Caltech's High Contrast High-Resolution Spectroscopy for Segmented telescopes Testbed (HCST)

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High contrast imaging on the ground

- Ground-based 8-meter class telescopes:
  - SPHERE & GPI large surveys halfway through (current yield on the low side)
  - SCExAO reaching science operations
  - P3K/P1640 nearing end of life (Gene Serabyn's SDC still in operations)
  - LBTAO returning great image quality, struggling with DSM/weather issues
  - MagAO king in visAO Hα niche
  - First-generation facilities winding down with a few exceptions (L-band niche at Keck-NIRC2, VLT-NACO, LMIRCAM at LBT, all equipped with state-of-the-art vortex coronagraphs)

- Extremely Large Telescopes under construction (sort of):
  - First generation instrument unlikely to be optimized high contrast imagers (some interesting capabilities with TMT-IRIS and ELT-METIS though).
  - **R&D for second-generation planet finder starting now**

High contrast imaging in space

- HST now: archival data and disks, not very competitive for planets (mostly due to limited telescope time access)

- JWST 2018: great for transit spectroscopy. Inner working angle will be >0”.5 (NIRCAM & MIRI)

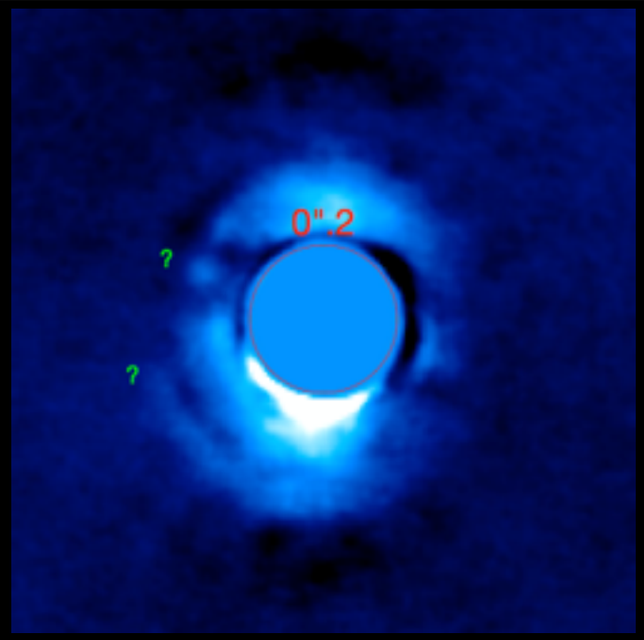
- WFIRST 2025: excellent contrast, very low throughput, yield and spectroscopic capabilities will be modest (tech demo)

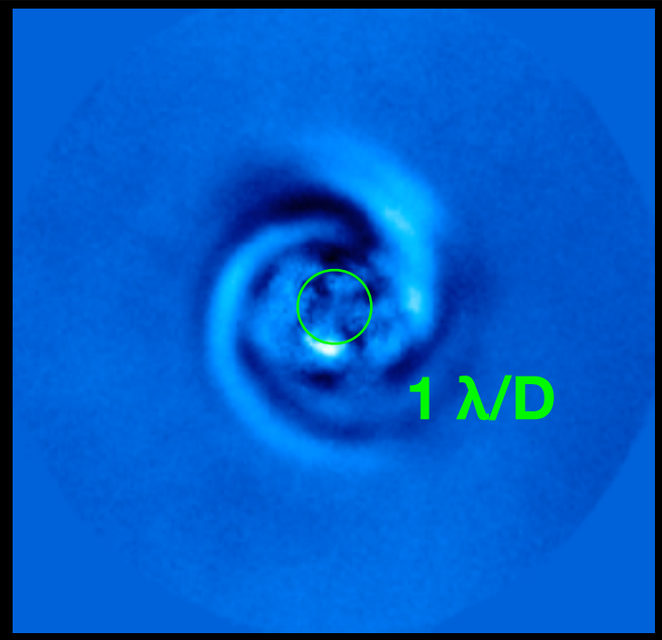
- LUVOIR/HDST/HabEx 2035: currently being defined, opportunity for synergistic developments (this meeting is a good start!)

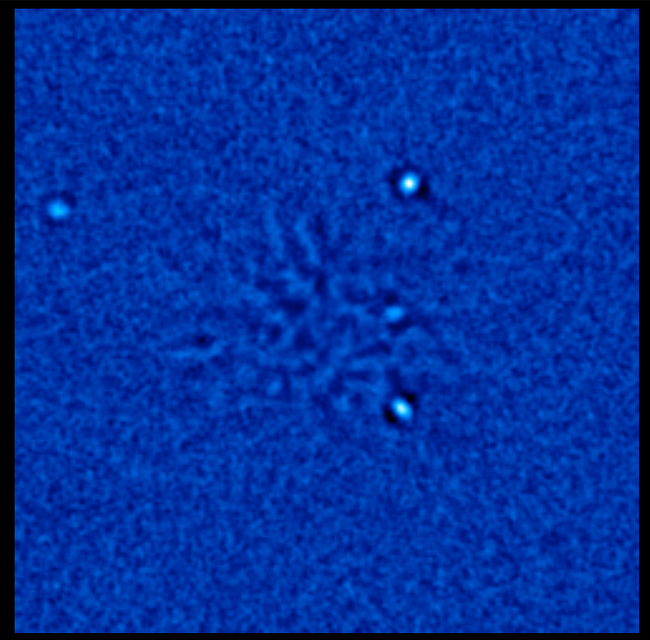
Most future telescopes will be large and segmented (HabEx?)

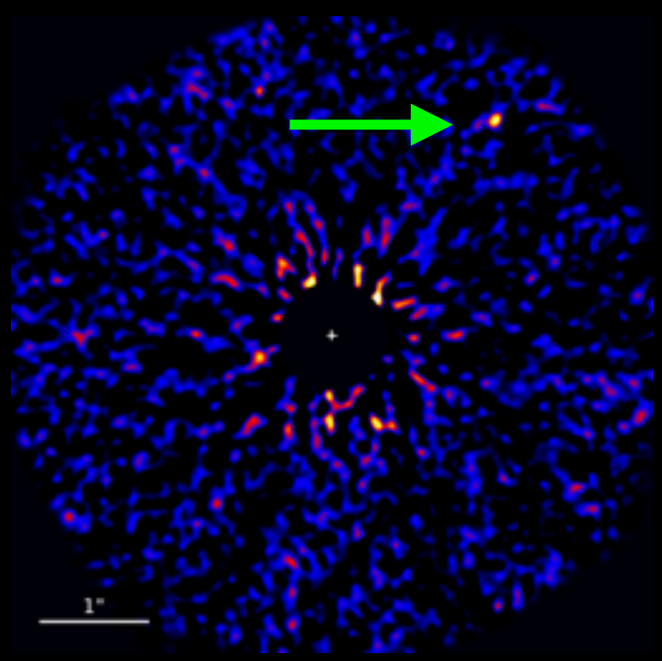
- Need to develop coronagraph and wavefront technologies for large segmented telescopes
- Many theoretical designs exist (APLC, PIAACMC, RAVC, etc.)
- Very few lab demonstrations of these concepts so far (none?)
- # HCI facilities in the US dedicated segmented telescopes: 2
  - **HiCAT at STScI**, focussing on space-based projects
  - **Keck telescope !!!**

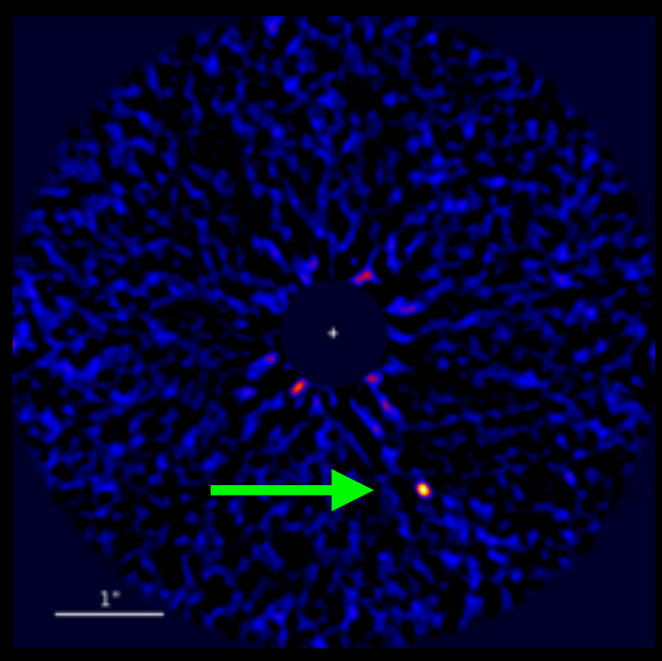
Coronagraphy on segmented telescope now:
Keck NIRC2 L-band vortex

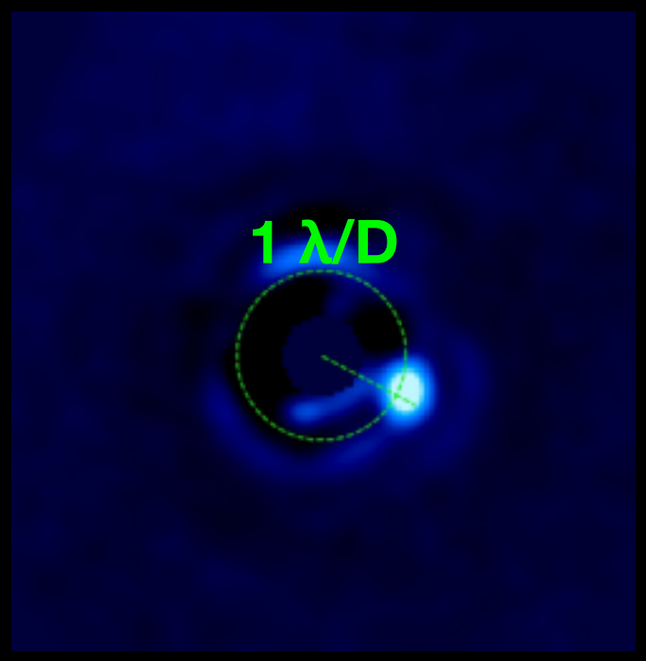












Absil, Bottom, Campbell, Carlogmano, Choquet, Delacroix, Femenia, Gomez, Huby, Jolivet, Karlsson, Matthews, Mawet, Reggiani, Serabyn, Wertz, Wizinowich

Large telescopes enable high resolution spectroscopy

- Interesting concepts merging HCI and HRS have been proposed (Snellen et al. 2015)

- And demonstrated!

- *The future of high contrast imaging of planets is high contrast high resolution spectroscopy*

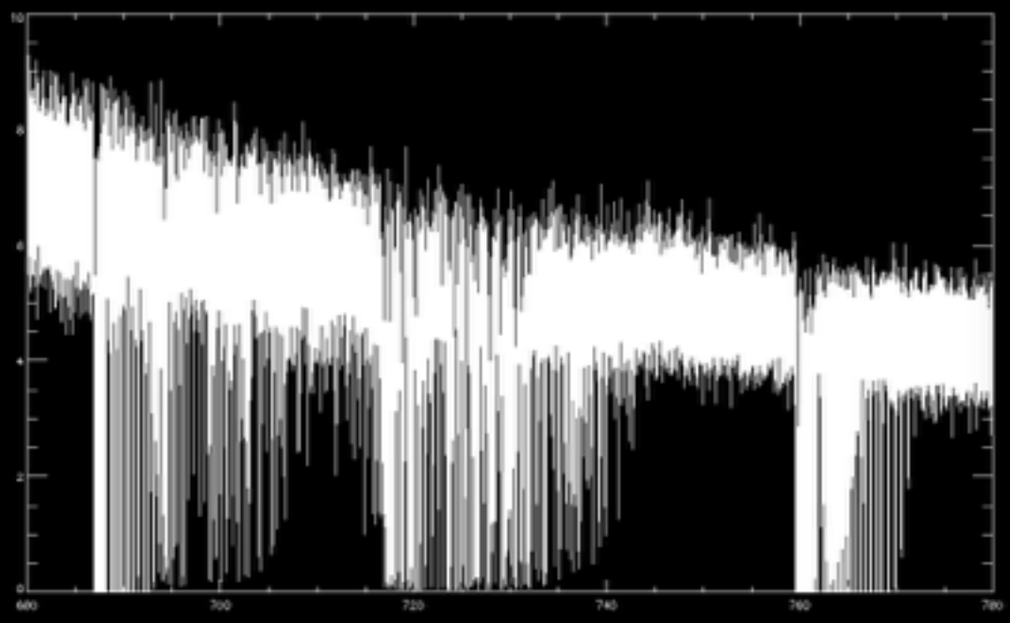
YES there are enough photons!

- Not trying to measure/trace individual lines.
- The line profile, or cross-correlation peak combines the information of 1000s of molecular lines theoretically resolved at high spectral resolution
- (think about how RV gets to <1m/s, with 1-10km/s resolution per line)

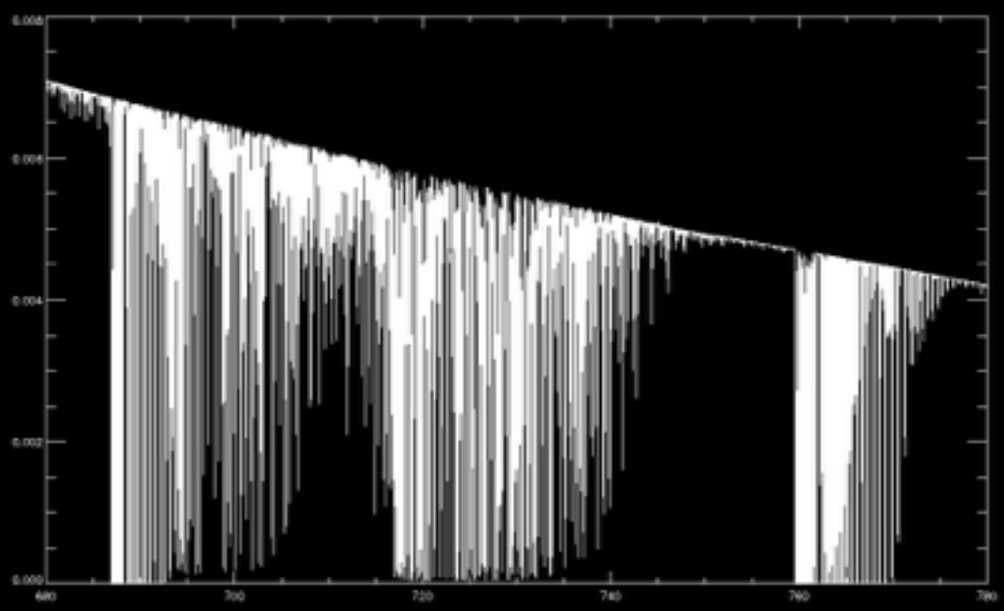
$$SNR_{per\ ch,lowres} = \frac{\eta S_{planet}}{\sqrt{S_{star} + Speck\ noise + det/bg\ noise}}$$

$$SNR_{line\ prof,highres} = \frac{\eta S_{planet}}{\sqrt{S_{star} + det/bg\ noise}} \sqrt{N_{lines}}$$

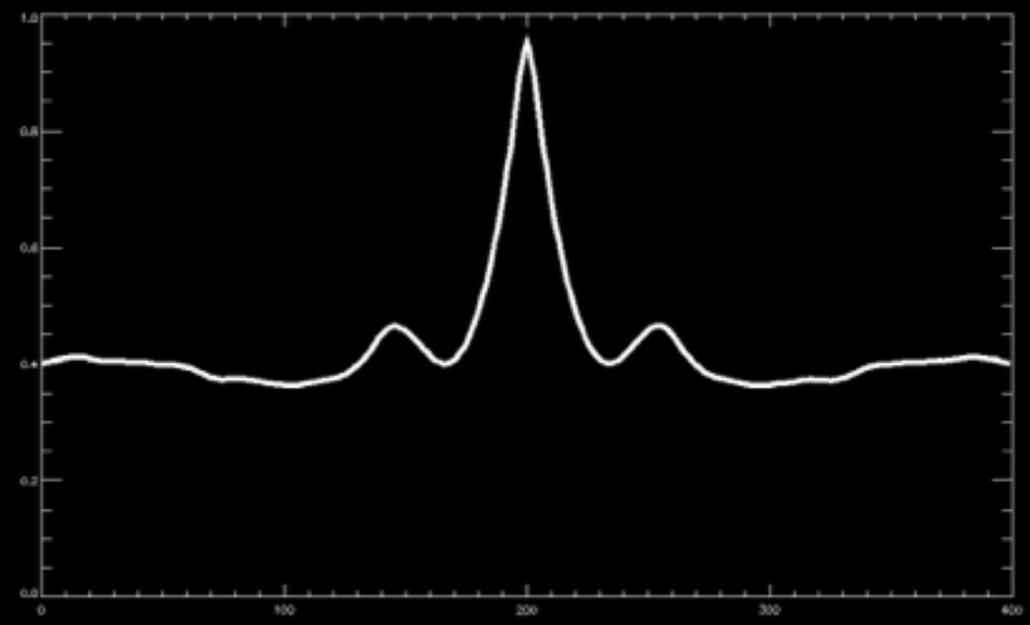
speckle noise mostly irrelevant,
part of the continuum



noisy highres data



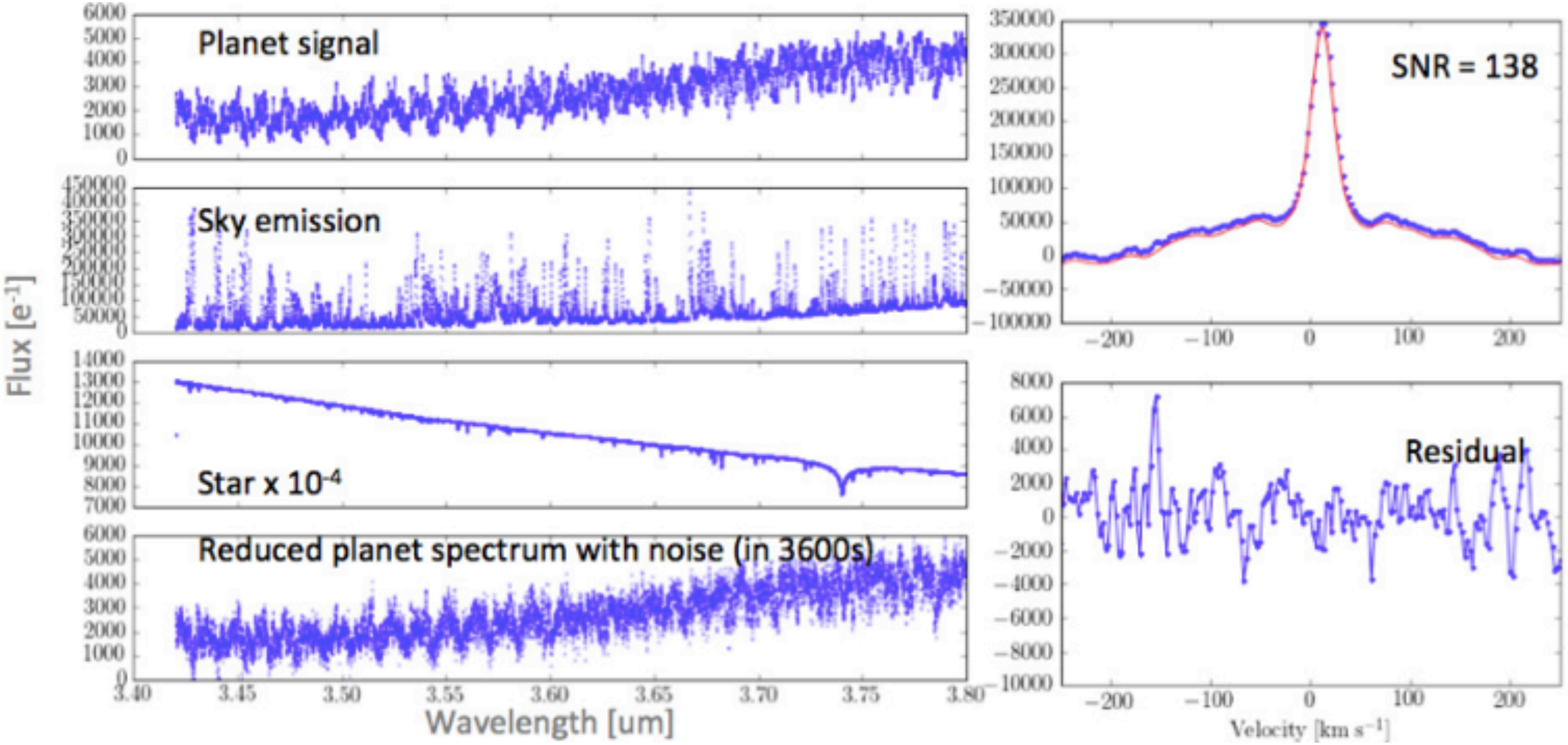
highres noiseless
theoretical template



cross-correlation peak

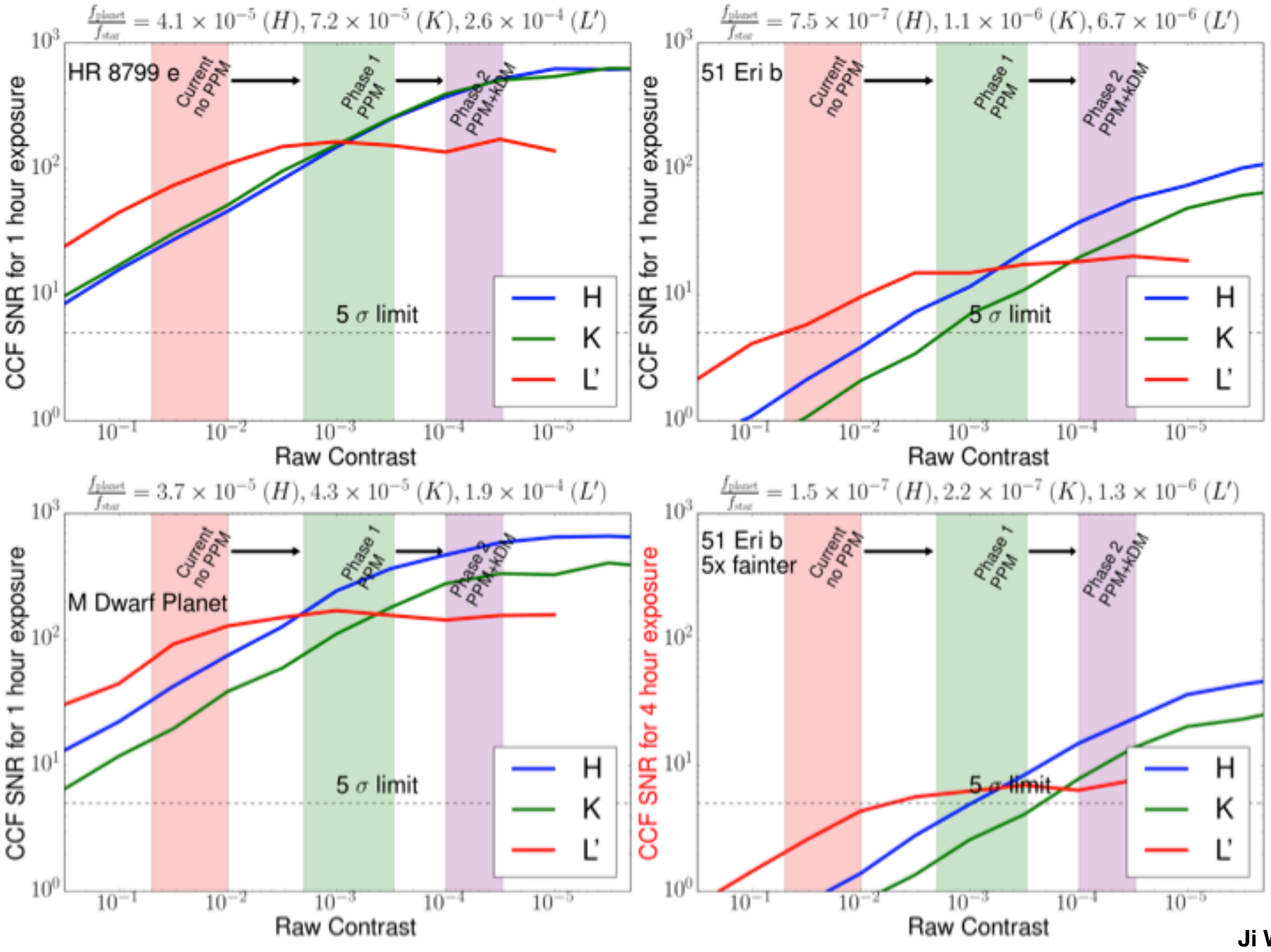
Renyu Hu (JPL)

Cross correlation signal extraction from noisy data



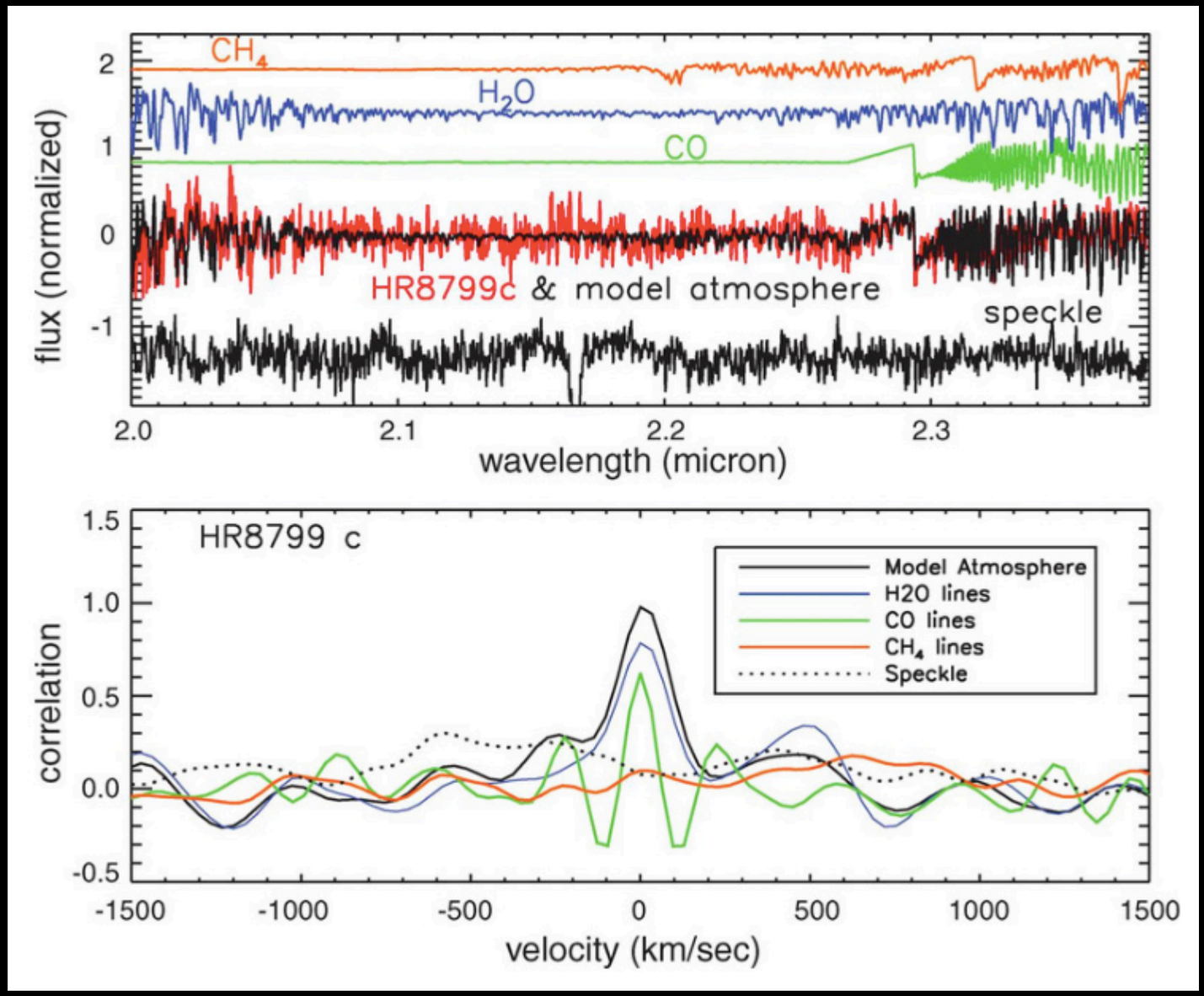
Ji Wang (Caltech)

Science and technology demonstrator at Keck



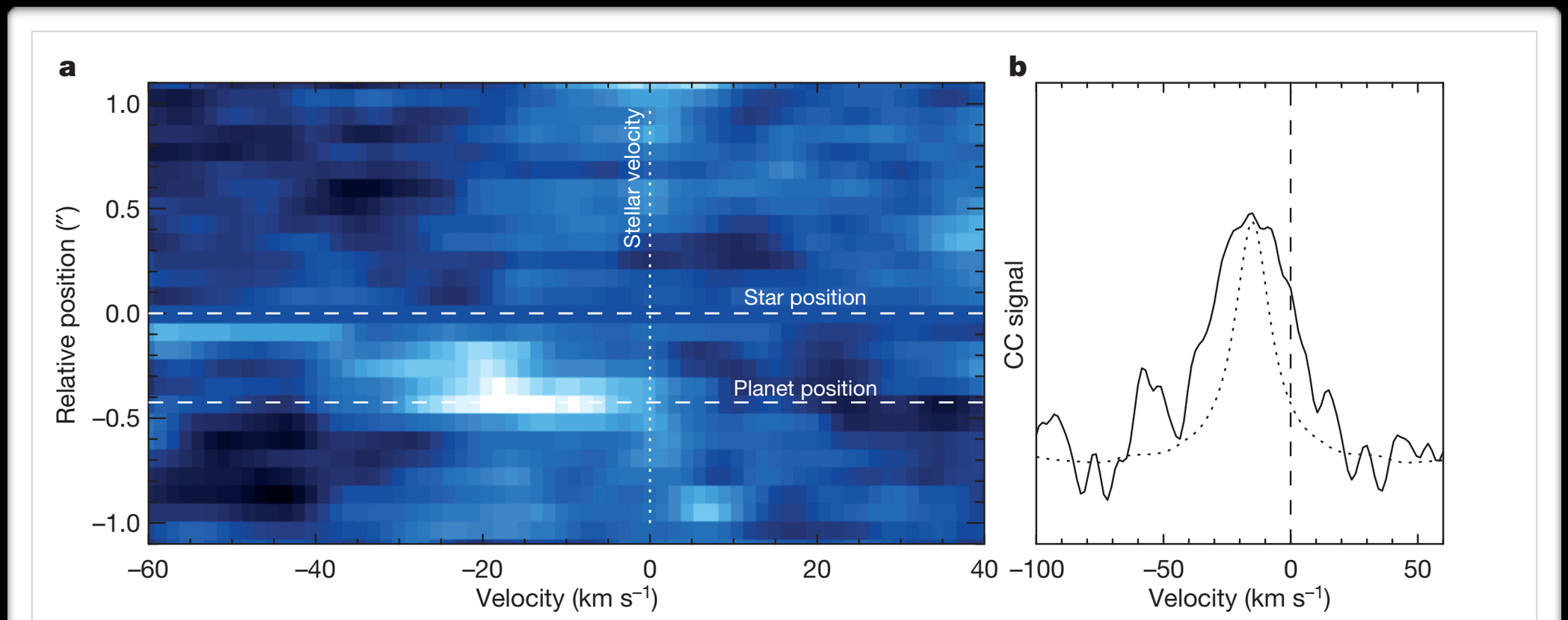
Ji Wang (Caltech)

Cross-correlate with spectral templates of molecular species



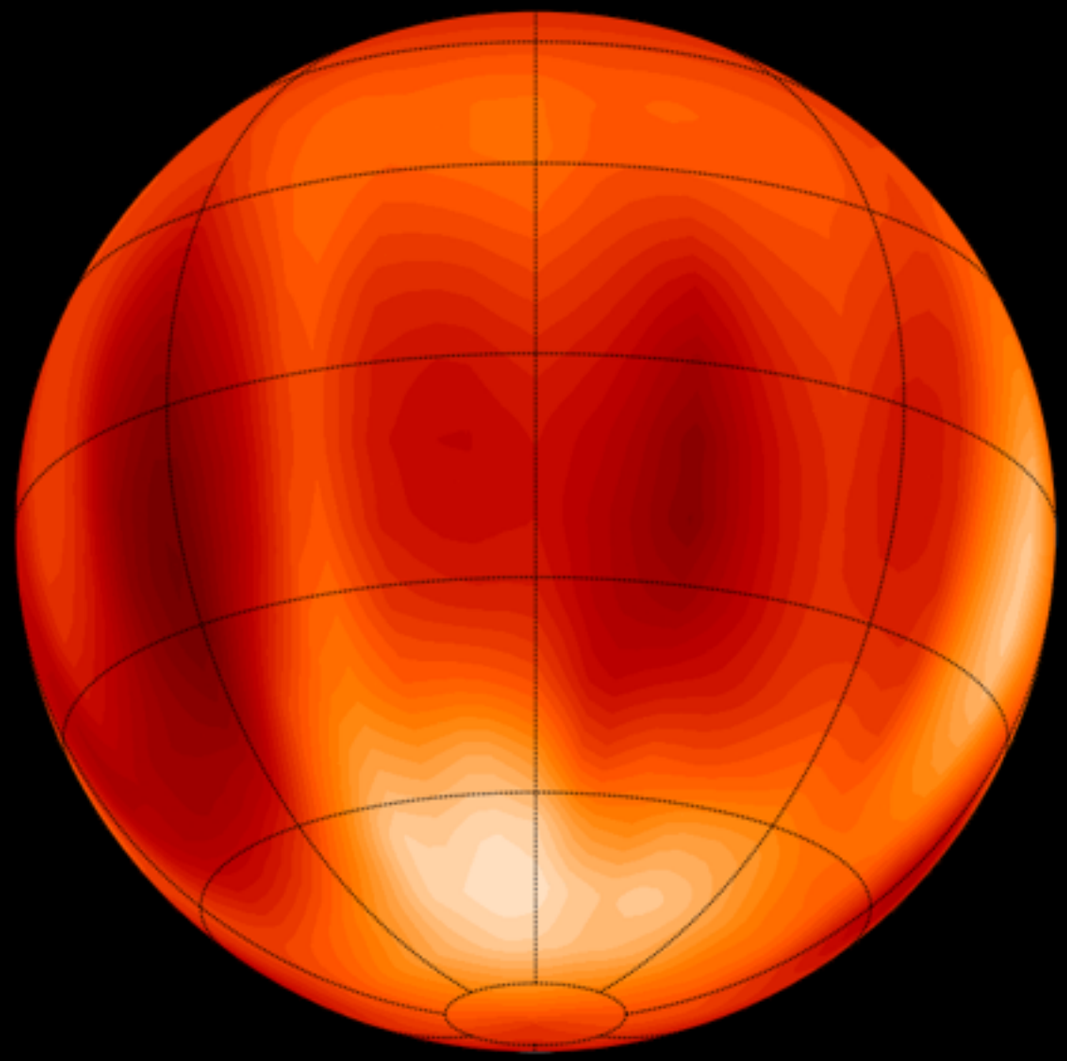
Konopacky et al. 2013

Measure planet spin



Snellen et al. 2014

Doppler imaging => maps



Luhman 16
(Crossfield et al. 2014)

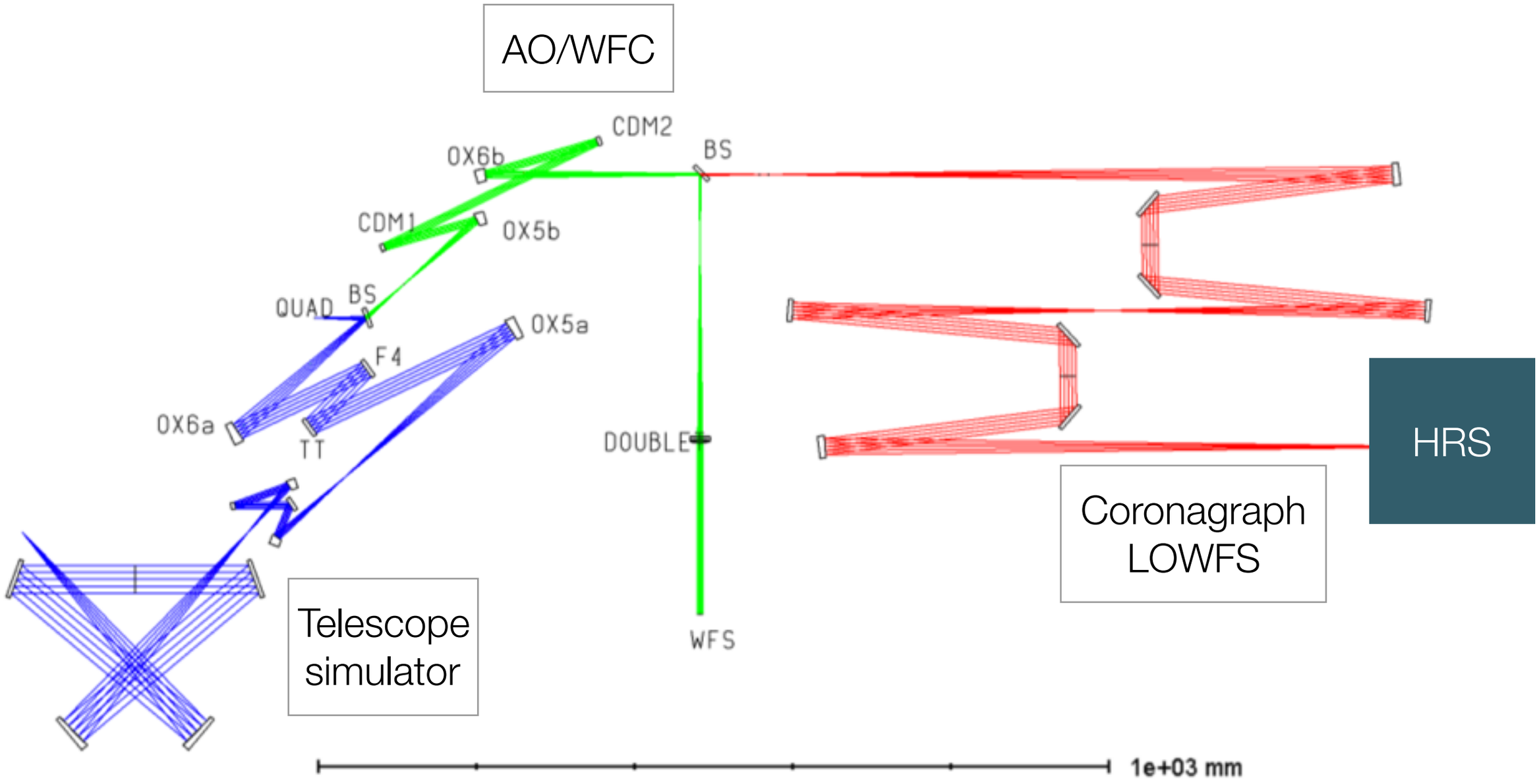
Caltech HCST goals

- Simulate realistic segmented apertures:
  - Keck
  - TMT
  - **LUVOIR/HDST (HabEx?)**
- (Simulate atmospheric turbulence)
- Includes adaptive optics/wavefront controller, with a dynamic wavefront sensor and options for amplitude control (2DM EFC, ACAD, etc)
- Includes classical 3-plane single stage coronagraph (apodizer, focal-plane mask, Lyot stop)
- Includes a back-end instrument
- Goal: high-res fiber-fed diffraction limited low-noise spectrograph

Top-level requirements

- Realistic telescope simulator
  - match F number of Keck & TMT first
  - simulate segment cophasing errors
- Wavelength range: 0.6 to 1.8 microns
- Keck / TMT: WFS at Y or J, Science at H / K
- Space-based telescope: 0.6 to 1 microns
- IWA ~ 1-2 λ/D, OWA ~ 15 λ/D (superNyquist possible)
- Accommodate various transmissive coronagraph designs
- Minimize Talbot effects (design philosophy similar to HiCAT)
- Contrast goals (average over dark hole):
  - Raw, phase control only (static, no turbulence): 1e-5
  - Raw, phase & amplitude (static, no turbulence): 1e-7
  - After HRS: 1e-8, actual limits to be explored
- Inject starlight and faint planet light (with distinct spectral signature) => unique feature

Latest HCST design

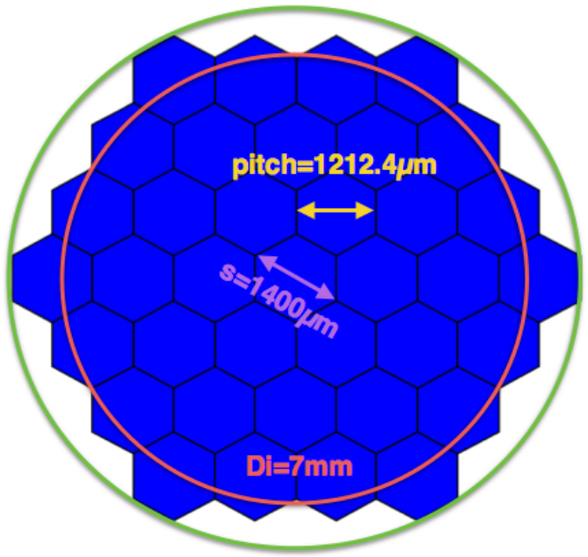


J. Fucik (Caltech) / J.K. Wallace (JPL)
Many thanks to HiCAT team (E. Choquet, M. N'Diaye, R. Soummer

Telescope simulator based on IRIS AO segmented DM

37 Segments (Keck)

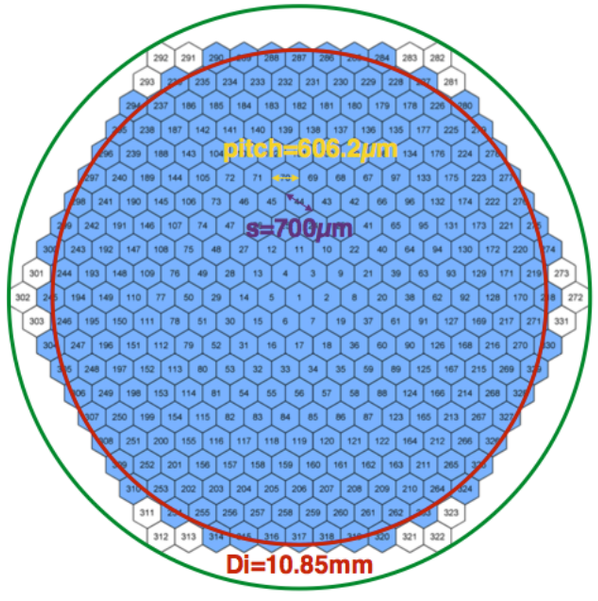
PTT111-L



Circumscribed Diameter Dc =8.51mm
Inscribed Diameter: Di=7mm
Segment size (flat-to-flat): pitch=1212.4μm
Segment size (vertex-to-vertex): s=1400μm

313 Segments (TMT)

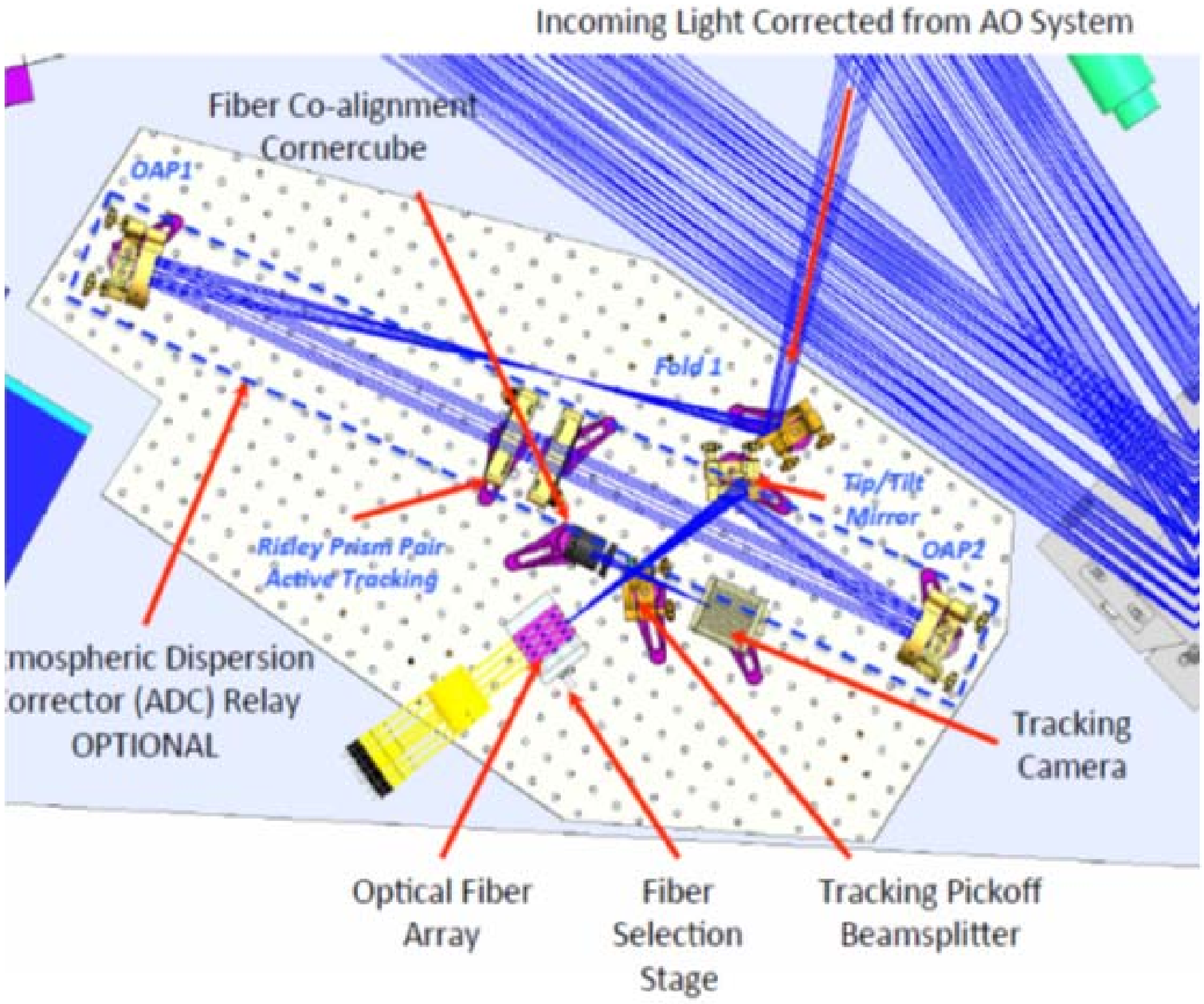
PTT939



Circumscribed Diameter Dc =11.18mm
Inscribed Diameter: Di=10.85mm
Segment size (flat-to-flat): pitch=606.2μm
Segment size (vertex-to-vertex): s=700μm

NOTE: Latest TMT primary mirror design has 492 segments

Coupling AO / coronagraph to IR HRS



Keck AO to NIRSPEC Fiber Injection Unit concept

J.K. Wallace (JPL)

HCST status

- Big items acquired:
  - 1 BMC 32x32 MEMS DM (2nd DM pending funding)
  - Supercontinuum source + fibers
  - HASO WFS
  - IR and visible cameras
- All optics specified, *purchase request is out*
- Wish list: OCAM2K, CRed-one (First light imaging), second BMC DM
- Dream list: Large format IR-APD arrays (2Kx2K), two 2K BMC DMs

Short term goals & priorities

- Support to privately funded Keck fiber injection unit (FIU) project: link from Keck AO to NIRSPEC to do high-resolution spectroscopy of known young giant planets

- Support for Keck FIU coronagraph APRA proposal:
  - Several phenomenon not scalable wrt wavelength cannot be reproduced in the lab (segment gaps) and needs the real full scale demonstration => Keck

- Support demonstration of coronagraph concepts for future segmented telescopes: TMT, LUVOIR/HDST, HabEx