High-Contrast Polarimetry: Lessons Learned

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Leiden Observatory Expertise

	Astronomy	Remote Sensing	Biomedical Imaging
Polarimetry	HARPSPol, ExPo, SPHERE, EPICS	SPEX, iSPEX, LOUPE, …	looking for opportunities
Adaptive optics	ExPo, Fast & Furious		2-photon microscopy
Image Reconstruction	phase diversity, deconvolution		
Hyperspectral Imaging	pIFU	SPEX, LOUPE	looking for opportunities

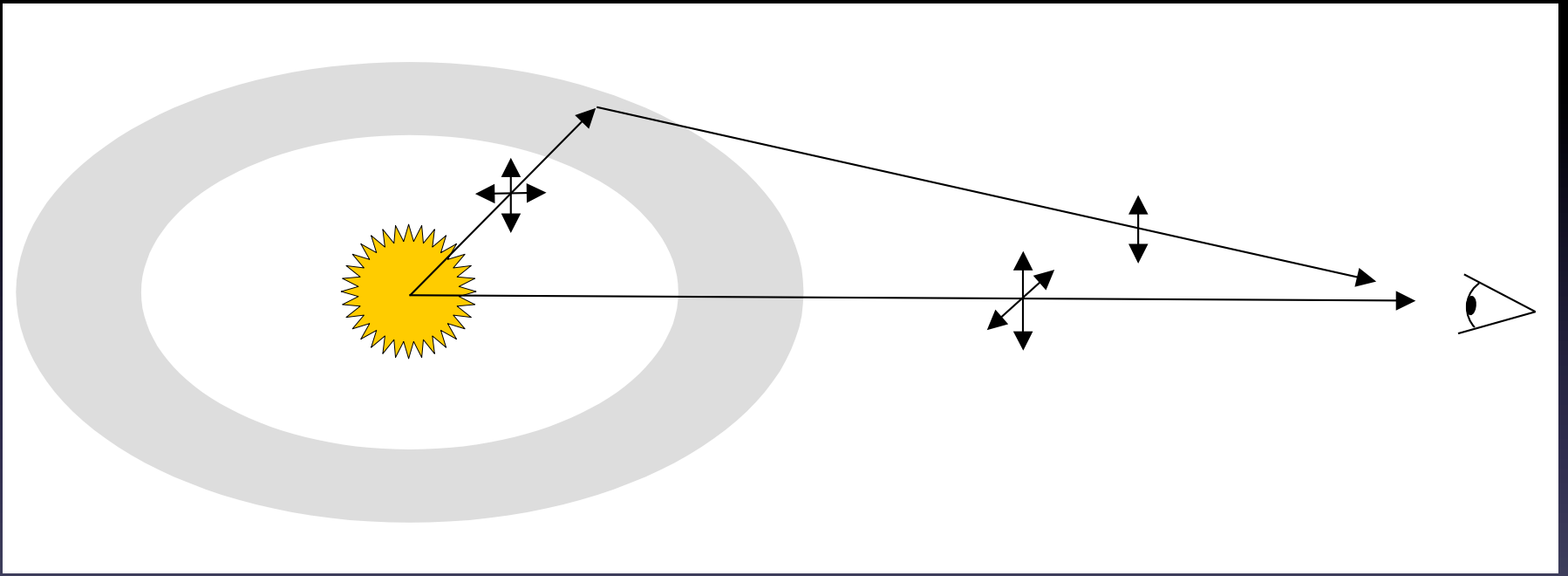
Direct Imaging of Exoplanets

- **C**ontrast: 10^{-9} and better
- **C**onfirmation: distinguish from background
- **C**haracterization: atmosphere, surface, weather, life?

Contrast: 10^{-9}

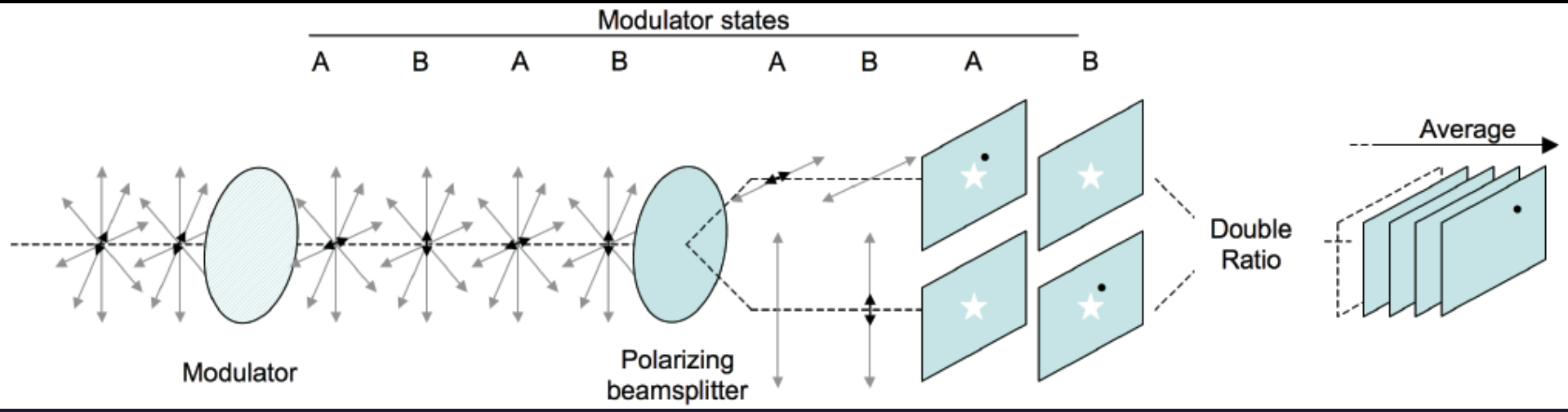
en.wikipedia.org/wiki/File:Everest_kalapatthar_crop.jpg

Polarization Contrast



- Central star is unpolarized
- Scattered/reflected light is linearly polarized

Dual Beam Exchange



(Semel et al. 1993; Kuhn 1995; Keller 1996)

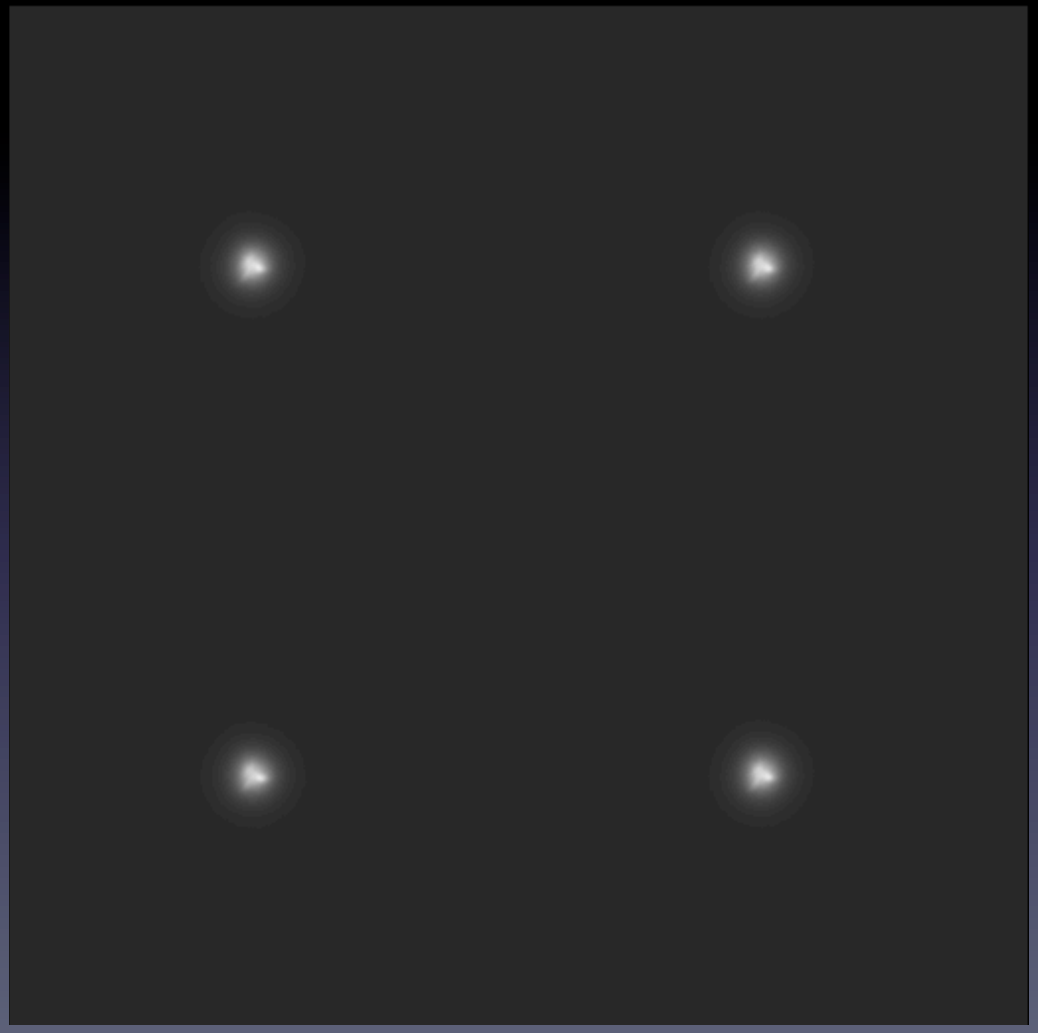
- combines temporal and spatial modulation
- strongly reduces effects of detector gain variations and scene changes

left beam

right beam

FLC state A

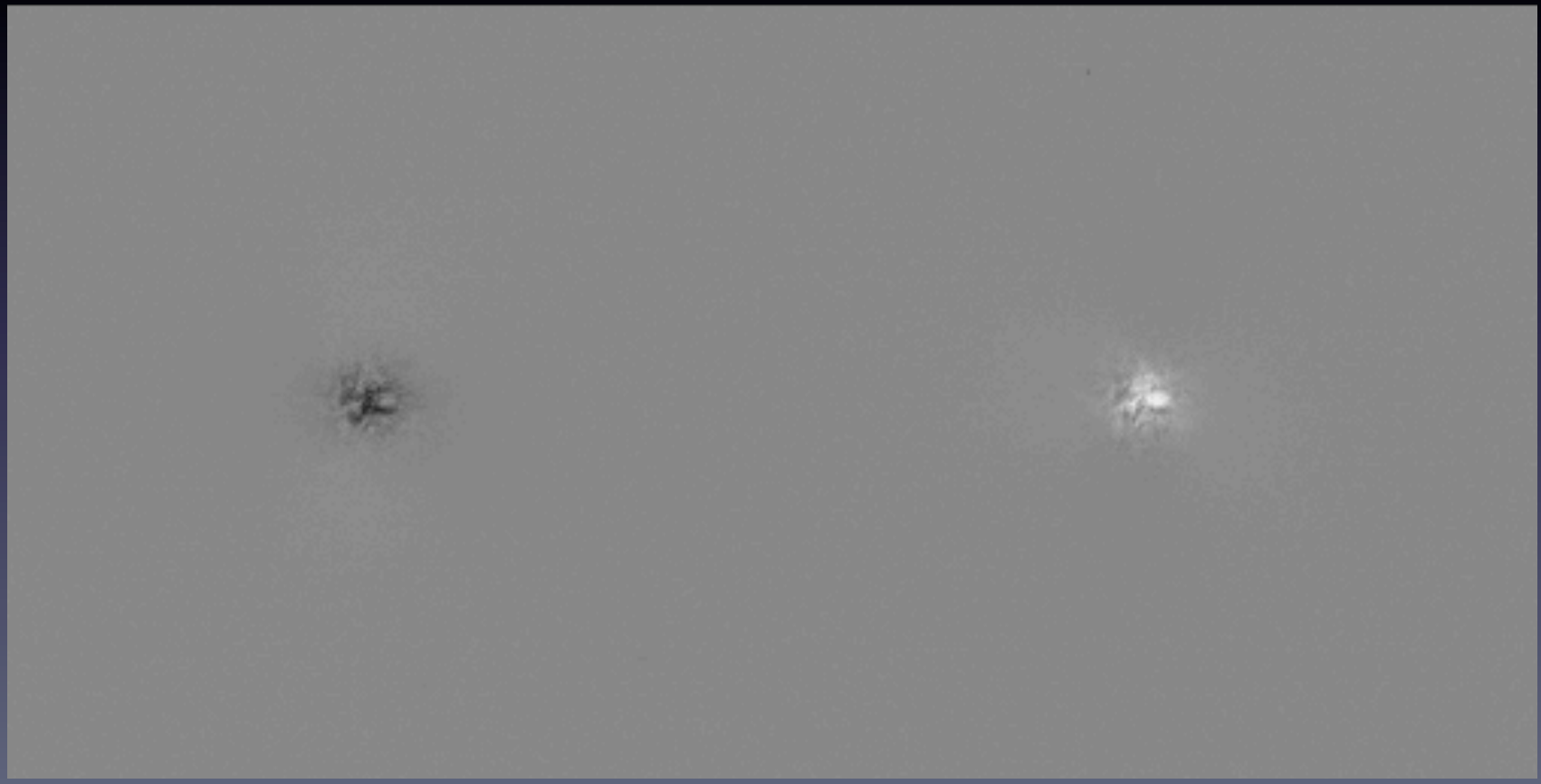
FLC state B



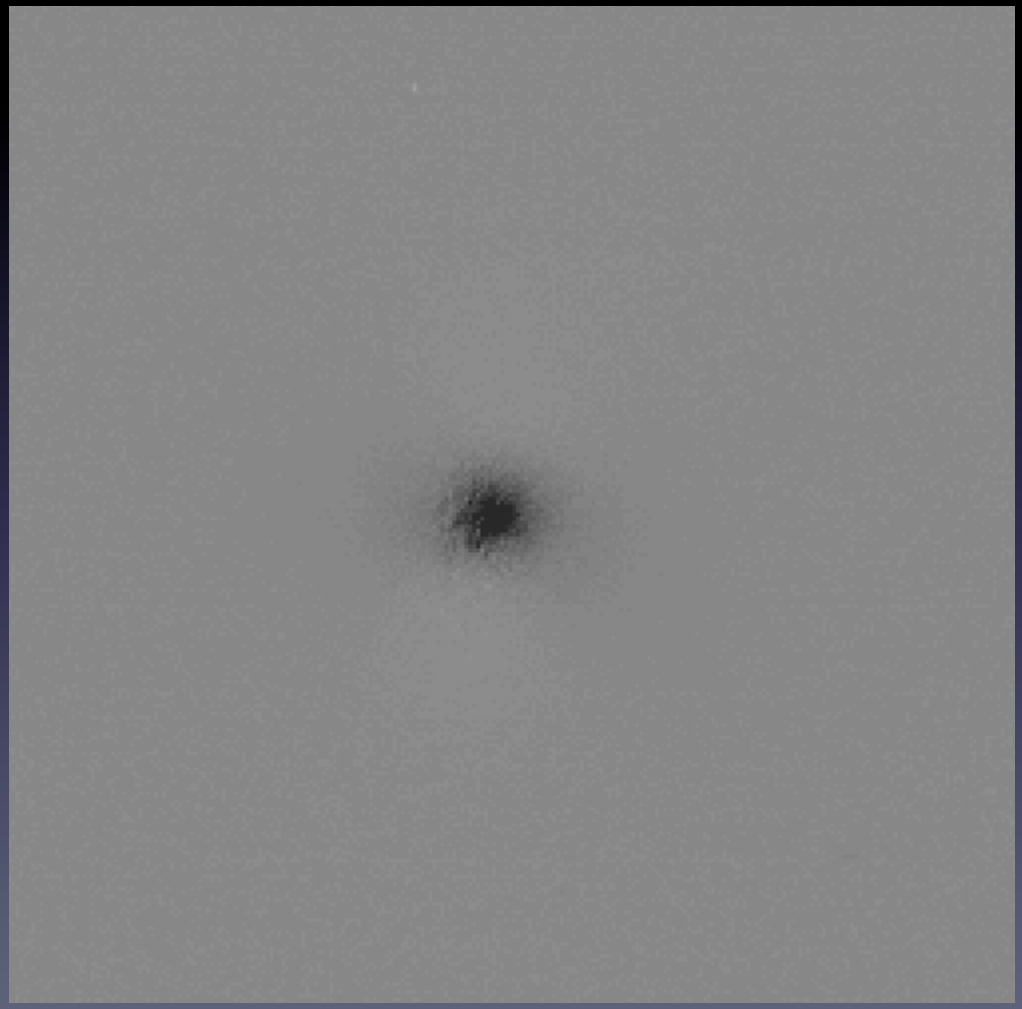
FLC states (A-B)

left beam

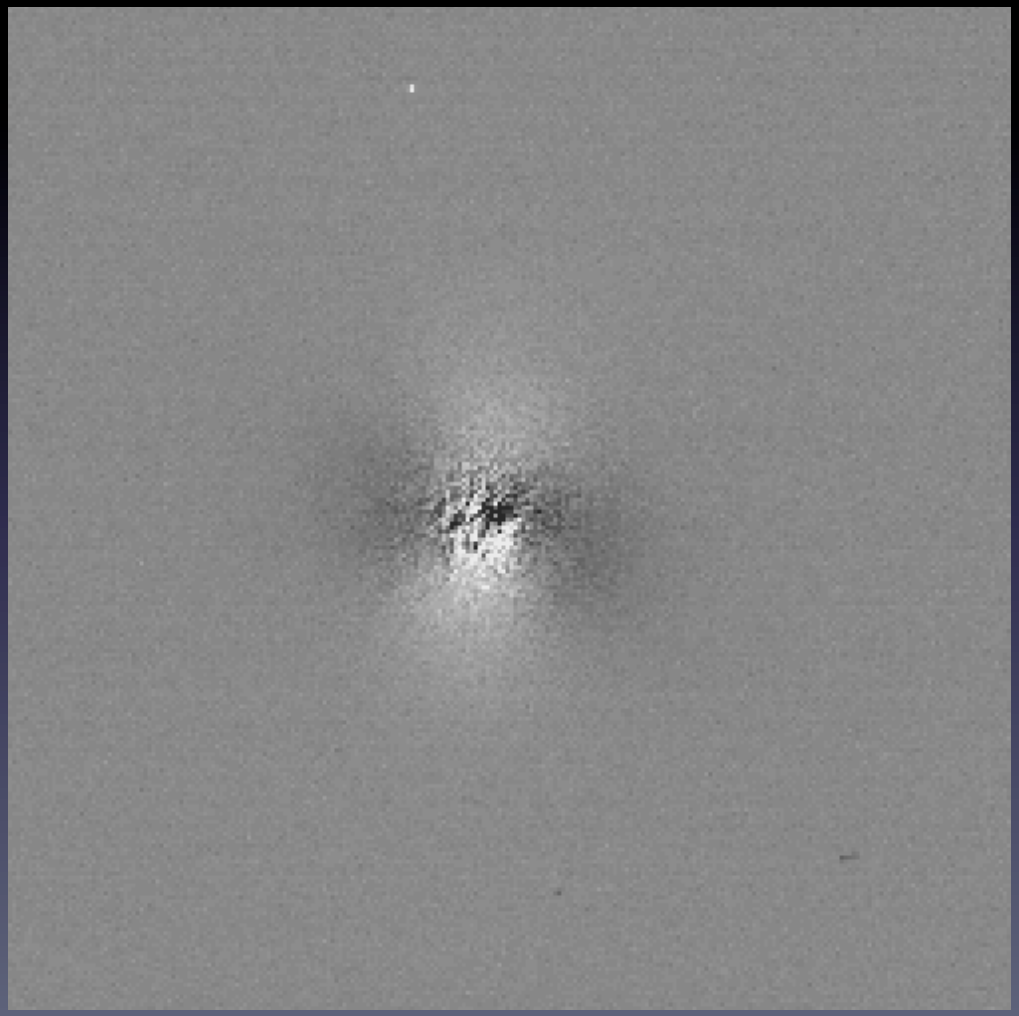
right beam



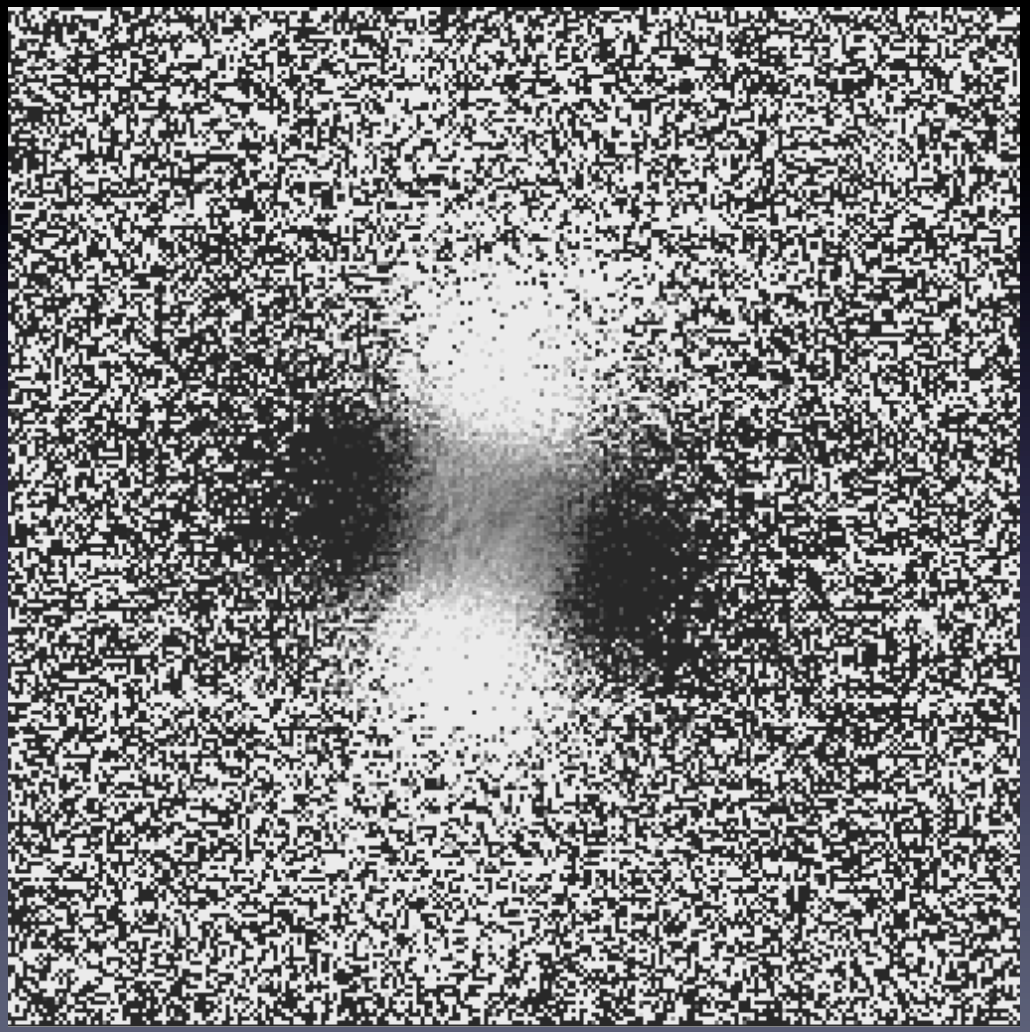
$$(A\text{-}B)_{left} - (A\text{-}B)_{right}$$



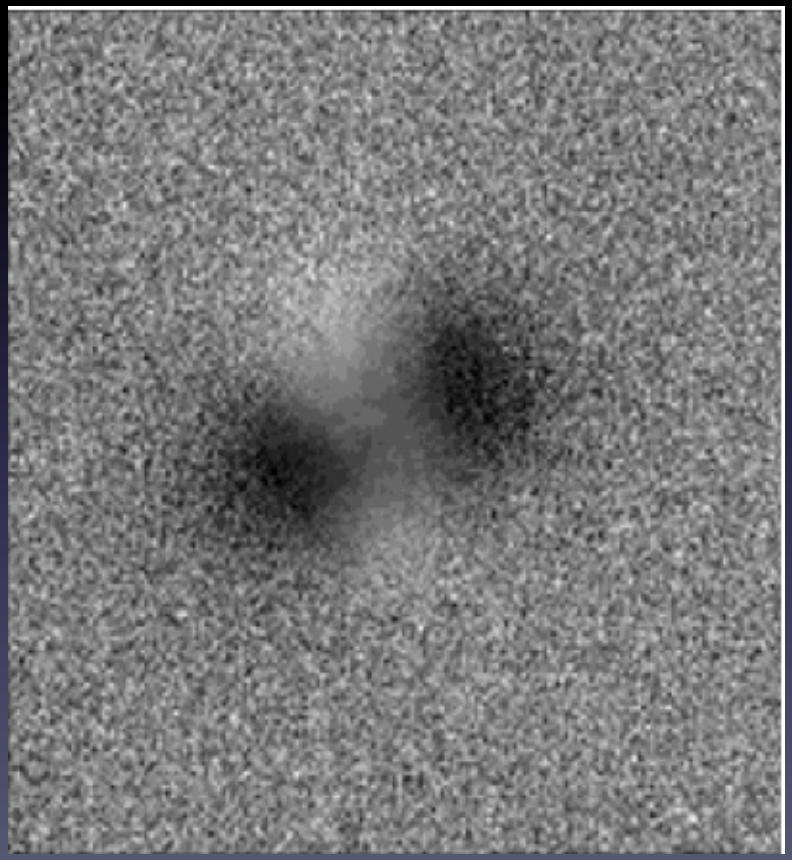
+ 0.7% * intensity

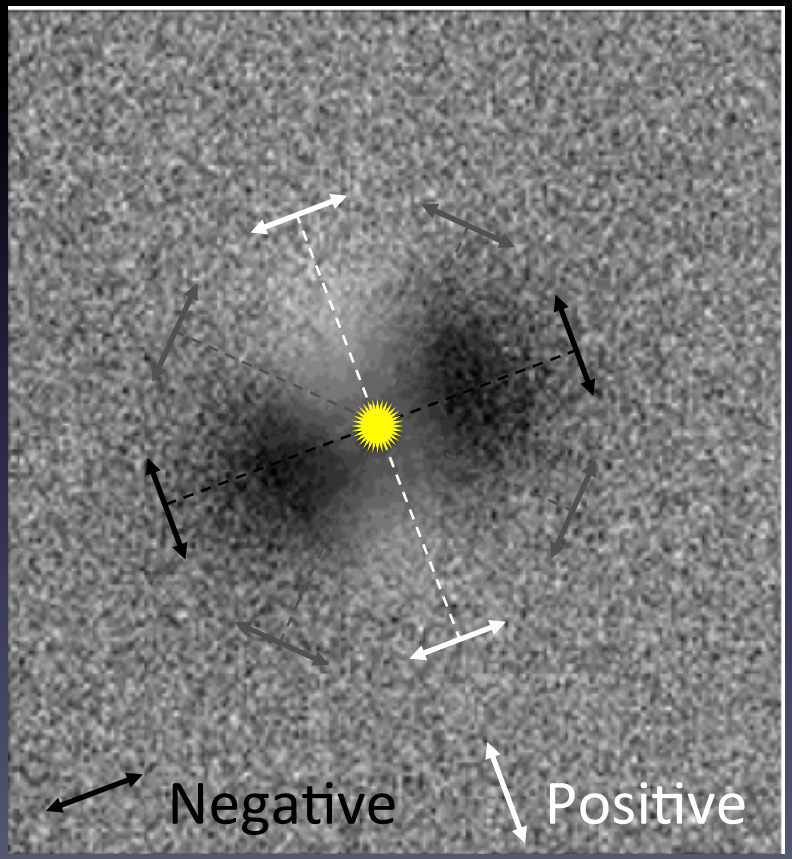


Division by Intensity



Scattering Polarization ‘Butterfly’

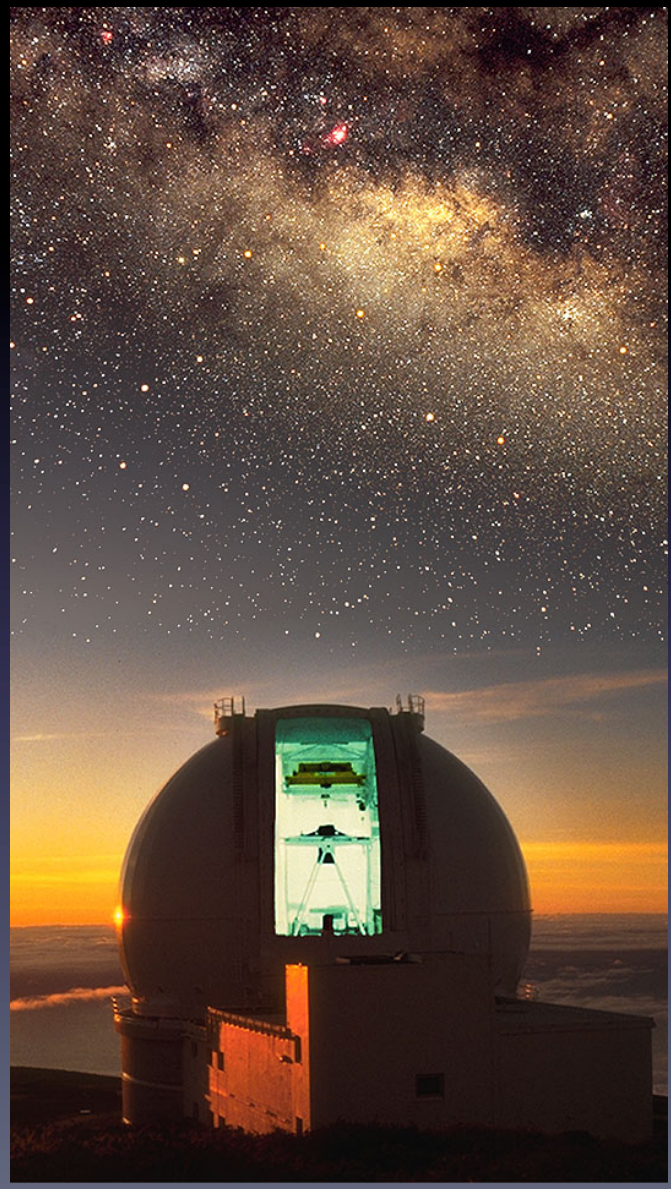




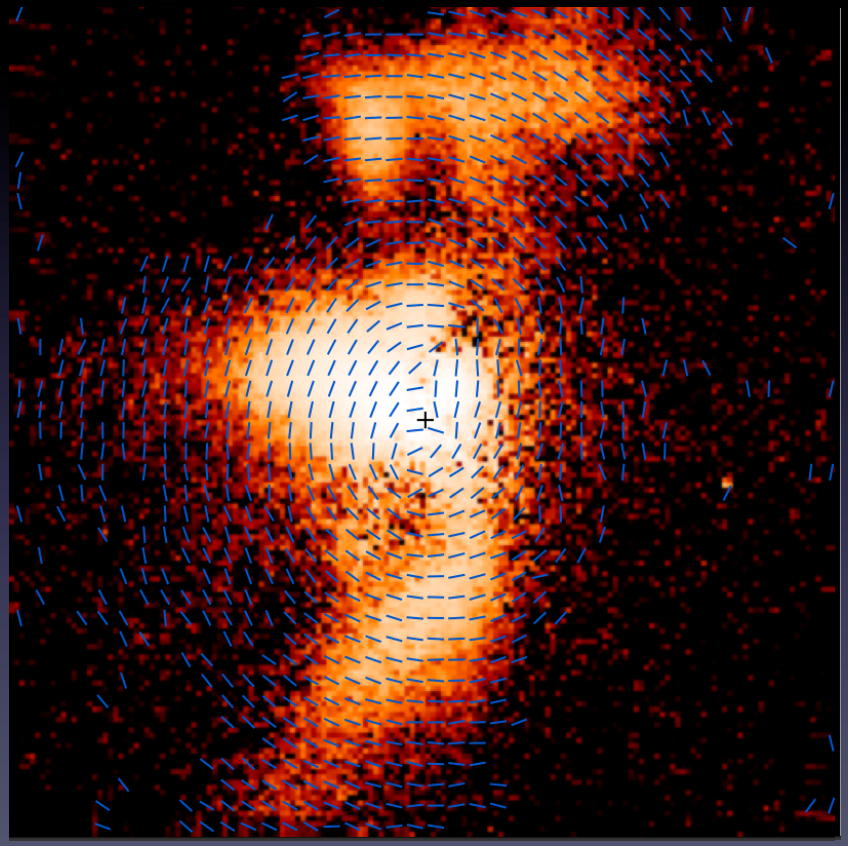
Extreme Polarimeter (ExPo)

- imaging polarimetry testbed

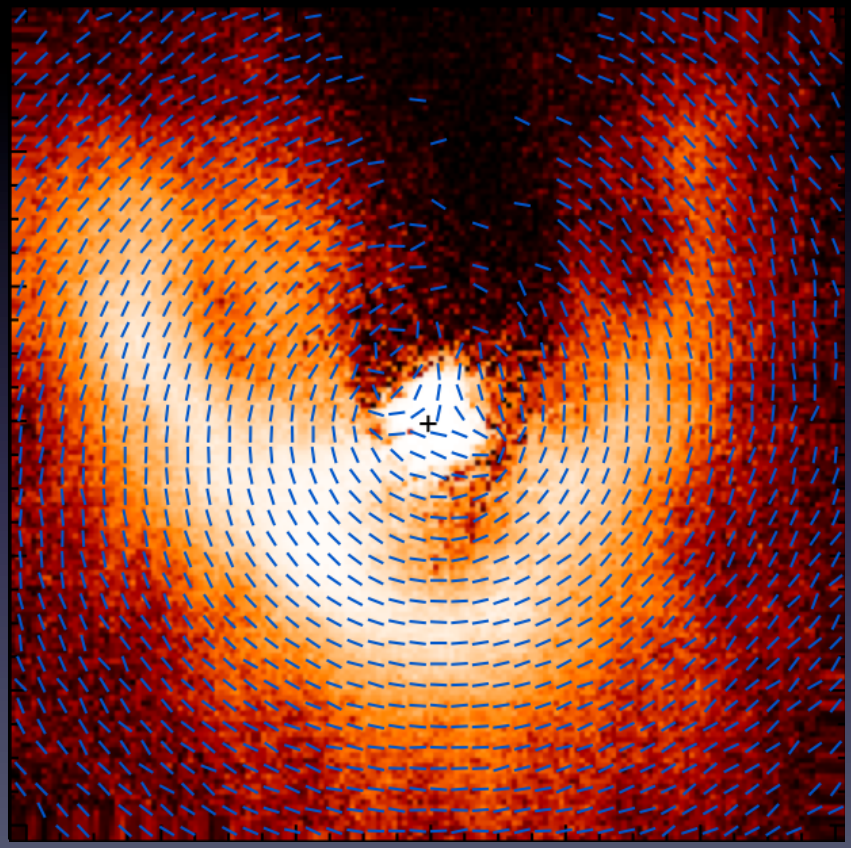
  at 4.2-m William Herschel Telescope
- 500-900nm dual-beam, FLC
- EM-CCD, <35 frames/s, <1e^- RON
- sCMOS, 50 frames/s, ~1e^- RON
- 97-actuator Adaptive Optics



Contrast

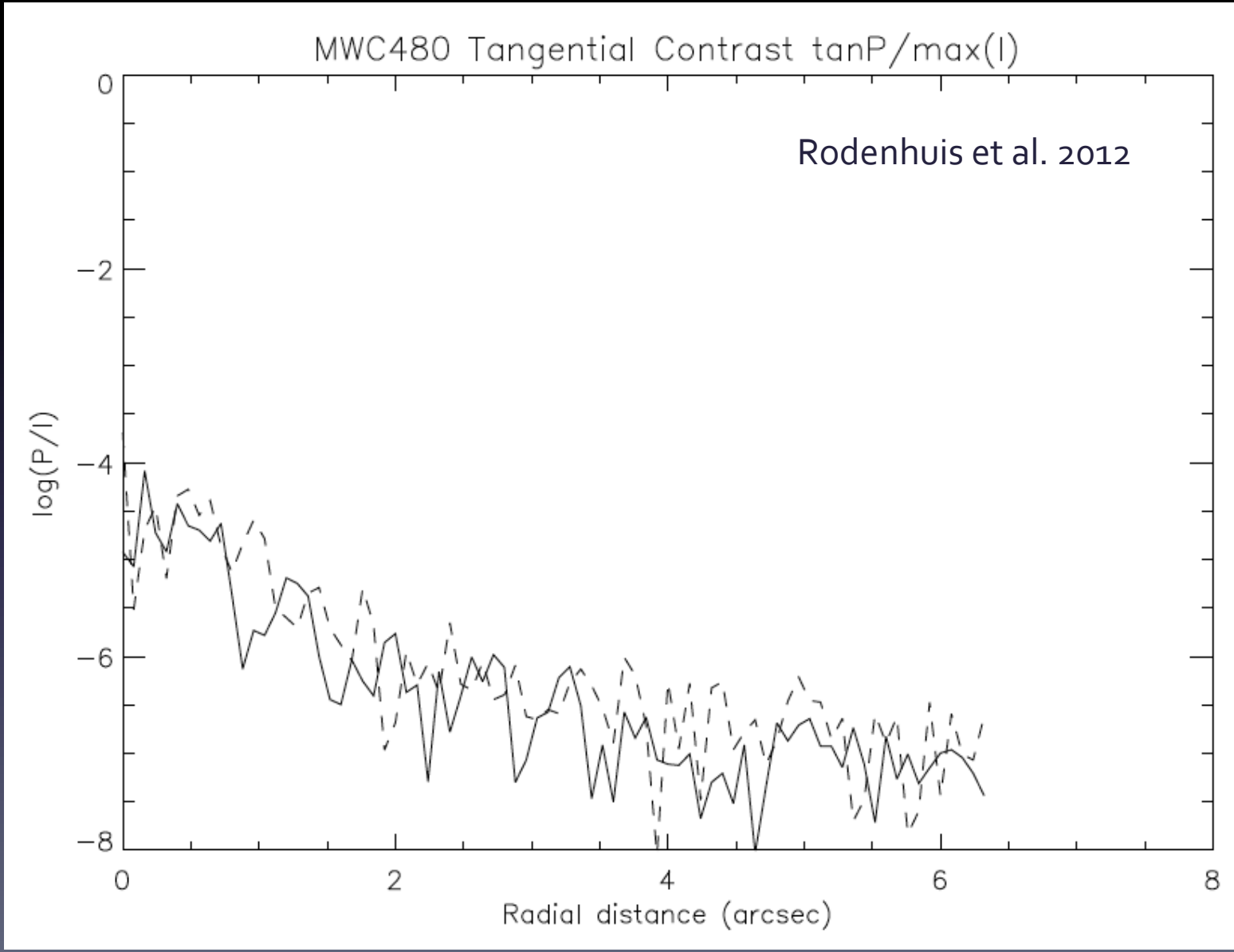


T-Tauri

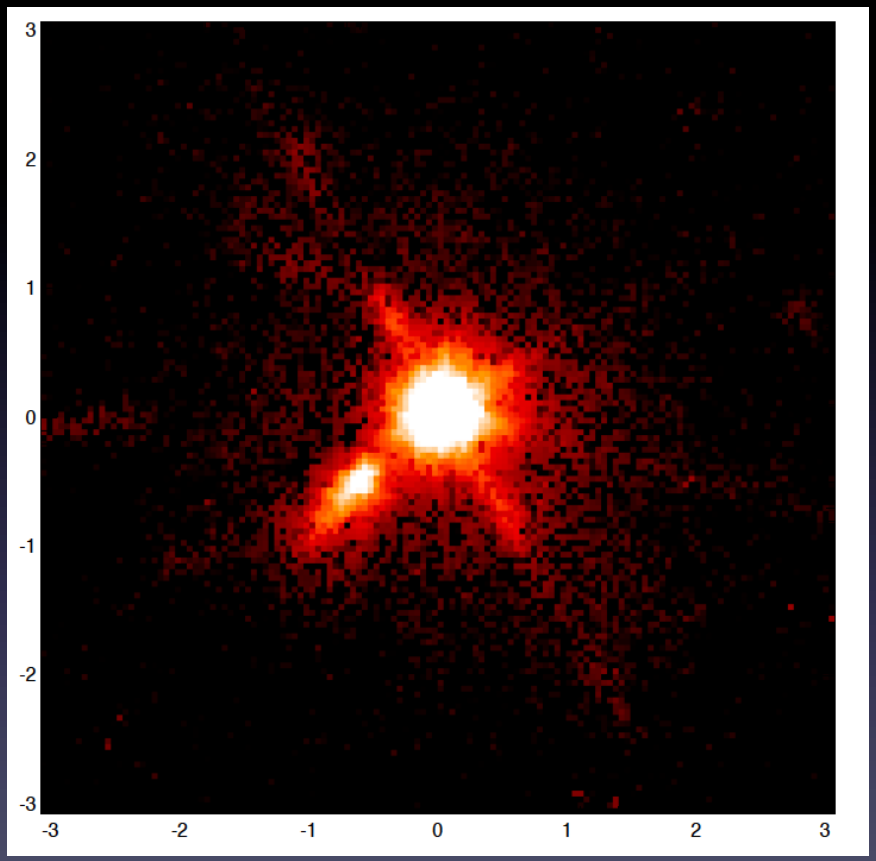


MWC147

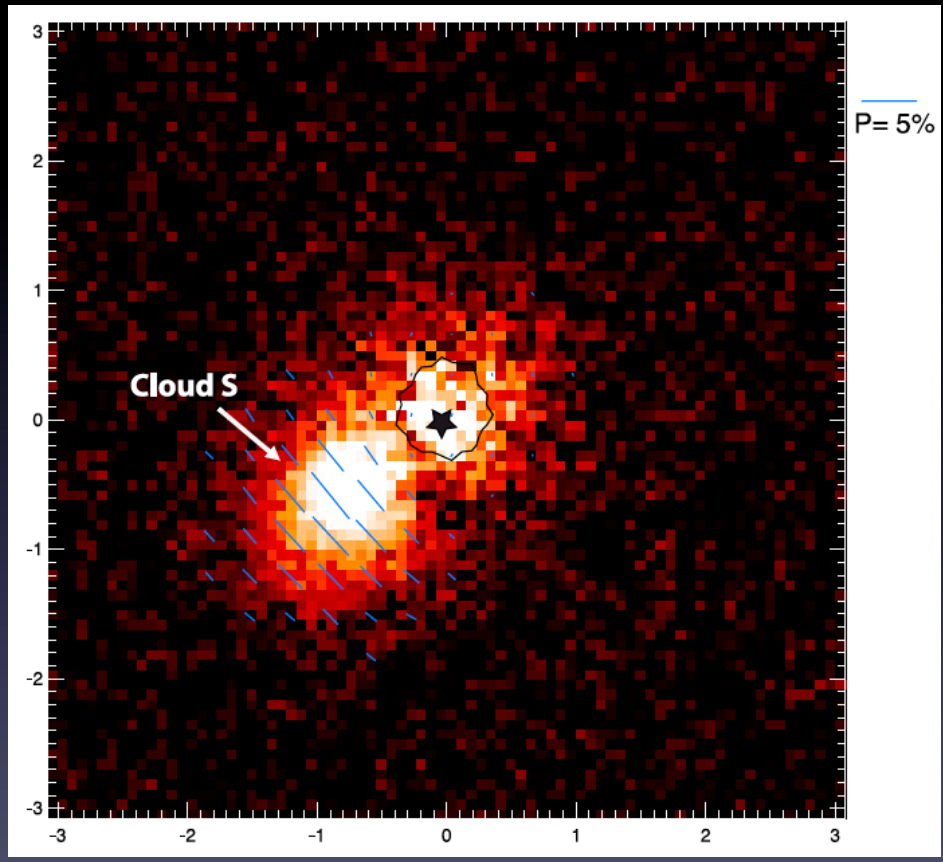
ExPo Contrast



Confirmation (R Coronae Borealis)

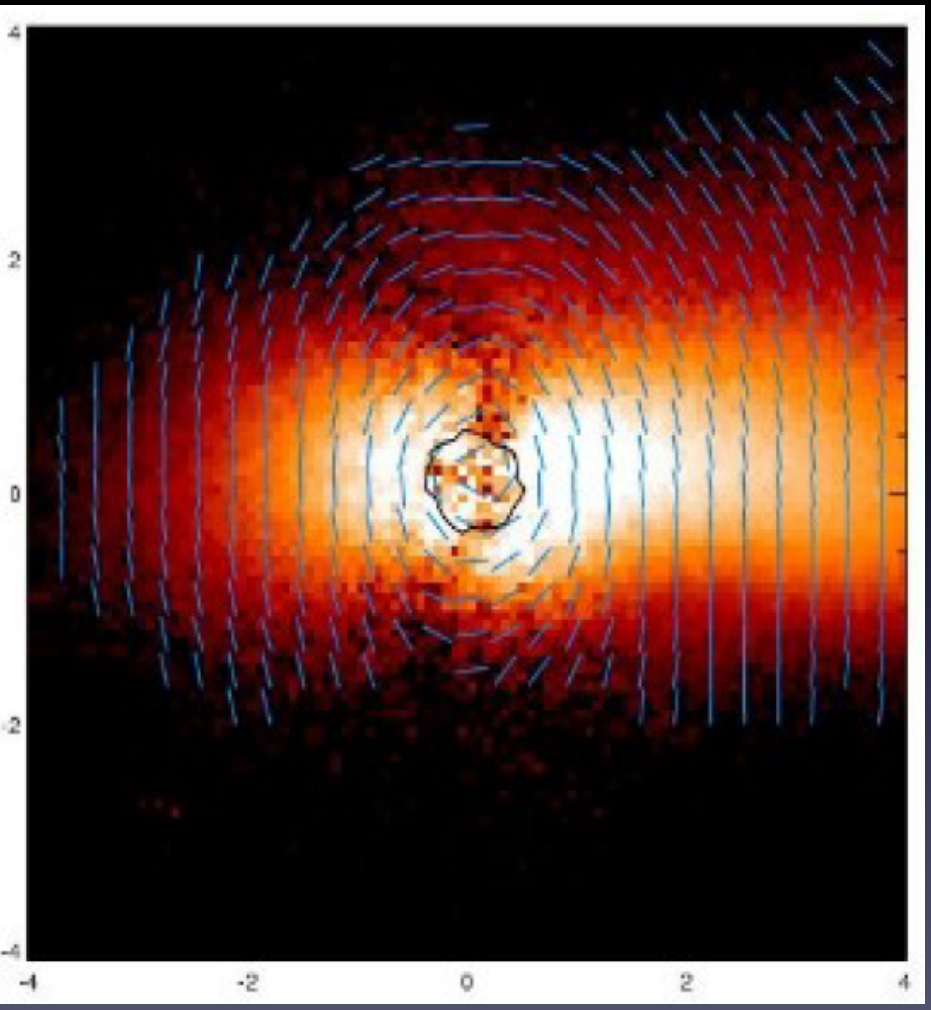


Intensity (HST)

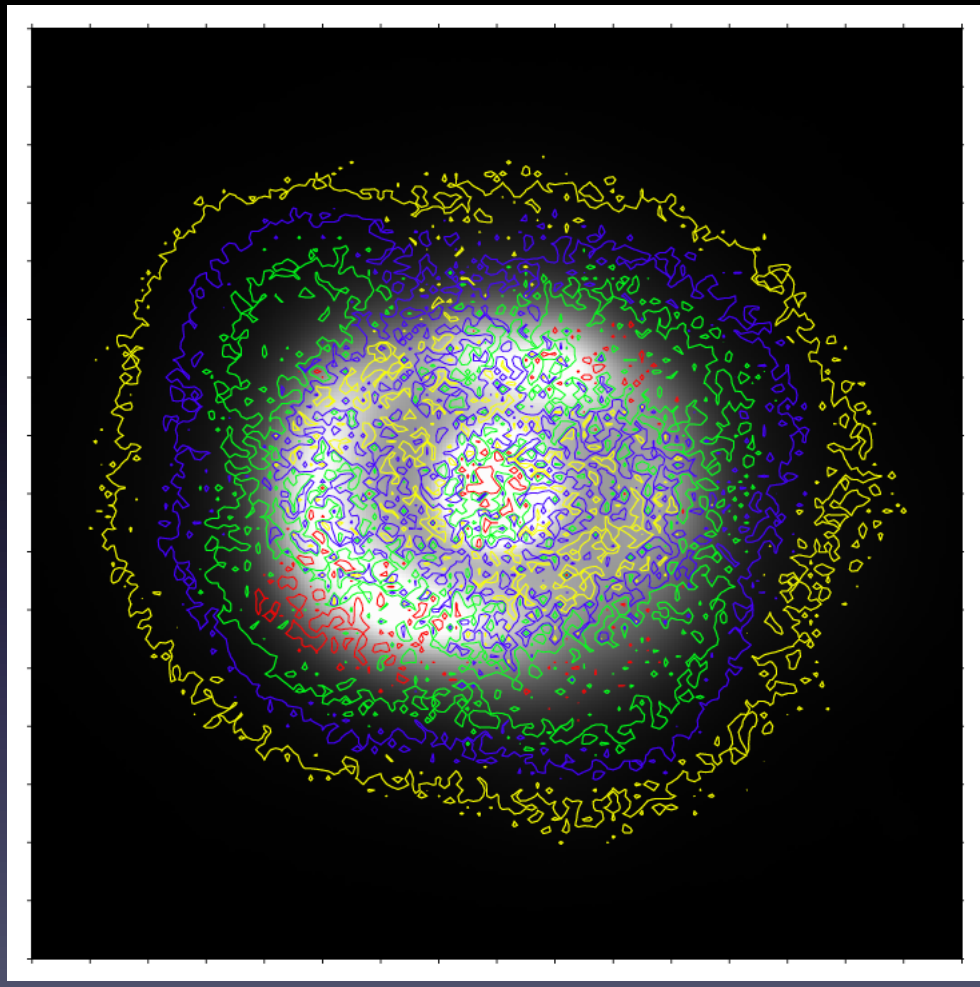


Linear Polarization (WHT)
(Jeffers et al. 2012)

Characterization

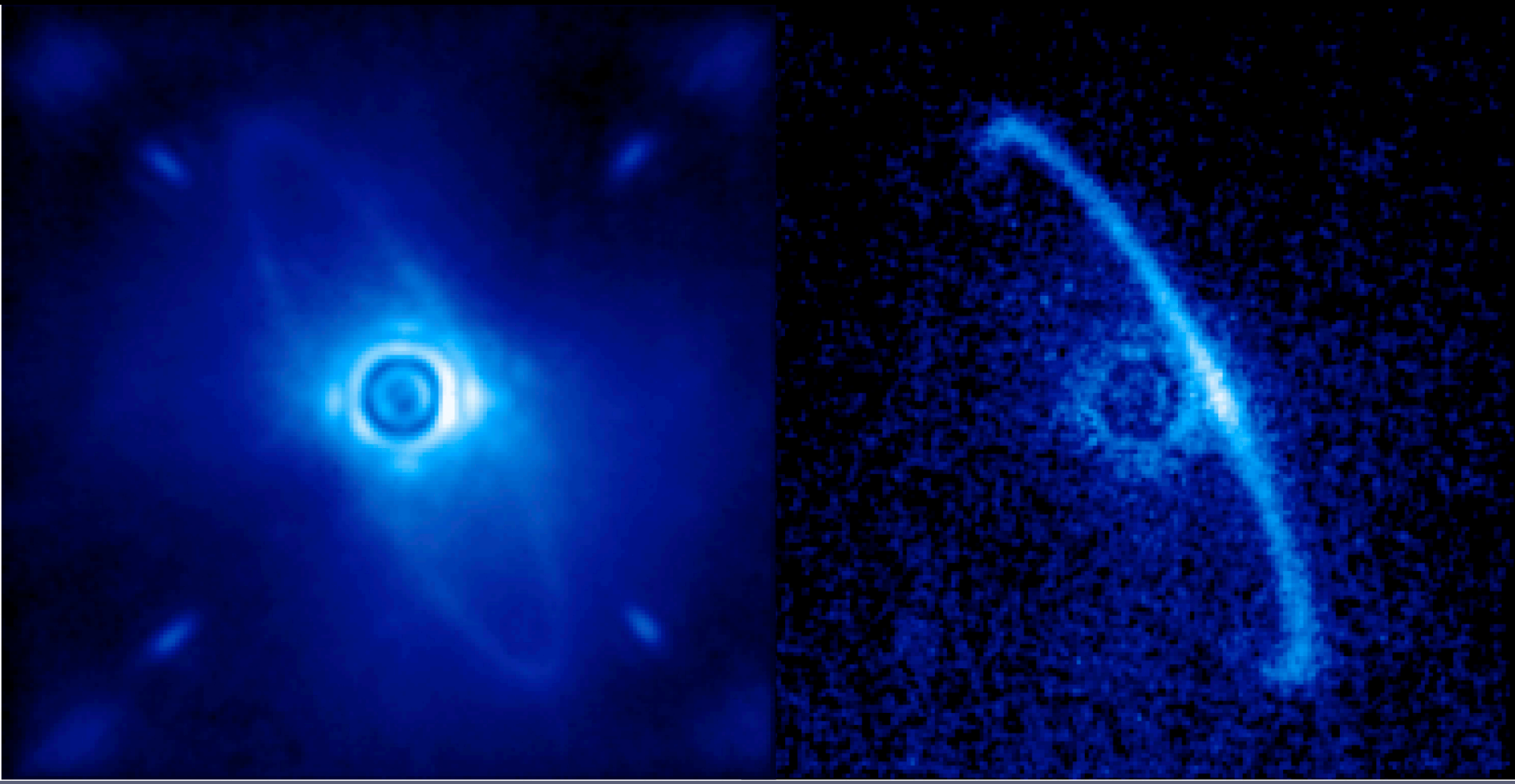


SU Aur (Jeffers et al. 2013)



BD 303639 (Canovas 2011)

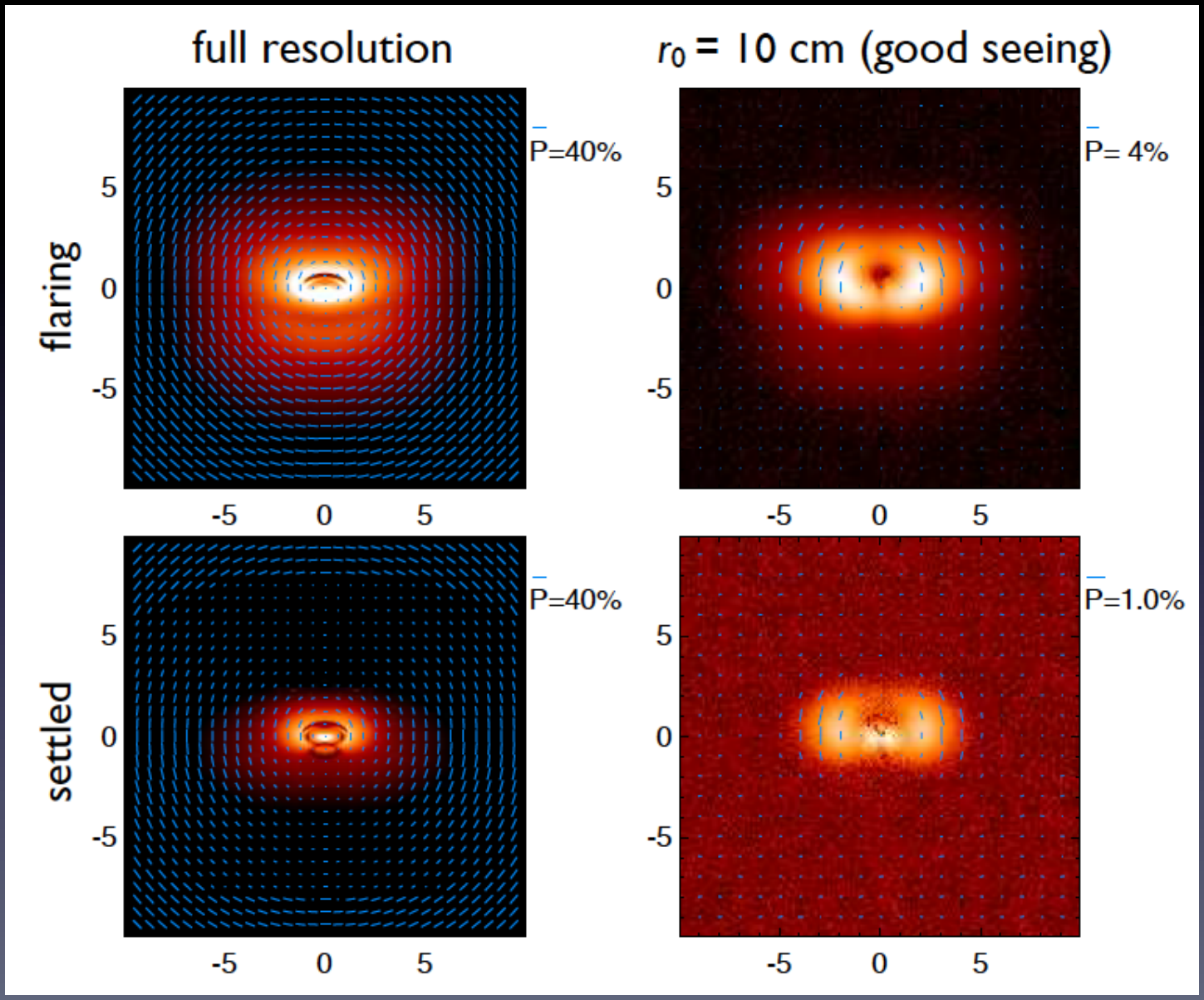
Characterization



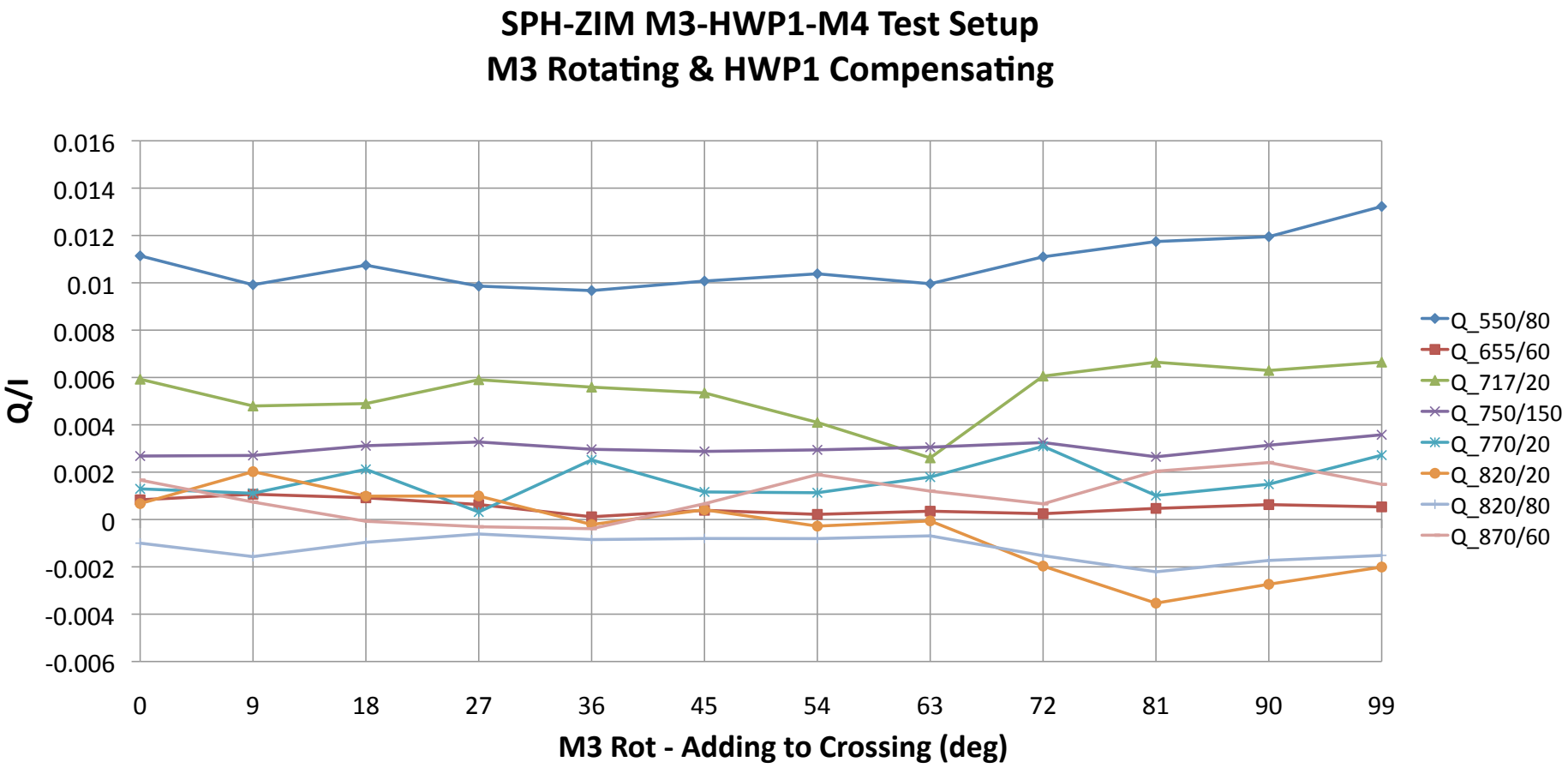
GPI First Light HR4796A (Image credit: Processing by Marshall Perrin, STScI)

Problems

Relative Polarimetry

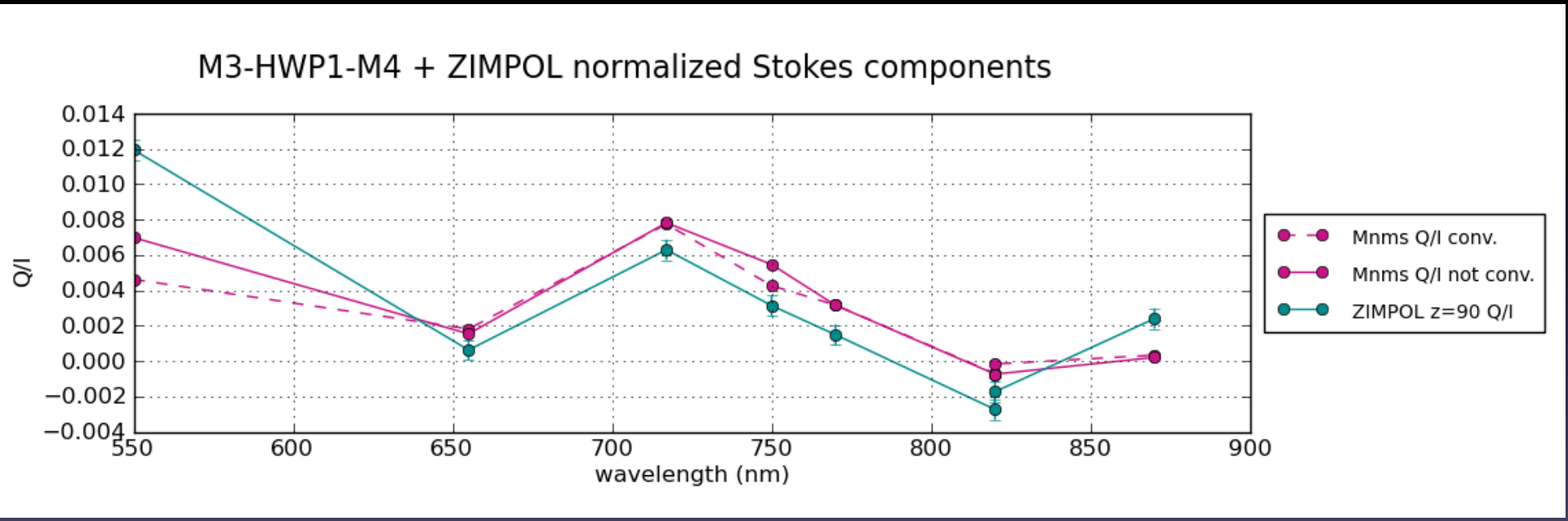


Instrumental Polarization



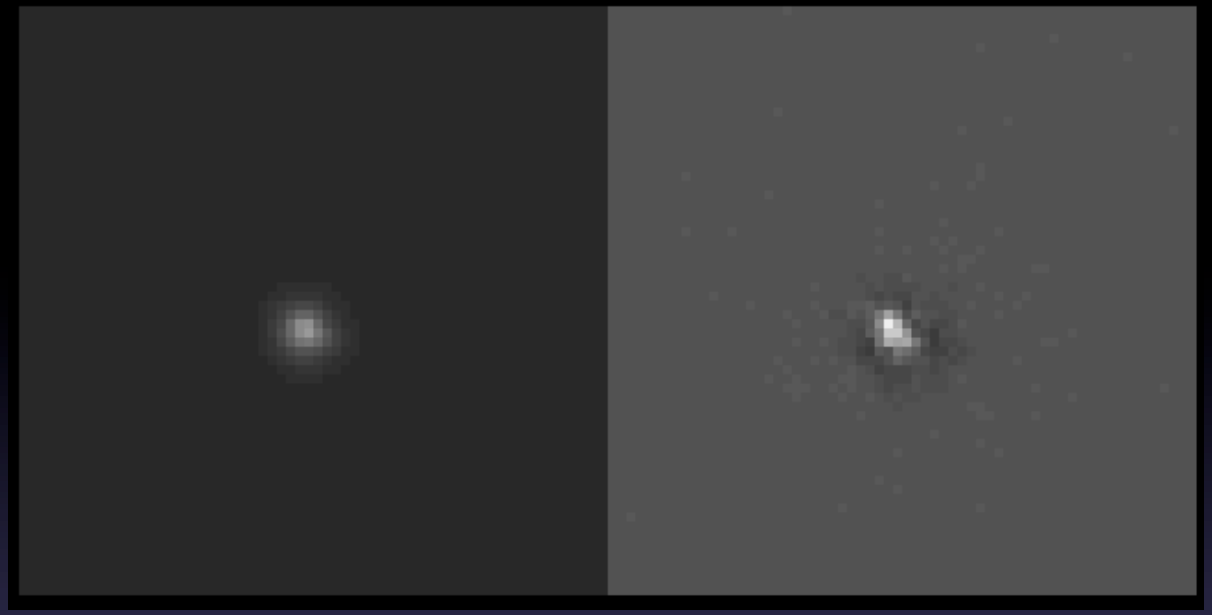
Roelfsema et al. (2012)

FLC Polarized Interference Model



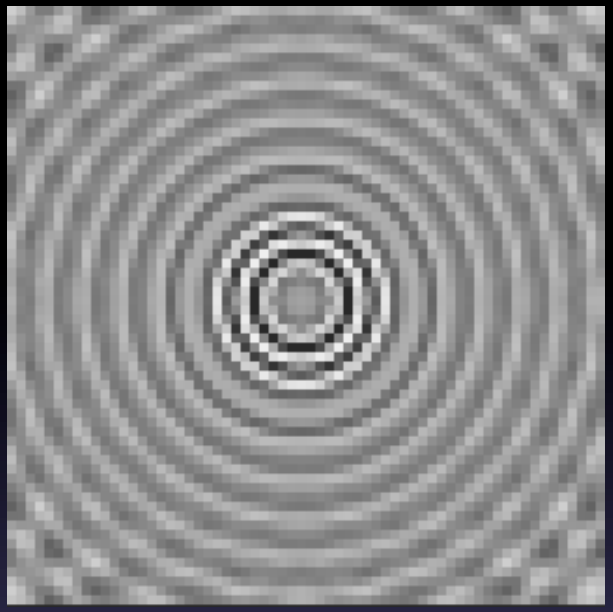
de Juan Ovelar et al. (2012)

Polarized Airy Rings



Unpolarized Star I

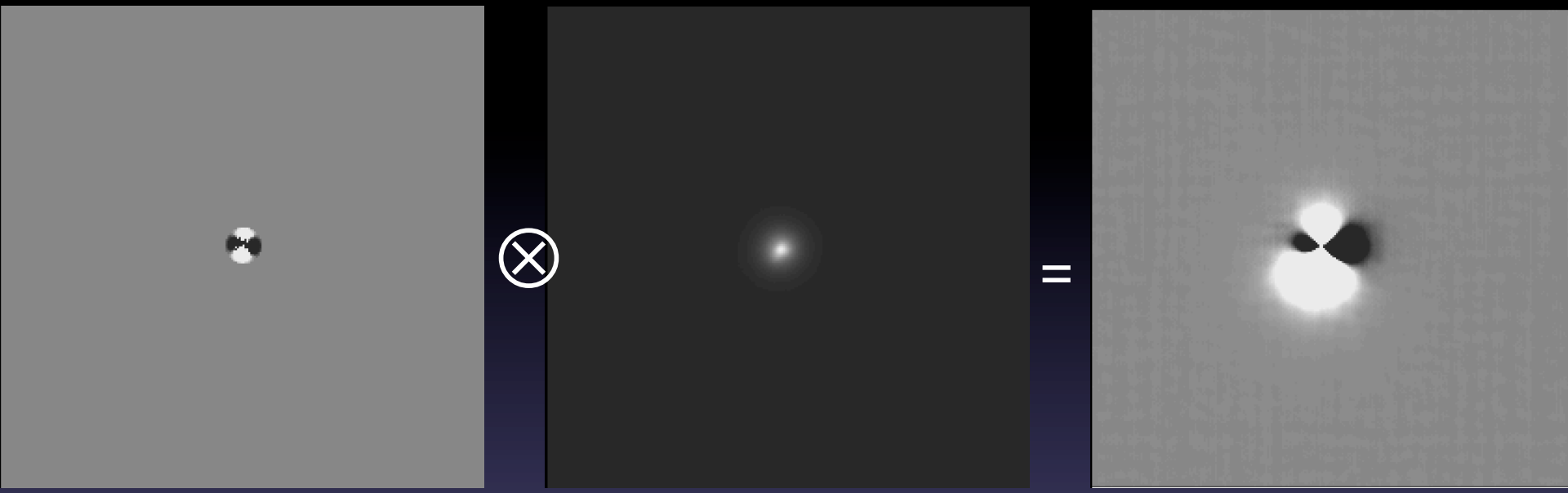
Unpolarized Star Q/I



Simulated Airy Pattern Q/I

- FLC induces strongly λ-dependent polarization up to 1%
- chromatic aberrations, diffraction make λ-dependent structures
- instrumental polarization no longer proportional to intensity
- expect polarized Airy rings at $1*10^{-3}$ level

Polarized Smeared Light



- only partial AO correction → PSF has significant wings
- polarized light from inner disk is smeared over very large area
- difficult to observationally determine outer radius

Lessons Learned

- huge intensity gradients + beam shifts = significant problem
- optical elements = more problems than solutions
- dual-beam exchange removes many problems
- non-common aberrations between beams matter
- absolute polarimetry is difficult
- broadband polarimetry is difficult
- unknown polarization noise at 10^{-8} contrast in lab