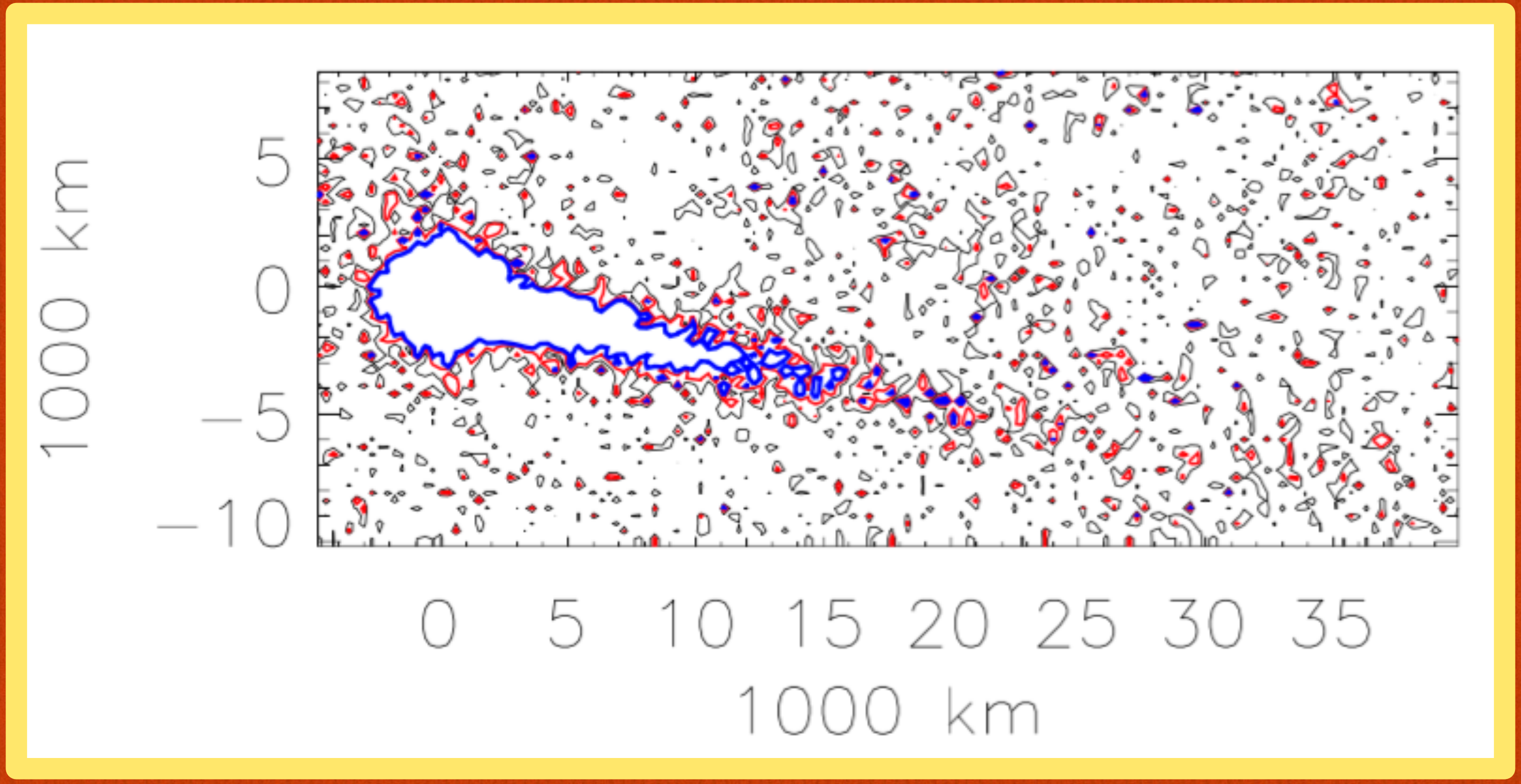
Polarimetrically it's a different story



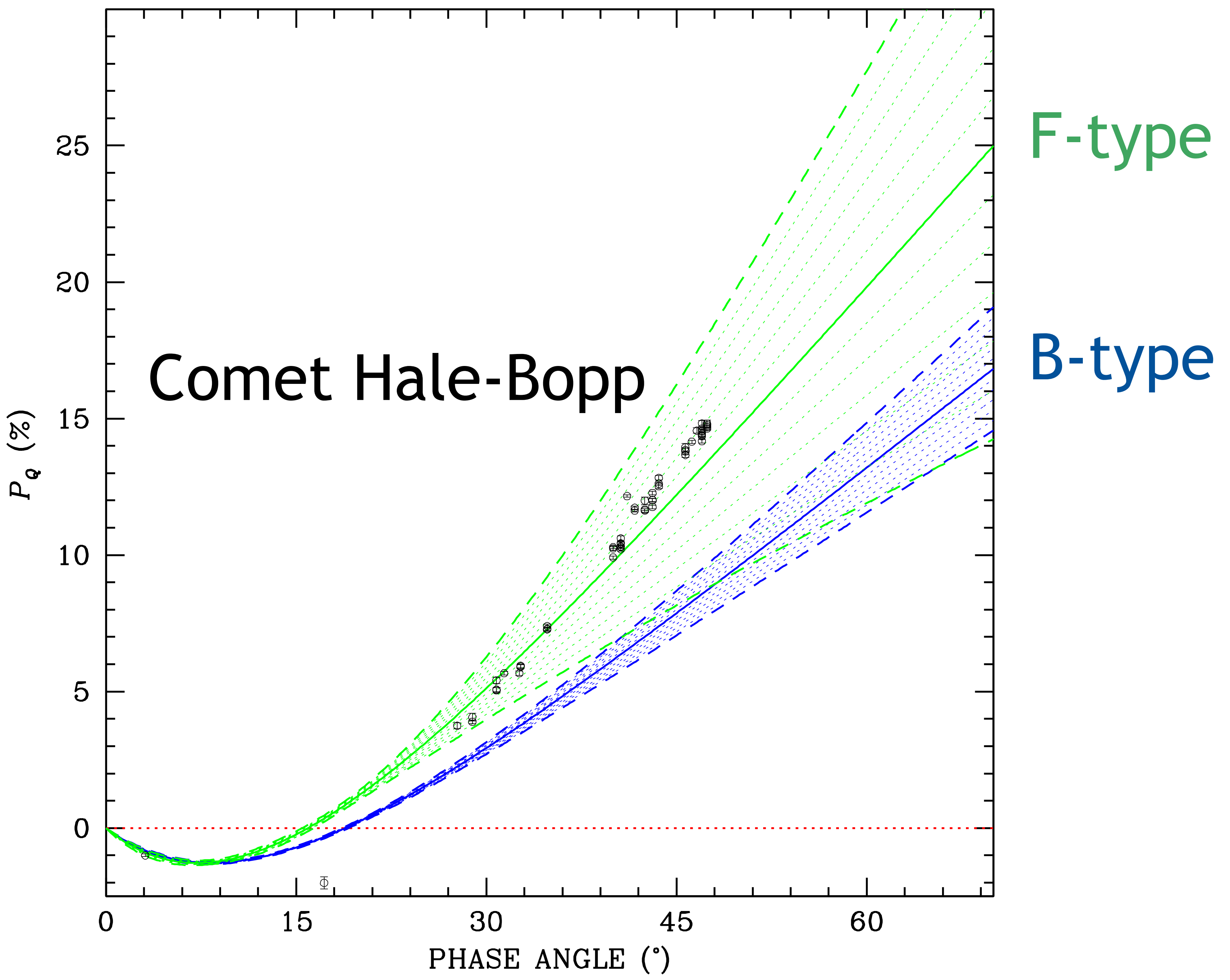
B-type
P_Q (%)
PHASE ANGLE (°)
0
5
10
15
20
25
0
15
30
45
60


F-type
B-type
P_Q (%)
PHASE ANGLE (°)
0
5
10
15
20
25
0
15
30
45
60

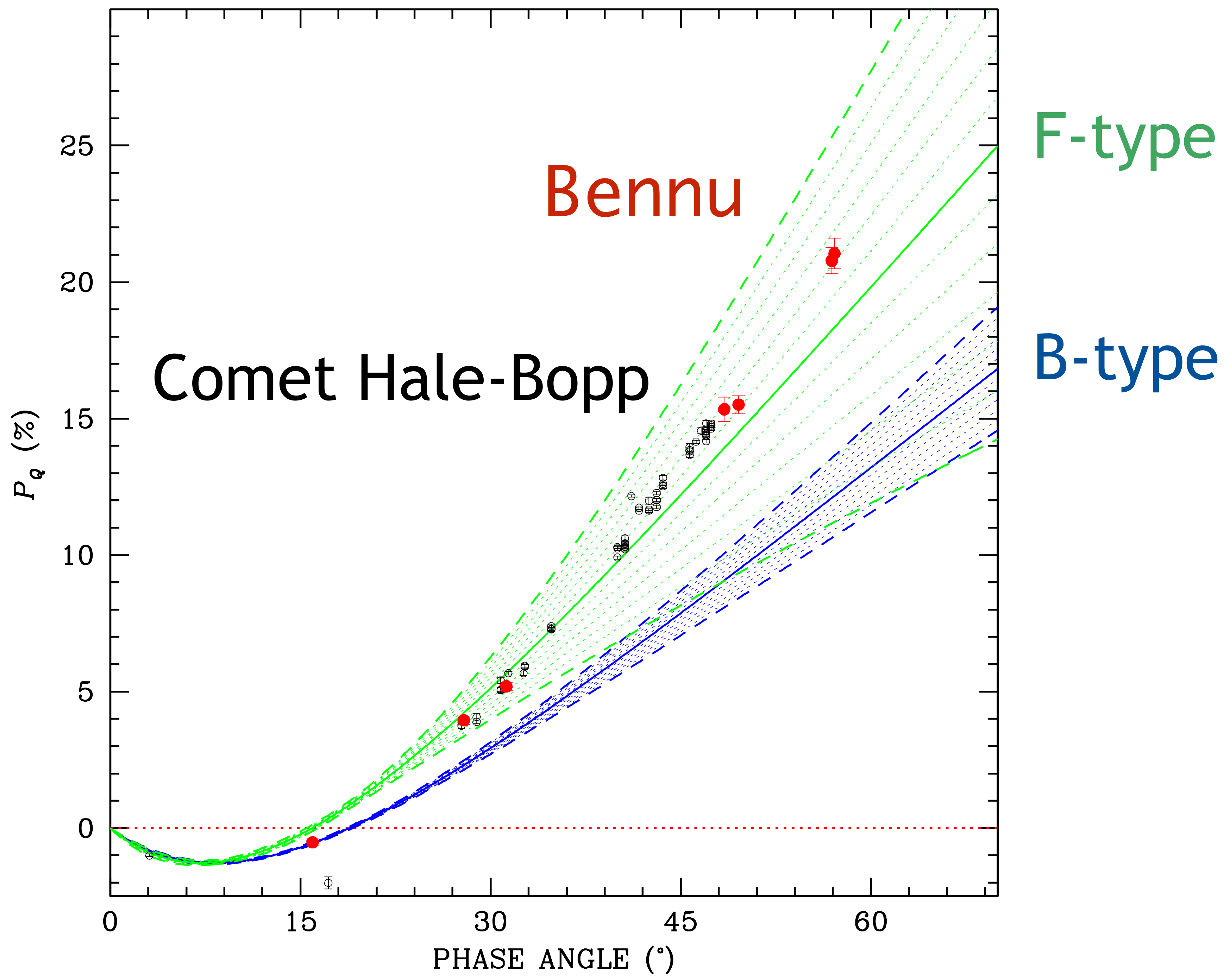
133P/Elst-Pizarro



Bagnulo et al. (2010)



Comet Hale-Bopp
F-type
B-type
P_Q (%)
PHASE ANGLE (°)
0
15
30
45
60
5
10
20
25



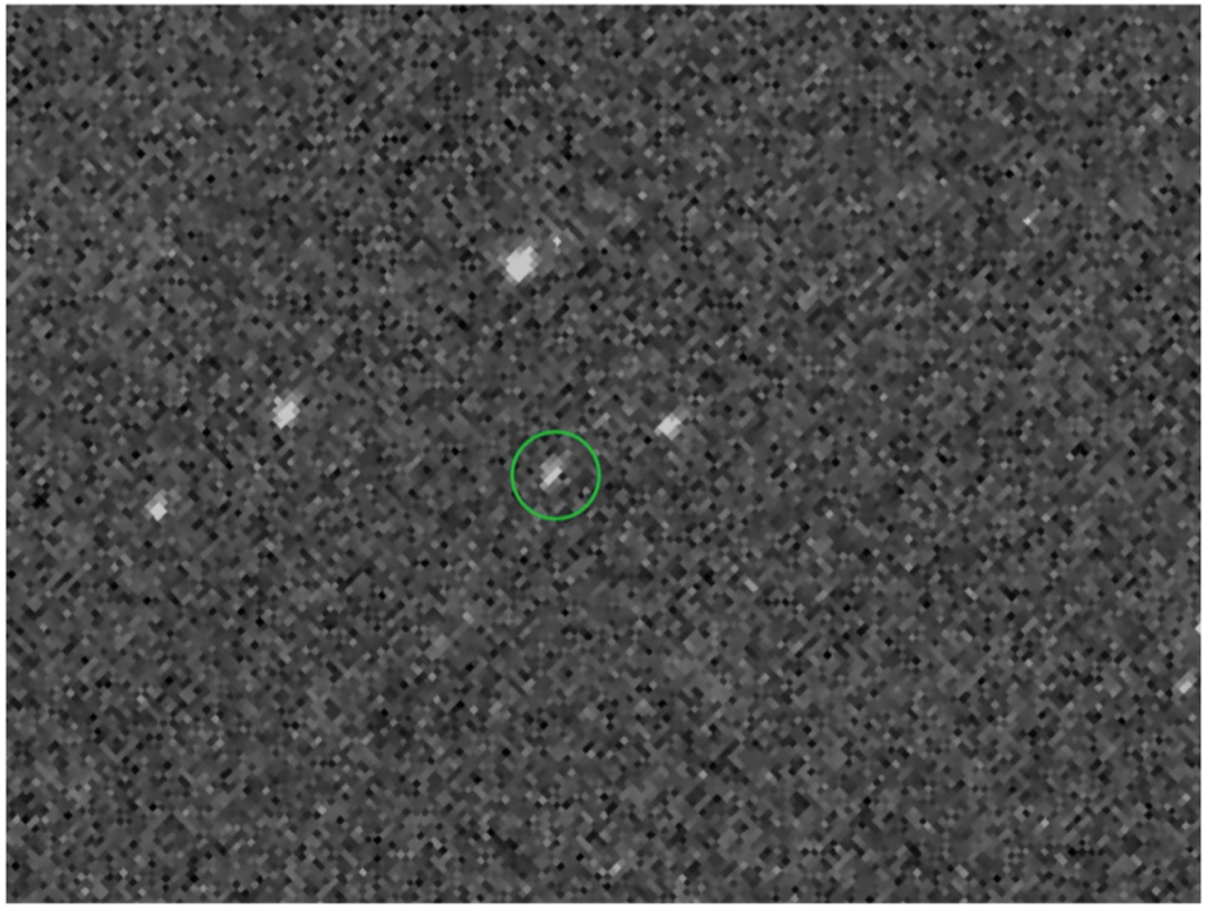
Cellino et al. (2018)

research highlights

ASTEROIDS

Cometary Bennu?

Mon. Not. R. Astron. Soc. Lett. **481**, L49–L53 (2018)

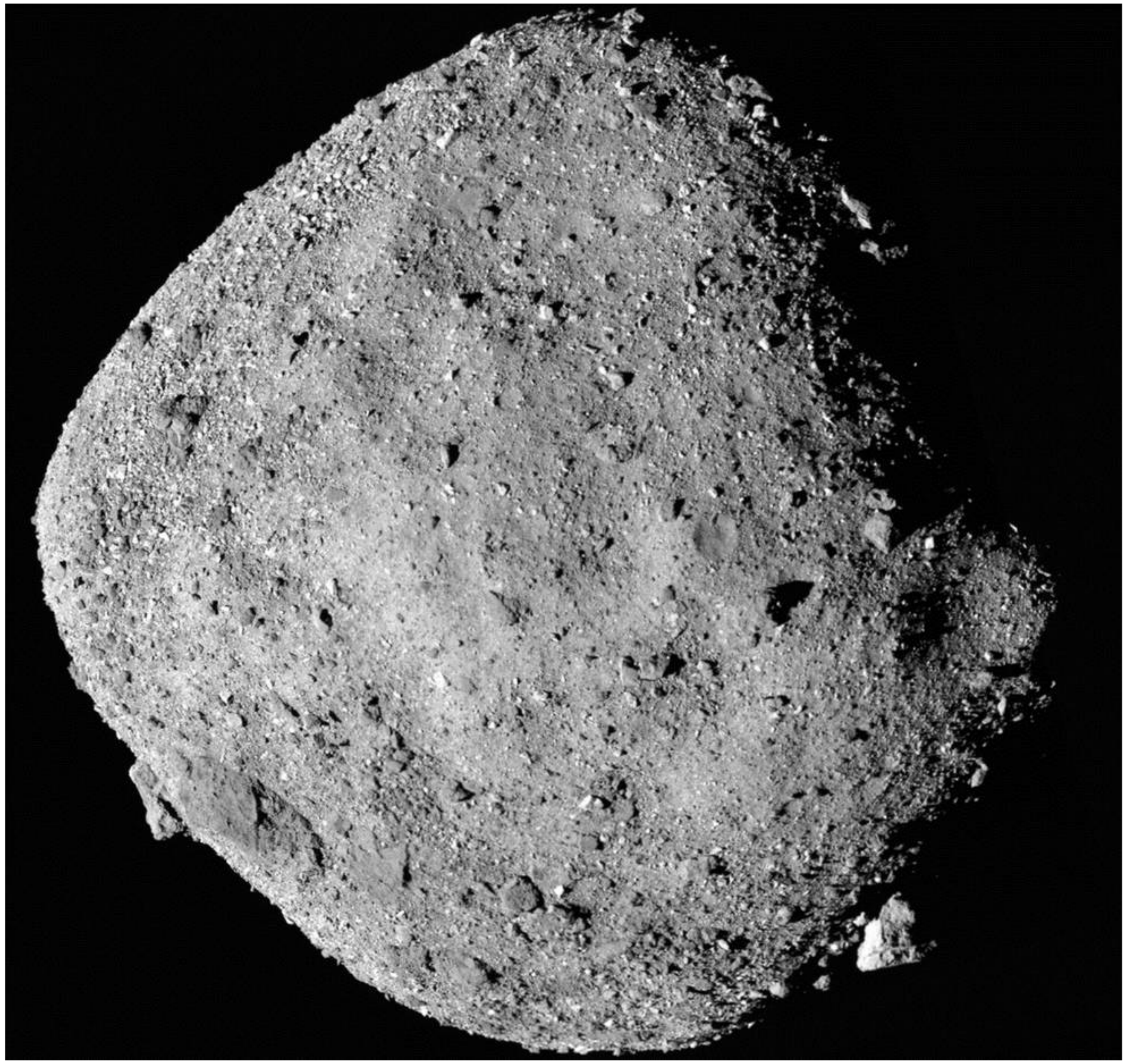


Credit: NASA/Goddard/University of Arizona

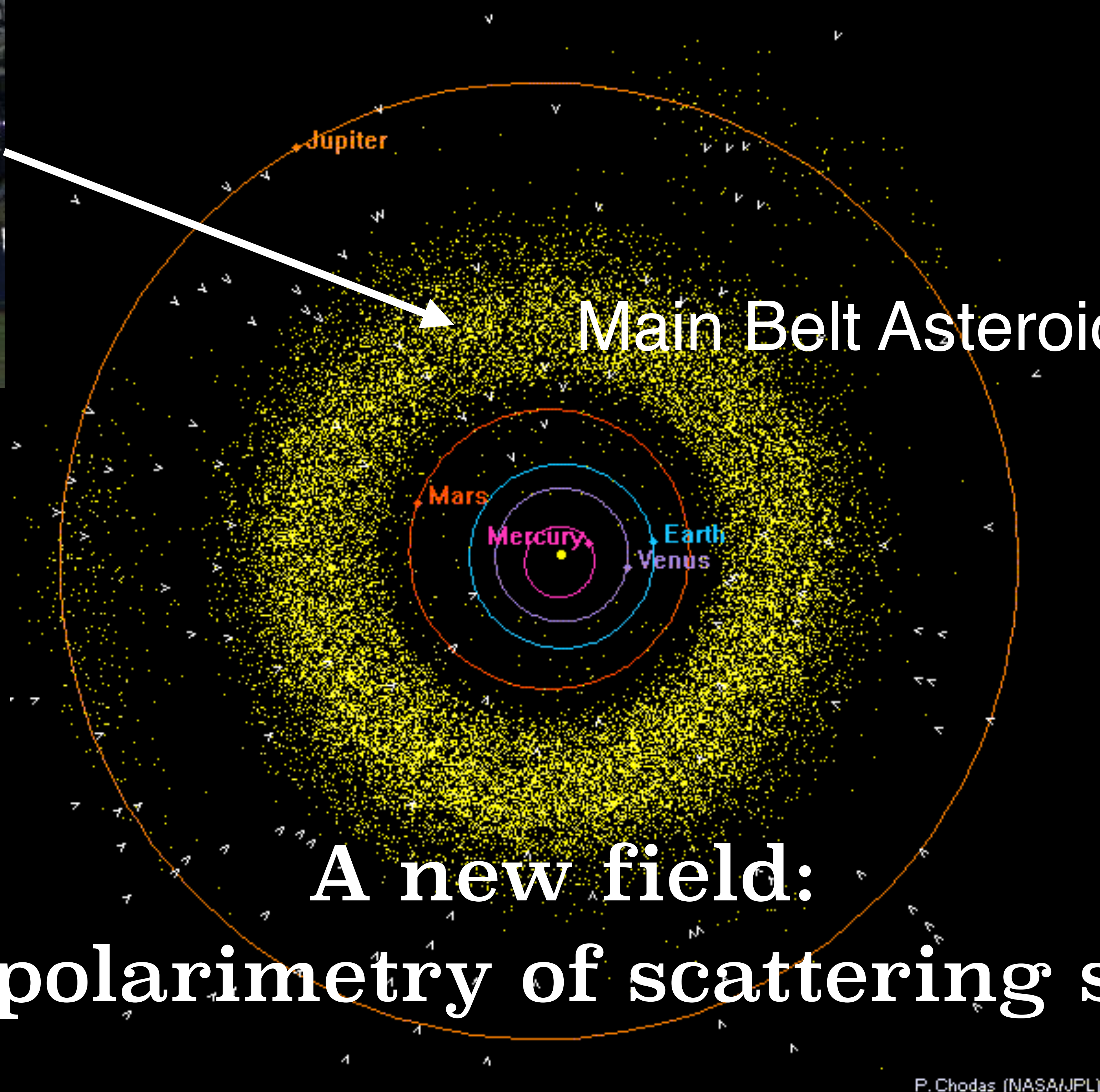
Dec. 10, 2018

RELEASE 18-114

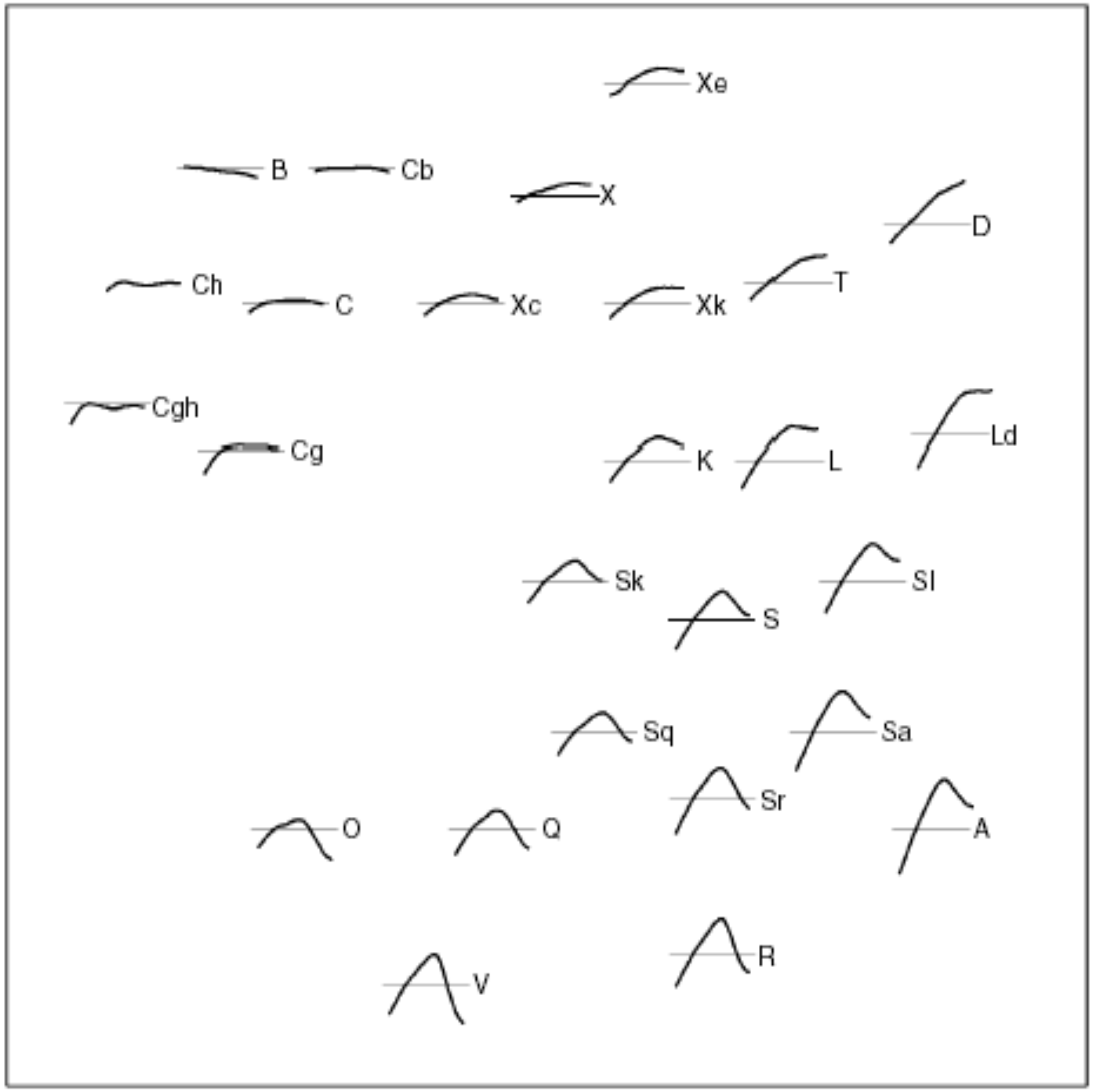
NASA's Newly Arrived OSIRIS-REx Spacecraft Already Discovers Water on Asteroid



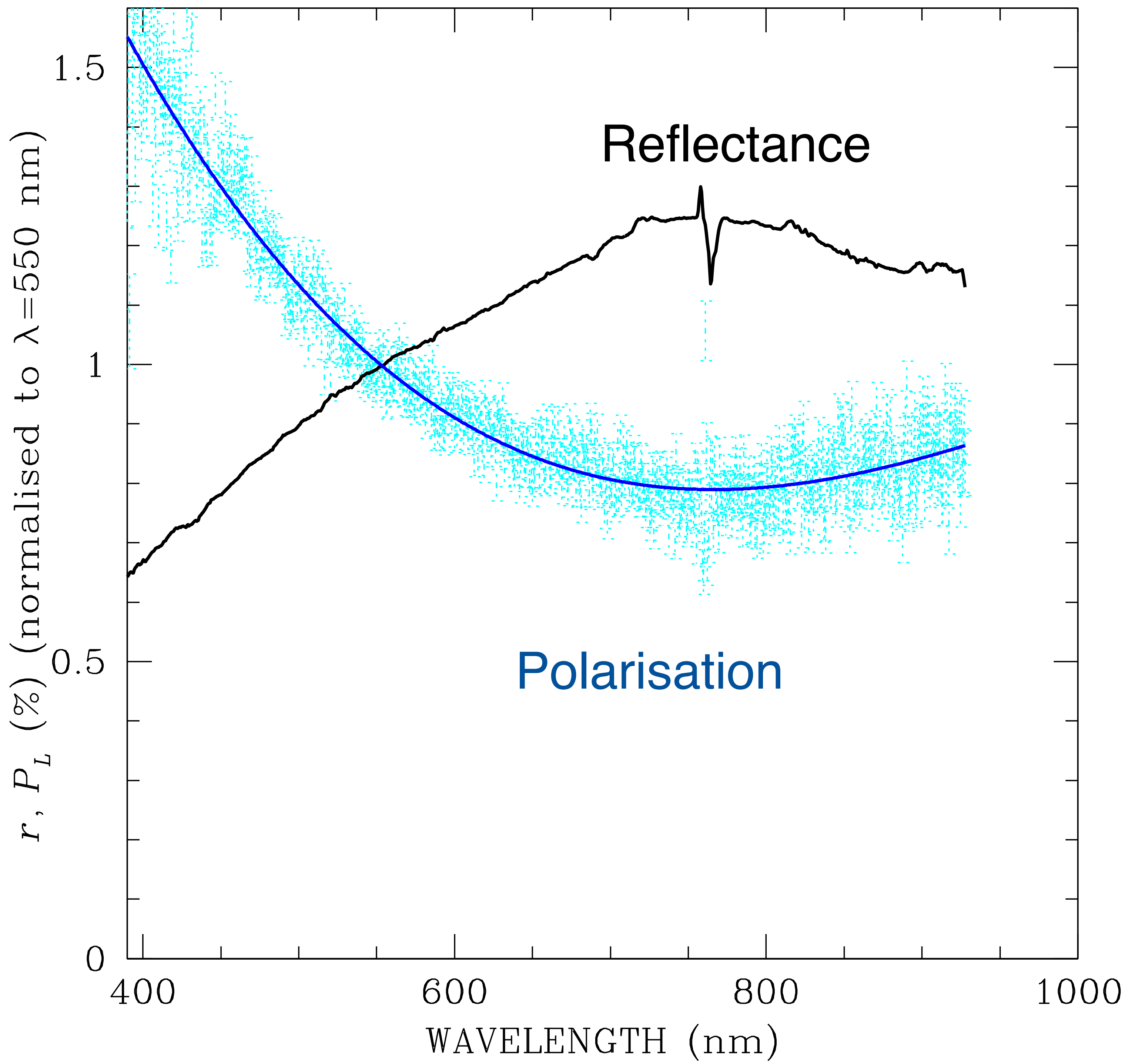
This mosaic image of asteroid Bennu is composed of 12 PolyCam images collected on Dec. 2 by the OSIRIS-REx spacecraft from a range of 15 miles (24 km).
Credits: NASA/Goddard/University of Arizona



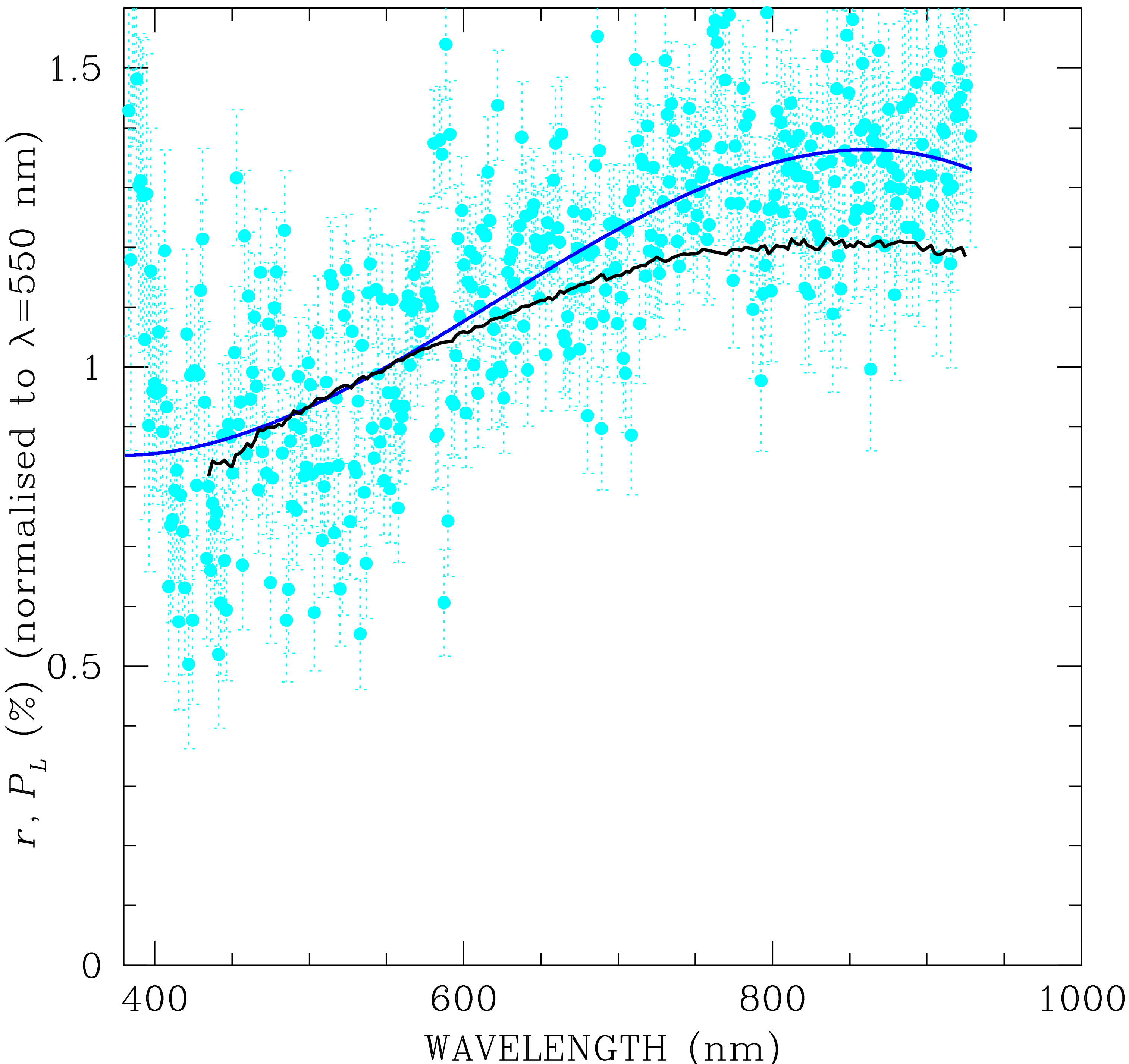
A new field:
spectropolarimetry of scattering surfaces



Xe
B
Cb
X
D
Ch
C
Xc
Xk
T
Cgh
Cg
K
L
Ld
Sk
S
Sl
Sq
Sa
Sr
O
Q
A
V
R



(433) EROS (S-type)



Violation of the Umov law!

Bagnulo et al. (2015)

(236) HONORIA (L-type)

Spectropolarimetry of atmosphere-less bodies is trying to tell us something (but we do not know yet exactly what)

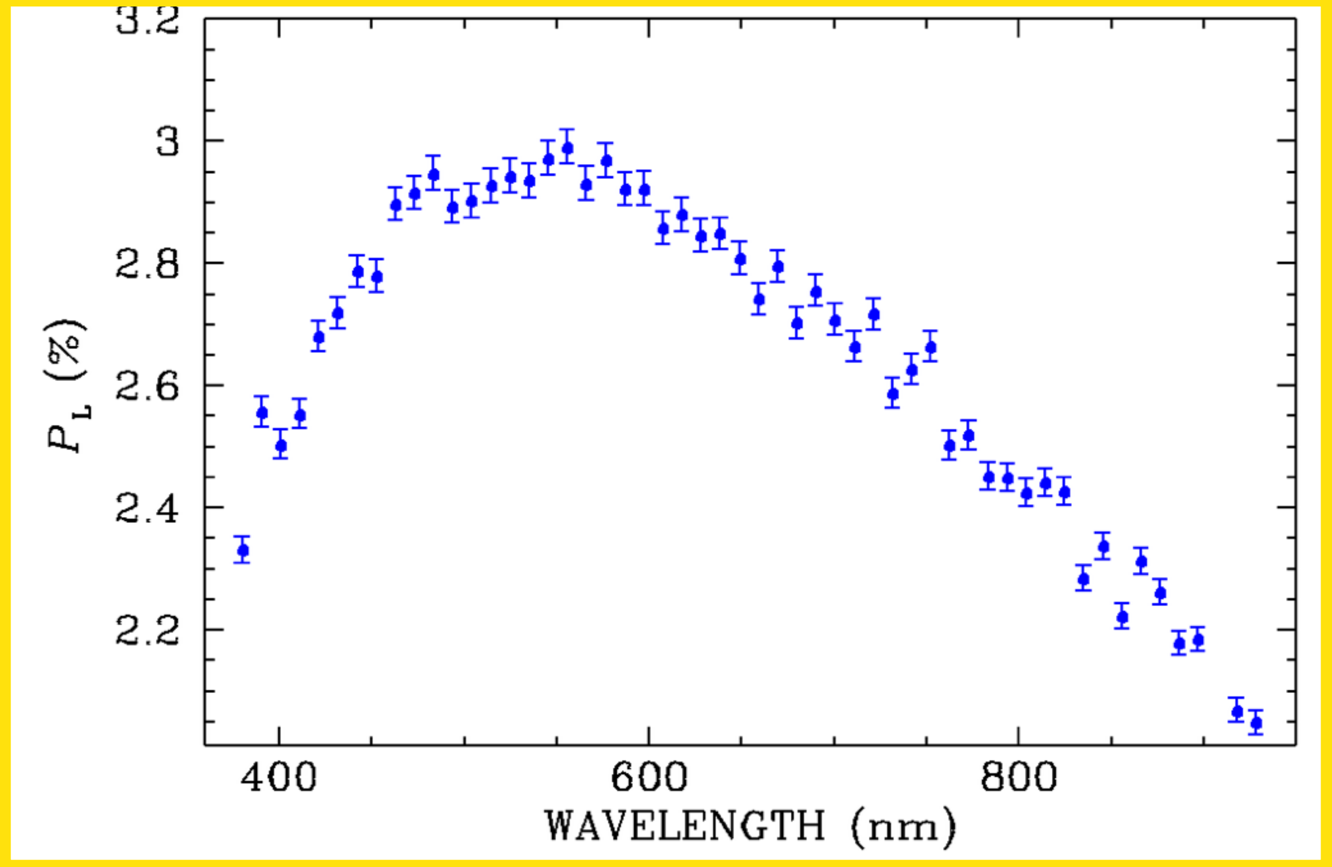
It provides constraints that cannot longer be ignored

Polarisation is produced also when light is scattered by dust even in transmission

- The component of the electric field along the elongated dust grain is absorbed, and optical light is polarised in the direction perpendicular to the long axis of the dust grain

- At longer wavelengths, emitted light is polarised in the direction parallel to it

Exploring the ISM

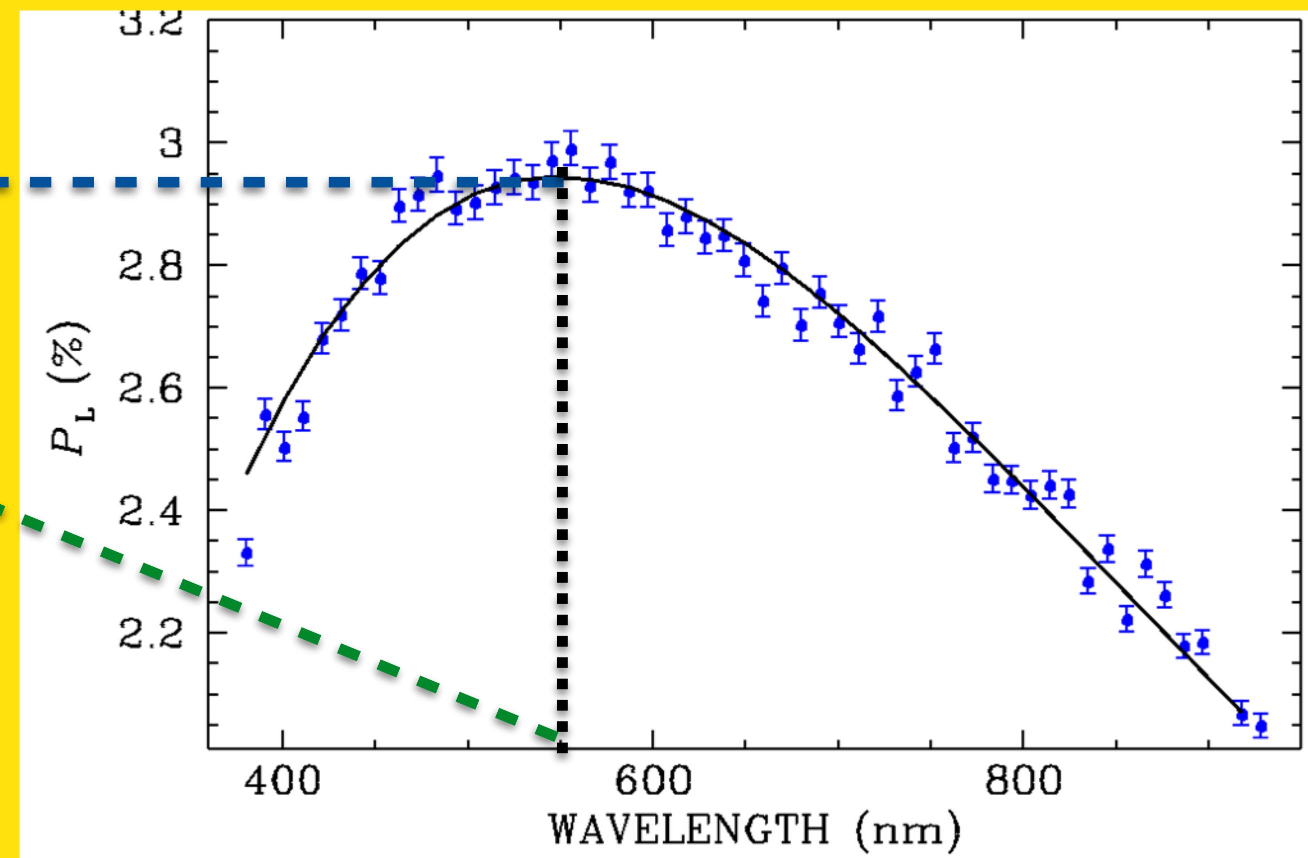


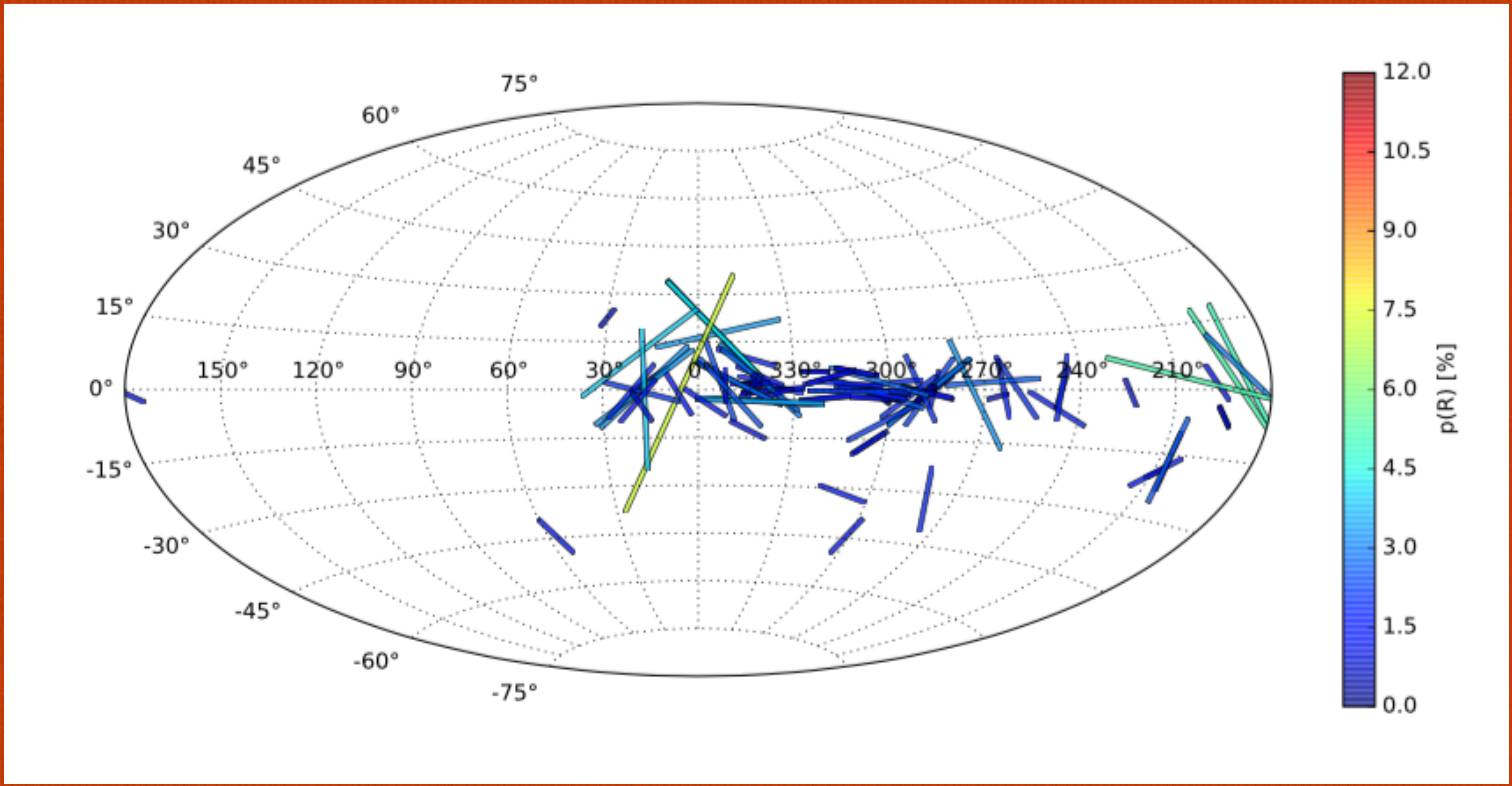
Bagnulo et al. (2018)

Exploring the ISM

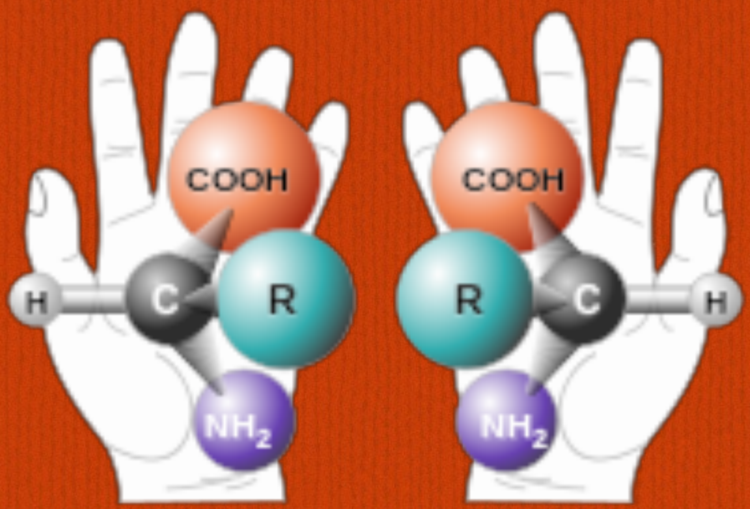
$$P(\lambda) = P_{\max} \, \exp\left[-K \ln^2 \left(\frac{\lambda_{\max}}{\lambda}\right)\right]$$

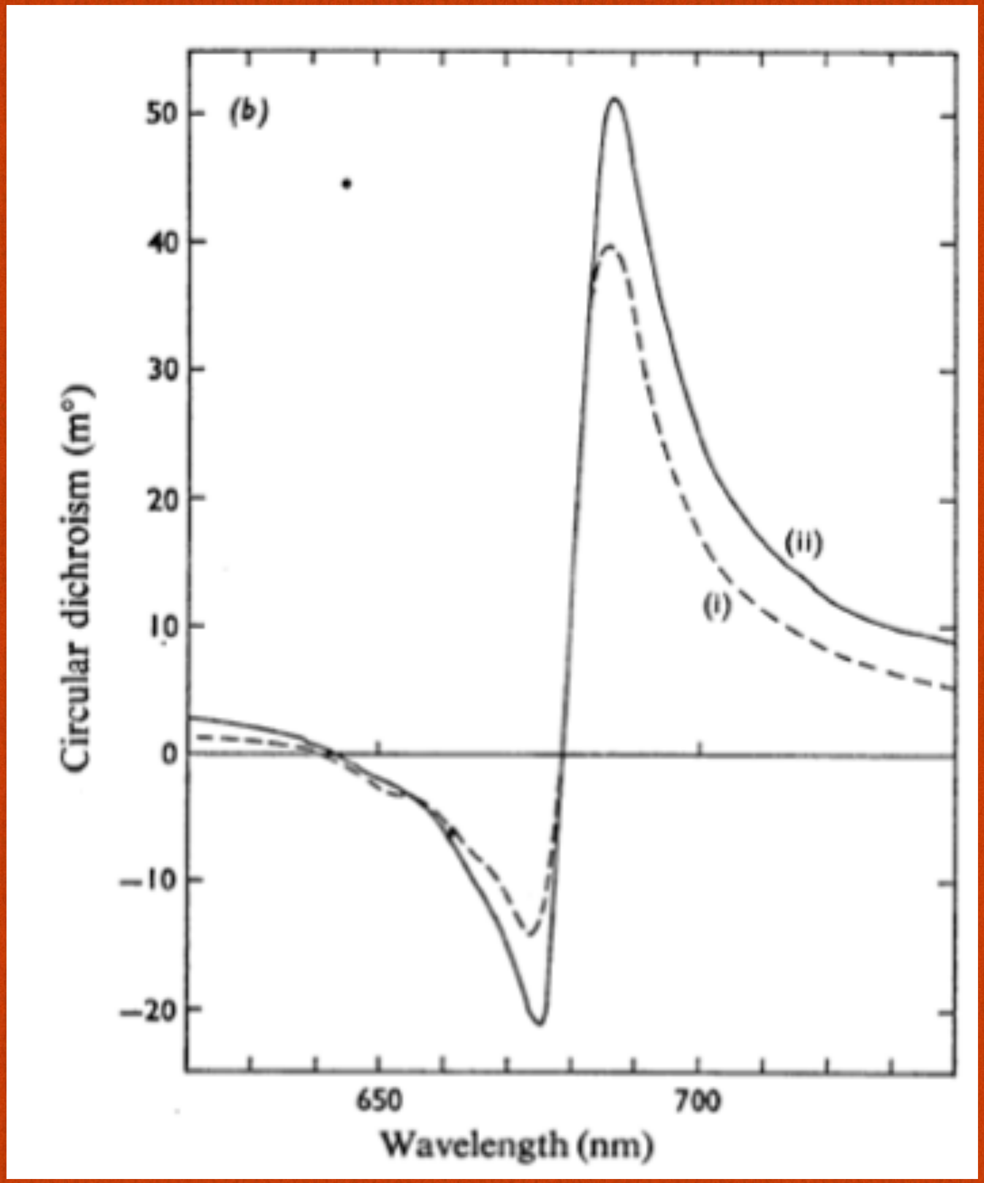
Serkowski law




75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0
p(R) [%]

Can polarimetry help us to find extra-terrestrial life?

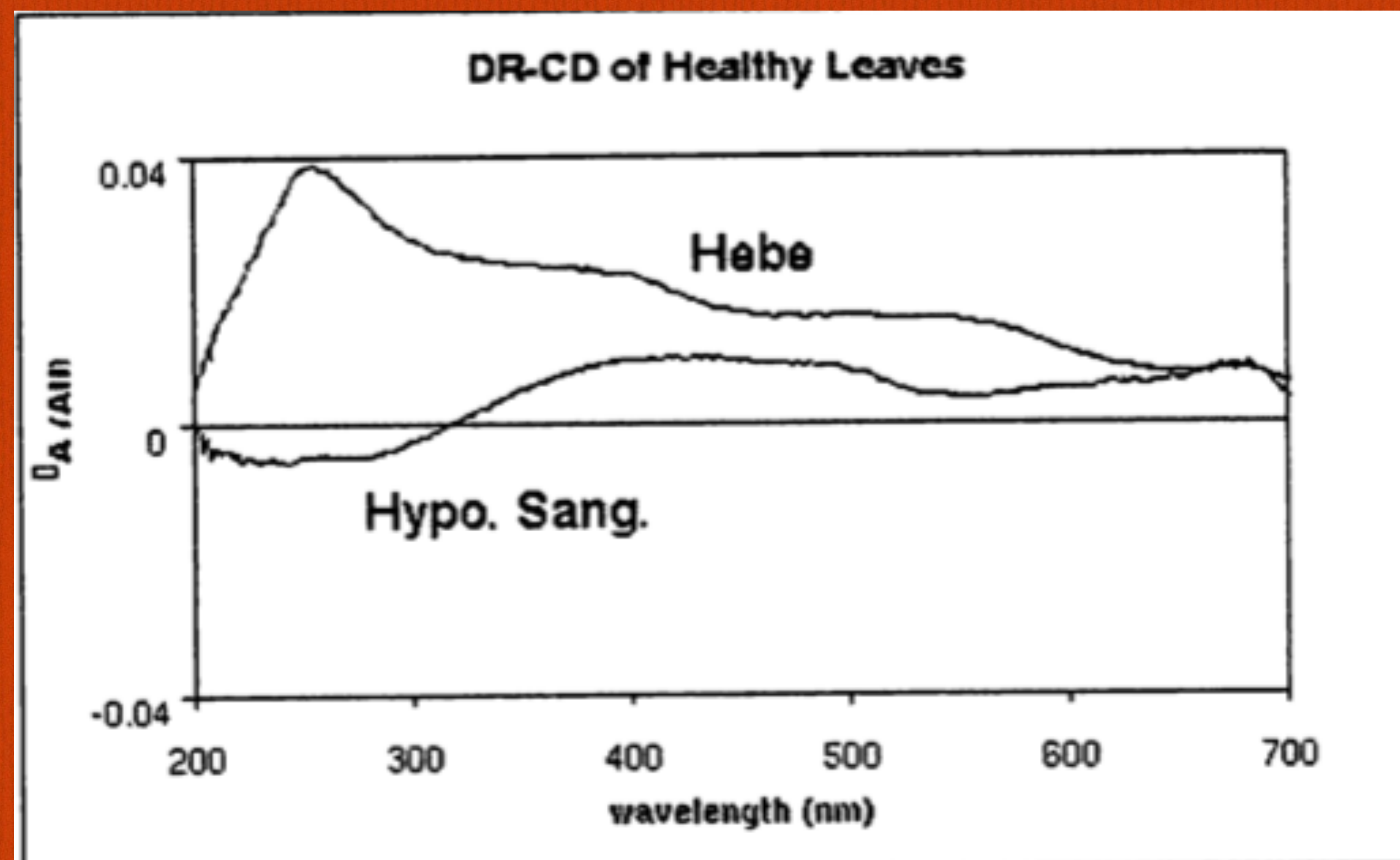




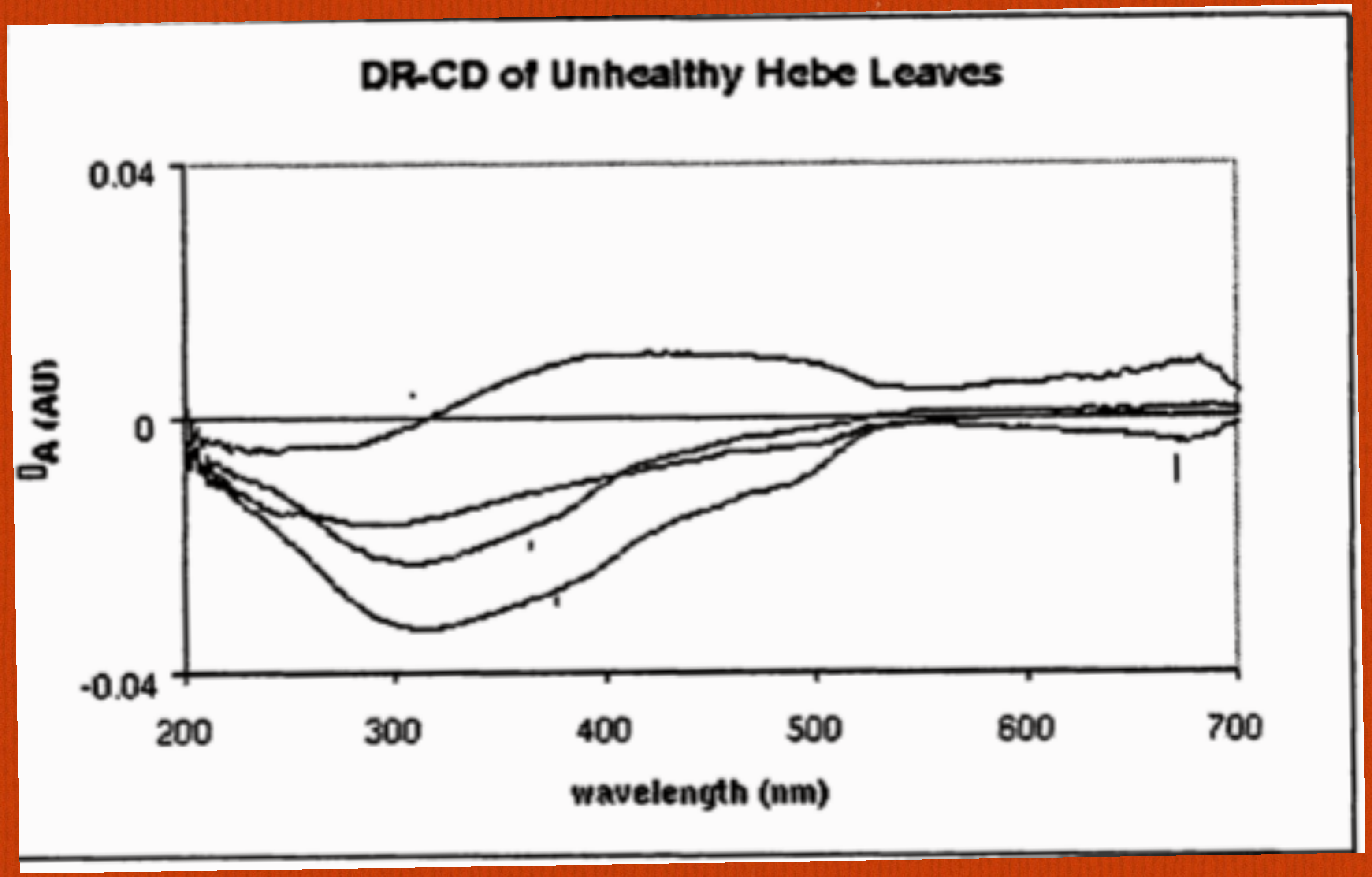
Gregory & Raps (1974)

S. Bagnulo 12 March 2019

Wolstencroft et al. (2004)

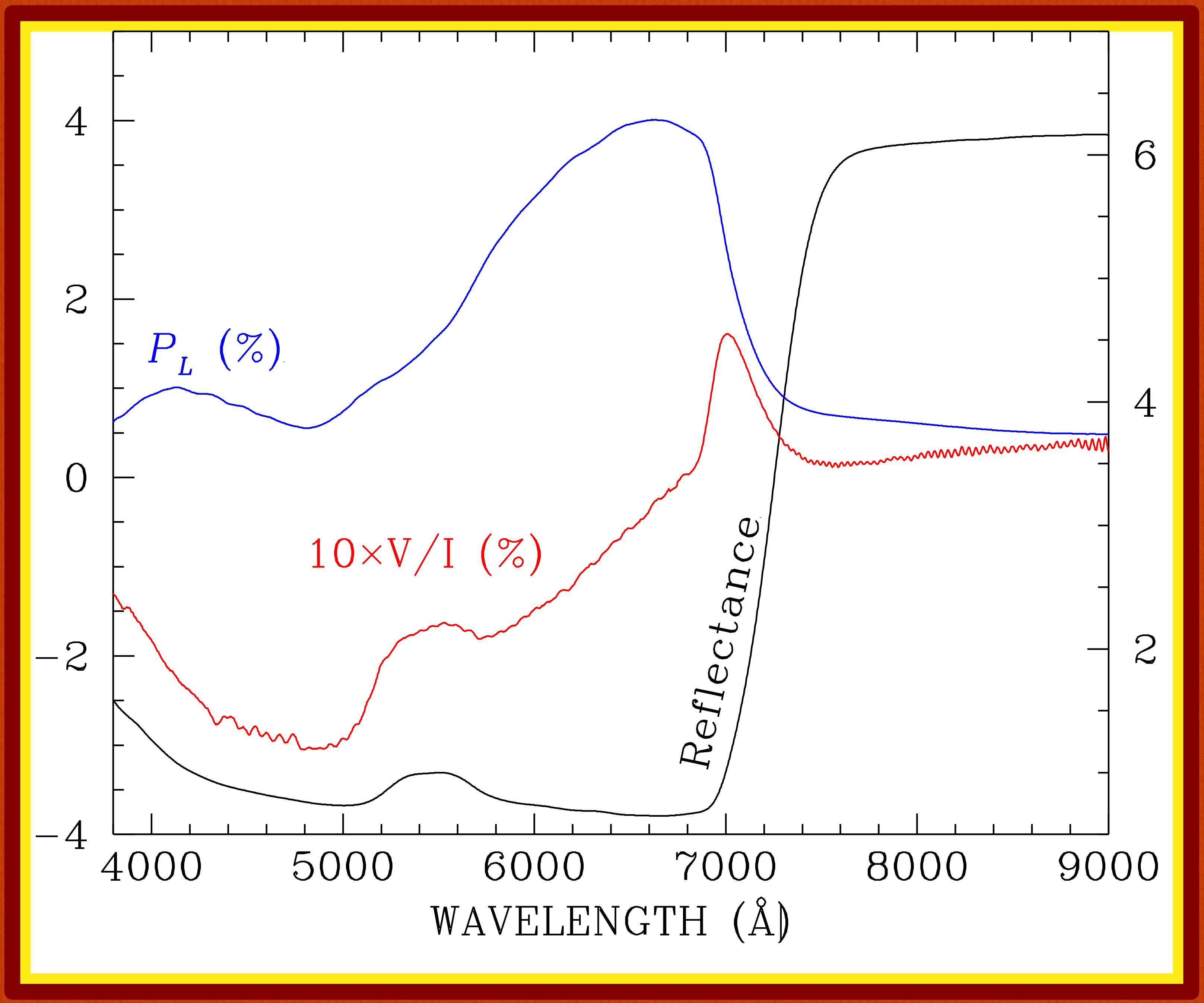


Wolstencroft et al. (2004)



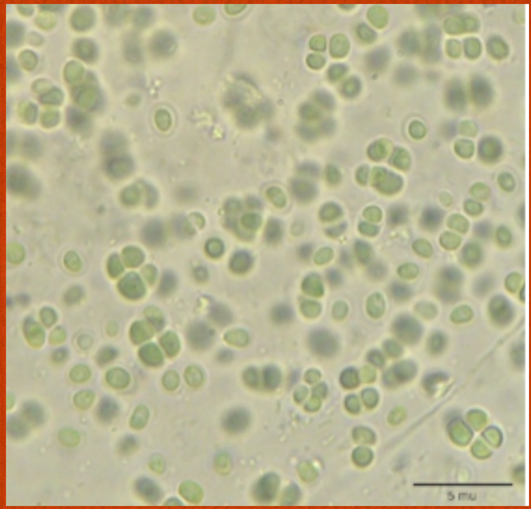

FONDO DE PROTECCION AMBIENTAL 2008
AQUI SE EJECUTA EL PROYECTO DE ESTUDIO:
Biodiversidad del Salar de Llamara
FINANCIAMIENTO CONAMA $ 9.000.000
OBJETIVO: Desarrollar una línea base sobre biodiversidad de la flora y fauna terrestre y acuática del Salar de Llamara. Esto permitirá tener las bases para proponer este lugar como Sitio Prioritario para la Conservación de la Biodiversidad y como sitio de interés turístico.
ORGANISMO EJECUTOR
Universidad Arturo Prat
ORGANISMOS ASOCIADOS
Universidad Católica del Norte
Universidad Austral de Chile
Civet Adventure
Sernatur
SQM S.A.
Fuerza Aérea de Chile

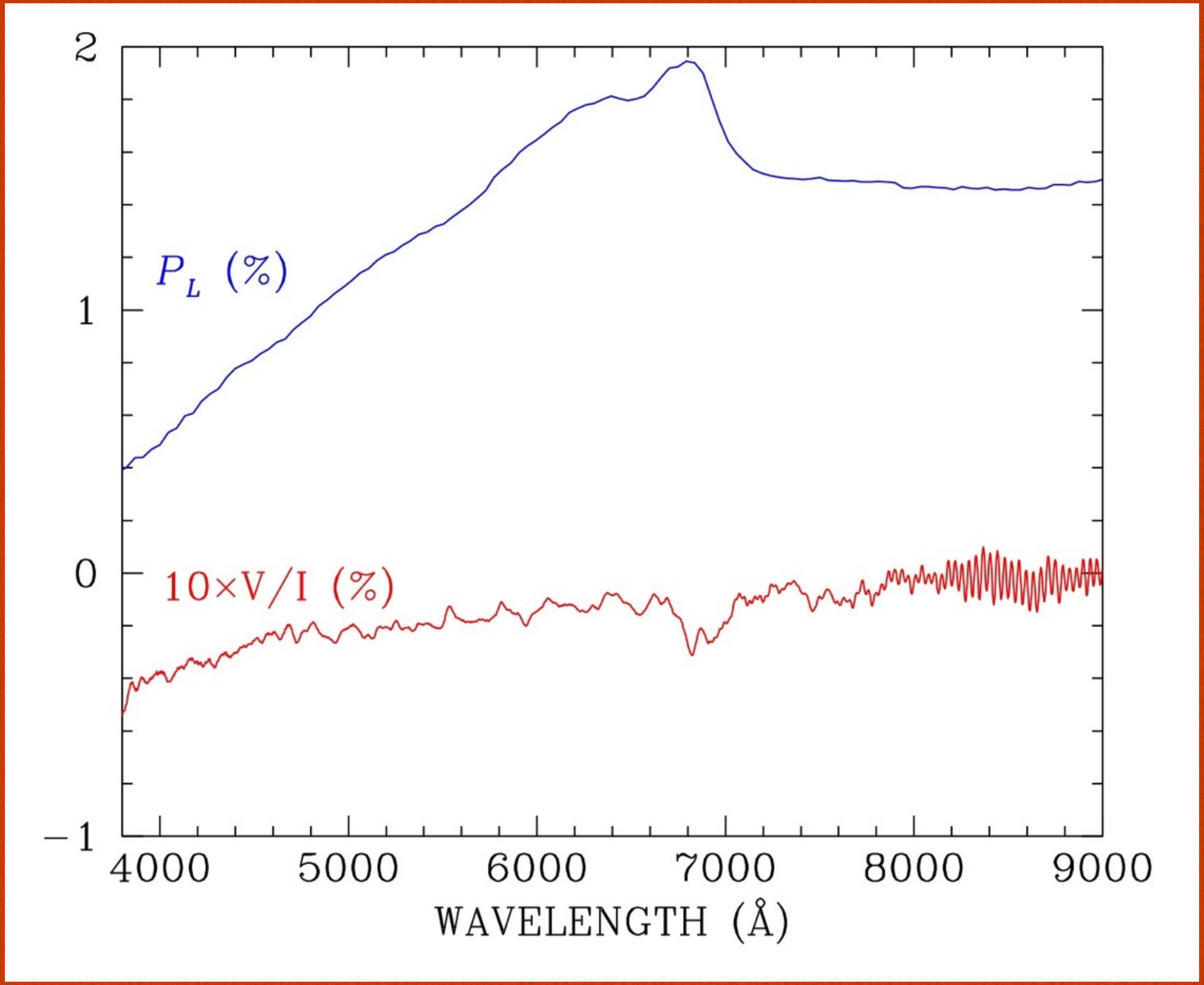
Philodendron

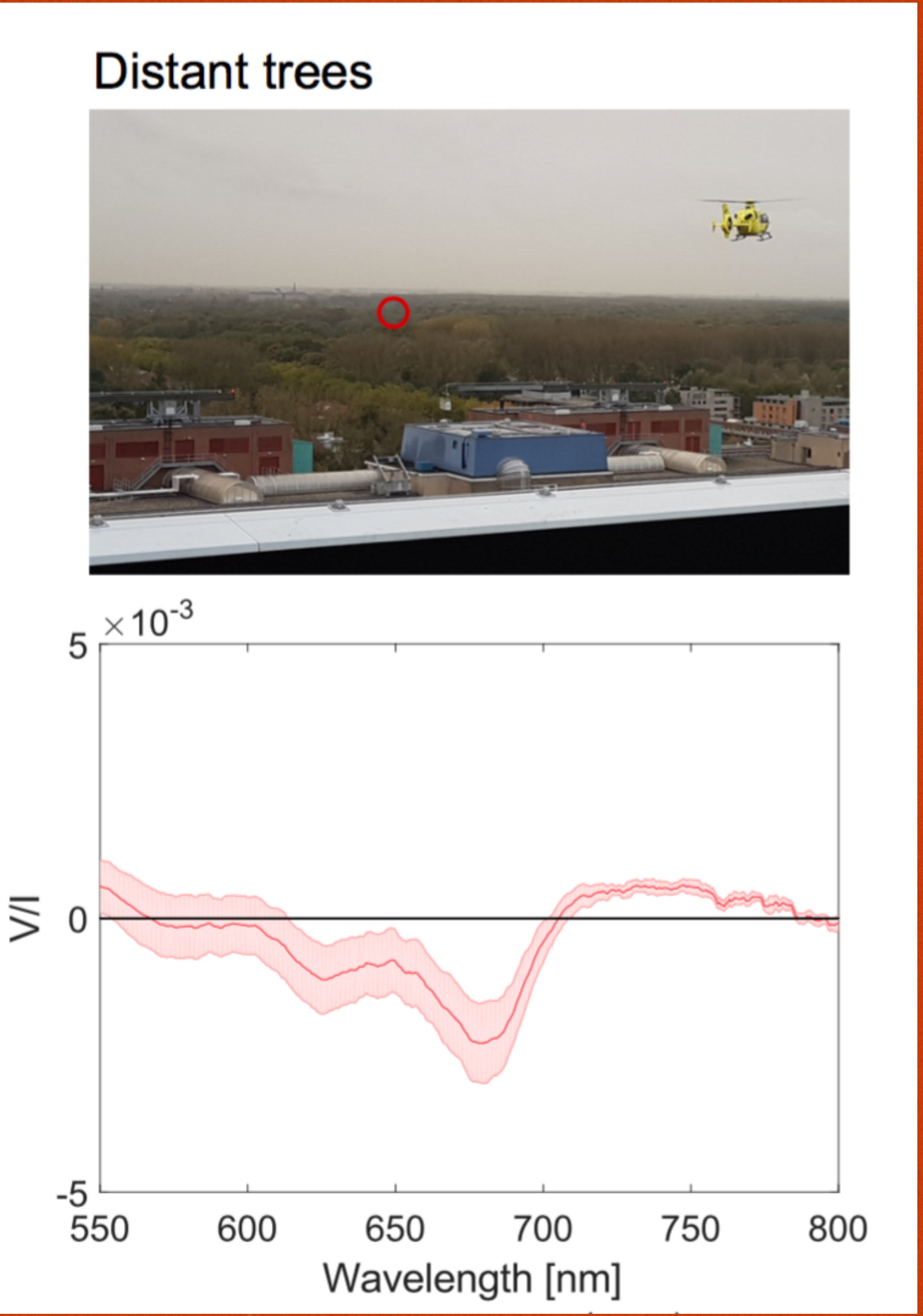


Sterzik et al. (2010) Bagnulo et al. (2015)

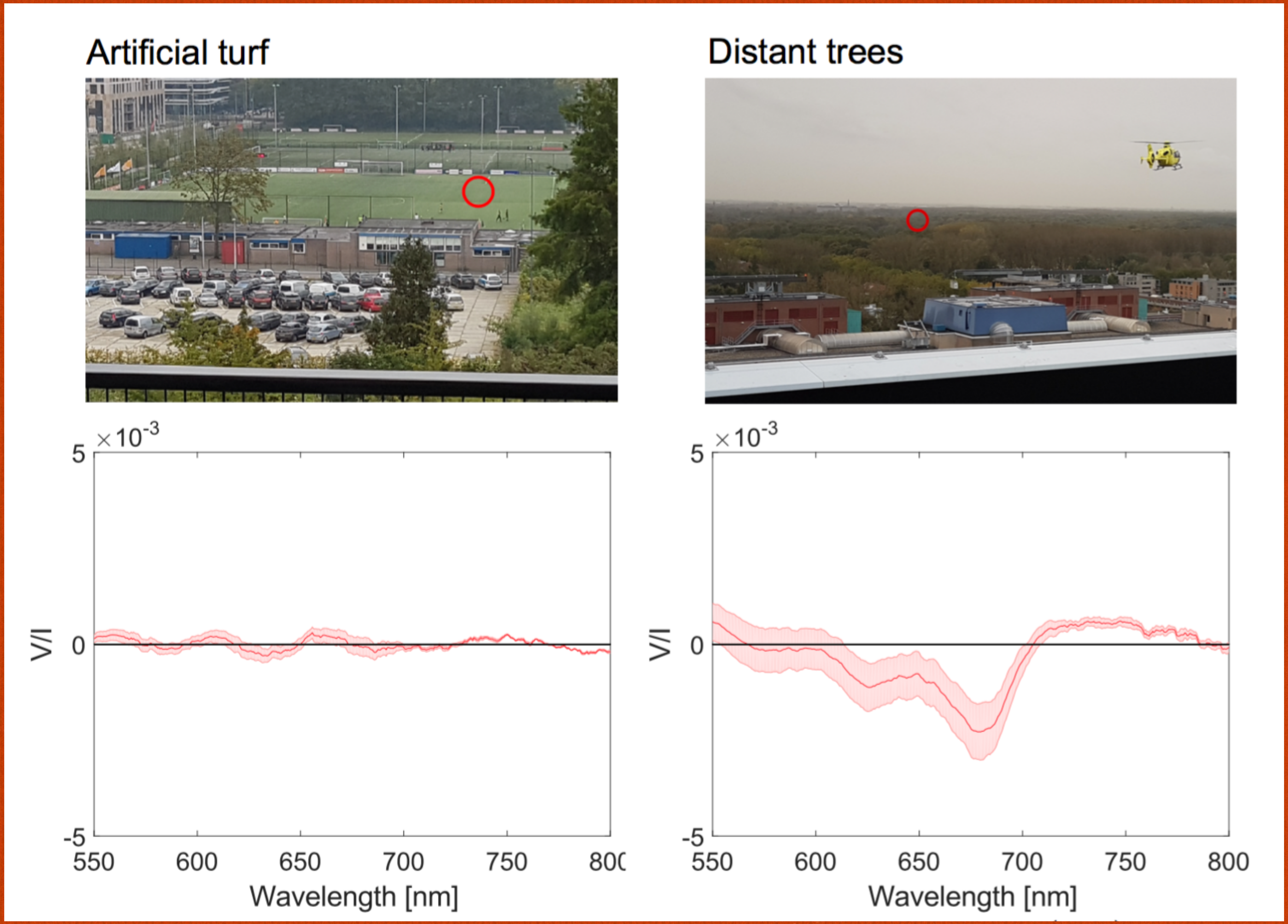
Chrooccoccidiopsis







Lucas Patty et al. (2019)



Lucas Patty et al. (2019)

SEARCH FOR CHIRAL SIGNATURES ON MARS 743

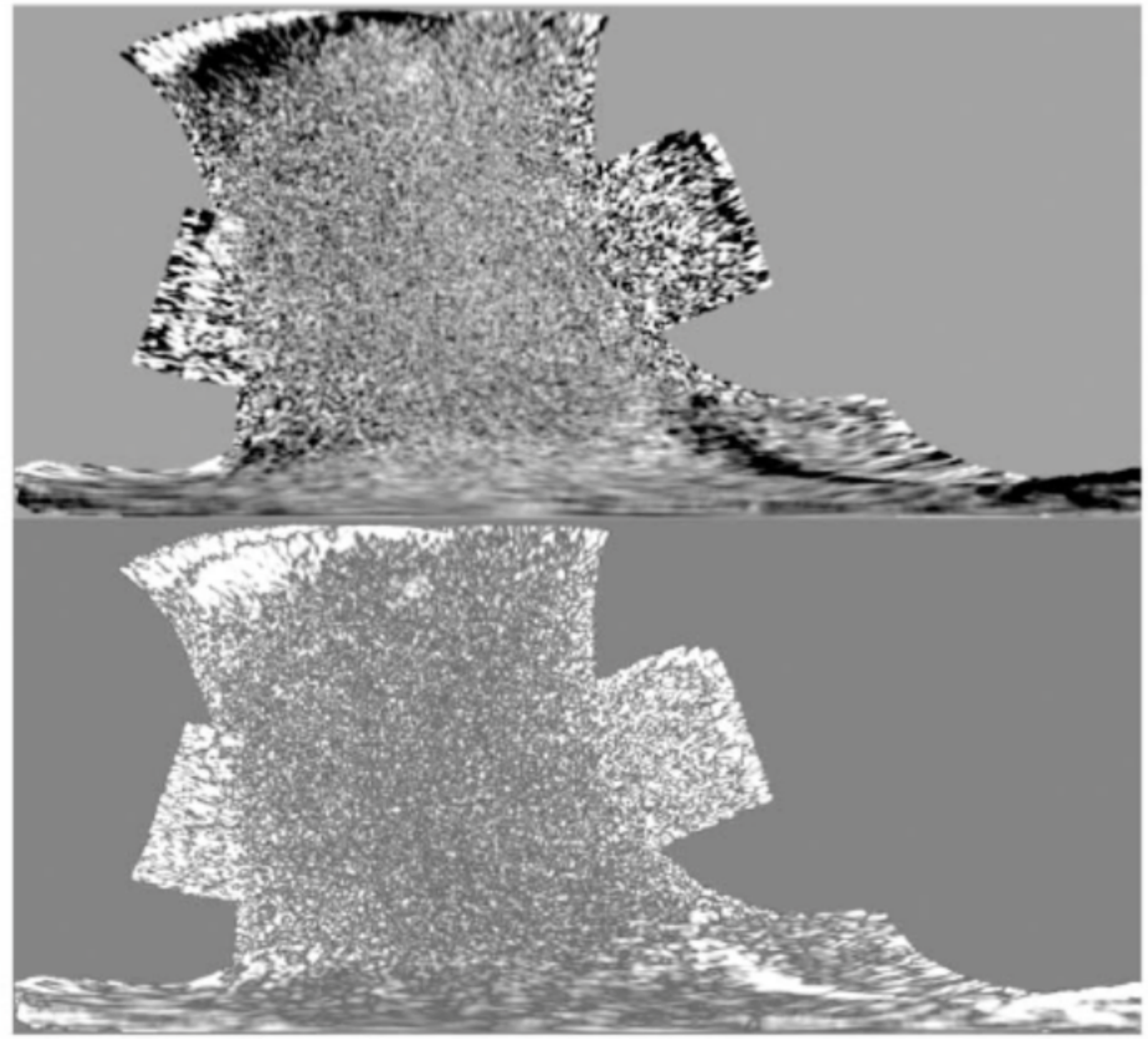
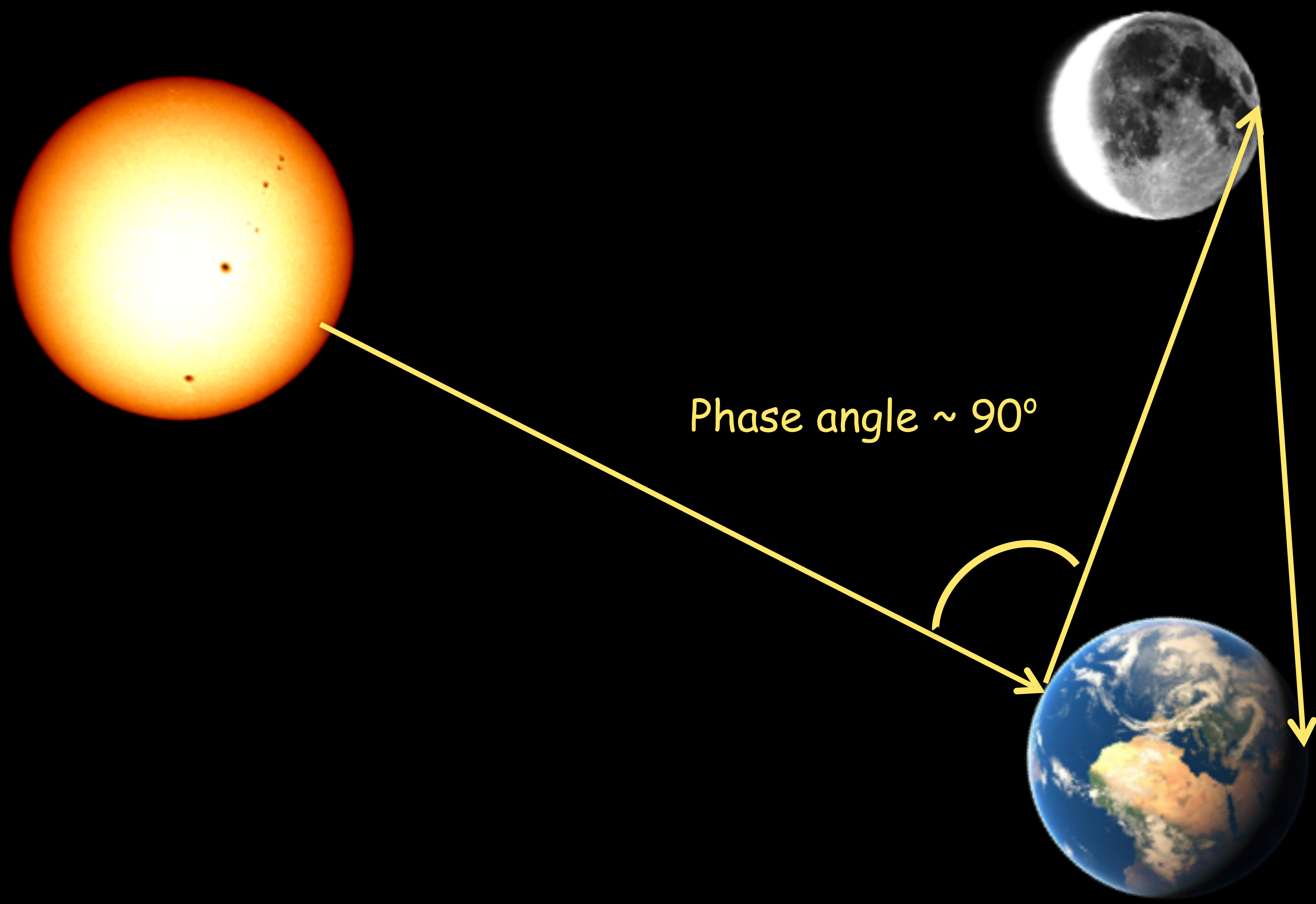
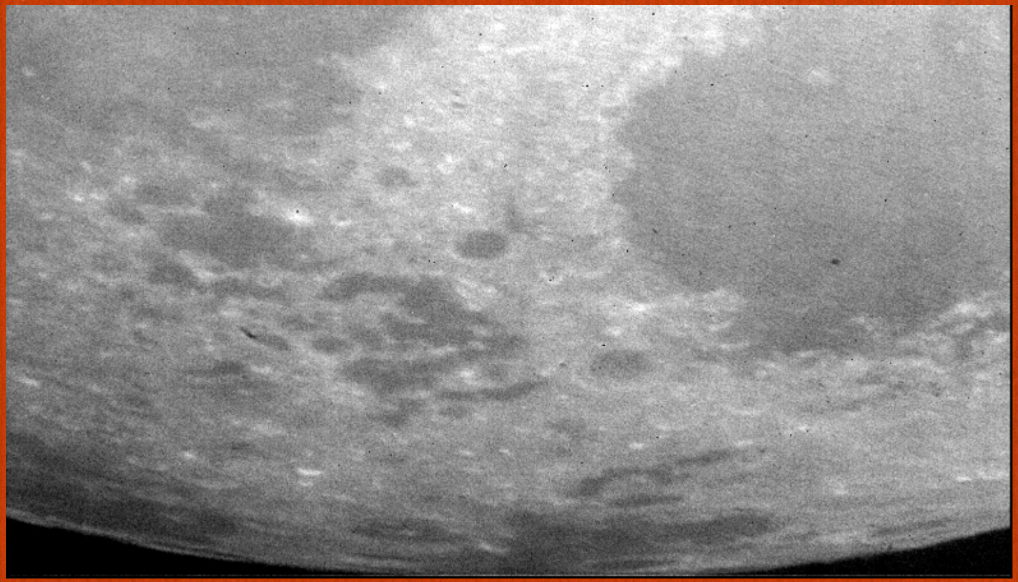


FIG. 4. Images of circular polarization: Blue data. Average blue Stokes-v images were smoothed with Gaussian $\sigma_G = 1.0$ pixels displayed $\pm 3.5\sigma$. The upper image is the Stokes-v image, and the lower, its zero-point adjusted absolute value. The data are displayed from polarization degree -0.003 (black) to 0.0023 (white) and -0.001 to 0.0022 (**upper and lower panels**, respectively), with the global mean of 3.52×10^{-4} added to the image of absolute value. (The patch center top is due to imperfect cancellation of artifacts in a region of steep intensity gradients.)

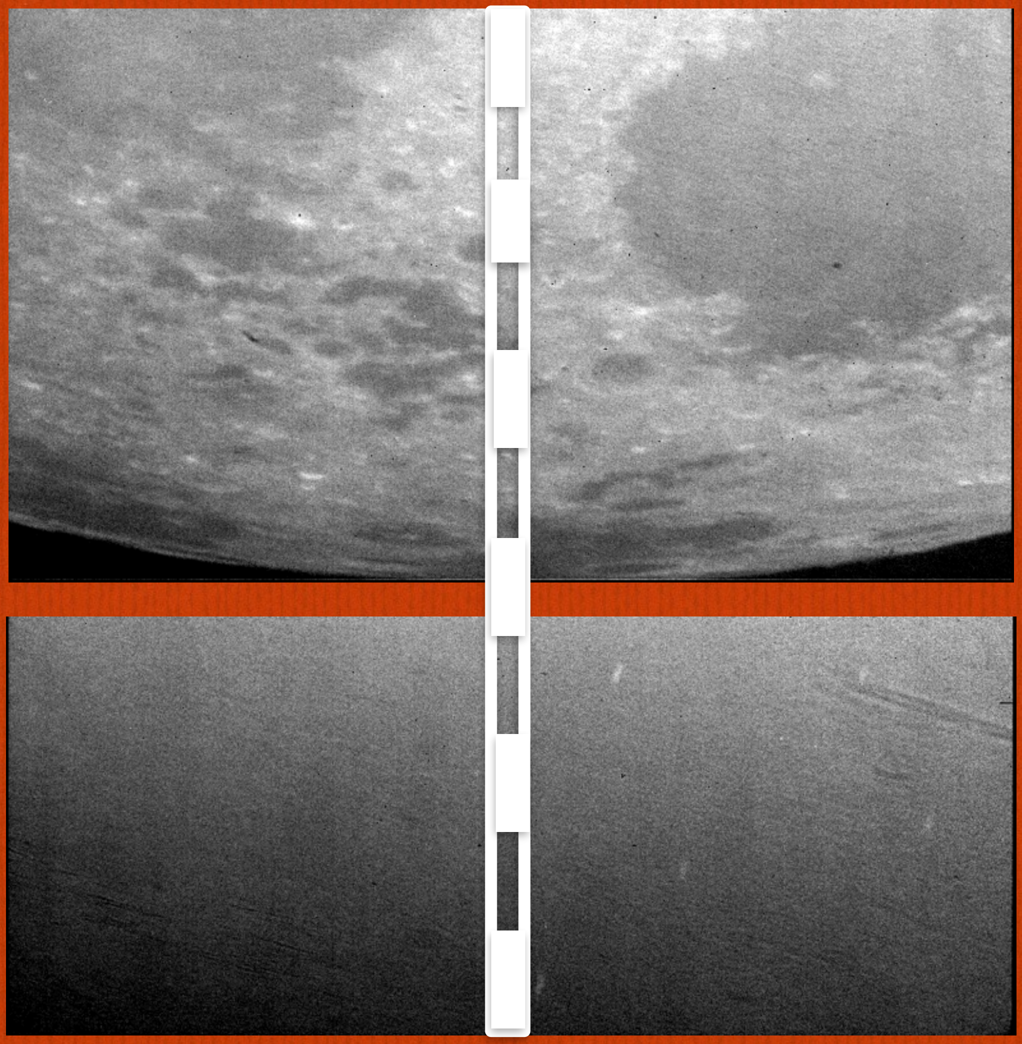
Sparks et al. (2005) failed to detect circular polarisation on the surface of Mars (V/I<0.1%)

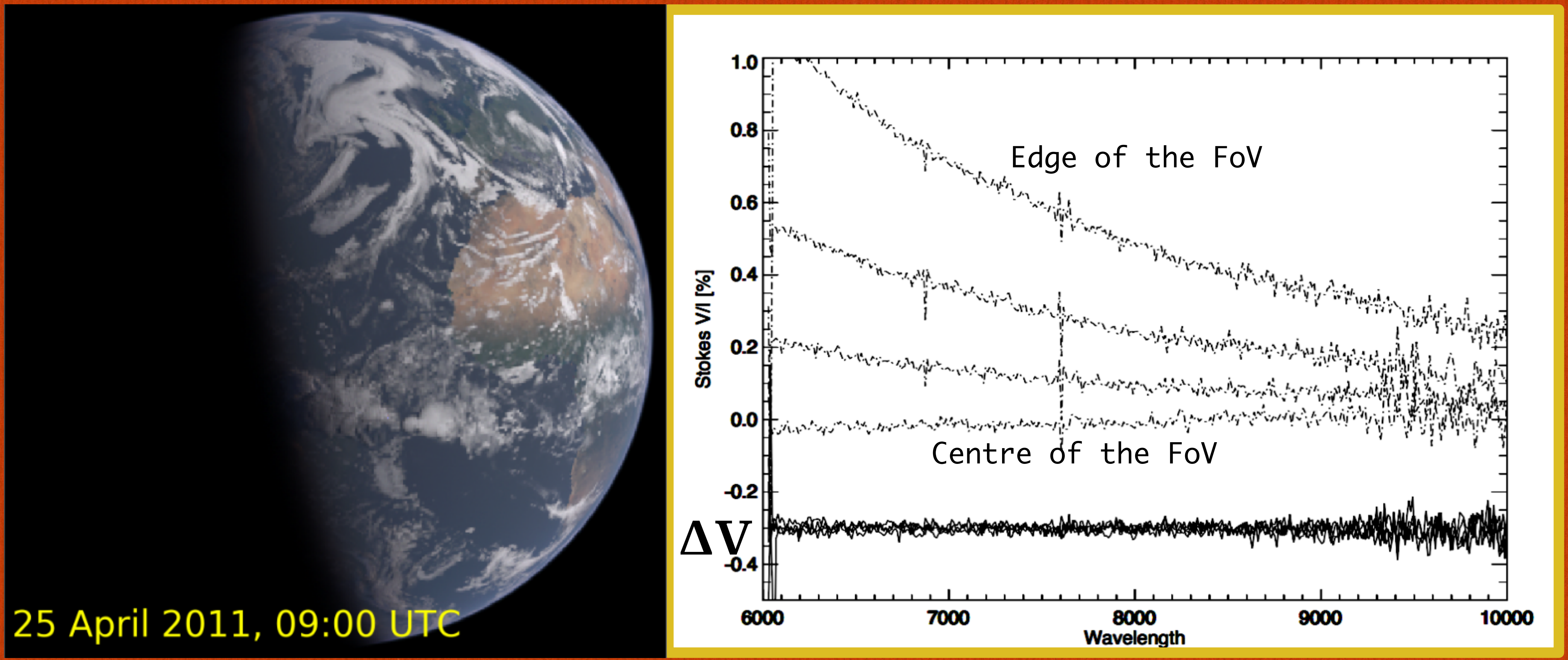

Phase angle ~ 90°


25 April 2011, 09:00 UTC



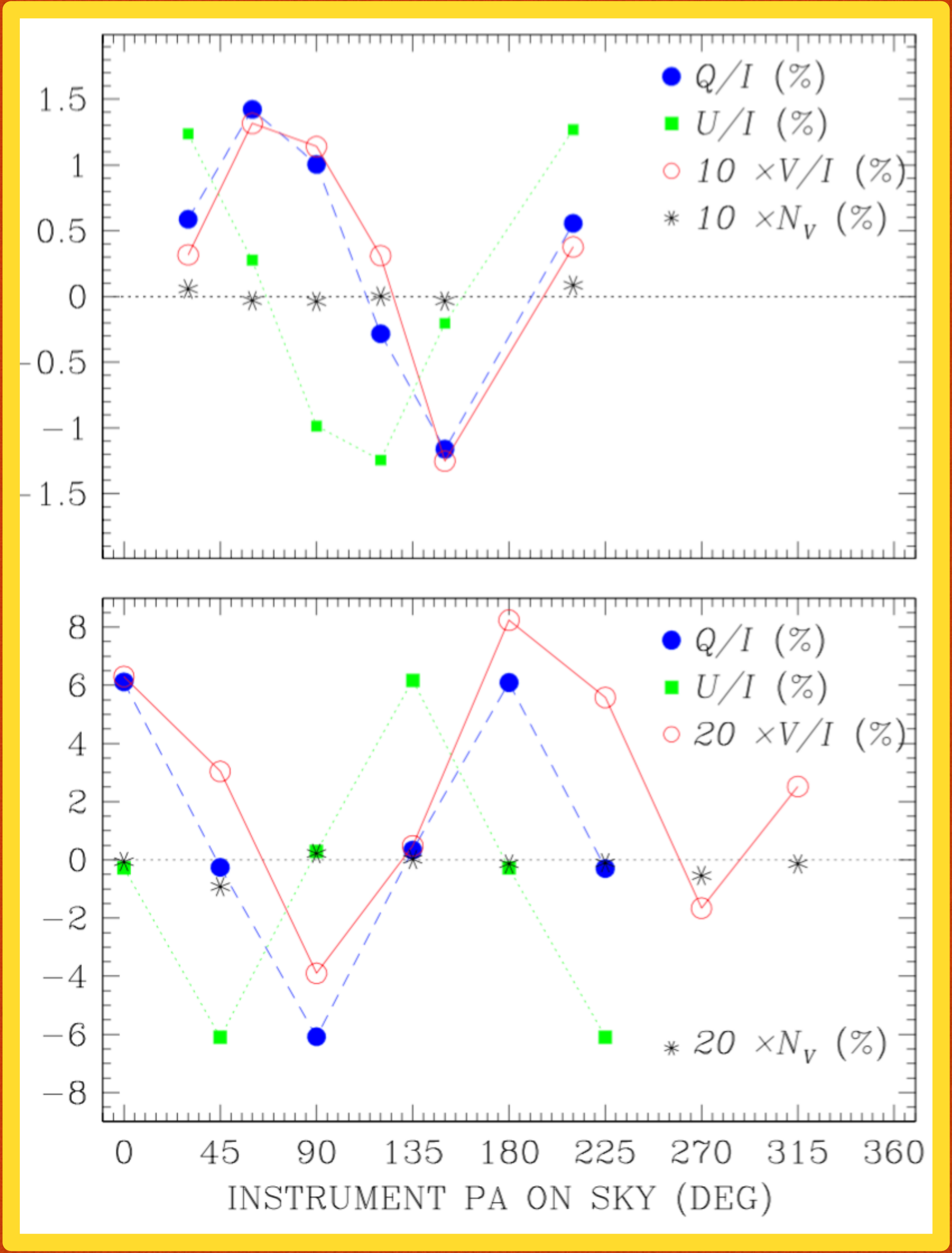

25 April 2011, 09:00 UTC





25 April 2011, 09:00 UTC
Edge of the FoV
Centre of the FoV
ΔV
Stokes V/I [%]
Wavelength
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
6000
7000
8000
9000
10000

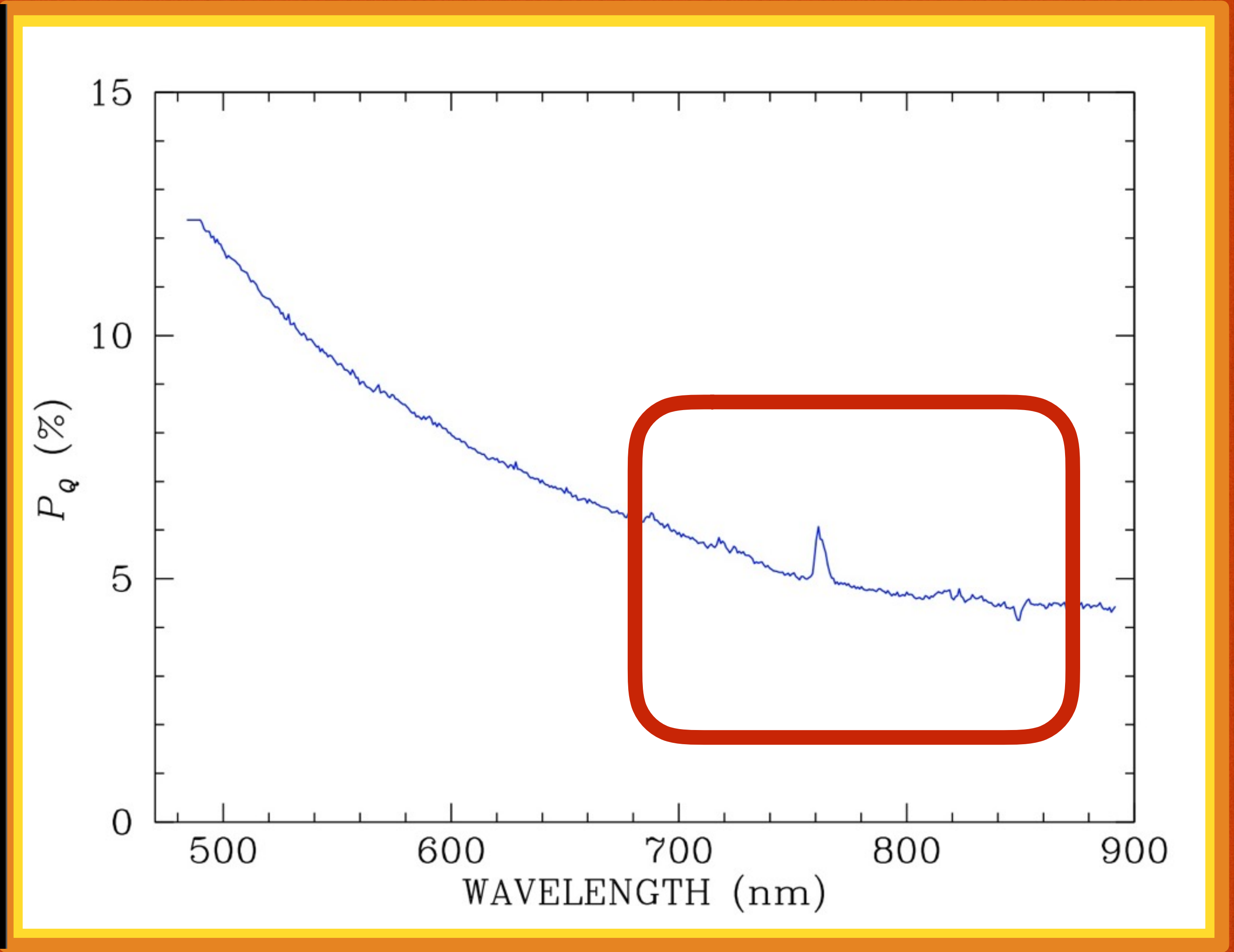
$$
\begin{aligned}
P'_Q &= \cos(2\chi)\,P_Q + \sin(2\chi)\,P_U \\
P'_U &= -\sin(2\chi)\,P_Q + \cos(2\chi)\,P_U \\
P'_V &= P_V\ .
\end{aligned}
$$

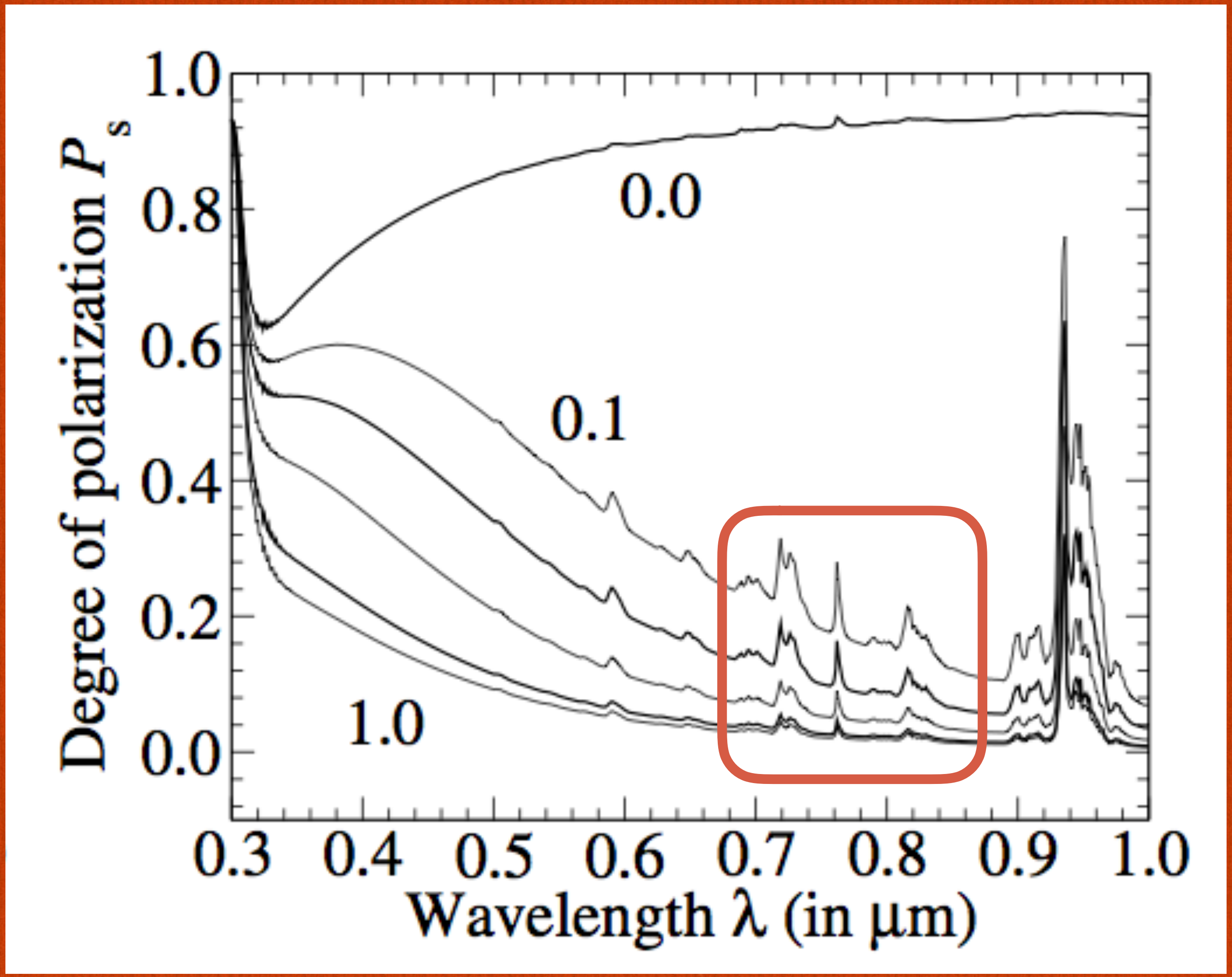


SR collimator

HR collimator

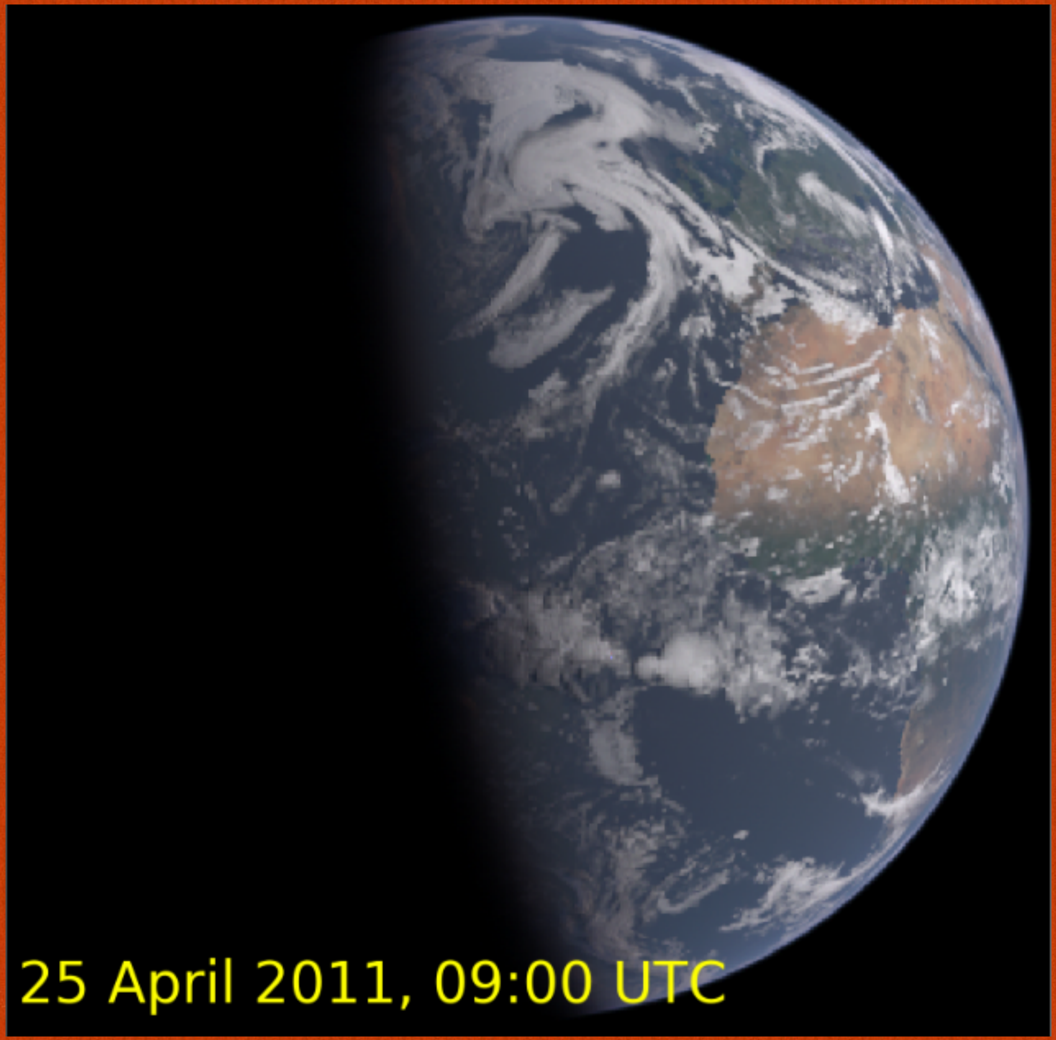

25 April 2011, 09:00 UTC

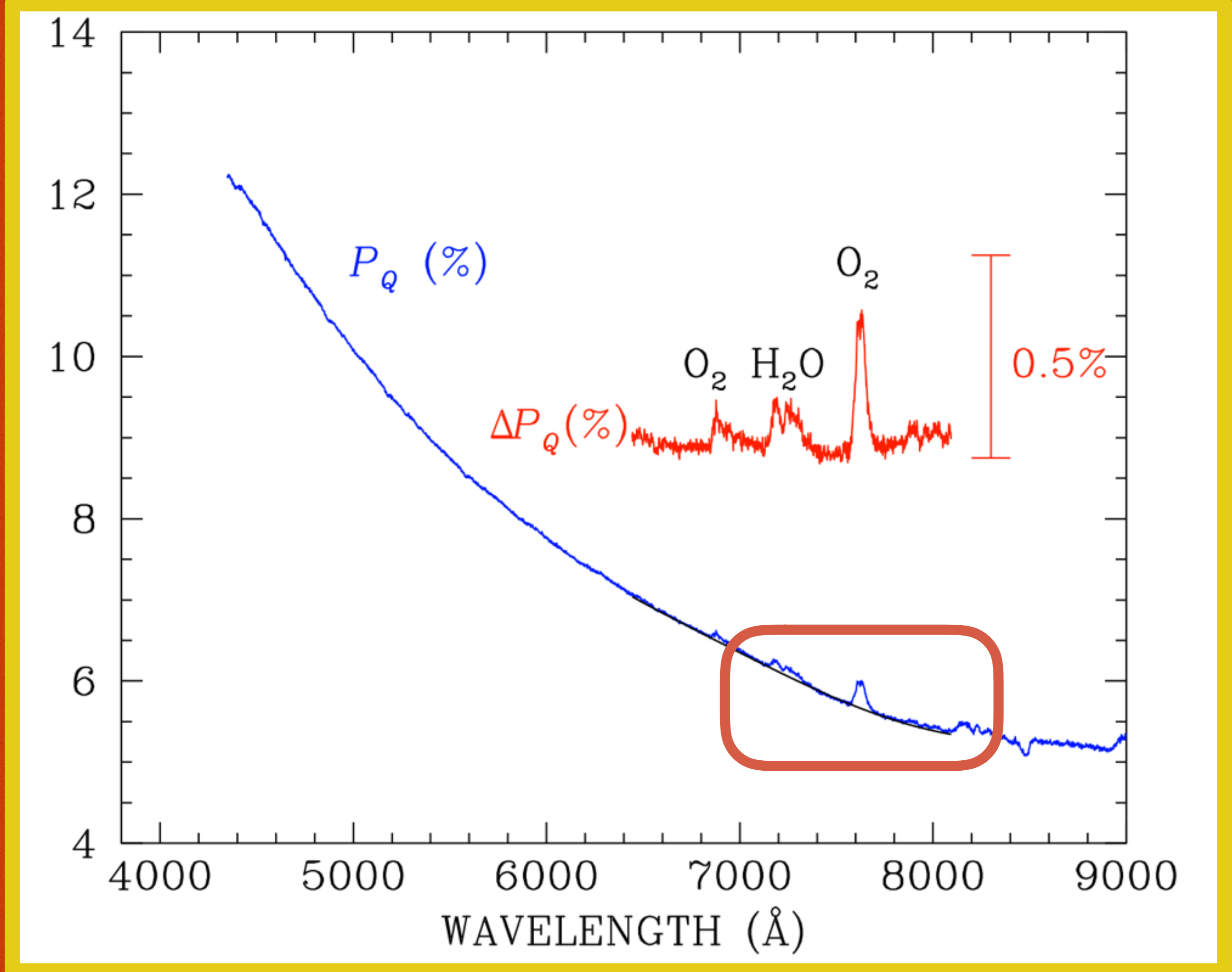

15
10
5
0
P_Q (%)
500
600
700
800
900
WAVELENGTH (nm)



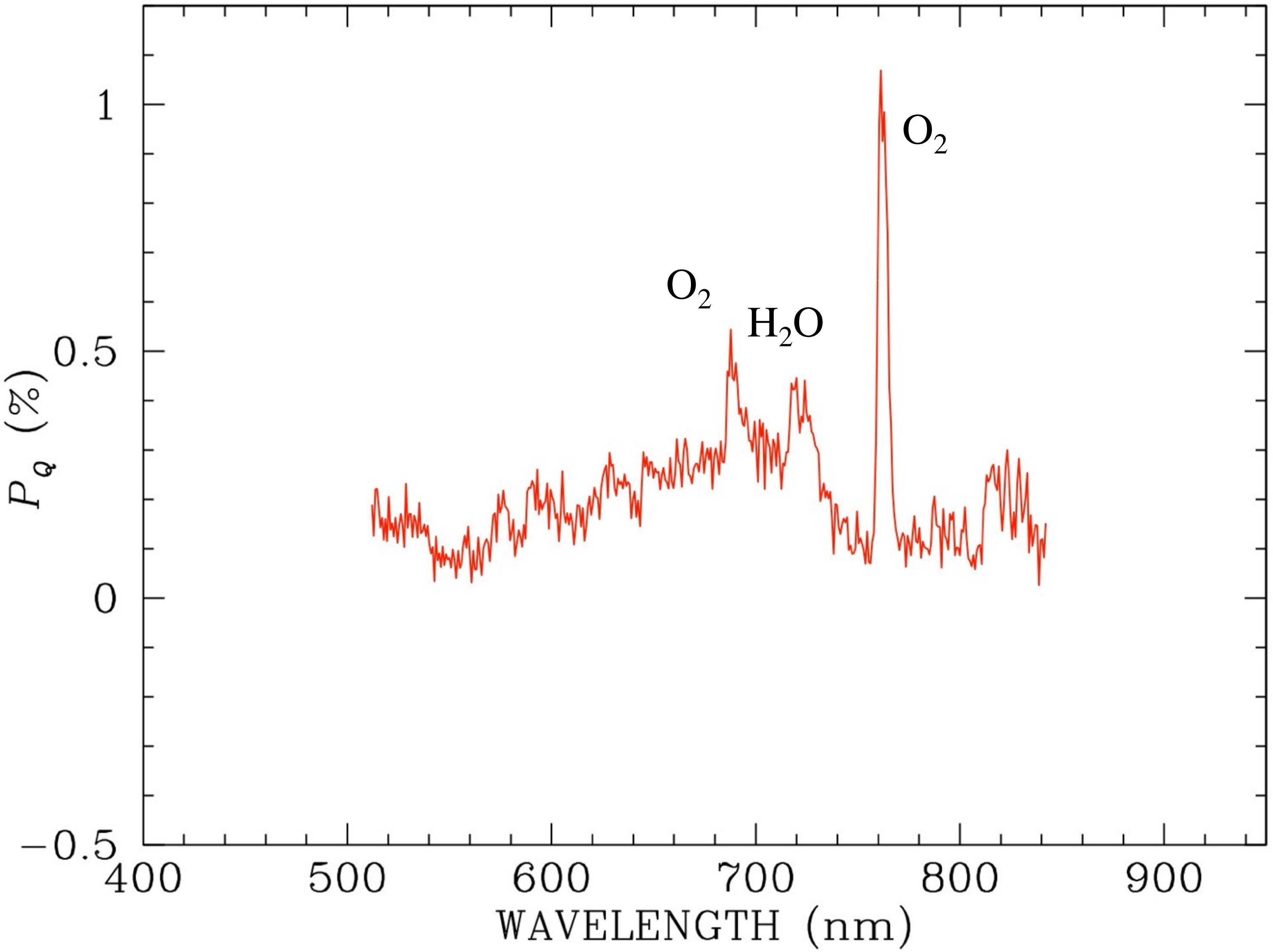
Degree of polarization P_s
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
1.0
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Wavelength λ (in μm)

Stam (2008)

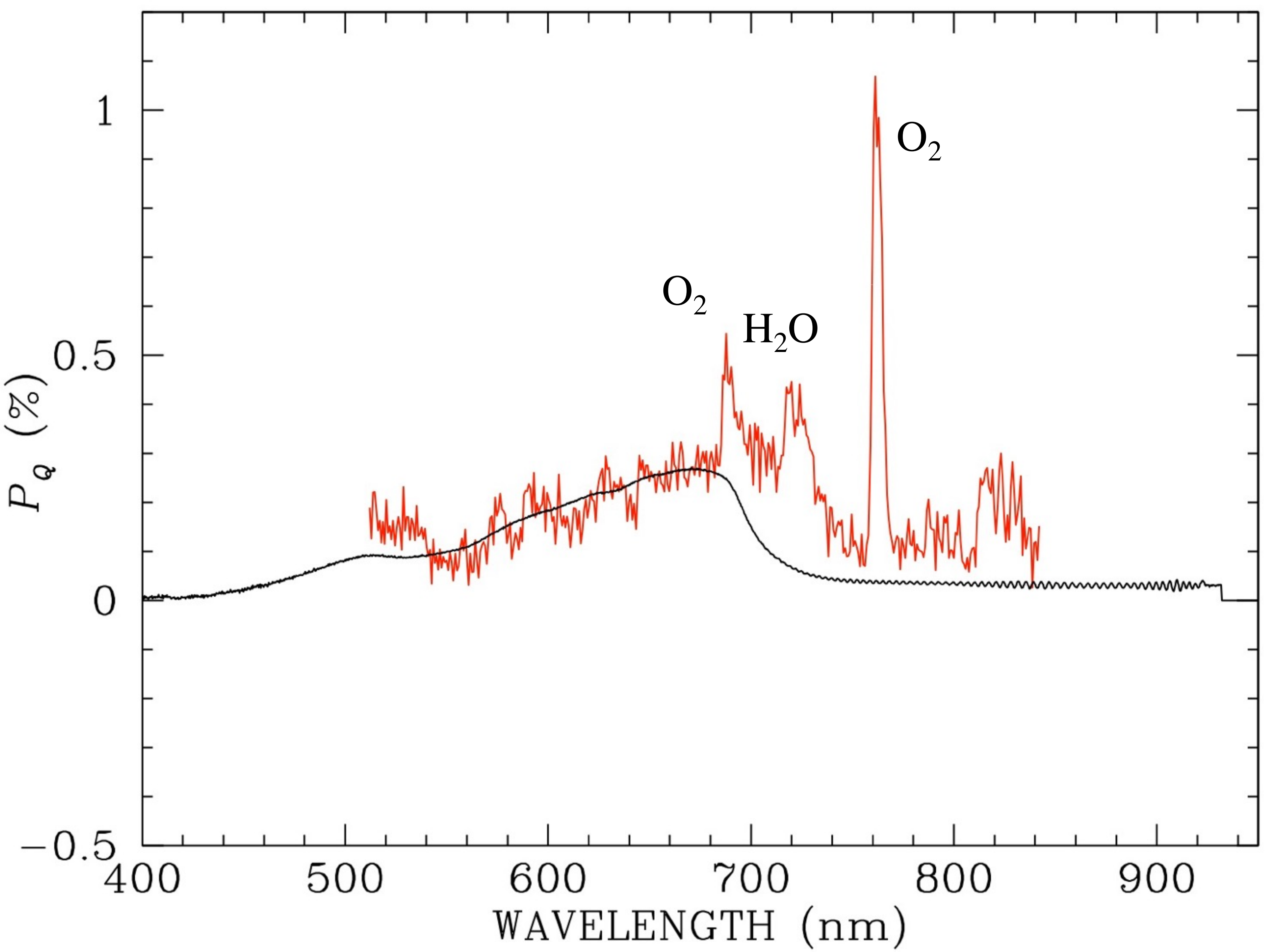




Sterzik et al. (2012)
for detailed modelling see also
Emde et al. (2017)



1
0.5
0
−0.5
P_Q (%)
O_2
O_2
H_2O
400
500
600
700
800
900
WAVELENGTH (nm)



O_2
O_2
H_2O
P_Q (%)
1
0.5
0
−0.5
400
500
600
700
800
900
WAVELENGTH (nm)