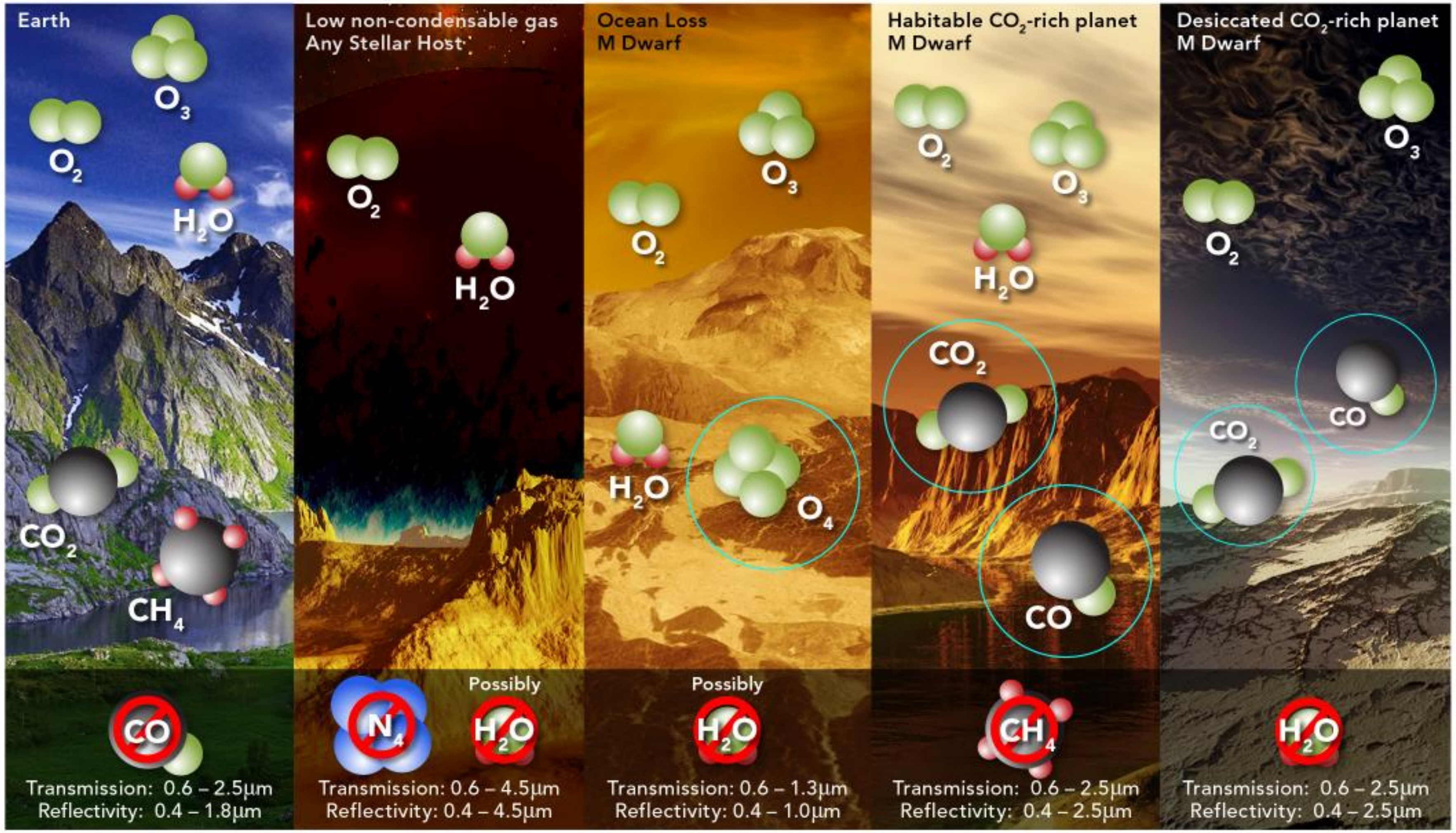
# Future Space and Ground Astronomical Capabilities for Searching for Life on Exoplanets




Meadows, 2017 (Credit: Hasler, Meadows, & Domagal-Goldman)

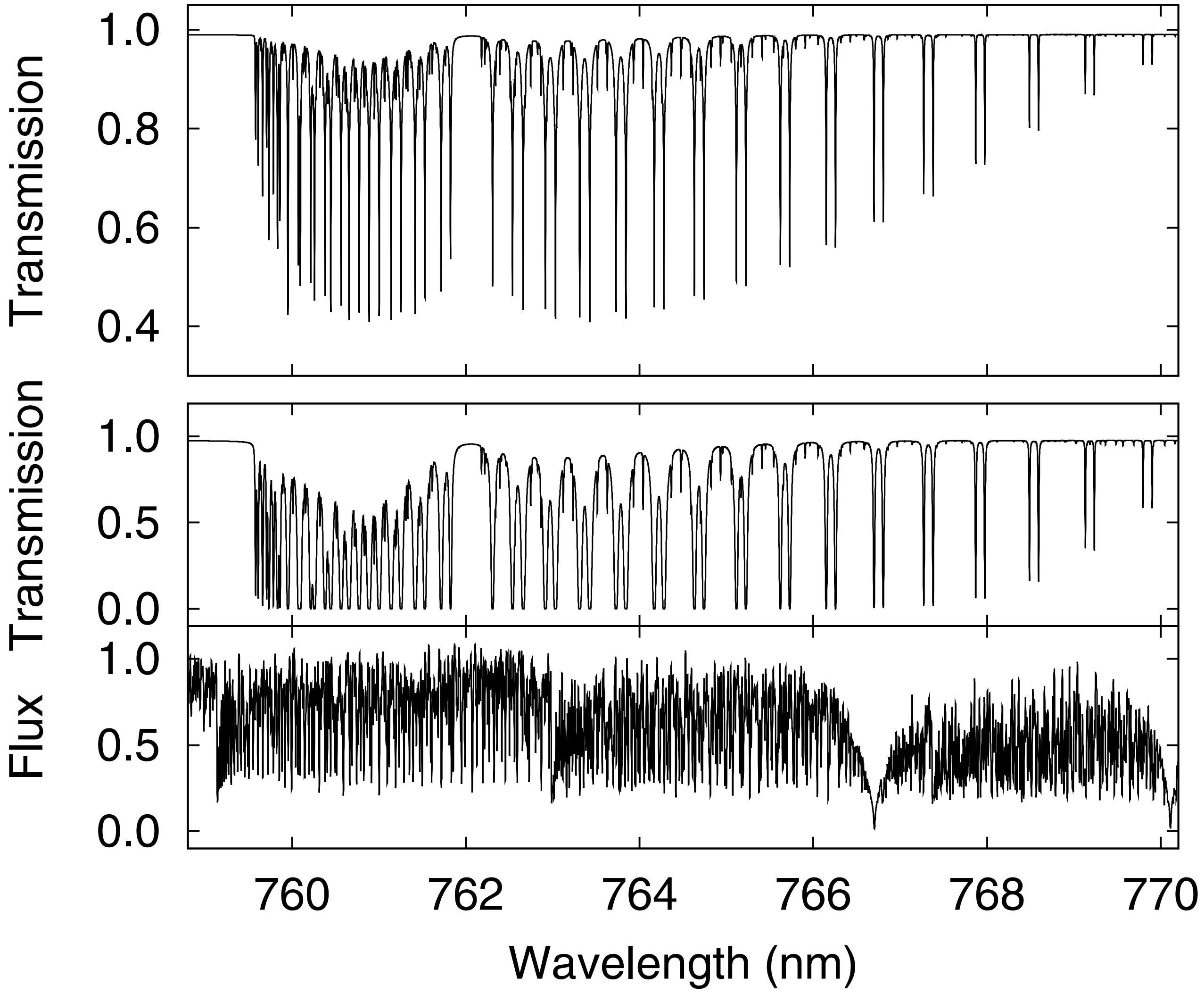
# Ground Based Extremely Large Telescopes

- Two advantages of ELTs over space telescopes
  - Aperture:
    - 25 m (Giant Magellan Telescope)
    - 30 m (Thirty Meter Telescope),
    - 39 m (European Extremely Large Telescope)

    **= spatial resolution and collecting power**
  - High Resolution Spectroscopy ($\lambda/\Delta\lambda \sim 100{,}000$) = line shifts / kinematics

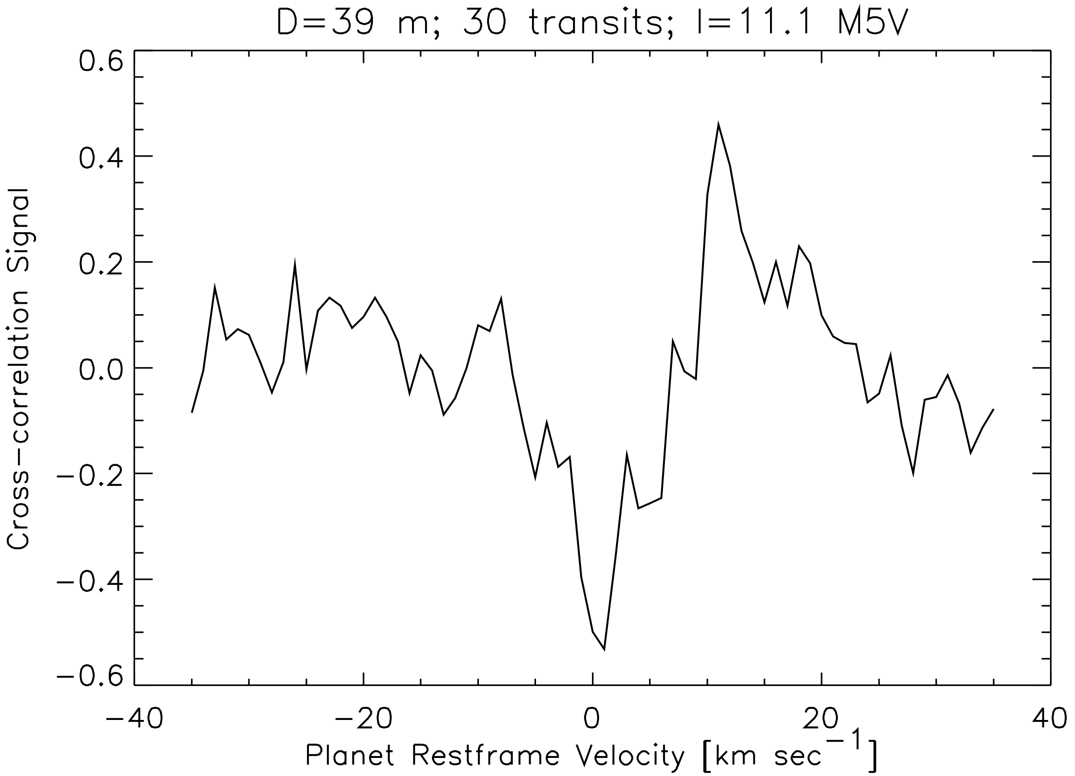
# 1. Exoplanets in Transit

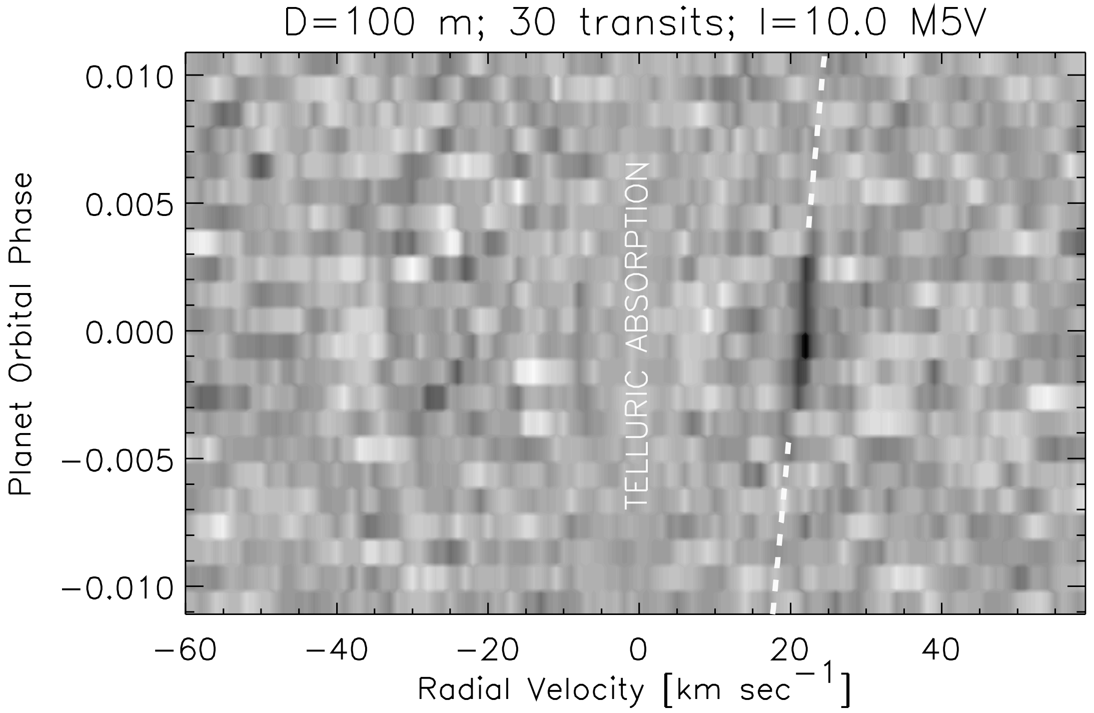
- $O_2$ (Snellen et al. 2013, Rodler & Lopez-Morales 2014)
- Advantages to M stars (over Solar-type)
  - Higher transit signal because $R_{planet}/R_*$ is larger
  - Higher transit probability because Habitable Zone is closer in
  - Higher transit frequency because Habitable Zone is closer in
- Doppler shift is key – takes exoplanet's spectral lines away from Earth's telluric lines




Rodler & Lopez-Morales 2014

# Simulation of Snellen 2013

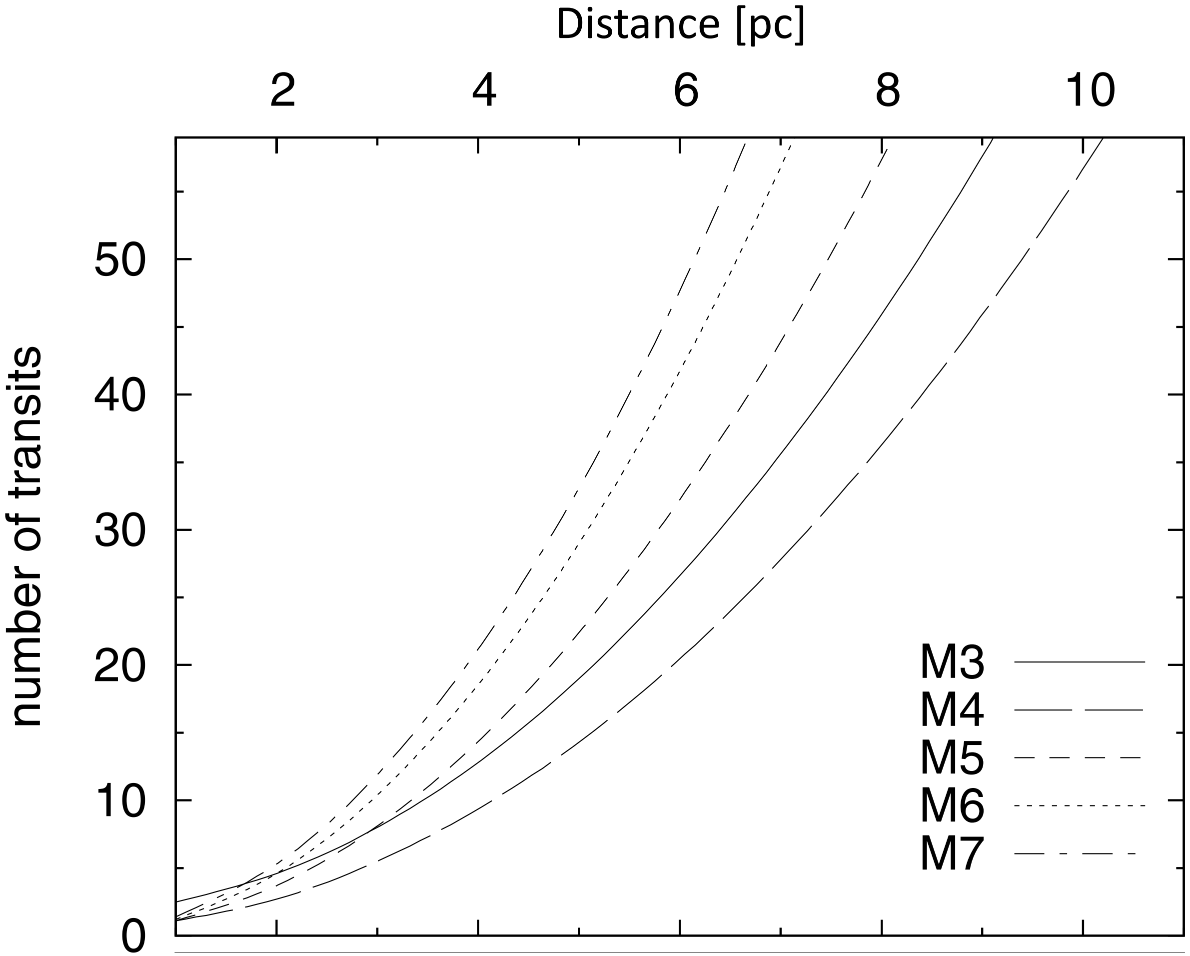



30 transits at 3 / yr → 10 years

# Simulation of Rodler & Lopez-Morales (2014)

Multiply by ~1.5 to account for red noise

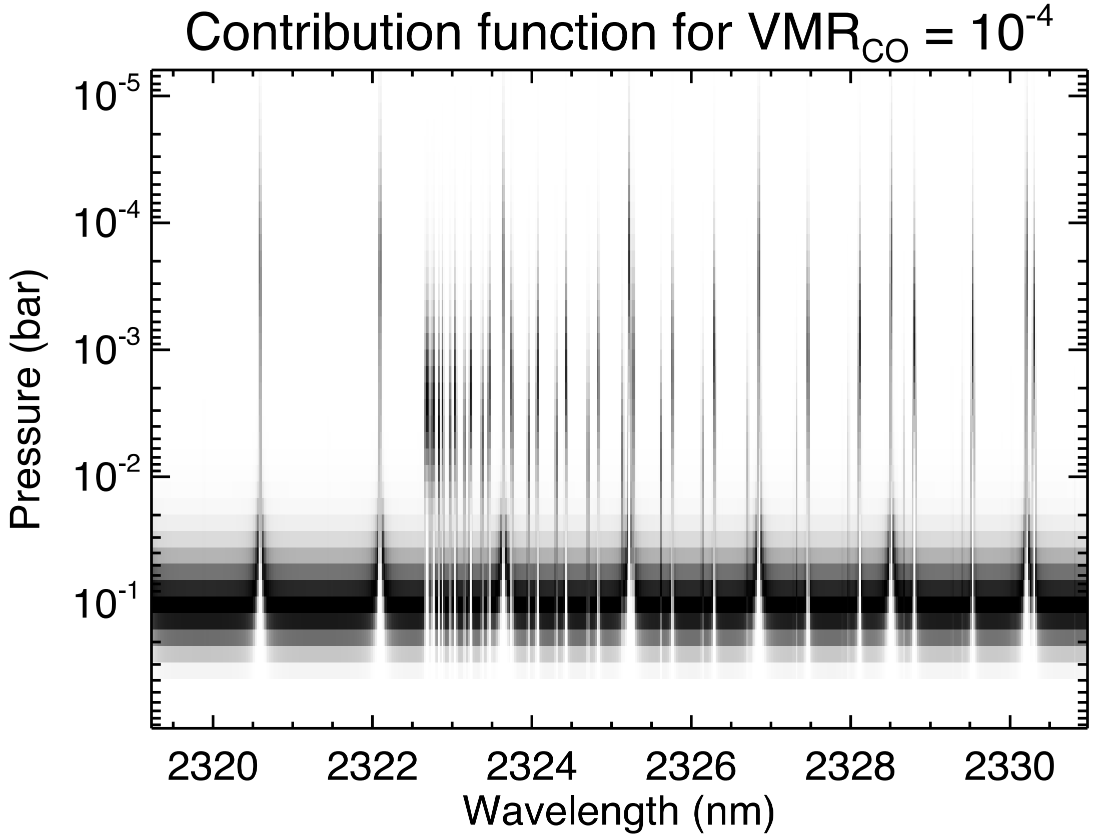



G-CLEF-like instrument on the 39 m

Bottom line: For an Earth-like planet around an M4 (M6) star at 5 pc, we need 60 (84) transits; that will take 12 (25) years to accumulate.

# Getting Abundances from Cross-Correlations

Forward model: Depends on P-T profile and volumetric mixing ratios
Mixing ratio is probably a lower limit




- Higher pressure lines are broader = harder to detect
- Clouds block some layers
- Refraction can block lines from small scale heights

Hot Jupiter HD 179949b: Brogi et al. 2014

# Exoplanets in Transit: Other Biomarkers

- $H_2O$, $CH_4$, CO, $CO_2$ all have near-infrared absorption lines
- CO and sometimes $H_2O$ detected in transiting and non-transiting hot jupiters:
  - HD 209458 (Snellen 2010),
  - $\tau$ Boo (Brogi 2012, Rodler 2012),
  - 51 Peg (Brogi 2013, Birkby 2017),
  - HD 189733 (de Kok 2013, Brogi 2013),
  - HD 179949 (Brogi 2014)
- Harder than $O_2$ due to extra telluric absorption

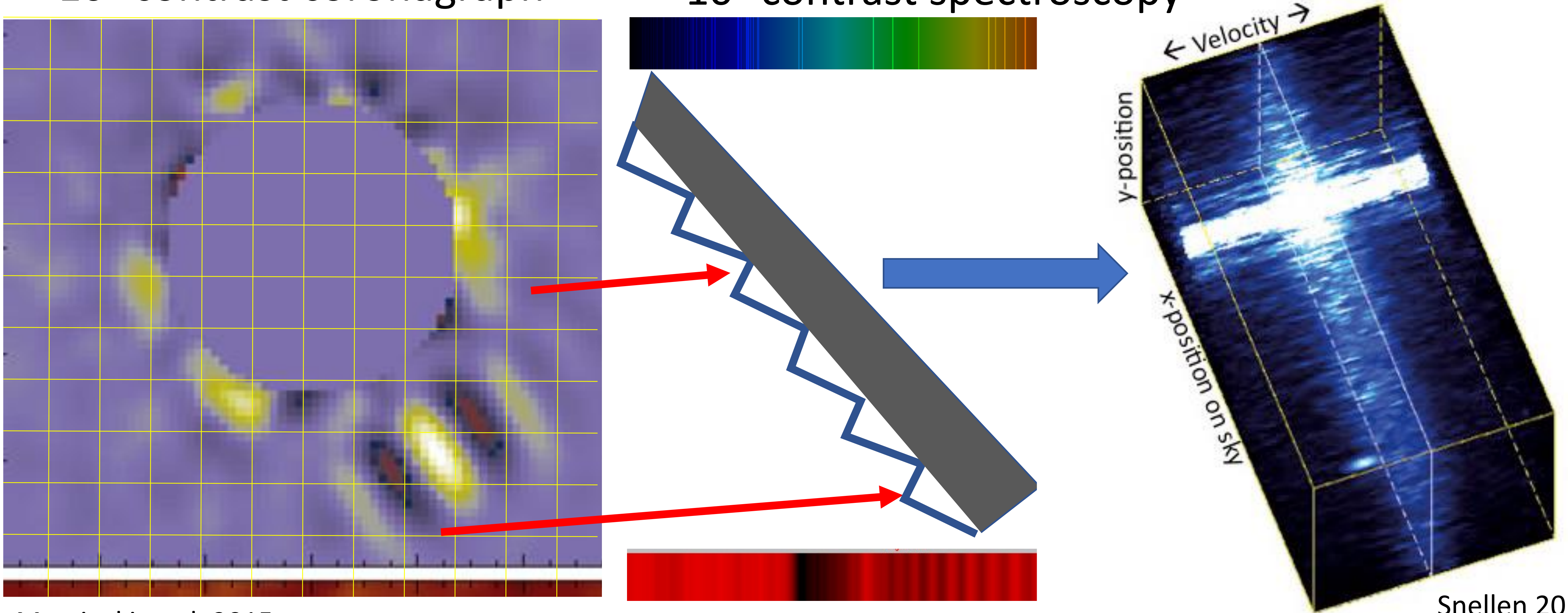
# 2. High Resolution Spectroscopy + High Contrast Imaging

- Proxima b sits 0.05 AU from its star at 1.3 pc = 38 mas
- Inner working angle > 2$\lambda$/D
  - D 2$\lambda$/D at 760 nm and 2.2 $\mu$m
  - 10m 32mas 91 mas
  - 25m 12 mas 36 mas
  - 39m 8 mas 23 mas
    - It's very hard to work closer than 2-3 $\lambda$/D
- For a Solar Type Star, 1 AU is at 2$\lambda$/D at 83 pc

# Combining coronagraphy and spectroscopy

Advantage: non-transiting planets!

$10^5$ contrast coronagraph x $10^3$ contrast spectroscopy



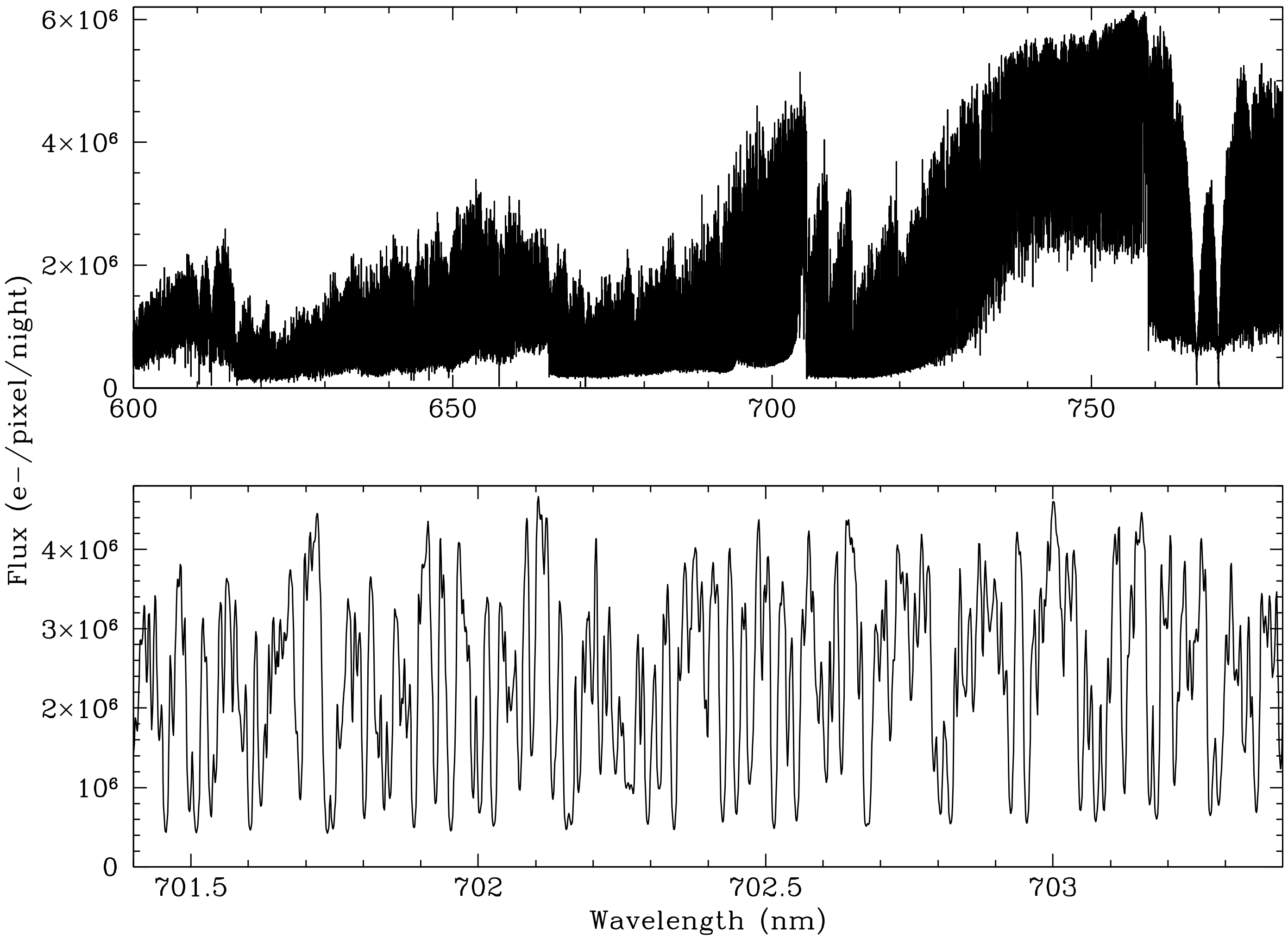

Morzinski et al. 2015

Snellen 2015

# Easiest: Broad-Band Albedo

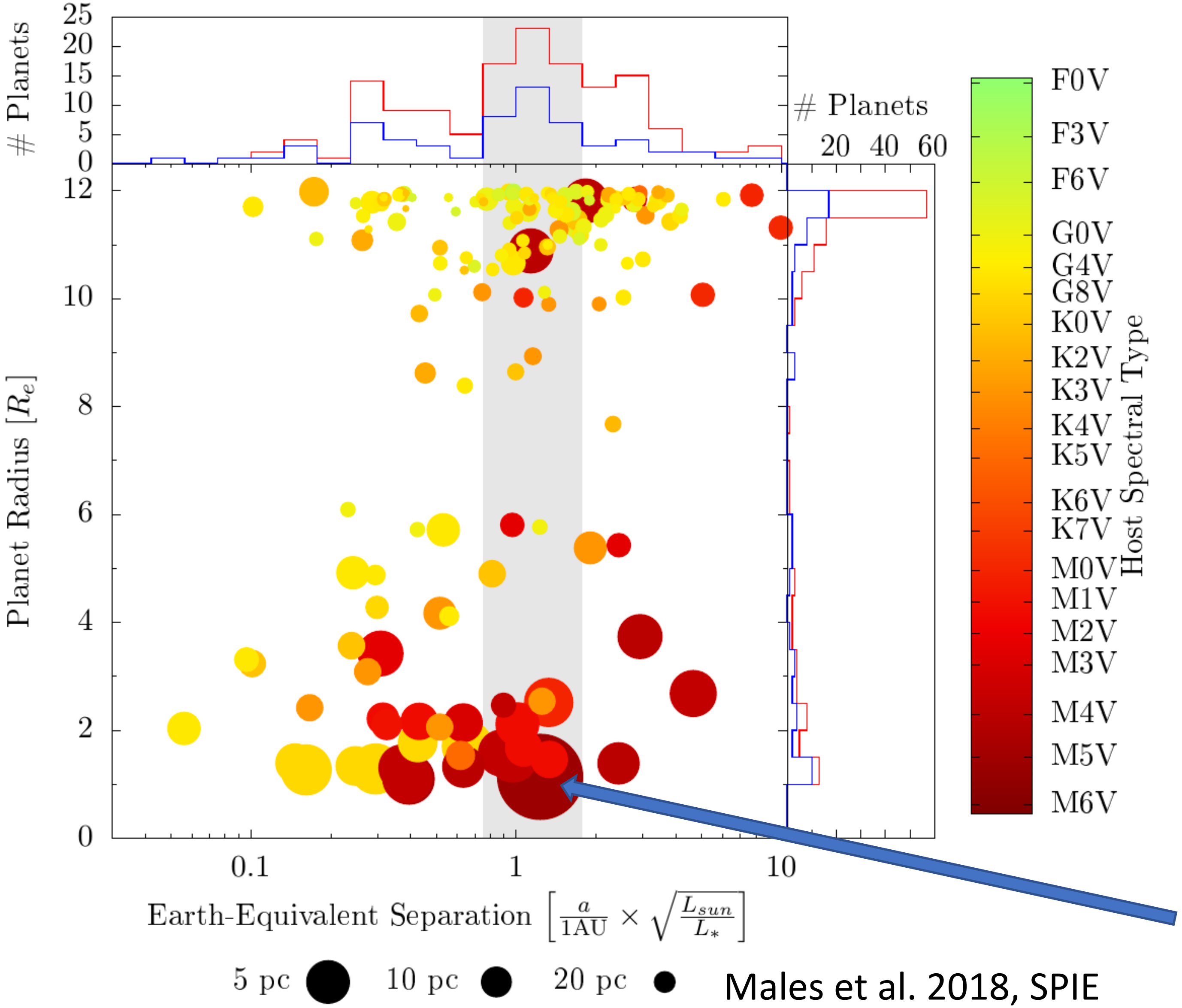
Look for the reflected spectral lines of the star, Doppler shifted from the planet

Signal $\propto \sqrt{N_{lines}}$




Lovis et al. 2017

# Simulated Yield of Albedo Measurements




Males et al. 2018, SPIE

All of these are known planets

Sample program: 28 nights

Current AO technology: 62 planets

15 with R<1.6 $R_{Earth}$

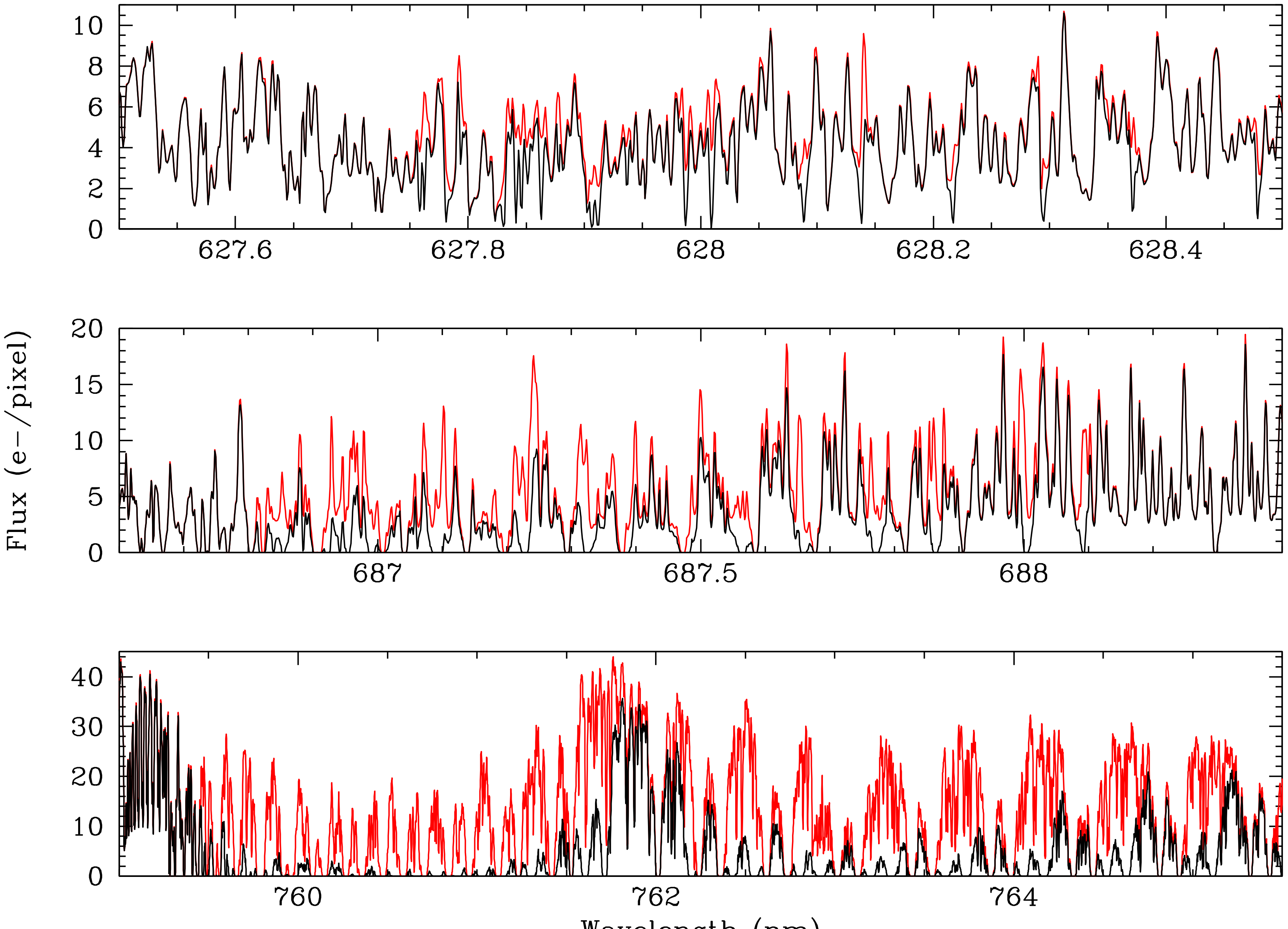
20 in habitable zone with

R<4 $R_{Earth}$

Advanced control: 146 planets

Proxima b

# Next step: Same idea, but carve up spectral space




Lovis et al. 2017 comparison of spectrum with (black) and without $O_2$ (red) in 60 nights (3 years) of observation. 3.6σ detection.

# Ground Based ELTs…

- Detection of molecules in transiting **and non-transiting** planets possible
- Detection of albedos of a large number of known planets possible

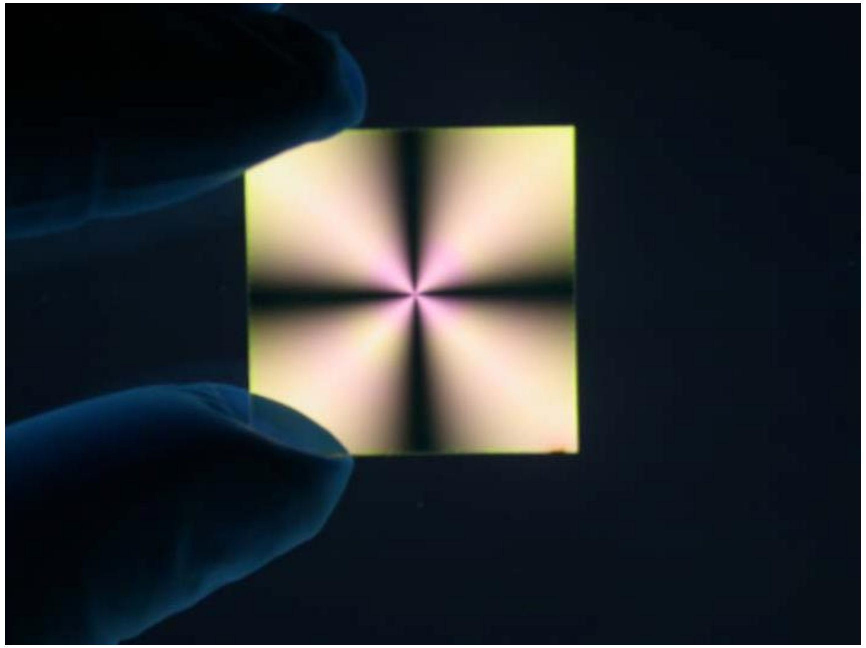
# Some quick summaries of anticipated space capabilities

# HabEx – a 4m off-axis monolithic mirror space telescope

Survey ~120 stars within 10 pc multiple times at $10^{-10}$ contrast

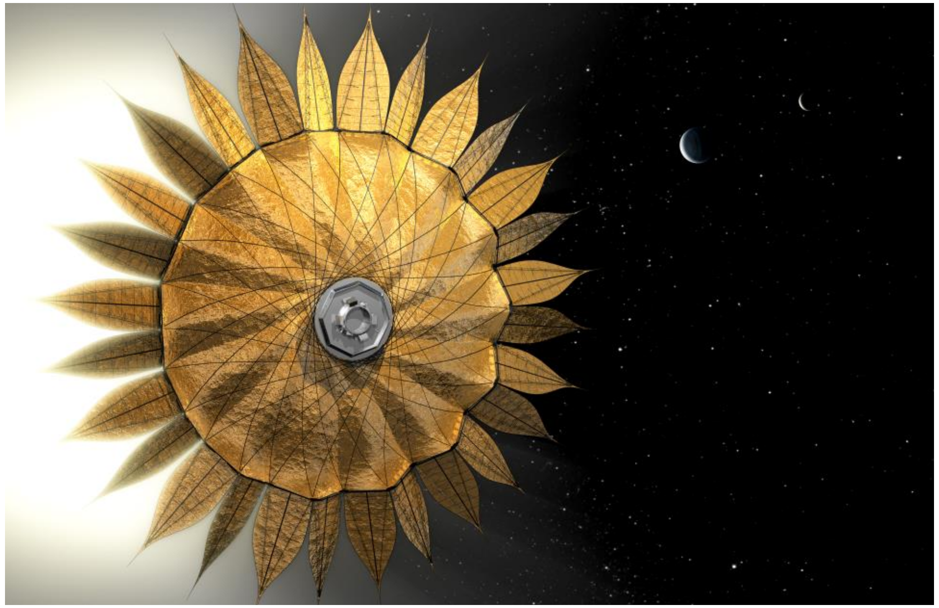
HabEx shall combines the strengths of two diametrically opposed starlight suppression systems:

**Internal CORONAGRAPH**



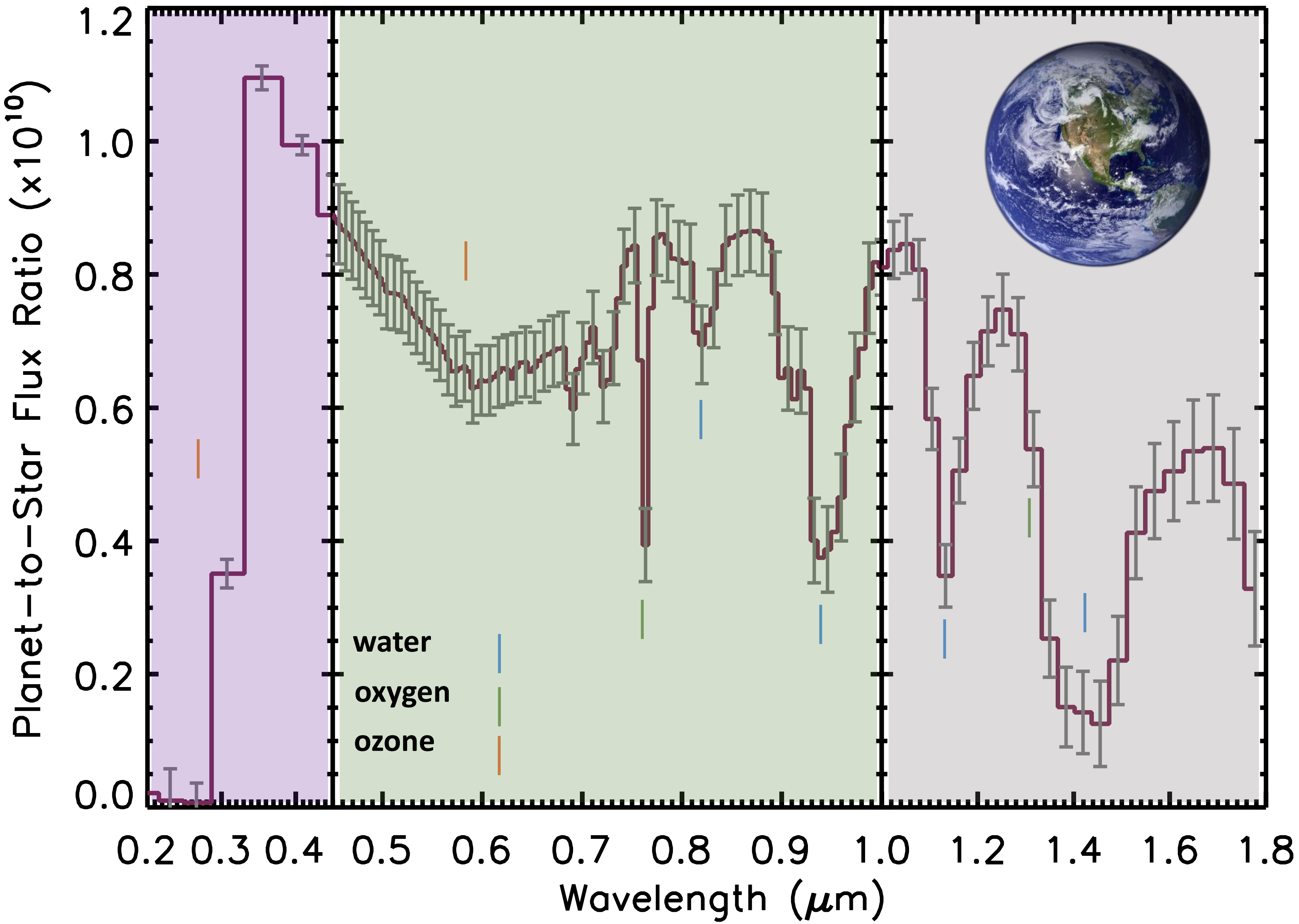
+

**External STARSHADE**



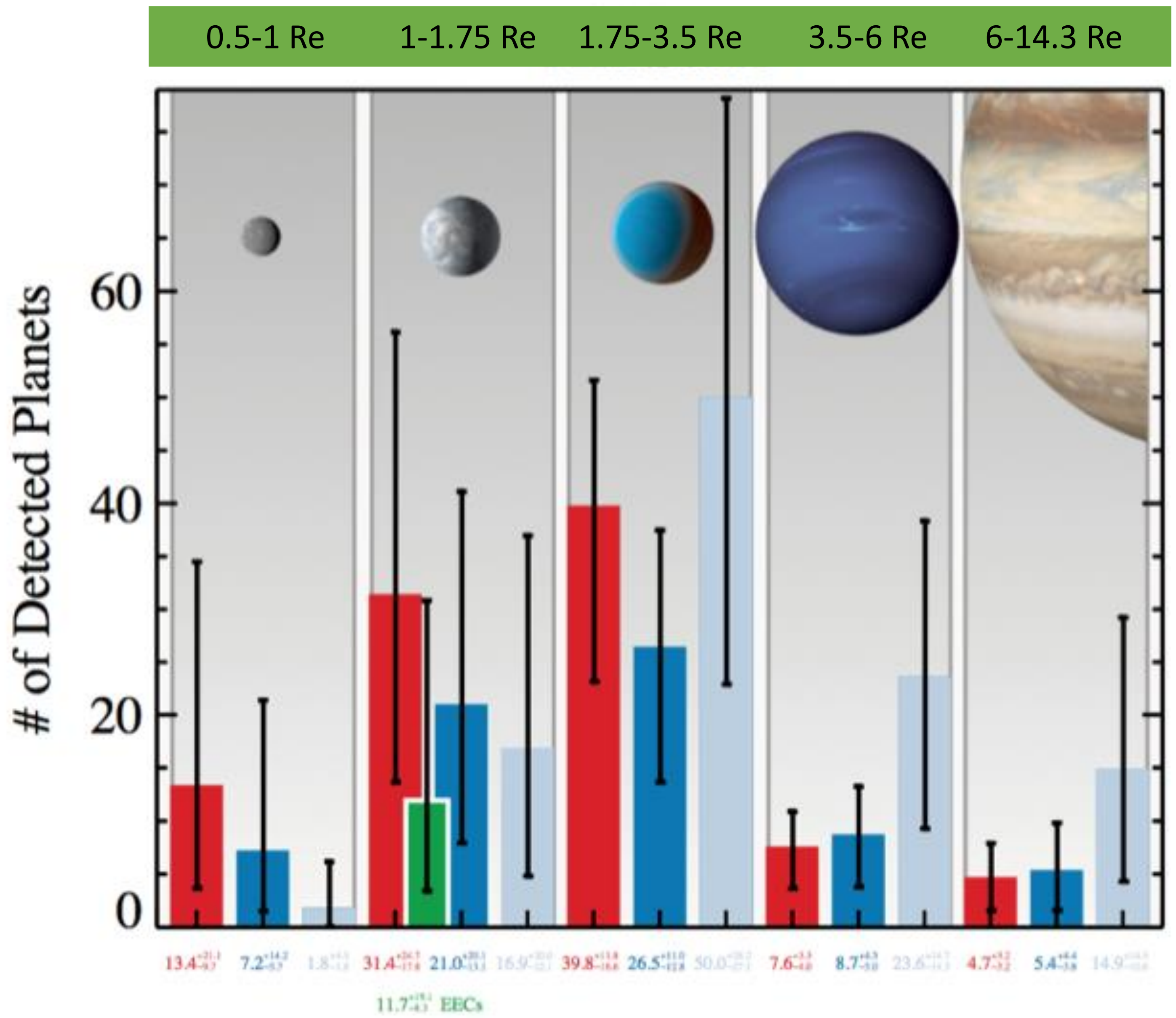
- Very nimble
- Searches for planets around many stars
- Takes images at multiple visits to measure orbits

- Very "photon" efficient
- Accesses closer-in planets at a given $\lambda$
- Takes broad spectra of all planets found in ~50-100 most interesting systems



Planet-to-Star Flux Ratio (x10¹⁰)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.2 1.4 1.6 1.8
Wavelength (μm)
water
oxygen
ozone

# Planet Yields

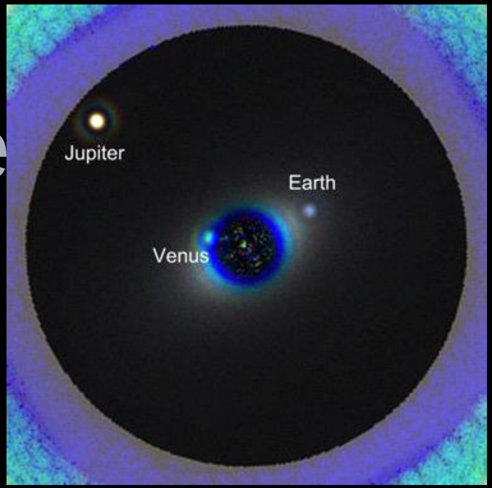



92 rocky planets
Incl. 12 HZ exo-earths

116 sub-Neptunes

65 Neptunes and Jupiter analogs

# LUVOIR – Large UV / Optical / Infrared Surveyor – a 15 m telescope




## Observational challenge

Faint planets next to bright stars

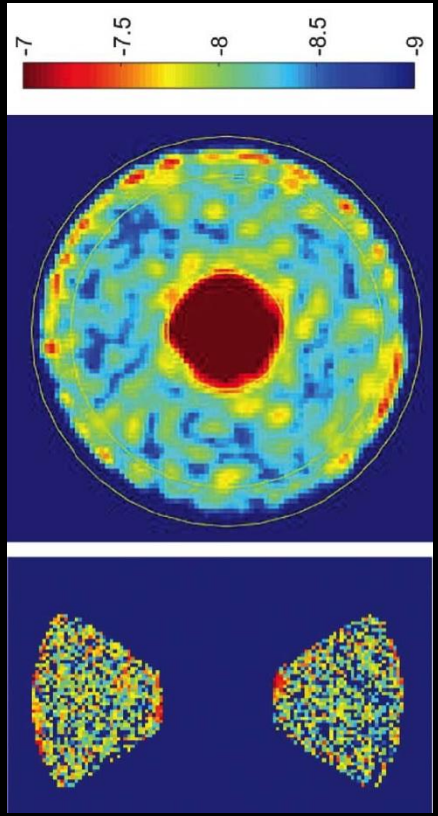
## Extreme Coronagraph for LIving Planetary Systems (ECLIPS)

Contrast < $10^{-10}$

Low resolution imaging spectroscopy

Bandpass:  0.2 µm to 2.0 µm

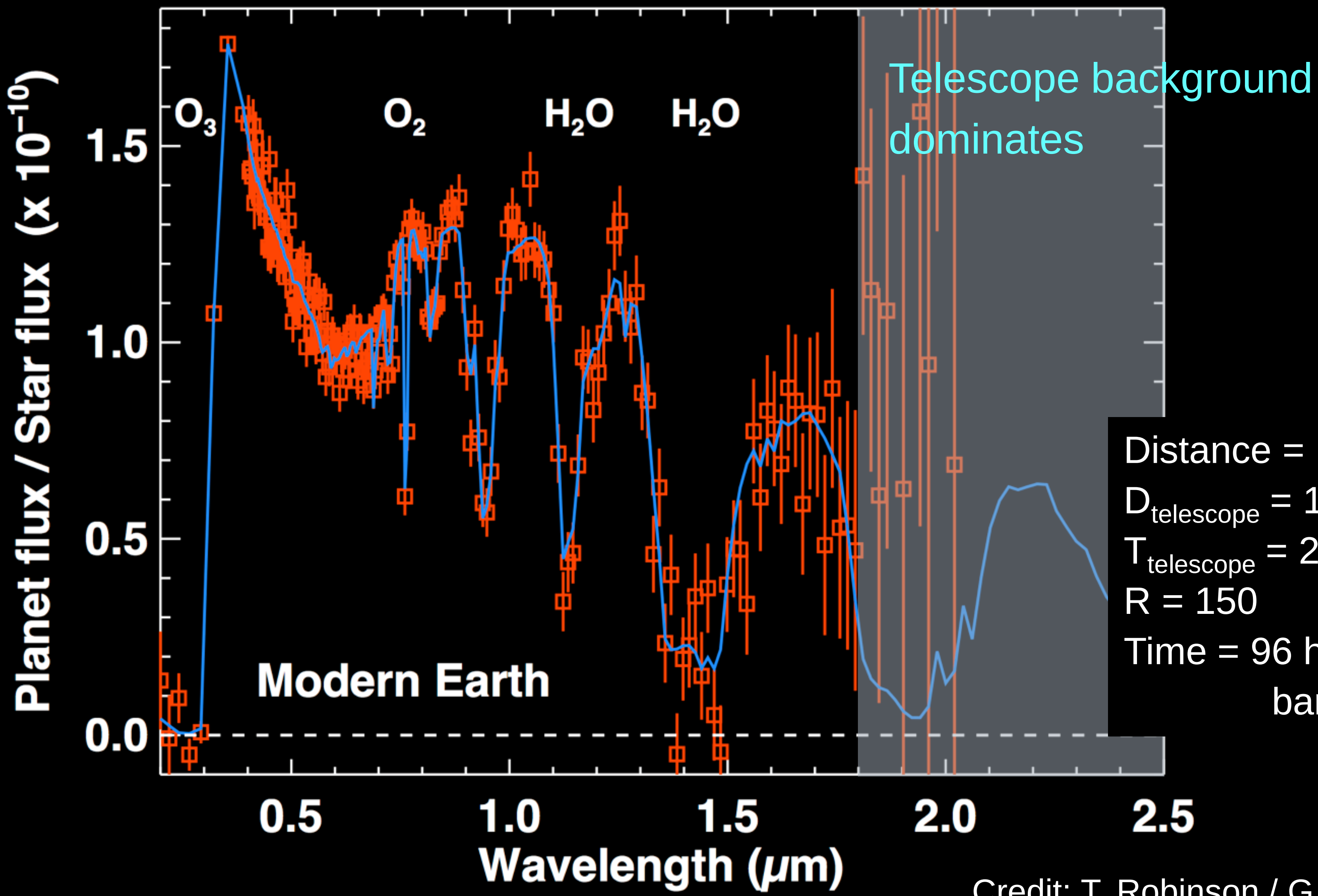
Tech development via WFIRST coronagraph




WFIRS
T
HLC

WFIRS
T
SPC

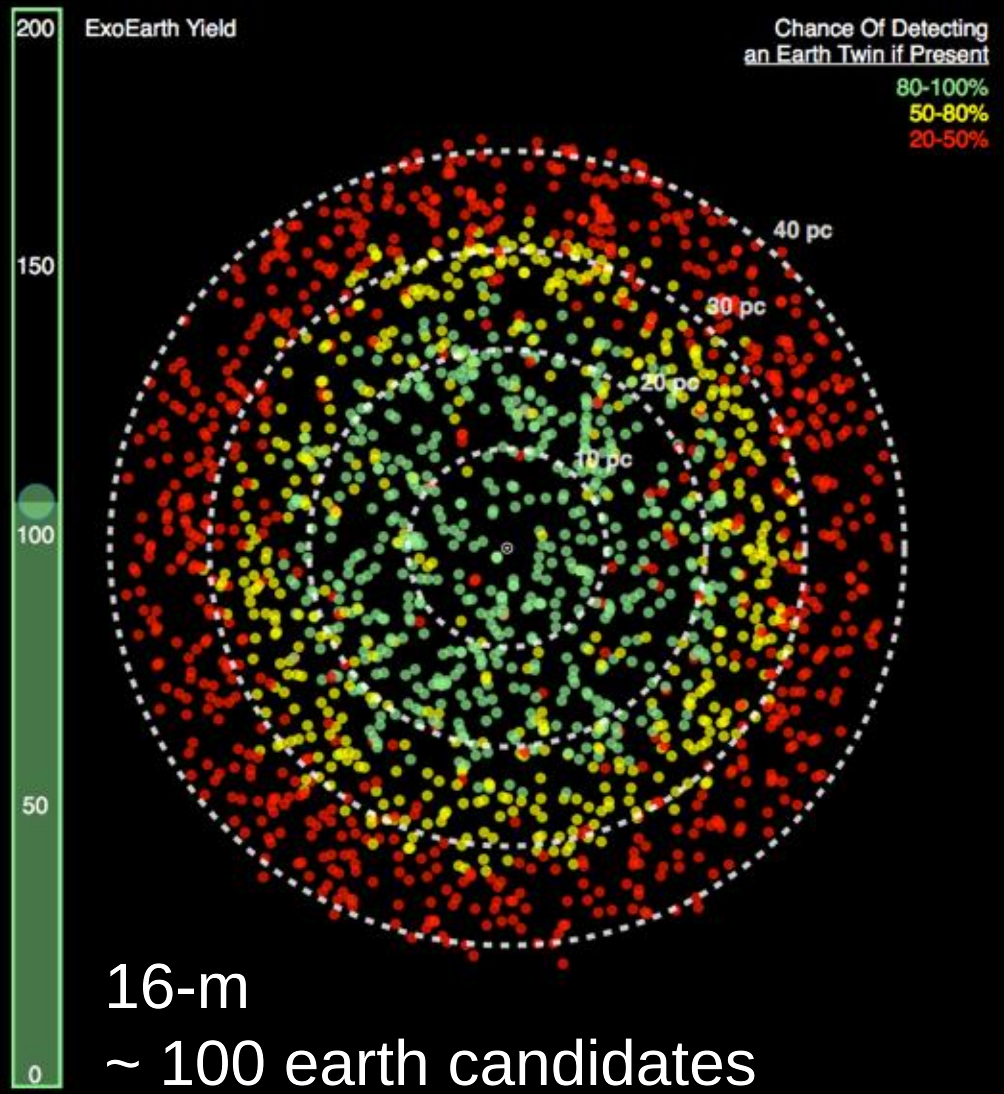
# Simulation of Earth on 15 m LUVOIR




Distance = 10 pc
$D_{telescope}$ = 15-m
$T_{telescope}$ = 270 K
R = 150
Time = 96 hrs per band

Credit: T. Robinson / G. Arney

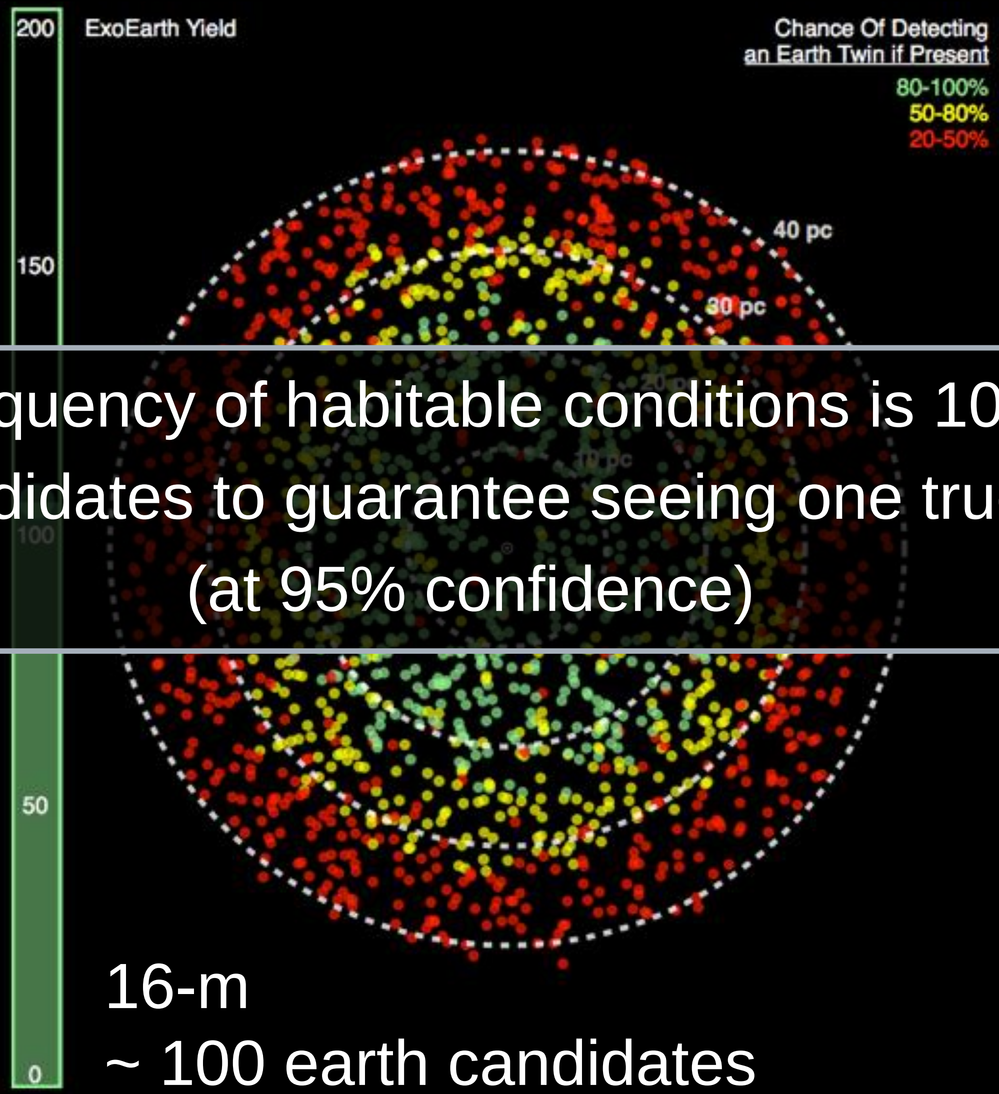
# ExoEarth candidates vs. aperture




16-m
~ 100 earth candidates

Stark et al. (2014)

# ExoEarth candidates vs. aperture




If frequency of habitable conditions is 10%,
need 30 candidates to guarantee seeing one true exoEarth
(at 95% confidence)

16-m
~ 100 earth candidates

Stark et al. (2014)

ORIGINS
Space Telescope

# The Origins Space Telescope (OST)

**From First Stars to Life**

Margaret Meixner, Community co-chair for OST, STScI/JHU/NASA Goddard
Jonathan Fortney, Exoplanet co-chair for OST, UC Santa Cruz

# Opacities in the

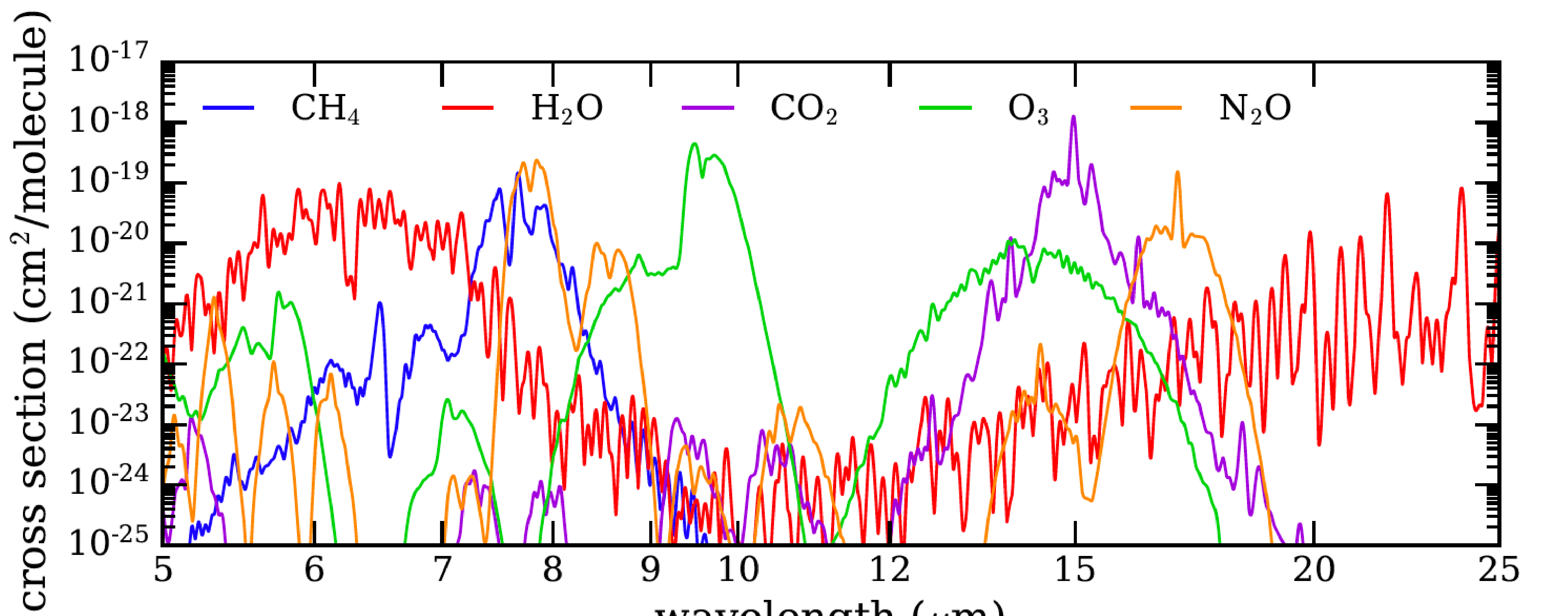
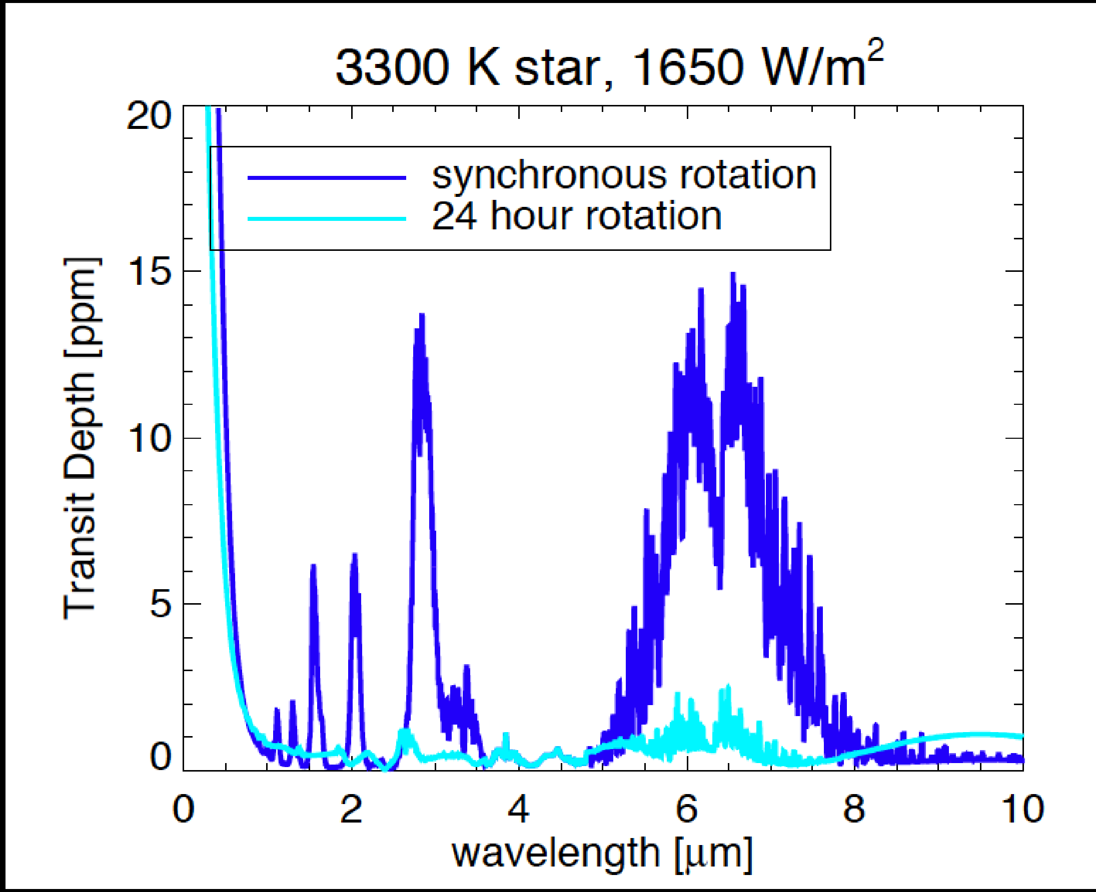



Figure from Caroline Morley

- A host of important molecular features for cool planetary atmospheres
- Extremely broad wavelength coverage to provide critical atmospheric context

# Transmission Spectra

- Molecular detections at the atmospheric terminator
- Pressure level of any opaque clouds
  - Long wavelengths may allow for seeing through the clouds, depending on particle size, yielding additional cloud constraints
- Spectral resolution of MISC + concurrent ground-based monitoring + long wavelengths will mitigate effects of inhomogeneous stellar photosphere (Rackham et al., 2018) on $H_2O$ features




Kopparapu et al. 2017, ApJ

# Timeline

ELTs First Light – 2024-2027ish

HABEX, LUVOIR, OST: 2035 and beyond