High Contrast Imaging and Spectroscopy

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with slides from Matthew Kenworthy and Frans Snik

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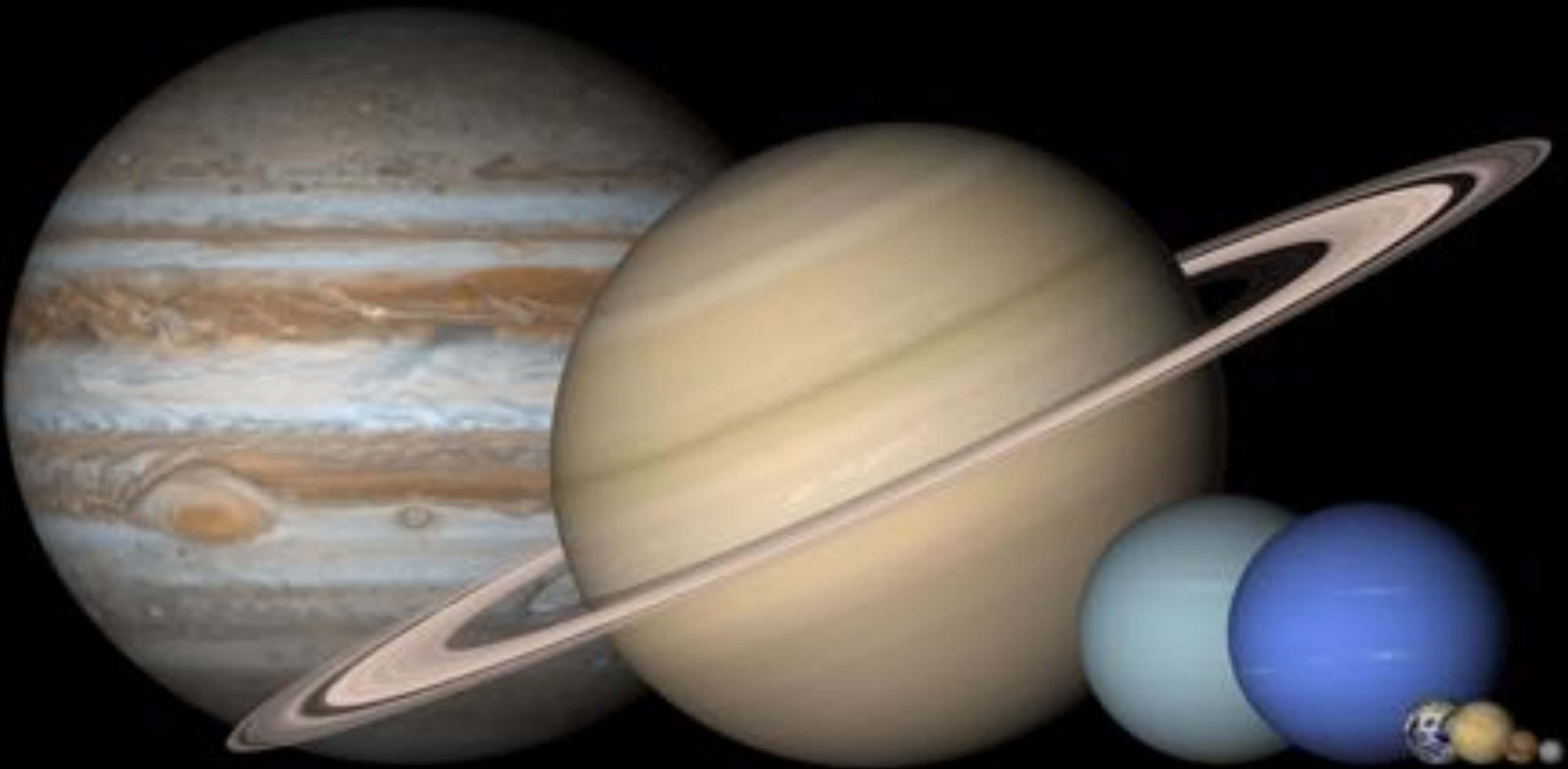
Direct Exoplanet Imaging & Characterization

- Direct imaging is unique in that no other planet-finding technique can accomplish the combination of
  - detection
  - spectroscopy
  - determination of orbital elements
- Reflected starlight from cold planets
- Non-transiting planets with long orbital periods
- Rotation, weather, seasons, moons, …

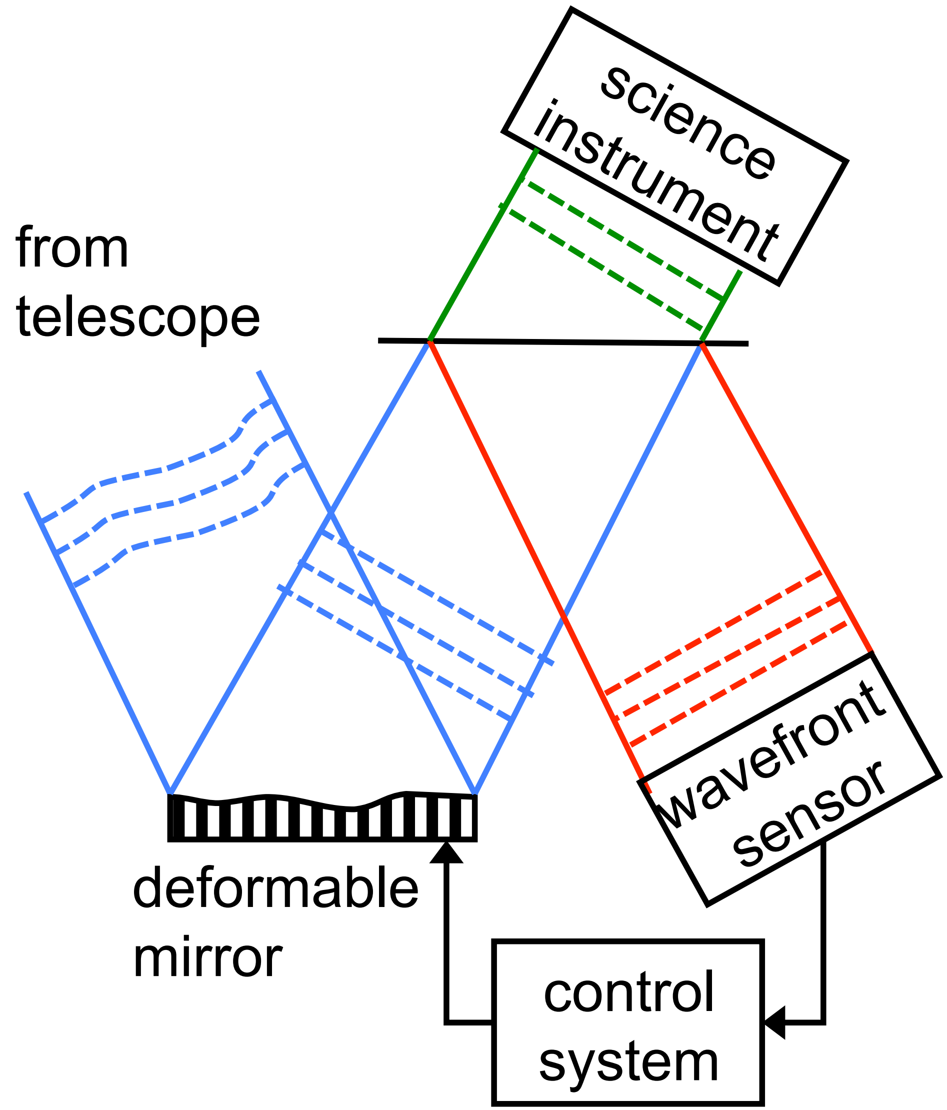


Jupiter: 10^{-9} ×Sun   Earth: 10^{-10} ×Sun

10^{-9} Contrast (Intensity Ratio)

Combination of Approaches

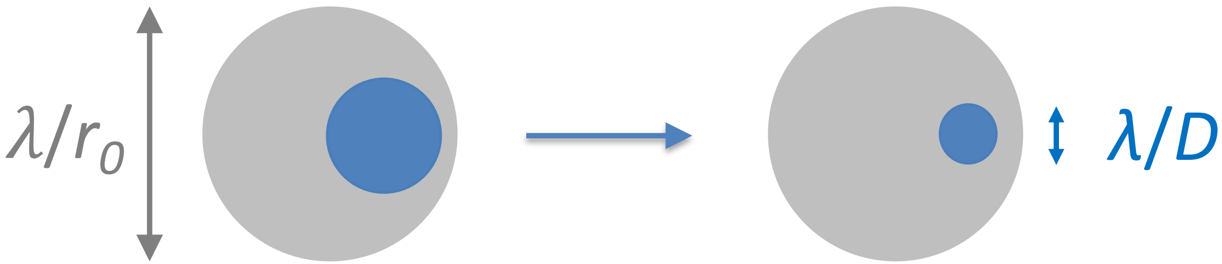
1. Large telescope
2. Extreme adaptive optics
3. Coronagraph
4. Focal-plane wavefront sensing
5. Diversity between star and planet
6. Data reduction



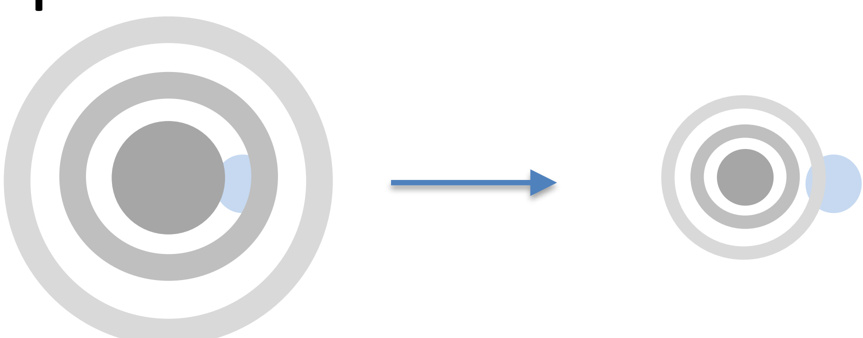
Need for Large Telescopes

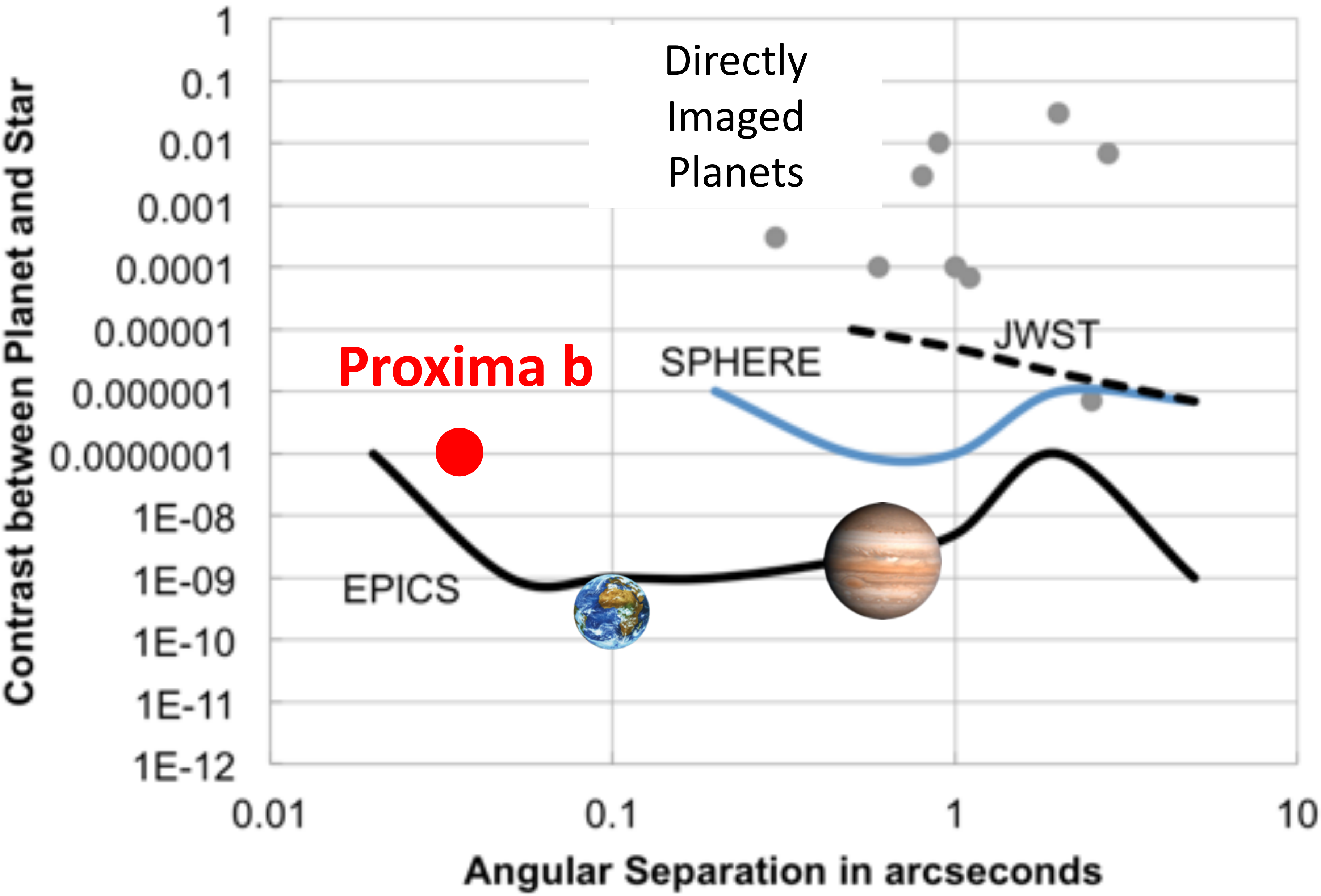
- Light bucket: signal $\sim D^2$

- Point-source area on seeing halo $\sim D^2$



- Drop-off of stellar diffraction $\sim D^2$



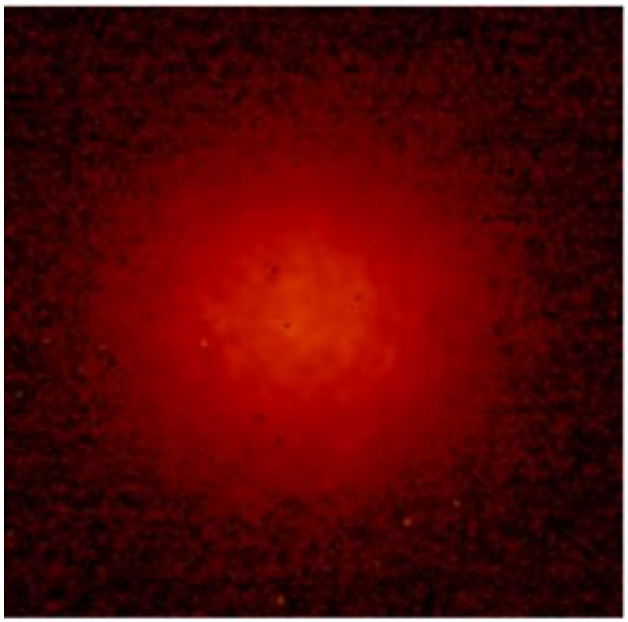

Directly
Imaged
Planets
Proxima b
SPHERE
JWST
EPICS
Contrast between Planet and Star
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
1E-08
1E-09
1E-10
1E-11
1E-12
0.01
0.1
1
10
Angular Separation in arcseconds

Wavefront Requirements

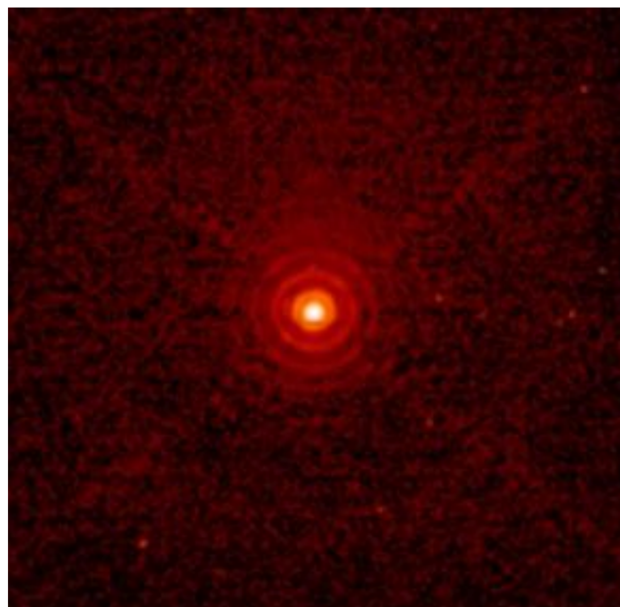
- 10^{-10} contrast at 760 nm (Oxygen O_2 A-Band) requires **0.1 nm rms total wavefront error**
- Ground-based telescopes now: ~100 nm rms
- Need subatomic optical path-length control
- Deformable Mirror requirements
  - 4’000 → 40’000 actuators
  - 1nm → 50pm resolution
  - 1kHz → 10kHz

Extreme AO – XAO

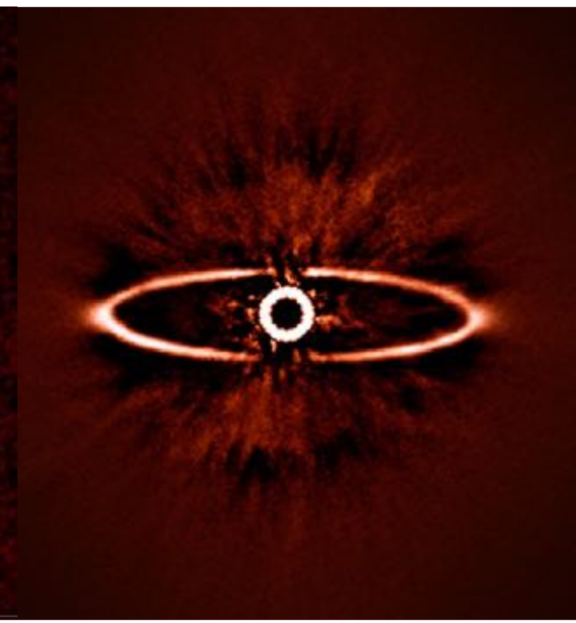
- >80% Strehl on-axis and small corrected field-of-view
- requires many thousands of deformable mirror actuators
- requires exquisite optical performance
- SPHERE on VLT, GPI on Gemini, SCExAO on Subaru



Seeing limited image
$5.2 \pm 2\%$ SR



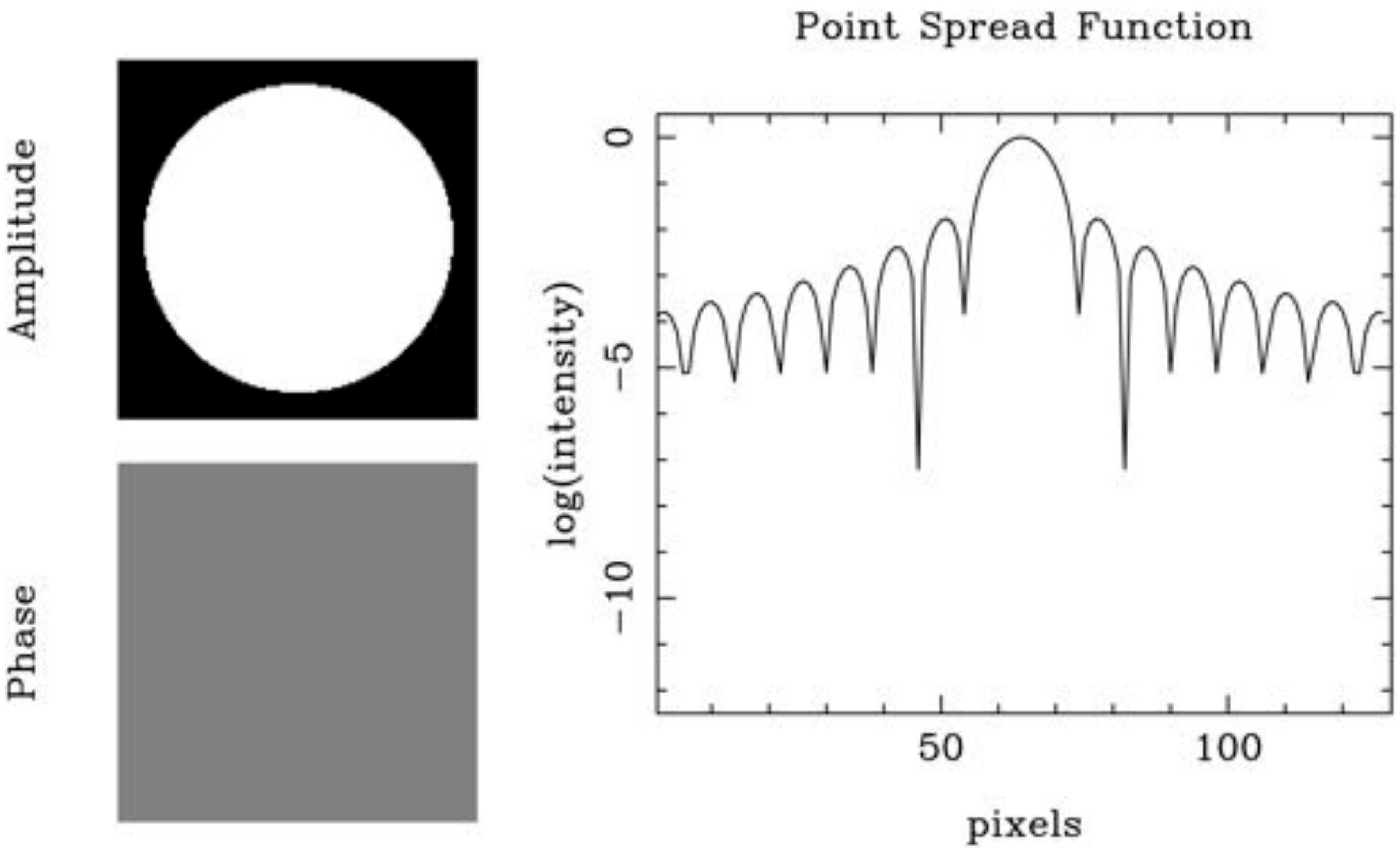
AO corrected image
$90.3 \pm 2\%$ SR



Wavefront Errors Everywhere

Hubble Space Telescope

Diffraction ☹



Ideal ELT Point-Spread Function

39m telescope pupil

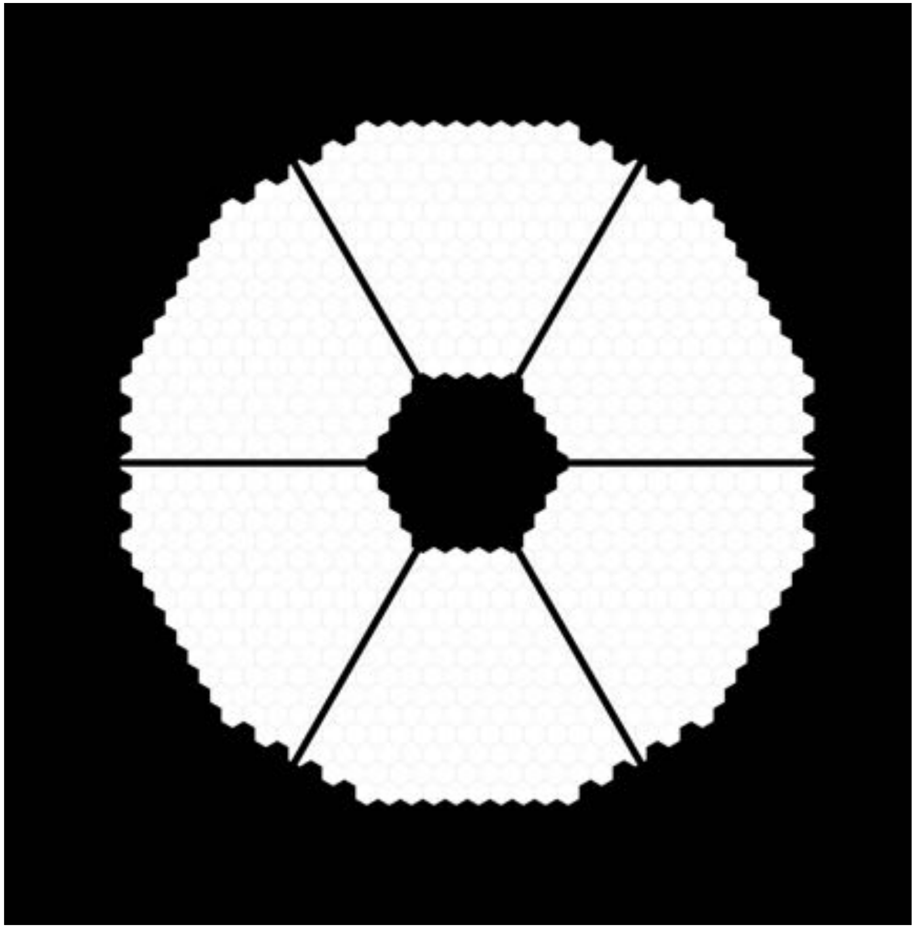
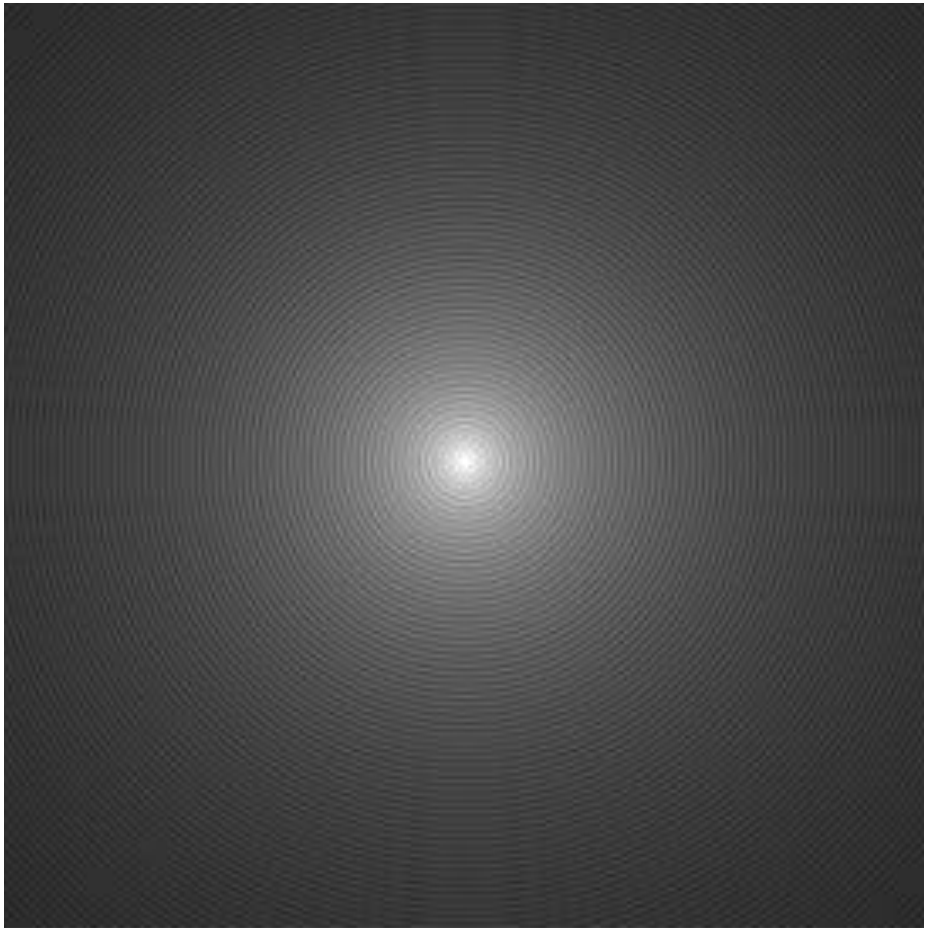


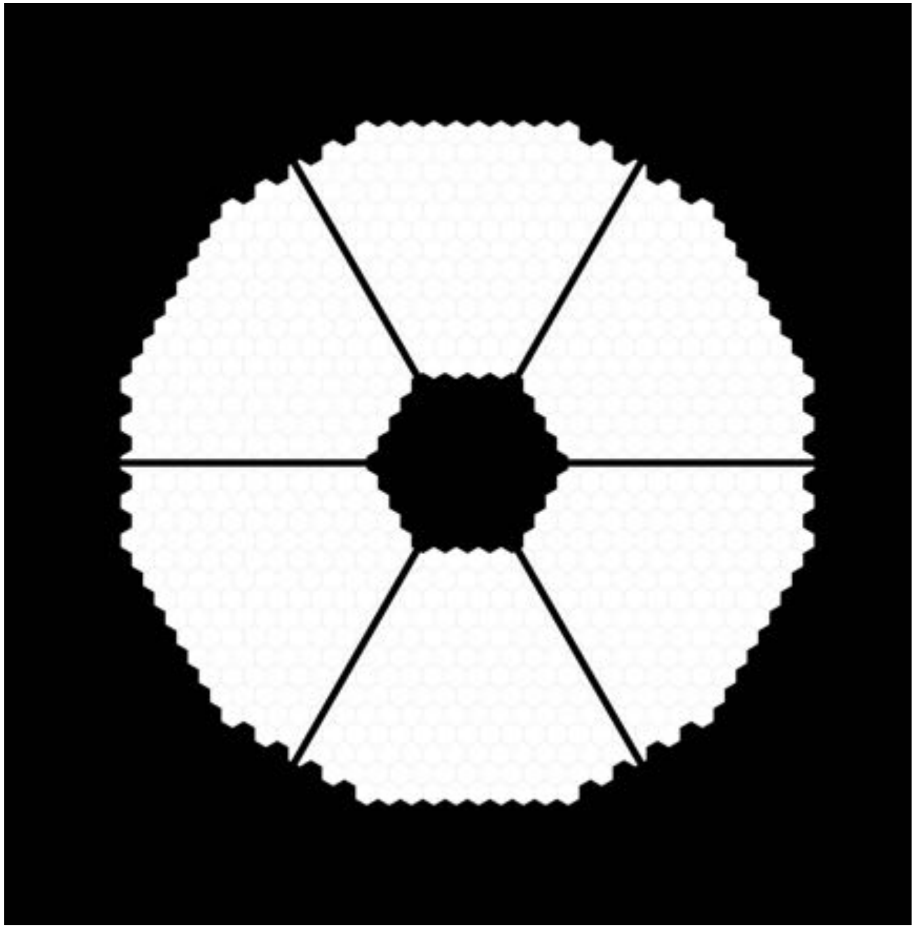
image of a point source (log scale)



courtesy Frans Snik

Ideal ELT Point-Spread Function

39m telescope pupil



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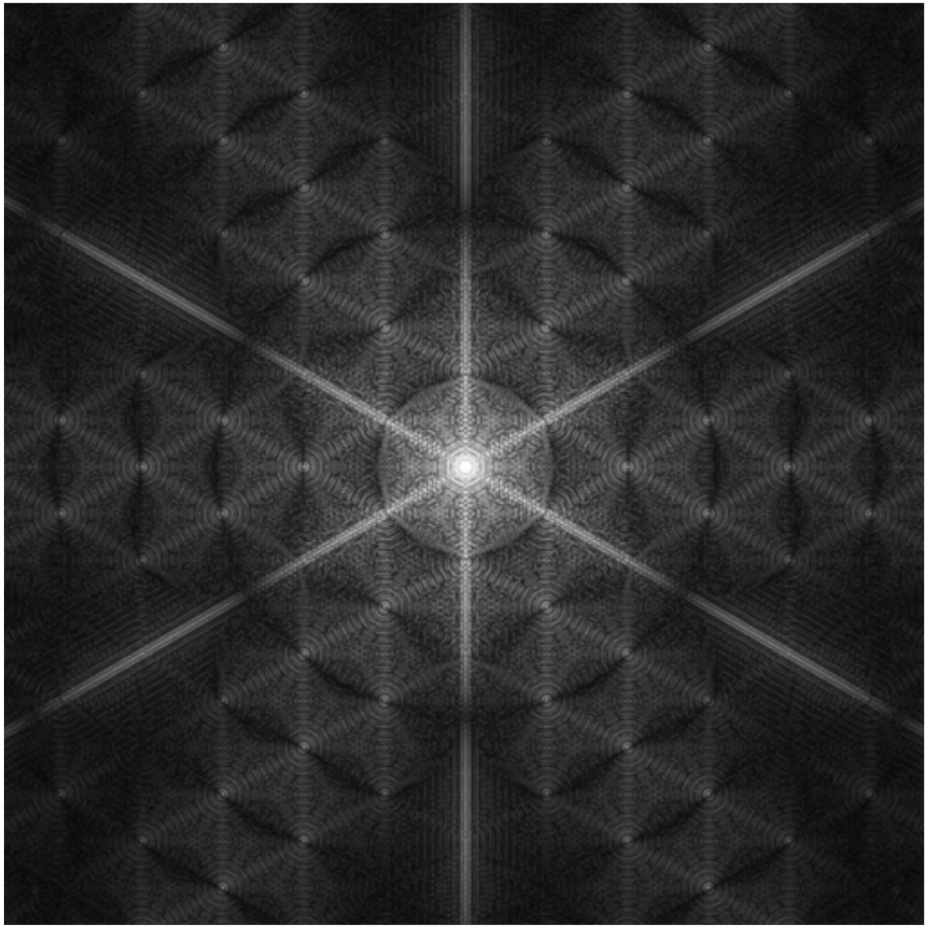
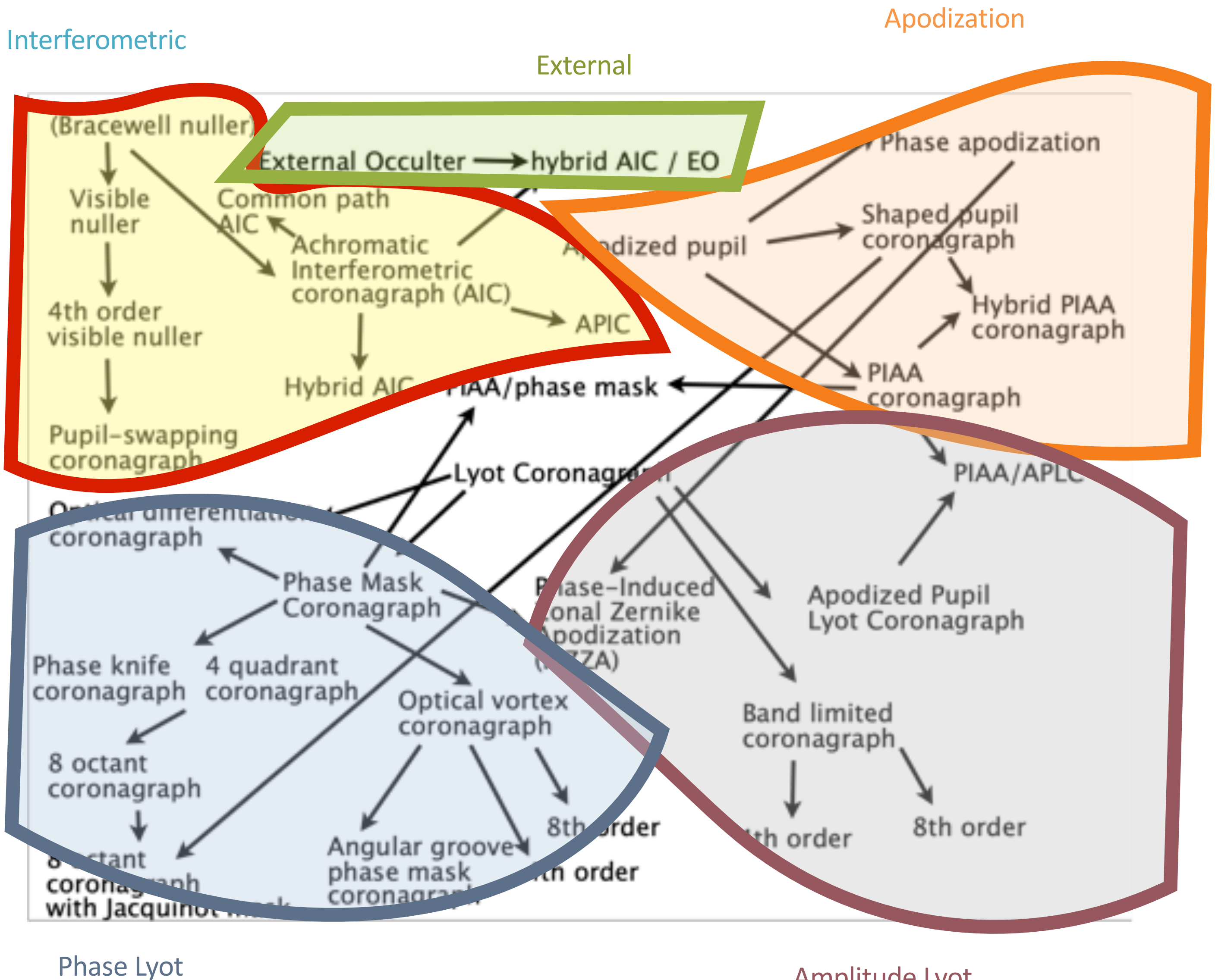
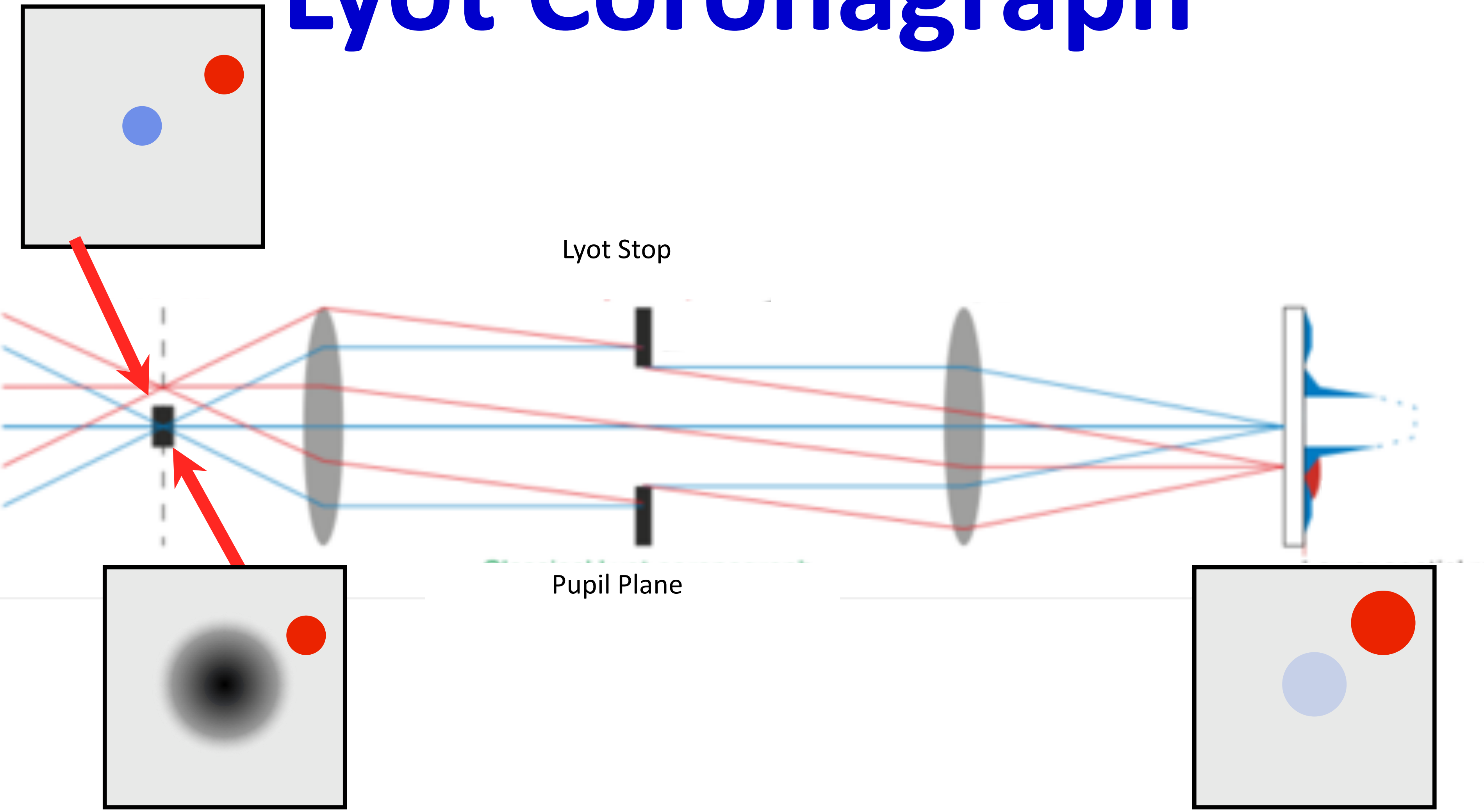


courtesy Frans Snik

Many Types of Coronagraphs

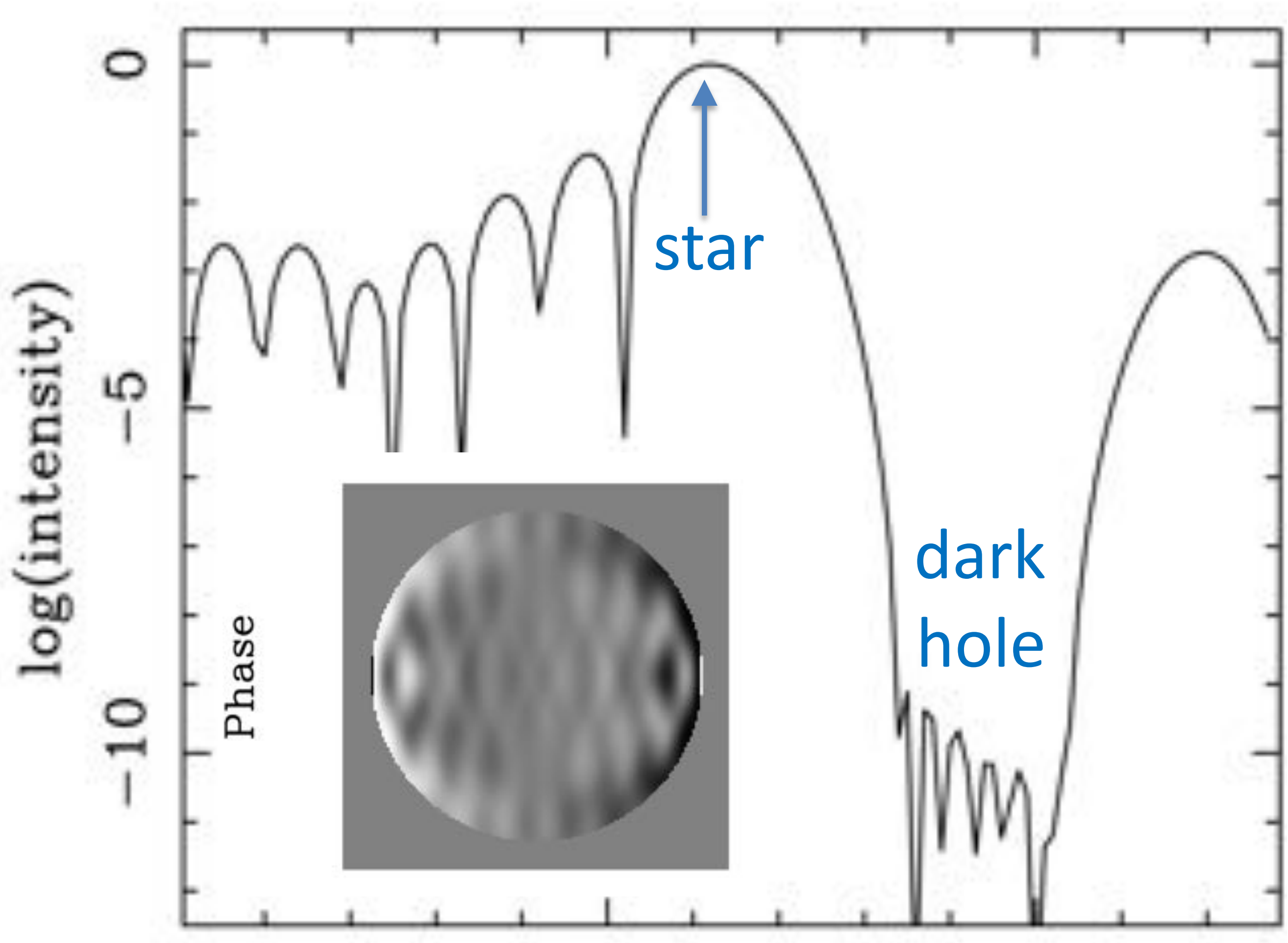


Lyot Coronagraph



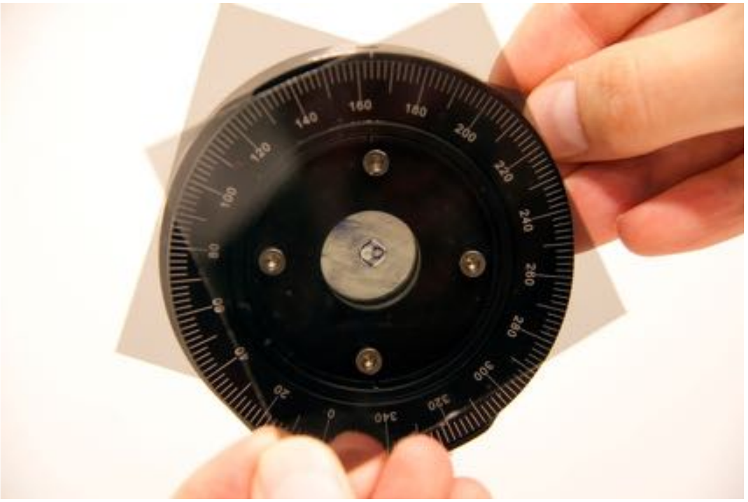
Controlled Aberrations

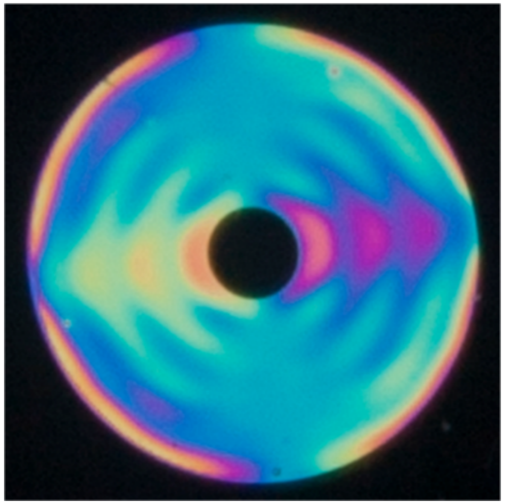
- Inherently independent of position of star
- Arbitrary aperture
- Arbitrary dark hole
- Perfect small dark holes



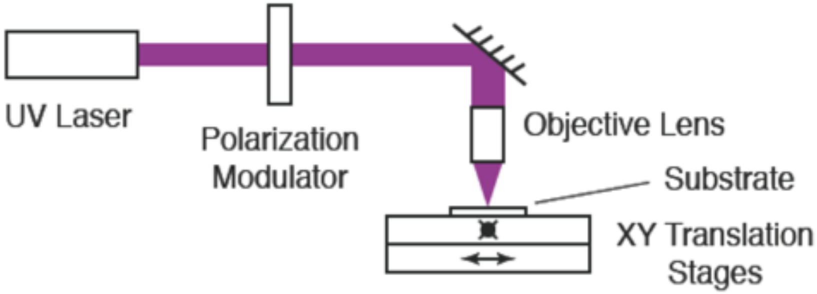
Frans Snik

Achromatic Geometric Phase Plate



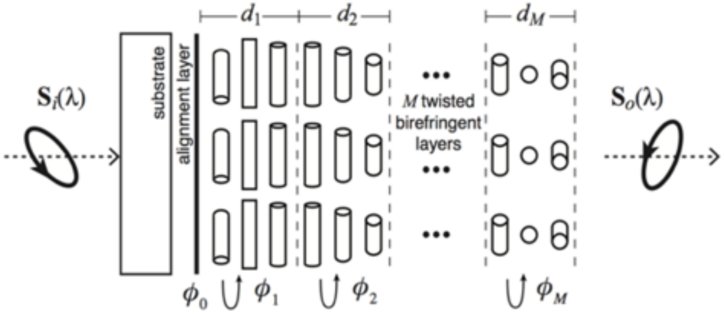


any phase pattern thanks to direct-write technique



Miskiewicz & Escuti (2014

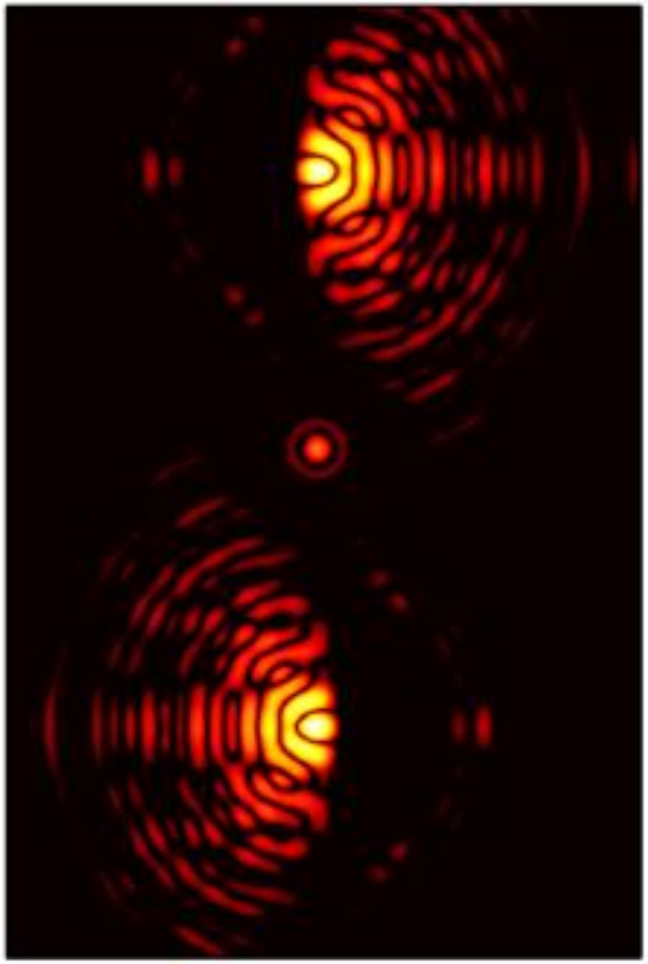
achromatic thanks to (self-aligning) multi-twist retarder

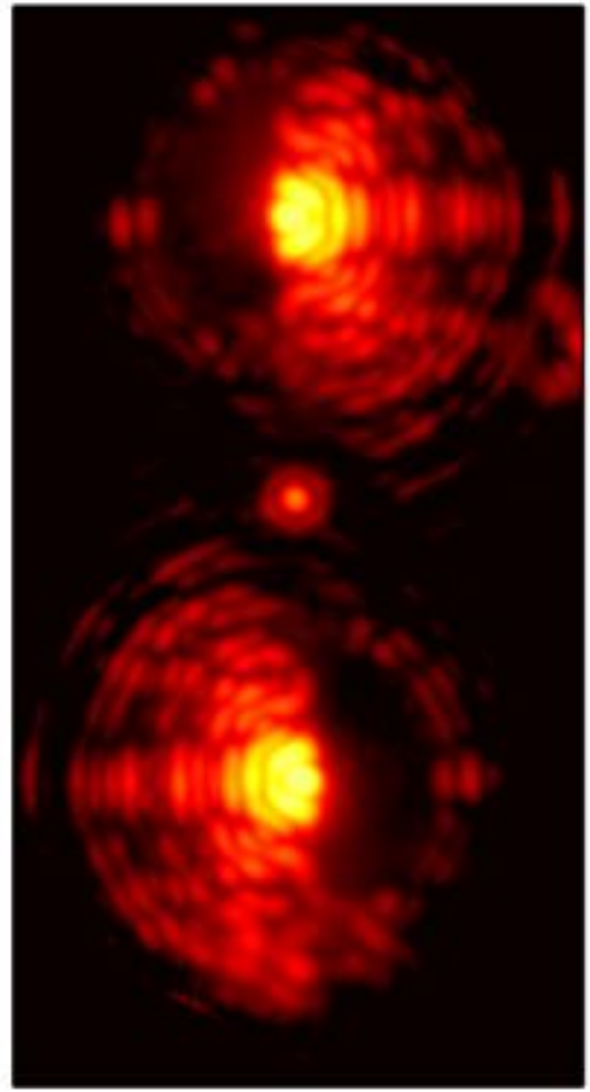


Komanduri et al. (2013)

Apodizing Phase Plate Coronagraph

simulation



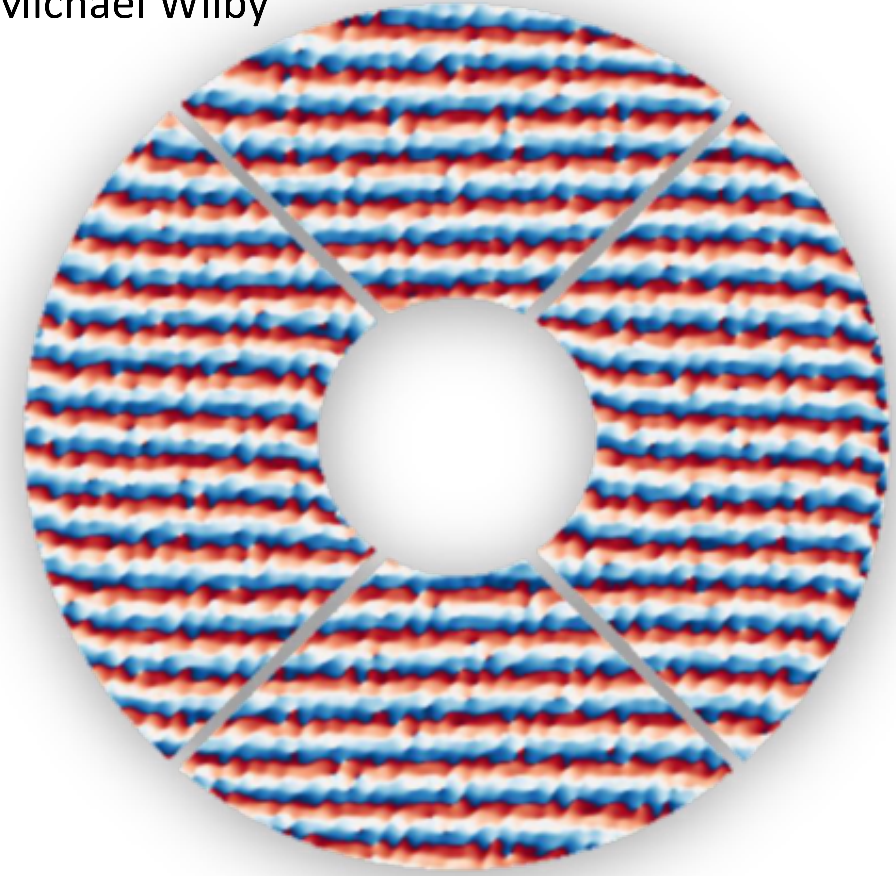


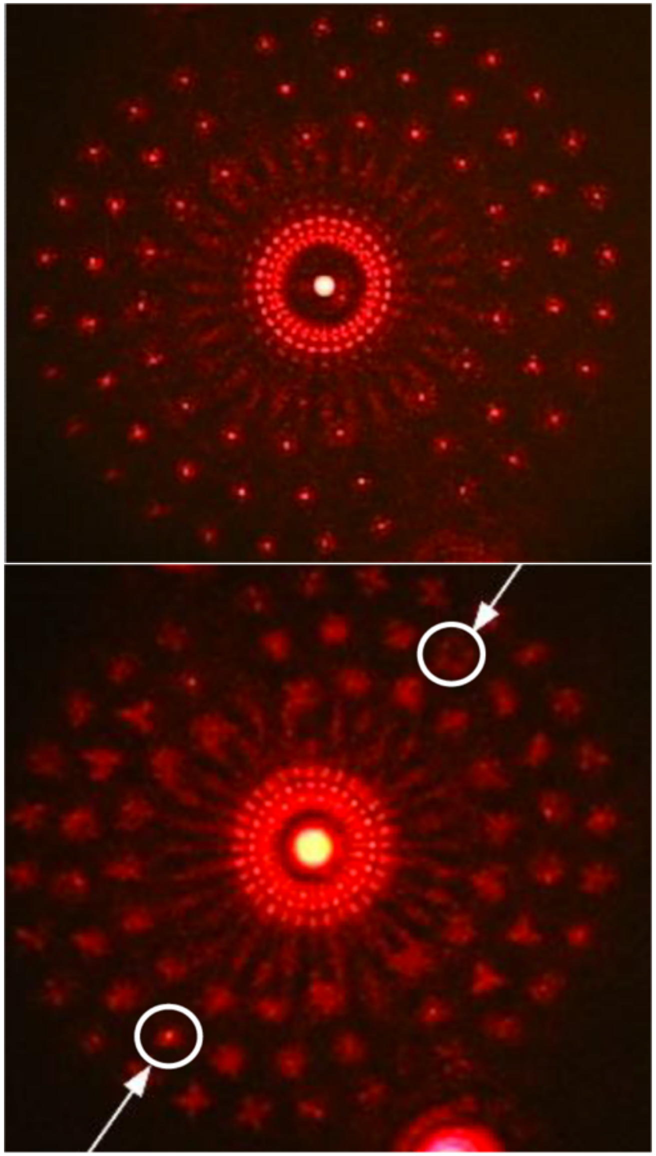
on-sky

Otten et al. 2015

Holographic Wavefront Sensing

Michael Wilby

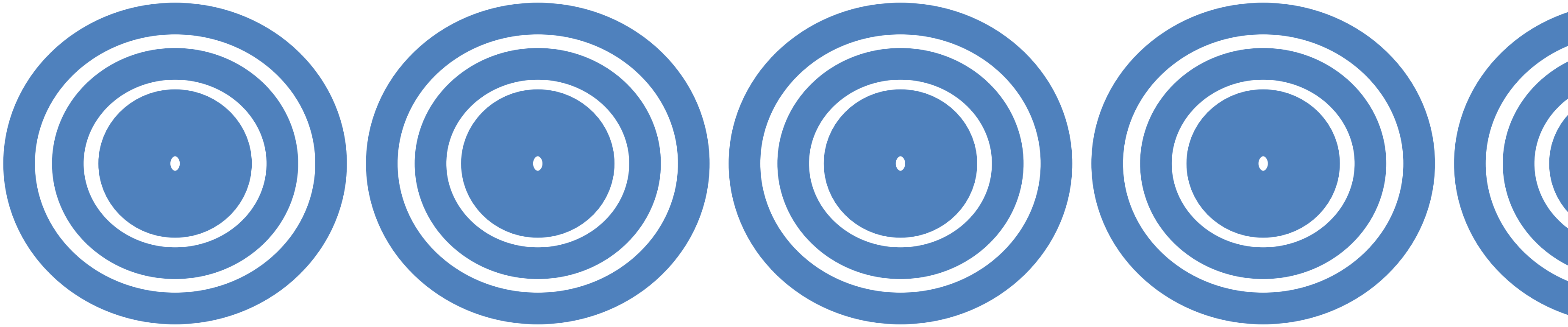




Wilby et al. 2016, 2017

Diversity Between Star and Planet

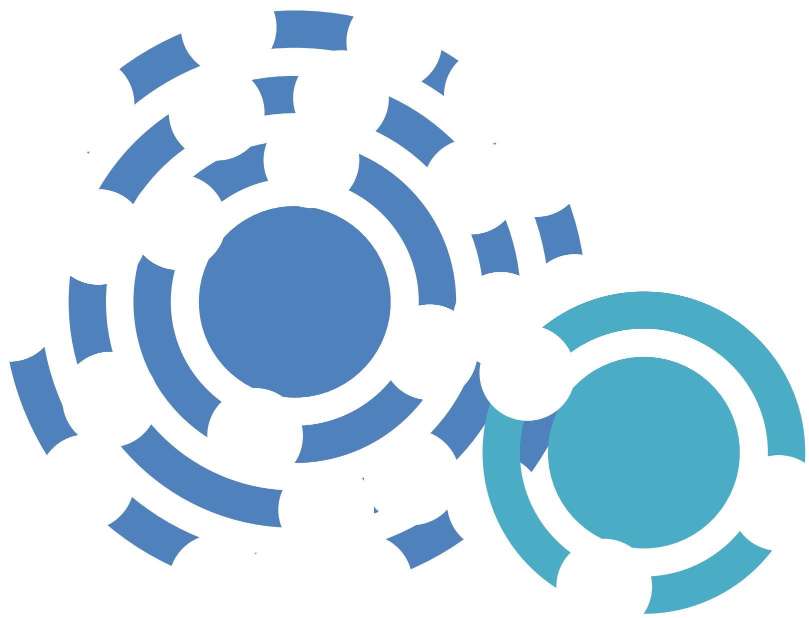
- Angular Differential Imaging
- Reference Star Differential Imaging
- Spectral Differential Imaging
- Polarimetric Differential Imaging
- High Dispersion Spectroscopy



I_1 I_2 I_3 $\cdots$

Angular Diversity

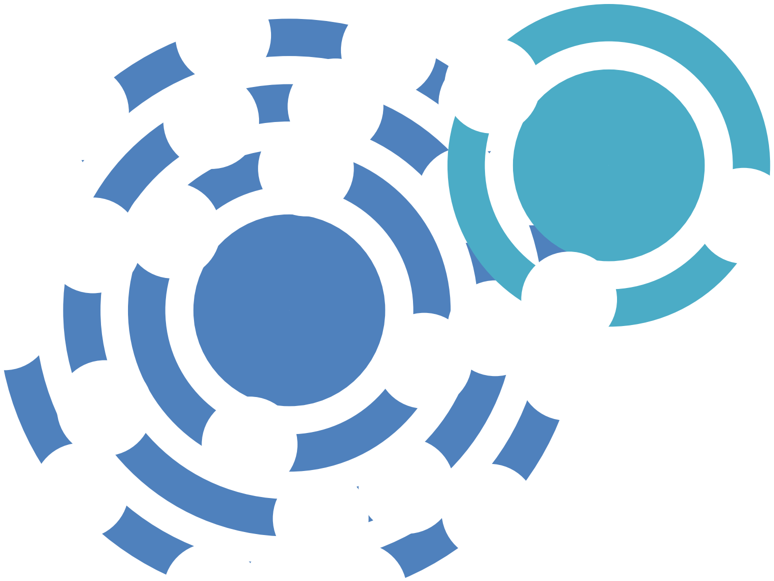
$$I_n = I(\theta_n, t_n)$$



The telescope optics are fixed with respect to the science detector and the sky rotates around

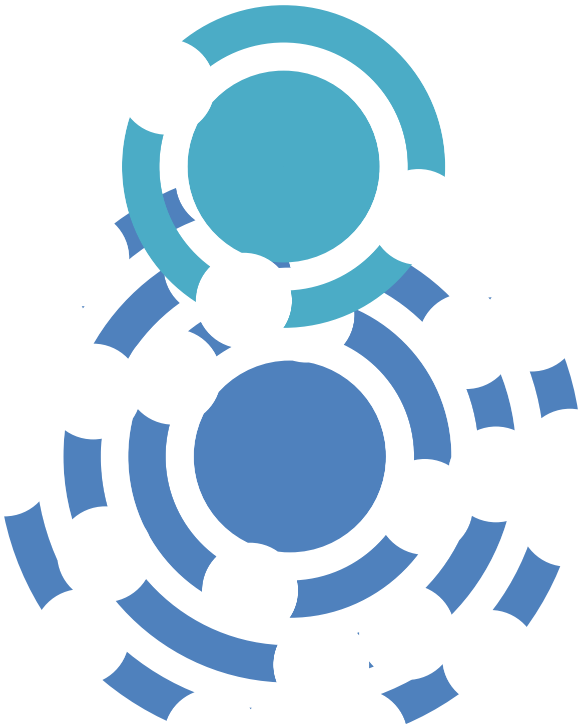
Angular Diversity

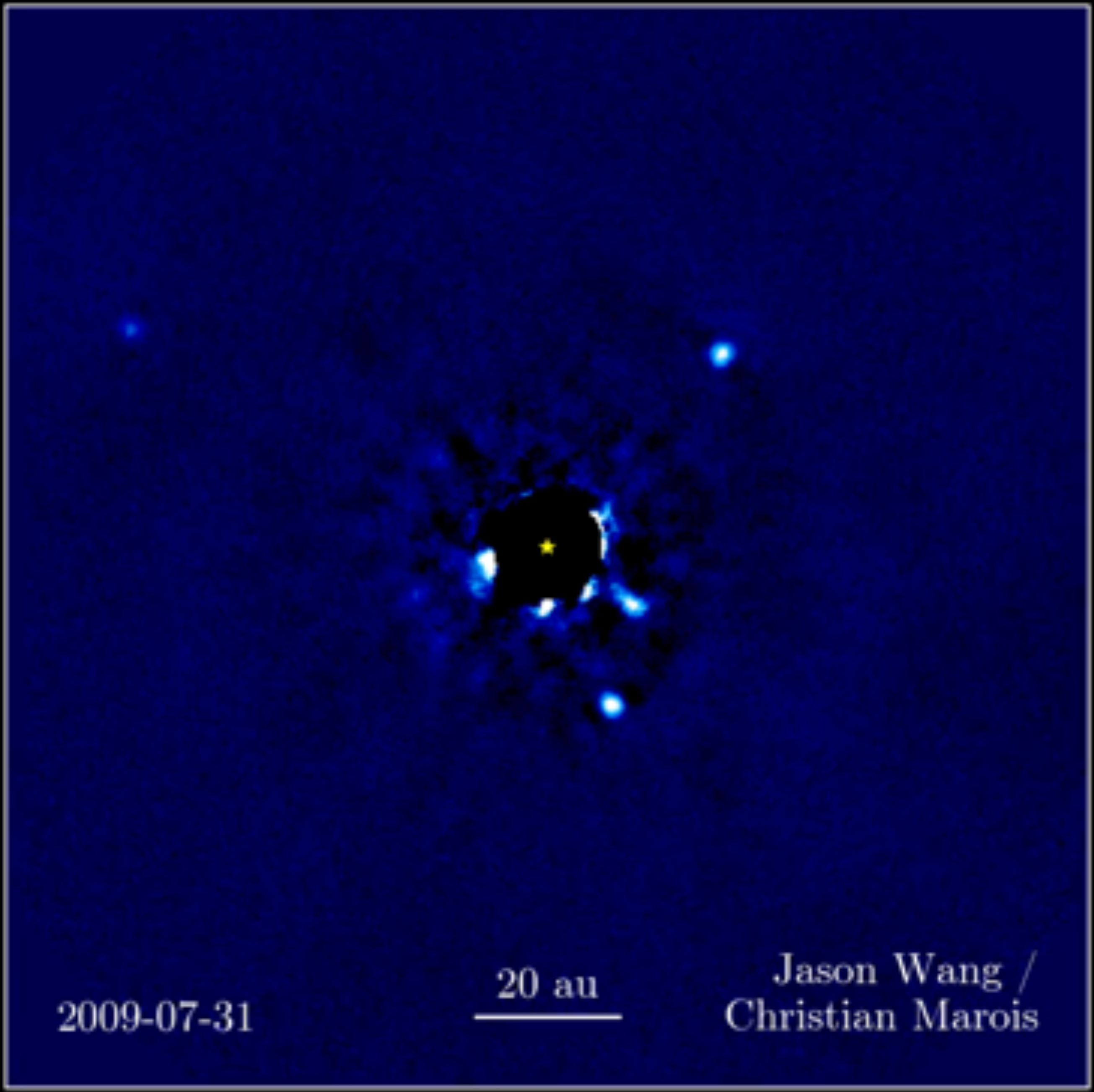
$$I_n = I(\theta_n, t_n)$$



Angular Diversity

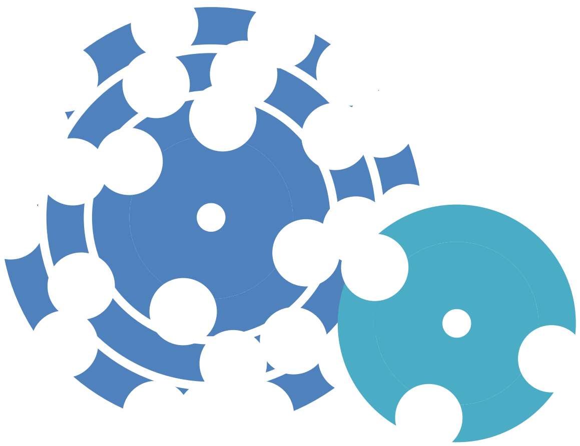
$$I_n = I(\theta_n, t_n)$$




20 au
2009-07-31
Jason Wang /
Christian Marois

Spectral Diversity

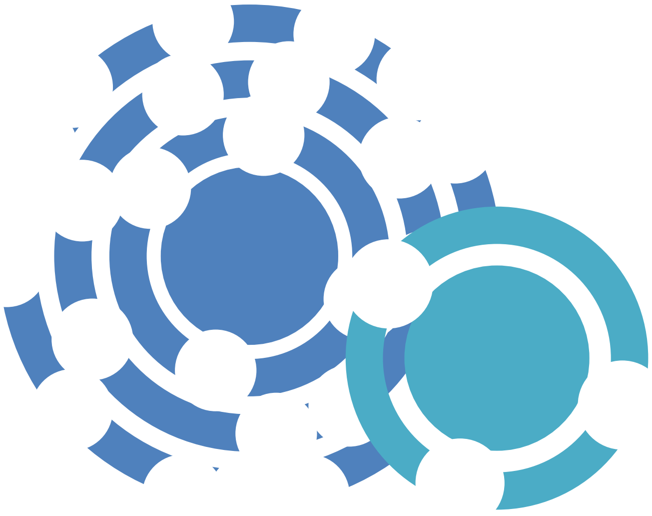
$$I_1 = I(\lambda_1)$$



PSF scales as $\frac{\lambda}{D}$.

Spectral Diversity

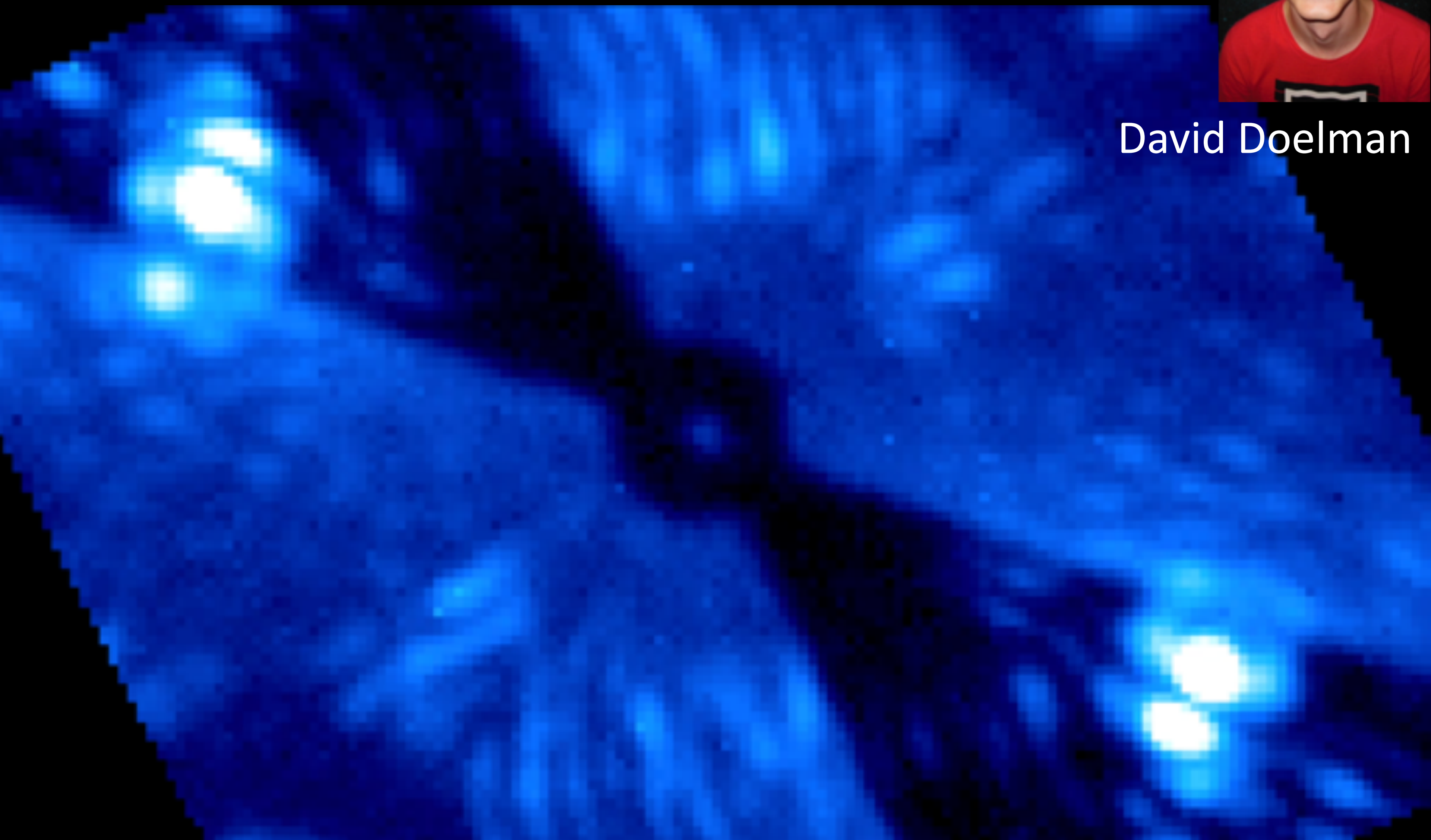
$$I_2 = I(\lambda_2)$$



Spectral Diversity

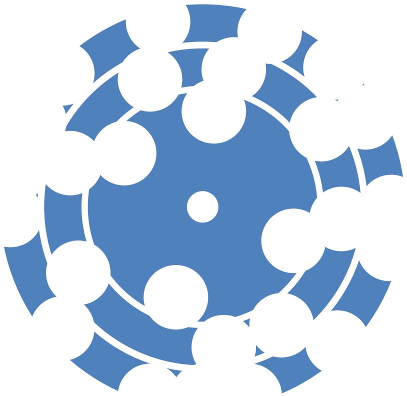
$$I_n = I(\lambda_n)$$

CHARIS/Subaru

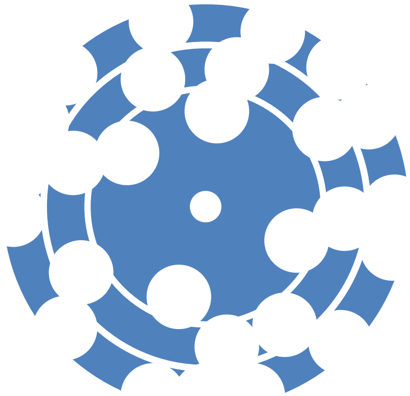


David Doelman

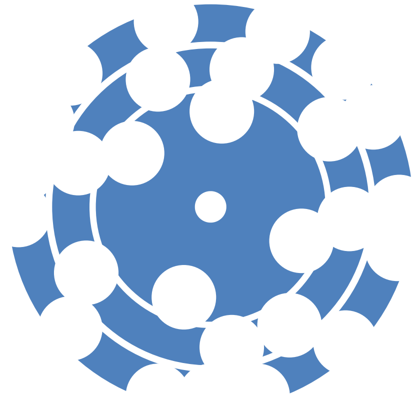
PSF Library



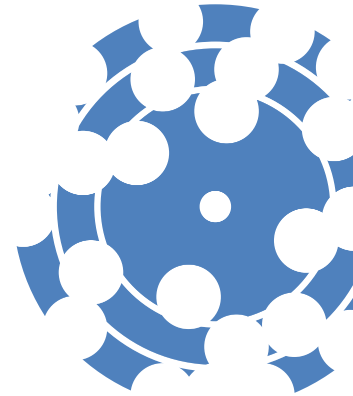
$I_1 = I(\text{Star 1})$



$I_2 = I(\text{Star 2})$



$I_3 = I(\text{Star 3})$

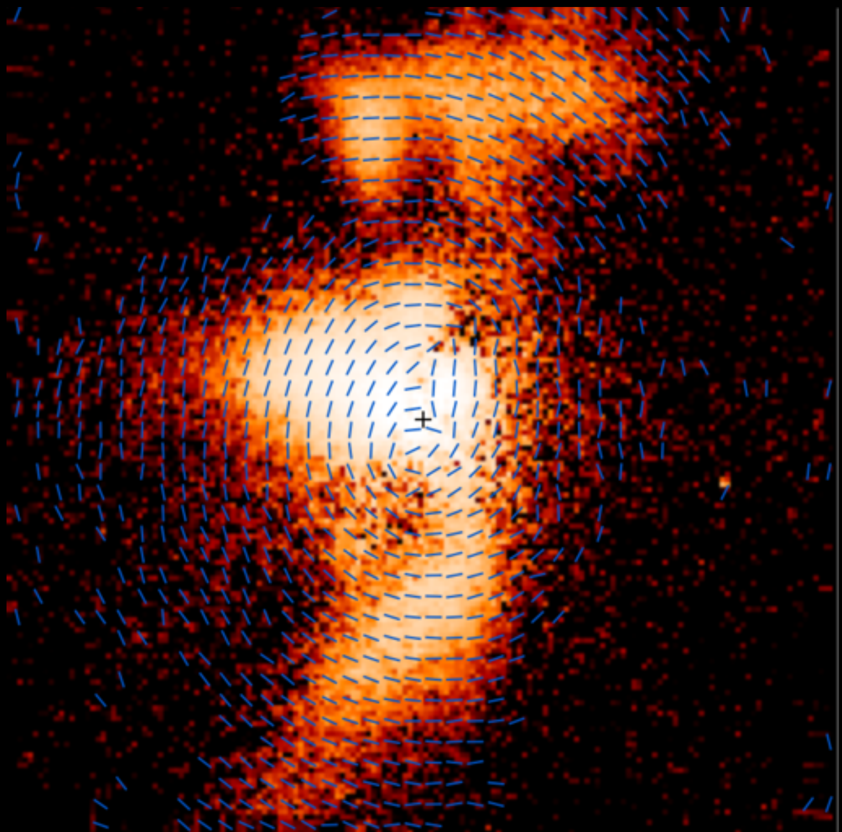


$\cdots$

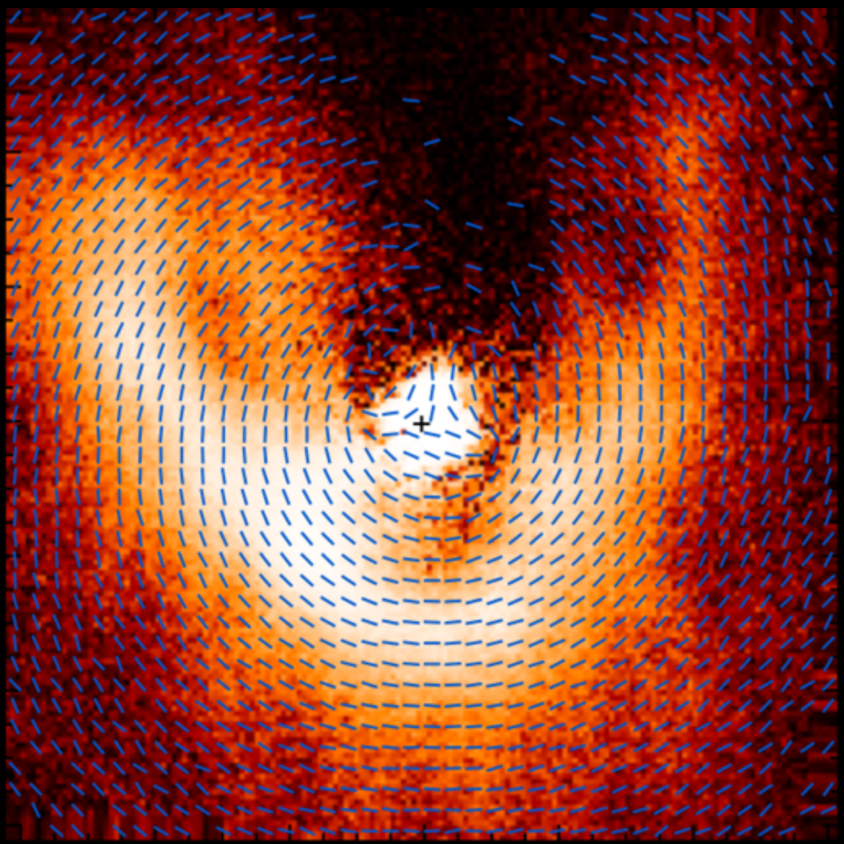
Use other stars without planets

Polarimetry

Extreme Polarimeter at William Herschel Telescope



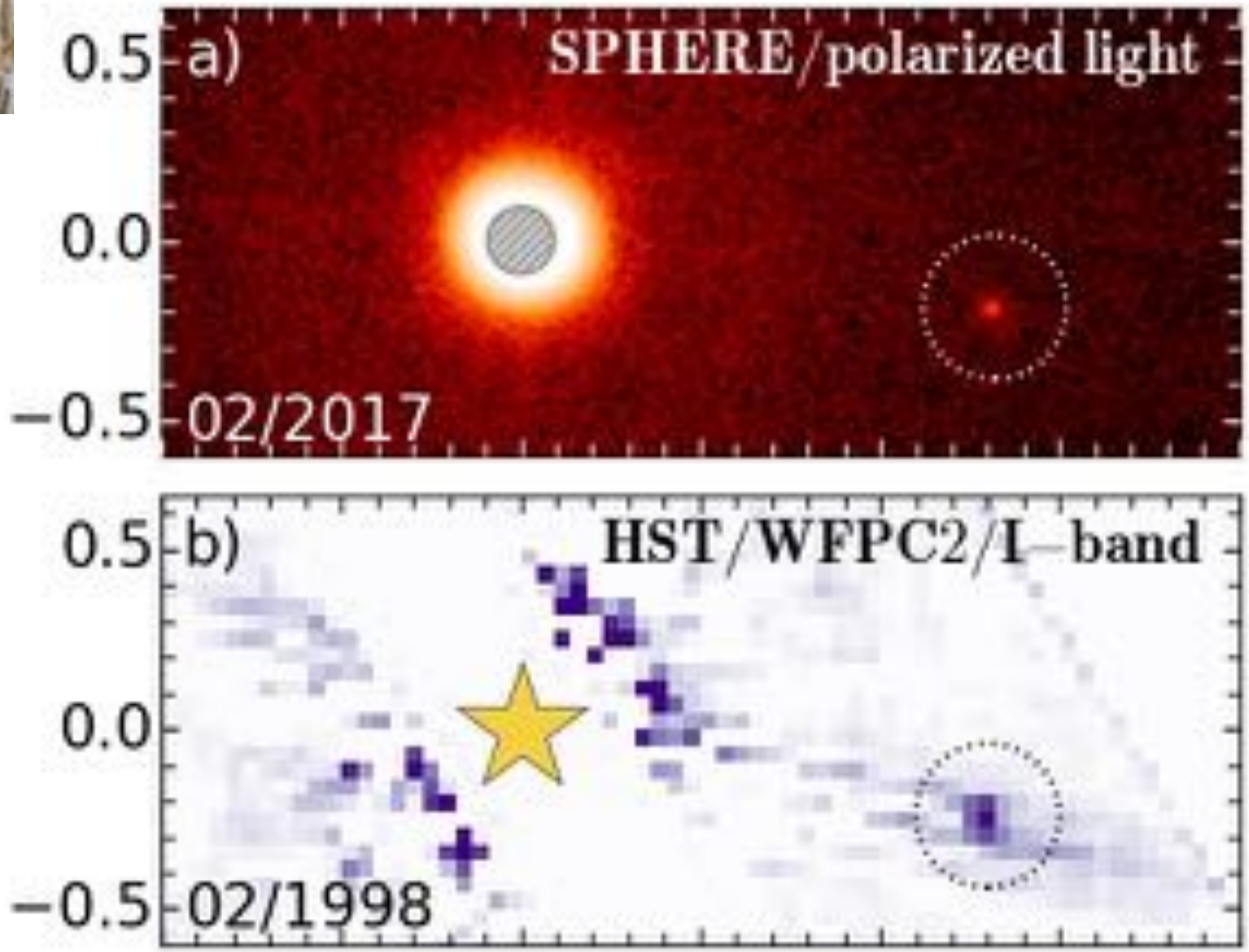
T-Tauri



MWC147

Christian Ginski

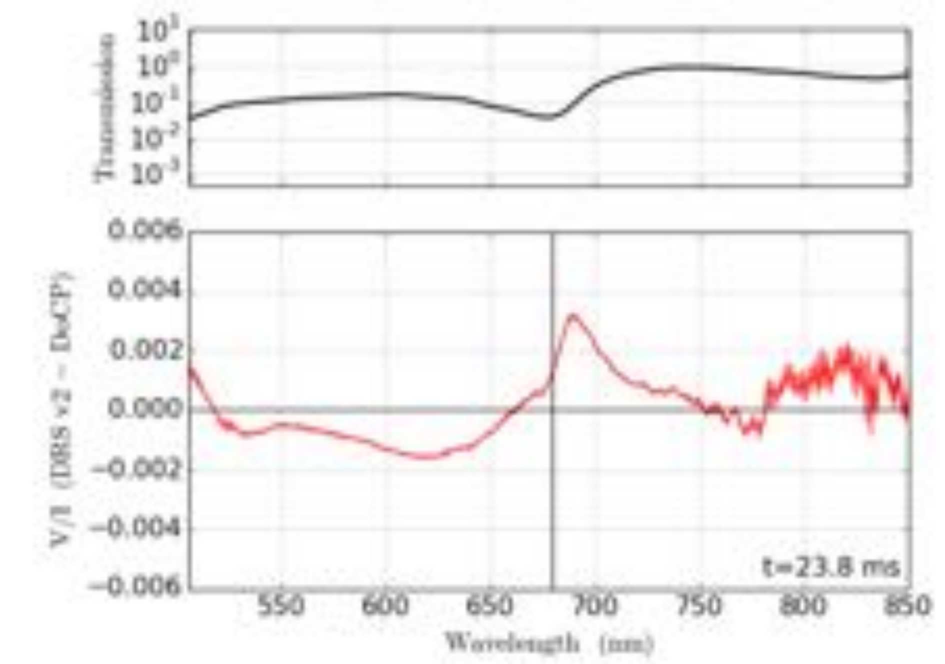
Polarized CS Cha b/B



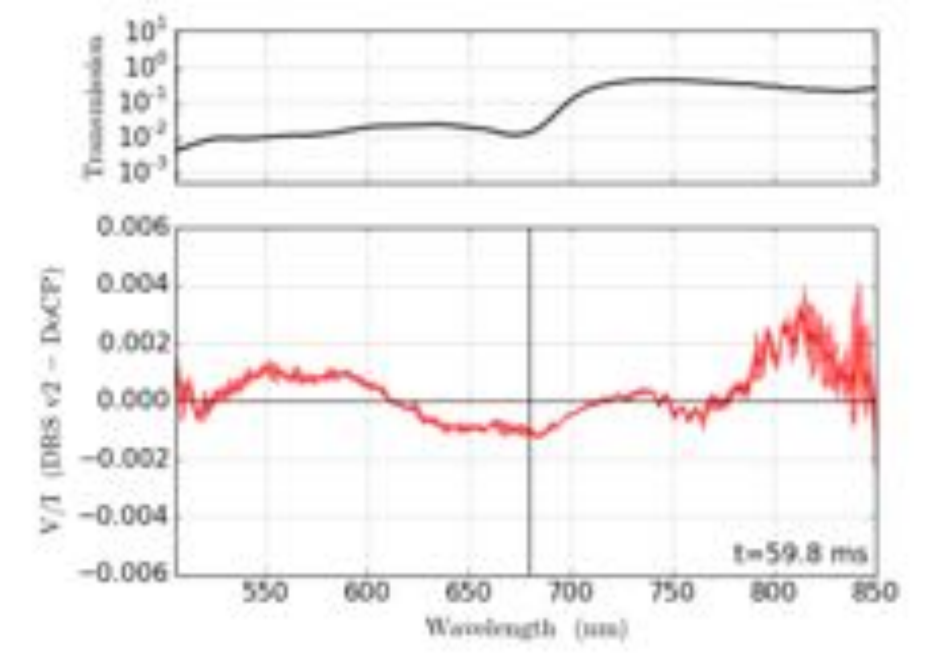
Ginski et al. 2018

red cotinus leaf (transmission)

freshly picked

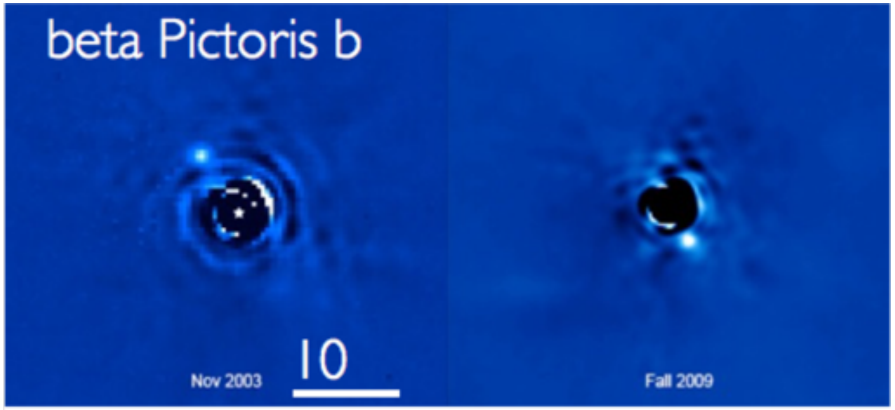


after a week

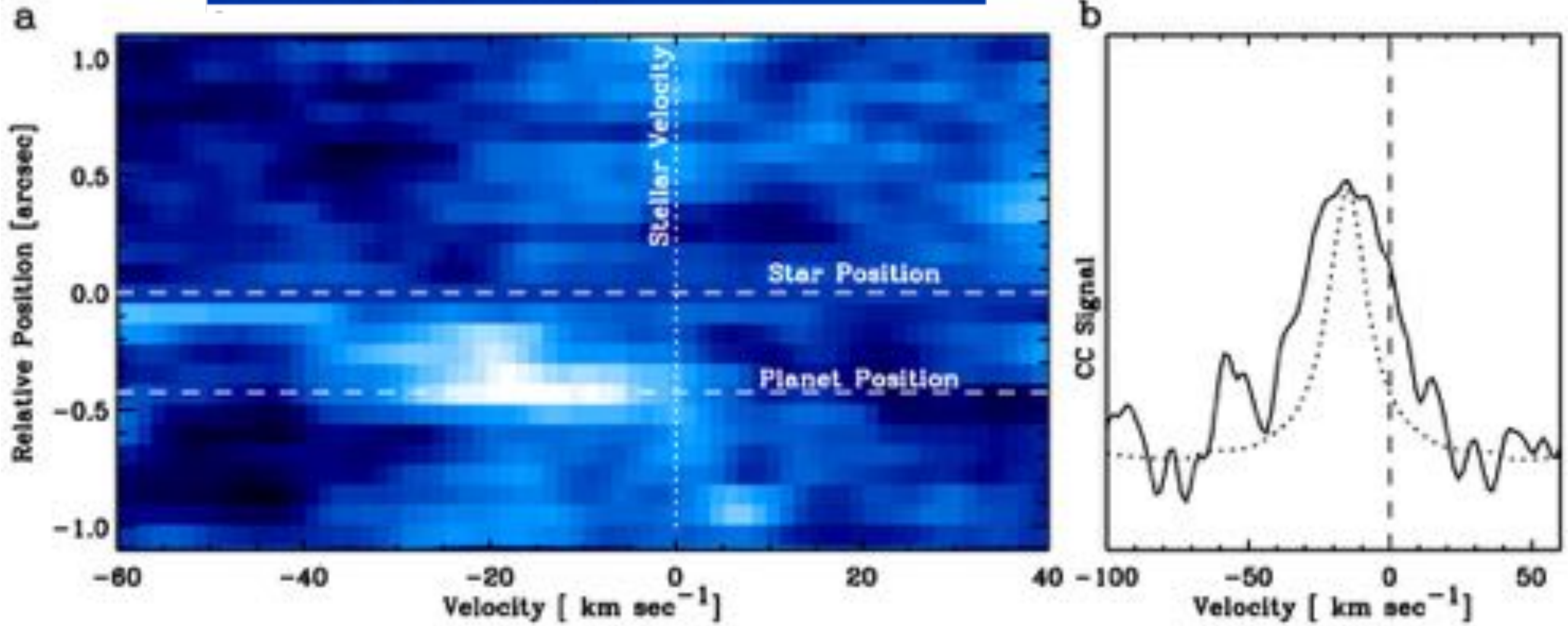


Visser & Snik (2014)

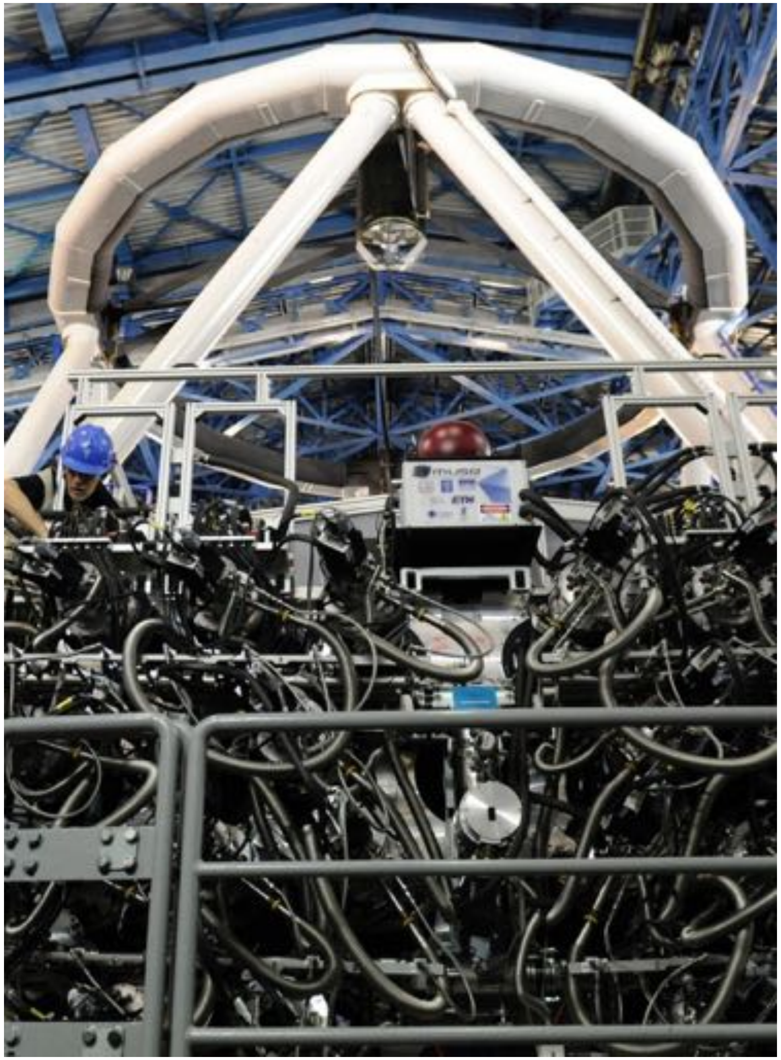
Imaging & High-Dispersion Spectroscopy



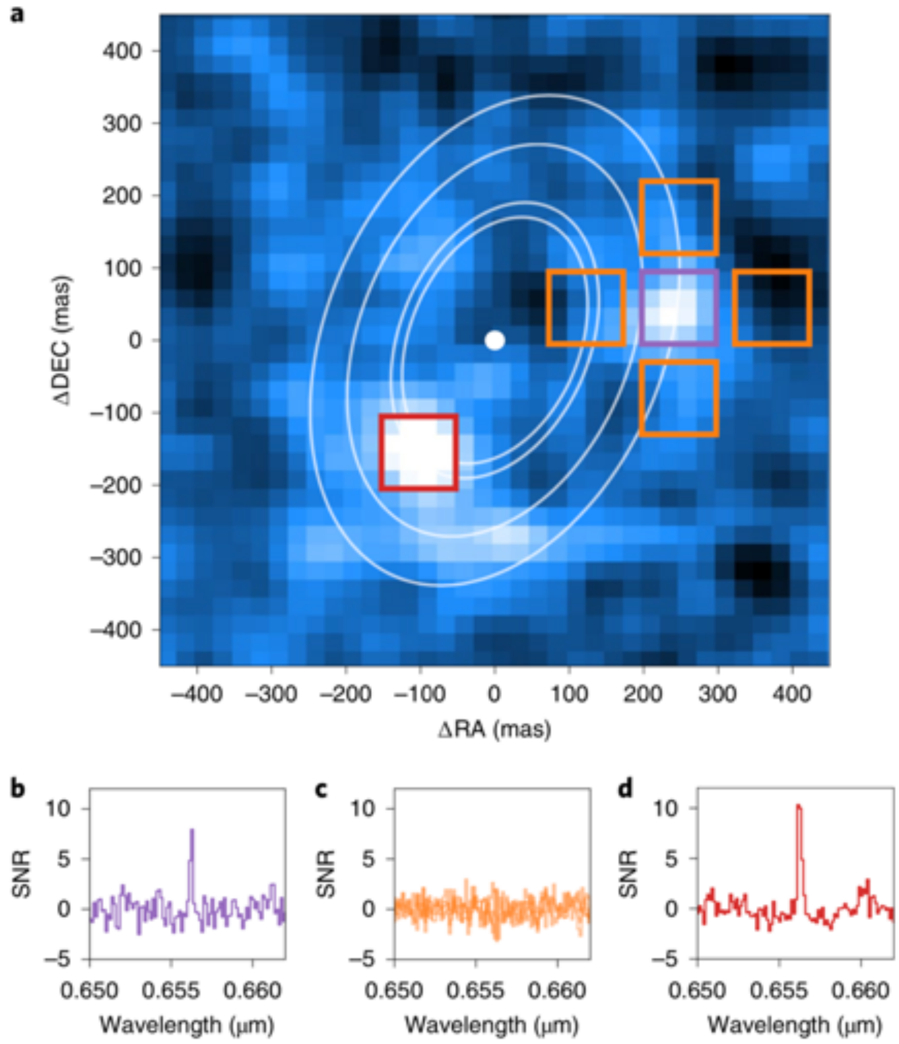
Snellen et al. 2014



PDS70b,c with MUSE at VLT

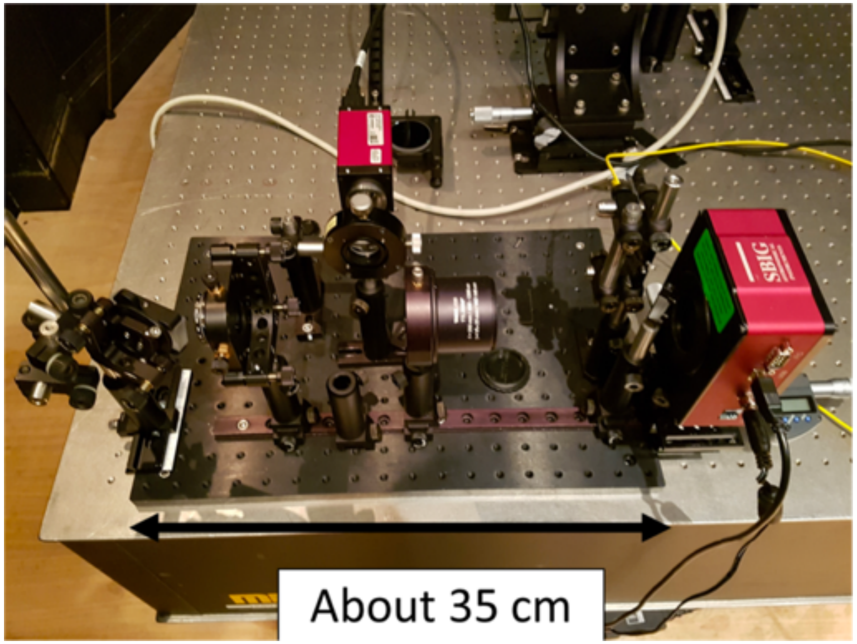


muse-vlt.eu/science/cropped-dsc0194-jpg



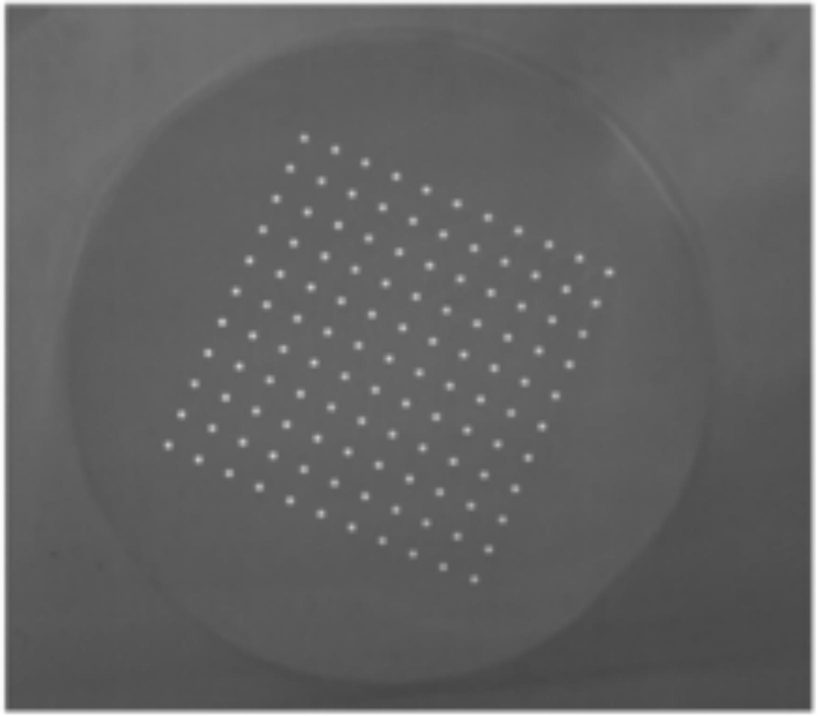
Haffert et al. (2019)

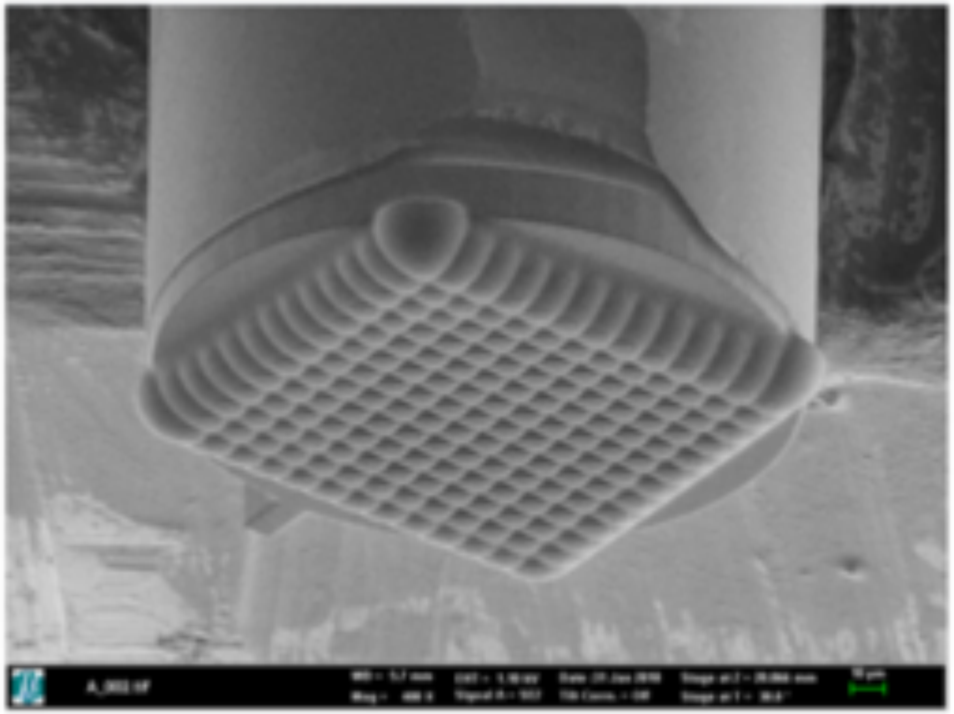
Diffraction-Limited Hires Spectrograph



LEXI Multi-Core Fiber SCAR

Sebastiaan Haffert





Major Remaining Issues

- Polarization aberrations
  - aberrations depend on polarization state
  - flat mirror is a polarizing beamsplitter
- Chromatic wavefront correction
  - wavefront aberration depends on wavelength
  - current systems limited to ≤10% bandwidth
  - characterization requires large wavelength coverage
- Primary mirror with variable missing segments

Outlook

- Current on-sky final contrast limit: 10^{-7}
- Larger telescopes help towards 10^{-9}
- Contrast limit given by coupled system of telescope, instrument, and data reduction
- Space-based telescopes face many of the same problems