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

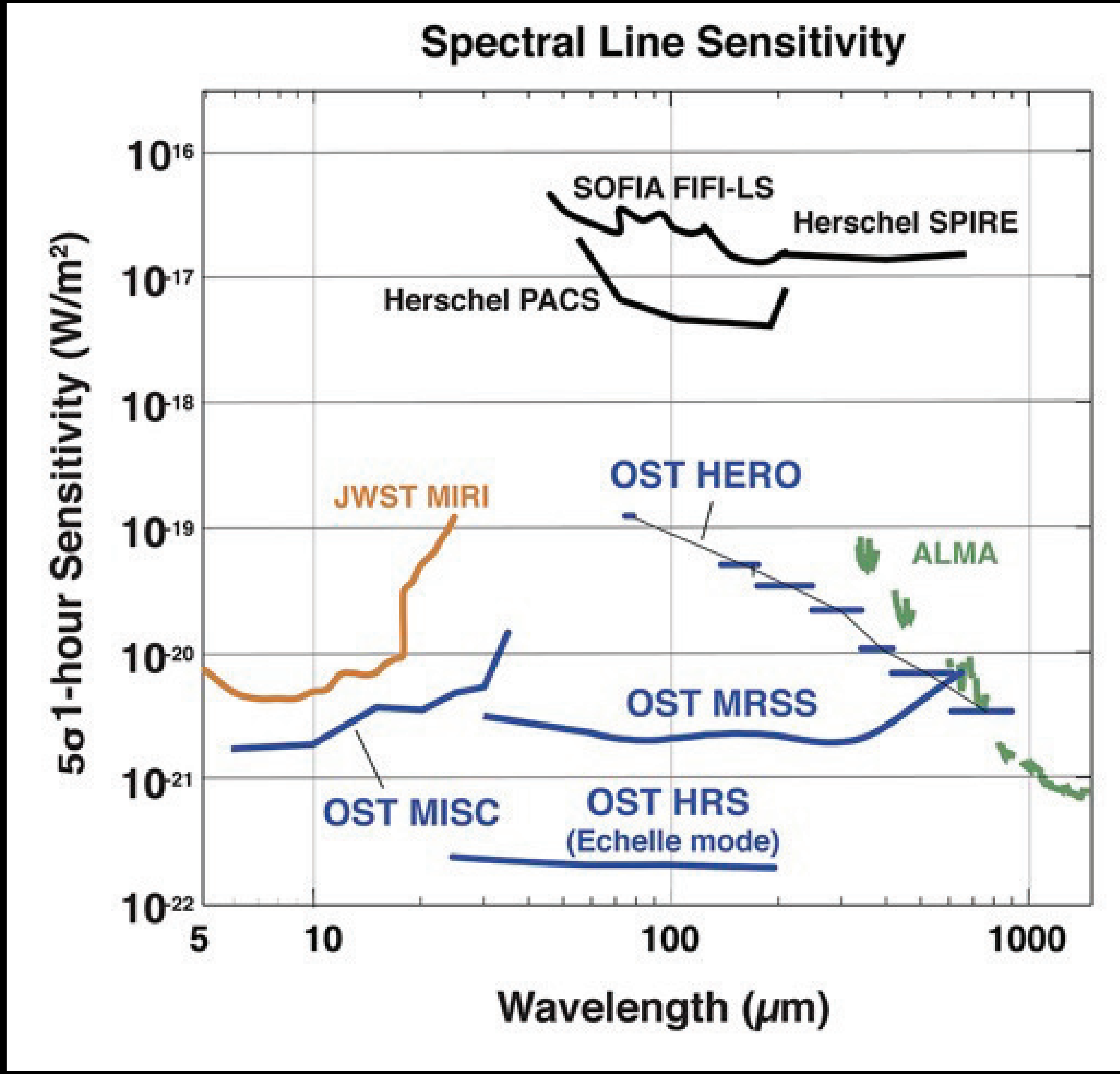
The OST NASA Decadal Study

- Mission concept for NASA Astrophysics Roadmap Enduring Quests, Daring Visions; formerly known as Far-Infrared Surveyor
- Operating wavelengths: 5-660 μm
- Goal: large general astronomy mission with exciting science that is technologically executable in 2030s
- Both Science Definition & Technological Implementation important
- OST study has two concepts:
  - Mission Concept 1, completed, described here
  - Mission Concept 2, started – optimization


Are we alone?
How does the Universe work?
How does the Universe work?
How did we get here?
Ingredients of life and habitable worlds
Growth of black holes and galaxies
Charting the rise of metals and dust
Our solar system in context

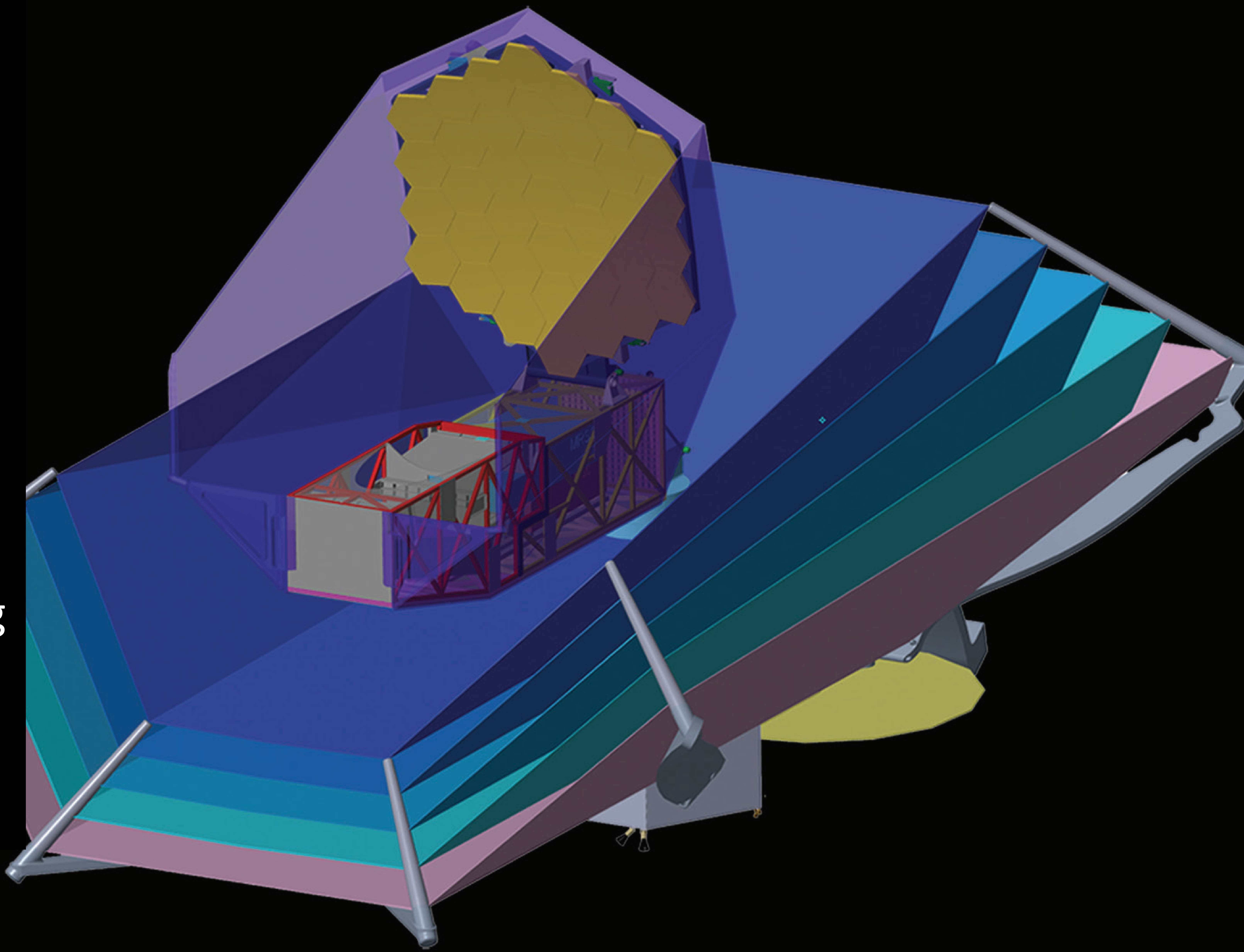
OST Gains in sensitivity because it is COLD (4 K)

Equivalent telescope diameter difference needed for an optical telescope to achieve 1000 times higher sensitivity



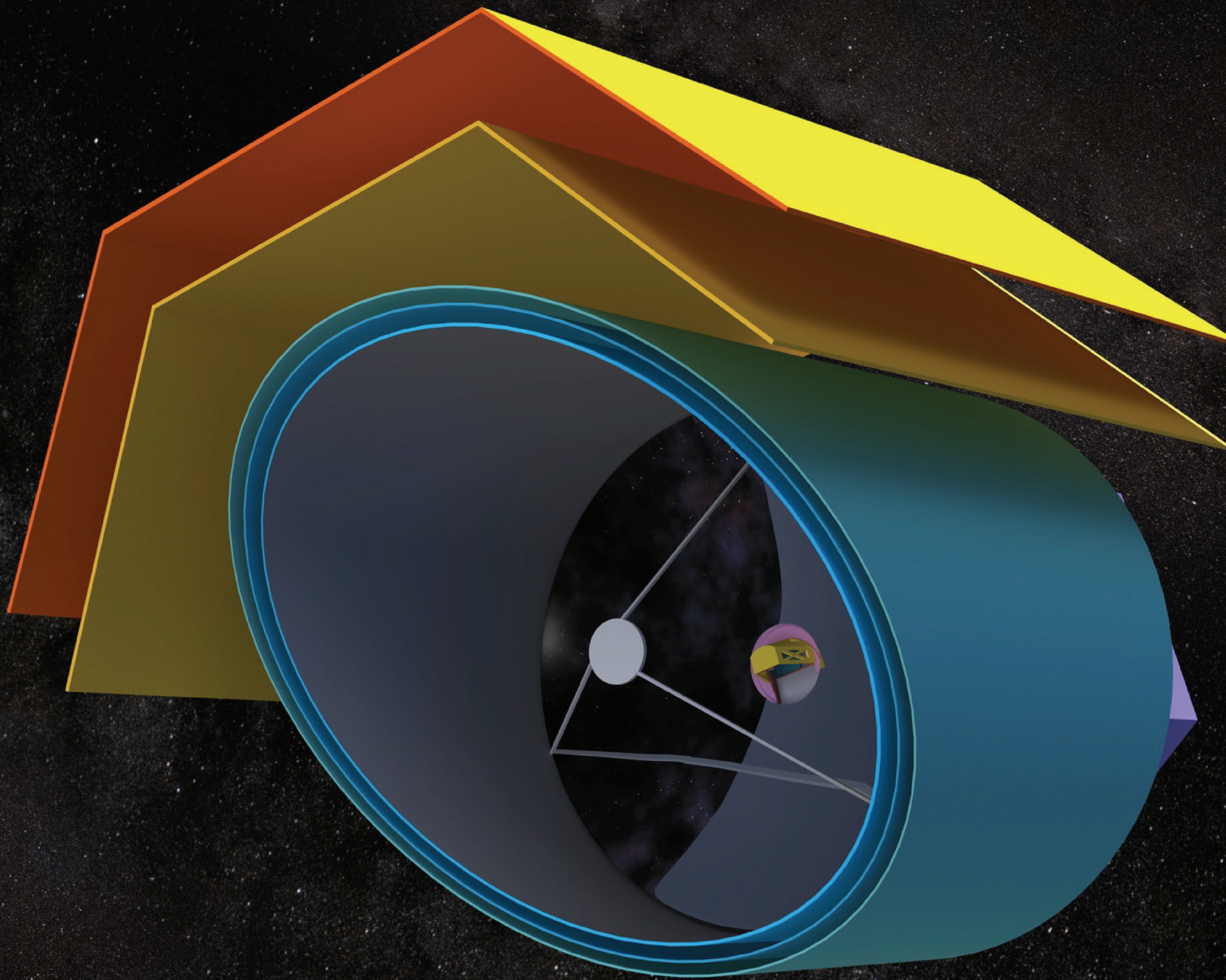
Mission Concept 1

- 9.1 m off-axis primary mirror
- Cold (4 K) telescope
- Wavelengths 5-660 µm
- 5 science instruments:
  - MISC - 5-38 µm
  - MRSS 30-660 µm
  - HERO 63-66; 111-610 µm
  - HRS 25-200 µm
  - FIP 40, 80, 120, 240 µm
- 100 arcseconds/second mapping
- Launch 2030s
- Sun-Earth L2 orbit
- 5 year lifetime, 10 year goal

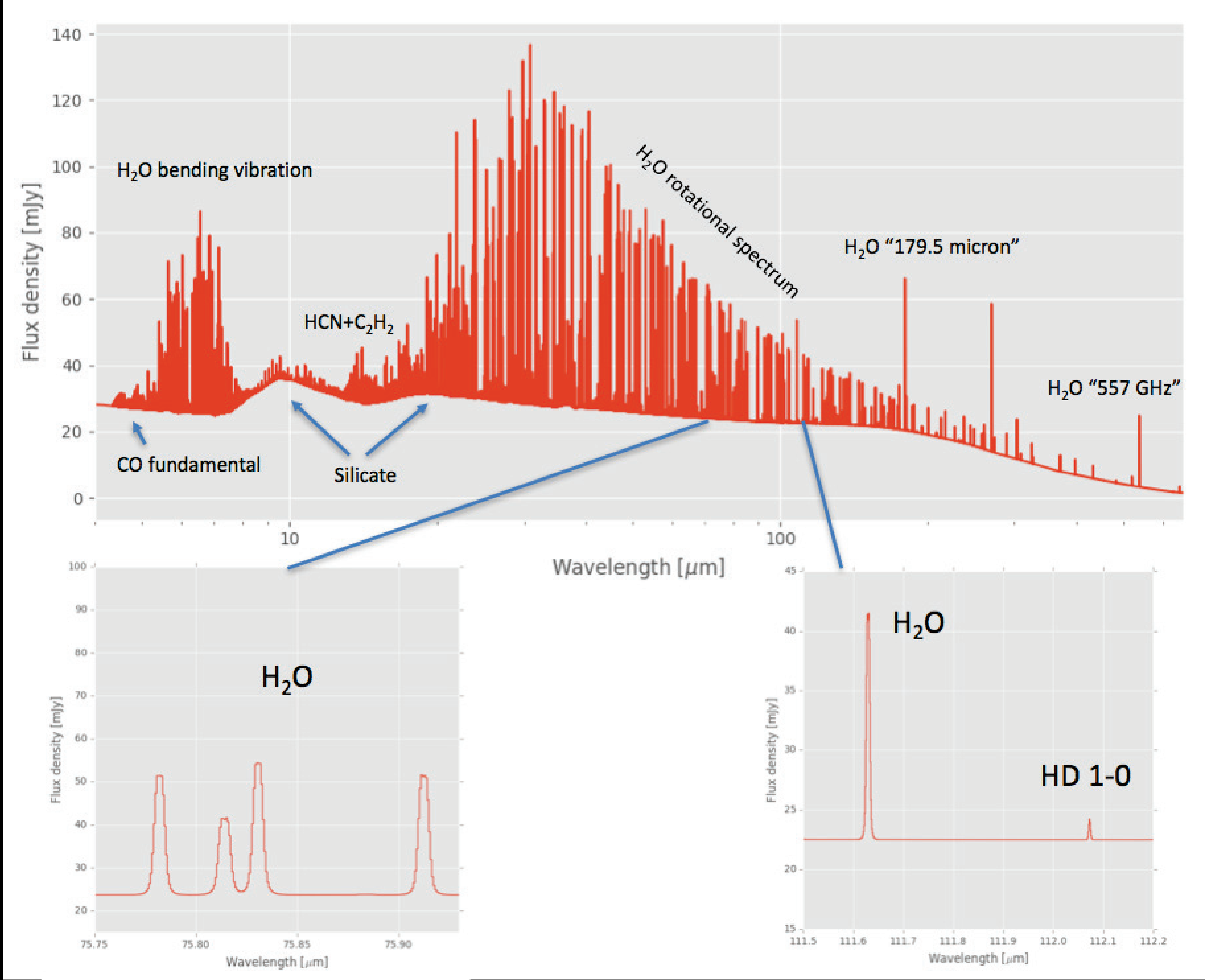


Mission Concept 2

- 5.9-m circular aperture
- Cold (4 K) primary
- Spitzer-like baffle, with Sun shield
- Minimal deployment
- Fewer (≤4), science-optimized instruments
- Preliminary designs started, to be completed by end of summer 2018




Following the formation of planetary systems
from the interstellar medium to life-bearing worlds
Interstellar medium
HERO, FIP
Protoplanetary disks
MRSS, HRS, HERO
Planetary systems
MRSS, HRS
Exoplanets
MISC

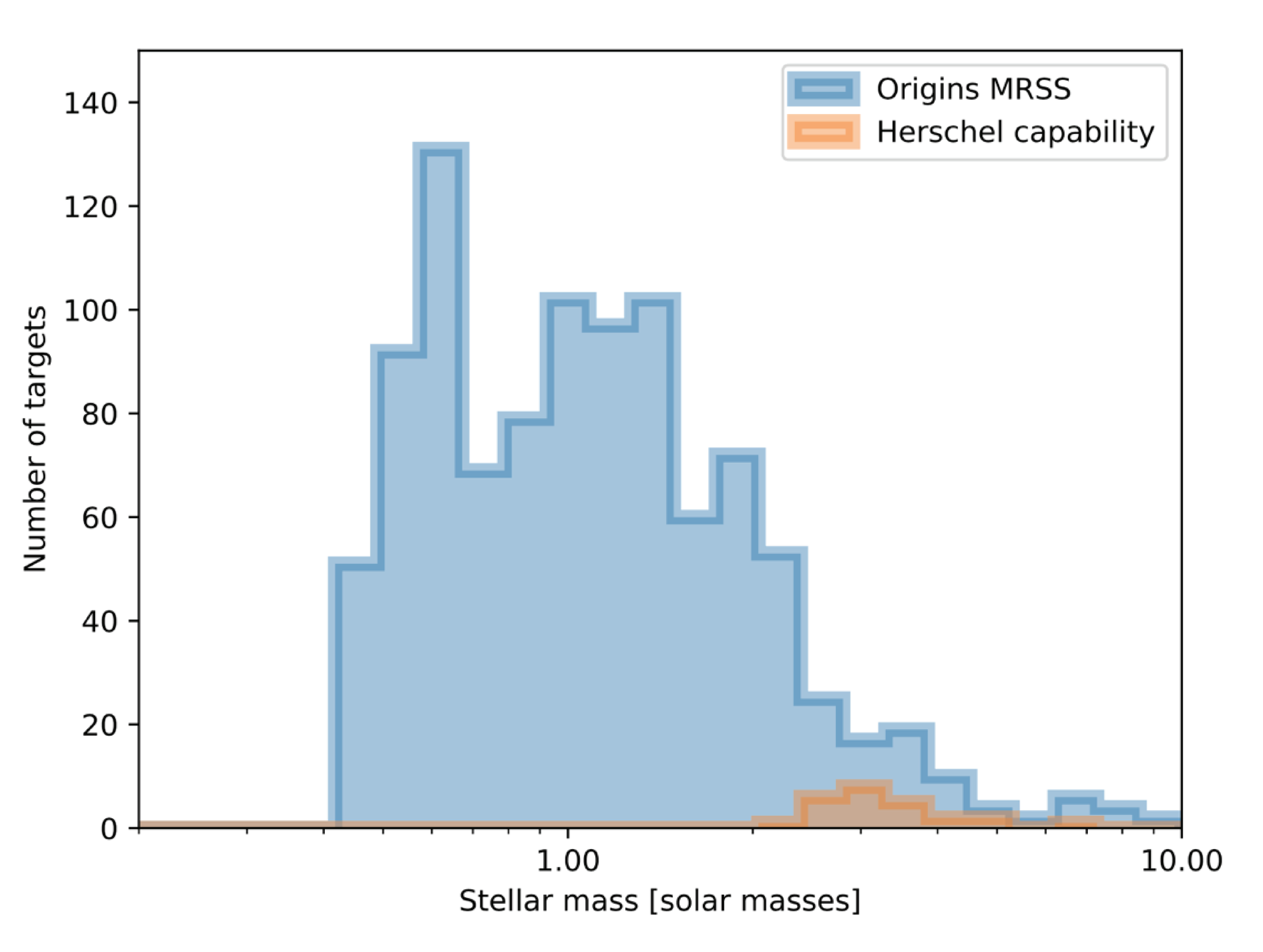

Flux density [mJy]
Wavelength [μm]
H_2O bending vibration
CO fundamental
Silicate
$HCN+C_2H_2$
H_2O rotational spectrum
H_2O "179.5 micron"
H_2O "557 GHz"
H_2O
HD 1-0
Flux density [mJy]
Wavelength [μm]

The OST Disk Survey

- 1000 planet-forming disks around stars of all masses
- Complete map of water vapor+ice from 1-100 AU
- Determine origin of water in >100 comets
- Water from the pre-stellar phase to exoplanets

✓ Measure planet-forming mass in the galaxy
✓ Measure planet-forming water in the galaxy
✓ Follow the trail of water at all stages to understand its availability for habitability

✓ Time required with 5.64 meter OST – 1500 hrs

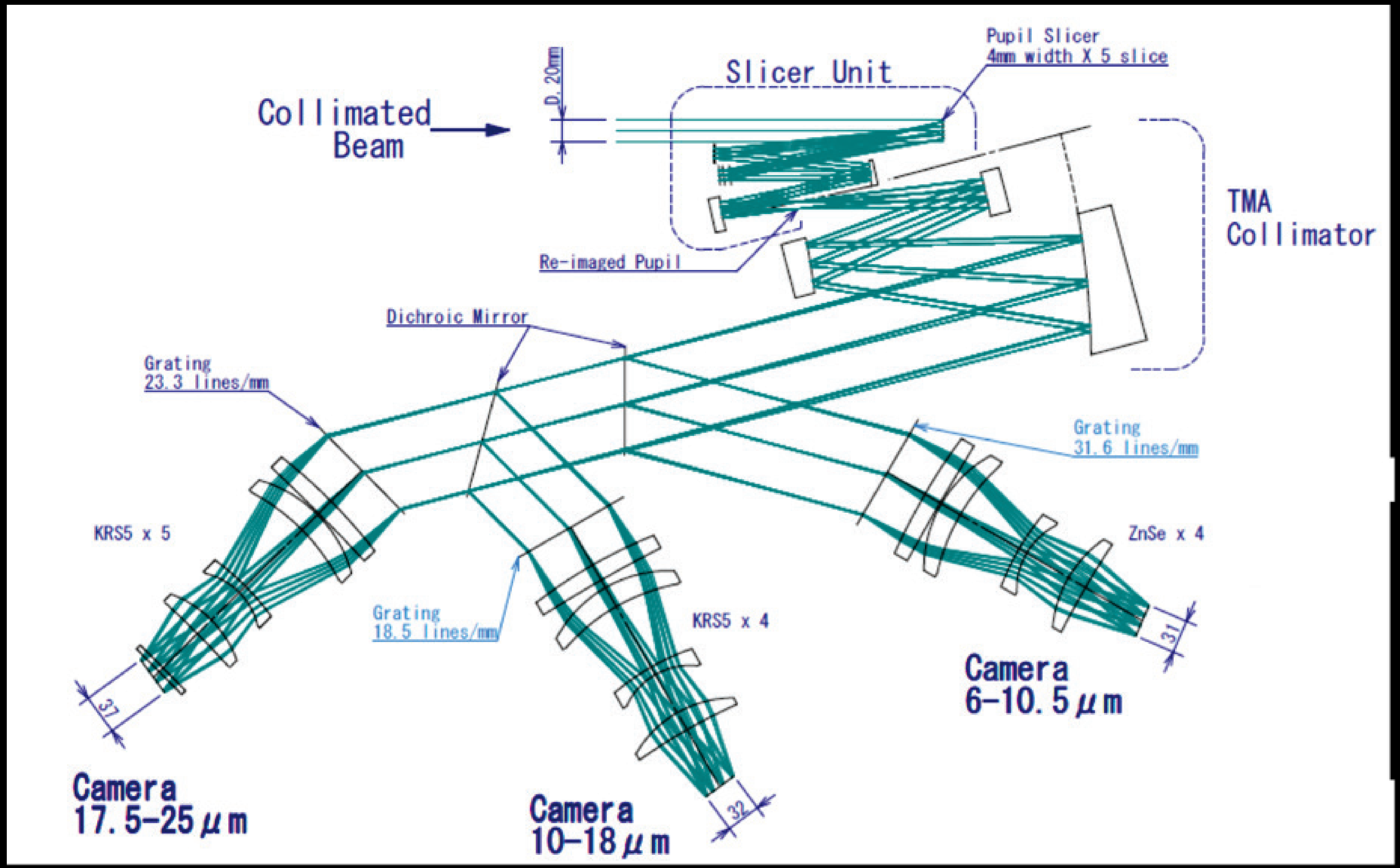


The Mid-Infrared Imager, Spectrometer, and Coronagraph (MISC) instrument

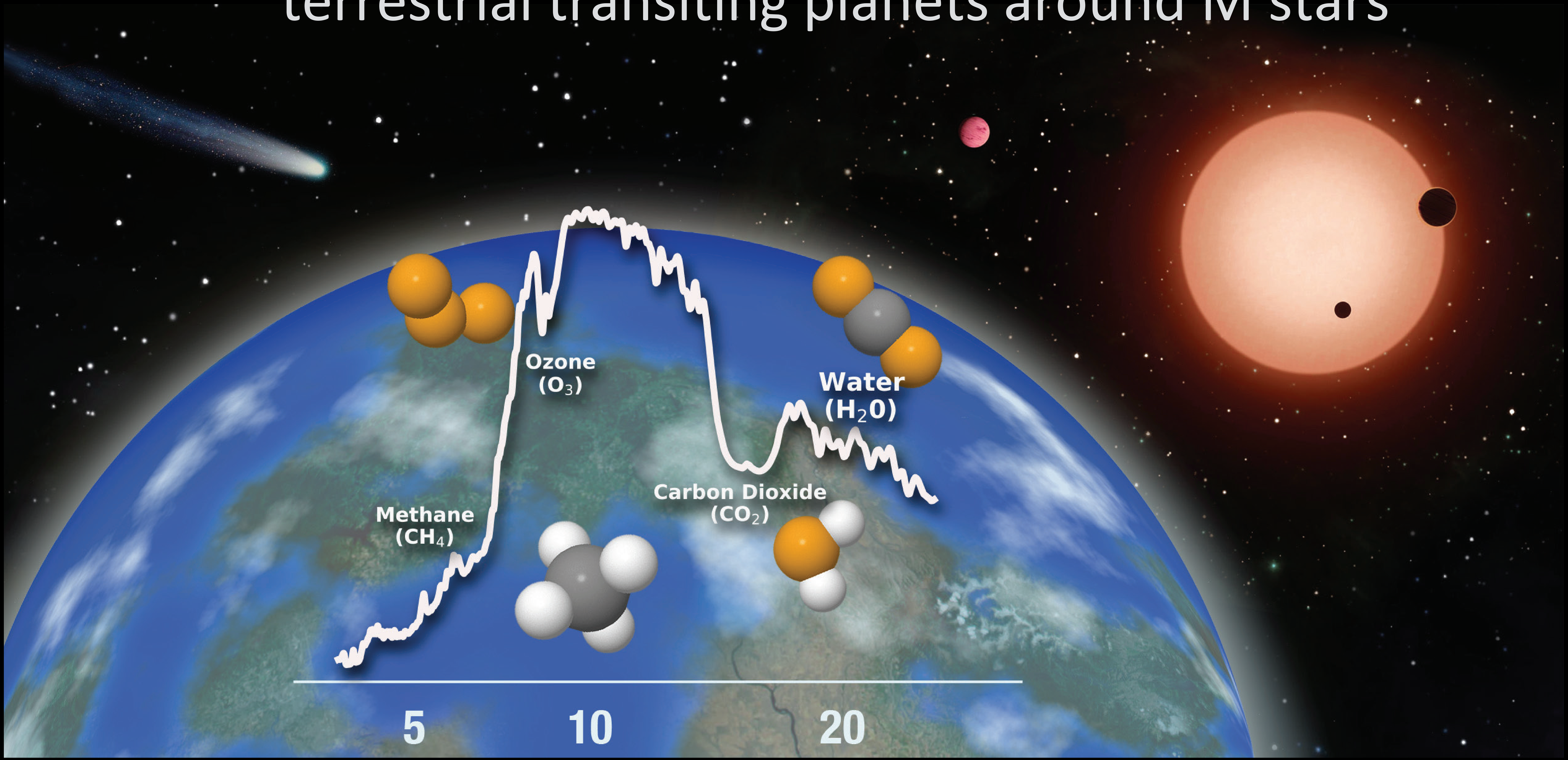
- Suite of spectroscopic and imaging modes from 5-38 microns
- lambda/delta lambda ~ 15, 300, 1200, 10^4
- Instruments for exoplanet science
  - Transit Spectrometer: < 5 ppm stability
  - Coronagraph: 10^{-5} contrast

MISC Transit Spectrometer

- Gets entire 5-28 micron spectrum *simultaneously*
- Densified Pupil Spectrometer (Matsuo et al. 2016)
- Spreads light over multiple pixels to mitigate minor telescope pointing and jitter issues
- Has reference pixels to remove detector gain drifts
- Mid-IR detectors will be developed to meet requirements

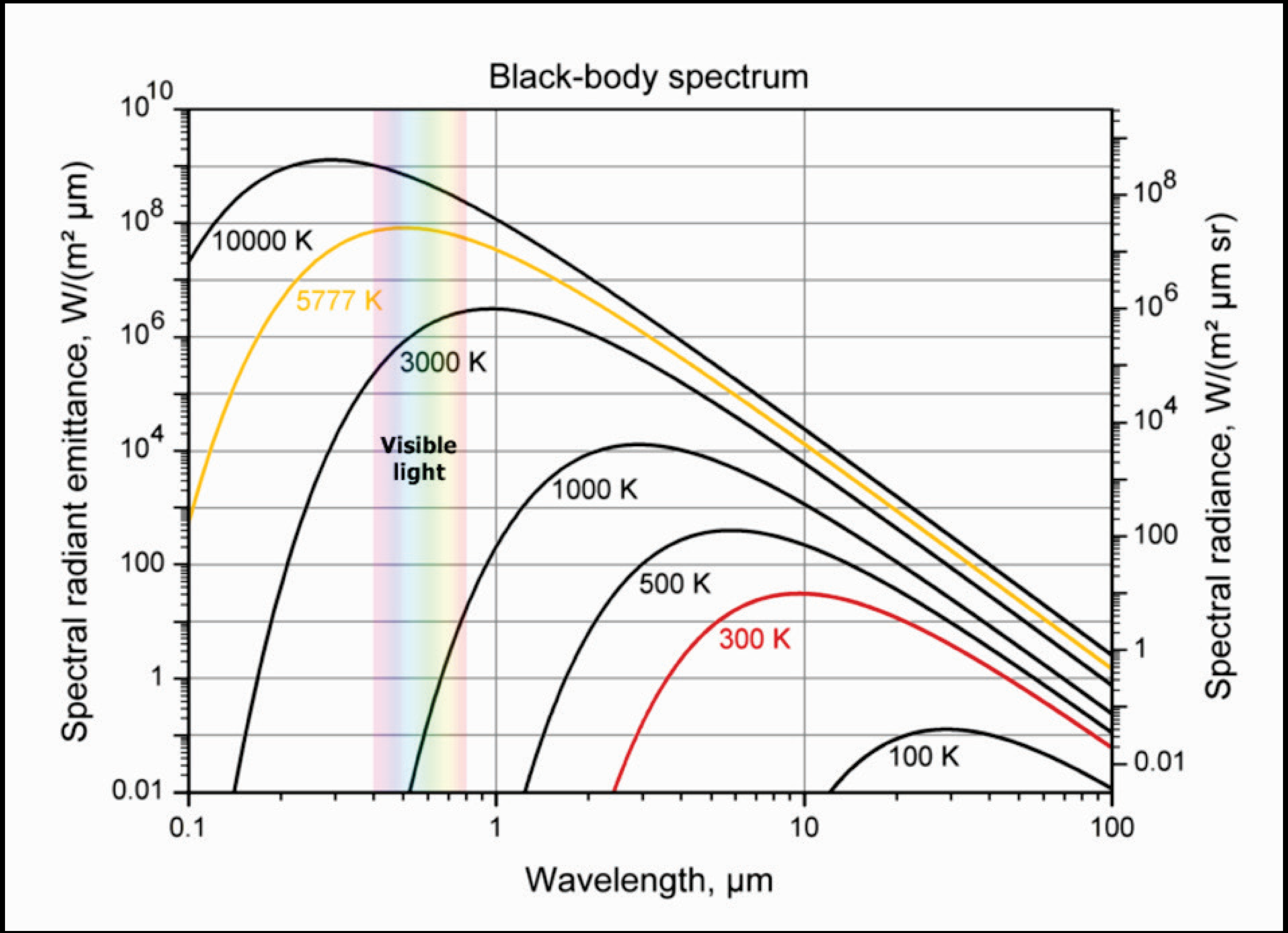


Searching for biologically significant gasses at mid-IR wavelengths for temperate terrestrial transiting planets around M stars



Temperate Planets in the Mid-IR

- OST MISC bandpass provides *simultaneous* 5-25 micron coverage across peak planetary brightness at the most favorable planet-to-star contrast



Molecular Opacities in the Mid-IR

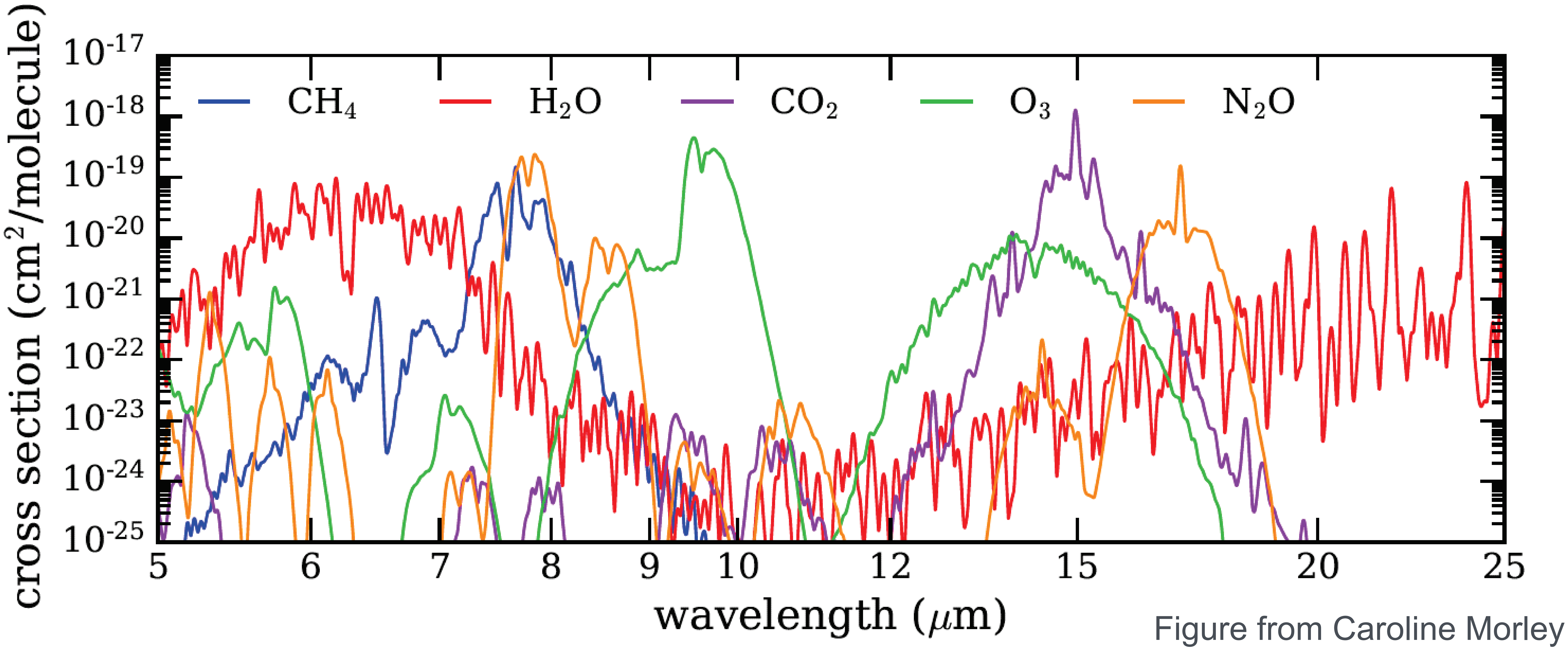


Figure from Caroline Morley

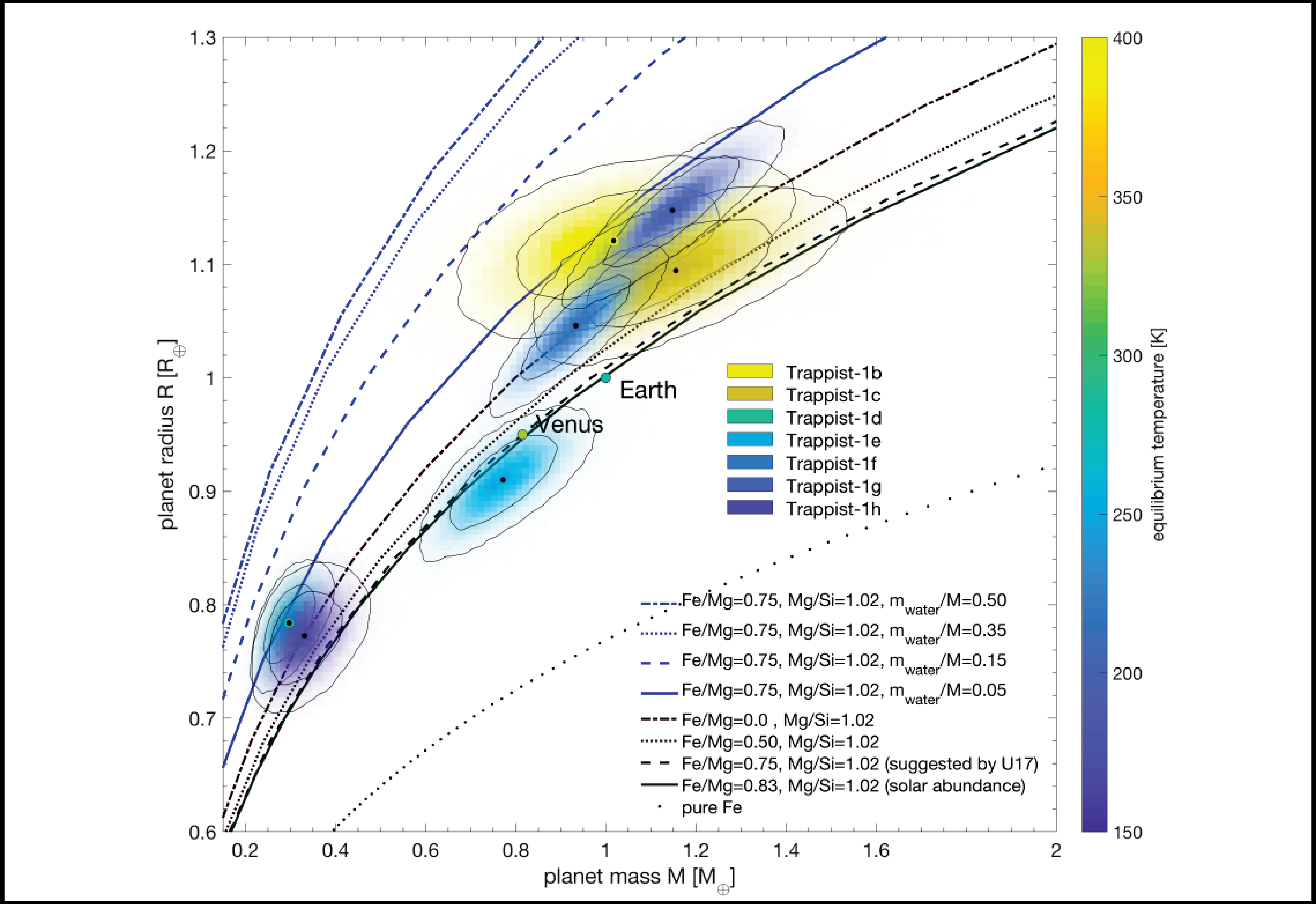
- A host of important molecular features for cool planetary atmospheres
- Extremely broad wavelength coverage to provide critical atmospheric context

Thermal IR Advantages

- Wavelength coverage where the planets are brightest and contrast is best
- Access to thermal emission and the temperature structure of atmospheres
- Absorption features for a range of interesting gases
- Broad wavelength coverage for context and the detection of the unexpected

Why Transits?

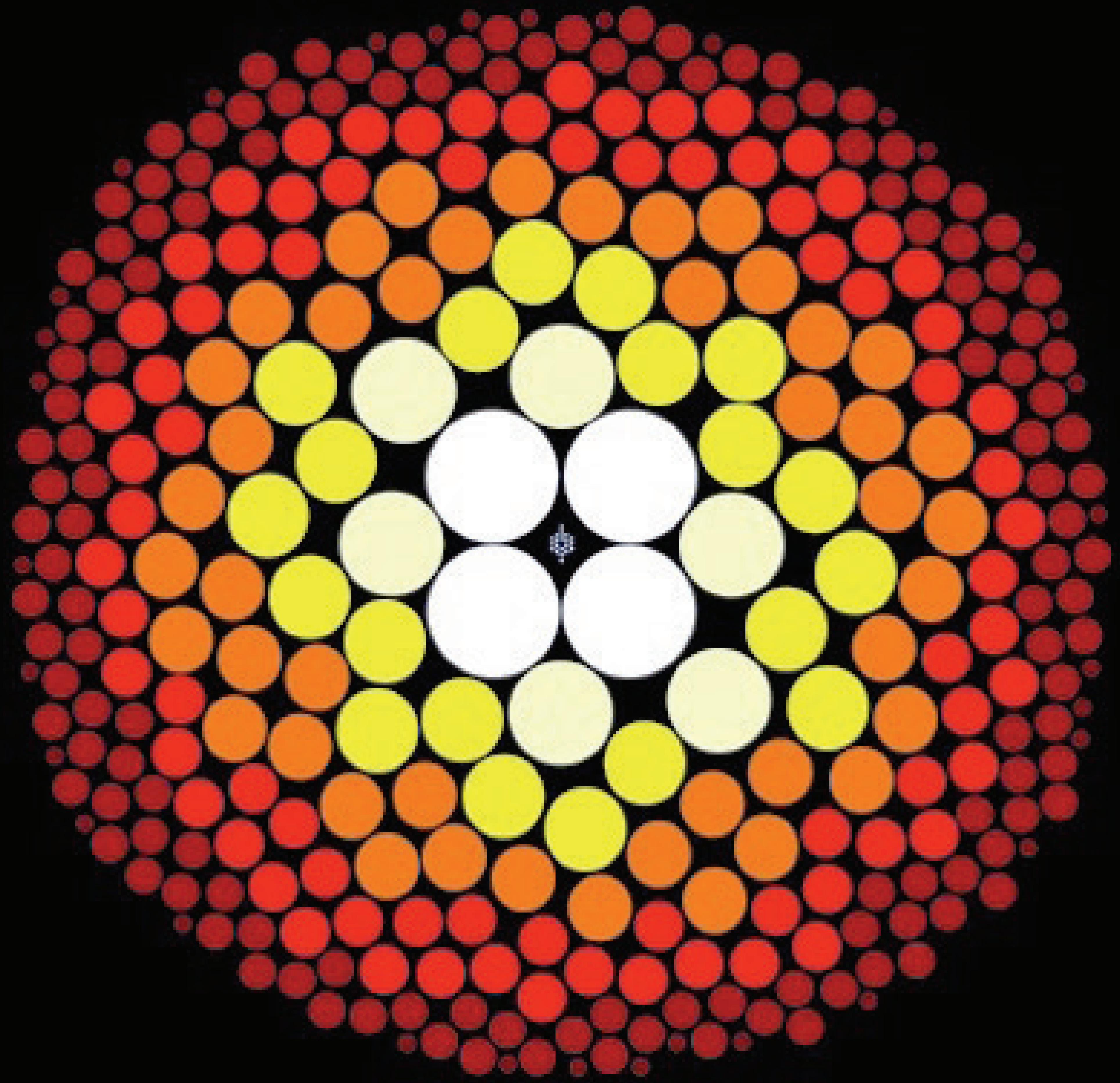
- Precisely determined masses and radii
- Stellar (and planetary) radii to ~5% with GAIA
- Bulk densities for planetary classification before atmospheric characterization
- Target planets known to be predominantly rocky



Why M Stars?

- 75% of stars within 15 pc are M dwarfs
  - –Mid-to-late M dwarfs provide the best signal when searching for life
  - –Expect to detect about a dozen HZ exoplanets transiting mid-to-late M dwarfs within 15 pc (later slides)
  - –Four such planets are already known (TRAPPIST-1d,e,f and LHS-1140b)

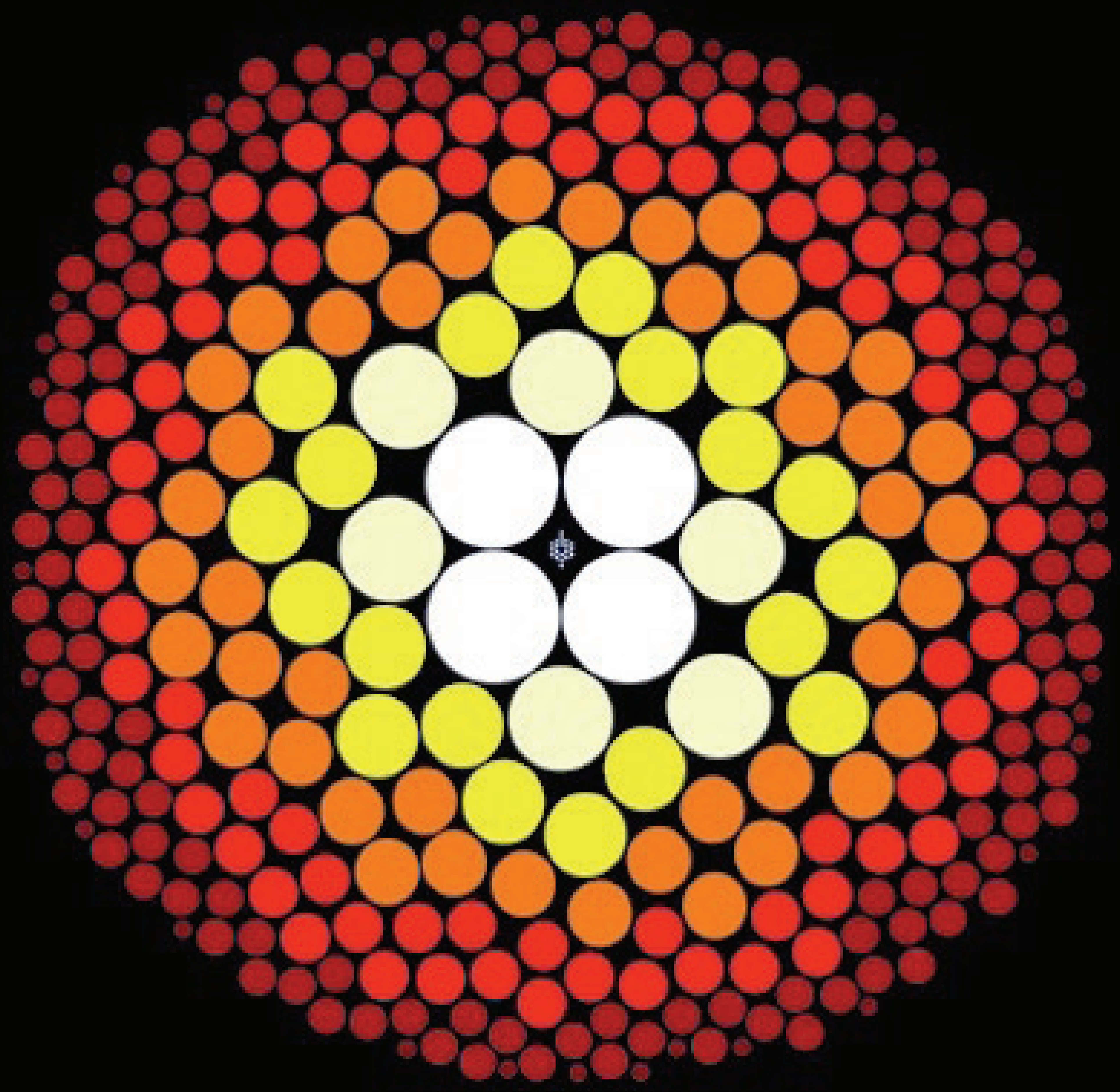
- Advantages of planets transiting smaller stars
  - –Larger transit depths
  - –Closer habitable zones (5 – 100 days)
  - –Increased transit probability in HZ



T. Henry, RECONS

Why M Stars?

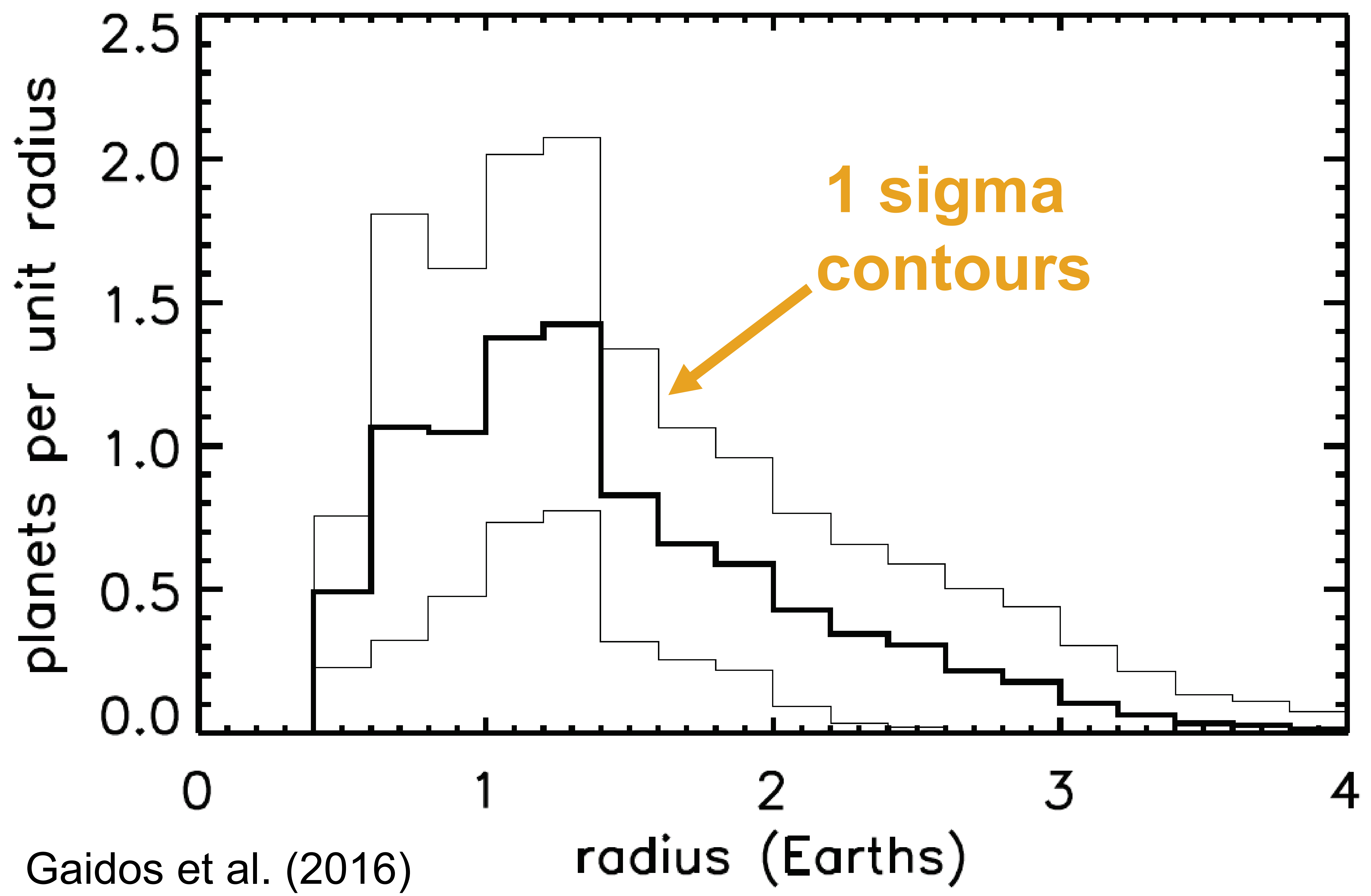
- Atmospheric Observations via Transits, Eclipses, and Phase Curves
  - Proven techniques that builds off the legacy of HST, Spitzer, and JWST



T. Henry, RECONS

Occurrence Rates

- Most M dwarf planets are about the size of Earth
- Average 2.2 planets with periods < 180 days



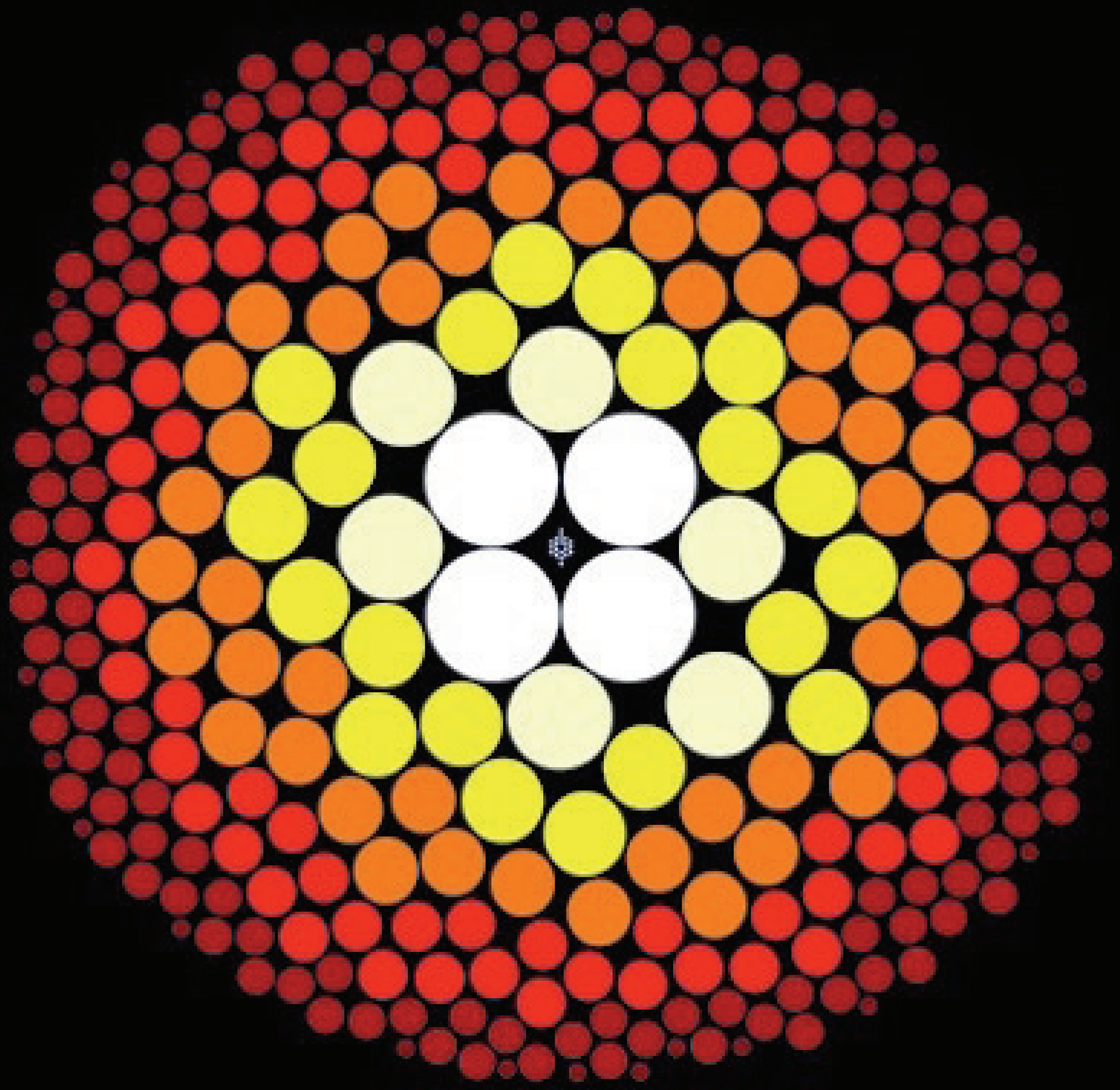
Gaidos et al. (2016)

ORIGINS Space Telescope

M Star Challenges

NASA

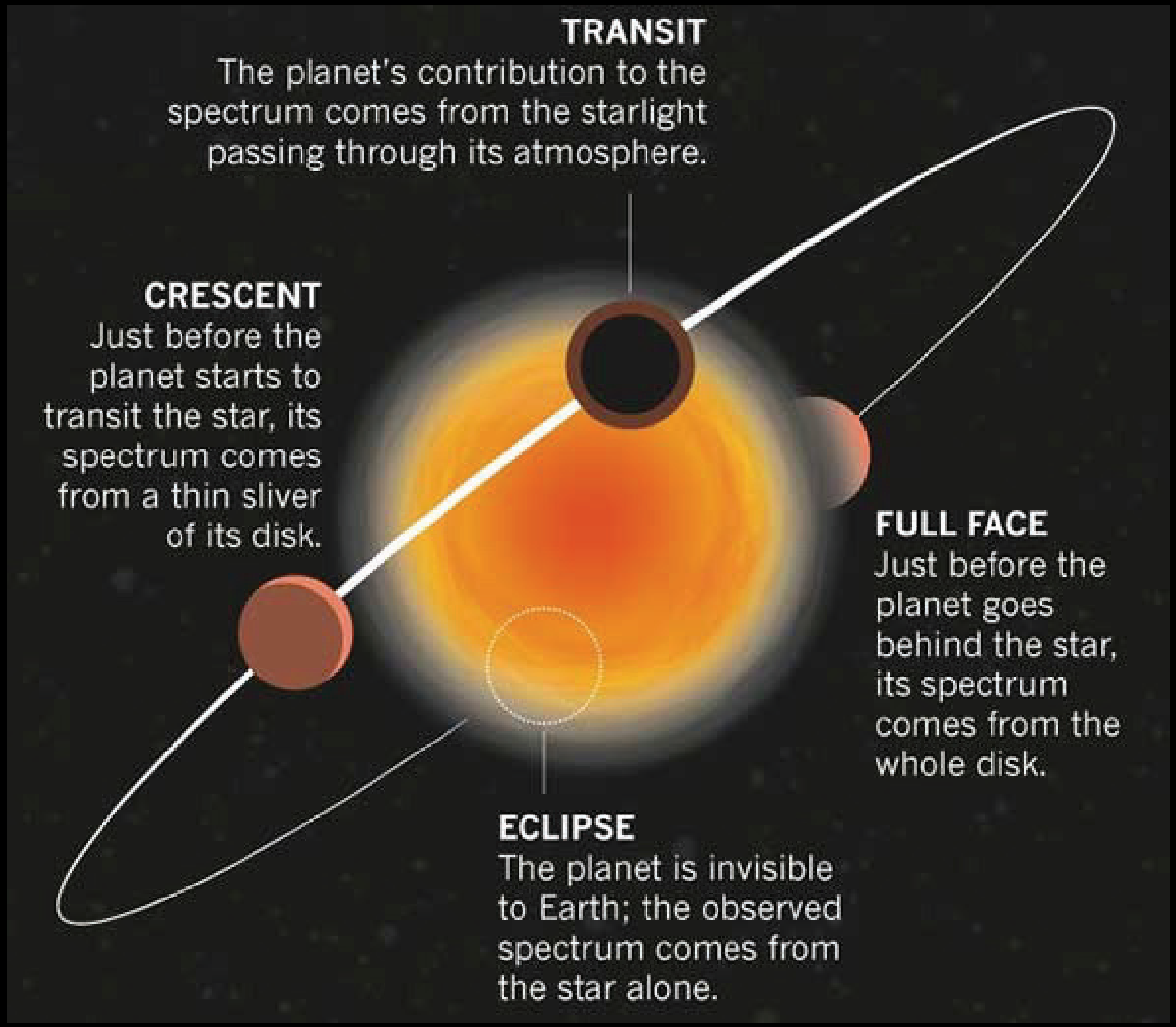
- **"HZ planets around M dwarfs don't have atmospheres"**
  - Planets are diverse with a range of initial atmospheric conditions!
  - JWST will test presence of atmospheres
  - TRAPPIST-1 planet masses are mostly consistent with having large volatile inventory atmospheres
- **"M dwarfs are too active during first Gyr, will boil away oceans and build up abiotic O_2"**
  - Planets in resonances can migrate inwards after formation
  - Volatiles could be modestly replenished through later cometary material
- **"HZ planets might be tidally locked"**
  - Planets with substantial atmospheres (>~ 1 bar) can redistribute heat to nightside
  - Mercury is a fine counter-example



T. Henry, RECONS

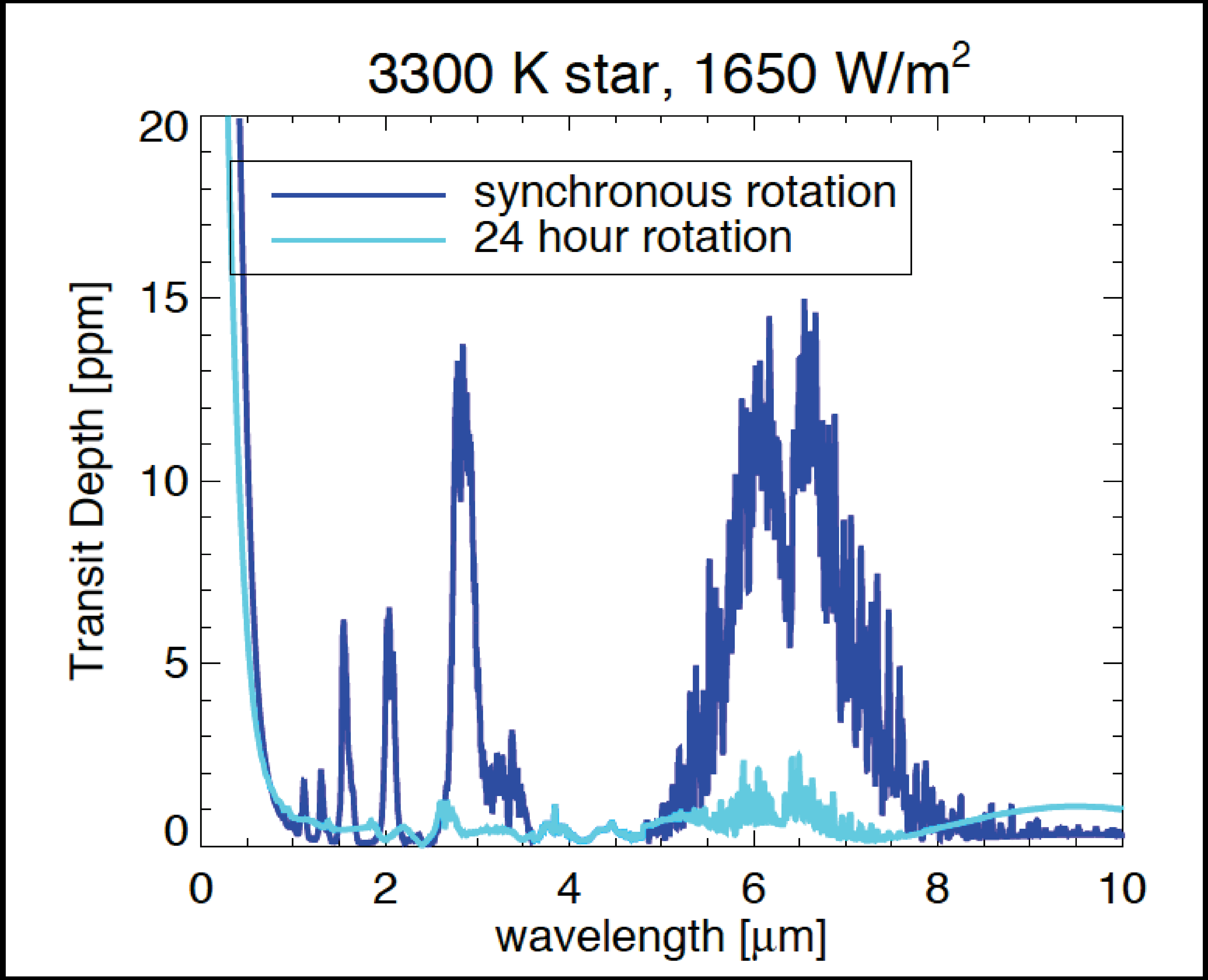
Observational Techniques

- Primary transit
  - Molecular abundances and role of clouds
- Secondary eclipse
  - Temperature structure and molecular abundances
- Spectroscopic Phase Curves
  - Presence of atmospheres and atmospheric circulation
- Eclipse Maps
  - Temperature distribution



Transmission Spectra

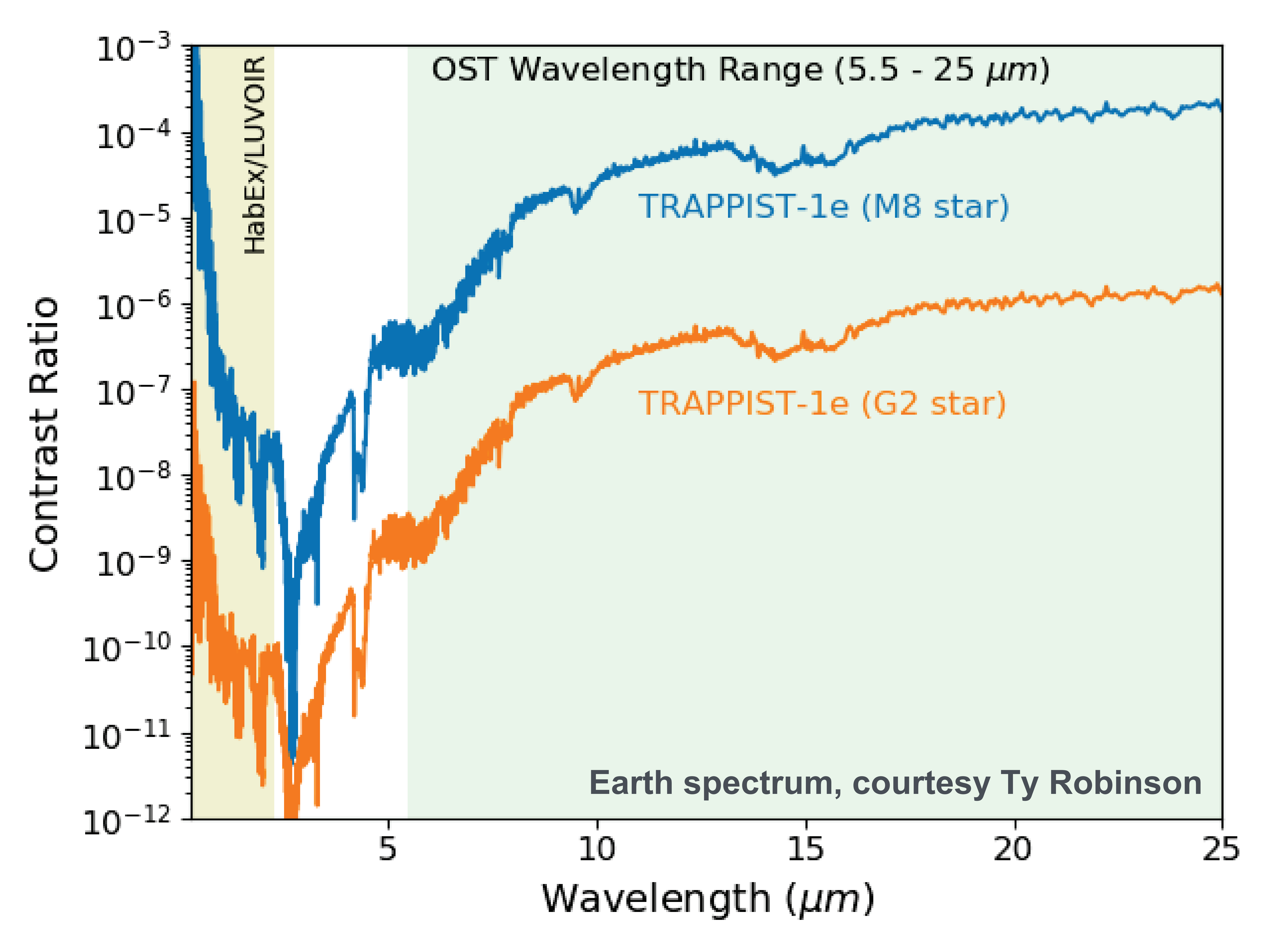
- Molecular detections at the atmospheric terminator
- Pressure level of any opaque clouds
  - Long wavelengths may allow for seeing through the clouds, depending on particle size, yielding additional cloud constraints
- Spectral resolution of MISC + concurrent ground-based monitoring + long wavelengths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



Kopparapu et al. 2017, ApJ

Emission Spectra

- Planet-to-star flux ratios are favorable at thermal infrared wavelengths
- Ability to determine temperature structure

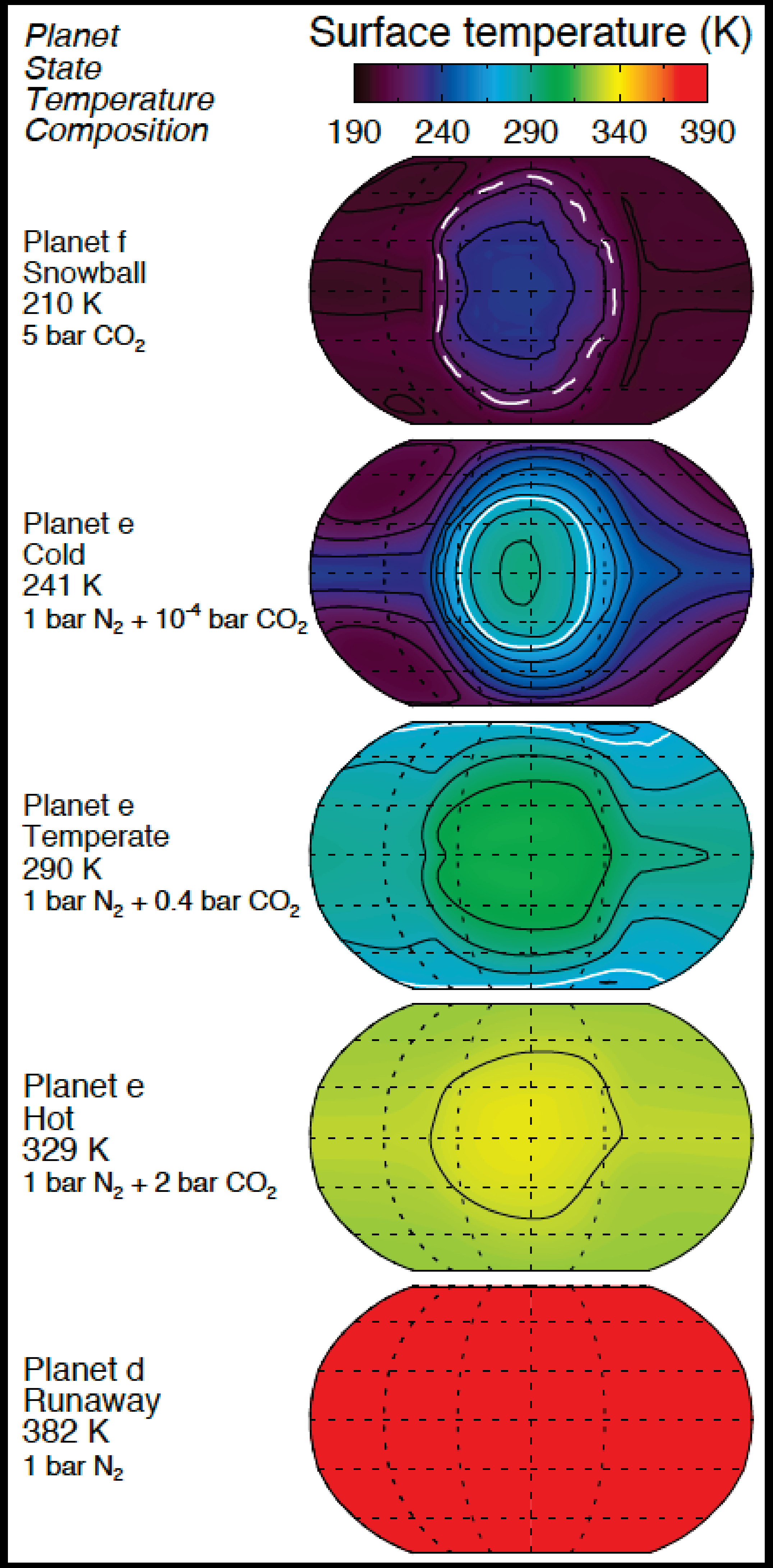


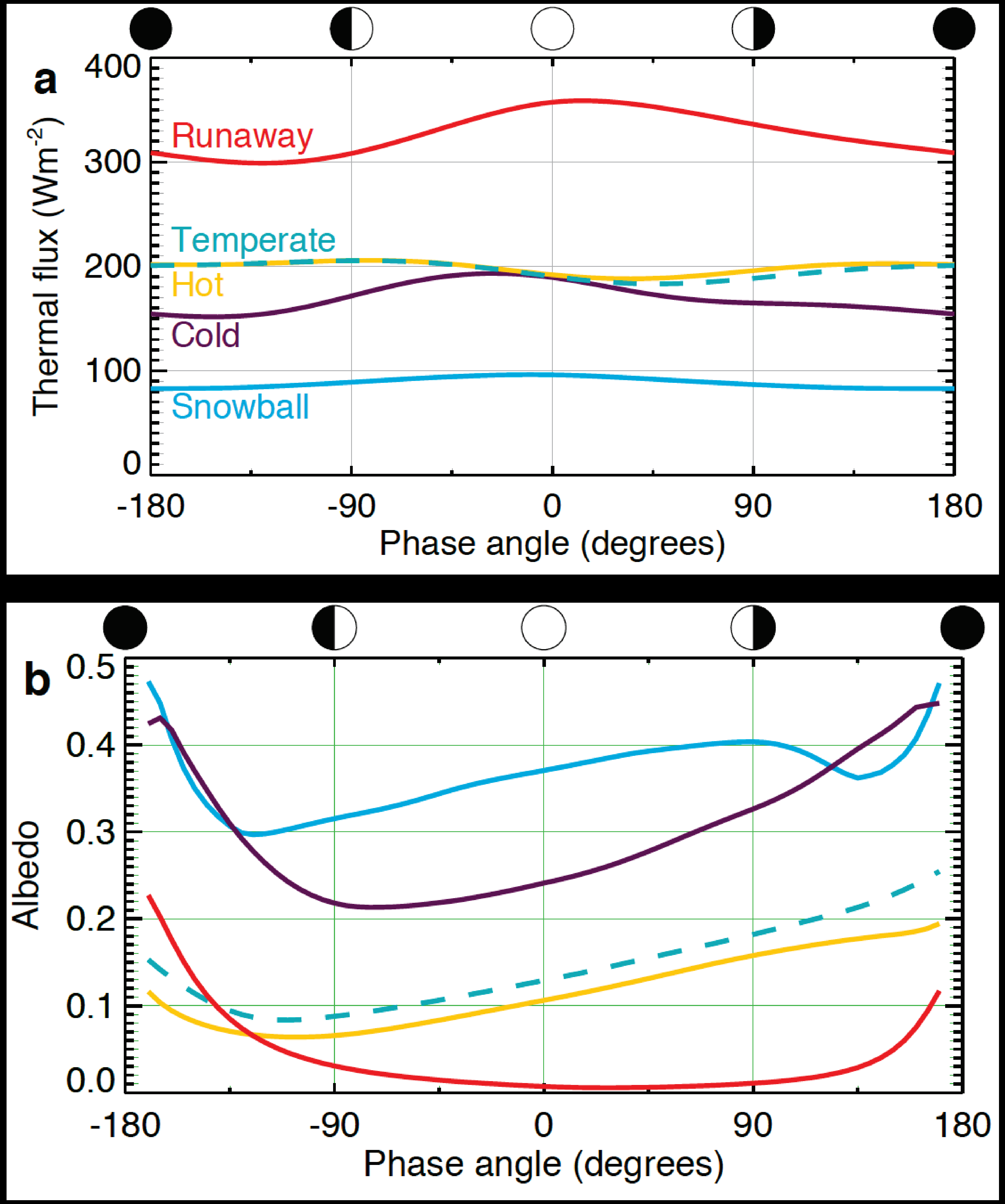
Phase Curves

TRAPPIST 1 d,e,f: Wolf 2017

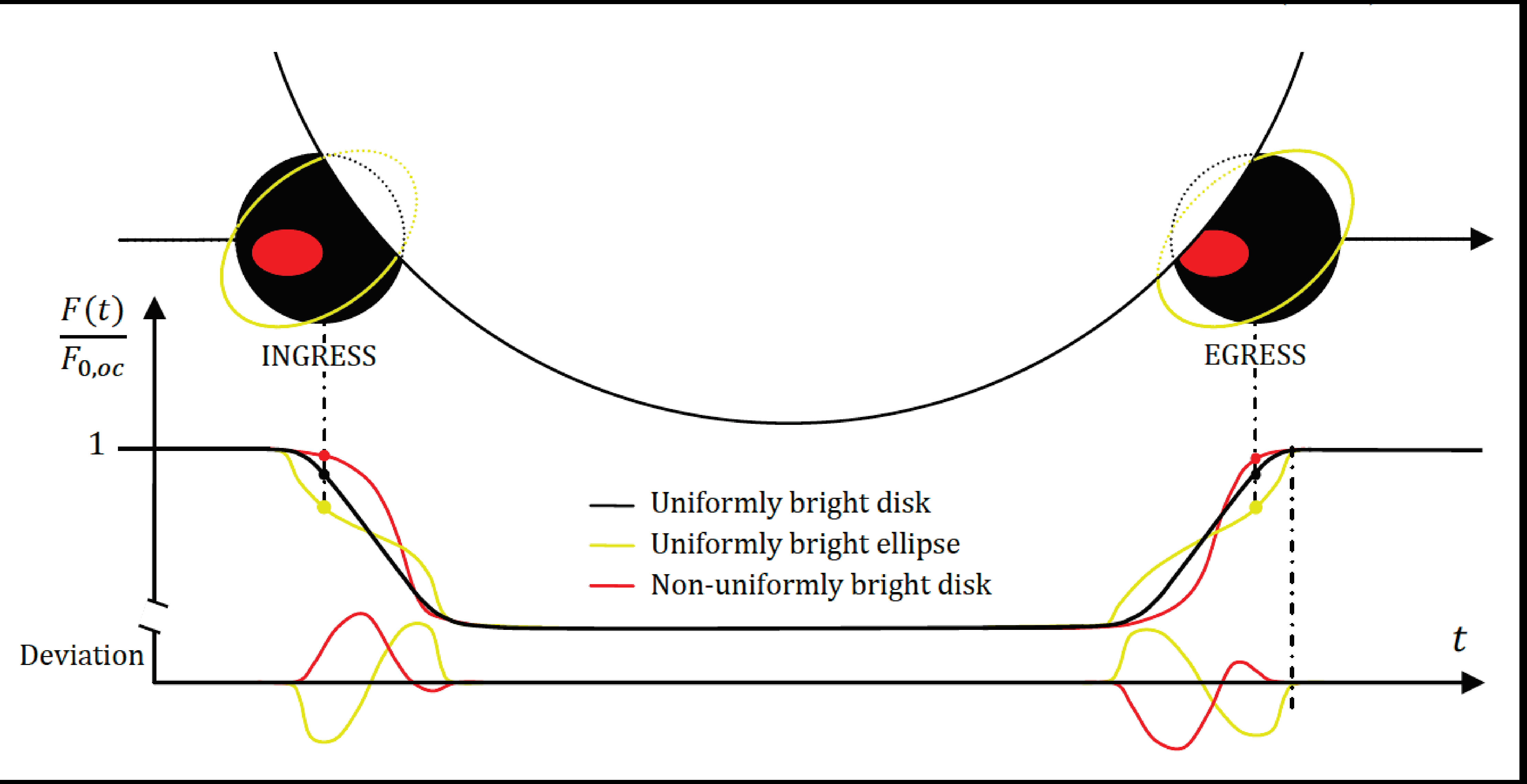
Thermal phase-curve observations in the mid-IR, we have the opportunity to probe the 3D properties of rocky planets that could be habitable

—Also constrain A_{Bond}



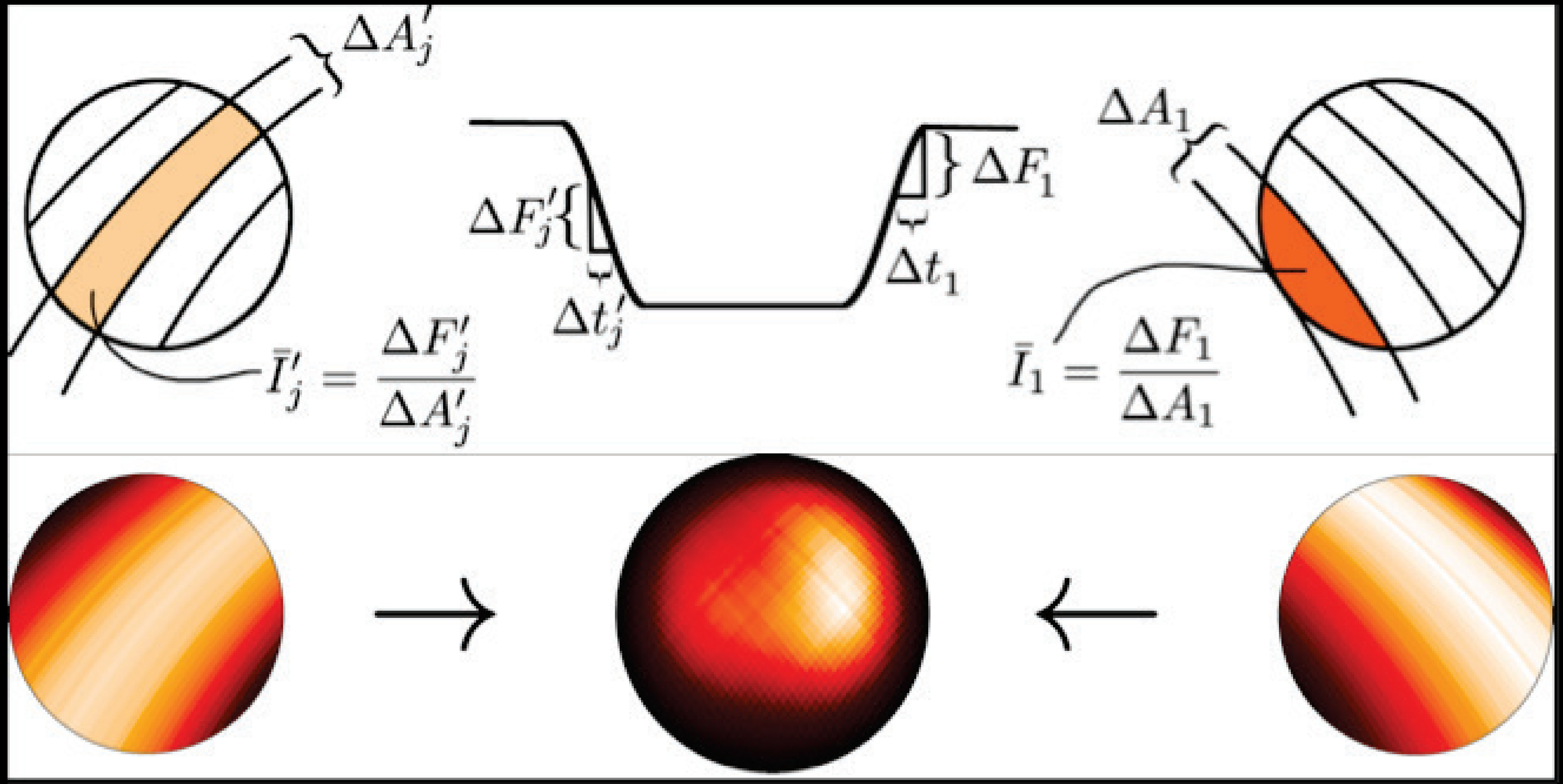


Eclipse Mapping

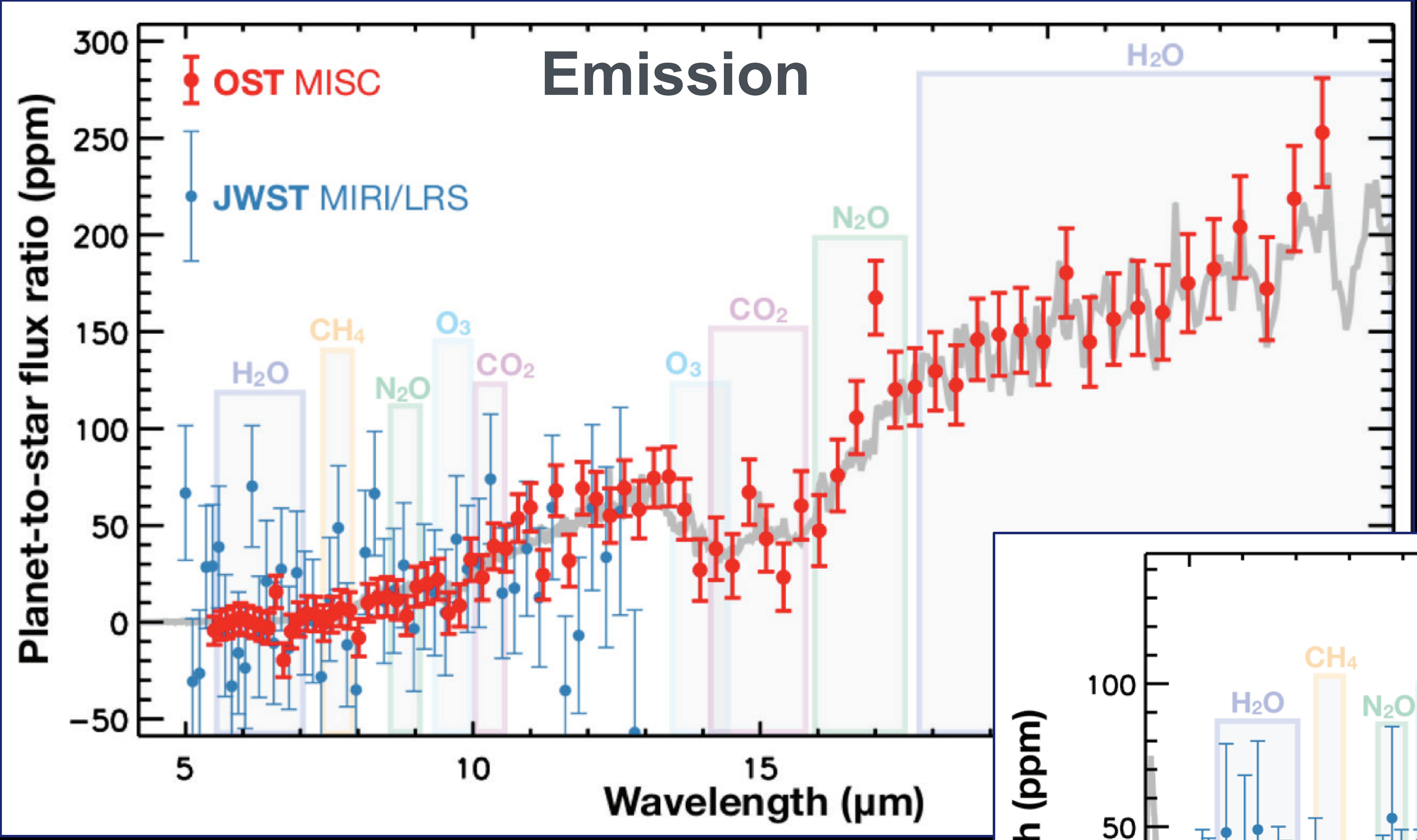


de Wit et al. (2012)

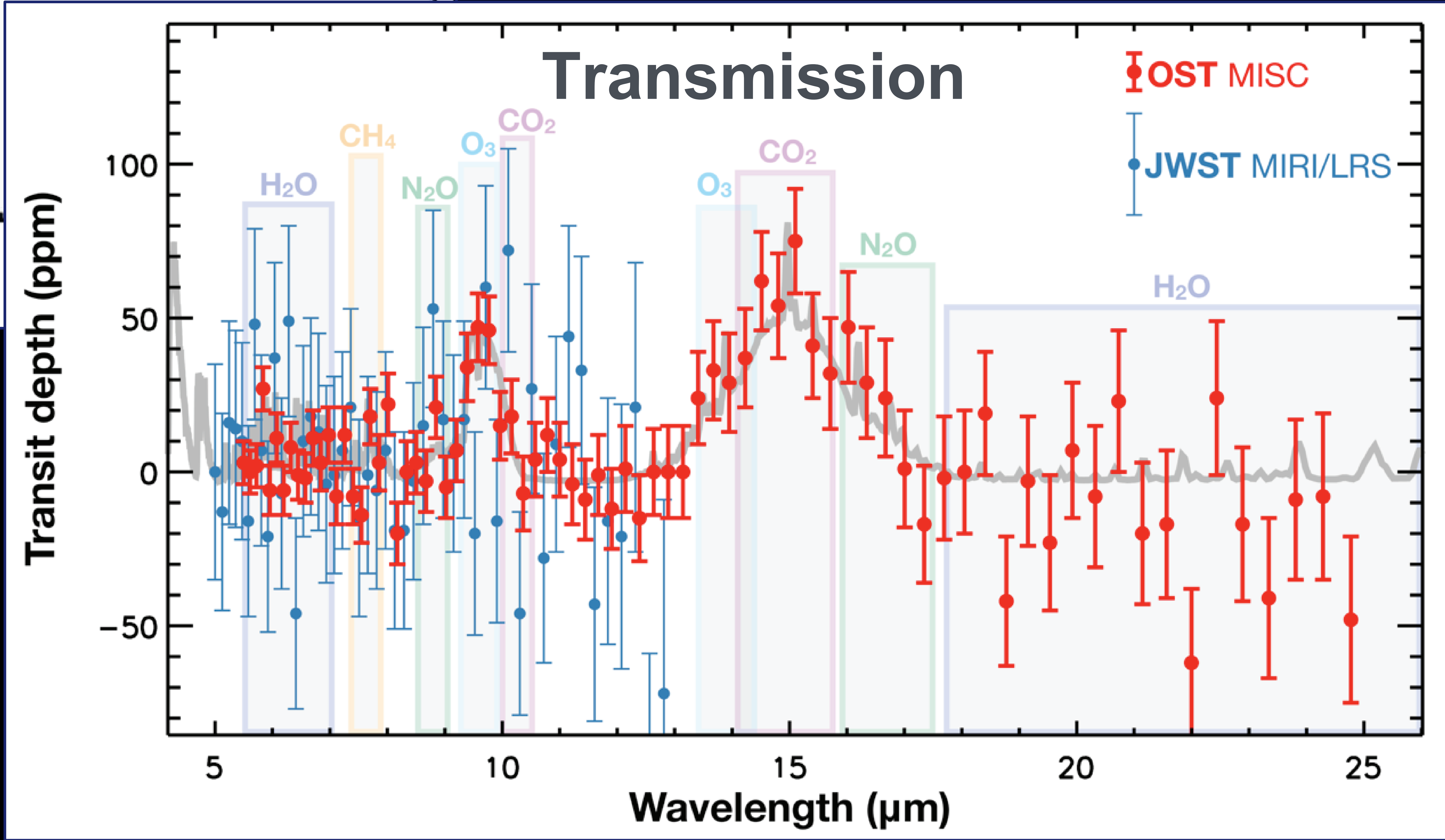
- Spectroscopic eclipse mapping
  - 3D map of planetary dayside
  - Latitudinal information



Majeau et al. (2012)



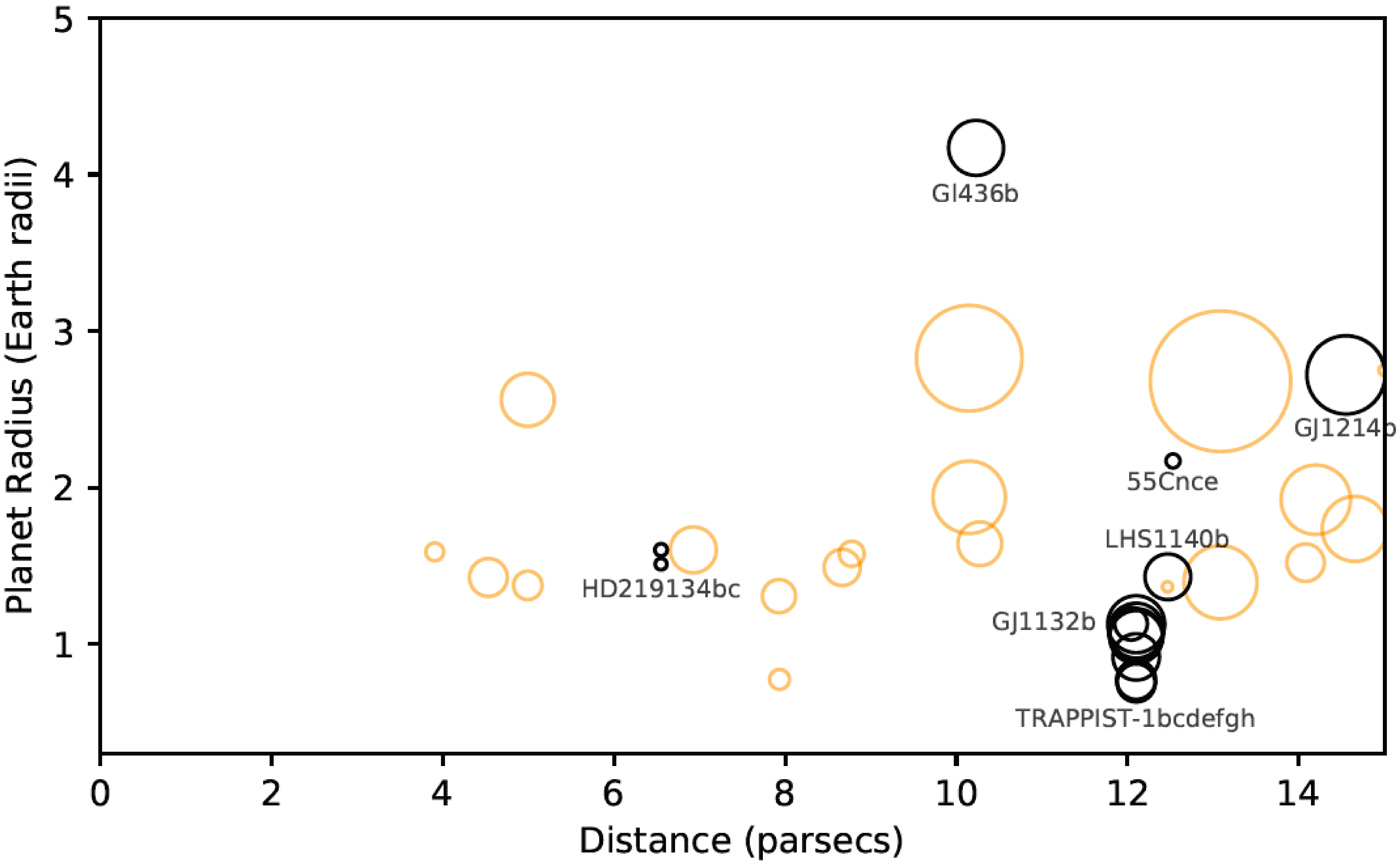
- Model TRAPPIST-1e-*like* emission/transmission spectra with simulated uncertainties
- 30 visits each, K_{mag} = 8
- Optimistic 30 ppm noise floor for MIRI/LRS

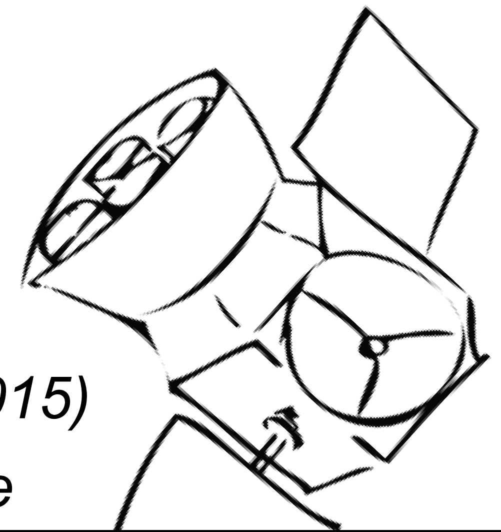


What Are the Targets?

- A variety of techniques have already found < 1.5 R_{Earth} transiting planets around nearby M stars
  - MEarth, TRAPPIST, follow-up of known RV planets
- There are new and favorable prospects in the very near future
  - TESS for early-to-mid M stars
  - SPECULOOS for late M stars

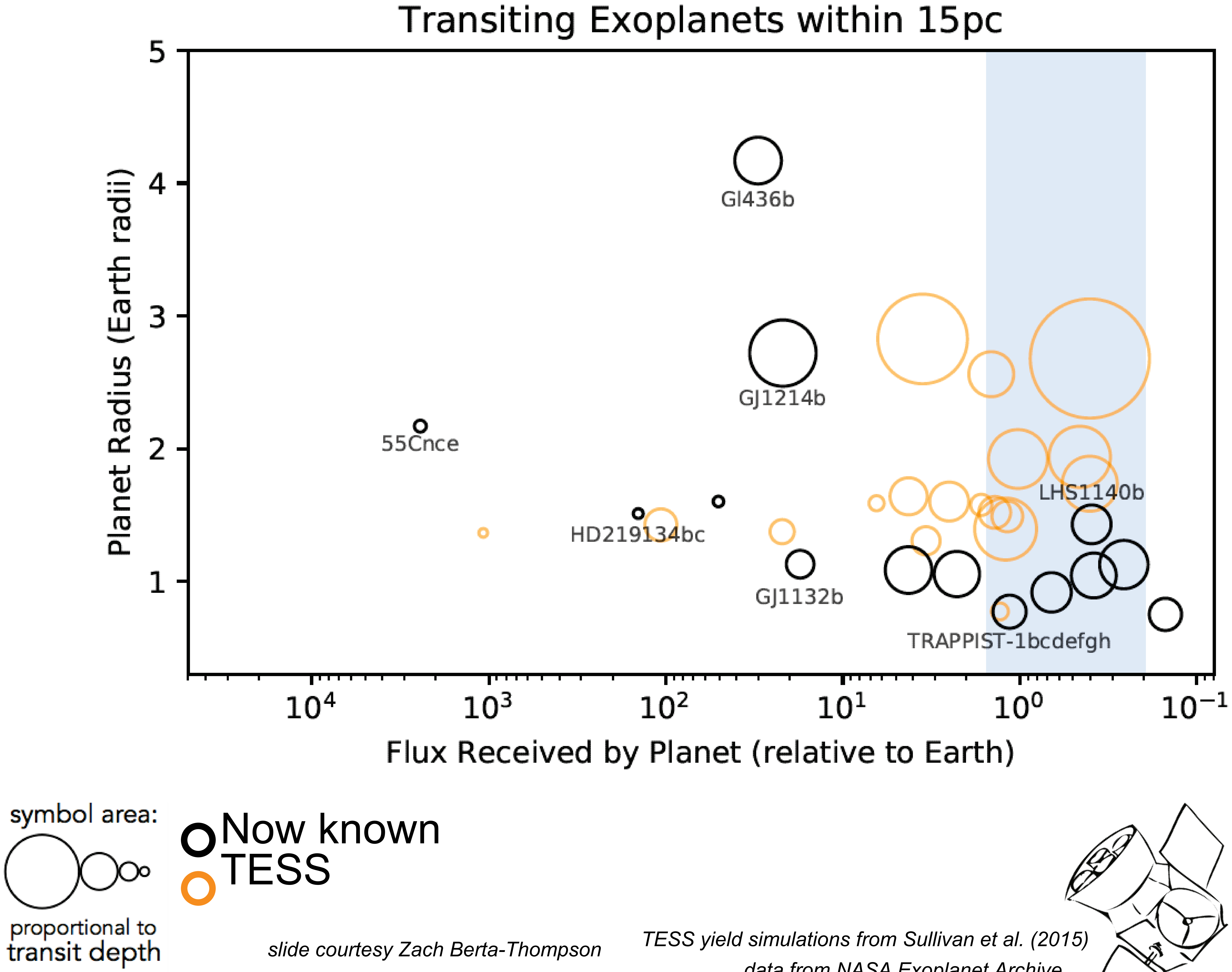
ORIGINS Space Telescope





slide courtesy Zach Berta-Thompson *TESS yield simulations from Sullivan et al. (2015)*

data from NASA Exoplanet Archive



slide courtesy Zach Berta-Thompson

TESS yield simulations from Sullivan et al. (2015)
data from NASA Exoplanet Archive

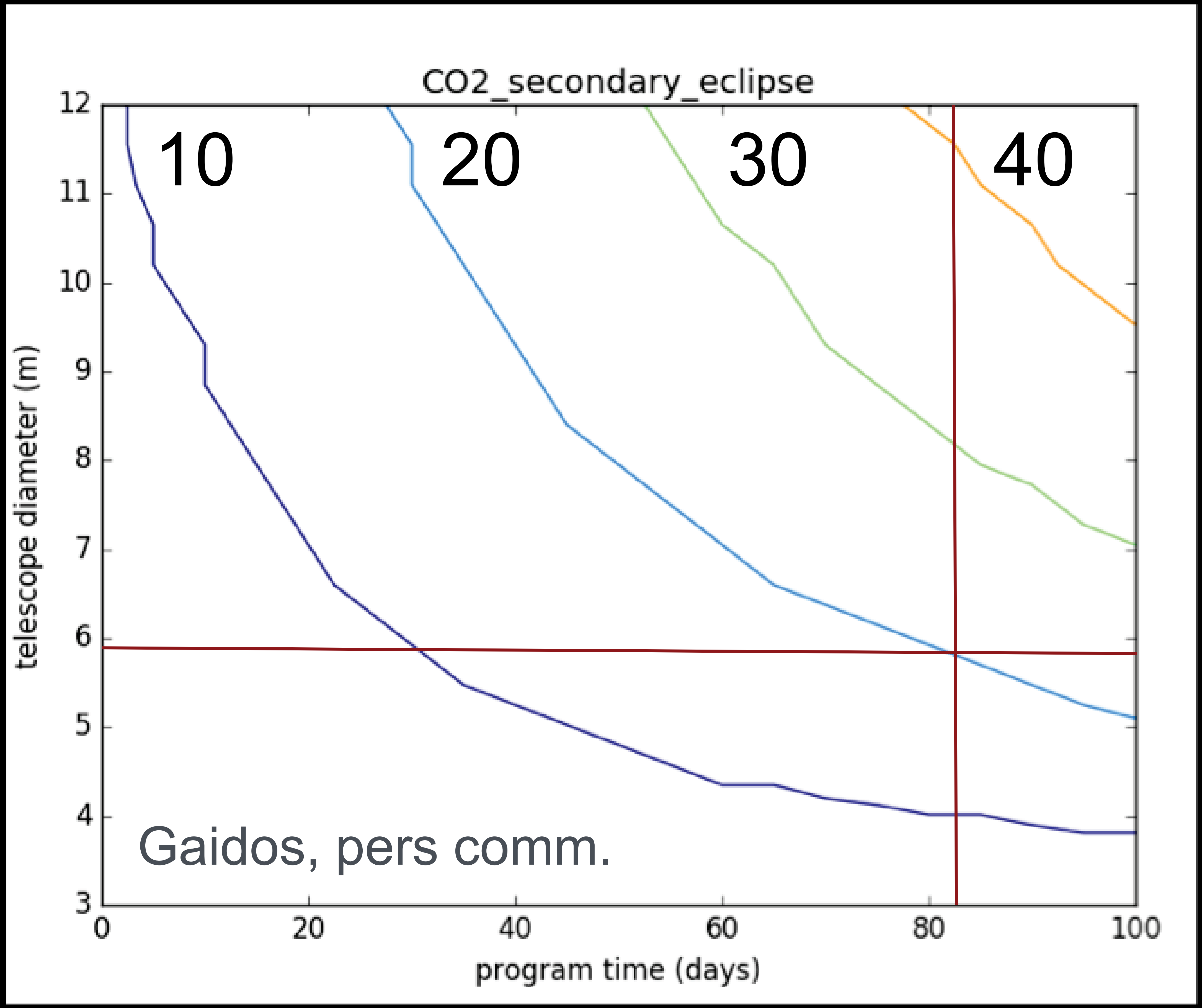
Late M Stars

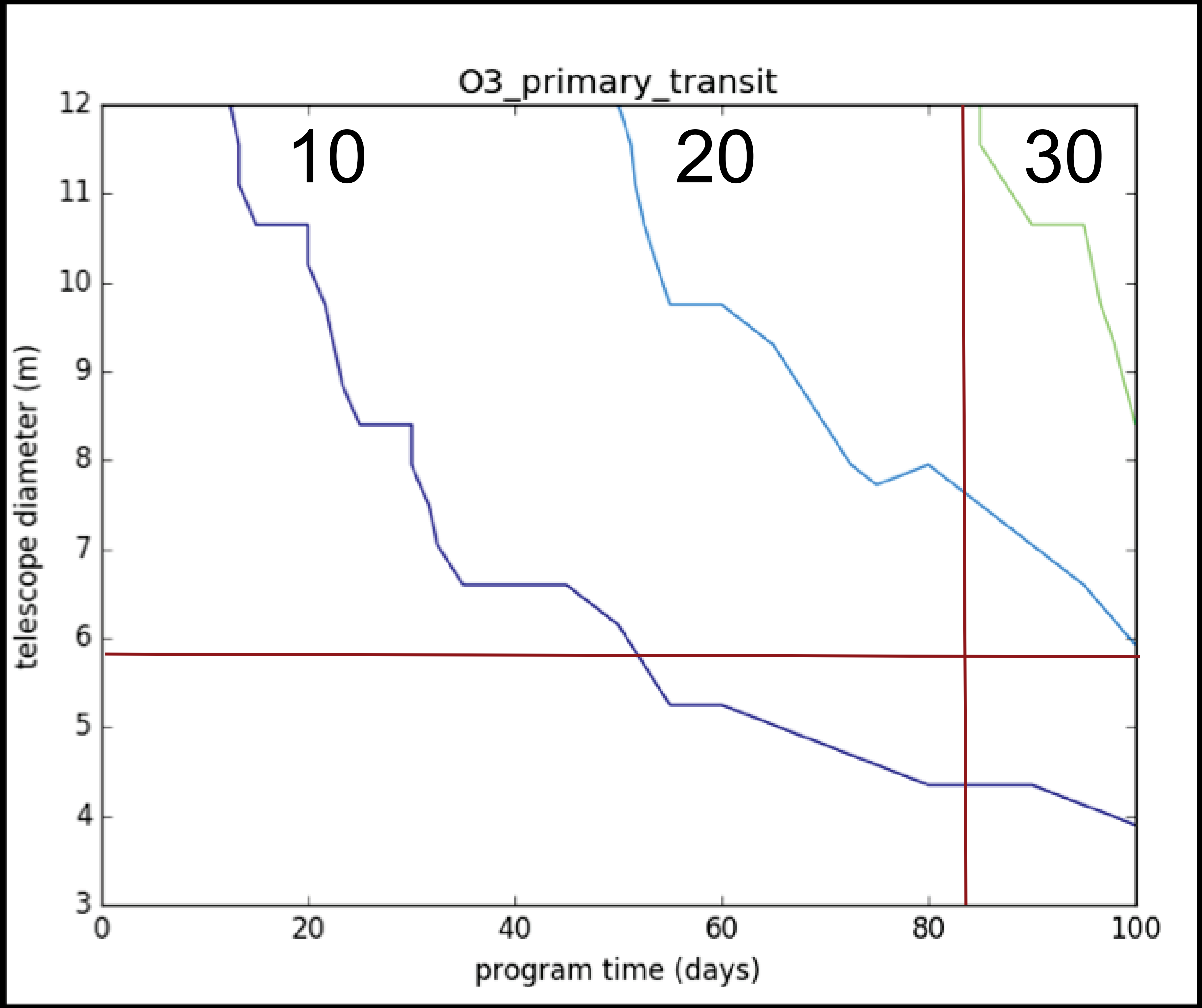
- TESS will have little sensitivity to late M
- 1000-target SPECULOOS observes mostly M7-M9
  - No "yield paper" yet but M. Gillon estimates 1-2 *systems* within 10 pc, 2-5 within 15 pc
- **MEarth+TESS+SPECULOOS+Others yields ~dozen temperate terrestrials around mid/late M**

What Would an OST Exoplanet Survey Look Like?

- Reconnaissance of all suitably-bright targets within 15 pc
- Measure planetary thermal emission
  - Constrain dayside equilibrium temperature
- Further investigations to detect molecular absorption of CO_2 and/or H_2O
  - Determine presence of substantial atmosphere, confirm presence of bio-indicators
  - Disregard planets with tenuous atmospheres
- Perform in-depth study of remaining planets in search for biosignatures
  - O_3/N_2O & CH_4

CO_2 & O_3 Detection Yields

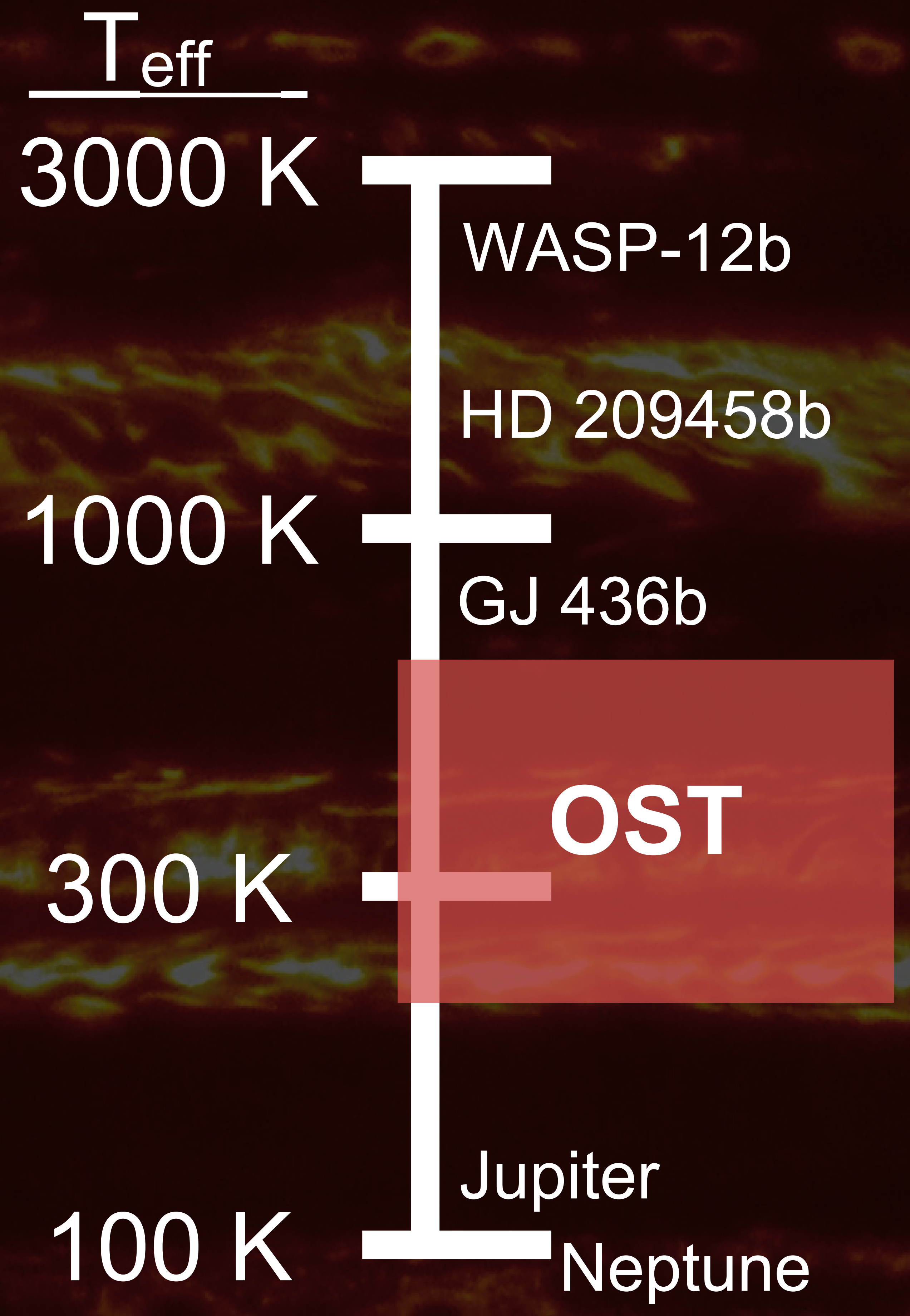




A 5.9 meter OST with 2000 hours could detect CO_2 in ~20 planets and O_3 in ~14 planets

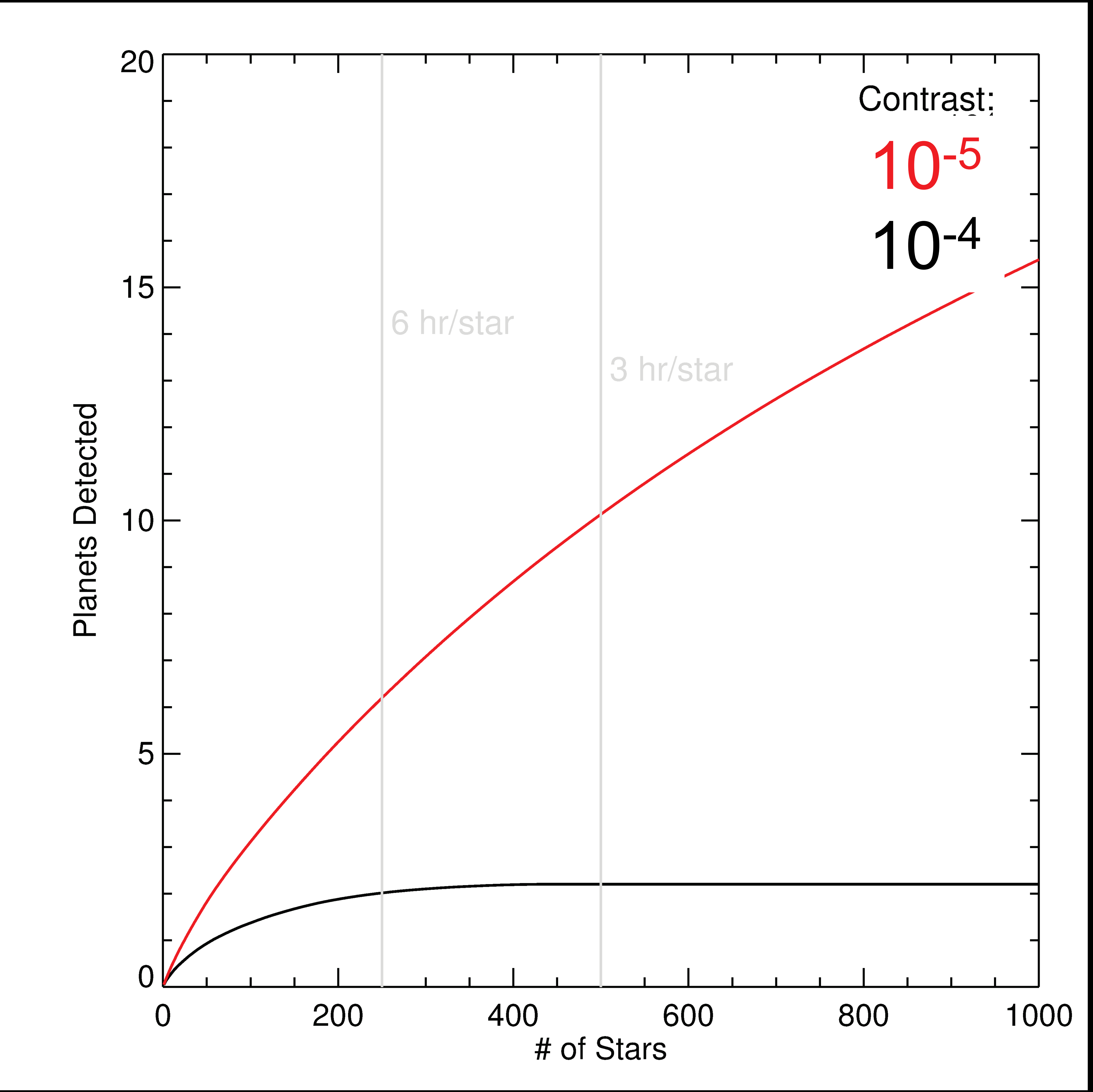
OST Comparative Planetology

- Thermal infrared is excellent for the science of transiting cool Jupiter-class, Neptune-class, and mini-Neptune planets
  - Characterizing atmospheres at closer to solar system temperatures, beyond the reach of JWST
  - CH_4, NH_3, rich photochemistry
- Jupiter and Saturn analogs through time via Coronography



OST Coronagraph

- Motivation
  - Gas giant planet formation and evolution
- Goals
  - Determine occurrence rates of gas giants (down to Saturn masses)
  - Trace planet evolution during first 1 Gyr after formation
- Advantages of thermal emission over reflected light
  - Higher contrast ratio
  - Larger stellar population fraction (~17% vs youngest 1-2%)
- Disadvantage of thermal emission
  - Larger inner working angle



OST SWG activities for 2018

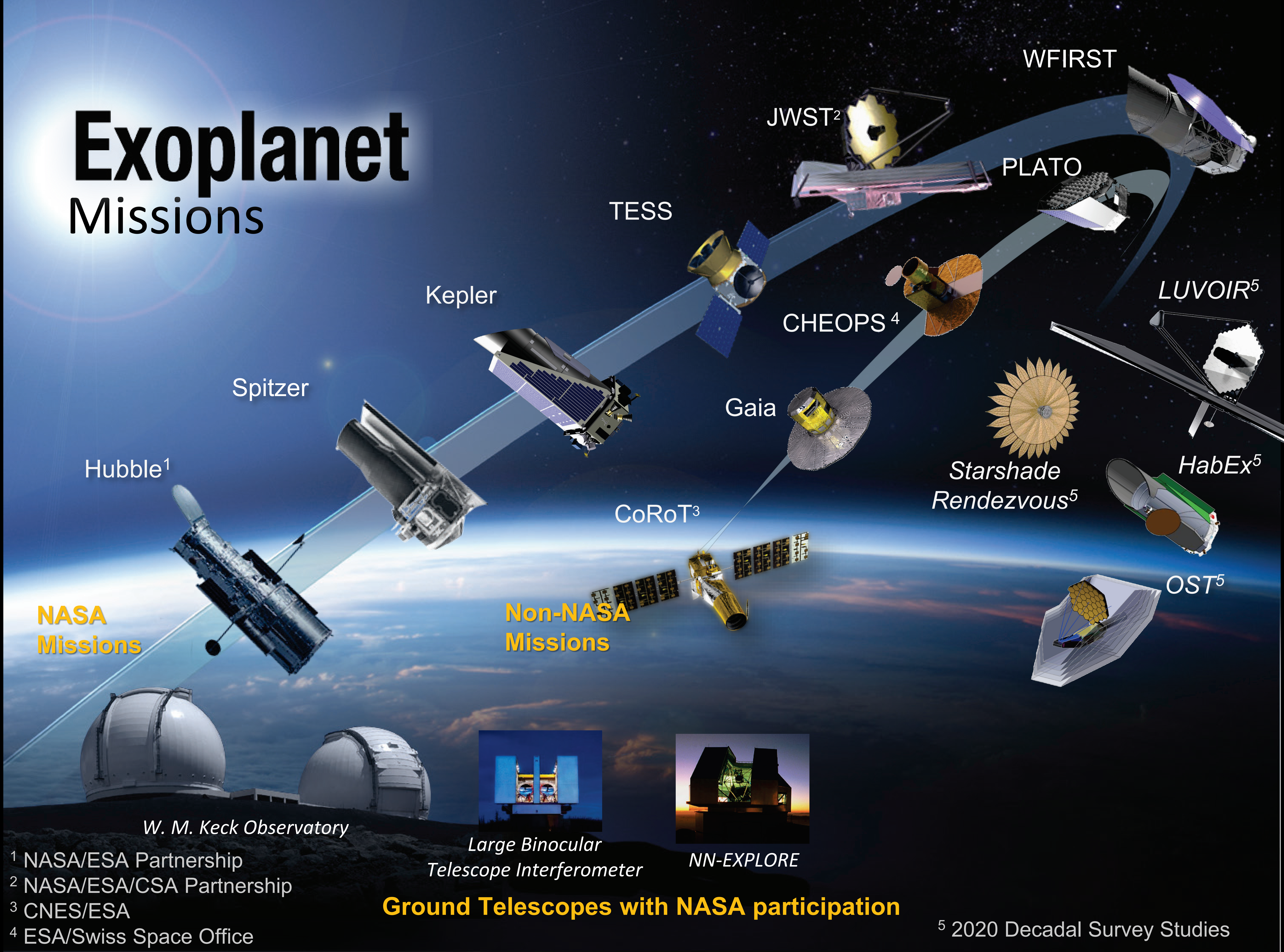
- **Paper 1:** Observing known temperate Earth-sized planets with OST
  – Assuming different atmospheric compositions how many observations are needed for high-S/N molecular detections of temperate rocky planets?
  – Heritage in Morley et al. (2017) paper for JWST

- **Paper 2:** OST Trade-Space Study
  – How well can atmospheric molecular abundances be retrieved for an ensemble of M-dwarf HZ planets as a function of star/planet properties (e.g., stellar mag, planet type)?
  – Will aid in tracing science objectives to MISC technical requirements
  – Heritage in Chapman et al. & Zellem et al. (2017) FINESSE studies

- Engagement with community and other flagship mission studies
  – Joint workshop? White papers? We want your input!

Conclusions

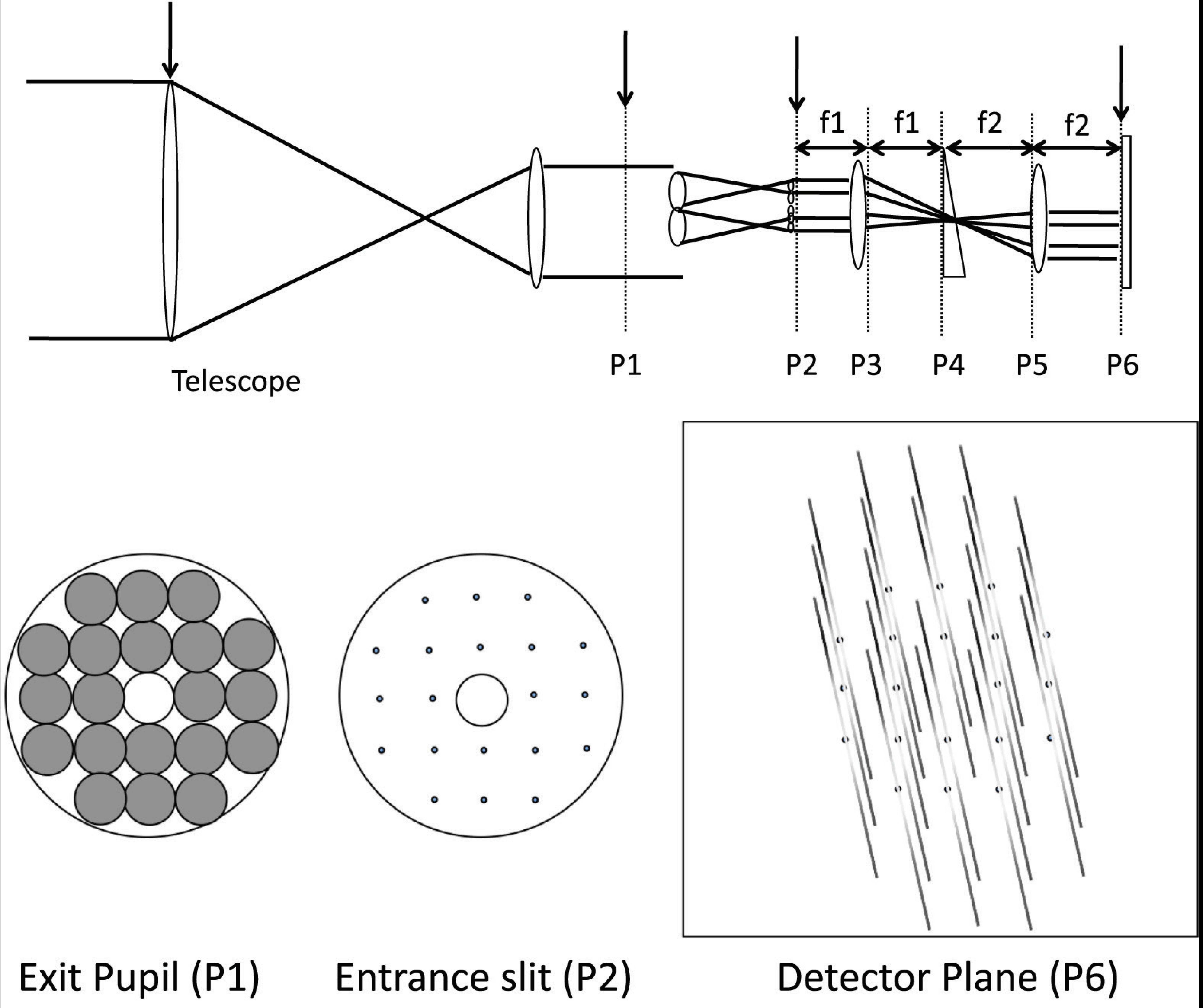
- The Atmospheres of Transiting Temperate Terrestrial Planets can be Characterized with OST
  – Transits provide known targets with known masses and radii
  – Wide thermal IR wavelength range:
    – Includes many important molecules, such as O_3, CH_4, H_2O, CO_2
    – Enables determination of temperature structure in pressure, longitude, and latitude
– OST disk science informs planet formation and initial conditions
– OST Exoplanet Science is Complementary to Other Large Missions



Exoplanet
Missions
WFIRST
JWST2
PLATO
TESS
Kepler
CHEOPS 4
LUVOIR5
Spitzer
Gaia
Hubble1
Starshade
Rendezvous5
HabEx5
CoRoT3
OST5
NASA
Missions
Non-NASA
Missions
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
Ground Telescopes with NASA participation
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
4 ESA/Swiss Space Office
5 2020 Decadal Survey Studies

Extras

MISC Imager and Spectrometer Module



Schematic for densified pupil transit spectrometer

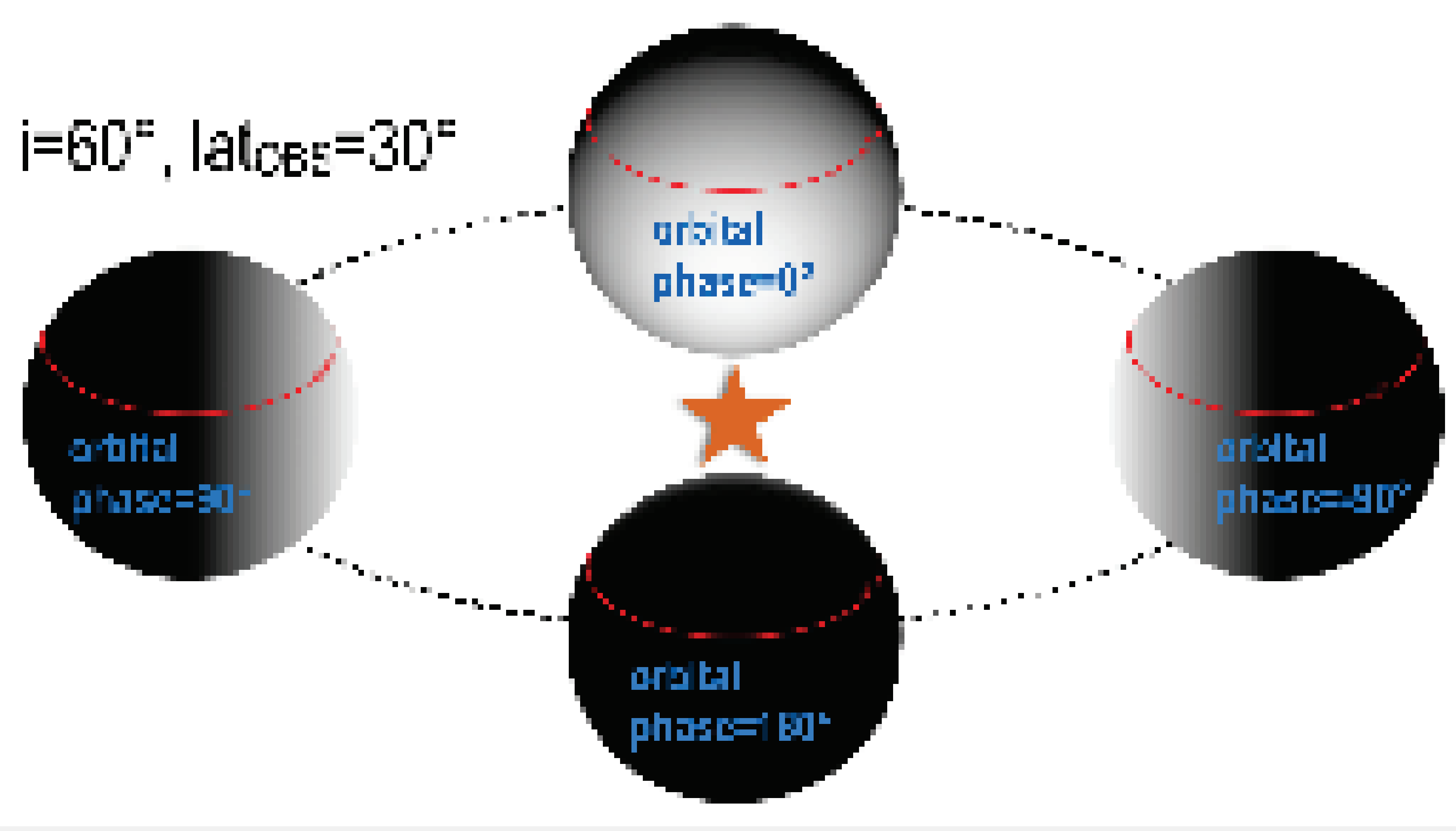
MISC Coronagraph Module

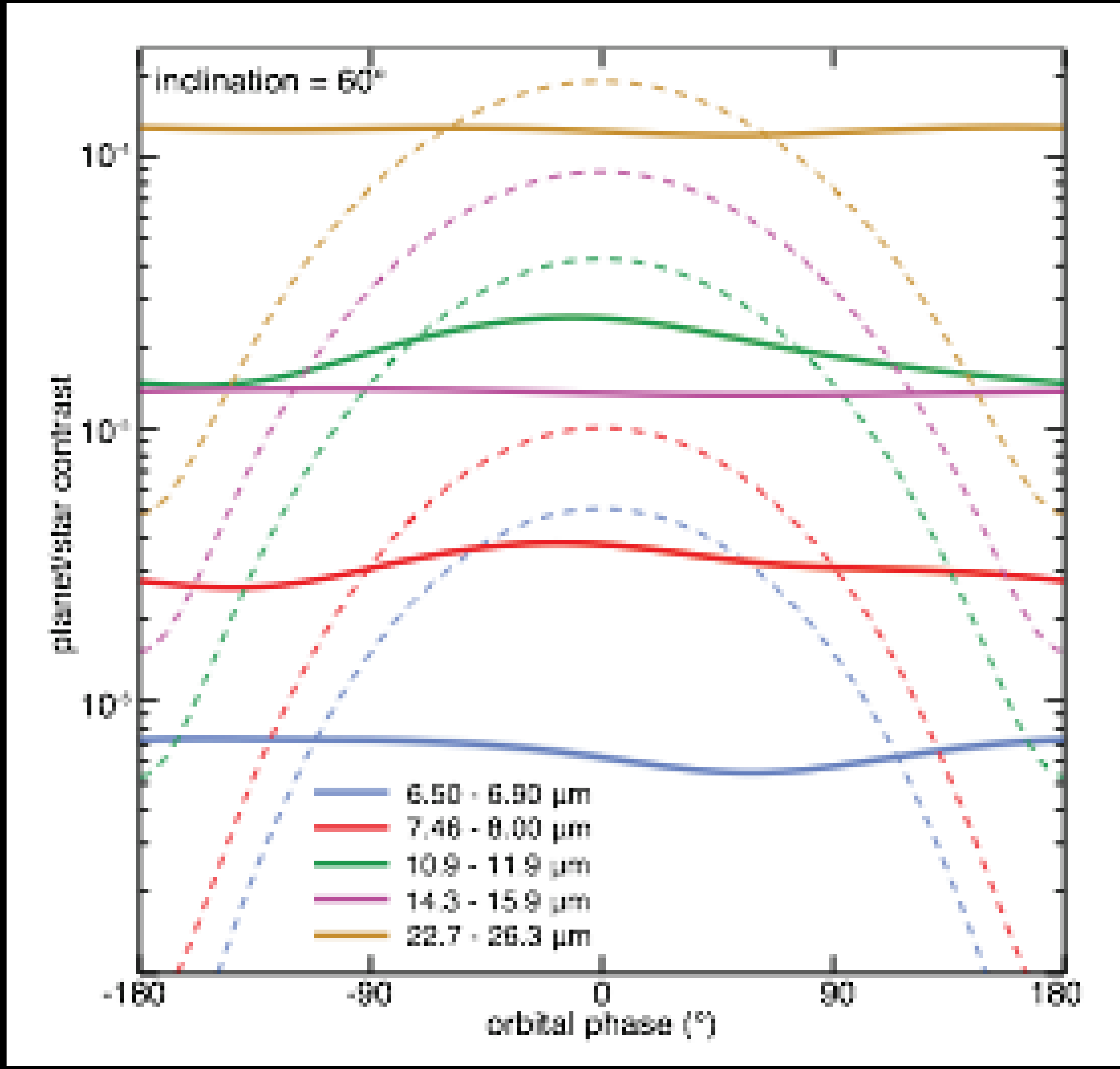
MISC Transit Spectrometer Module

Module	Mid-IR Imager Spectrometer Channel			Transit Channel	Coronagraph Channel
	Imager/Low-Res Spec.	Medium-Res Spec.	High-Res Spec.	(Densified Pupil Spec.)	(PIAACMC)
	WFI-S/-L	MRS-S/-M/-L	HRS-S/-L	TRA-S/-M/-L	COR-S/-L
Bandpass (μm)	6-38	5-36	12-18, 25-38	5--26	6-38
Spectral Resolution	5-10 [Imager] 300 [Low-Res Spec.]	1000-1500	20,000-30,000	>100 (TRA-S, TRA-M) 300 (TRA-L)	300
Full FOV	3 arcmin x 3 arcmin [Imager]	3 arcsec x 5 arcsec [with IFU]		3 arcsec x 3 arcsec	5.5 arcsec x 5.5 arcsec
Slit for Spectroscopy	Length; 3 arcmin Width; 0.26 arcsec (WFI-SG1) 0.40 arcsec (WFI-SG2) 0.65 arcsec (WFI-LG1) 1.00 arcsec (WFI-LG2) [low-resolution Spec.]	Length; 3 arcsec (MRS-S/ MRS-M/MRS-L) Width; 0.33 arcsec (MRS-S) 0.55 arcsec (MRS-M) 1.0 arcsec (MRS-L) Mum of Slices; 11 (MRS-S) 9 (MRS-M), 5 (MRS-L)	Length; 1.0 arcsec (HRS-S) 2.0 arcsec (HRS-L) Width; 0.5 arcsec (HRS-S) 1.0 arcsec (HRS-L)		Length; 1 arcmin Width; 0.26 arcsec (COR-SG1) 0.40 arcsec (COR-SG2) 0.65 arcsec (COR-LG1) 1.00 arcsec (COR-LG2)
Detectors	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:As (30um/pix) [M] 1kx1k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 1kx1k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:As (30μm/pix) [M] 2kx2k Si:As (30um/pix) [L]	2kx2k Si:As (30μm/pix) [S] 1kx1k Si:Sb (18μm/pix) [L]
pixel scale	0.088 arcsec/pix	0.0615 arcsec/pix (MRS-S) 0.10 arcsec/pix (MRS-M) 0.15 arcsec/pix (MRS-L)	0.17 arcsec/pix [S] 0.34 arcsec/pix [L]	0.1 arcsec/pix	0.05 arcsec/pix (COR-S) 0.10 arcsec/pix (COR-L)
Specification (Sensitivity/ Stability/ Contrast)	**Sensitivity [Imager] ;** *1-hour 5σ Continuum Sens . for a Point Source* 0.027μJy@5μm, 0.16μJy@10μm, 0.26μJy@15μm, 0.37μJy@20μm, 0.55μJy@25μm, 0.63μJy@30μm, 0.7μJy@35μm **Sensitivity [Low-Res Spec.];** *1-hour 5s Continuum Sens. for a Point Source* (R=300) 0.6μJy@5μm, 1.3μJy@10μm, 4.0μJy@15μm, 5.0μJy@20μm, 8.8μJy@25μm, 11.2μJy@30μm, 37.5μJy@35μm	**Sensitivity;** *1-hour 5s Continuum Sens. for a Point Source (R~1200)* 3μJy@7μm, 10μJy@15μm, 30μJy@24μm,100μJy@32μm 1-hour 5s Line Sens. for a Point Source $1x10^{-21}$ W/m² @7μm, $2x10^{-21}$ W/m² @15μm, $3x10^{-21}$ W/m² @24μm, $1x10^{-20}$ W/m² @32μm	**Sensitivity;** 1-hour 5s Line Sens. for a Point Source $1x10^{-21}$ W/m² @15μm, $3x10^{-21}$ W/m² @30μm	**Photometric stability;** better than 10 ppm on timescales of hours to days (excluding the fluctuation of detector gain)	**Average contrast;** $7x10^{-6}$ for 10% band $1x10^{-6}$ for 4% band in 0.88-3.6λ/D

Thermal phase curves of non-transiting planets can constrain composition, inclination.

Proxima Centauri b





Turbet+2016