



Near-Infrared Polarimetry with Keck NIRC2

Rebecca Zhang

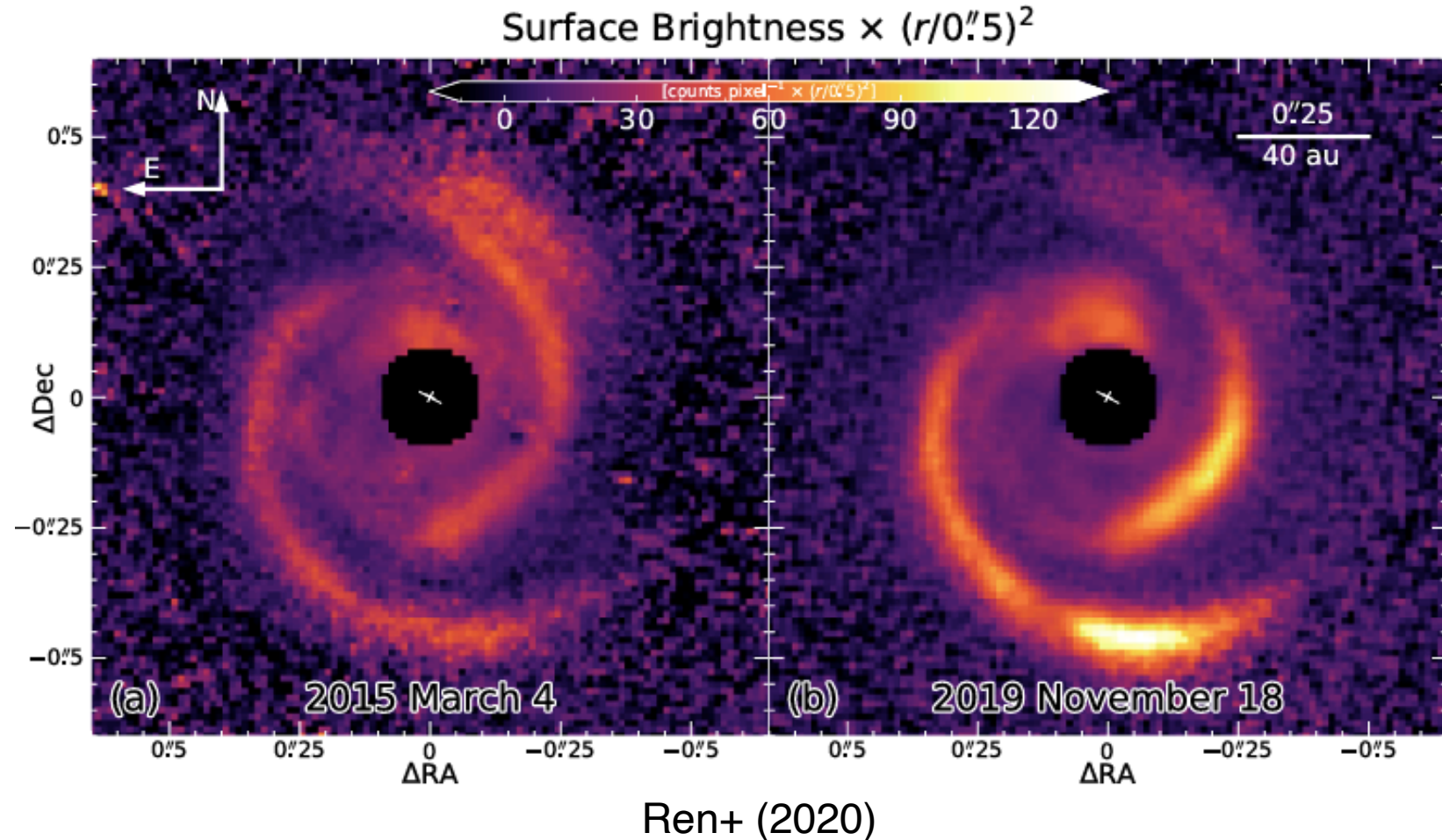
University of California, Santa Barbara



+ Max Millar-Blanchaer (UCSB), Briley L. Lewis (UCSB), Eduardo Marin (Keck), Will Melby (U of A), Mike Fitzgerald (UCLA), Dimitri Mawet (Caltech), Keith Matthews (Caltech), Nem Jovanovic (Caltech), Scott Lilley (Keck), Ed Wetherell (Keck), Jacob Taylor (Keck), Mahawa Cisse (Keck), Lauren Simmons (Keck), Paul Richards (Keck), Carlos Alvarez (Keck), Percy Gomez (Keck), Trisha Harmmen (Keck), Jayke Nguyen (UCSD) and more

Circumstellar Disks

- Interactions between stars, planets, and disks are imprinted on...
 - Disk Structure
 - Spatial Distributions
 - Physical Conditions of the Disk Material
- Test out planet formation theories
- Generate predictive formation theories

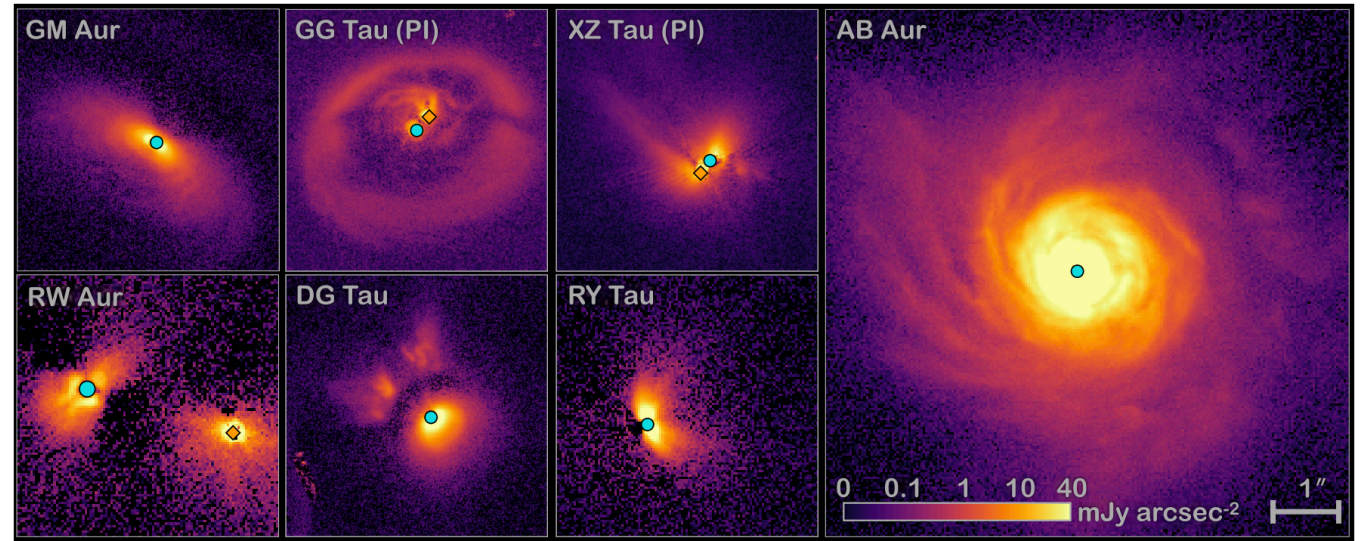


Near-Infrared Imaging

- Caused by small micron sized dust grains suspended in the gas

Advantages

- High resolution
- Tight coupling helps trace hydrodynamical models



Garufi+ (2024)

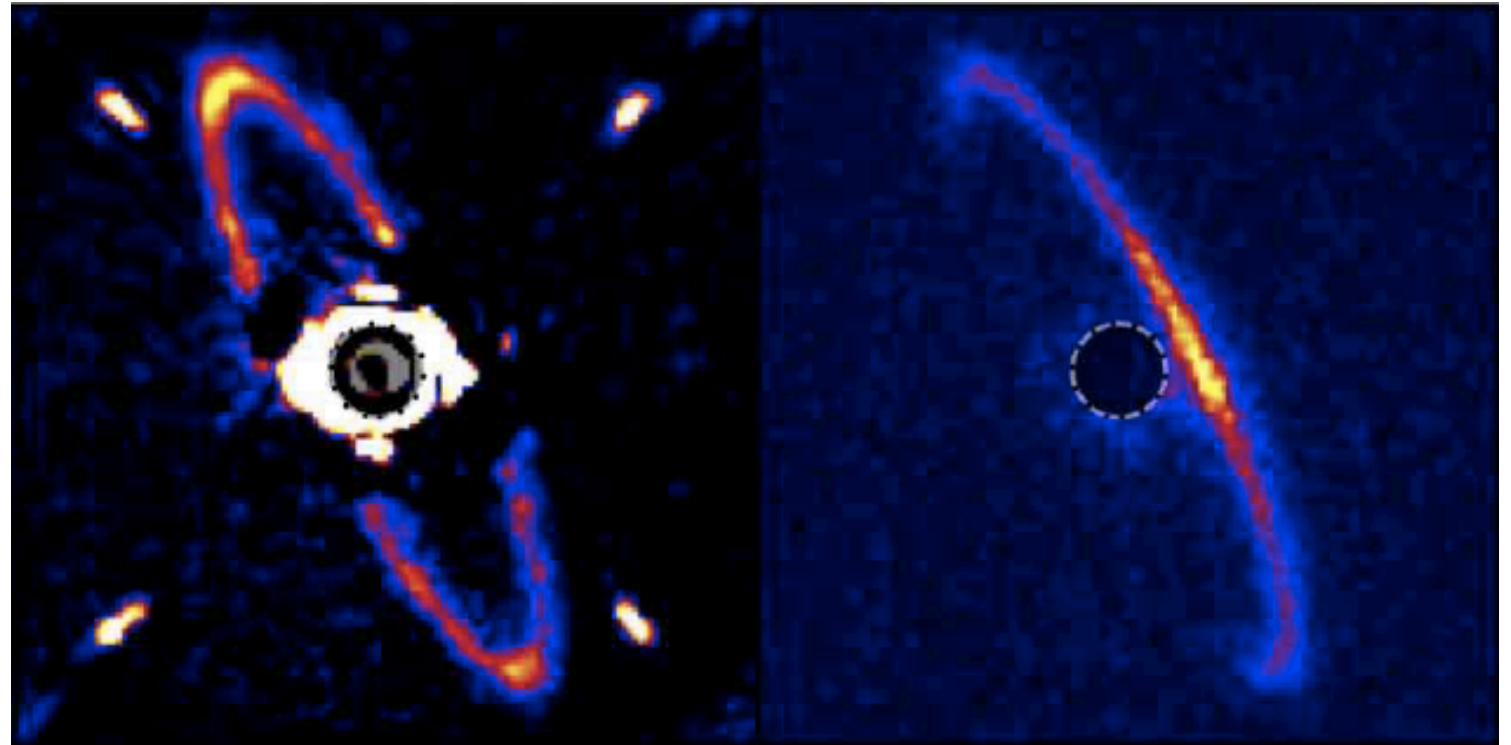
Polarimetry

Advantages

- Higher contrast
- Does not suffer from self-subtraction
- Scattering particle characterization
- Insight gained from even unresolved sources

PSF Subtracted
Total Intensity

Polarized Intensity



Perrin+ (2015)

High-Contrast Polarimeters



Subaru: VAMPIRES & CHARIS



VLT: ZIMPOL & IRDIS



Gemini: GPI



Keck: NIRC2

High-Contrast Polarimeters



Subaru: VAMPIRES & CHARIS



VLT: ZIMPOL & IRDIS



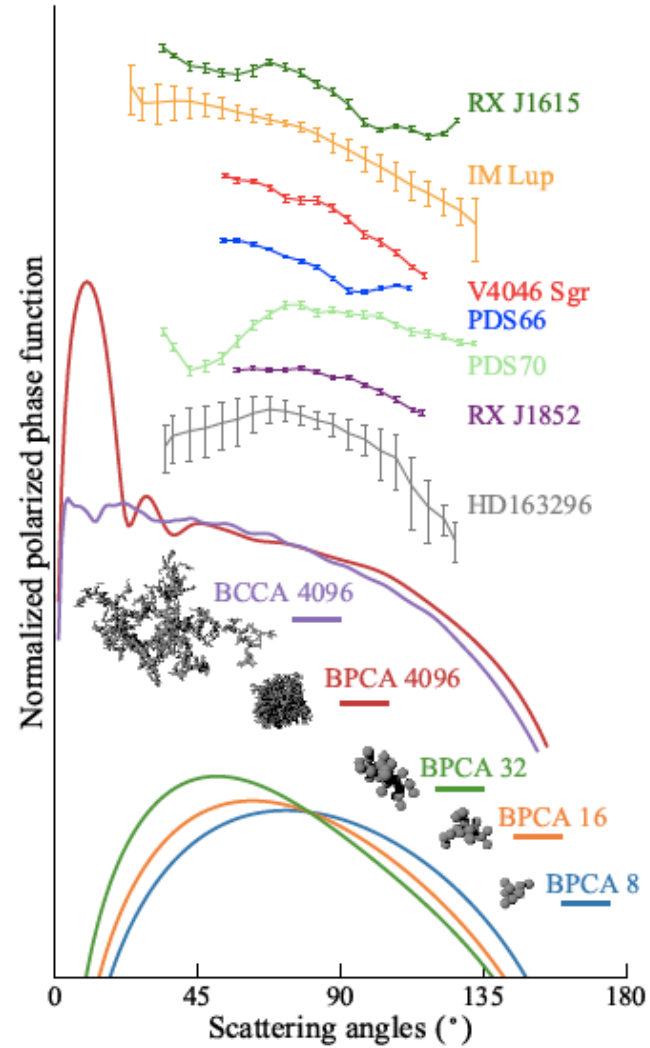
Gemini: GPI



Keck: NIRC2

Open Questions

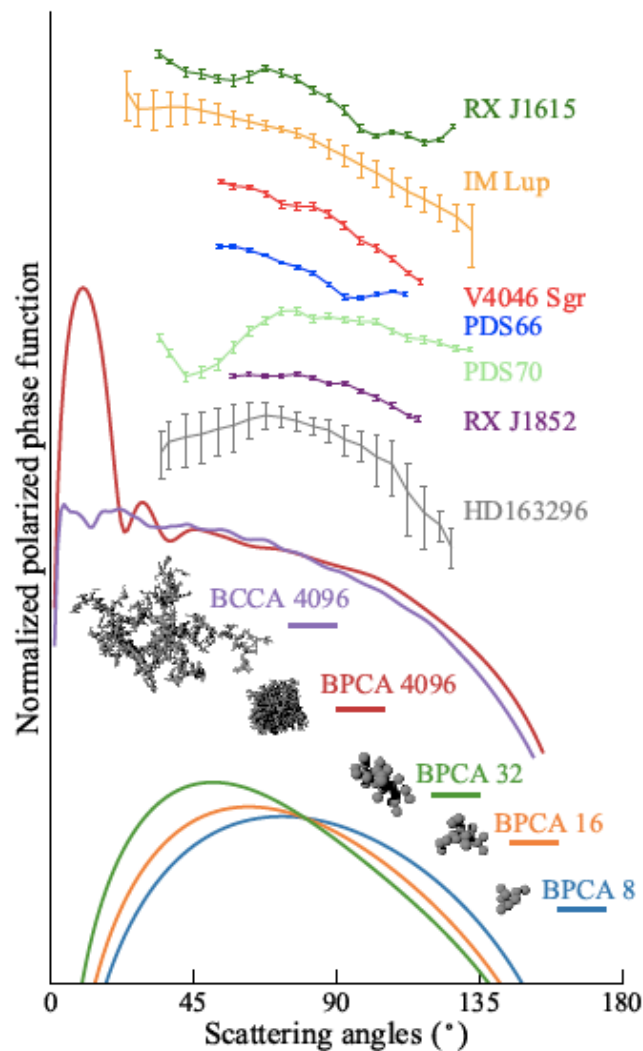
- Dust Properties



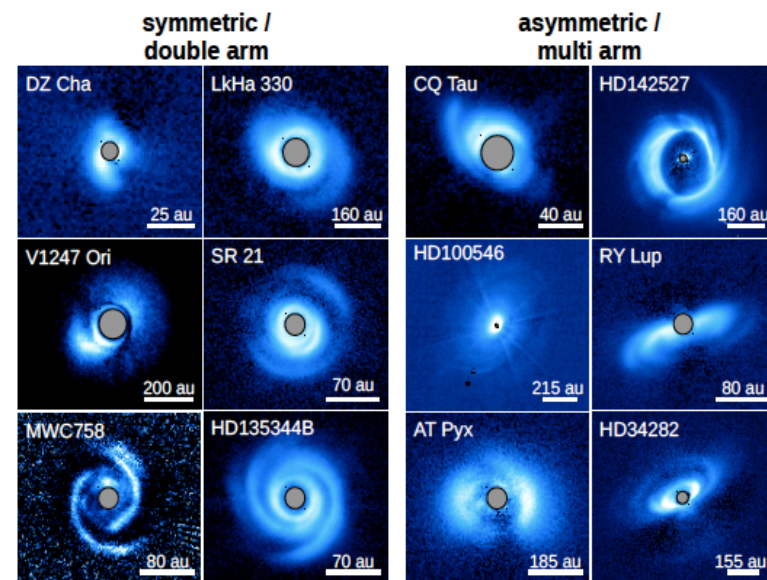
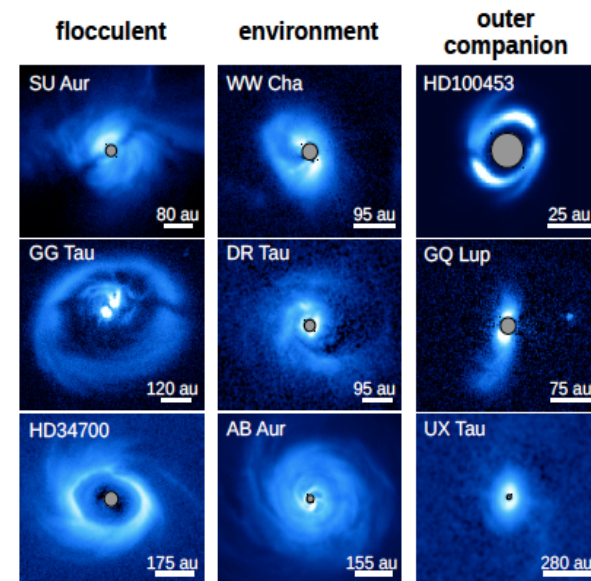
Ginski+ (2021)

Open Questions

- Dust Properties
- Quantitative Disk Substructures
 - Density Contrasts
 - Particle Sizes
 - Kinematics



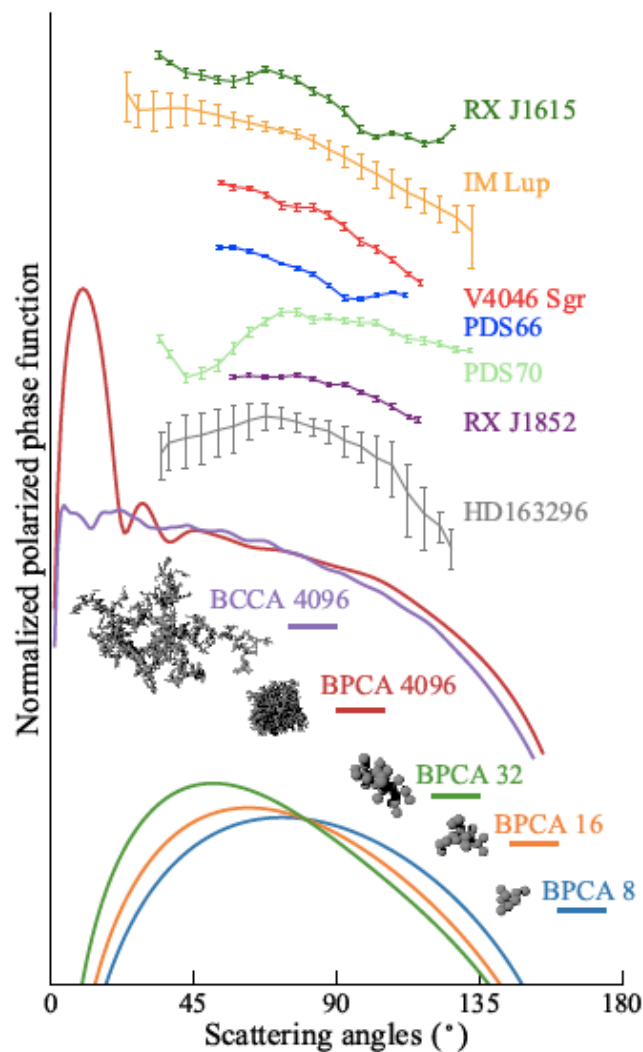
Ginski+ (2021)



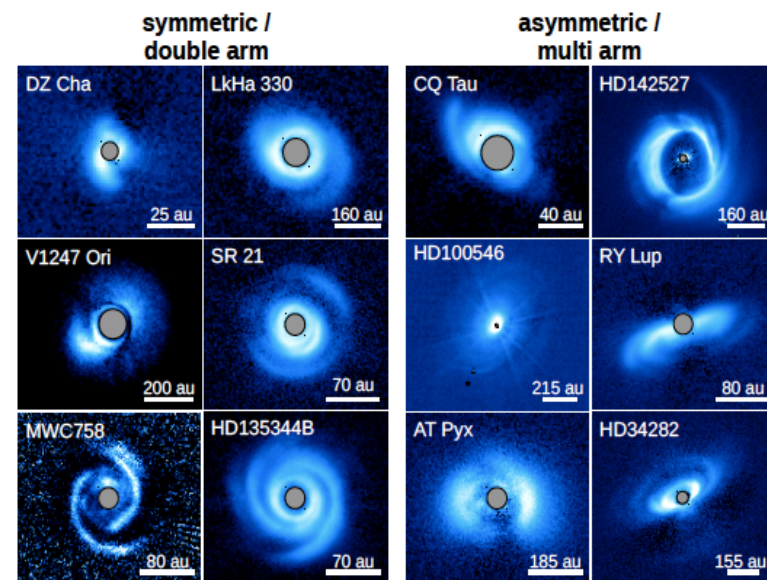
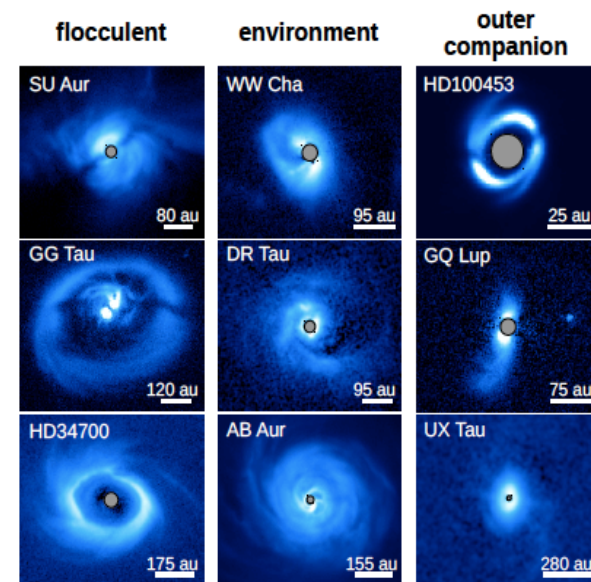
Benisty+ (2020)

Open Questions

- **Dust Properties**
- **Quantitative Disk Substructures**
 - Density Contrasts
 - Particle Sizes
 - Kinematics
- **Planet Formation**
 - Likelihood of formation based on dust properties or locations within circumstellar disks
 - Role of substructures



Ginski+ (2021)



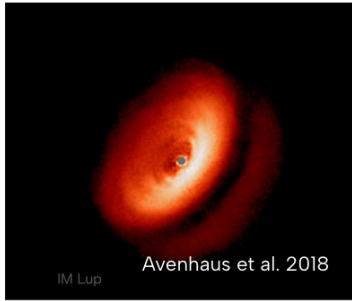
Benisty+ (2020)

NIRC2 Polarimetry

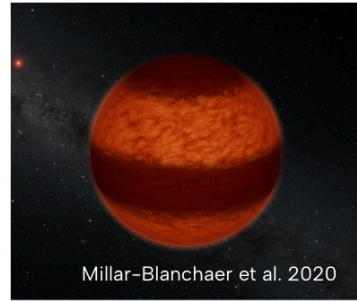
Capabilities

- J, H, K, L' bands
- 5" x 10" field of view
- NGS or LGS, tip tilt stars up to 30" away
- Can be combined with many existing NIRC2 modes:
 - Grism spectropolarimetry
 - Imaging polarimetry
 - High-contrast coronagraphic polarimetry

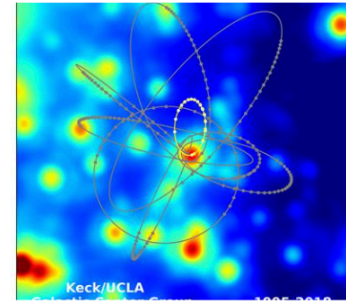
Science Cases



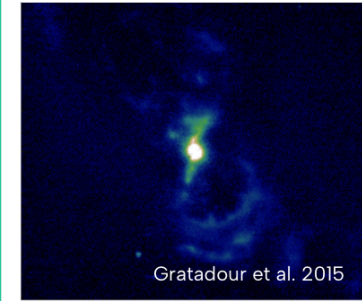
Circumstellar
Disks



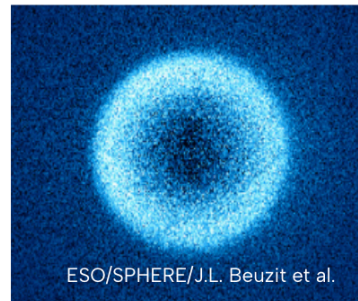
Brown dwarf /
directly imaged planet
atmospheres



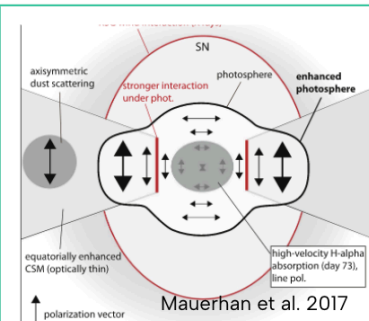
Galactic Center
Polarimetry



Polarimetry of
AGN



Solar System
Science

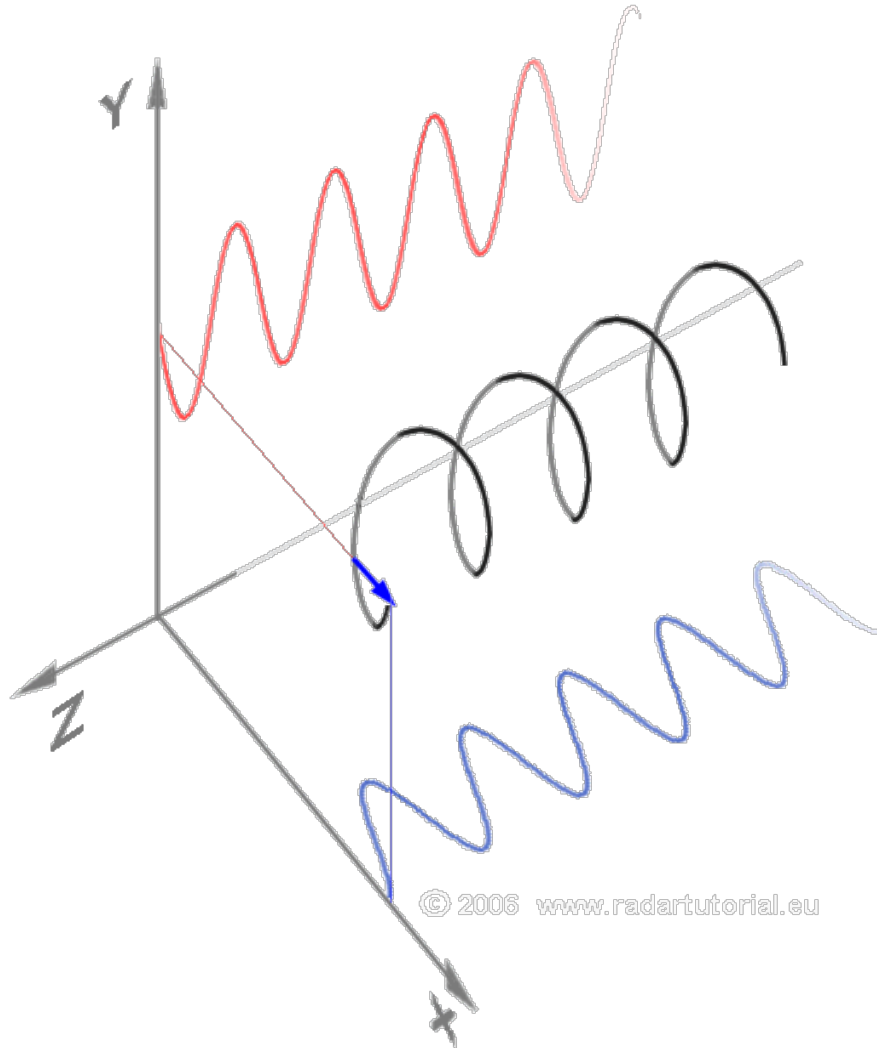


Supernovae

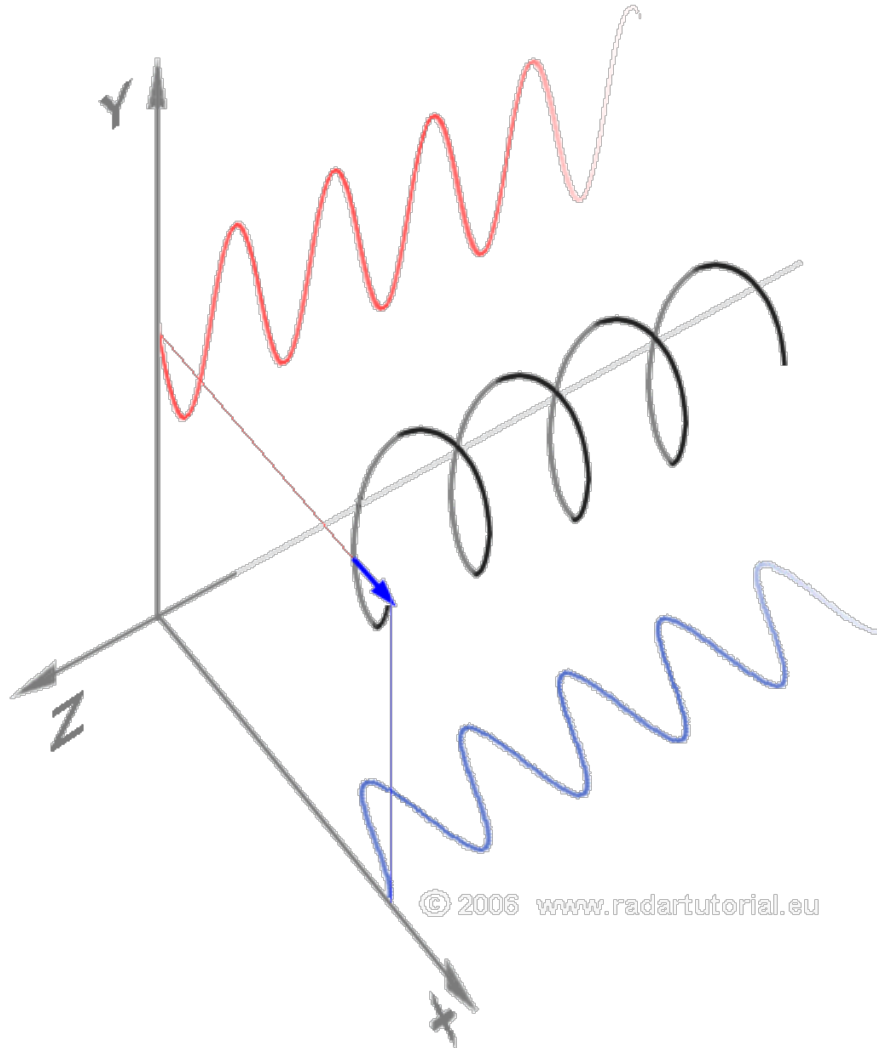


Your Science
Here!

Polarimetry Basics



Polarimetry Basics



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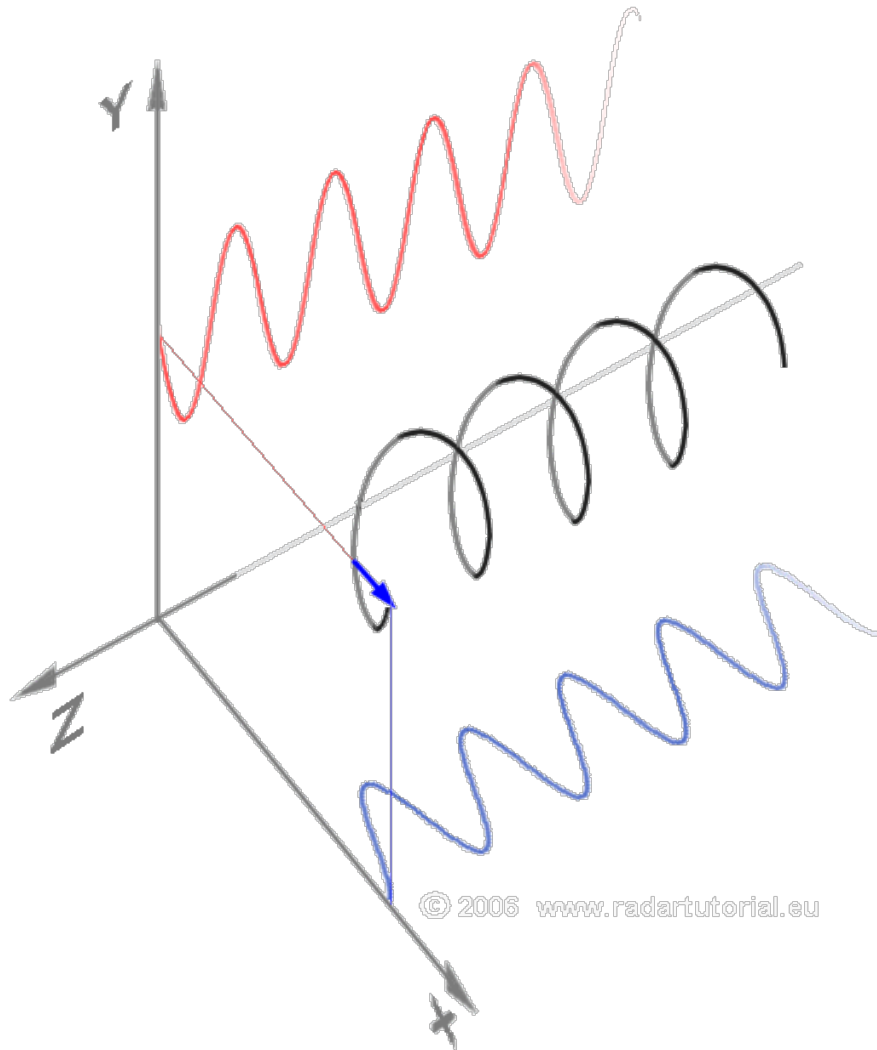
I Total Intensity

Q $\updownarrow$ - $\longleftrightarrow$

U $\nearrow$ - $\searrow$

V $\curvearrowright$ - $\curvearrowleft$

Polarimetry Basics



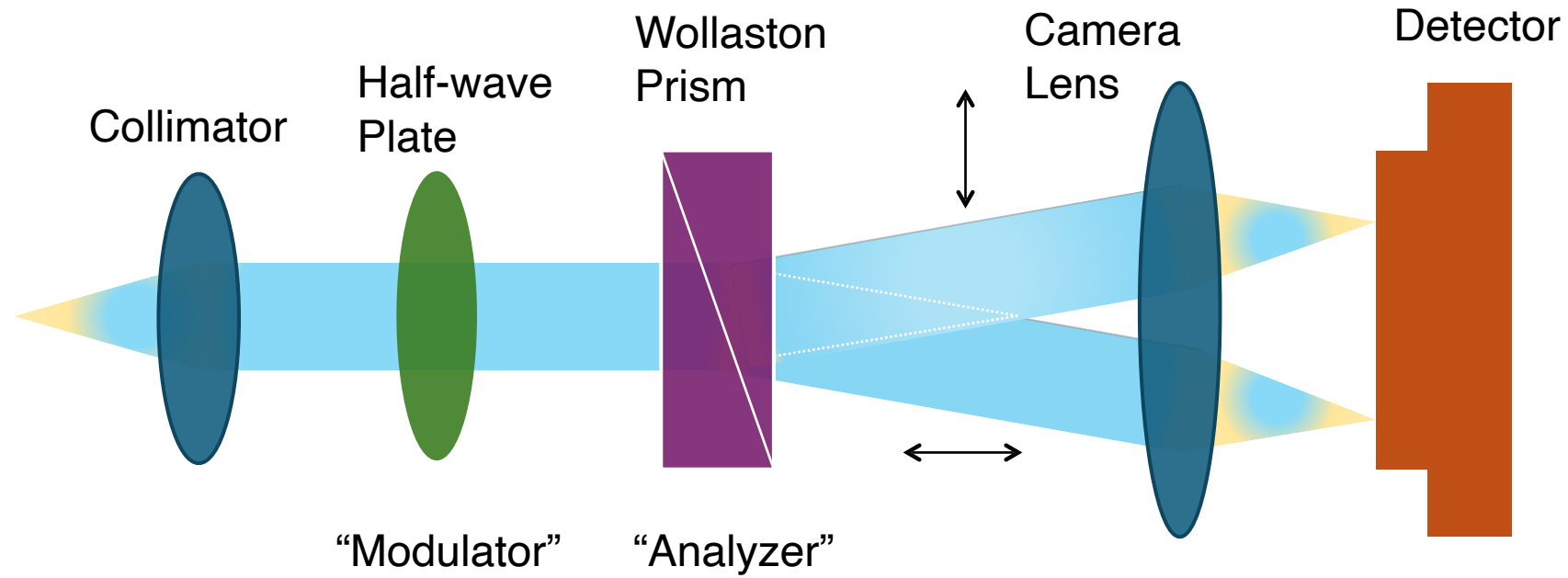
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I Total Intensity

Q	$\updownarrow$	-	$\leftrightarrow$
U	$\swarrow$	-	$\nearrow$

V $\curvearrowright$ - $\curvearrowleft$

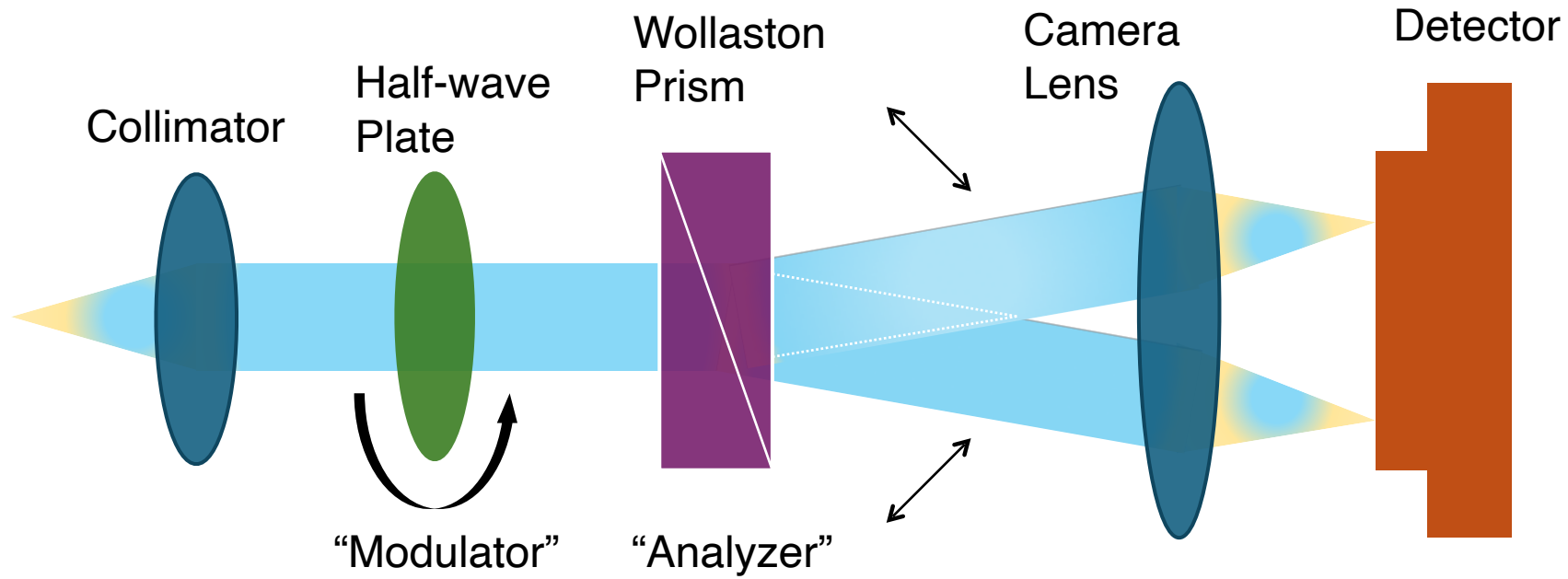
Measuring Polarization



$$\begin{aligned} I &= \text{star} + \text{star} \\ Q &= \text{star} - \text{star} \end{aligned}$$

The diagram shows the mathematical representation of the measured intensities. The first equation, $I =$, is followed by two star-shaped light patterns. The first star has a vertical double-headed arrow, and the second star has a horizontal double-headed arrow, with a plus sign between them. The second equation, $Q =$, is followed by two star-shaped light patterns. The first star has a vertical double-headed arrow, and the second star has a horizontal double-headed arrow, with a minus sign between them.

Measuring Polarization



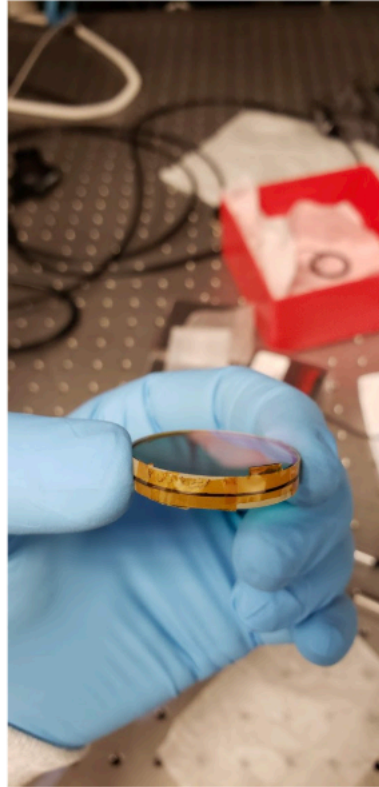
$$U = \text{star} - \text{star}$$

The equation shows the variable U followed by an equals sign, then two star-shaped light patterns with double-headed arrows inside, separated by a minus sign. The stars represent the intensity profiles of the two polarized beams.

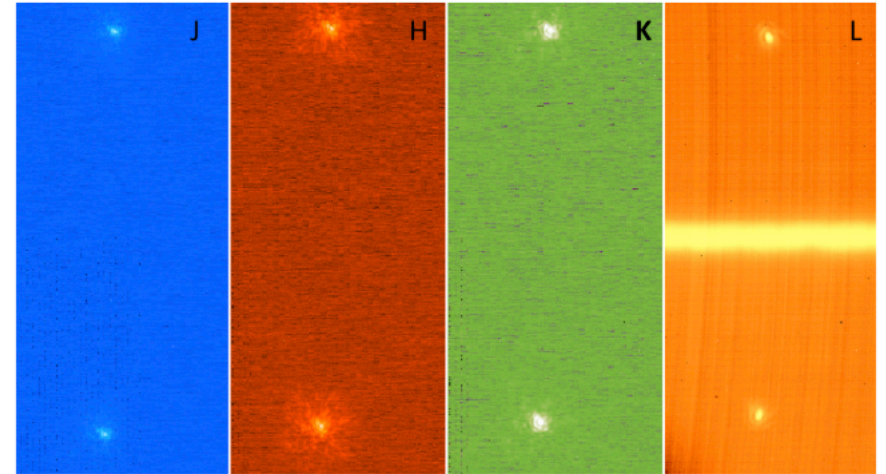
Wollaston Prism

- Wollaston installed in NIRC2 in Jan. 2019
- On-sky tests done for all JHKL wavelengths
- Arc lamp data for grism spectropolarimetry taken

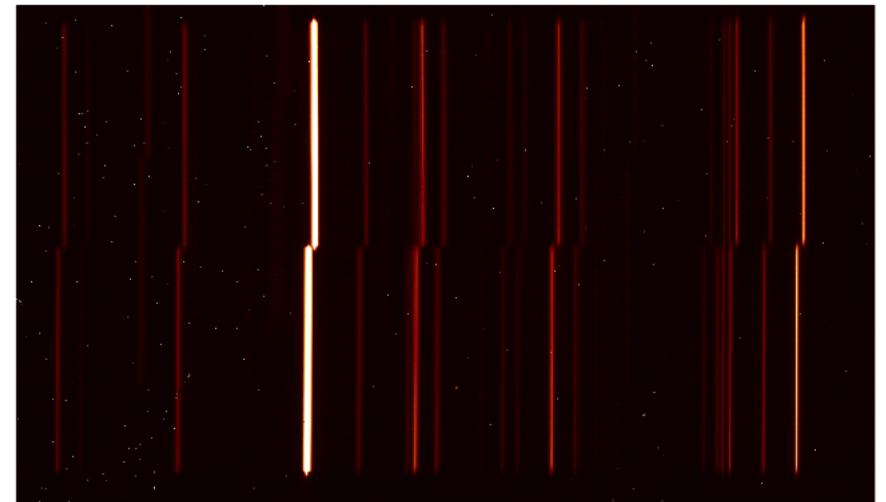
Wollaston



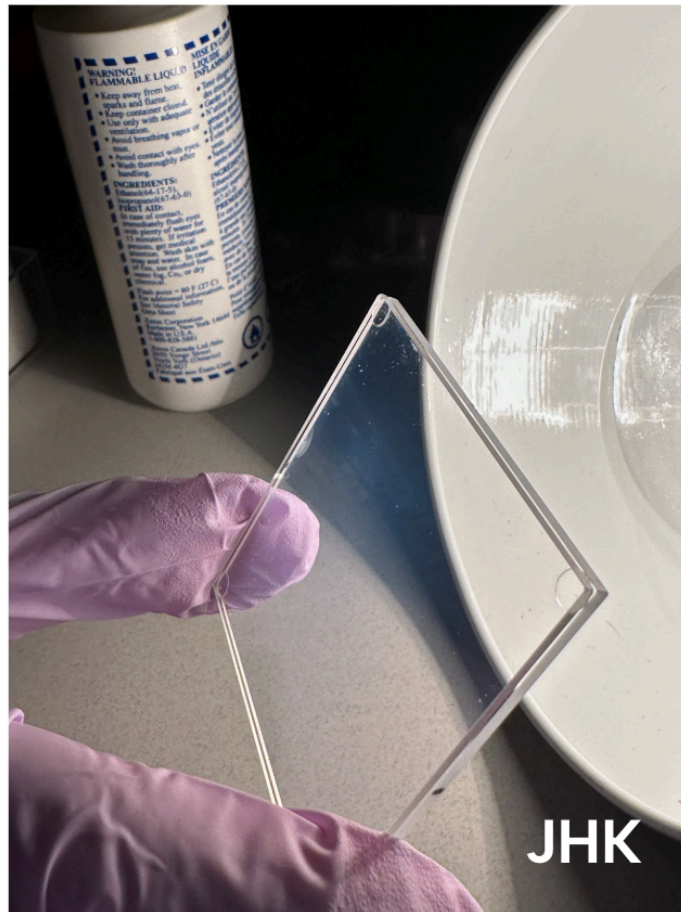
JHKL Beamsplitting



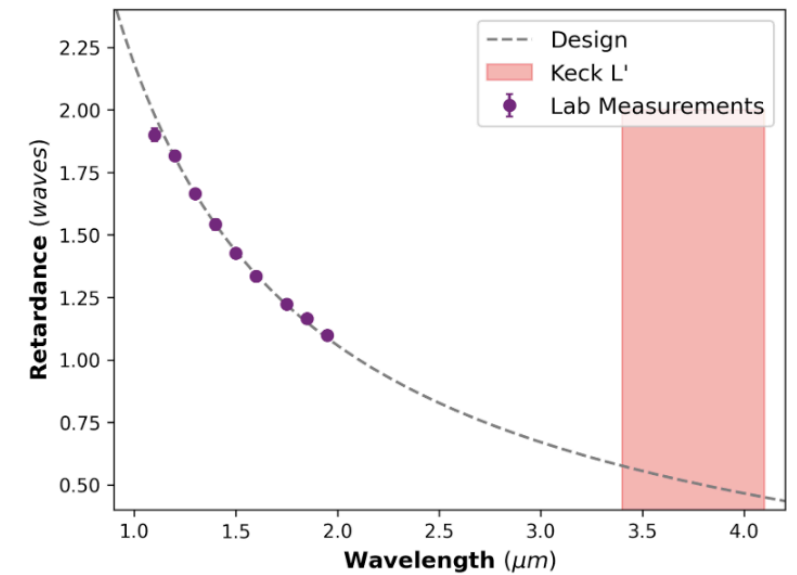
Arc Lamp & Grism



HWPs Characterized in Lab

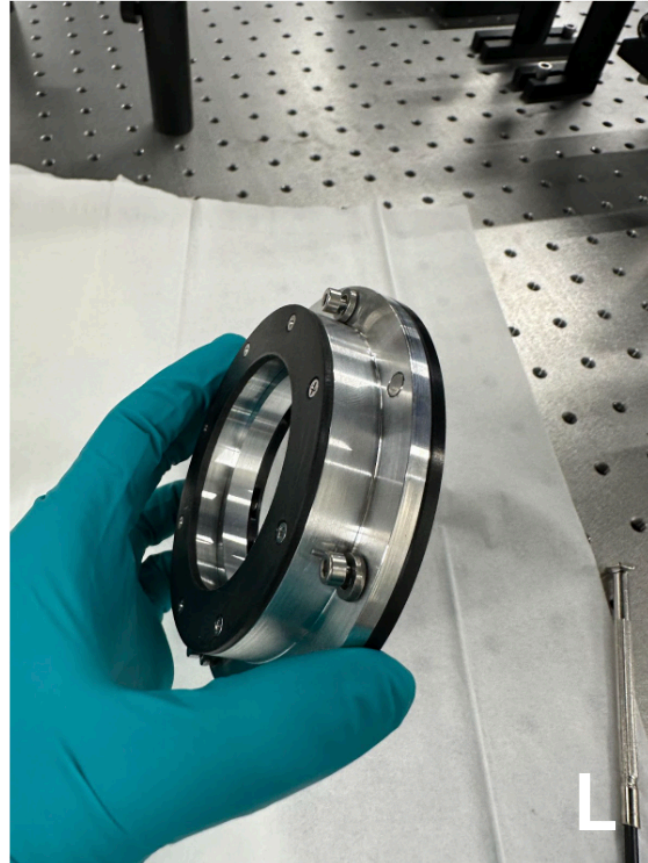
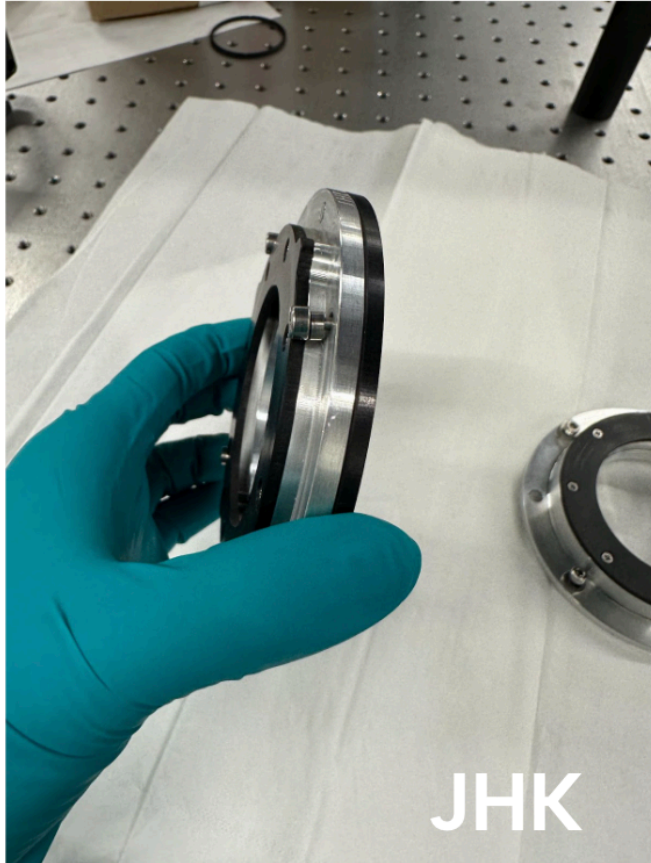


U of A grad student
(former UCSB undergrad)
Will Melby



Both HWPs are within 10%
of target retardance

June 2025: HWPs Shipped to Keck

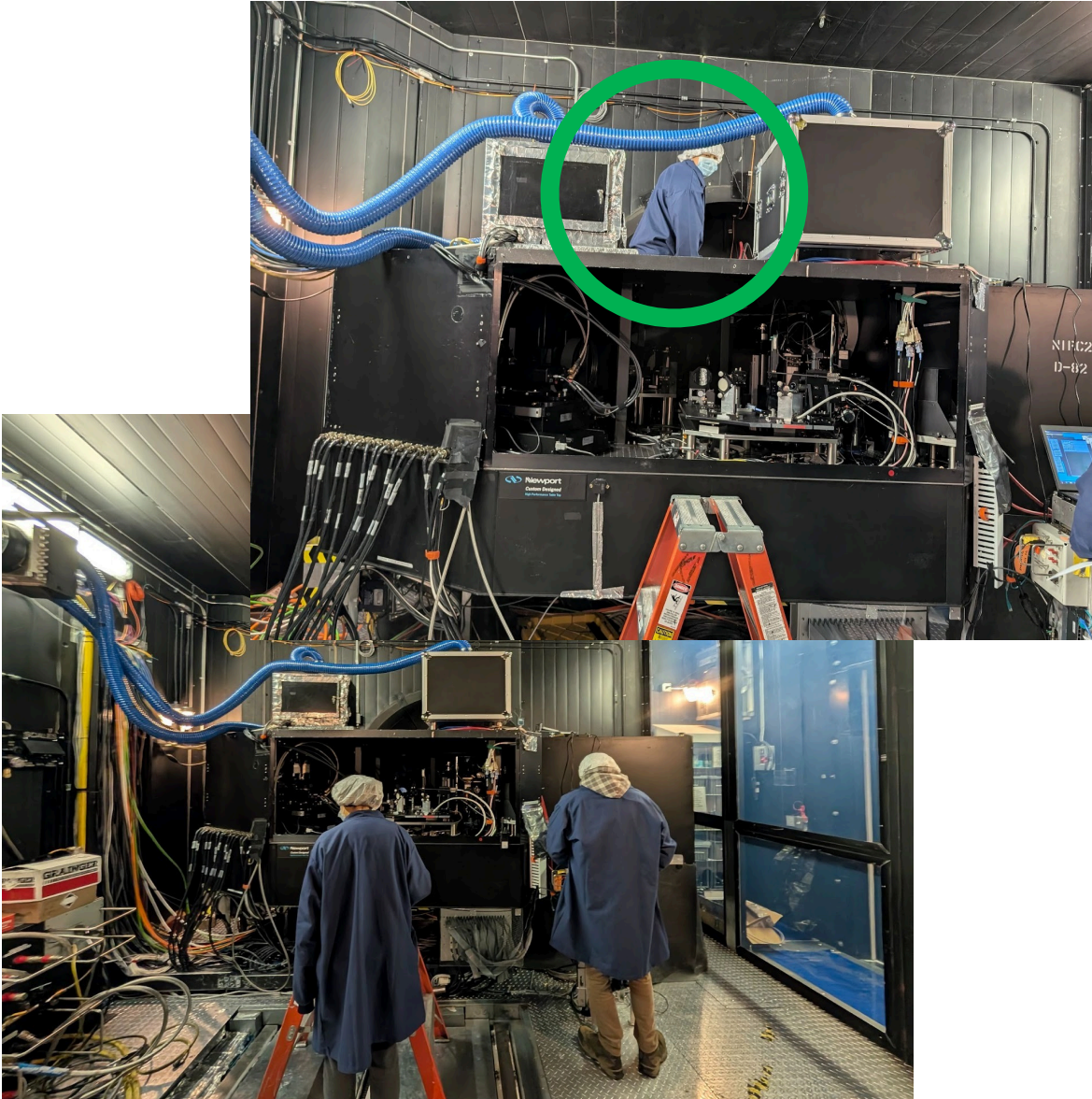


UCSB
Undergrad
Thomas
McIntosh

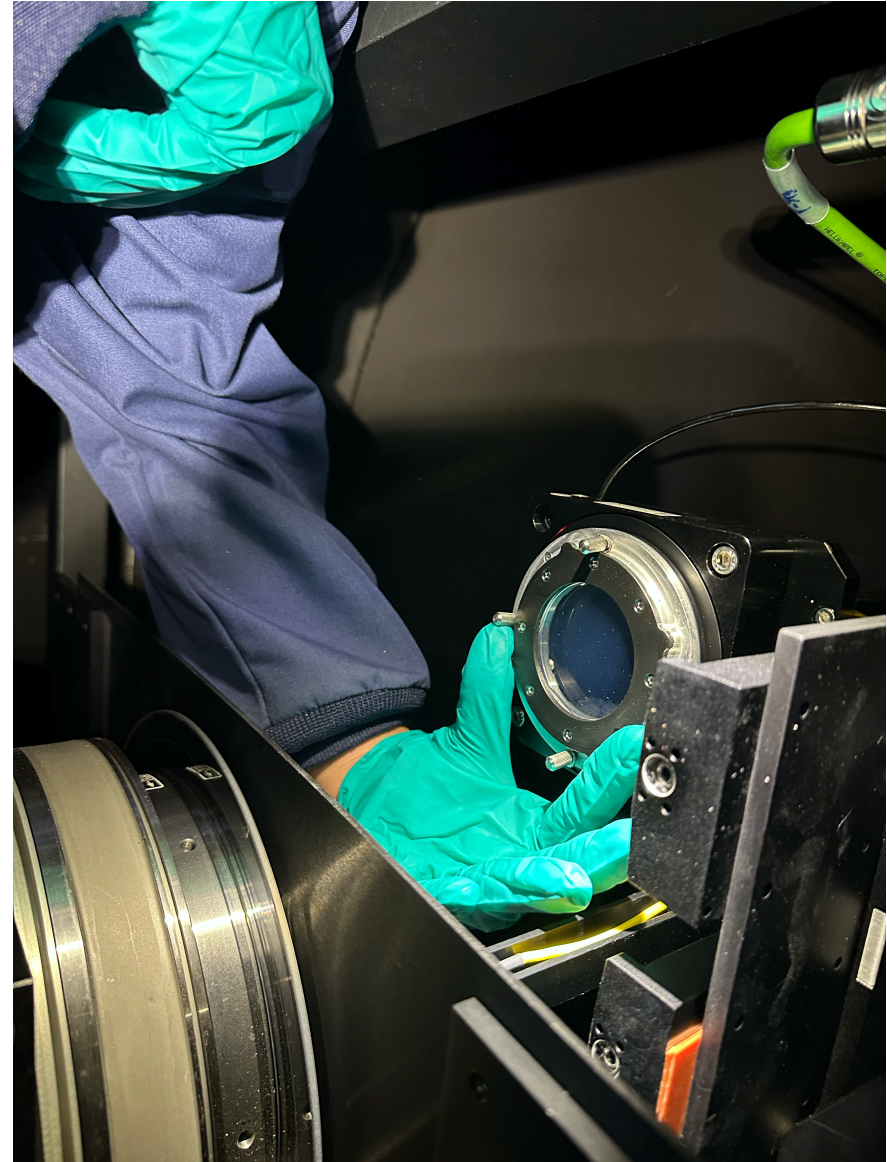
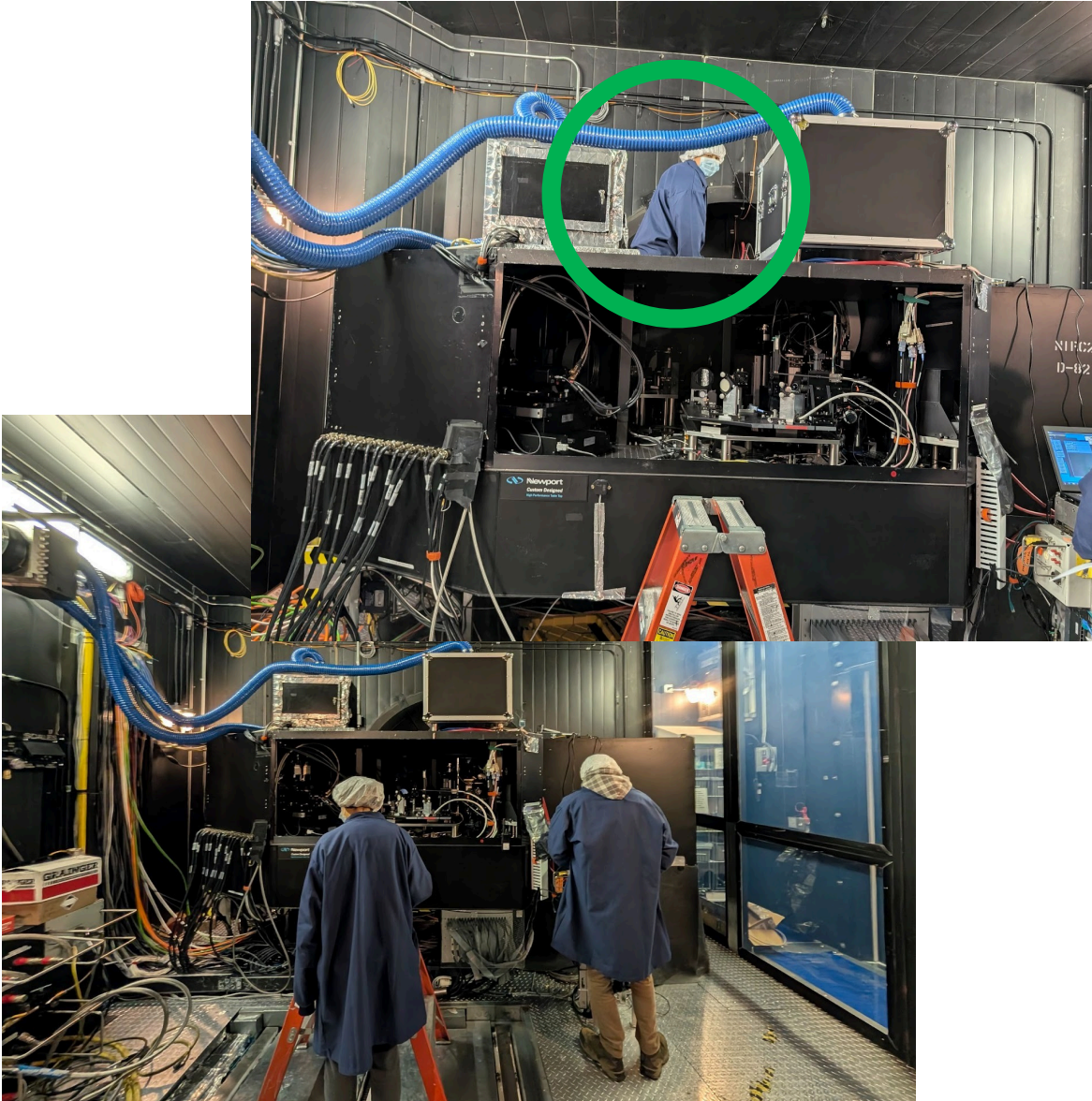


UCSB AAPF
Postdoc
Briley Lewis

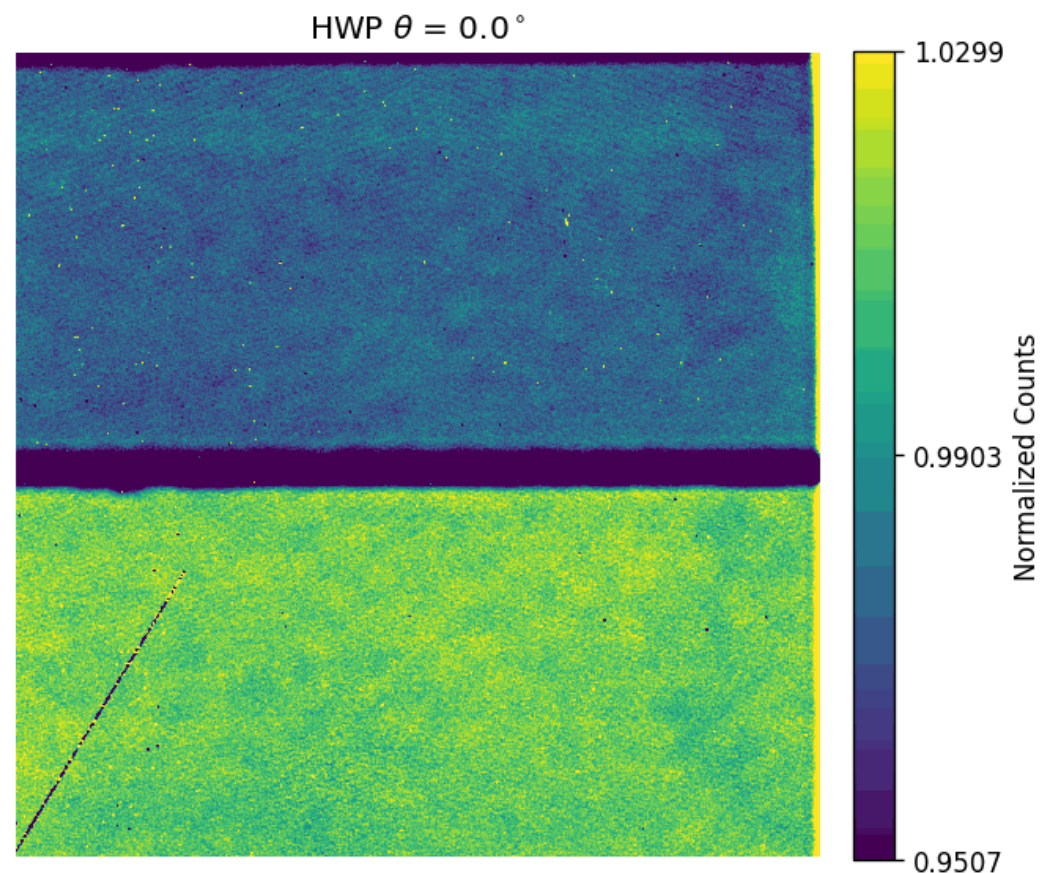
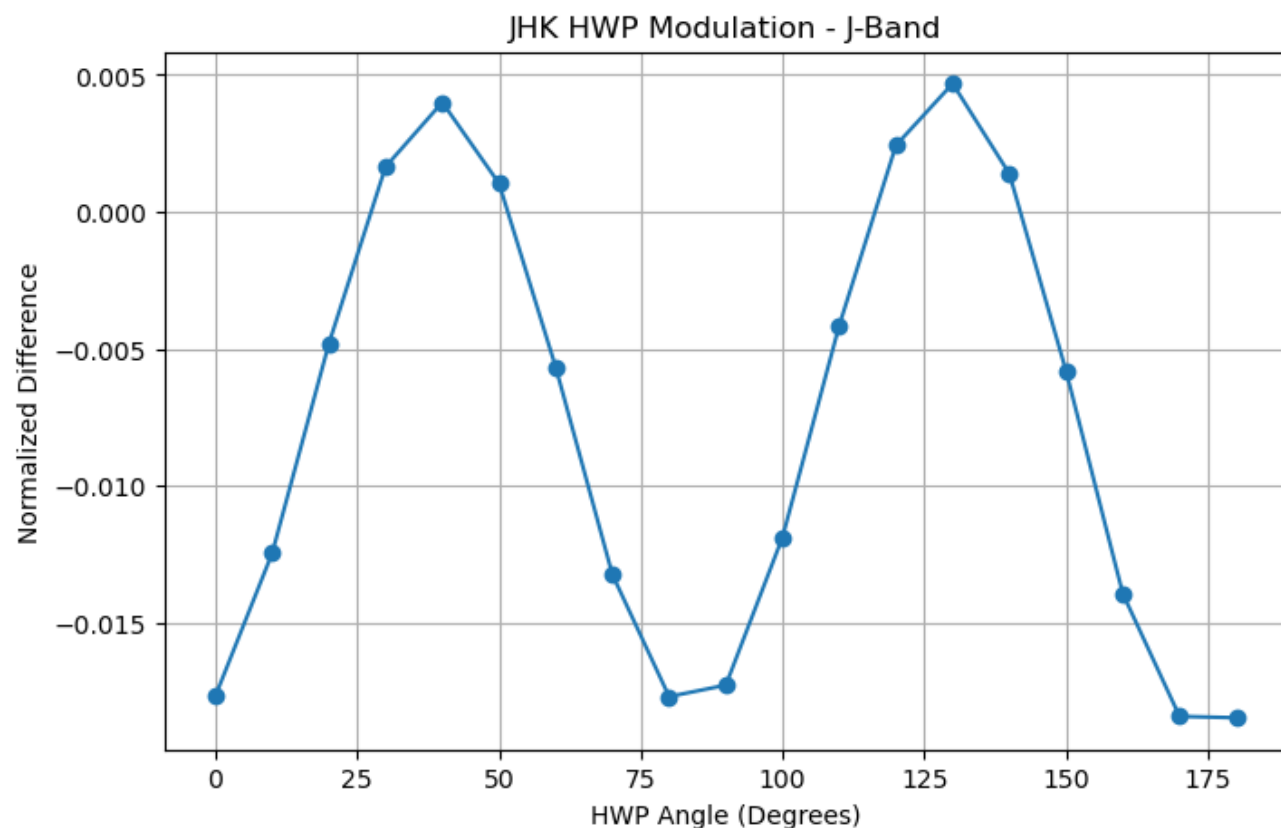
August 2025: HWP Installed at Keck



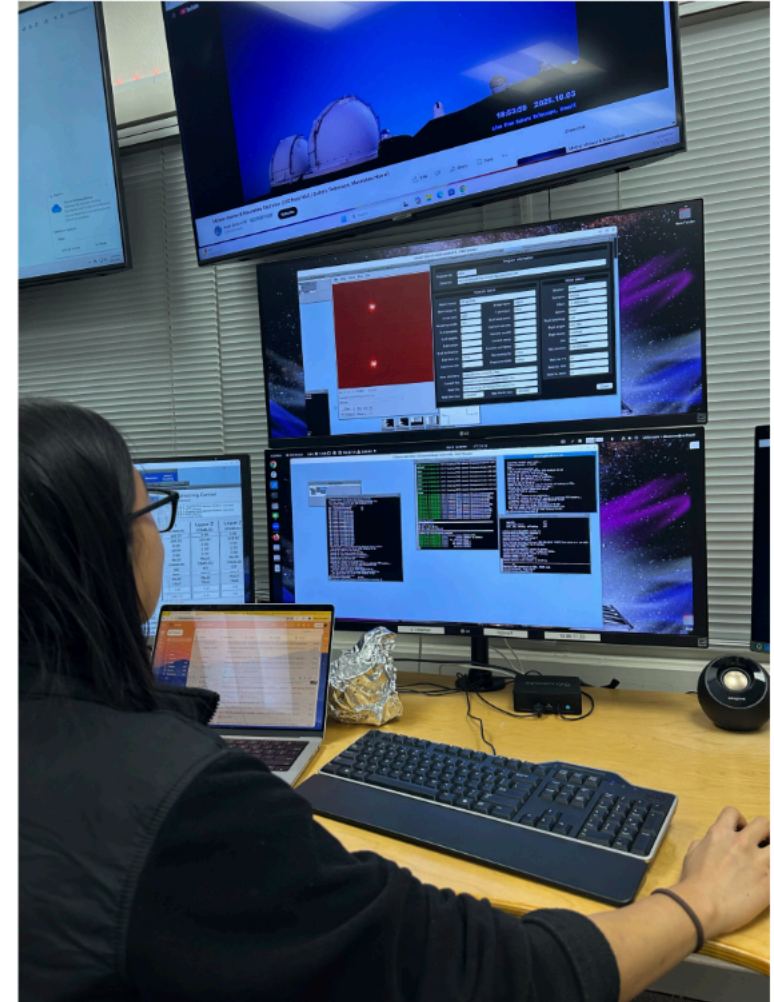
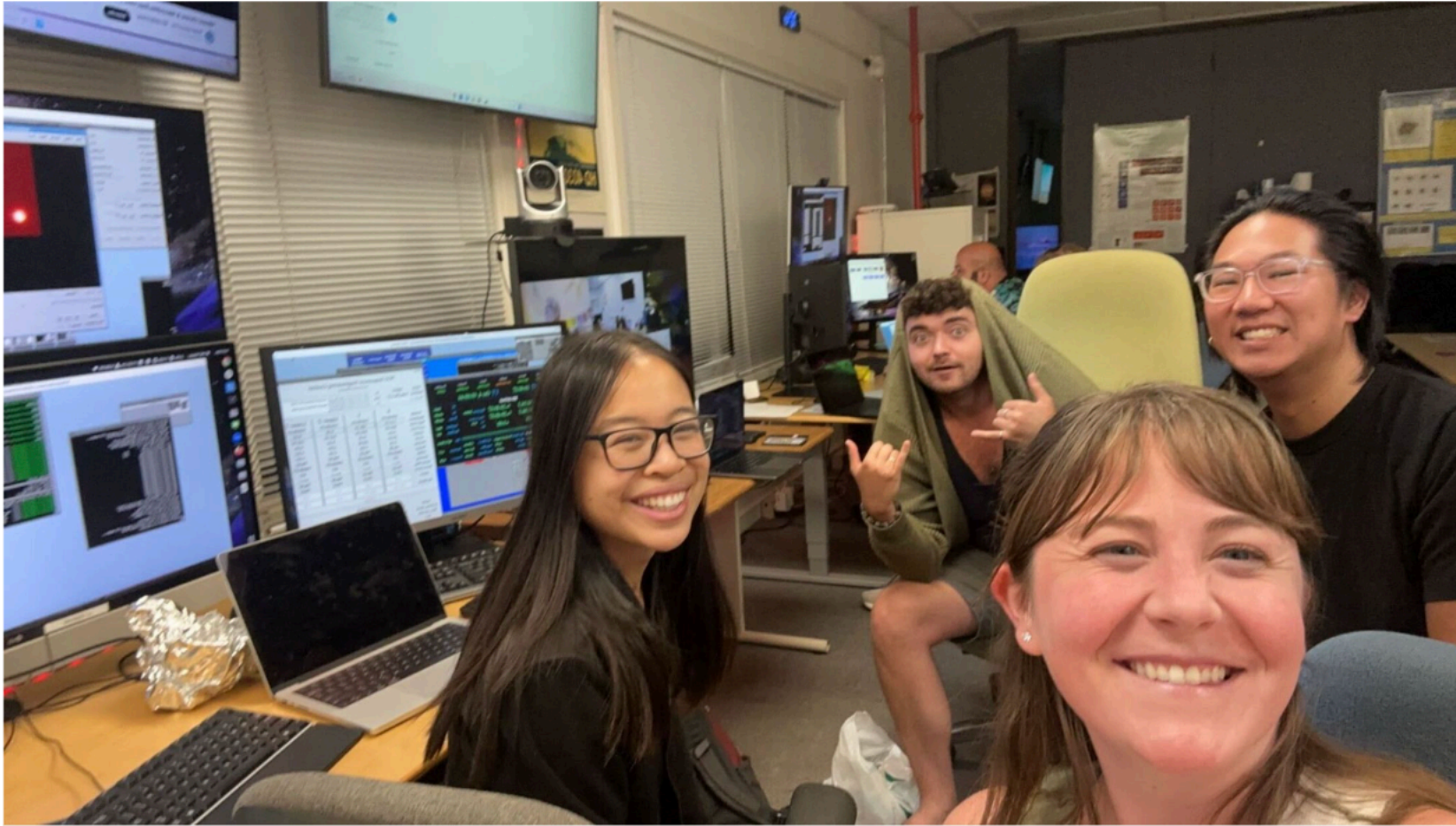
August 2025: HWP Installed at Keck



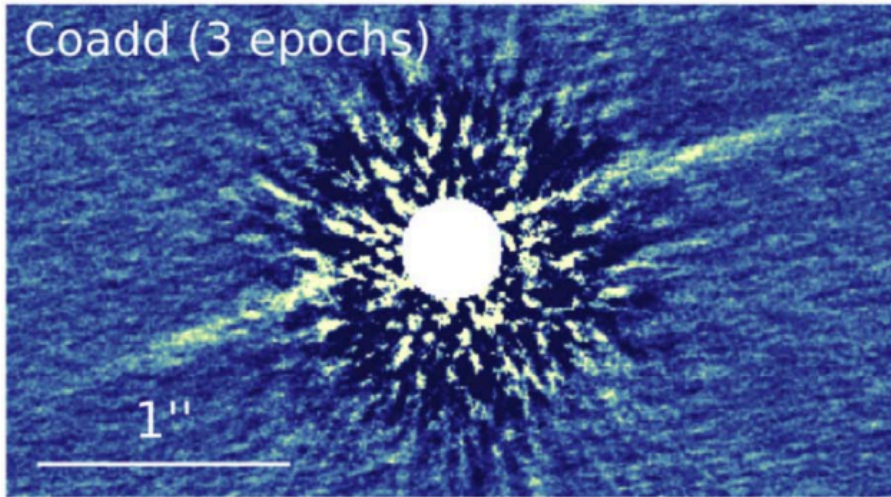
August 2025: HWP Installed at Keck



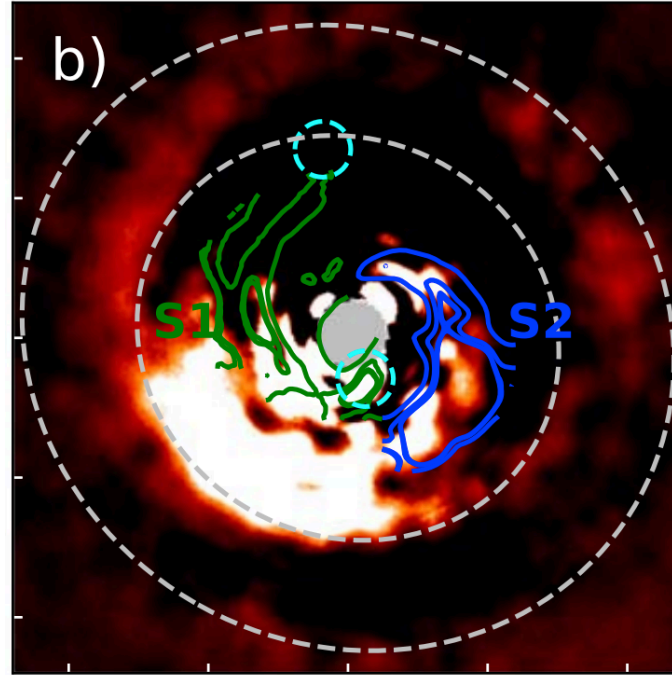
October 2025: First on-sky nights!



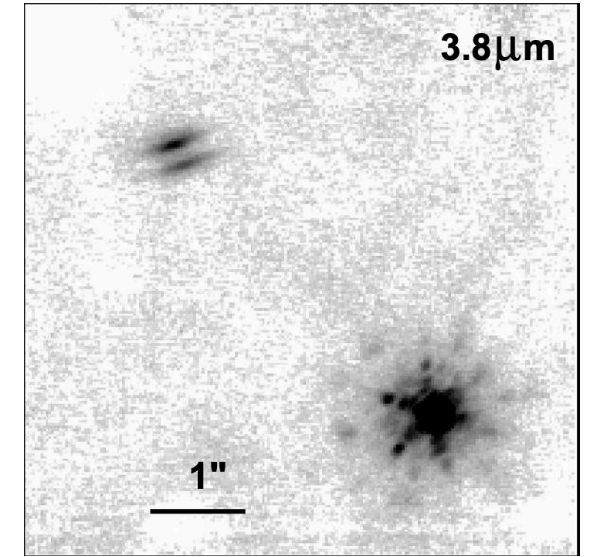
Observed Targets



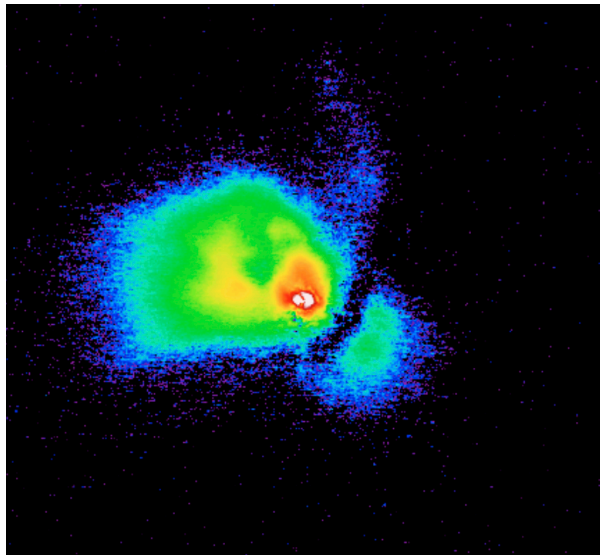
BD+45 598 (Hinkley+ 2021)



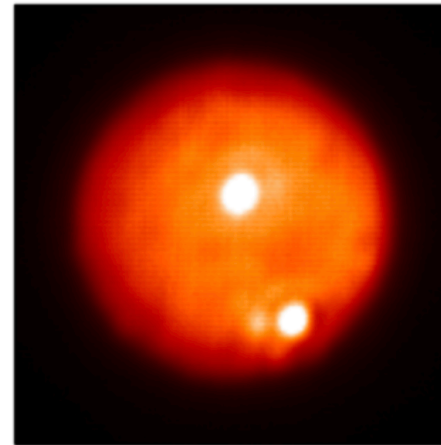
AB Aur (Jorquera+ 2022)



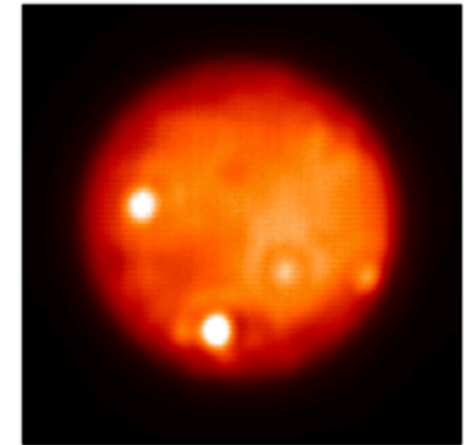
HV Tau C (Duchêne+ 2009)



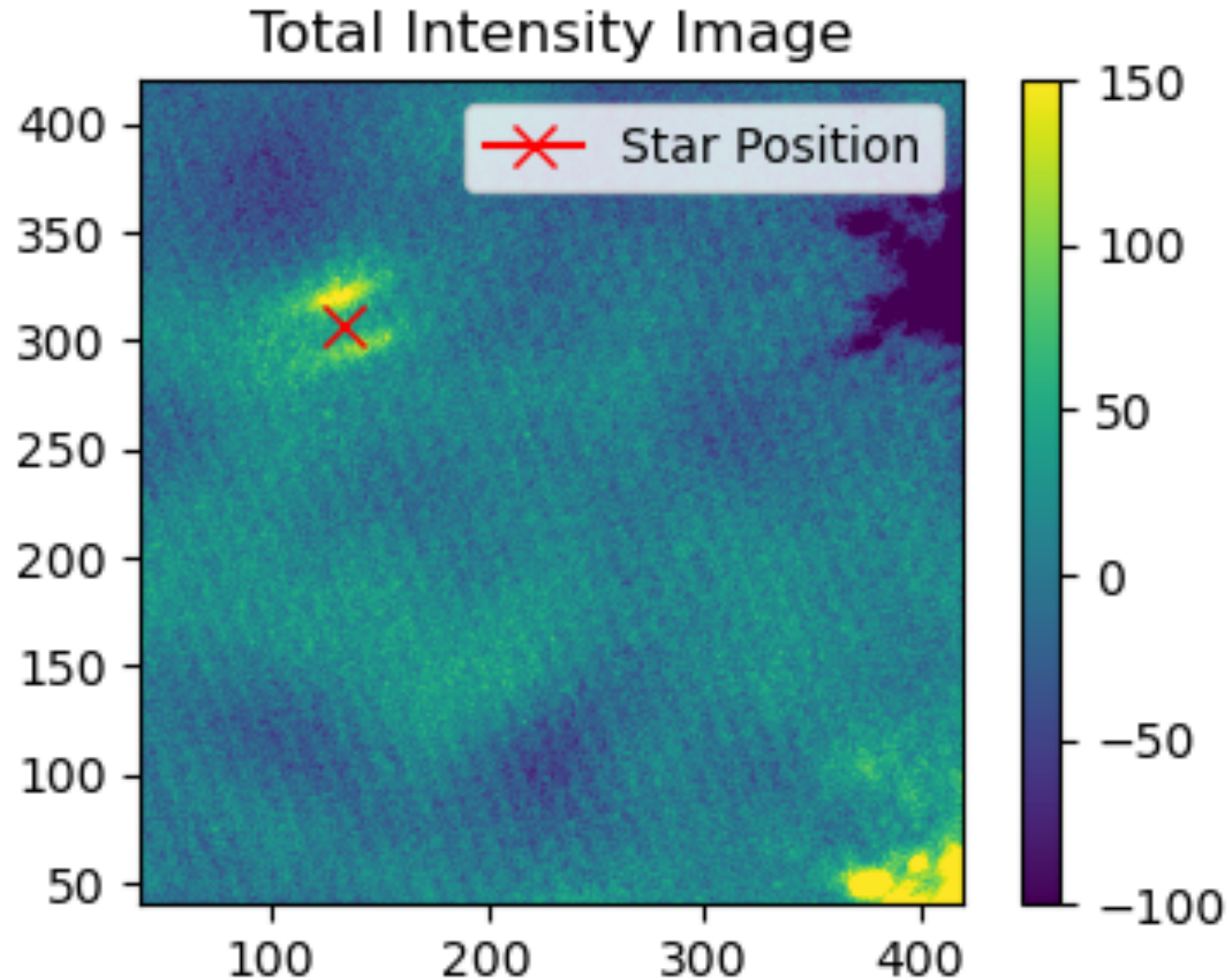
HL Tau (Murakawa+ 2008)



Io (Photo Credit: WMKO)



Early Science Results - HV Tau C



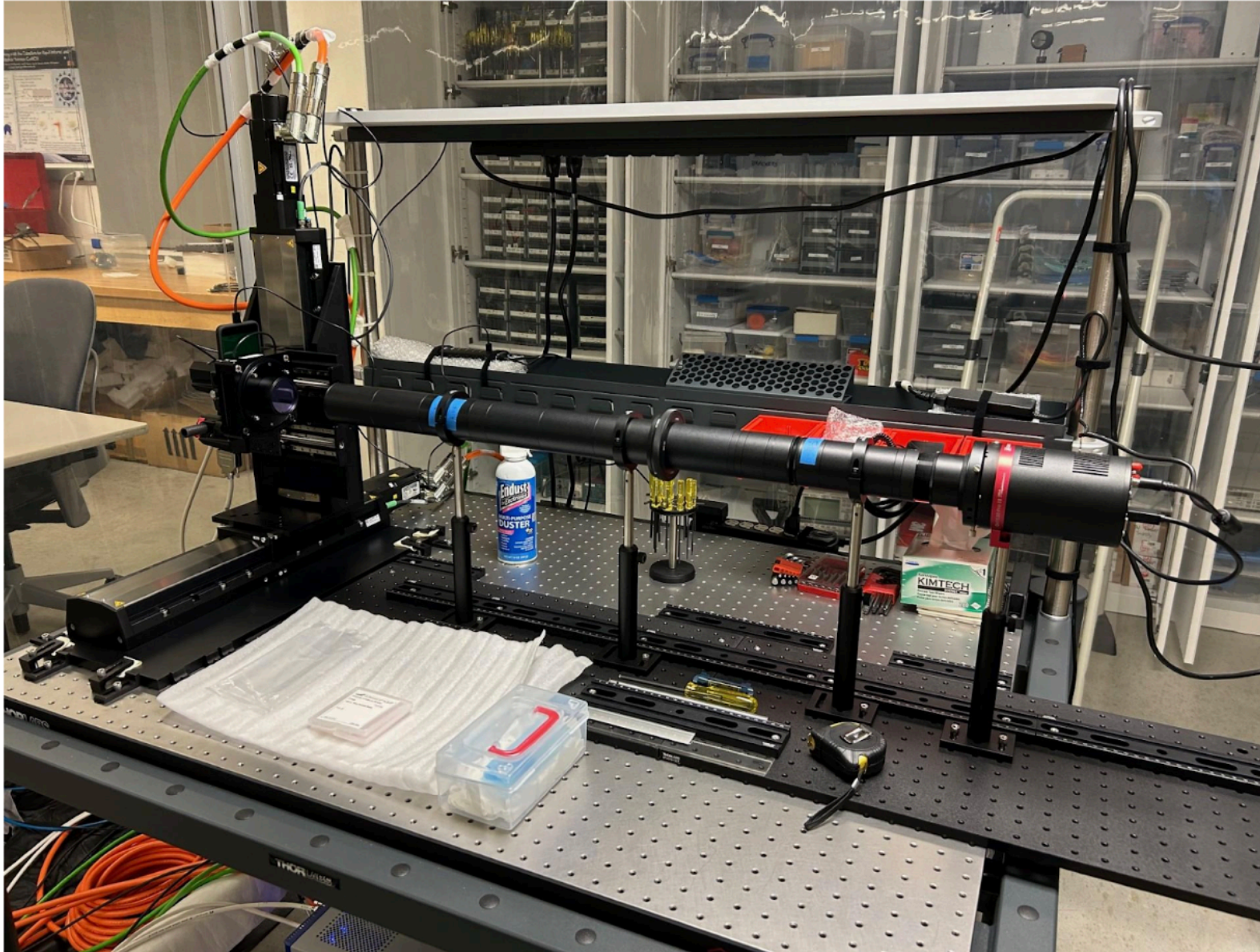
Next Steps

- Many upcoming observation nights
 - Additional JHK and L-band commissioning tasks in December and January
 - 8+ nights of on-sky time in 2026A
- Plans to create open-source data processing pipeline for NIRC2 polarimetry, quantitative Mueller matrix model for calibration
- Already open for shared-risk use
- Goal for open use in **26B**

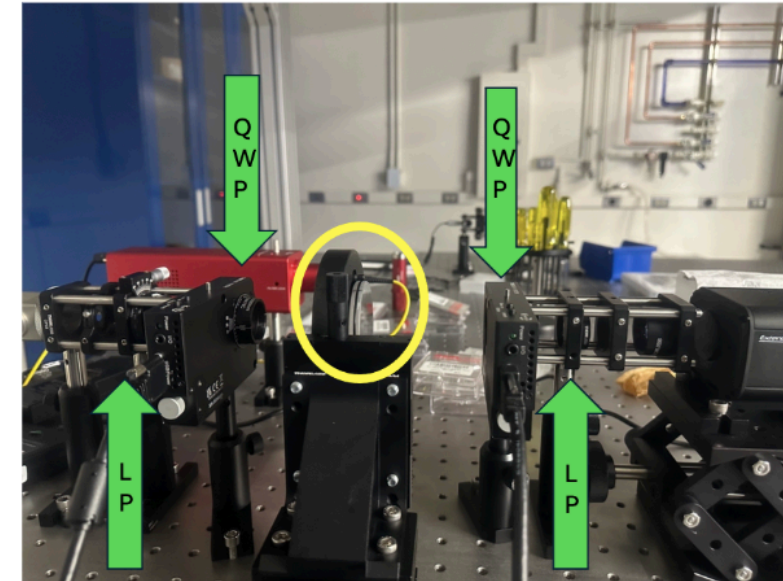
Thank You!

Back-Up Slides

Beamwalk + DRRP Set-Up Image

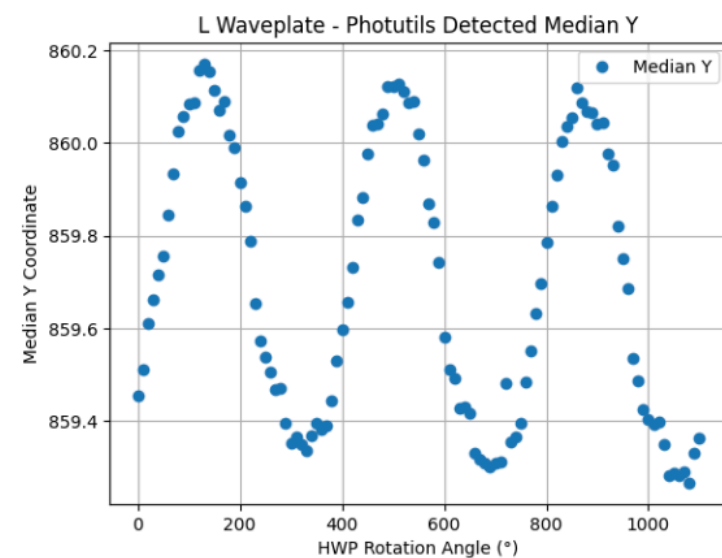
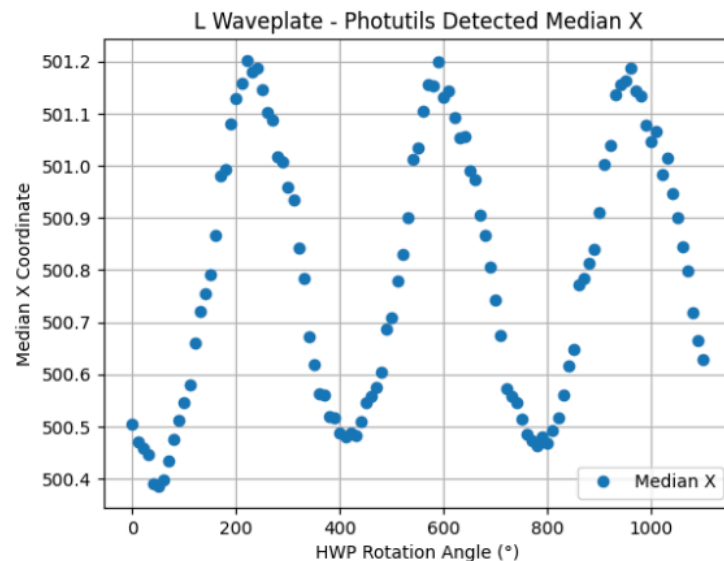
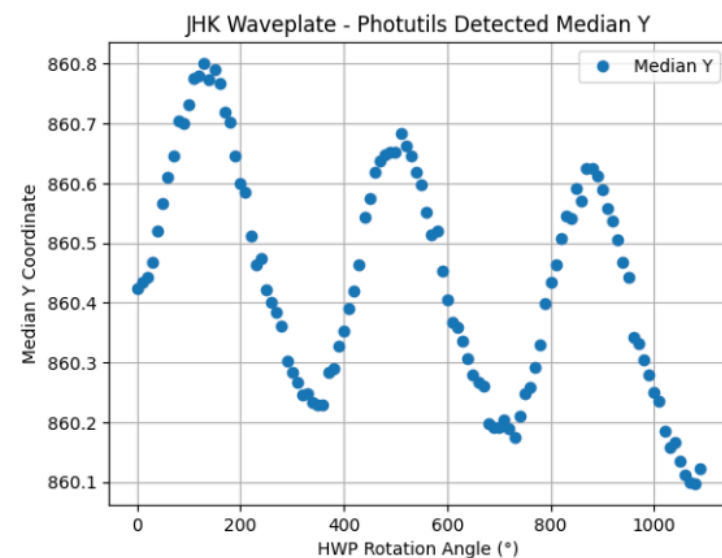
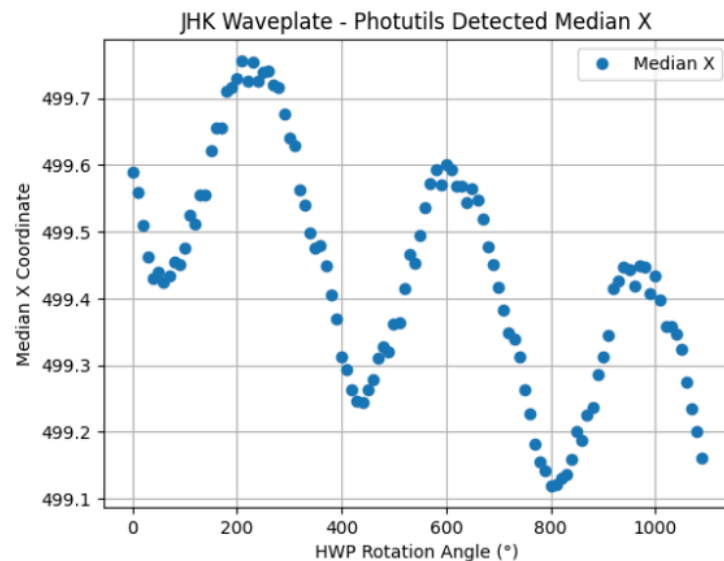


DRRP

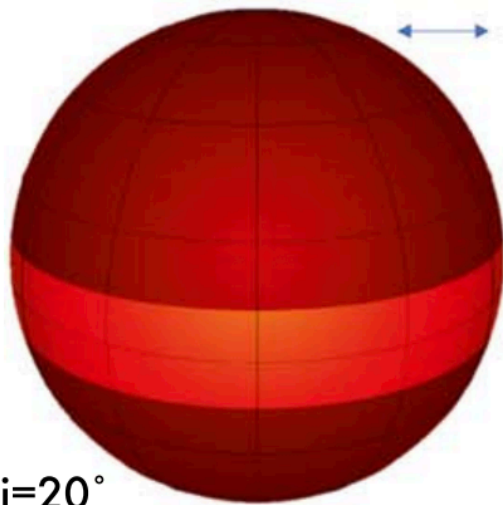


HWPs - PCU2 Integration

- **NOTE:** Include just the final on-sky angular shift instead, and no need to show beamwalk plots
- JHK HWP: $3.2\ \mu\text{m}$ shift in the object plane
 - $\sim 16''$ tilt
- L HWP: $5.2\ \mu\text{m}$ shift in the object plane

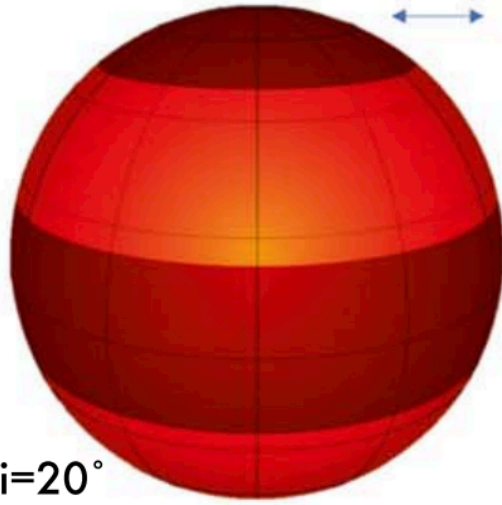


$p = 0.018\%$ $\psi = 90^\circ$



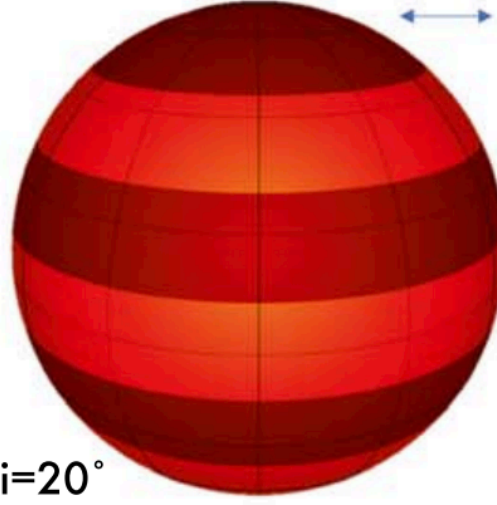
$i=20^\circ$
One band

$p = 0.030\%$ $\psi = 90^\circ$



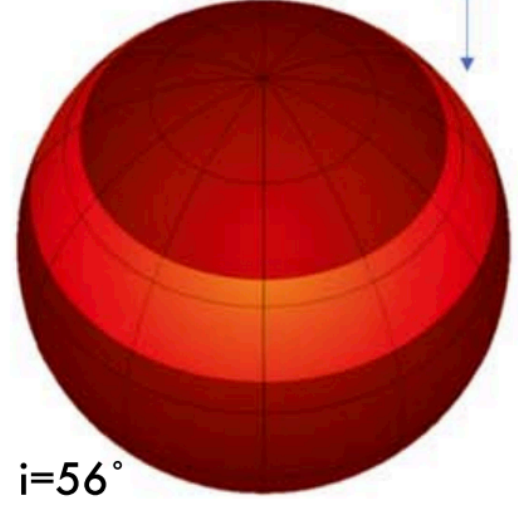
$i=20^\circ$
Two bands **Luhman 16A**

$p = 0.012\%$ $\psi = 90^\circ$



$i=20^\circ$
Three bands

$p = 0.021\%$ $\psi = 0^\circ$



$i=56^\circ$
Two bands

Measurements

$p_A = 0.031 \pm 0.004\%$ $\psi_A^* = -32 \pm 4^\circ$
 $p_B = 0.010 \pm 0.004\%$ $\psi_B^* = 73 \pm 12^\circ$

Banded Models

Consistent with Luhman 16A

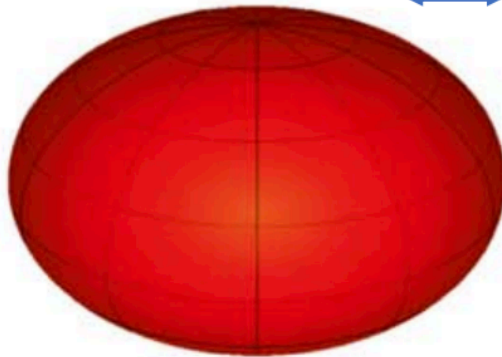
Consistent with Luhman 16B

Oblateness Models

Inconsistent with Luhman 16A

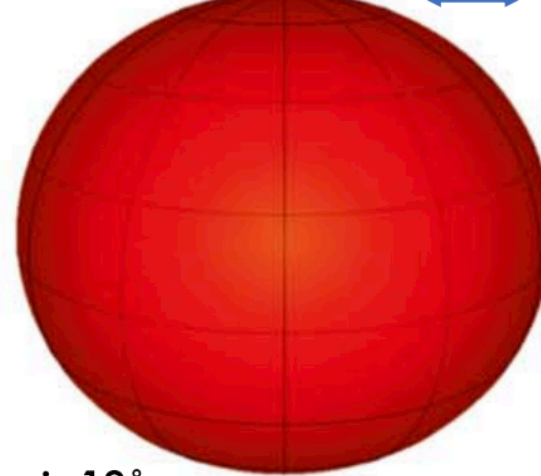
Consistent with Luhman 16B

$p \leq 0.030\%$ $\psi = 90^\circ$



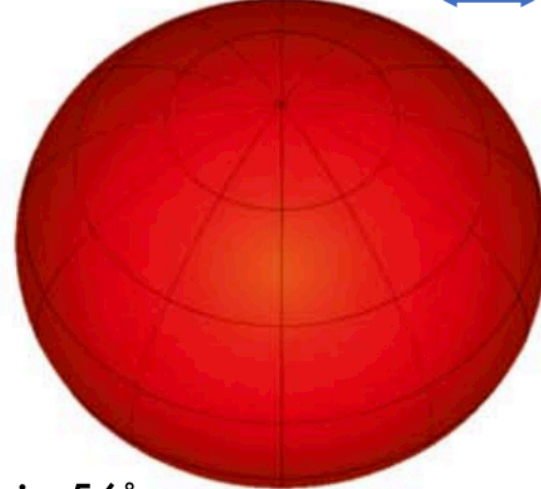
$i = 26^\circ$
Oblateness: 0.013*
Luhman 16B

$p \leq 0.008\%$ $\psi = 90^\circ$



$i = 18^\circ$
Oblateness: 0.003*
Luhman 16A

$p \leq 0.009\%$ $\psi = 90^\circ$



$i = 56^\circ$
Oblateness: 0.009*
Luhman 16A

* Pictured oblateness has been inflated by a factor of 30 for display purposes