Basic limits on exoplanet biosignature false positives: trickster planets

Edwin Kite (kite@uchicago.edu)

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Today: *Given realistic uncertainty in observational constraints on the planetary context of a bioindicator detection, what limits can be placed on rocky habitable-zone exoplanets as a source for abiotic false positives?*

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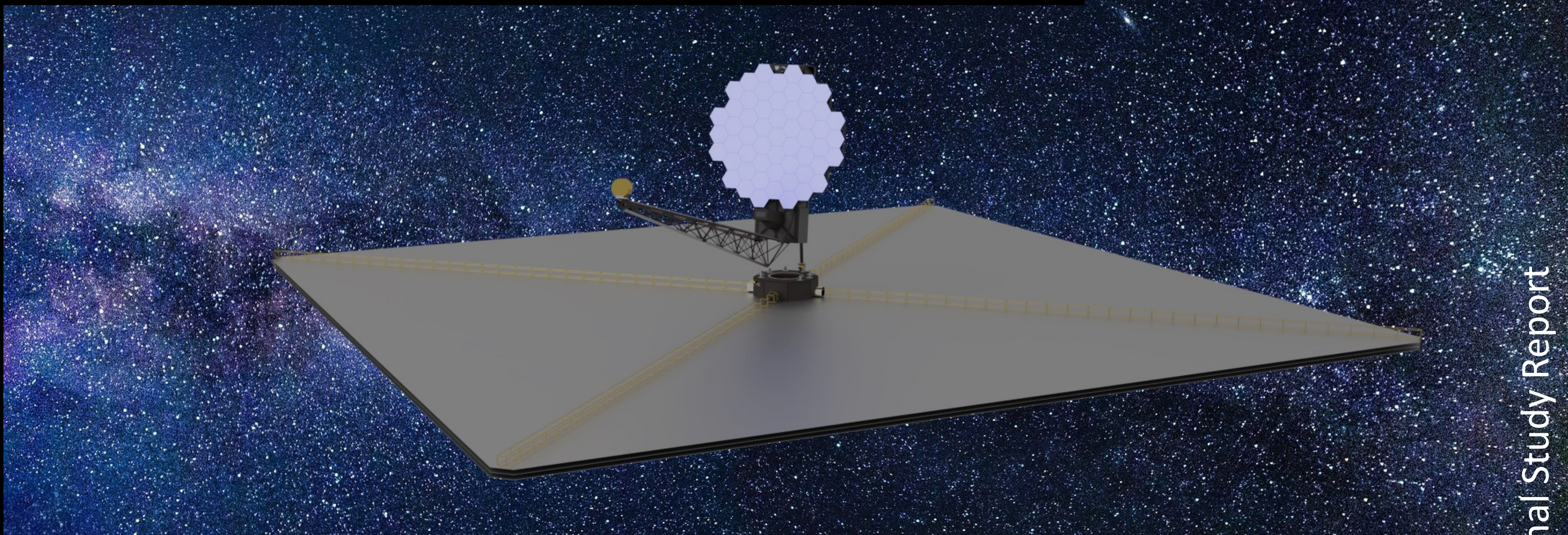
Astronomy’s future (in the US): entwined with the search for life on exoplanets



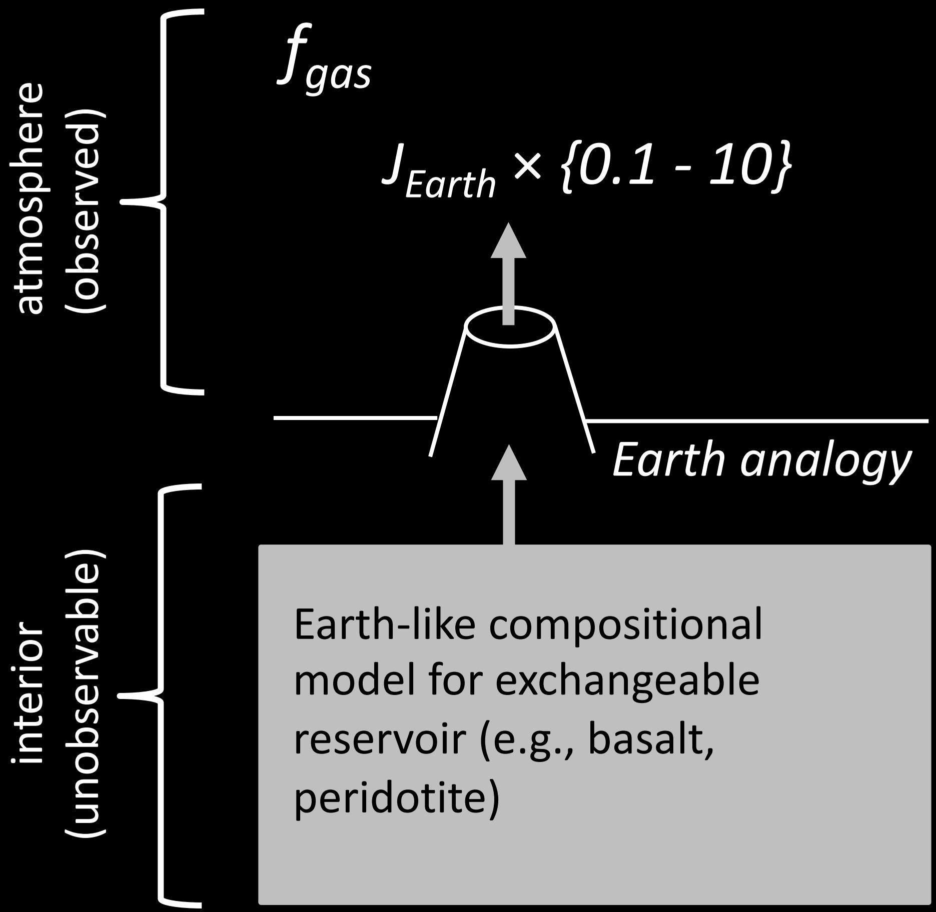
*“**Inspired by the vision of searching for signatures of life** [...] the survey recommends that the **first [flagship]** is a **large (~6 m aperture) infrared/optical/ultraviolet (IR/O/UV) space telescope** [...] search for **biosignatures** from a robust number of ~25 habitable zone planets [...]”*

National Academies Decadal Survey in Astronomy & Astrophysics, 2021

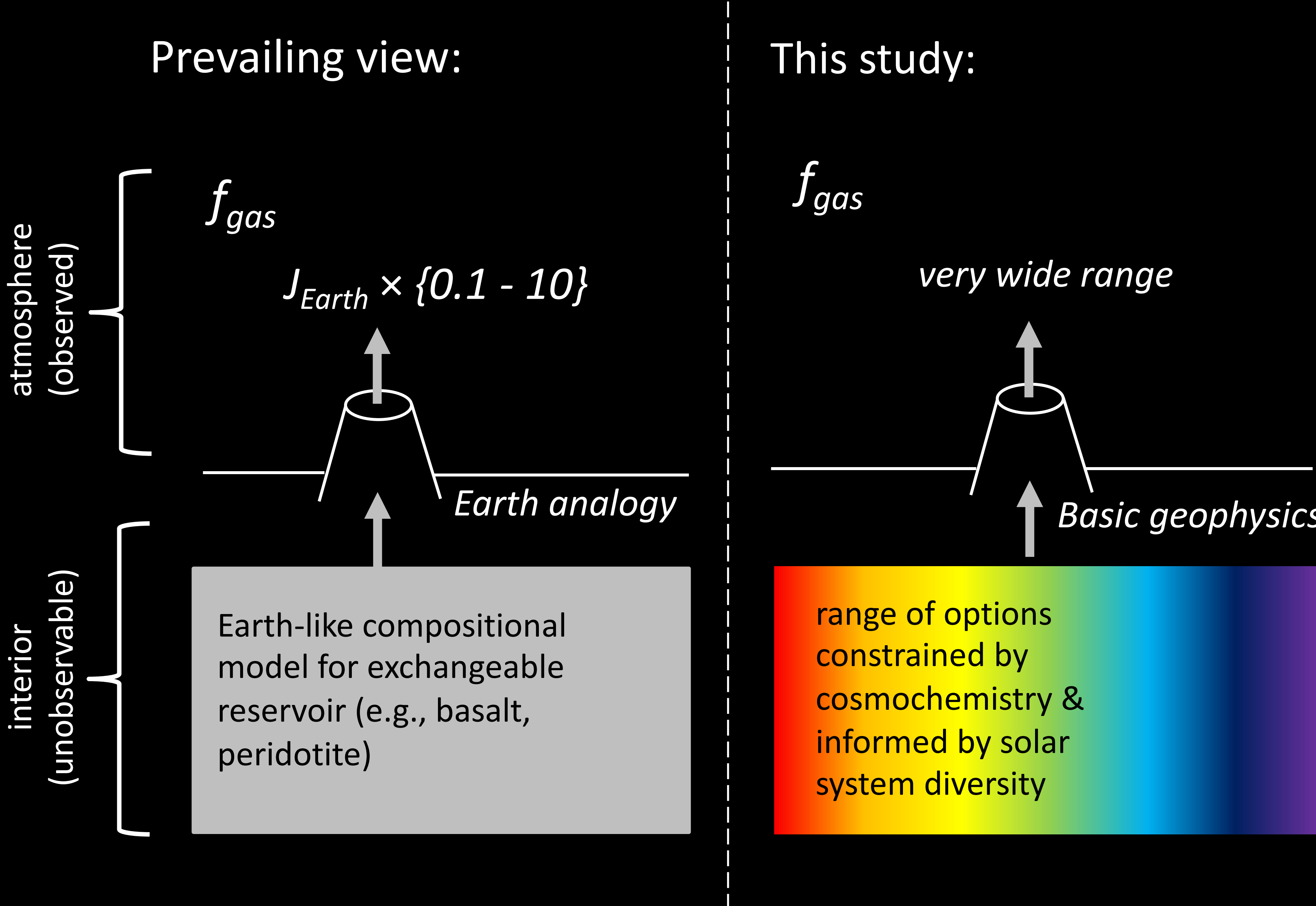
O_2, O_3, N_2O, CO_2, CH_4

e.g. Meadows et al. 2018, Schwieterman et al. 2018, DesMarais et al. 2002, Selsis et al. 2002, Thompson et al. 2022, Seager et al. 2005, Domagal-Goldman et al. 2011, Kasting et al. 2014.

Prevailing view:



e.g. Krissansen-Totton et al. 2018, Catling & Kasting 2017, Foley & Smye 2018, Lehmer et al. 2020, Guzman-Marmolejo 2013, Krisssansen-Totton et al. 2022, Thompson et al. 2022.



Forerunners of approach suggested here: e.g. Tyrell 2020, Moore et al. 2017, Kite & Ford 2018, Ranjan+ 2022.

The procedure for calculating the probability *P* that life has been detected on an exoplanet has problems

$$P(\text{life} \mid \text{data, context}) = \frac{P(\text{data, context} \mid \text{life})P(\text{life})}{P(\text{data, context} \mid \text{life})P(\text{life}) + P(\text{data, context} \mid \text{no life})P(\text{no life})}$$

$$= \frac{P(\text{data} \mid \text{context, life})P(\text{context} \mid \text{life})P(\text{life})}{P(\text{data} \mid \text{context, life})P(\text{context} \mid \text{life})P(\text{life}) + P(\text{data} \mid \text{context, no life})P(\text{context} \mid \text{no life})P(\text{no life})}$$

Catling et al. 2018

*bioindicator data (**D**)*

*observational constraints on planetary context of bioindicator detection (**C**)*

Problems:

1) P(*life*) is uncertain by ~10^{122} orders of magnitude.[1]

2) false positive probability P(***D*** | ***C***, *no life*) is hard to evaluate. Current/planned telescopes offer weak constraints on ***C***, and we know little about how habitable-zone rocky planets form or evolve.[2]

1. e.g. Lacki 2016, Tegmark 2014, Monod 1970, Balbi & Grimaldi 2020. 2. Johansen et al. 2021. Burger et al. 2020.

Uncertainty in resurfacing rate is wide, implying wide uncertainty in abiotic gas fluxes

ξ = rate of release (kg/yr) of mass at the solid surface of planet, normalized to planet mass

World	ξ (s^{-1})	Notes
Earth	2×10^{-11} yr^{-1}	including intrusions
Mars	$<1 \times 10^{-12}$ yr^{-1}	multi-Myr average
Enceladus	6×10^{-10} yr^{-1}	
Io	3×10^{-8} yr^{-1}	
Venus	Unknown	Our nearest-neighbor planet.
Theoretical upper limit for magmatism	$\sim 10^{-7}$ yr^{-1}	uncertain partial melt rheology → true upper limit could be higher

Thought experiment: what if Earth's Late Veneer had not been mixed into the mantle?
(*e.g. Schaefer & Fegley Icarus 2010*)

e.g. Kite et al. 2009, Noack et al. 2017, Dorn et al. 2018, Zandanel et al. 2021, Spaargaren et al. 2020

Clathrate runaway: very high peak rate of ξ

Step 1: CO_2-CH_4 clathrate forms at waterworld seafloor.

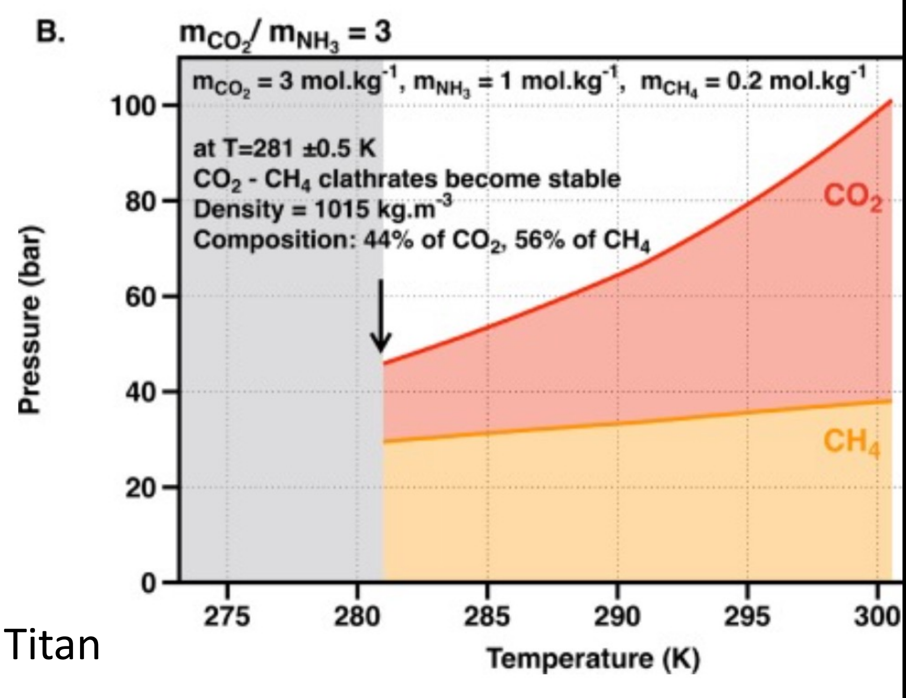


figure from Marounina et al. 2018

Step 2: Star brightens on main sequence and waterworld warms, CH_4 and CO_2 released from clathrate.

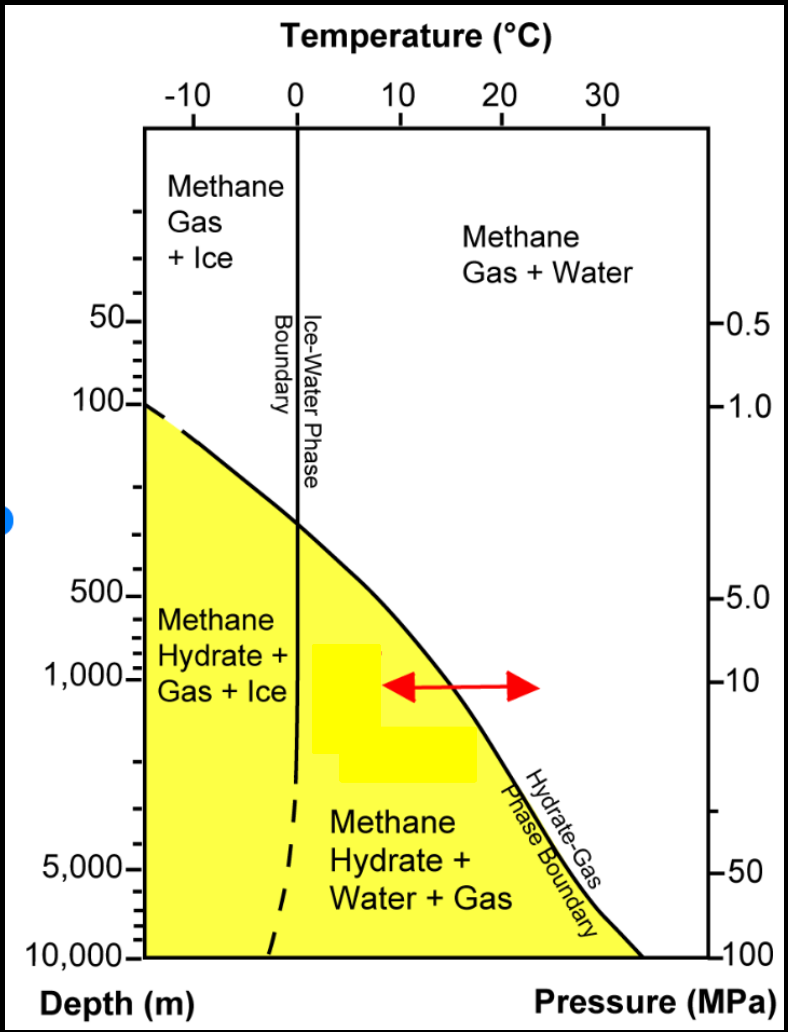


figure from Bohrmann & Torres 2006

q.v. proposals of CH_4 + CO_2 coexistence as a biosignature

Also: mantle overturn events, Large Igneous Provinces

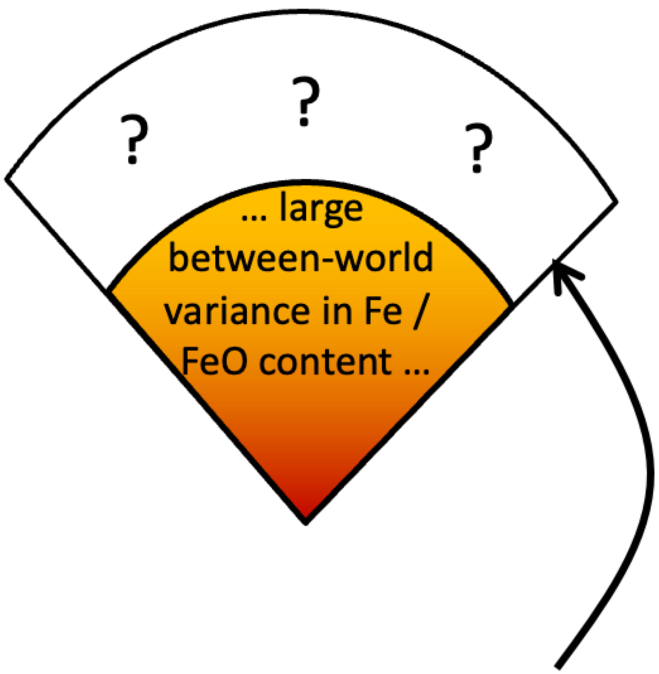
Can planet density distinguish between an Earth clone and a migrated super-Europa?

Unfortunately not!

One example of a “trickster planet” …

The shell of uncertainty

Even supposing perfect mass and transit-radius measurements …

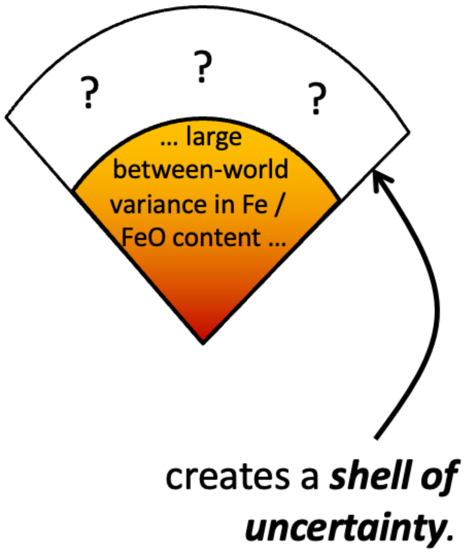


creates a ***shell of uncertainty***.

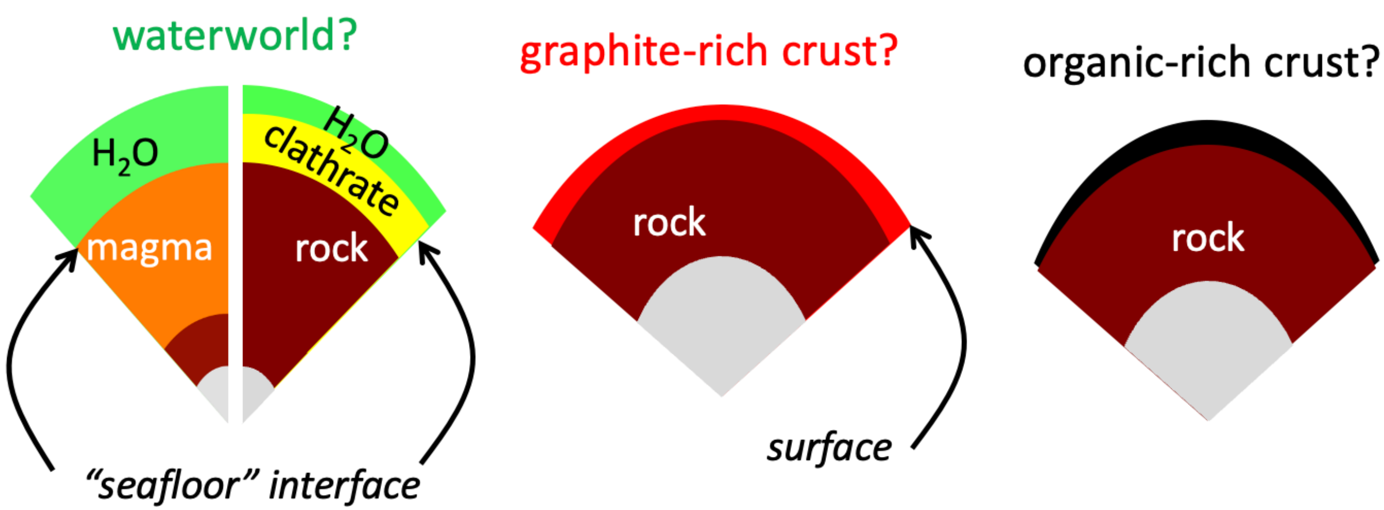
e.g. Elkins-Tanton & Seager 2008, Dorn et al. 2015, Santerne et al. 2018, Bower et al. 2019, Doyle et al. 2019, Hu et al. 2021

“Trickster planets”

Even supposing perfect mass and transit-radius measurements …



Any cosmochemically-plausible thing for which there is a plausible origin scenario can go in the shell, and many of these can produce abiotic false positives …



migrated super-Europa?

migrated super-Mercury?

migrated super-Ceres?

Magma
Solid rock
Fe-metal core
High-molecular-weight volatile envelope (e.g. H_2O)

e.g. Marchi et al. “Vesta and Ceres” book 2022, Peplowski et al. 2016, Hughes et al. 2018, Miyazaki & Korenaga 2022

Example: H_2 from water-rock reaction

- Earth: ~20 km^3/yr of basalt magma.
- Yields up to 3 x 10^{11} kg/yr H_2 in steady state.
- Energy for escape-to-space of this H_2 ~1 TW → 0.01 W/m^2.
- For efficiency = 0.01, this is much more than the XUV flux at Earth today.
- Earth's current rate of magmatism is not the upper limit on the exoplanet rate of magmatism.
- Therefore, H_2 build-up from serpentinization is possible.

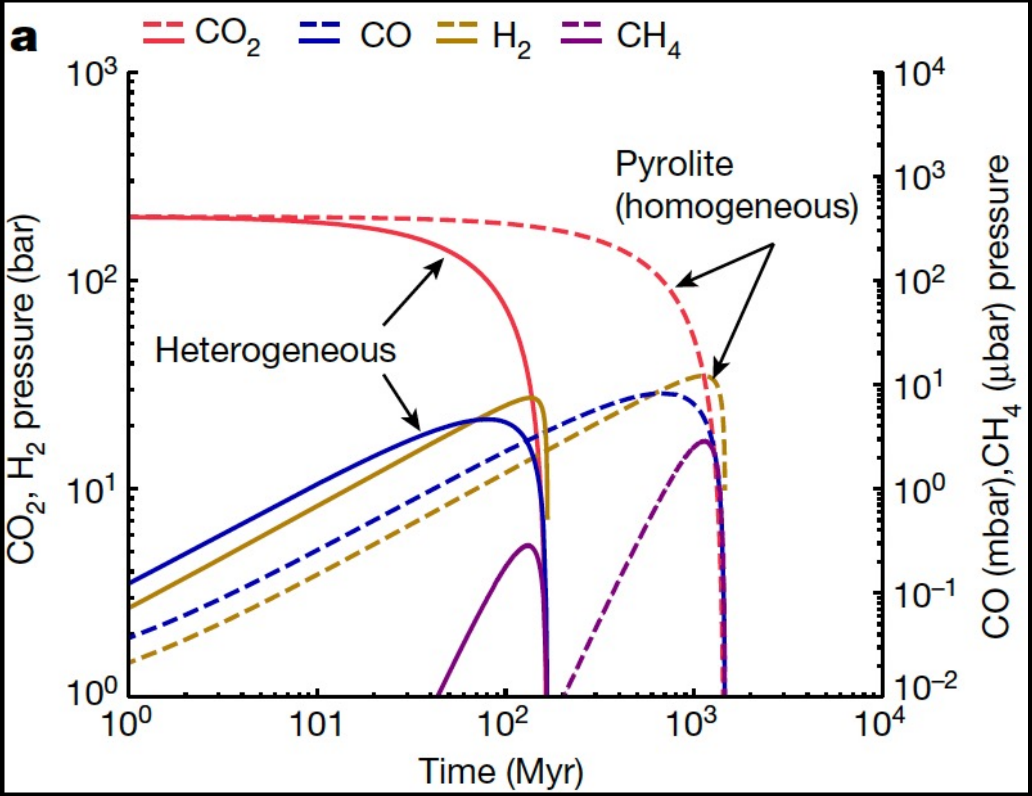


figure from Miyazaki & Korenaga Nature 2022

A potential disequilibrium biosignature / feedstock for CH_4

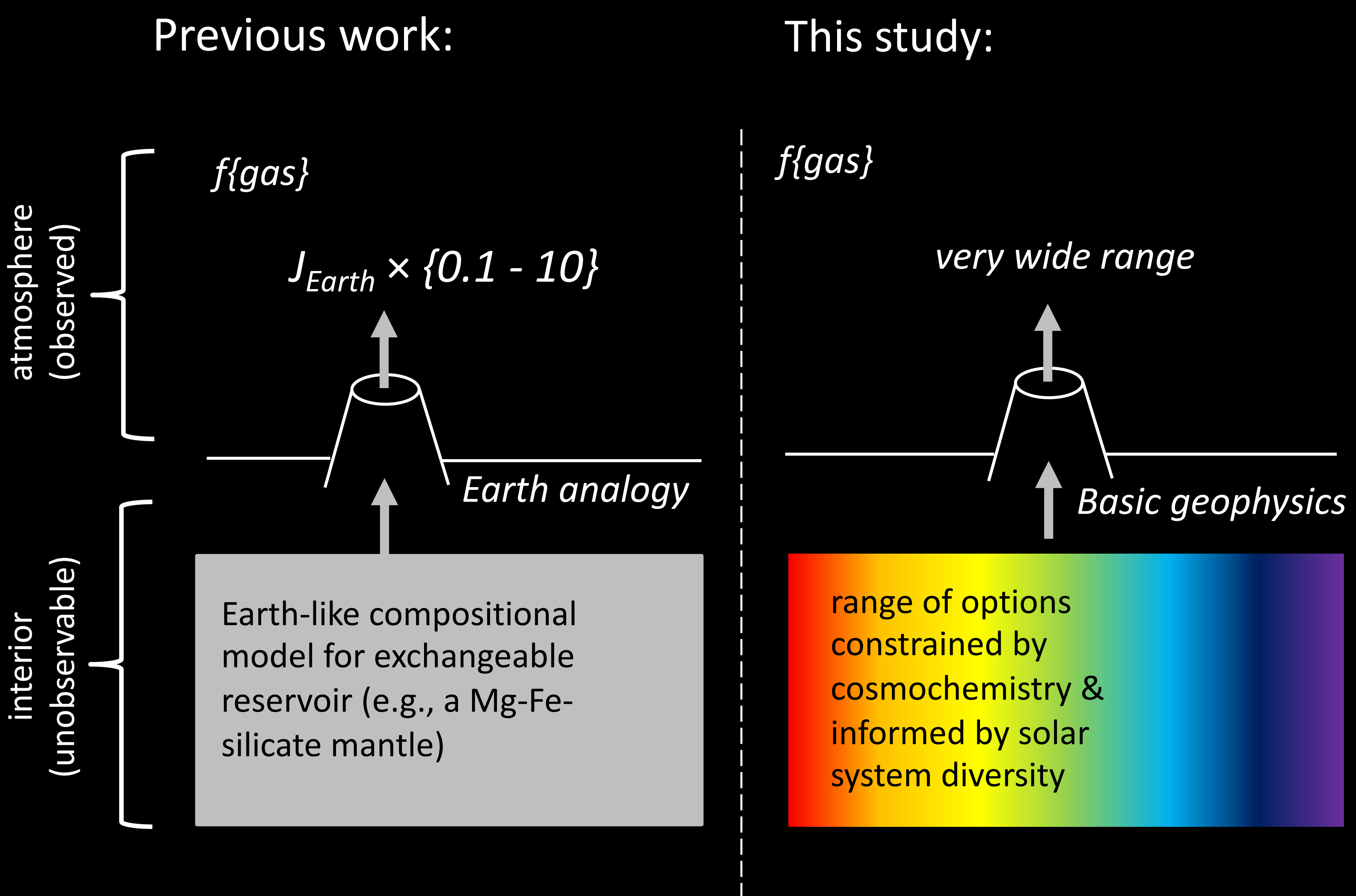
qv. Guzman-Marmaolejo et al. 2013 Astrobiology

Are there ways around the problem of “trickster planets” ?

- Perhaps exoplanets are less diverse than expected?
- Statistical gradients across the inner HZ boundary are not a good test: many false-positive-producing processes require liquid water.
- Constraining the atmospheres of different planets in one system might constrain the extent of *orderly* whole planet migration, but migration can involve planet-swapping, leaving initial volatile inventories *disordered* in terms of distance from the star (Izidoro et al. 2021).

Summary: Abiotic correction is harder than biosignature detection.

The ~6 m diameter telescope recommended by the National Academies may be under-powered for its exoplanet life detection mission.



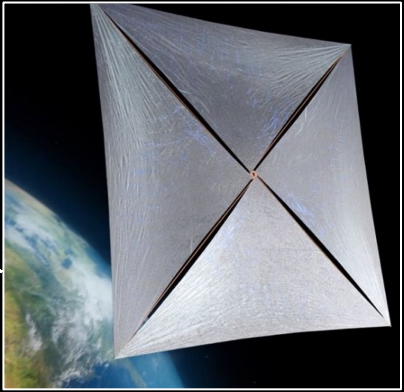
Summary: **Abiotic correction is harder than biosignature detection!**

The ~6 m diameter telescope recommended by the National Academies may be under-powered for life detection.

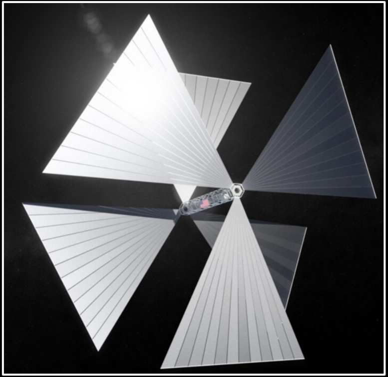
Sufficient contextual information might be acquired with **transformative technology.** Some options:

1) Space telescopes with very large light gathering area (Bixel & Apai 2021). This would greatly expand the database of non-living planets against which we could test and improve our false-positive models, and might open the search for biosignatures that are less likely to have an abiotic source (Seager et al. 2013, but see Zhan et al. 2021).

2) Technology development for an interstellar probe: one current limiting factor is the cost of lasers (Lubin, "The Path", 2022).



3) Technology development for a mission to the solar gravity focus ~550 AU from the Sun (Turyshev & Toth 2022).



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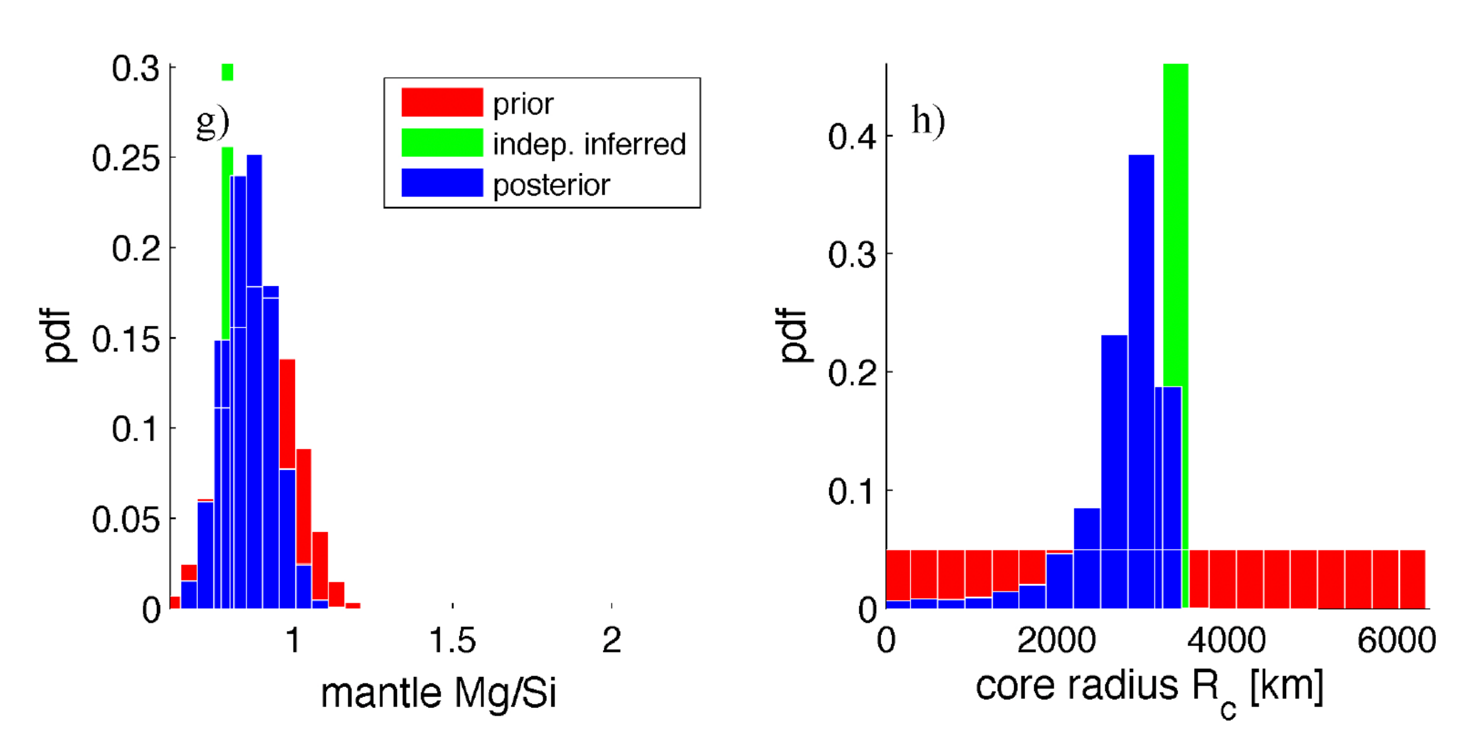
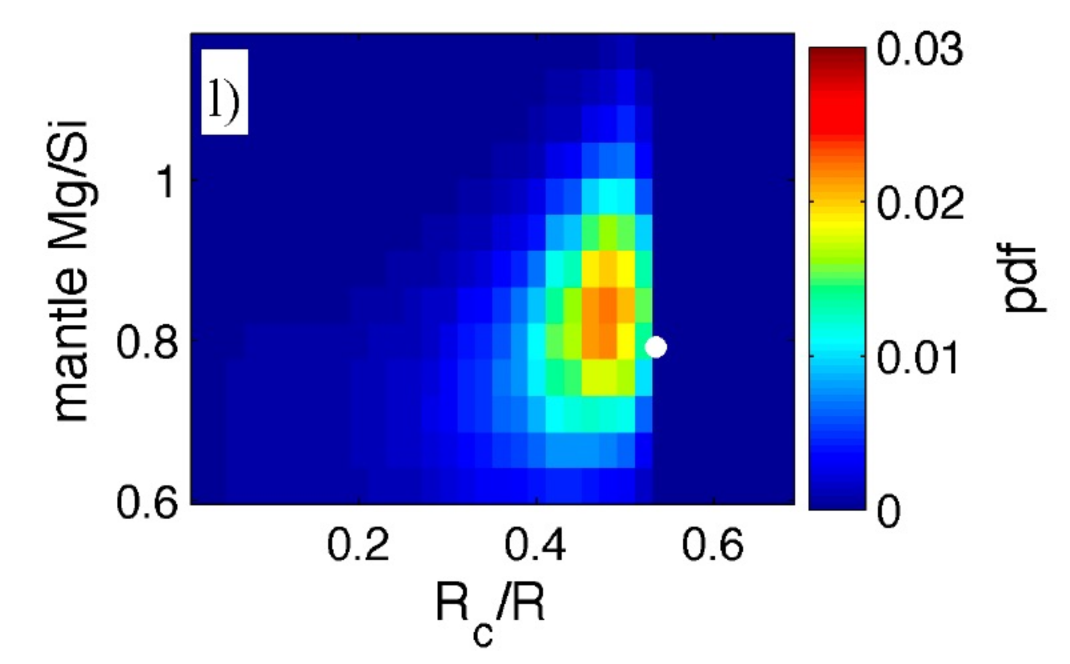
Bonus Slides

Dorn et al 2015 A&A





Earth
M, R, and
stellar abundance constraints

False positives for the “$CH_4 + O_2$” bioindicator

- Rapid burial/cycling of tholin (thermal decomposition)
- Fast CH_4 production
- Recent CH_4 delivery
- Large moon (Rein et al. 2014 PNAS)
- Titan like leakage (need net production and verry slow destruction)
- Shaw 2016 Geology

We can’t use high O_2 levels as a fingerprint for an abiotic false positive.

O_2 can be produced abiotically by H_2O photolysis followed by H_2 escape. The HABEX Team Report, relying in part on Harman (2018), argues that O_2 is a good biosignature, on Sunlike stars, provided that atmospheric pressure is high, so that high temperatures are required to defeat the tropospheric cold trap and allow H_2O to get to high enough altitudes that it can be photolyzed. However, (i) atmospheric pressure can vary by orders of magnitude over a planet’s geologic history (e.g. Mars), so that observations of a planet’s pressure today do not adequately constrain the time-integrated history of abiotic O_2 accumulation, and (ii) what matters is not the atmospheric pressure but rather the mixing ratio of H_2O to noncondensible gas, which is exponentially sensitive to T and so permits rapid O_2 build-up for habitable ($T<400K$) temperatures even when there is 10 bars of background gas (Wordsworth & Pierrehumbert 2013). Moreover,

- N_2 production by NH_3 photolysis is unlimited so can dilute O_2.
- O_2 can build up to high levels (>1 bar) before suppressing photosynthesis. On Earth it’s limited by fire.

Therefore, we can’t use high O_2 levels as fingerprint of false positive

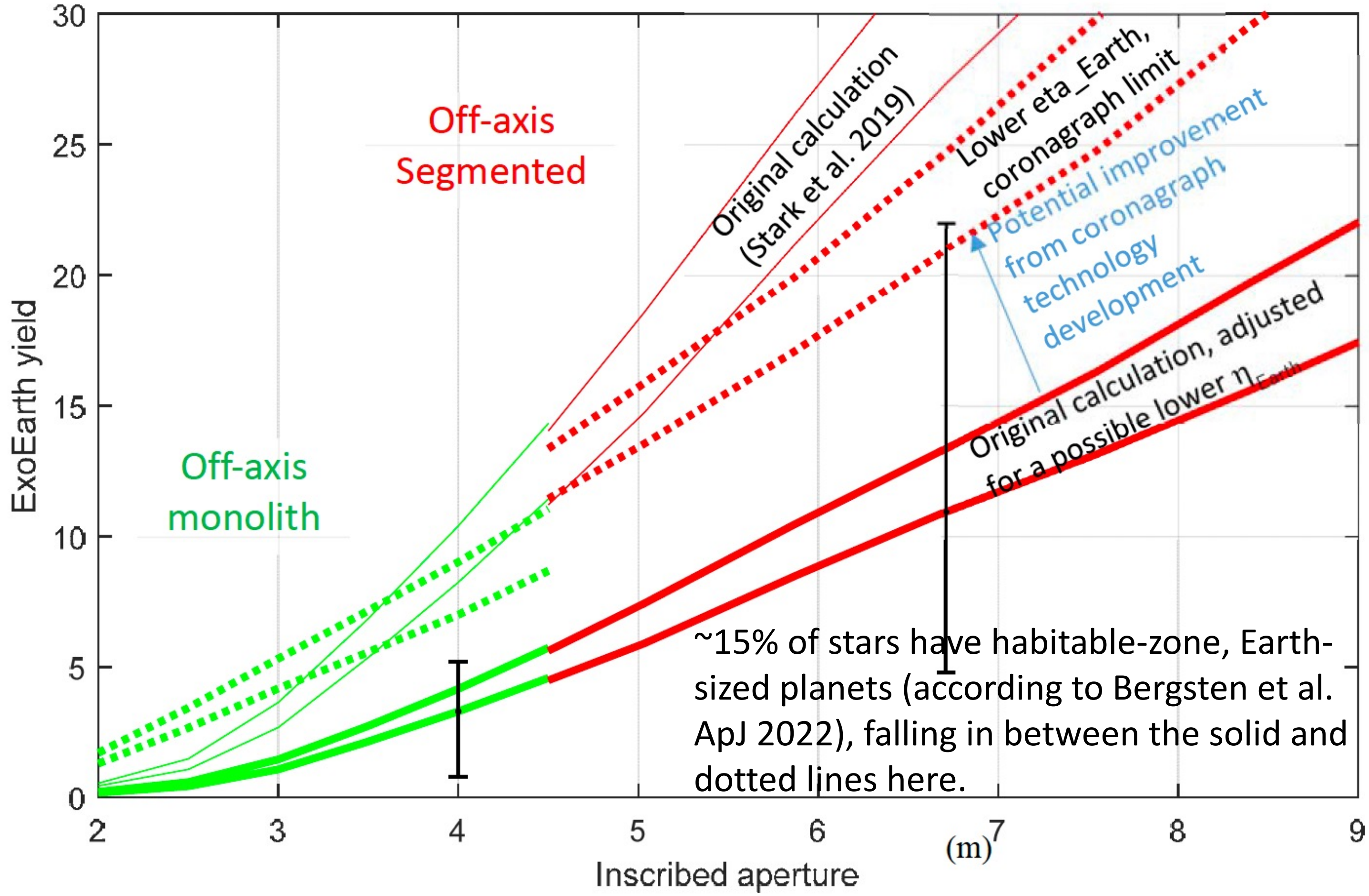


FIGURE I.2 Exoearth yields, showing the effects of a reduced η_{Earth} as well as potential improvement from future technology development in coronagraphs. The thin pair of curves labeled "Original calculation (Stark et al., 2019)" is the same as the red and green curves in Figure I.2. (The two curves span the range between "high-throughput" and "low-throughput" scenarios.) The thick curves at the bottom show the reduction based on the assumption that η_{Earth} is 2.5 times lower than what was assumed in the LUVOIR and HabEx reports. Black uncertainty bars, placed at the inscribed apertures for HabEx 4H and LUVOIR-B, represent uncertainties in η_{Earth}, exozodi, and astrophysical realizations as described in Stark et al. Dotted red lines represent theoretical limits of coronagraphs for the pessimistic 2.5 times lower η_{Earth} case. The blue arrow represents a gap between current coronagraph designs and theoretically achievable performance, which can be closed by continued coronagraph technology development, and make up for a smaller η_{Earth}. (New designs created after the LUVOIR and HabEx reports appear to already close about 40 percent of this gap; see Section I.3.5.) The panel used a similar methodology as Stark et al. (2019) to produce the modified curves shown here.

National Academies Decadal Survey in Astronomy & Astrophysics 2021