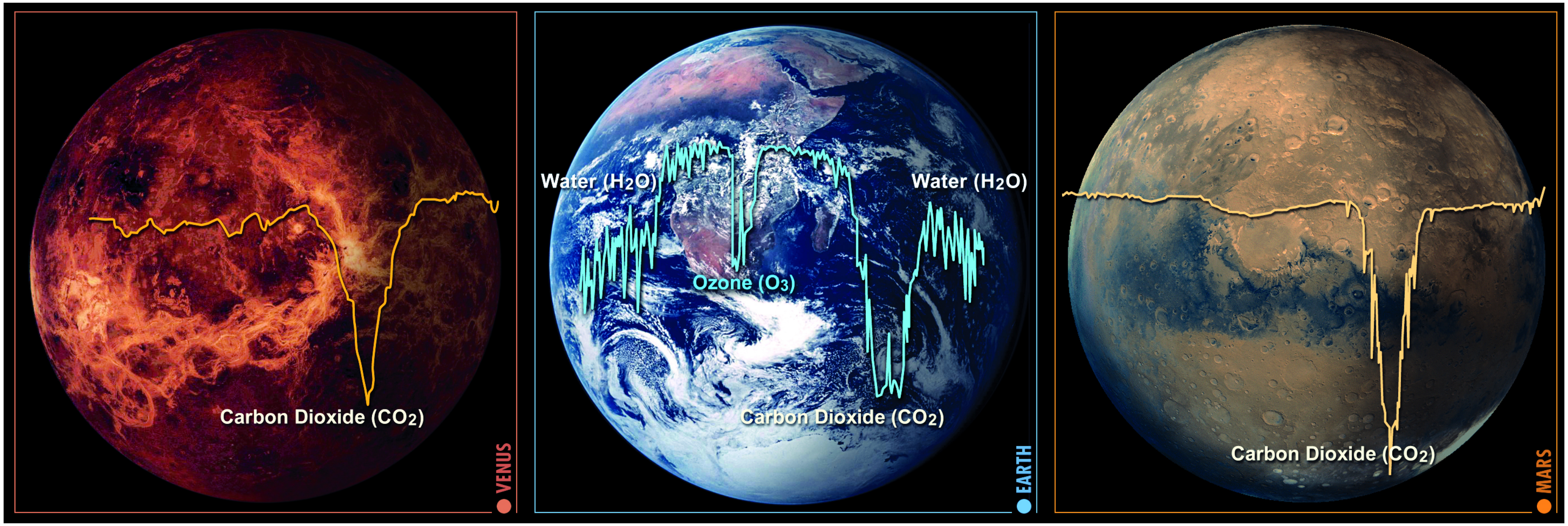
The New Frontier of Exoplanetary Science: High Dispersion Coronagraphy (HDC)

Ji Wang

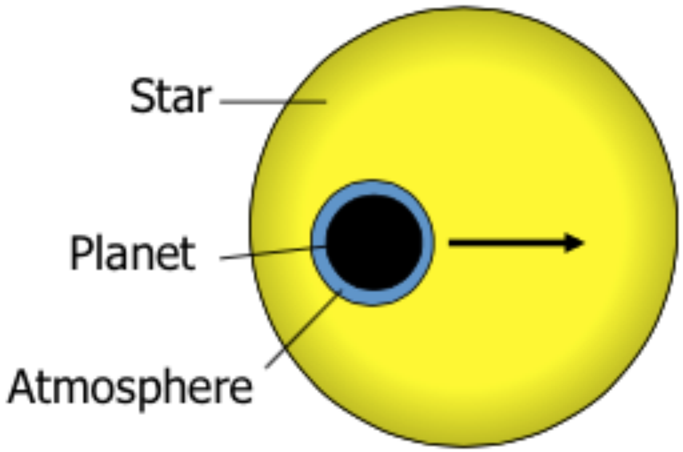
Caltech

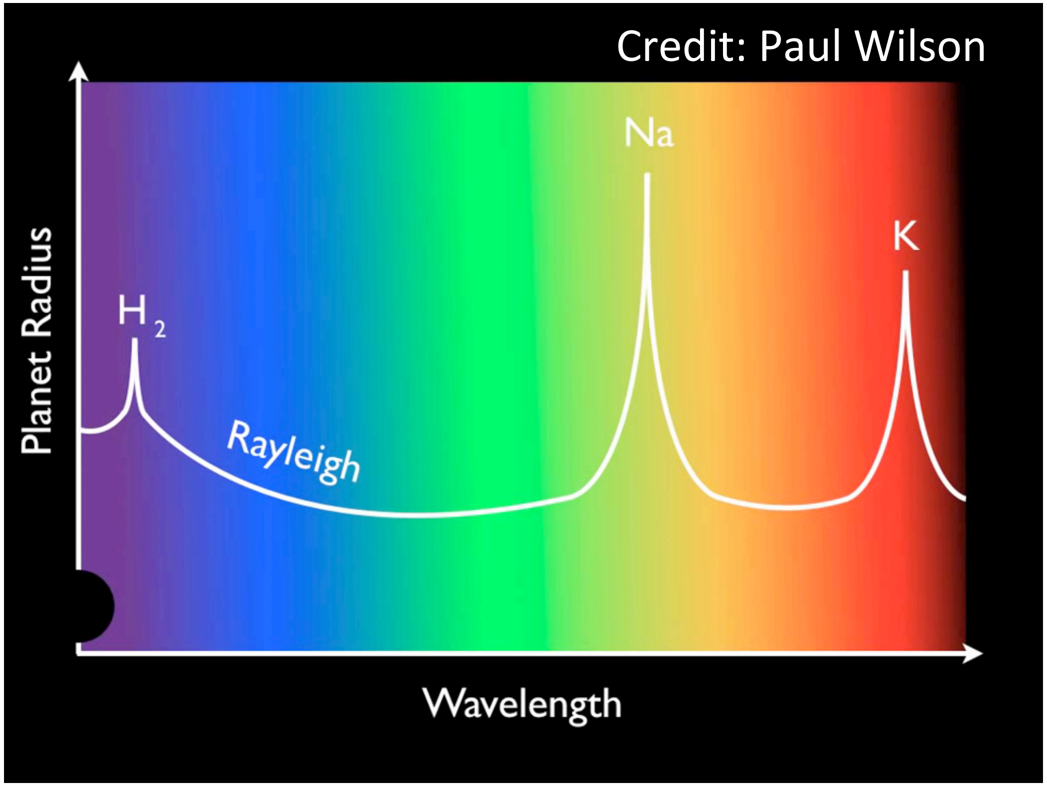
Collaborators: Dimitri Mawet, Garreth Ruane, Renyu Hu, Bjorn Benneke

The Ultimate Goal of Exoplanet Spectroscopy - Biomarker Detection

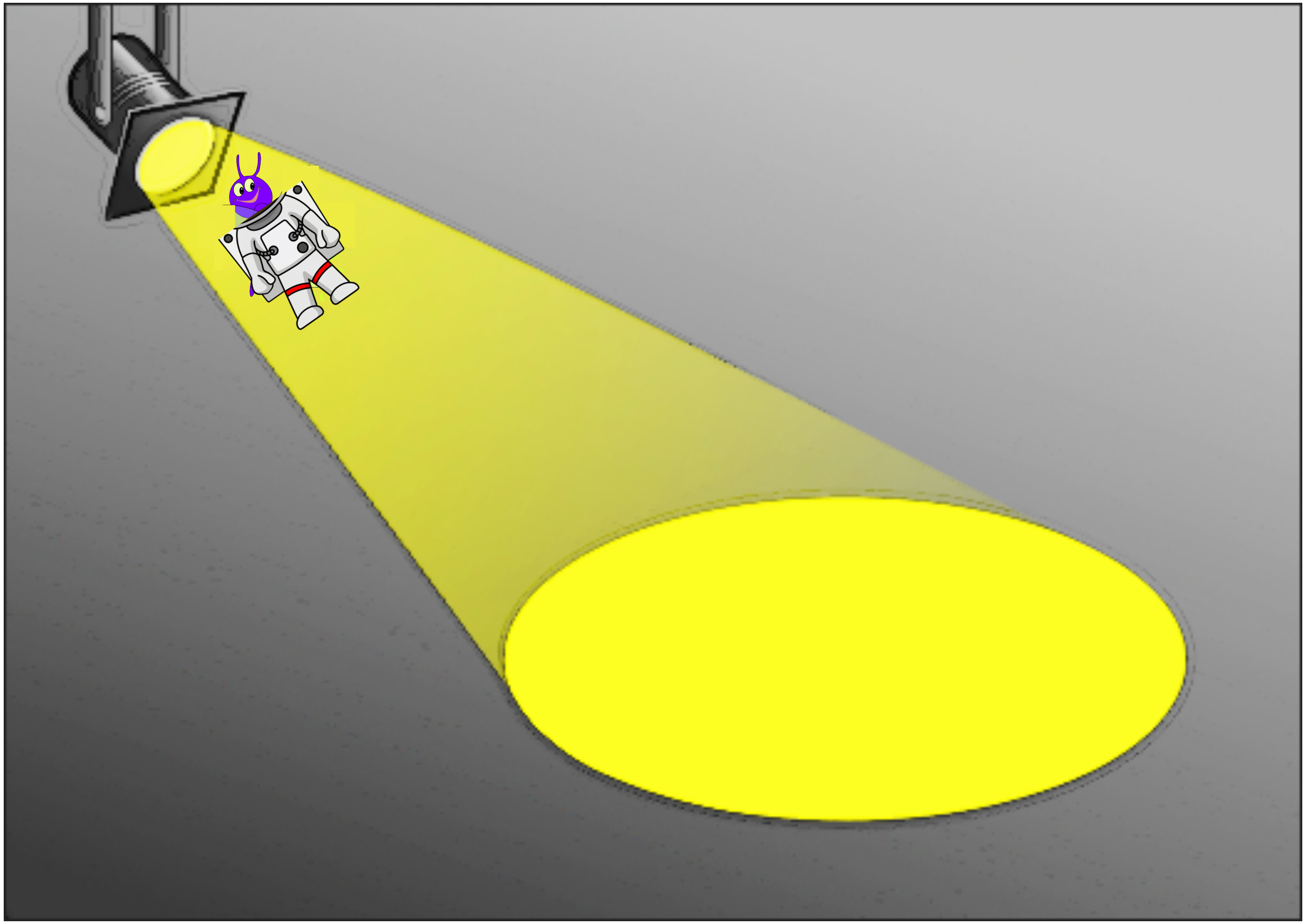


Transmission Spectroscopy

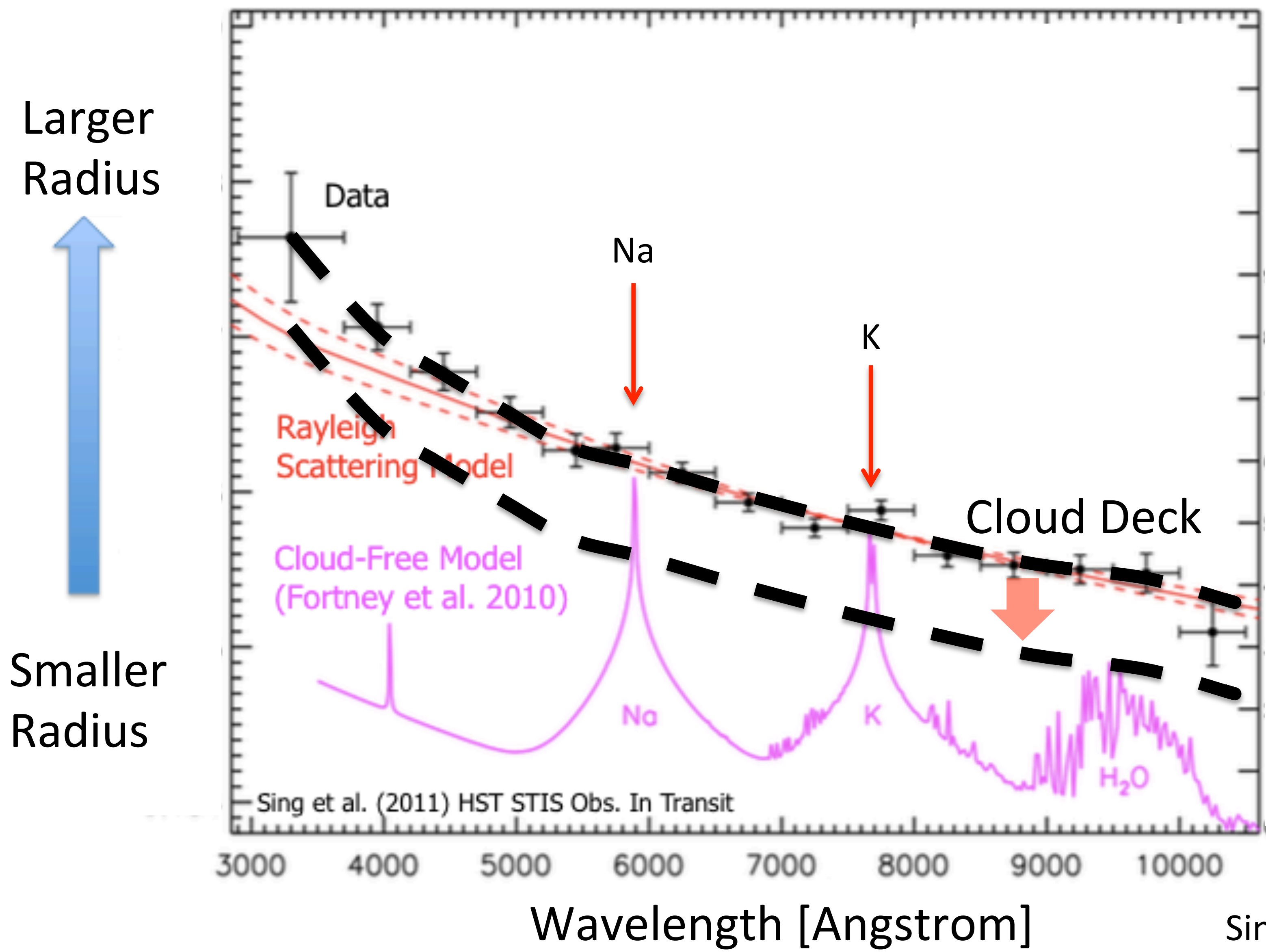




Firefly – Spot Light Analogy

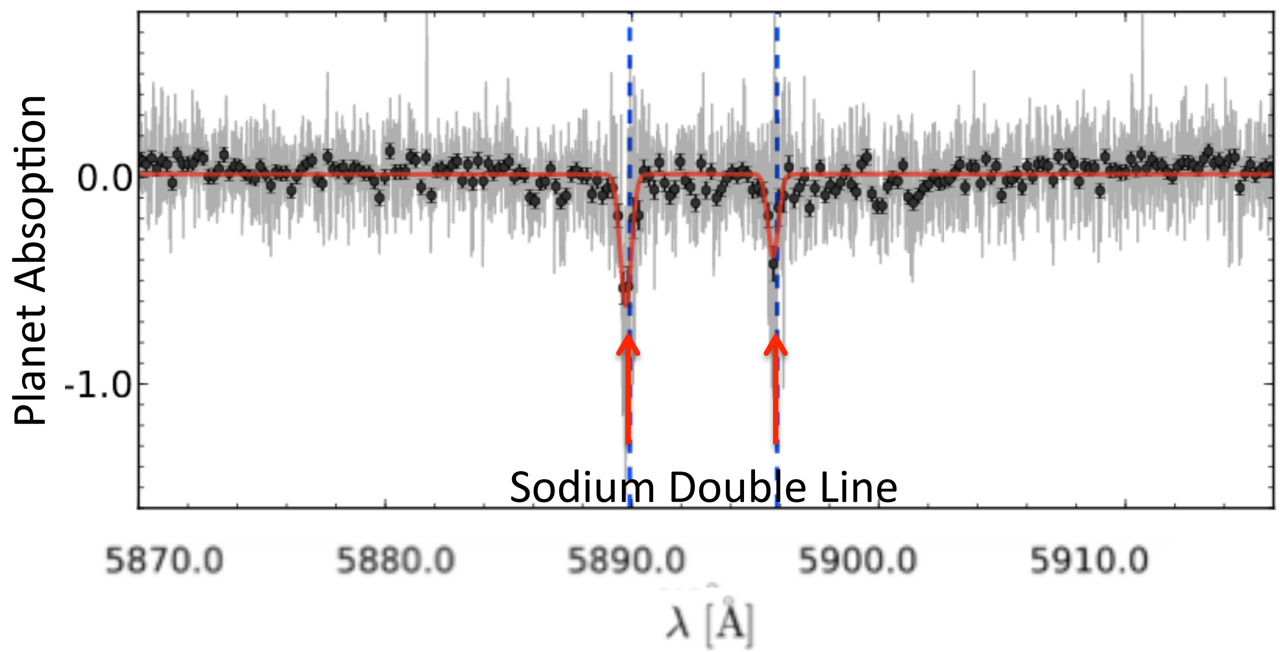


Cloud Obscuration



Sing et al. 2011

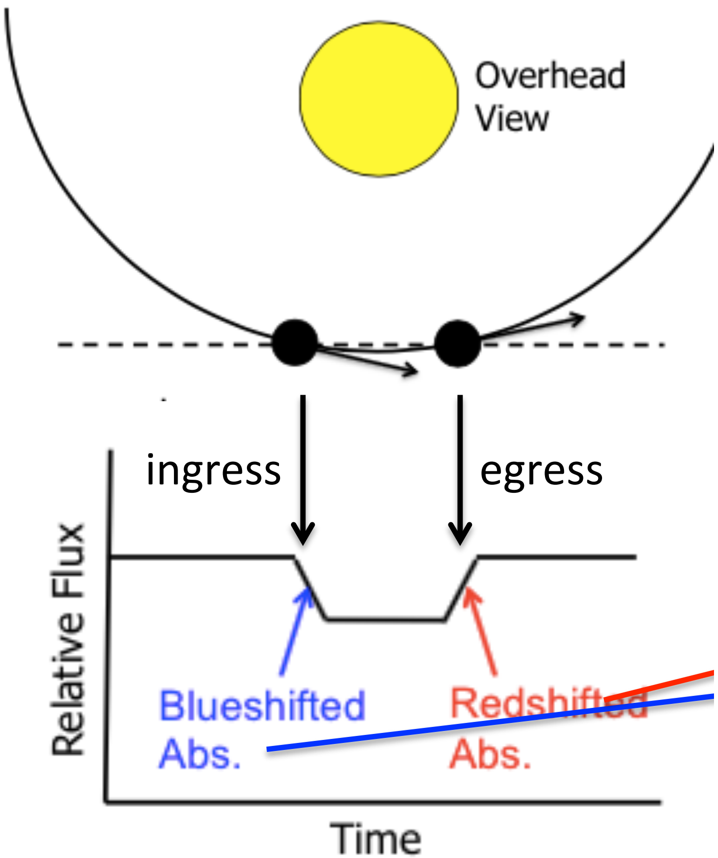
High Resolution Spectroscopy Increases Signal



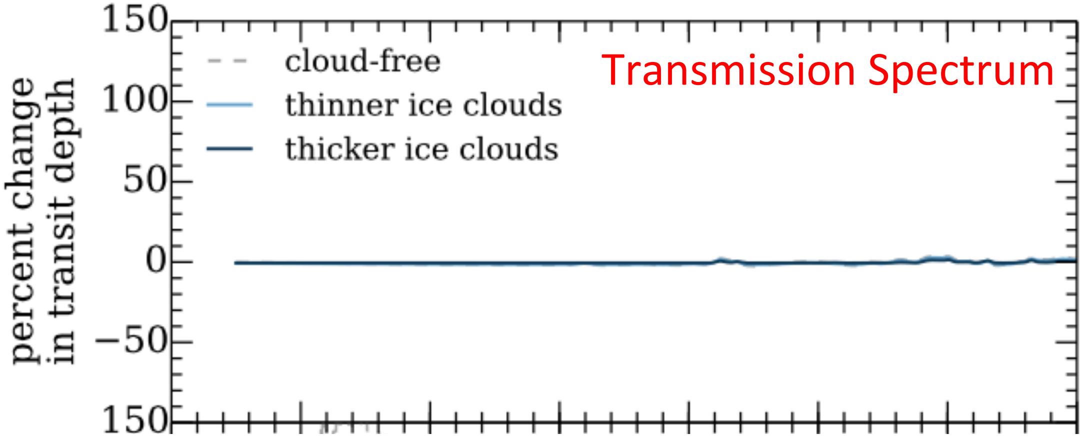
Wyttenbach et al. 2015
HD 189733b

See also Khalafinejad et al. 2016

Detection of CO
From High-Resolution Spectroscopy



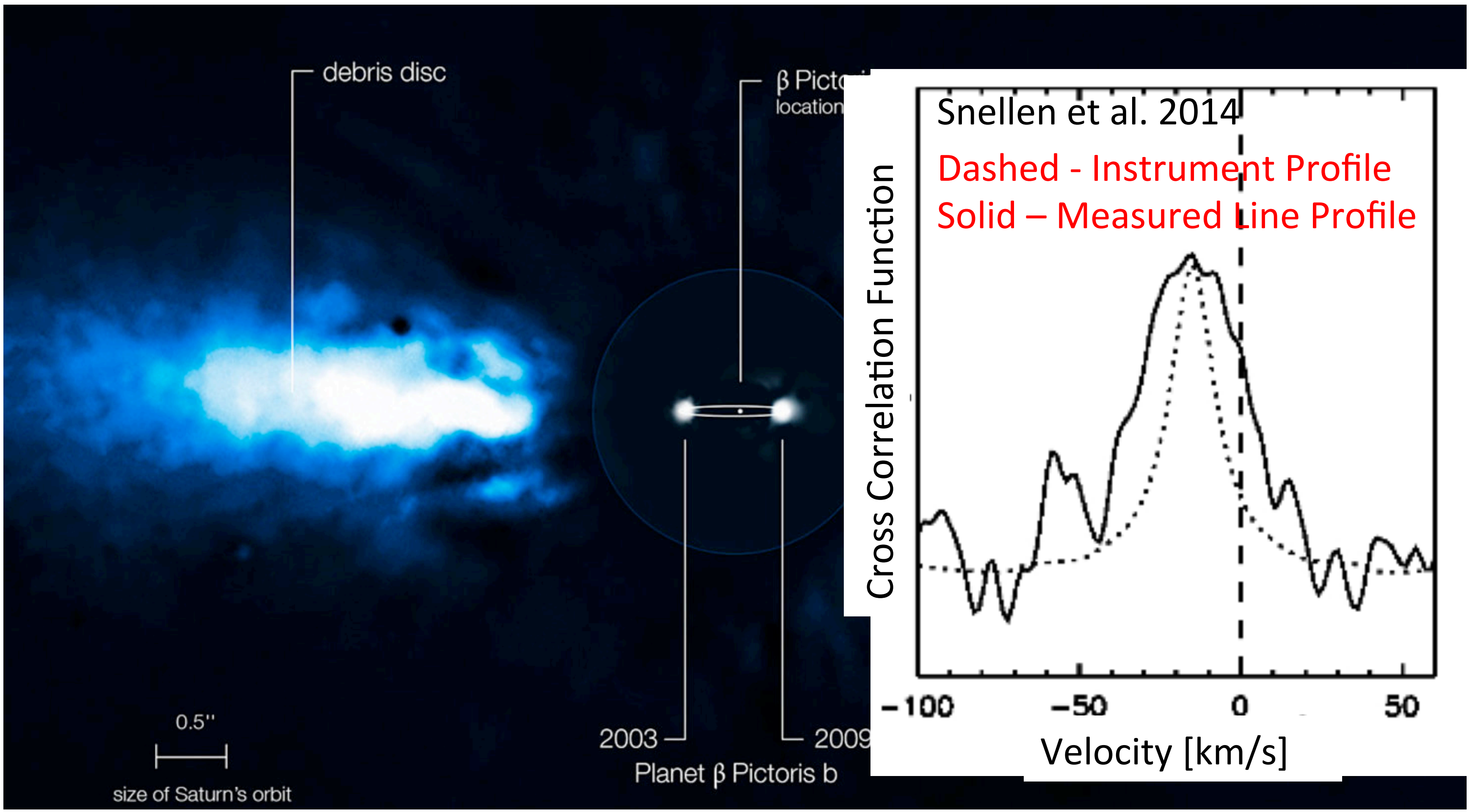
Transmission vs. Emission / Reflection - another way of disentangling cloud effect



Morley et al. 2015

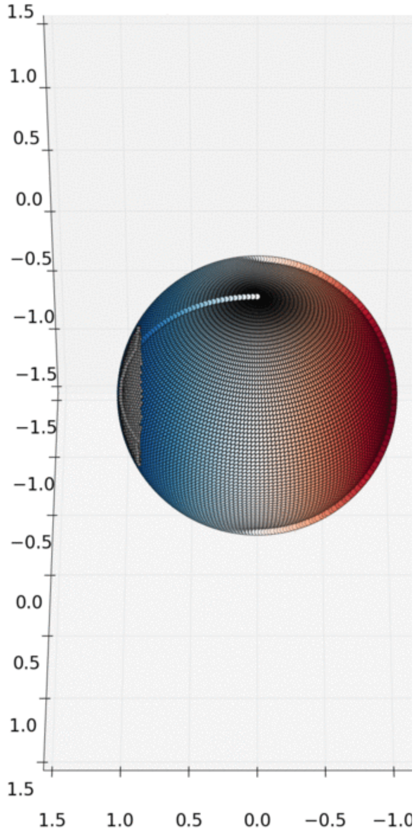
Firefly – Spot Light Analogy

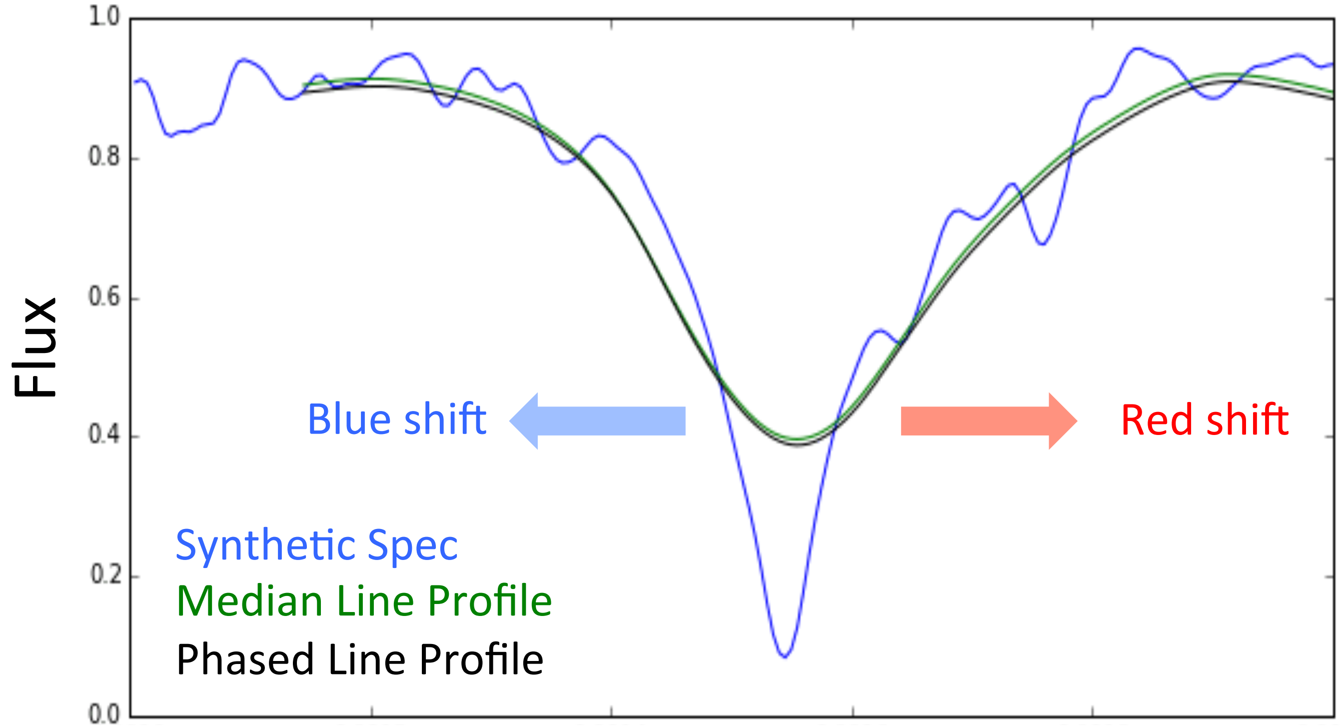
Planet Rotation – Beta Pic b



Doppler Imaging

(from my simulation code)

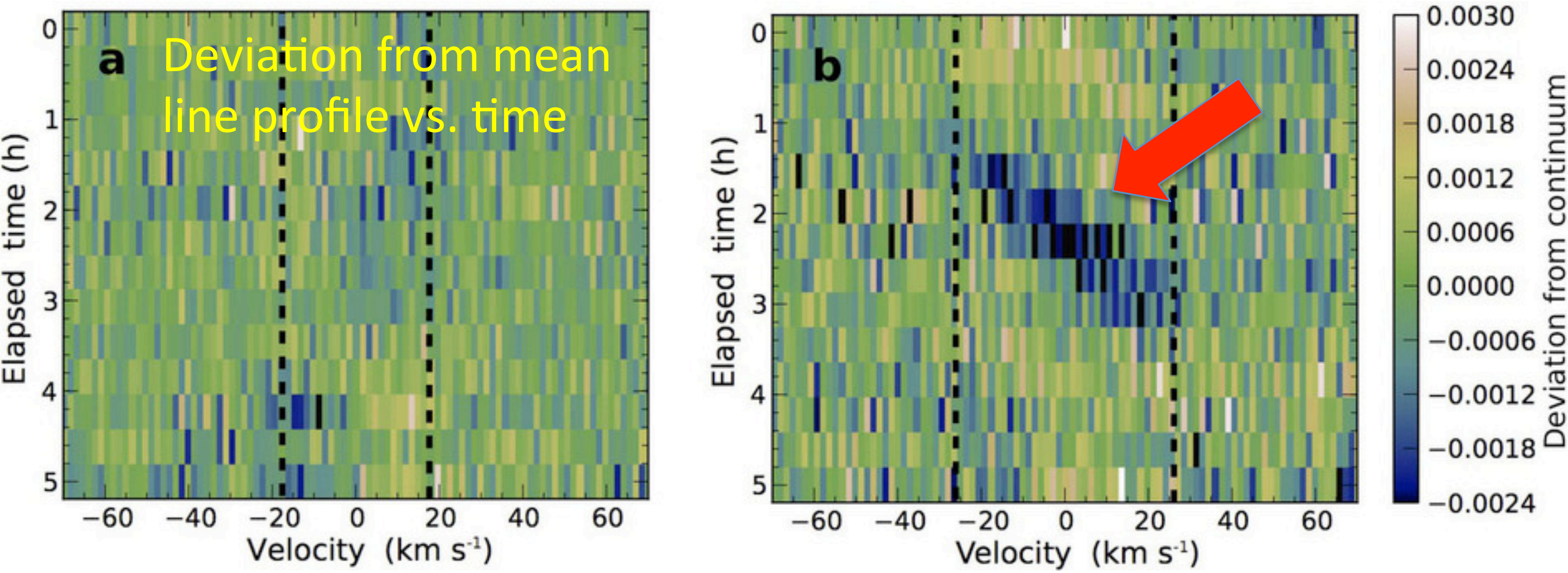




Wavelength [um]

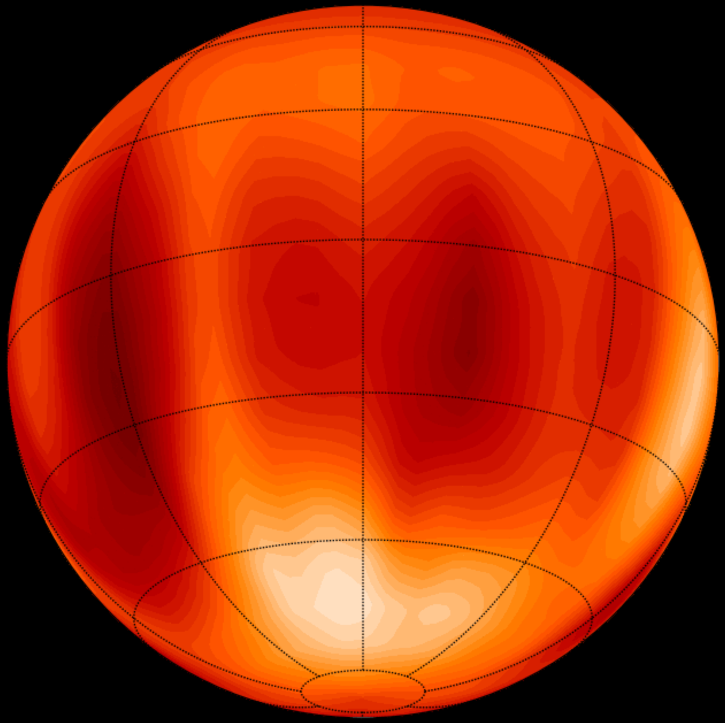
Surface Features ← Line Profile

Doppler Imaging – Luhman 16 A & B



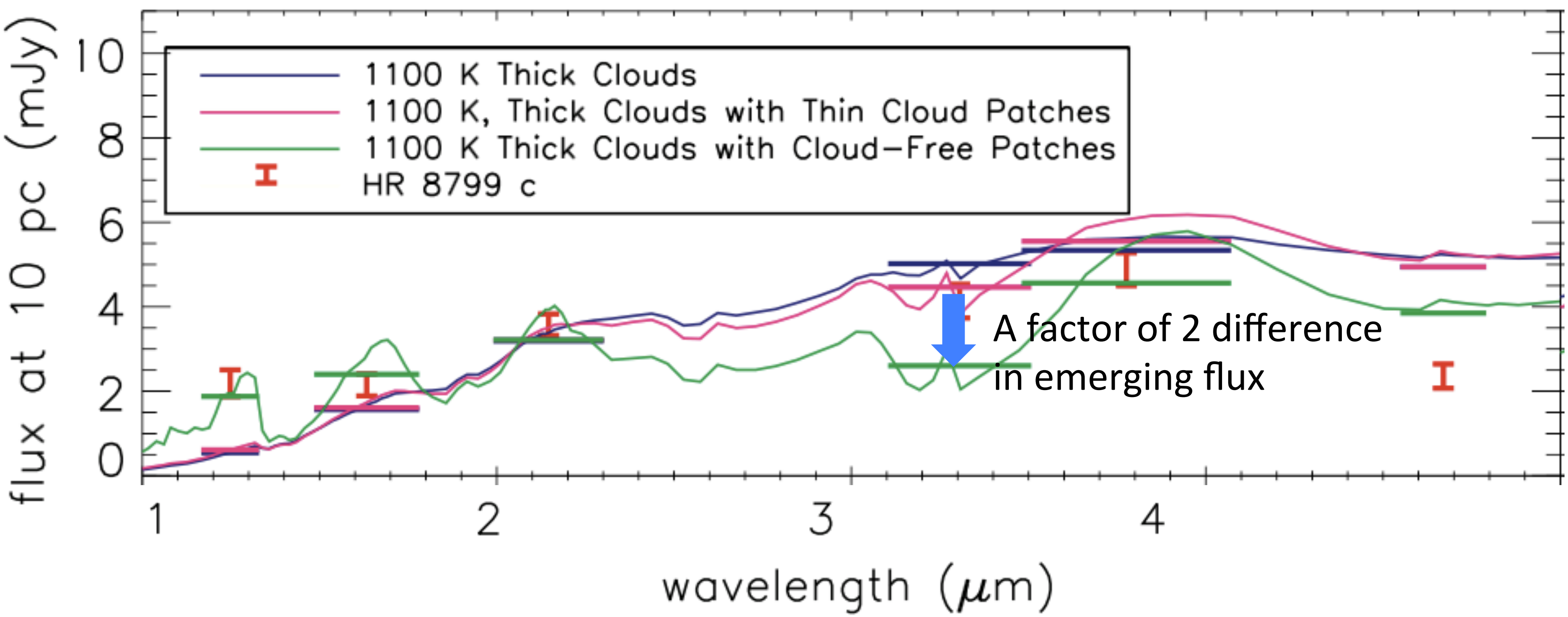
Crossfield et al. 2014

Cloud map of Lunman 16 B



Luhman 16 B (Crossfield et al. 2014)

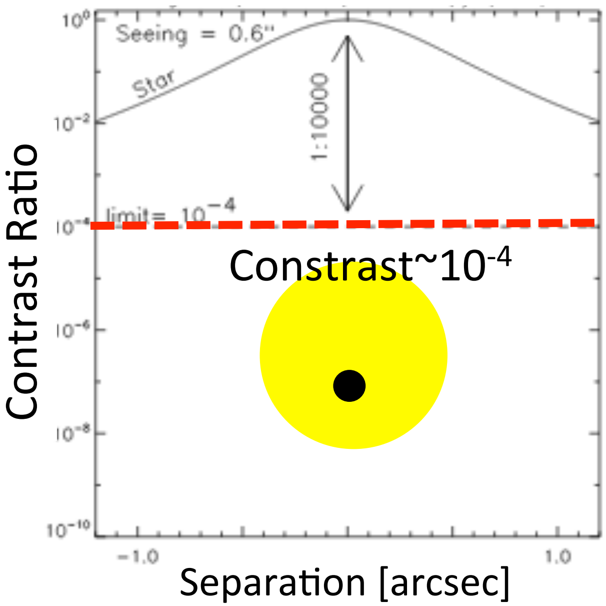
Clouds Sculpt Emerging Spectra



Skemer et al. (2014)

Adaptive Optics + High Resolution Spectroscopy

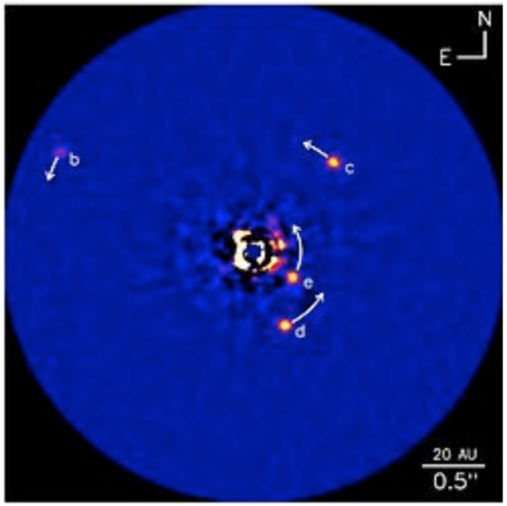
High Resolution Spectroscopy

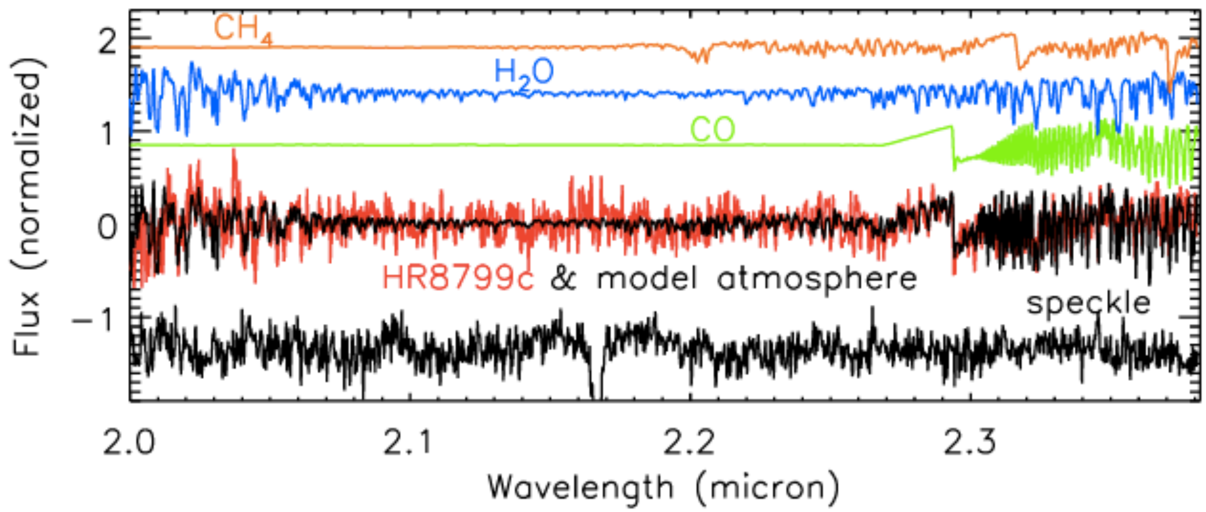


- HRS -> 10^{-4}
- AO -> 10^{-3}
- HRS + AO -> 10^{-7} (the planet-star contrast of Proxima Cen b)

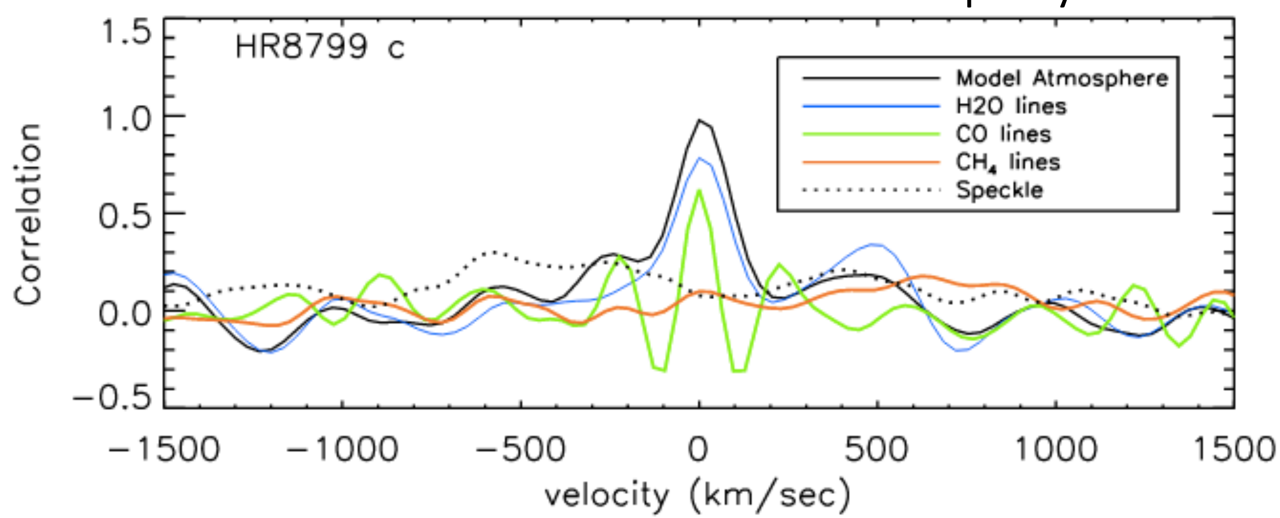
Snellen et al. 2015

Detection of H_2O and CO on HR 8799 c

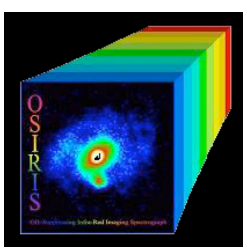




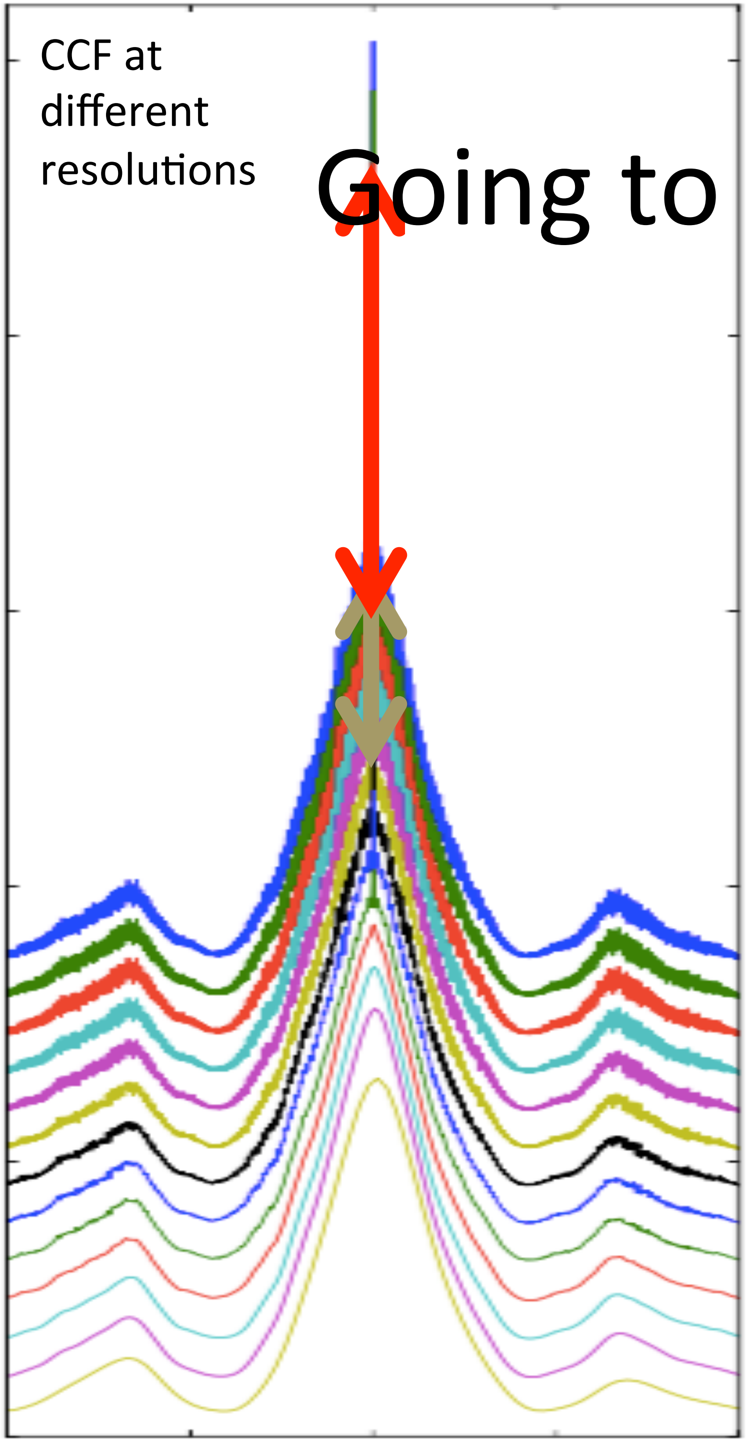
Konopacky et al. 2013

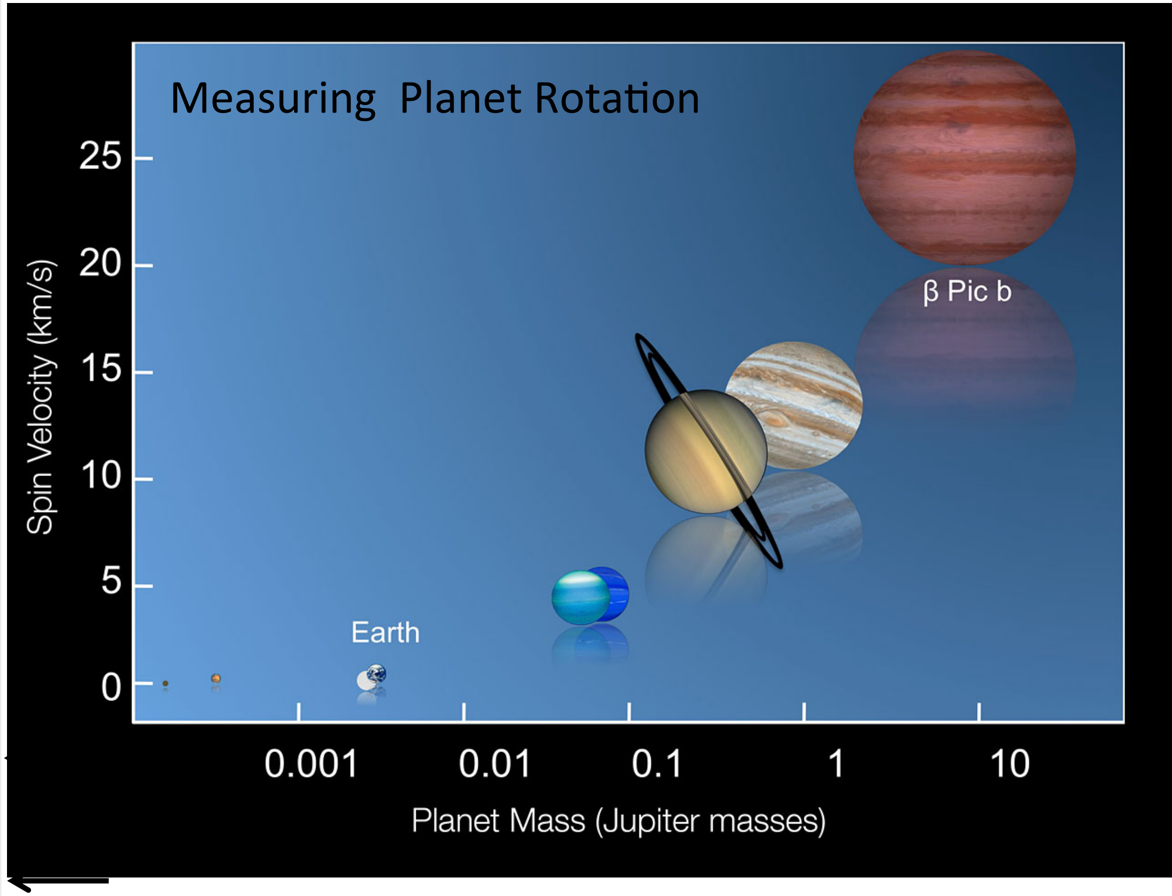


Keck OSIRIS



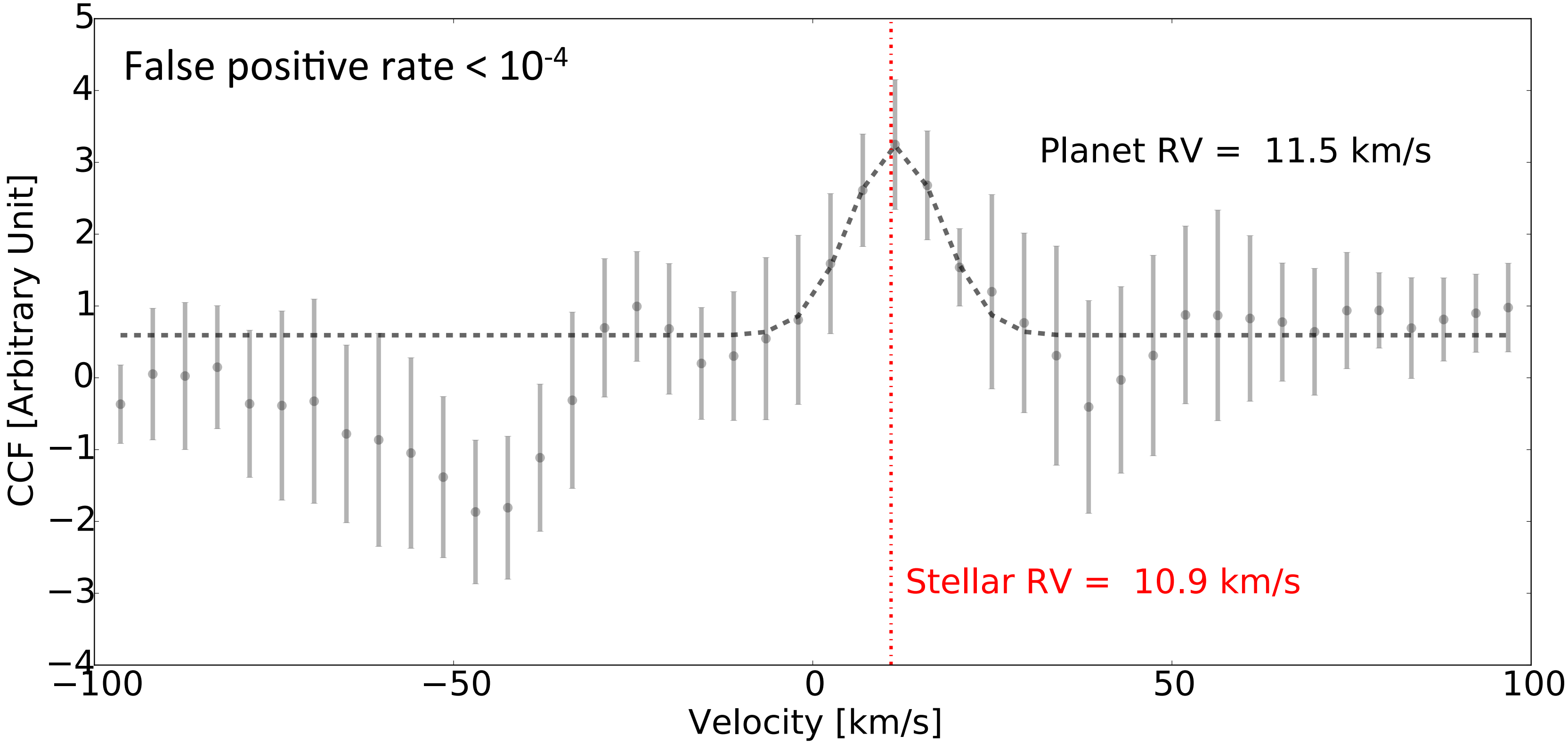
Going to Higher Resolution





Credit: ESO/I. Snellen

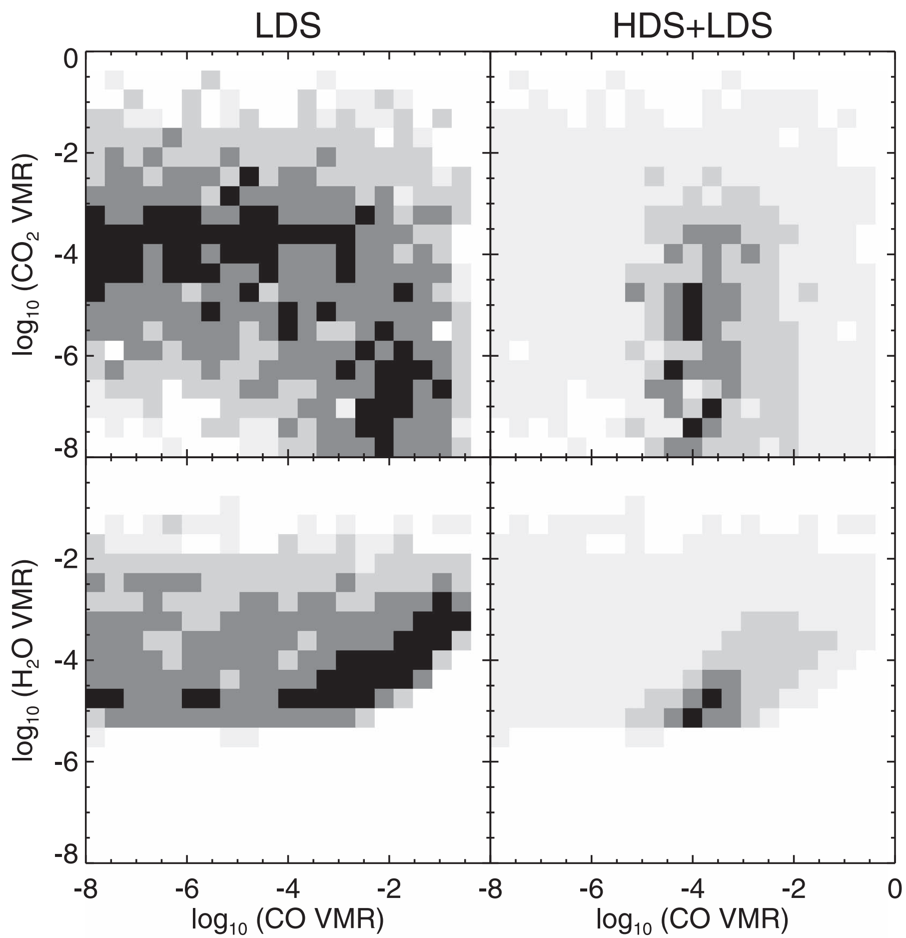
HR 8799 c in L band
Detection of CH_4



- Spin measurement is consistent with face-on configuration

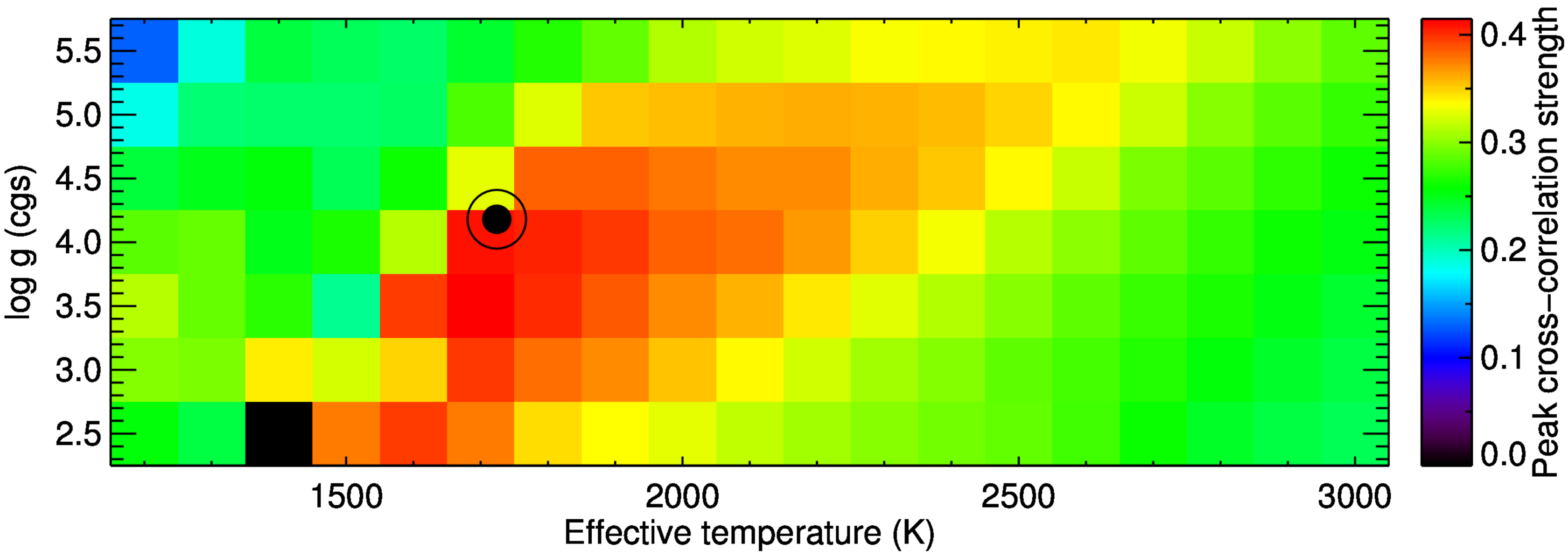
Wang et al. (2017c) in prep.

LDS + HDS



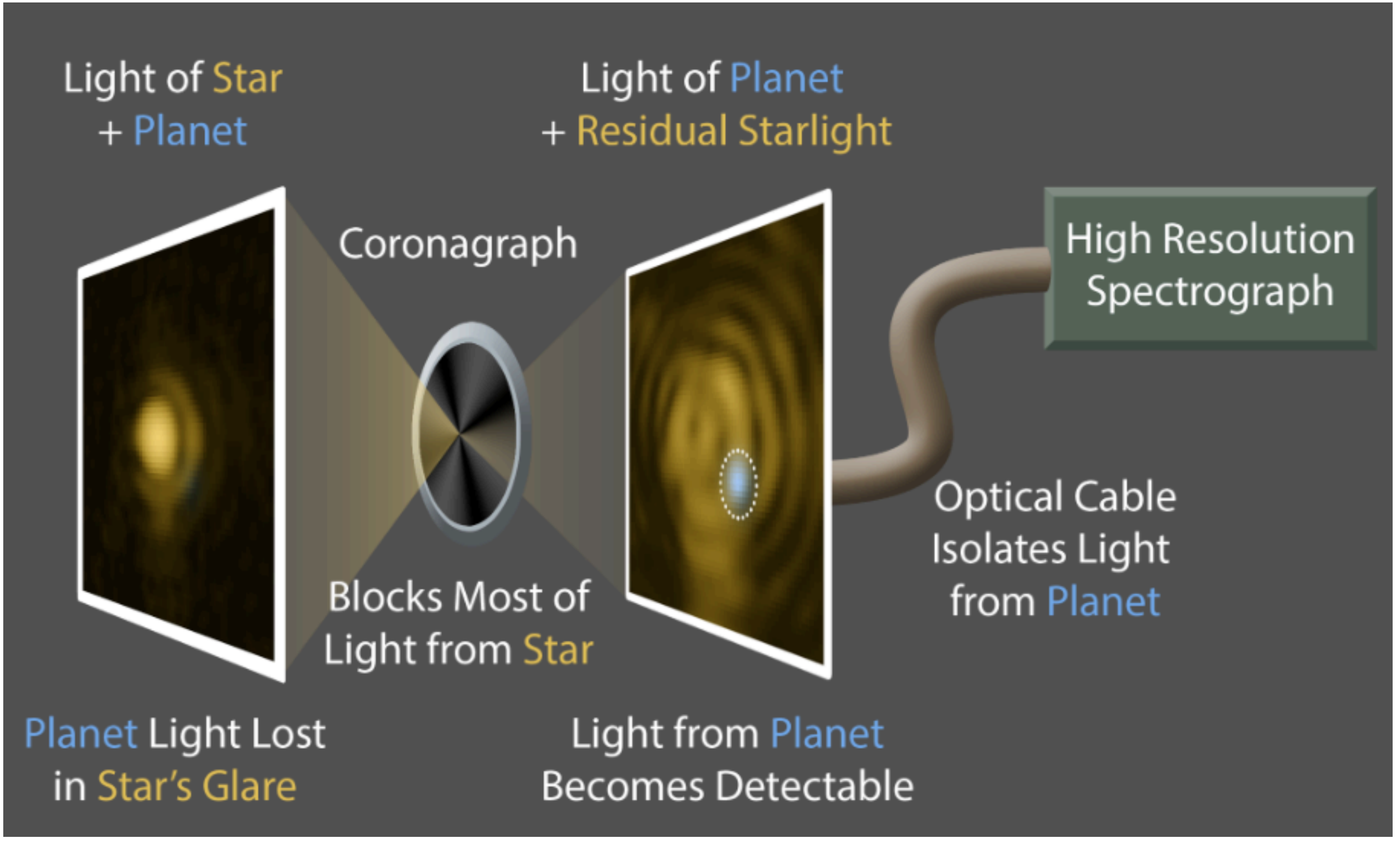
HD 209485 b, Brogi et al. 2017

Molecular Mapping

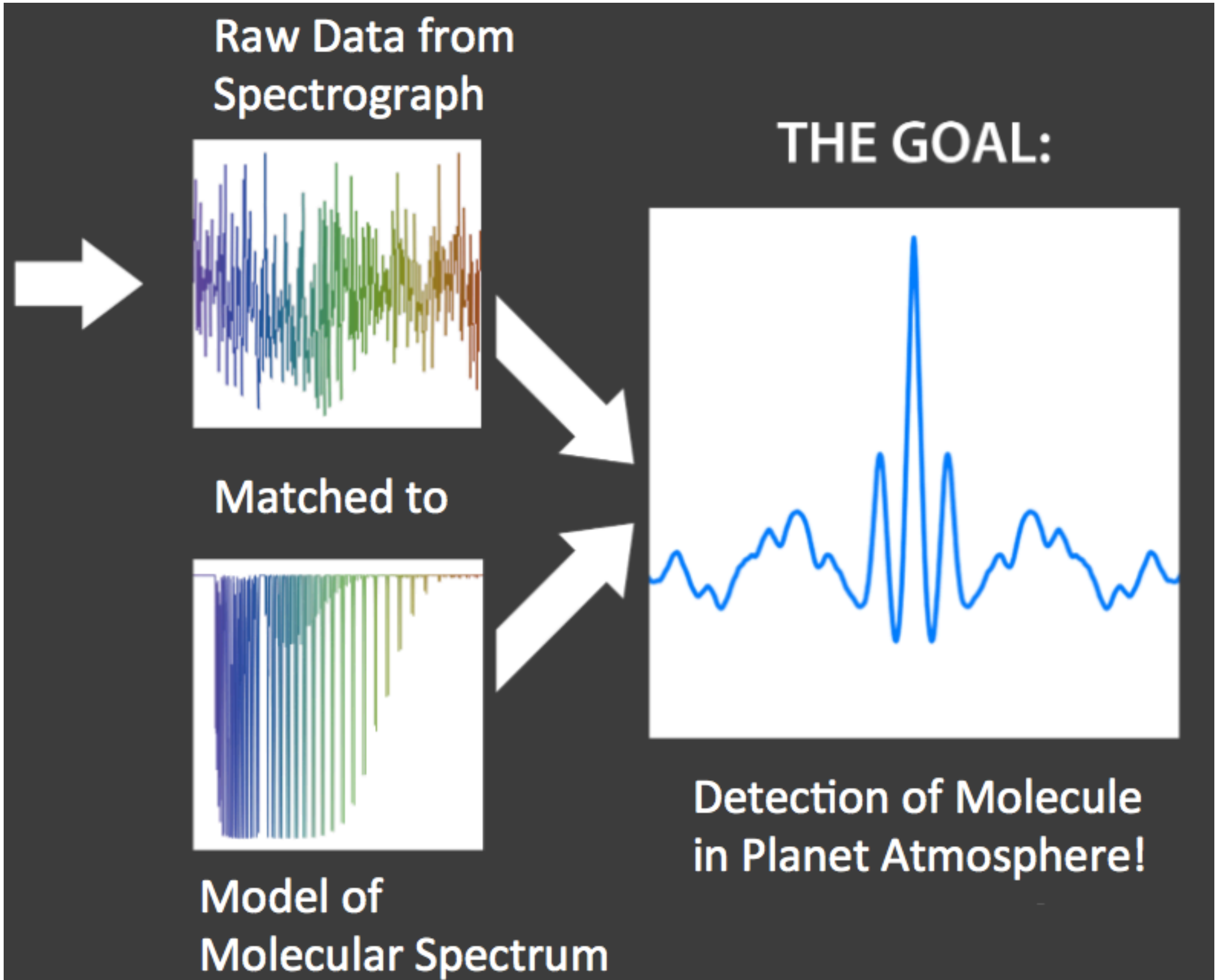


Beta Pic b, Hoeijmakers et al. 2018

High Dispersion Coronagraphy - bridging the contrast gap

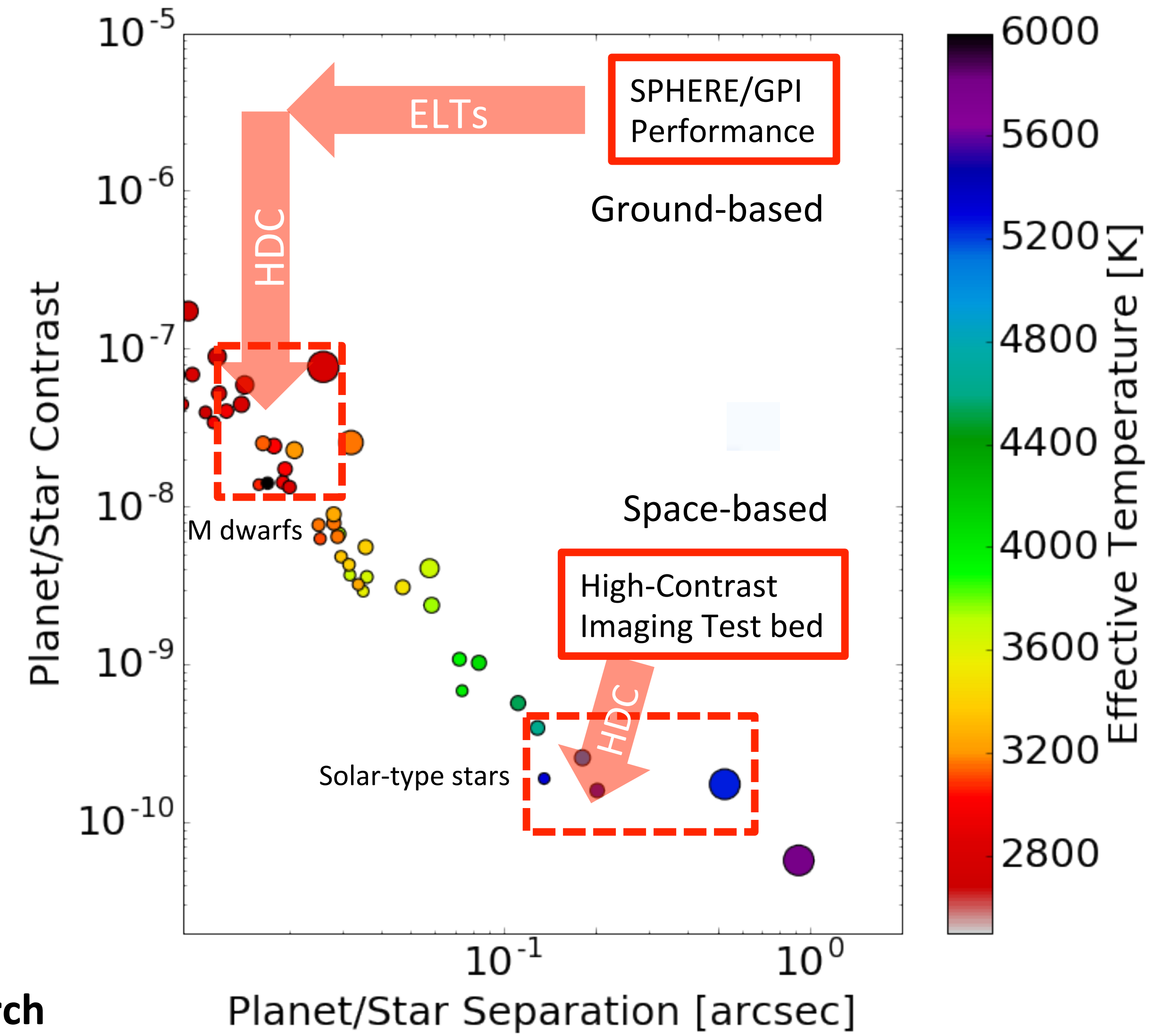


High Dispersion Coronagraphy - bridging the contrast gap



Wang et al. 2017
Mawet et al. 2017

Reflection Light of Habitable Planets
Ground ELTs vs. Space Missions



Biomarker Search

HDC Instruments

- SPHERE + CRIRES
- SPHERE + ESPRESSO
- SCExAO + IRD
- MagAO-X + RHEA
- Keck Planet Imager and Characterizer (KPIC)
- TMT Planetary Systems Imager (PSI)
- Space (LUVOIR/HabEx)

NIR HCI+HRS 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*}

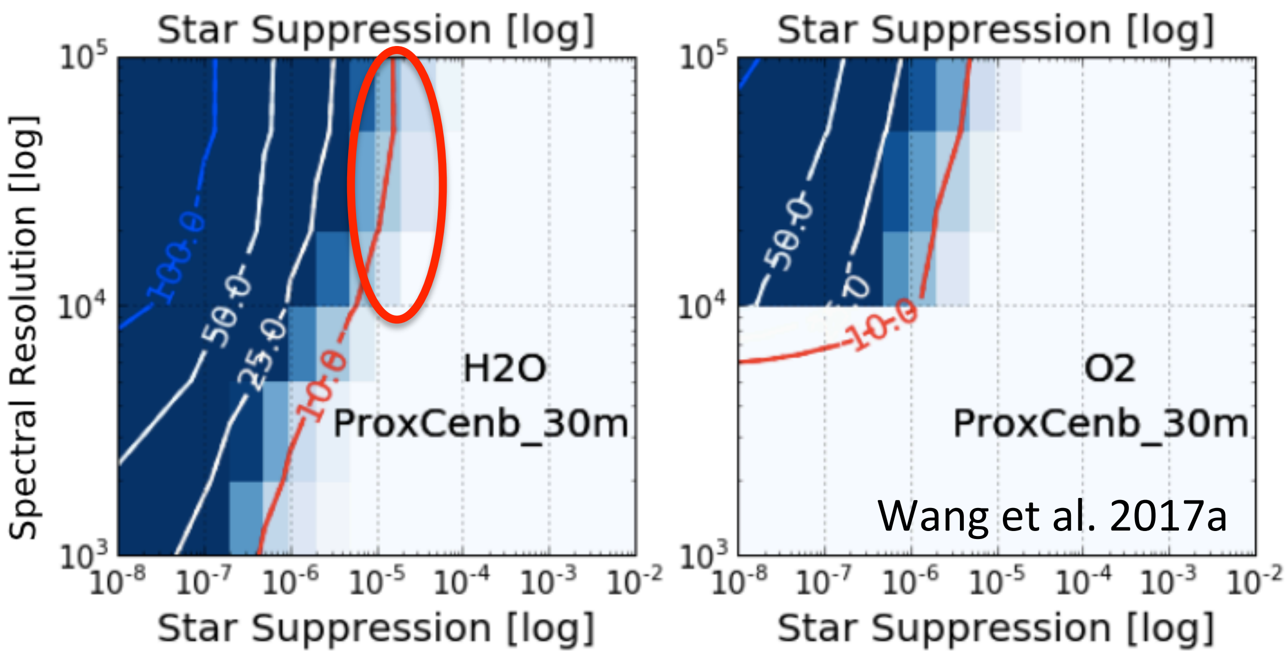
Note. — *: Based on H2RG detector specification (Blank et al. 2012)

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.

HDC Simulation For Proxima Cen b

- H2O and O2 are detectable at 10^{-5}-10^{-6} starlight suppression level (in *J* band)

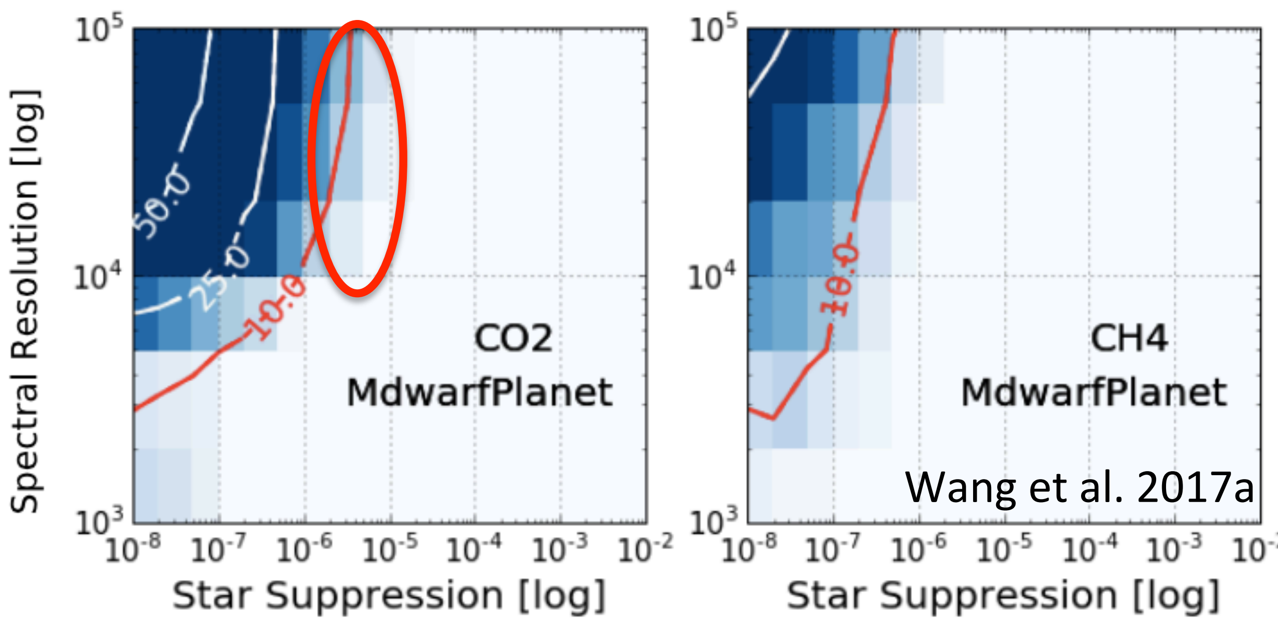


- Requirement for starlight suppression is relaxed by 100 times.

A clear pathway to search and characterize planets around M dwarfs

HDC Simulation For a M Dwarf Planet in the HZ at 5 pc

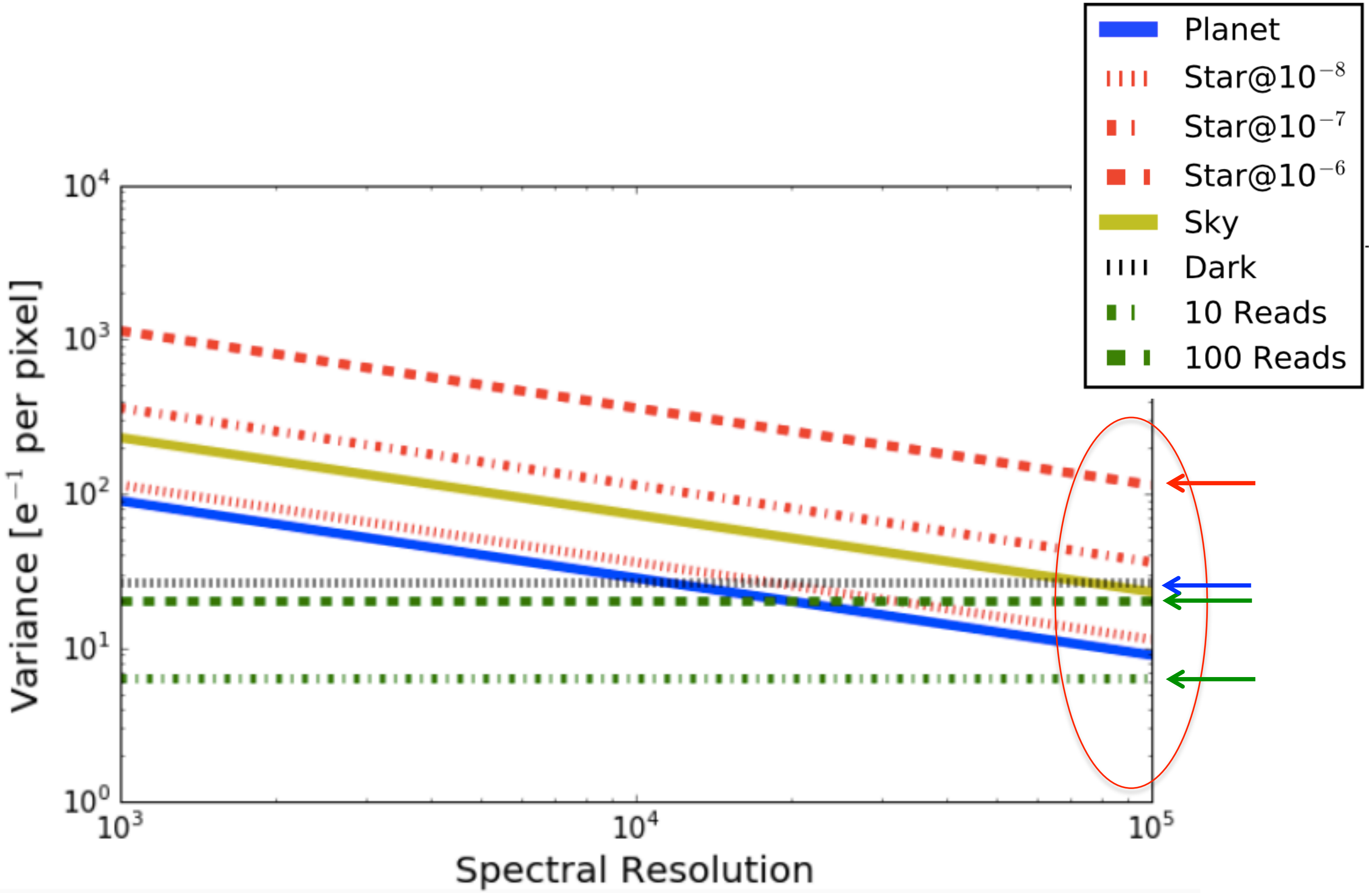
- CO_2 can be detected at 4×10^{-6} starlight suppression level (in *K* band)



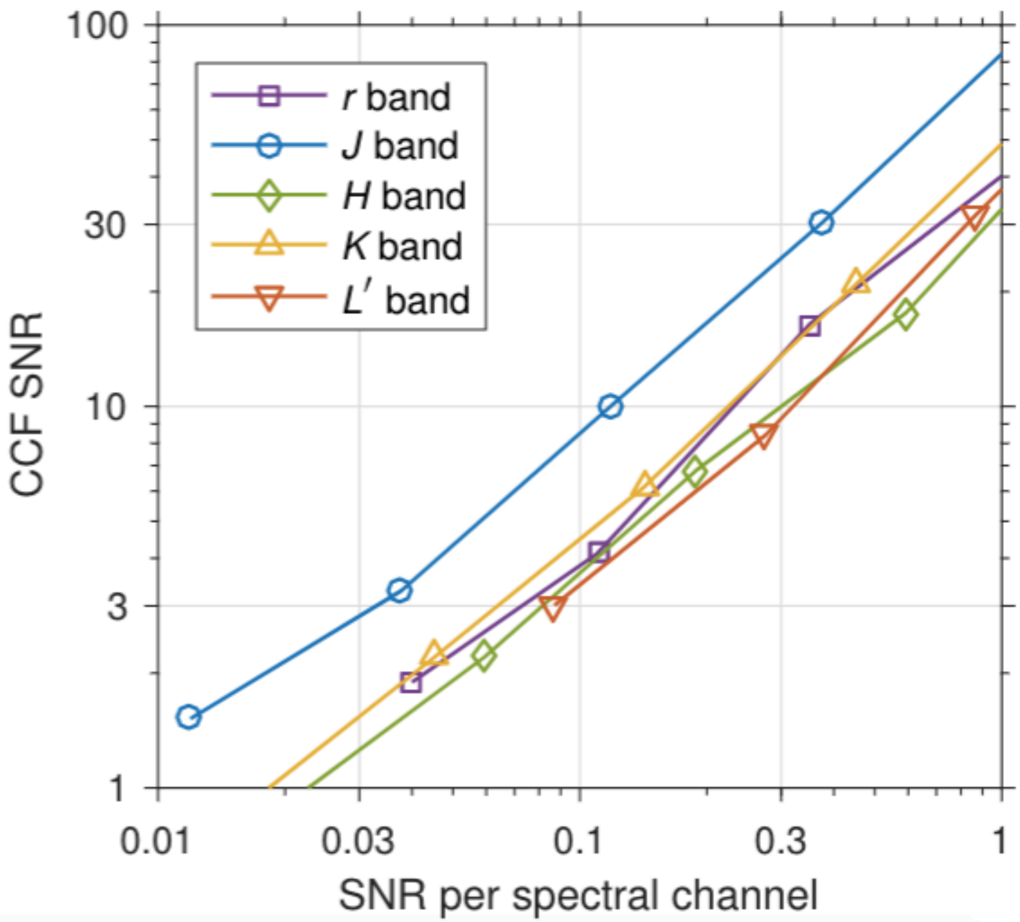
- Requirement for starlight suppression is relaxed by 600 times (vs. 6×10^{-9} planet/star contrast).

A clear pathway to search and characterize planets around M dwarfs

Stellar noise dominates error budget



HDC boost factor:
Pixel SNR -> CCF SNR

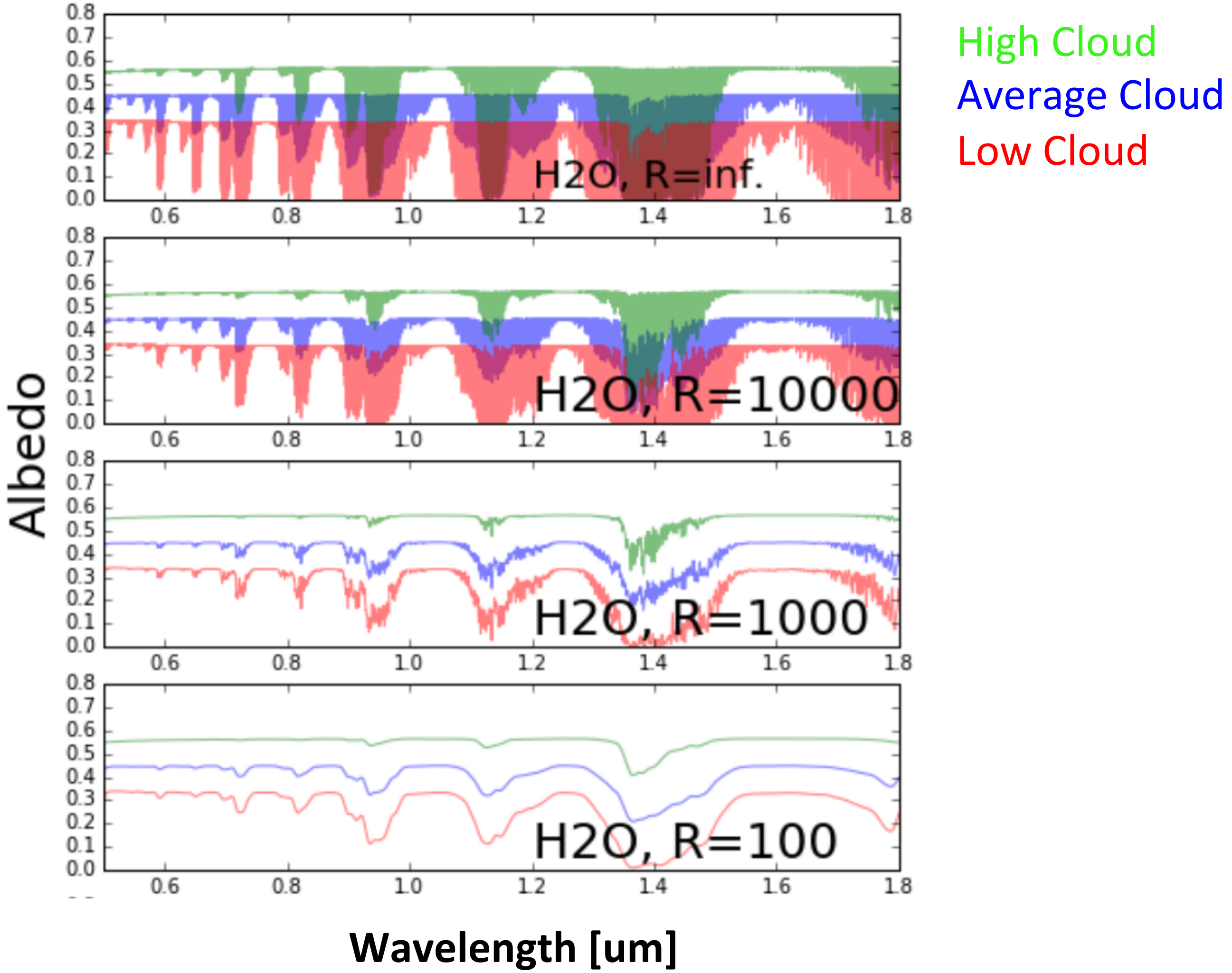


Ruane, Wang et al. 2018
submitted to ApJ

When comparing results …

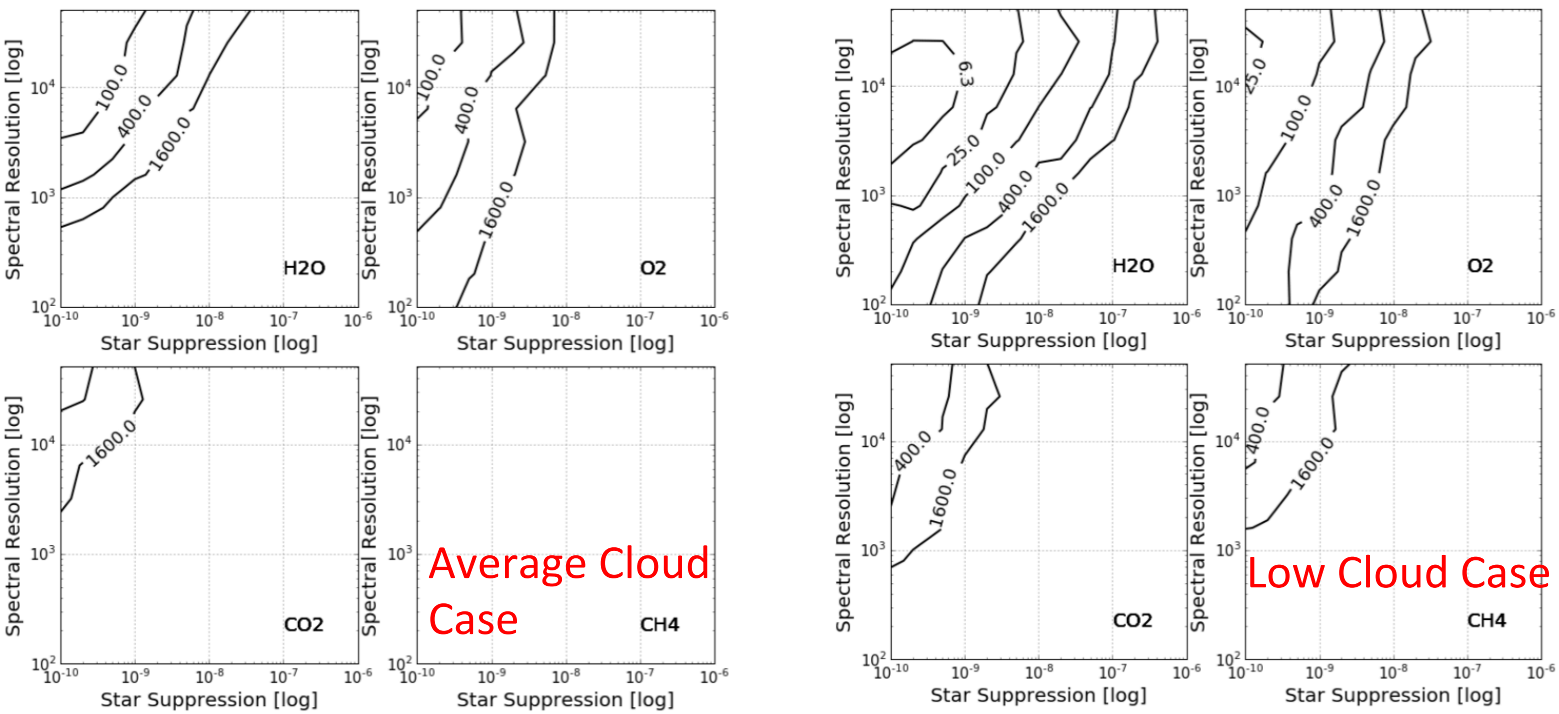
- Make sure all parameters are the same
- HDC boost factor vs. sqrt(N_{lines})
- Planet + star spectrum vs. molecular spectrum only
- Cloud coverage

Cloud effect



Baseline Requirements For HabEx

Telescope/Instrument		Star		Planet	
Telescope Aperture	4 m or 12 m	$T_{\rm eff}$	5800 K	Contrast	6×10^{-11}
End-to-End Throughput	10%	log(g)	4.5	Planet Radius	$1.0\ R_\oplus$
Spectral Resolution	varied	$V \sin i$	2.7 km/s	$V \sin i$	0.5 km/s
Exposure Time	varied	Orbital Inclination	50 deg	Orbital Phase	0.25
Wavelength	0.5-1.8 μm	Radial Velocity	0.0 km/s	Radial Velocity	20.4 km/s
Detector Noise	0	Distance	5 pc	Semi-major Axis	1 AU



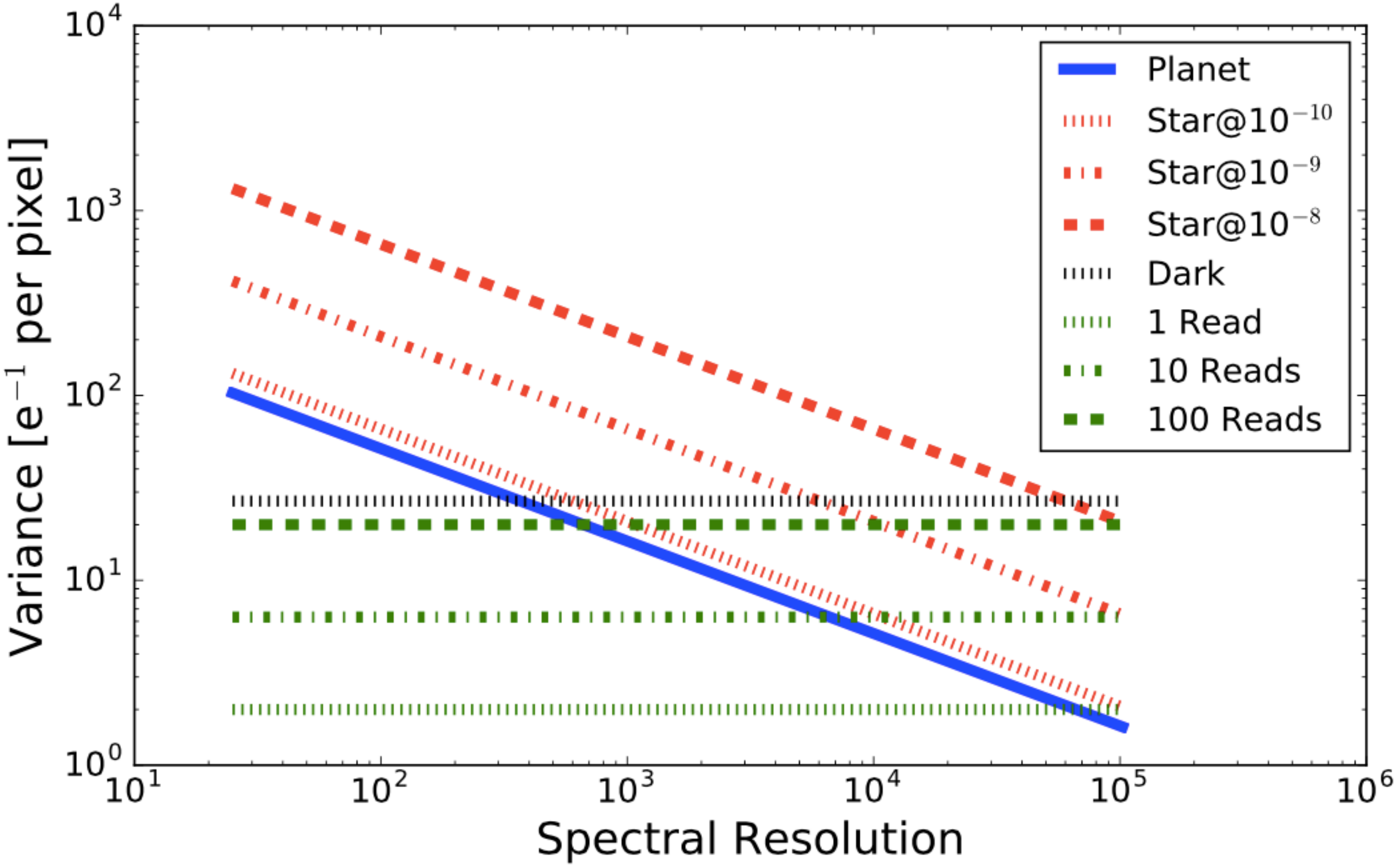
Wang et al. 2018, JATIS in review

Stay tuned …

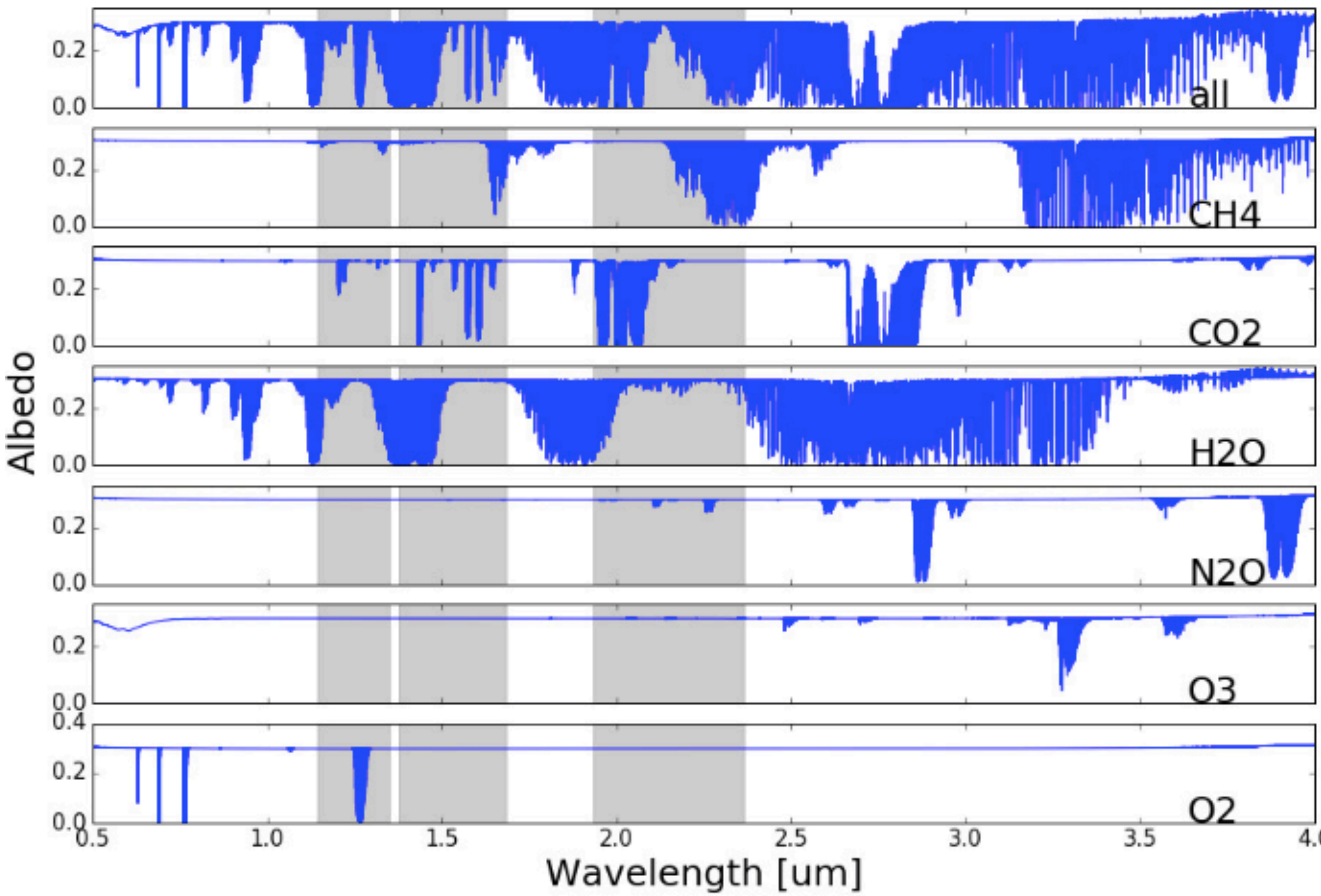
- Full parameter space study for future space missions (Carl Coker, NPP at JPL)
- Optimal band for molecular search (Carlos Sosa, SURF at Caltech)
- TMT PSI full-fledged simulation (Ji Wang)

Thank you!

Source of Noise



Absorption bands vs. lines



Absorption bands vs. lines