Direct Imaging Detectability of Tidally Heated ExoMoons (THEM)

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We investigate the possibility that **THEMs (Tidally Heated ExoMoons) could be directly imaged (and perhaps already have been)** with existing ground and planned future direct imaging instruments.

- Tidally heated exomoons can plausibly be far more luminous than their host exoplanet and as much as 0.001 as bright as the system's stellar primary
- Because emission from exomoons can be powered by tidal forces, their luminosites are independent of their separations from the system's stellar primary
- THEMs may remain hot and luminous for Gyrs and could be **visible around old stars as well as young ones**
- They may be **luminous at large separations from the system primary**, thus reducing or eliminating the contrast and high angular resolutions required to image "habitable zone" Earth-like exoplanets
- Tidal heating **depends so strongly on the orbital and physical exomoon parameters**, that quite plausible systems will result in terrestrial planet sized objects with effective temperatures as high as ~1500K
- The effective temperature of a tidal heated moon is given by[1–3, 6]

$$T_s = \left(\left(\frac{392\pi^5 G^5}{9747\sigma^2}\right)^{1/2}\left(\frac{R_s^5\rho^{9/2}}{\mu Q}\right)\left(\frac{e^2}{\beta^{15/2}}\right)\right)^{1/4} \approx 279K\left[\left(\frac{R_s}{R_\oplus}\right)^{\frac{5}{4}}\left(\frac{\rho}{\rho_\oplus}\right)^{\frac{9}{8}}\left(\frac{36}{Q}\cdot\frac{10^{11}\text{dynes cm}^{-2}}{\mu}\right)^{\frac{1}{4}}\right]\times\left[\left(\frac{e}{0.0028}\right)^{\frac{1}{2}}\cdot\left(\frac{\beta}{8}\right)^{-\frac{15}{8}}\right]$$

Equation Parameters	
R_s	Radius of moon
ρ	Density of moon
β	Semi-major axis in Roche radii
e	Moon's eccentricity
μ	Moon's elastic rigidity
Q	Moon's dissipation function

- Based on this equation, **if Io were as massive as Earth, it would be bright enough for JWST to detect at 5pc!**
- Fig. 1 displays the steep temperature dependence on R_s, ρ, β and *e*.

Eccentricity vs. effective temperature of a THEM | *Semi-major orbital axis vs. effective temperature of a THEM*

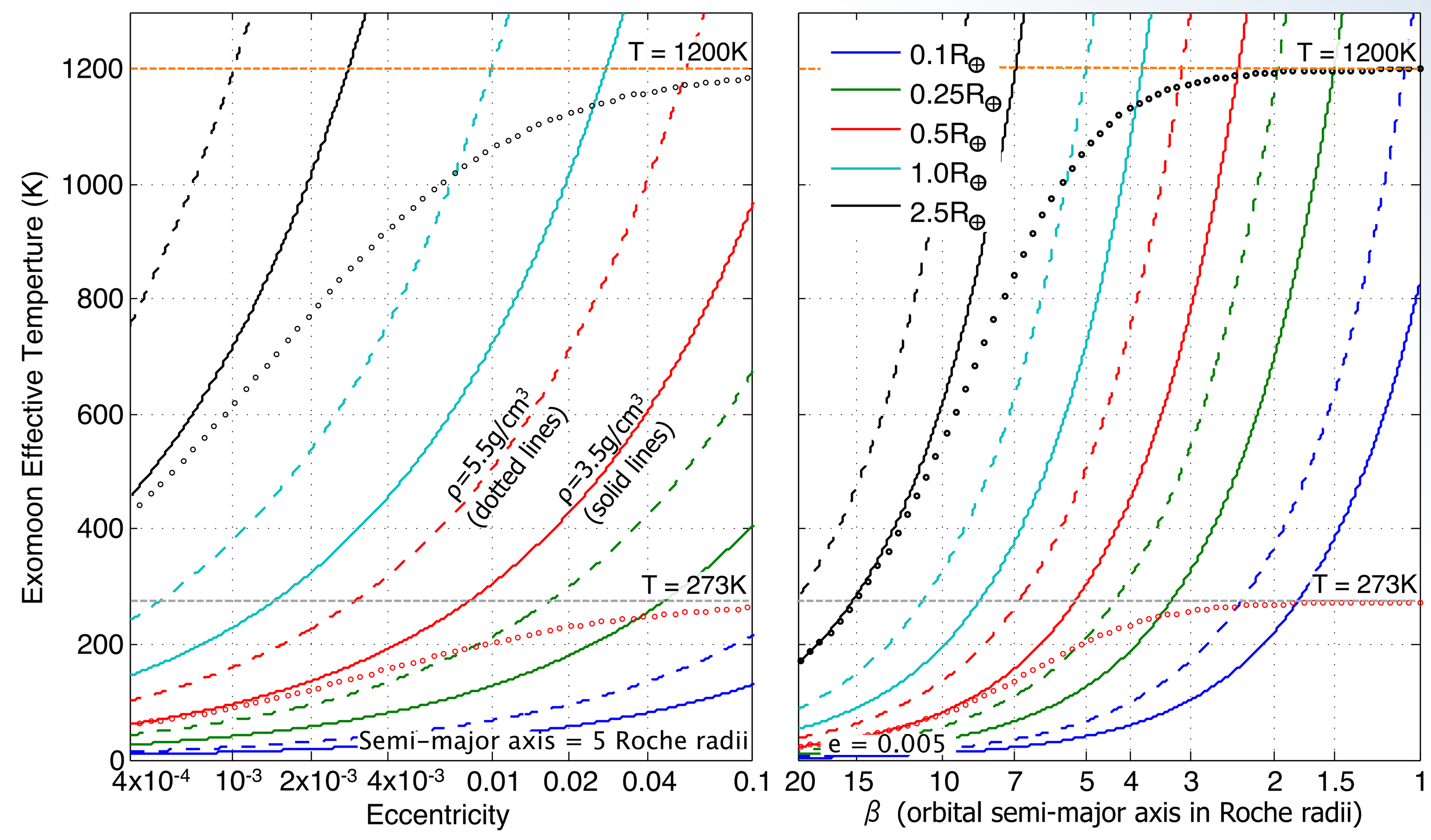

Fig. 1.— Each line color corresponds to a different THEM radius listed in the legend. The gray and orange dashed horizontal lines correspond to the melting temperature of water and rocks, respectively. The dotted red and black lines give the radius of the THEM for a moon that approach the horizontal lines illustrate that **Q and μ increase with increased tidal heating**, and perhaps cause the THEM's temperature to approach its melting point.

Direct imaging detection of physically plausible, tidally heated exomoons is possible

- **Existing instrumentation** (such as the Spitzer's IRAC) is capable of imaging THEMs **with T_{eff} ≥ 600K and R ≥ $1R_\oplus$** (see Fig. 2 below)
- Future mid-infrared space telescopes such as JWST's MIRI will be capable of directly imaging even cooler THEMs
  - **JWST's MIRI** will be able to directly image **THEMs around the nearest ~25 star systems with T_{eff} ≥ 300K and R ≥ $1R_\oplus$ orbiting at ≥ 12AU** with 5σ confidence in 10^4 second integration time.
  - Fig. 3 (right) shows MIRI's THEM temperature/radius detection limit
  - Fig. 4 (bottom right) shows the eccentricity/β (semi-major axis in Roche radii) parameter space for 4 different radii exomoons at the MIRI's detection limit

Detection Limit of THEMs with JWST's MIRI (includes THEMs in the "Habitable Zone")

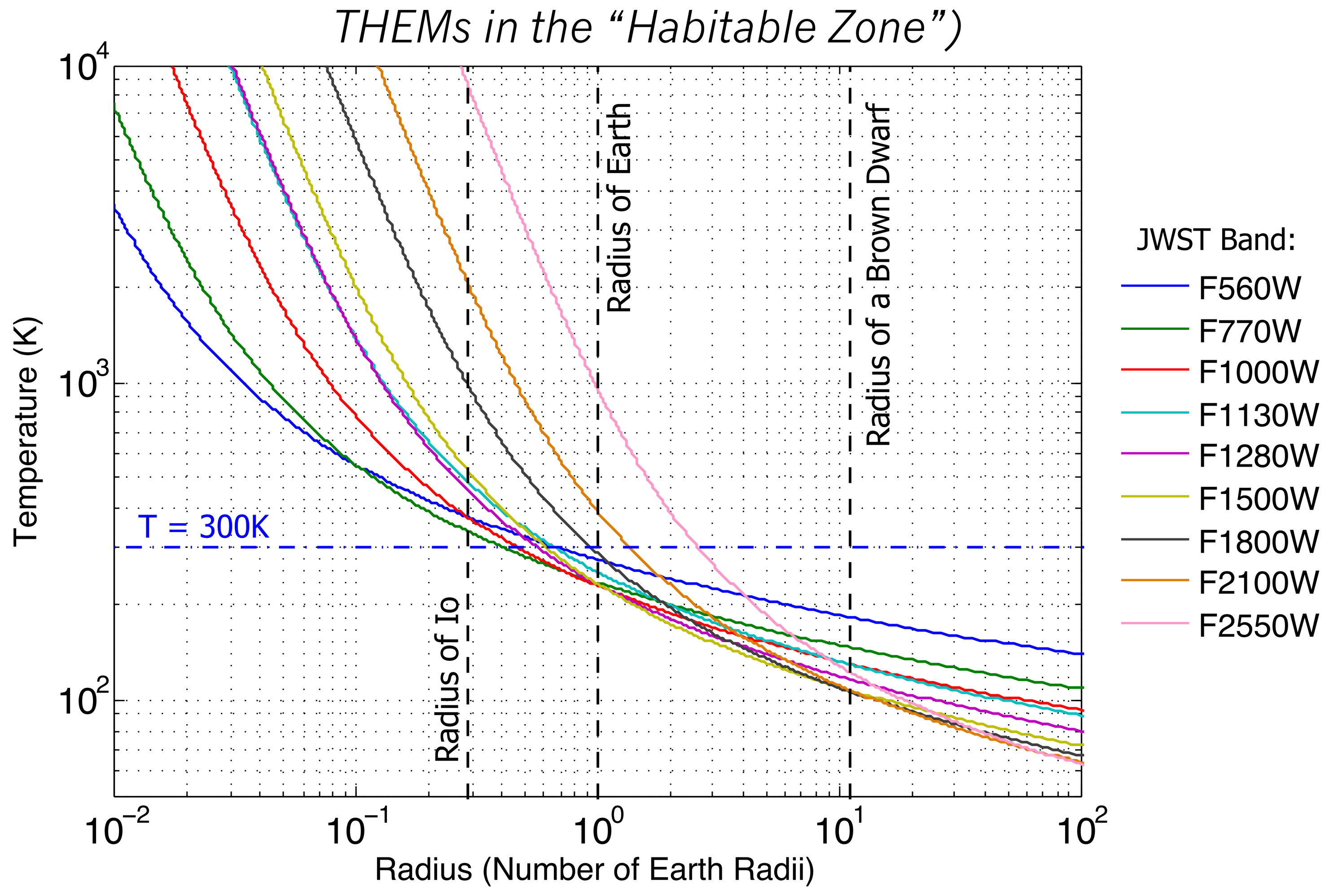

Fig. 3. — Plot of the JWST MIRI radius-temperature THEM 5σ detection limit with 10,000s integration time for a star 3pc for the nine MIRI imaging bands. Dashed vertical black lines give the radius of Io, Earth and a brown dwarf from left to right. Note that the name of the MIRI bands correspond to the wavelength in microns times 100 (for example, F560W has a center wavelength of 5.6μm). Calculation assumes that THEMs are perfect blackbodies.

Detectability of THEMs with existing space-based and future ground instruments

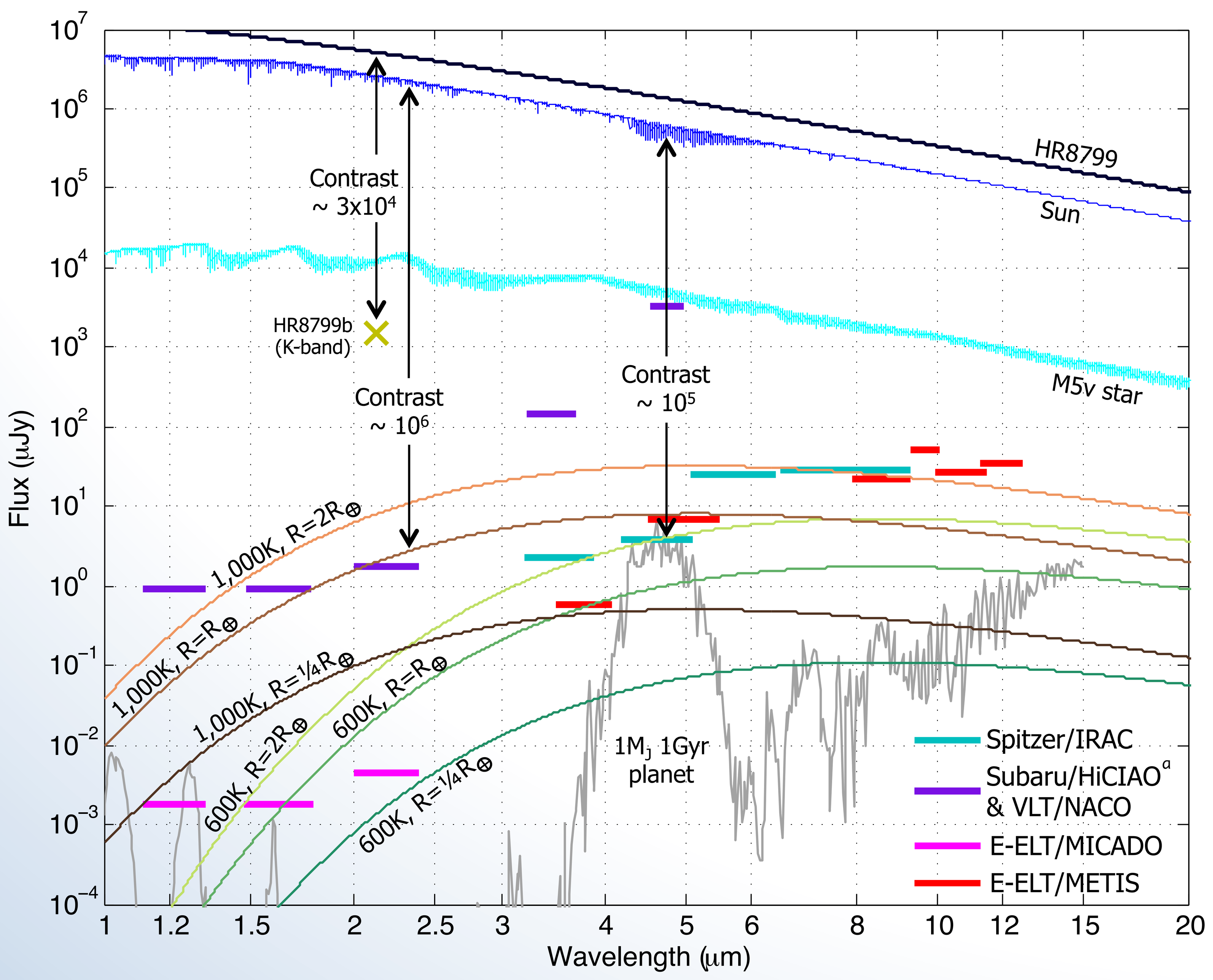

Fig. 2.— Plot shows the flux vs. wavelength of stars, an exoplanet, and various THEMs as well as the sensitivity of many instruments. The top 3 lines are the flux received from 3 different stars at a distance of 5pc. The lines labeled with a temperature and radius are 6 plausible THEM blackbody curves. The gray line is a modeled exoplanet $1M_J$, 1Gyr old[5]. The horizontal bars are the detection limits for various instruments. Detection limits assume 5σ detections and 10,000s integration times. THEMs are assumed to be perfect blackbodies.

ᵃHiCIAO operates in J-, H-, and K-bands.

Orbital Parameters of THEMs that are detectable with MIRI

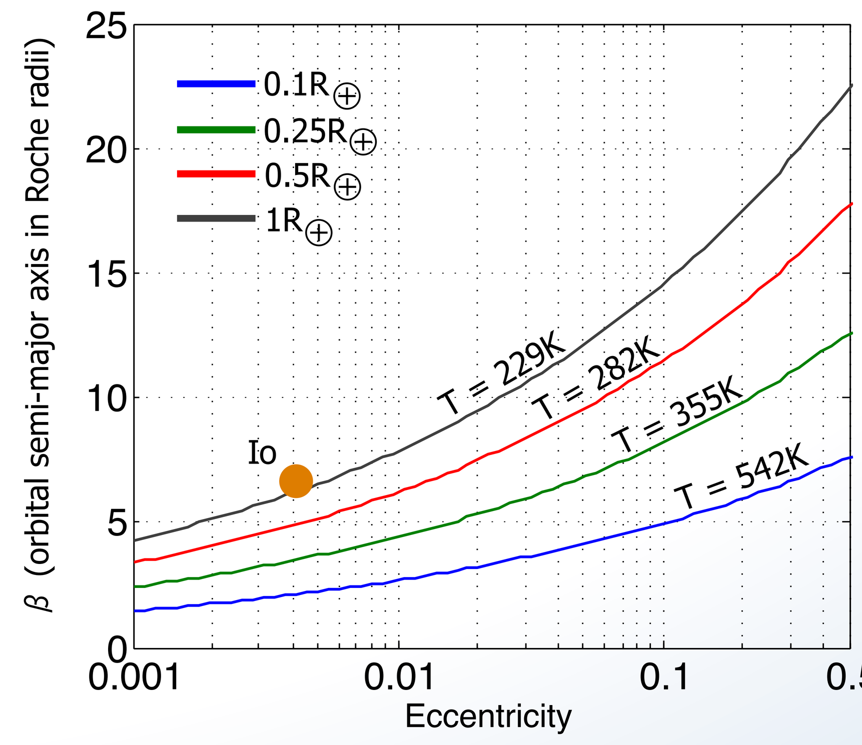

Fig. 4.— Minimum detectable orbital parameters based on Fig. 2 for moons varying in size from $0.1R_\oplus - 1R_\oplus$. All calculations assume the values of Q, μ and ρ stated in the equation above. The eccentricity and beta for Io is shown (orange dot) for comparison. All objects to the right and below the curved lines will be detectable by MIRI at 3pc assuming they are sufficiently well separated from their host star.

If such tidally heated exomoons exist and are sufficiently common (and thus nearby), **it may be easier to directly image an exomoon** with surface conditions that allow the existence of liquid water than it will be to resolve an Earth-like planet **in the classical Habitable Zone** from its primary.

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References: 1. Reynolds et al. (1987), 2. Segatz et al. (1988), 3. S. J. Peale (1978), 4. Kurucz (1970), 5. Spiegel & Burrows (2012), 6. Peters & Turner (2012) (Full citation for all references is given in Peters & Turner (2012) – full title and URL listed below)

For more details, see Peters & Turner, "On the Direct Imaging of Tidally Heated Exomoons", 2013 ApJ 798, 98 (On the arXiv at arxiv.org/abs/1209.4418)