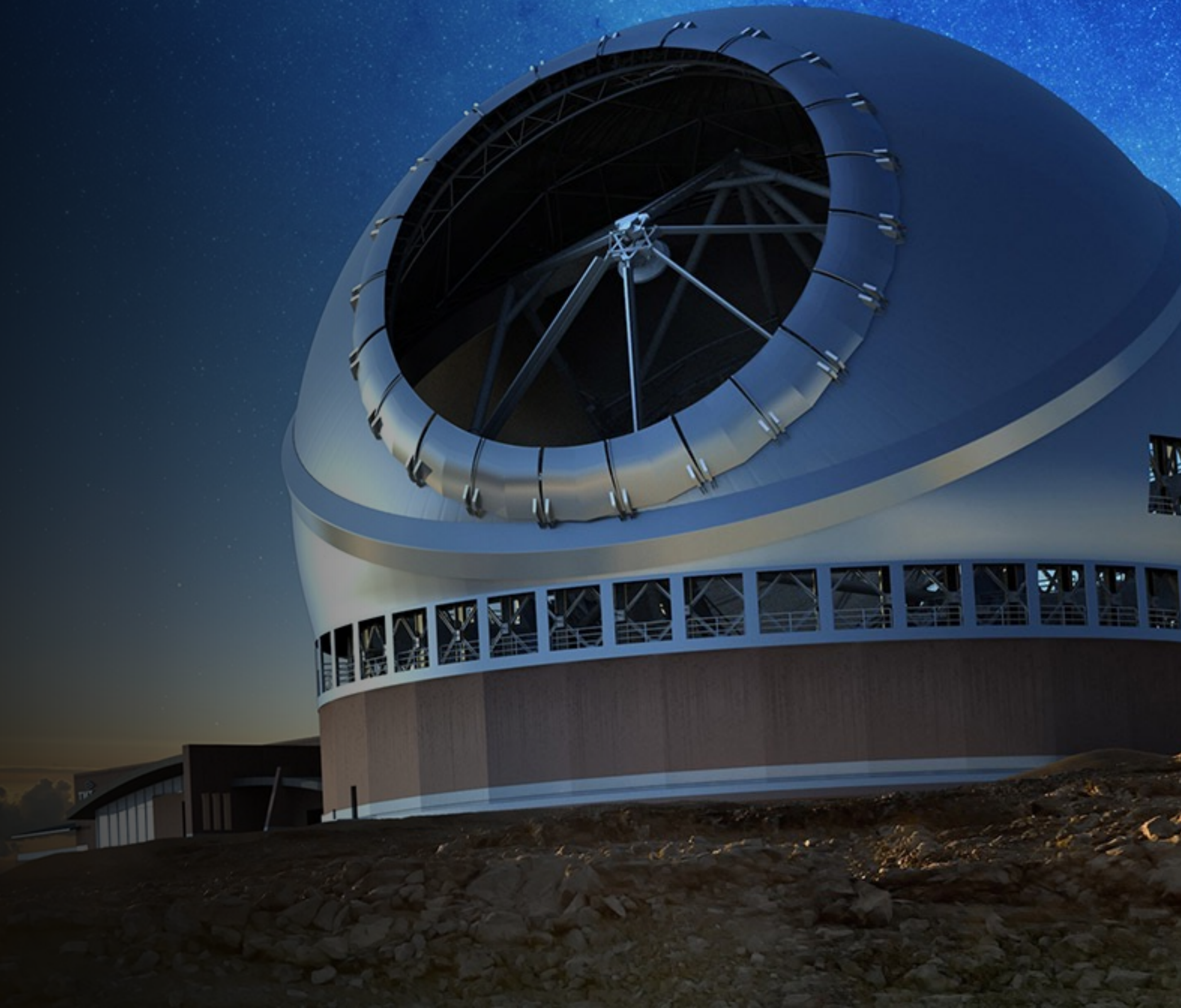
Multi-Objective Diffraction-limited High-resolution Infrared Spectrograph



Dimitri Mawet (CIT, PI), Michael Fitzgerald (UCLA, co-PI), Quinn Konopacky (UCSD, PS), Larry Lingvay (CIT, PM), Hiroshi Terada (TMT, PM), Dave Andersen (TMT, IPM), on behalf of the MODHIS team

TMT Webinar, 27 April 2023

MODHIS team

Etienne Artigau, U de Montreal (EPRV, TS)
Ravinder Banyal, IIA (EPRV)
Thomas Beatty, U of Arizona (Lead TS, DI)
Chas Beichman, Caltech/JPL (SSA)
Björn Benneke, U de Montreal (Canada PS, Lead DI)
Geoff Blake, Caltech (SF)
Adam Burgasser, UCSD (EPRV, TS, SA)
Gabriella Canalizo, UCR (BH)
Guo Chen, Purple Mountain Obs. (TS, DI)
Tuan Do, UCLA (BH, SA)
Greg Doppmann, Keck Obs. (SF)
Rene Doyon, U de Montreal (Canada PI)
Courtney Dressing, UCB (EPRV, TS)
Min Fang, Xiamen U. (SF)
Mike Fitzgerald, UCLA (Co-PI)
Tom Greene, NASA Ames (SF, TS)
Greg Herczeg, KIAA Peking (DI, SF)
Lynne Hillenbrand, Caltech (SF, TS)
Andrew Howard, Caltech (EPRV)
Nem Jovanovic, Caltech (Tech Lead)
Stephen Kane, UCR (DI, EPRV, TS)
Tiffany Kataria, JPL (TS)
Eliza Kempton, U of Maryland (TS)
Heather Knutson, Caltech (DI, TS)
Quinn Konopacky, UCSD (PS)
Takayuki Kotani, ABC-NINS (EPRV)
David Lafrenière, U de Montreal (Lead TS, DI)
Chao Liu, NAOC (SA)
Dimitri Mawet, Caltech (PI)
Stan Metchev, Western U. (DI, SA)
Max Millar-Blanchaer, UCSB (DI, SA)
Norio Narita, NAOJ (EPRV, TS)
Shogo Nishiyama, Miyagi Education U. (BH, SA)
Gajendra Pandey, IIA (SA)
Peter Plavchan, George Mason U (Lead EPRV)
S.P. Ragajuru, IIA (SA, TS)
Paul Robertson, UCI (EPRV, SA)
Colette Salyk, Vassar (SF)
Bunei Sato, Tokyo Institute of Tech. (EPRV)
Everett Schlawin, U of Arizona (TS)
Sujan Sengupta, IIA (SA, TS)
Thirupathi Sivarani, IIA (SA)
Warren Skidmore, TMT
Motohide Tamura, NAOJ (Lead Japan, Lead EPRV)
Hiroshi Terada, TMT-J (TMT PM, SF)
Gautam Vasisht, JPL (DI, EPRV)
Ji Wang, Ohio State U (Lead DI, TS)
Chikako Yasui, TMT (SA, SF)
Hui Zhang, Nanjing U (EPRV, TS)

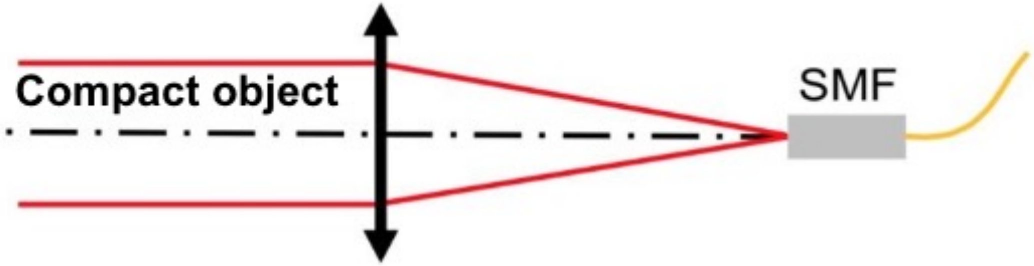
Key: **BH** = Black Holes; **DI** = Direct Imaging; **EPRV** = Extreme Precision Radial Velocities; **PI** = Principle Investigator; **PM** = Project Manager; **PS** = Project Scientist; **SA** = Stellar Astrophysics; **SF** = Star/Planet Formation; **TS** = Transit Spectroscopy; **SSA** = Senior Science Advisor

TMT MODHIS

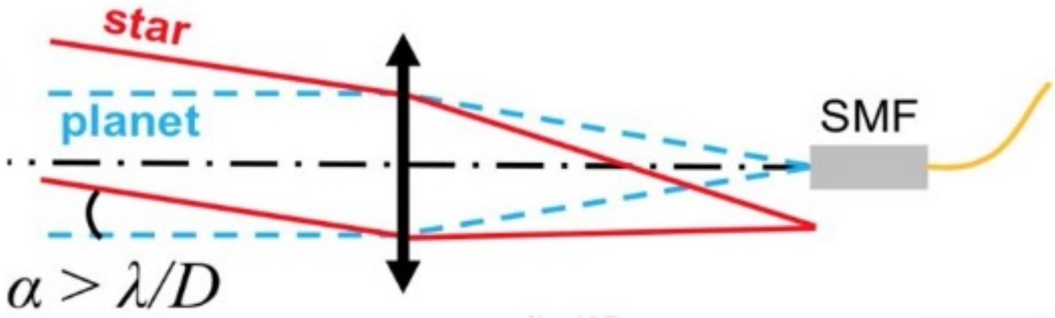
What is MODHIS – top-level requirements

	Requirements	Comments
Wavelength Range	0.98-2.46 µm	Simultaneous
Field of View	~4-6” diameter (at the diffraction limit: 7-17 mas)	Acquisition and guiding
Spectral Sampling	3 pixel LSF	Doppler measurements
Resolving power	100,000 on average	Driven by transits
Efficiency	>10%	Internal (excludes atmosphere)
Observing modes	Single-object on-axis Off-axis, high contrast	See next slide
Acquisition and guiding	< 17 mag	Limited by AO performance
Internal RV precision	< 30 cm/s	Fiber to fiber

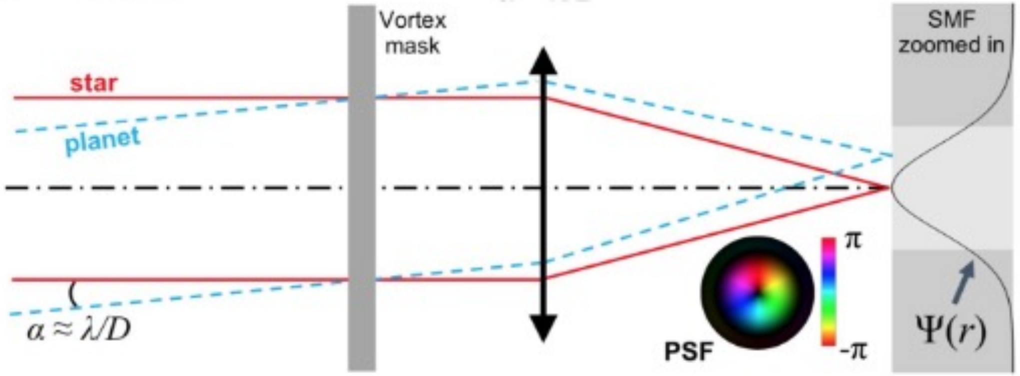
MODHIS observing modes



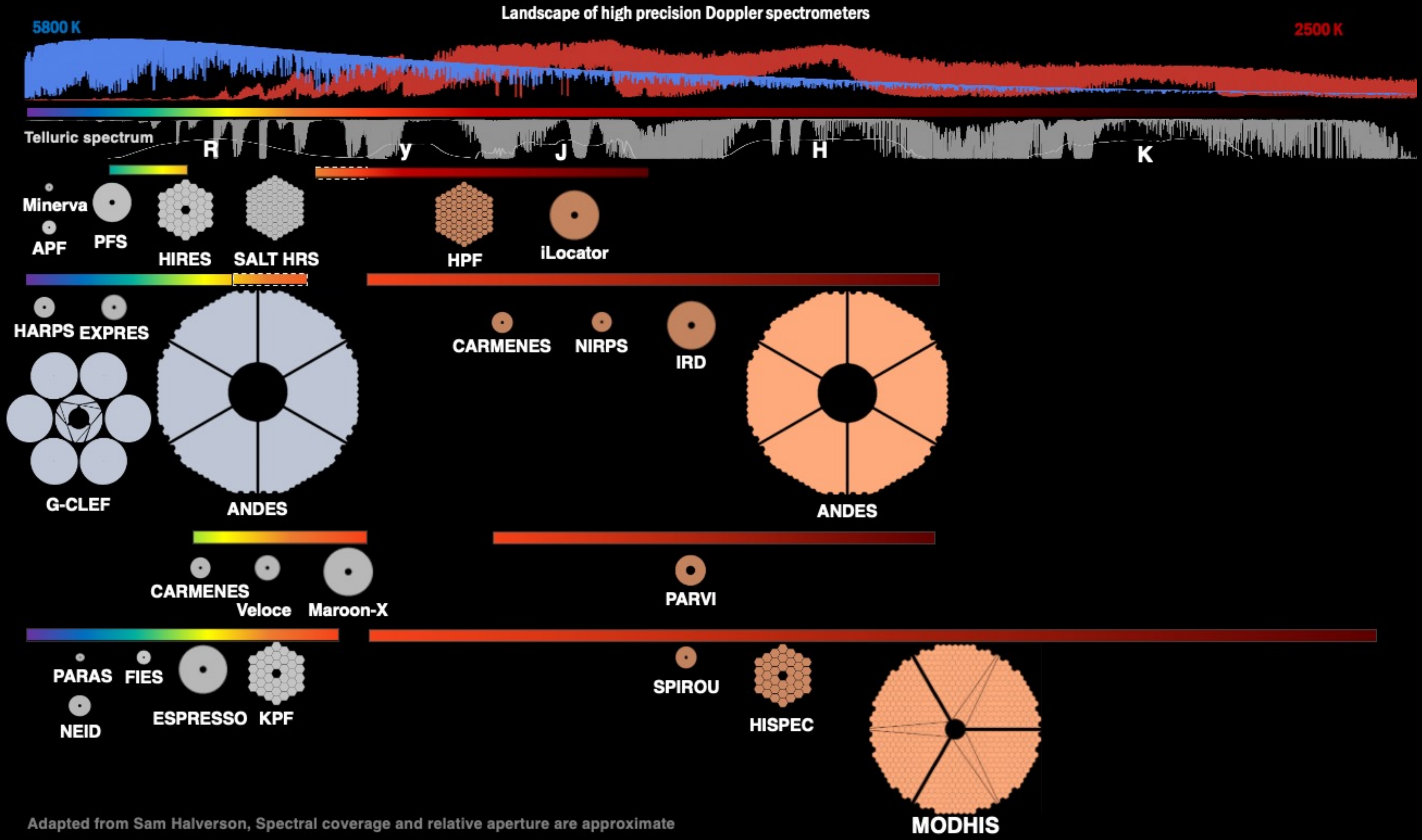
Single-object spectroscopy (e.g. PRV, transits) at high-angular resolution: SMF suppresses modal noise and sky background/OH lines by 2 orders of magnitude



High contrast scene,
Spectroscopic characterization only
(e.g. resolved exoplanets/substellar companions beyond the diffraction limit)



High contrast scene
at and within the diffraction limit,
(e.g. detection and characterization of close-in substellar companions, Gaia/RV follow-ups)

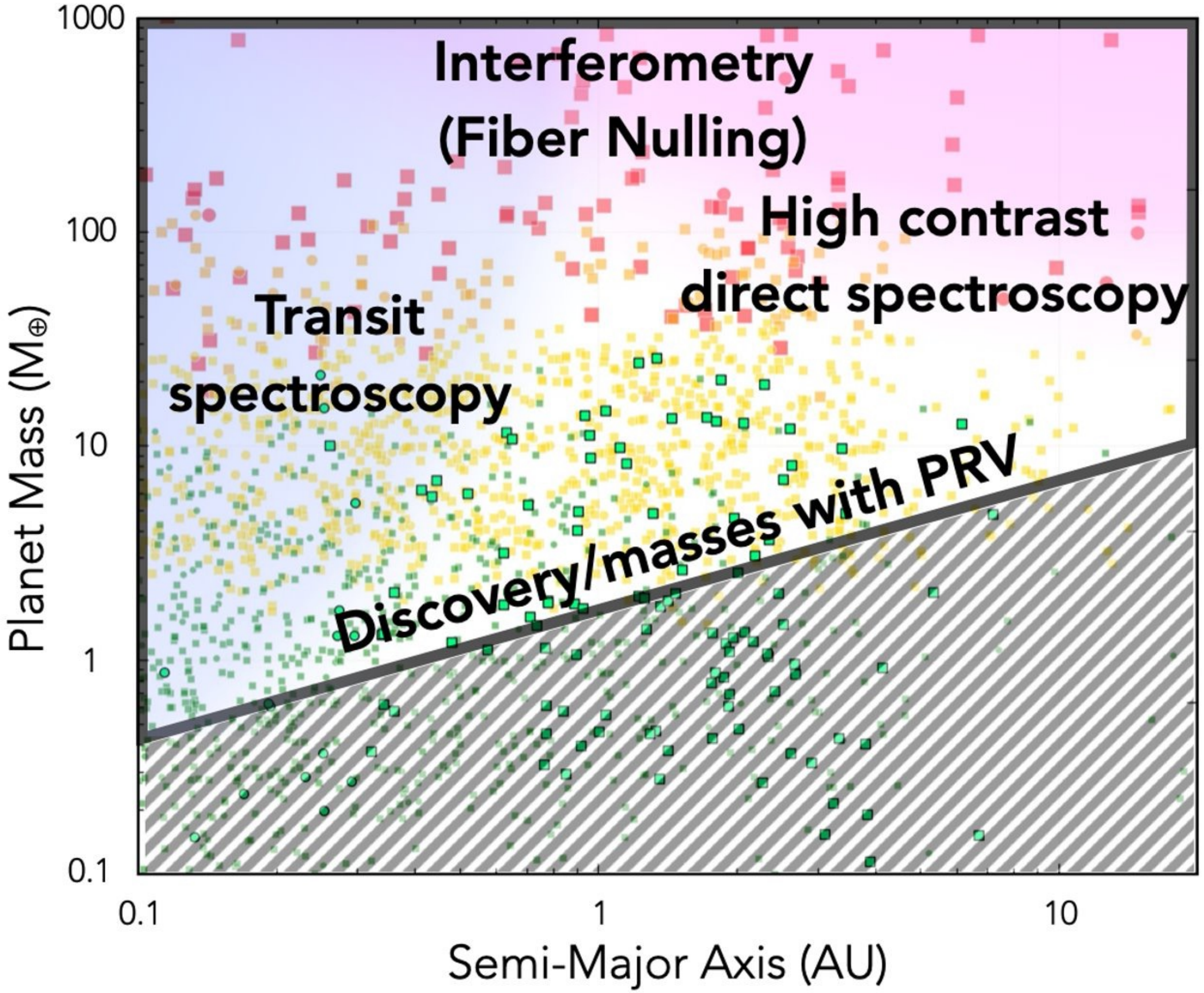

Landscape of high precision Doppler spectrometers
5800 K
2500 K
Telluric spectrum
R
y
J
H
K
Minerva
APF
PFS
HIRES
SALT HRS
HPF
iLocator
HARPS
EXPRES
G-CLEF
ANDES
CARMENES
NIRPS
IRD
ANDES
CARMENES
Veloce
Maroon-X
PARVI
PARAS
FIES
NEID
ESPRESSO
KPF
SPIROU
HISPEC
MODHIS
Adapted from Sam Halverson, Spectral coverage and relative aperture are approximate

MODHIS NIR PRV heritage across collaboration

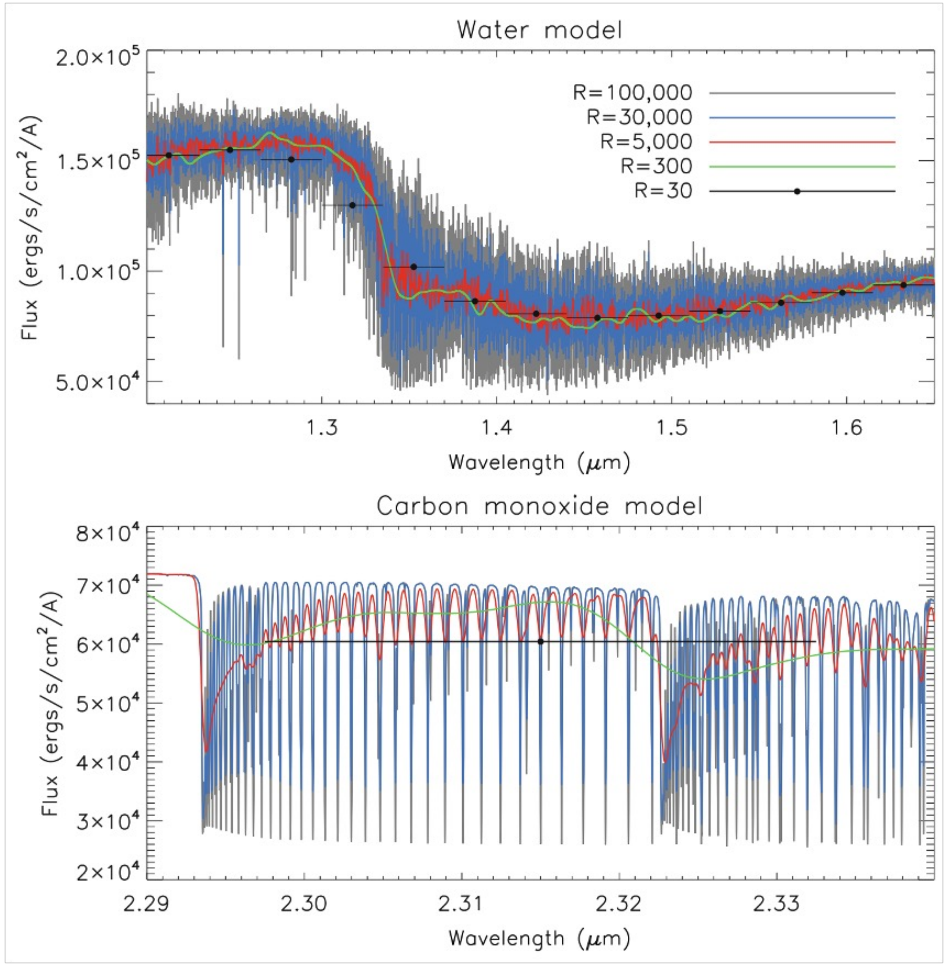
- Canada: CFHT-SPIRou, ESO-NIRPS (just achieved <1 m/s!)
- Japan: Subaru-IRD
- Caltech/JPL: Palomar-PARVI, Keck-HISPEC
- UC: NIRSPEC, IRIS-LIGER
- Plus many others to learn with and from: HPF, iLocater

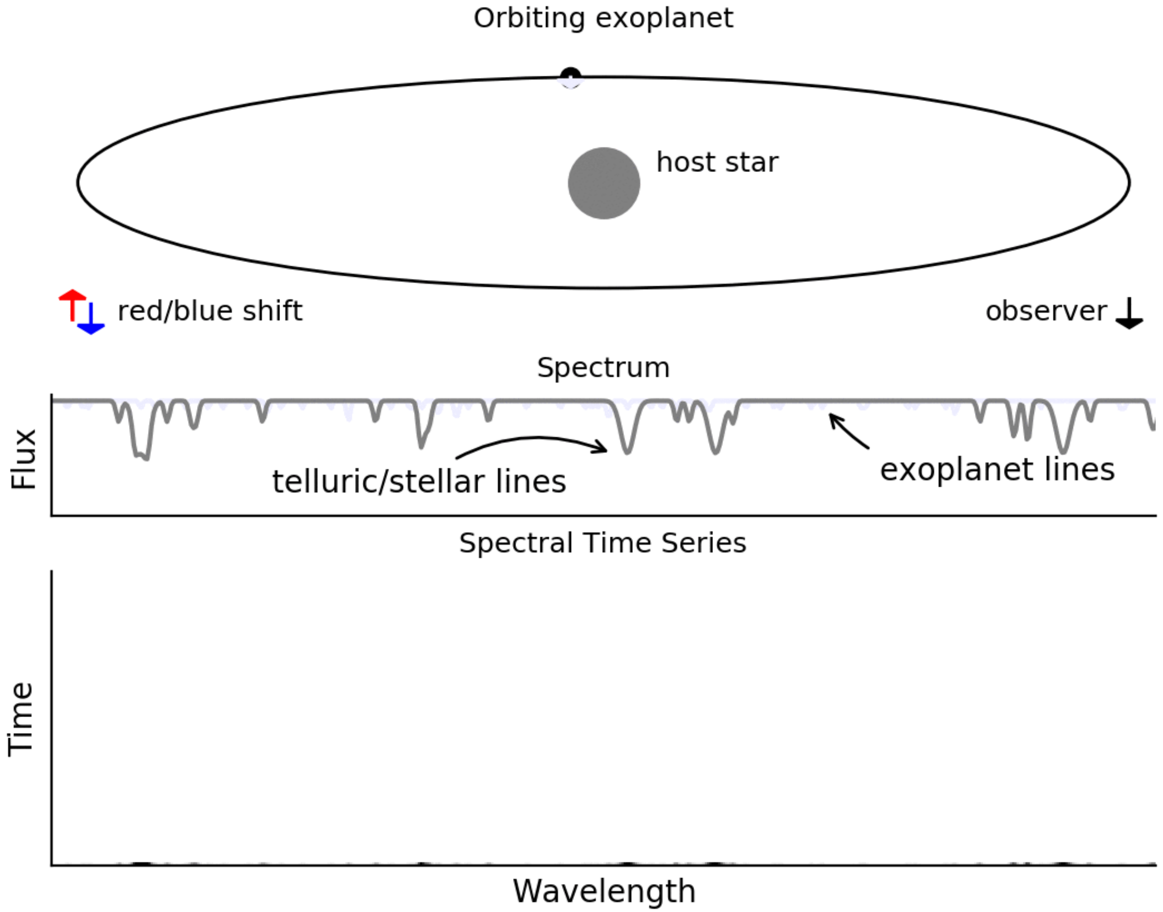
Exoplanet science

MODHIS enables four complementary exoplanet detection and characterization techniques covering a substantial phase space



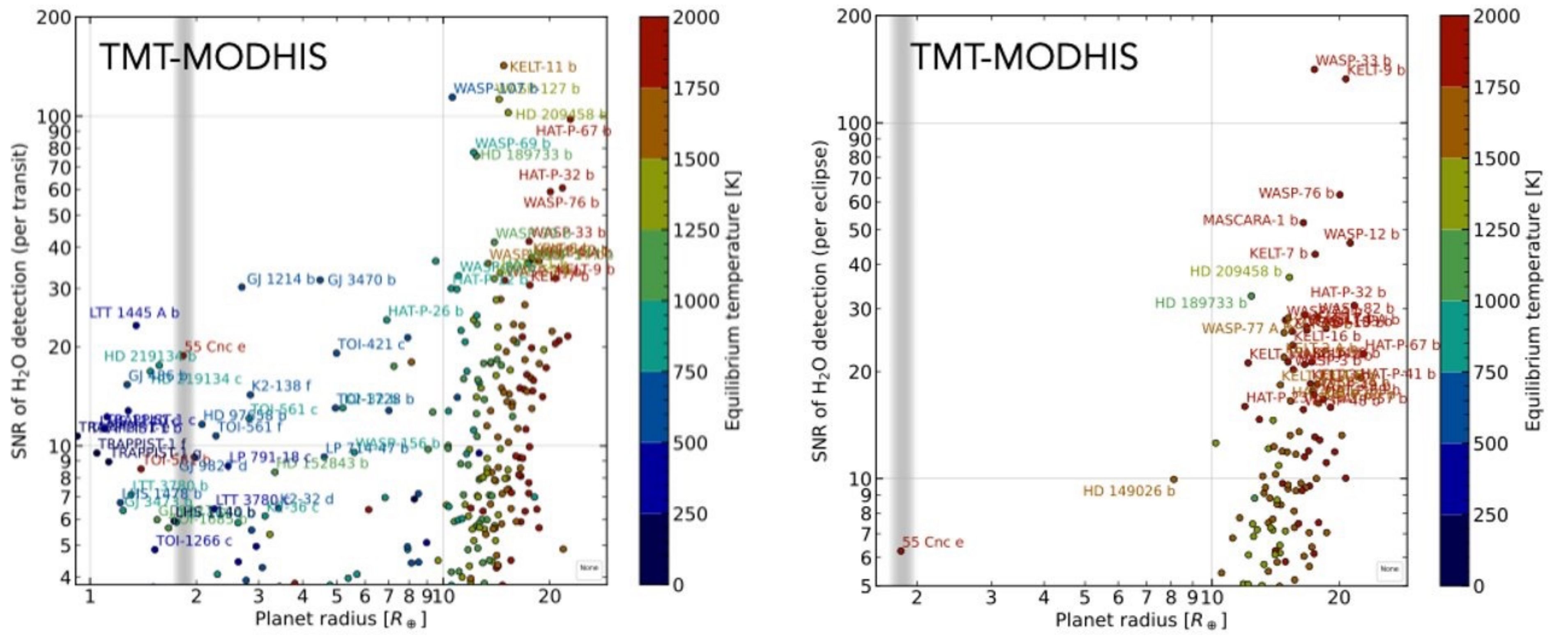
Close-in exoplanet (incl. Transit) spectroscopy: high-resolution spectroscopy unlocks full information content of molecular lines



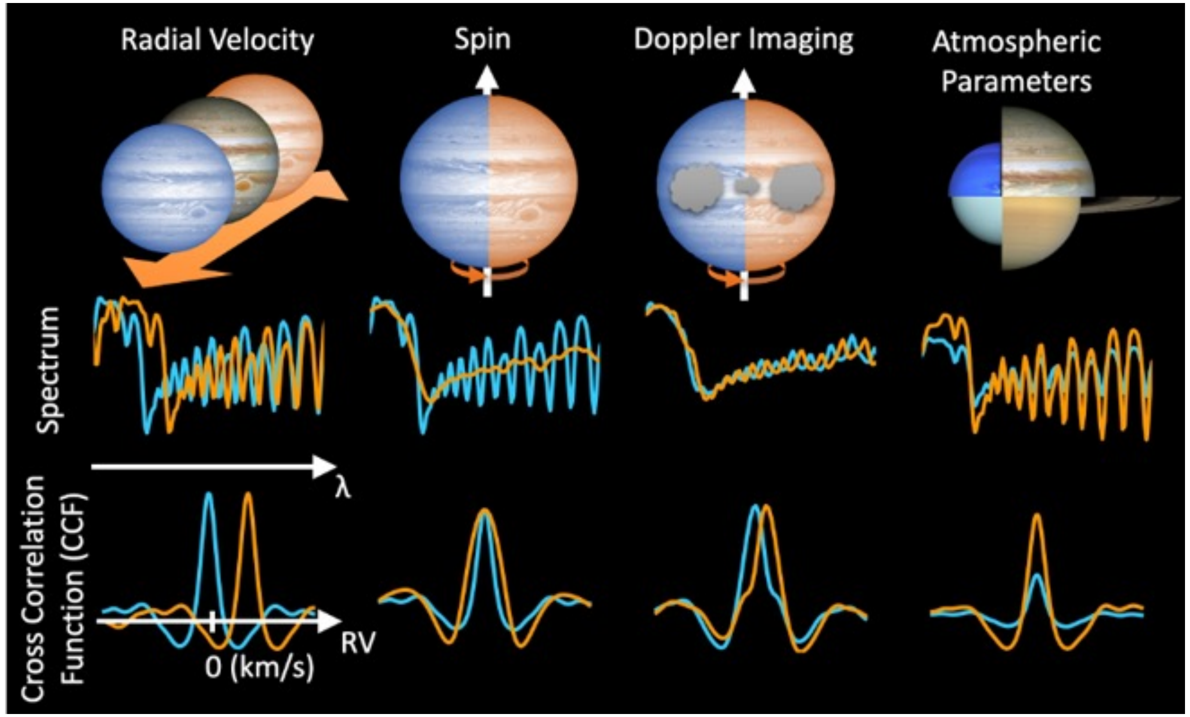


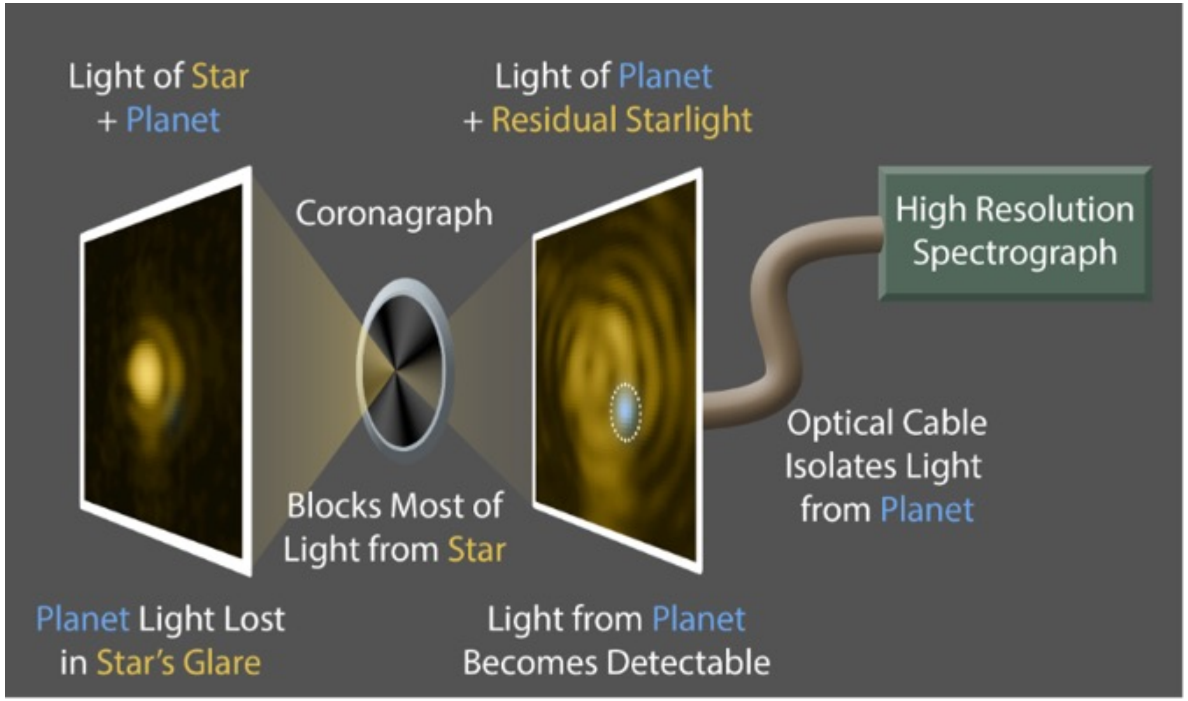
Animation by Lennart van Sluijs

MODHIS will characterize the atmosphere of many exoplanet types from hot Jupiters to mini-Neptunes, Super-Earth, and Earth-size planets



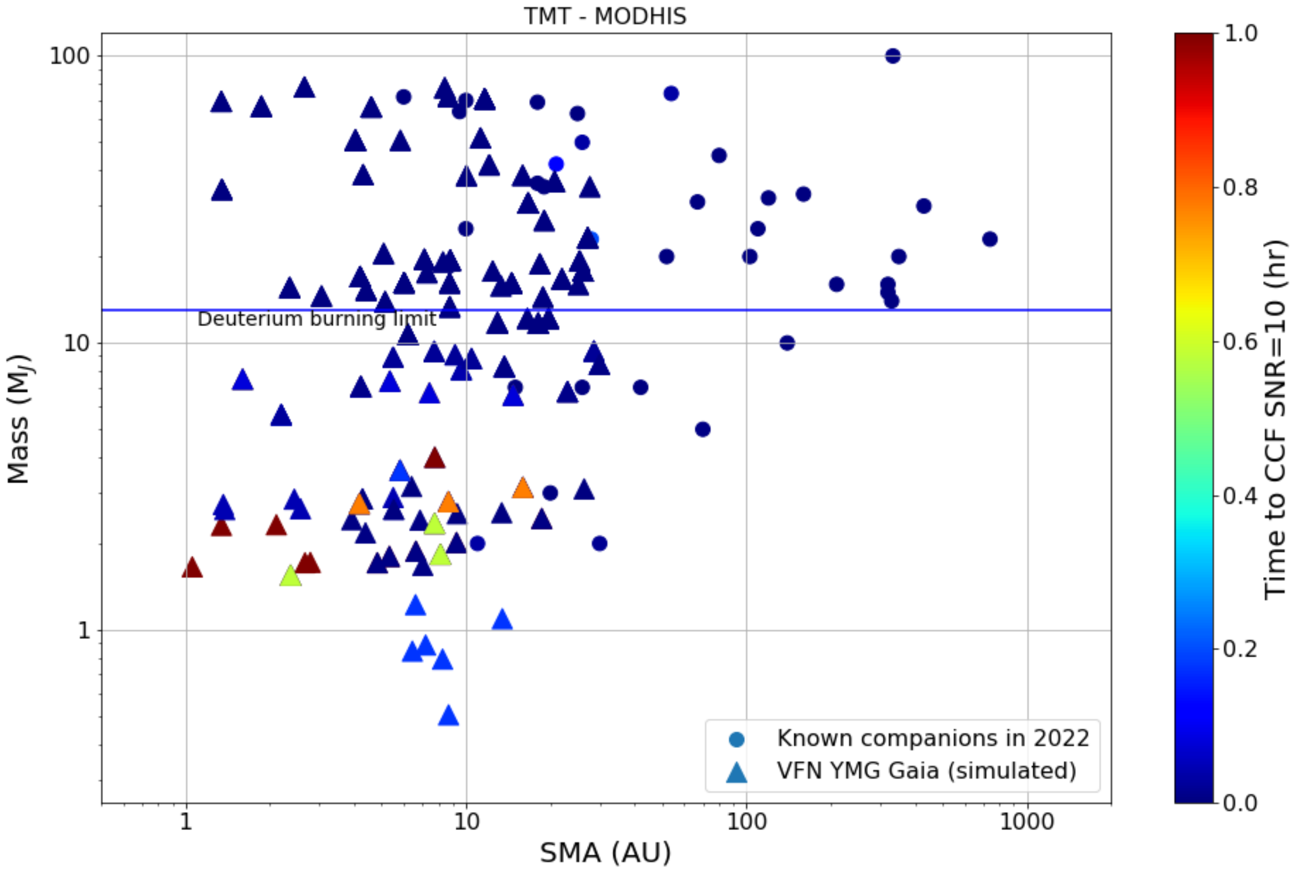
High-Dispersion Coronagraphy: characterization of off-axis substellar companions and gas giants at high contrast





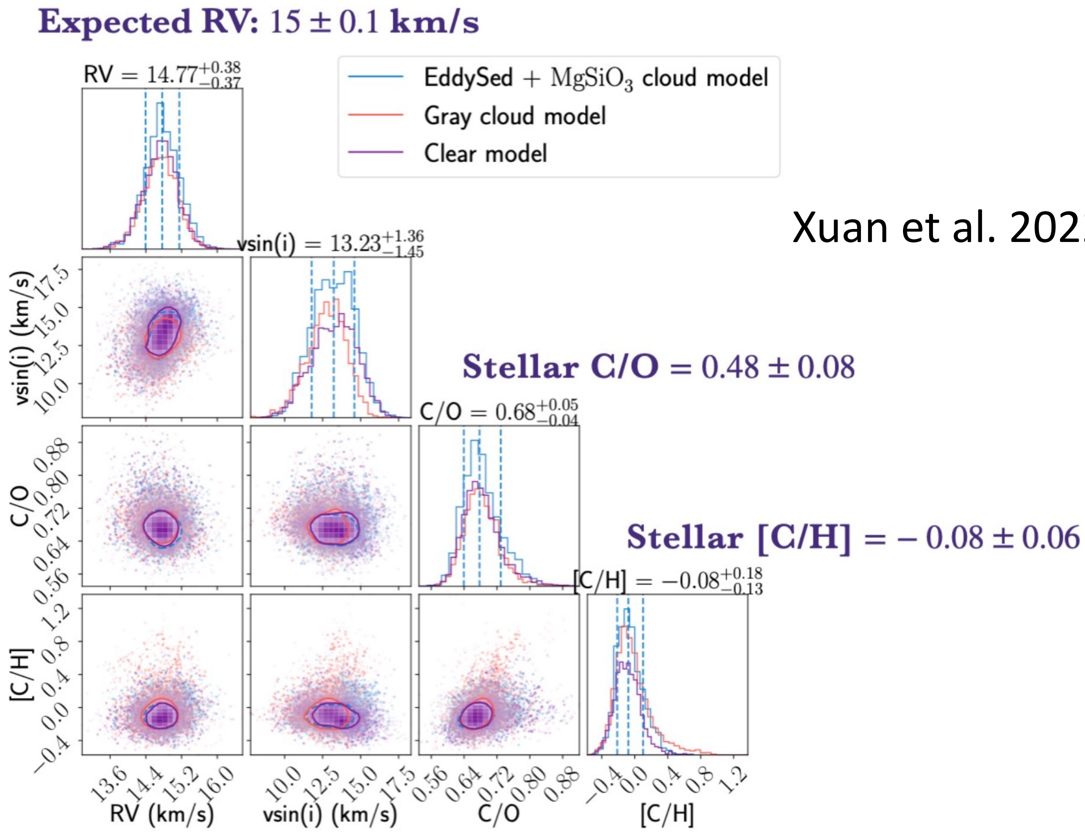
MODHIS HDC survey capabilities

- TMT-MODHIS will readily detect dozens of existing low-mass companions across the deuterium burning limit, investigating the formation and evolution of gas giants and through their shaping influence, whole planetary system
- Each detection through cross-correlation or forward modeling will enable extensive dynamical (spin and orbital) and atmospheric characterization

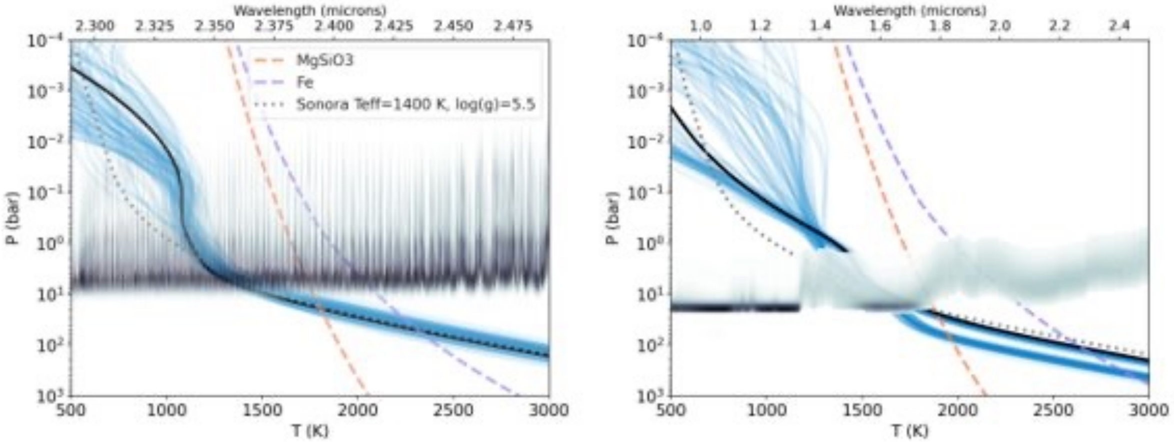


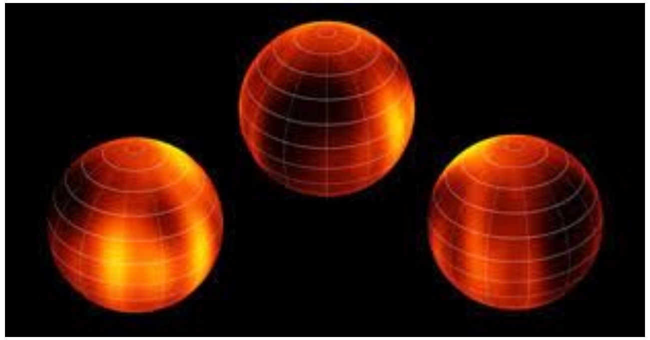
Abundance measurements and atmospheric dynamics

- Measuring abundances (e.g. C/O and Fe/H) at high spectral resolution probes a wide range of atmospheric pressures below, at, or above the clouds
- High-resolution spectroscopy is sensitive to minor species such as isotopologues (formation tracers)
- High-resolution spectroscopy on large telescopes (high SNR) enables Doppler imaging, revealing 3D cloud structure, oblateness and dynamics

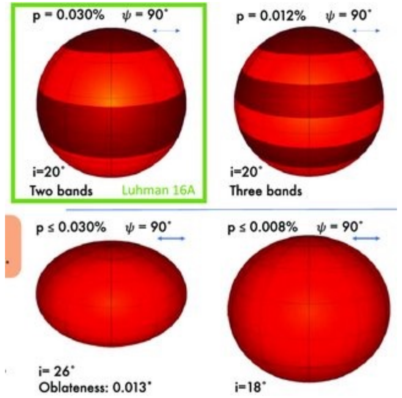


Xuan et al. 2022



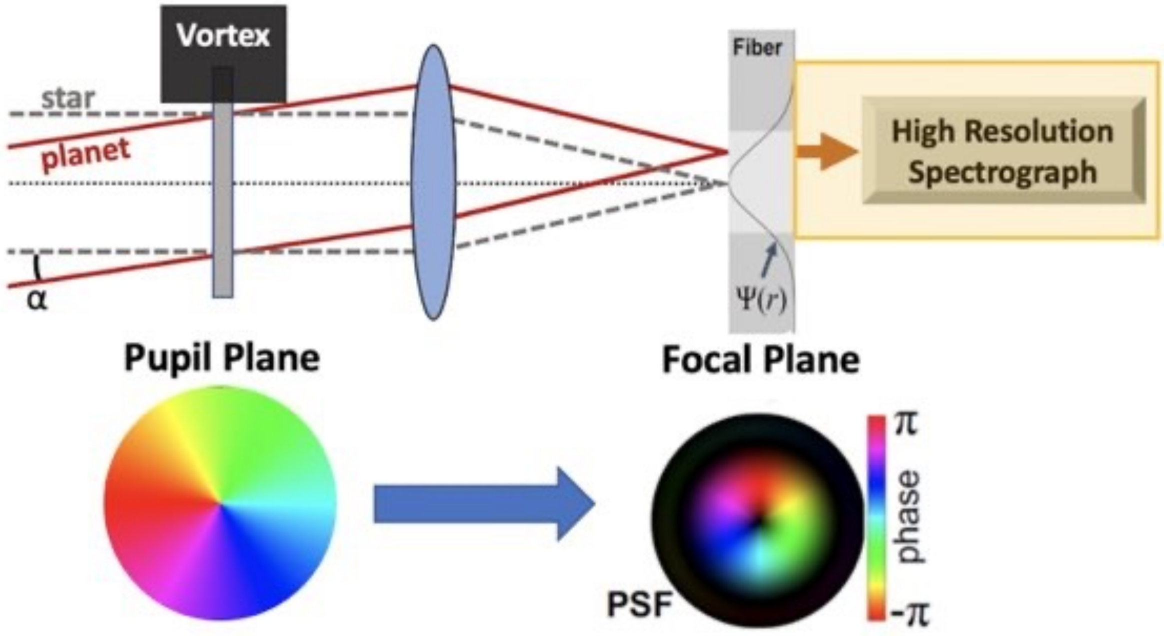


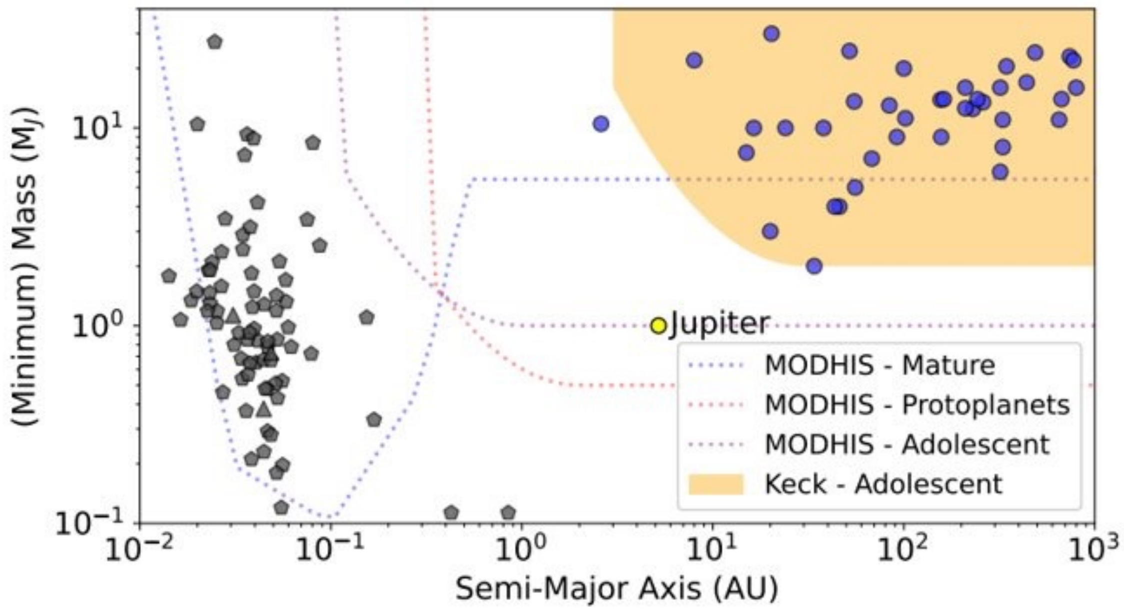
Luh 16



Millar-Blanchaer+19

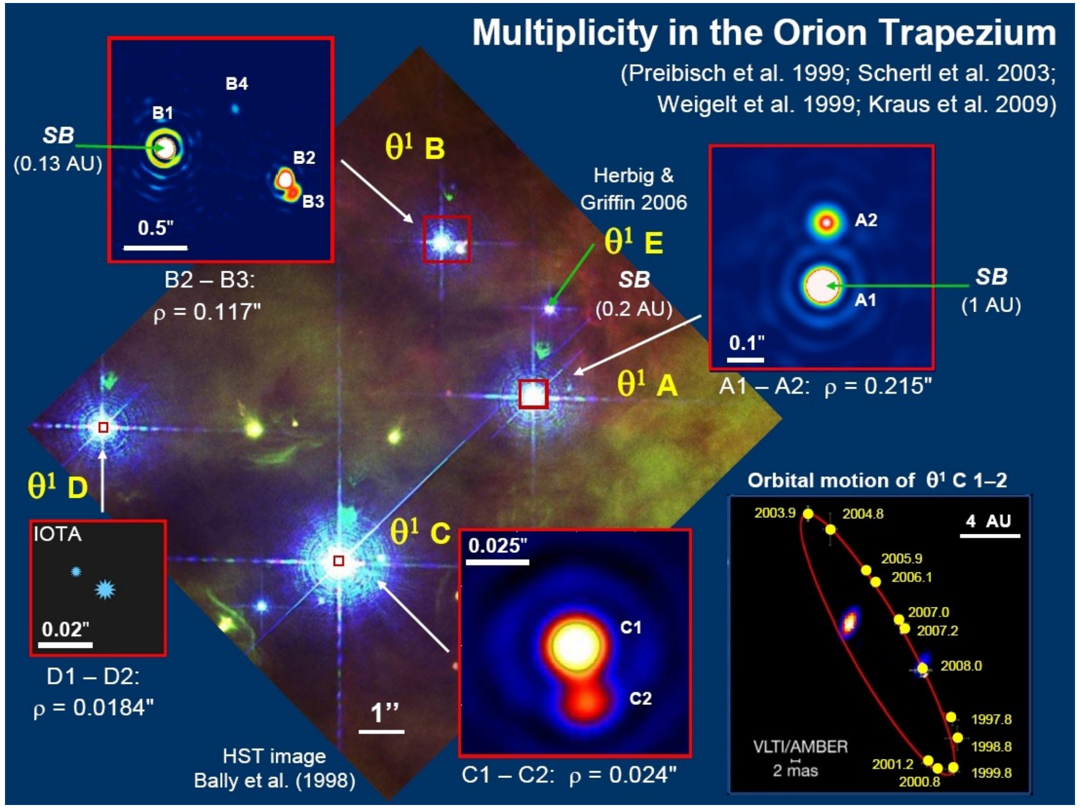
Fiber nulling with TMT-MODHIS enables the detection and spectroscopic characterization of exoplanet at or within the diffraction limit (Solar system scales and close-in planets around M dwarfs)

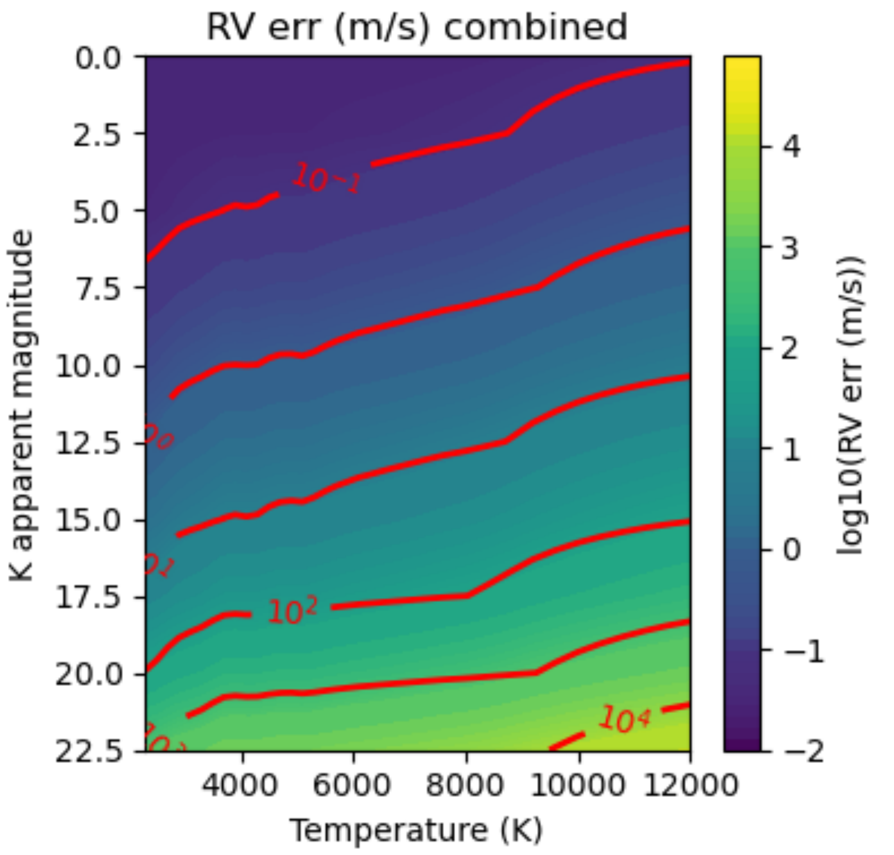




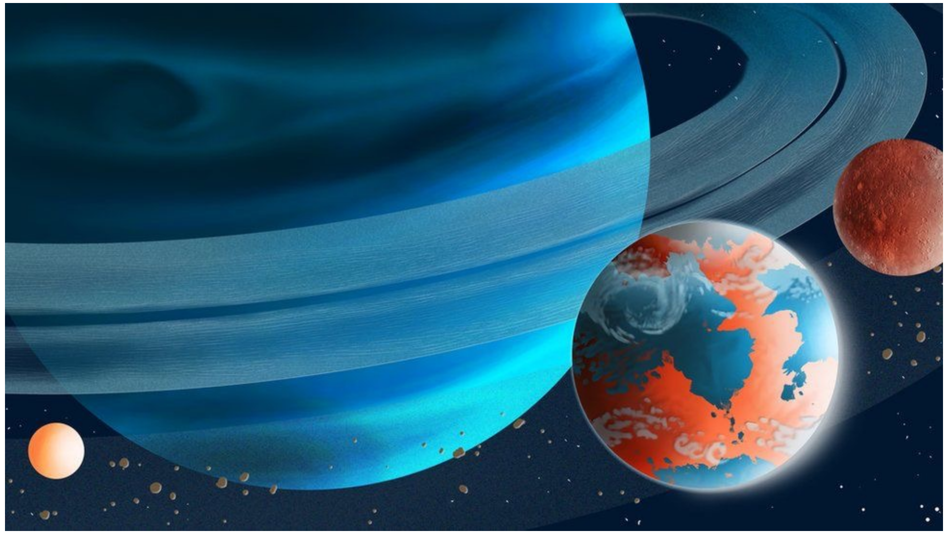
NIR Precision Radial Velocity

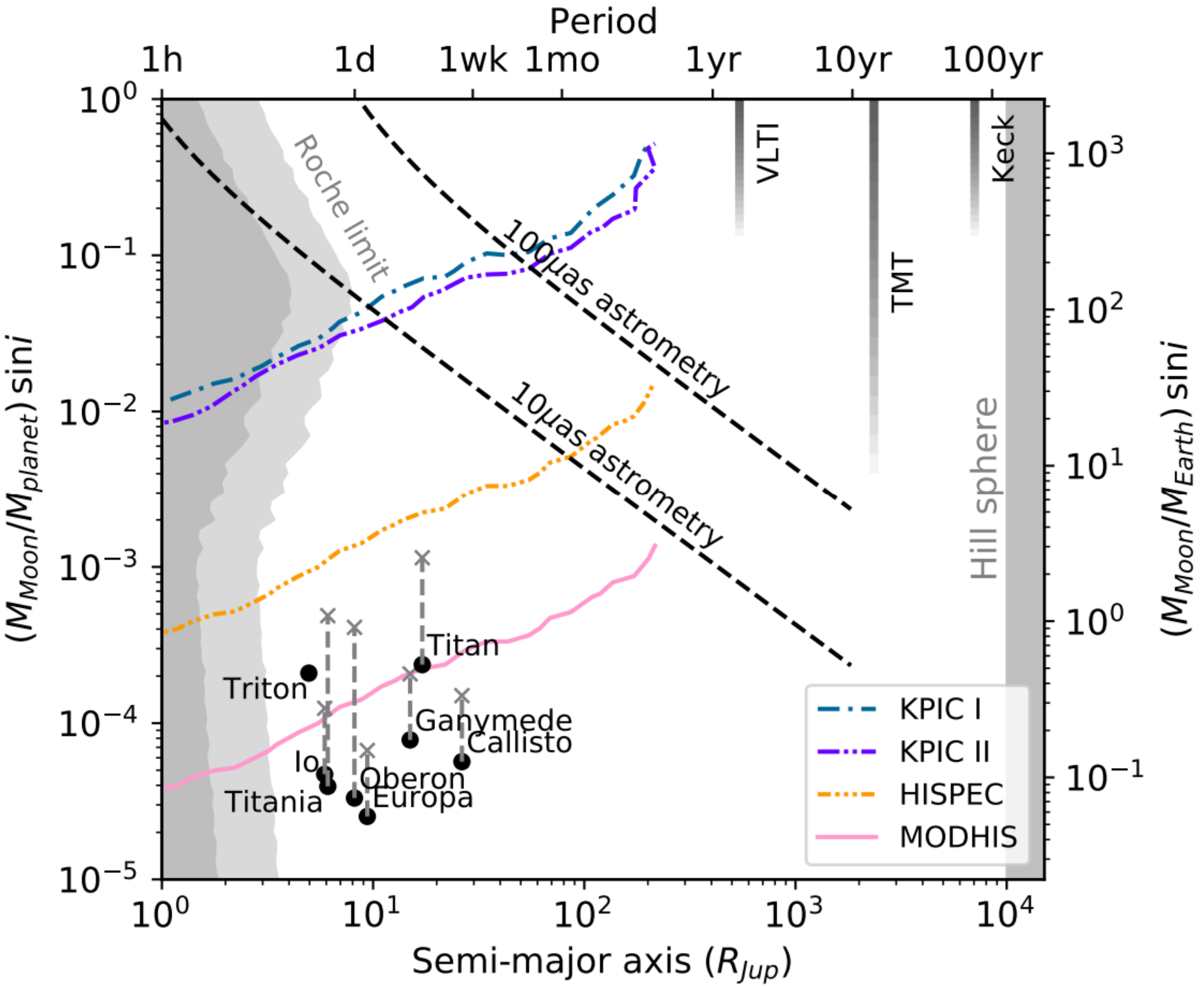
- NIR PRV enables the following science on large telescopes:
- Exoplanet demographics in young systems. NIR PRV has demonstrated 2-4x less stellar jitter than optical PRV
- Orbital Obliquity of Planets Orbiting Young and/or Cool Stars via the RM effect
- Demographics in binary or multiple systems inaccessible to seeing-limited instruments and smaller telescopes





Exomoons around young giant exoplanets

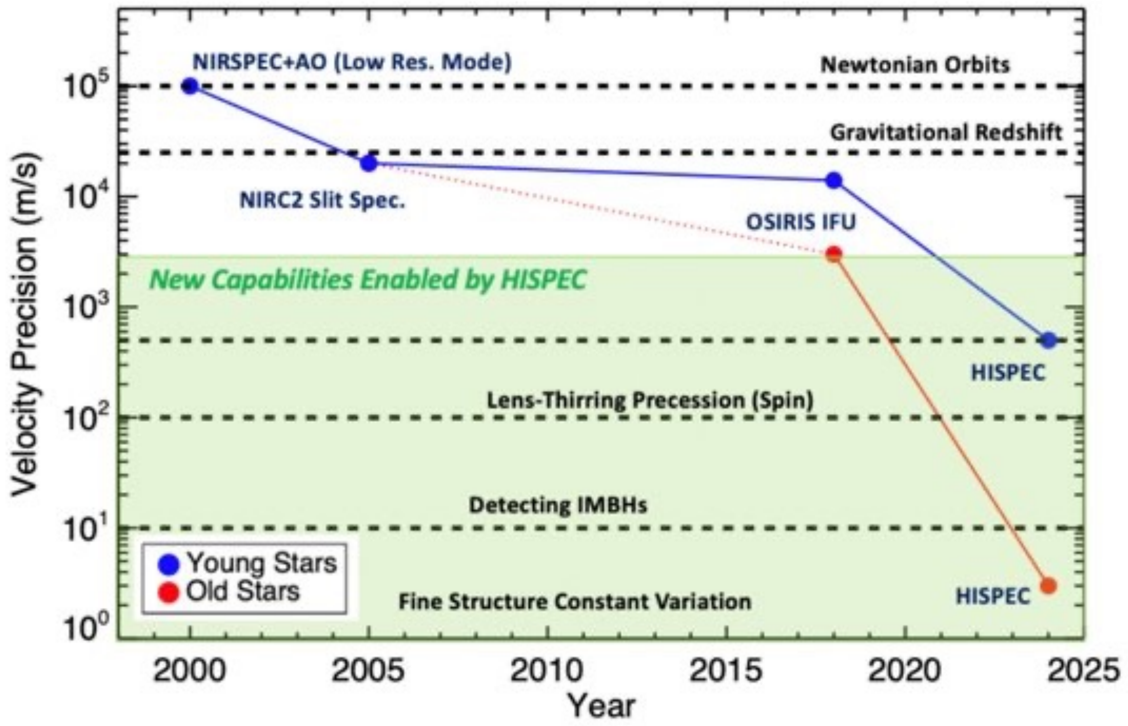




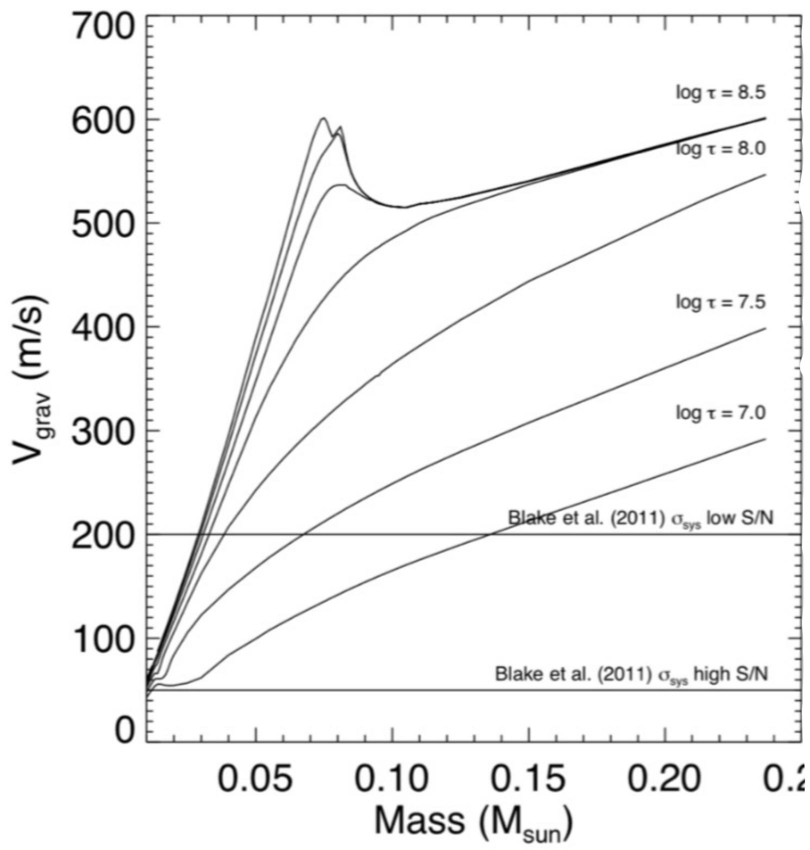
Ruffio et al. 2023

Galactic Center

- MODHIS will enable a 2+ order of magnitude improvement in radial velocity measurements at the Galactic Center, providing the necessary complement to astrometry (Gravity) in velocity space, enabling the following science:
    - Fine Structure Constant measurements
    - Central black hole spin
    - Intermediate-mass BHs
- 3x better angular resolution than Keck



Ultracool Dwarfs



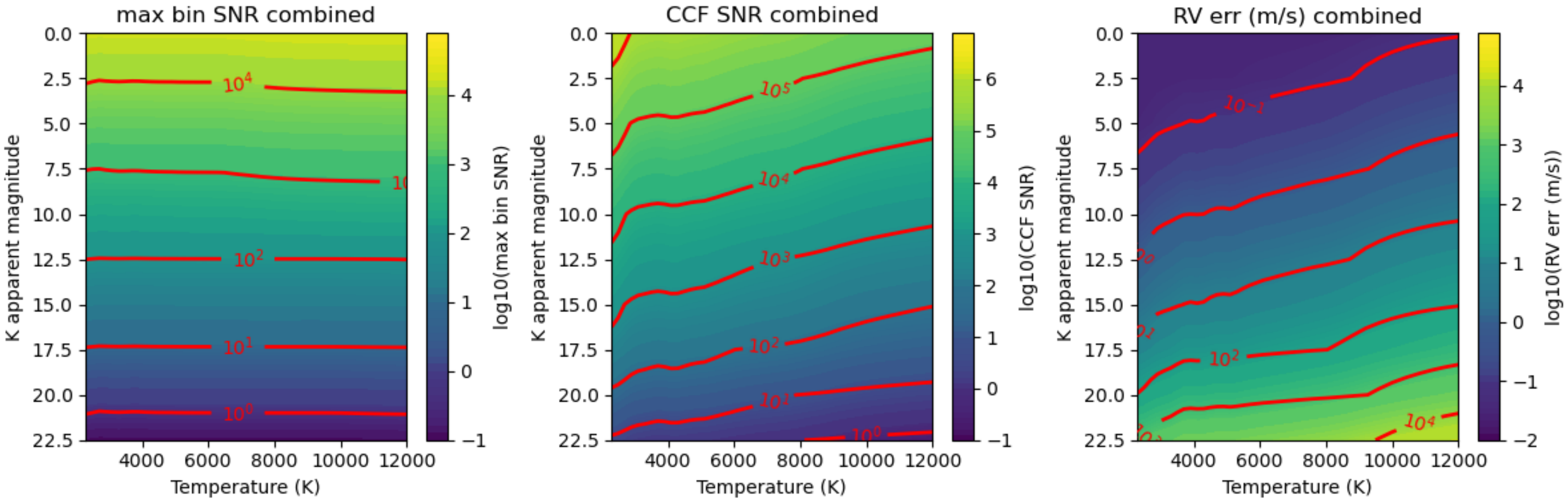
- Brown dwarfs across the full range of spectral types (MLTY) are often too faint to study at high spectral resolution with 8–10-meter telescopes
- MODHIS will perform a range of science on brown dwarfs:
  - Observations can look for very small companions, or measure the gravitational redshift (which gives mass and radius information)
  - Improved sensitivity to auroral features
  - High spectral resolution offers the ability to look for Zeeman line splitting; Doppler imaging of magnetic surface structures and/or clouds is of significant interest

Gravitational Redshift Signal, Burgasser et al. 2019

Other Science

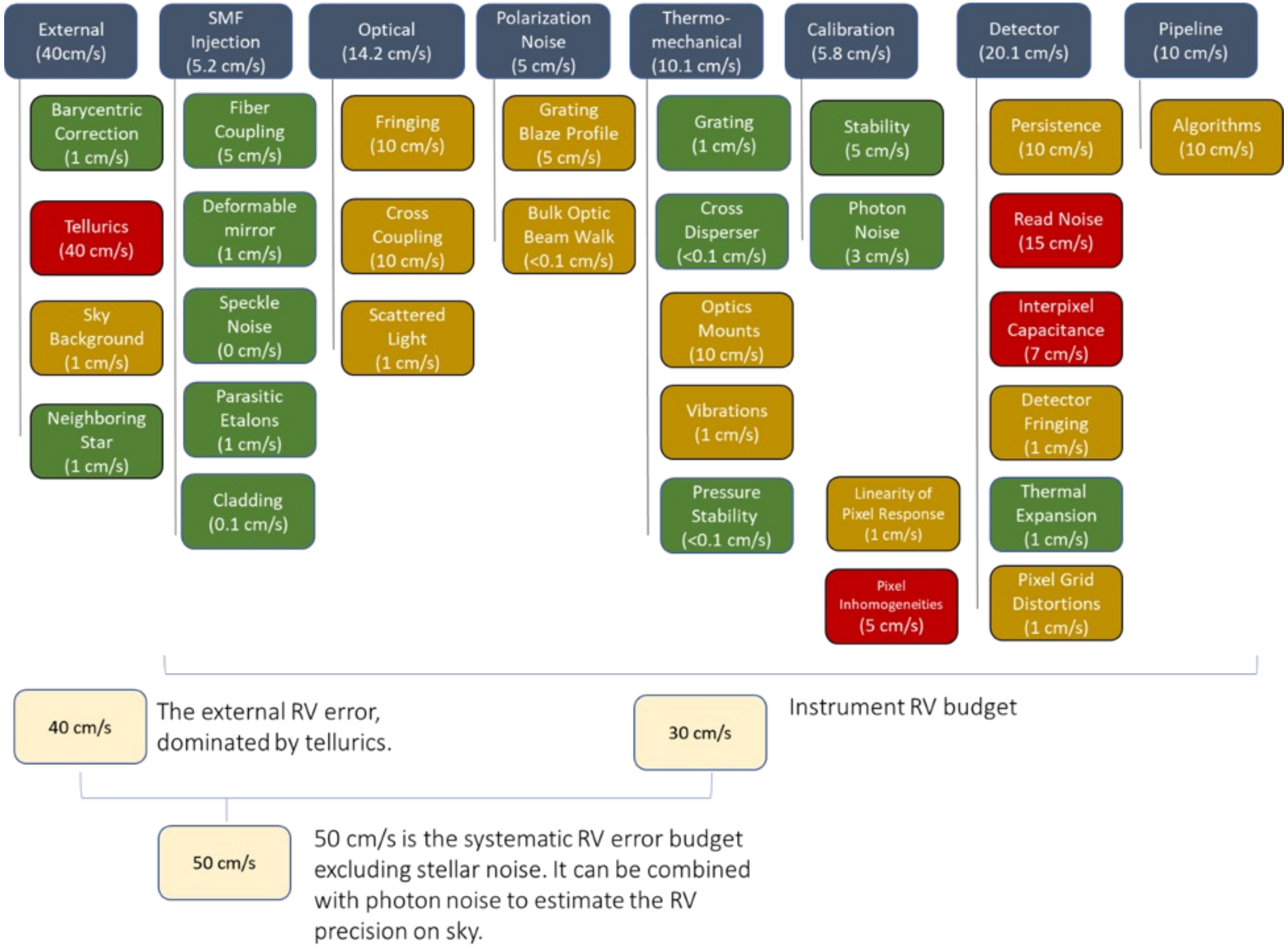
- Proto-planetary and circumplanetary disk dynamics
- Global circulation models for Venus through ultra-precise wind measurements
- Abundance measurements in Galactic bulge (subject to confusion with traditional means)
- Internal kinematics of stars in dwarf galaxies
- Probe AGN-driven outflows close to the SMBH sphere of influence
- More to be explored with science team during CoDP-2

MODHIS sensitivity (preliminary) – 10 min

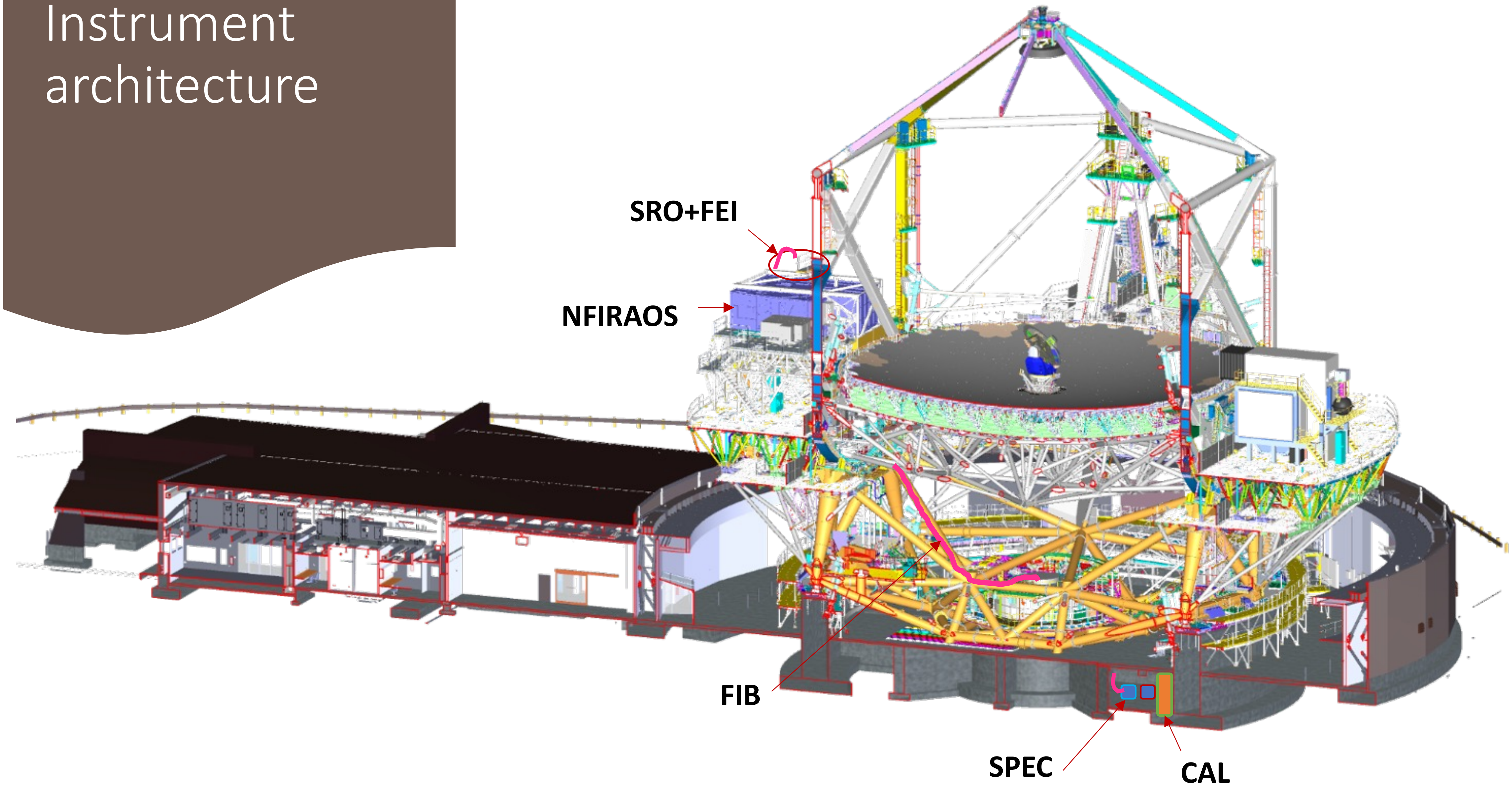


https://www.tmt.org/page/modhis-sensitivity
https://github.com/planetarysystemsimager/psisim

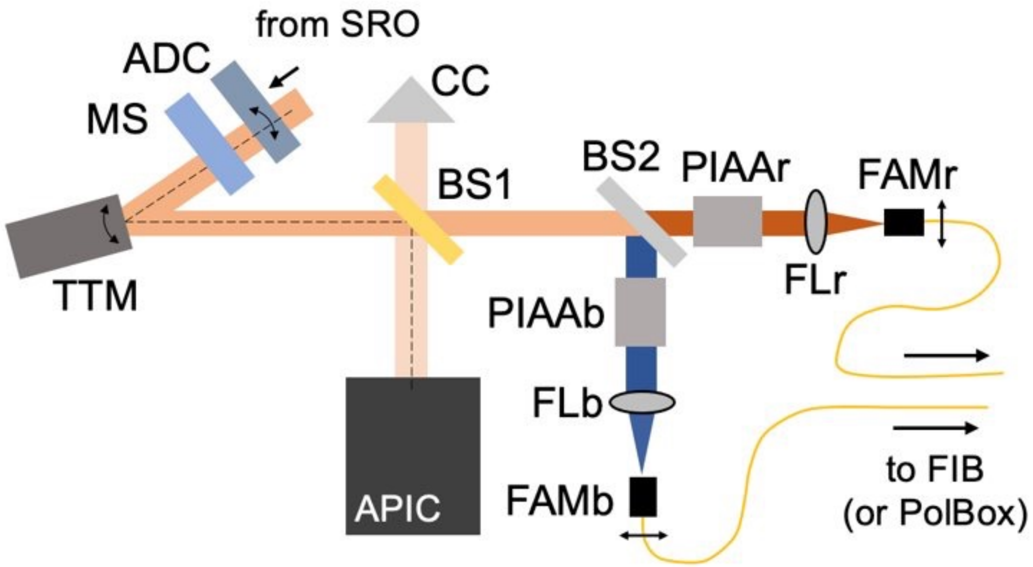
MODHIS RV precision (HISPEC placeholder)



Instrument architecture

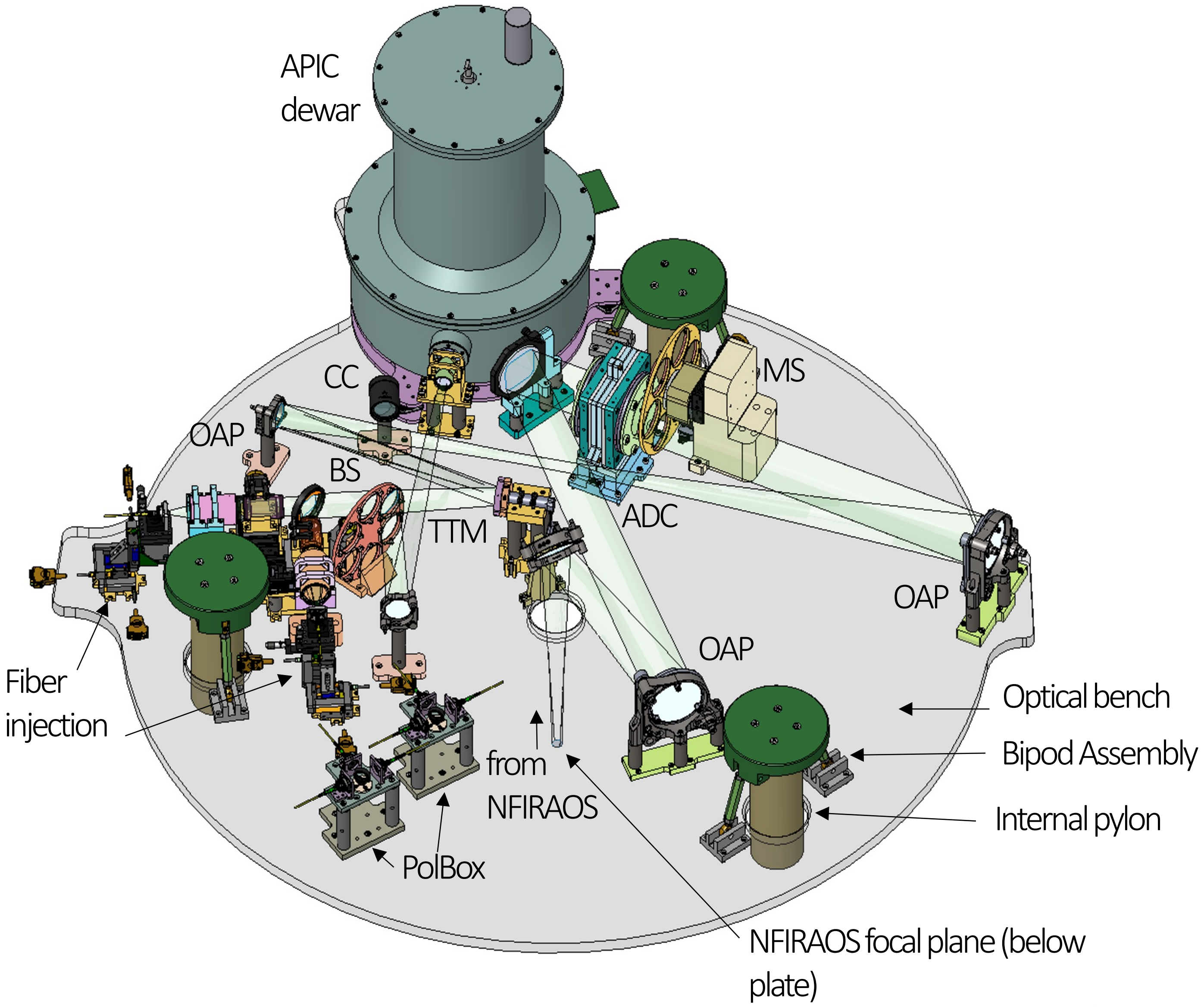


FEI schematic overview

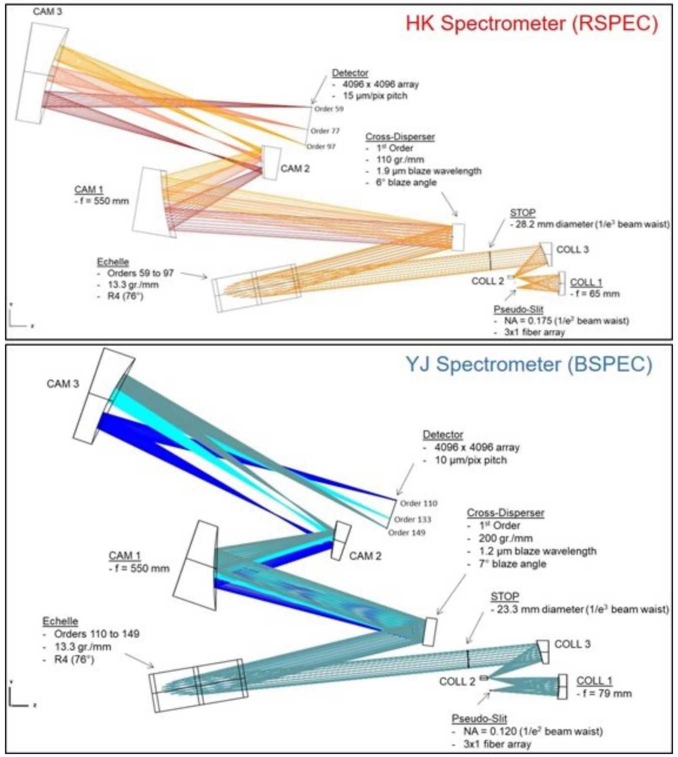


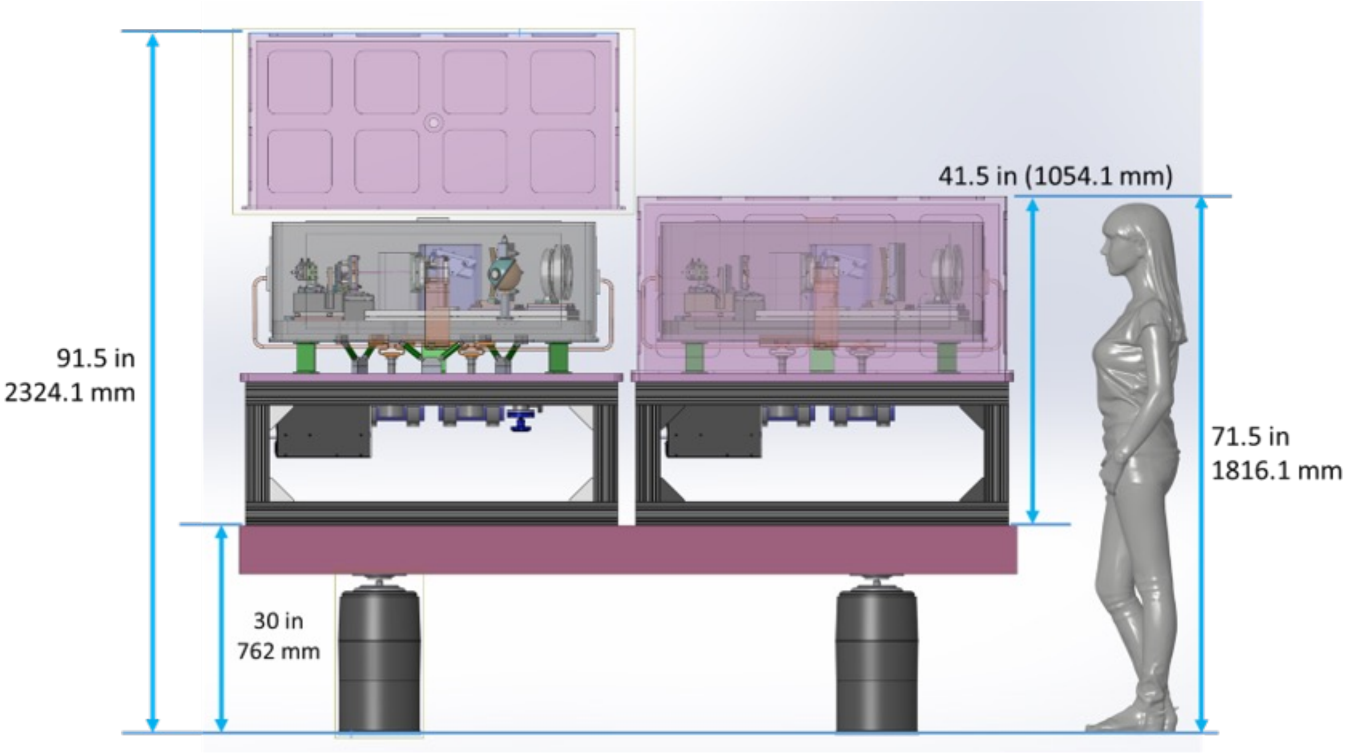
ADC - Atmospheric dispersion compensator
MS - Mask selector
TTM - Tip/tilt mirror
BS - Beam splitter (dichroic)
CC - Corner cube (retroreflector)
APIC - Acquisition/tracking, and pupil imaging camera
PIAA(b/r) - Phase induced amplitude apodizer
FL(b/r) - Focusing lens
FAM(b/r) - Fiber alignment mechanism

FEI mechanical design



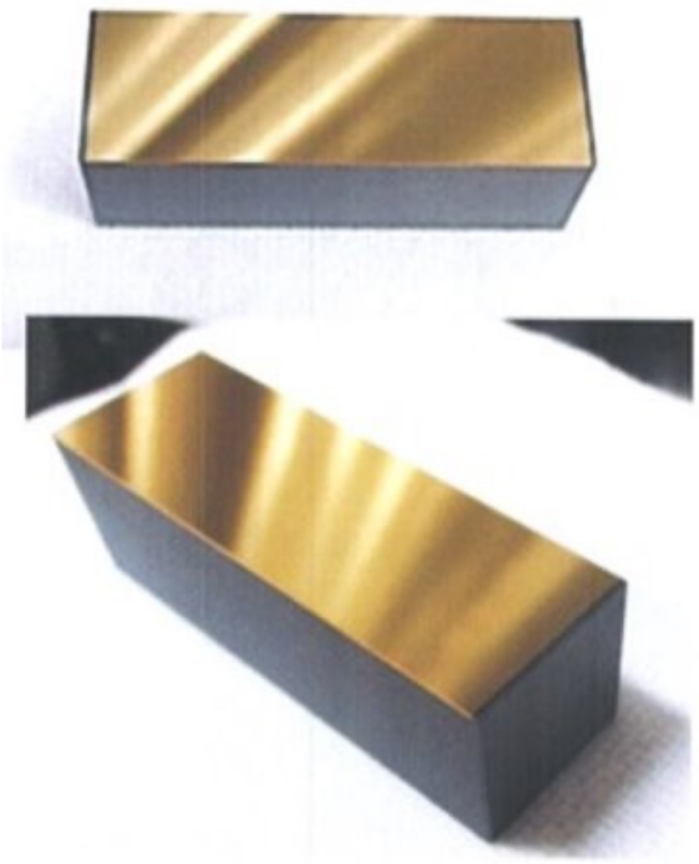
Spectrometers



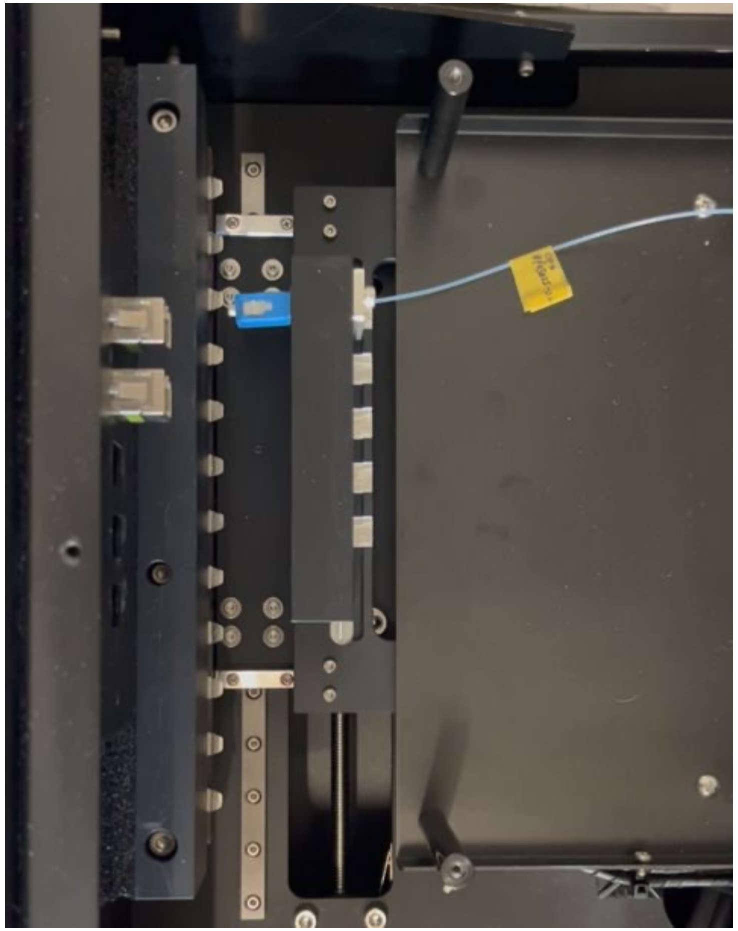


MODHIS's crown jewels (*)

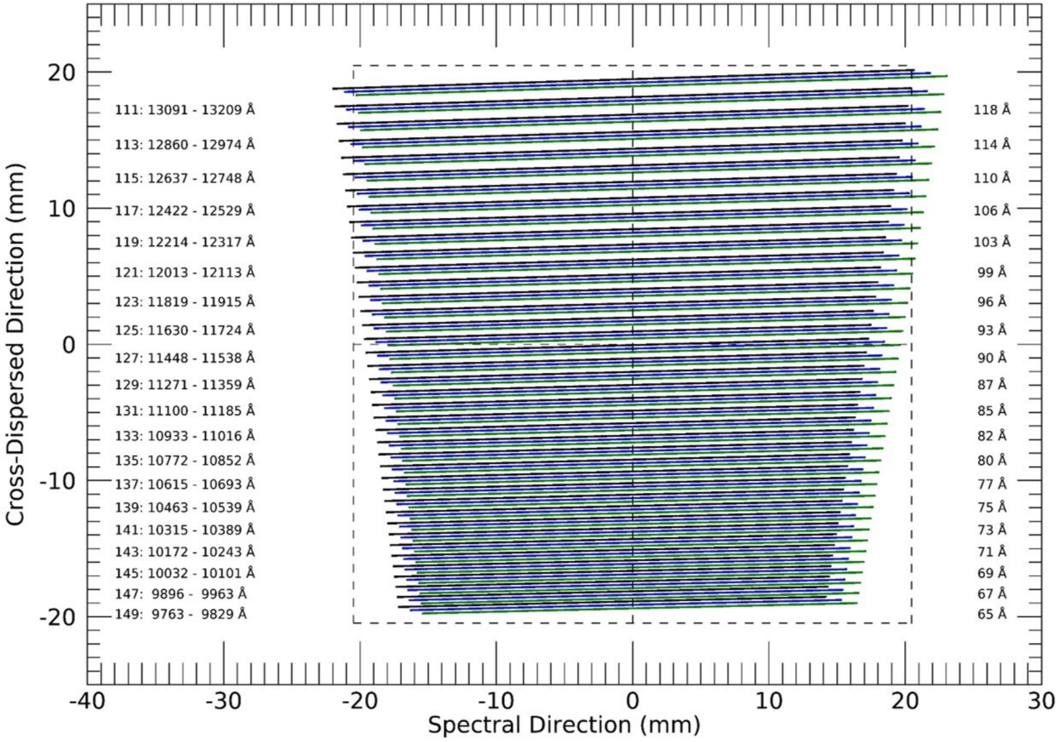
High-efficiency echelle grating from Canon and robotic fiber switchers (ABC contributions)

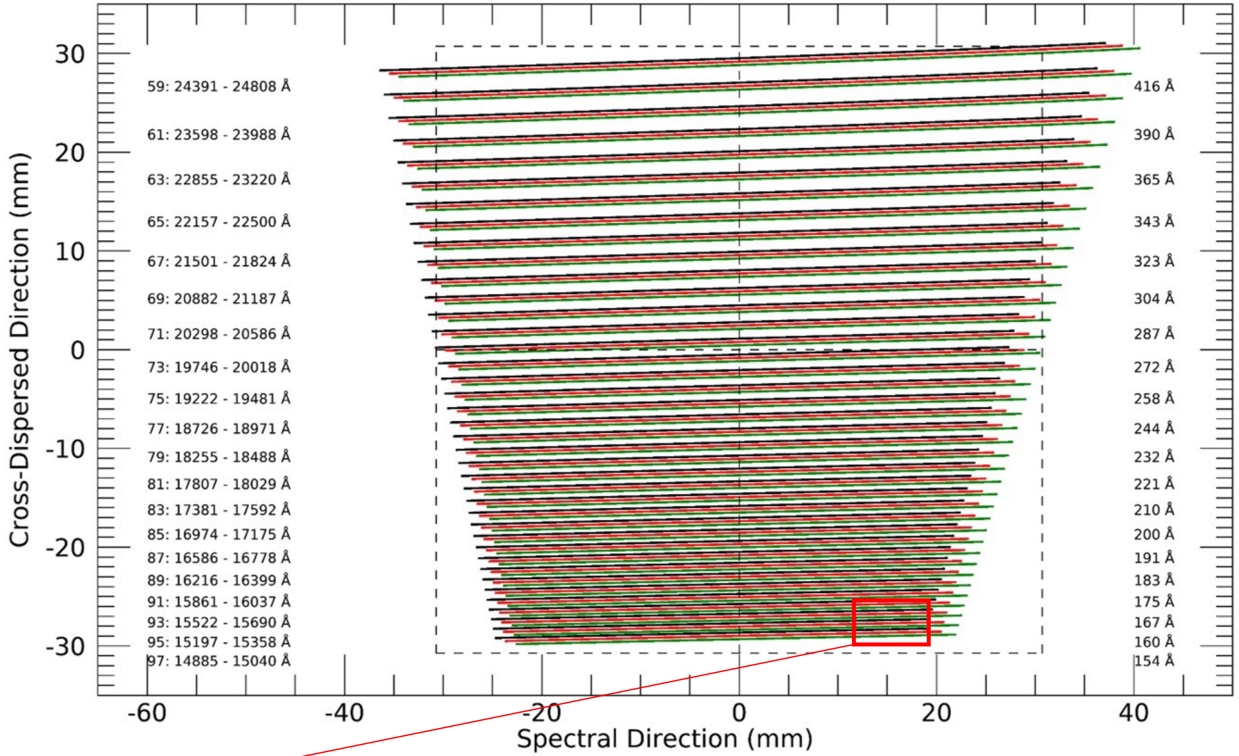


(*) contingent upon reusing HISPEC's spectrographs

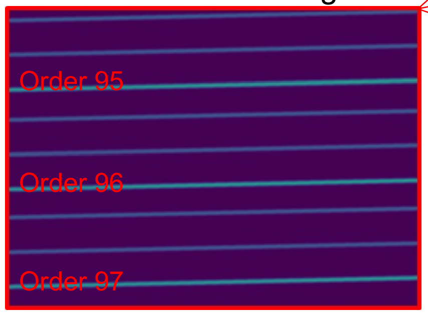


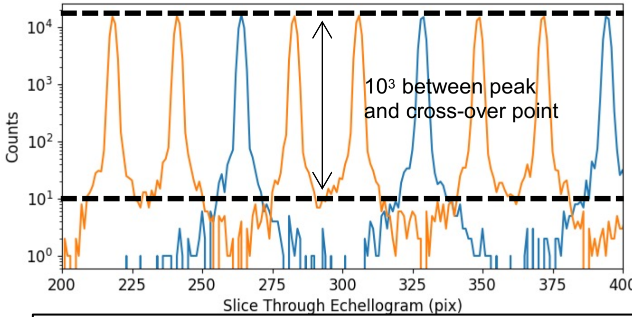
Echellograms





ROI of Simulated Image

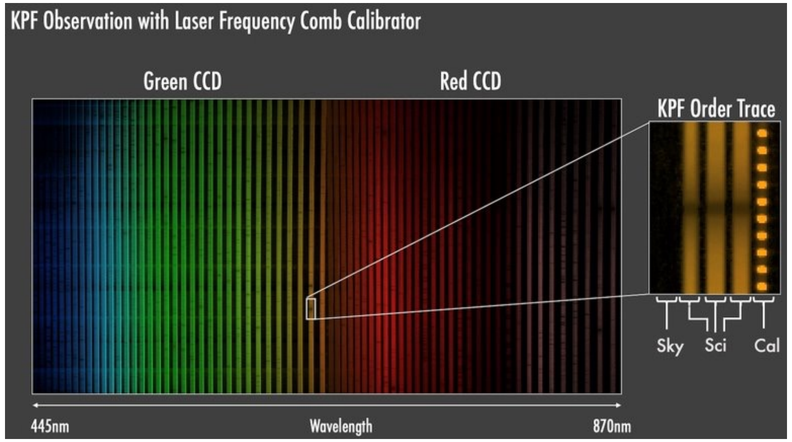


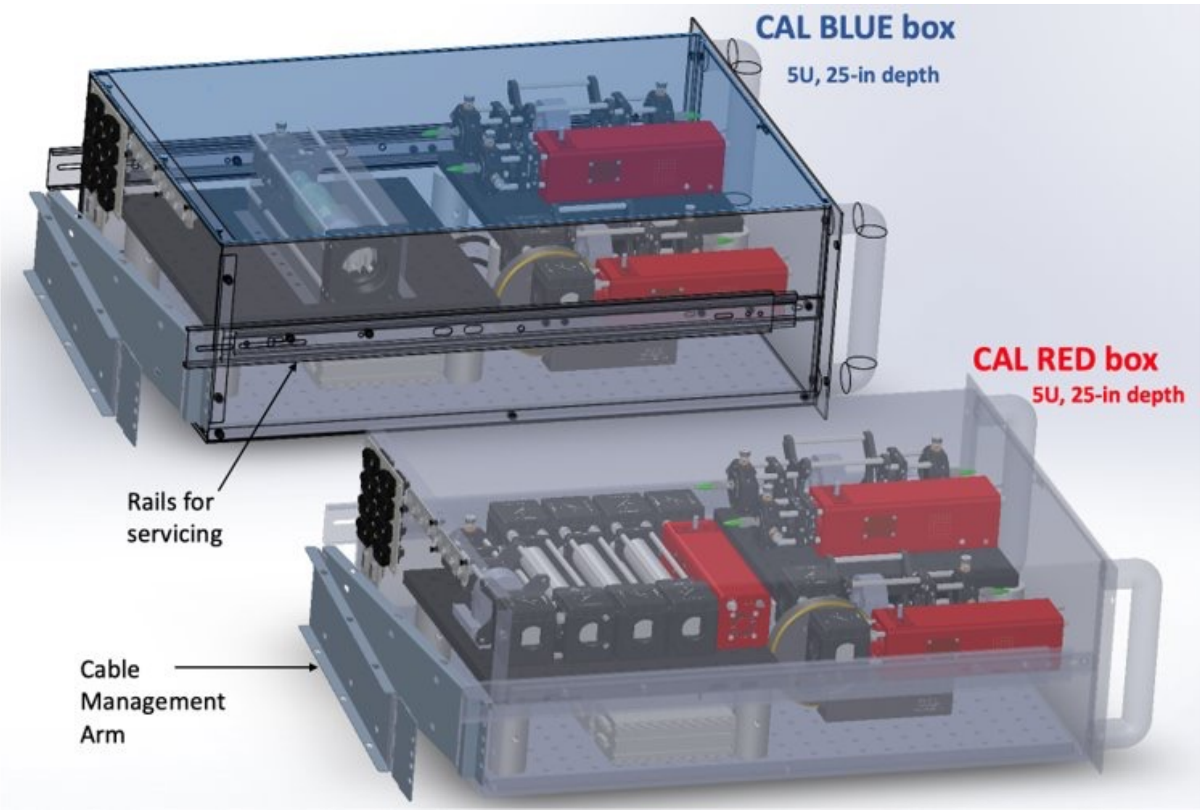


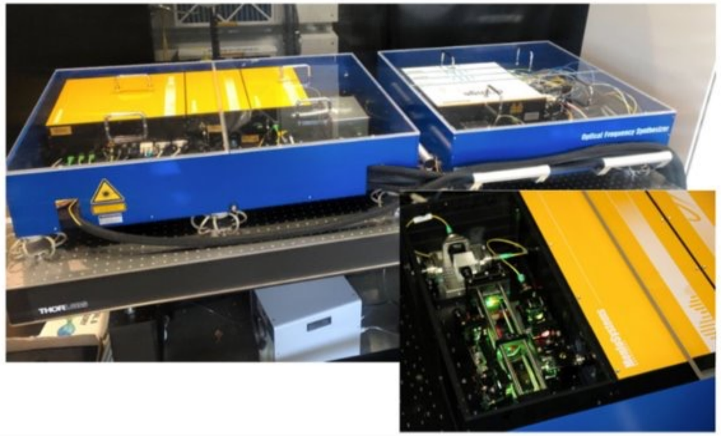
Overlap between adjacent traces < 0.1%

Extensive suite of calibration sources

- Fabry-Perot Etalons
- Laser Frequency Combs
- Gas/arc lamps
- Flat field lamp







MODHIS status

- Finalizing CoDP-1
- Entering CoDP-2
  - Flesh out other science cases (e.g. Solar system science)
  - Spectro-polarimetric science case
  - NFIRAOS Support Structure, Rotator, and On-Instrument Wavefront Sensor (SRO) interface
  - Fiber routing and spectrograph location
- Precursor instrument HISPEC passed PDR and entering Full-Scale Development