

Mapping the Atmospheres and Surfaces of the Nearest M-Star Rocky Planets with **MIRECLE** (Mid-InfraRed Exoplanet CLimate Explorer)

*Initial Science/Instrument Team (but growing):
Avi Mandell¹, Johannes Staguhn^{1,2}, Kevin Stevenson³, Jake Lustig-
Yaeger³, Ted Johnson⁴, Dale Fixsen¹, Elmer Sharp¹, Kristin Sotzen³*

¹NASA Goddard, ²Johns Hopkins U., ³JHU Applied Physics Lab, ⁴UNLV

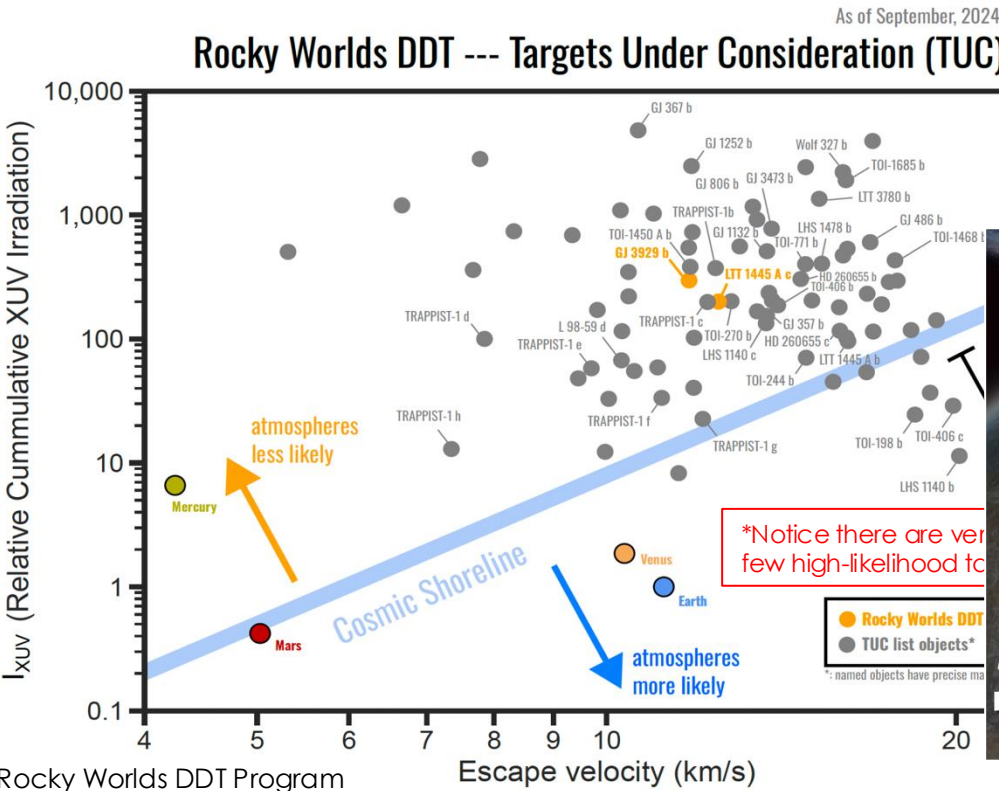
Also see:

Staguhn et al. 2019 (arXiv), Stevenson 2020 (ApJL), Mandell et al. 2022 (ApJ),
Staguhn et al. 2024 (SPIE), Johnson & Mandell 2026 (AJ)

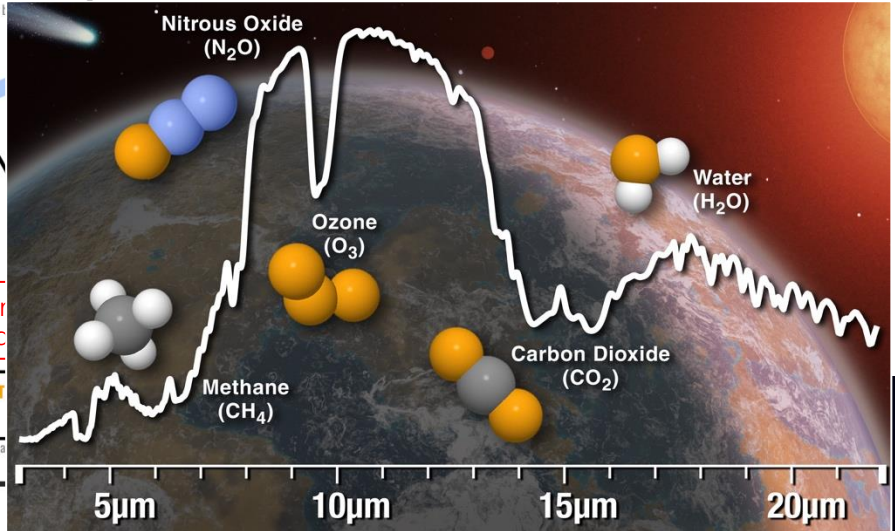


Questions Driving M-Earth Exploration

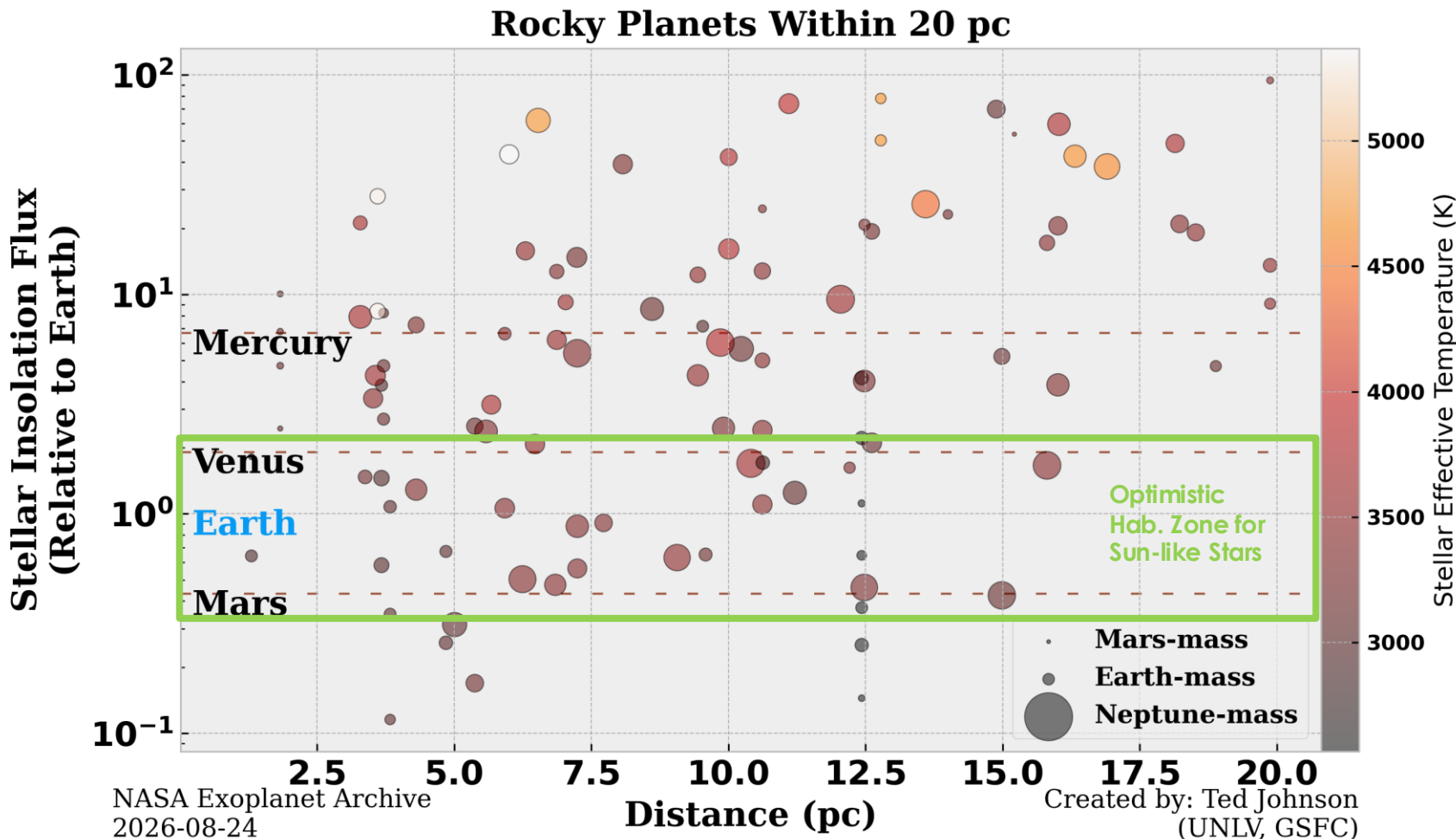
Which M-star rocky planets can maintain a secondary atmosphere?



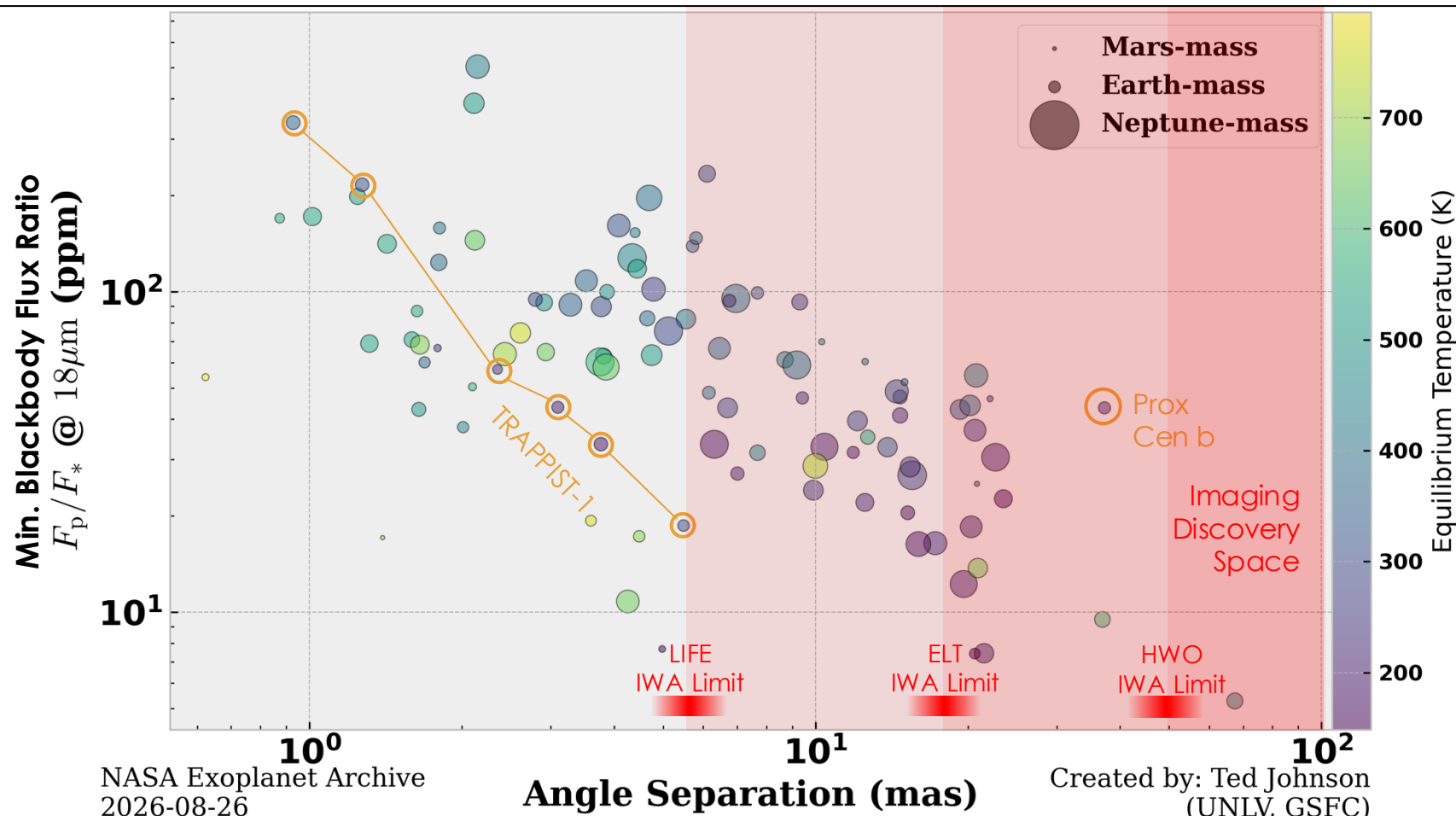
If we find temperate M-Earths have atmospheres, what will they be made of – and will they show signs of habitability or inhabitation?



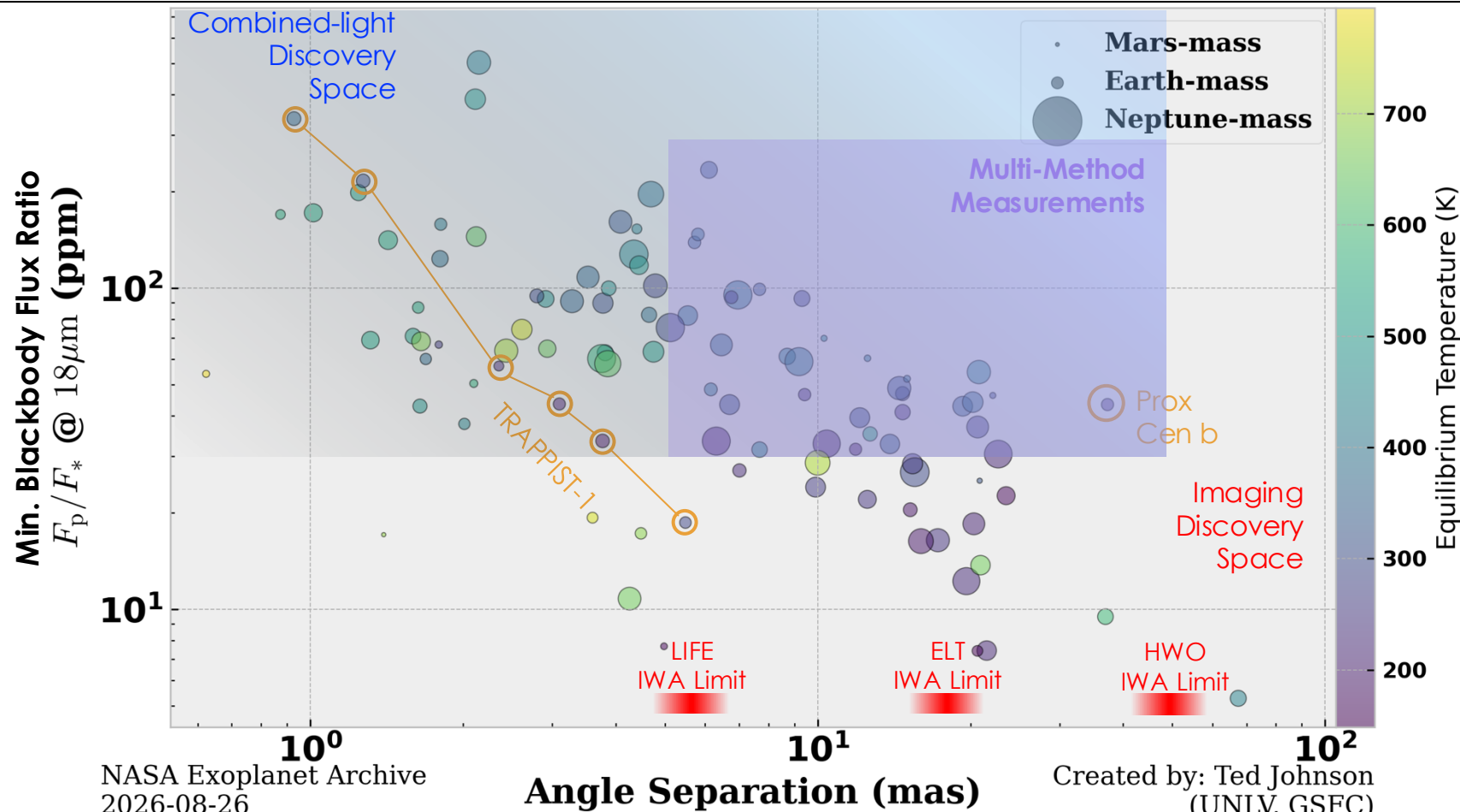
Almost all of the small, cool nearby exoplanets orbit M-dwarfs...



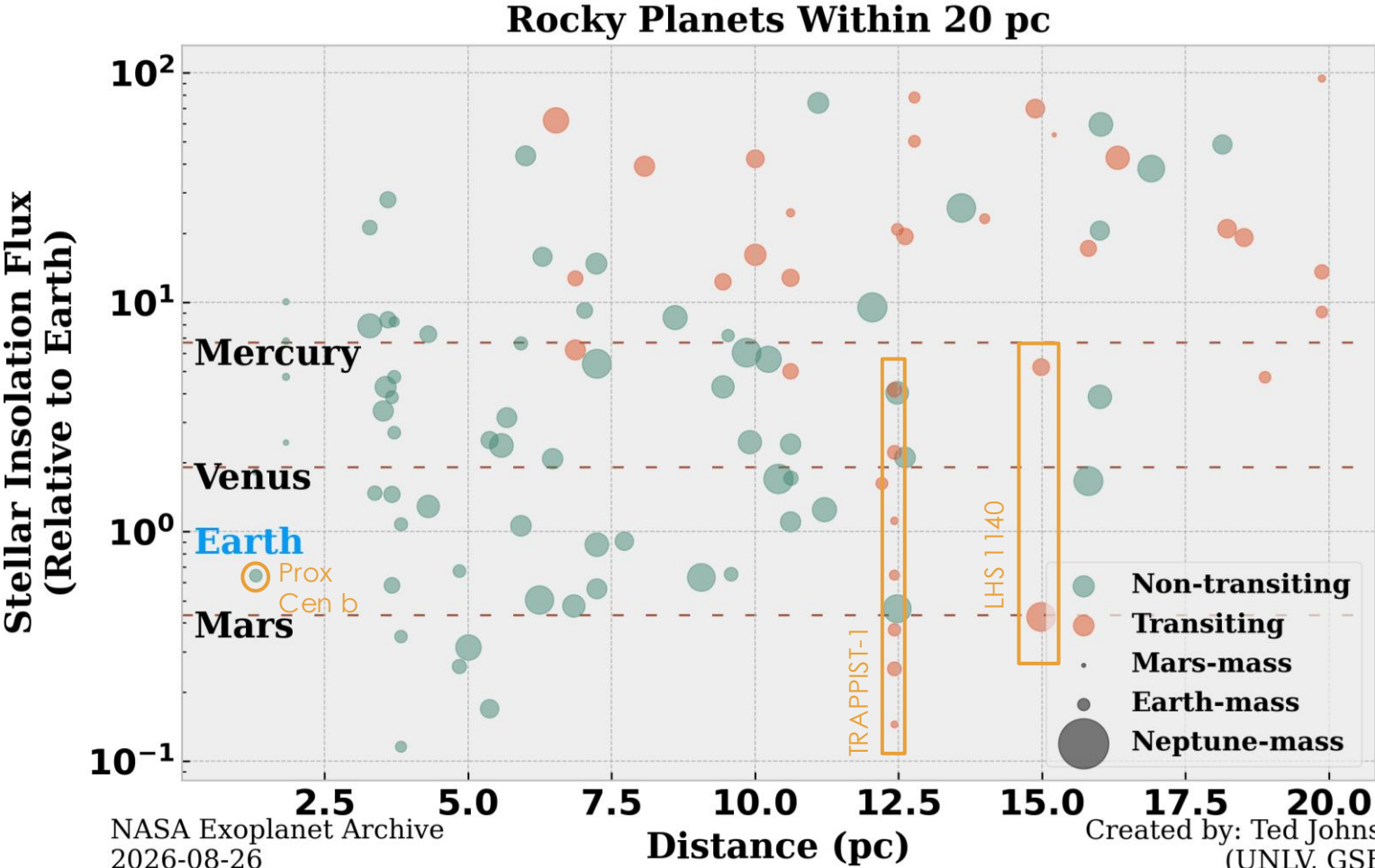
"Combined-light" flux measurements and direct imaging are complementary



"Combined-light" flux measurements and direct imaging are complementary



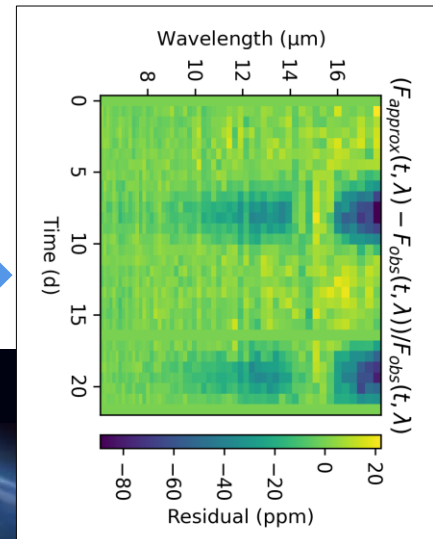
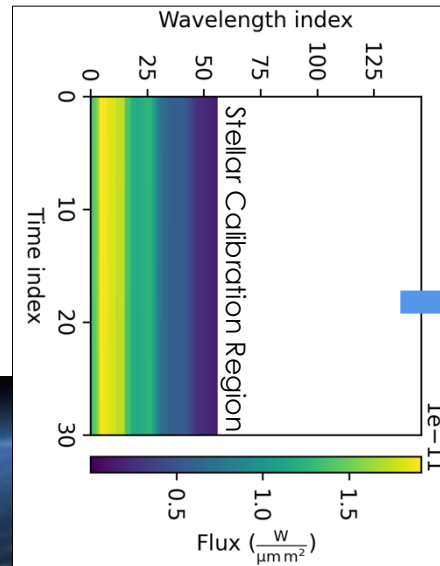
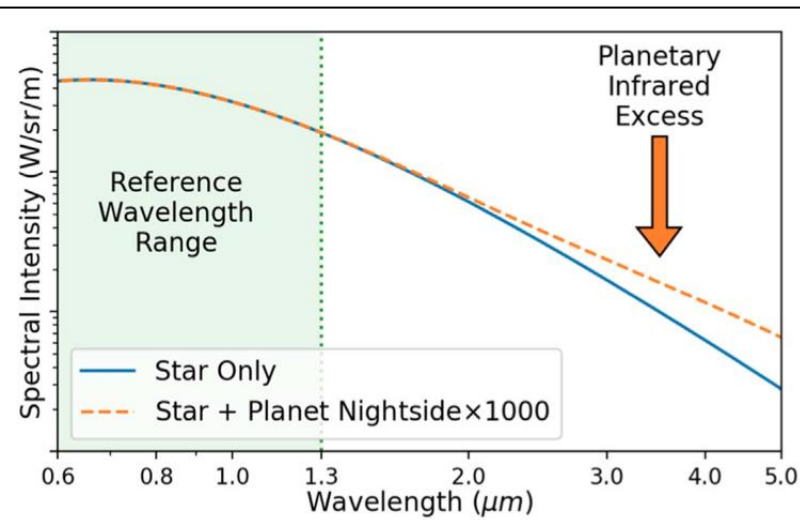
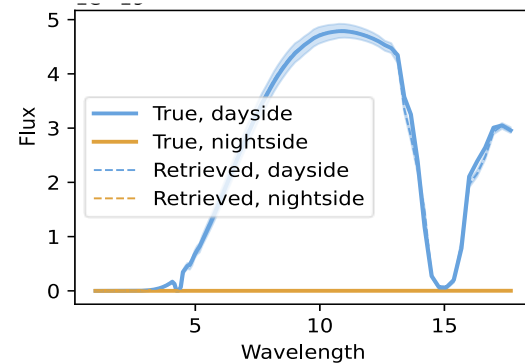
The challenge for combined-light: almost NONE of the cool nearby M-Earths transit!



In Development: Revealing day-night thermal variations for nearby non-transiting M-Earths

Sufficiently broad wavelength coverage may allow planet and star to be spectroscopically resolved ("Planetary IR Excess", or PIE; Stevenson 2020, ApJL)

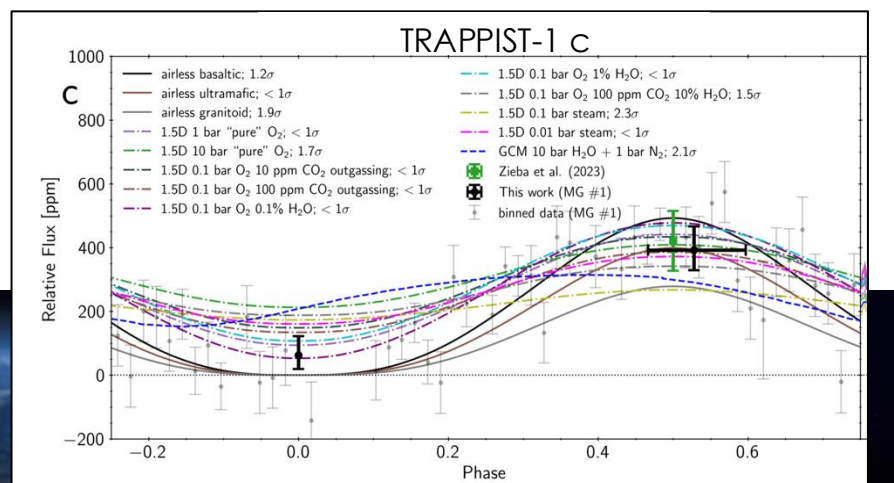
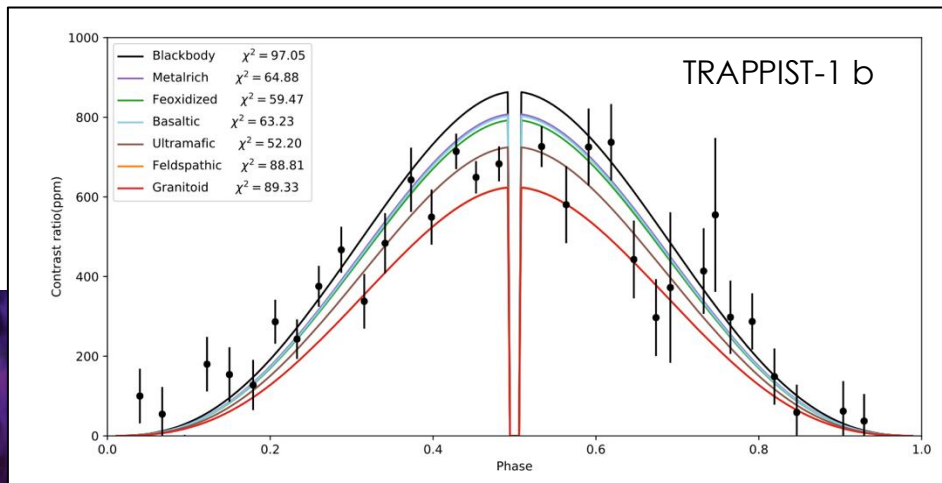
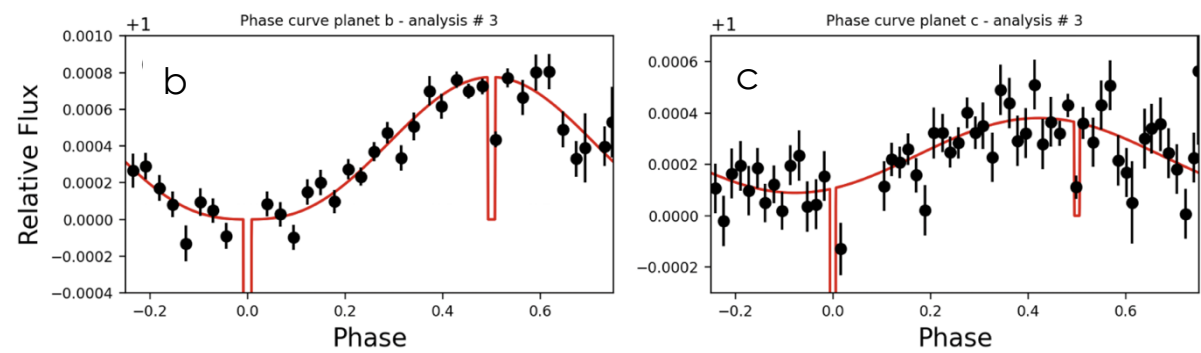
Simulated Star+Planet Phase Curve Extraction ("VPIE"; see Johnson & Mandell 2026, AJ)



Day-Night Emission Measurements Provide a Holistic Picture of Planet Properties

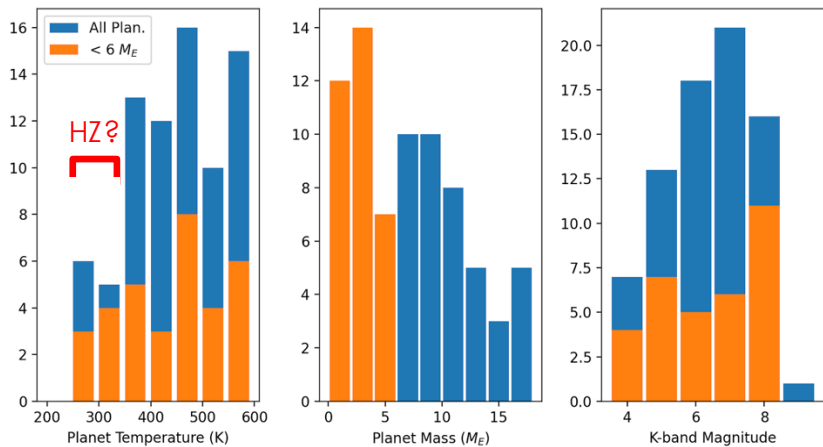
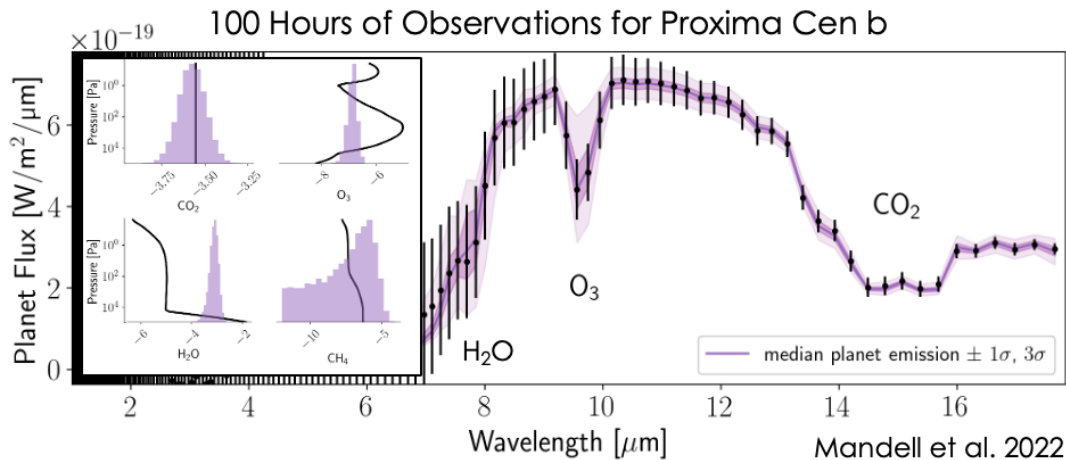
- Heat Redistribution
- Surface albedo/emissivity
- Bulk atmospheric mass
- Atmospheric absorbers
- Full phase cov. provides 2D emissivity/composition map

TRAPPIST-1 b&c, from Gillon & Ducrot, et al. 2026



Initial Science Yield Analysis for 2-meter MIRECLE Concept

- Spectroscopy from 2 – 18 μm could constrain presence of H_2O , O_3 , and CO_2 on an Earth-like planet
- **24-month prime mission could observe ~50 - 75 planets, including ~10 with $T_{\text{eq}} < 350 \text{ K}$**
- Very preliminary – many assumptions made for instrument specs and analysis efficacy – and list of potential targets is evolving...



MIRECLE Baseline Observatory Concept

- Fully Aluminum 1.5 - 2m telescope operating at L2, passively cooled to 35-40K (Heritage from JWST)
- Main science instrument: MIR spectrometer, $R = 25 - 50$, with detector temperature stabilized to 25K
 - Next-gen MIR-sensitive HIRG - simultaneous spectral coverage from 2 - 18 μm
 - Optimized detector operation and on-board reference calibration to achieve time-averaged noise floor of ≤ 5 ppm flux measurement stability, post-processing
- Goal: high-precision MIR emission and phase curve spectroscopy for characterizing rocky planets around the nearest M-stars, and characterization of host stars
- Mission Duration: 2 year baseline, 4 year goal

Instrument is very compact – can be paired with other instruments on a larger or multi-aperture mission concept



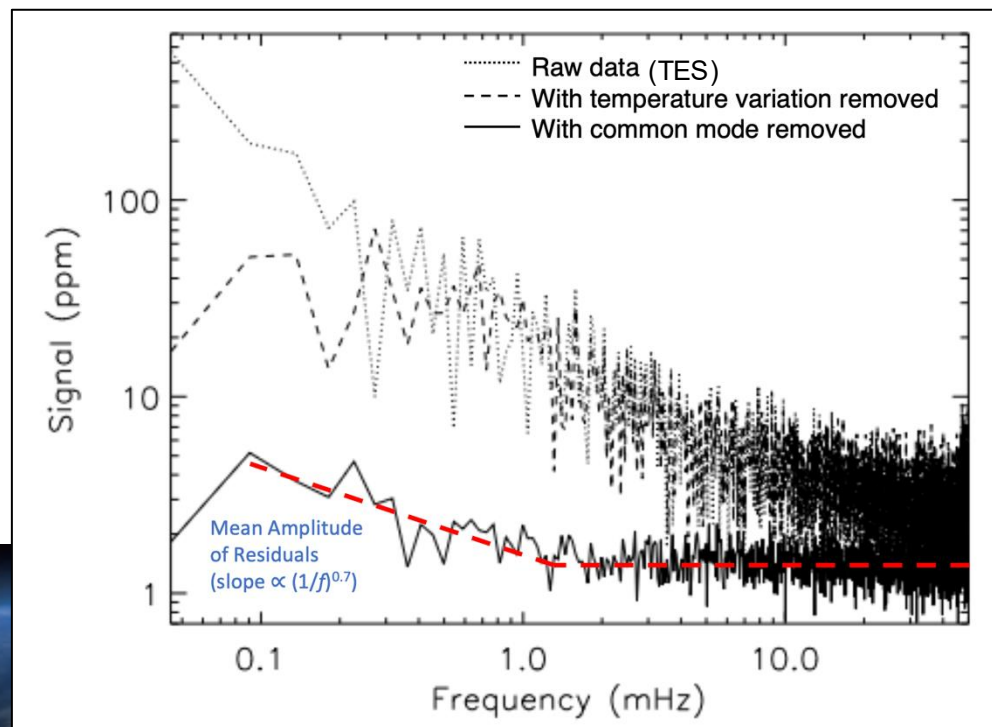
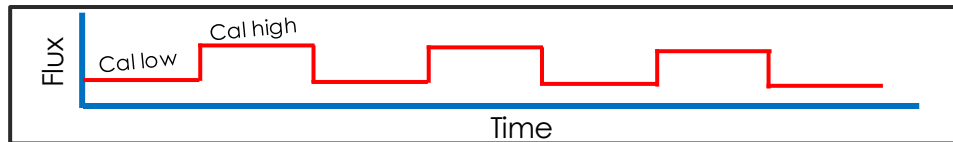
Key Enabling Technologies

MIRASET Testbed @ GSFC

Lab demonstration of temperature-stabilized and continuously calibrated instrument design

1st-generation testbed examined ultra-stable Transition Edge Sensor arrays, in order to demonstrate the absolute floor that can be achieved (Fixsen et al. 2025)

- Current 2nd-generation testbed is beginning to test a VLW HIRG engineering-grade array from Univ. of Rochester



Key Enabling Technologies

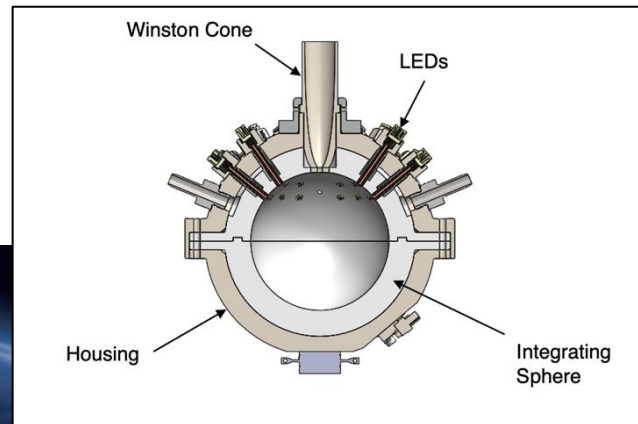
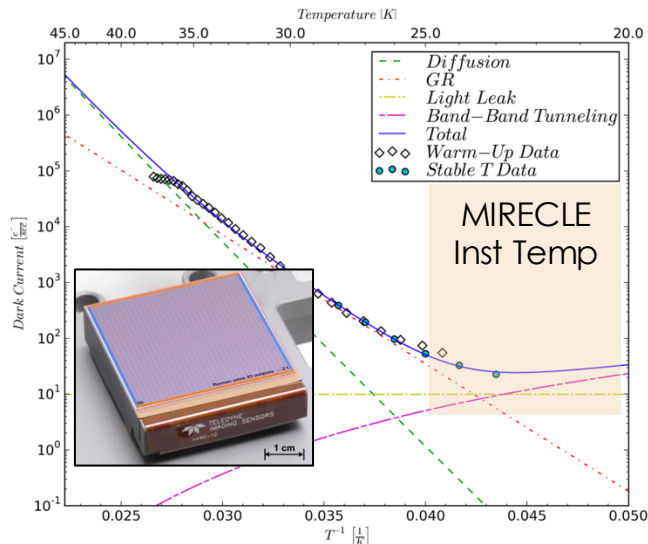
Detector: New “very long wavelength” (VLW) HIRG array from Teledyne – extension of NEO Surveyor arrays

High-TRL, relatively low noise and high sensitivity demonstrated to $17\ \mu\text{m}$ (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 w/ good temp. control)

WFI Simplified Relative Calibration System (sRCS) uses on-board integrating sphere to provide continual reference spectrum for updating calibration

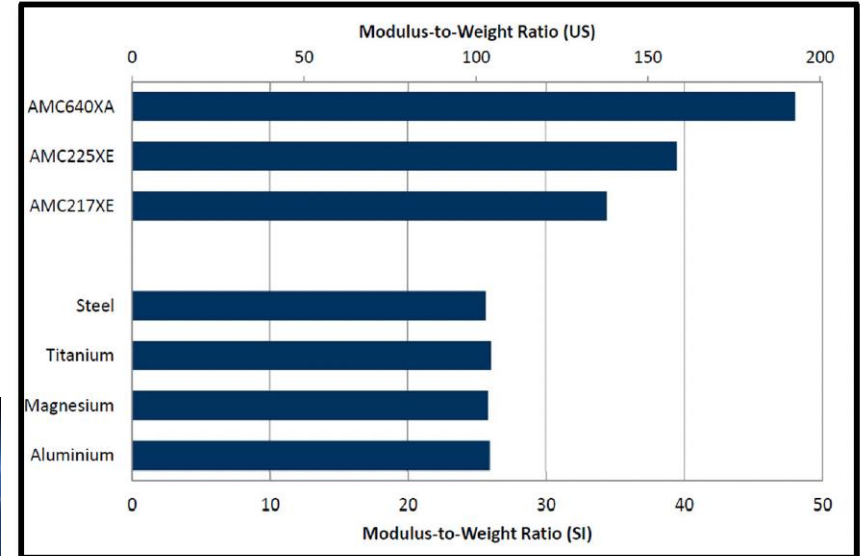
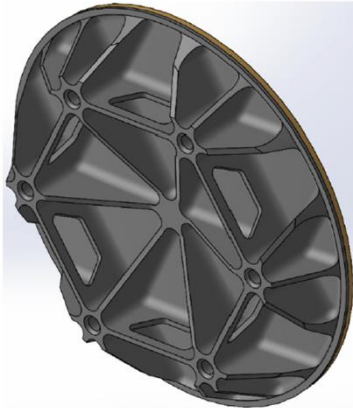


Key Enabling Technologies

Low-density Large Aluminum mirrors

Combines the machinability of traditional aluminum alloys with the high strength and thermal performance of Si and/or SiC structures

Ongoing APRA program associated w/ MSFC to demonstrate a 1.25m mirror baselined for MIRECLE specifications



Summary: A High-TRL Path to Next-Gen M-Earth Science

- **The MIRECLE driving science case is compelling:** Following up the exciting JWST M-star rocky planet reconnaissance with 2D mapping of the nearest planets -- including potentially habitable planets such as Prox Cen b and possibly “golden” transiting HZ planet targets
 - Many potential secondary science cases: time-variability of close-in rocky planets, BD mapping, SNe/GRB follow-up, Sol Syst monitoring/mapping – more?
- **The telescope and instrument technologies have heritage and high-TRL components** - many already demonstrated at close to required performance
- **Multiple mission size regimes are possible:** trade-offs in cost and TRL versus compelling science
- **Contributions:** we are looking for both individual and institutional partnerships. Science needs include improving data analysis strategies, defining key science cases, design reference mission definition, precursor demonstrations