Exoplanet Imaging with CHARIS and Future Synergies with WFIRST CGI

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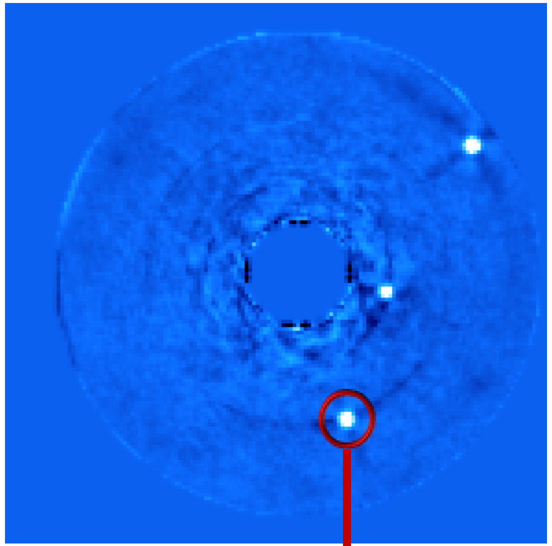
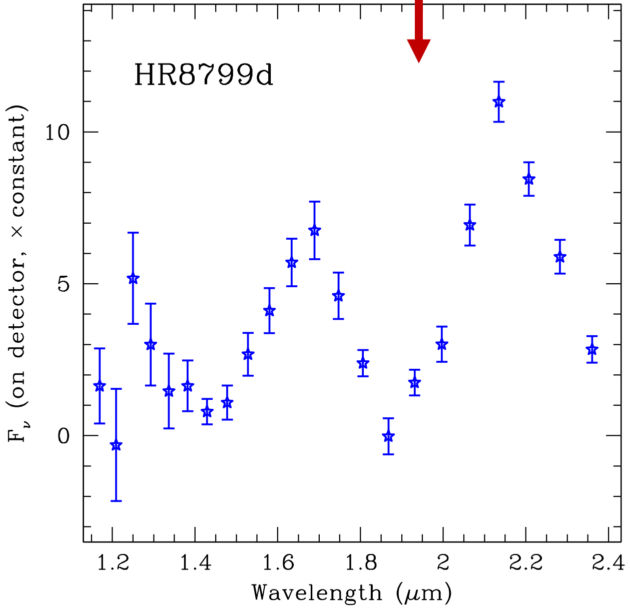
LUVOIR Team: Thanks especially to Laurent Pueyo, Qian Gong, Matt Bolcar

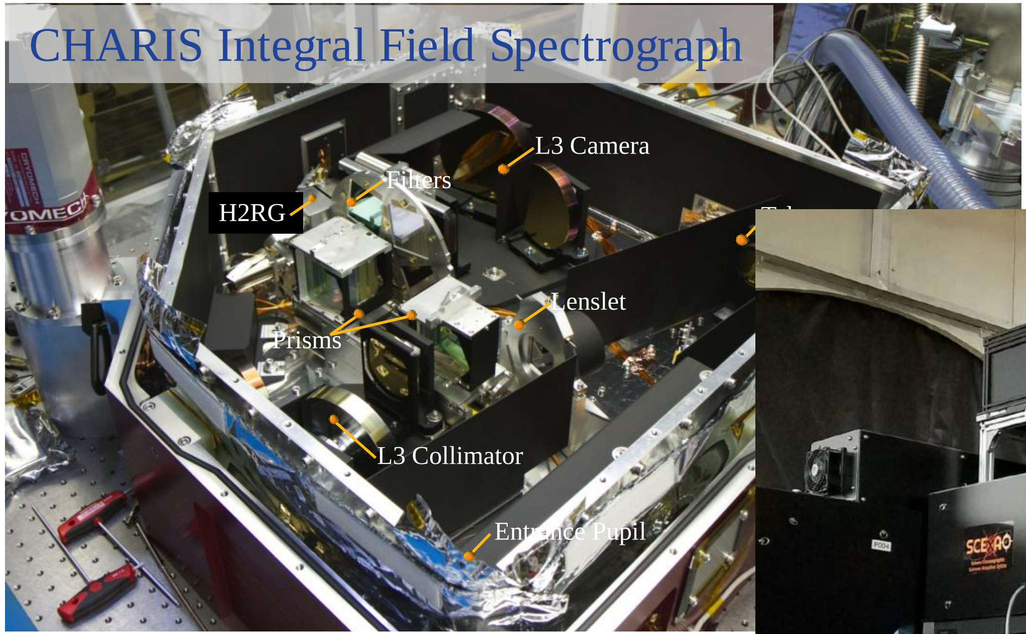
SCExAO and CHARIS: Takeaways toward CGI

HR8799 ADI + SDI





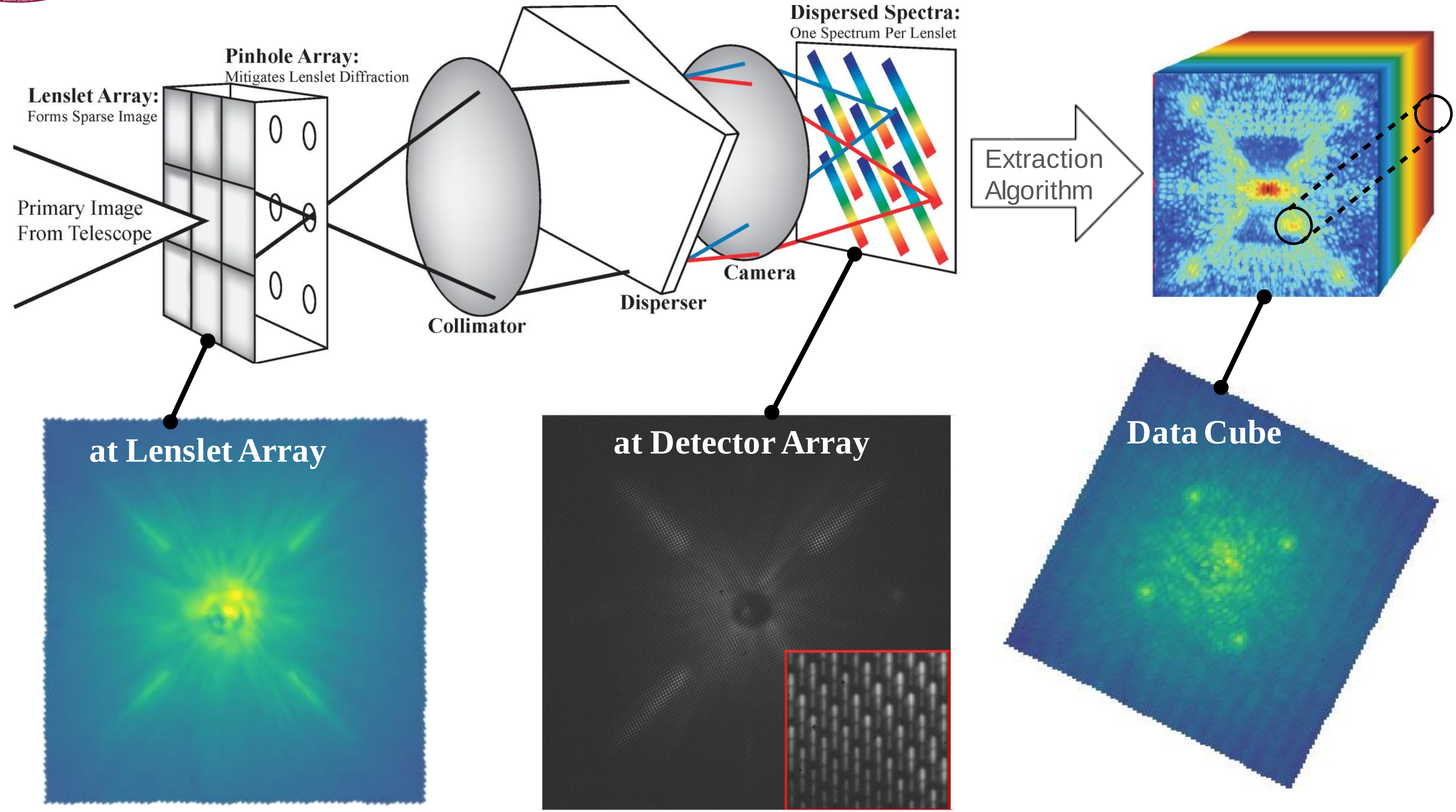
1. Block starlight: Coronagraph
2. Fix Aberrations: Wavefront Control
3. Get a spectrum of the image plane: Integral Field Spectrographs
4. Data Post-Processing for speckle subtraction: Necessary on the ground and in space



<u>**Our primary goal is to take spectra of the planets we discover.**</u>

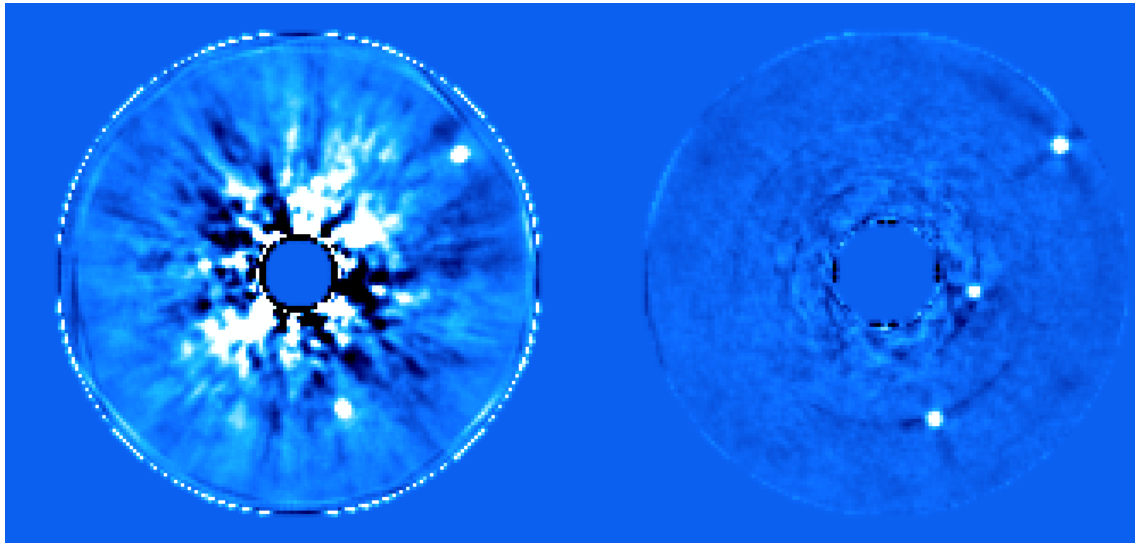
HR8799 data processing by Tim Brandt from CHARIS Engineering Data

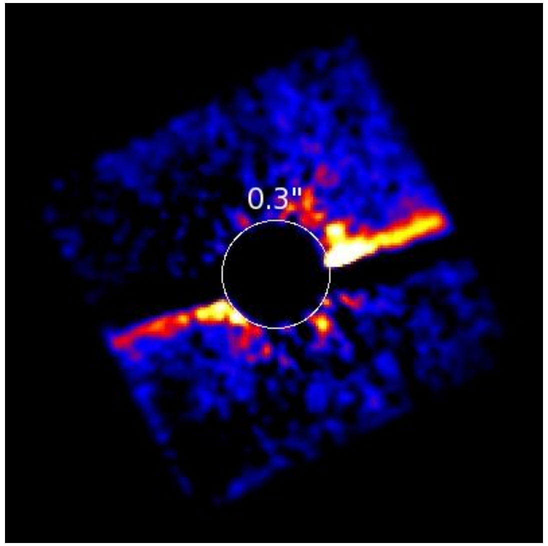
Integral Field Spectroscopy - Concept



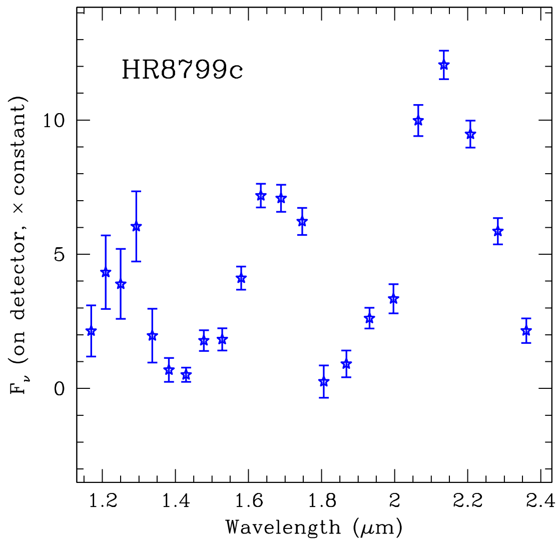
CHARIS First detections

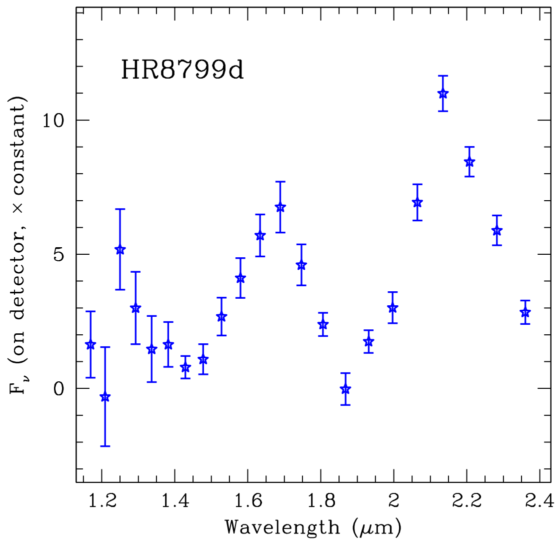
HR8799 ADI only | HR8799 ADI + SDI | HD32297 Roll Subtracted

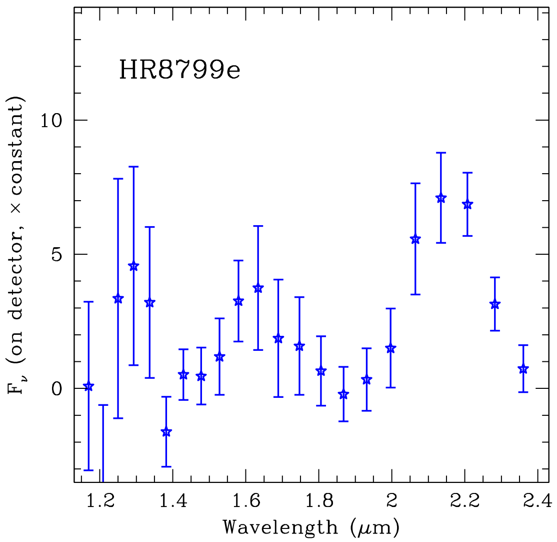




ADI+SDI detection of HR8799 c,d,e at SNR of 50, 35, and 15 respectively (~2-3 x 10^{-5})



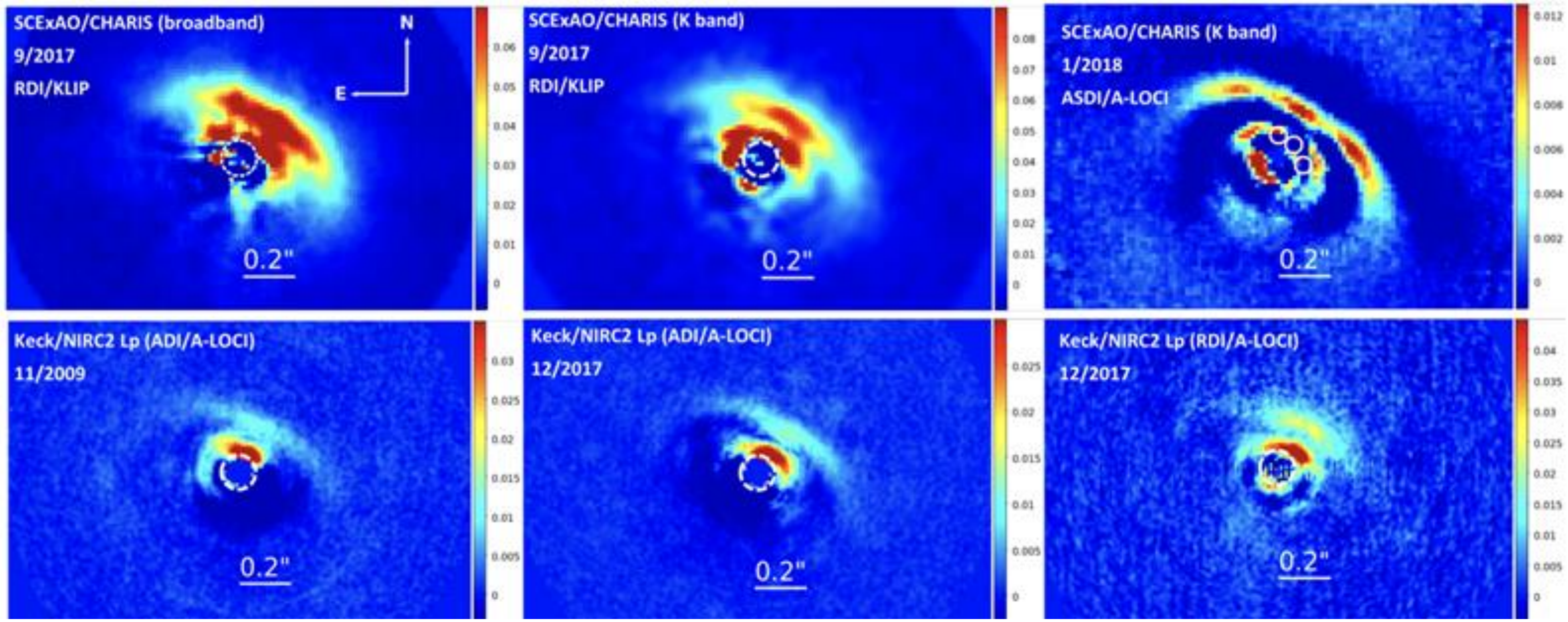




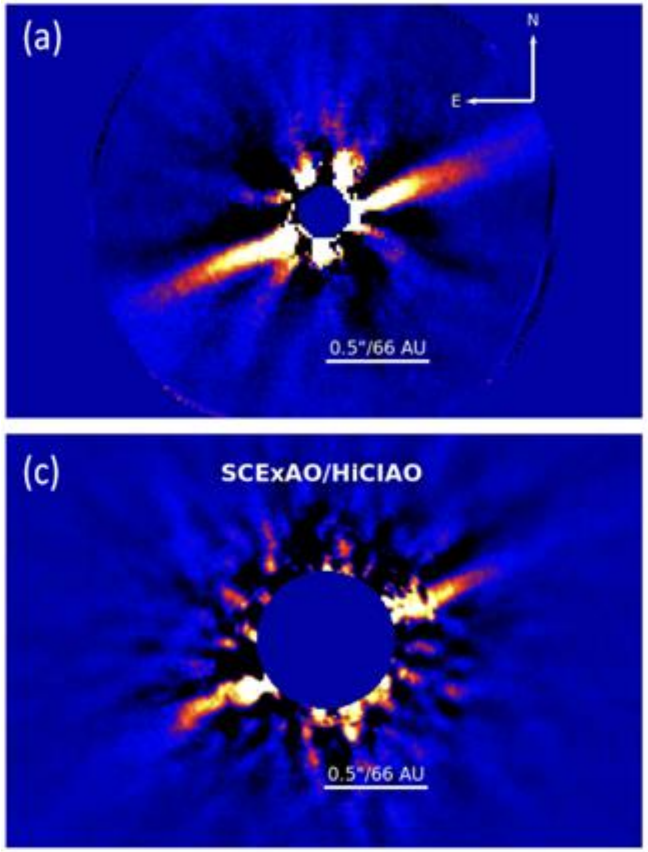
HR8799 preliminary data processing by Tim Brandt, HD32297 Processing by Thayne Currie

CHARIS Disk Publications

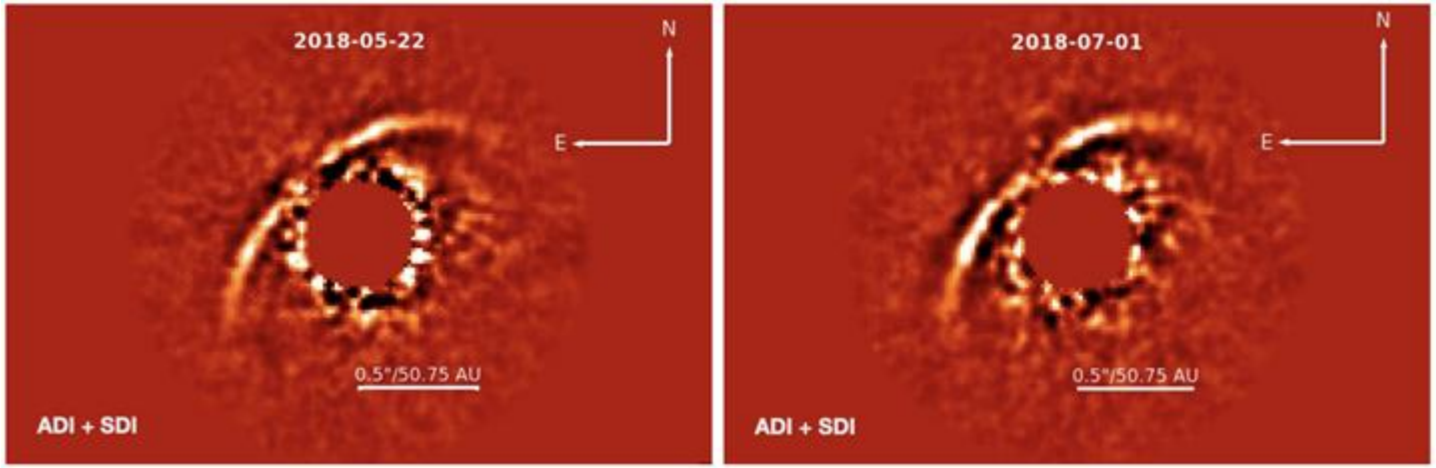
Currie+ LkCa 15



Goebel+ HIP 79977

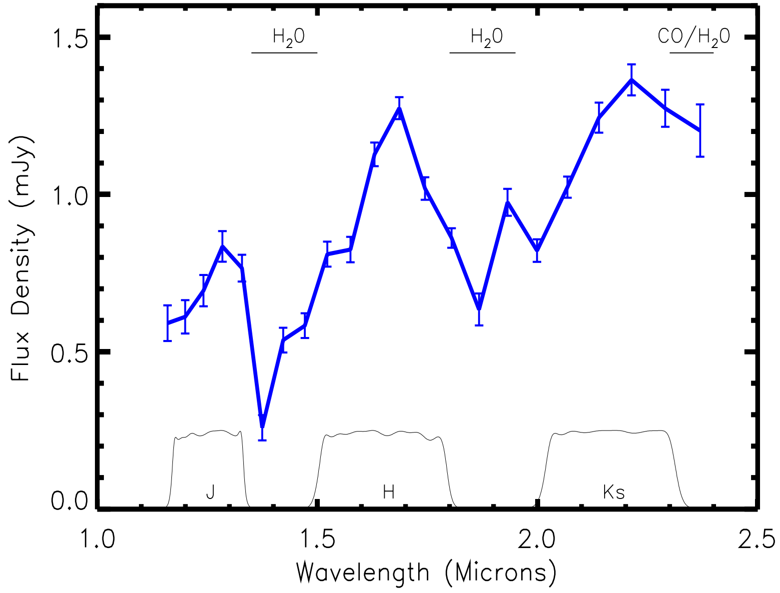


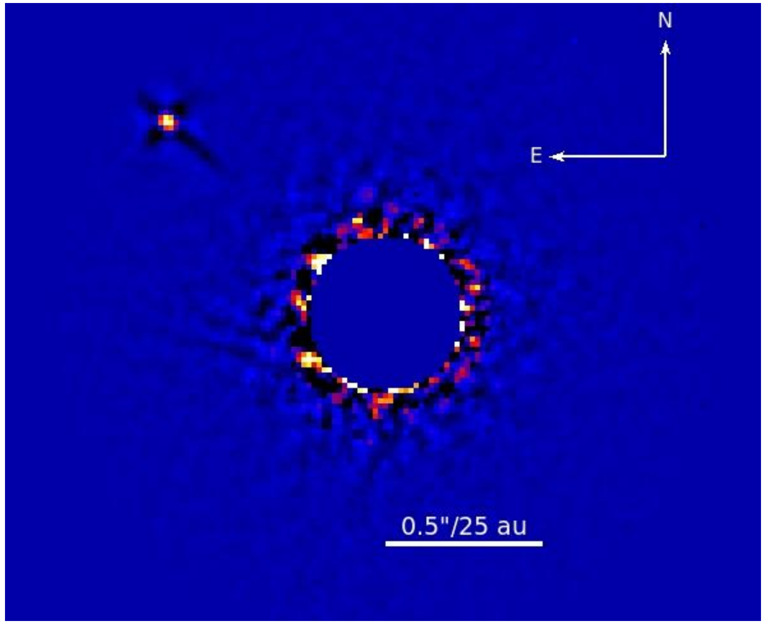
Rich+ HD 163296



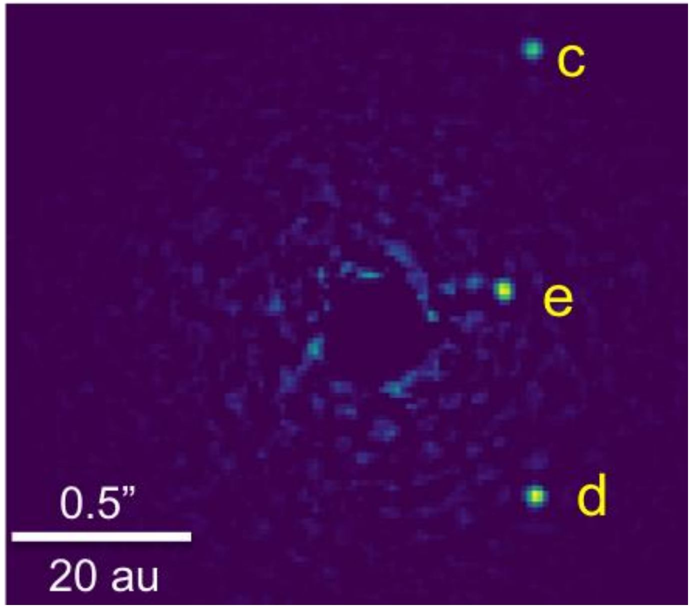
CHARIS Science Highlights - kappa And b and HR8799

Kappa And b (Currie et al. 2018, AJ, 156, 291)

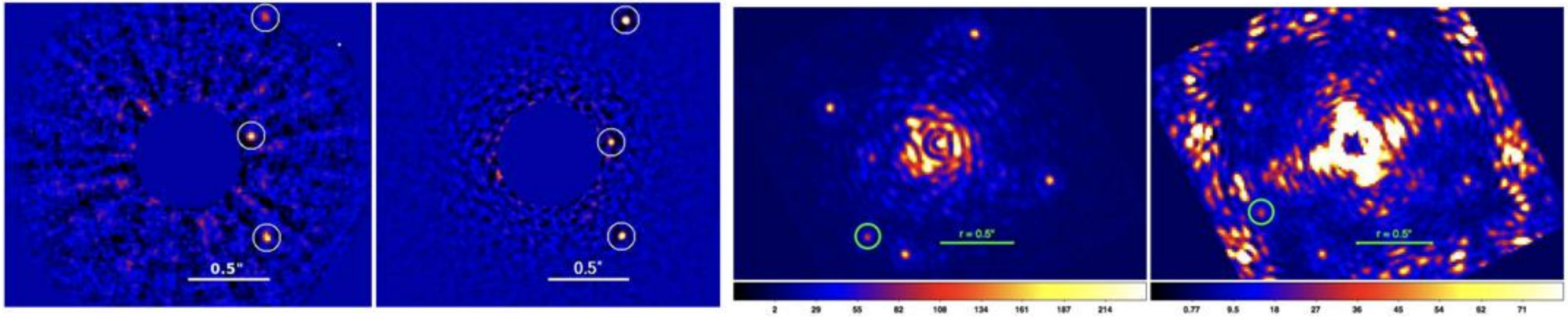




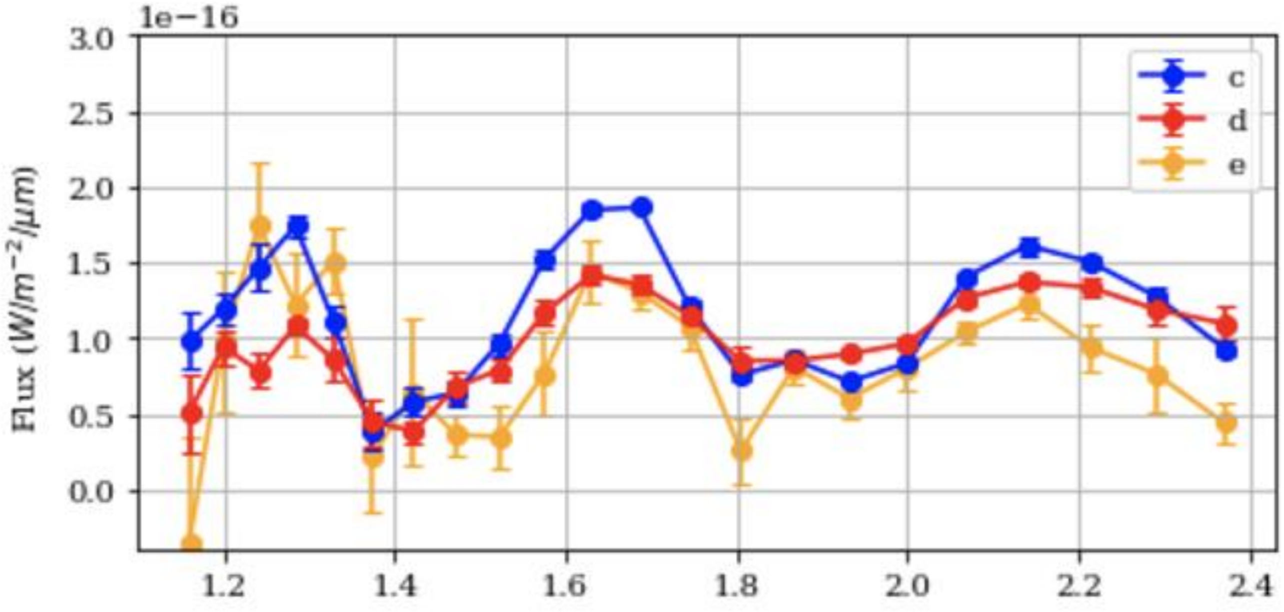
HR8799 (Currie)

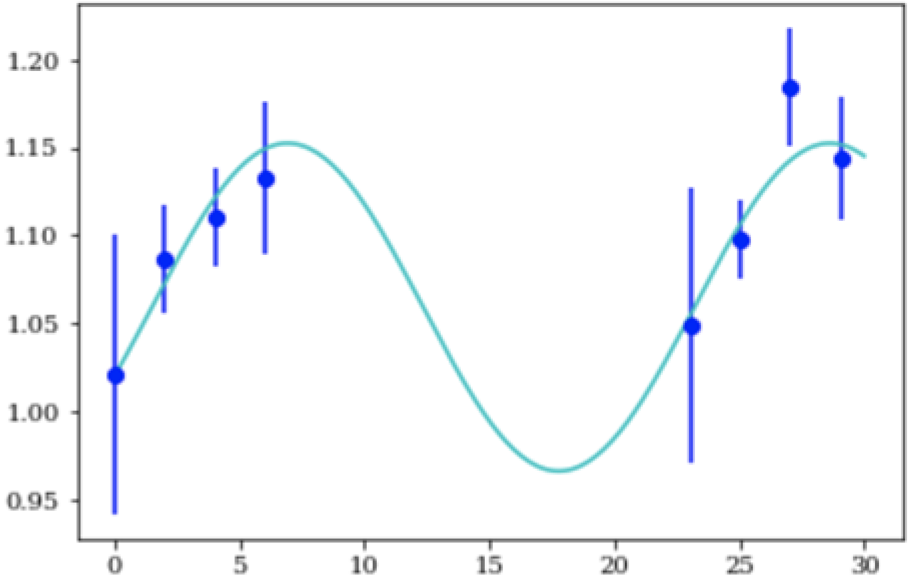


Shaped Pupil Testing on HR8799 and Kappa And b (Currie+ 2018)



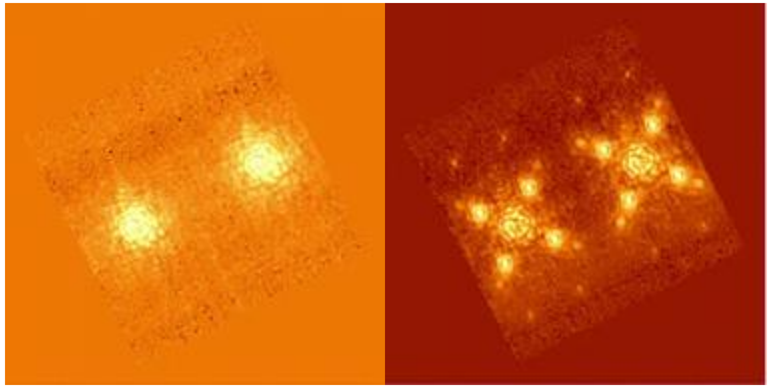
J. Wang et al., in prep





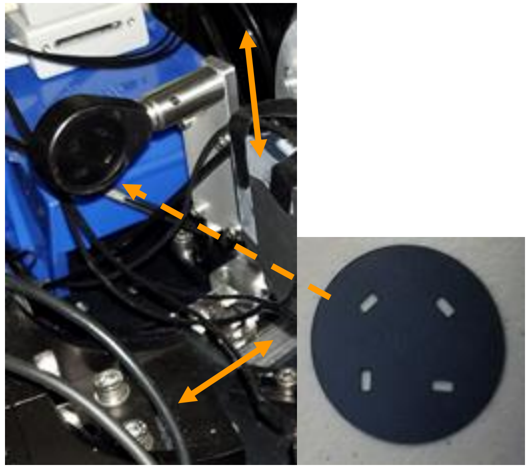
- Planet spectra based upon 2 full nights of CHARIS
- Possible planet variability seen with CHARIS
- CHARIS is the only instrument currently capable of making these precise observations

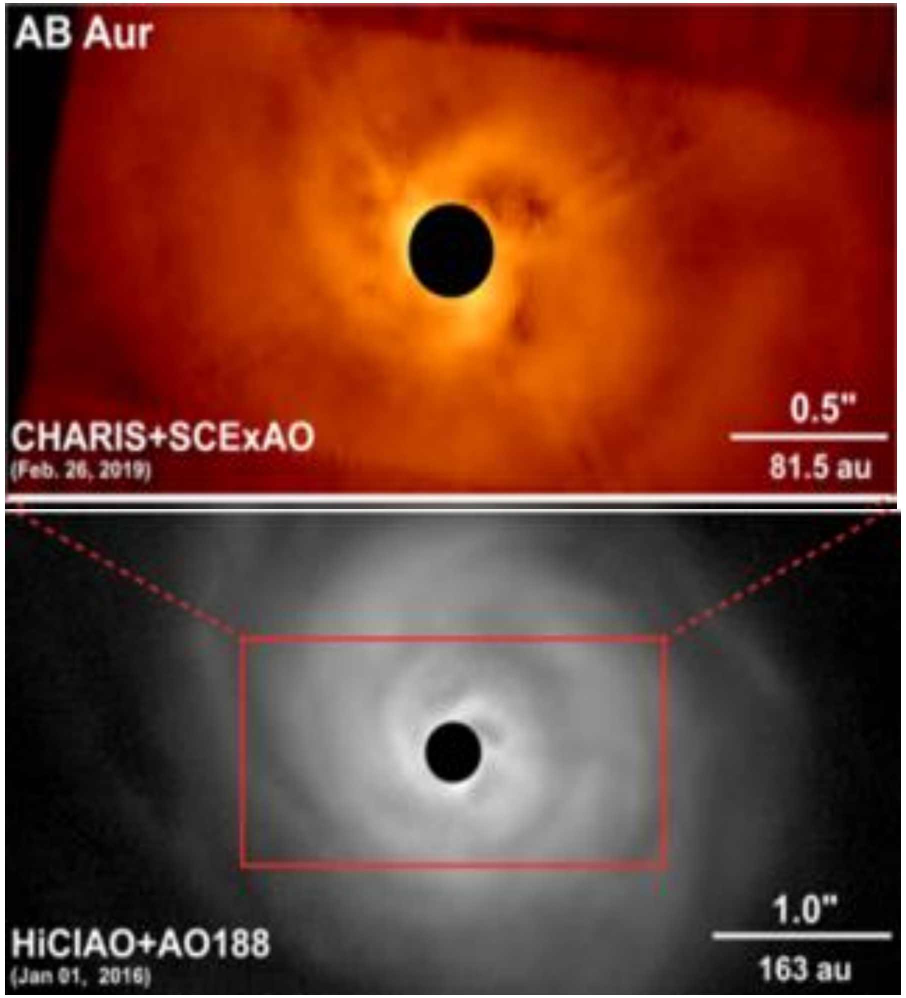
- New Wollaston Spectro-polarimetry mode for CHARIS
  - CGI has a Wollaston mode as well, contributed by JAXA



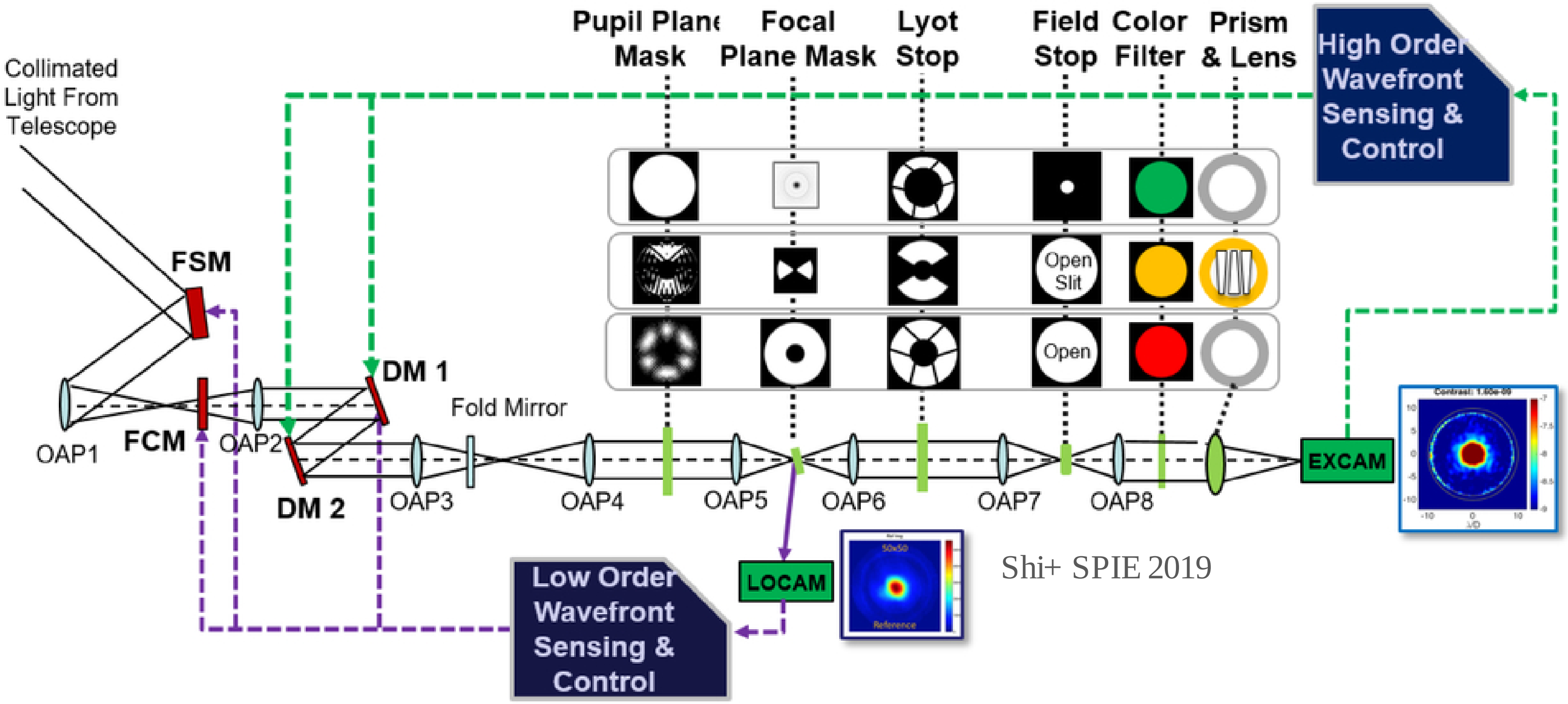
field stop, no speckle grid

field stop, speckle grid



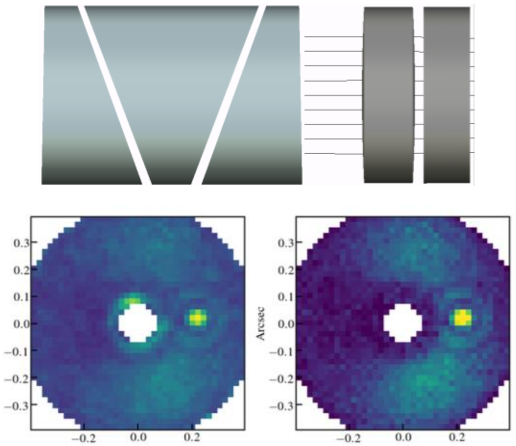


WFIRST CGI Characterization Modes



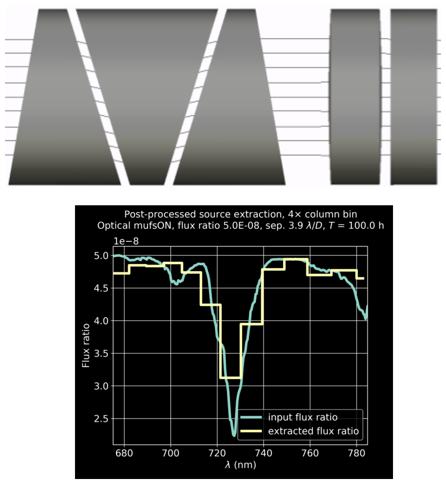
Shi+ SPIE 2019

Polarization

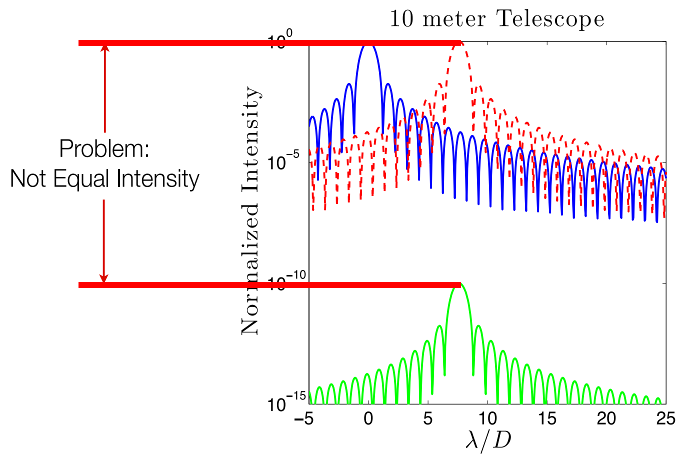


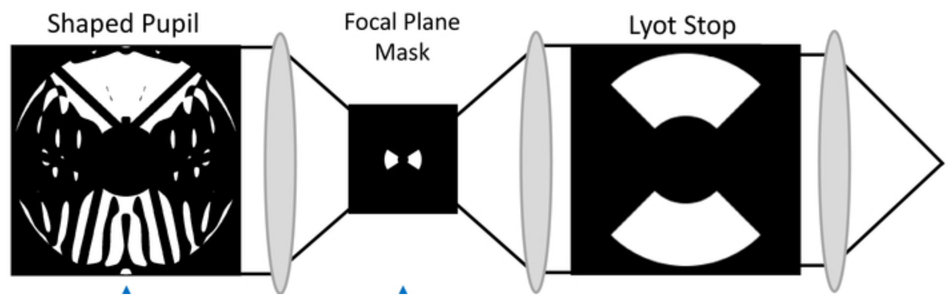
Mennesson+ SPIE 2019

Spectroscopy



Zimmerman

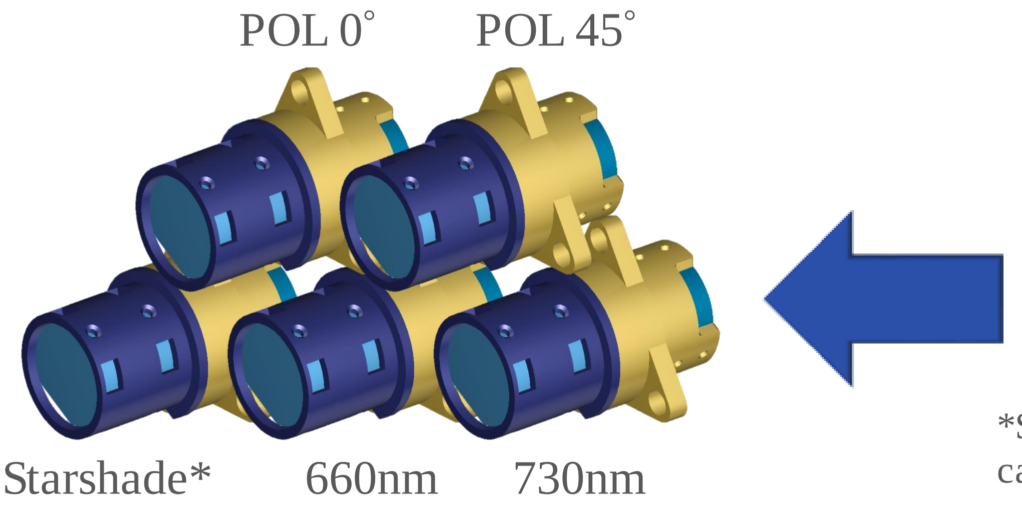




Riggs+ SPIE 2019

What is WFIRST and CGI: Focusing on Characterization

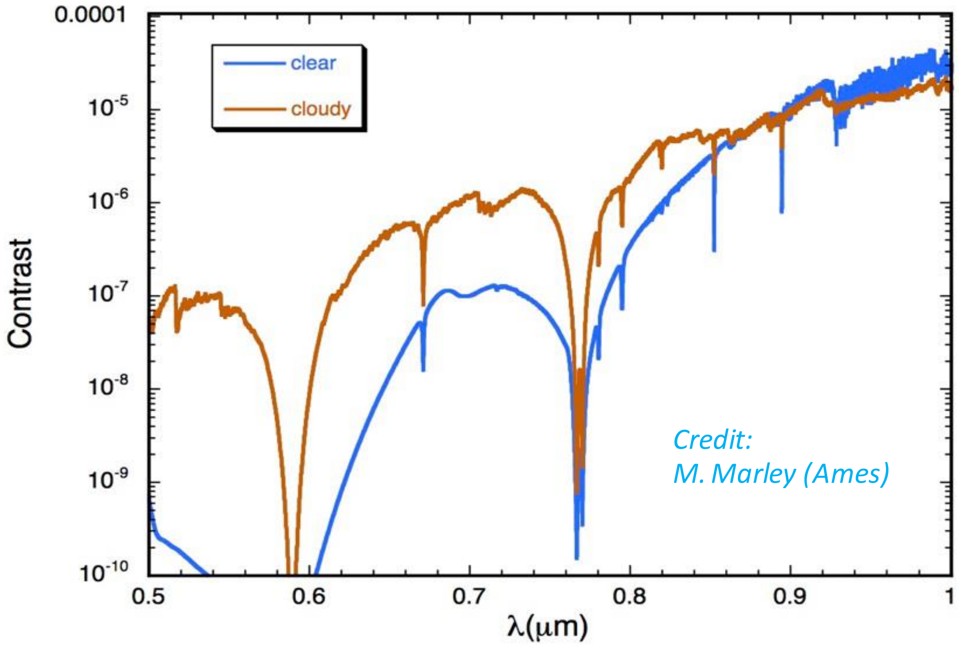
- WFIRST is the next NASA flagship mission (launch 2025)
  - Primary Instrument: Wide Field Instrument (WFI)
  - Technology Demonstration: CoronaGraph Instrument (CGI)
- CGI is the first **full system demonstration** in space for future missions that must reach 10^{-10} contrast detection limits
  - Ground state of the art is $\sim 5 \times 10^{-6}$
  - Paving the way for future missions capable of taking spectra of Earth analogs, furthering the search for life in the Universe
- Along the way, CGI will do groundbreaking science in direct imaging and **spectroscopy** of exoplanets and protoplanetary disks
- Goddard is building the spectroscopy modes for CGI



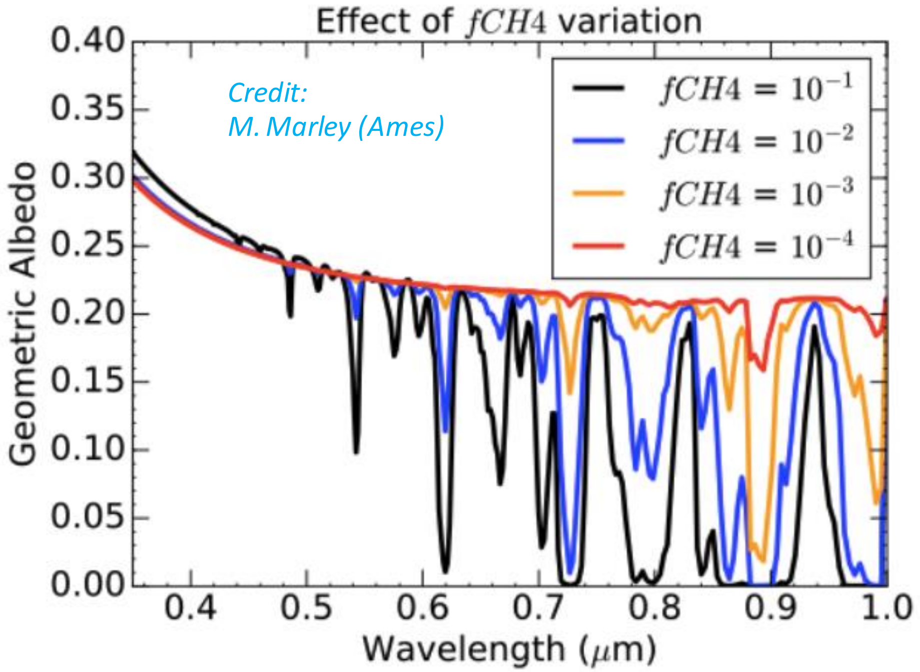
IFS is now rescoped to a direct imaging prism+slit

*Slot available for accommodation, prism would be an added capability funded by starshade

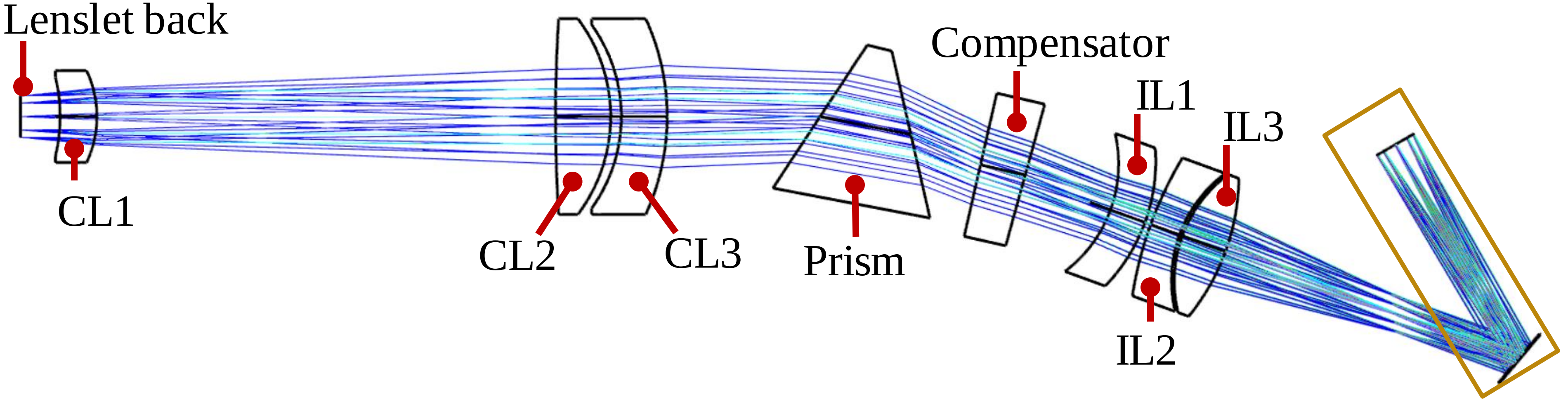
Self-luminous, young super Jupiters: atm. properties



Mature Jupiter analogues in reflected light: mass & atm. properties



Old CGI Mode: IFS



Baseline Filter Bands	Center	Cut-on	Cut-off	Bandwidth %
CGI Band 2 (Shaped Pupil)	660	600	720	18.2
CGI Band 3 (Shaped Pupil)	760	690	830	18.2
Starshade Band 1	728	656	800	20
Starshade Band 2	887	799	975	20

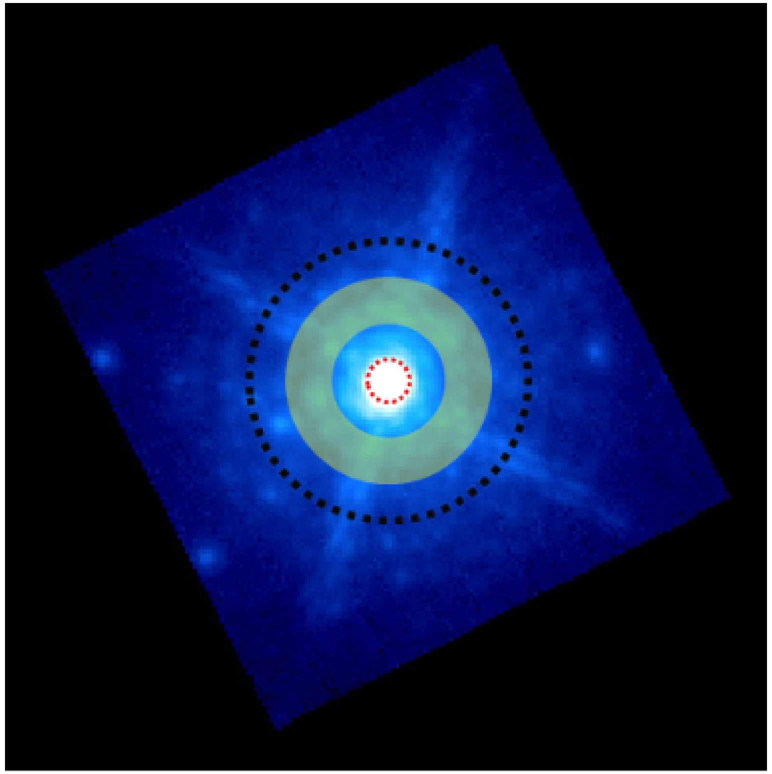
Phase A IFS Specifications

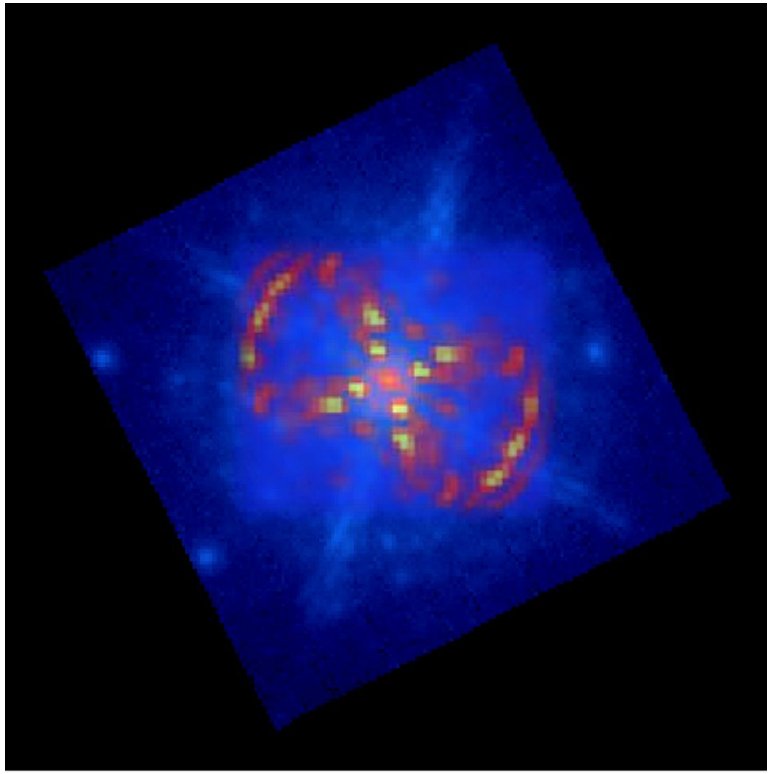
	Band 2	Band 3
# of dispersed pixels	18	18
Lenslet pitch (µm)	174	174
sampling at λ_c	2	2.33
Spectral resolving power	50	50

- All lens surfaces are spherical.
- The spectral dispersion is achieved with a prism and a compensator

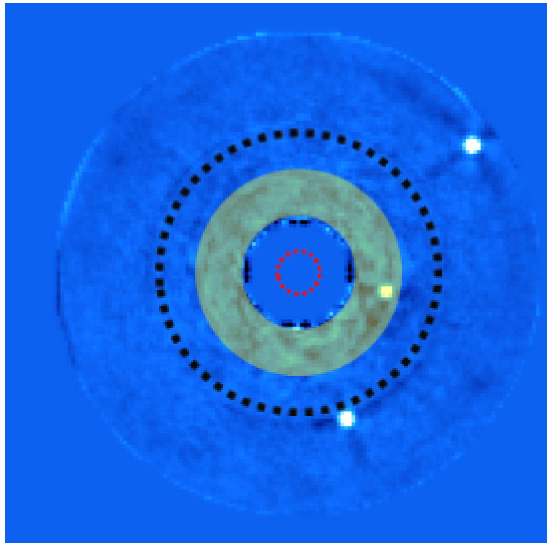
Example Observational Overlap

M5 Globular Cluster





HR8799
w/Post-Processing



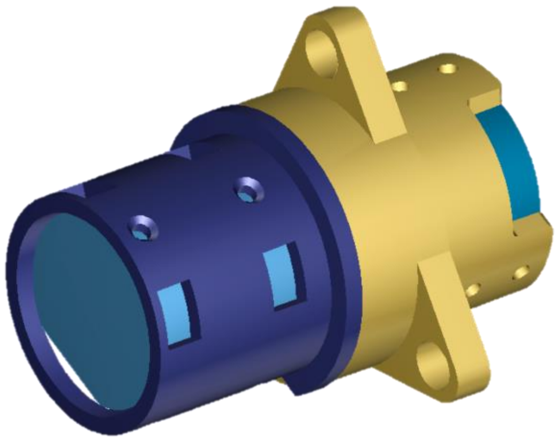
Published CGI FOV overlaid onto a CHARIS image from the Subaru telescope

10 λ/D (~0.5”) Coronagraph outer working angle

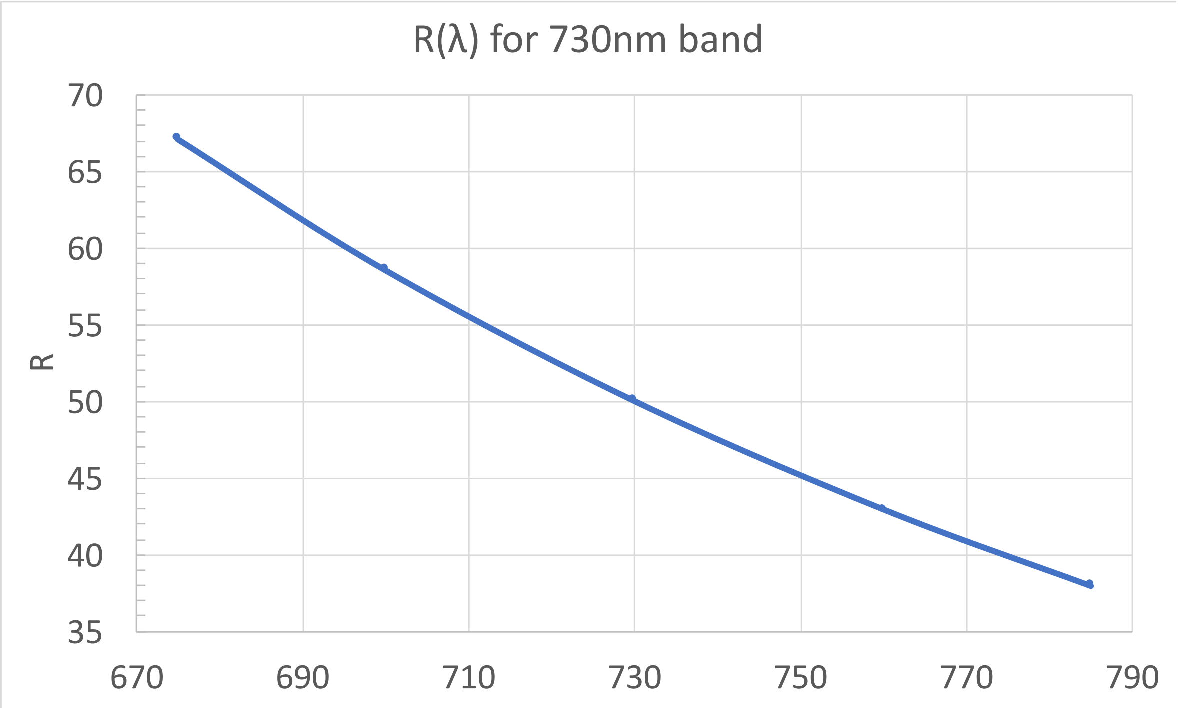
3 λ/D radial inner working angle

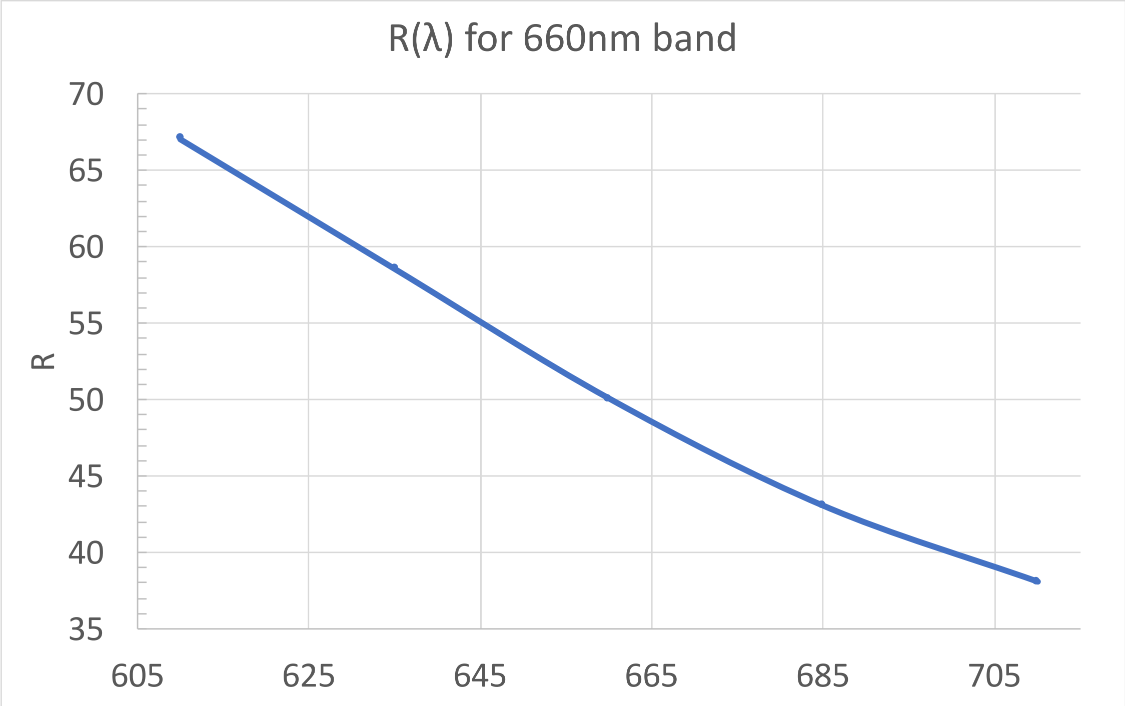
Angular separation where requirements are set

New Dispersion Mode: Zero Optical Deviation Prism



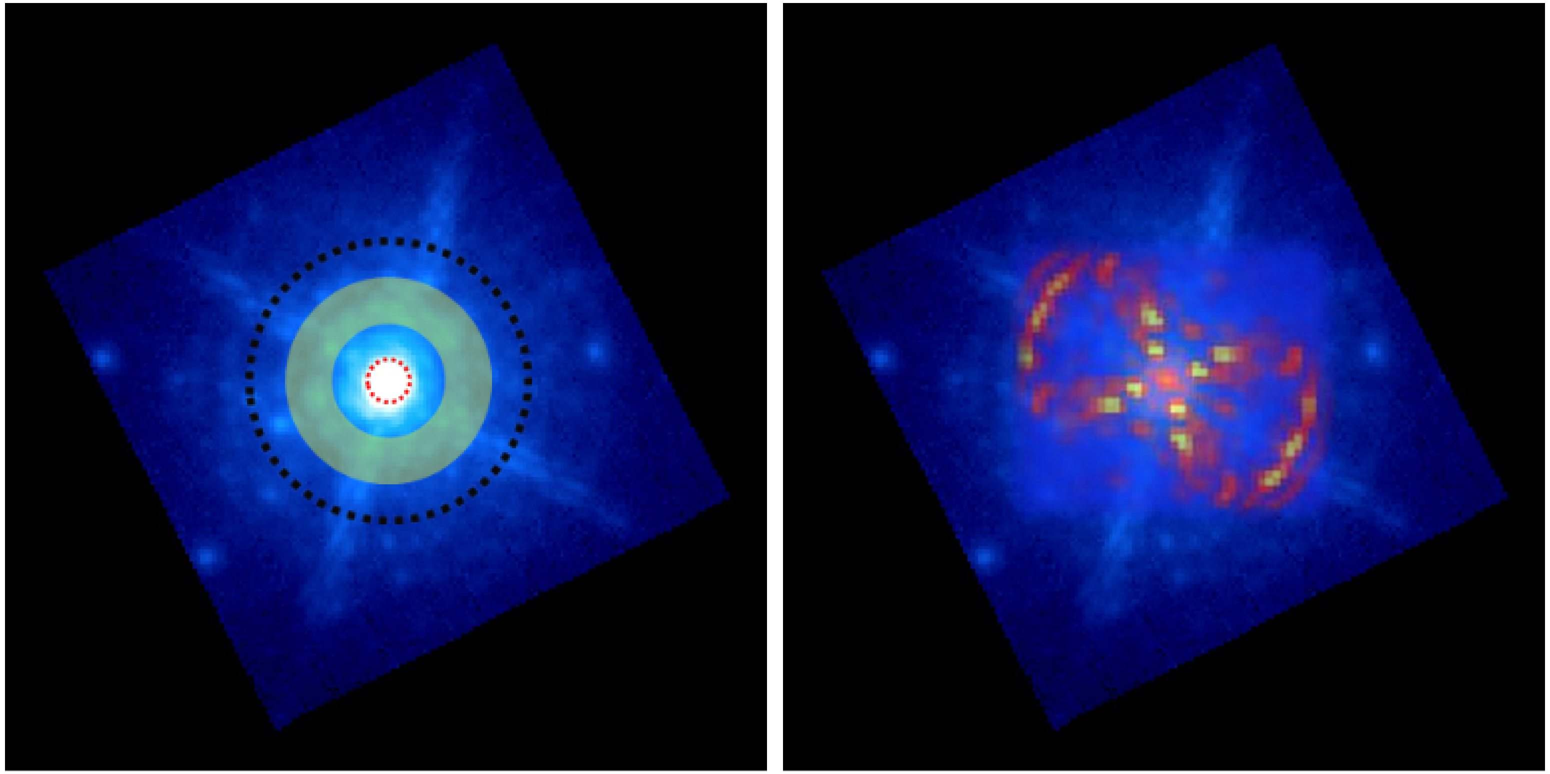
Baseline Filter Bands	Center	Cut-on	Cut-off	Bandwidth %
CGI Band 2 (Shaped Pupil)	660	610	710	15.2
CGI Band 3 (Shaped Pupil)	**730**	**675**	**785**	**15.1**
Starshade Band 1	728	656	800	19.8
Starshade Band 2	887	799	975	19.8



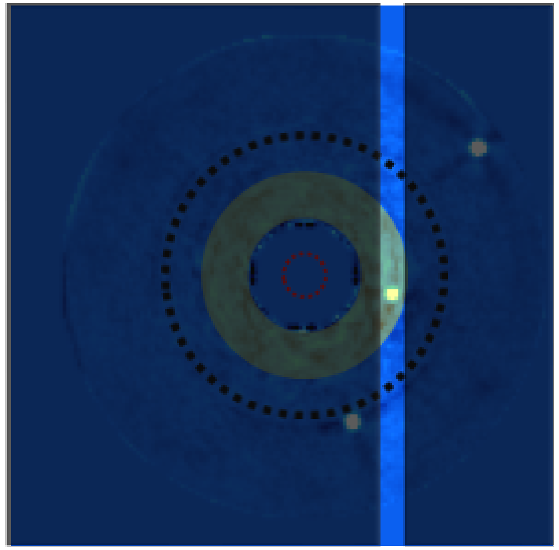


Example Observational Overlap: Amended to a Deployable Slit

M5 Globular Cluster



HR8799
w/Post-Processing

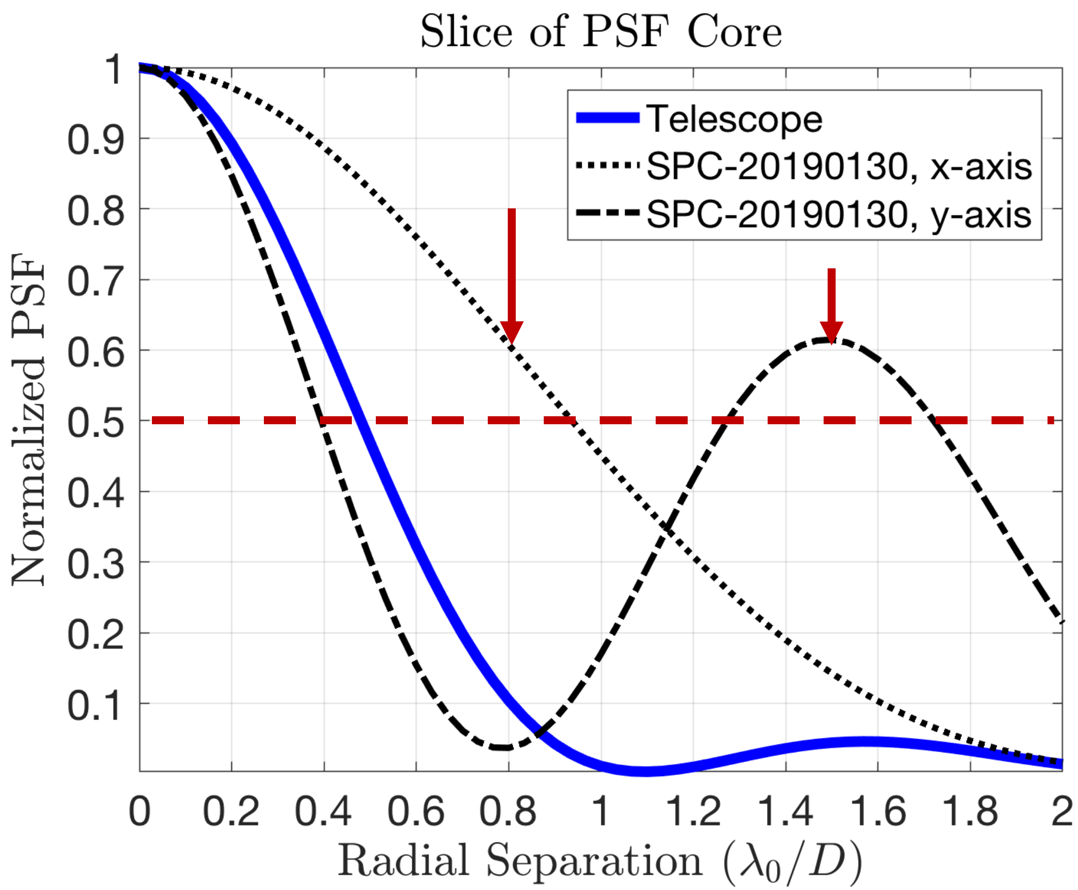


Published CGI FOV overlaid onto a CHARIS image from the Subaru telescope

- 10 λ/D (~0.5") Coronagraph outer working angle
- 3 λ/D radial inner working angle
- Angular separation where requirements are set

FWHM of PSF Core for SPC

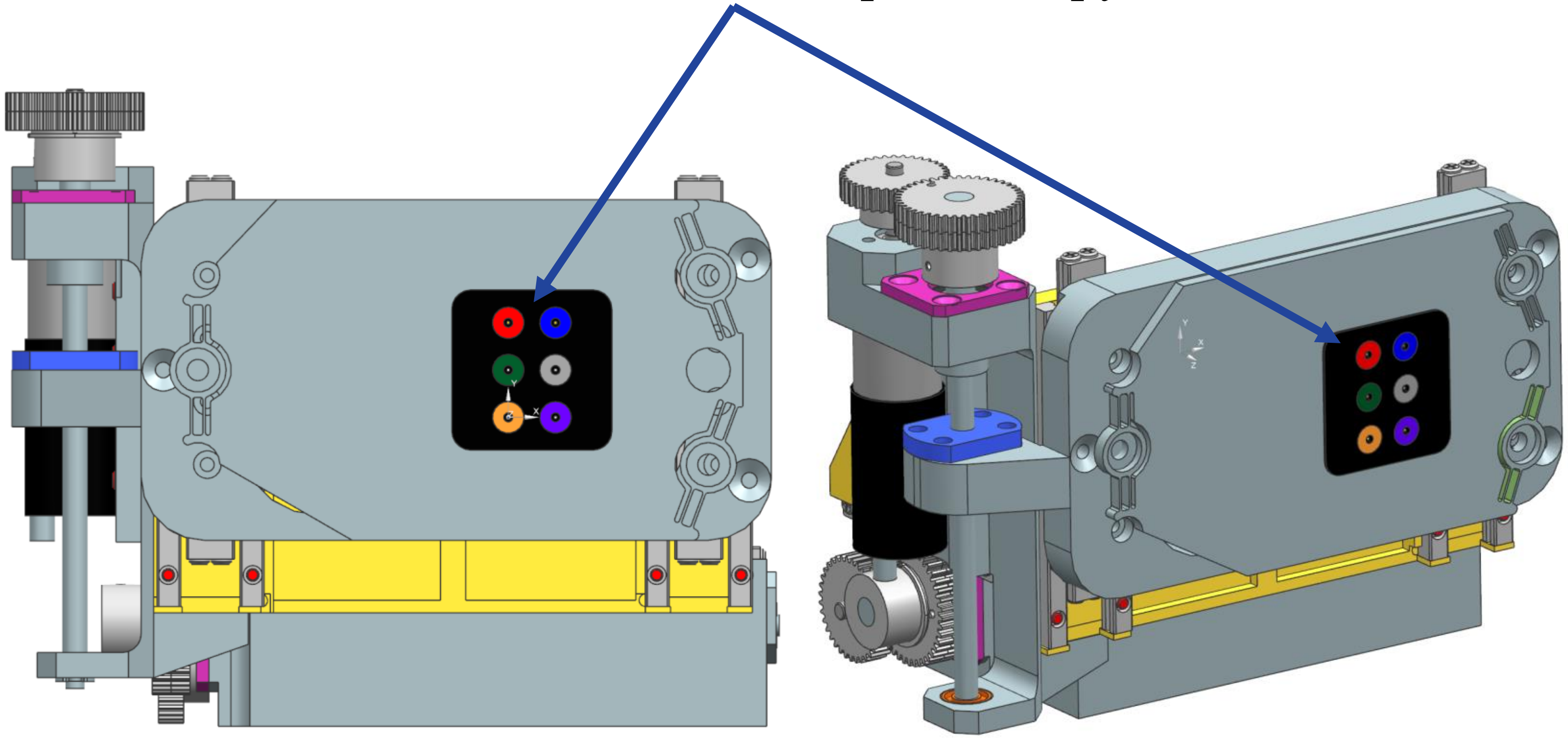
- The slit size is a function of PSF core
- Shaped Pupil FWHM is assymmetric
  - Nyquist sampled at 500nm
- R=50 is **minimum** at onset of methane feature in that band.
- Core = 1.9 x 0.8 FWHM area in λ/D
  - 5 pixels / FWHM in X direction @ 660nm



Courtesy A.J. Eldorado Riggs

Slits Within Field Stop Alignment Mechanism

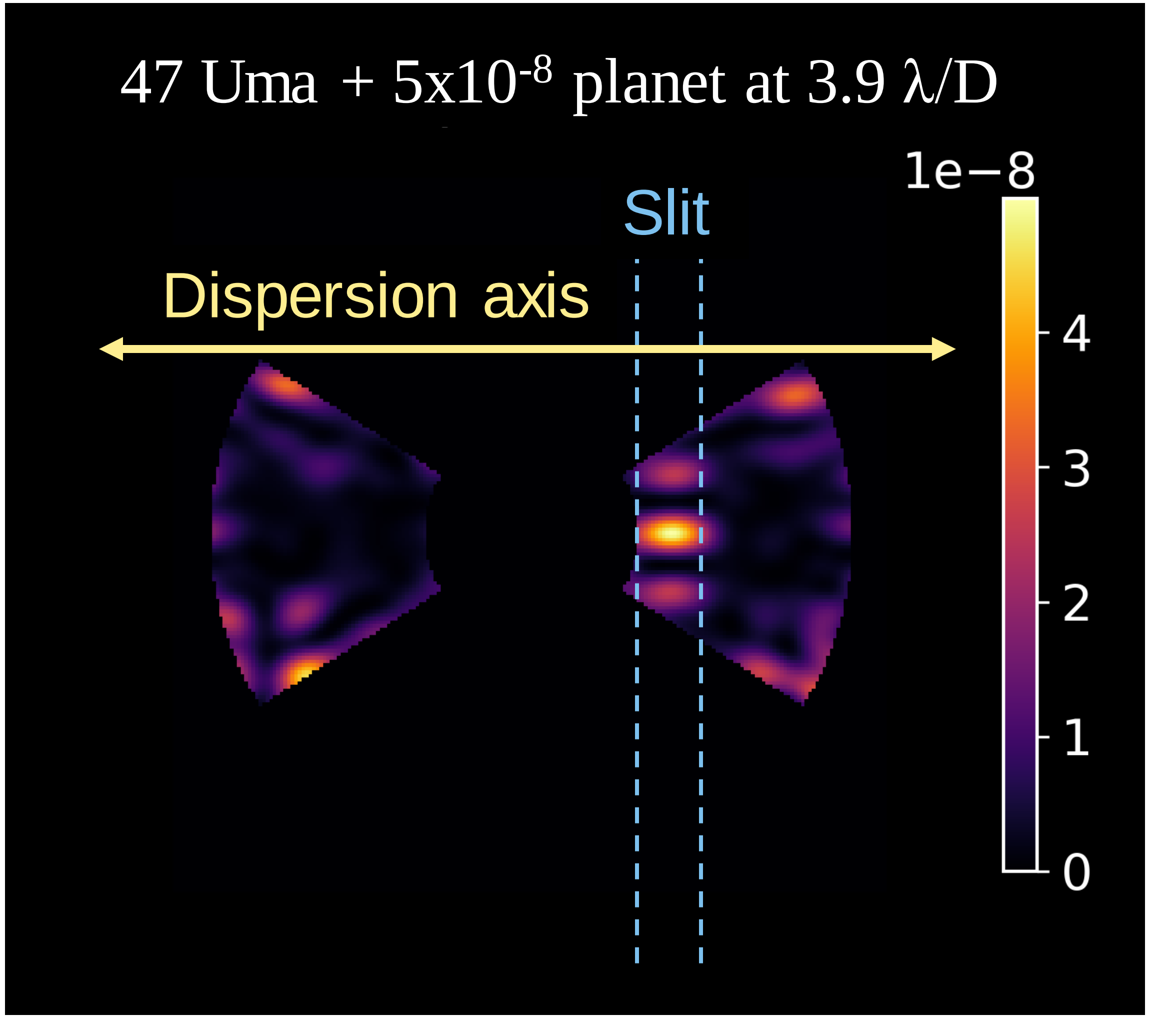
Added Slits for Planet Spectroscopy



- Slits are integrated into the upstream field stop mechanism
- Several slits per mode
  - No slit
  - Different slit widths
  - Perhaps clever apertures for better speckle statistics
- After planet is detected
  - Slit deployed over the planet
  - Prism is engaged

Simulating the Slit Spectroscopy Mode

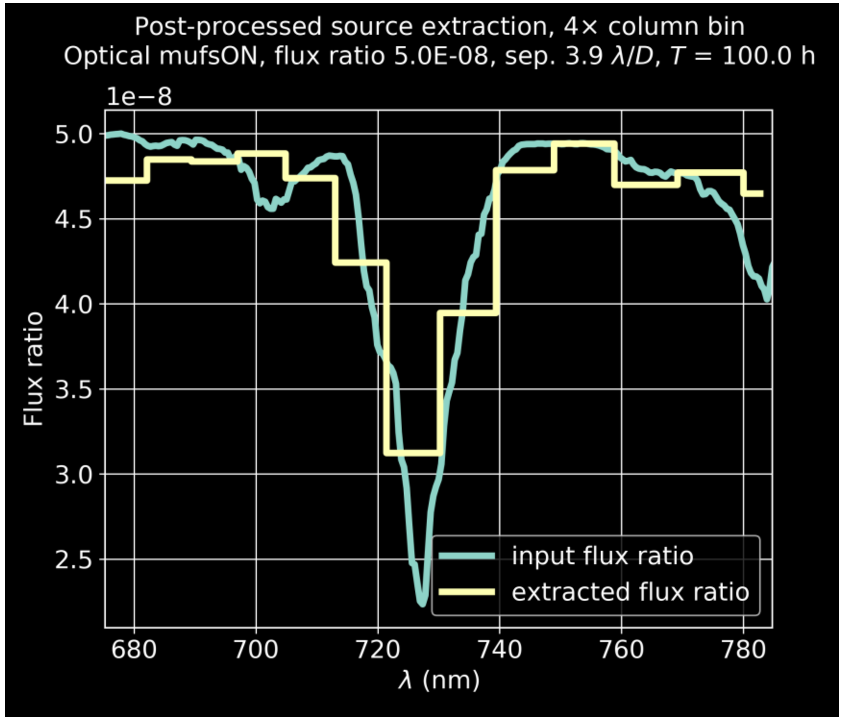
- OS6 SPC model (2018) by John Krist
- The slit mask is oriented perpendicular to the bowtie
- Two cases simulated:
  - Requirements performance
    - Optical MUFs applied
    - Fiducial 5×10^{-8} flux ratio @ 4 λ/D
  - Science performance case
    - 5×10^{-9} flux ratio planet
    - Optical MUFs turned off

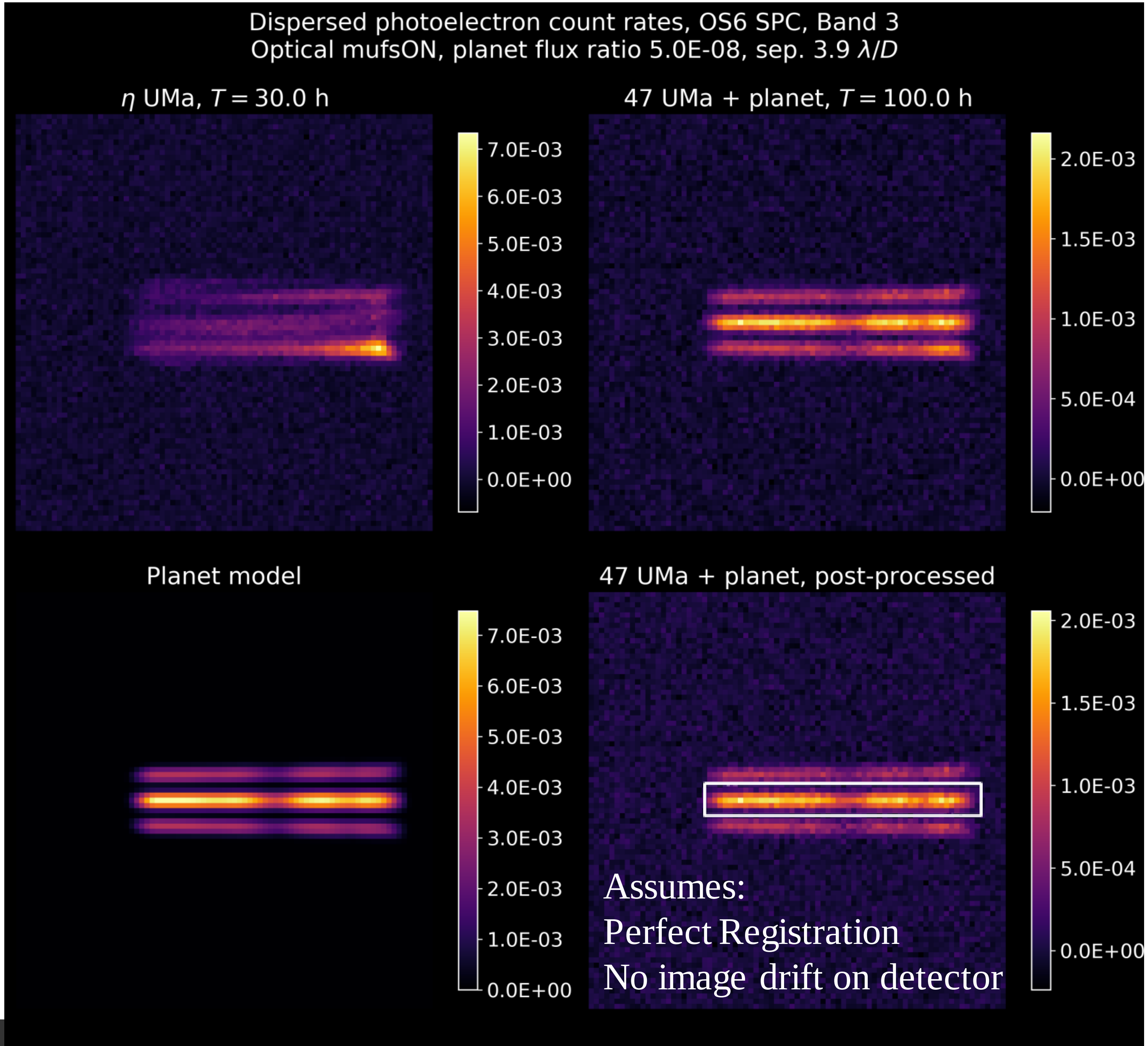


Simulation by Neil Zimmerman

Simulating the Slit Spectroscopy Mode: 730nm band

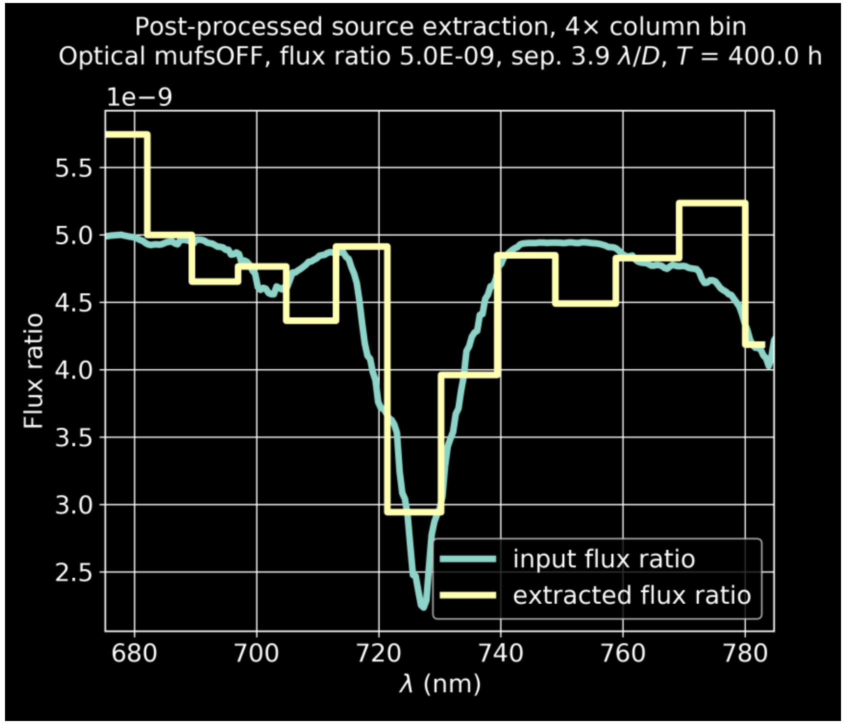
Albedo spectrum model by Nikole Lewis
Simulation by Neil Zimmerman

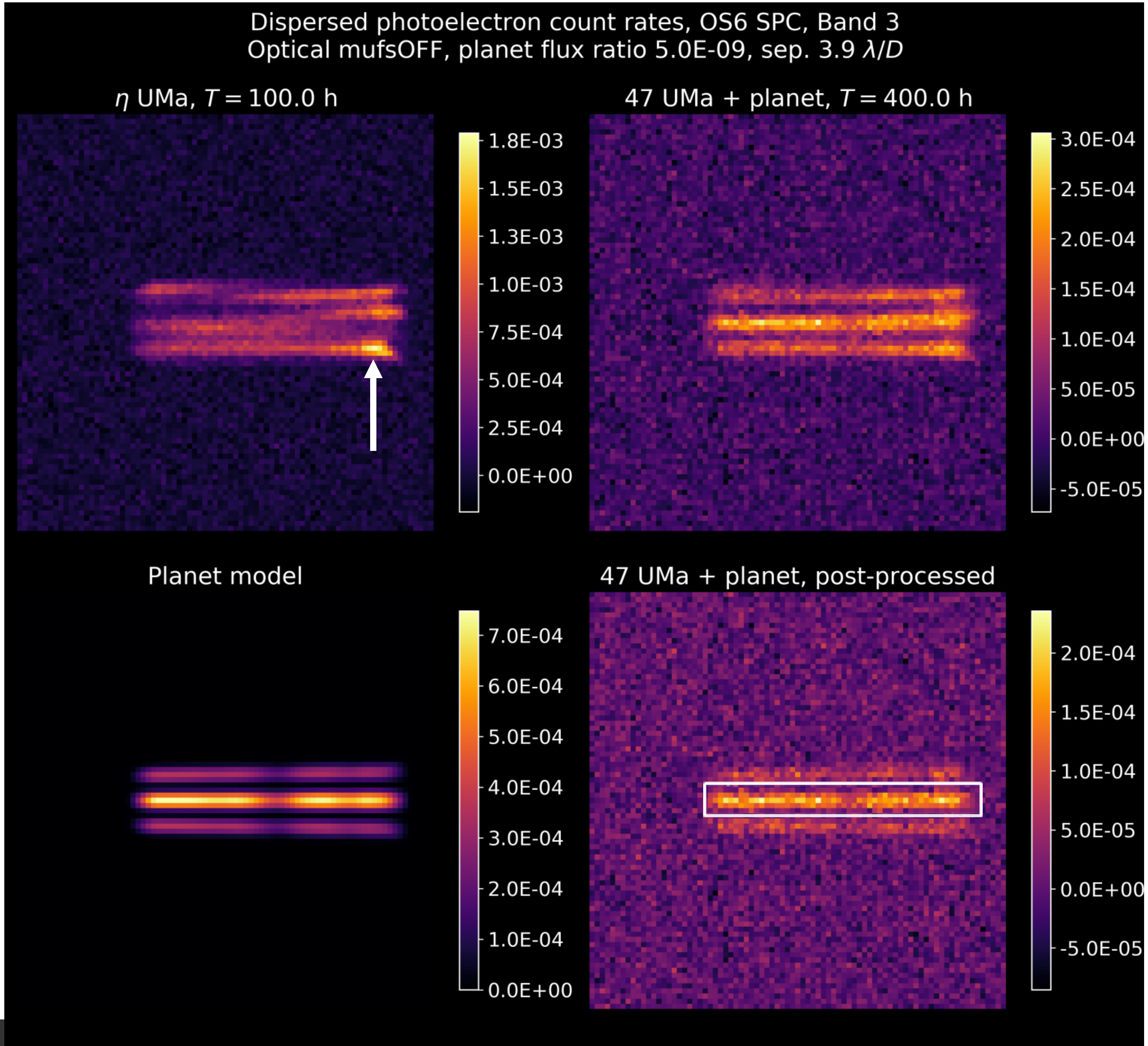




Simulating the Slit Spectroscopy Mode: 660nm band

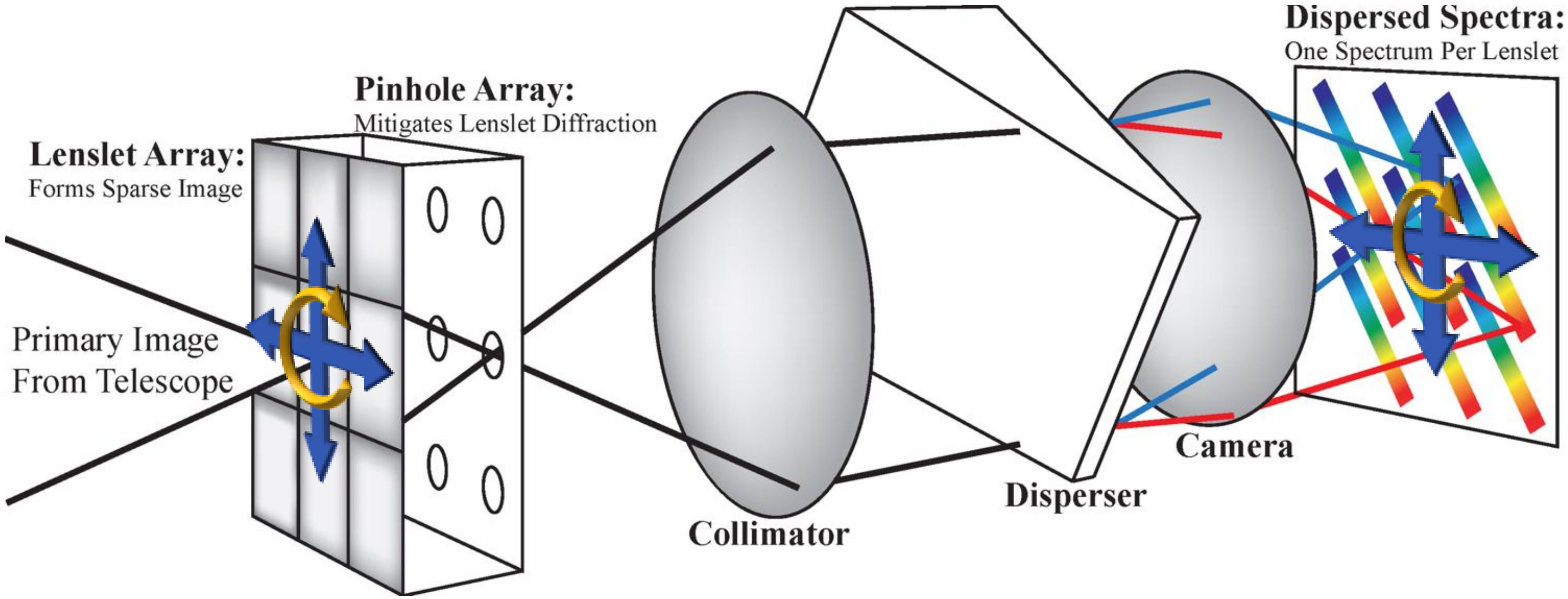
Albedo spectrum model by Nikole Lewis
Simulation by Neil Zimmerman



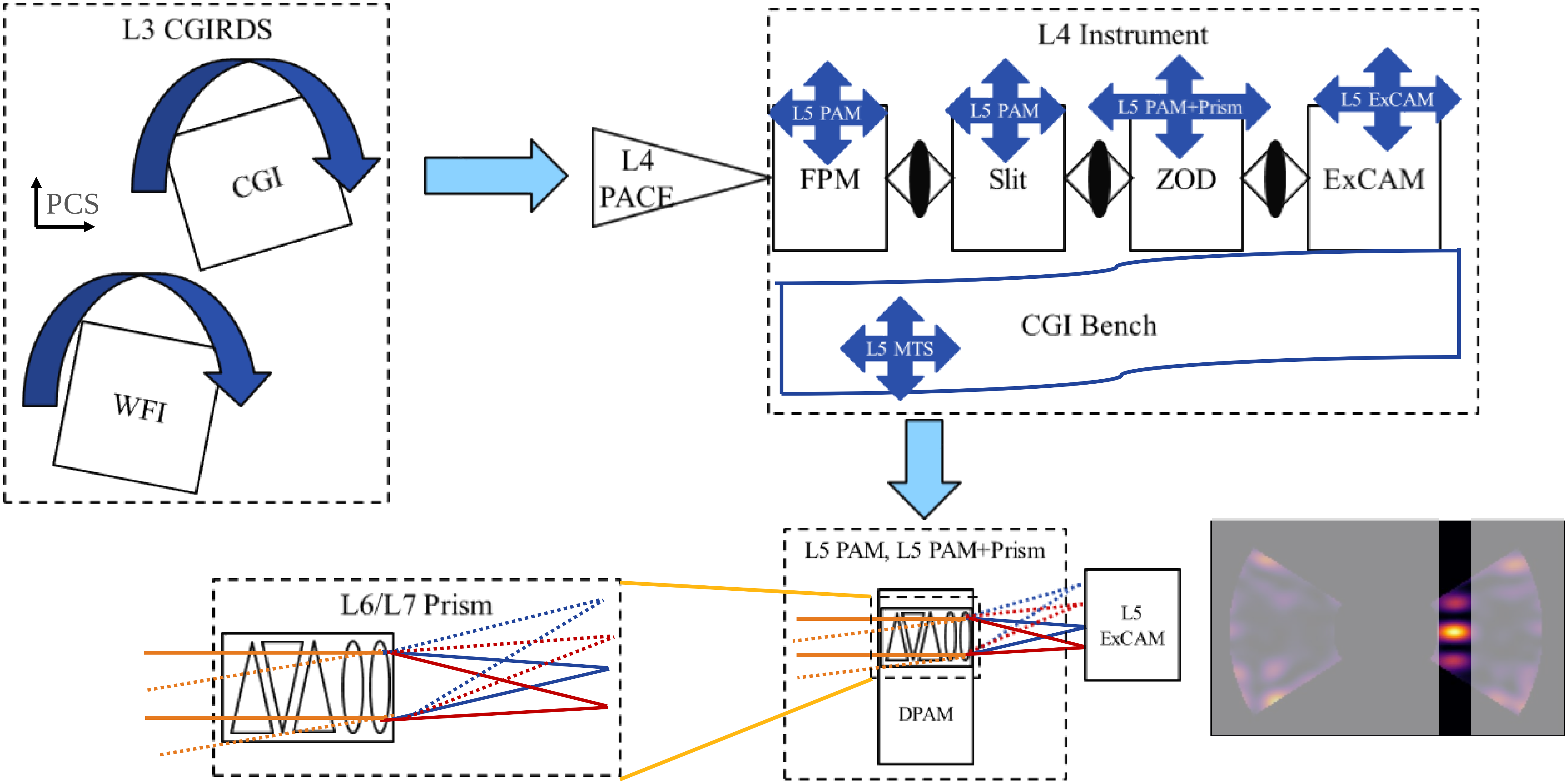


Requirements: All About Stability

- Ground-to-Orbit Stability: The final focal plane must stay within tolerance
- Jitter Stability: Alignment disturbance from observatory structural dynamics (~100 seconds)
- Thermal Stability: Alignment disturbance from observatory thermal drift (~10 hours)
  - Limited by telescope pointing and time between opportunities to recalibrate the IFS
- These periods drive stability requirements on:
  A. The stellar point spread function (PSF) on the lenslet array
  B. The lenslet PSFs (PSFlet) reimaged on the detector

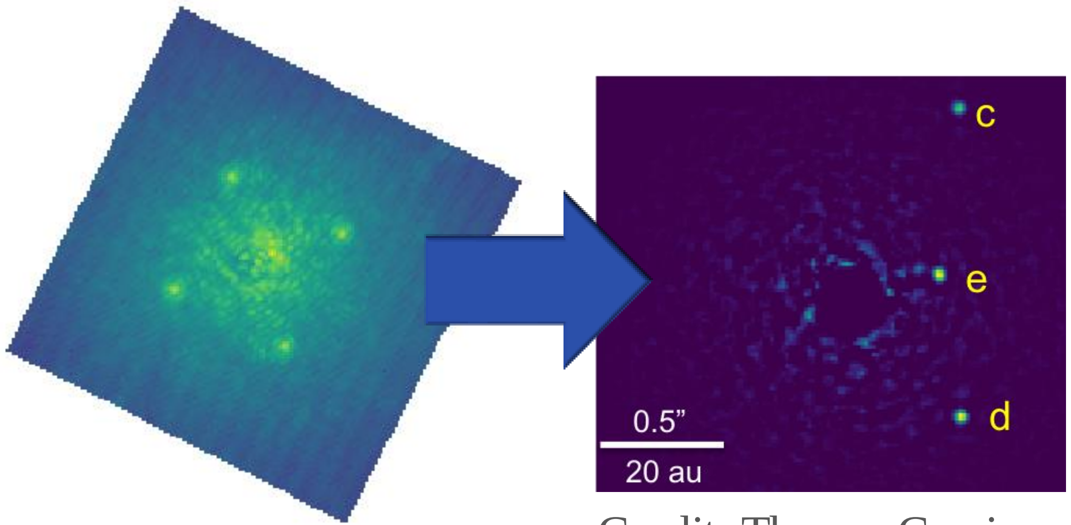


Wavelength Accuracy of the Slit Spectroscopy Mode

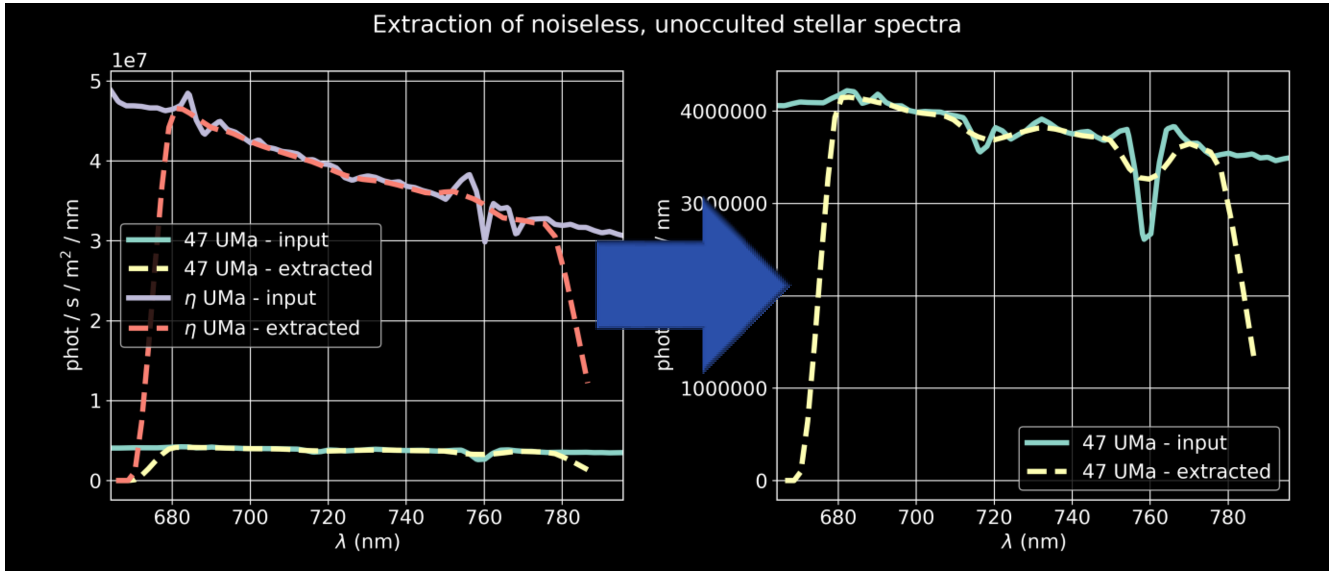


Post-Processing and Data Calibration

- Post-processing the CGI prism/slit data requires subtracting speckles via Reference Differential Imaging (RDI)
  - difference in the stars' spectra complicate this procedure
- CHARIS relies on advanced speckle subtraction techniques, ADI/SDI/KLIP/LOCI etc.
- Time domain and speckle statistics is a new hot topic
- As we move forward, we should consider how our post-processing advancements on the ground will translate to CGI and future missions such as LUVOIR/HabEx



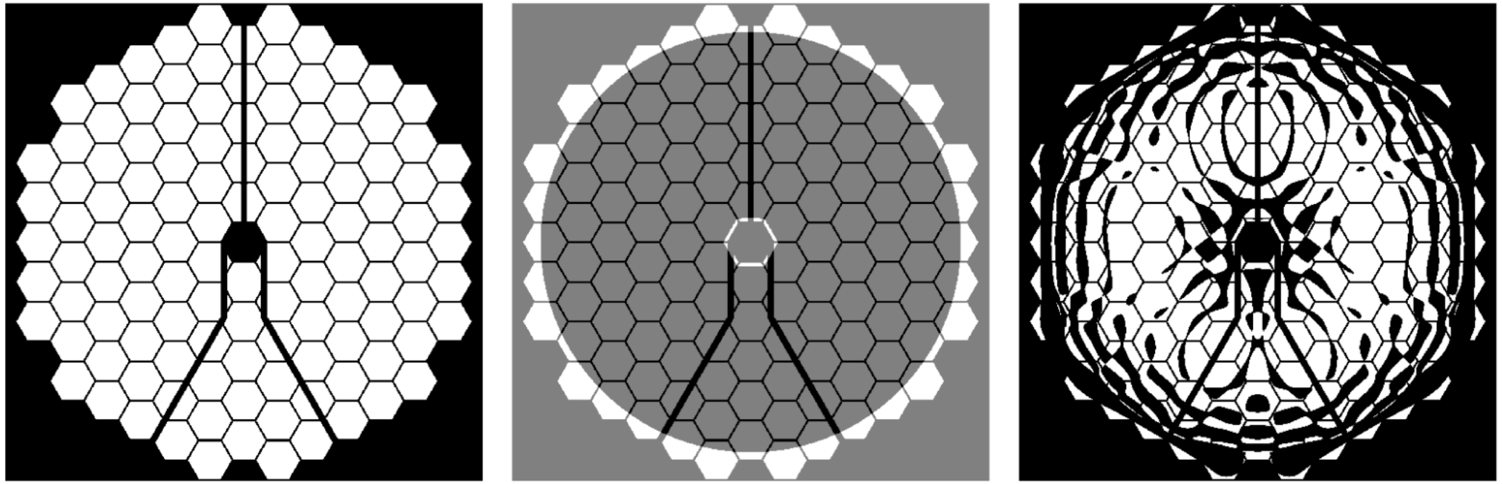
Credit: Thayne Currie

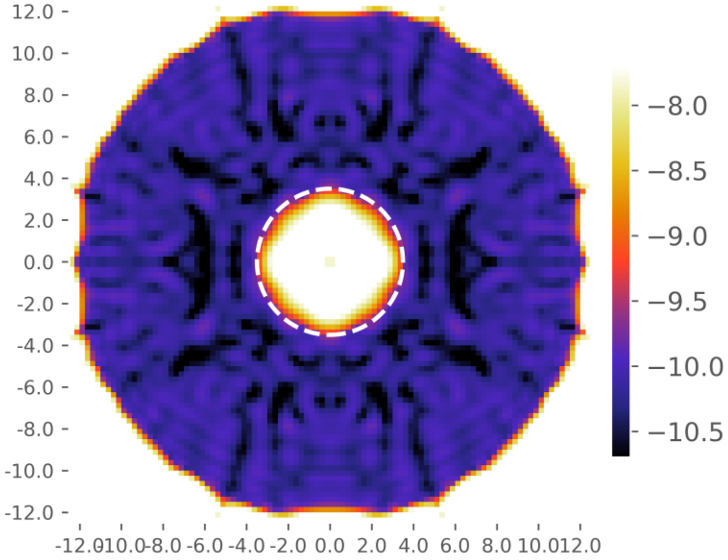


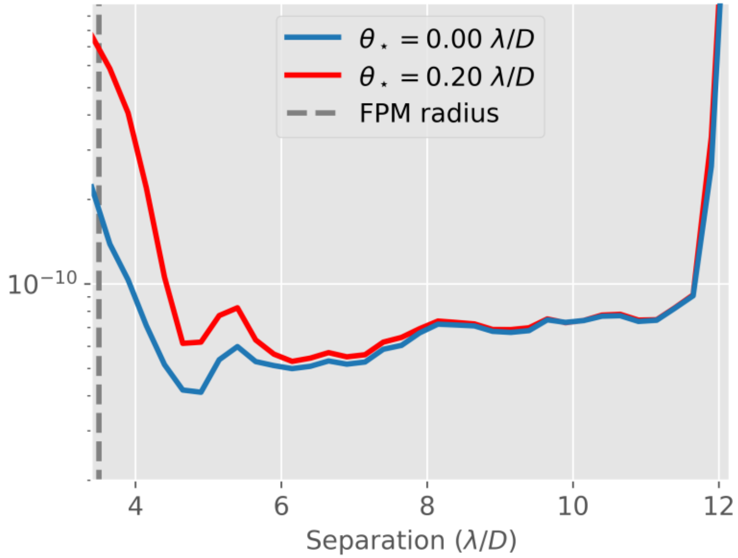
Credit: Neil Zimmerman

Beyond CGI: An Example for LUVIOR

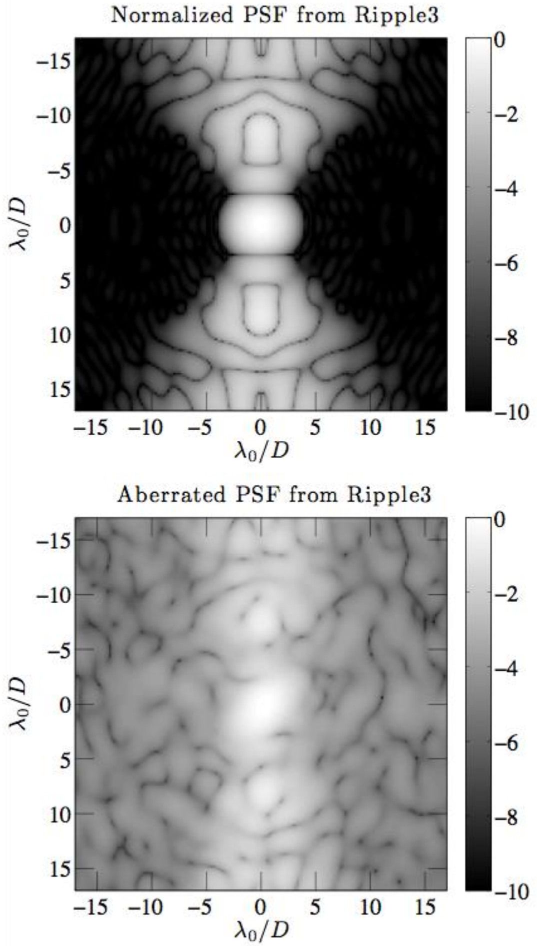
- Example design by Neil Zimmerman for LUVOIR Architecture A





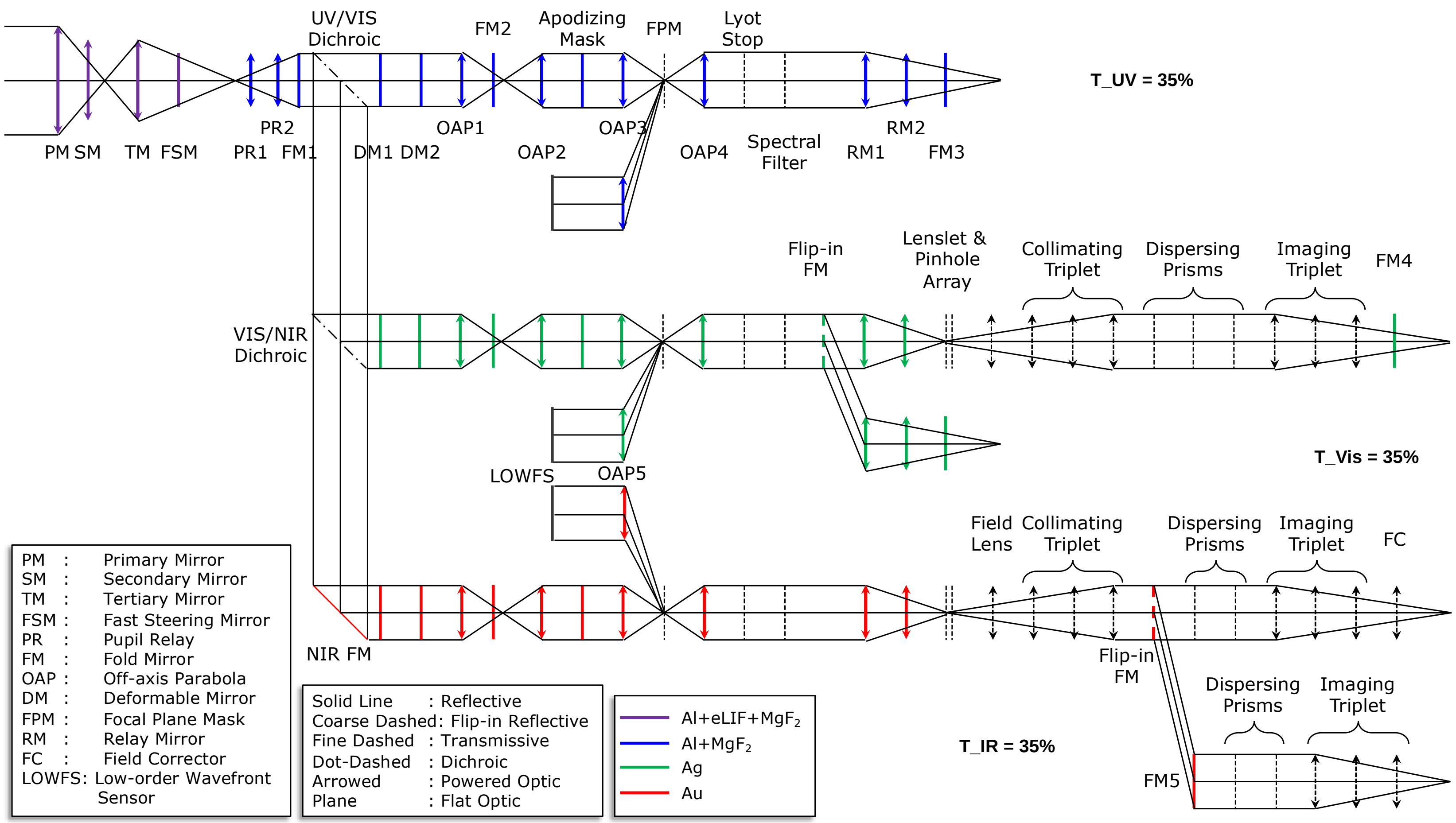


The Problem: Aberrations



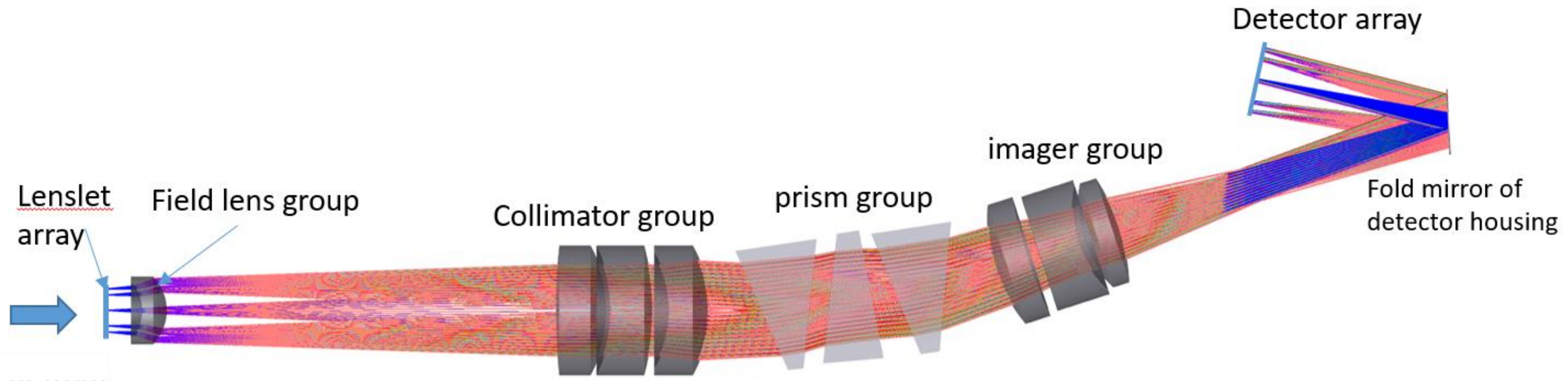
- Not only looking at diffraction limited performance…have to handle resolved sources!
- Now we are at the point of systems level optimizations of coronagraph, wavefront control, and telescope

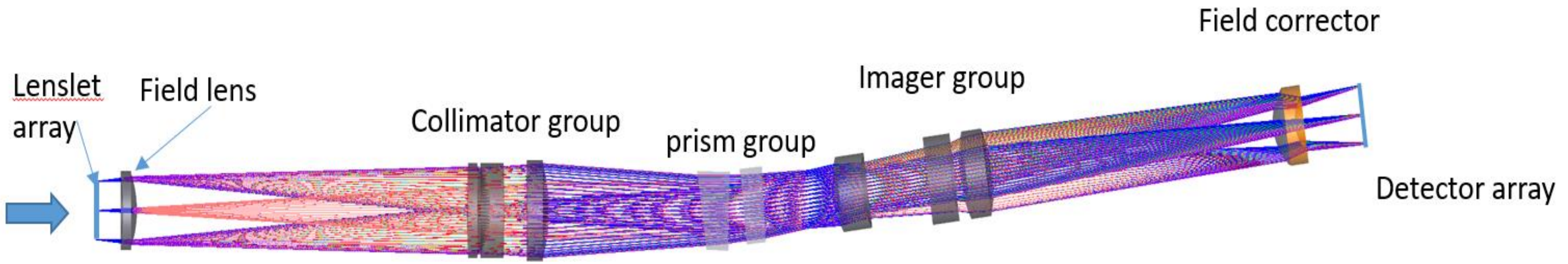
Instrument overview



SPIE Conference, Optics and Photonics, 2019

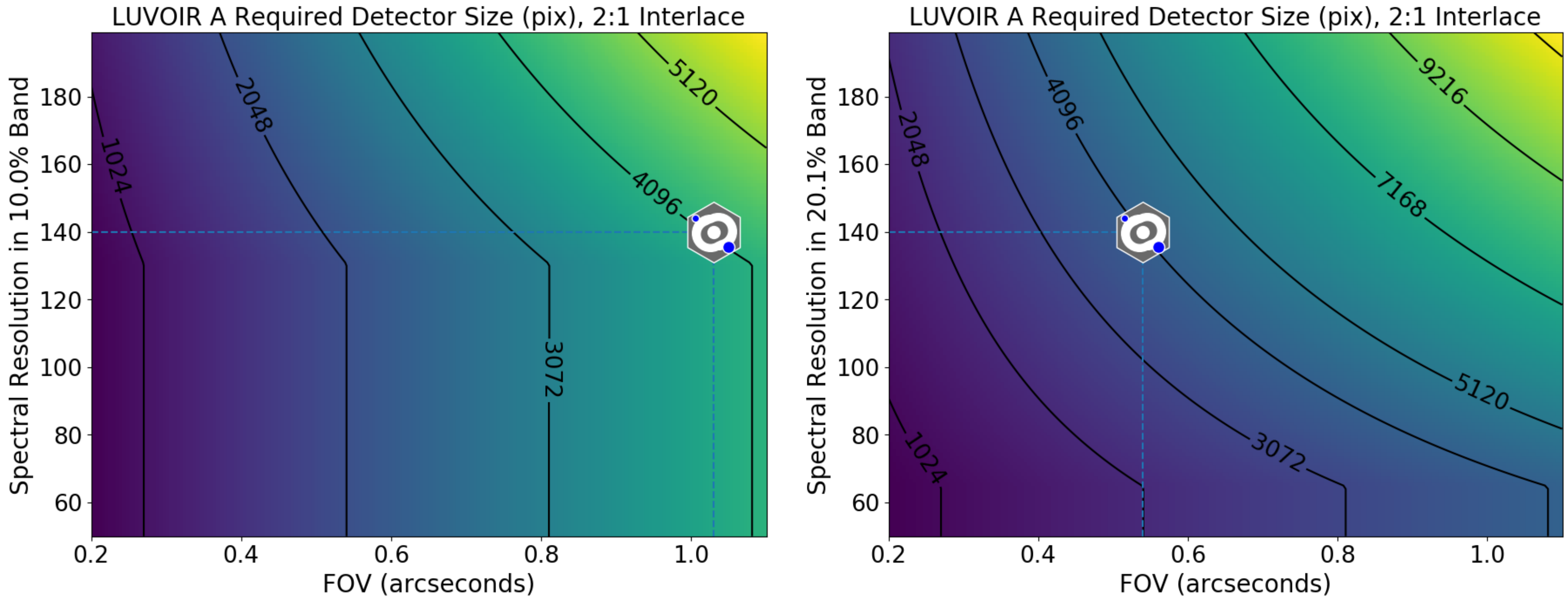
Credit: Matt Bolcar and Laurent Pueyo





Qian Gong et al. , JATIS 2019

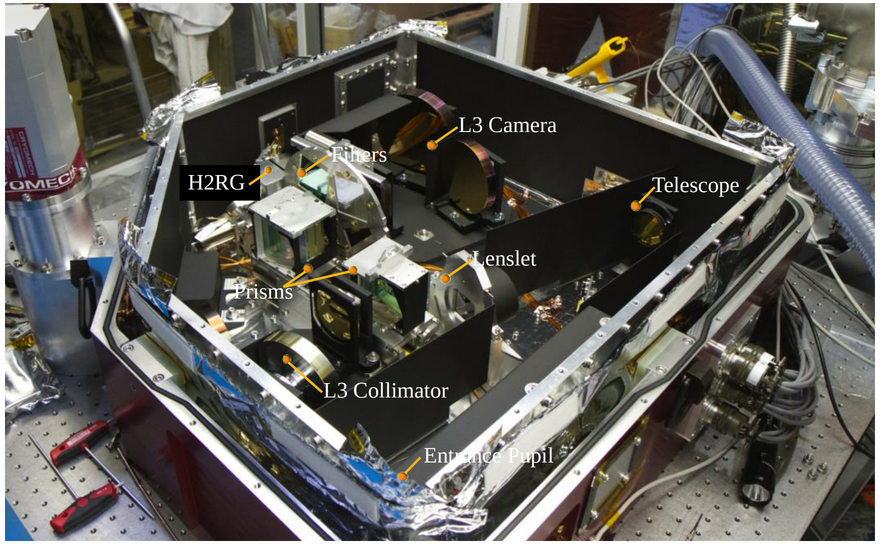
- Trades for back end spectrograph
  - IFS: more mature concept, more efficient to identify planets, hard to obtain “high resolution” and necessary field of view (limited pixel real estate).
  - Fiber fed and Slit Spectroscopy: less mature an efficient, however provides the precious high resolution in the near-IR.



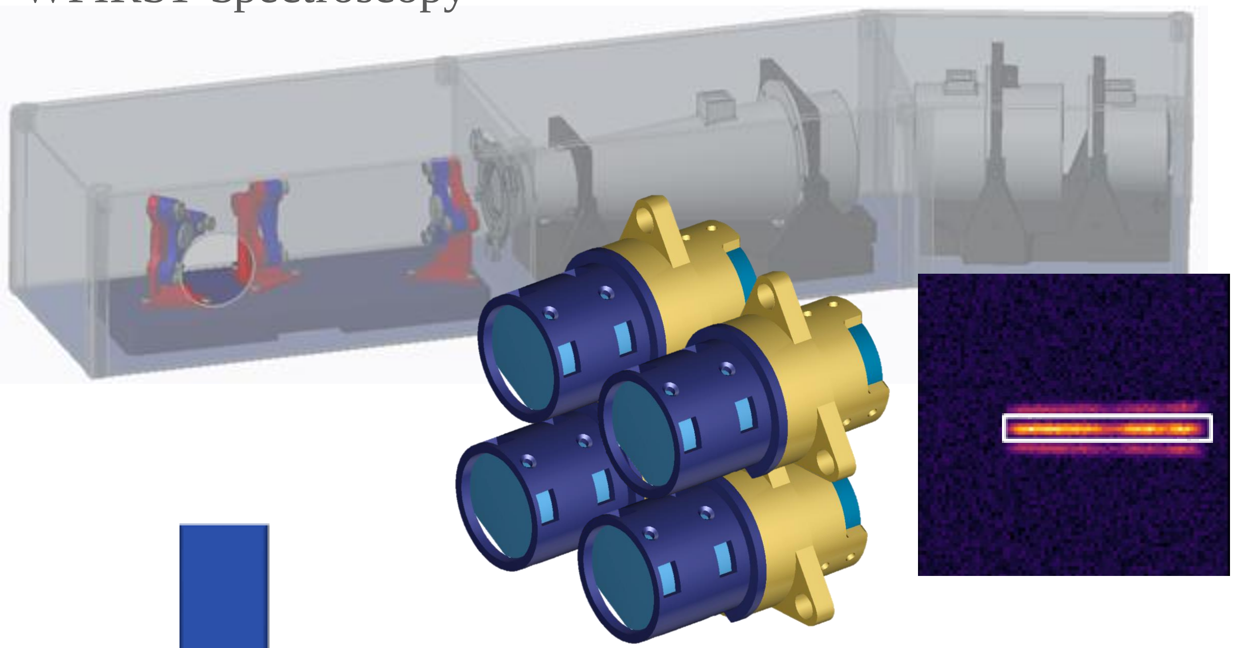
SPIE Conference, Optics and Photonics, 2019

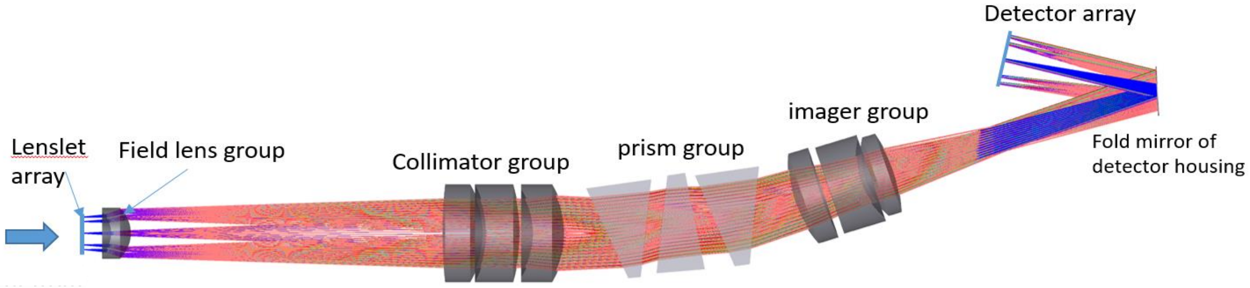
Conclusions

CHARIS



WFIRST Spectroscopy





- Science
  - CHARIS and SCExAO lend interesting precursor observations
  - Advances in science driven post-processing will directly benefit
- Technology
  - Data cube extraction and retrievals flowed directly from CHARIS
  - Requirements, Implementation, Lessons Learned
- Setting the stage for future missions

END

CHARIS Performance/Operation/Hardware Status

- Regular Maintenance Items
  - Cryomech
    - Molecular Sieve Adsorber replacement every 15,000 hours
      - Last replacement was at 19,571 hours in August 2018
      - ~10,500 hours of run time since then
      - New part must be ordered and next replacement in ~200 days
  - Hard Disks
    - Data offload management ~once/year