The Keck Planet Imager and Characterizer:

KPIC

Nemanja Jovanovic on behalf of the team

ExEP science meeting

17th June 2021

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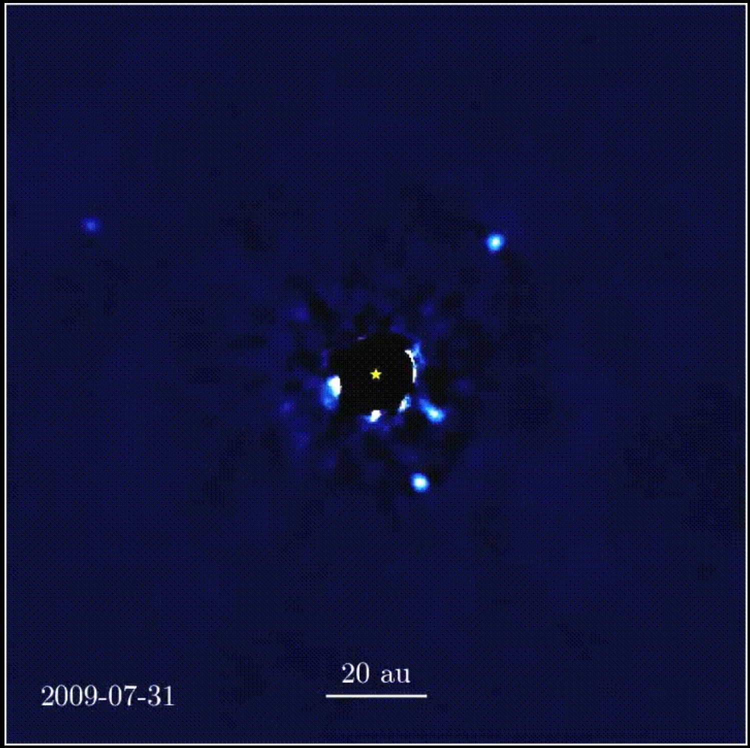
NASA NSF HEISING-SIMONS FOUNDATION

Science goals

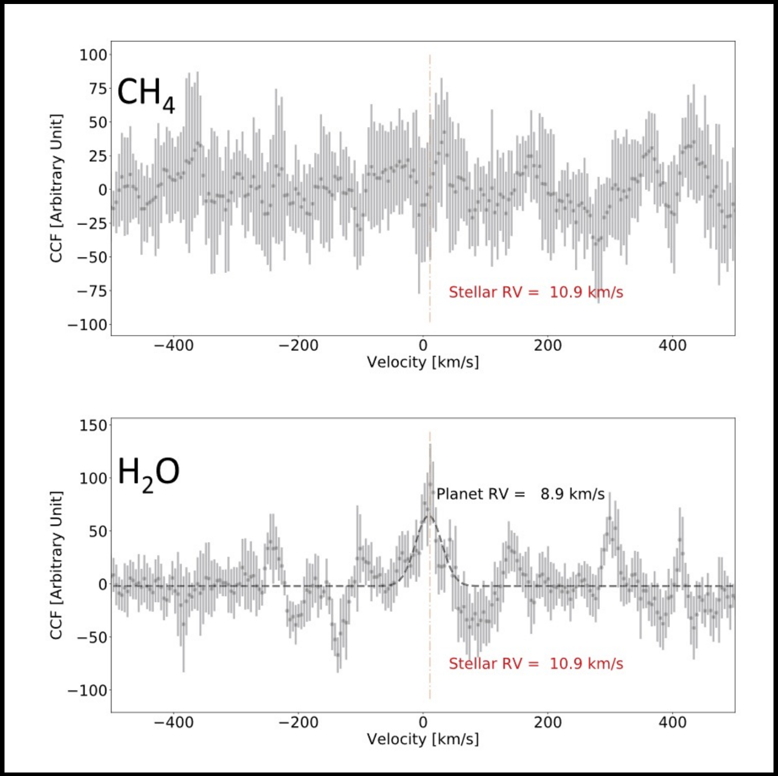
Science motivation

Two key science themes:

1. **Direct imaging of exoplanets** – to detect and improve photometry and astrometry
2. **Spectral characterization of exoplanets** – R>30k

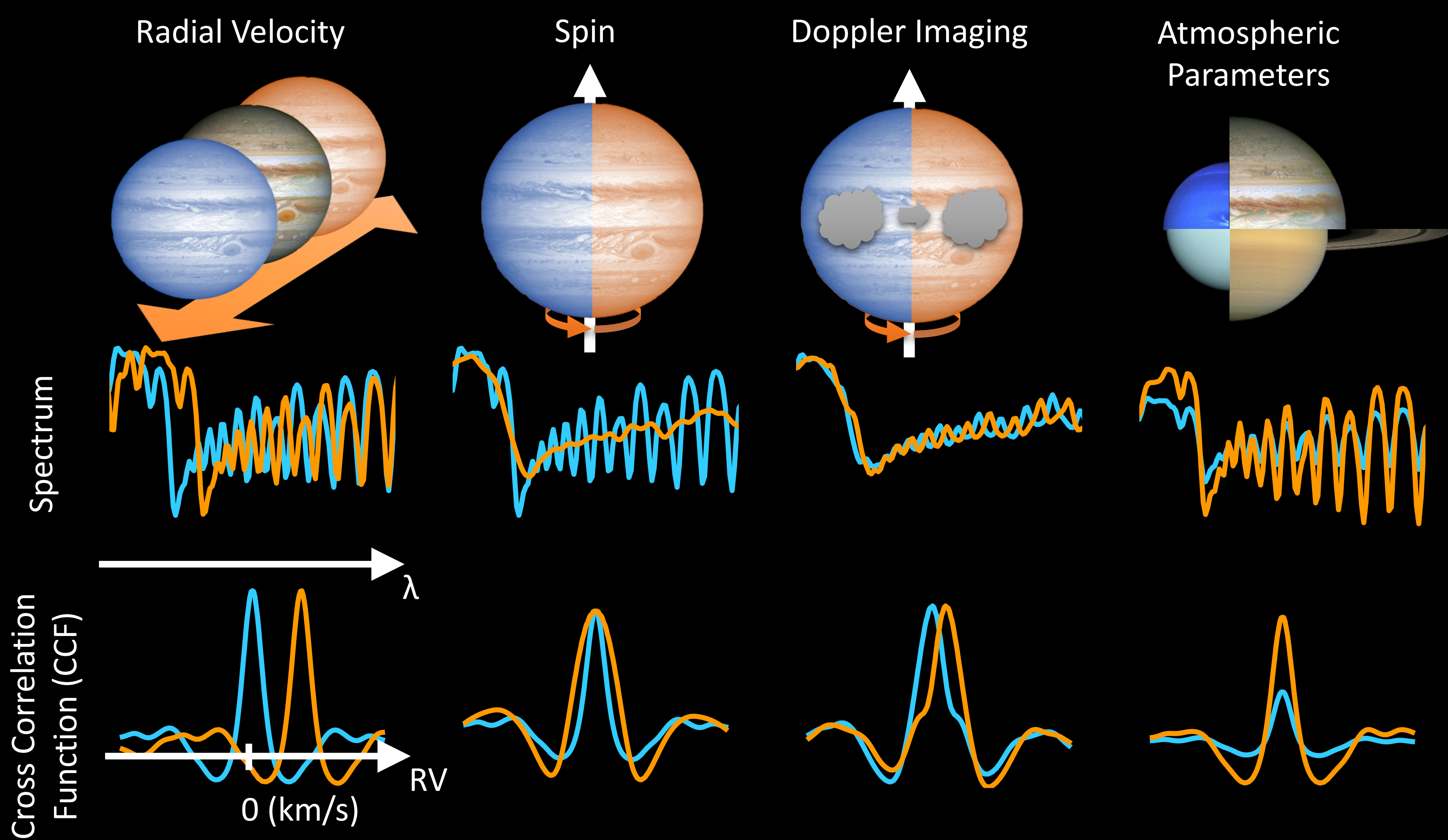


By Jason Wang, et al - https://www.youtube.com/watch?v=KVgKidAuf4o



Ji Wang et al. 2018

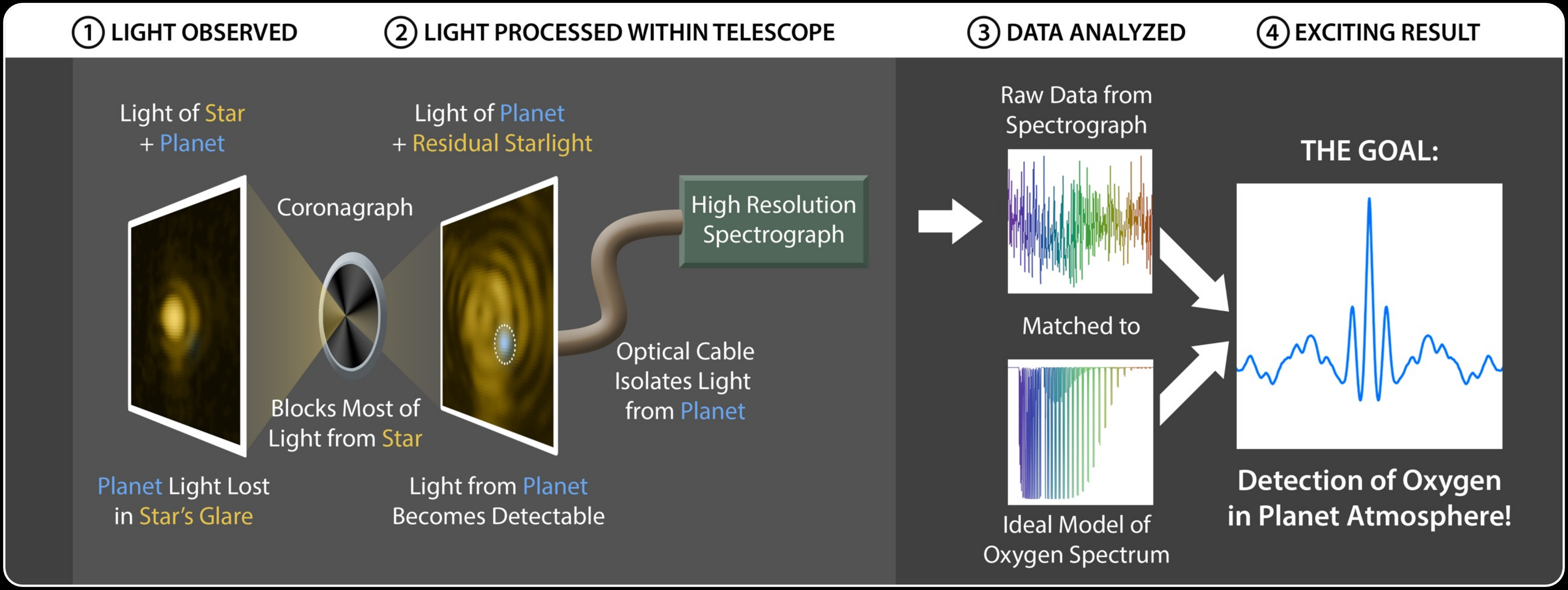
Motivation for high resolution spectroscopy



Courtesy of J.-B. Ruffio

High Dispersion Coronagraphy (HDC)

Proposed by Sparks and Ford, Riaud & Schneider 2007, and Snellen et al 2015



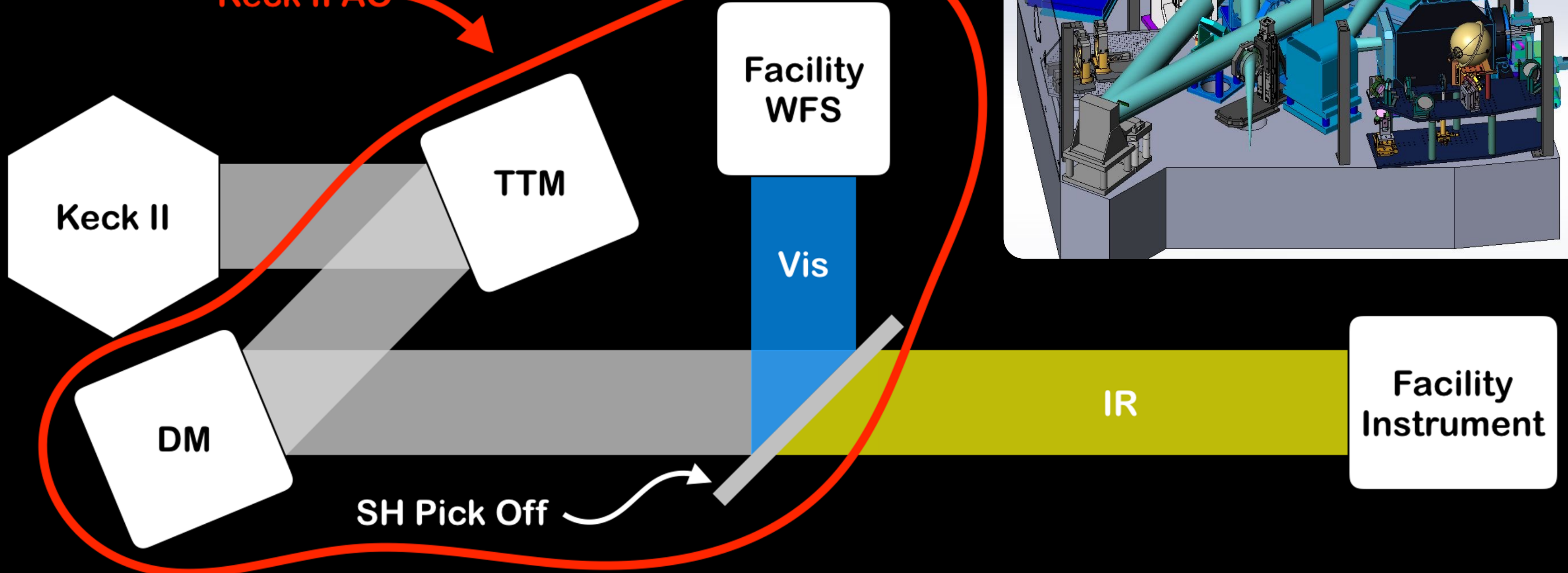
See Wang et al 2017 & Mawet et al 2017

The Instrument and Status

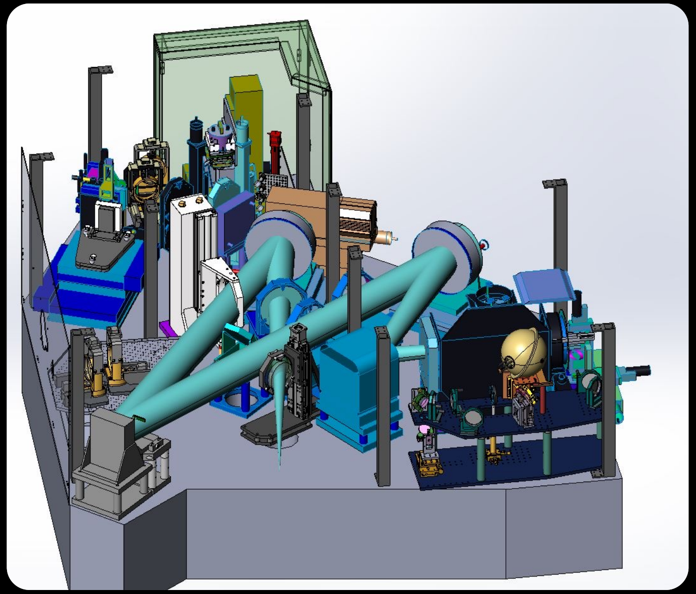
Keck II adaptive optic system

Key points:

- DM 21x21 actuators.
- Facility WFS: Shack Hartmann in Visible.
- Most productive AO system in the world.



3D Model



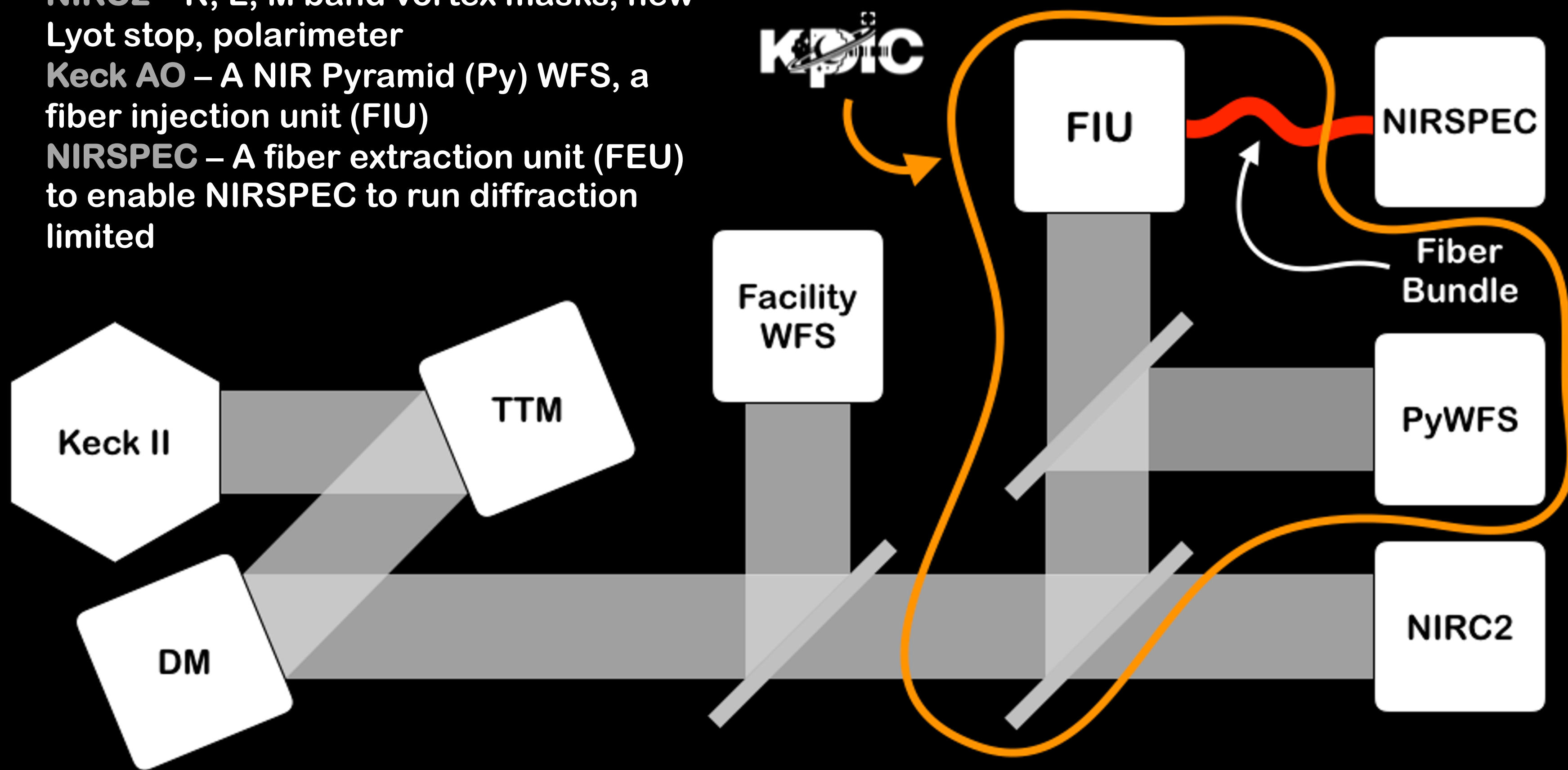
Facility instruments:

- NIRC2: High Resolution & high contrast infrared imager (coronagraphic capabilities).
- Nirspec: High Resolution spectrograph (Resolution > 37,000 in K band)

KPIC Block Diagram

KPIC is a series of upgrades to Keck AO, NIRC2 and NIRSPEC:

- **NIRC2** – K, L, M band vortex masks, new Lyot stop, polarimeter
- **Keck AO** – A NIR Pyramid (Py) WFS, a fiber injection unit (FIU)
- **NIRSPEC** – A fiber extraction unit (FEU) to enable NIRSPEC to run diffraction limited



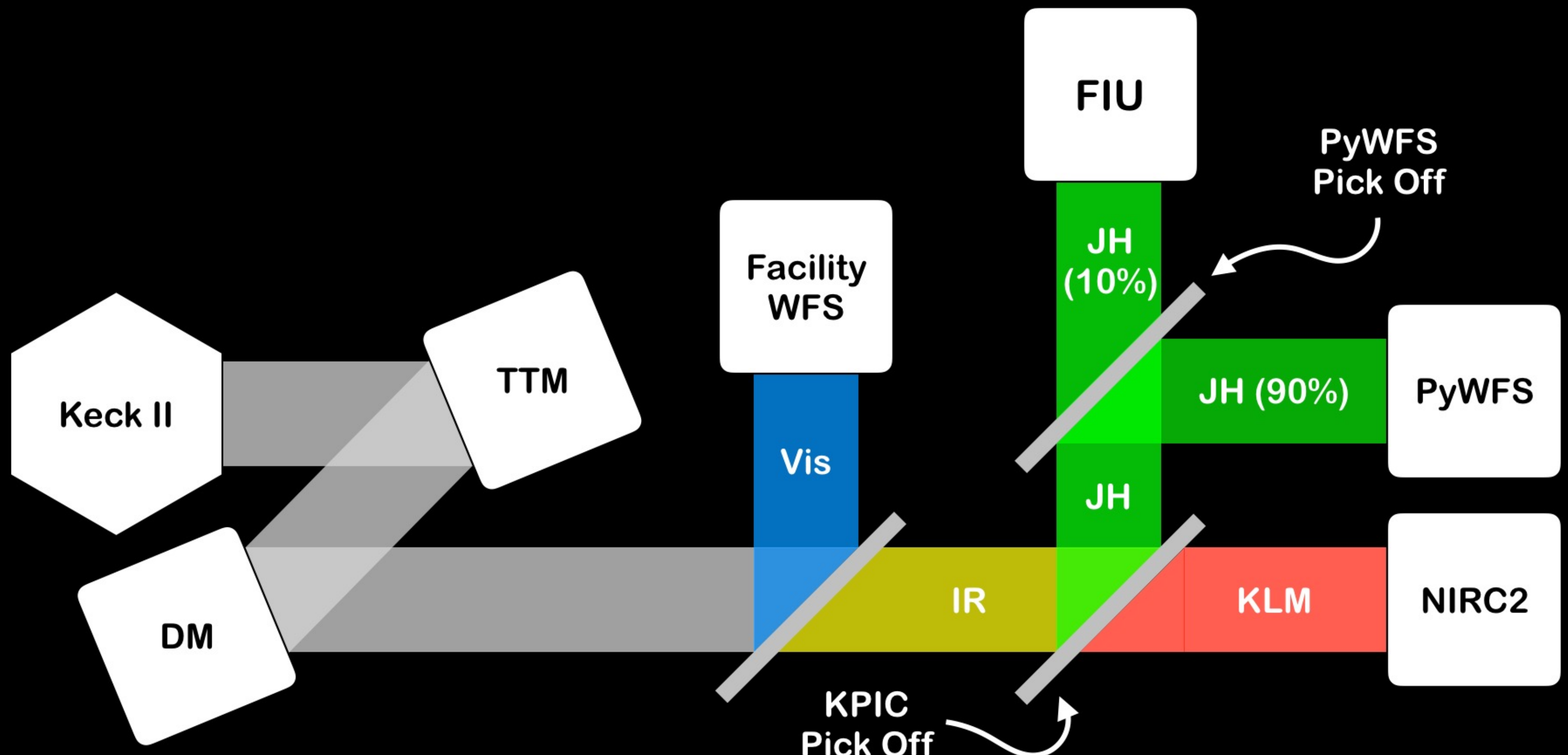
Planet Imager/Finder Mode

Key points:

- **Will be facilitized.**

Goals:

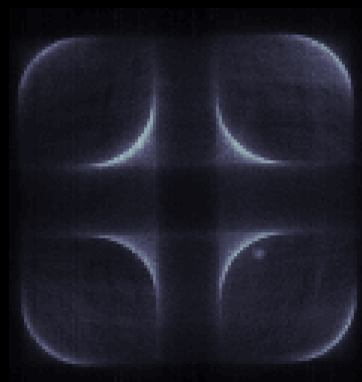
- Detect & image low mass companions.

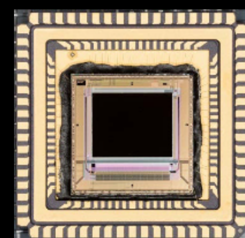


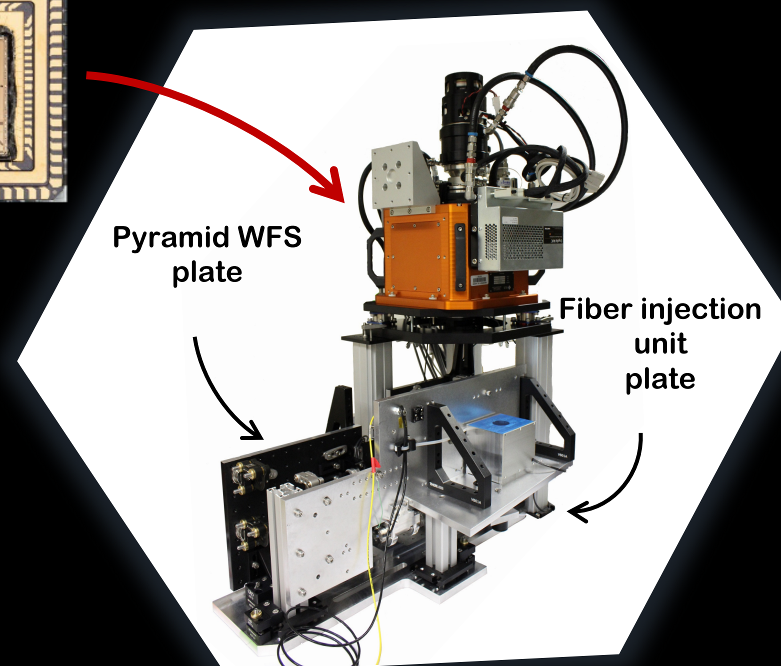
Keck Infrared Pyramid (Py) WFS

SAPHIRA: infrared avalanche photodiode array

- High frame rate (1.5kHz).
- Low noise (<1e).





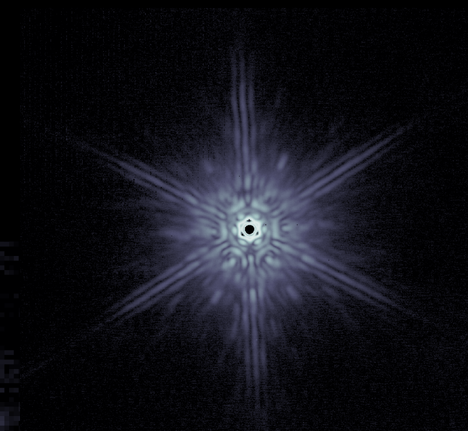


- Sensor wavelength: H-band
- 40 pixels across the pupil
- Correction:
  - Phase 1: 21x21 Keck DM
  - Phase 2: 32x32 Mems DM
- Real time control: CACAO

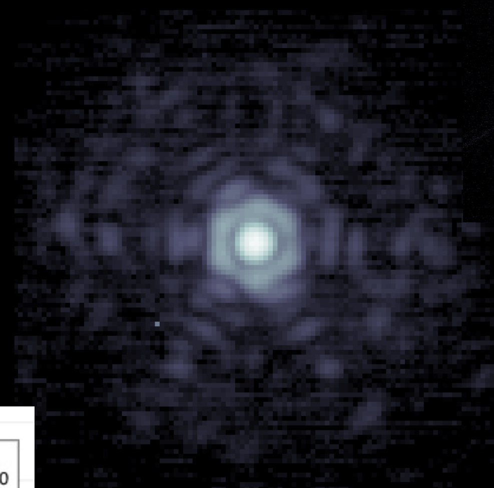
Planet Imager/Finder Mode

Key points:

- **PyWFS is routinely outperforming the Shack Hartmann**
- **Achieving Strehl approaching 90% in L band**

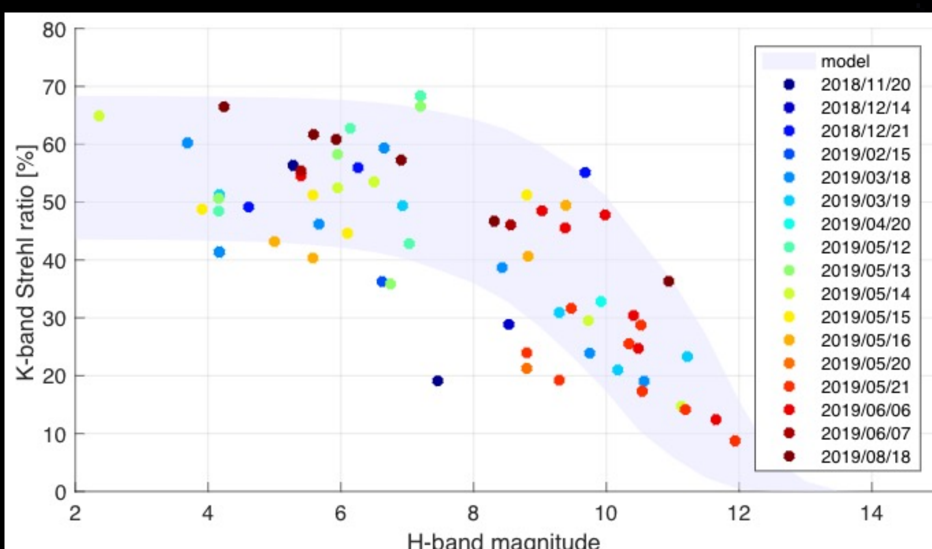


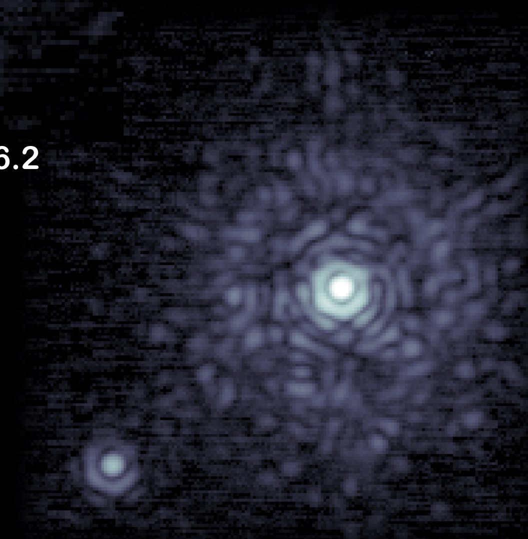
L-band image, H = 2.35



K-band PSF, H = 6.2
SR = 60%

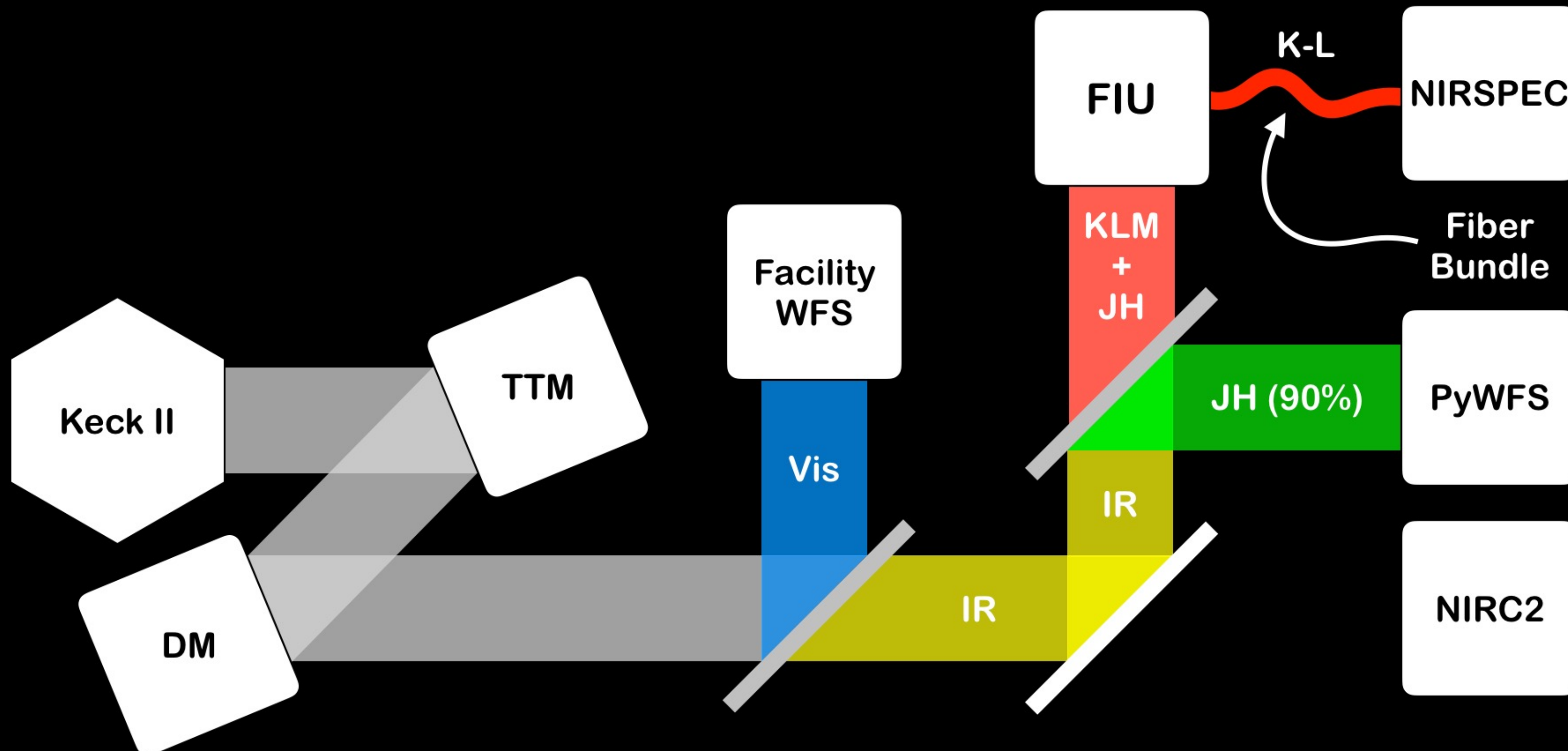
C. Bond et al JATIS, 2020



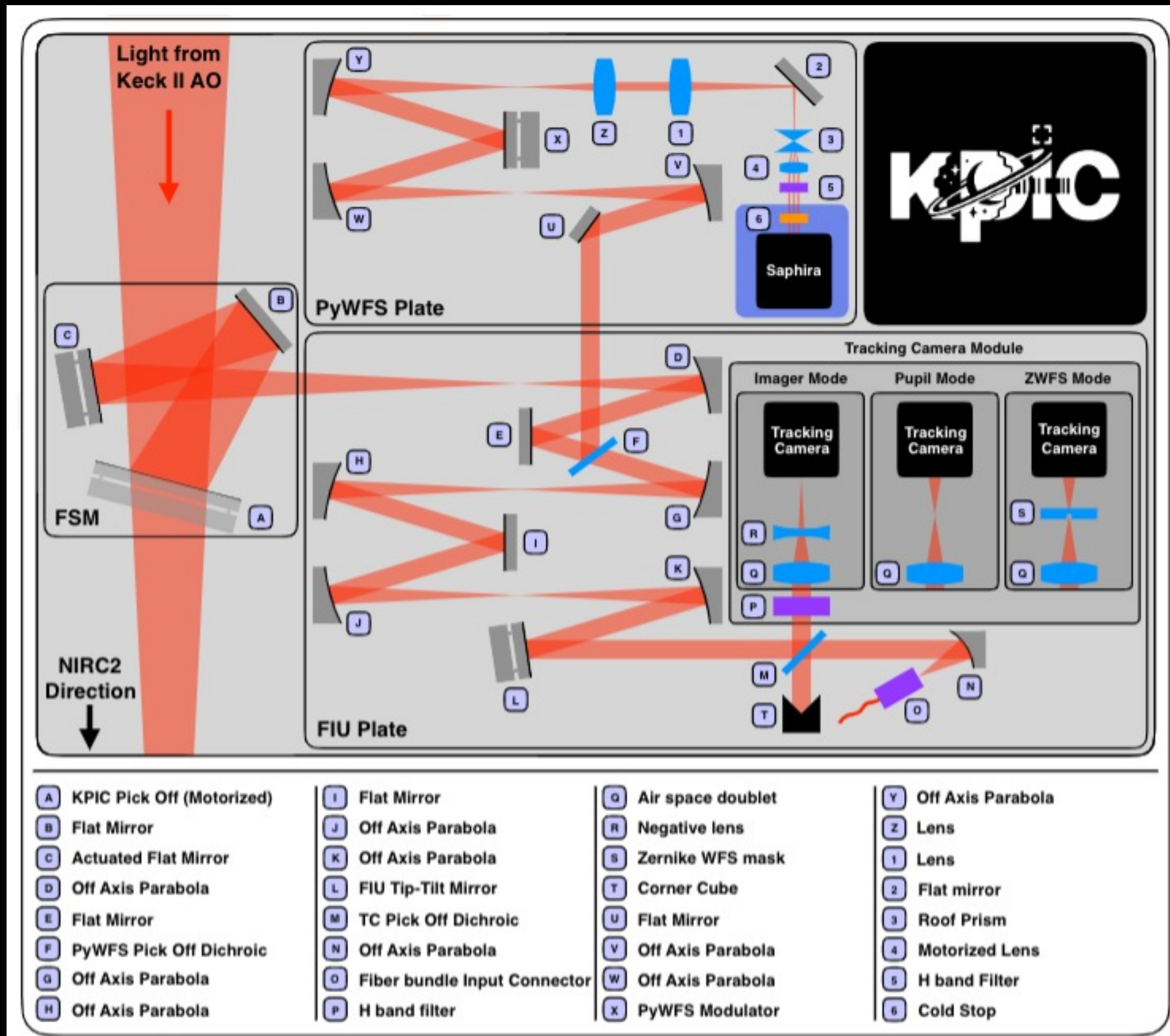


K-band image, binary

Planet Characterizer Mode

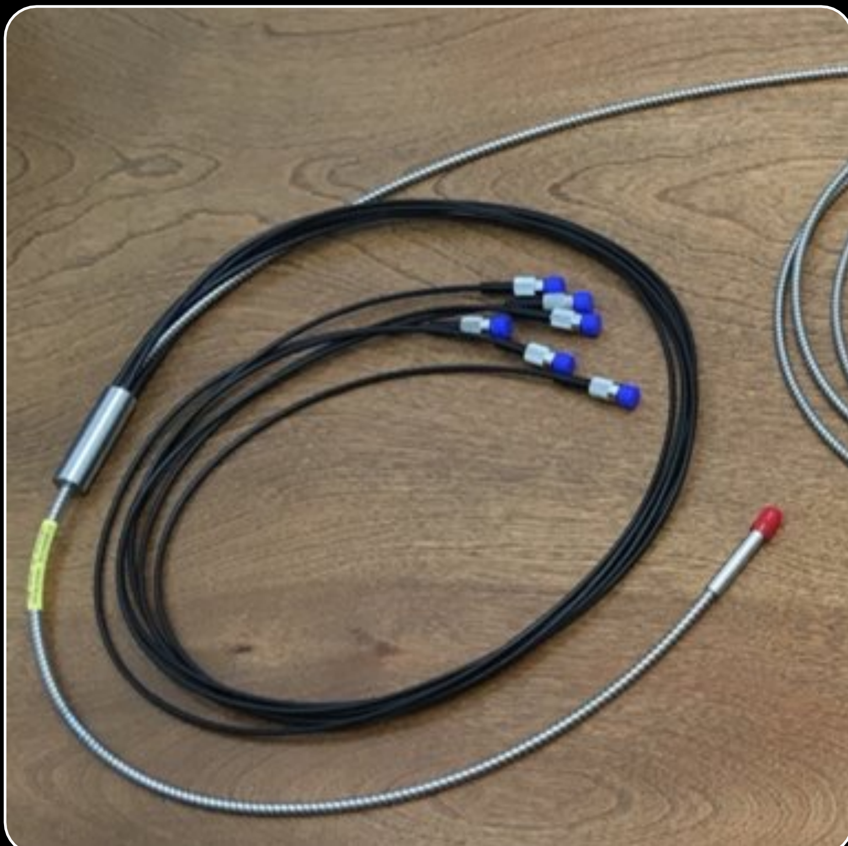


Planet Characterizer Mode

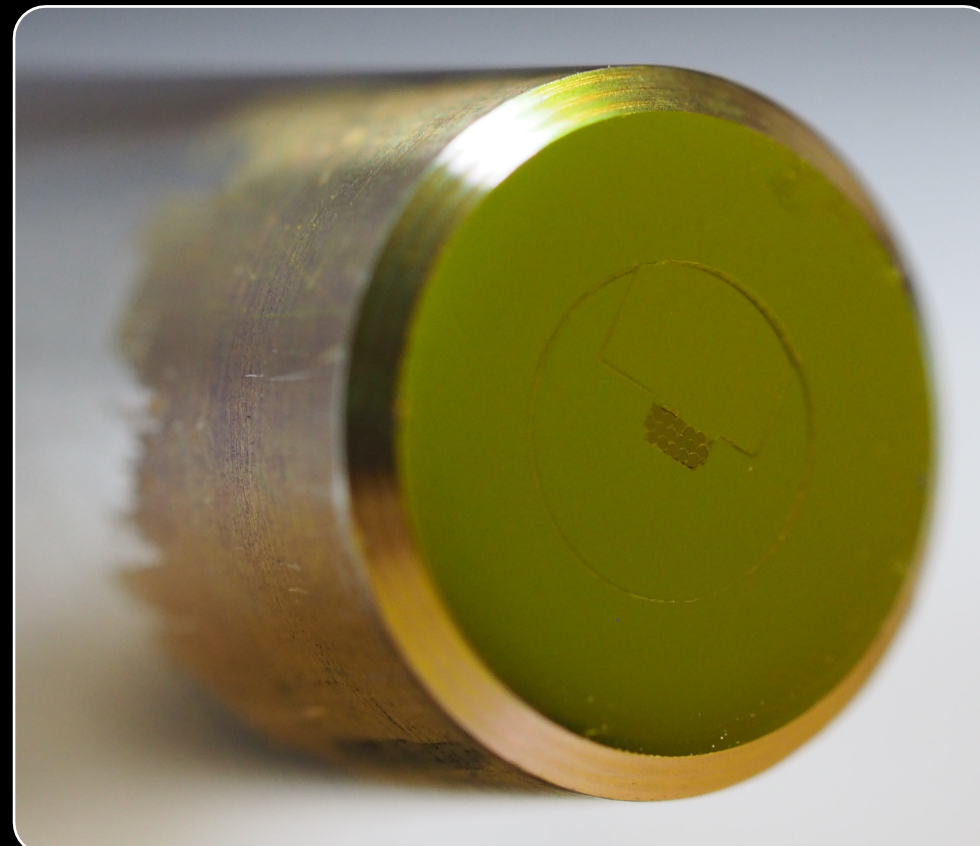


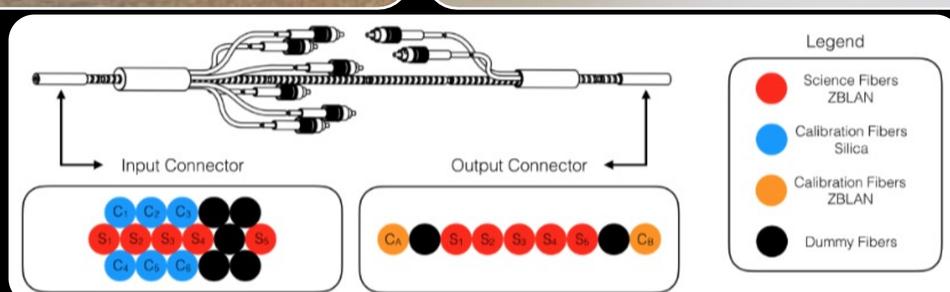
Fiber Bundle

Input side of the bundle



Input connector





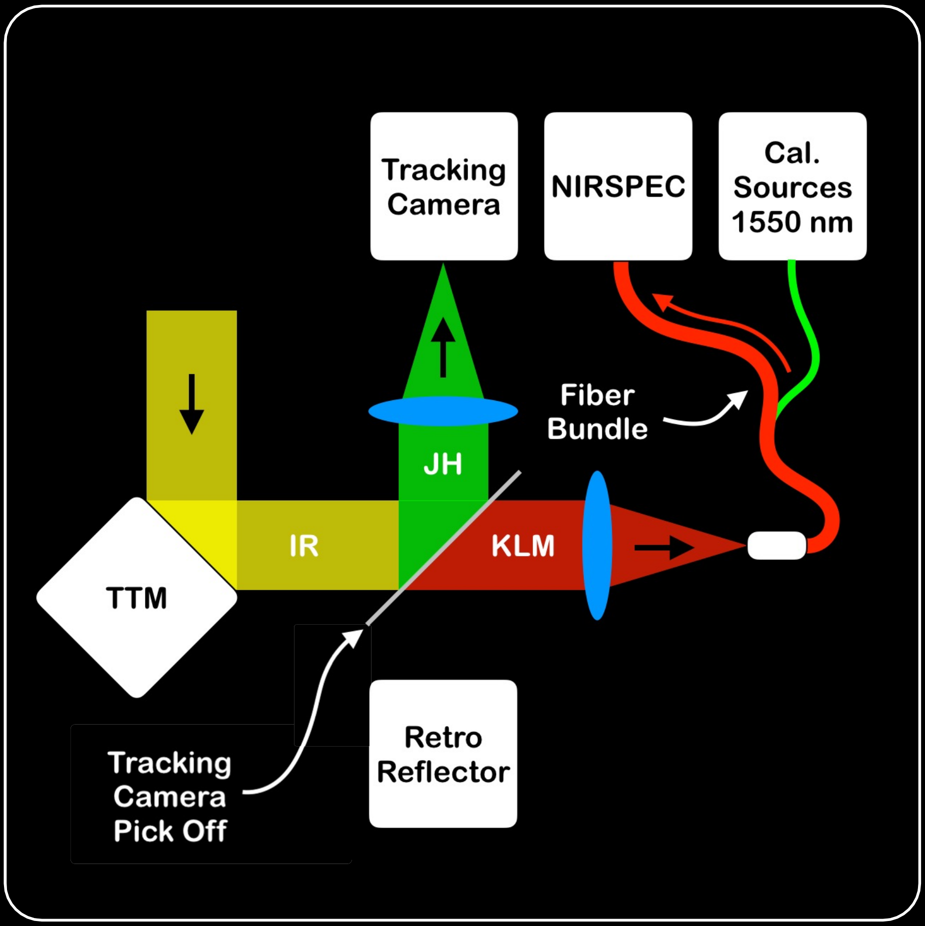
NIRSPEC

Key points:

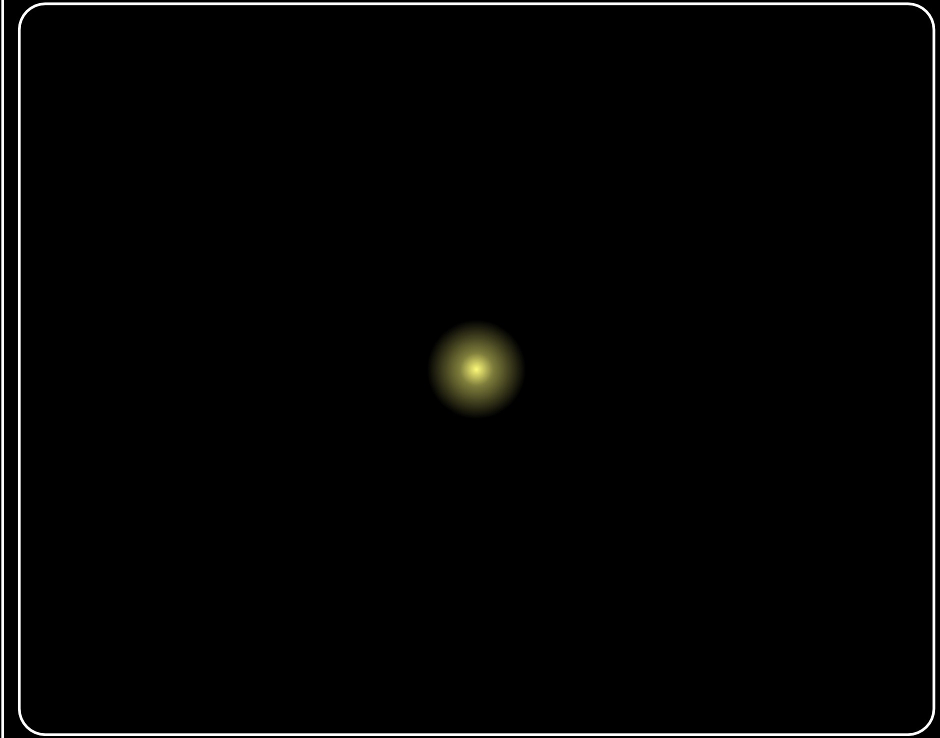
- High resolution spectroscopy over the wavelength region 0.95 to 5.4 microns
- K band resolution: ≈ 37K
- Modified to be fiber fed (single mode fibers)

Step 1: Star Acquisition Close AO Loop

Light from the telescope

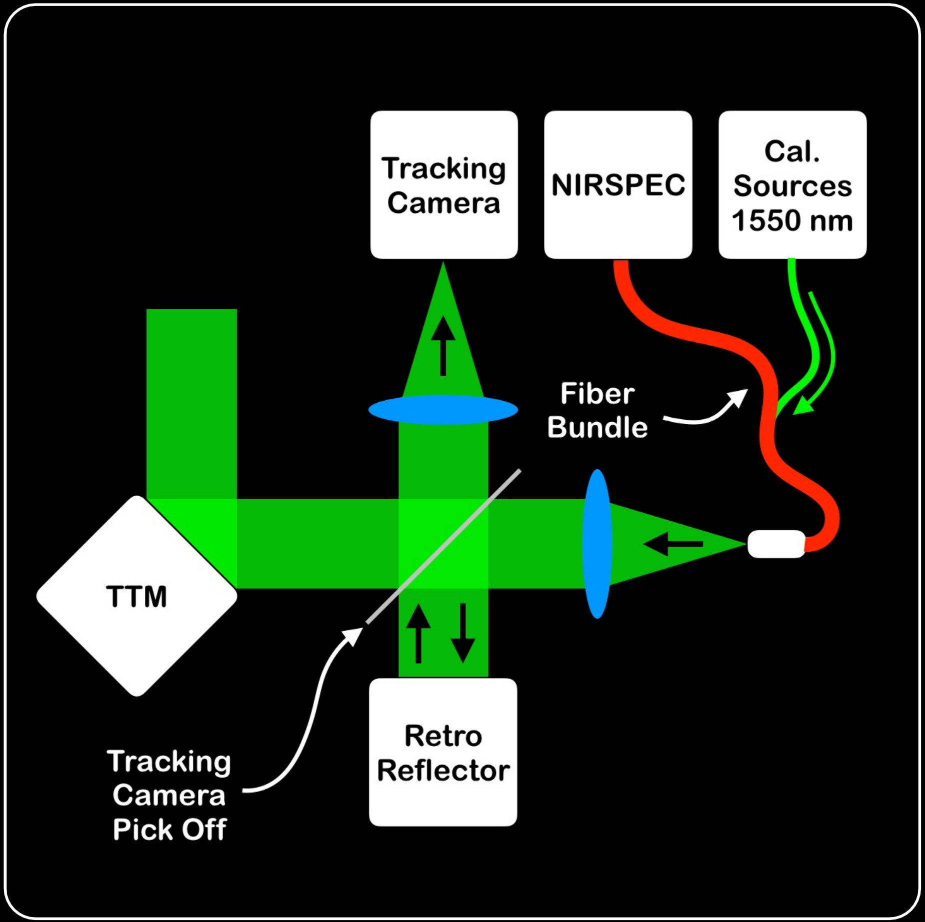


Tracking Camera Image

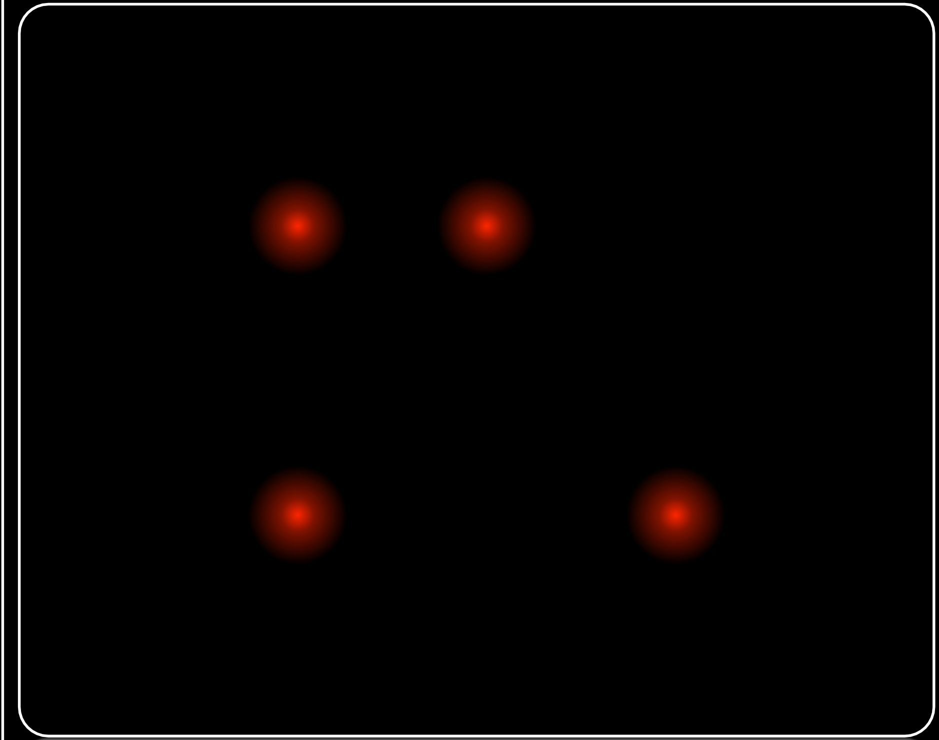


Step 2: Retro Feed Calibration Fibers

Light from calibration source

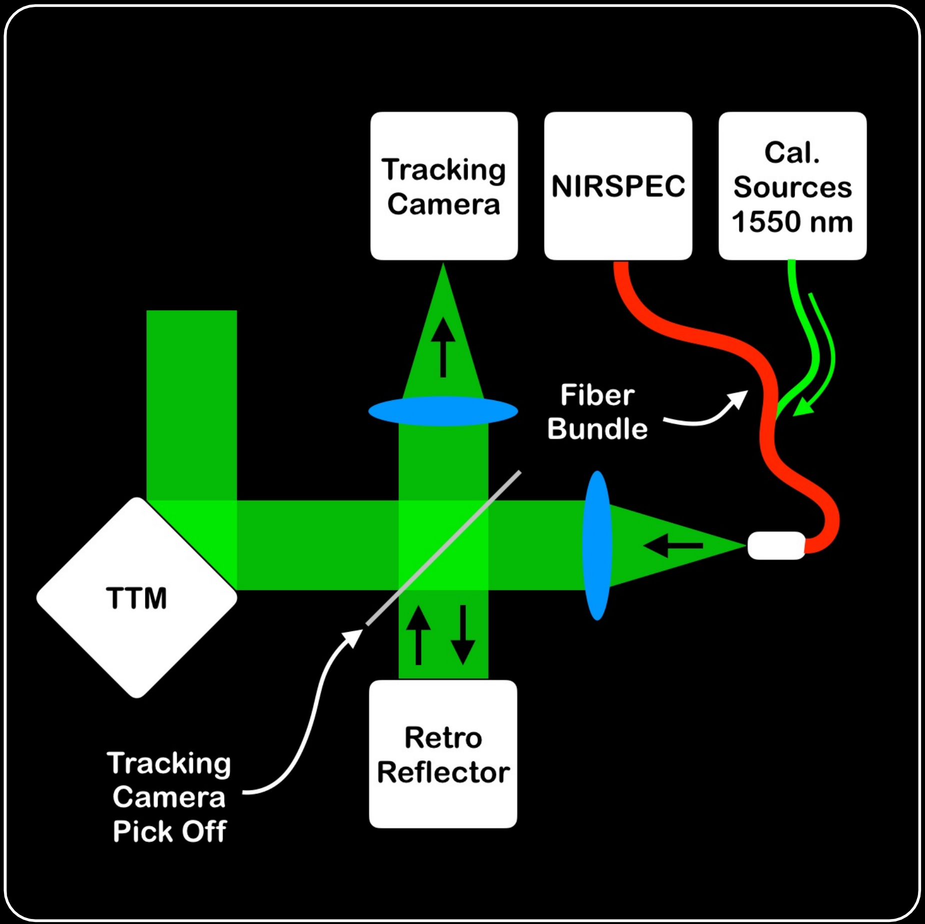


Tracking Camera Image

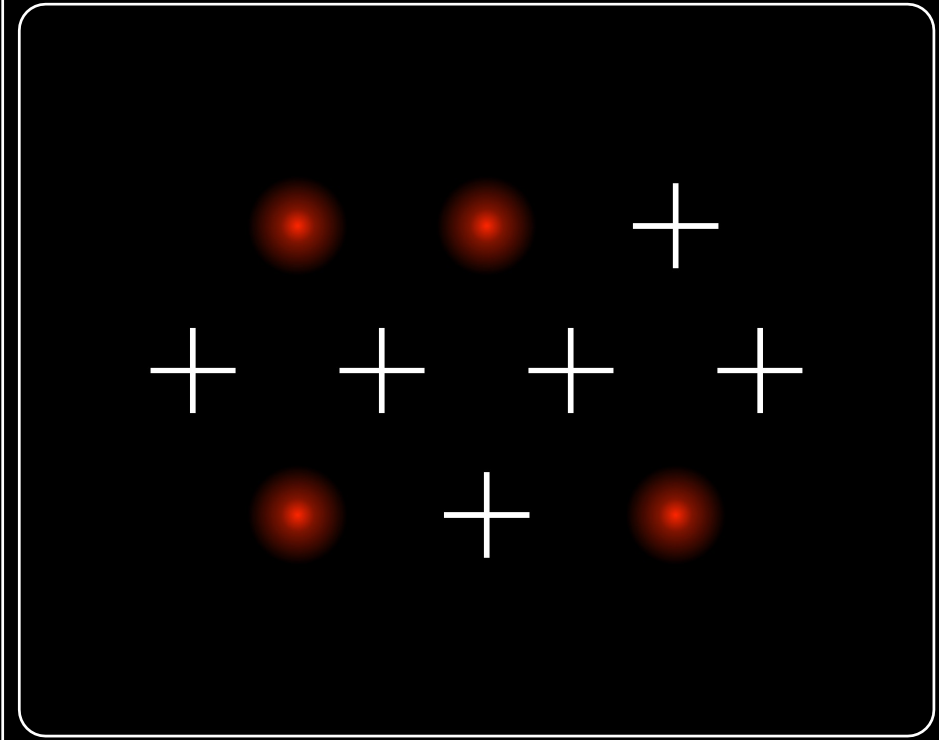


Step 3: Science Fiber Positions

Light from calibration source

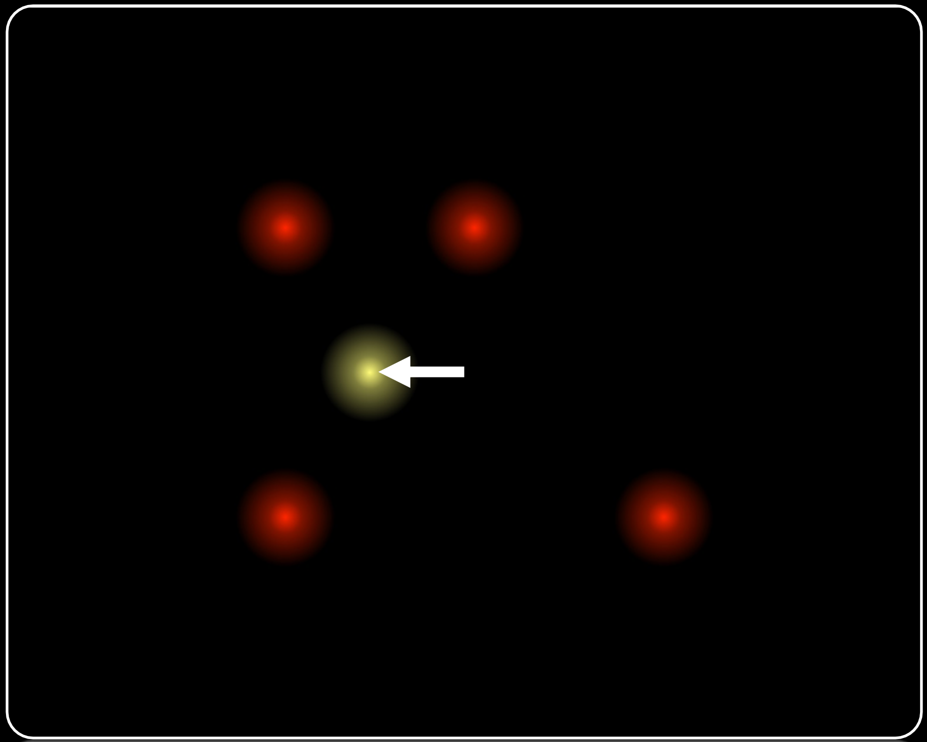


Tracking Camera Image

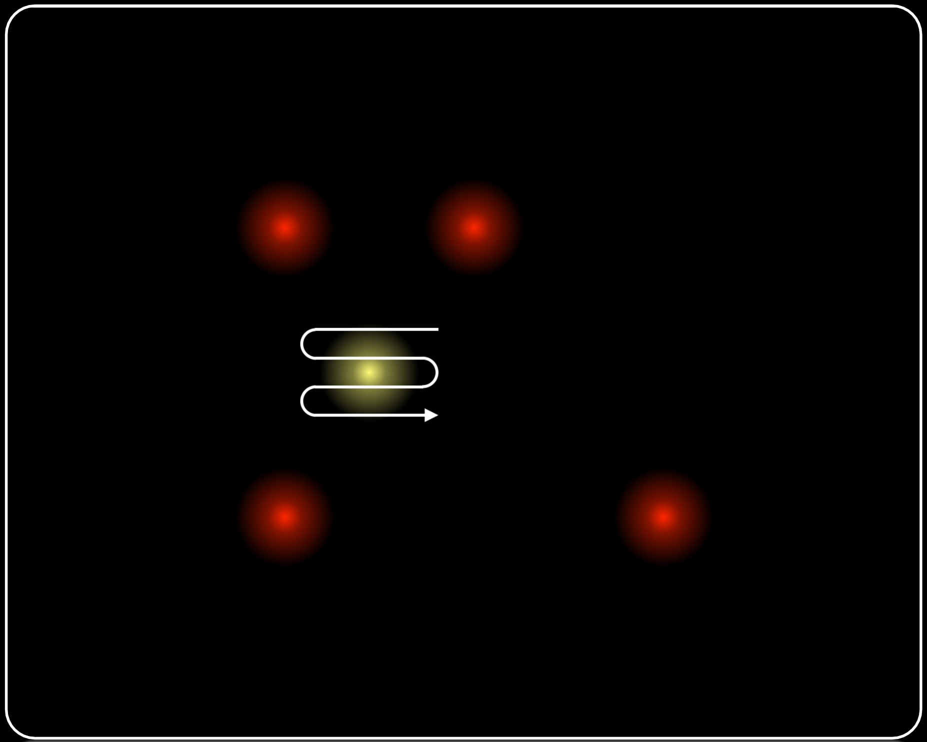


Step 4: Optimize Star Light Injection

Star alignment with science fiber

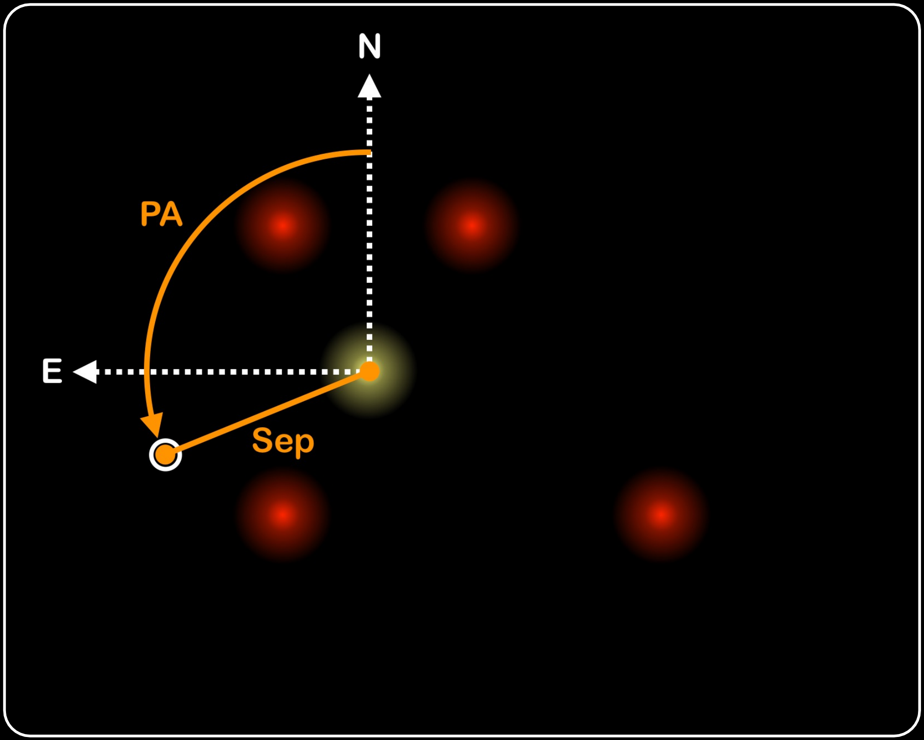


Scan science fiber to optimize injection

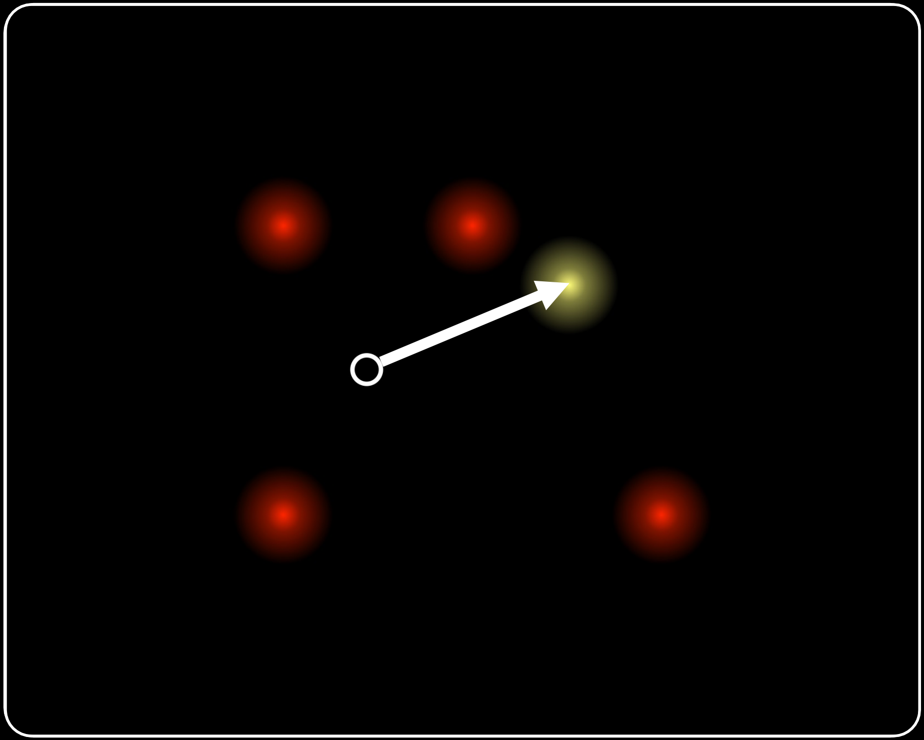


Step 5: Blind Offset to Planet Position

Astrometry of the target



Apply a blind offset



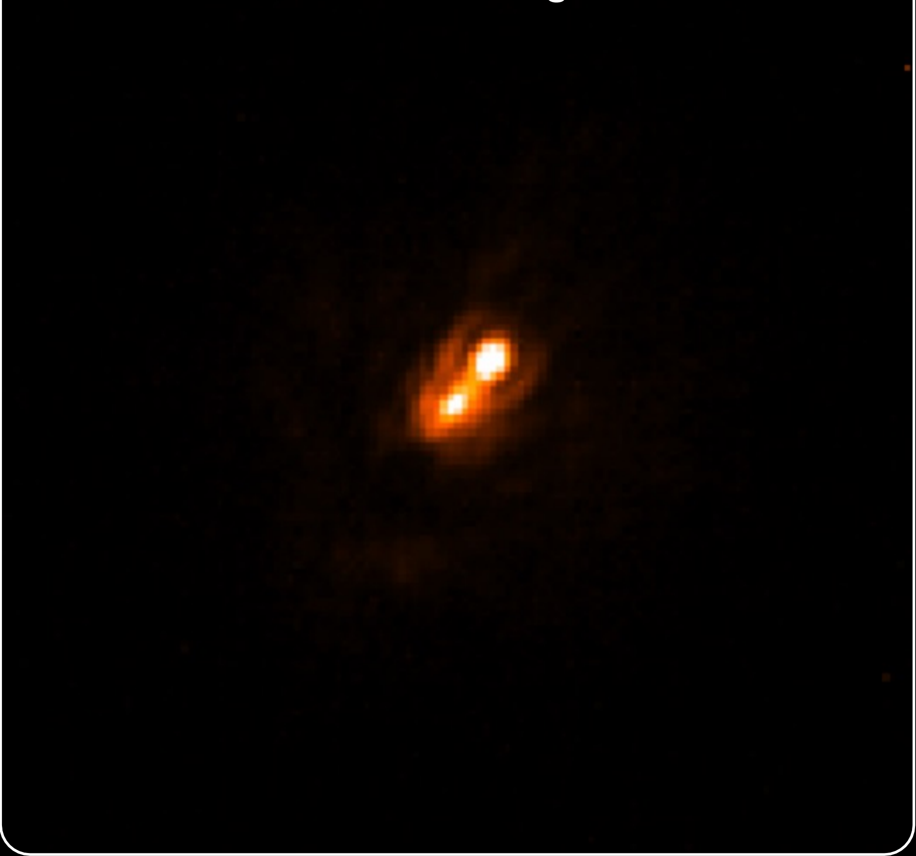
Requires accurate knowledge of the

- Plate scale
- Orientation and
- Distortion map

Step 6: Compensating DAR

- Keck has no Atmospheric dispersion compensator
- Need to offset pointing to compensate for offsets between the tracking and science bands

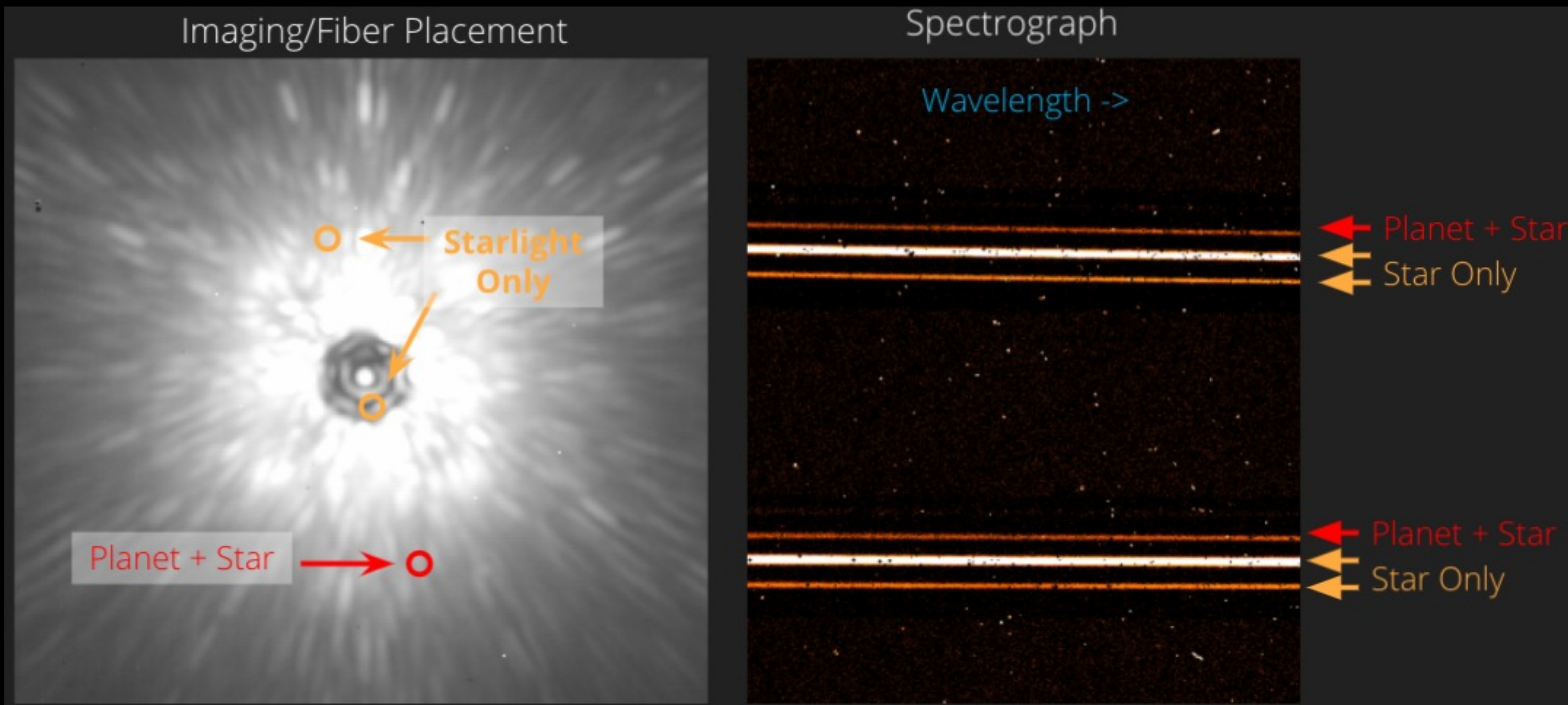
Elevation 49.26° – Target HR 8799



Raw detector images (HR 8799)

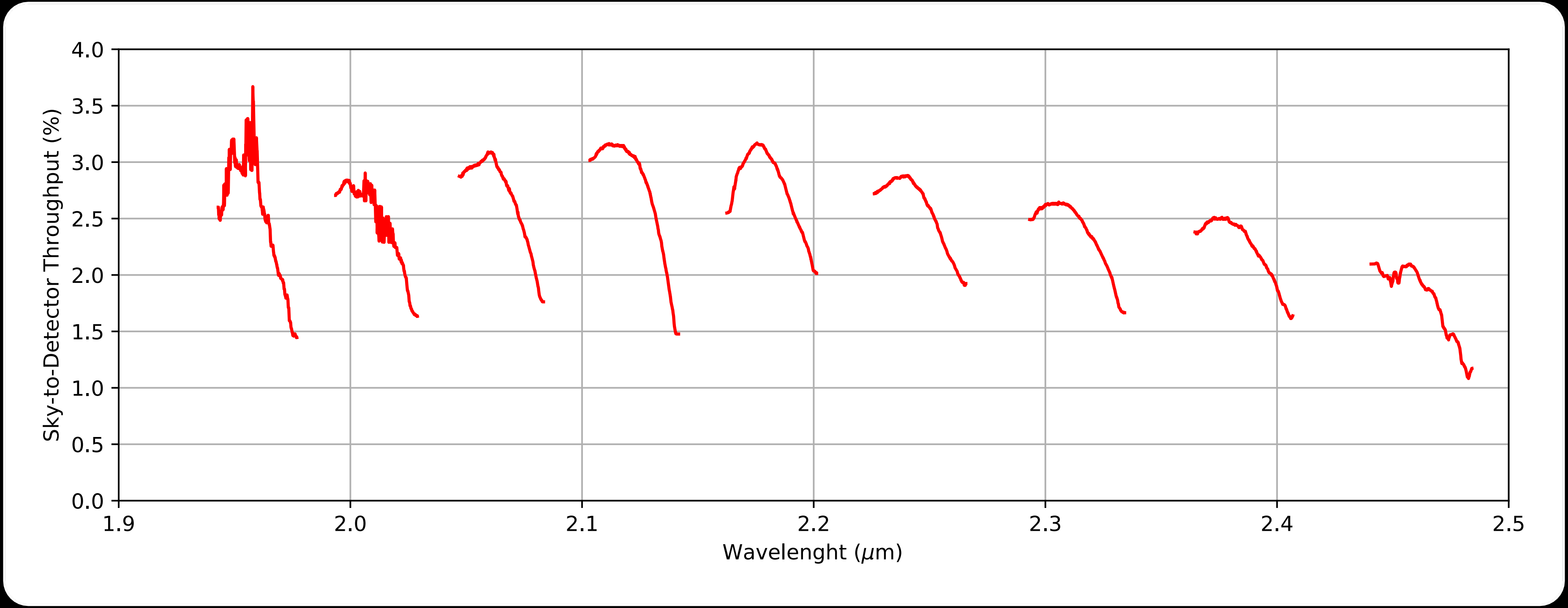
Tracking camera - InGaAs

Science detector - H2RG



Overall Throughput of the System

Throughput measured on Kappa And (July 3rd 2020 – Elevation 64.6º)

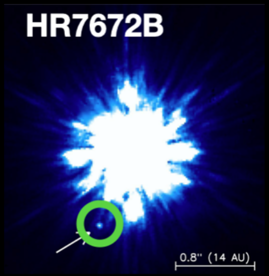


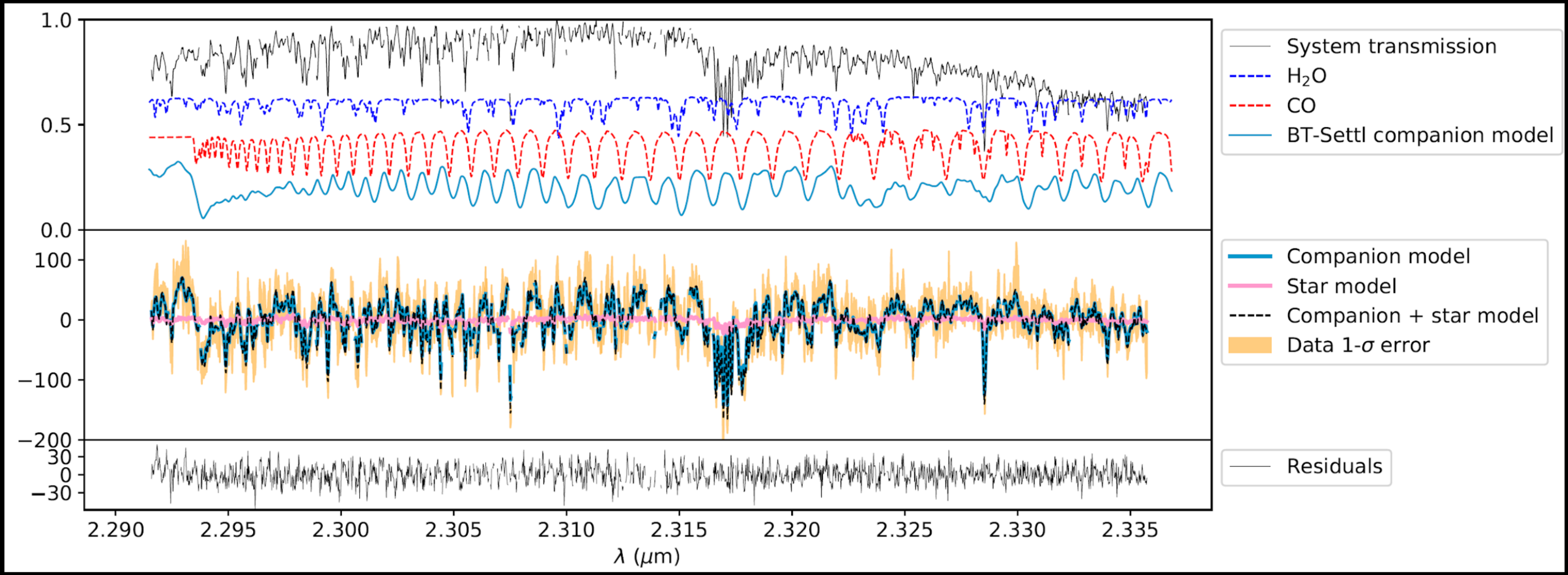
- ~40% injection/propagation efficiency (other losses include sky, telescope, Keck AO, optics, NIRSPEC)
- Throughput is similar to NIRSPAO

Data products

Preliminary reductions exist for all the data on a Caltech machine (hcig1)

1D spectra, Line width, & wavelength calibration



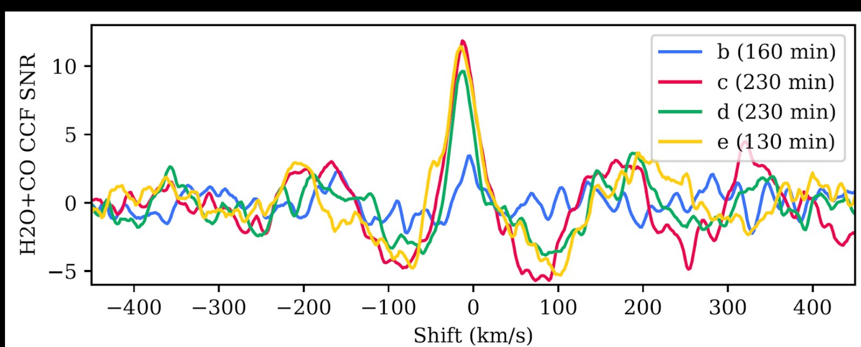


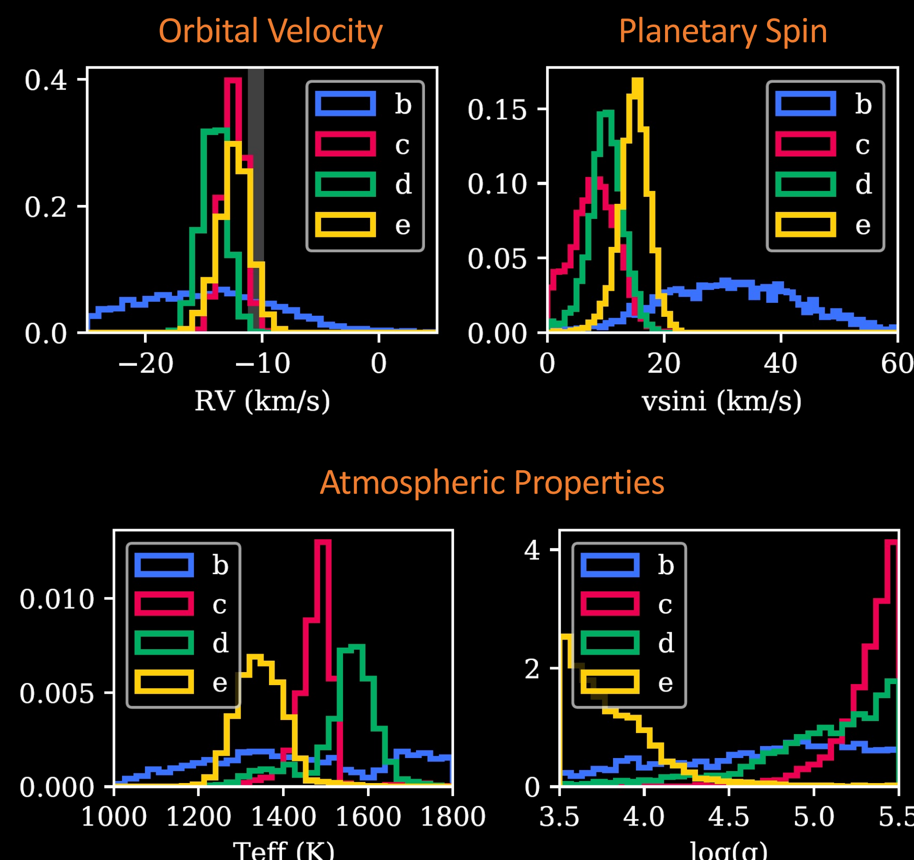
Delorme et al, in review

Courtesy of J.-B. Ruffio and J. Wang

HR8799 bcde detections

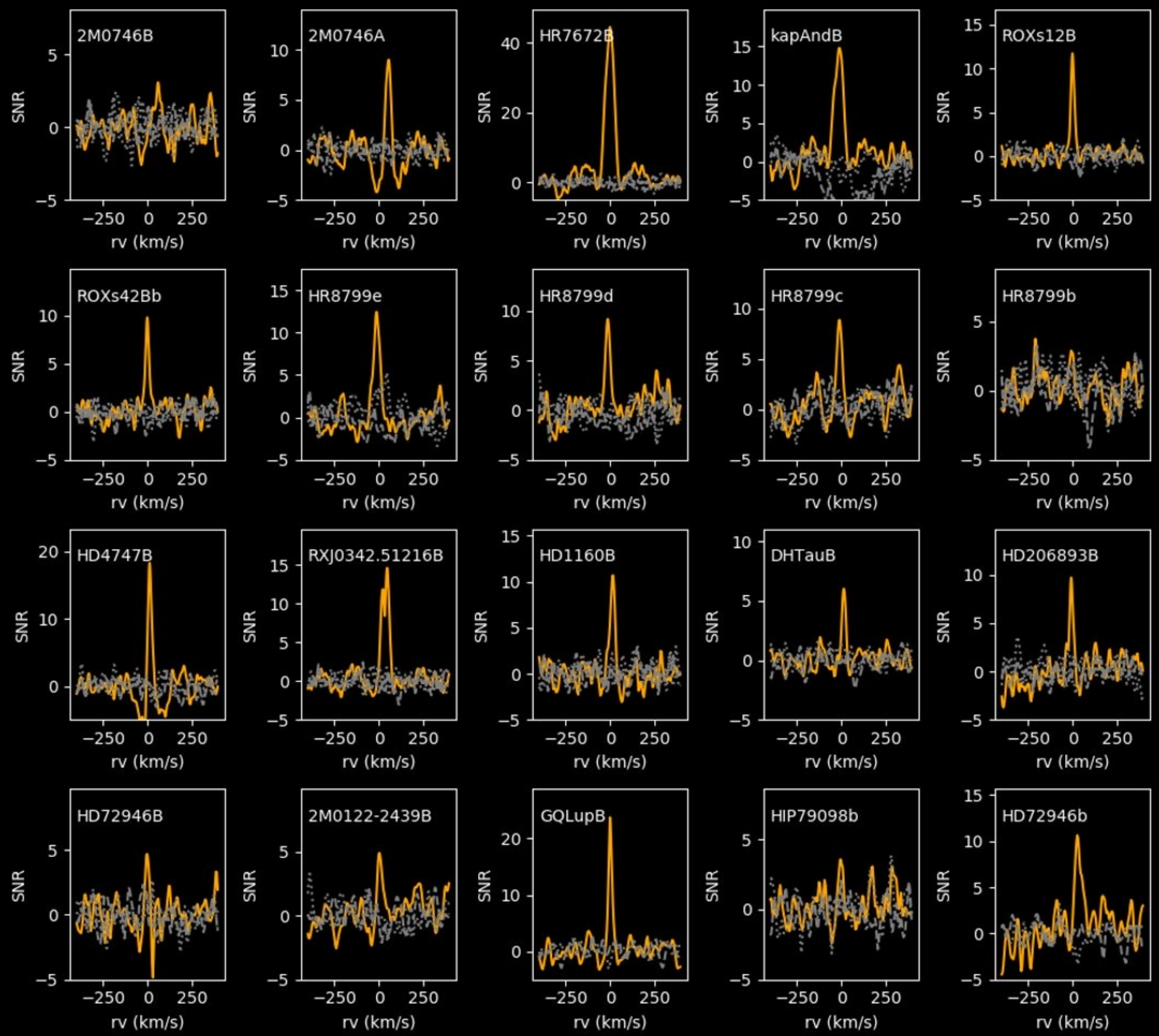
First detections of HR 8799 d & e at R > 10,000
2x better detection of HR 8799 c with 4x less time than NIRSPAO





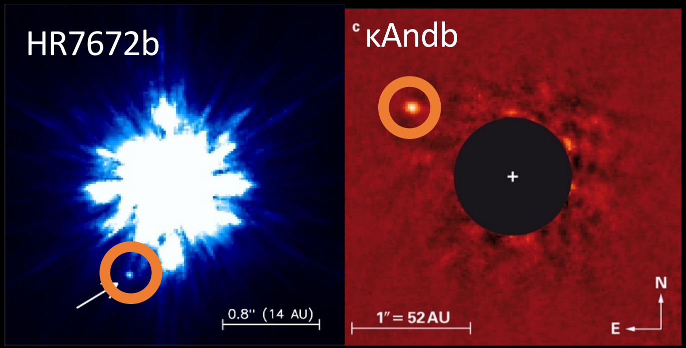
Wang et al 2021, in review

A survey is underway



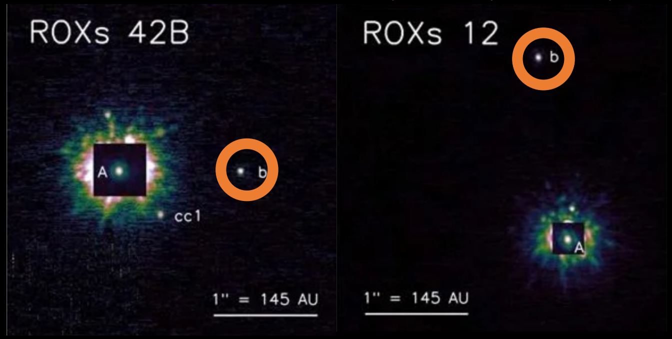
On-going survey:

- ~20 companions detected
- Additional 12 nights already scheduled in 2021



Liu et al. 2002

NAOJ / Subaru / J. Carson / T.

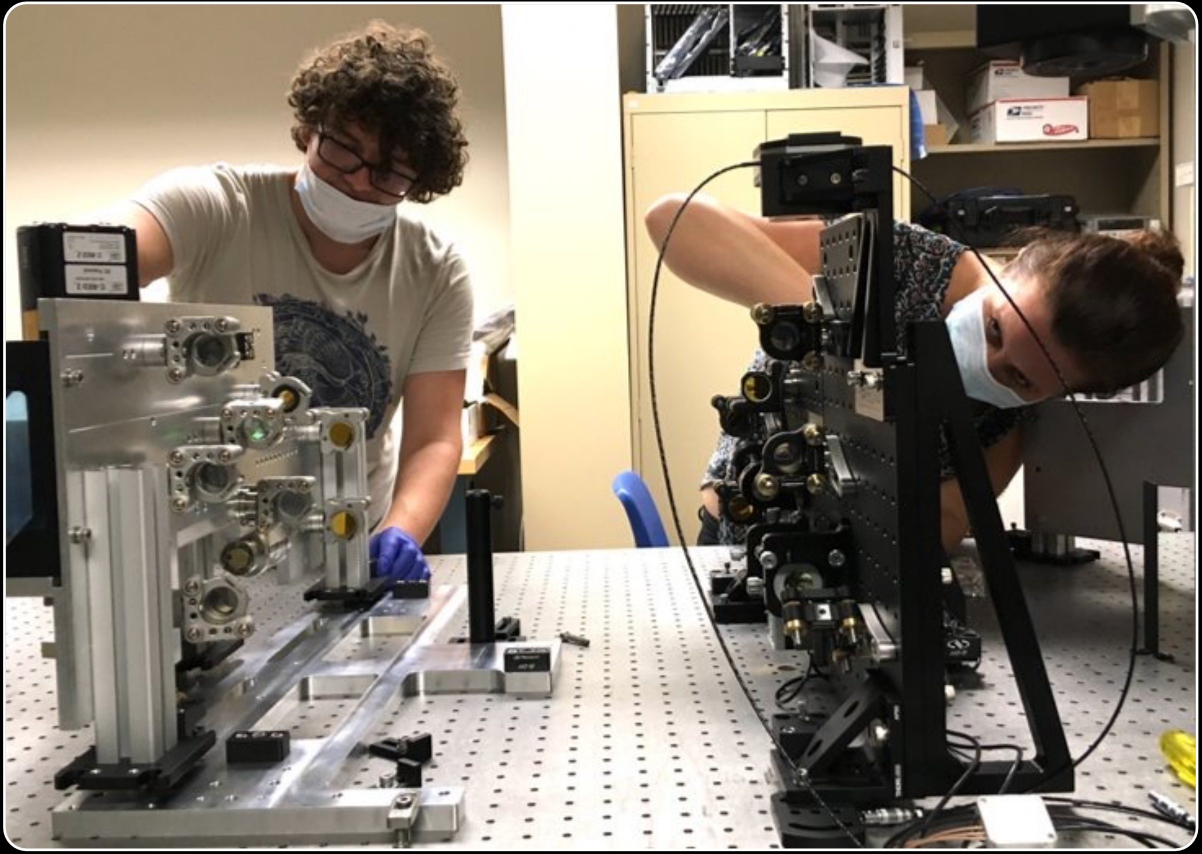


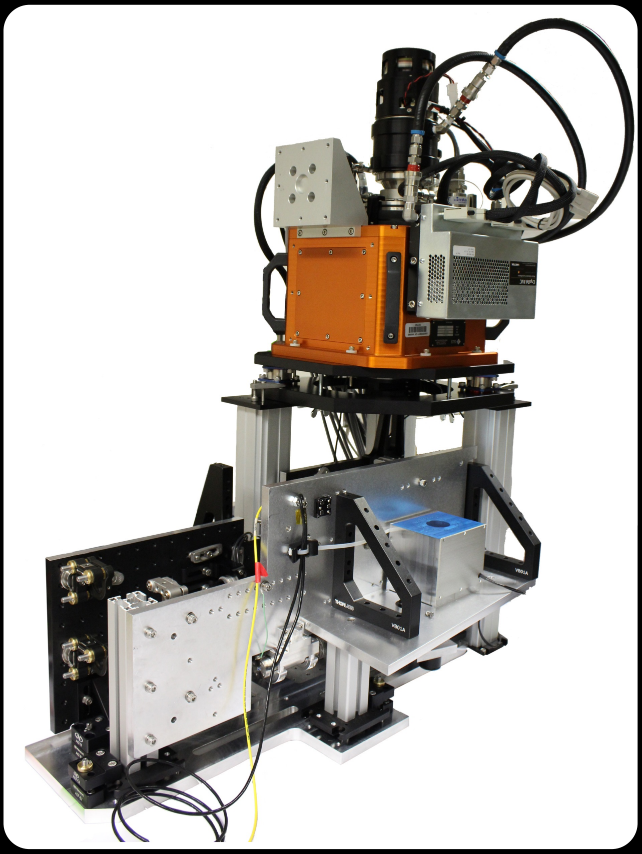
Kraus et al. 2013

KPIC Phase I

KPIC phase I modules implemented :

- **NIRC2** : K, L, M band vortex masks, new Lyot stop and a polarimeter
- **Keck AO** : A NIR Pyramid PyWFS and a fiber injection unit (FIU), Zernike WFS
- **NIRSPEC** : A fiber extraction unit (FEU)





KPIC-FIU Timeline

KPIC-FIU Phase #1 – Currently on Sky

2015 -- KPIC white paper
December 2017 -- Design Review
September 2018 -- KPIC install at Keck
November 2018 -- First light without NIRSPEC
January 2019 -- First stellar spectra
May 2019 -- First Science night
Since May 2019 -- 20+ science targets observed

KPIC-FIU Phase #2 – Work in progress

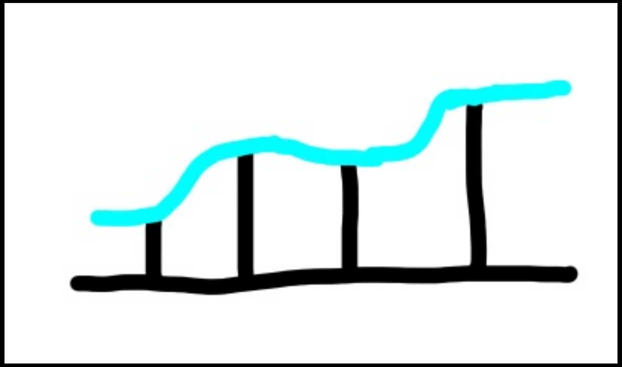
May 2019 -- Design Review
Summer 2021 -- Lab integration
Winter 2021 -- Installation at Keck

Next Steps for KPIC

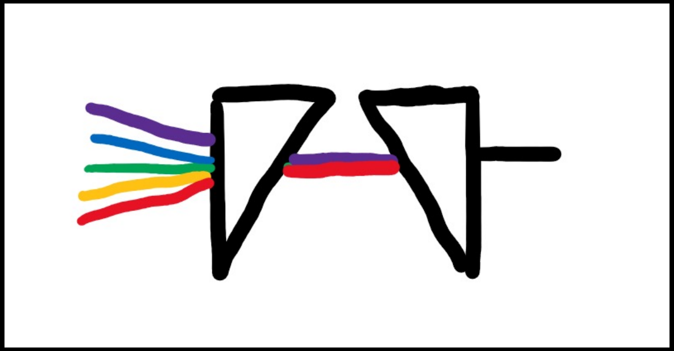
Phase II upgrades

Increase planet throughput and suppress star light

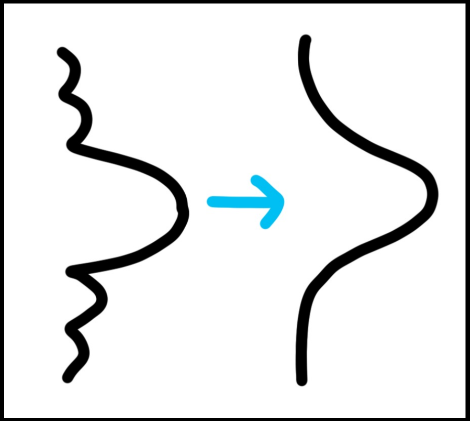
High-order DM – 1k BMC



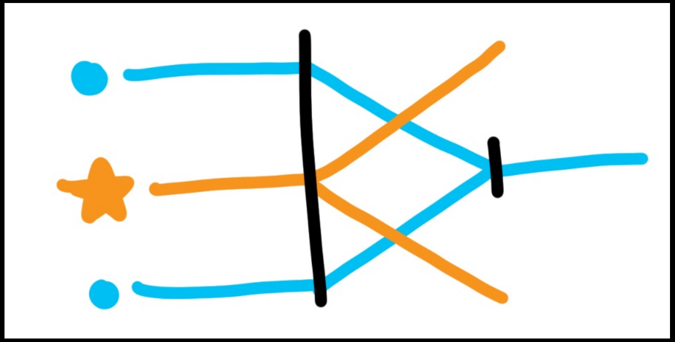
Atmospheric dispersion compensator (ADC)



Beam shaping optics (PIAA)



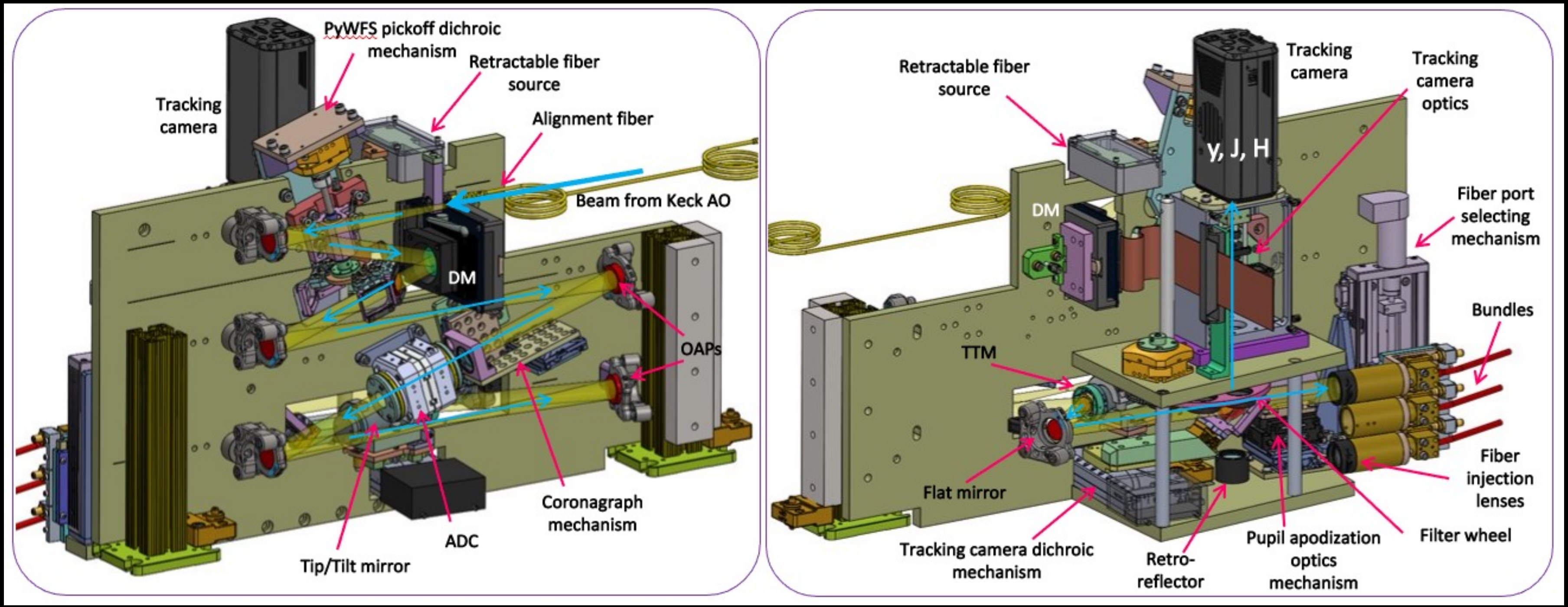
Fiber nulling coronagraph



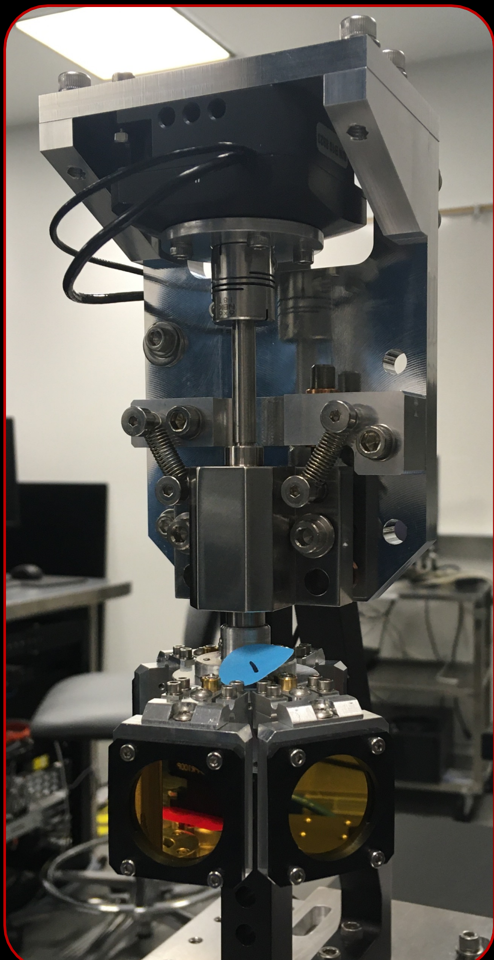
+LFC

FIU Phase II upgrades

Near final CAD of the phase II plate

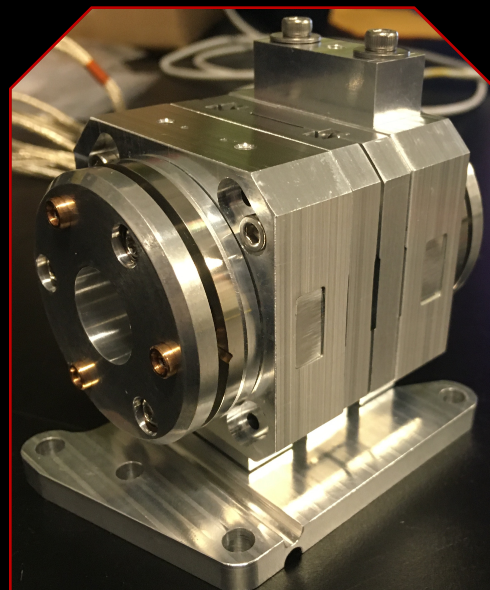


Images from integration

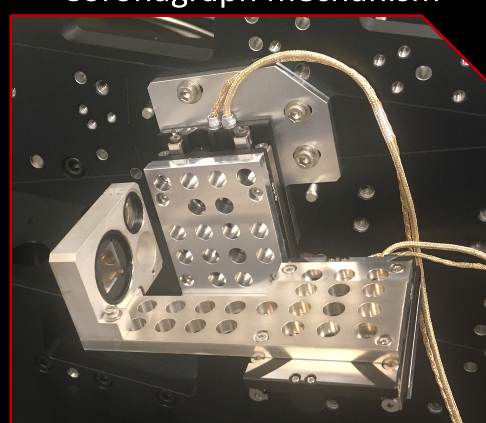


PyWFS pickoff mechanism

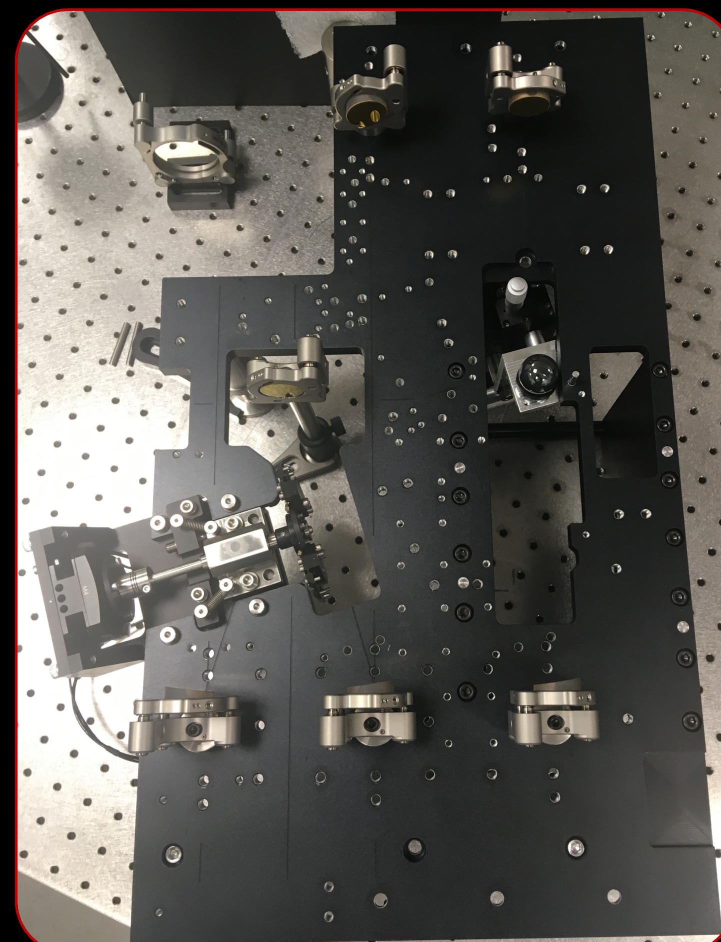
ADC mechanism



Coronagraph mechanism



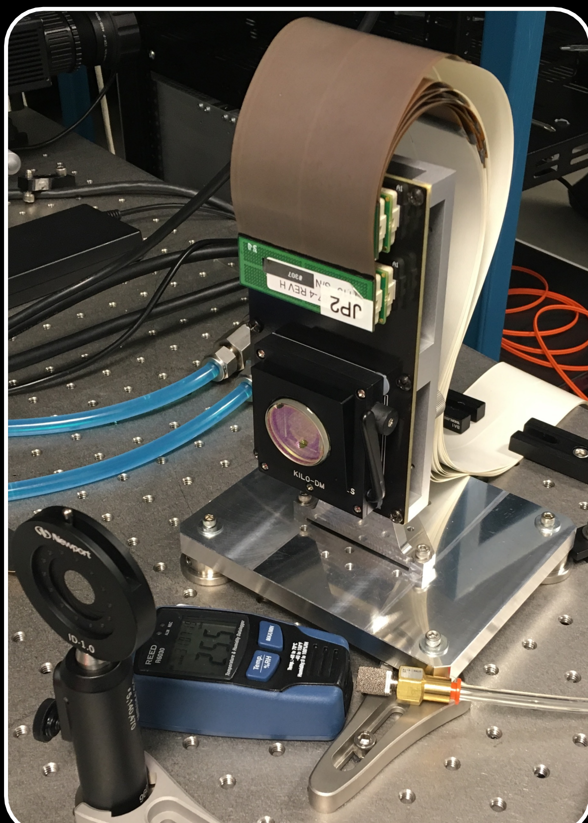
OAP alignment



High Order Deformable Mirror

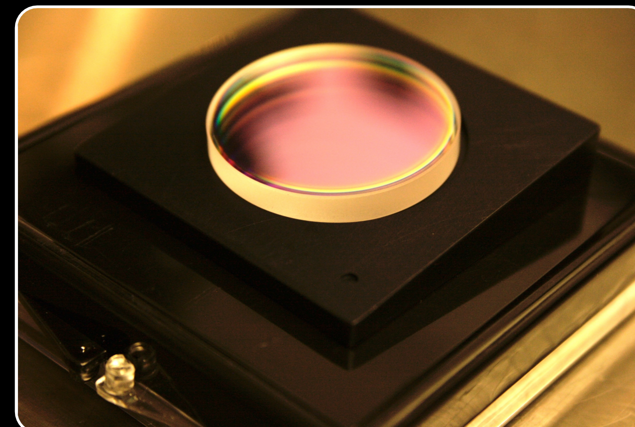
Purpose: ***enhanced wavefront control***

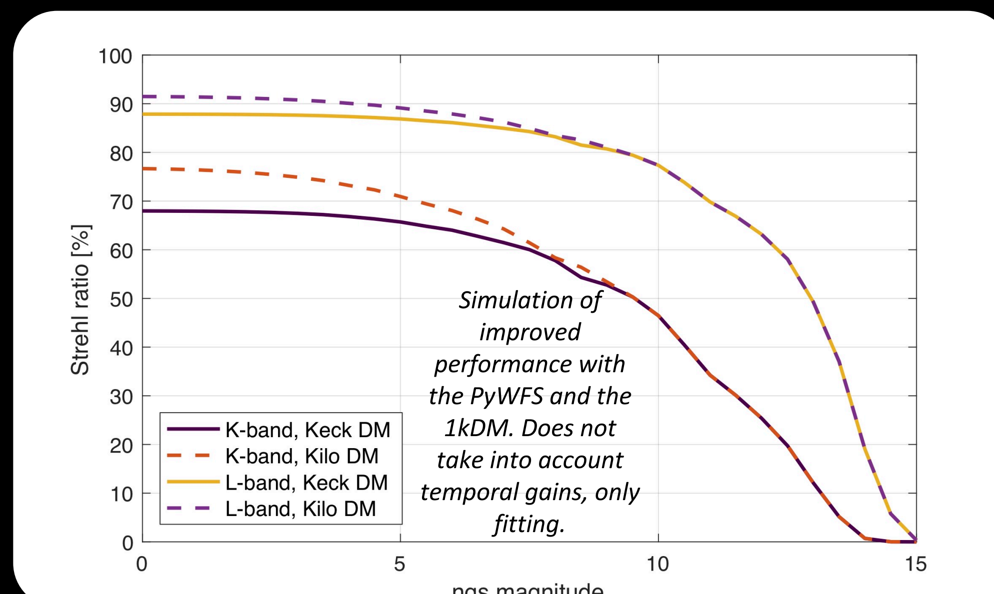
- **More actuators and faster response time for better PyWFS correction**
  &
- **For advanced focal plane wavefront control techniques**



Custom CaF2 Window

Throughput >97% H, K, L and M single pass

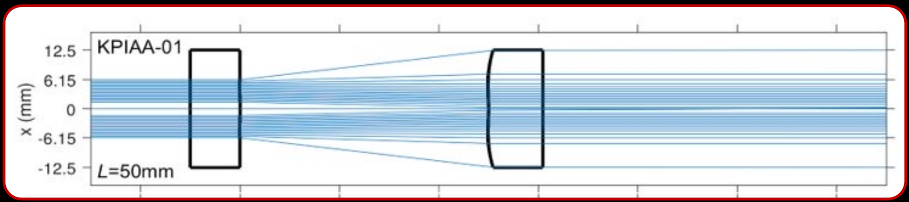




Phase Induced Amplitude Apodization

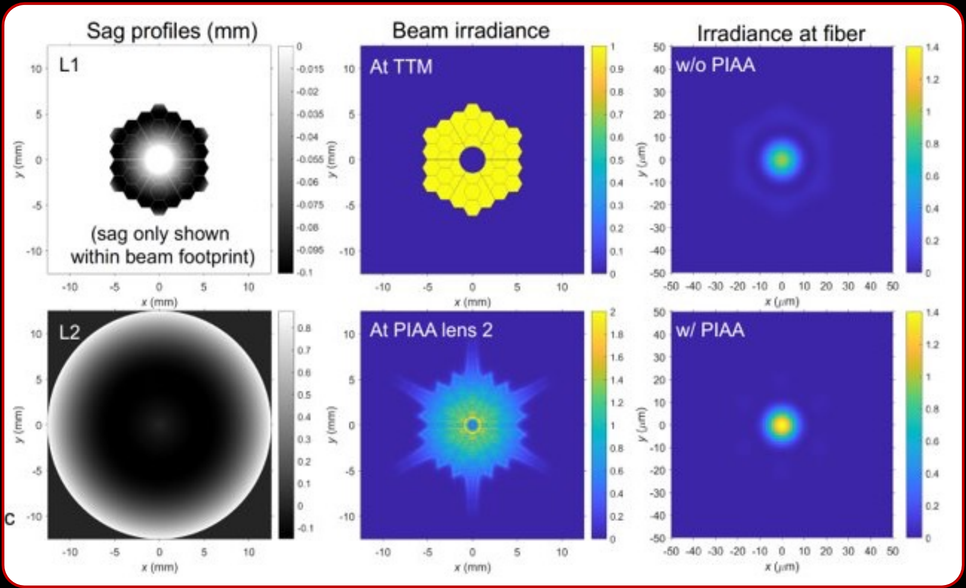
Key points: Improve the light injection into SM fiber

KPIC PIAA design



Design courtesy of Garreth Ruane

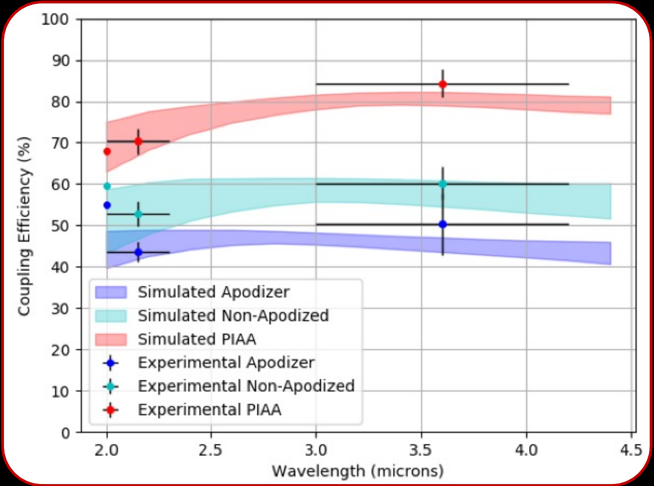
KPIC PIAA concept



On-sky demo conducted on SCExAO: Jovanovic et al, A&A, 2017

First Batch of KPIC PIAA Lenses

Measured injection gain



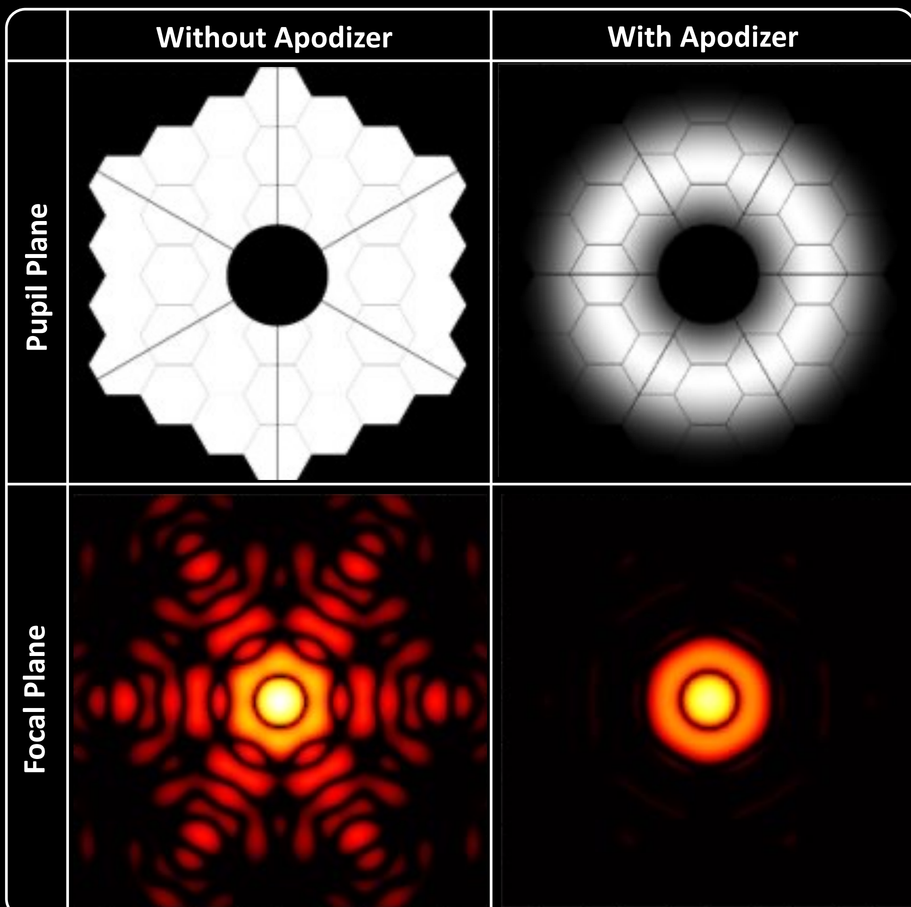
Lab results for KPIC optics: Calvin et al, PASP, 2021

Coronagraphs

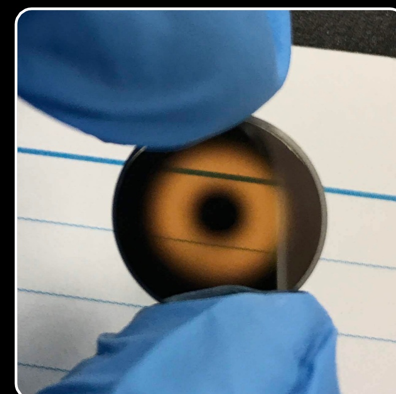
Key points:

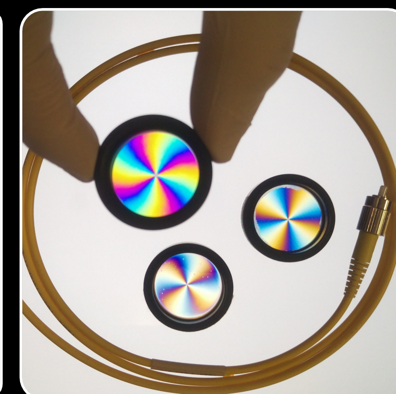
- Two types of coronagraphs: apodizer and a vortex in the vortex fiber nulling (VFN) mode.
- The apodizer will reduce leaked starlight into the fiber.
- The VFN will enable detection and spectroscopy of exo-planets at or within 1.5λ/D.

KPIC Apodizer Concept

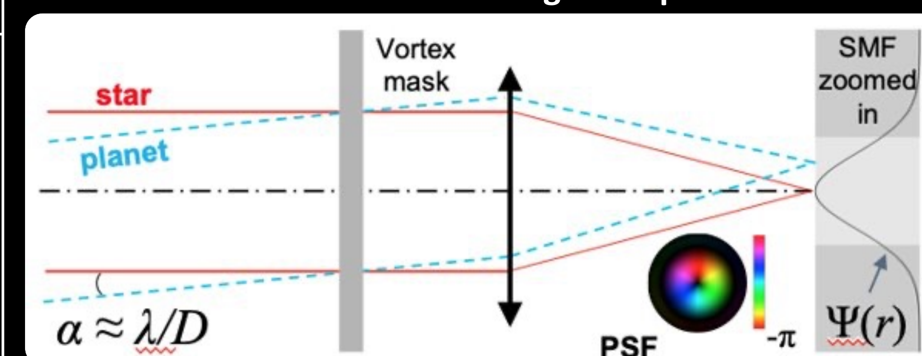


Apodizer and vortex currently tested at Caltech





Vortex fiber nulling concept

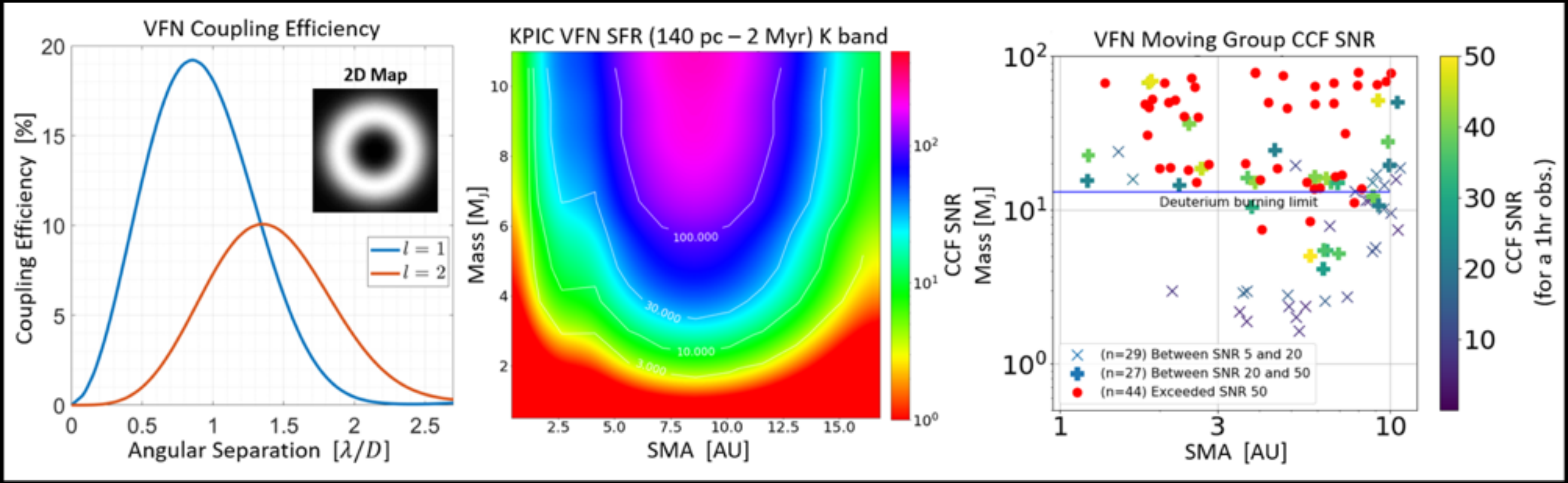


Ruane et al. ApJ 867 (2018) & Echeverri et al. Opt. Lett. 44 (2019)
Echeverri et al, SPIE, 11117-33 (2019)
& Ruane et al, SPIE, 11117-43 (2019)

Vortex Fiber Nulling

Key points:

- Planet throughput with charge 1 vortex mask can be as high as 20% at 0.8 lambda/D.
- 25% when combined with PIAA optics
- Assuming 1 mas tip/tilt residuals at Keck (3x improvement from the current performance), with a charge 1 vortex KPIC could directly characterize 20 previously uncharacterizable giant planets!!!

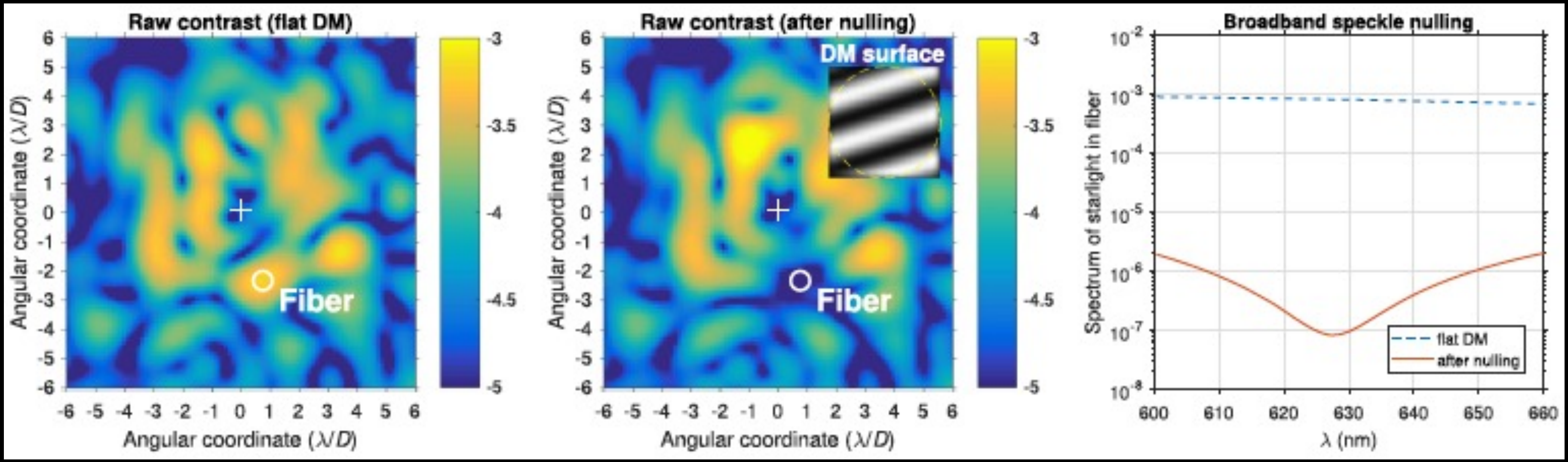


Echeverri et al in prep.

Advanced wavefront control

Key points:

- Predictive control on the PyWFS – this will bring large gains in performance (McEwen et al. AAS, 233 (2019)).
- Speckle nulling in the focal plane through the fiber (Sayson et al JATIS, 5, 2019) to further suppress the unwanted starlight. Reduction in speckle noise floor by a factor of 2-3 even with static NCPA compensation (Mawet et al. AJ, 838 (2017)).
- Kalman filtering to implement the focal plane wavefront control.

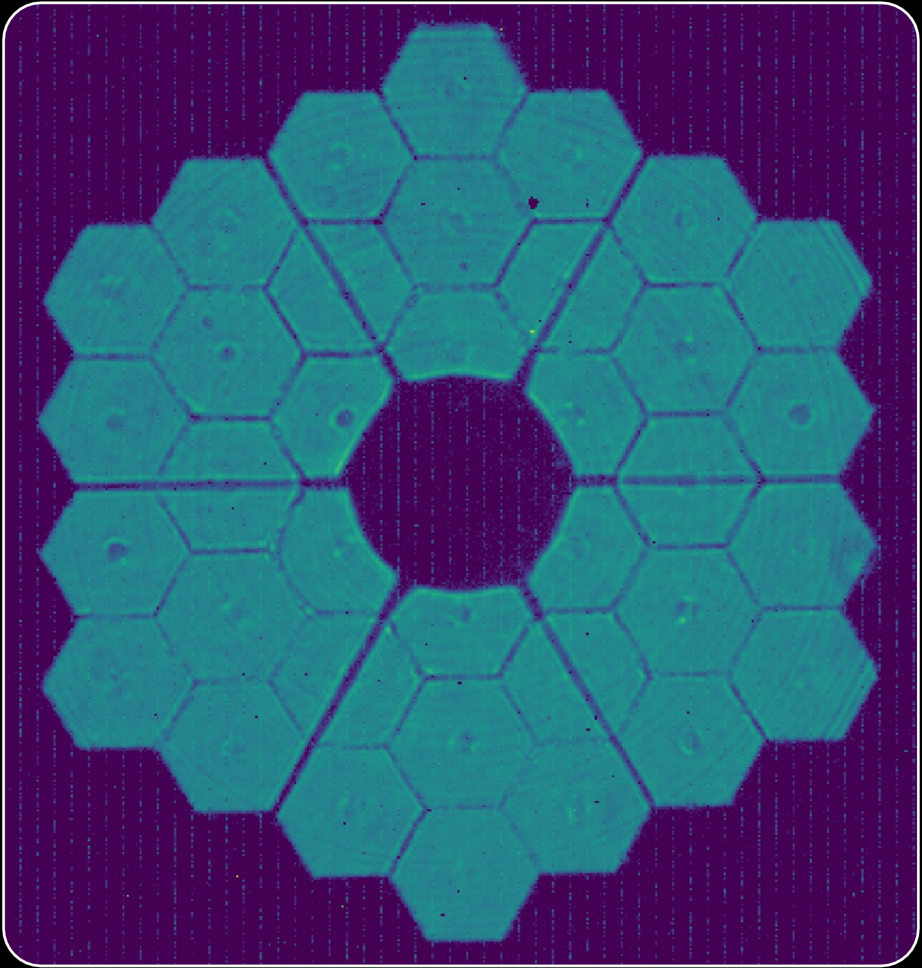


Mawet et al. AJ, 838 (2017)

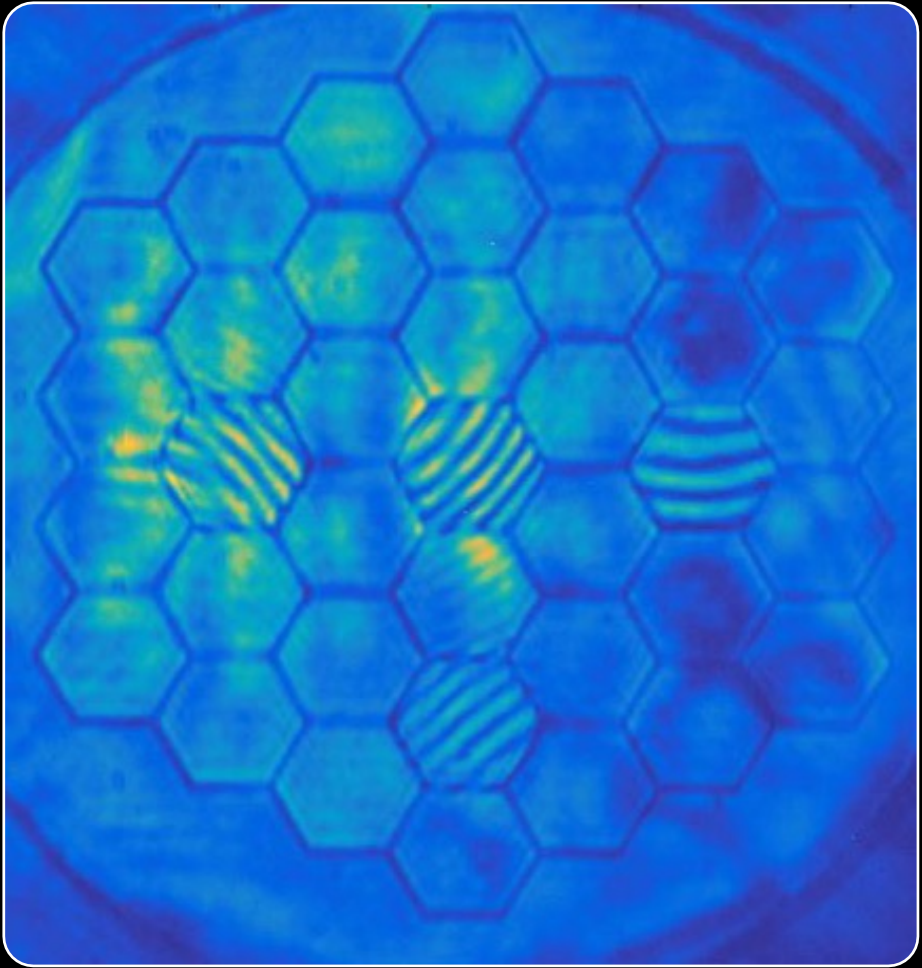
Zernike Wavefront Sensor

Key points: Measure primary mirror co-phasing error

Keck pupil image – w/o ZWFS – On sky data



Segmented DM – with ZWFS – Lab data

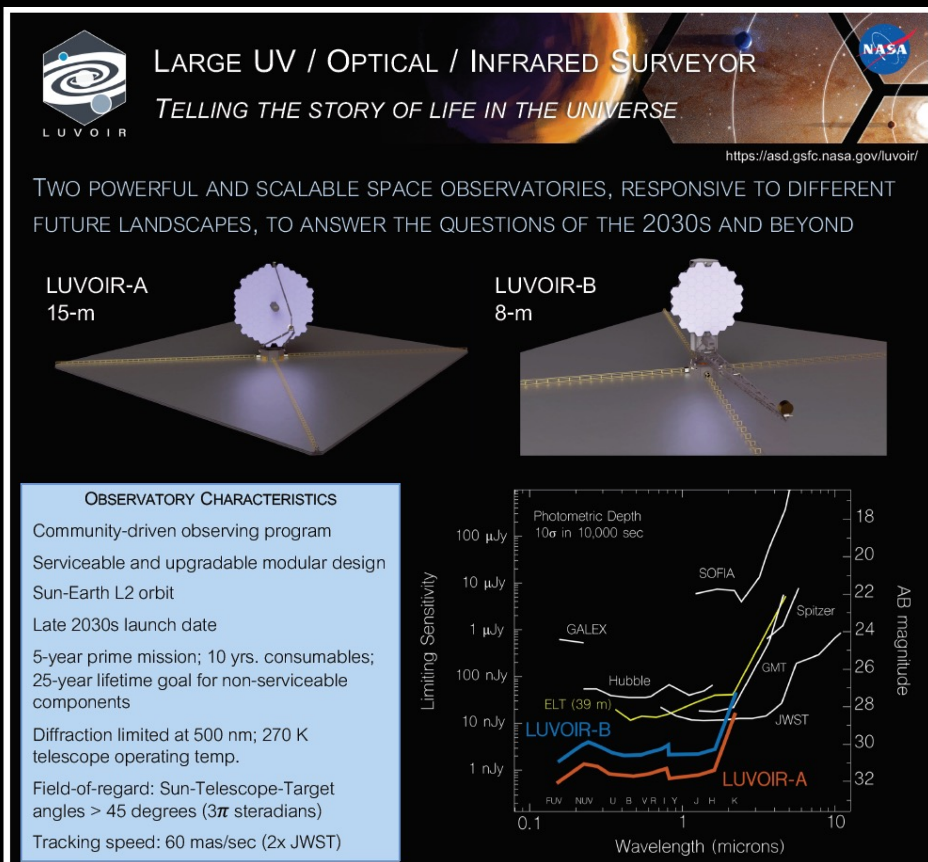


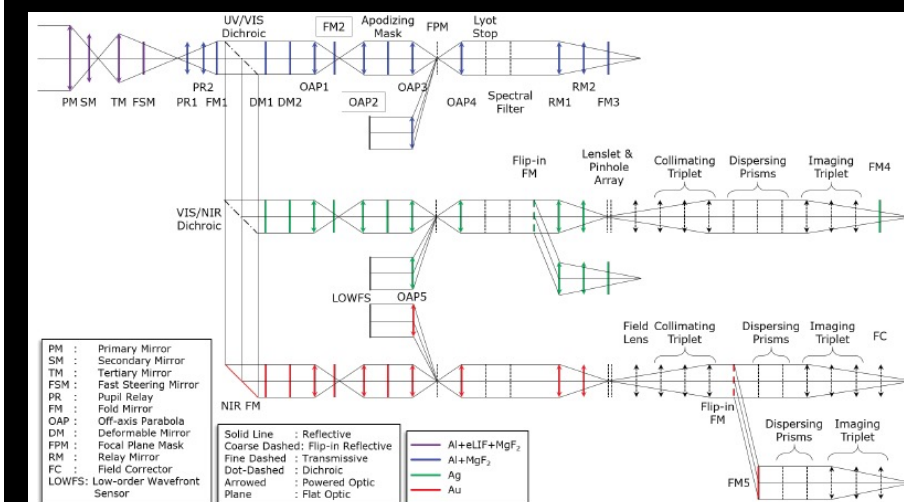
Looking to future missions

LUVOIR/HabEx

Key points:

- **LUVOIR and/or HabEx should include point spectrographs fed by SMFs to enable HDC**
- **This characterization tool nicely compliments the IFS detection tool.**



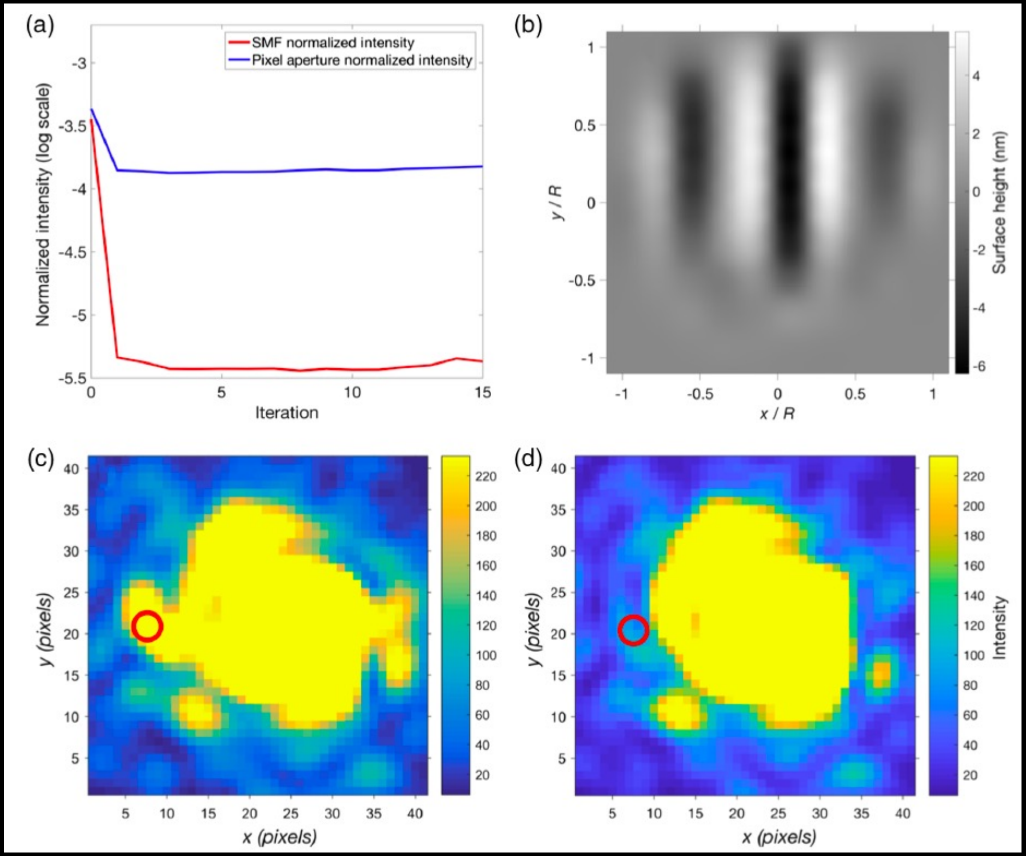


Credit: LUVOIR Final report, NASA

Pushing SMF WFC

Key points:

- **Pairwise probing/EFC through a SMF has been demonstrated in the lab – Caltech ETL**
- **With an unoptimized testbed and a vortex coronagraph, we've demonstrated >10^{-5}**

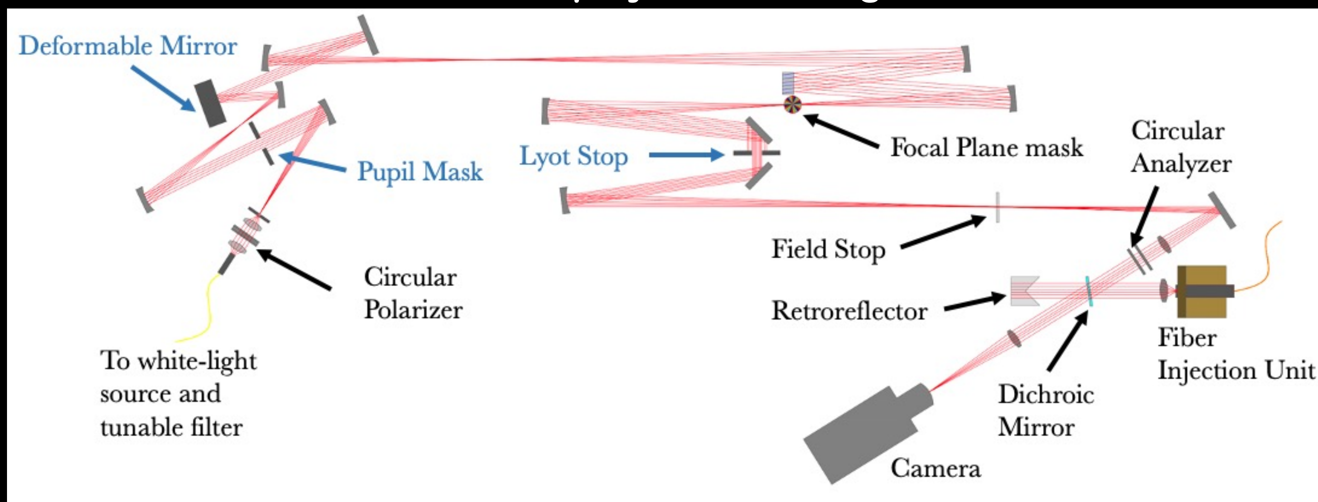


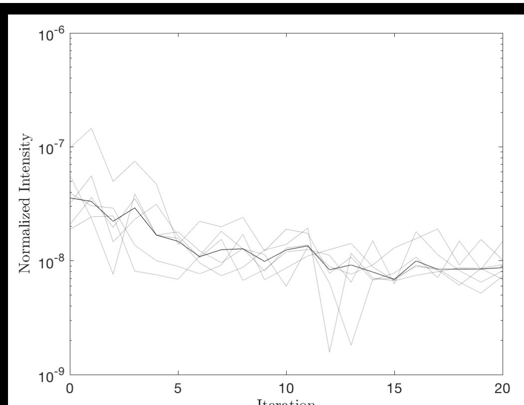
Llop-Sayson et al. JATIS, 2019

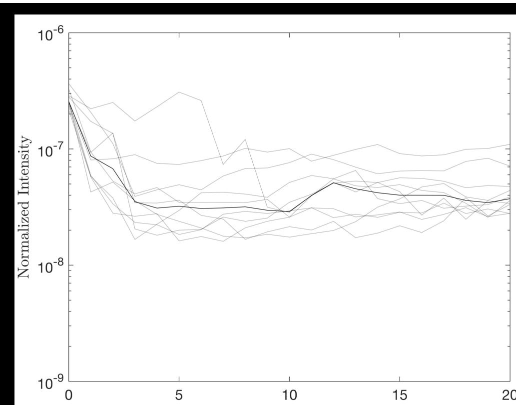
Pushing SMF WFC

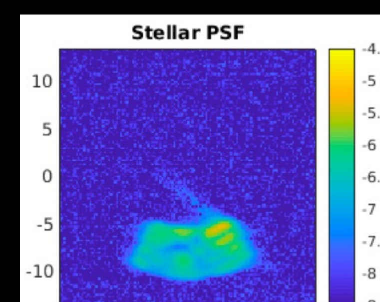
Key points:

- Pushed the contrast in a high-performance testbed – HCST – Caltech
- Funded through a NASA SAT TDEM
- First 2 milestones achieved
  - 10^{-8} contrast at 780 nm in 1% polychromatic light
  - 3×10^{-8} contrast at 780 nm in 20% polychromatic light



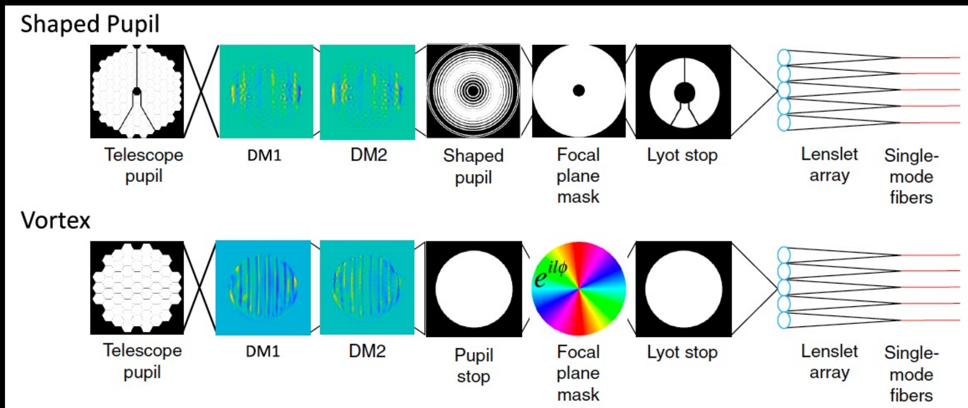


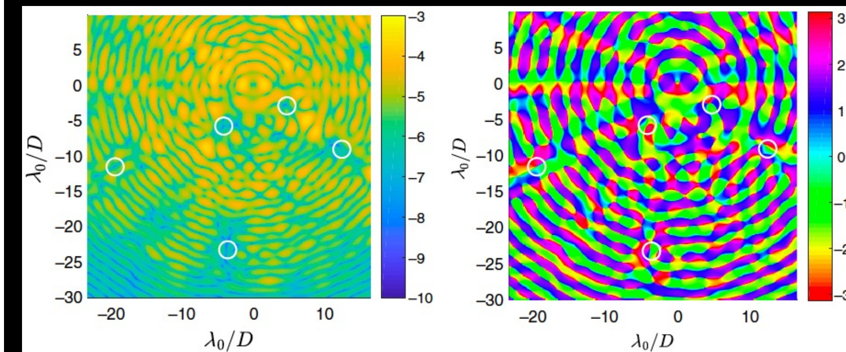


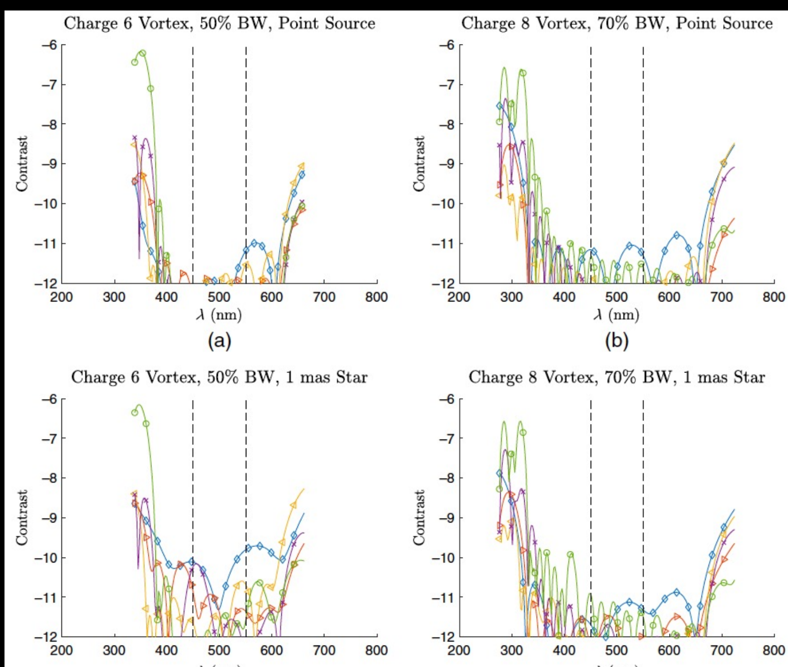


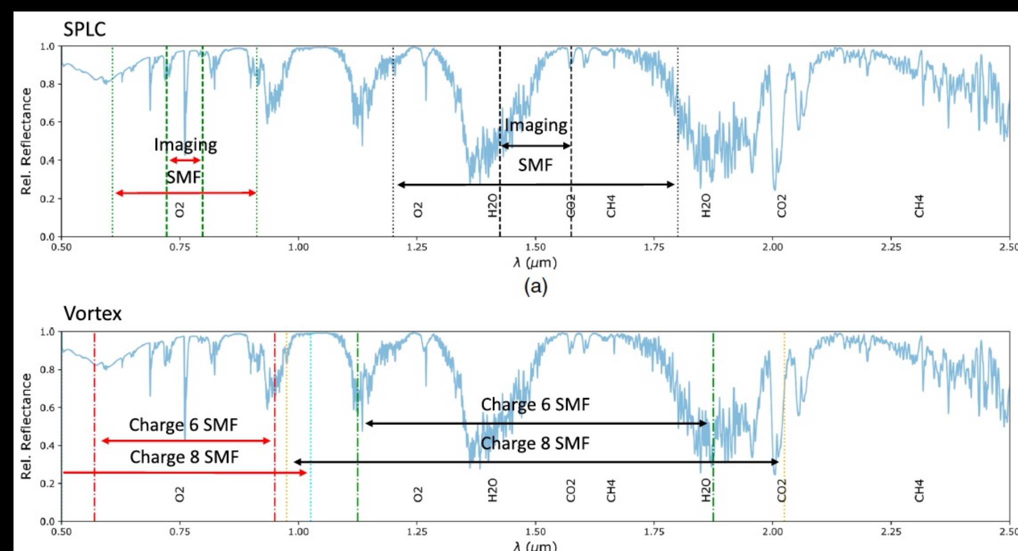
Llop-Sayson et al. paper coming

Pushing SMF WFC









Coker et al. JATIS, 2019

Questions?

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