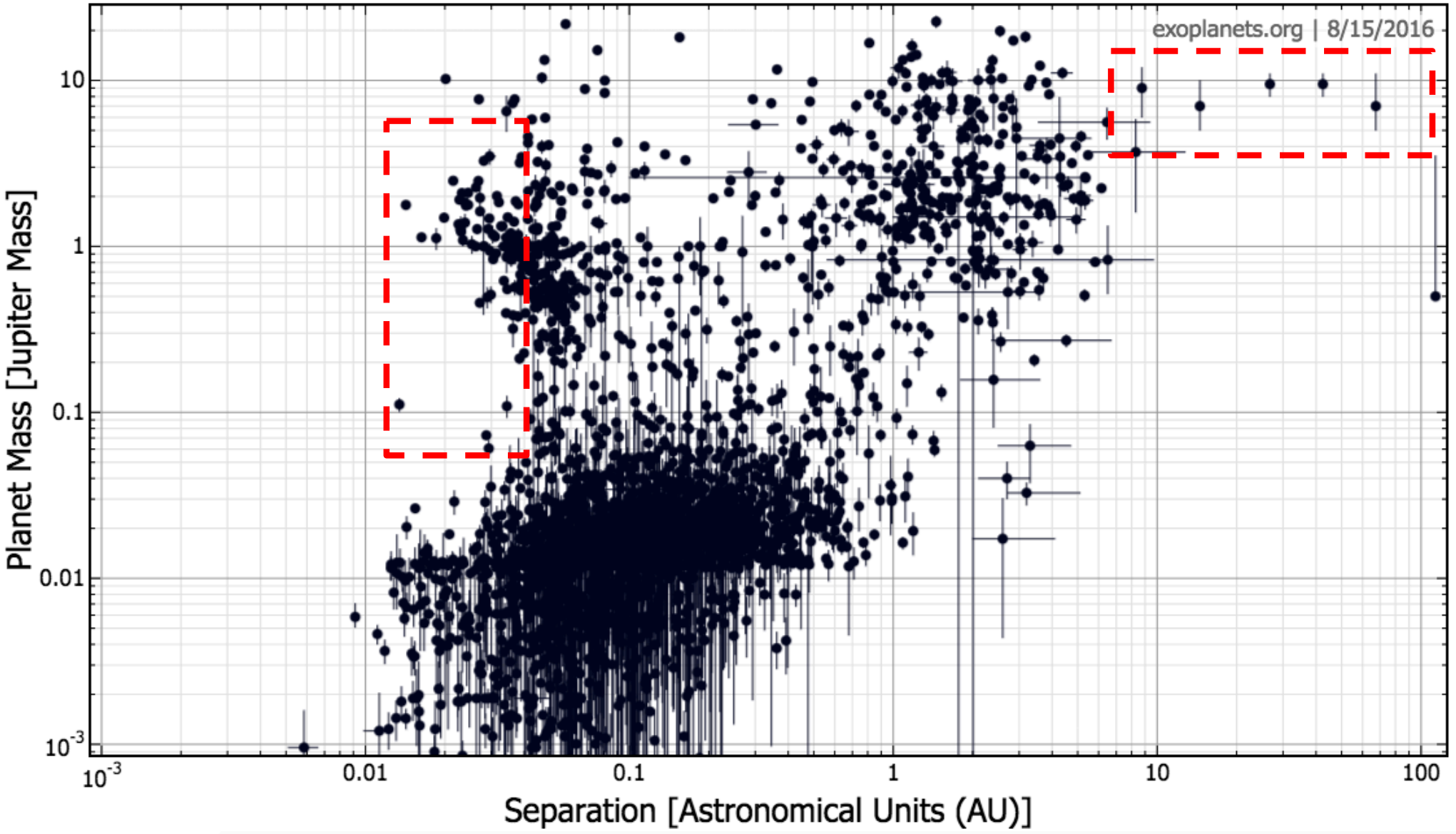
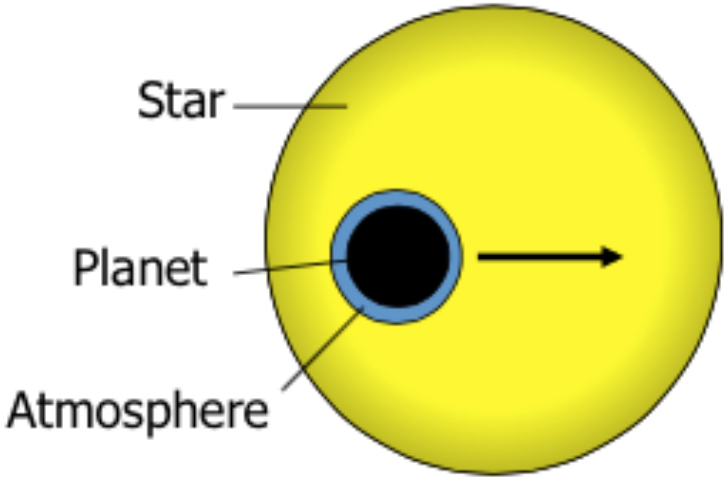
New Front of Exoplanetary Science: High Dispersion Coronagraphy (HDC)

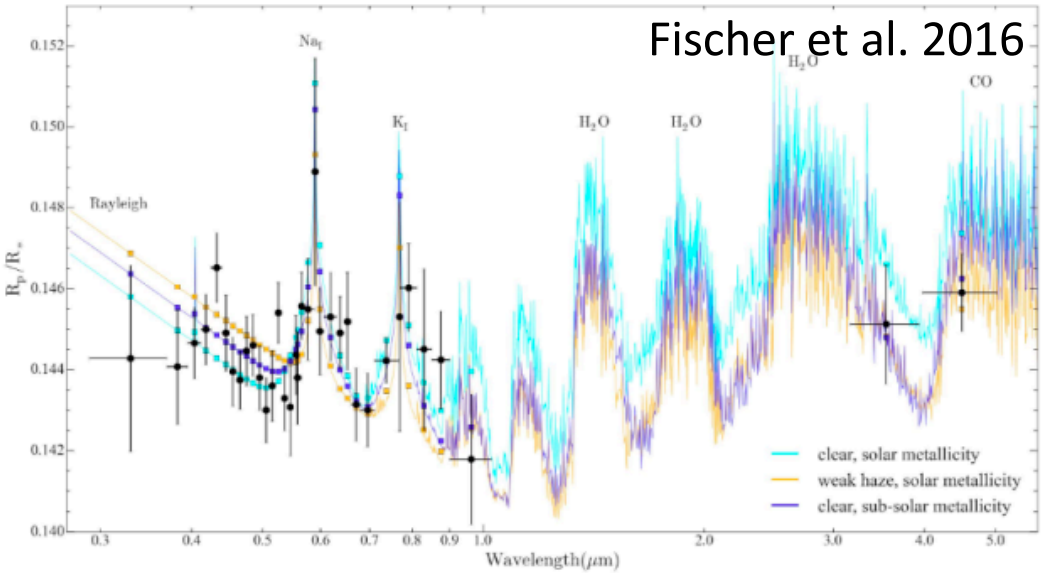
Ji Wang

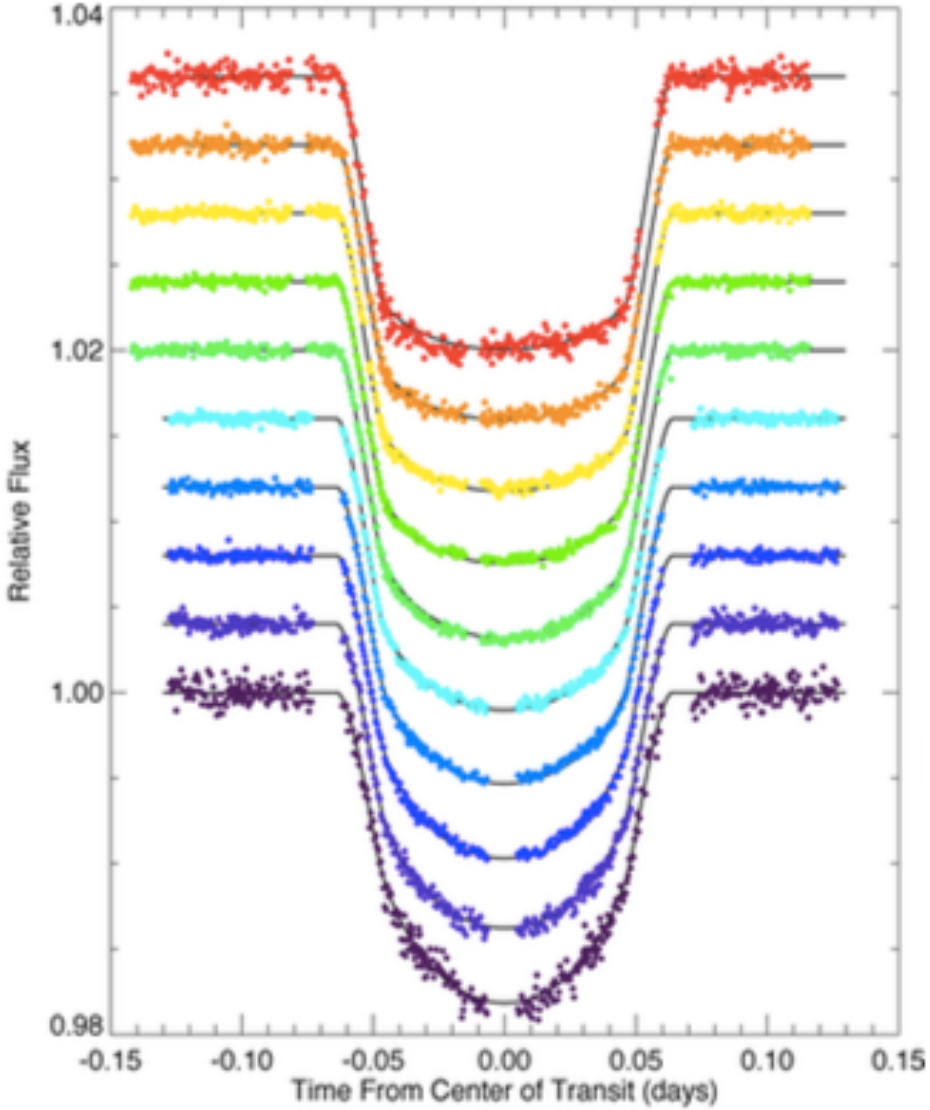
Caltech


exoplanets.org | 8/15/2016
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^-3
10^-3
0.01
0.1
1
10
100
Separation [Astronomical Units (AU)]

Transmission Spectroscopy

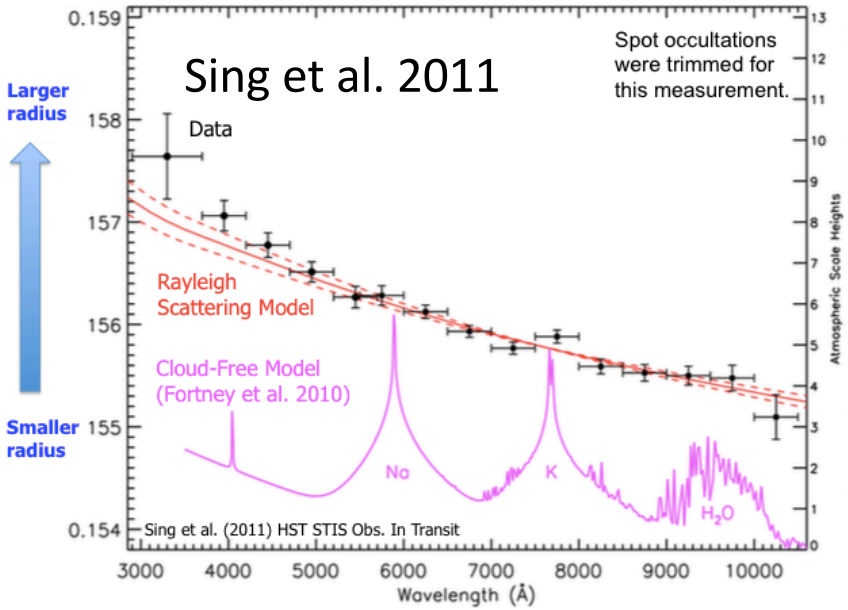


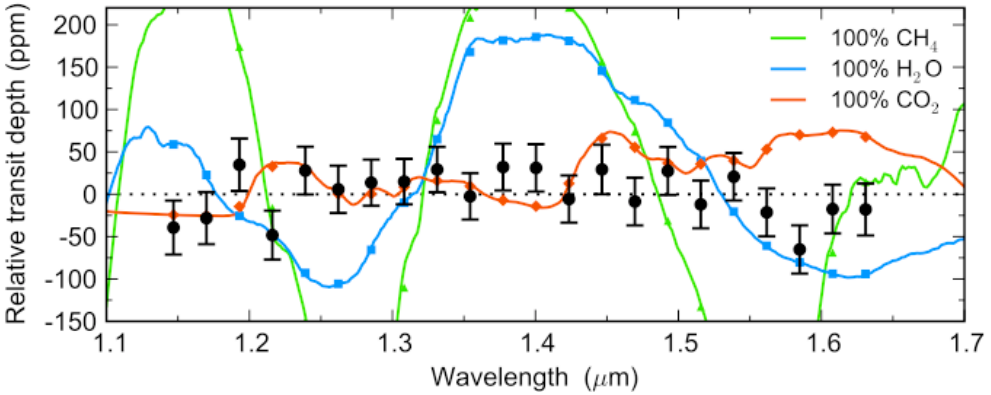




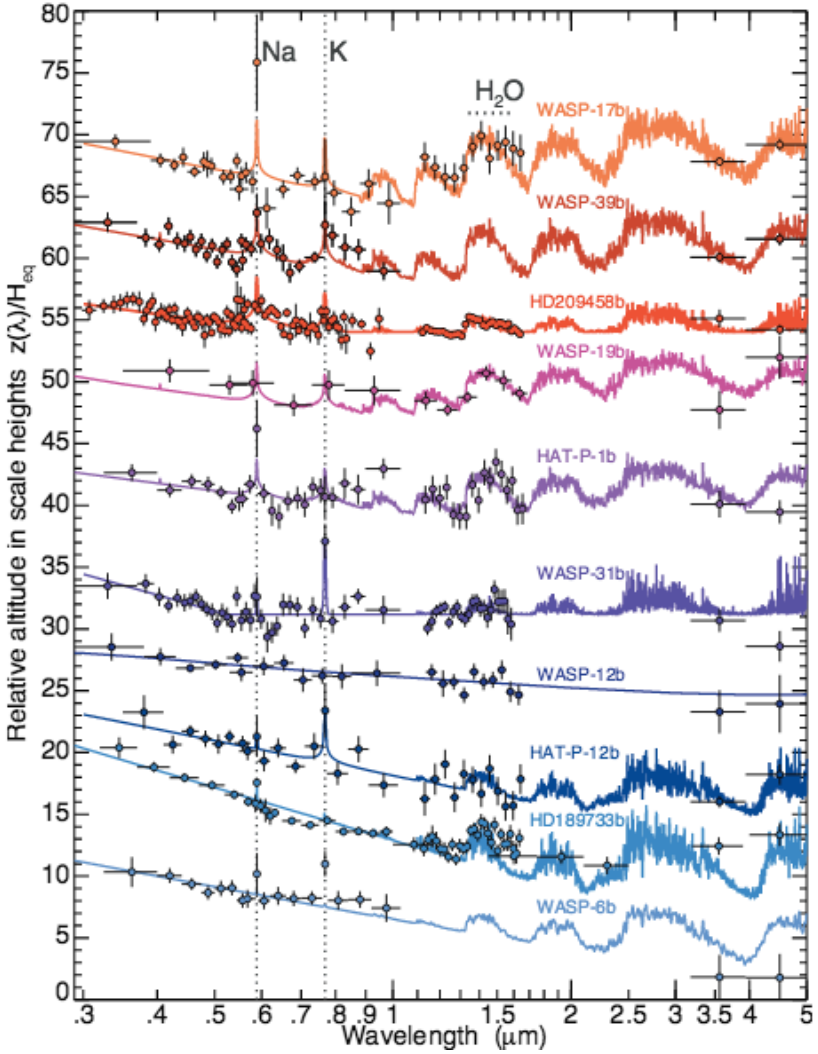
Knutson et al. 2007

Cloud and Haze



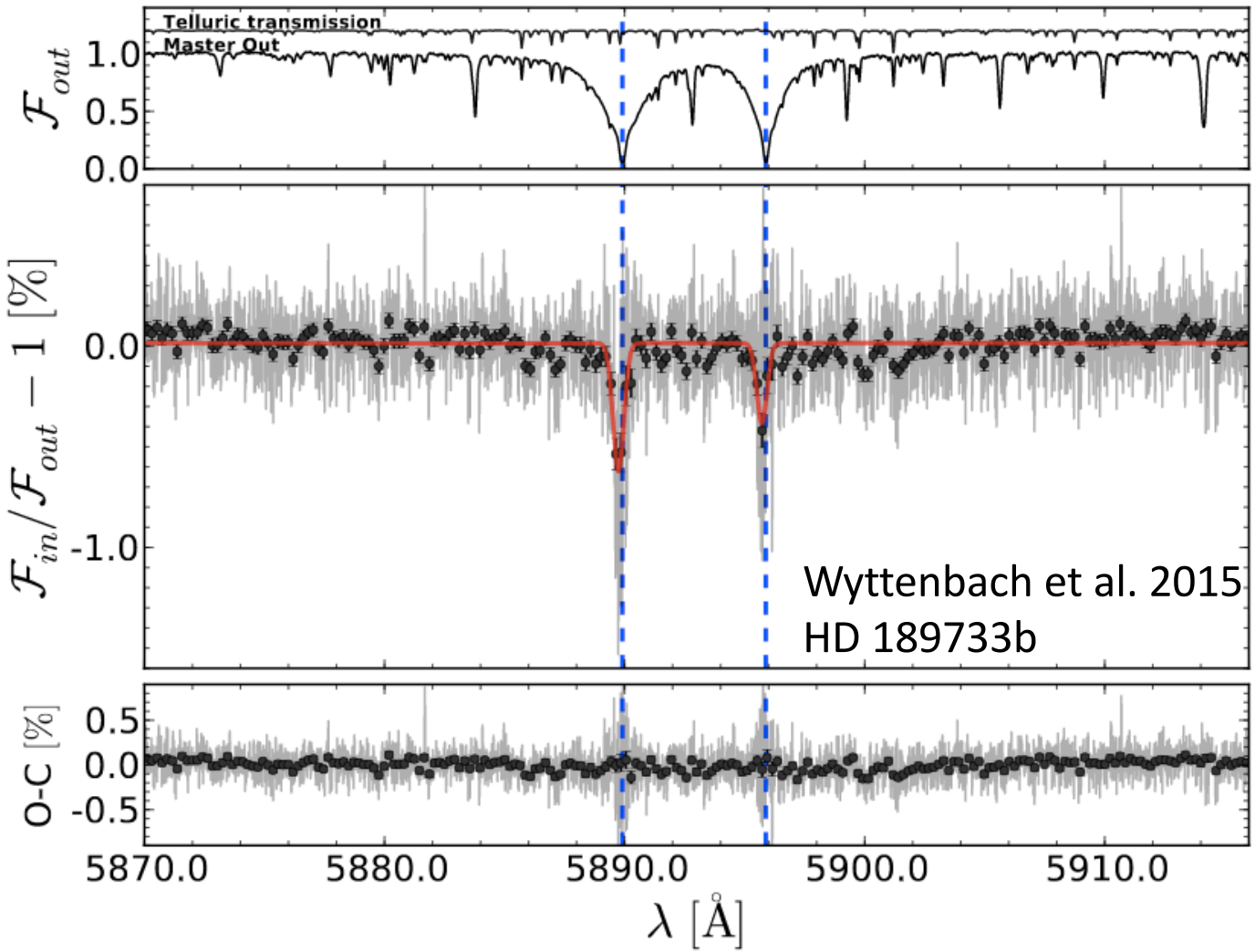


Kreidberg et al. 2014



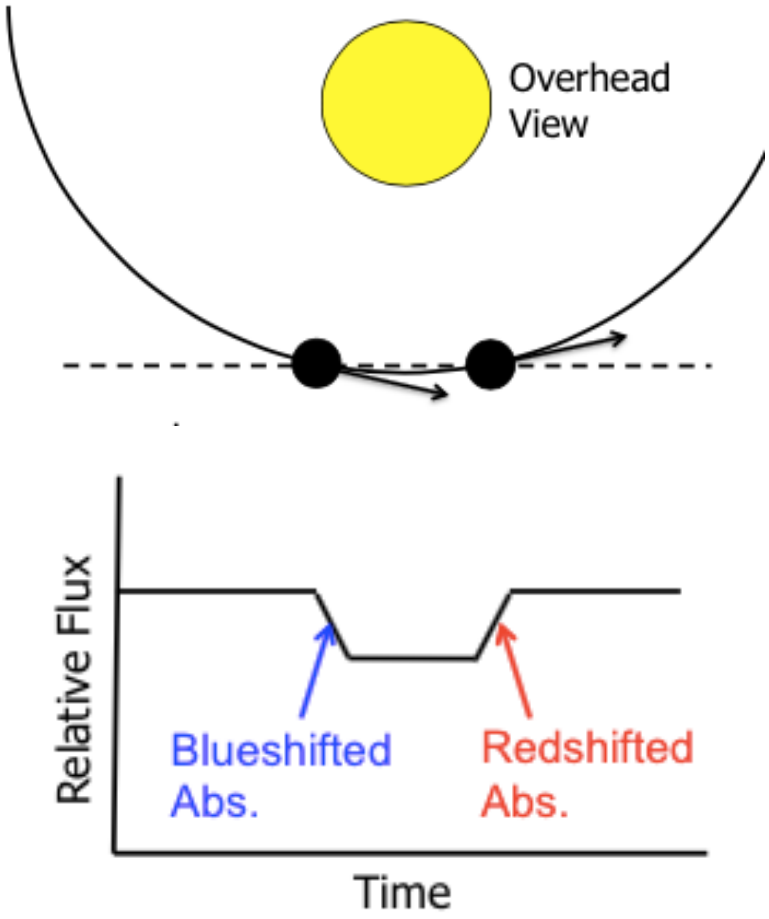
Sing et al. 2016

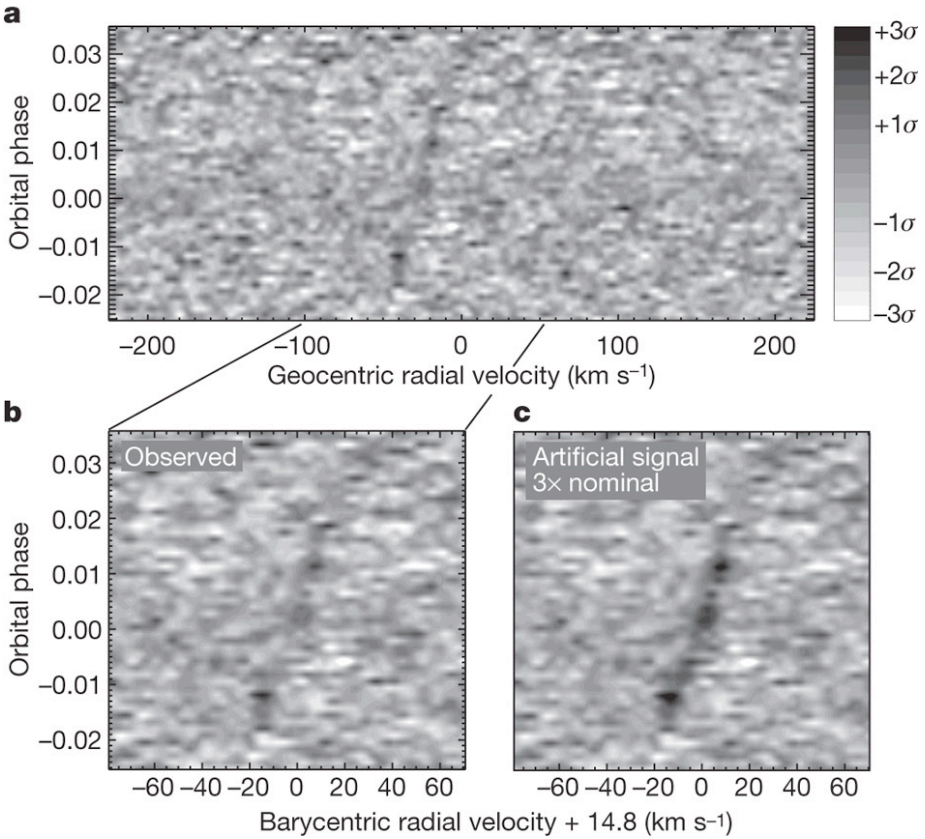
High Resolution Spectroscopy



See also Khalafinejad et al. 2016

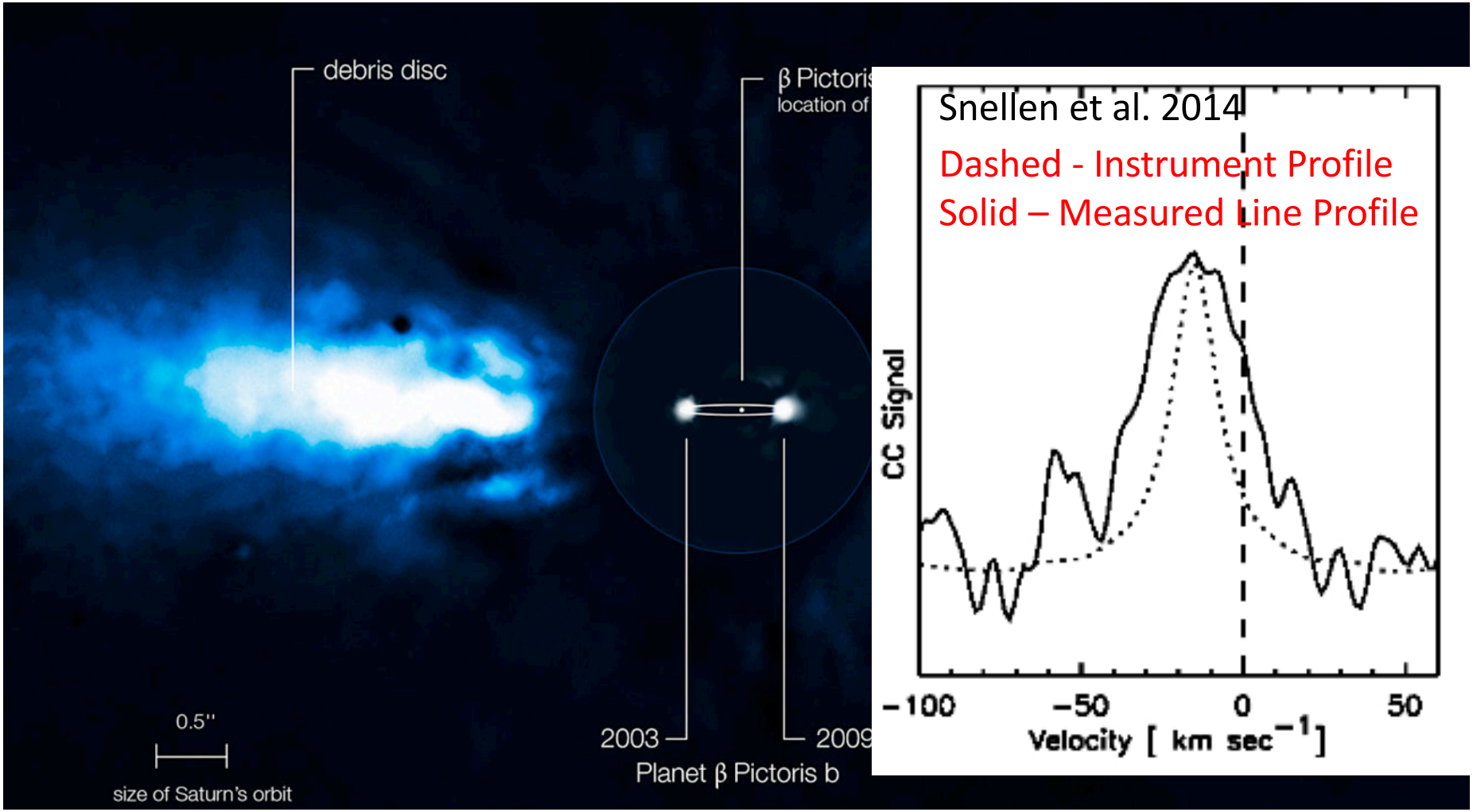
Atmospheric Composition From High-Resolution Spectroscopy



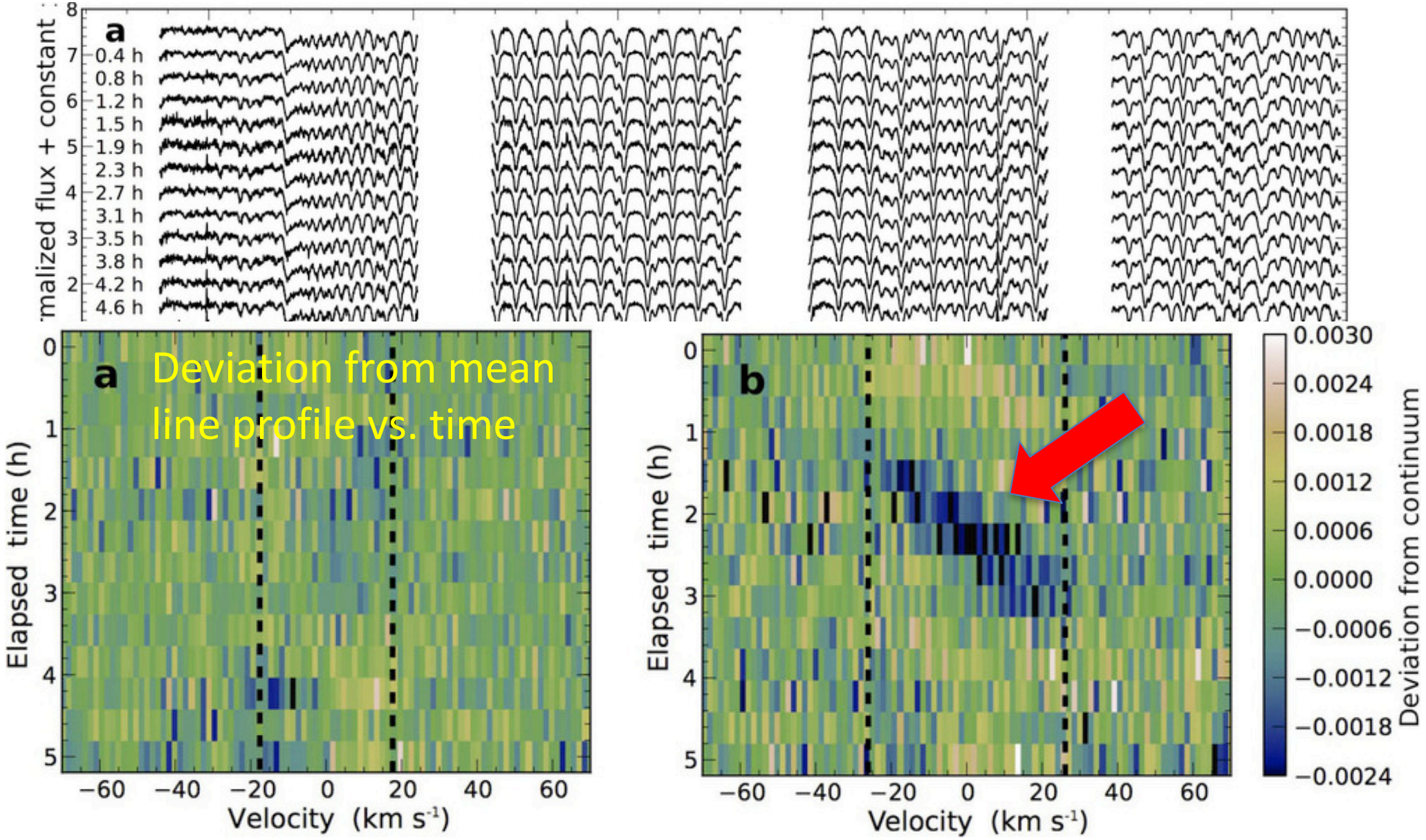


HD 209458, Snellen et al. 2010

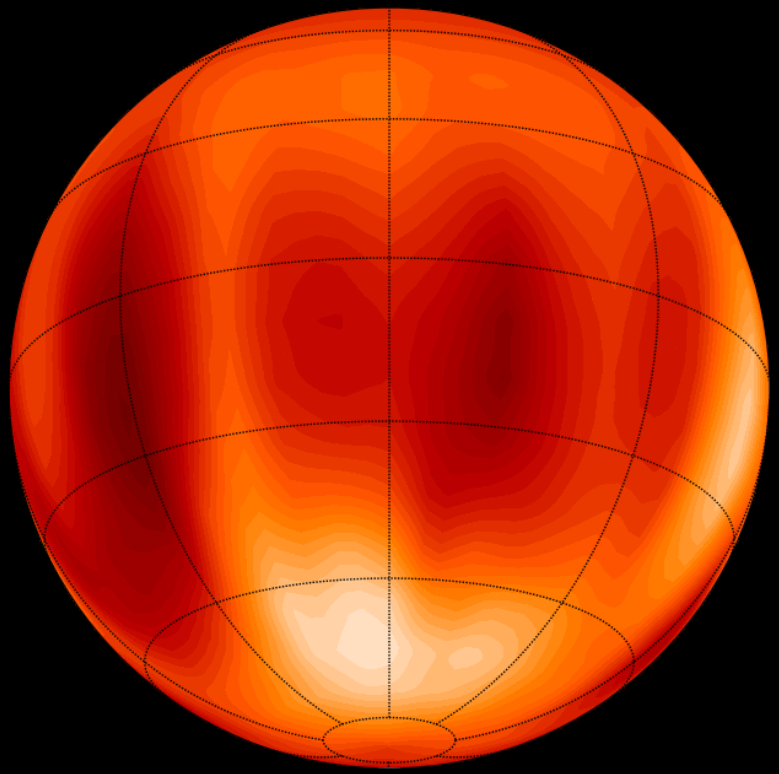
Planet Rotation – Beta Pic b



Doppler Imaging – Luhman 16 A & B

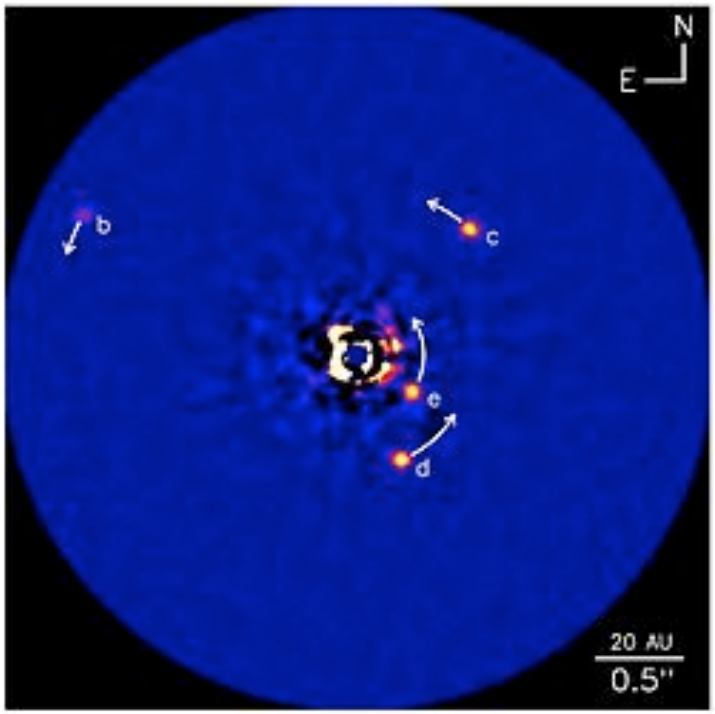


Cloud map of Lunman 16 B

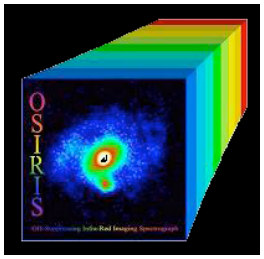


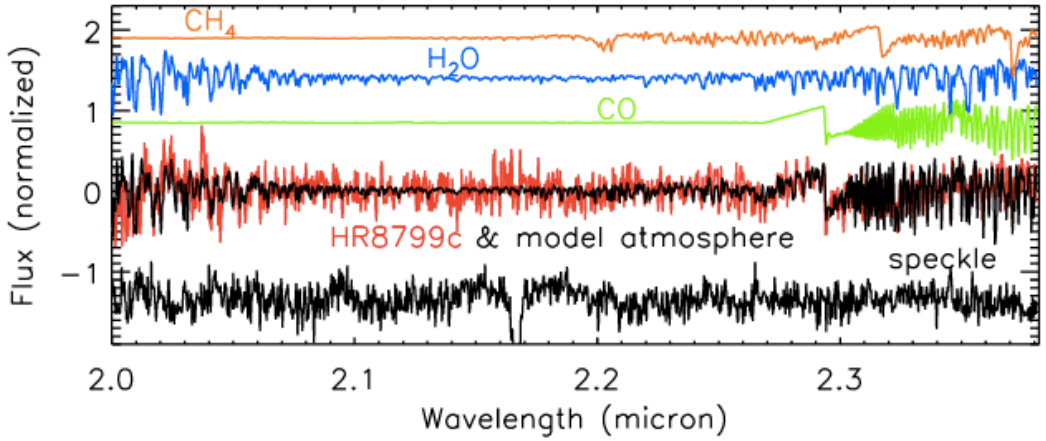
Luhman 16 B (Crossfield et al. 2014)

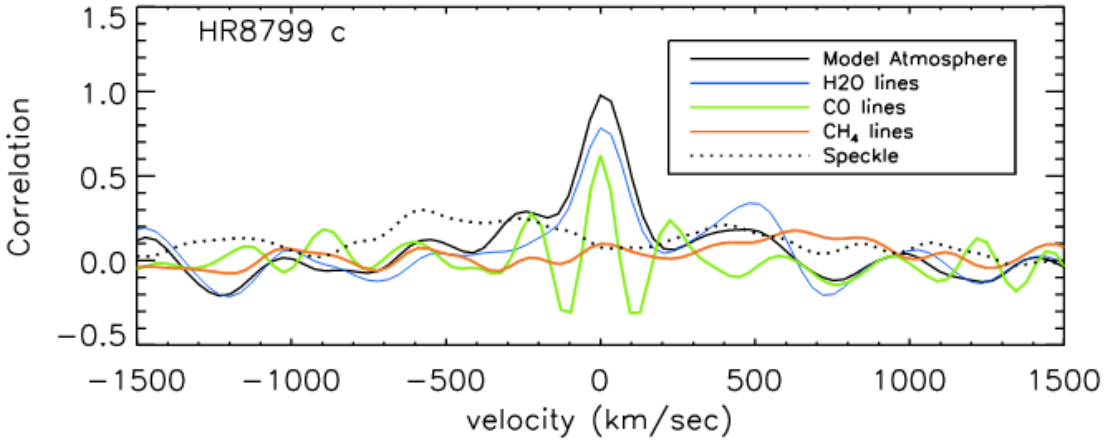
Detection of H_2O and CO on HR 8799 c



Keck OSIRIS

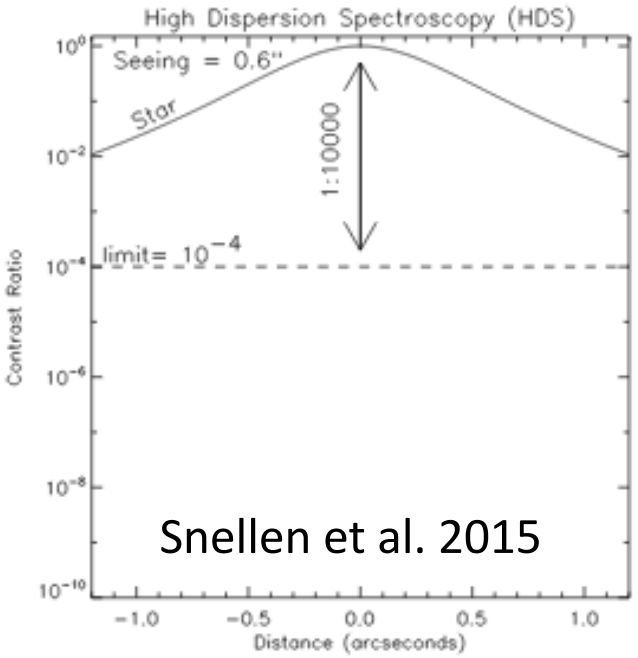


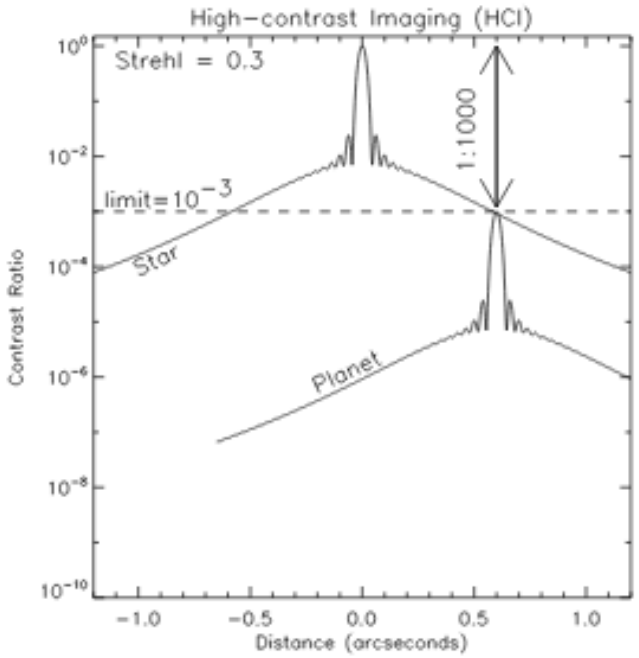


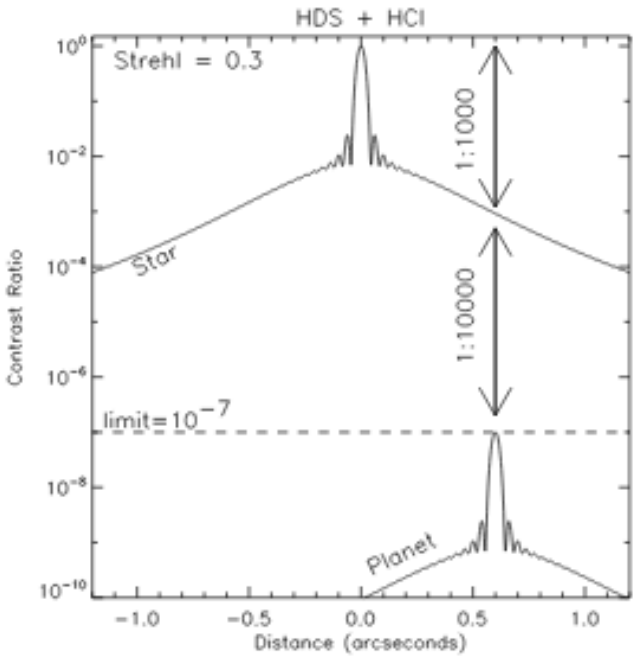


Konopacky et al. 2013

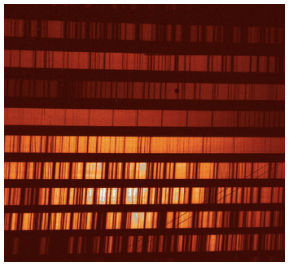
High Dispersion Coronagraphy



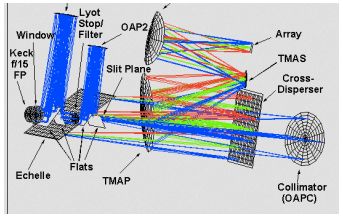


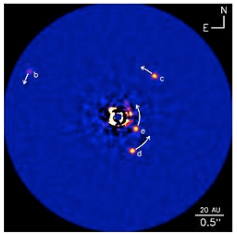


Snellen et al. 2015

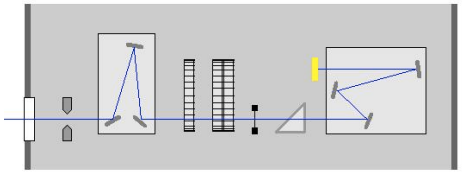


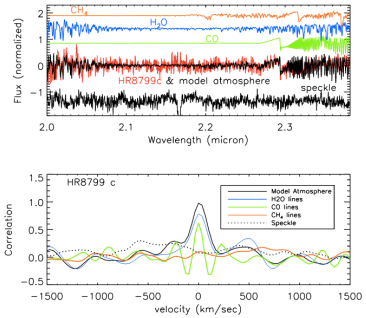
Keck NIRSPEC





Keck NIRC2 Vortex





Keck Planet Imager and Characterizer

PI: D. Mawet (Caltech)

- Upgrade to Keck II AO and instrument suite:
  - L-band vortex coronagraph in NIRC2 - deployed
  - IR PyWFS – funded (NSF)
  - SMF link to upgraded NIRSPEC (FIU) - funded (HSF & NSF)
  - High contrast FIU – seeking funding
  - MODIUS: New fiber-fed, Multi-Object Diffraction limited IR Ultra-high resolution (R~150k-200k) Spectrograph – design study encouraged by KSSC

- Pathfinder to ELT planet imager exploring new high contrast imaging/spectroscopy instrument paradigms:
  - Decouple search and discovery from characterization: specialized module/strategy for each task
  - New hybrid coronagraph designs: e.g. apodized vortex
  - Wavefront control: e.g. speckle nulling on SMF

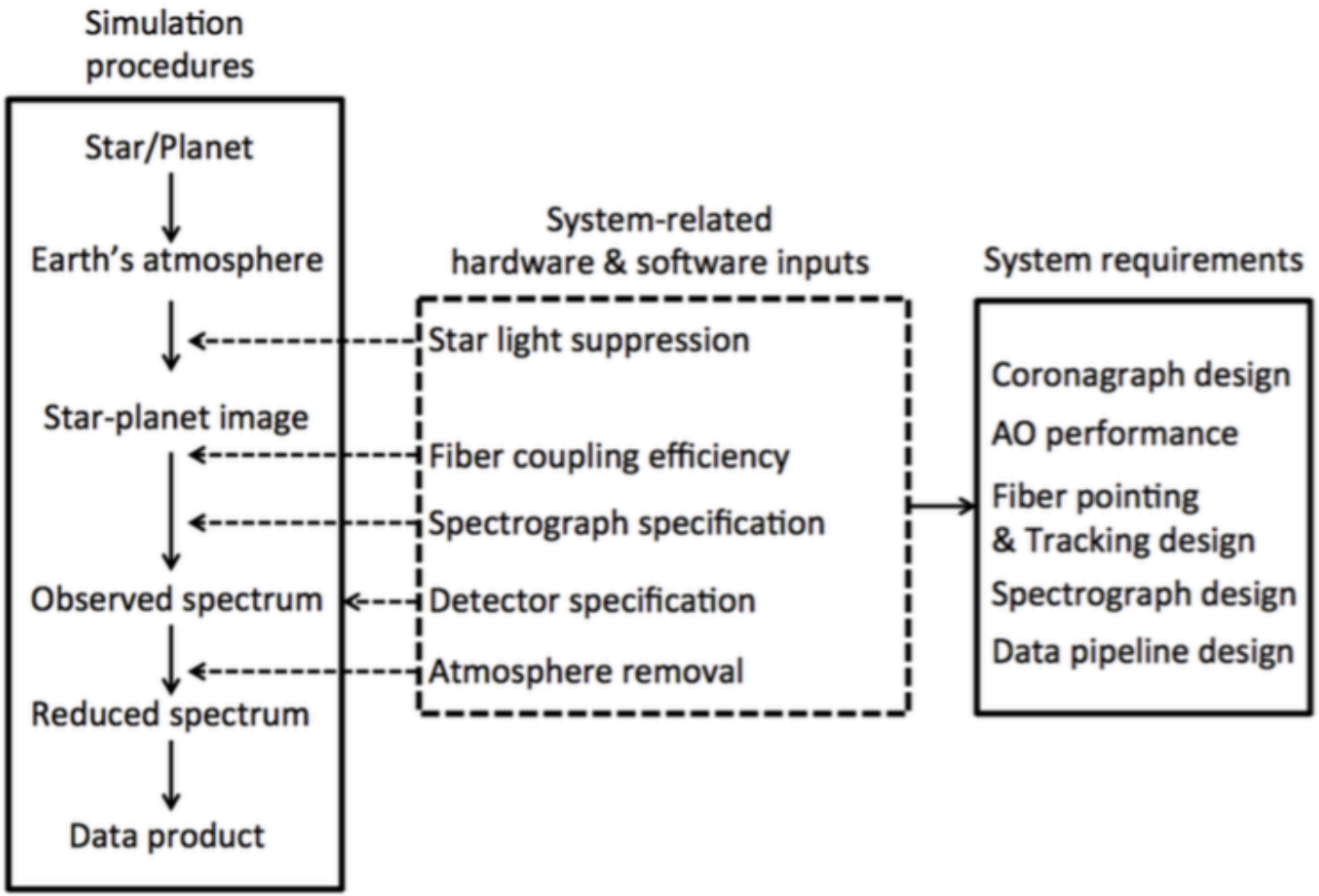
HDC Instruments

- CRIRES
- SPHERE + ESPRESSO
- SCExAO + IRD
- MagAO-X + RHEA
- Keck Planet Imager and Characterizer (KPIC)

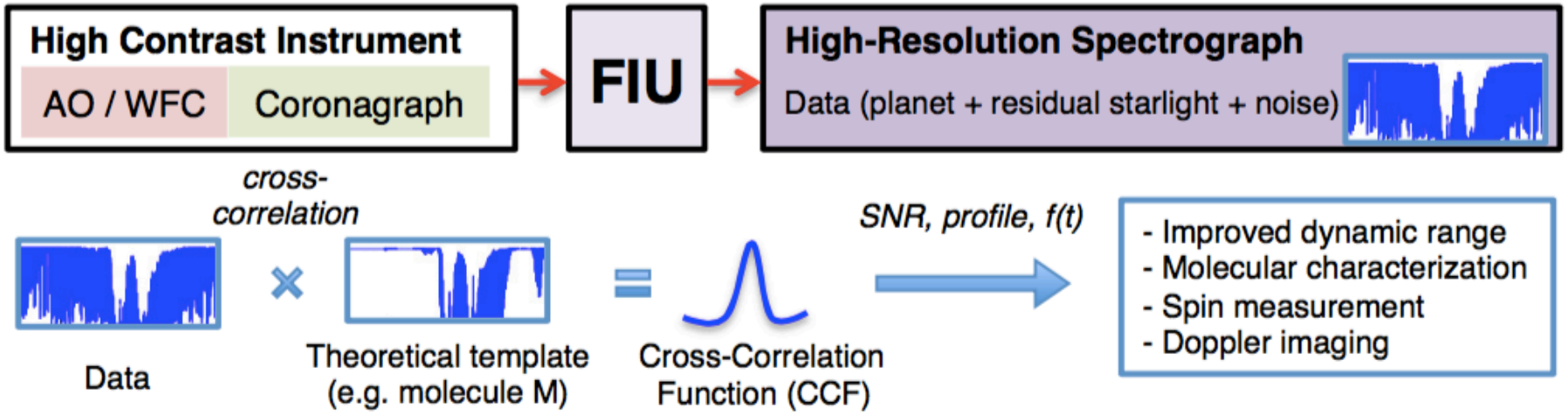
Science cases for HDC

- Planet detection and confirmation at moderate contrast from ground
- Detecting molecular species in planet atmospheres
- Measuring planet rotation
- Measuring cloud map for brown dwarfs and exoplanets

HDC Simulator



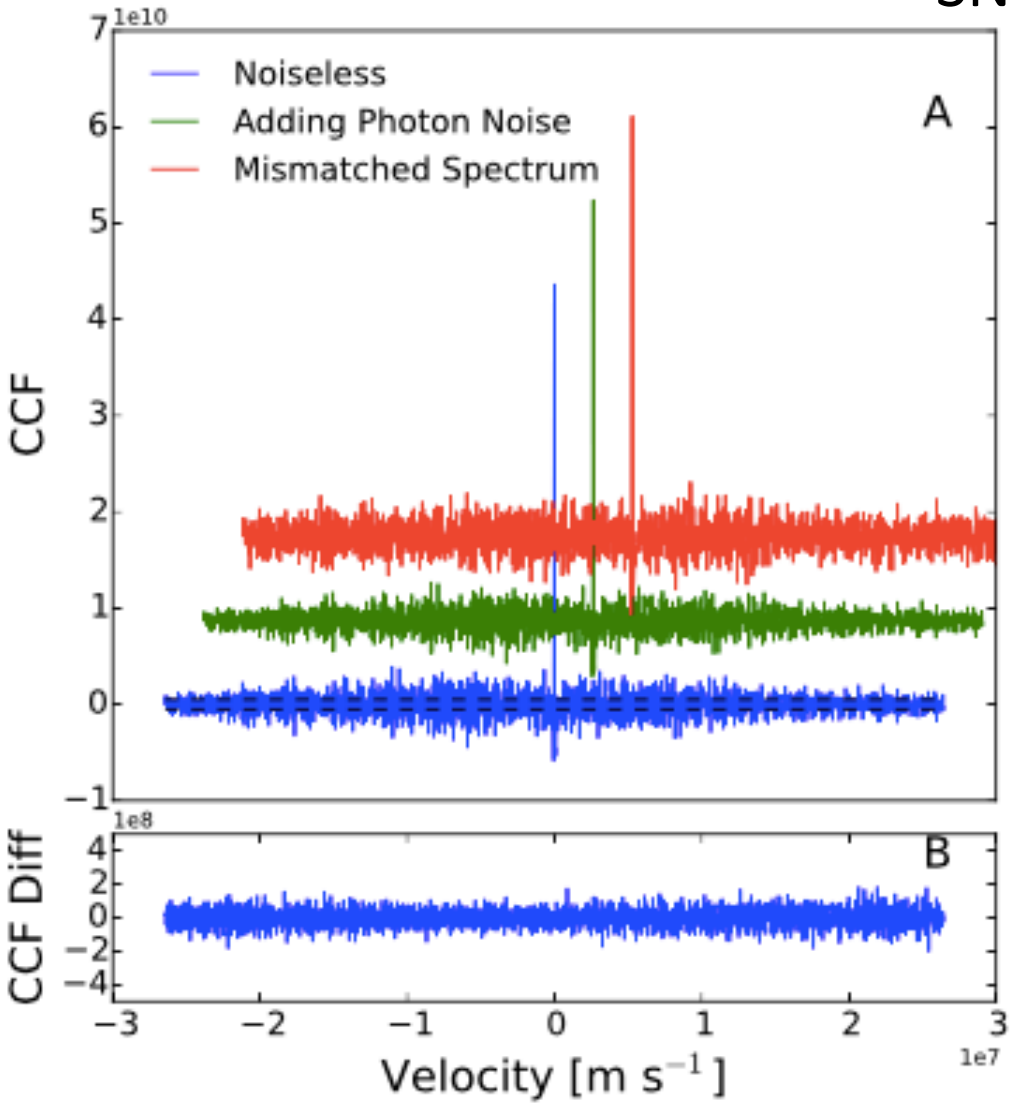
Template Matching



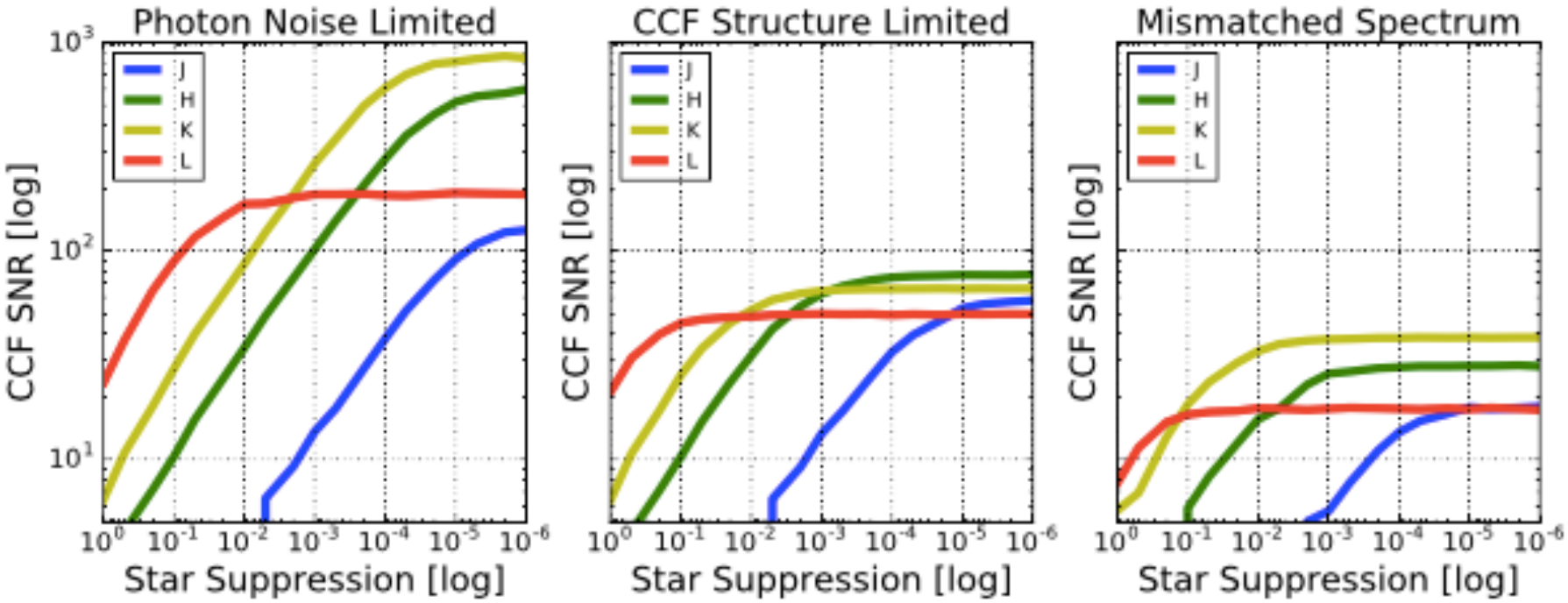
Mawet et al. 2016

CCF SNR

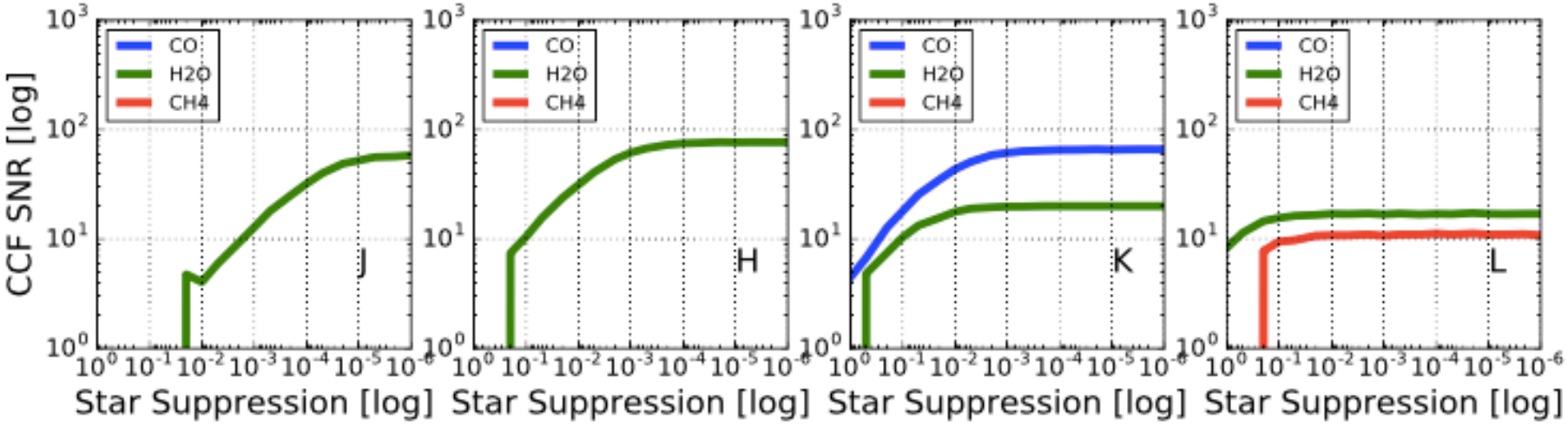
SNR = Peak / Fluctuation



Limiting Factors of CCF SNR for HR 8799e Observation



Detecting Molecular Species



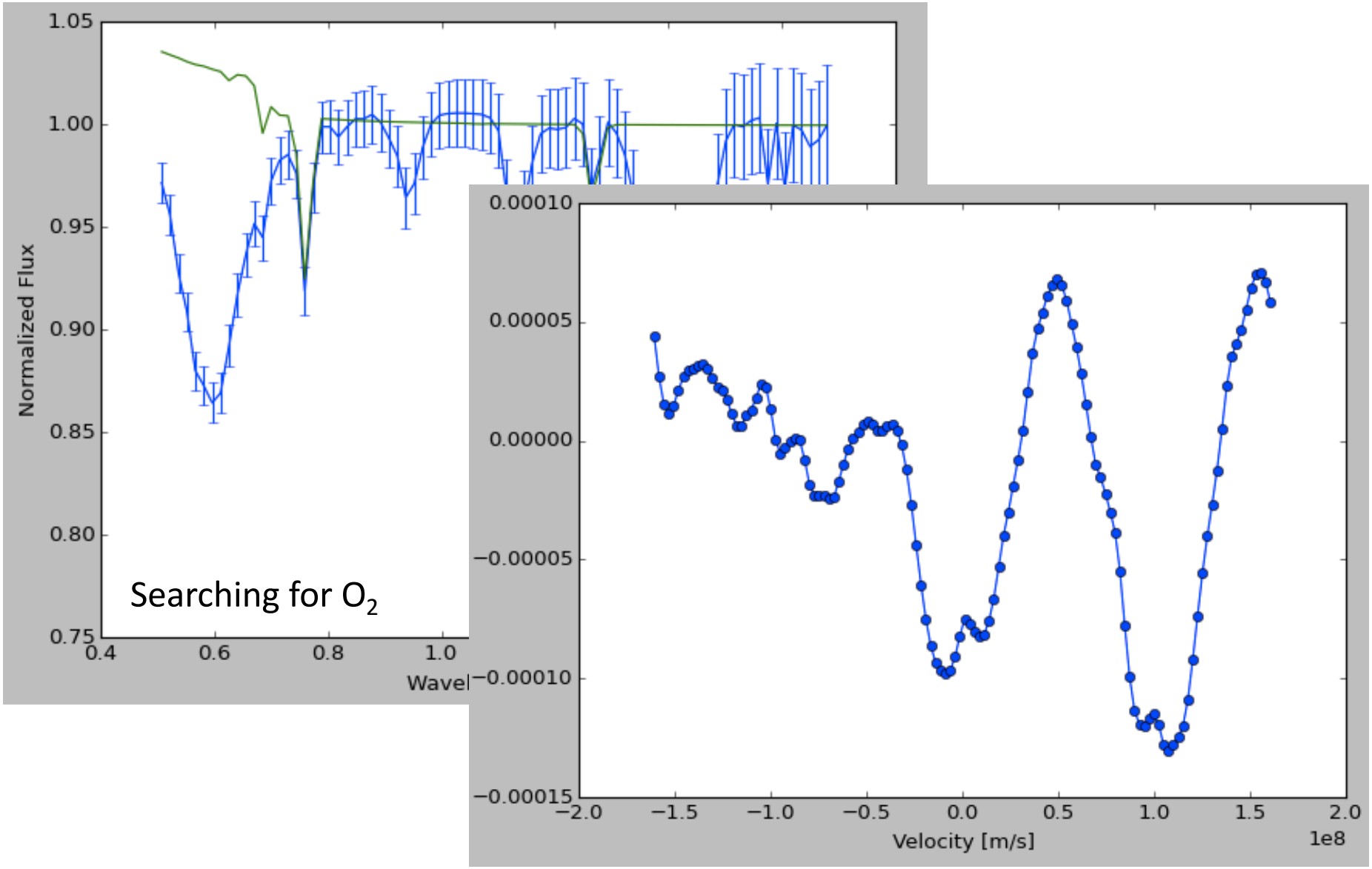
Space-based vs. Ground-based

- Non-cryogenic vs. cryogenic
- Atmosphere-free vs. atmosphere
- Absorption bands vs. lines
- Starlight suppression
- Inner working angle
- *Sun-Earth vs. M dwarf planet*

Redefining CCF SNR for Space-based Observation

- CCF does not work well in low spectral resolution (few data points)

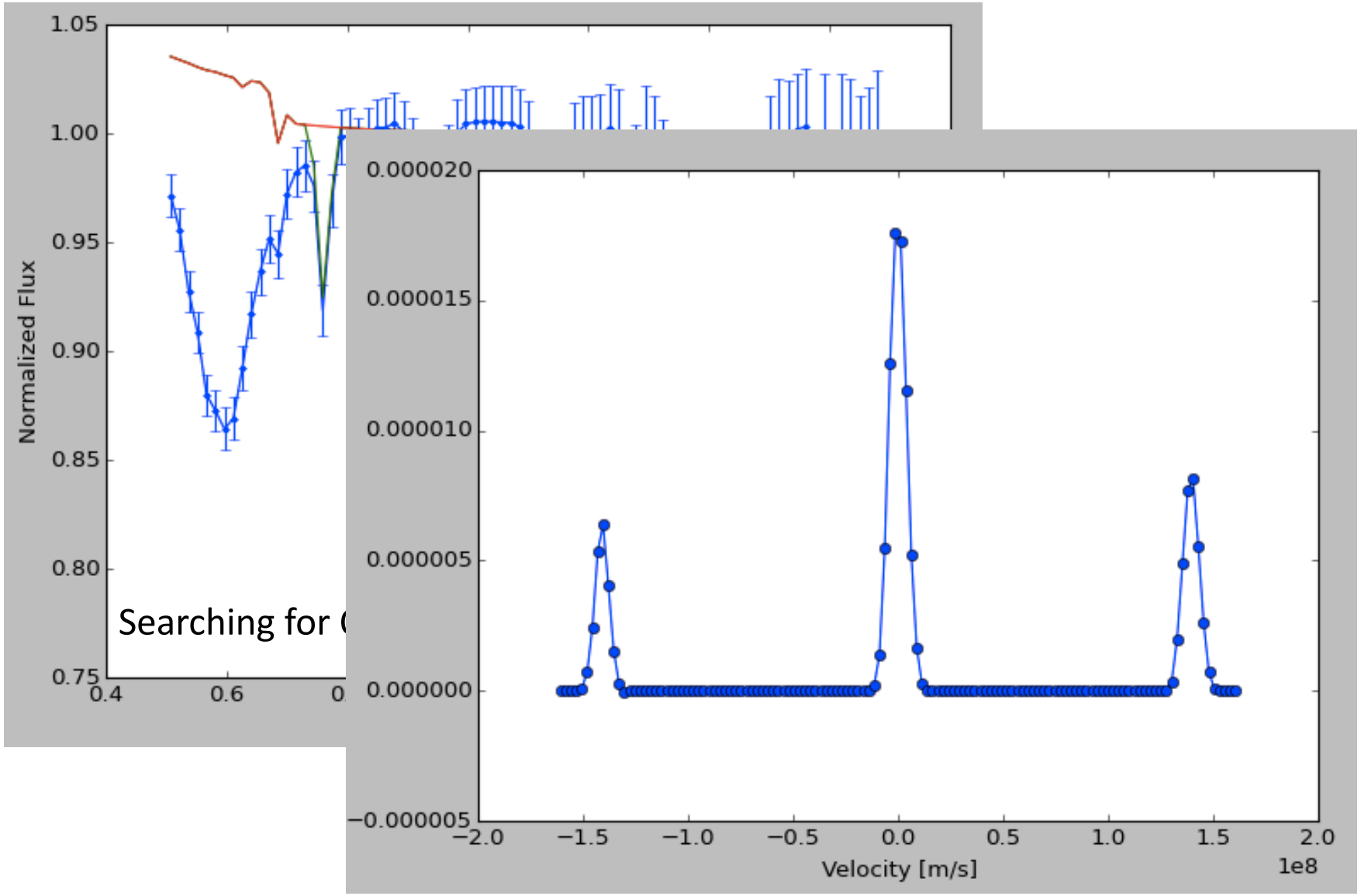
CCF at Low Resolutions



Redefining CCF SNR for Space-based Observation

- CCF does not work well in low spectral resolution (few data points)
- Masked cross correlation function

Masked Cross Correlation



Redefining CCF SNR for Space-based Observation

- CCF does not work well in low spectral resolution (few data points and speckle chromatic noise)
- Masked cross correlation function
- Photon-noise changes a factor of a few at two ends of spectrum (0.5 – 1.7 um)

Redefining CCF SNR for Space-based Observation

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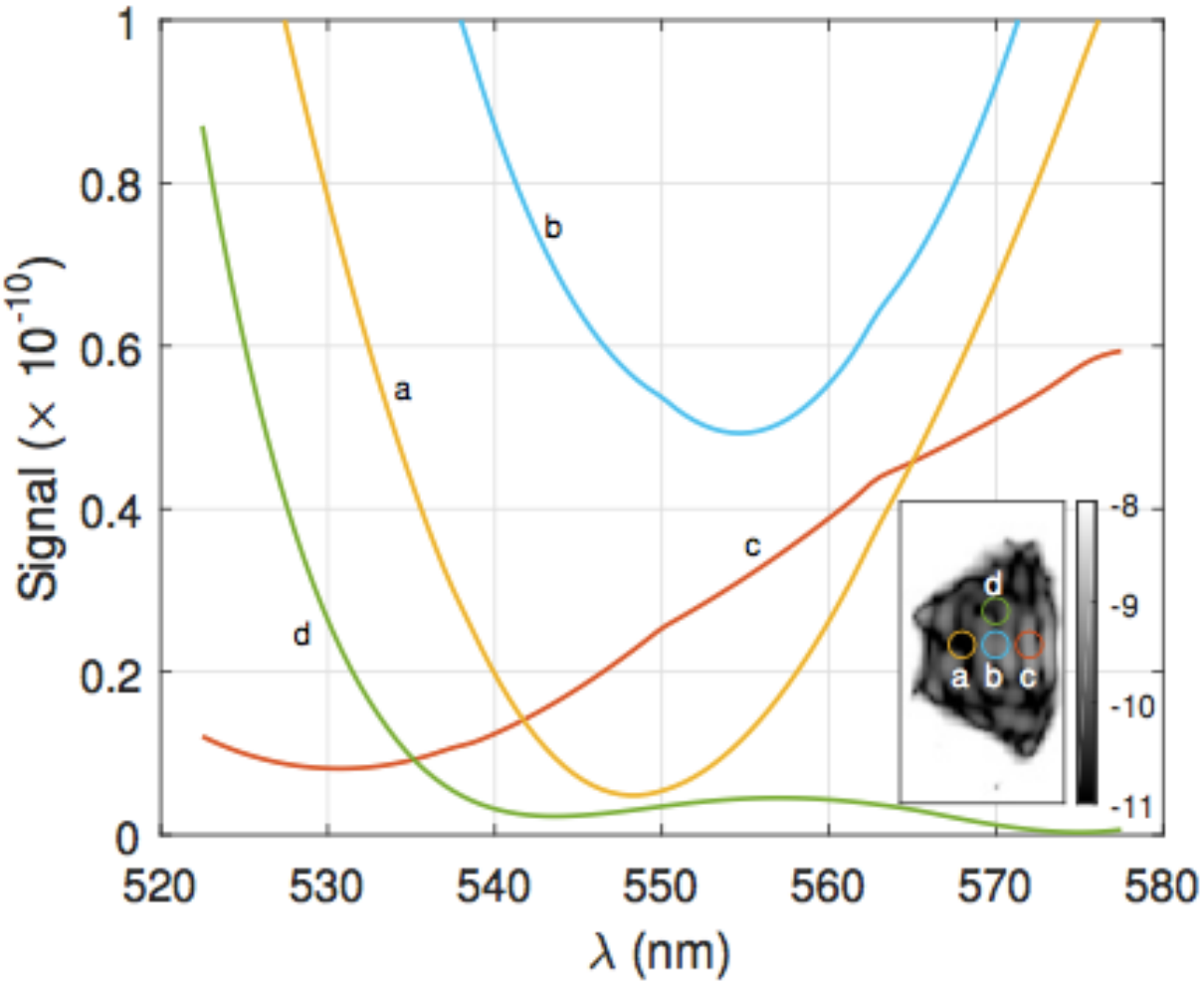
- Speckle chromatic noise

Speckle Chromatic Noise

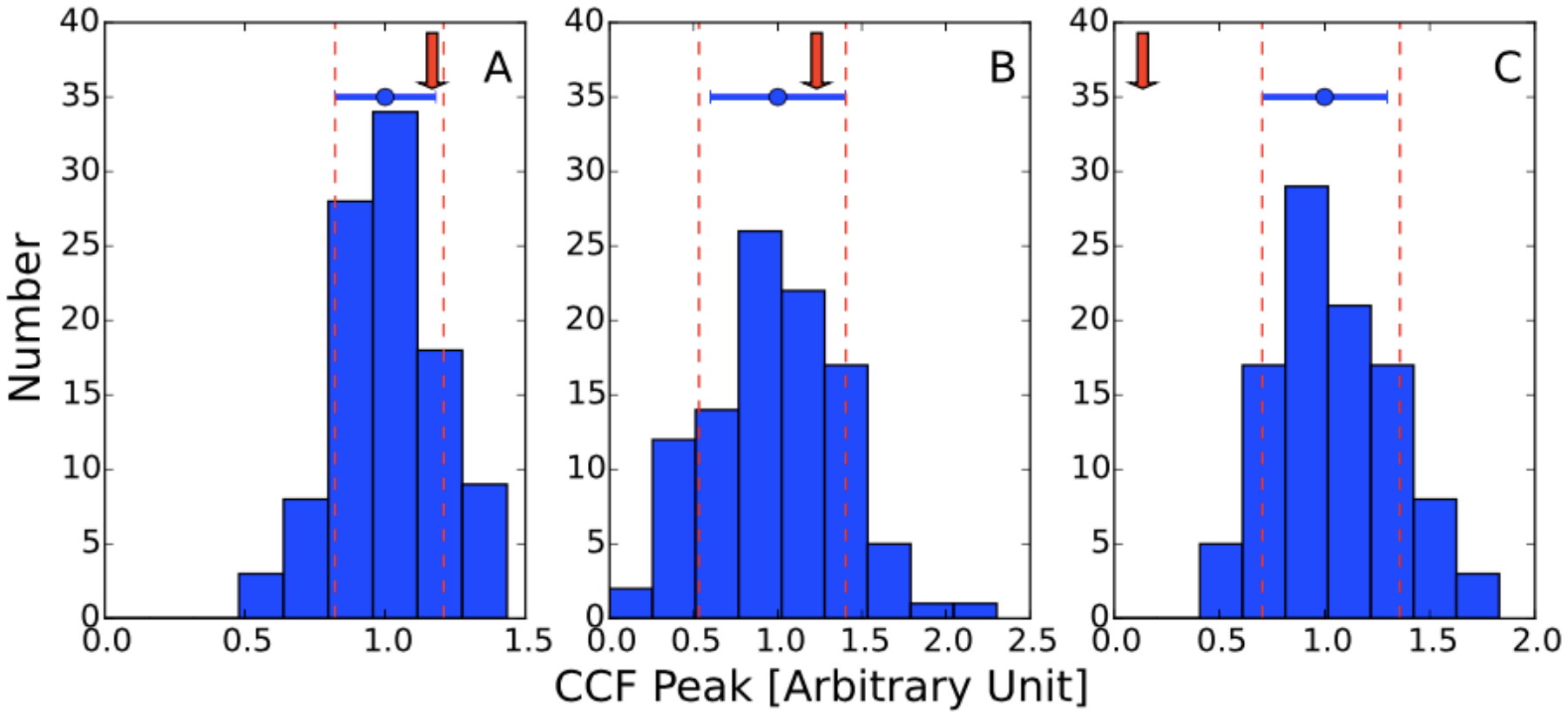


Simulation by Garreth Ruane

New Definition of CCF SNR

Red arrow – noiseless CCF peak

Blue error bar – median and 1-sigma range of simulated CCF peak distribution



LUVOIR

Telescope and instrument parameters for LUVOIR or HabEx.

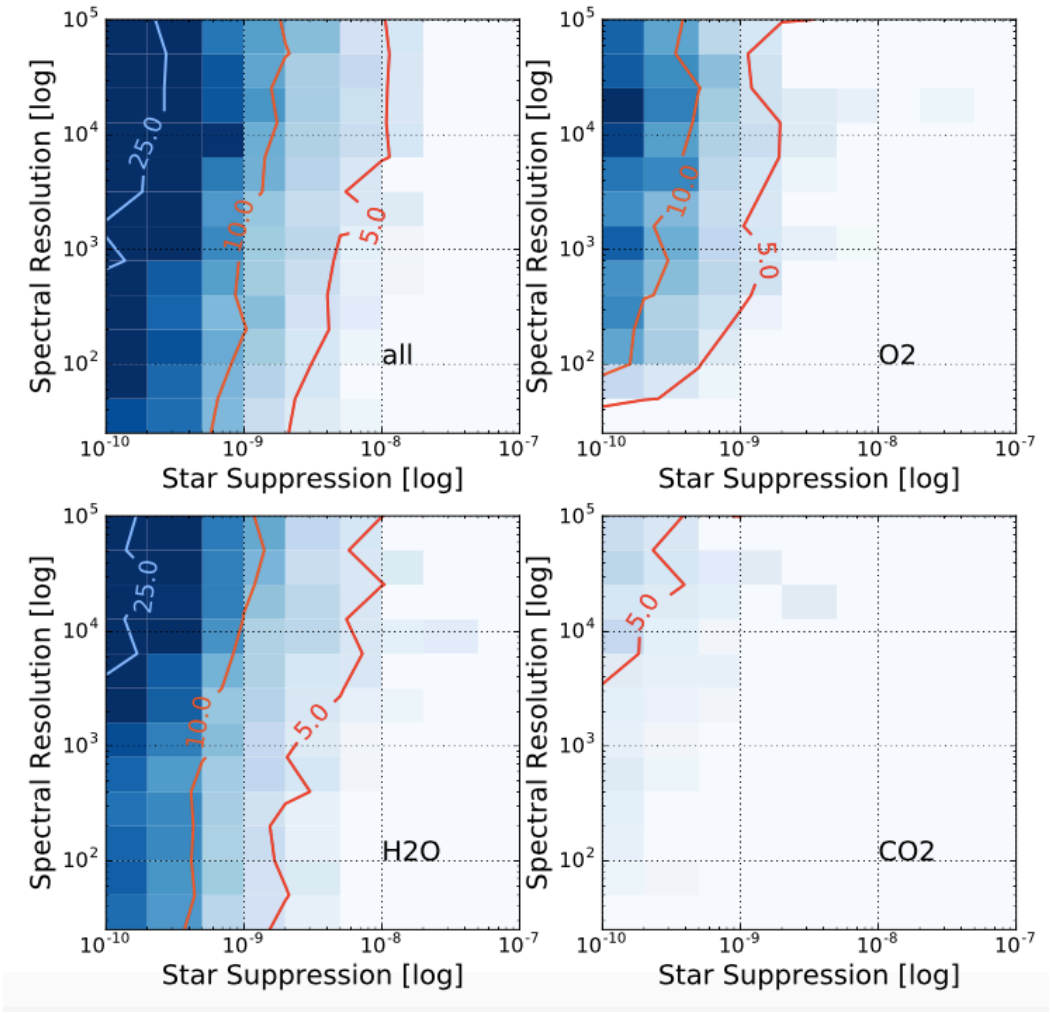
Parameter	Value	Unit
Telescope aperture	4.0 or 12.0	m
Telescope+instrument throughput	10%	...
Wavefront correction error floor	5	nm
Spectral resolution	varied	...
Spectral range	0.5 - 1.7	μm
Exposure time	400 or 100	hour
Fiber angular diameter	1.0	λ/D
Readout noise	0.0 or 2.0*	e^{-*}
Dark current	0.0 or 0.002 or 5.5×10^{-6}**	$e^{-} s^{-1}$

Note. — *: Based on H2RG detector specification (Blank et al. 2012) and e2v CCD specification. **: Used for O_2 detection.

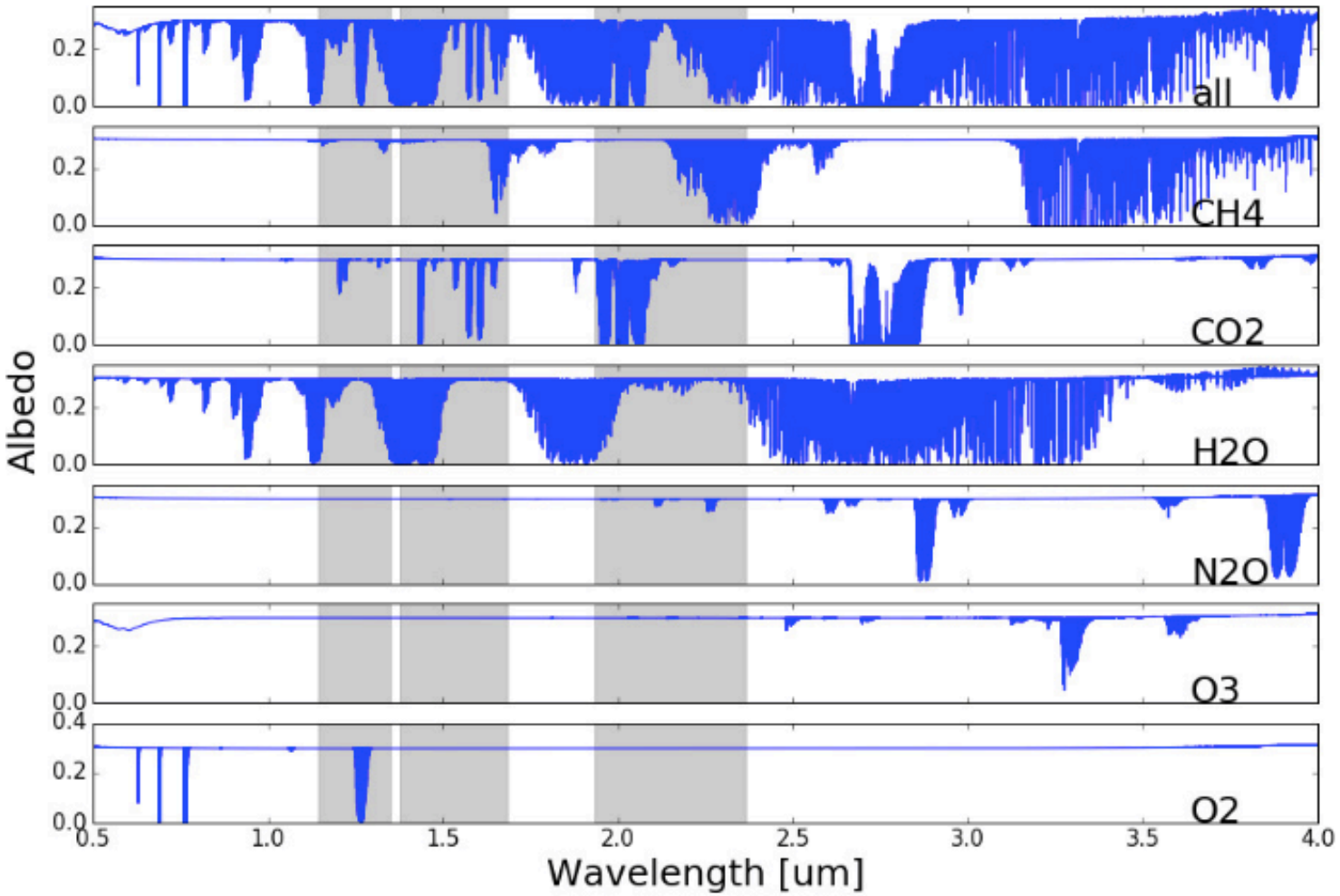
LUVOIR

Parameter	Value	Unit
Star		
Effective temperature (T_{eff})	5800	K
Mass	1.0	$M_\odot$
Radius	1.0	$R_\odot$
Surface gravity ($\log g$)	4.5	cgs
Metallicity ([M/H])	0.0	dex
Distance	5.0	pc
Rotational velocity	2.0	km s^{-1}
Inclination (i)	50	degree
Radial velocity	0,0	km s^{-1}
Planet		
Vsin i***	0.5	km s^{-1}
Inclination (i)	50	degree
Semi-major axis (a)	1.0	AU
Radius	1.0	$R_\oplus$
Radial velocity	20.4	km s^{-1}
Illuminated Area	0.5	...
Planet/Star Contrast	6.1×10^{-11}	...
Angular separation	200.0	mas
Angular separation at 1 μm for 12-m aperture	11.6	λ/D
Angular separation at 1 μm for 4-m aperture	3.9	λ/D

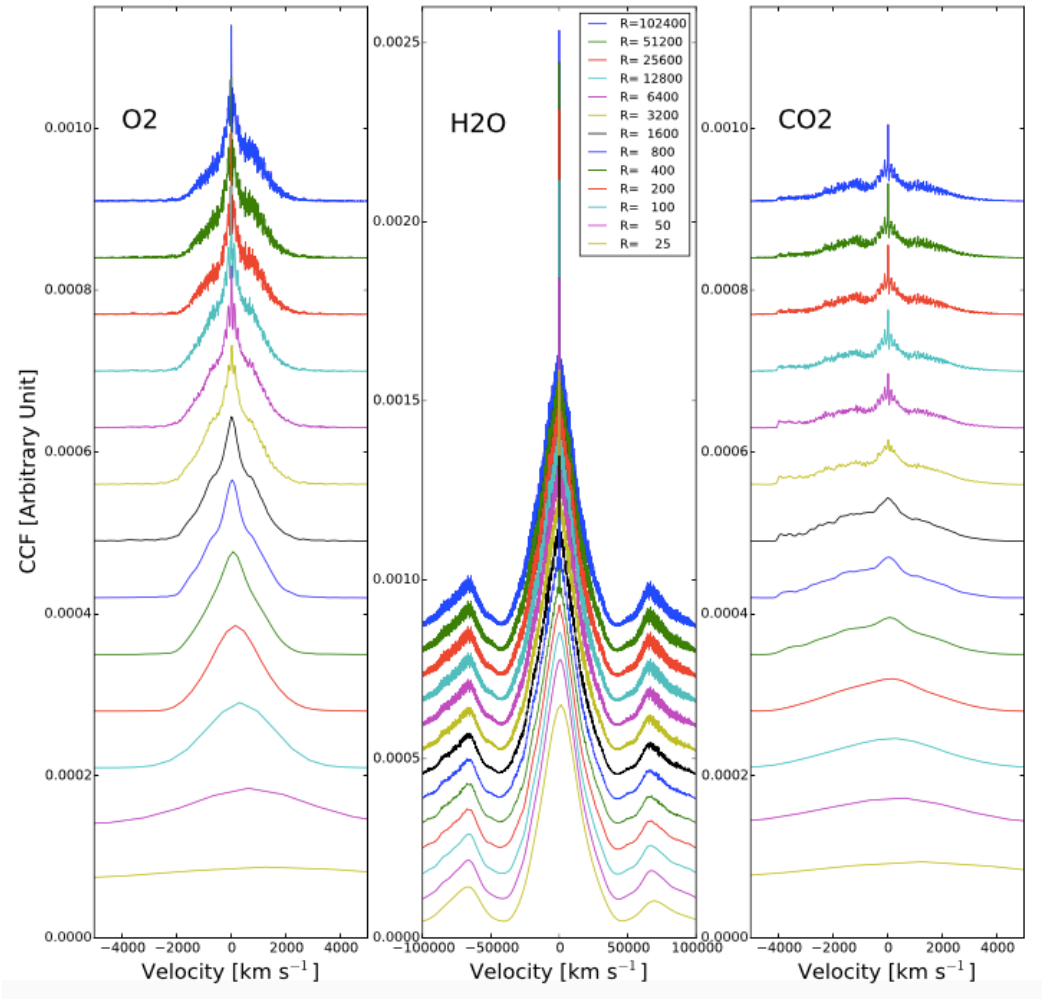
LUVOIR – photon-noise only



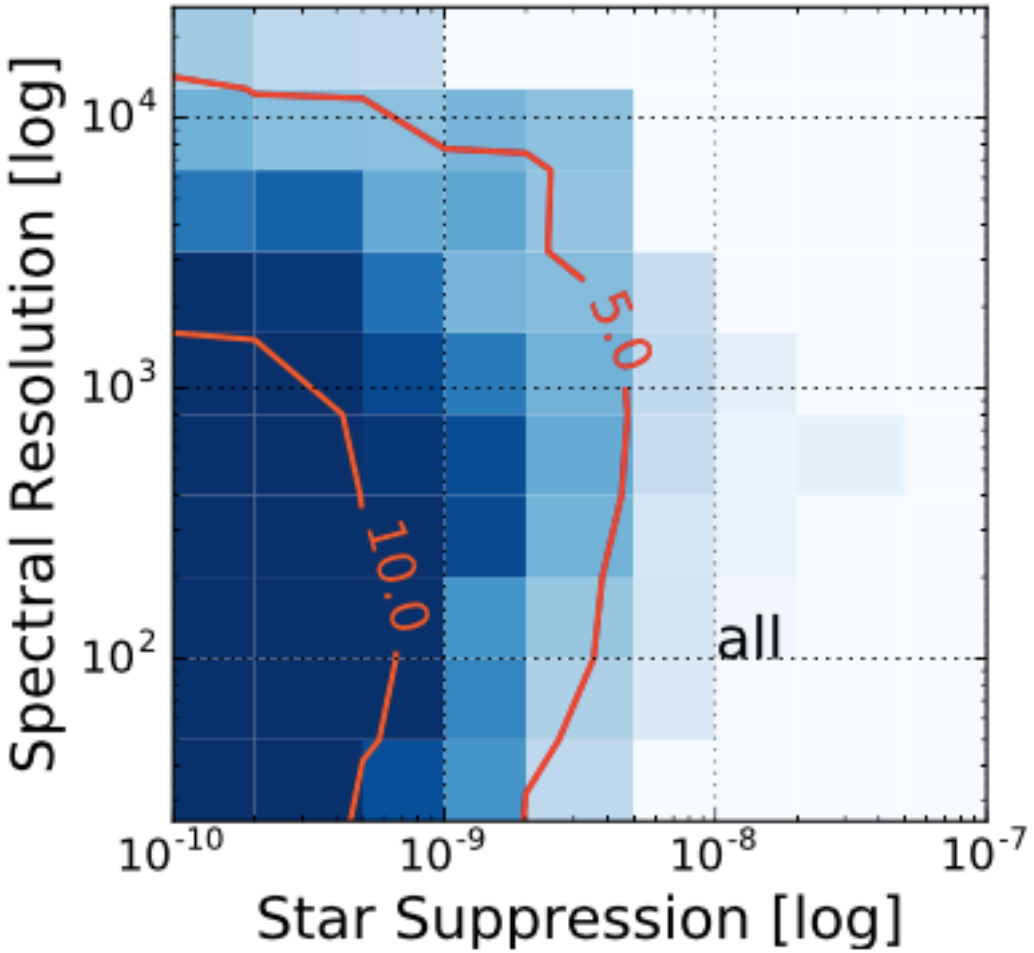
Absorption bands vs. lines



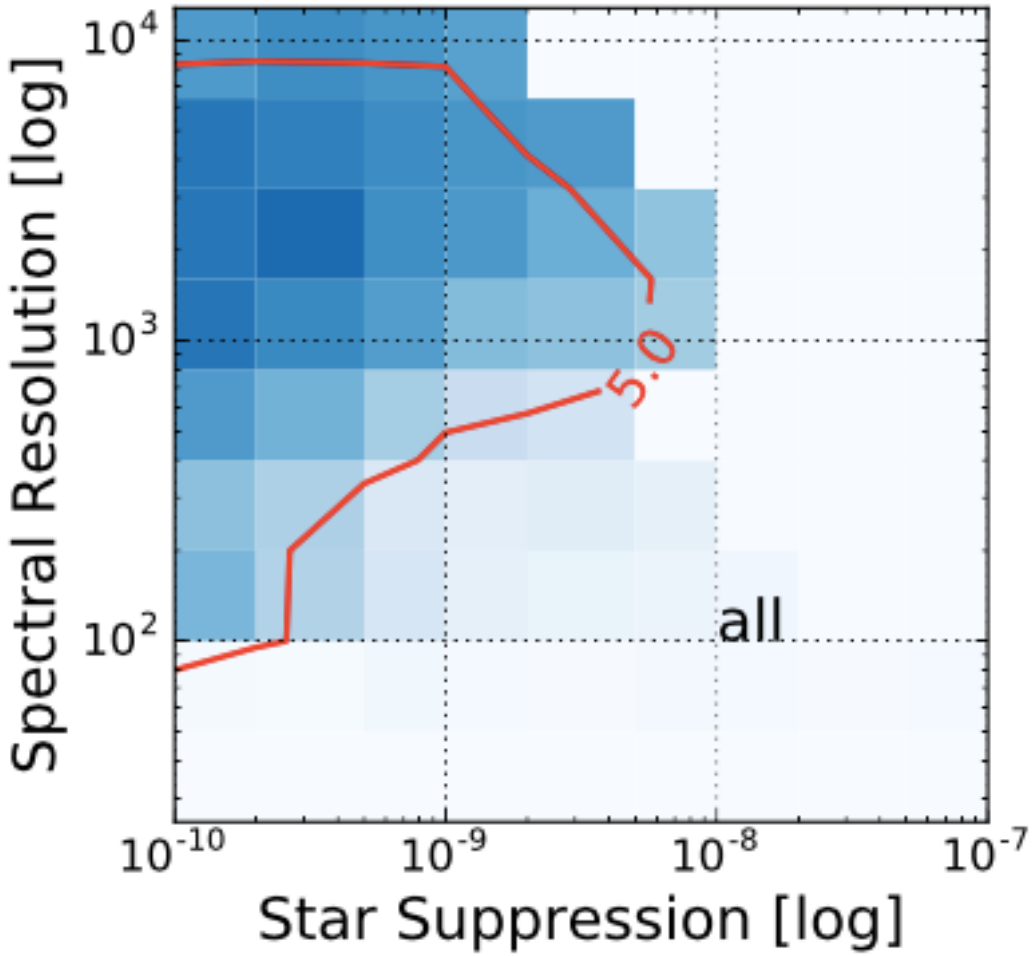
Absorption bands vs. lines



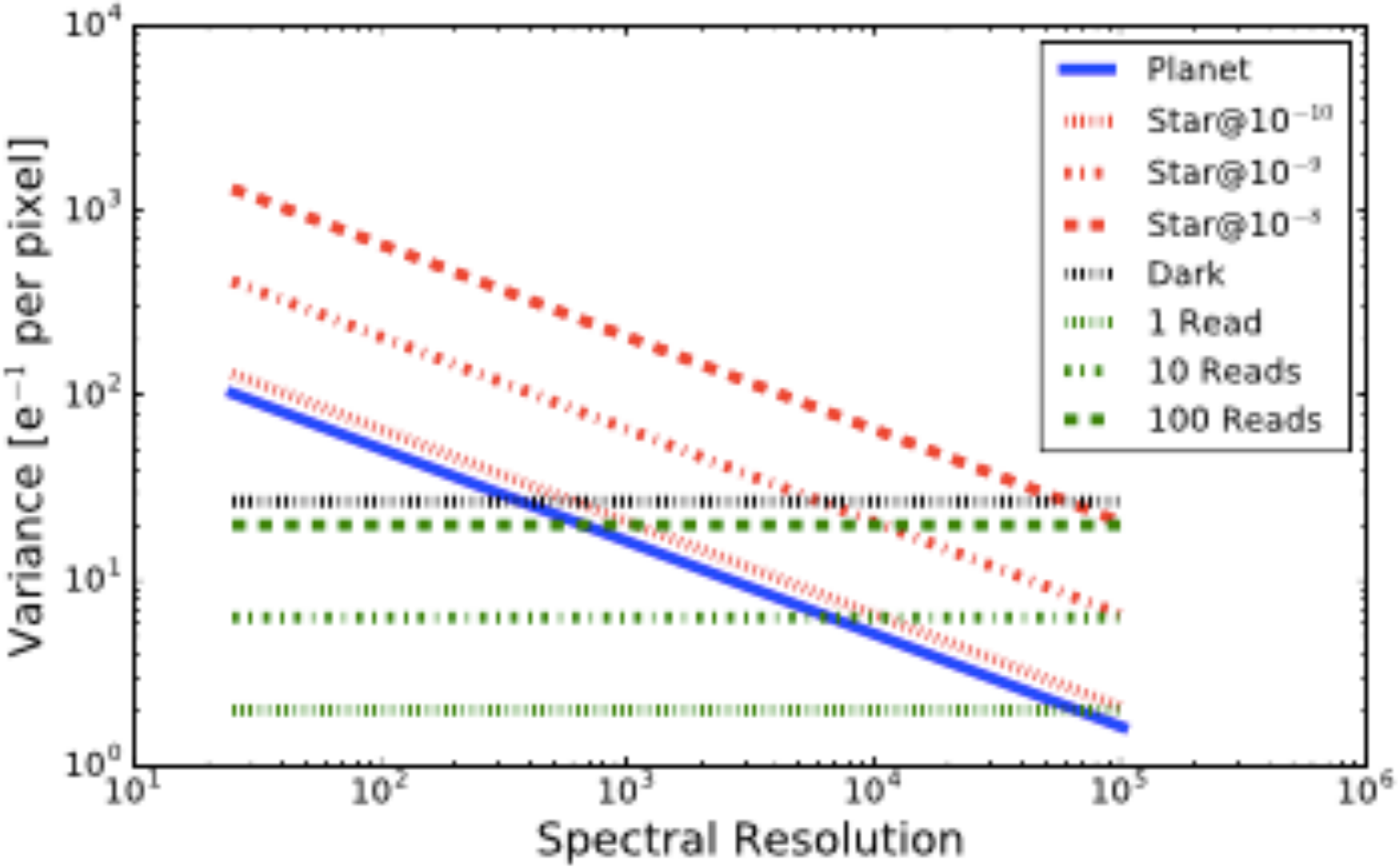
Adding Detector Noise



Adding Spectral Chromatic Noise



Source of Noise



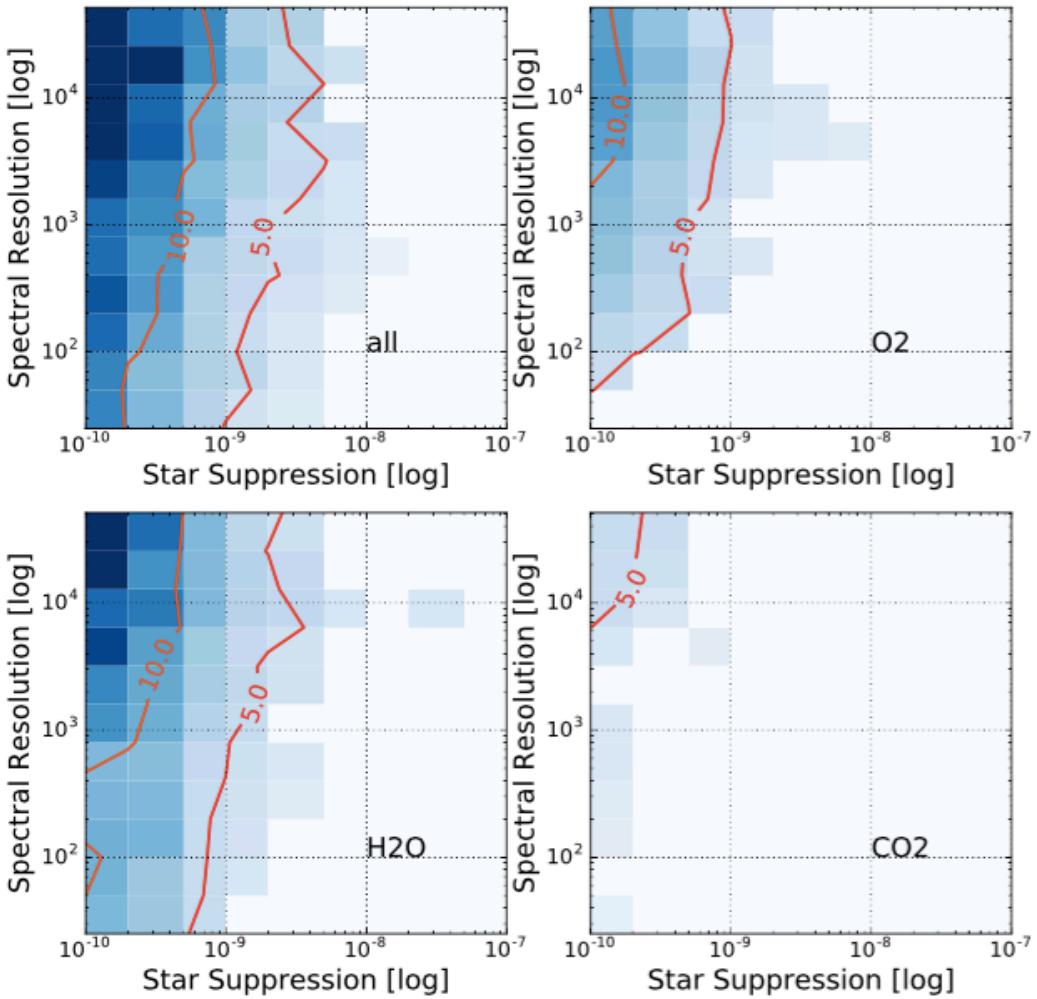
HabEx

Telescope and instrument parameters for LUVOIR or HabEx.

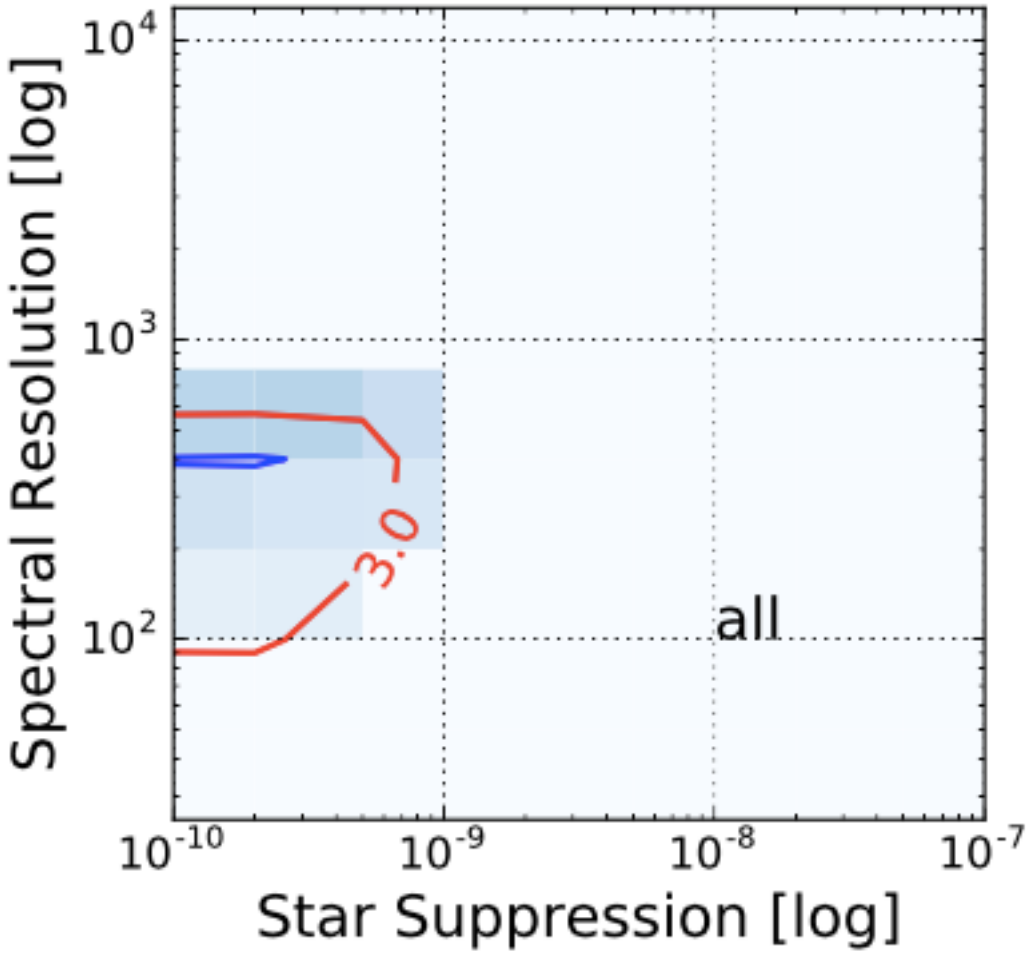
Parameter	Value	Unit
Telescope aperture	4.0 or 12.0	m
Telescope+instrument throughput	10%	...
Wavefront correction error floor	5	nm
Spectral resolution	varied	...
Spectral range	0.5 - 1.7	μm
Exposure time	400 or 100	hour
Fiber angular diameter	1.0	λ/D
Readout noise	0.0 or 2.0*	e^{-*}
Dark current	0.0 or 0.002 or $5.5 \times 10^{-6**}$	$e^{-} s^{-1}$

Note. — *: Based on H2RG detector specification (Blank et al. 2012) and e2v CCD specification. **: Used for O_2 detection.

HabEx– photon-noise only



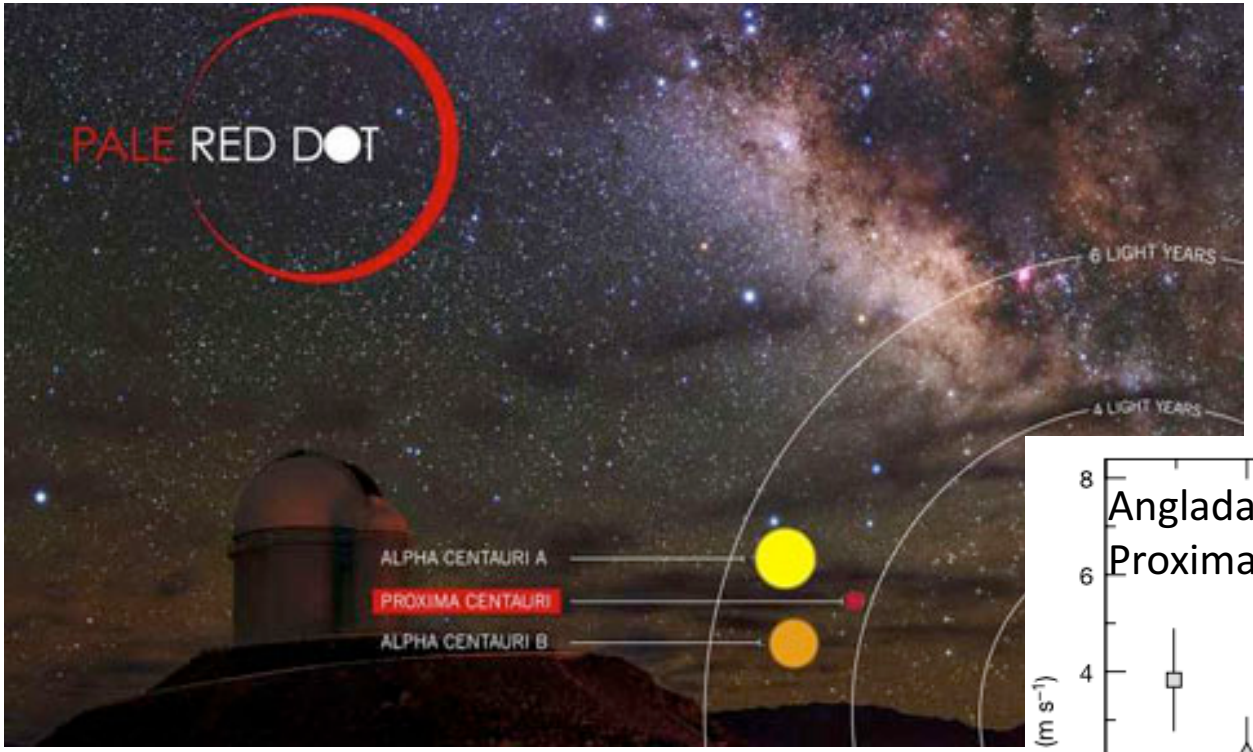
Adding Spectral Chromatic Noise

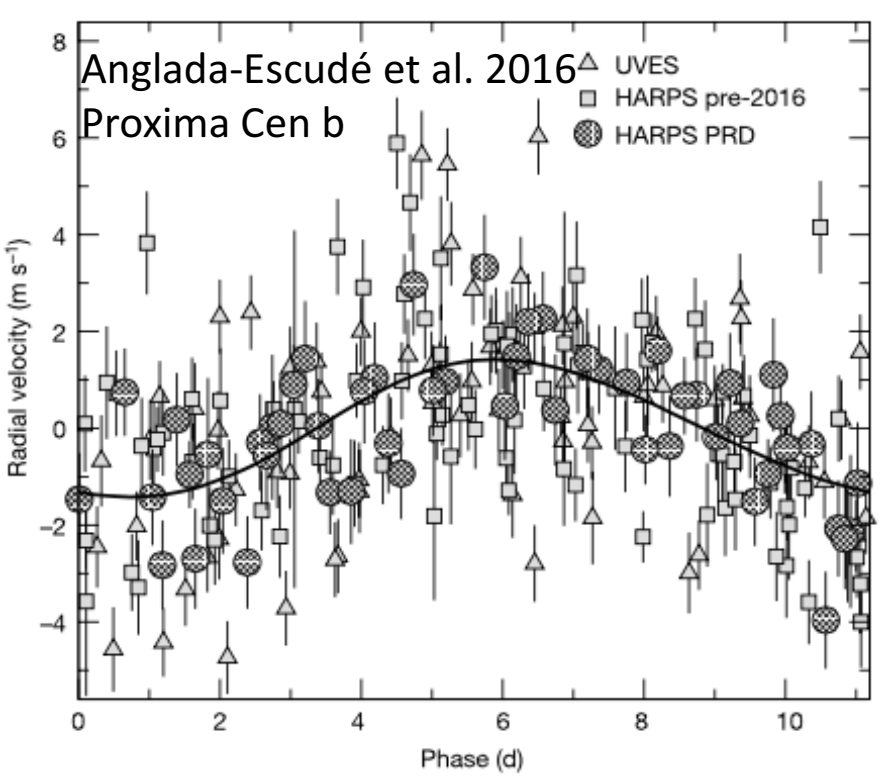


Summary

- We develop a framework to simulate performance of an HDC instrument.
- KPIC, a Keck HDC instrument, will be capable of characterizing directly-imaged giant exoplanets at high spectral resolution, e.g., HR 8799 bcde.
- Limiting factors for template matching technique are:
  - Photon noise
  - CCF intrinsic structure
  - Mismatched template
- HDC may be the only viable method to search and characterize Proxima Cen b and other planets around M dwarfs from ground using 30-m class telescope in near infrared.
- HDC relaxes star suppression level by 1-2 orders of magnitude for space-based mission to detect an Earth-like planet around a solar-type star
- Detector noise and speckle chromatic noise are two major factors that limit the performance of a space-based HDC instrument.

M Dwarf Planet “Frenzy”





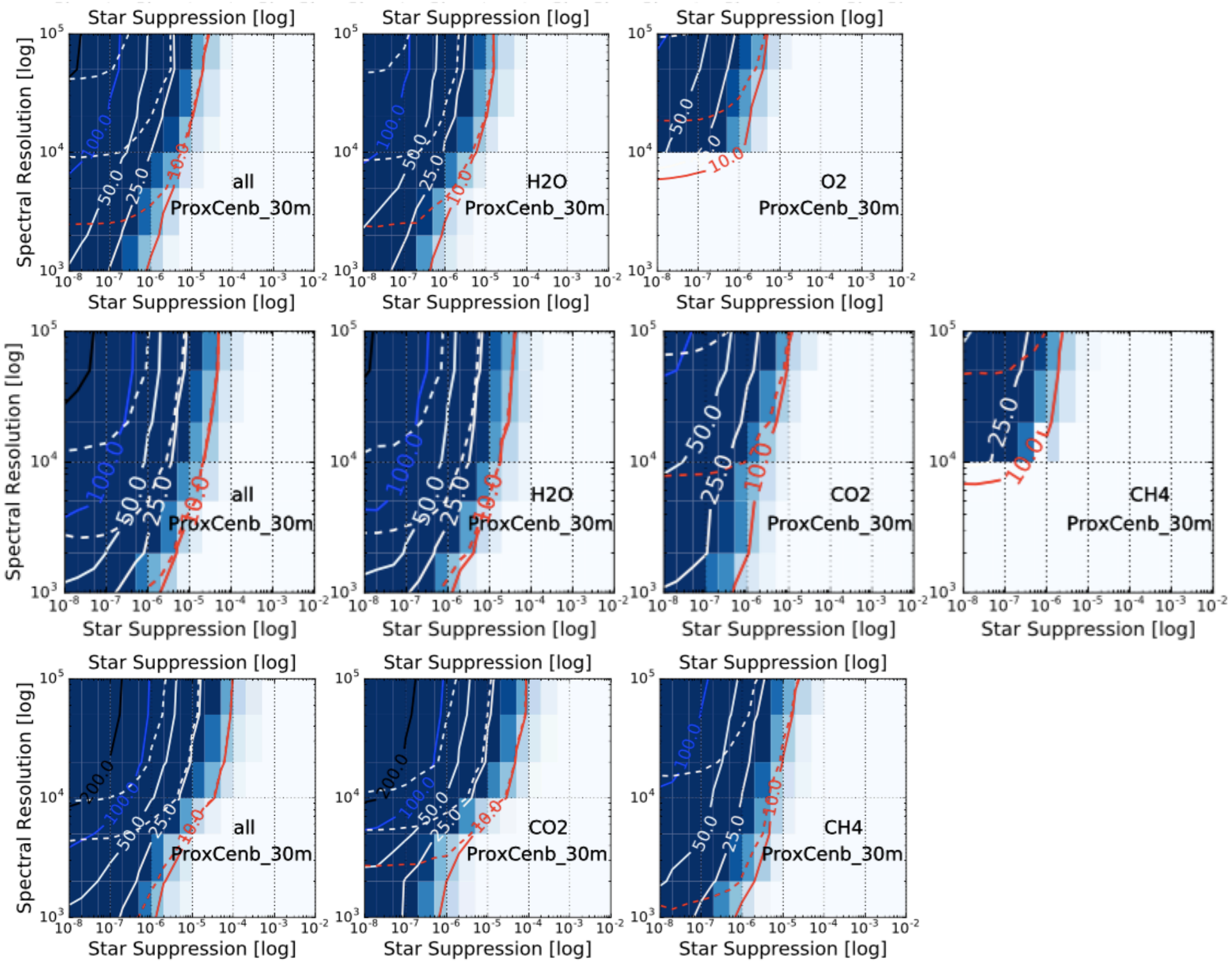
NIR HDC Observation of Prox Cen b with 30-m Class Telescopes

Parameter	Value	Unit
Telescope aperture	10.0 or 30.0	m
Telescope+instrument throughput	10%	···
Wavefront correction error floor	200	nm
Spectral resolution	varied	···
J band spectral range	1.143 - 1.375	μm
H band spectral range	1.413 - 1.808	μm
K band spectral range	1.996 - 2.382	μm
Exposure time	100	hour
Fiber angular diameter	1.0	λ/D
Readout noise	0.0 or 2.0	e^{-1*}
Dark current	0.0 or 0.002	e^{-1} s^{-1*}

Note. — ∗: Based on H2RG detector specification (Blank et al. 2012)

Parameter	Value	Unit
Star		
Effective temperature** (T_{eff})	3050	K
Mass	0.12	$M_\odot$
Radius	0.14	$R_\odot$
Surface gravity ($\log g$)	5.0	cgs
Metallicity ([M/H])	0.0	dex
Distance	1.295	pc
Vsin i	<1	km s^{-1}
Inclination (i)	20	degree
Radial velocity	-22.4	km s^{-1}
Planet		
Effective temperature (T_{eff})	234	K
Vsin i**	0.014	km s^{-1}
Inclination (i)	20	degree
Semi-major axis (a)	0.05	AU
Radial velocity	22.2	km s^{-1}
Illuminated Area	0.5	···
Planet/Star Contrast	1.6×10^{-7}	···

Note. — ∗: All values are from Anglada-Escudé et al. (2016). We use 3000 K in simulation. ∗∗: We assume that the planet is tidally locked.


Star Suppression [log]
Spectral Resolution [log]
all
ProxCenb_30m
H2O
O2
CO2
CH4
100.0
50.0
25.0
10.0
200.0

Sources of Noise