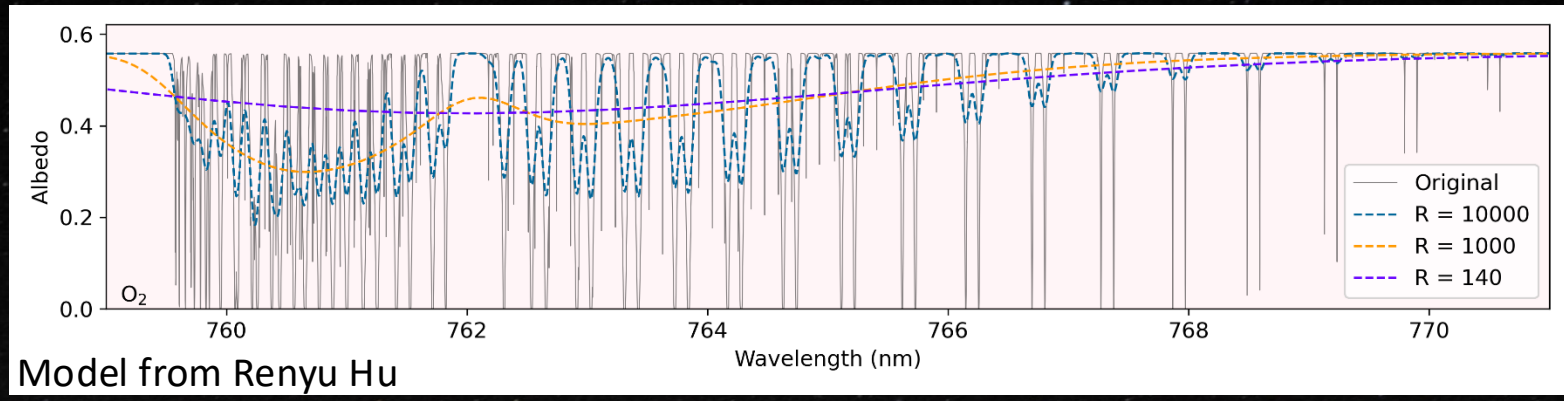
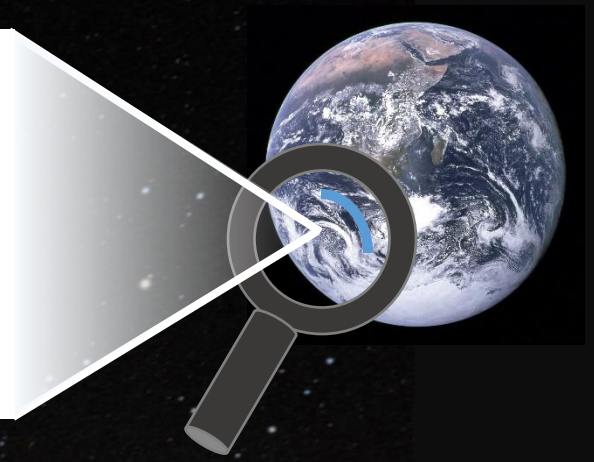
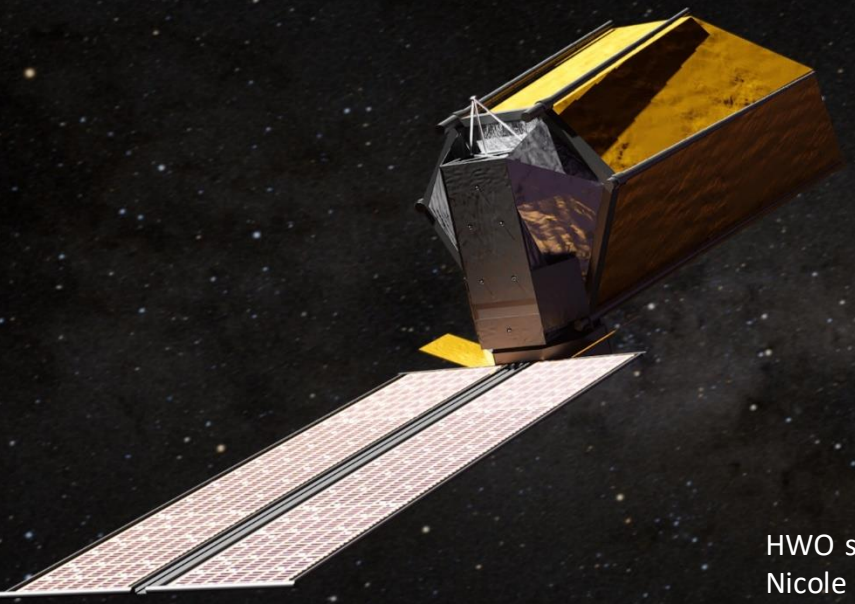


Model from Renyu Hu





The power of high-resolution spectroscopy: from self-luminous gas giants to ExoEarths and biosignatures

Jean-Baptiste Ruffio (https://www.jbruffio.com)
jruffio@ucsd.edu (UC San Diego), December 29, 2025

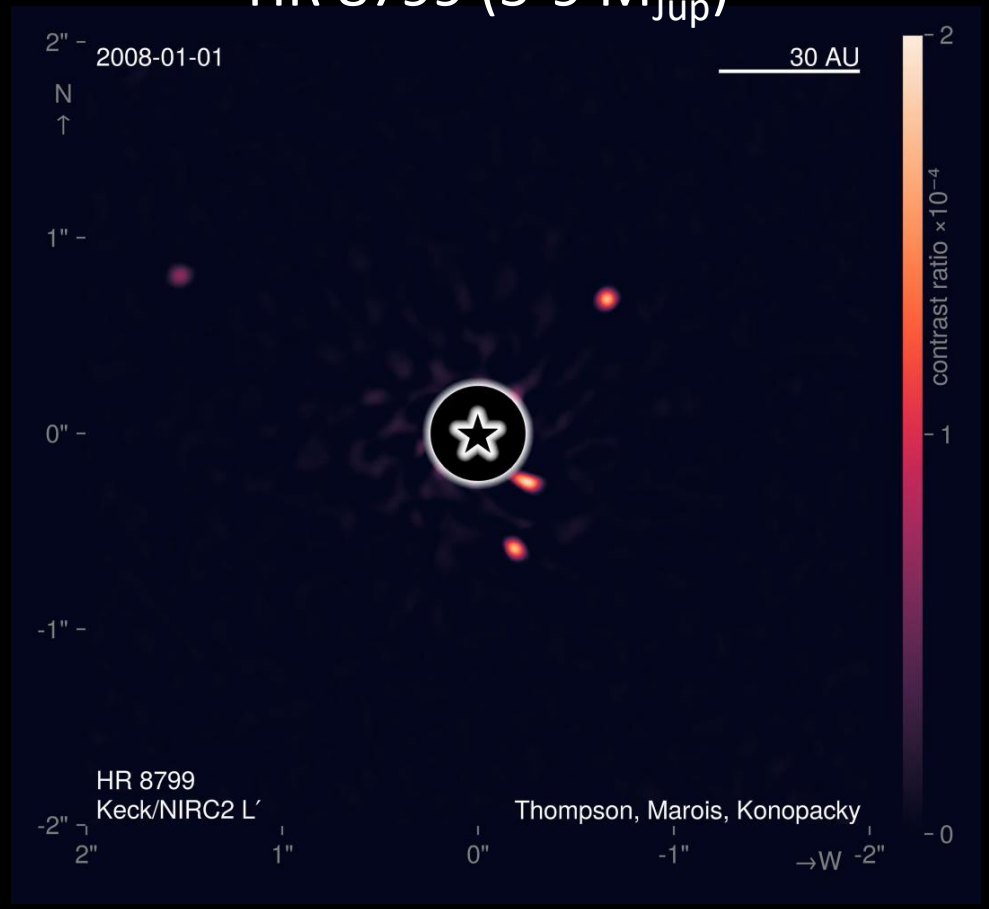
HWO simulations: Sarah Steiger, Corey Spohn, Bruce Macintosh, Dimitri Mawet, Laurent Pueyo, Bertrand Mennesson, Beck Dacus, Nicole Wolff, Renyu Hu, Kielan Hoch, Quinn M. Konopacky, Marshall D. Perrin, Dmitry Savransky, Michael W. McElwain, Shelley A. Wright, Ji Wang (王吉), Pin Chen, Tyler D. Robinson
& Spectral processing focus group (within COPP)

JWST/NIRSpec HR8799: Jerry W. Xuan, Yayaati Chachan, Aurora Kesseli, Eve J. Lee, Charles Beichman, Klaus Hodapp, William O. Balmer, Quinn Konopacky, Marshall D. Perrin, Dimitri Mawet, Heather A. Knutson, Geoffrey Bryden, Thomas P. Greene, Doug Johnstone, Jarron Leisenring, Michael Meyer, Marie Ygouf

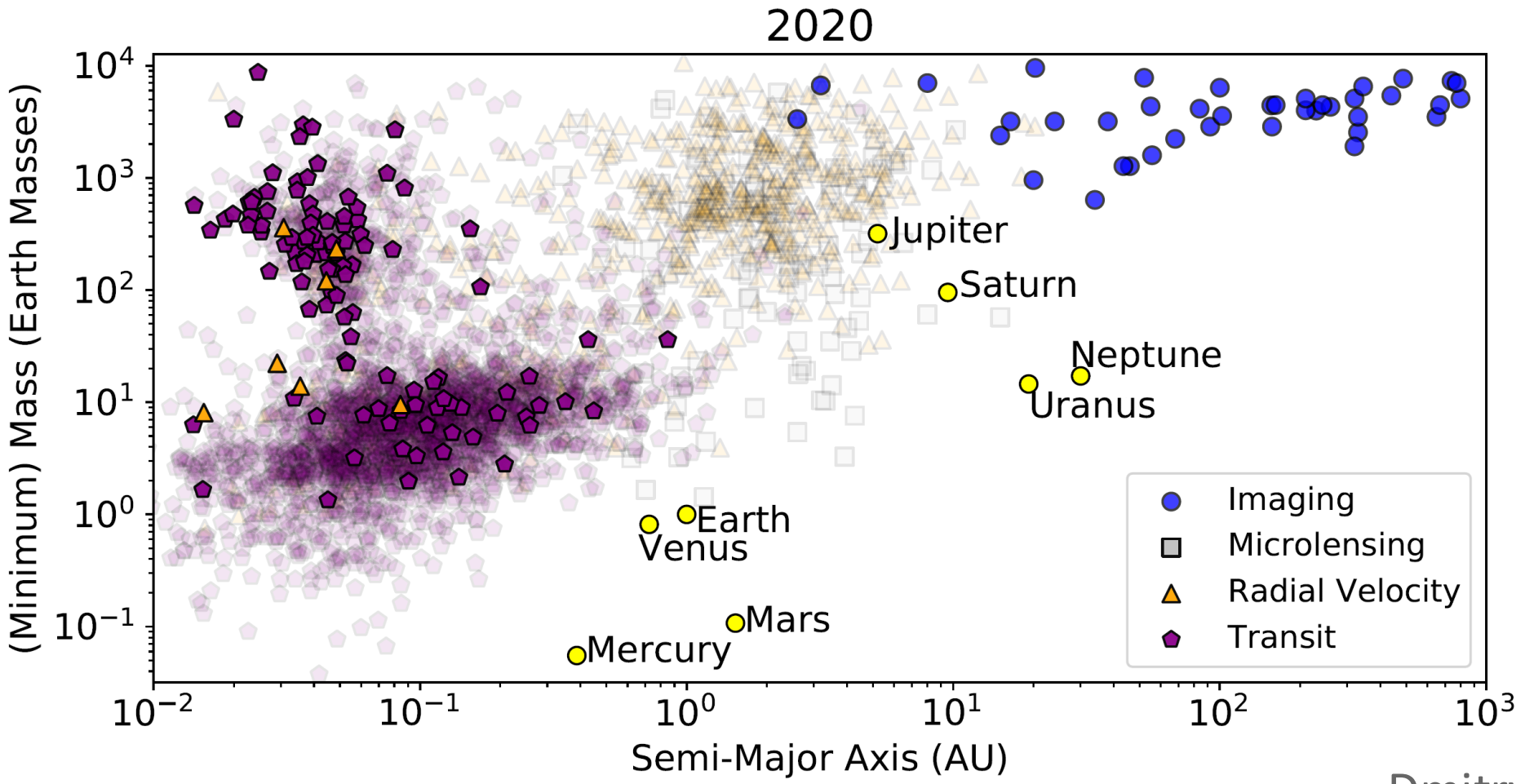
NASA's Goddard Space Flight Center Conceptual Image Lab

Direct imaging (2008-…

HR 8799 (5-9 M_{Jup})



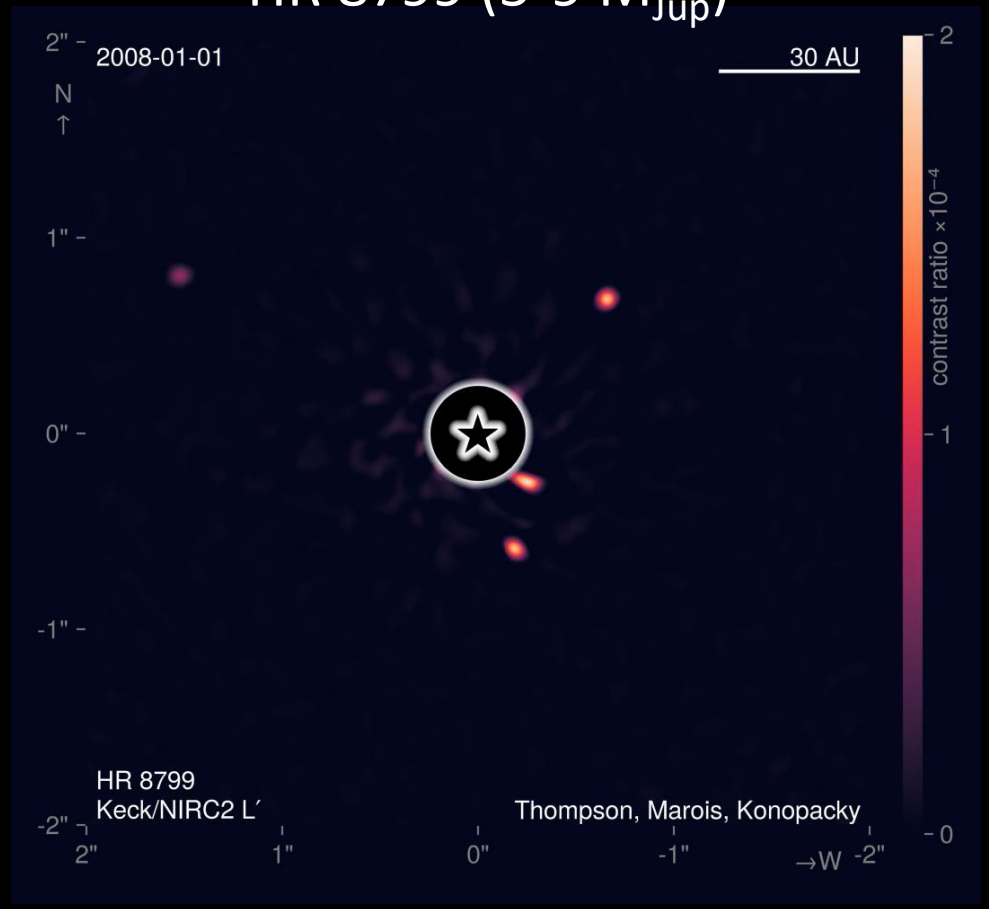
Direct-imaging enables detailed characterization of exoplanet atmospheres



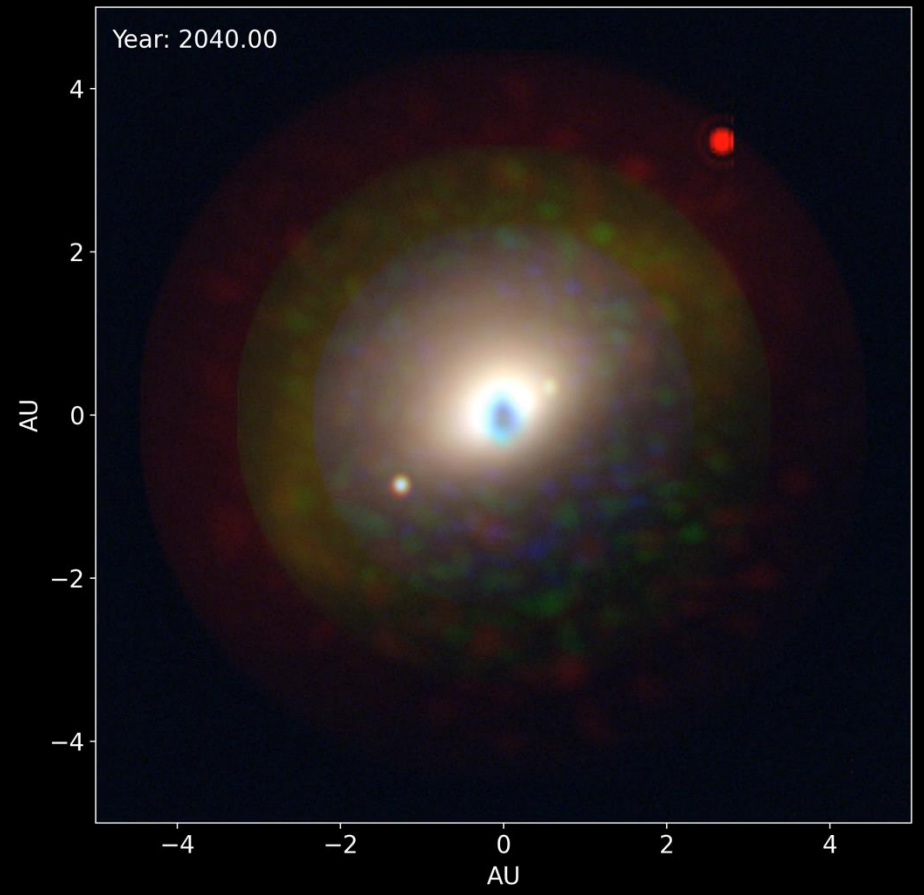
Dmitry Savransky

Direct imaging (2008-2040?)

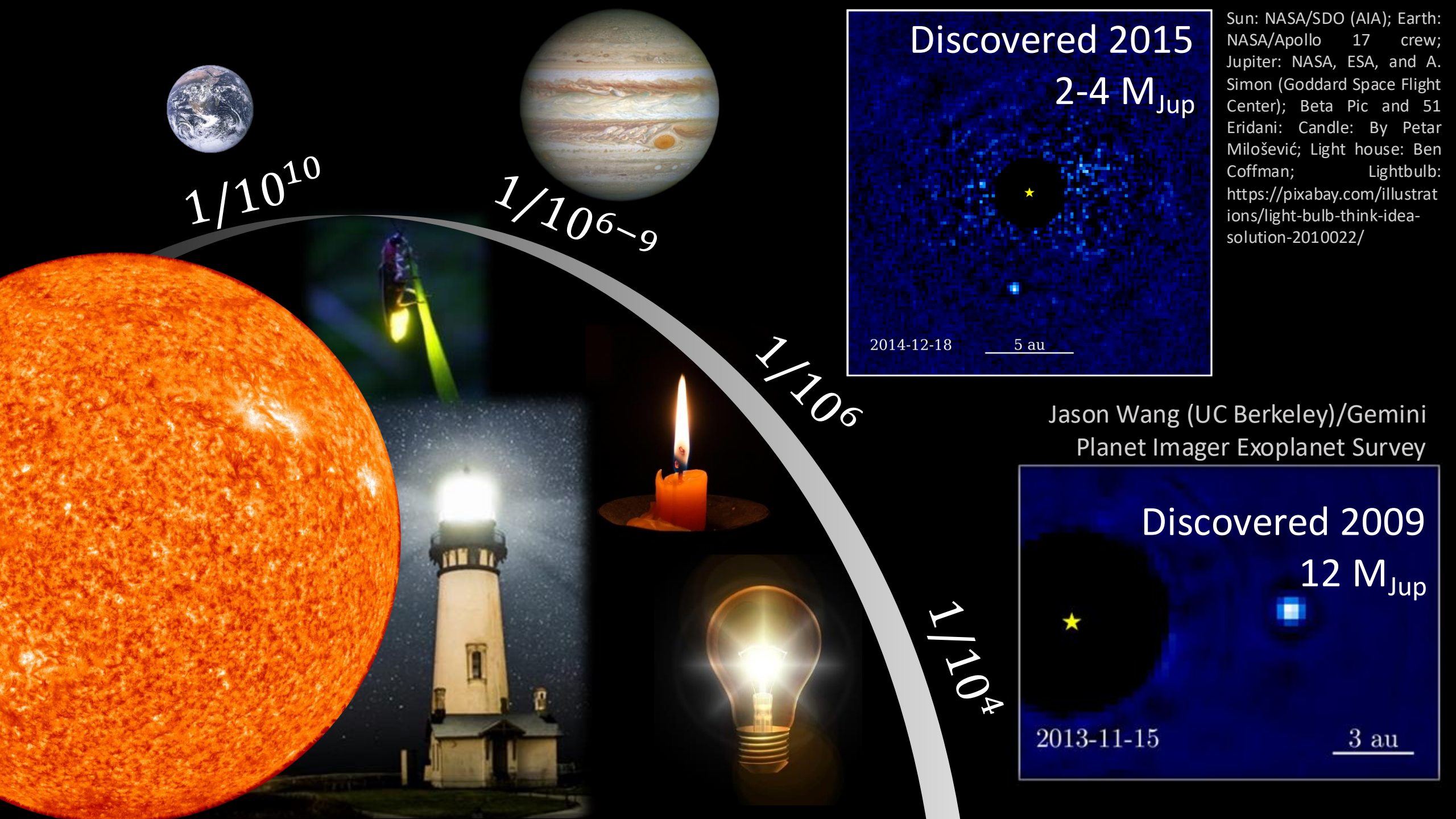
HR 8799 (5-9 M_{Jup})



Exo-Earths and biosignatures

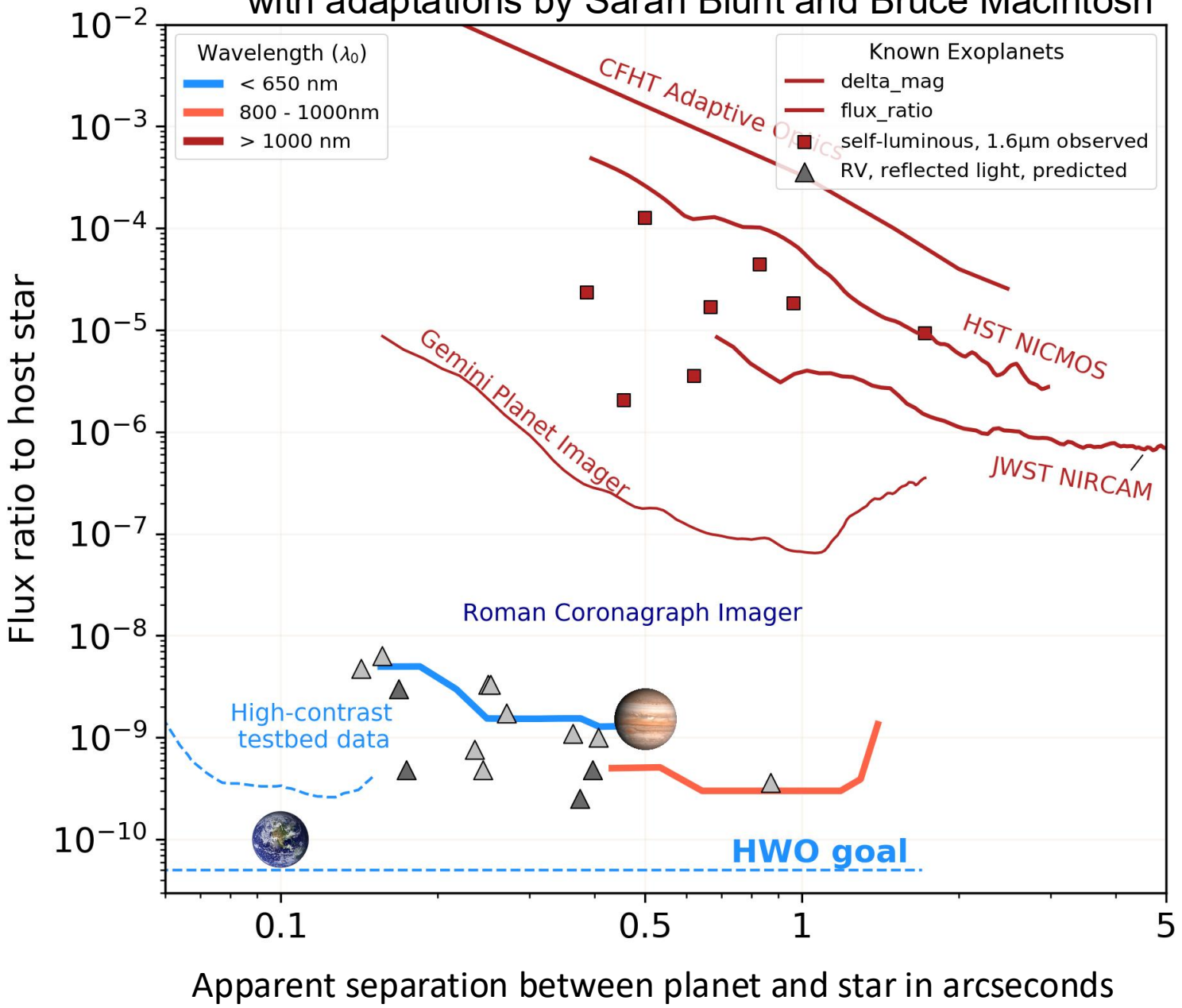


Corey Spohn (NASA Goddard)
Realistic astrophysical fluxes from ExoVista
Coronagraph PSFs from EAC1's AAVC; CDS pipeline


Discovered 2015
2-4 M_{Jup}
2014-12-18
5 au
Sun: NASA/SDO (AIA); Earth: NASA/Apollo 17 crew; Jupiter: NASA, ESA, and A. Simon (Goddard Space Flight Center); Beta Pic and 51 Eridani: Candle: By Petar Milošević; Light house: Ben Coffman; Lightbulb: https://pixabay.com/illustrations/light-bulb-think-idea-solution-2010022/
1/10^10
1/10^6–9
1/10^6
1/10^4
Jason Wang (UC Berkeley)/Gemini Planet Imager Exoplanet Survey
Discovered 2009
12 M_{Jup}
2013-11-15
3 au

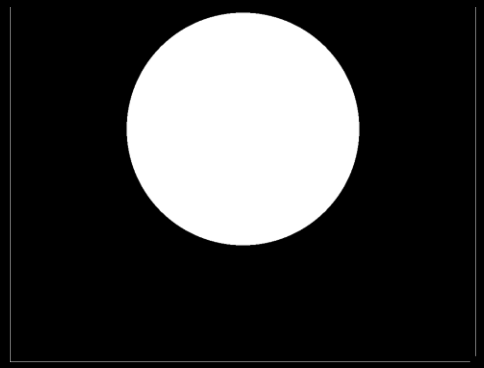
From massive self-luminous planets to reflected light solar system analogs.

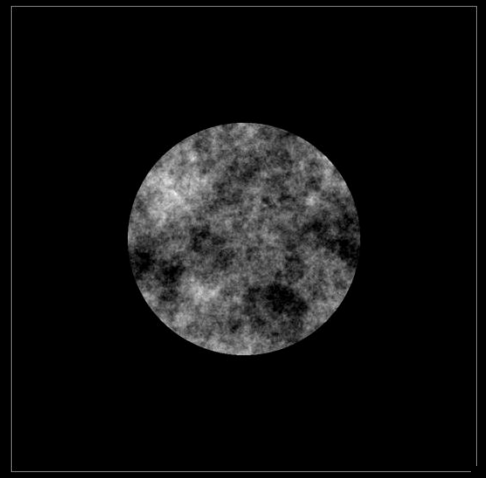
Vanessa Bailey
with adaptations by Sarah Blunt and Bruce Macintosh

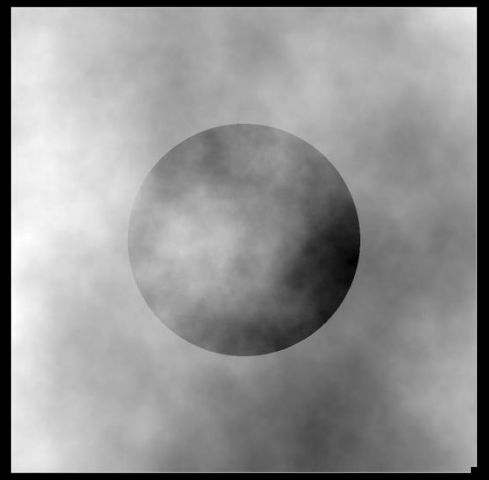


Optical distortions create speckle noise

Phase of the light wave (wavefront)





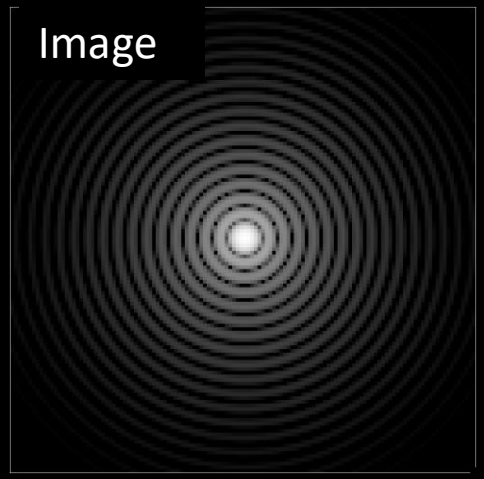


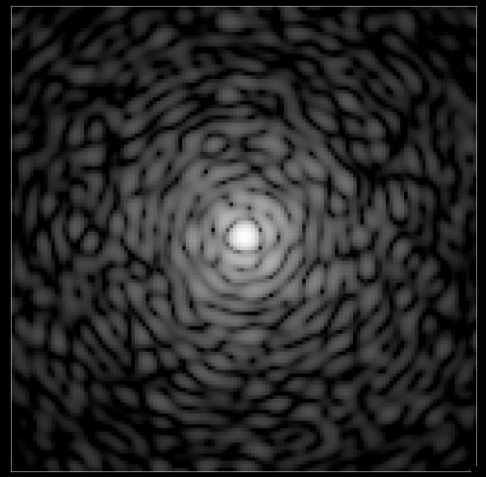
Perfect Telescope

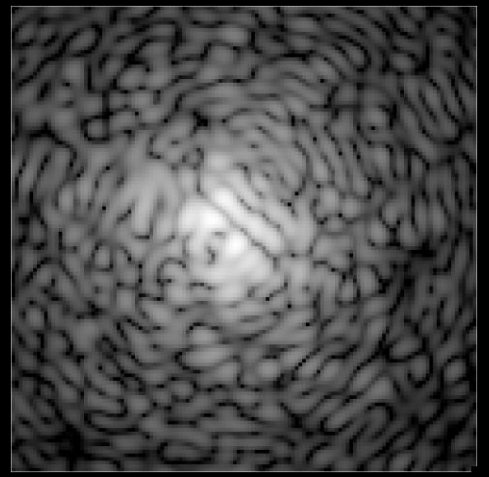
Polishing errors

Atmospheric turbulence

Image

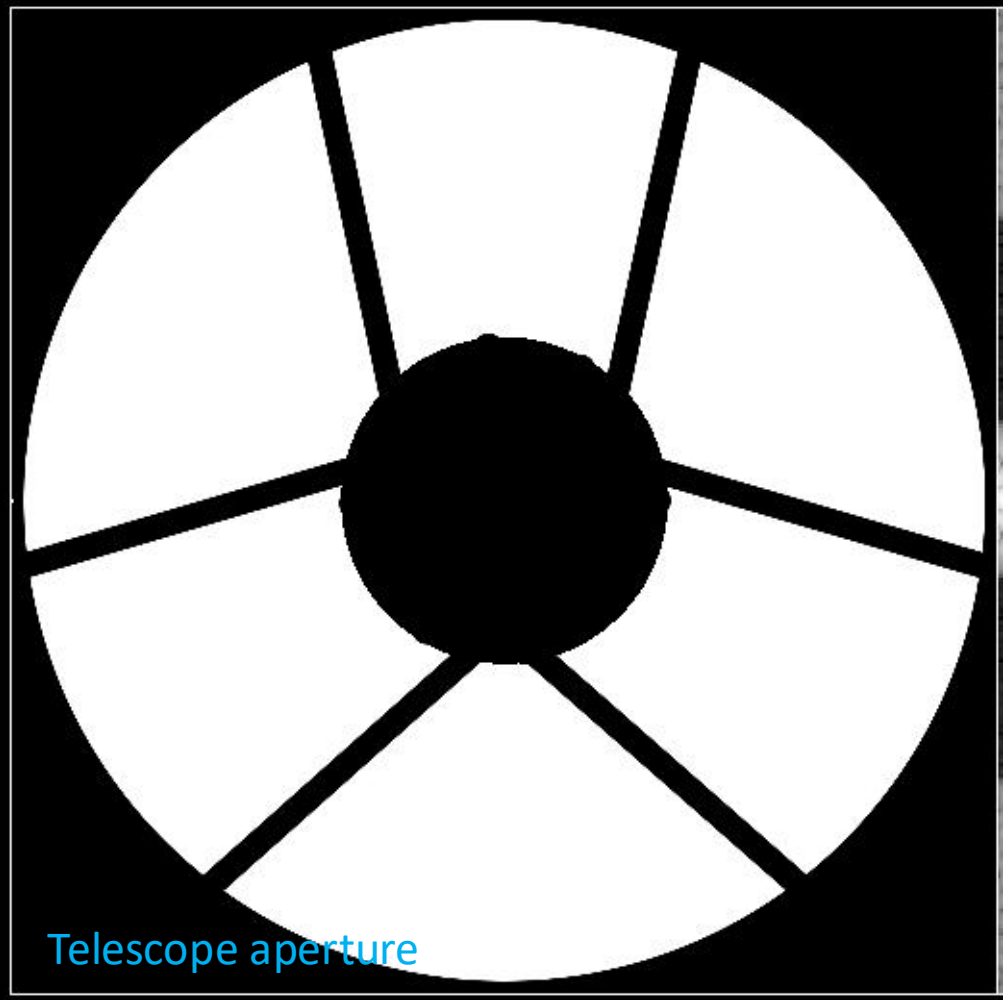




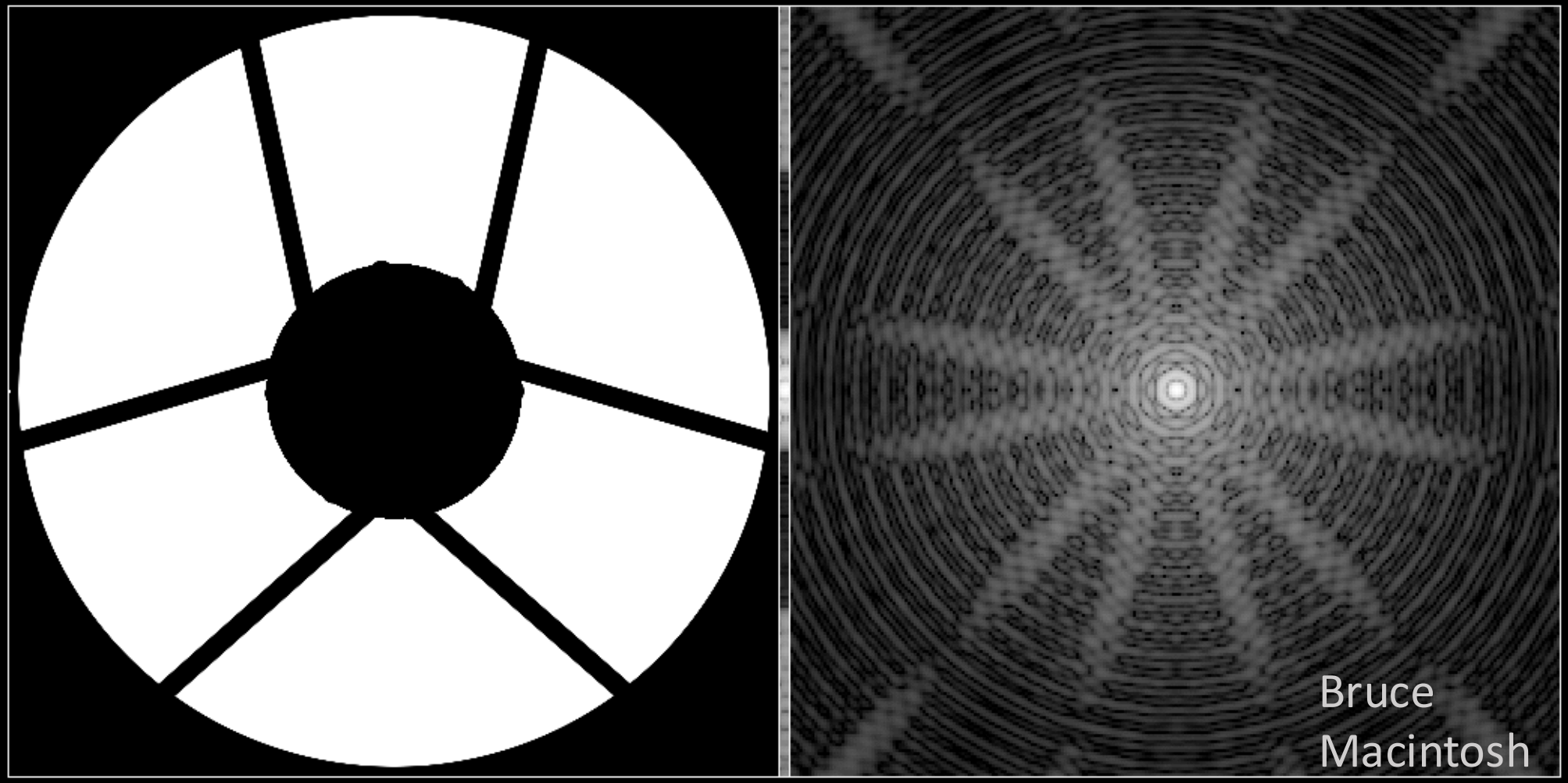


Bruce Macintosh

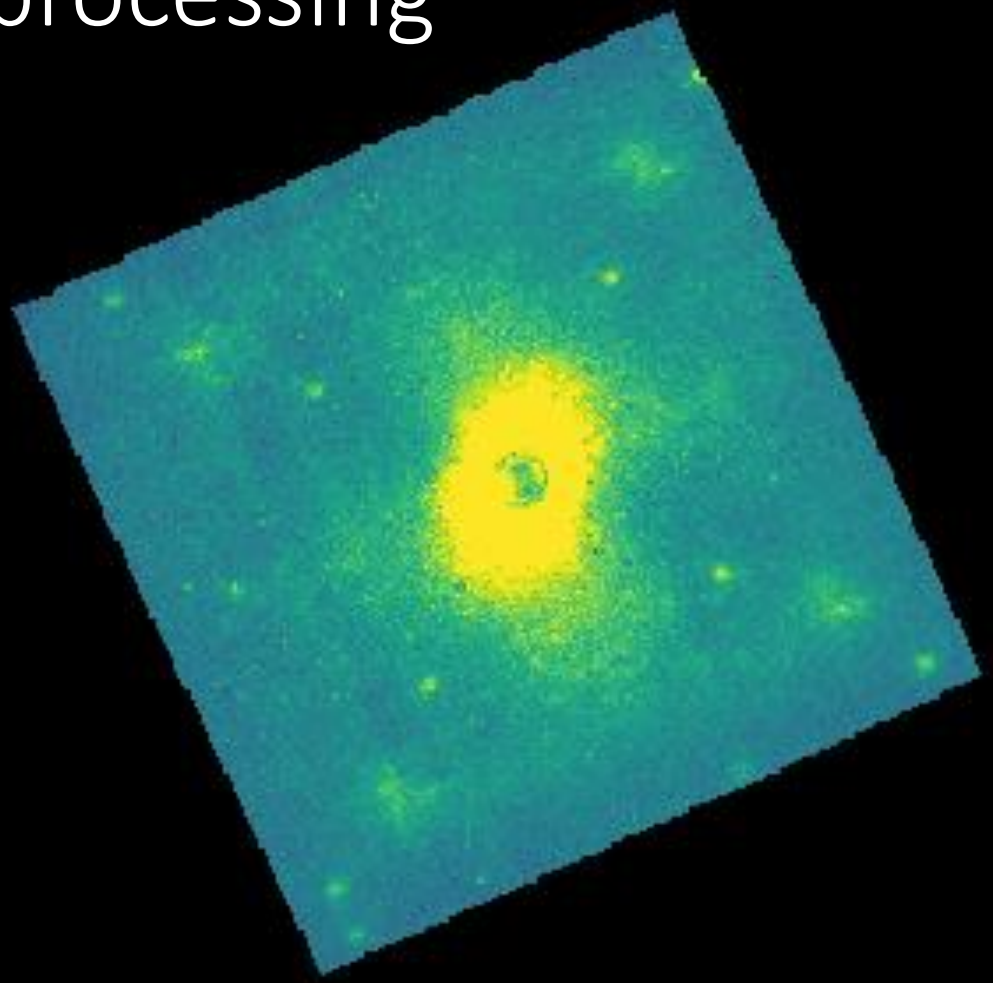
The diffracted starlight overwhelms the planet signal: e.g. Roman telescope aperture



A coronagraph reshapes the image of the star to create a “dark hole”

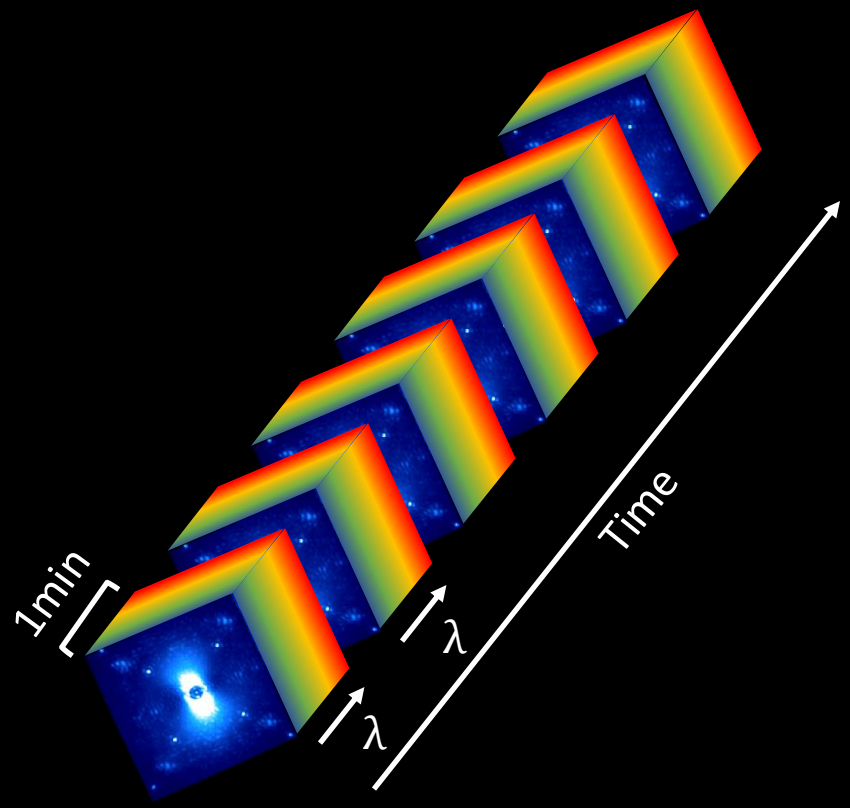


Residual speckles are then subtracted in post-processing

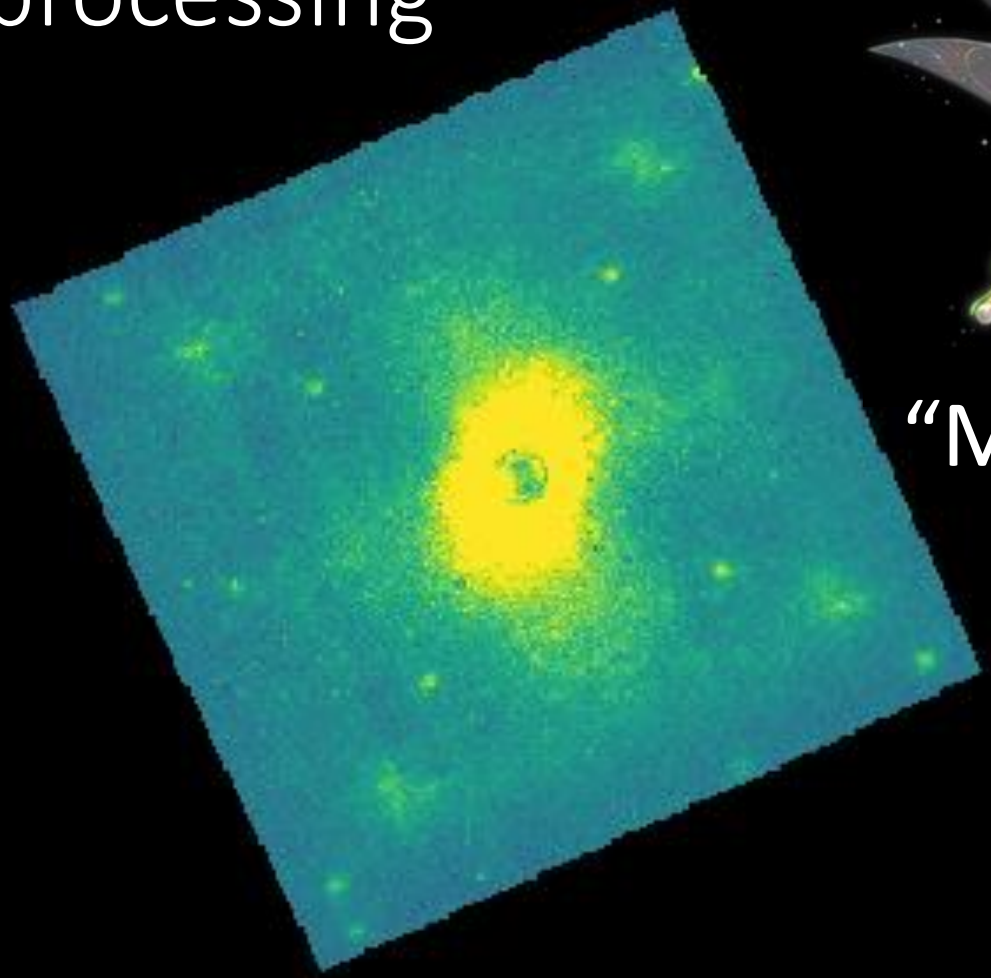


$\theta = -49.7° \; \lambda = 1.507 \mu m$

J-B. Ruffio & C. Vides



Residual speckles are then subtracted in post-processing



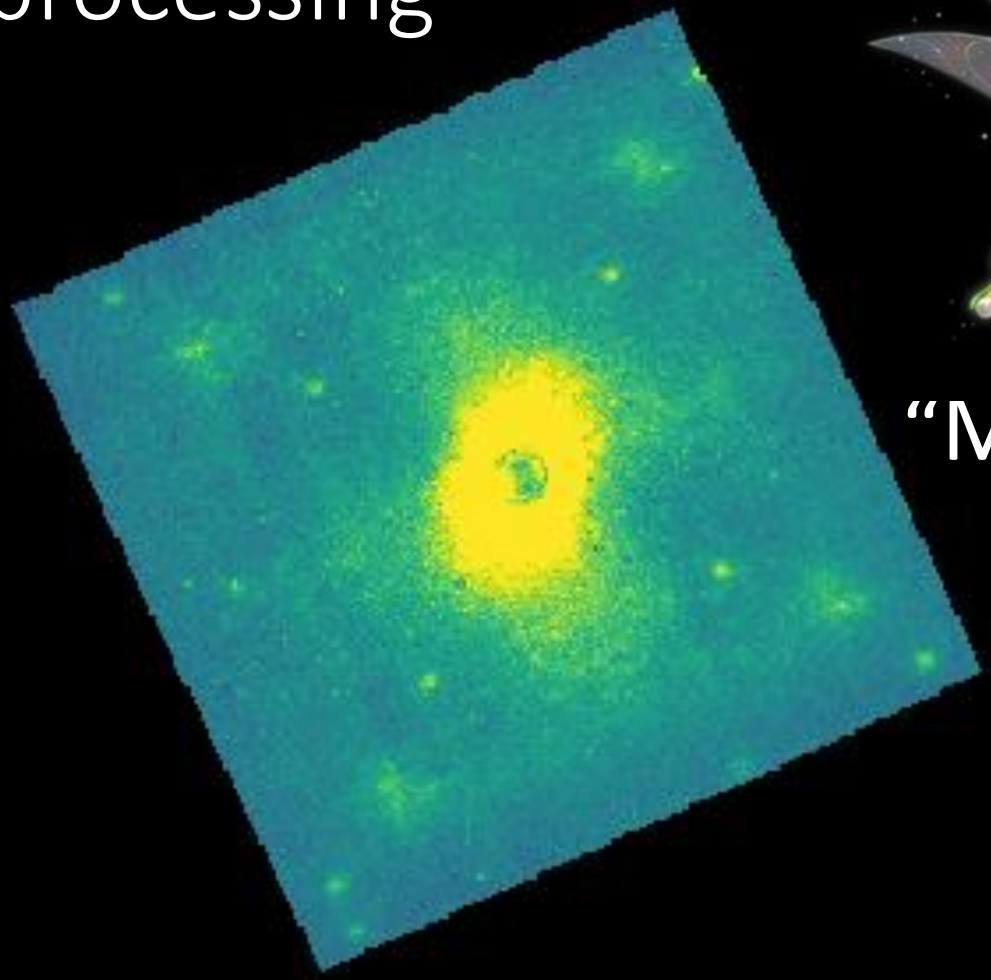
$\theta = -49.7° \; \lambda = 1.507 \mu m$

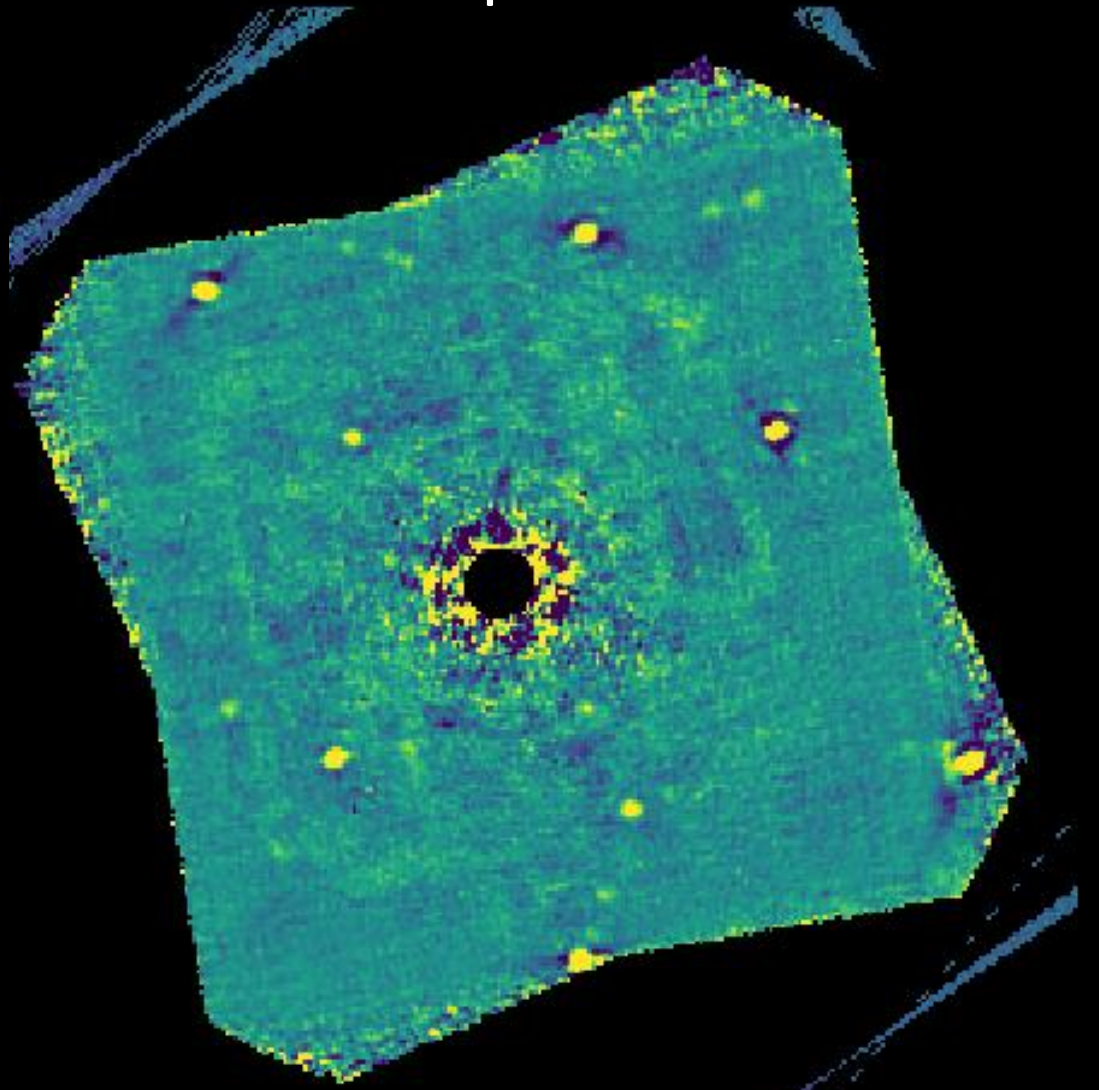
J-B. Ruffio & C. Vides

"Magic"

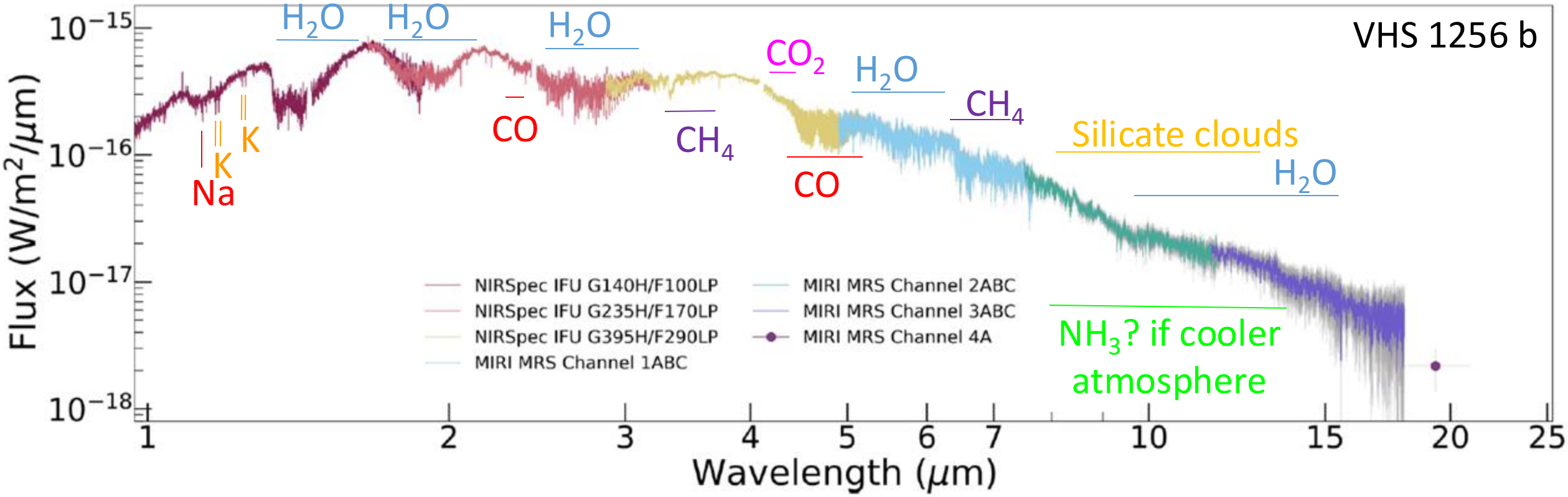
Residual speckles are then subtracted in post-processing

"Magic"





The molecular features themselves can also be used to disentangle the planet from the starlight

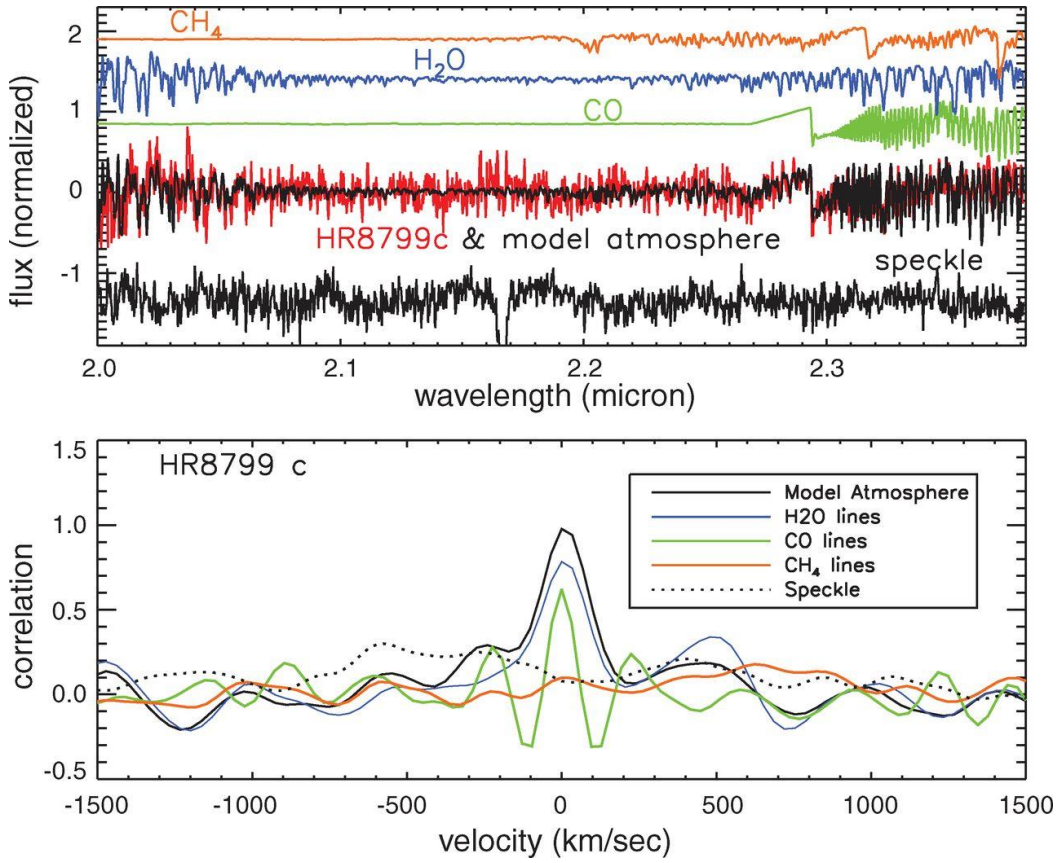


This does not look like a star!

Miles+2023

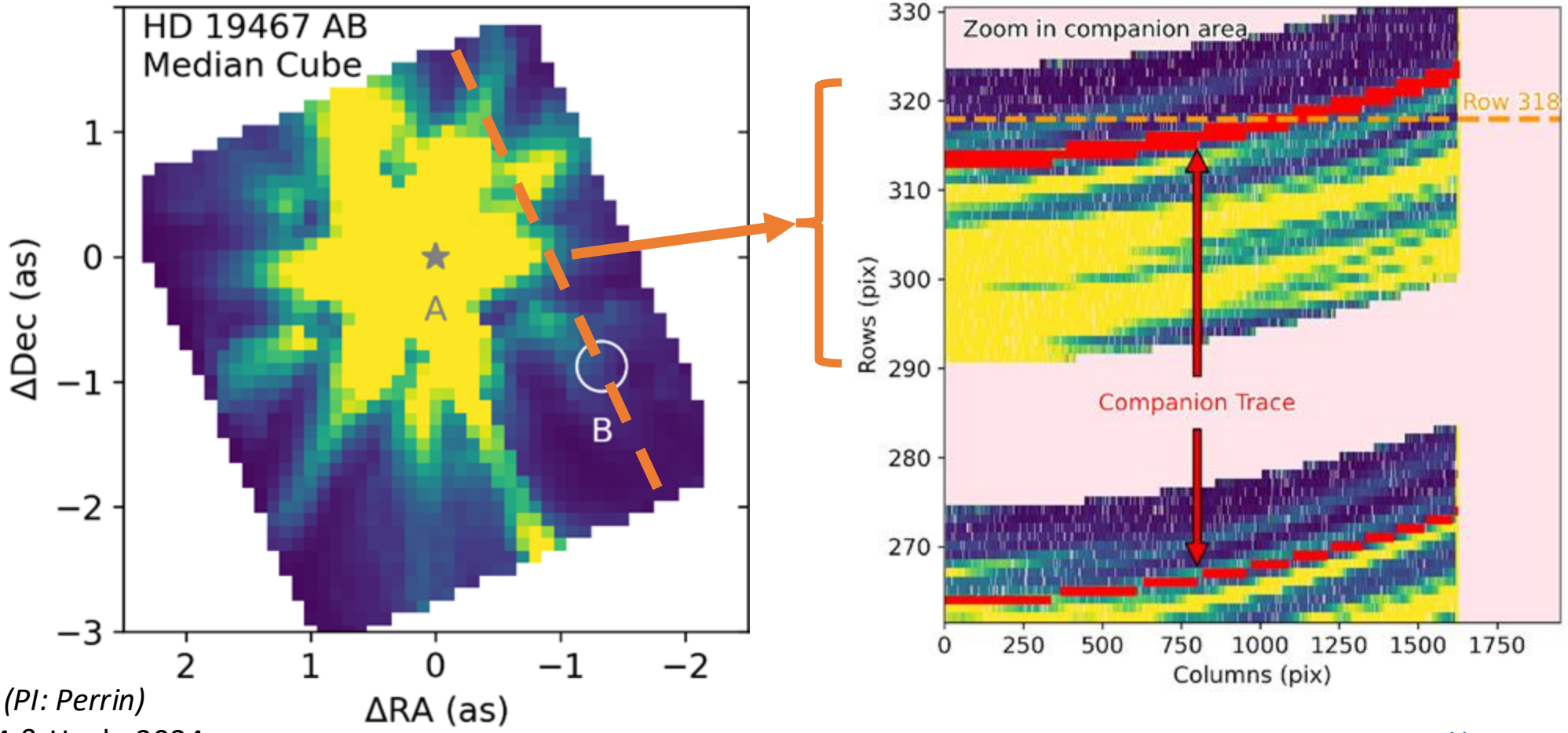
ERS 1386 (PI: Hinkley)

Molecules can be detected from cross correlation techniques at high spectral resolution (R>1,000)



Konopacky et al. (2013)

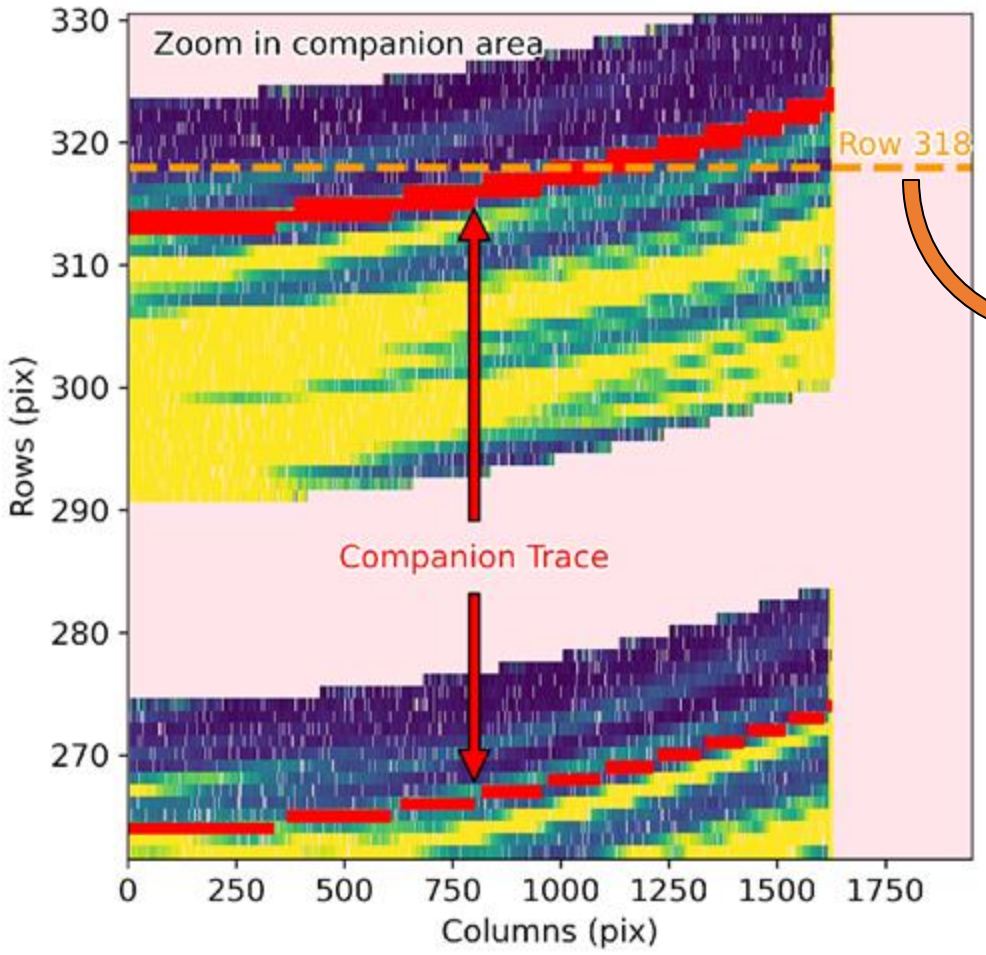
We have applied these techniques to JWST NIRSpec (R~2,700)

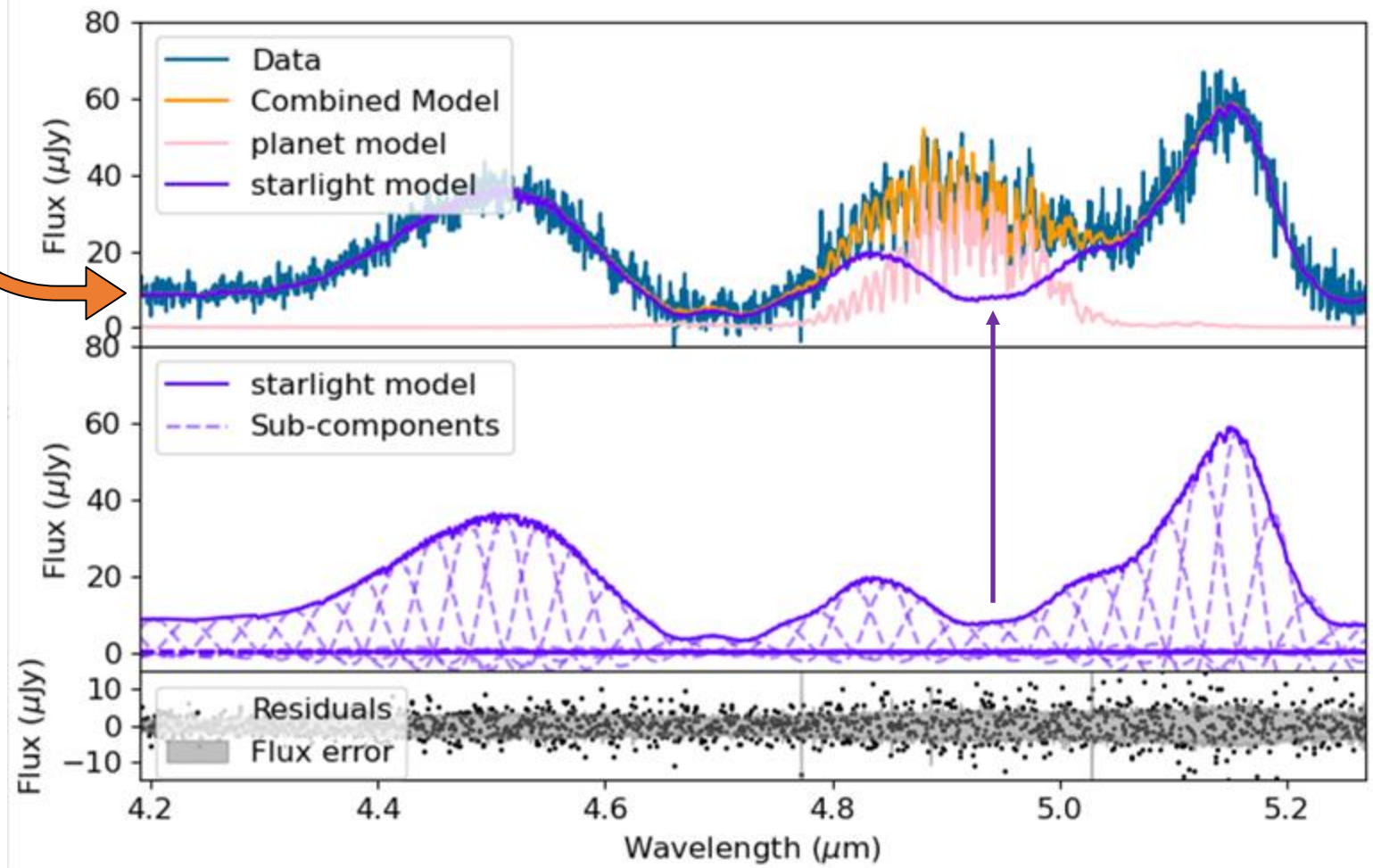


GTO #1414 (PI: Perrin)
Ruffio+2024 & Hoch+2024

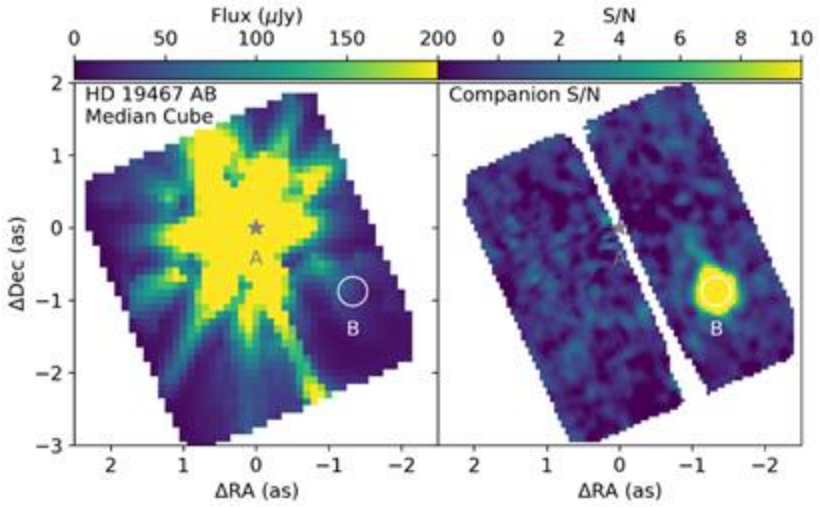
Ruffio+2024 https://github.com/jruffio/breads

We have applied these techniques to JWST NIRSpec (R~2,700)





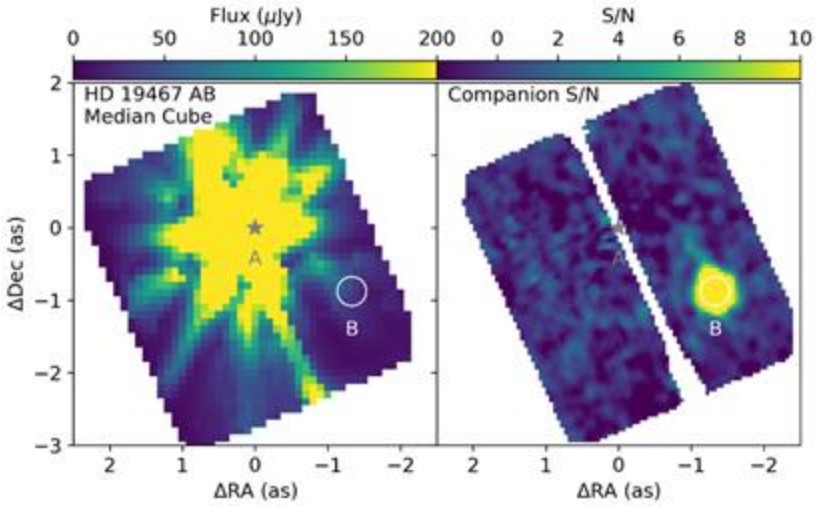
Ruffio+2024 https://github.com/jruffio/breads



….As of ExSoCal December 2023

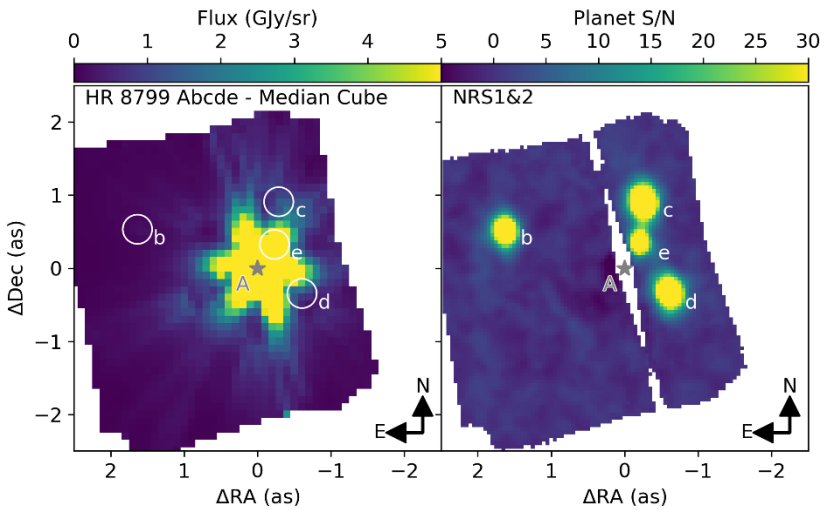
HD 19467 B *GTO #1414 (PI: Perrin)*

- Ruffio+2024
- Hoch+2024



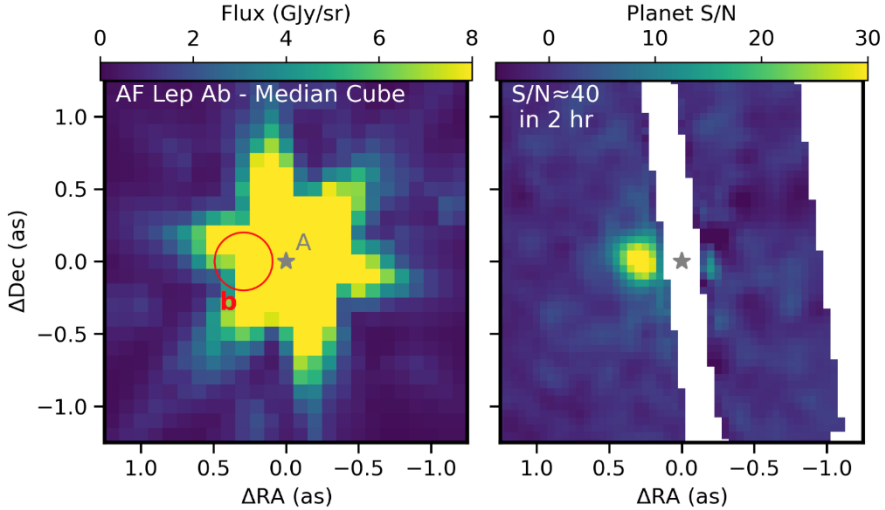
HD 19467 B *GTO #1414 (PI: Perrin)*

- Ruffio+2024
- Hoch+2024



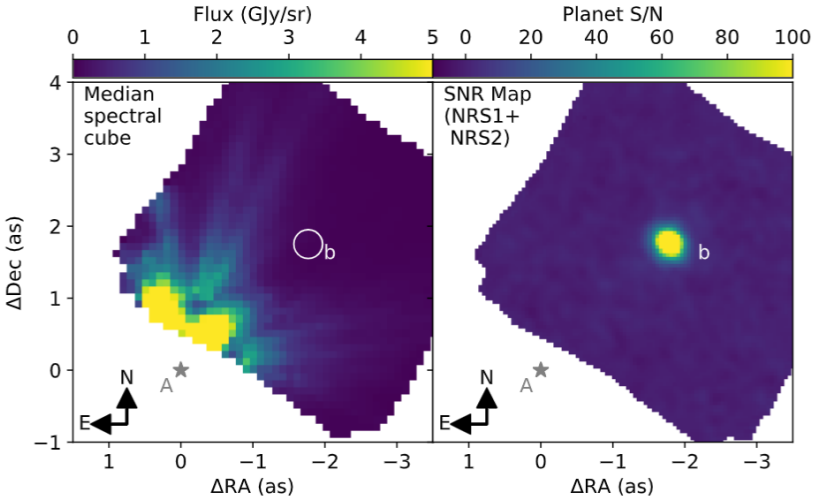
HR 8799 bcde *GTO #1188 (PI: Hodapp)*

- Ruffio & Xuan+ (Nature Ast.; Accepted in principle)
- Xuan & Ruffio+ (Submitted)



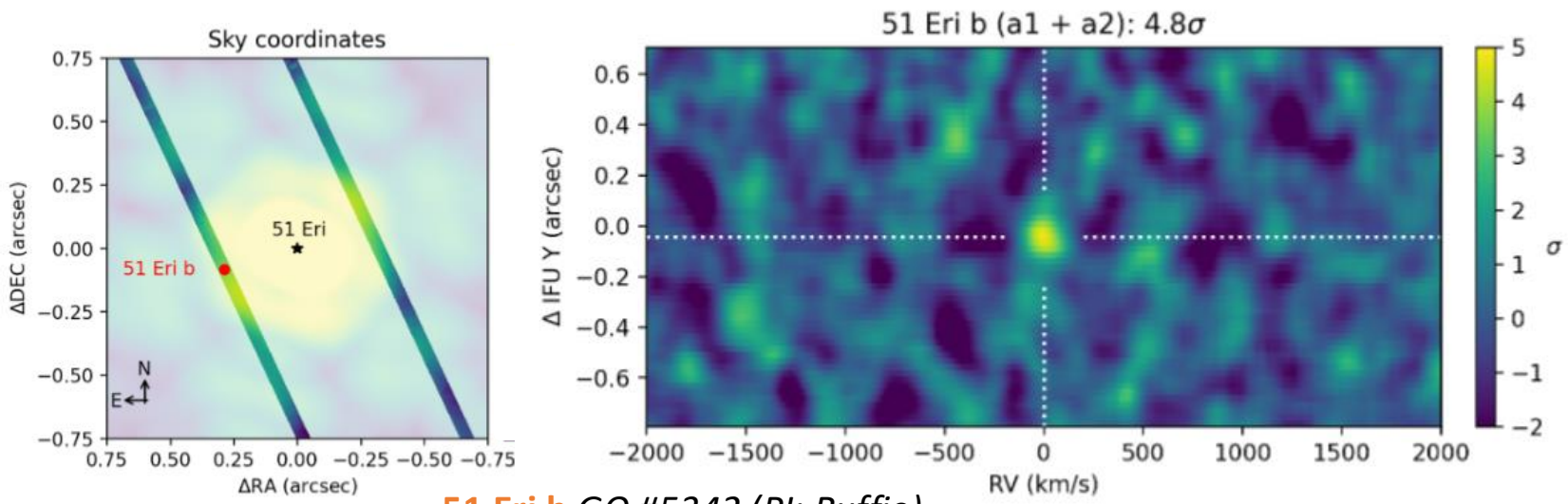
AF Lep b *GO #5342 (PI: Xuan)*

- Xuan+ (in prep.)



GJ 504 b *GTO #2778 (PI: Perrin)*

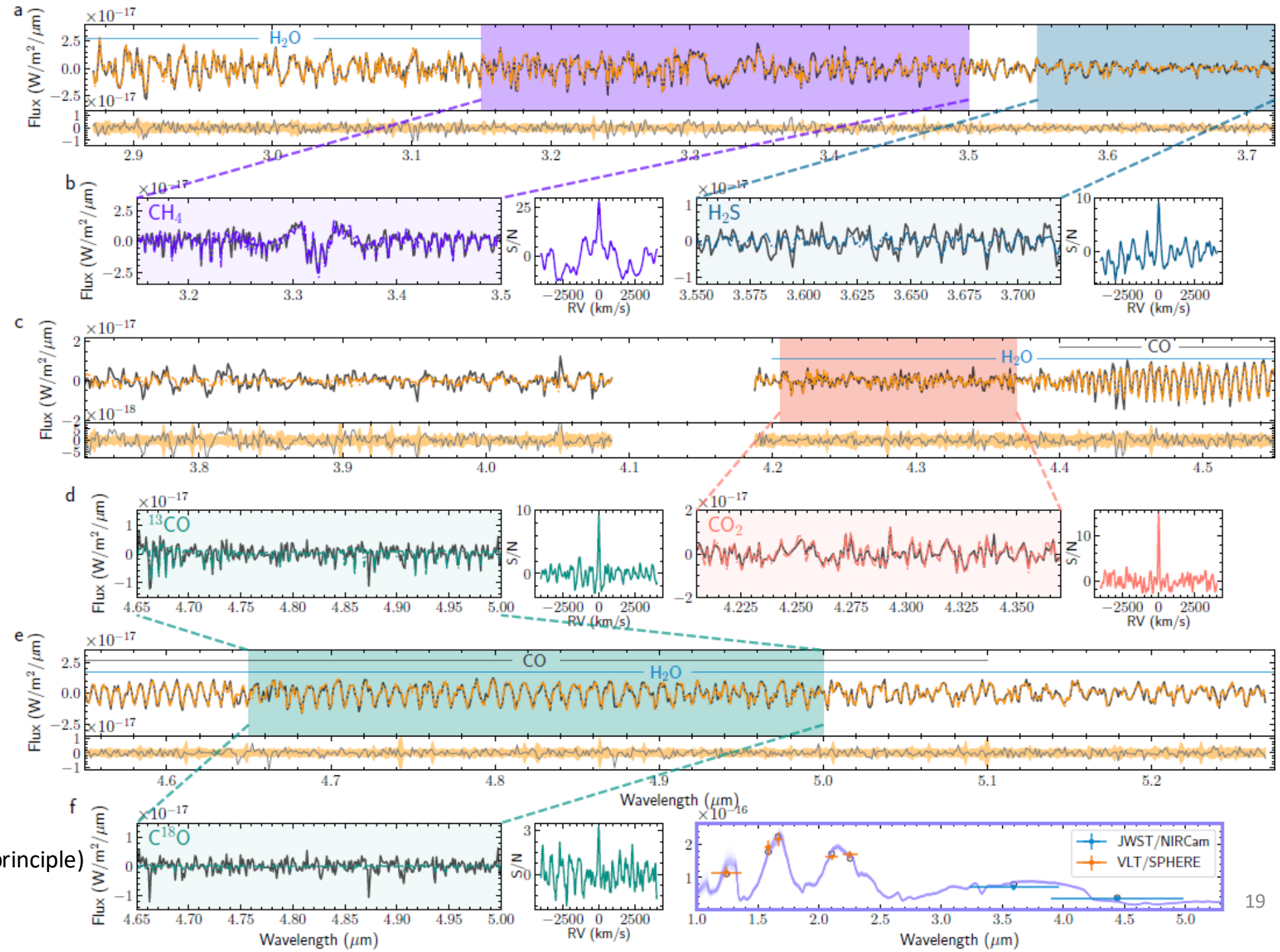
- Baburaj+ (in prep.)



51 Eri b *GO #5342 (PI: Ruffio)*

- Madurowicz+2025

HR 8799 c

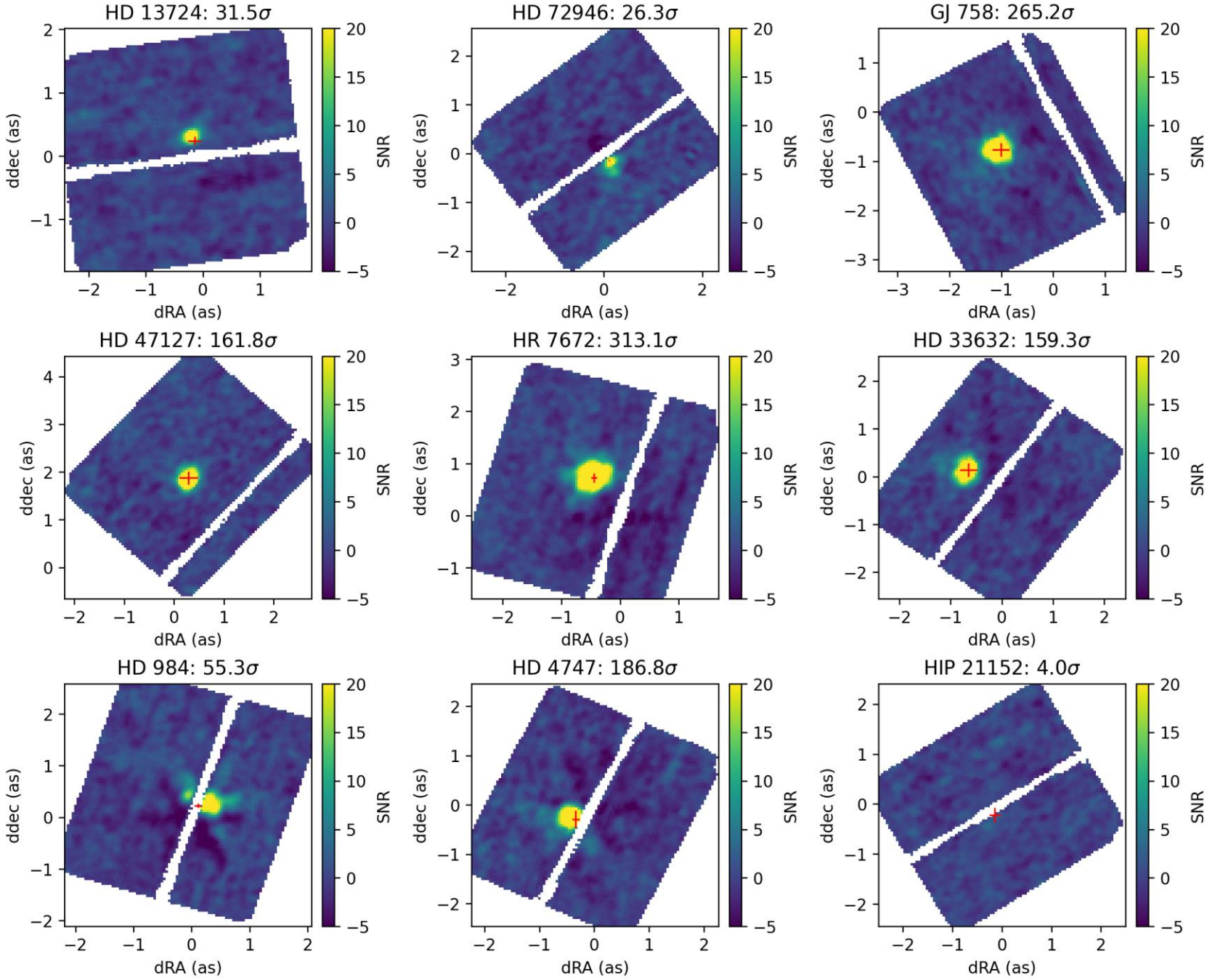


Ruffio&Xuan+ (Nat. Ast.; Accepted in principle)
Xuan&Ruffio+ (Submitted)
GTO #1188 (PI: Hodapp)

NIRSpec High-contrast spectroscopy is now “routine”

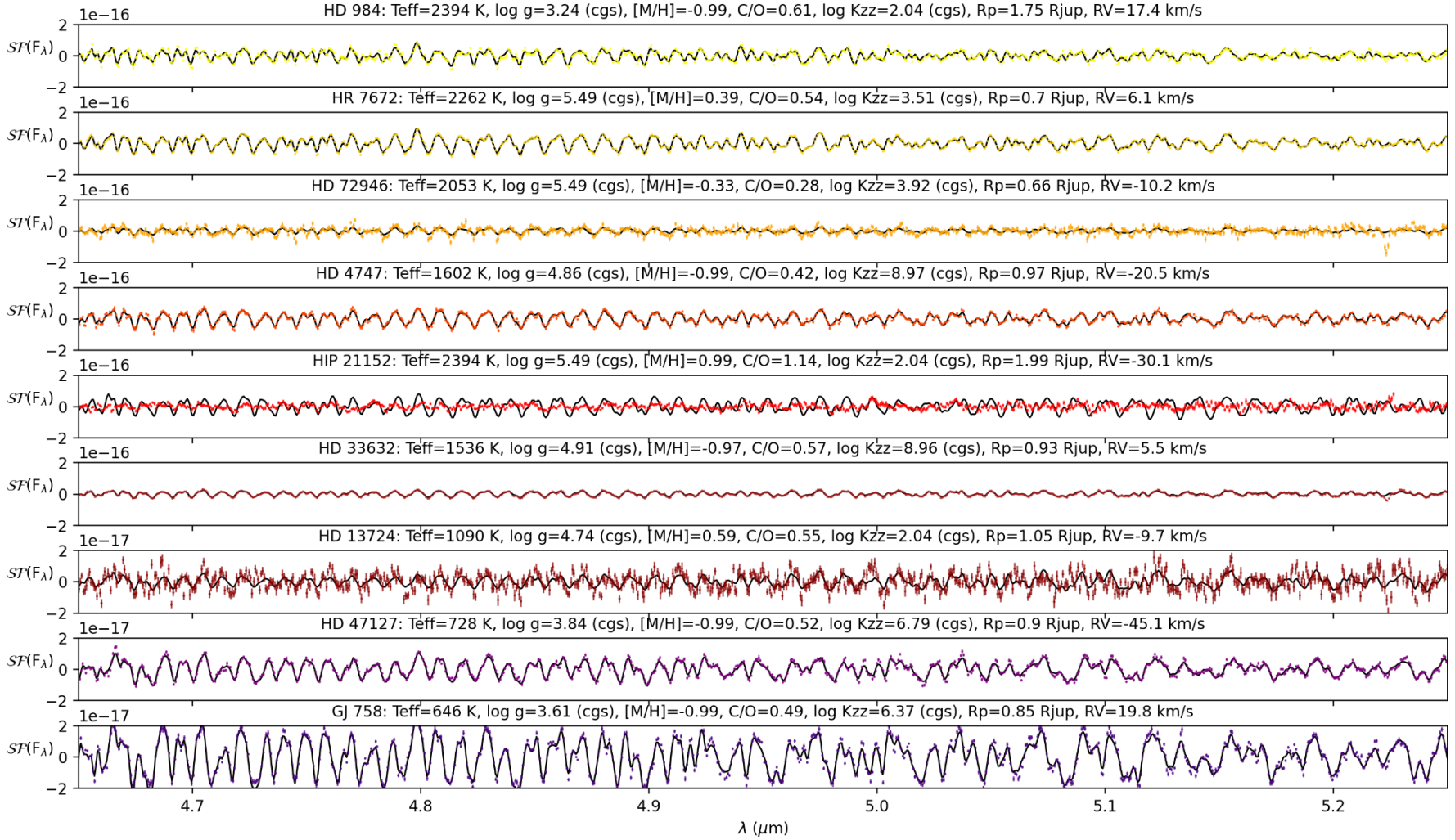
GO #6362 (PI: Rickman)

9x brown dwarfs with dynamical masses



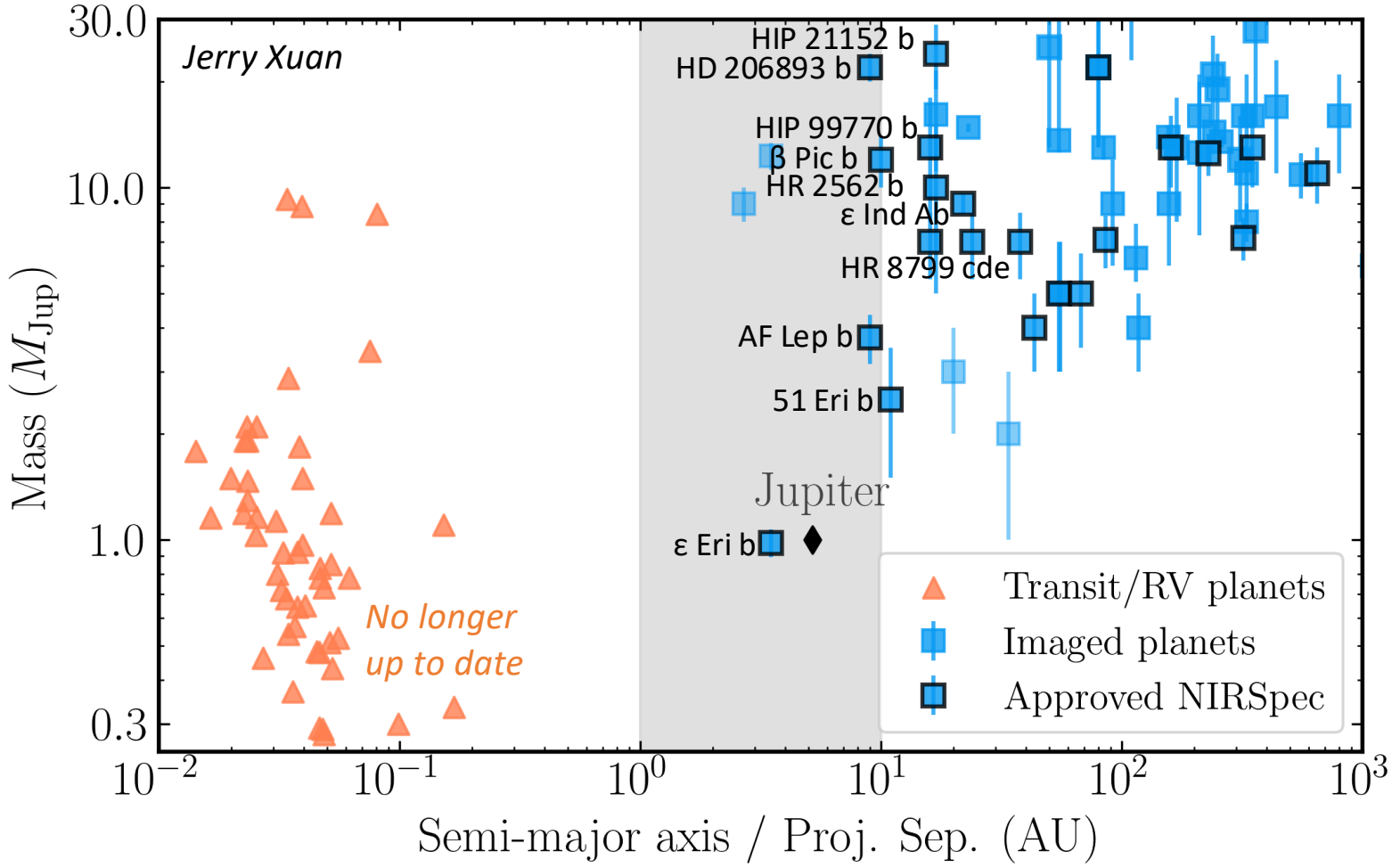
Alex Madurowicz (STScI)

A JWST/NIRSpec library of 9 brown-dwarf spectra with dynamical masses



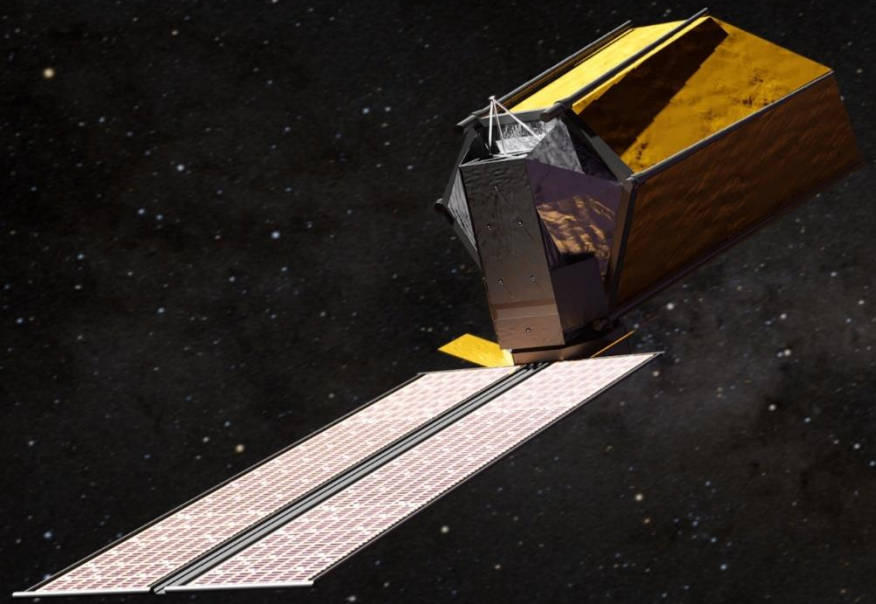
Alex Madurowicz (STScI)
GO #6362 (PI: Rickman)

JWST is disentangling planet from brown-dwarf formation. Ie, How big can a planet be?



What is the optimal spectral resolution to detect biosignature in Earth analogs?

Model from Renyu Hu

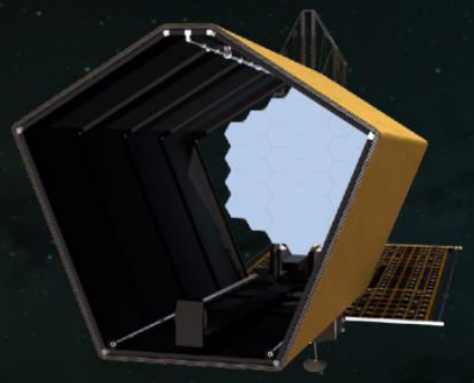


NASA's Goddard Space Flight Center Conceptual Image Lab

Telescope and Instruments

Telescope

Diameter	~6.0 m (inner)
Bandpass	~100–2500 nm



Fourth Instrument

To be defined

Coronagraph

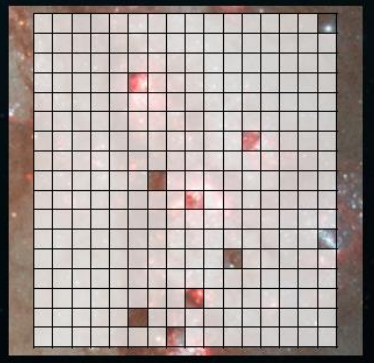
High-contrast imaging and imaging spectroscopy	
Bandpass	~200–1800 nm
Contrast	~1e-10
	Vis: ~140 NIR: ~70, 200

High-Resolution Imager

UV/Vis and NIR imaging	
Bandpass	~200–2500 nm
Field-of-View	3x2 arcmin
~67 science filters + grism	
High-precision astrometry?	

UV Multi-Object Spectrograph

UV/Vis multi-object spectroscopy and FUV imaging	
Bandpass	~100–1000 nm
Field-of-View	2x2 arcmin
Apertures	0.2 x 0.1 sec
Resolution	500–50,000



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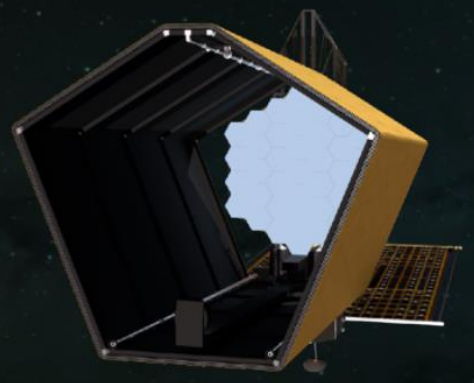

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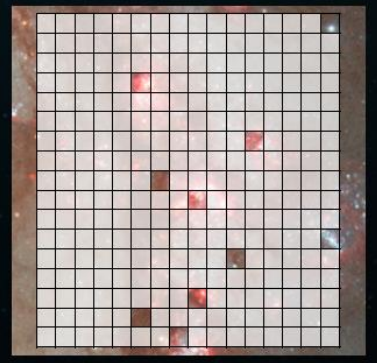
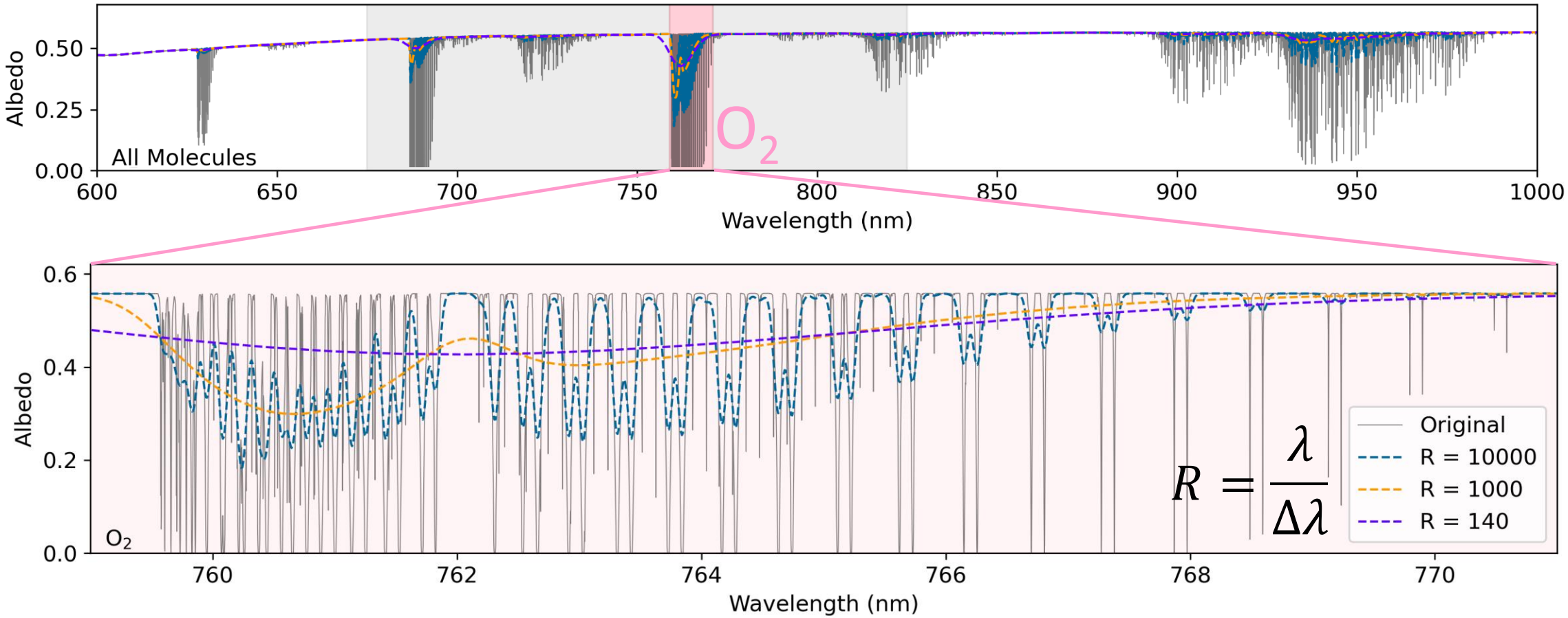
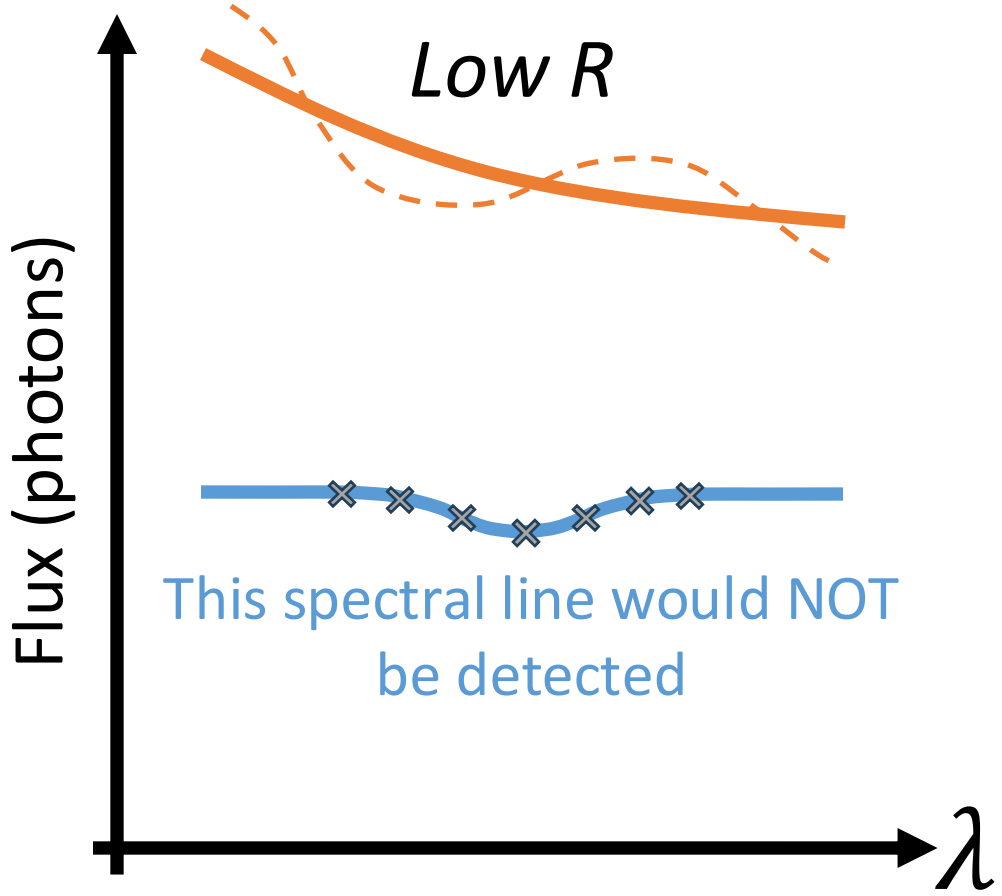


Moderate to high resolution spectroscopy can resolve Oxygen-specific spectral features

Model from Renyu Hu; used in Wang+2017



Correlated noise can prevent the detection of molecular features at low spectral resolutions



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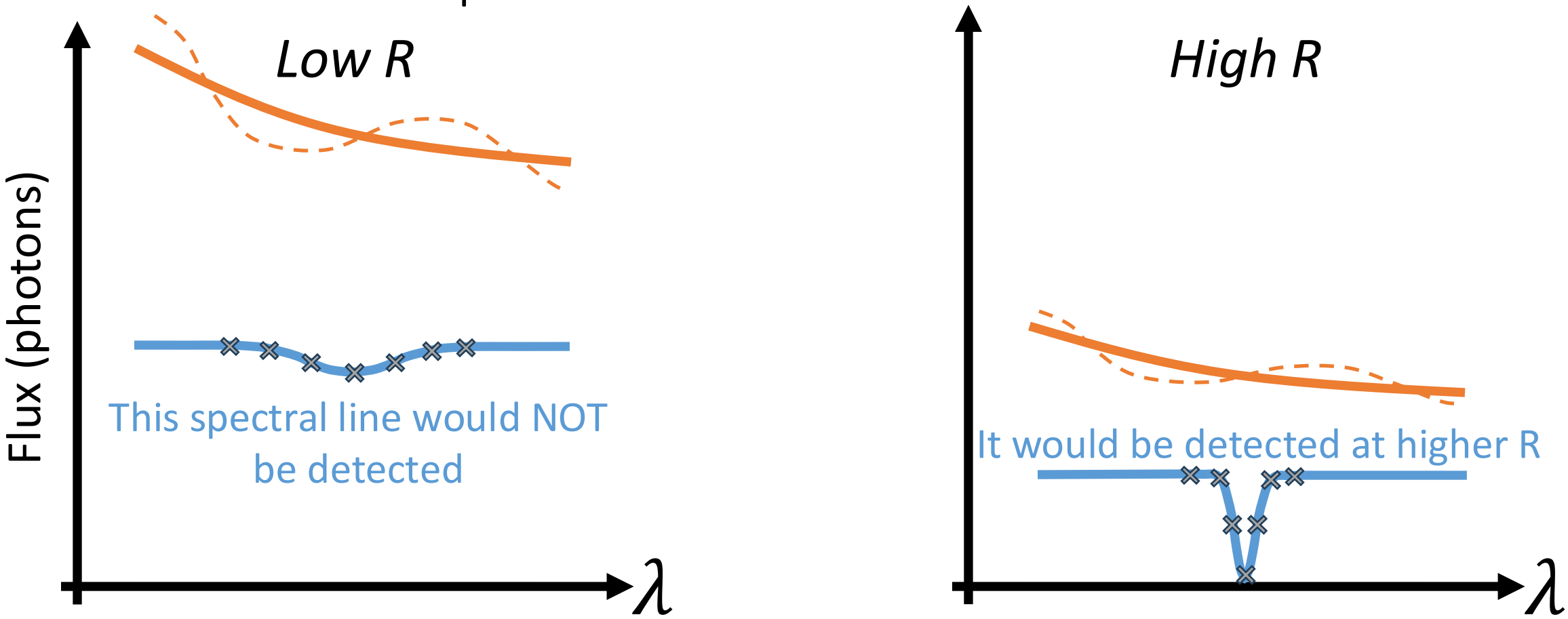
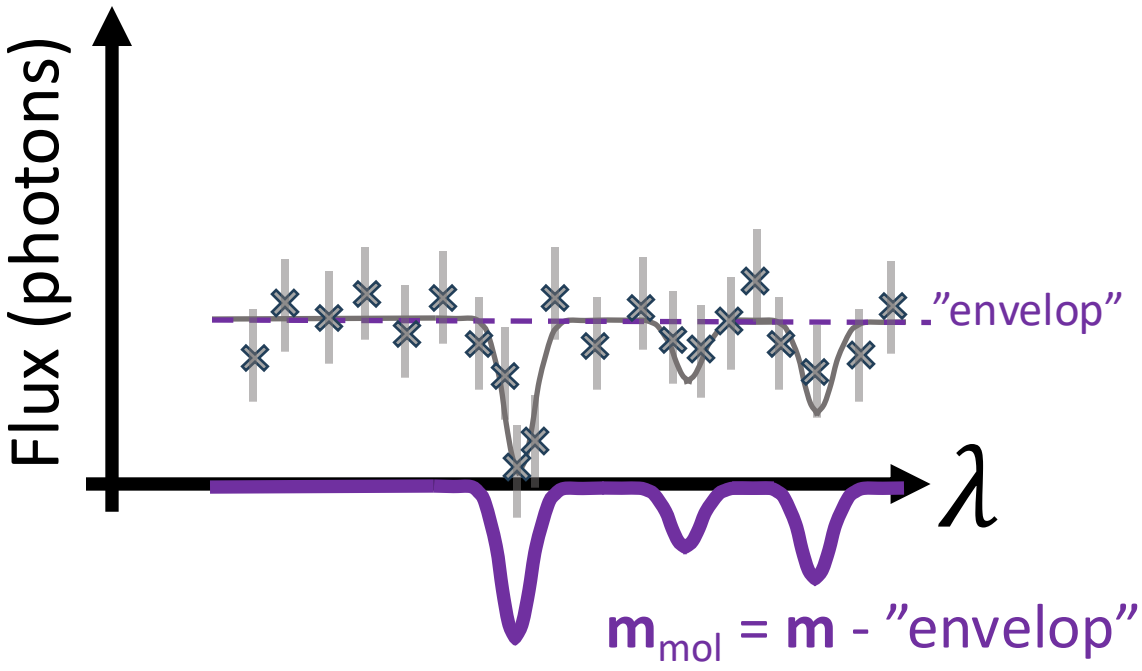


Defining a molecular detection S/N from template matching



Measuring deviation from a flat line:

$$S/N_{mol} = \sqrt{\boldsymbol{m}_{mol}^{\mathsf{T}} \boldsymbol{\Sigma}^{-1} \boldsymbol{m}_{mol}}$$

This definition:

- *is valid for any R*
- *includes noise covariance*
- *includes the “shape” of the spectral signature*

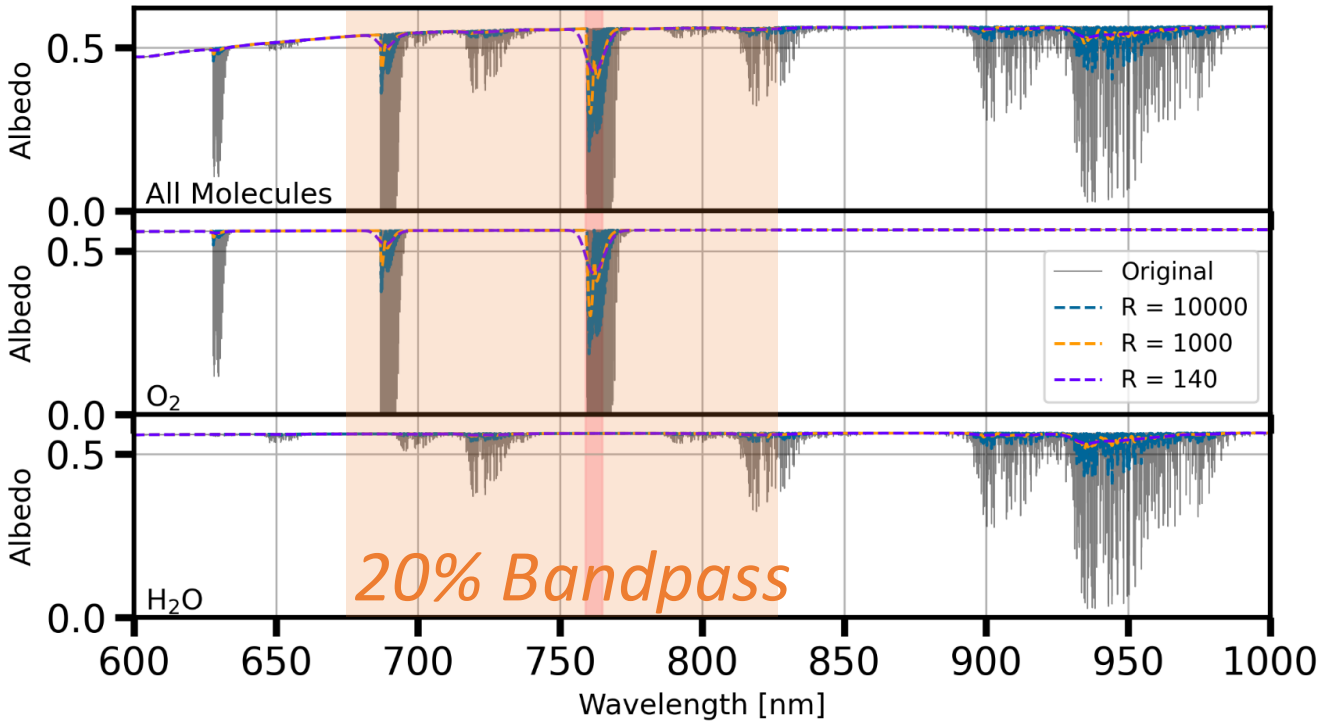
Ruffio+ in review

Simulating exo-Earth observations around 164 nearby stars with EXOSIMS

Updated EXOSIMS to compute template matching S/N

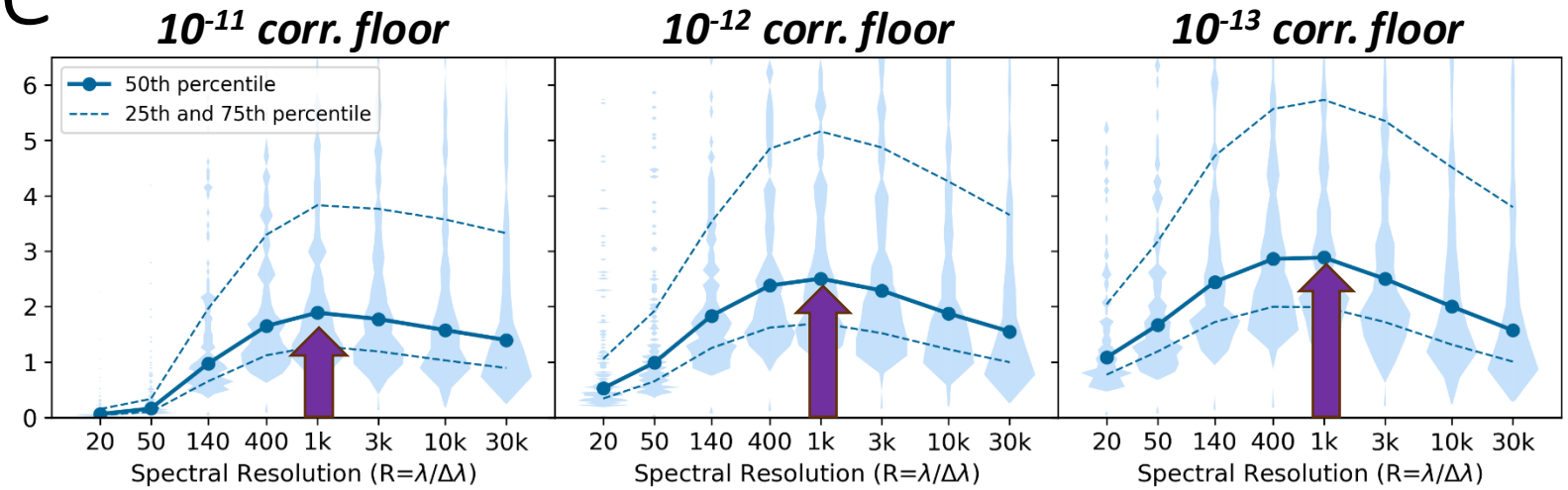
- ExEP HWO star List 2023
  - **164 stars**
  - **1 planet per star** (at 1 Earth equivalent distance)
  - Exozodi: 3x solar system value
- Observing strategy
  - Exposure time: **400 h/star**
  - **ADI**: x2 all noise sources (but planet)
- Observatory/instrument
  - **Pupil diameter 7.87 m** (~0.5 transmission)
  - λ: 750 nm & Bandpass: 20%
  - **Correlation length scale: 10 nm**
  - "Roman analog" noise:
    - Dark current: 3×10^{-5} phot/s
    - Read noise: 1.7×10^{-6} phot/ T_{exp}
    - CIC: 2.1×10^{-3} phot/T_{exp}
    - Individual T_{exp}: 300 sec
    - QE=0.675

Model from Renyu Hu; used in Wang+2017



A preliminary trade study: O_2 S/N

EMCCD detector
& Nyquist sampled spectra

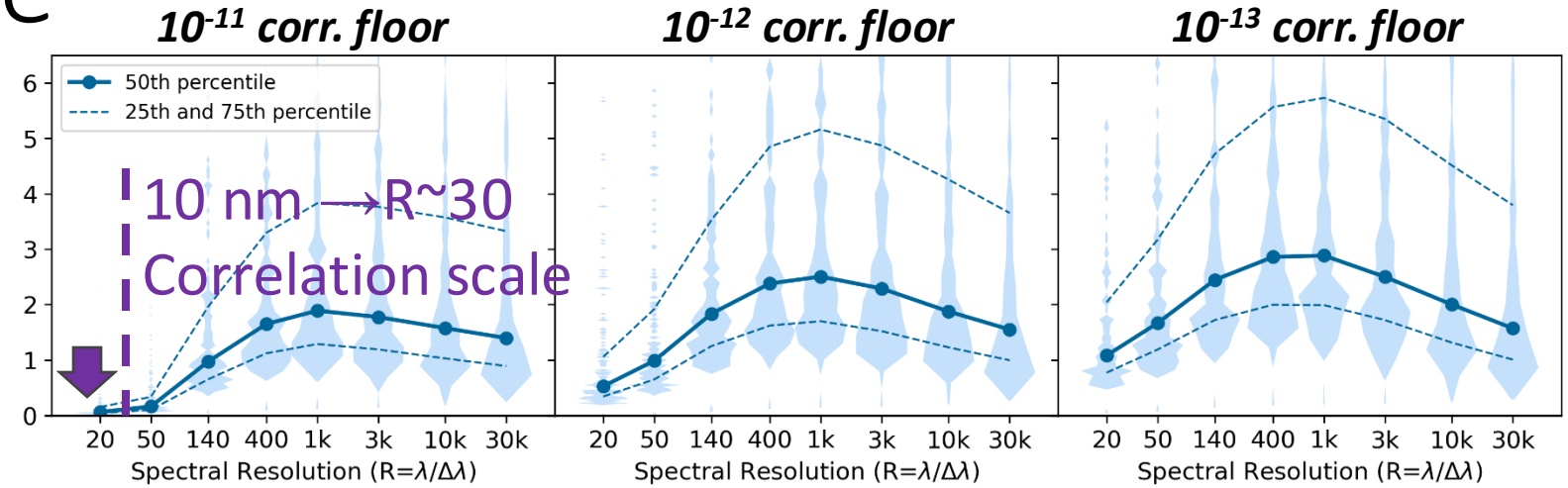


Less correlated noise → better the S/N

Ruffio+ submitted

A preliminary trade study: O_2 S/N

EMCCD detector
& Nyquist sampled spectra



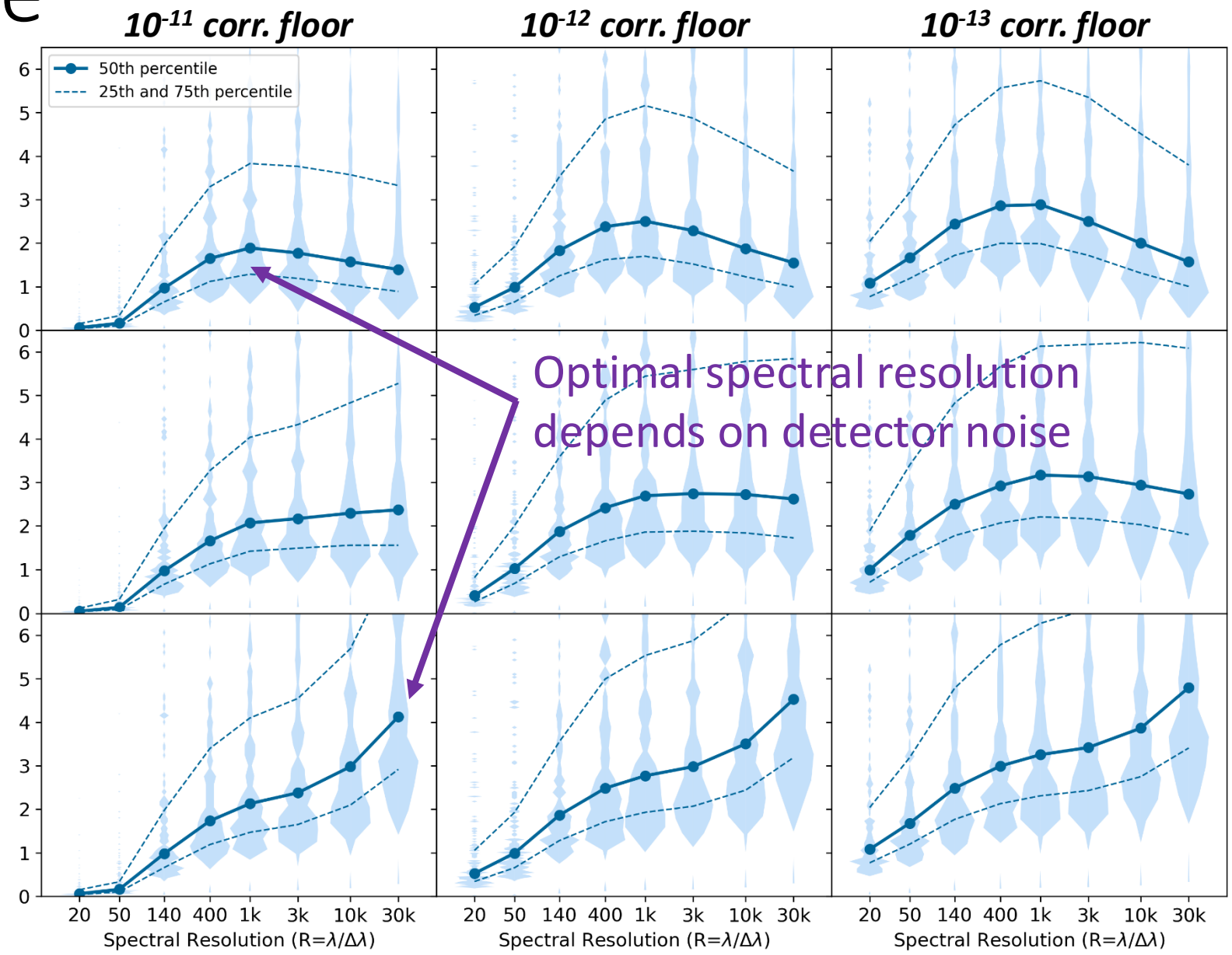
Ruffio+ submitted

A preliminary trade study: O_2 S/N

EMCCD detector & Nyquist sampled spectra

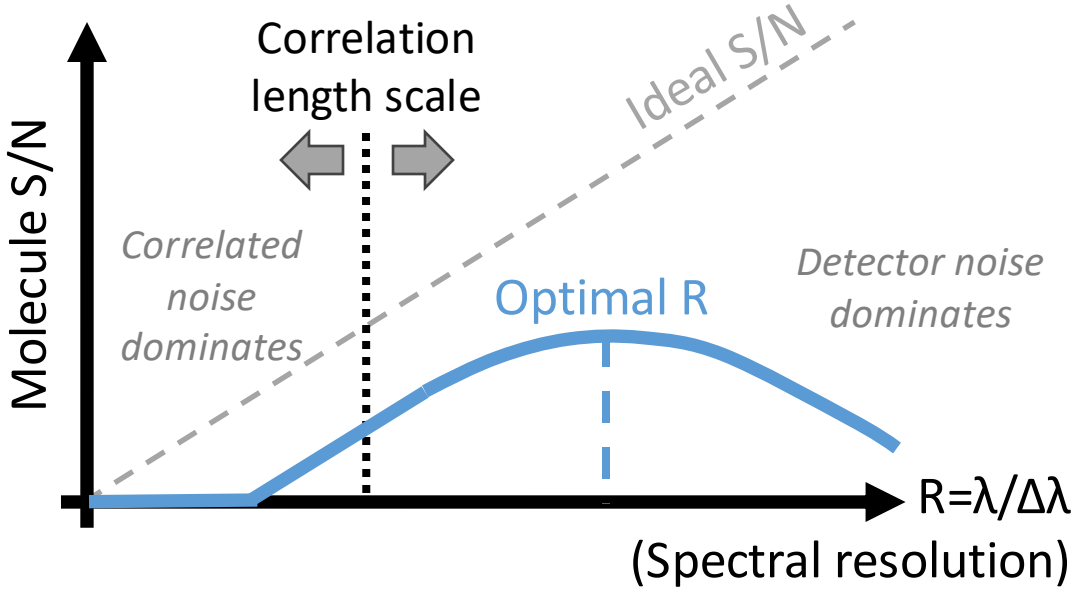
EMCCD detector & undersampled spectra

No detector noise



Ruffio+ submitted

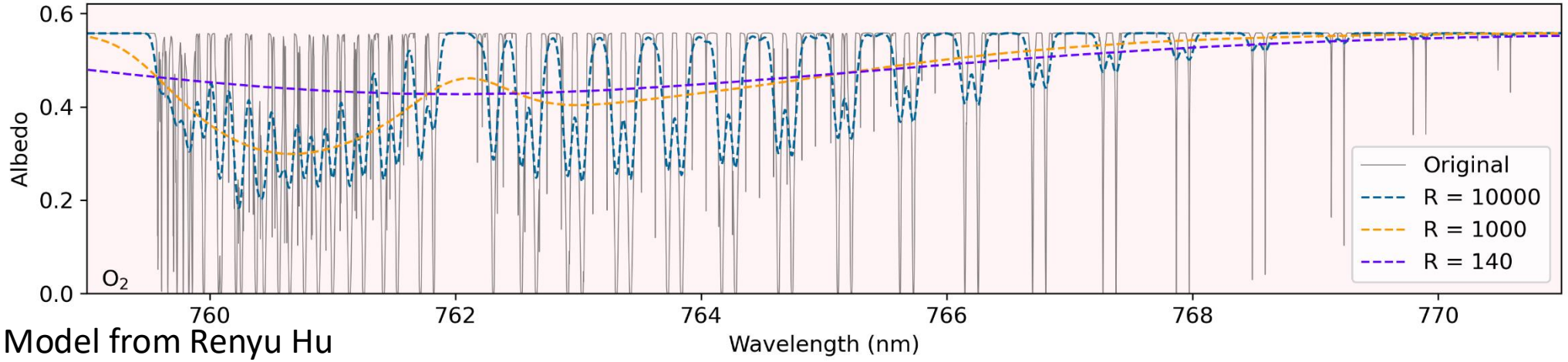
Main trade-offs for the spectral resolution



Ruffio+ submitted

Take aways…

- **R>1,000 "*might*" be necessary** to detect biosignatures
  - Accounting for **the correlated speckle noise is essential**
- **More science opportunities at R>1,000** than R~140
  - Potential to reduce false positives for planet detection and biosignatures
  - See poster from **Beck Dacus** on exoJupiters and exomoons.
- R~2,700 is **proving transformative for direct imaging with JWST**



Model from Renyu Hu

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