

# A Polarized Look at (Exo)Planet Atmospheres

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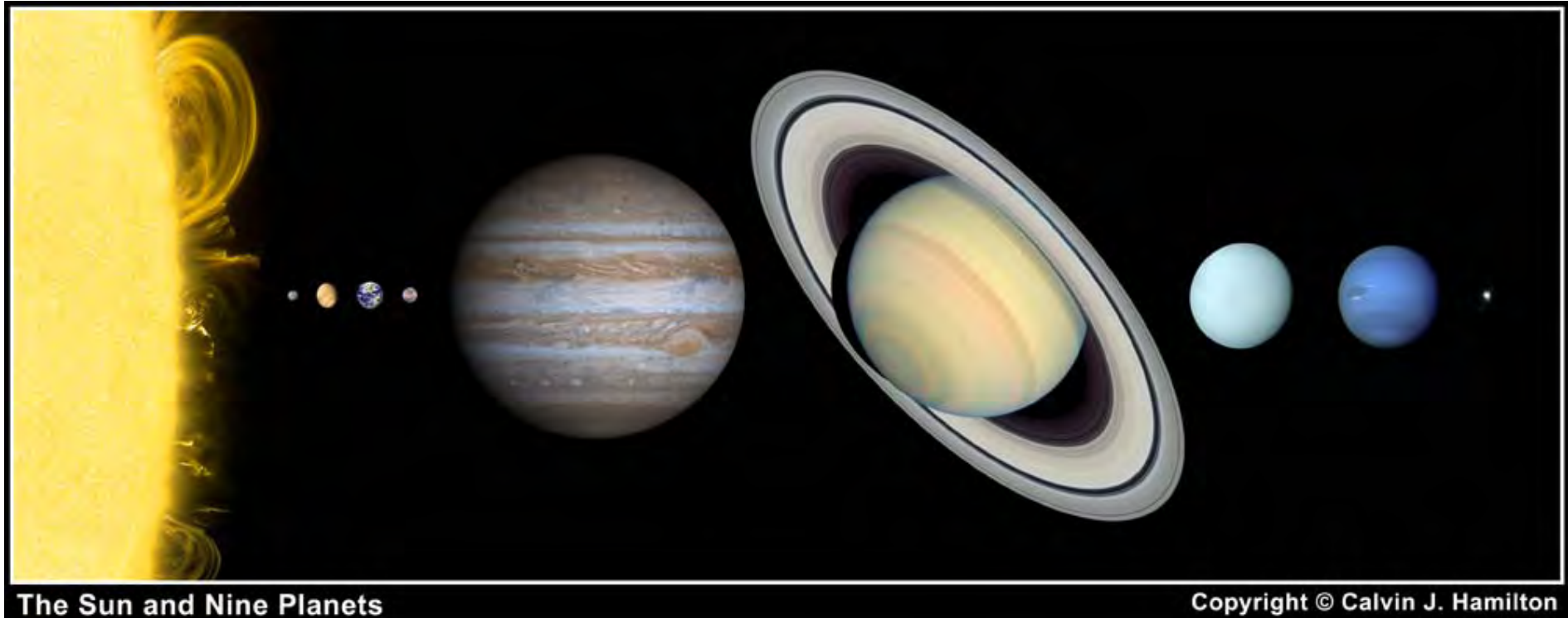


# Outline

1. Exoplanets
2. Polarized Light
3. Exoplanets in Polarized Light
4. Planet Polarimetry Instruments
5. Exoplanet Polarimetry Instruments



# Our Solar System

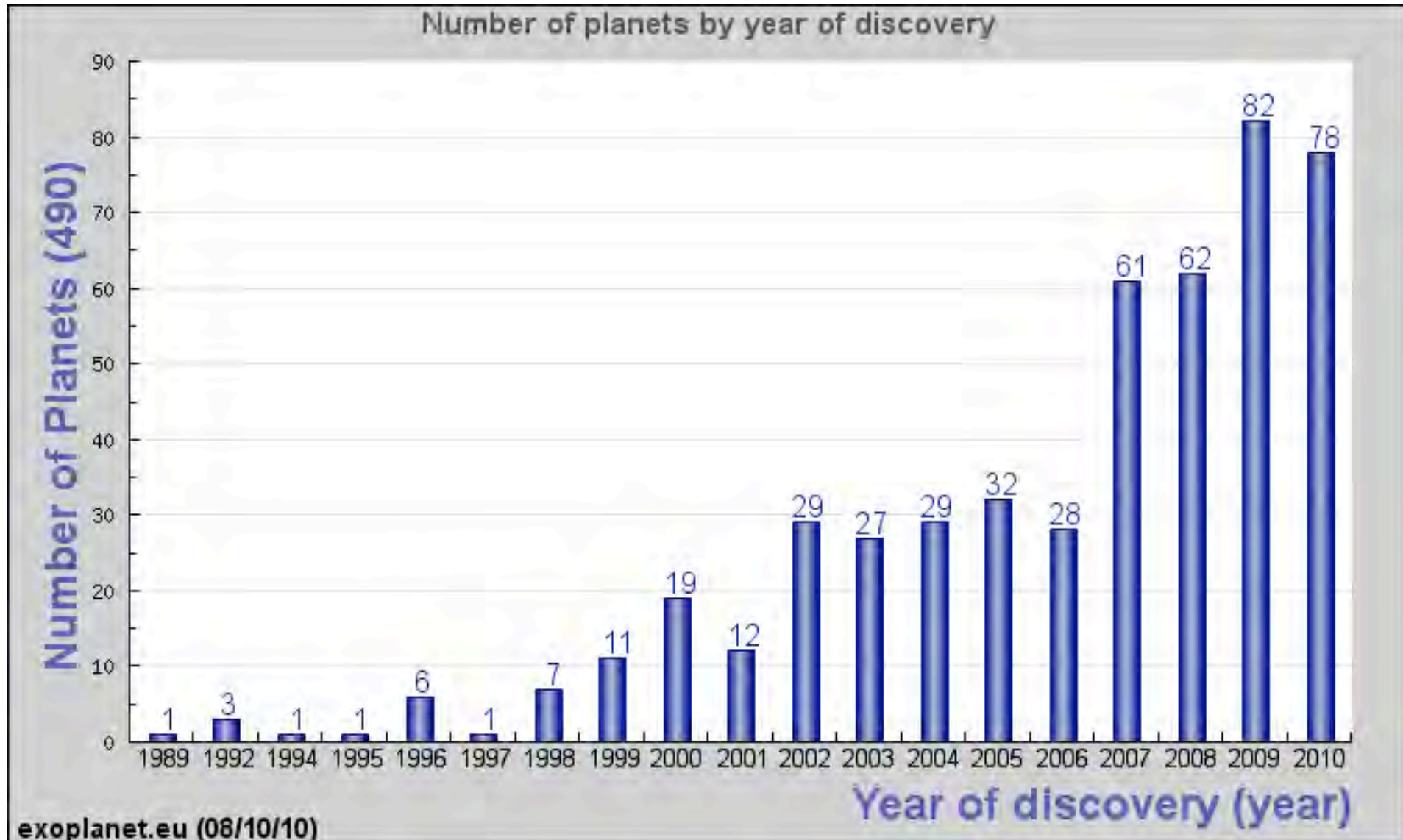


[www.solarviews.org/cap/misc/solarsystem.htm](http://www.solarviews.org/cap/misc/solarsystem.htm)

- Sun is  $4 \times 10^8$  times more luminous than Jupiter

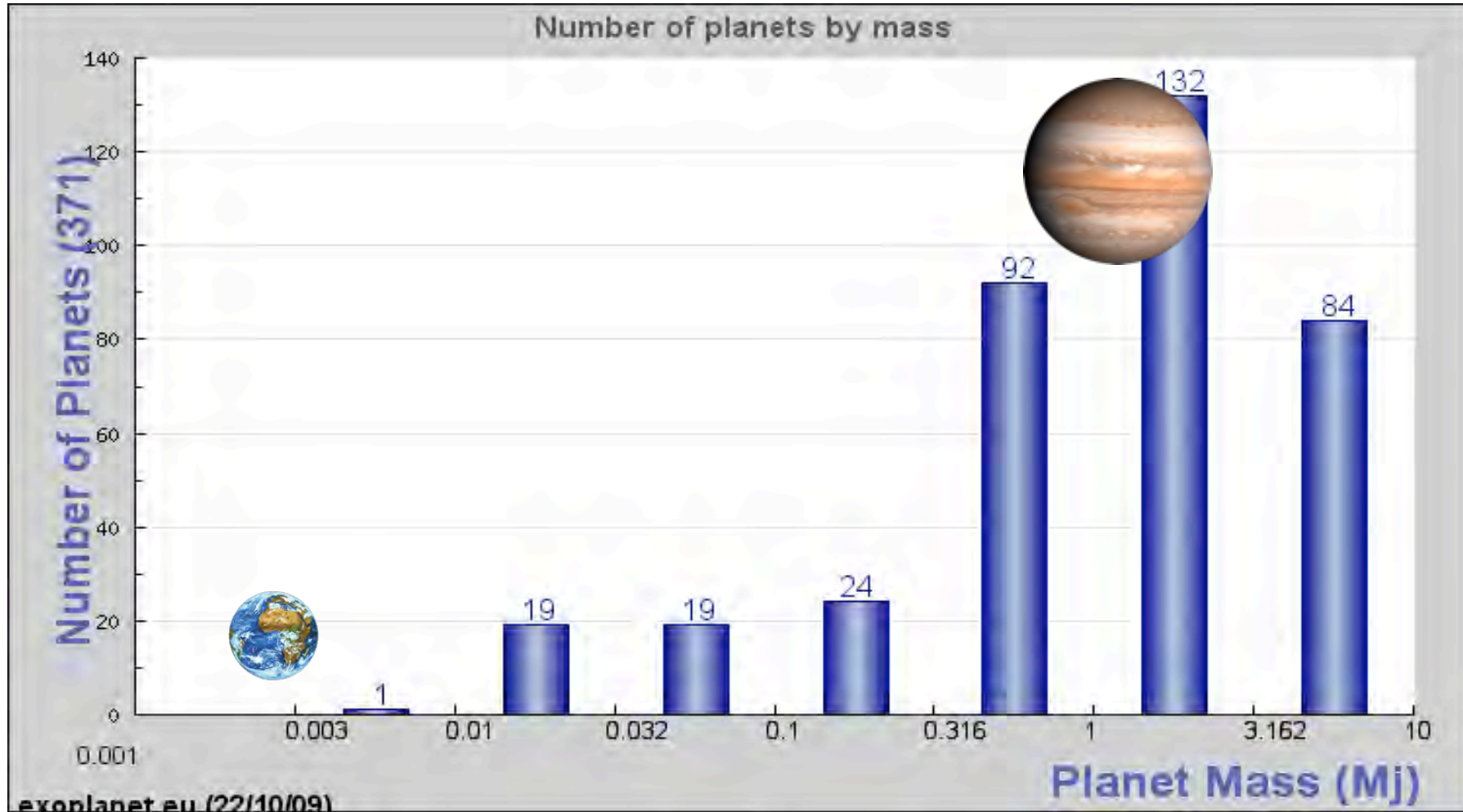


# Exoplanet Detection Rate



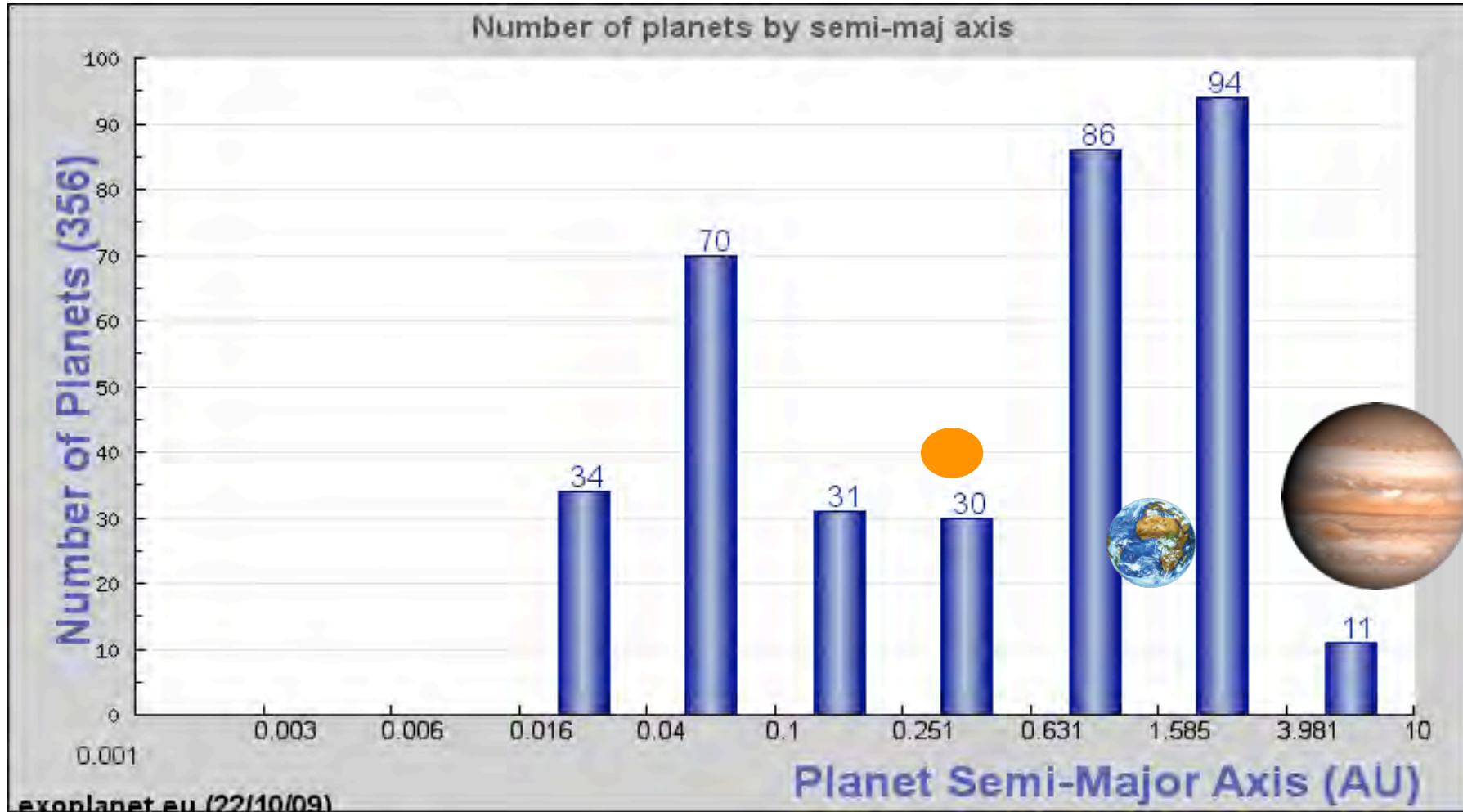


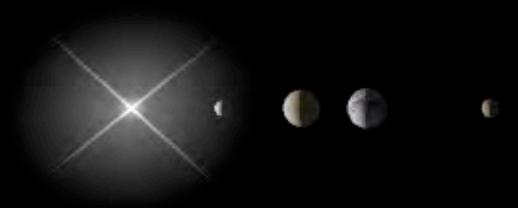
# Exoplanet Masses



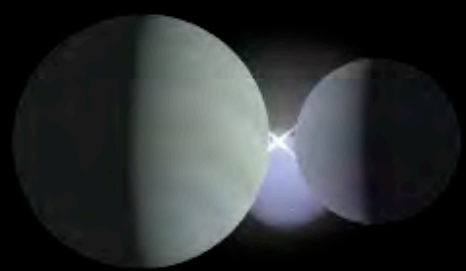


# Exoplanet Orbital Distances

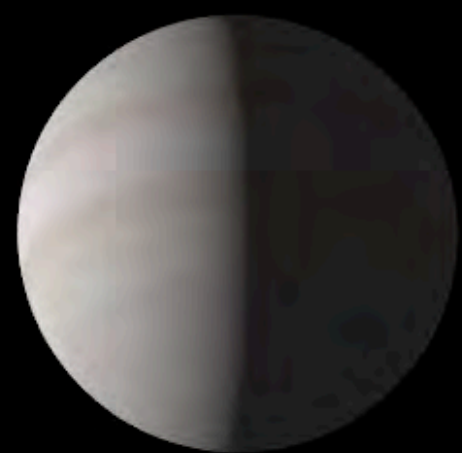




**Solar System**



**55 Cnc**





# Detection vs. Characterization

## Past: Detection

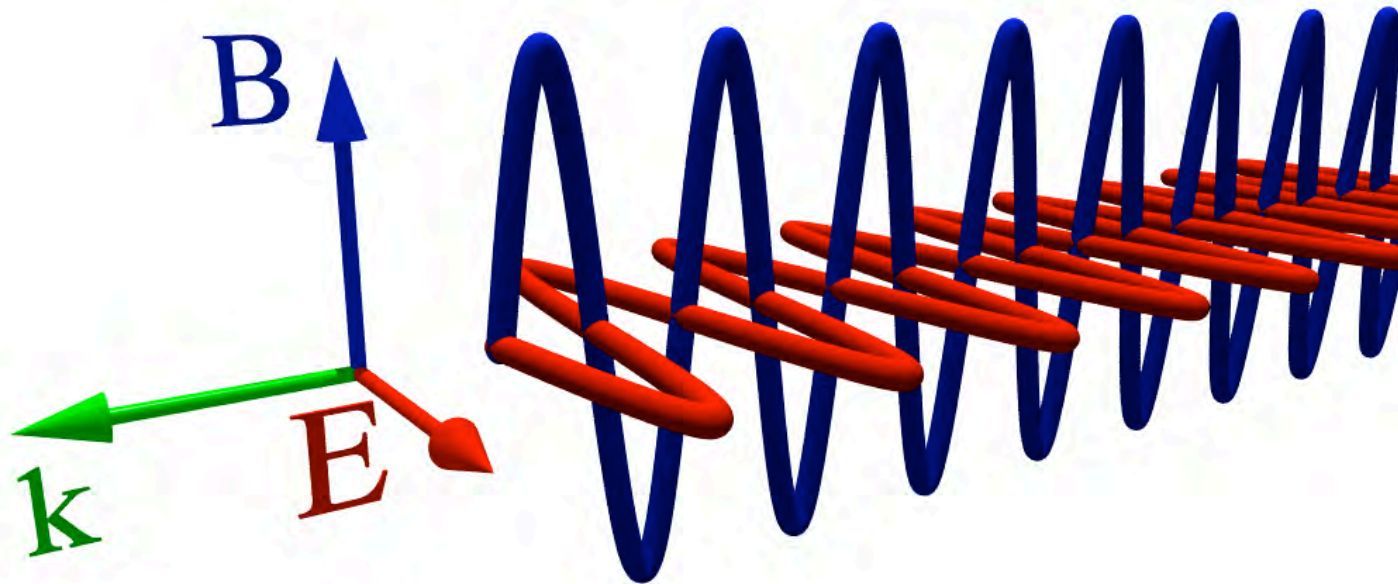
- Detect presence of exoplanet around a star
- Determine mass to distinguish from brown dwarf
- Determine orbit around star

## Future: Characterization

- Determine radius
- Determine surface properties
- Determine atmospheric properties
- Requires direct imaging

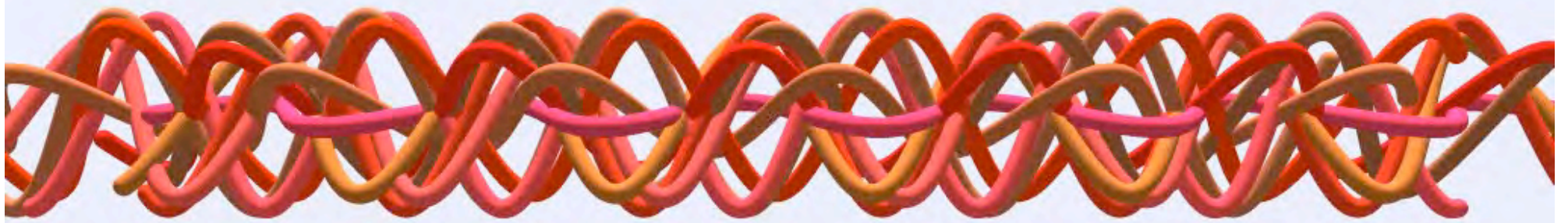


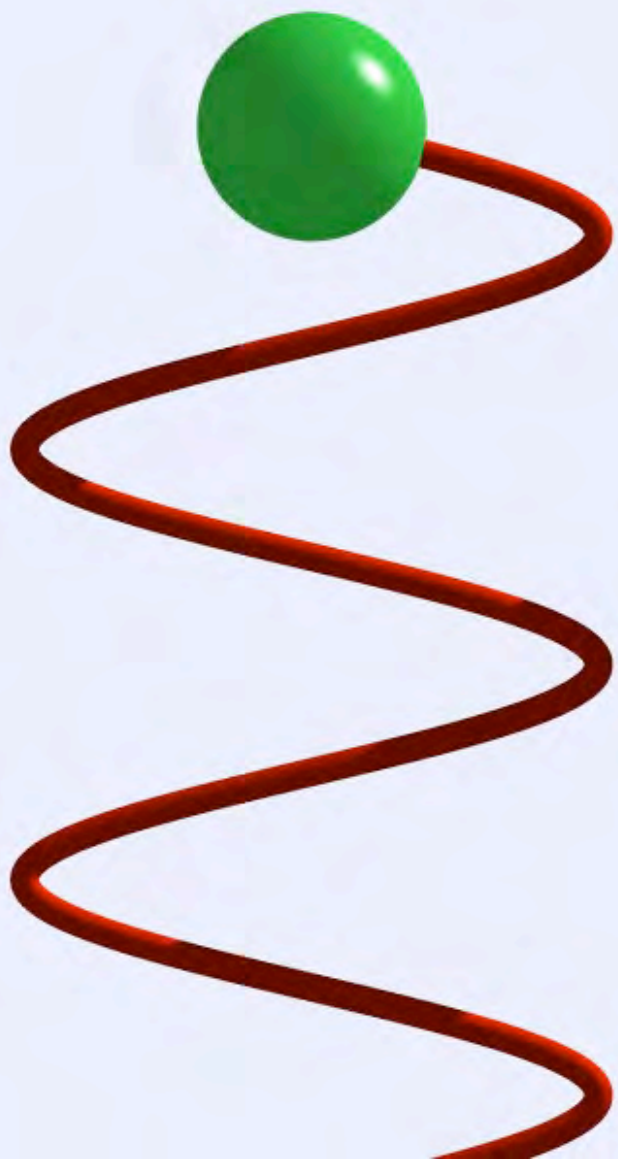
# Polarized Light

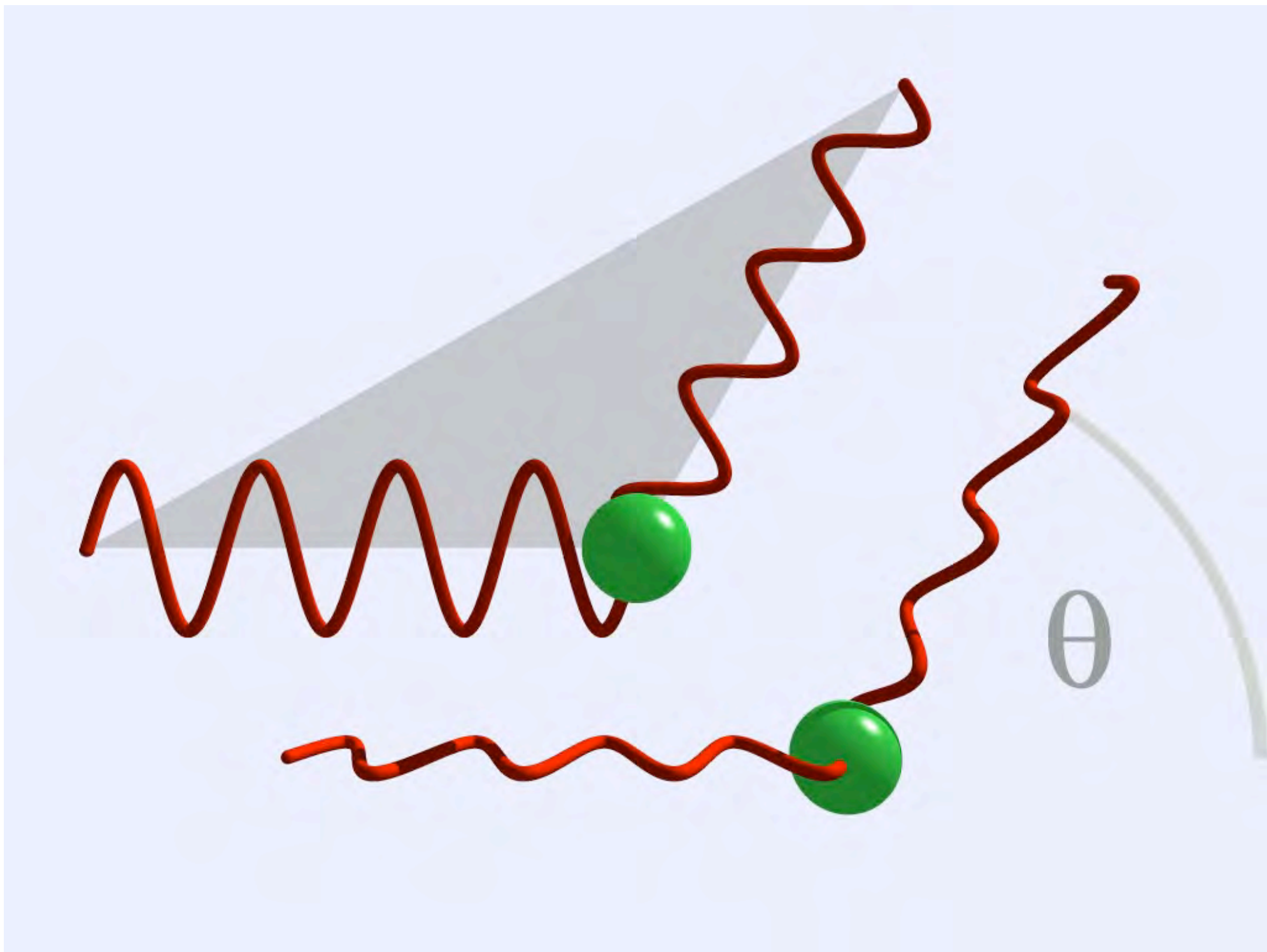


- Electromagnetic waves: direct consequence of Maxwell's equations
- Optics: interaction of electromagnetic waves with matter
- Polarization is an integral part of electromagnetic waves
- Human eye is not sensitive to polarization











# The Problem

- Central star much brighter than disks and planets
  - Disks: at least  $10^4$  times fainter than central star
  - Jupiter:  $10^9$  times fainter than Sun
- Telescope optics, Earth atmosphere make halo
  - halo:  $10^2$  to  $10^6$  times fainter than central star

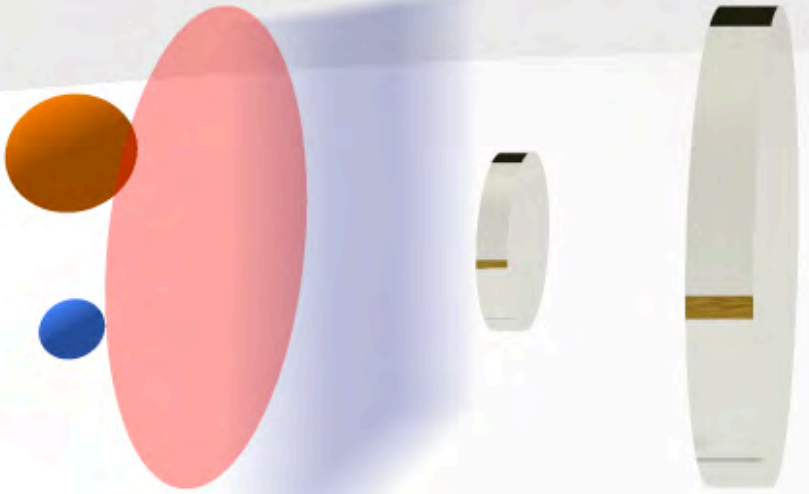


Hubble Space  
Telescope



# The Solution: Combine Techniques

- Minimize halo around star
  - (1) Adaptive Optics (reduces twinkling)
  - (2) Coronagraph (blocks much of central star)
- Polarized light only from circumstellar material, not from star
  - (3) Polarization measurements with  $10^{-5}$  sensitivity

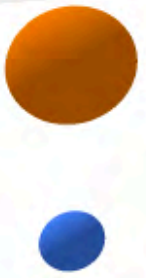


Adaptive Optics

Coronagraph

Polarimeter

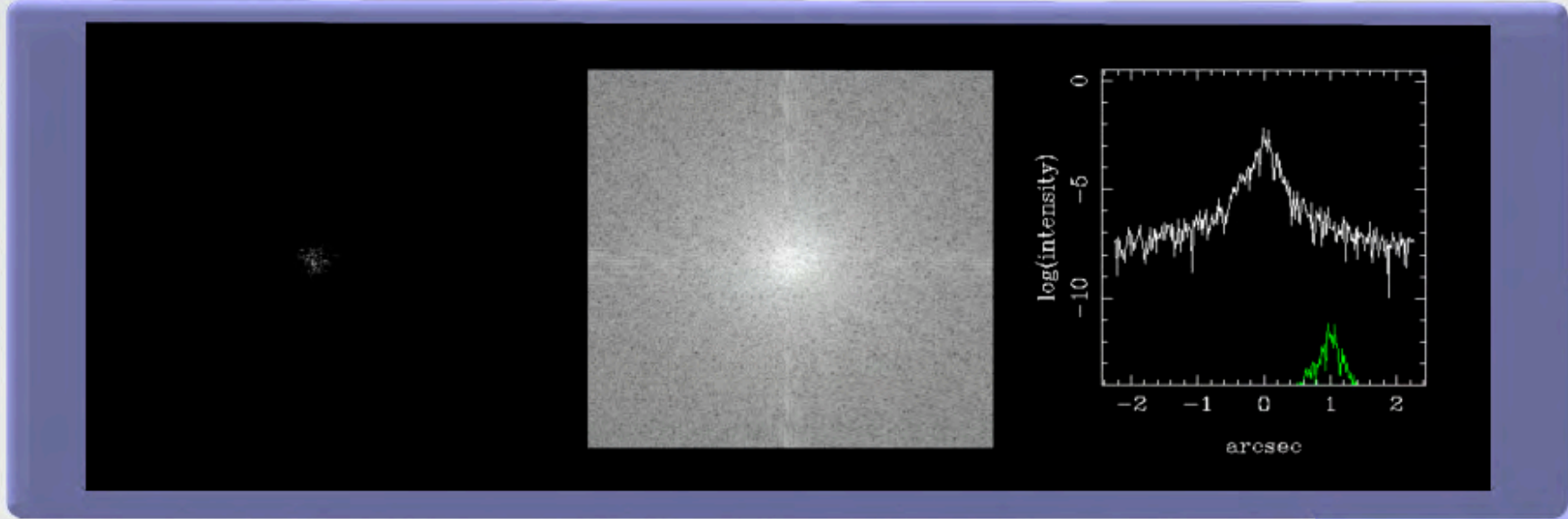


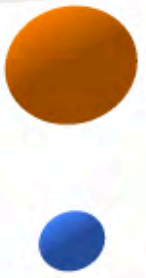


Adaptive Optics

Coronagraph

Polarimeter



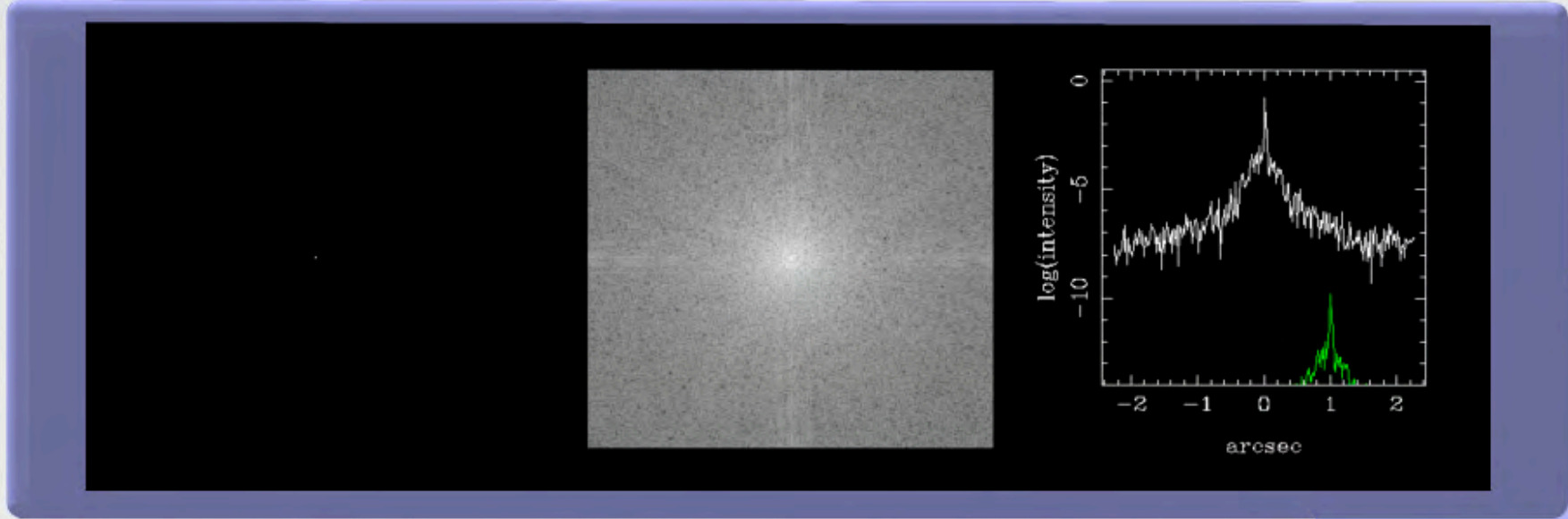


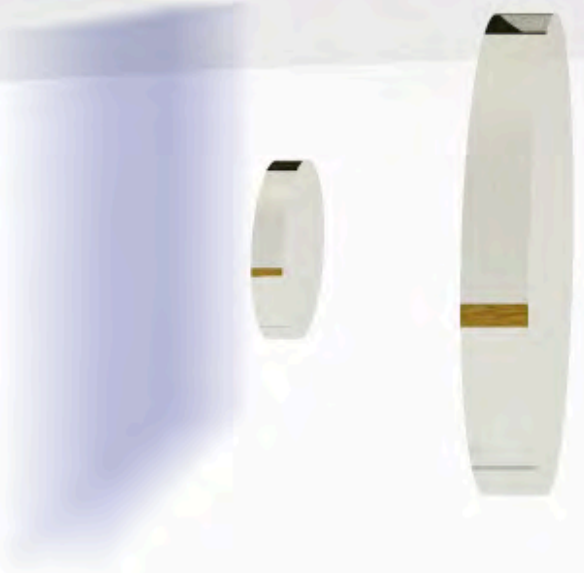
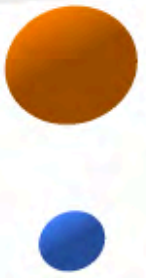
Adaptive Optics



Coronagraph

Polarimeter

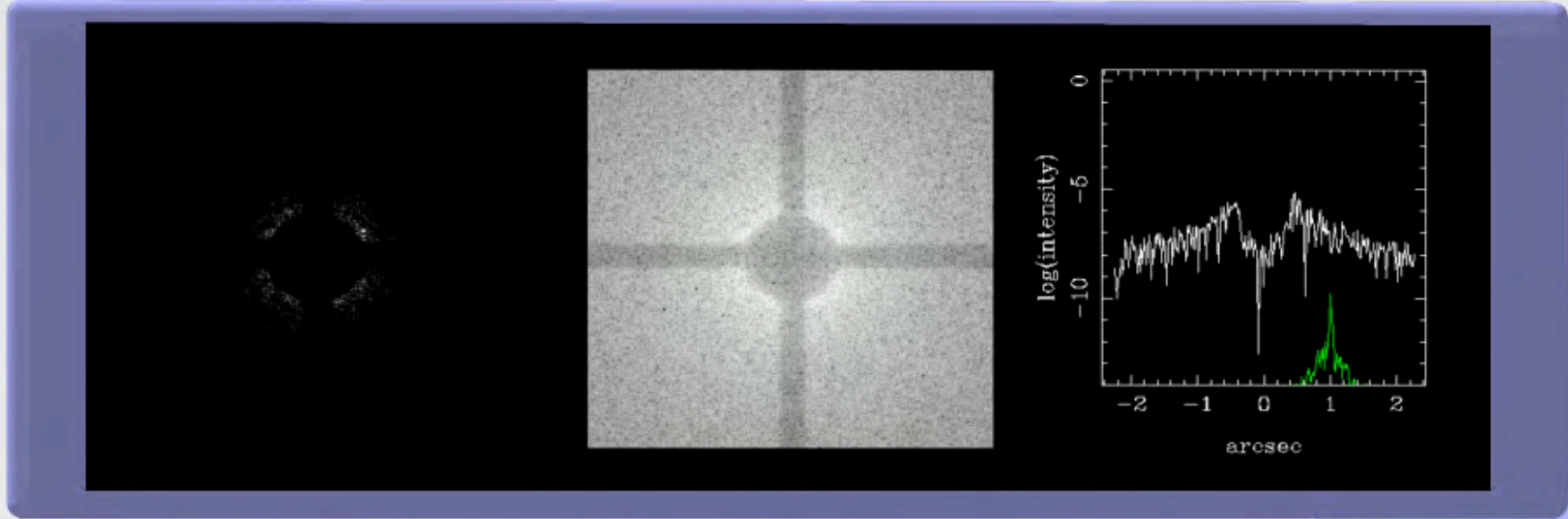


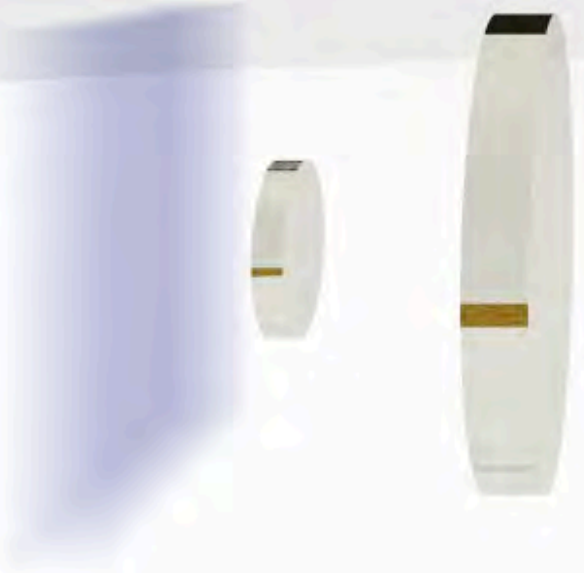


Adaptive Optics

Coronagraph

Polarimeter





Adaptive Optics

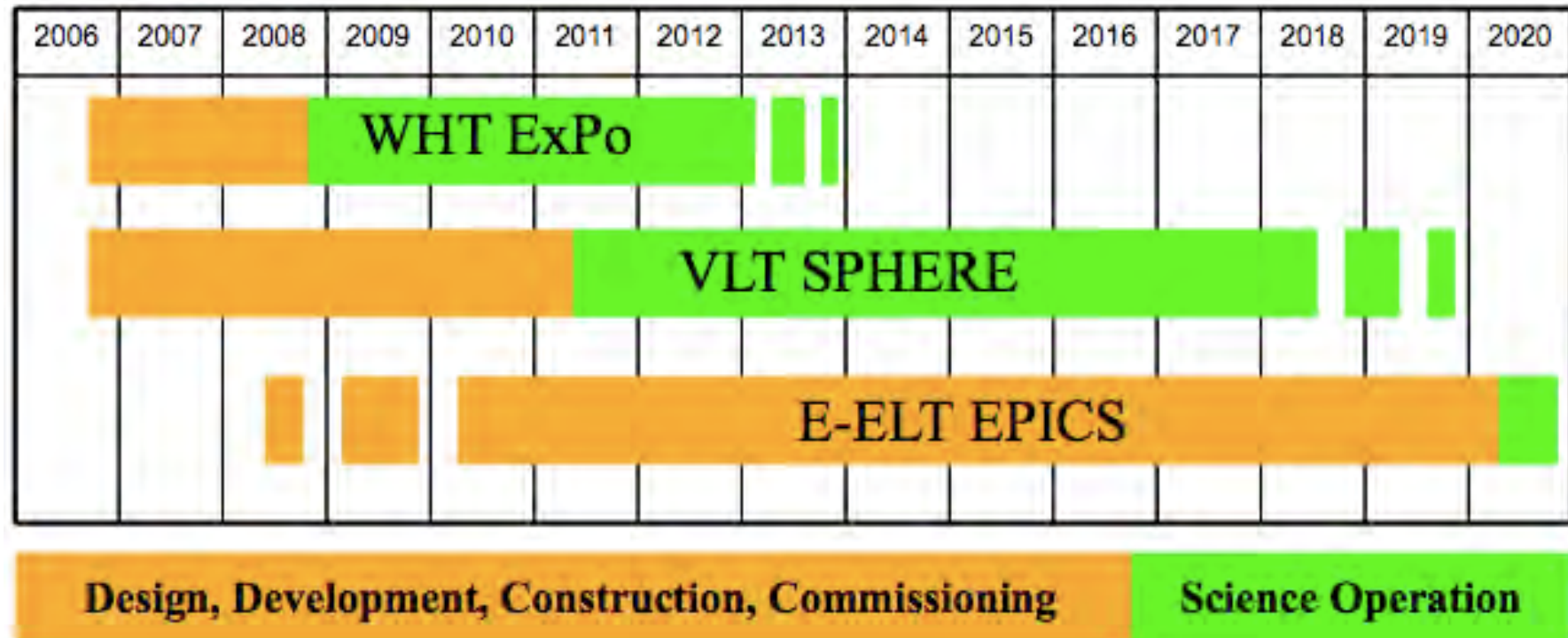
Coronagraph

Polarimeter





# Exoplanet Polarimetry Instruments

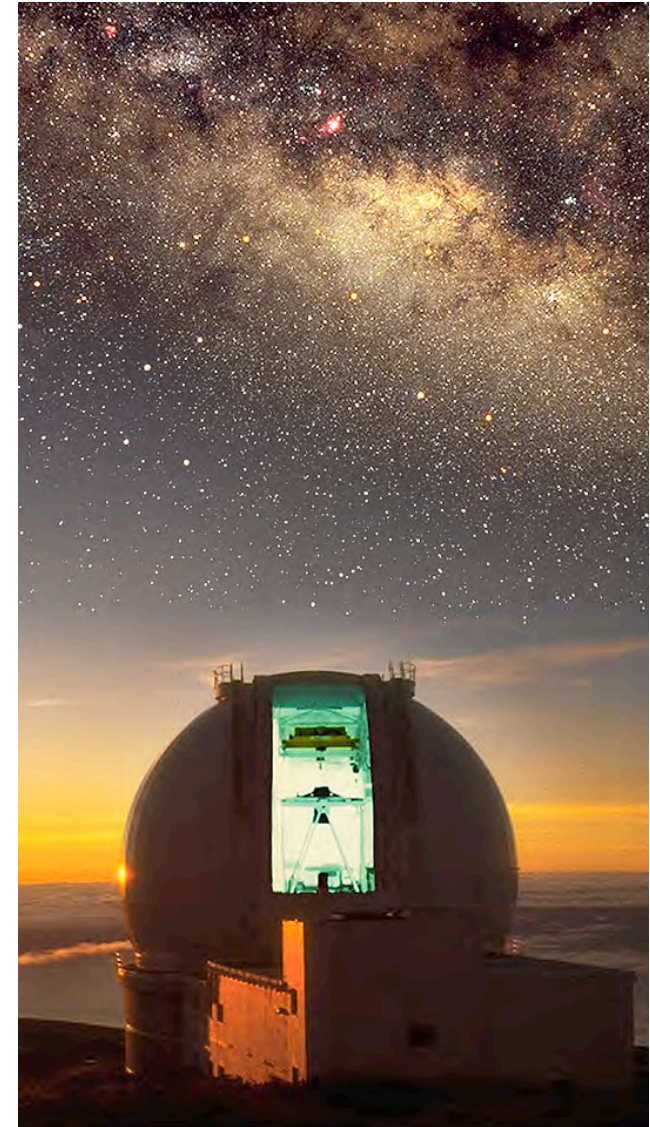


- ExPo on 4.2-m William Herschel Telescope
- SPHERE with ZIMPOL for the ESO 8.2-m Very Large Telescope
- EPICS with EPOL for ESO 42-m European Extremely-Large Telescope (E-ELT)



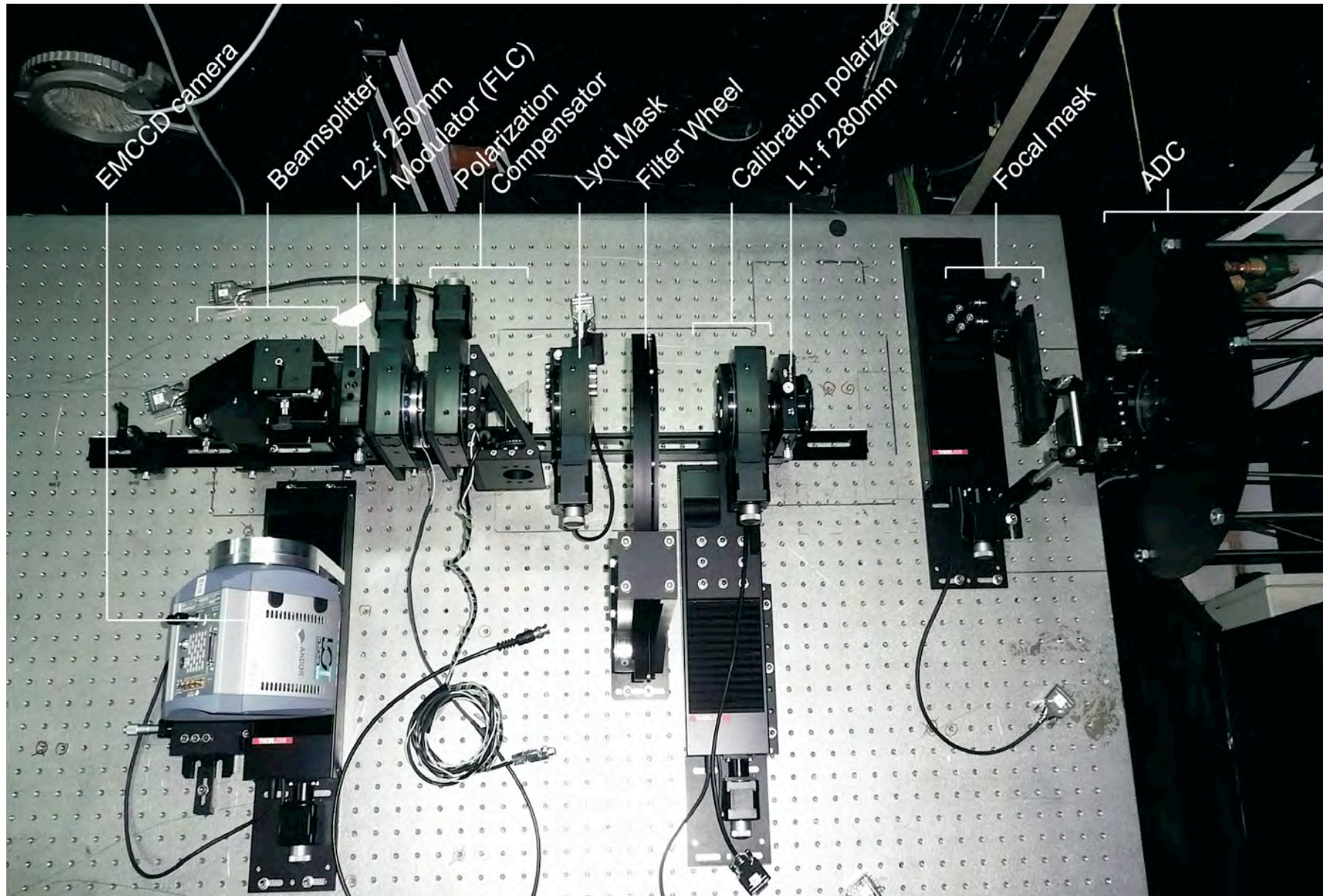
# Extreme Polarimeter (ExPo)

- Developed and built at Utrecht University
- Since 2008 at 4.2-m William Herschel Telescope in La Palma
- Pathfinder for VLT and E-ELT instruments
- Visible light: 600 – 900 nm
- Adaptive Optics (2011)
- Integral Field Spectro-Polarimetry (2012)





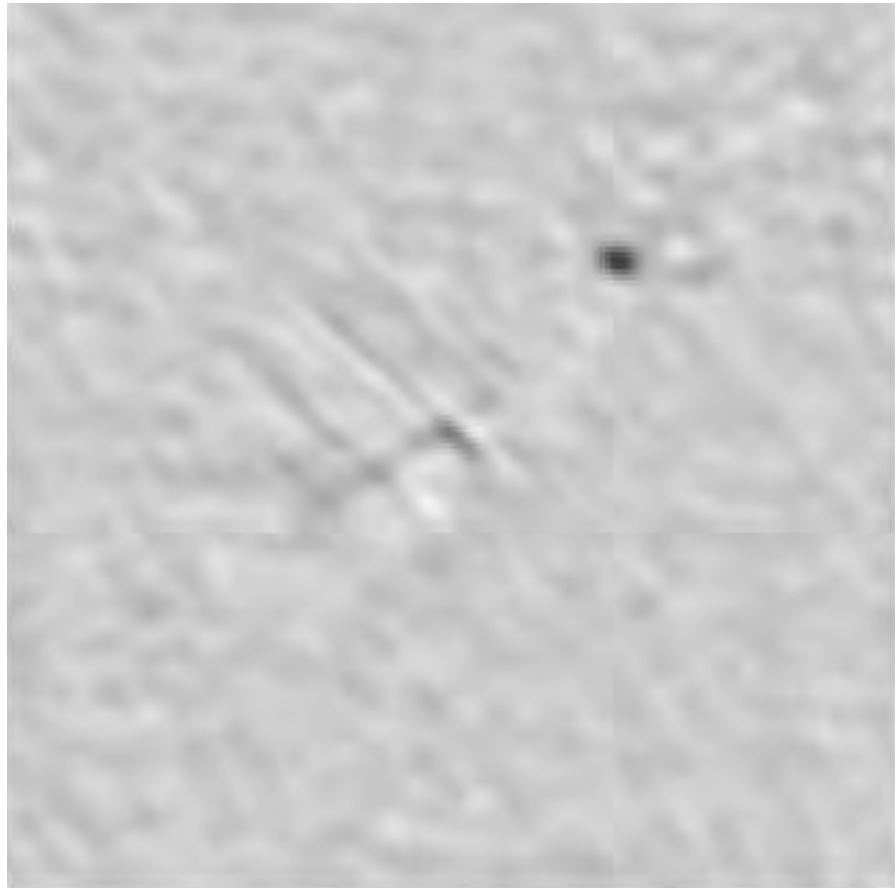
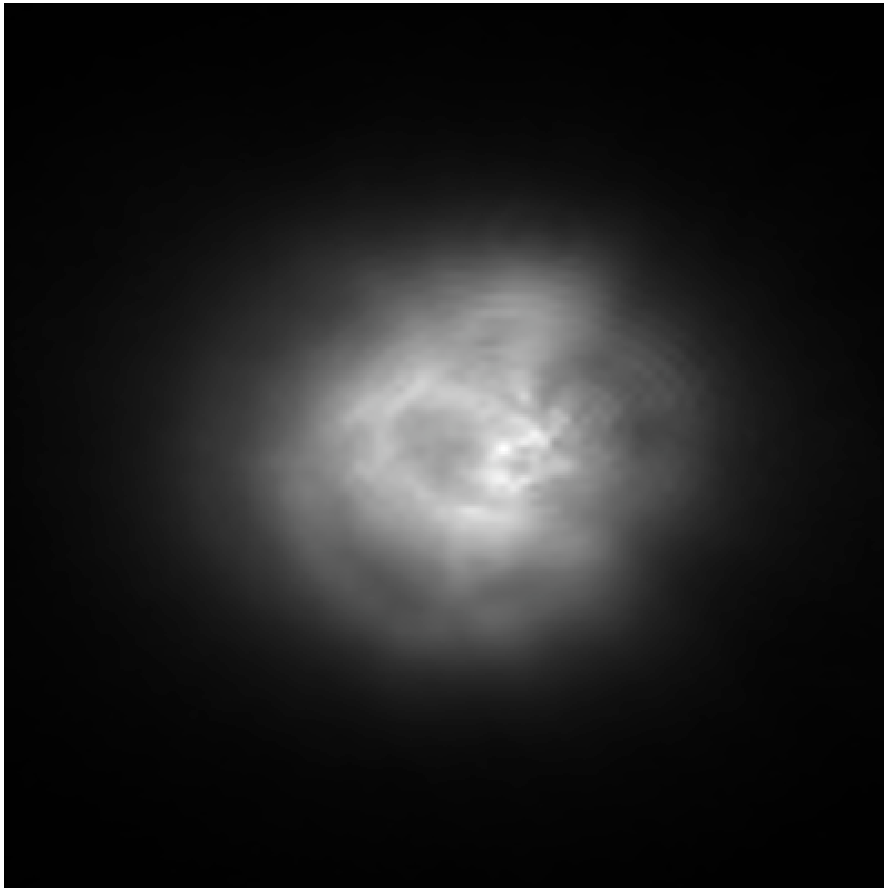
# ExPo at WHT



A Polarized Look at (Exo)Planet Atmospheres, Christoph U. Keller, Utrecht University, [c.u.keller@uu.nl](mailto:c.u.keller@uu.nl)



# Exoplanet in the Lab



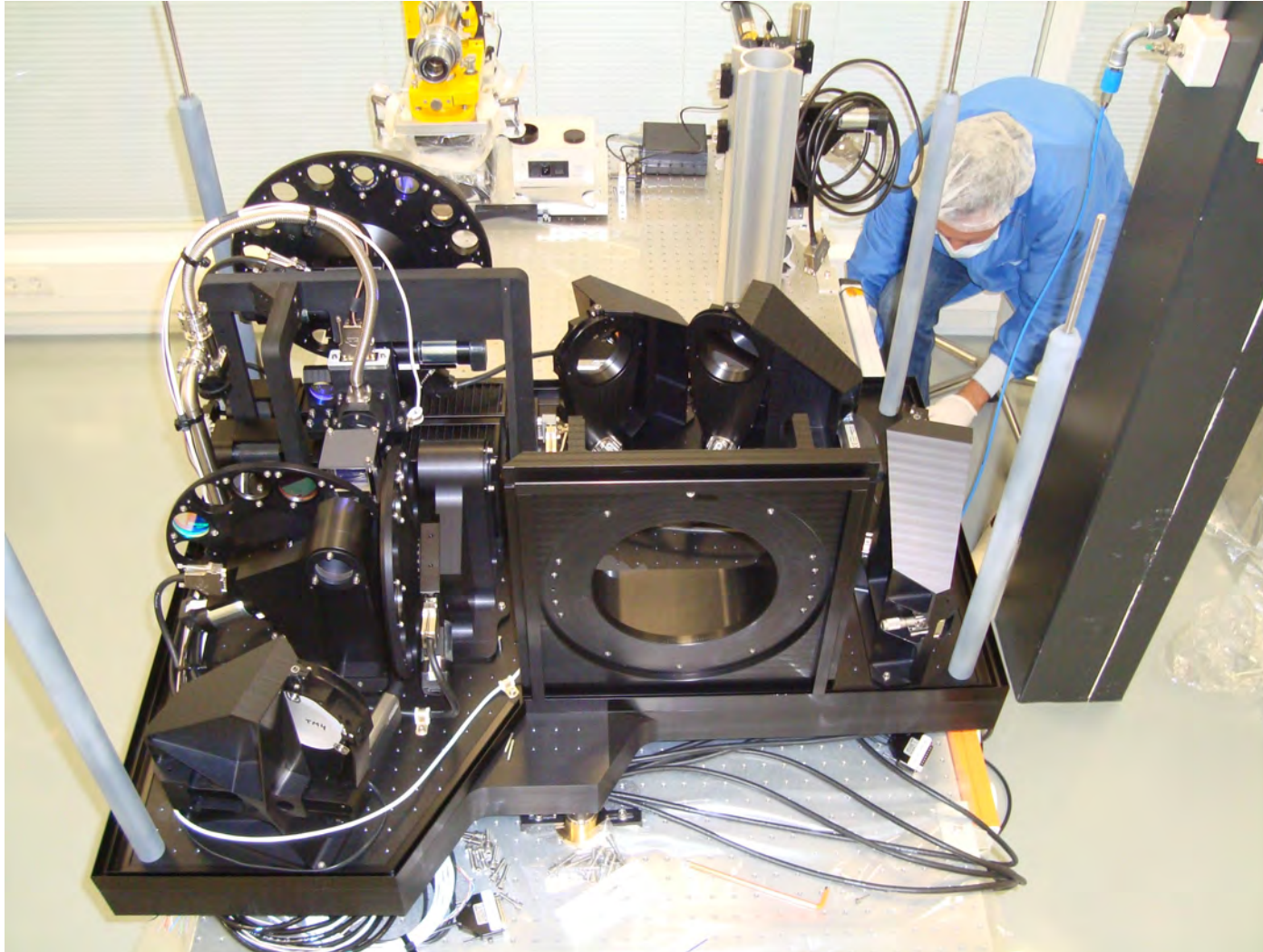


# SPHERE at the VLT

- Combined instruments to directly detect and analyze giant extrasolar planets
- Common extreme adaptive optics system
- 2 near-infrared instruments searching for selfluminous young planets
- ZIMPOL Imaging polarimeter detecting and analyzing reflected light from older planets
  - Dutch-Swiss collaboration



# Zurich Imaging Polarimeter





# EPICS for the E-ELT

- Exo-Planets Imaging Camera and Spectrograph
  - XAO: eXtreme Adaptive Optics
  - EPOL: visible-light imaging polarimeter
  - IFS: Integral Field Spectrograph, diffraction-limited in the near infrared
- Initial design study completed
- ESFRI-grant supports R&D efforts in NL from 2009-2013
- EPOL is Dutch-Swiss collaboration

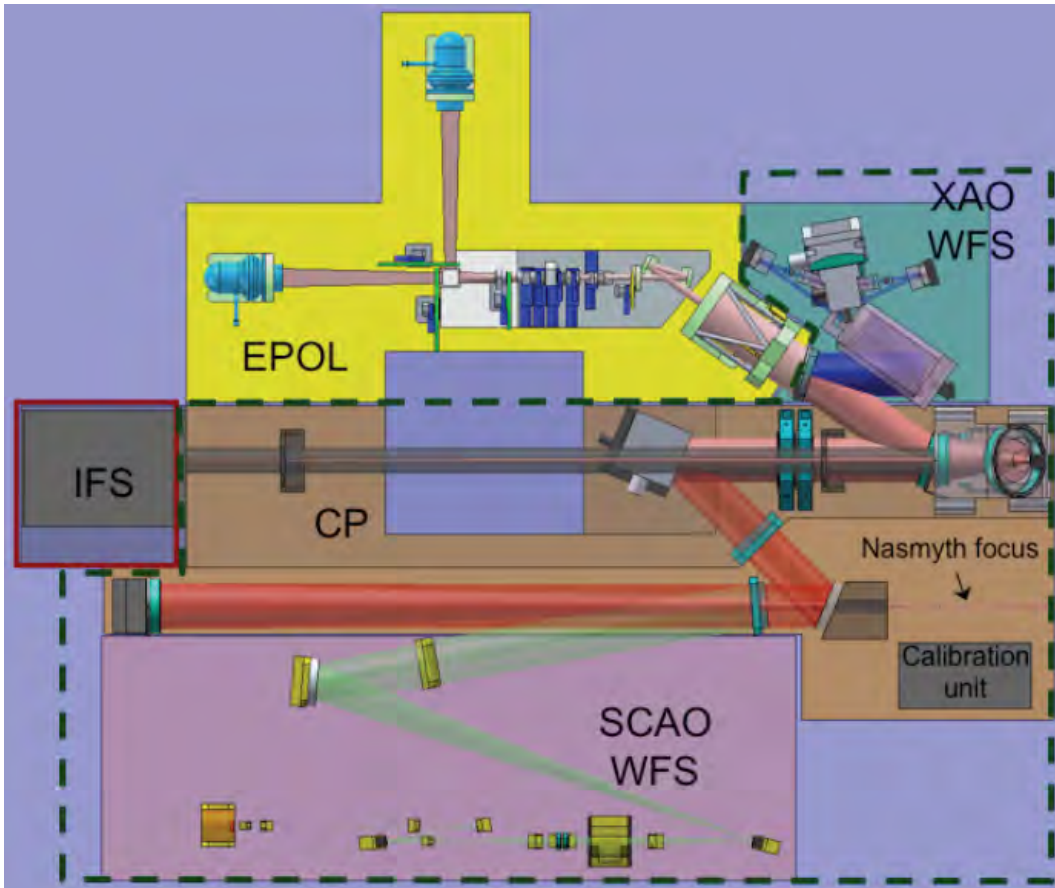


# Science Objectives

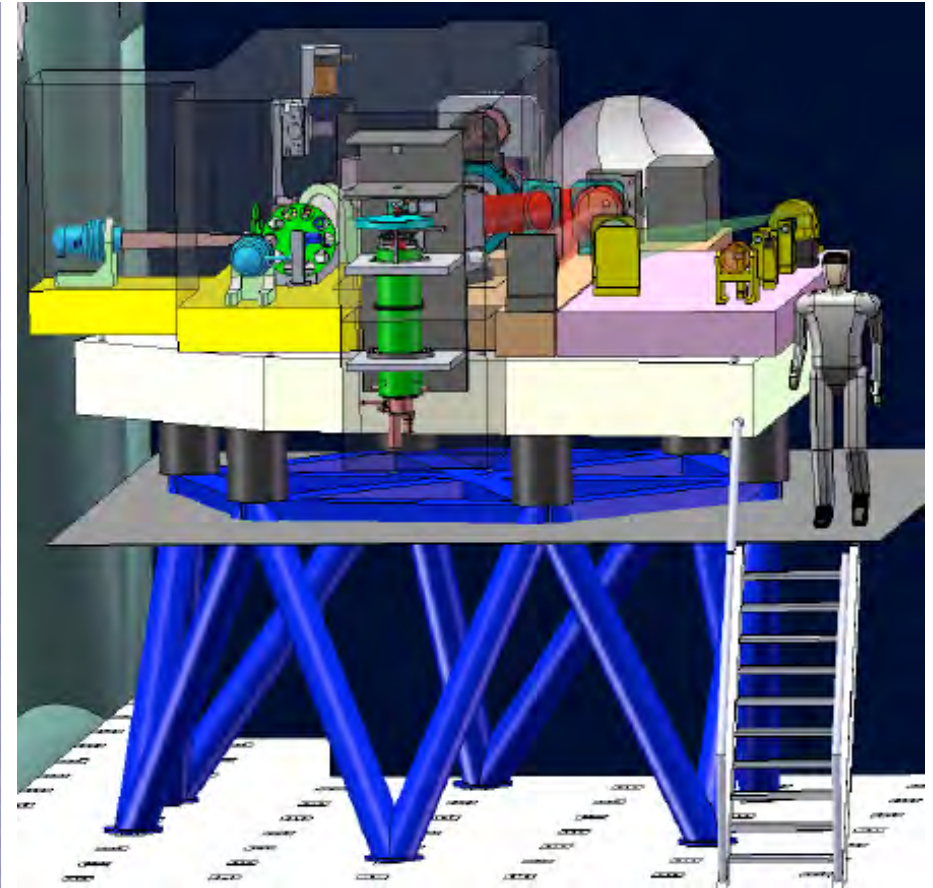
- Young self-luminous gas giants
  - Detection of young planets at separation  $> 3$  AU
- Mature gas giants at 5 - 15 AU in solar neighborhood ( $\leq 20$  pc)
  - Determine frequency and mass distribution of giant planets
- Warm or young gas giants discovered by radial velocity or direct imaging
  - Understand giant planets' atmosphere composition and structure
- Detection and initial characterization of terrestrial planets and super-Earths for very nearby stars ( $\leq 10$ pc)



# EPICS Concept



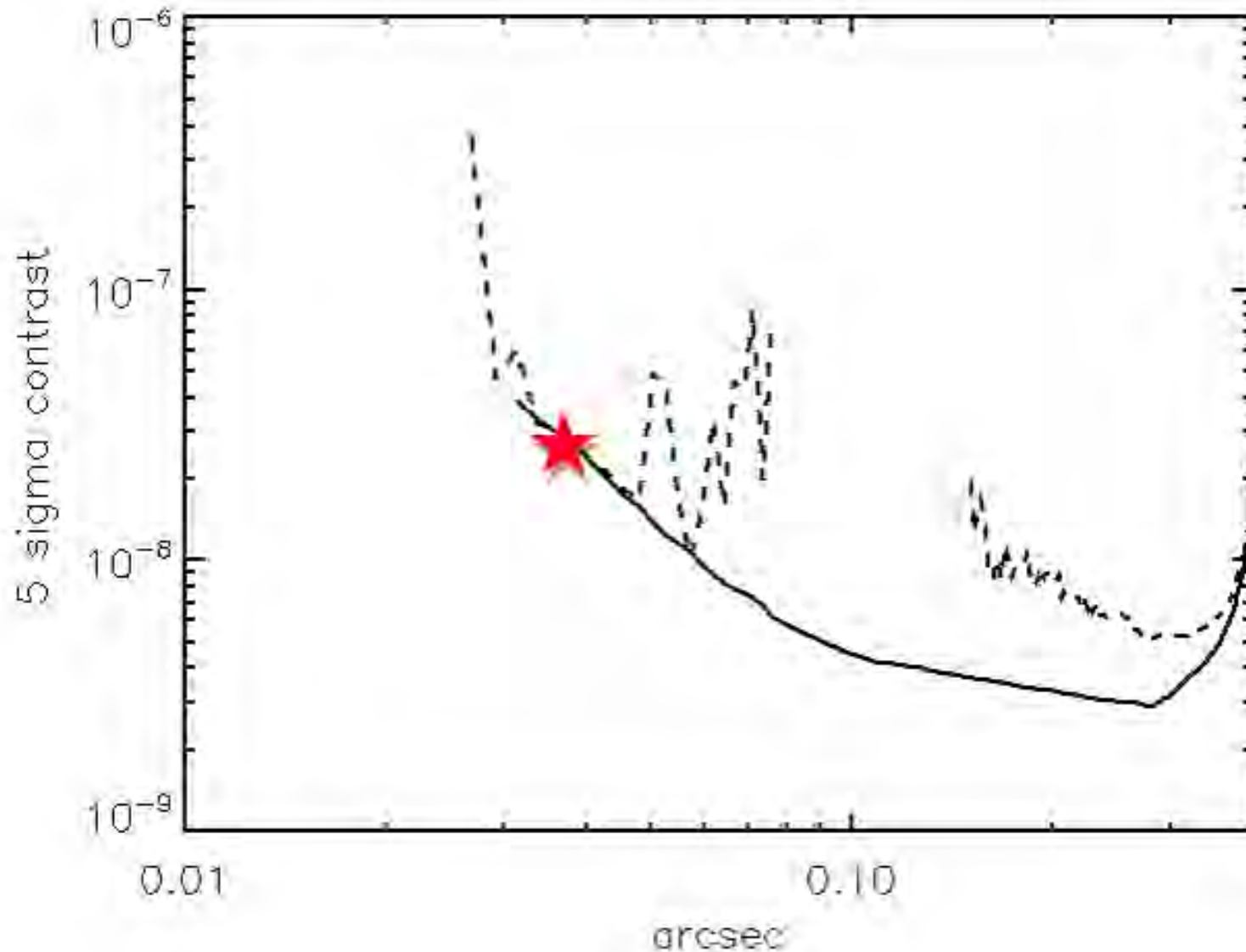
Top view



Nasmyth implementation



# Rocky Planet in HZ (Gliese 581 d)



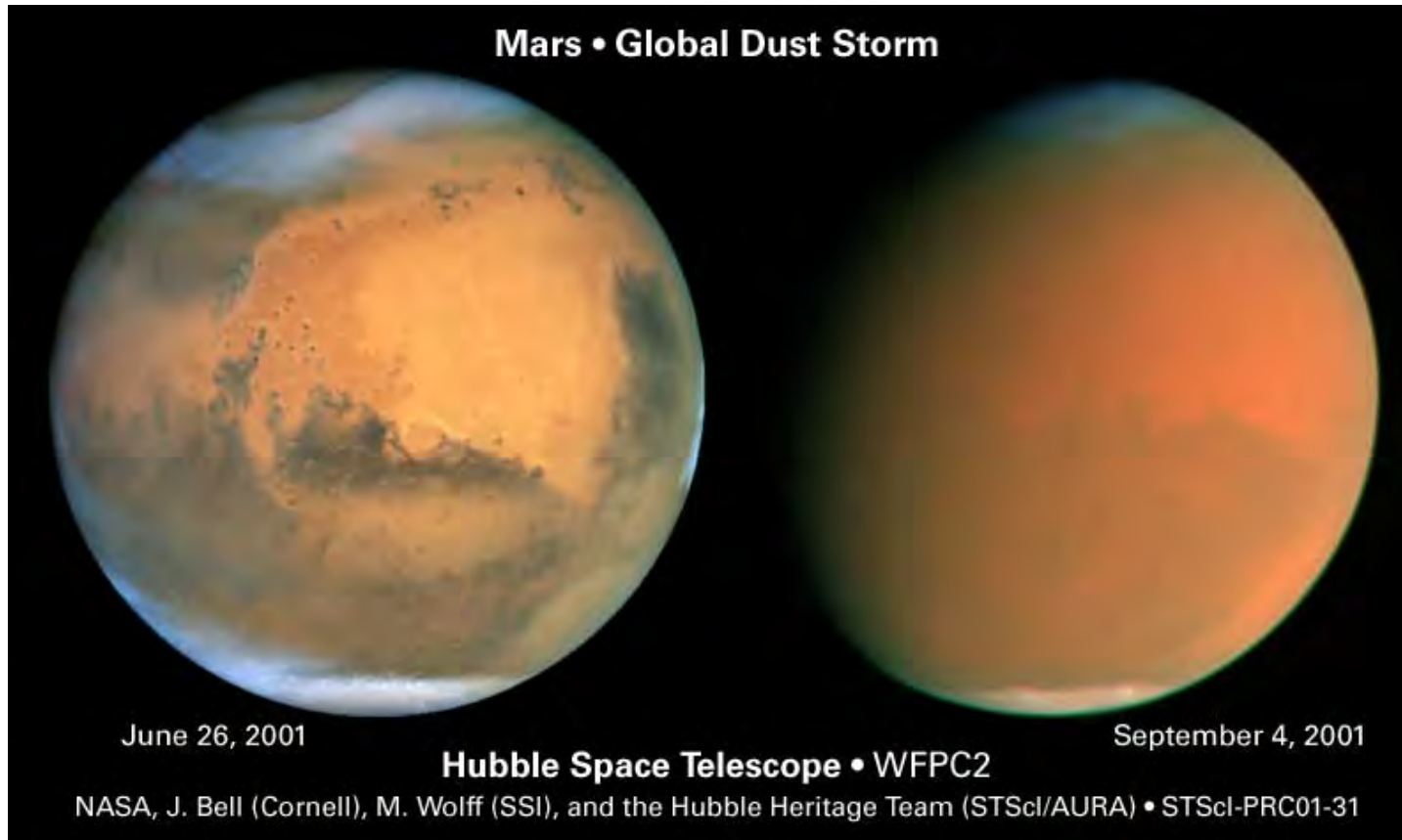


# SPEX

- Spectropolarimeter for **P**lanetary **EX**plorations
- study aerosol and dust in planetary atmospheres
- 10 times smaller and lighter than previous instruments
- preliminary patent application granted
- collaboration with SRON, TNO, Dutch Space



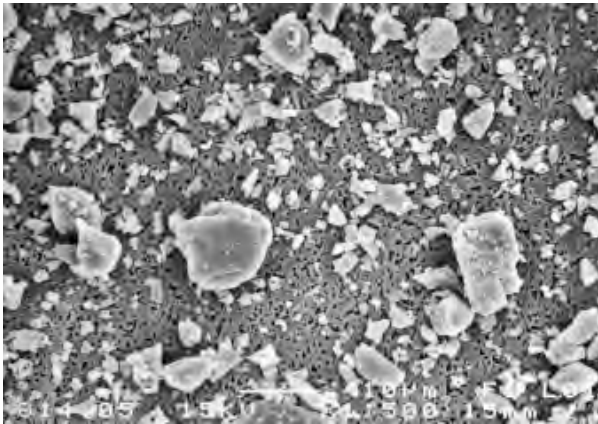
# Dust and Aerosol



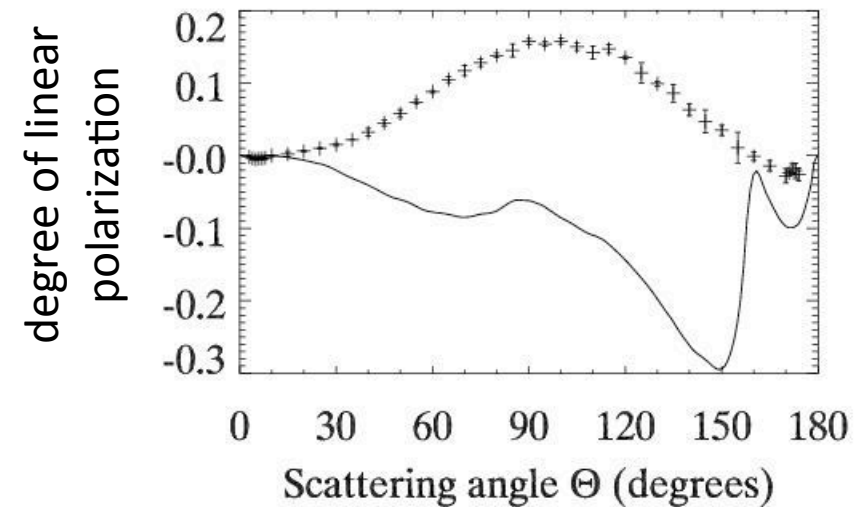
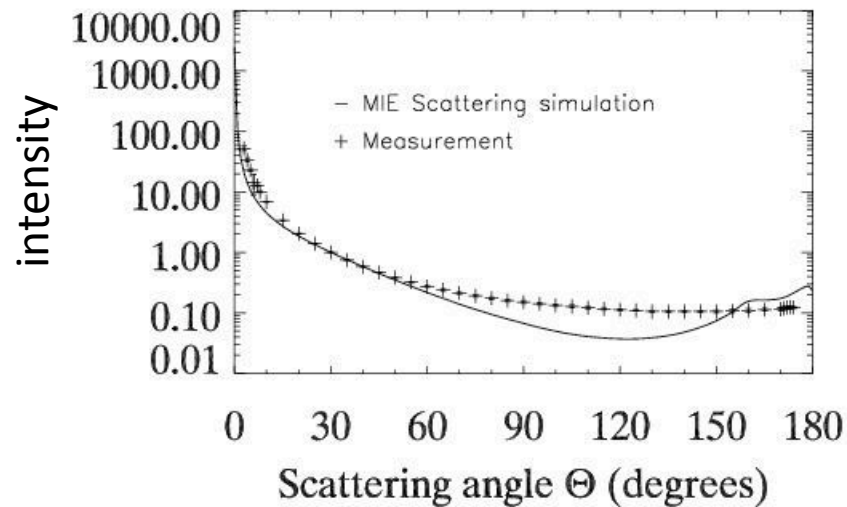
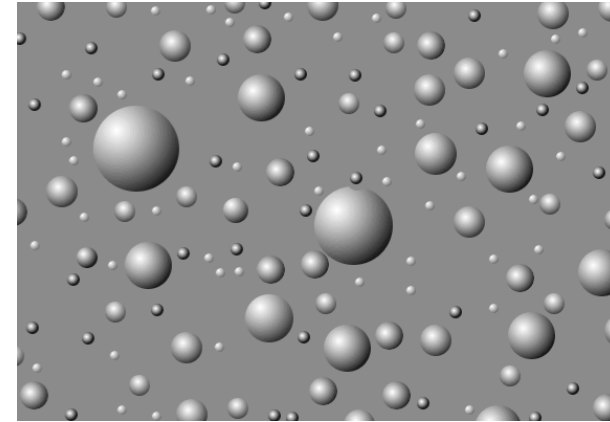
- Planetary warming
- Chemical reactions
- Condensation nuclei & transport
- Habitability



# Why Polarimetry?



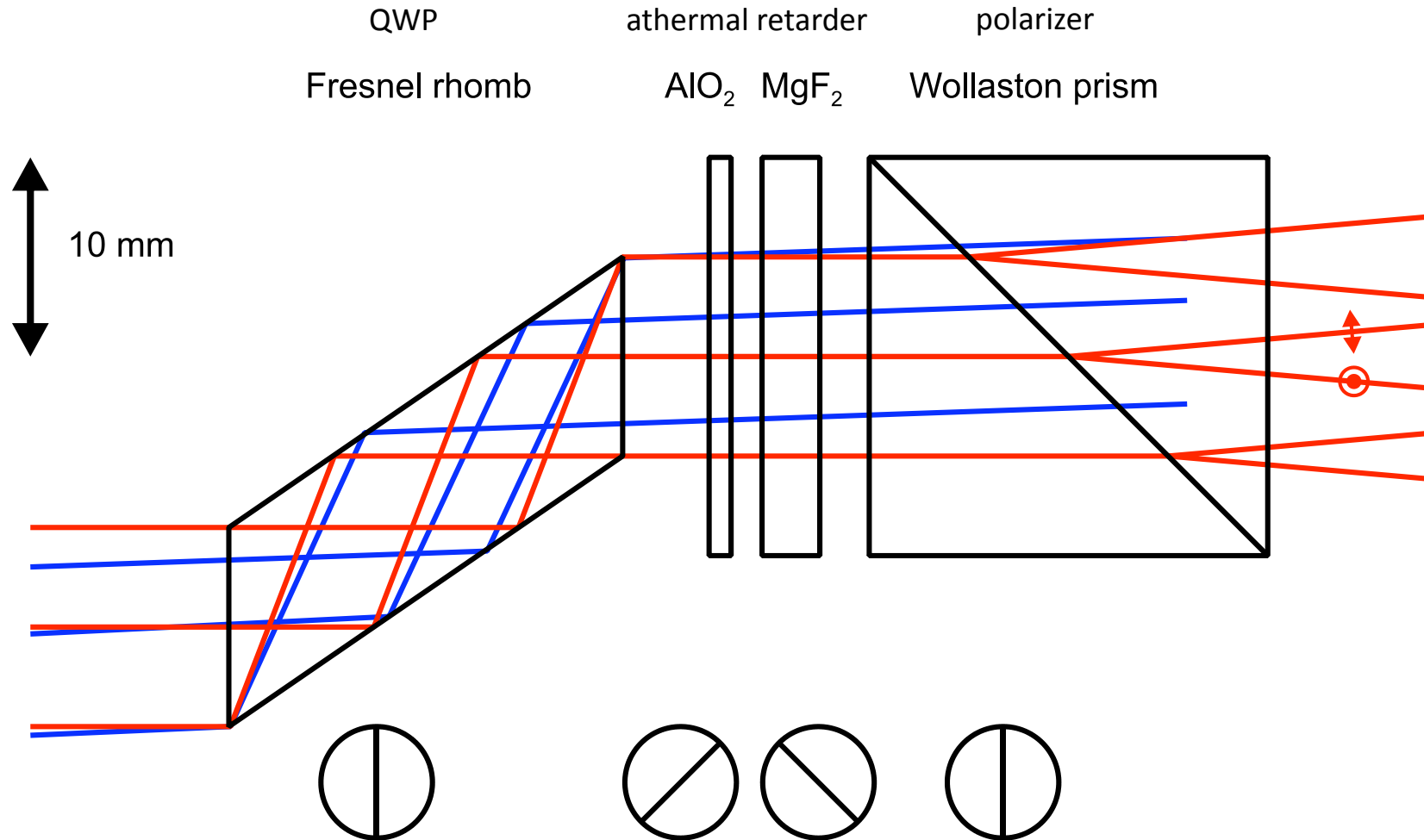
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*Laan et al (2007)*



# SPEX Polarization Analysis

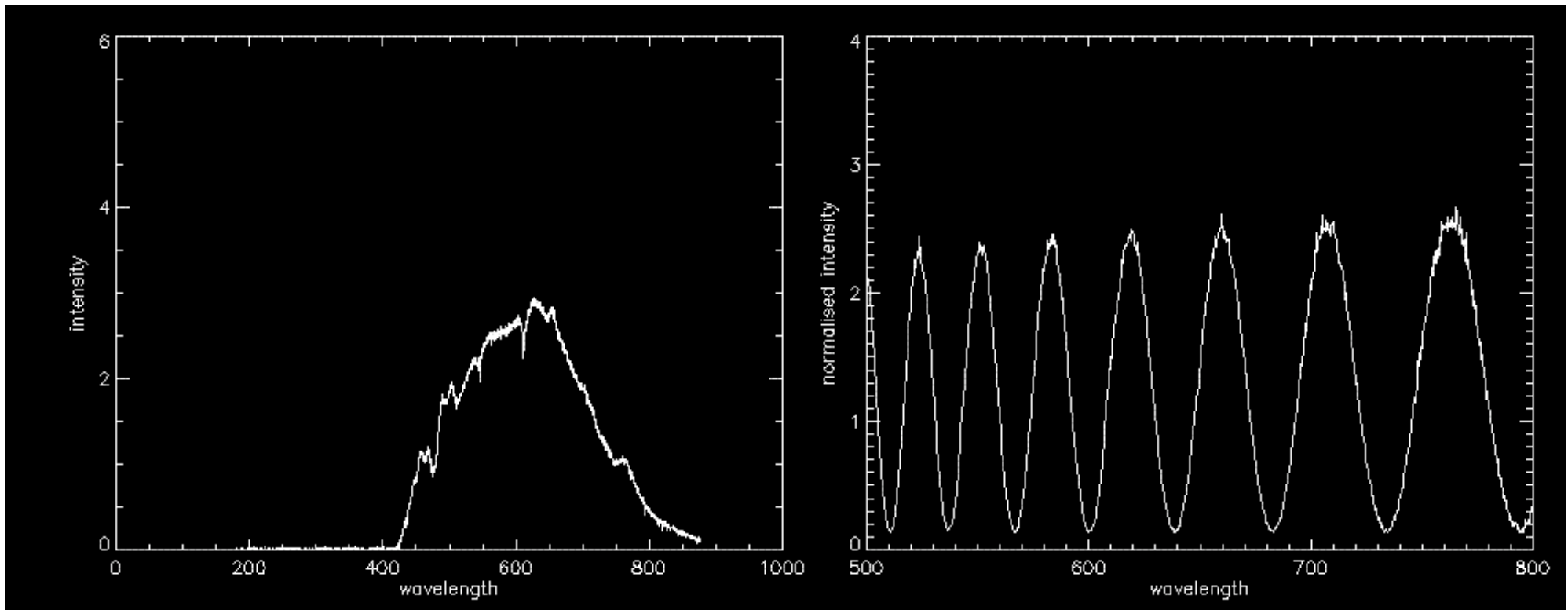


*Snik & Keller (2008) patent*

A Polarized Look at (Exo)Planet Atmospheres, Christoph U. Keller, Utrecht University, c.u.keller@uu.nl



# SPEX Polarization Measurement

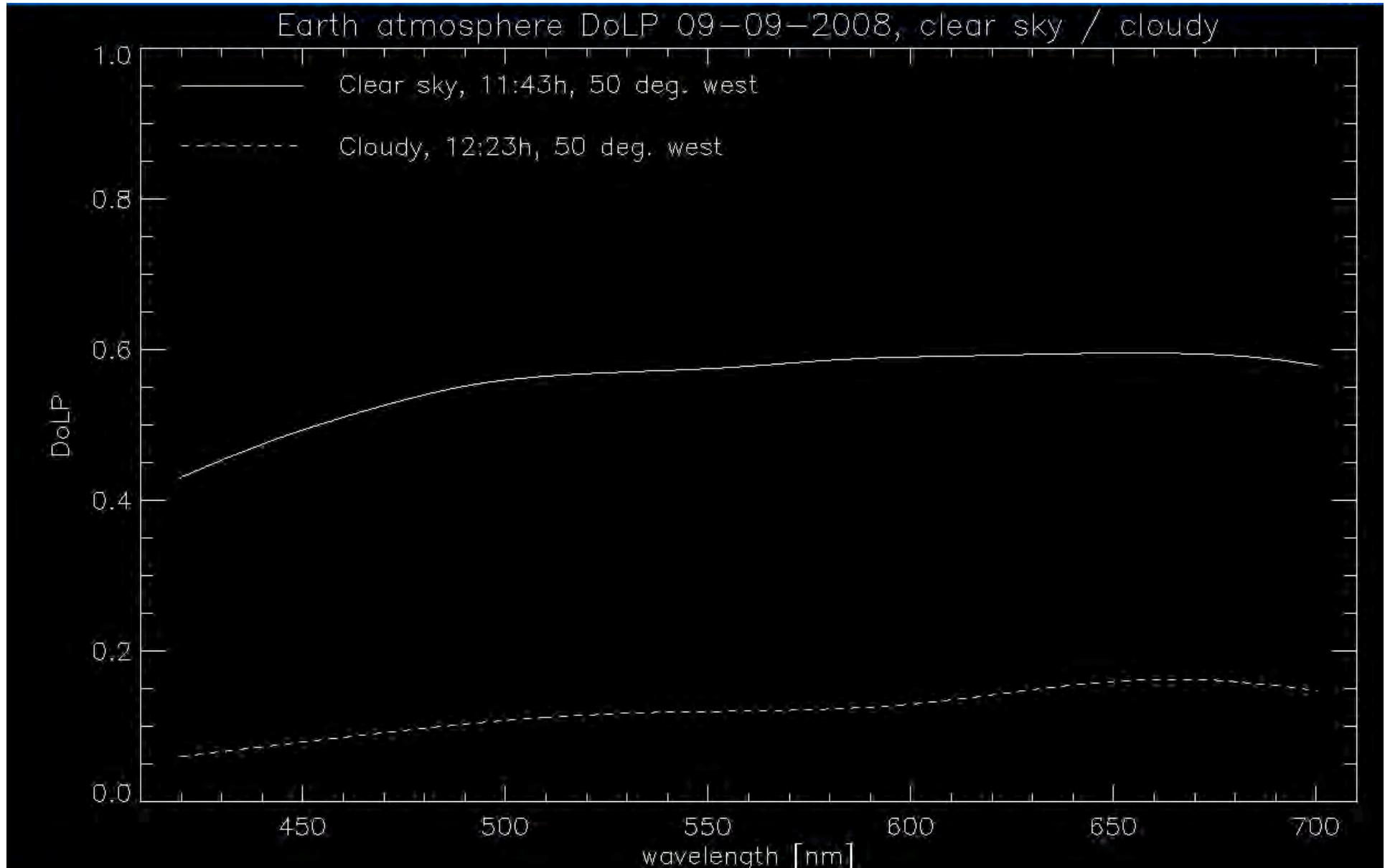


DoLP modulation

AoLP modulation

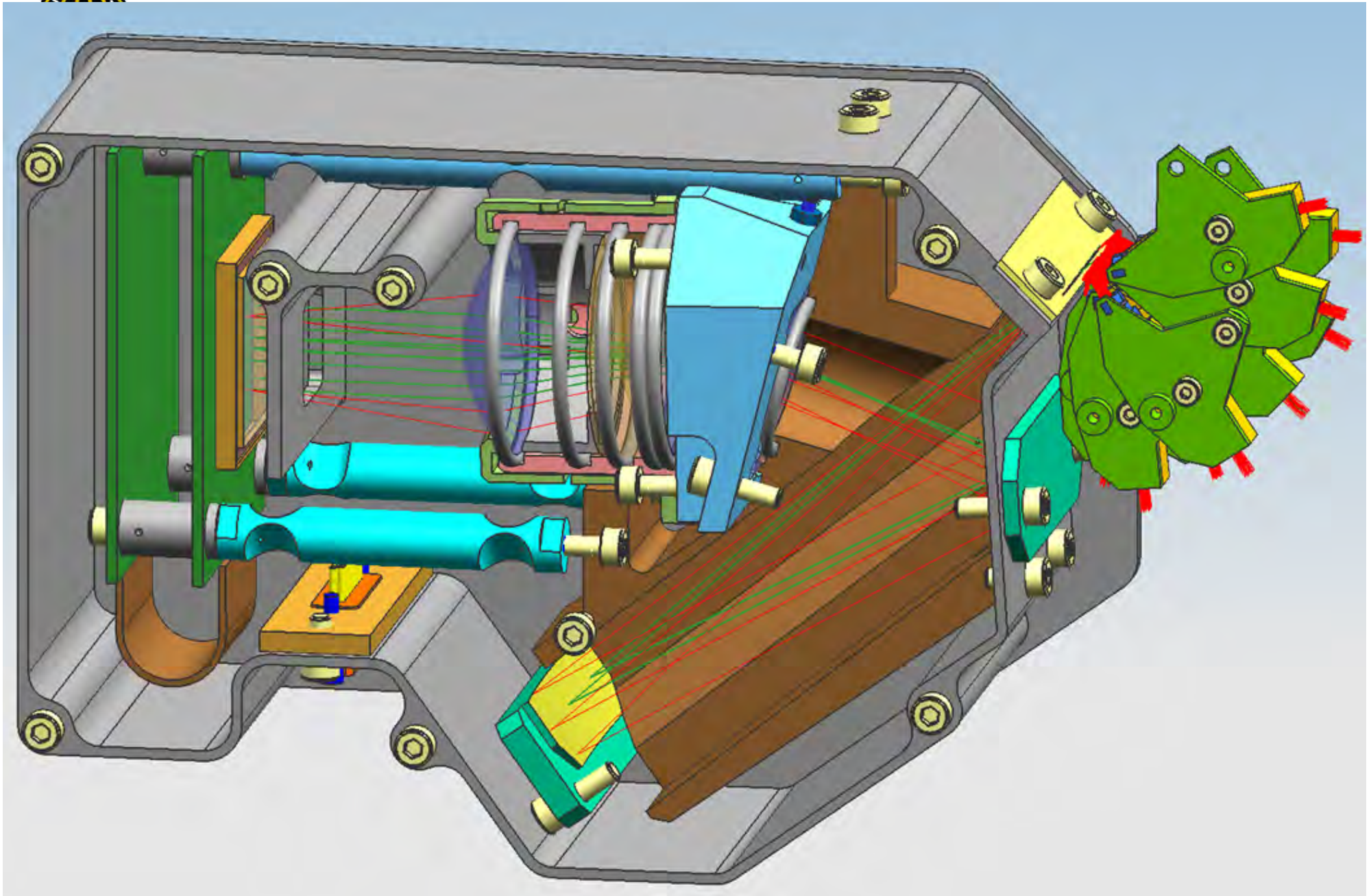


# SPEX Prototype Results





# SPEX Breadboard





# Other Polarimetry in Utrecht

- HARPSpol for ESO 3.6-m telescope at La Silla, Chile: Magnetic fields of stars that harbor planets
- S5T on Kitt Peak, USA: Weak solar magnetic fields
- New Worlds Observer and SPICES
- Beyond Astronomy
  - aerosols in Earth's atmosphere
  - Biomedical applications