MIRECLE:
Mid-IR Exoplanet CLimate Explorer

2023 Sagan Summer Workshop – July 28, 2023

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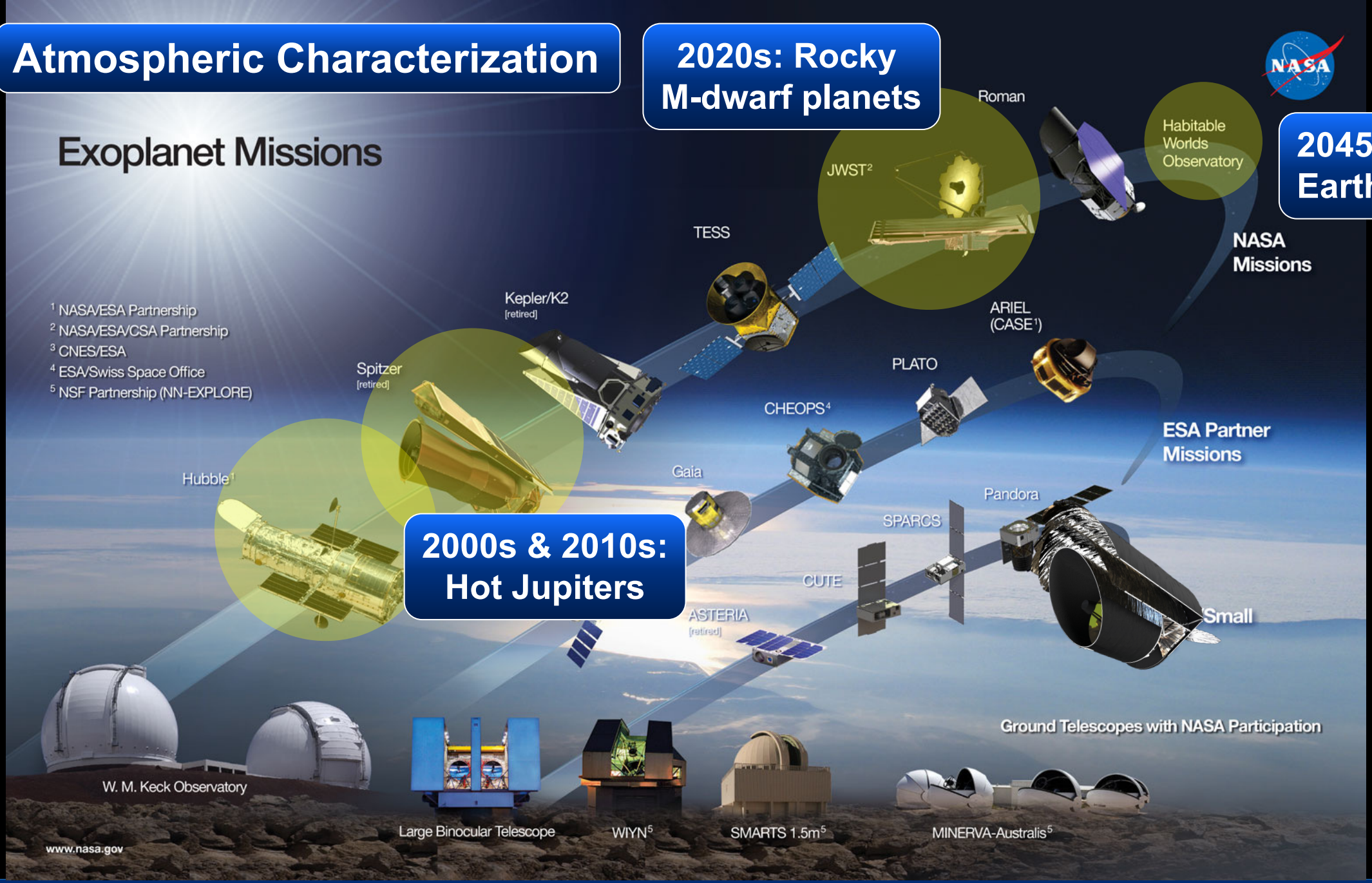
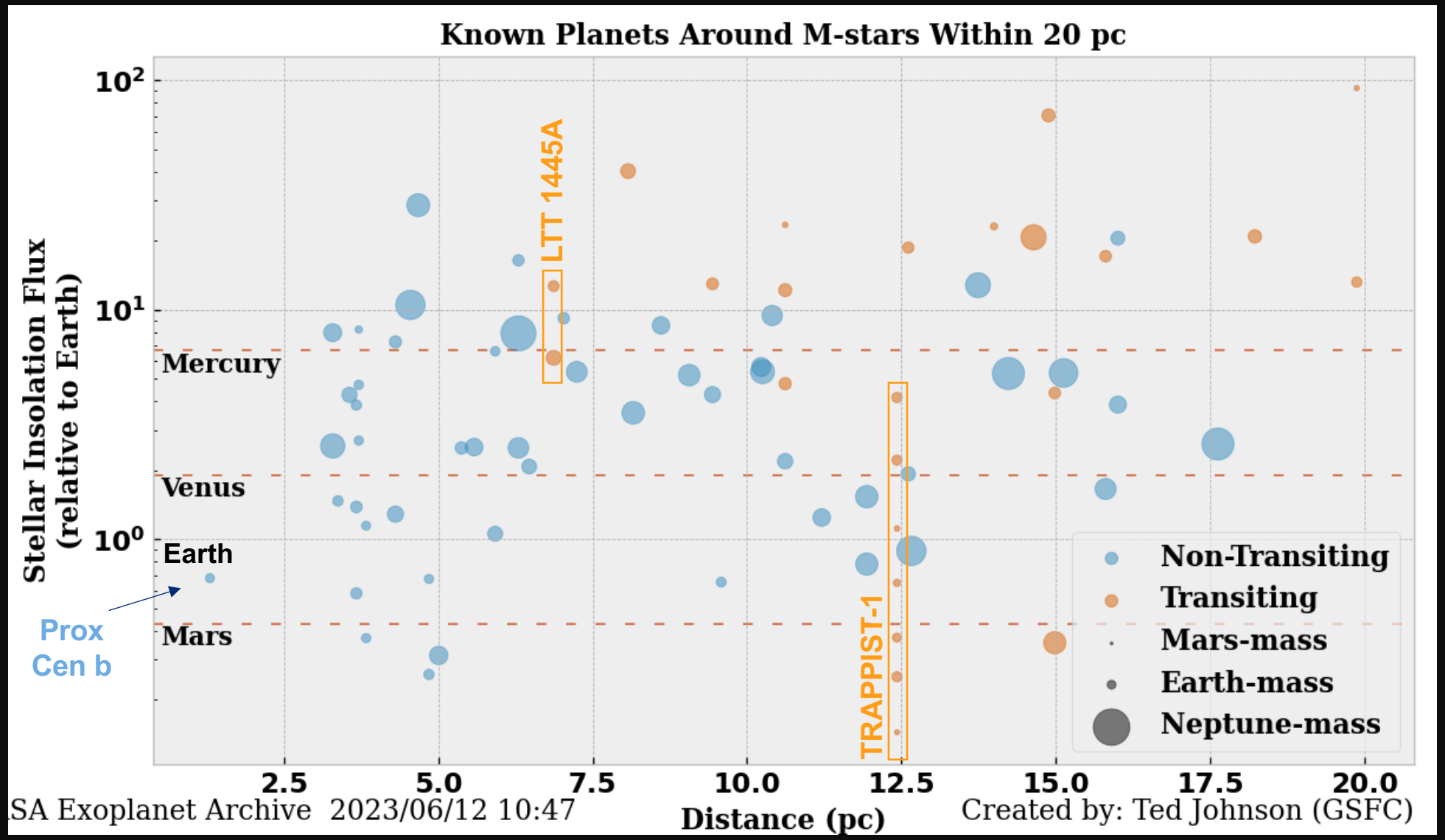
Atmospheric Characterization



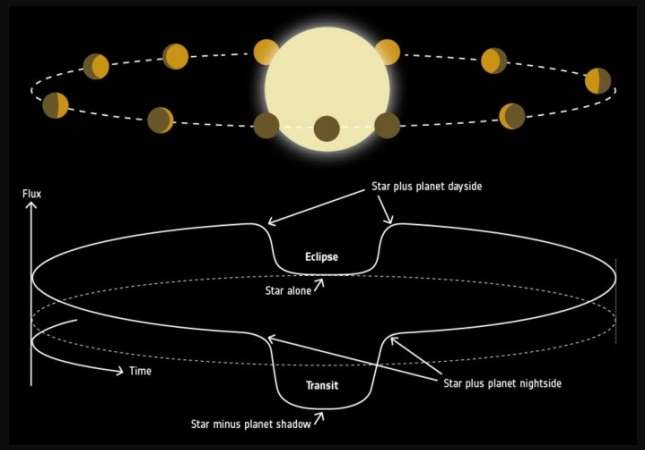
28 Nearest, Known Exoplanets are Non-Transiting

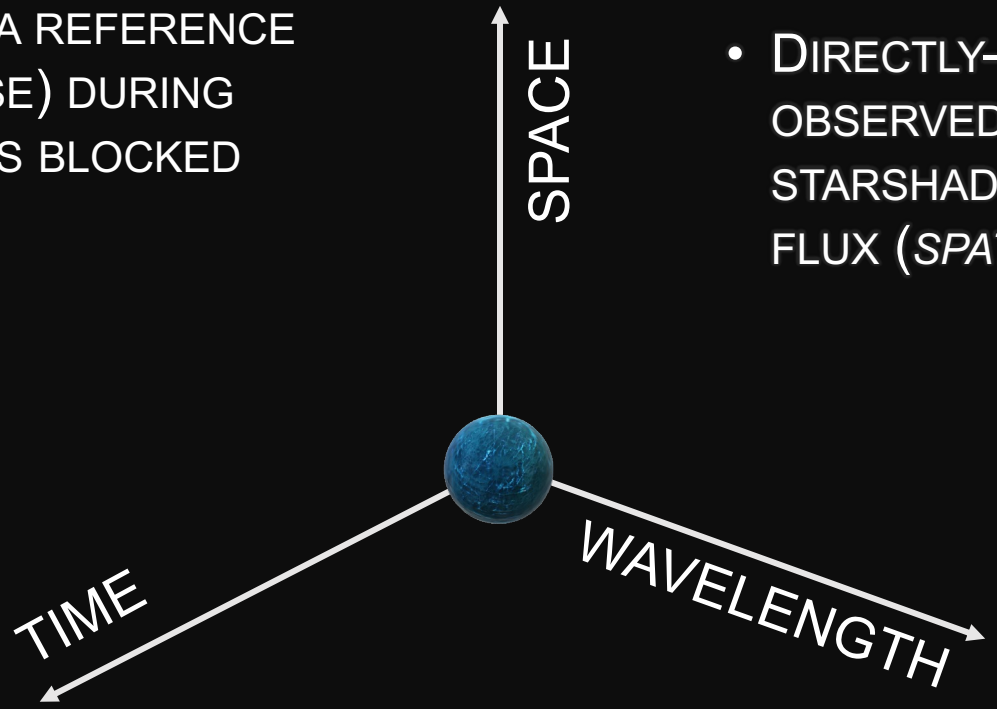


How Astronomers Resolve Bodies Within the Universe

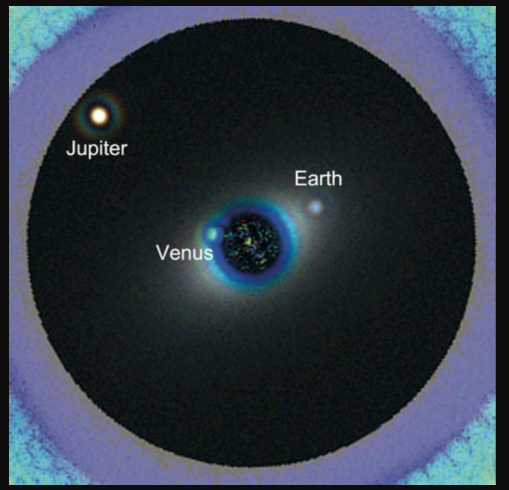
(and how it applies to exoplanet characterization)

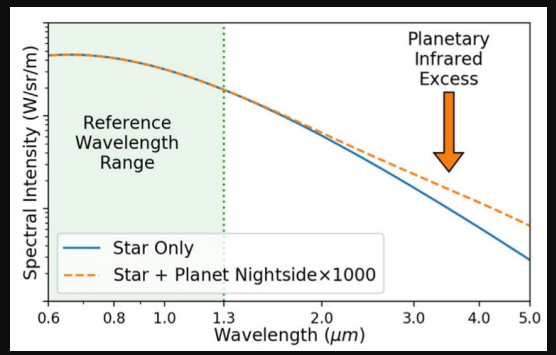
- TRANSITING PLANETS HAVE A REFERENCE IN TIME (SECONDARY ECLIPSE) DURING WHICH THE PLANET'S FLUX IS BLOCKED (*TEMPORALLY RESOLVED*)





- DIRECTLY-IMAGED EXOPLANETS MUST BE OBSERVED WITH A CORONAGRAPH OR STARSHADE TO OBSERVE THE PLANET FLUX (*SPATIALLY RESOLVED*)



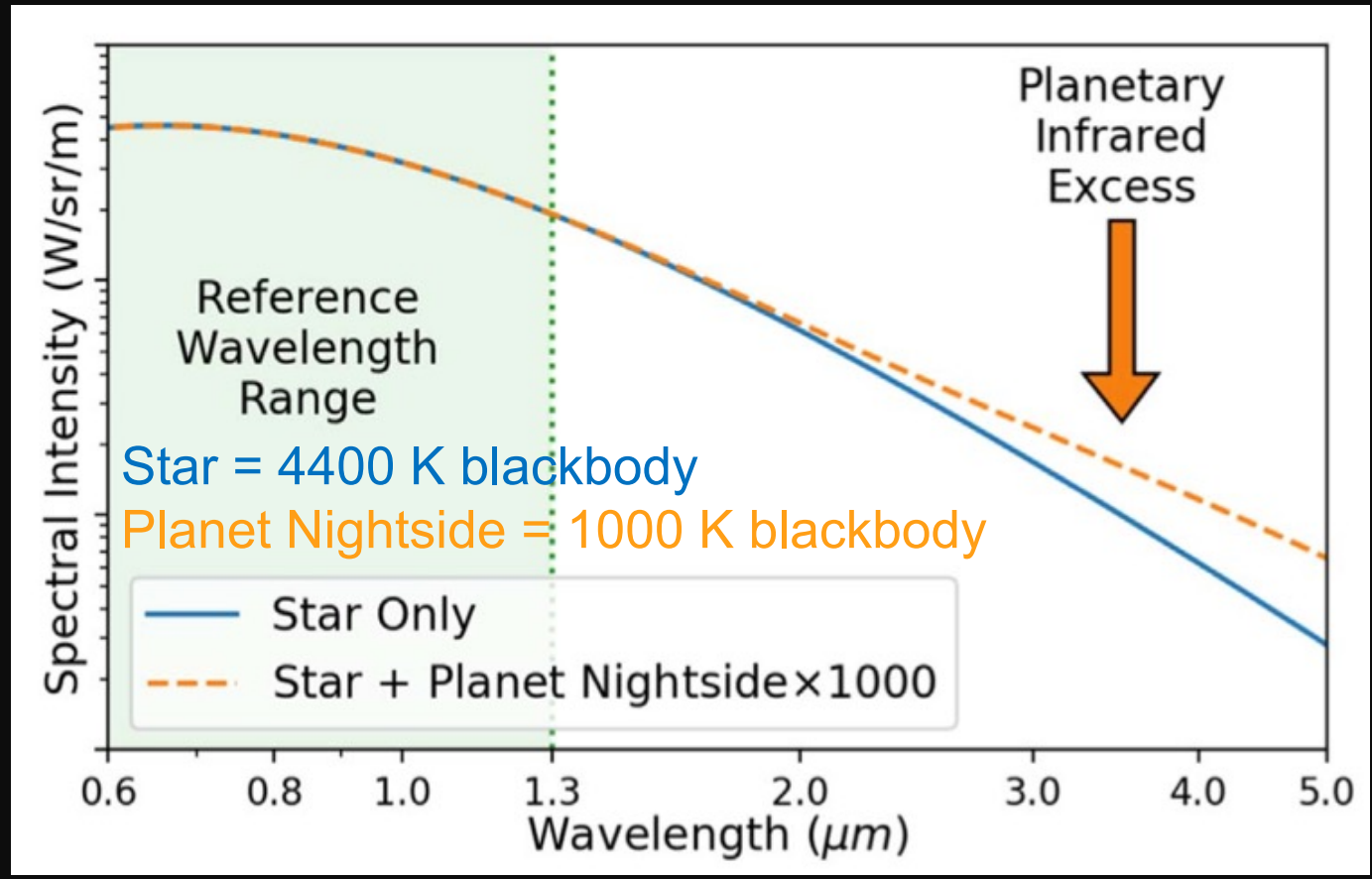


- STEVENSON (2020) PROPOSED THAT SUFFICIENTLY BROAD WAVELENGTH COVERAGE WILL ALLOW THE PLANET AND STAR TO BE *SPECTROSCOPICALLY RESOLVED*

First Slice of PIE

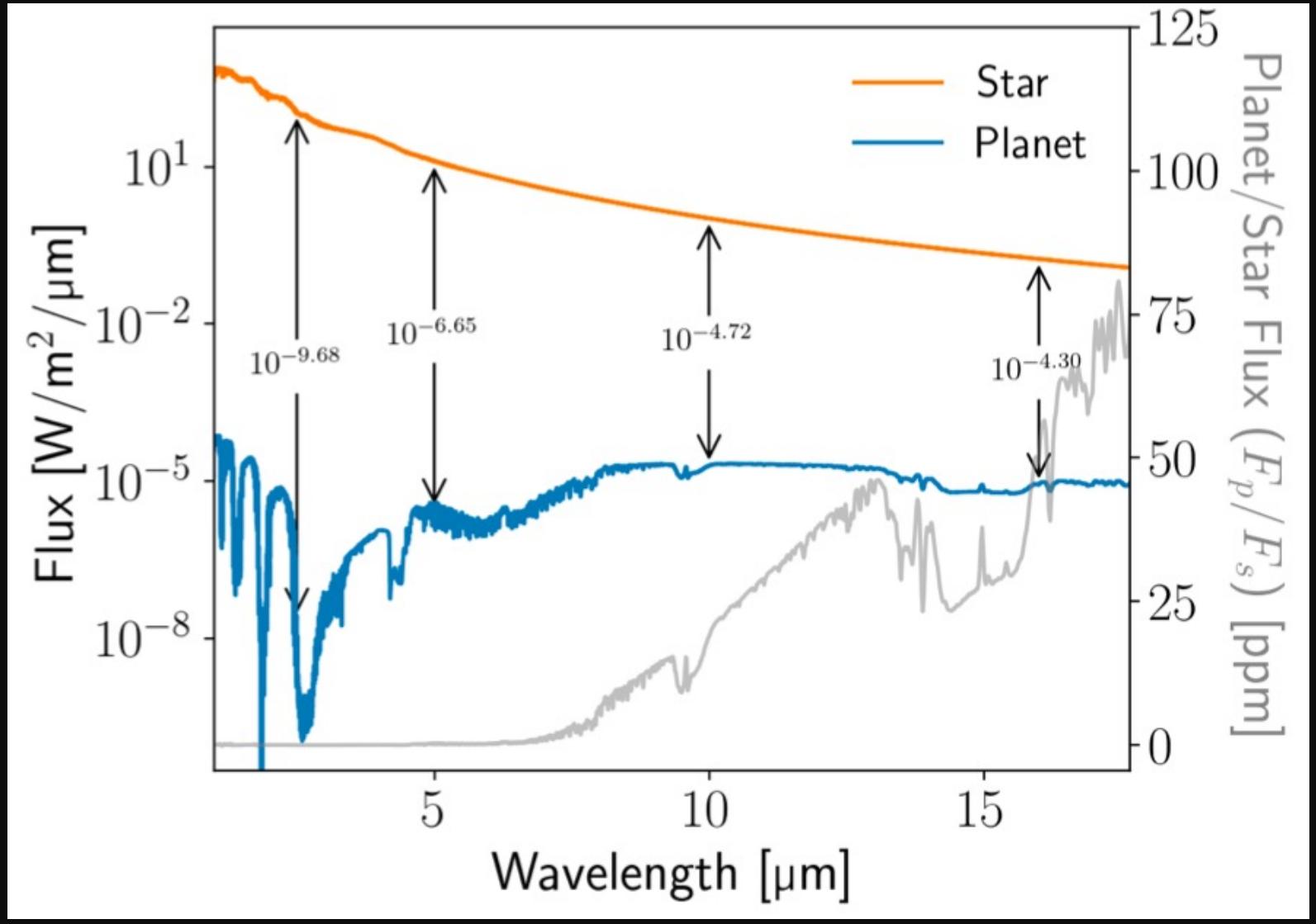
- Planetary Infrared Excess (PIE)
  - New observational and analysis technique
  - Meant for characterizing the atmospheres of both transiting and non-transiting exoplanets
  - Works best with simultaneous, broad-wavelength IR spectra
  - Capture the short-wavelength (Wien) side a planet's blackbody and peak emission

- Conceptualization
  - Similar to detecting circumstellar disks or performing 2-SED fit of binary stars
  - Use reference point in wavelength to constrain stellar spectrum
  - Extrapolate best-fit stellar model to longer wavelengths
  - Inferred infrared excess originates from planet

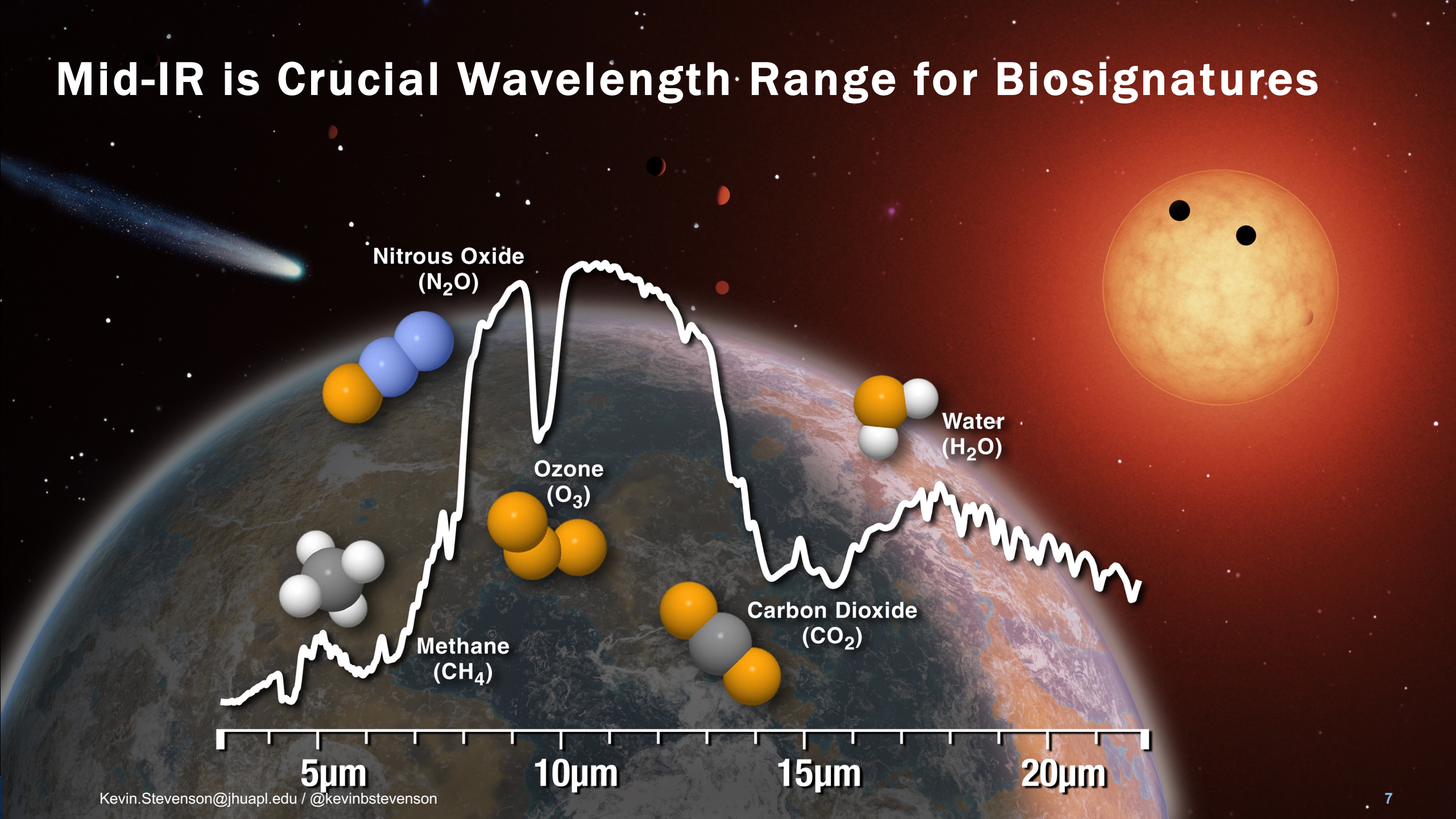


- Stevenson, K. B., ApJL, 898, L35 (2020); arxiv:2007.11438
- Lustig-Yaeger et al., ApJL, 921, L4 (2021); arxiv:2110.02247
- Mandell et al., AJ, 164, 176 (2022); arxiv:2207.13727
- Mayorga et al., (Submitted)

Planet & Stellar Flux of Prox Cen



Mid-IR is Crucial Wavelength Range for Biosignatures



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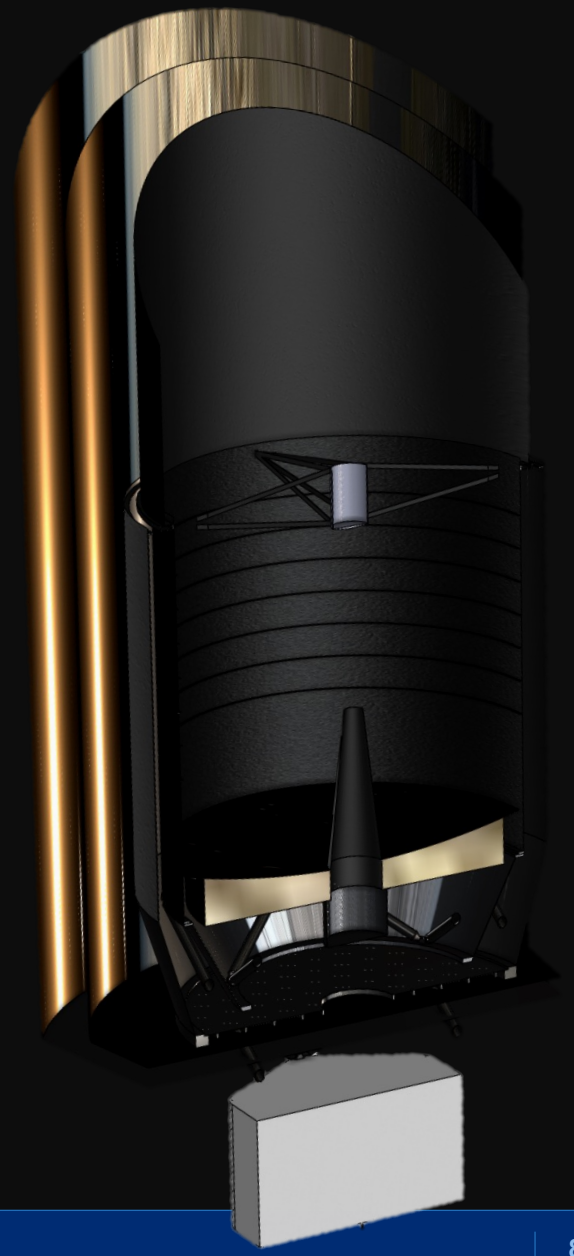
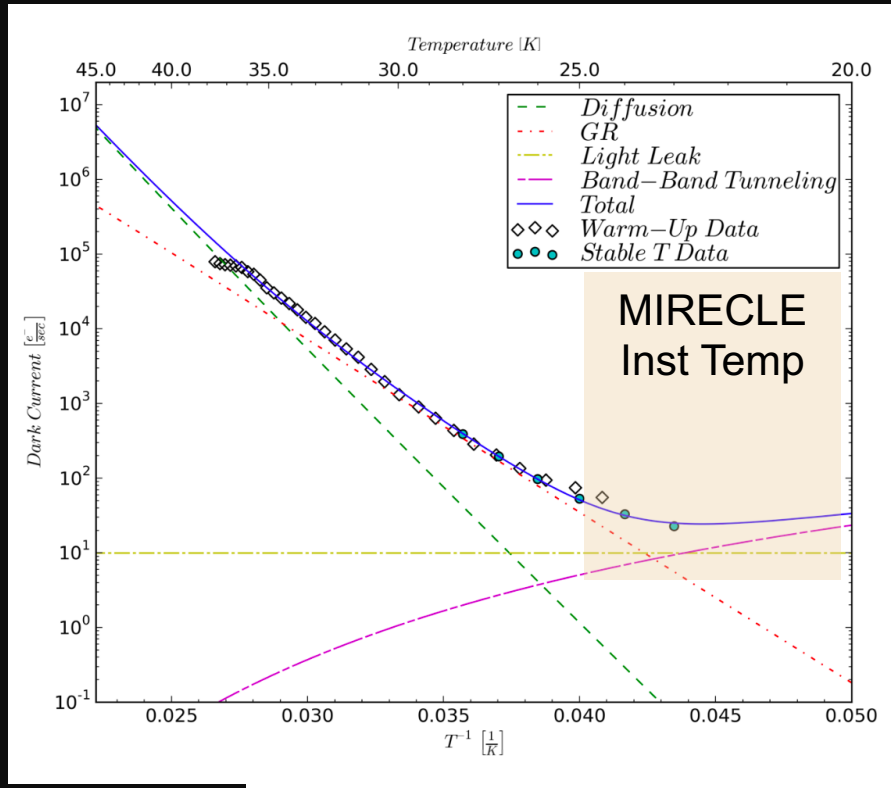
The MIRECLE Observatory Concept

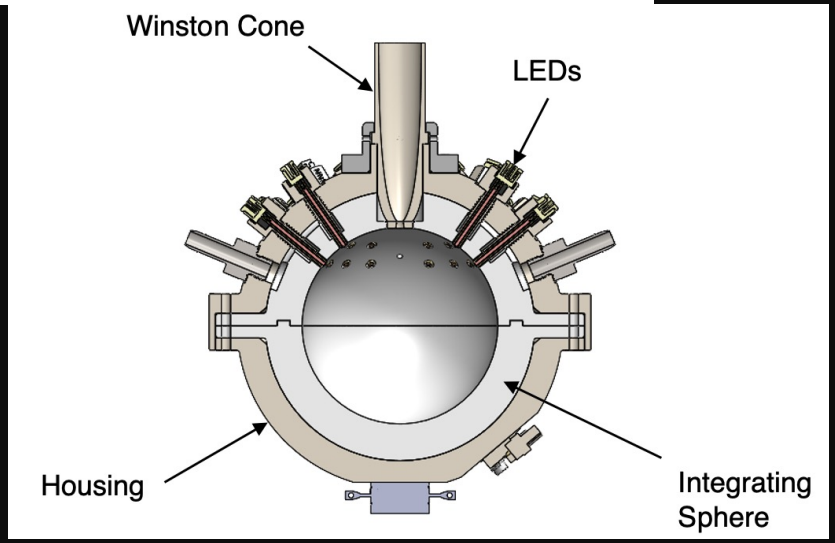
- Fully Aluminum ~2m telescope operating at L2, cooled to 35K
  - Heritage from JWST and ARIEL
- Instrument:
  - MIR spectrometer
  - Simultaneous spectral coverage from 2 - 17 μm
  - On-board reference calibration system
  - Achieve time-averaged flux noise floor of **≤ 5** ppm (after post-processing)
- Mission Duration:
  - 1 year baseline, 2 - 4 year goal
- NASA Mid-Explorer opportunity



Key Instrument Improvements

- New Teledyne detector:
  - VLW-doped H1RG array
  - Extension of NEO Surveyor arrays
  - High-TRL, relatively low noise and high sensitivity demonstrated to 17 μm (Cabrera et al. 2019)
- ASIC and Calibration:
  - New detector read-out and calibration system from Roman Space Telescope
  - ACADIA ASIC improves read-out stability and drastically diminishes 1/f noise (especially with good temperature control)
  - WFI Simplified Relative Calibration System (sRCS) uses on-board integrating sphere to provide continual reference spectrum for updating calibration





MIRECLE Science Goals

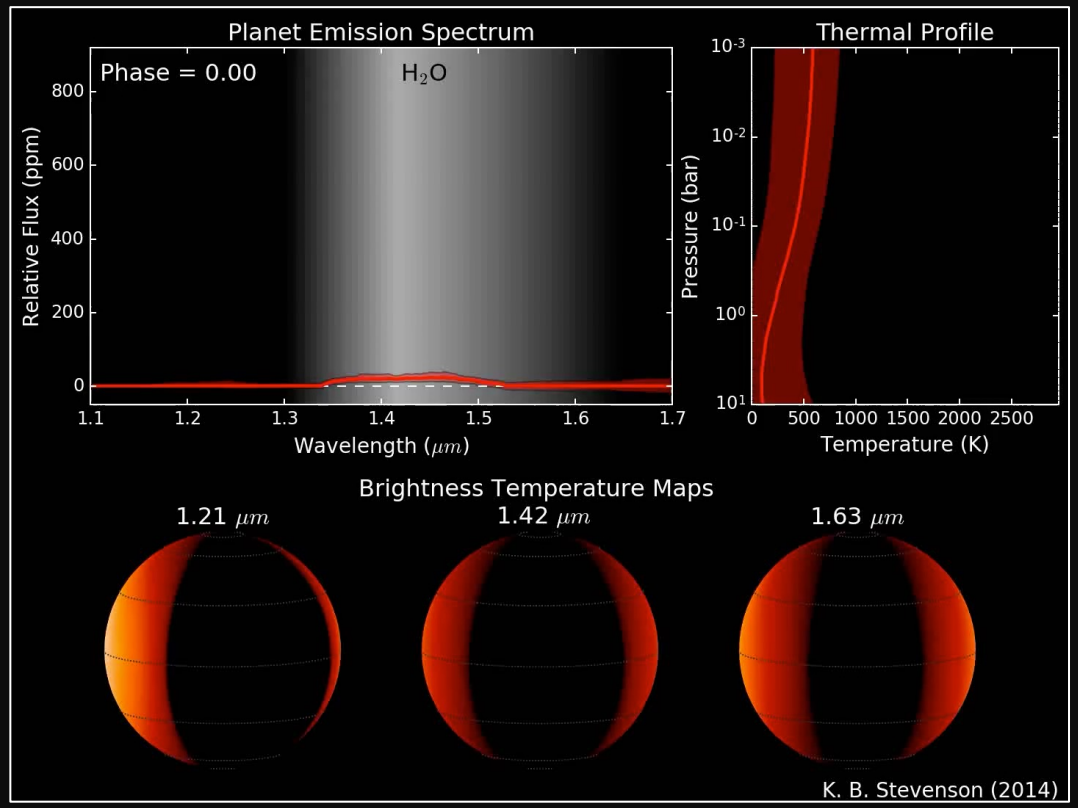
- Detect and characterize non-transiting rocky exoplanets orbiting the nearest M dwarfs
- Study host-star atmospheres and variability
- Constrain planet radius, temperature, and/or atmospheric composition of HZ planets

Observation Strategies:

1. Integrate over time to produce an average emission measurement to gather bulk diagnostics, or

2. Produce a time-resolved phase curve to explore day/night conditions

Thermal phase curve of the hot Jupiter WASP-43 b, based on data from HST/WFC3 (Stevenson et al. 2014)



MIRECLE Emission Survey Target Sample

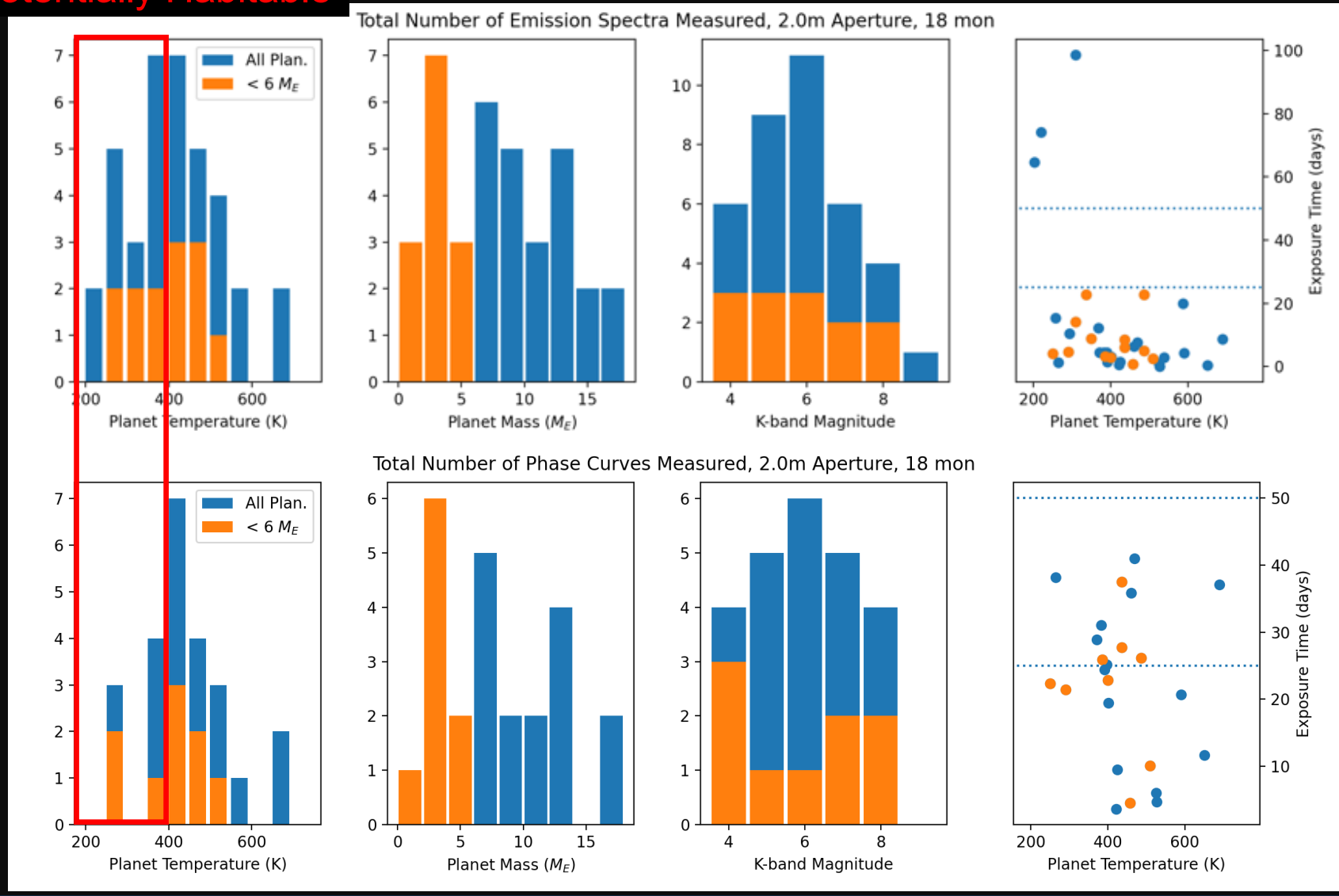
Potentially Habitable

Mission Scenario #1:
Integrated Emission Survey

- **37** planets surveyed with a 2-m aperture (background-limited)

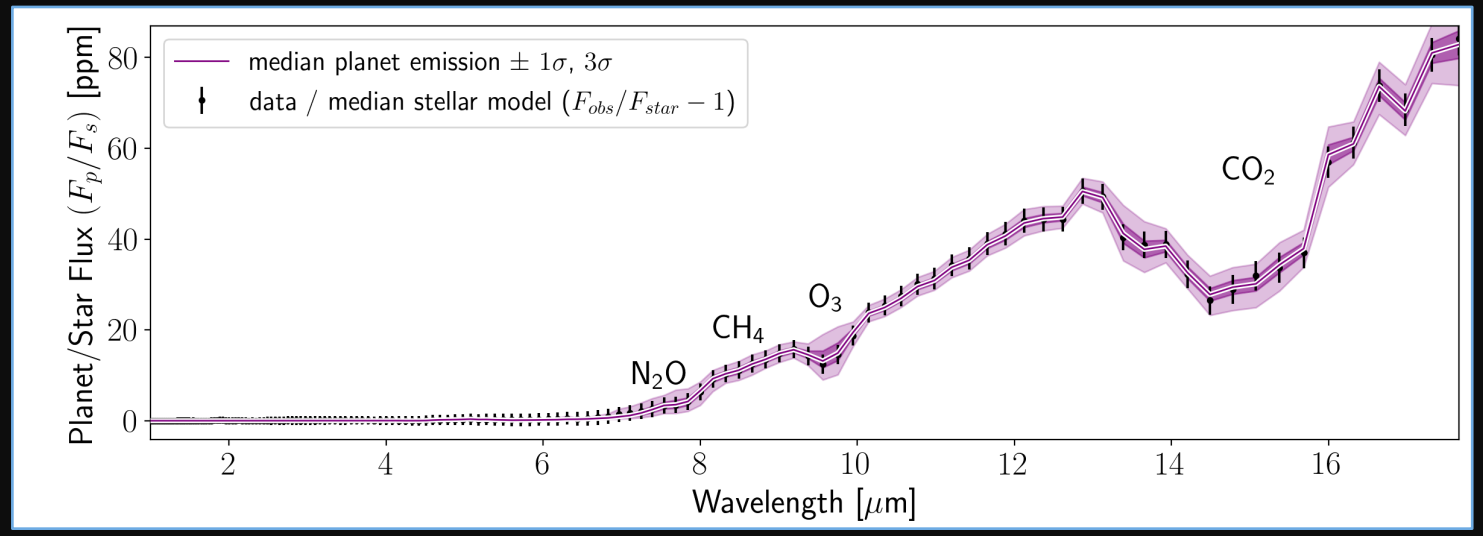
Mission Scenario #2:
4-Quadrant Phase Curve Survey

- **24** planets mapped with a 2-m aperture (exposure-time limited)

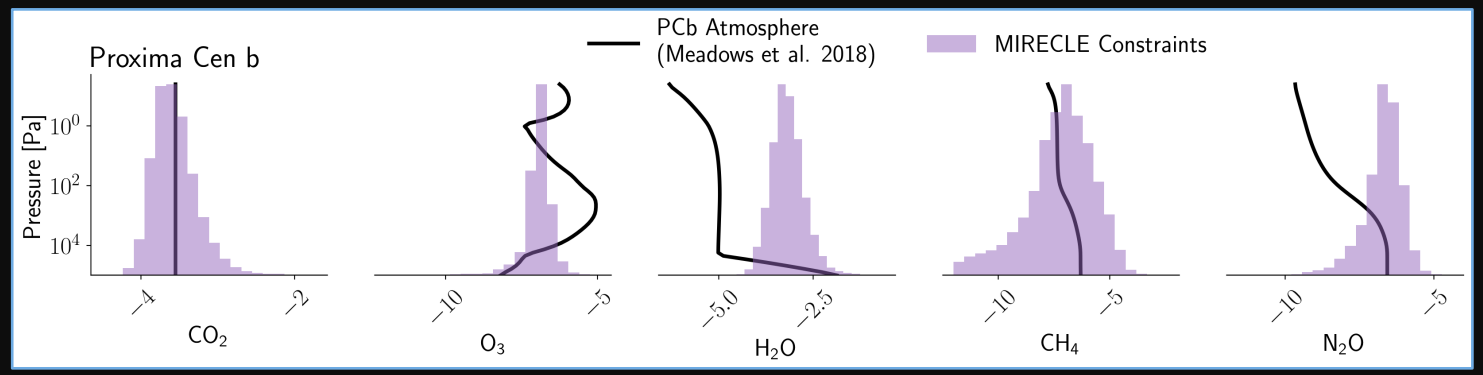


Case Study: Non-Transiting Exoplanet

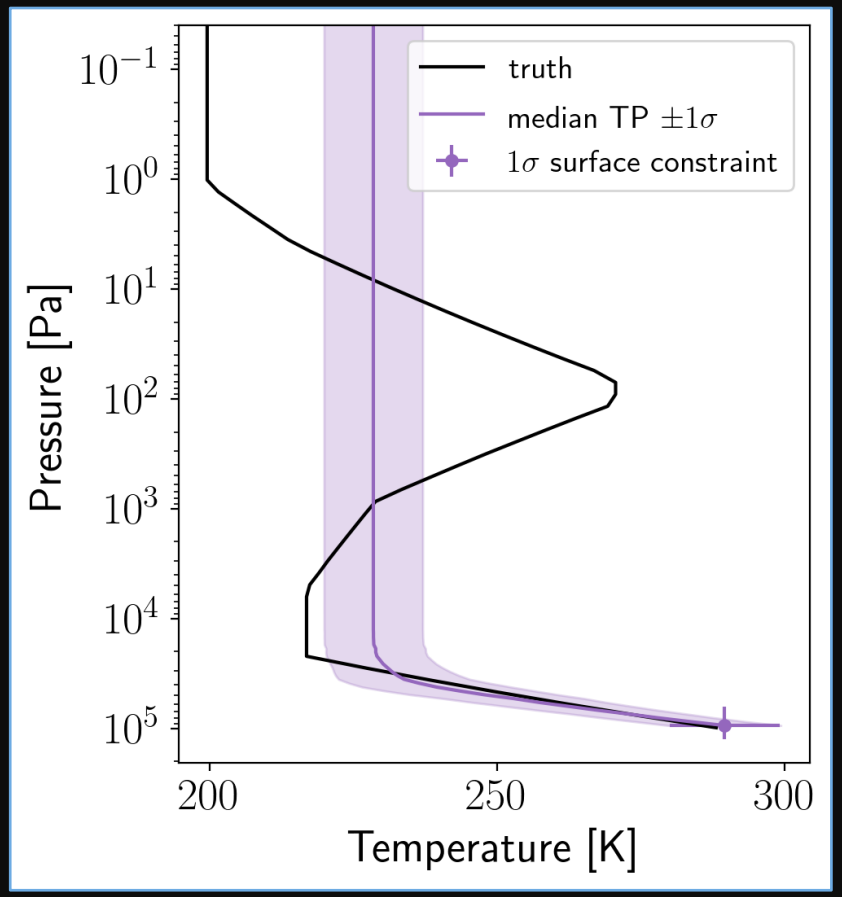
Mandell et al. (2022)



Simulated emission spectrum of Prox Cen b with realistic uncertainties assuming ~100 hours of integration with *MIRECLE*



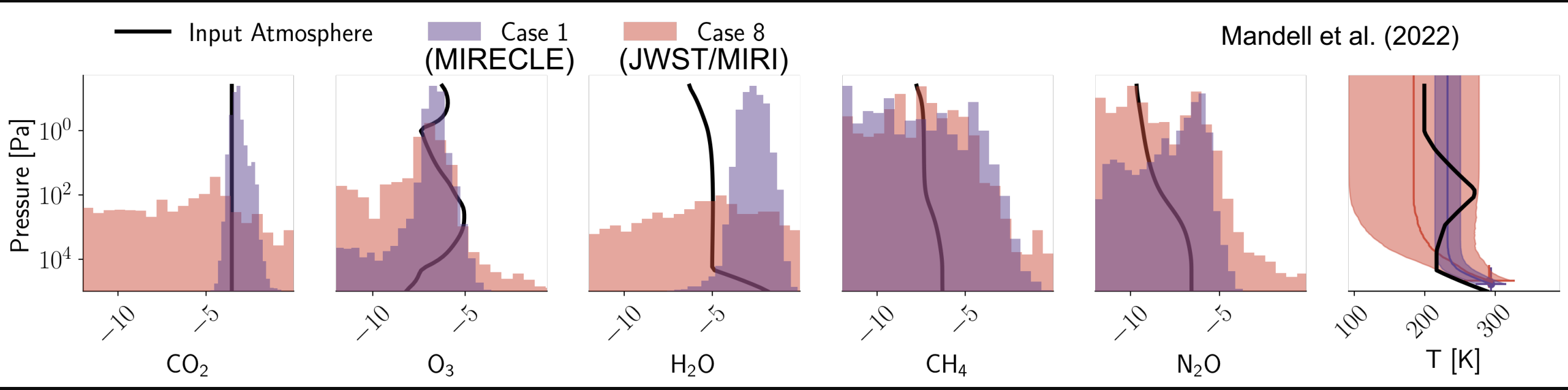
Retrieved atmospheric abundance constraints of Prox Cen b's dayside using *MIRECLE*



Retrieved thermal structure constraints of Prox Cen b

JWST/MIRI Will Not Achieve This Science Case

Case 1 (MIRECLE): Prox Cen b, 2m aperture, 100 hrs, 1–18 μm, 5ppm noise floor
Case 8 (JWST): Prox Cen b, 6.5m aperture, 12.6 hrs, 5–12 μm, 5ppm noise floor



A 2M MIRECLE WILL BE ABLE TO MEASURE THE RADIUS, TEMPERATURE, AND ATMOSPHERIC COMPOSITION OF THE NEAREST POTENTIALLY HABITABLE PLANETS AROUND M STARS

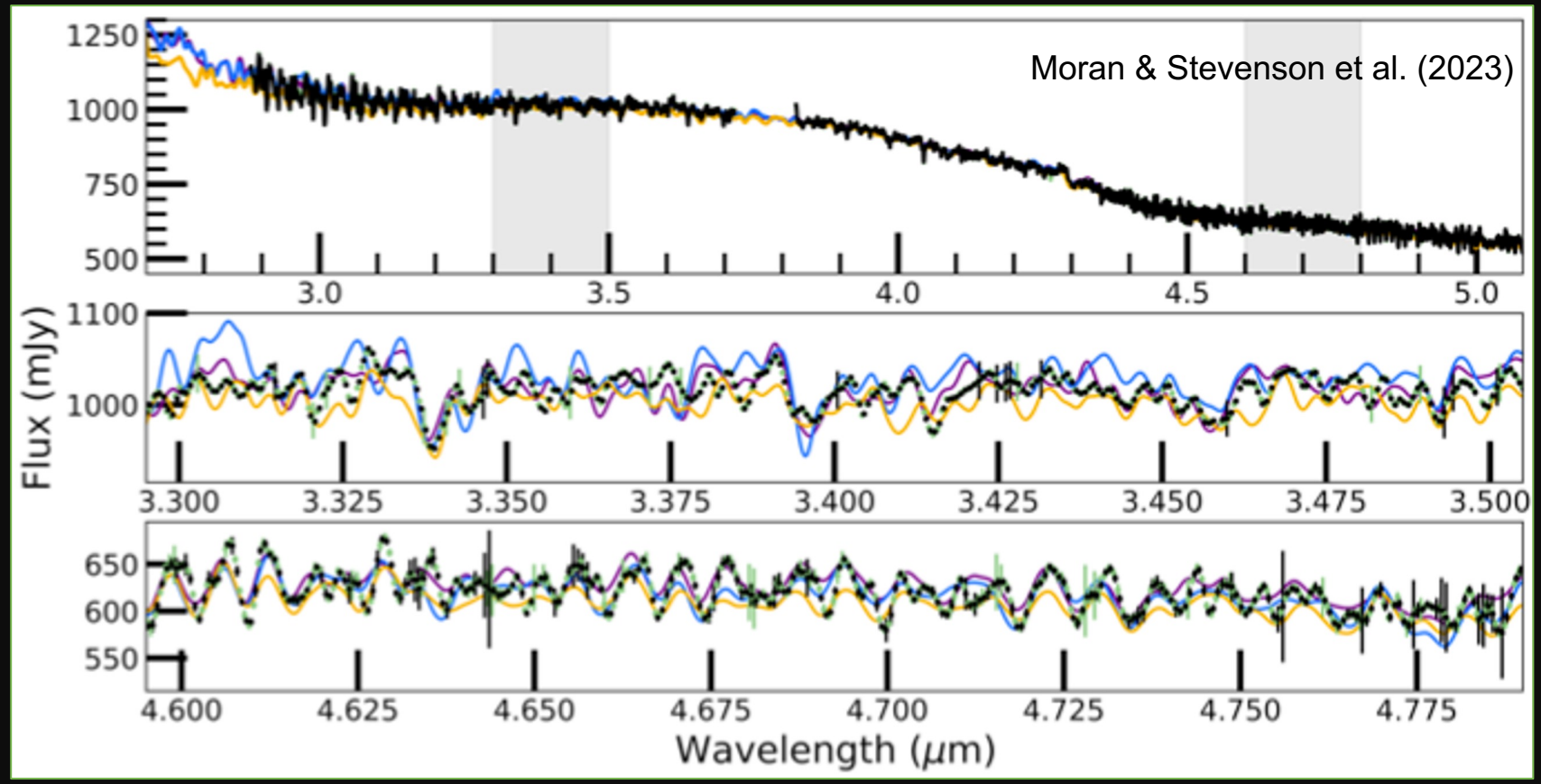
Two Open questions Relating to PIE

- How do you accurately fit the stellar flux?
- How do you resolve multiple planets within the same system?

How Do You Accurately Fit the Stellar Flux?

The biggest challenge for data analysis is to remove the stellar flux accurately to within the noise floor (5 ppm per channel at R=50).

- JWST transit analysis work is driving new stellar model developments
- New methods combining stellar models with detrending tools are under development…



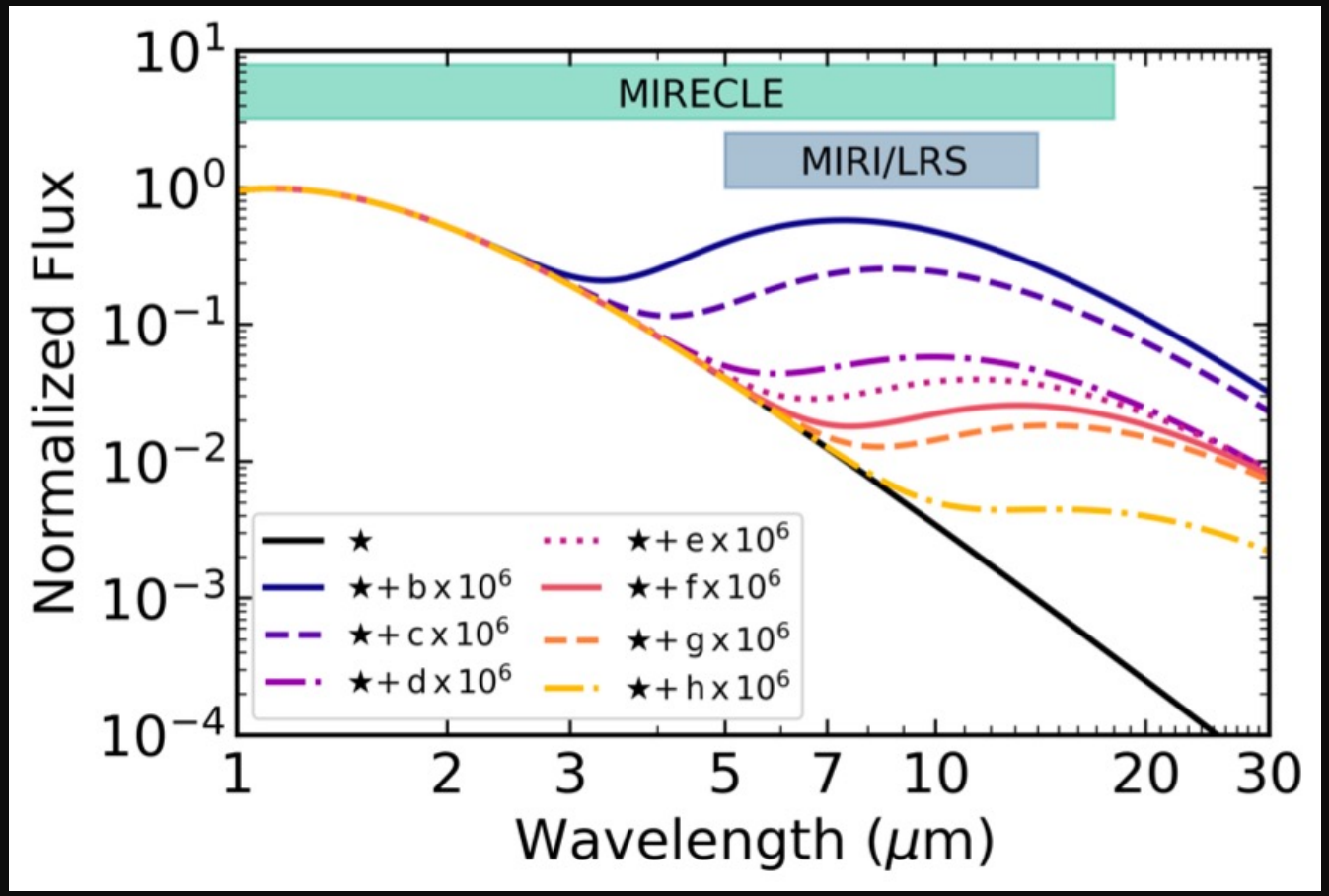
Two Open questions Relating to PIE

- How do you accurately fit the stellar flux?
- How do you resolve multiple planets within the same system?

Multi-PIE: A Case Study of TRAPPIST-1

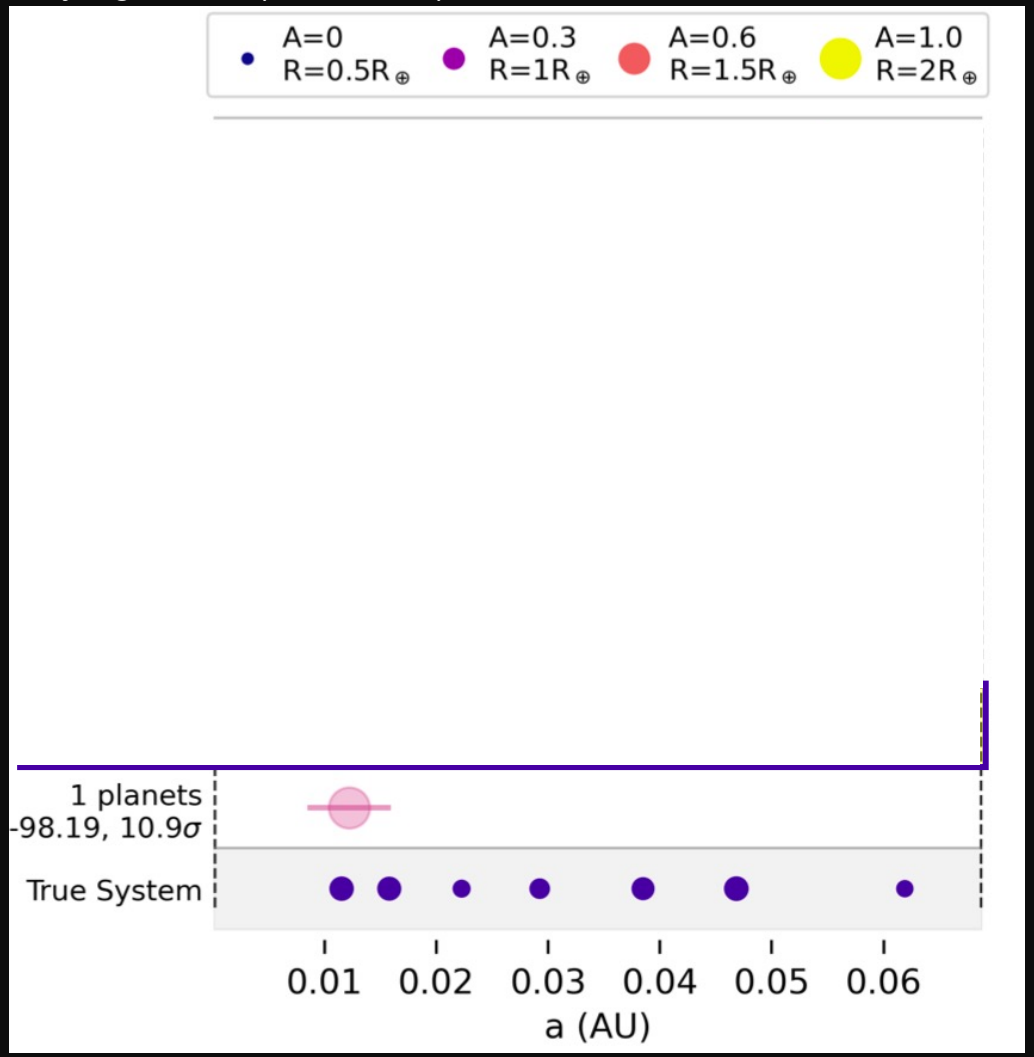
- Resolve TRAPPIST-1 planets at different epochs in time
  - 2015: no known planets
  - 2016: 2-3 known planets
  - 2017: 7 known planets, h poorly constrained
  - 2021: 7 known planets, h well constrained
- Assumptions
  - Planets and star are blackbodies
  - R = 100, 1 – 18 μm
  - Uniform 5 ppm noise
- Free parameters
  - Stellar temperature
  - Stellar radius
  - Planet radius
  - Planet semi-major axis
  - Planet bond albedo

Mayorga et al. (Submitted)



2015: MIRECLE Would Have "Found" 2 Planets

Mayorga et al. (Submitted)

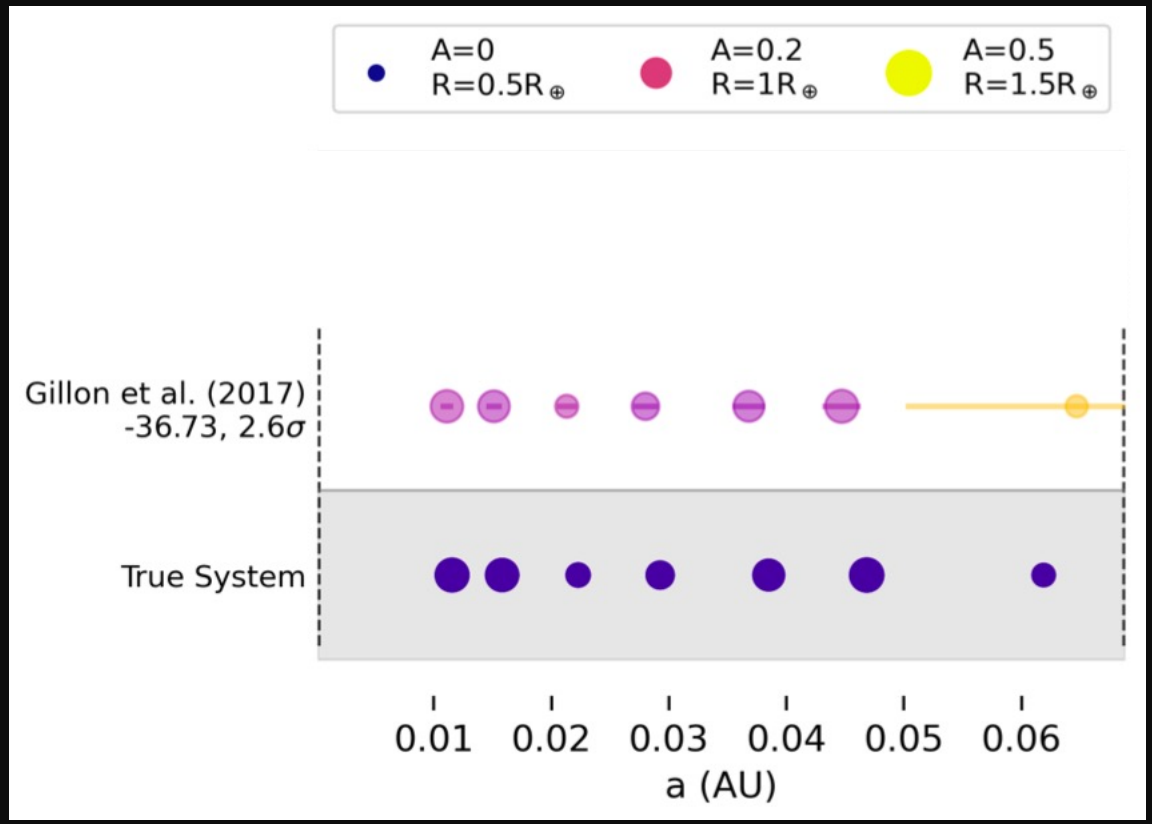


- Figure shows best-fit system using no priors on planet parameters
- Color → planet albedo
- Symbol size → planet size
- Y axis:
  - Assumed # of planets
  - Bayesian evidence
  - Significance against best-fit model

2017 – 2021: Transit Priors Constrain R_p & a

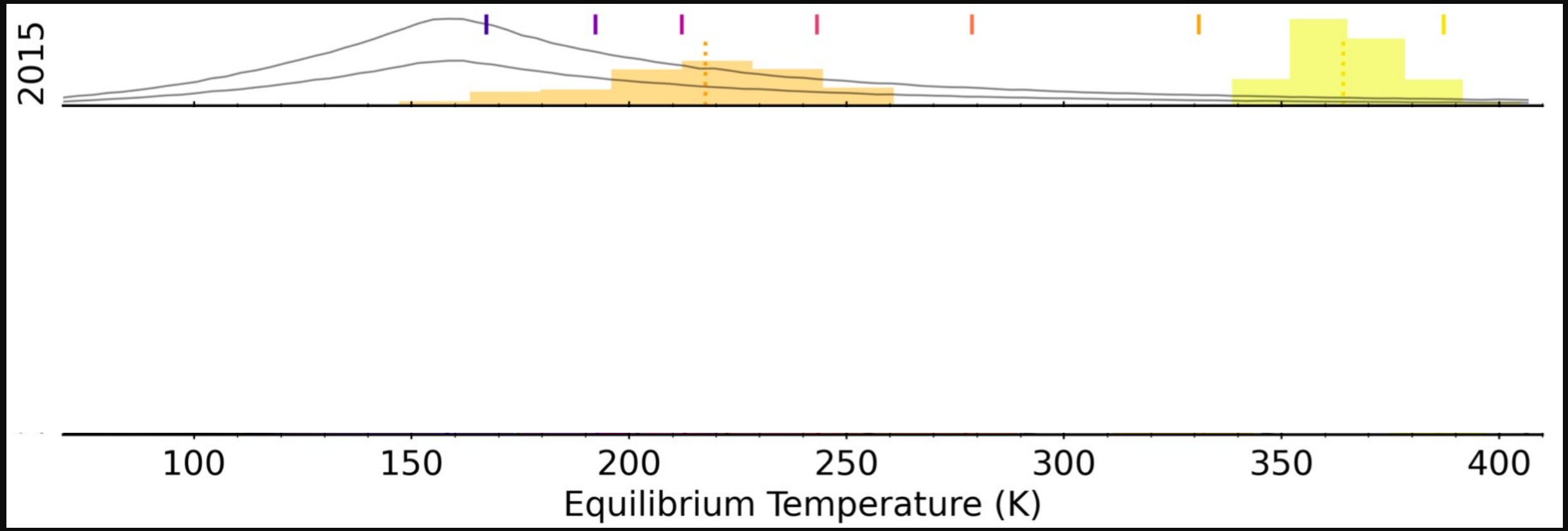
- Figure shows best-fit system using priors from listed publications
  - Gillon et al. (2017)
  - Agol et al. (2021)
- Color → planet albedo
- Symbol size → planet size
- Y axis:
  - Assumed # of planets
  - Bayesian evidence
  - Significance against best-fit model

Mayorga et al. (Submitted)



MIRECLE Constrains The Temperature

Mayorga et al. (Submitted)



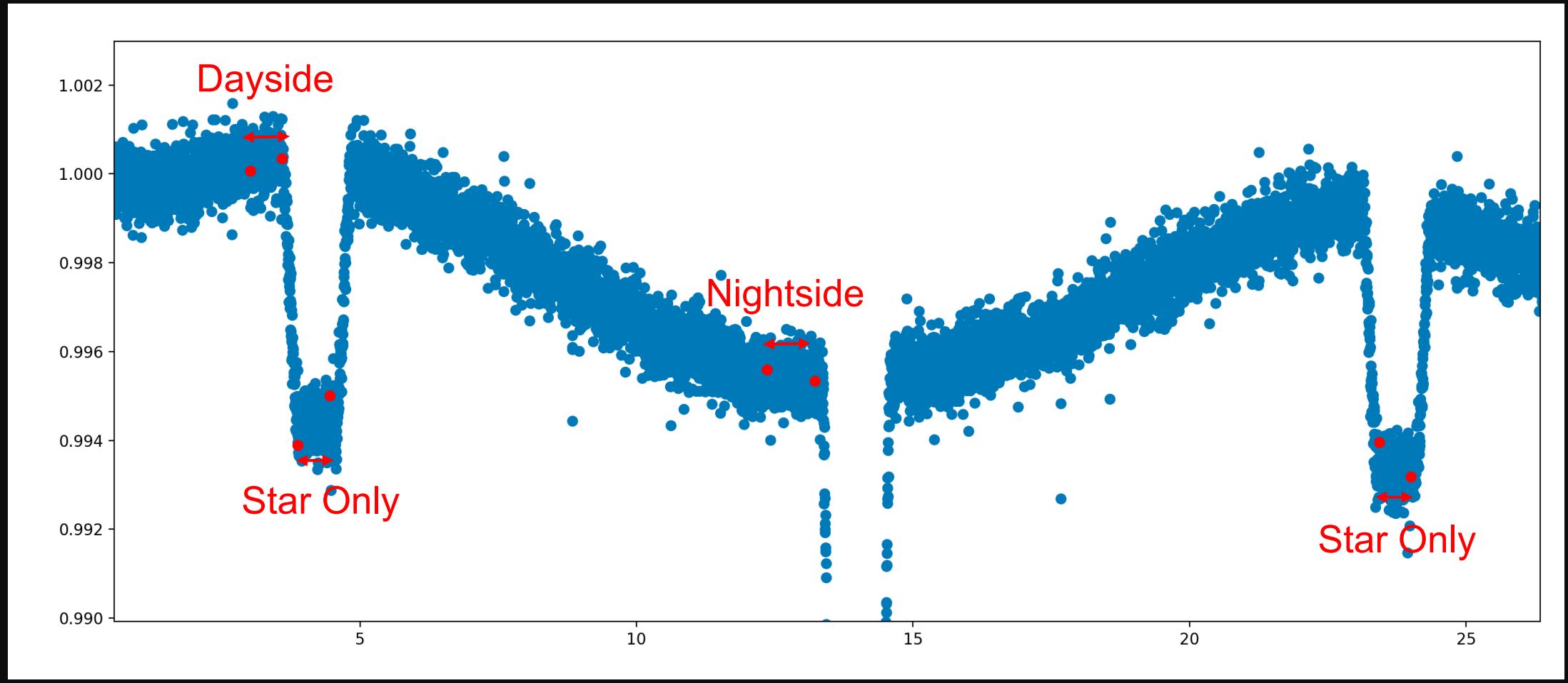
Grey Lines = Priors, Colored Histograms = Posteriors, Tick Marks = True values

Multi-PIE: Lesson Learned

- MIRECLE can find previously-unknown planets and constrain their sizes and orbital parameters
- MIRECLE has a hard time distinguishing many, similarly-sized planets in a compact system (i.e., with similar temperatures)
- MIRECLE can accurately resolve the temperatures of transiting planets in a multi-planet system

WASP-43b Nightside Emission

Credit: Guangwei Fu



WASP-43b Nightside Emission

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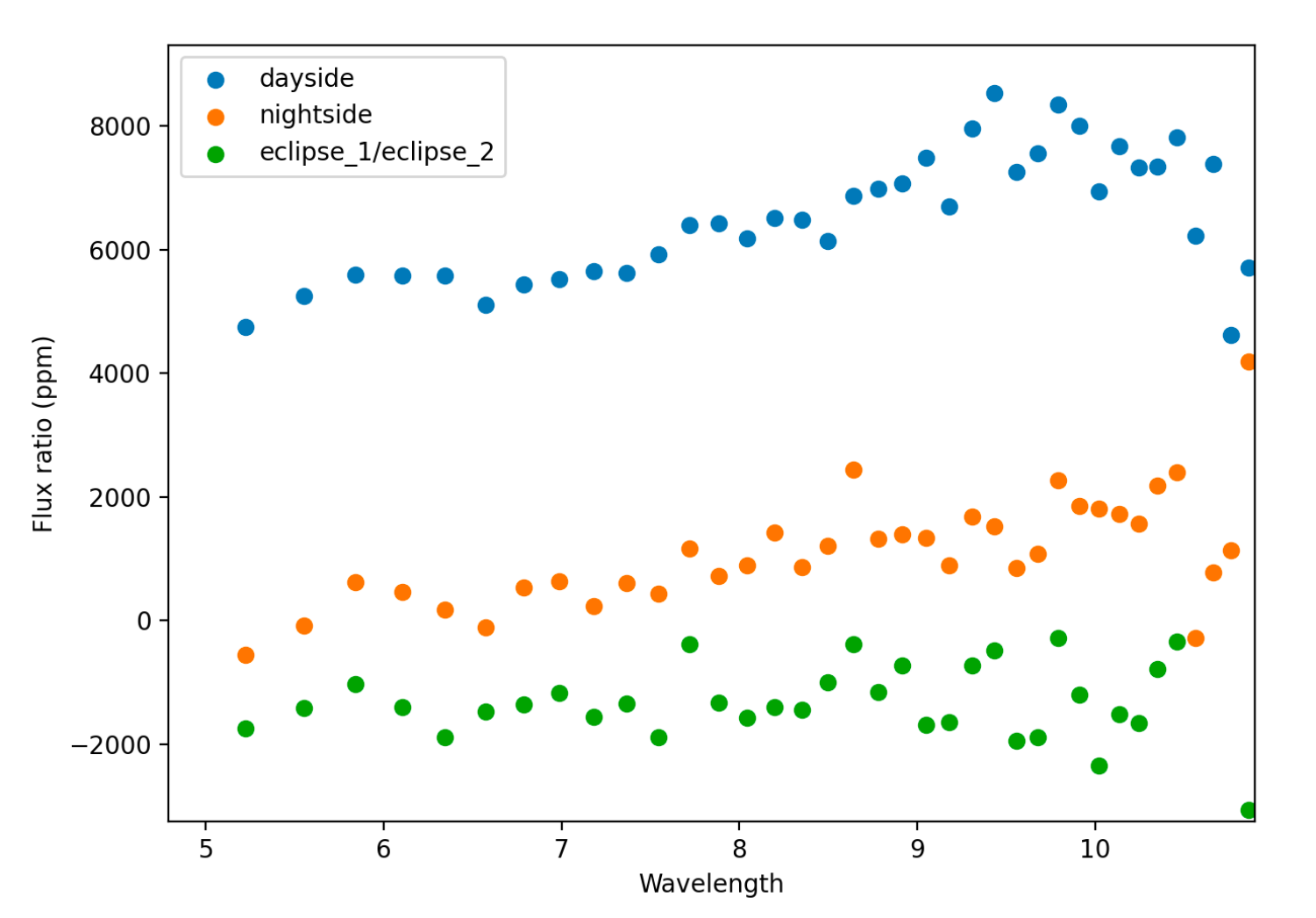

The Future is Bright… and Hopefully Full of Life

- Planetary Infrared Excess (PIE) could provide the next step in atmospheric characterization of rocky, non-transiting exoplanets
- Using PIE, MIRECLE could enable the atmospheric characterization of our nearest exoplanet neighbors
- Contact me if you're interested in helping