GEOS 22060/ GEOS 32060 / ASTR 45900

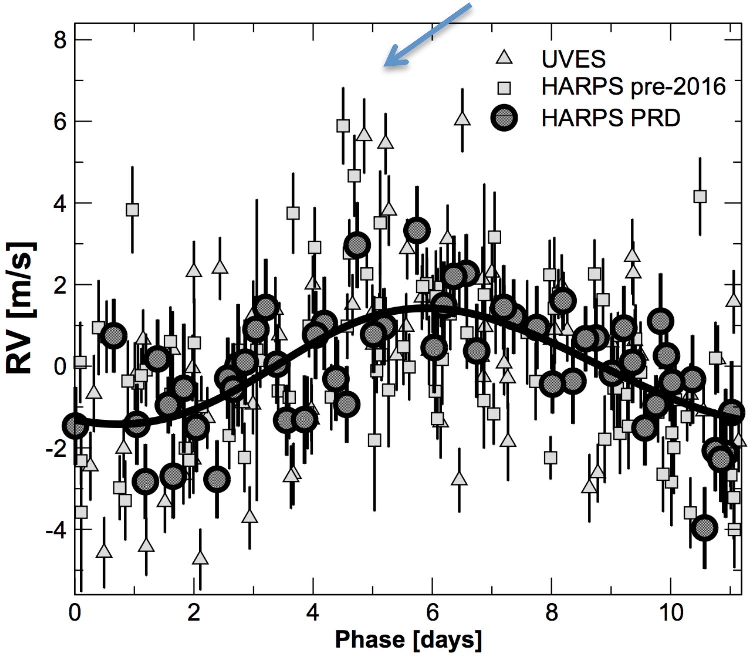
What makes a planet habitable?

Exoplanets

Lecture 18

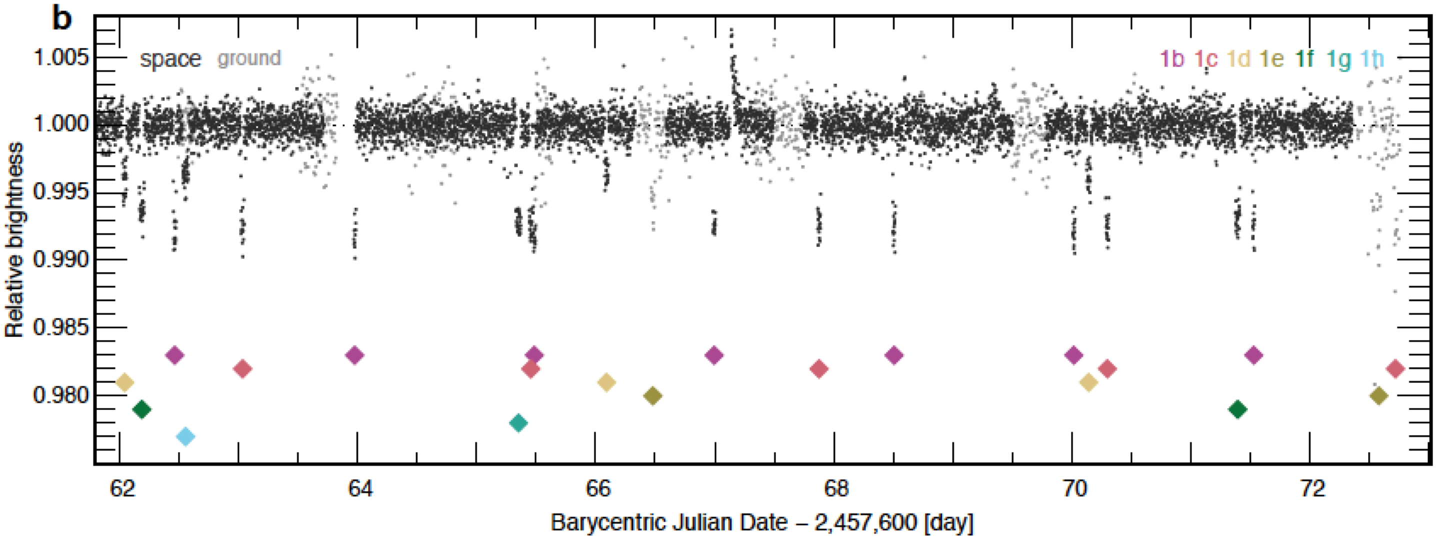
Thursday 5 March 2020

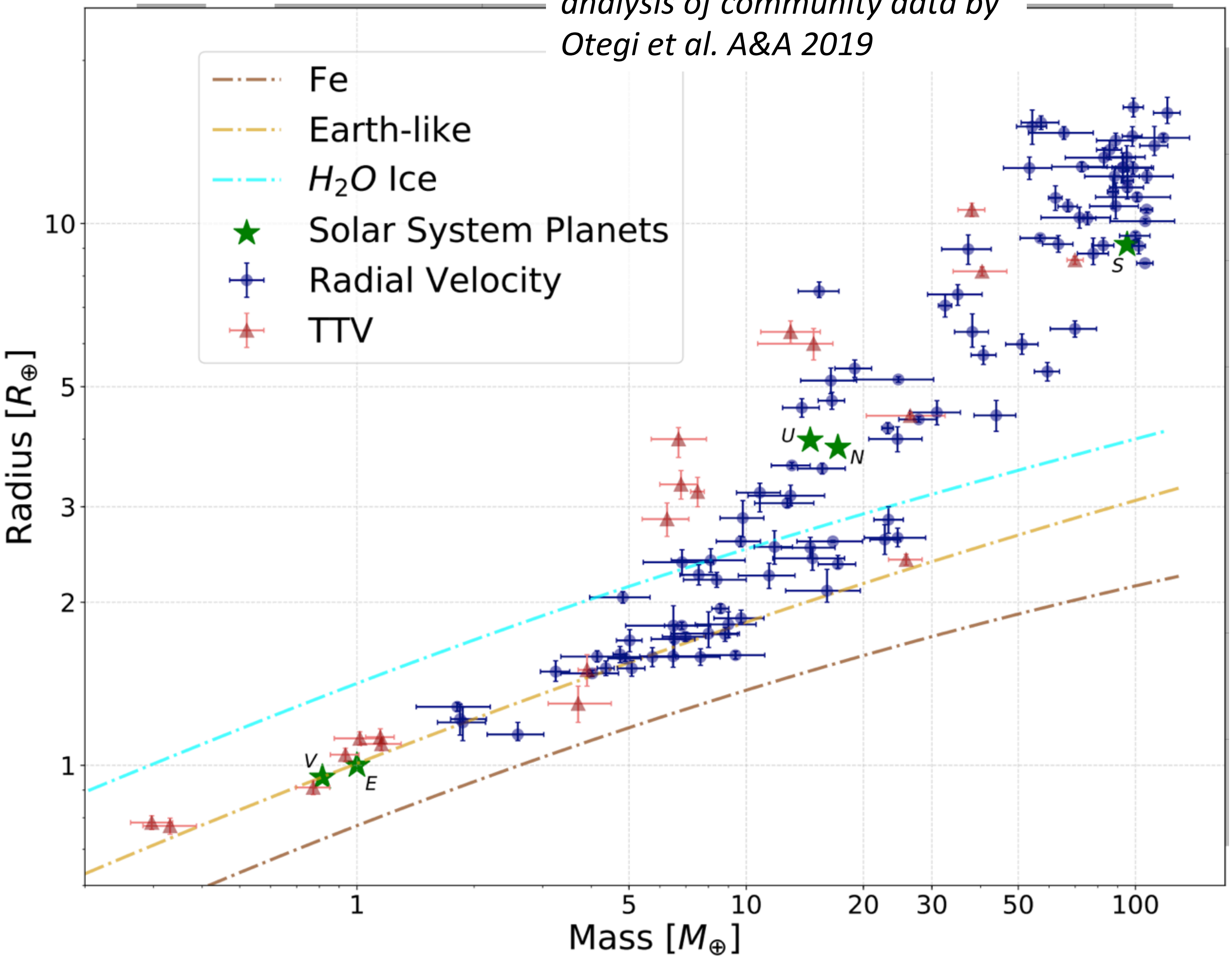
Exoplanets are detected mainly through radial velocity measurements and transits



Proxima Centauri b
Anglada-Escudé et al. 2016

TRAPPIST-1 (Gillon et al. 2016)





analysis of community data by
Otegi et al. A&A 2019

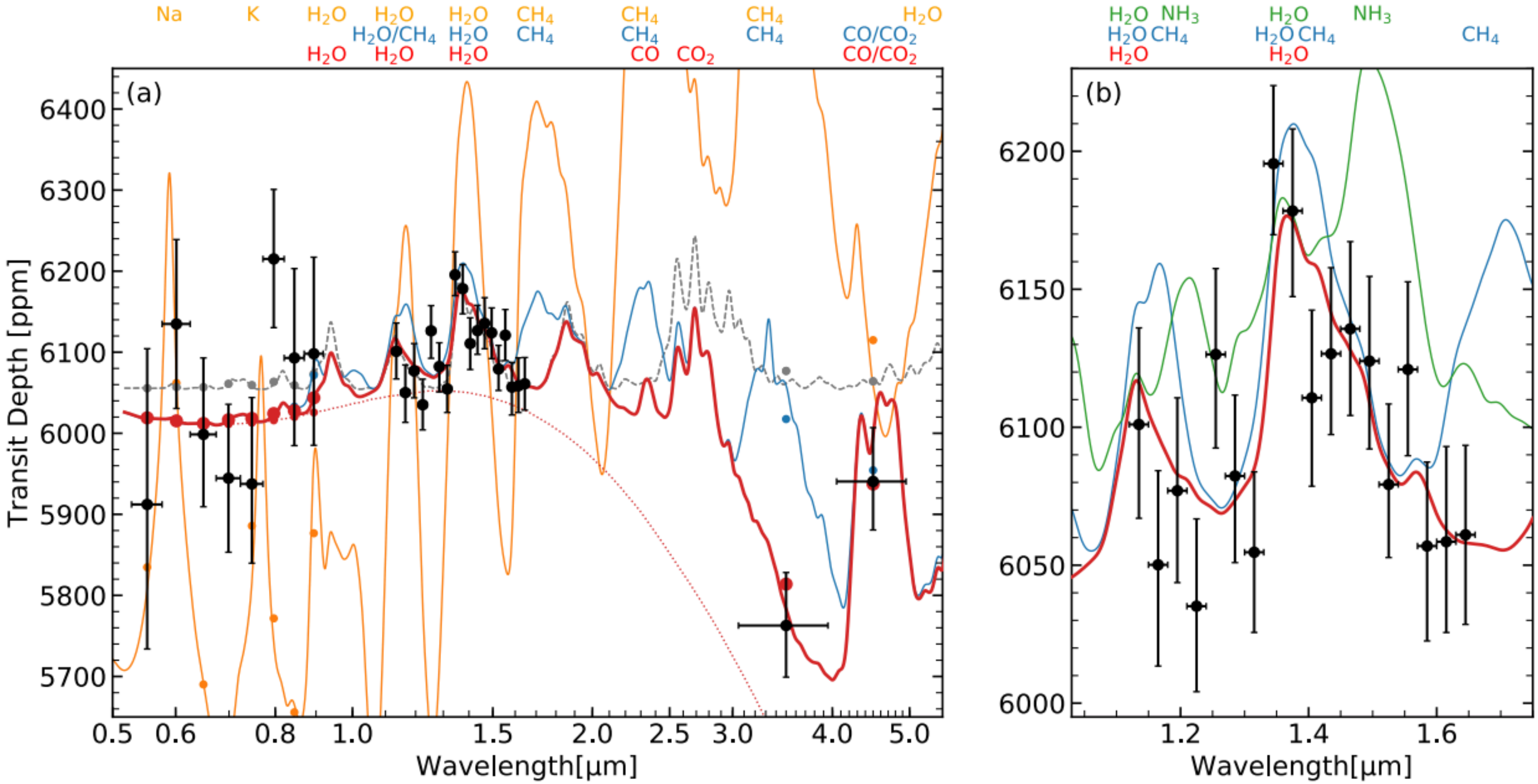
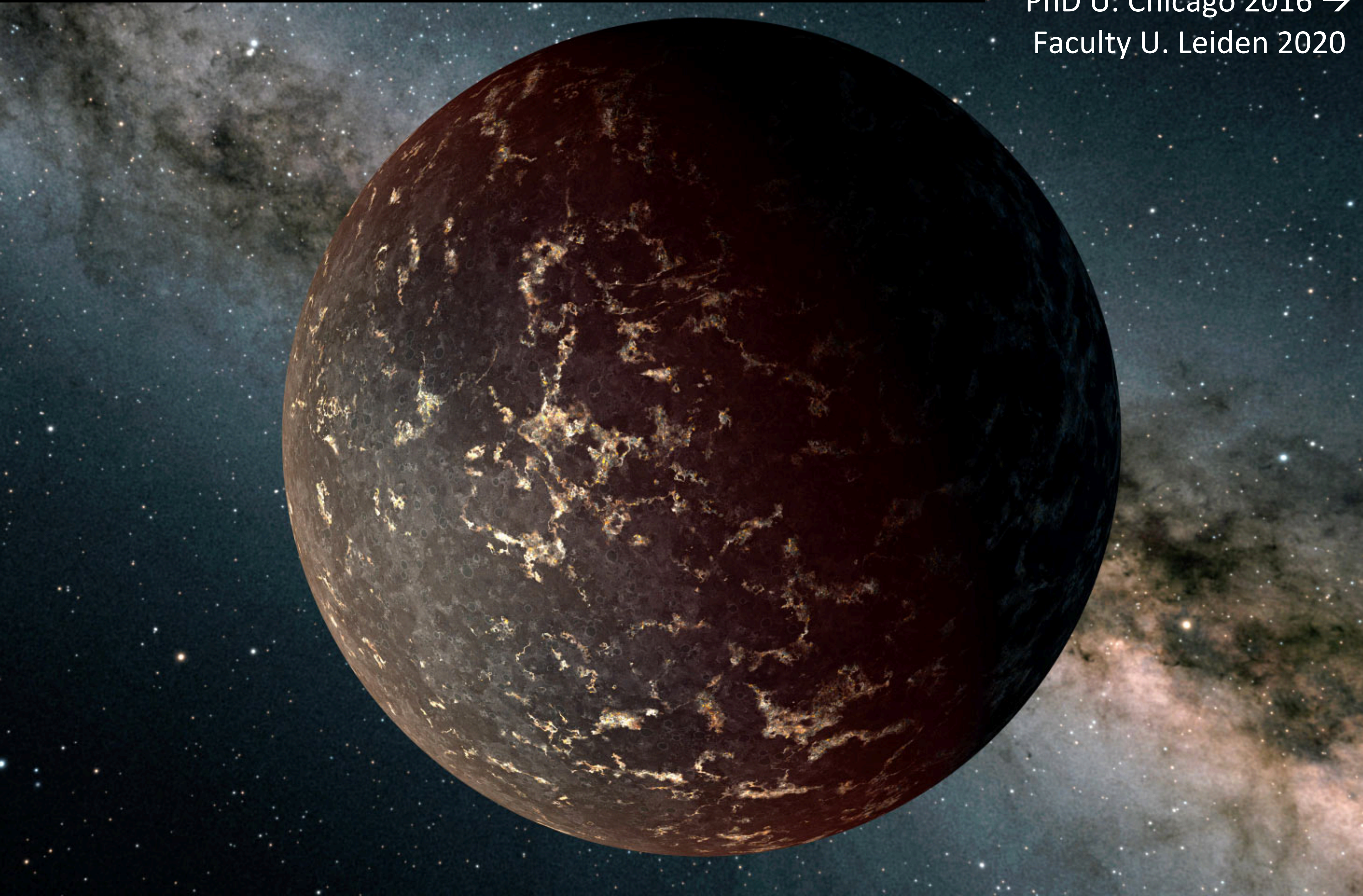


Figure 2: Transmission spectrum of GJ 3470b. Black data points show transit depth measurements from the HST/STIS, HST/WFC3, and Spitzer/IRAC observations analyzed in this study. Vertical and horizontal black bars indicate the 1σ transit depth uncertainties and the wavelength ranges of the measurements, respectively. The best fitting model with near-solar water abundance, Mie scattering clouds, and strong methane depletion is shown by the red curve, with circles indicating the bandpass integrated model. Water absorption results in increased transit depth at 1.4 µm (zoom in panel b). Finite-sized Mie-scattering particles (~0.6 µm) result in a characteristic drop off in cloud opacity beyond 2 µm (red dotted curved). Adding 100 ppm methane to the best fit model results in significant disagreement to the data at 1.6 and 3.6 µm (blue curve). Similarly, adding 100 ppm ammonia results in disagreement at 1.5 µm (green curve in panel b). A cloud-free solar metallicity model (orange curve) and the best-fitting gray cloud model (gray dashed curve) are shown in panel (a) for reference. Both provide a poor fit to the data. The dominant

Benneke et al. Nature Astronomy 2019

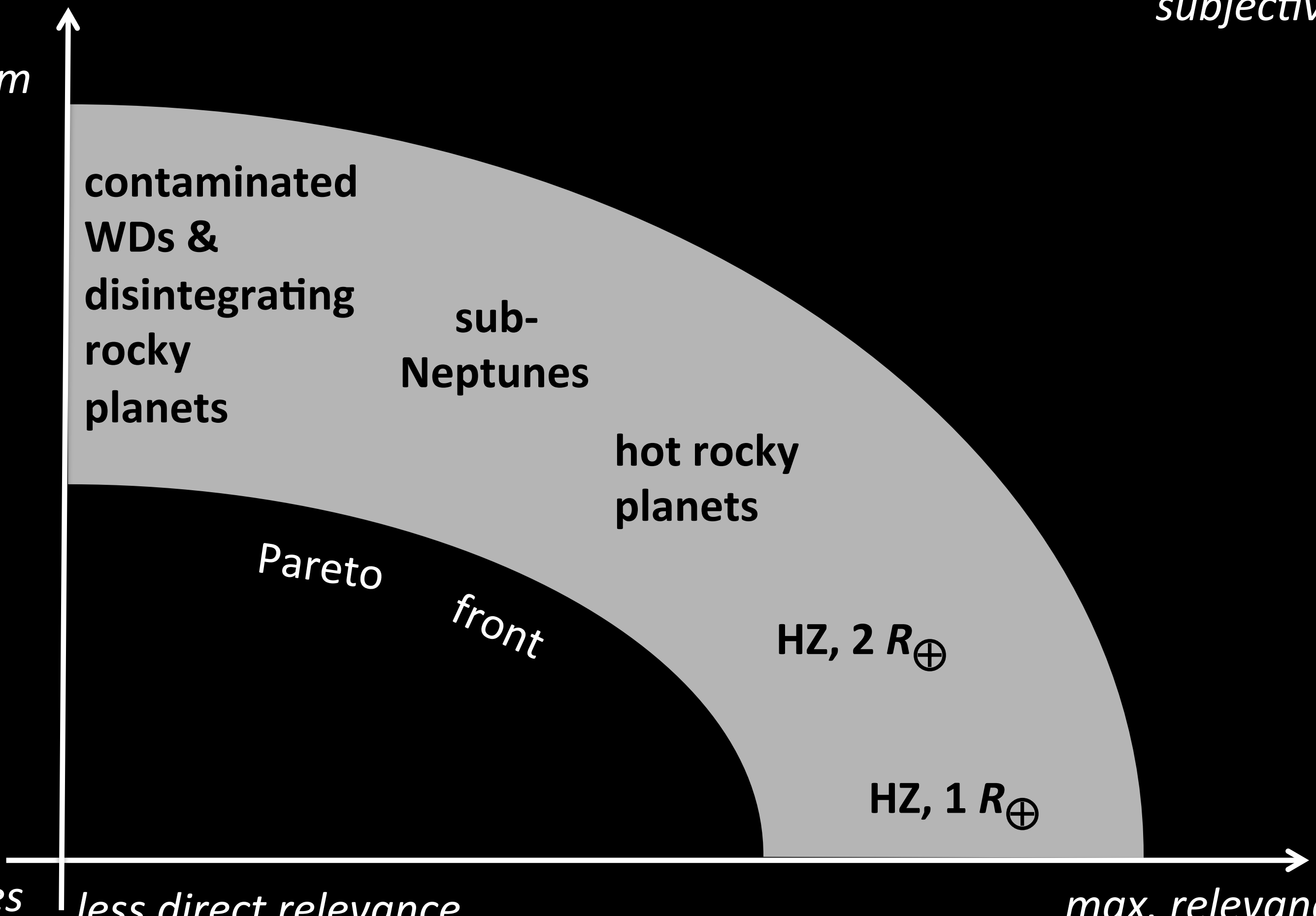
LHS 3844 b : First light from a exoplanet's surface (*Kreidberg et al. 2019*)



Laura Kreidberg
PhD U. Chicago 2016 →
Faculty U. Leiden 2020

Habitability insights from uninhabitable planets

subjective plot!



lots of data,
less attention from
first-principles
modelers

contaminated
WDs &
disintegrating
rocky
planets

sub-
Neptunes

hot rocky
planets

Pareto front

HZ, 2 $R_\oplus$

HZ, 1 $R_\oplus$

not much data,
lots of attention
from first-principles
modelers

less direct relevance
to habitability

max. relevance
to habitability

inspiration: Uri Alon's "How to Choose a Good Scientific Problem / Materials for Nurturing Scientists"

Exoplanet habitability

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE NUMEROUS

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

- MG/SI/FE
- WATER
- CARBON

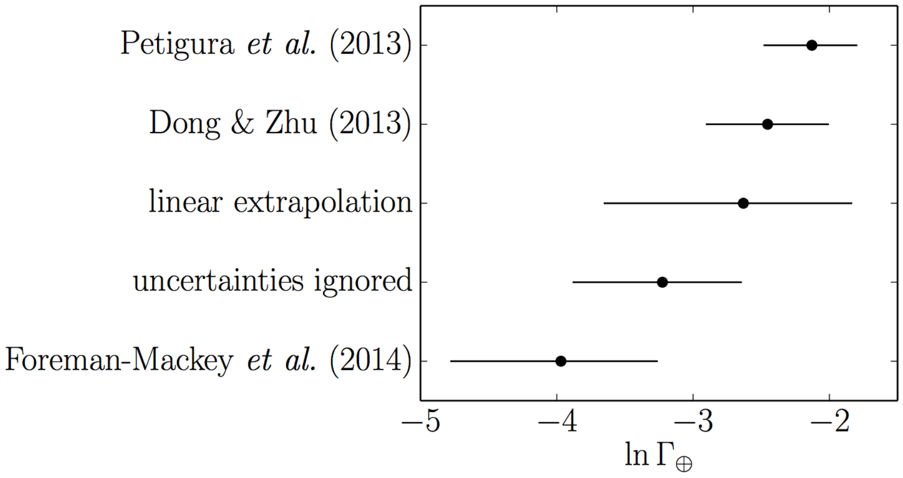
THE M-STAR OPPORTUNITY

- PROBLEMS FOR HABITABILITY FOR PLANETS ORBITING M-STARS

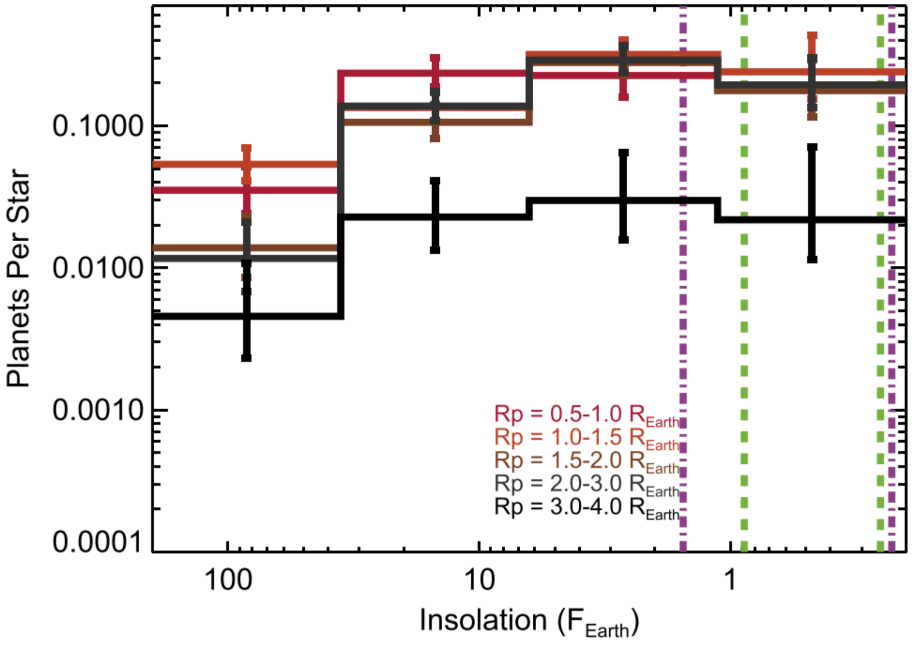
FUTURE MISSIONS

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE NUMEROUS

Sunlike (FGK) stars:

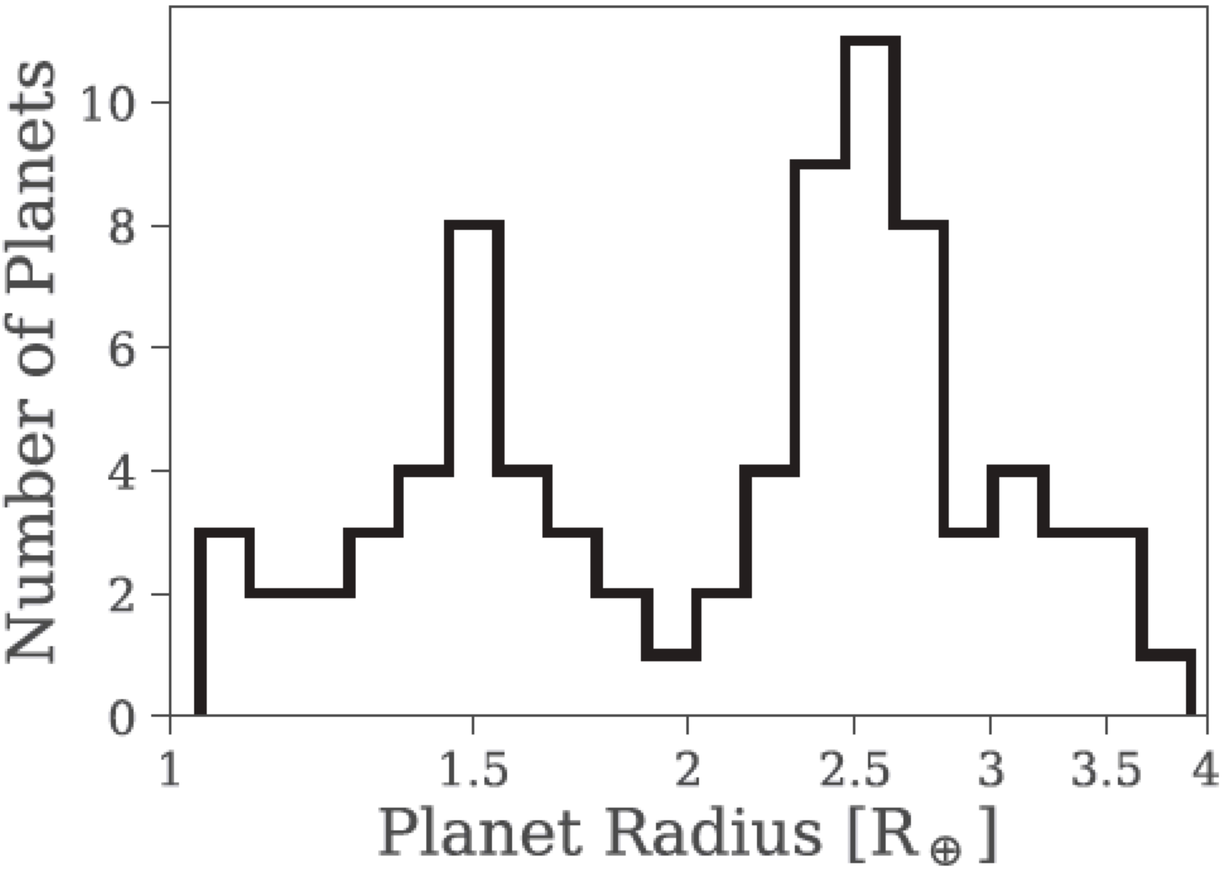


Red dwarf (M) stars:

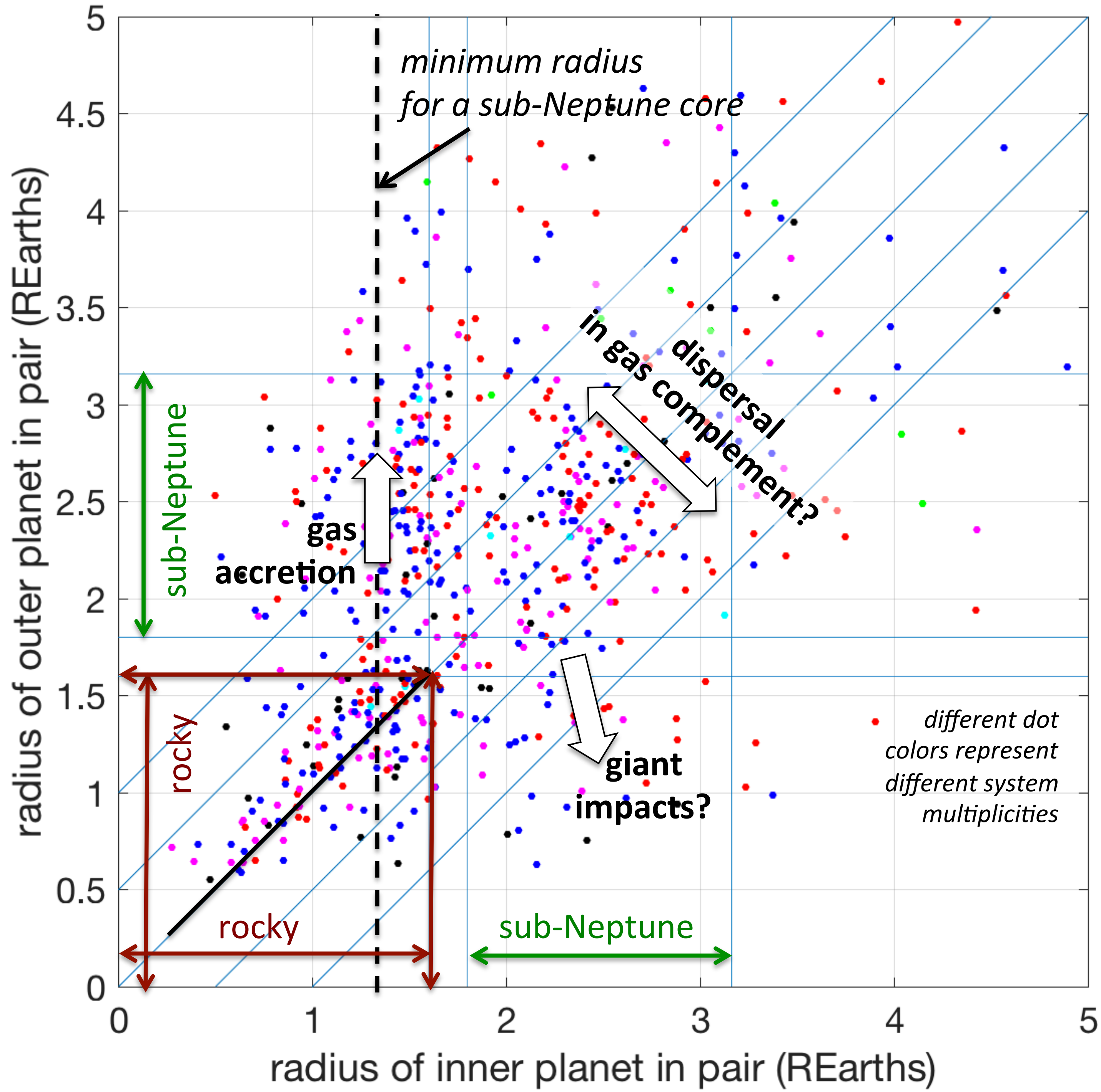


$$\Gamma_\oplus = \left.\frac{\mathrm{d}N}{\mathrm{d}\ln P\;\mathrm{d}\ln R}\right|_{R=R_\oplus,\,P=P_\oplus}$$

Dressing & Charbonneau ApJ 2015



Van Eylen et al. 2018



Rocky planet densities mostly consistent with Earth-like composition (e.g. Dai+ 2019)

Radii from Kepler DR25 + Gaia DR2 + CKS

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

- HYDROGEN
- MG/SI/FE
- WATER
- CARBON

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY - HYDROGEN

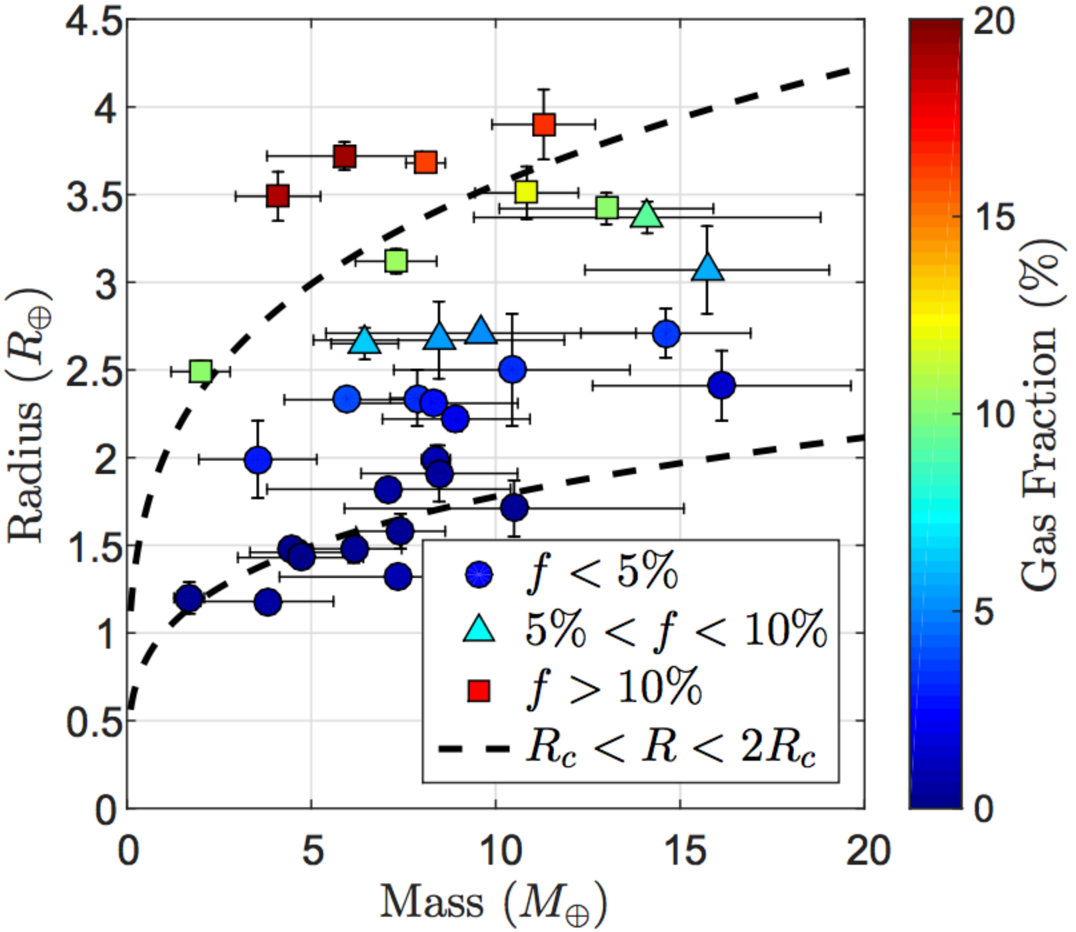
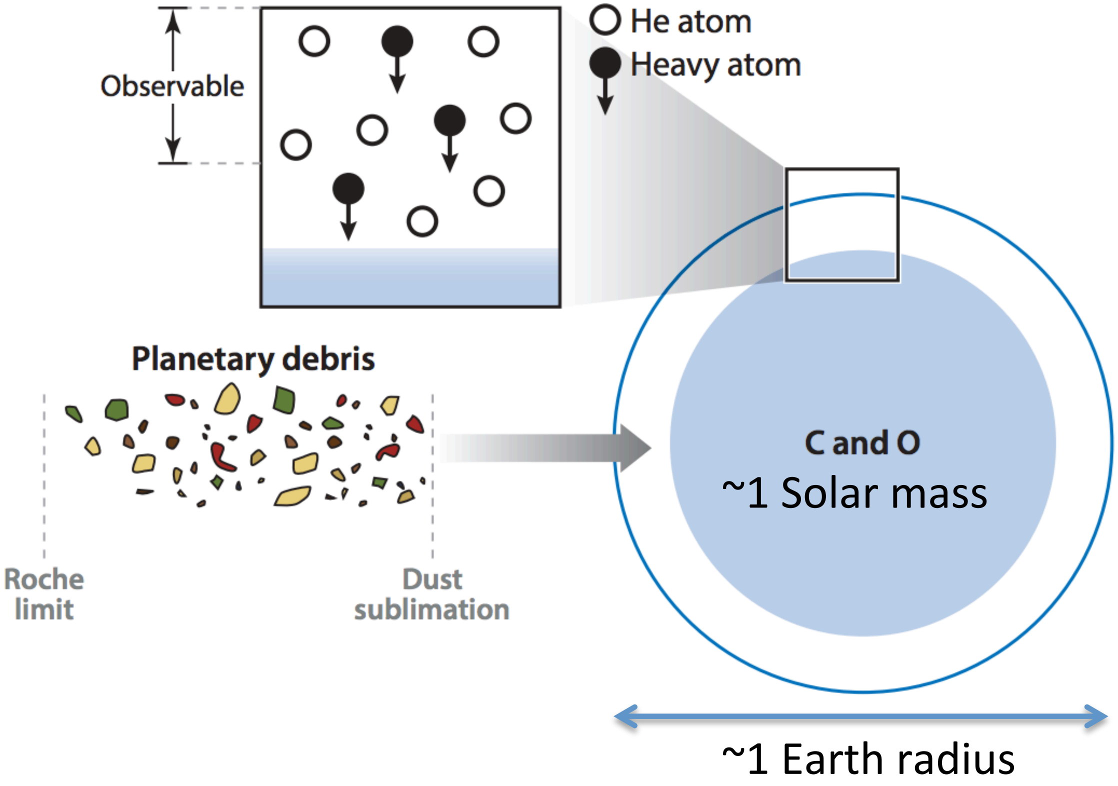


FIG. 2.— Observed super-Earth population (see text for details) from Weiss & Marcy (2014). The planets are grouped according to their gas mass fraction f, estimated by Equation (38), with low-density planets marked by triangles ($5\% < f < 10\%$) or squares ($f > 10\%$). The planet markers are also color-coded according to f. The two dashed black lines mark the radius of the rocky core $R_c(M_c)$ and $2R_c(M_c)$. Planets with substantial atmospheres are expected to be found roughly between the two lines.

Ginzberg et al.
ApJ 2016

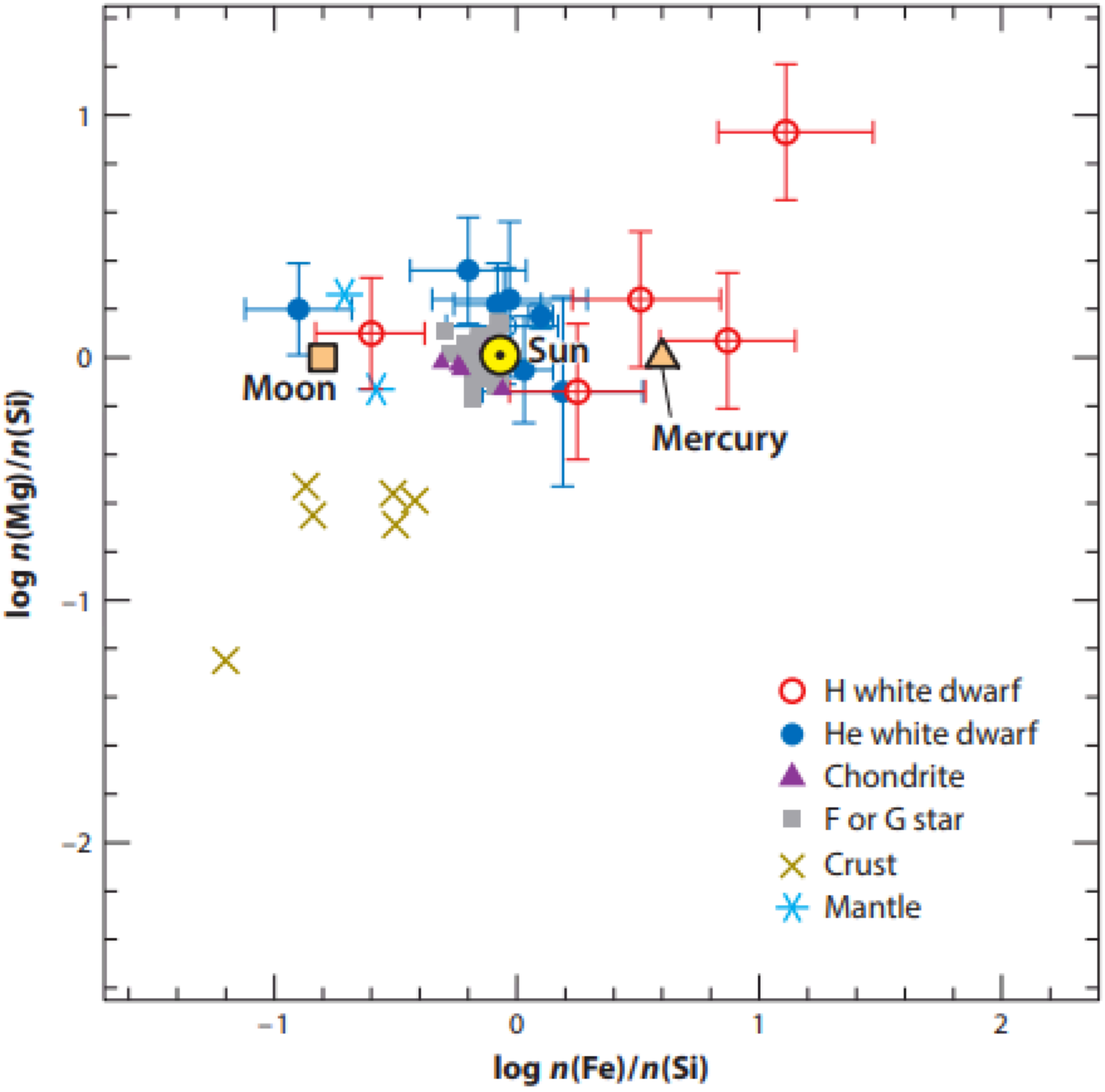
HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

- MG/SI, MG/FE, e.t.c.



Constrained mainly by compositions of white dwarfs that are accreting material fderived from tidally shredded planets.

Jura & Young, 'Extrasolar cosmochemistry,' Annual Reviews, 2014



Jura & Young, ‘Extrasolar cosmochemistry,’ Annual Reviews, 2014

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

- WATER

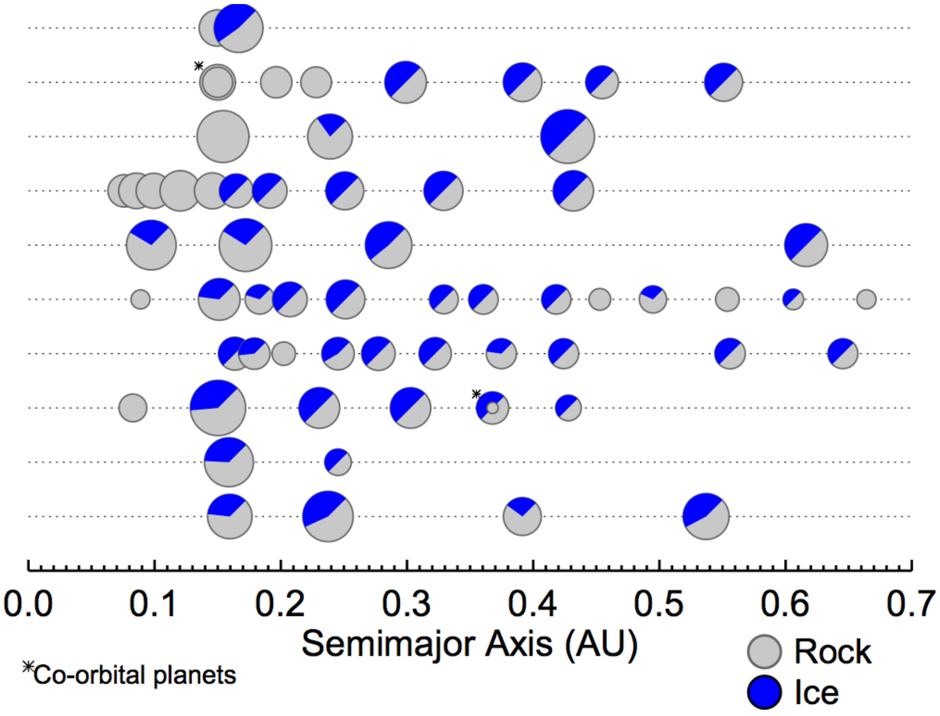
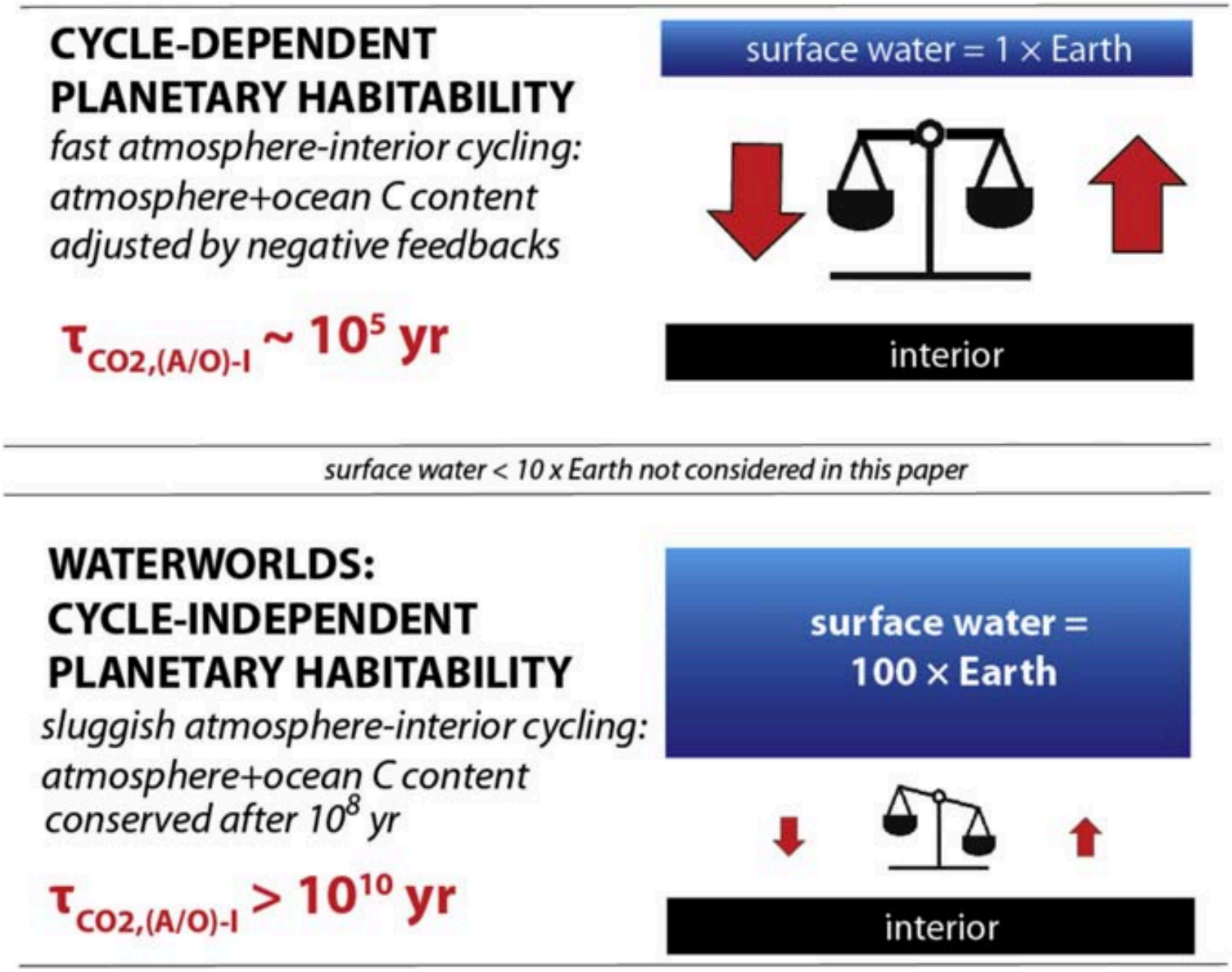


Figure 3. Final configuration of ten simulations illustrating the range of outcomes. Each planet's colors represent its rough composition: grey indicates rock and blue represents ice. Embryos that started past 5 AU started as 50-50 rock-ice mixtures and those from inside 5 AU were purely rocky. We do not account for various water loss processes and so the ice contents of simulated planets are certainly overestimates. The sizes of planets are scaled to their mass$^{1/3}$. The Kepler-36 analog system from Section 3 is at the top. Two co-orbital systems are marked with an asterisk.

Raymond et al.
MNRAS Letters 2018

CYCLE-INDEPENDENT PLANETARY HABITABILITY ON EXOPLANET WATERWORLDS?



CYCLE-DEPENDENT PLANETARY HABITABILITY

fast atmosphere-interior cycling: atmosphere+ocean C content adjusted by negative feedbacks

$\tau_{CO2,(A/O)-I} \sim 10^5$ yr

surface water < 10 x Earth not considered in this paper

WATERWORLDS: CYCLE-INDEPENDENT PLANETARY HABITABILITY

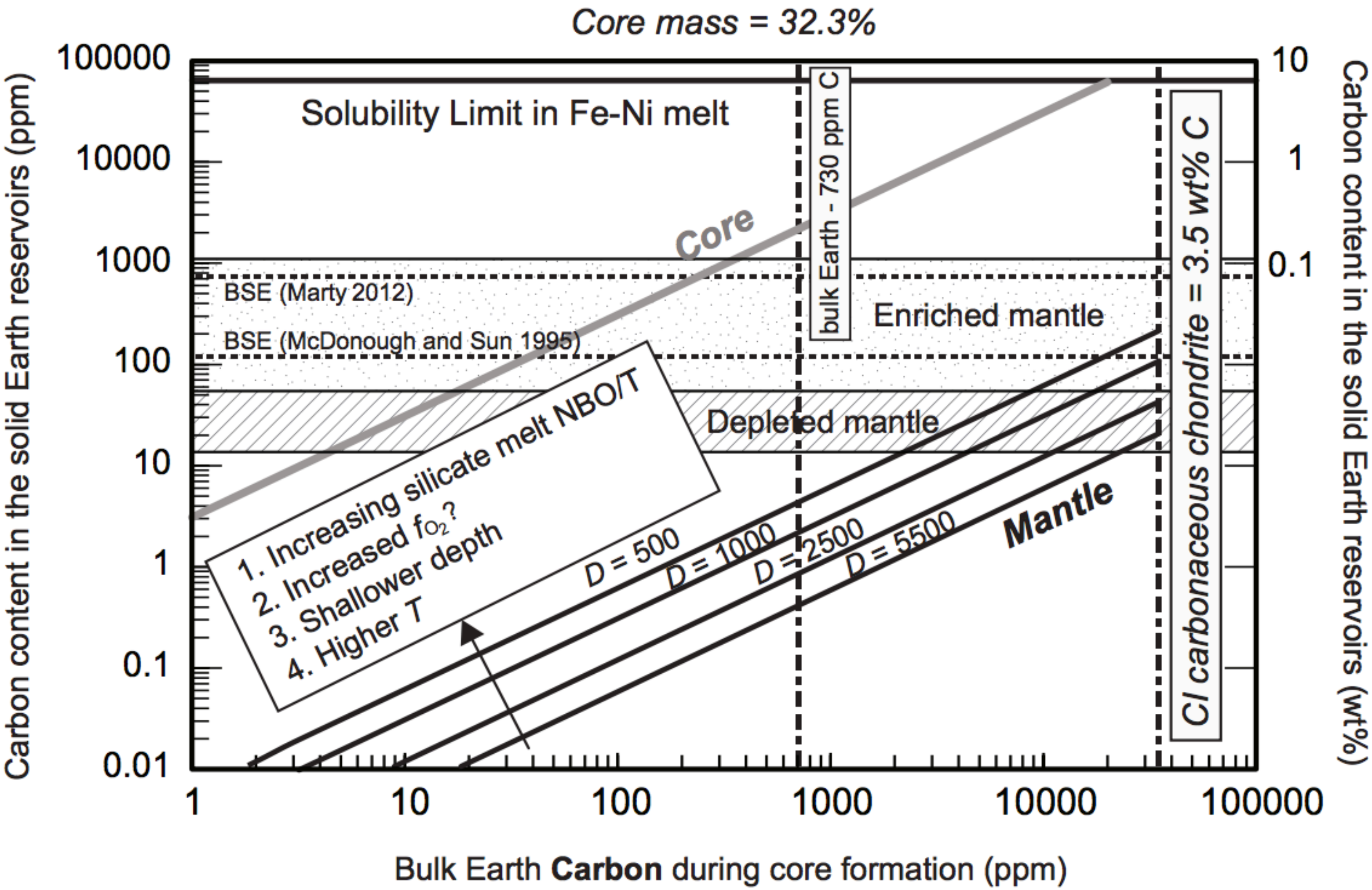
sluggish atmosphere-interior cycling: atmosphere+ocean C content conserved after 10^8 yr

$\tau_{CO2,(A/O)-I} > 10^{10}$ yr

Kite & Ford, ApJ 2018

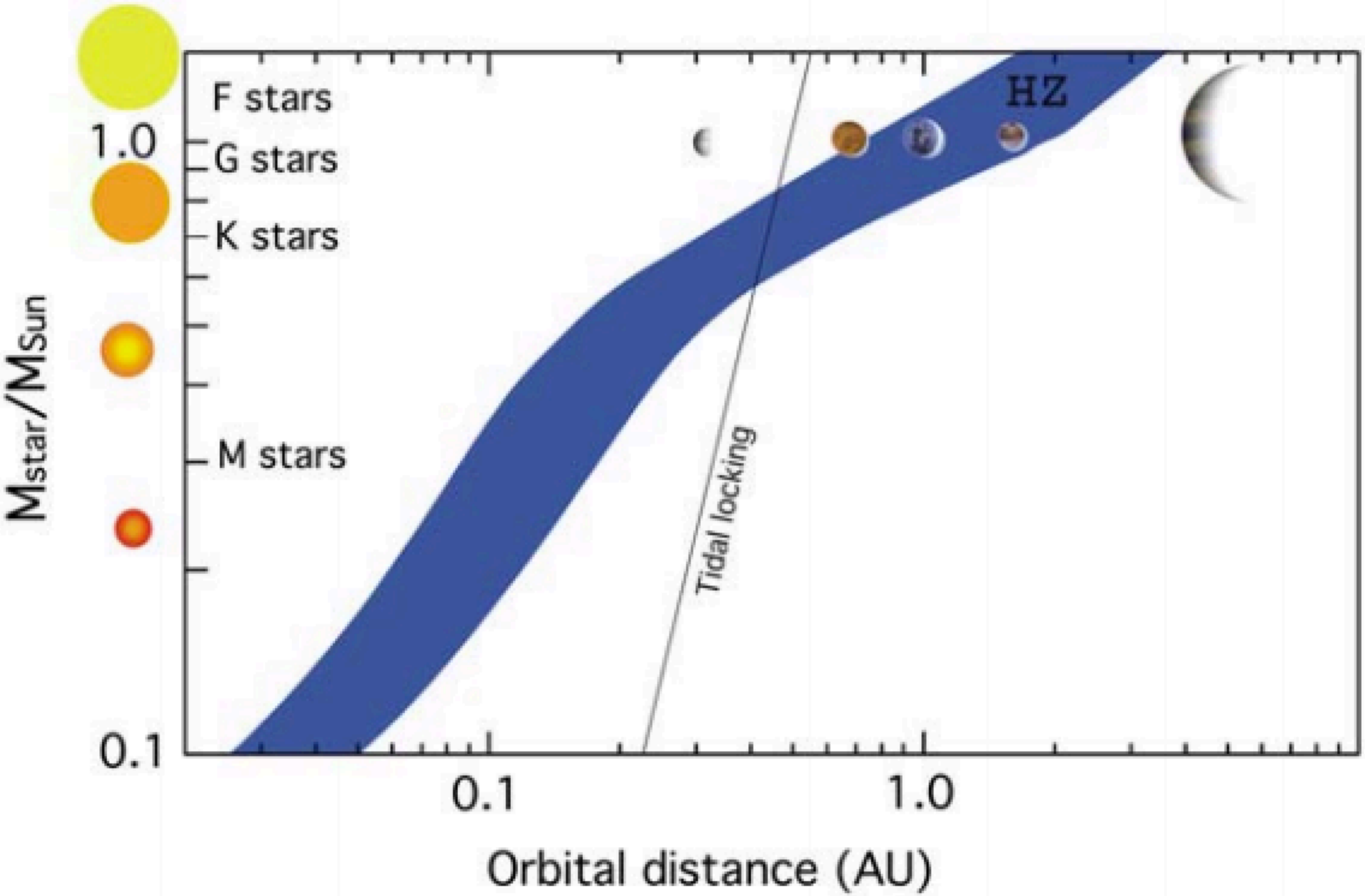
HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

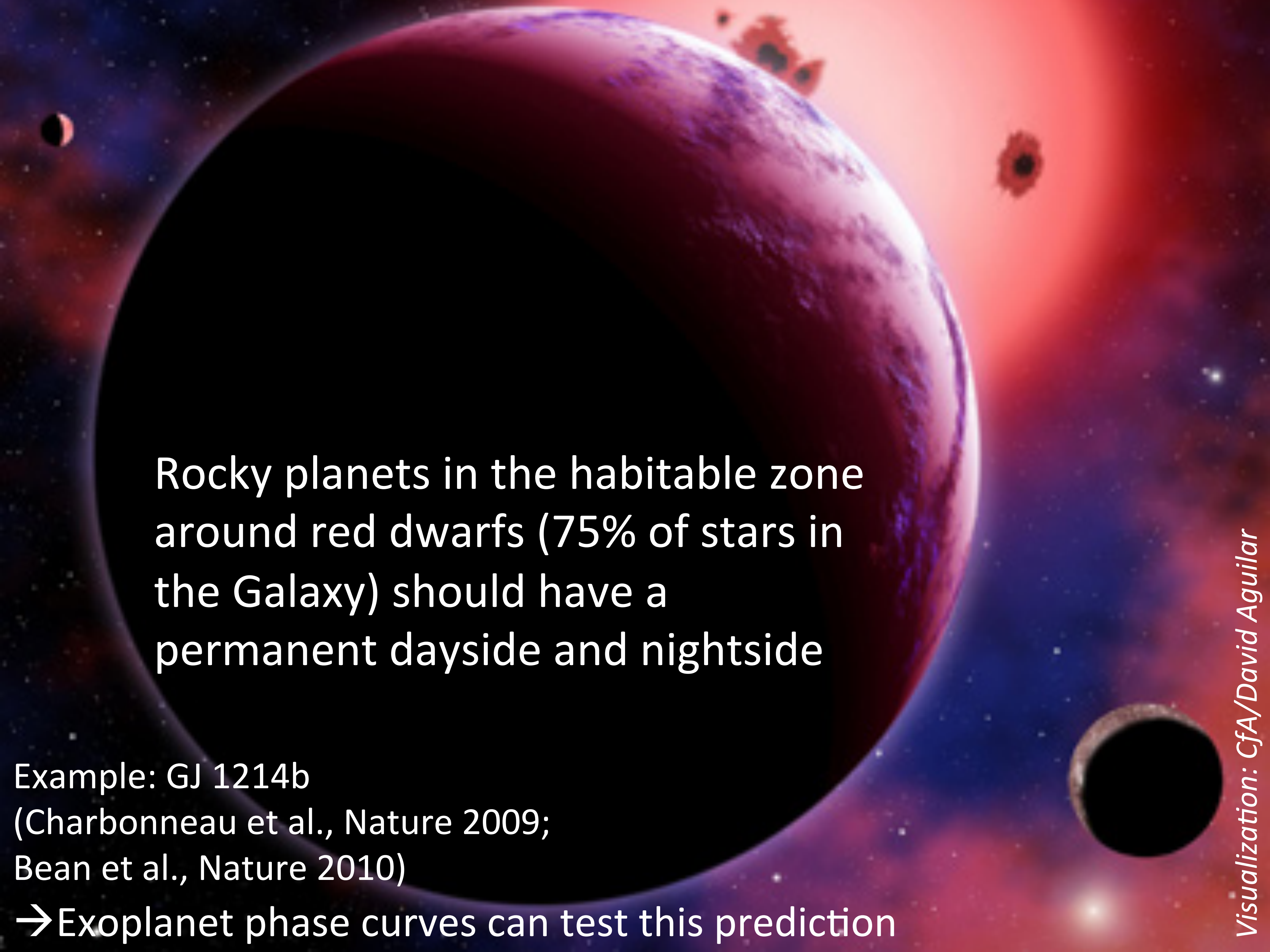
- CARBON



Dasgupta et al. 2013, Reviews in Mineralogy & Geochemistry

THE M-STAR OPPORTUNITY: RELATIVELY DEEPER AND MORE FREQUENT TRANSITS → EASIER TO DETECT & CHARACTERIZE



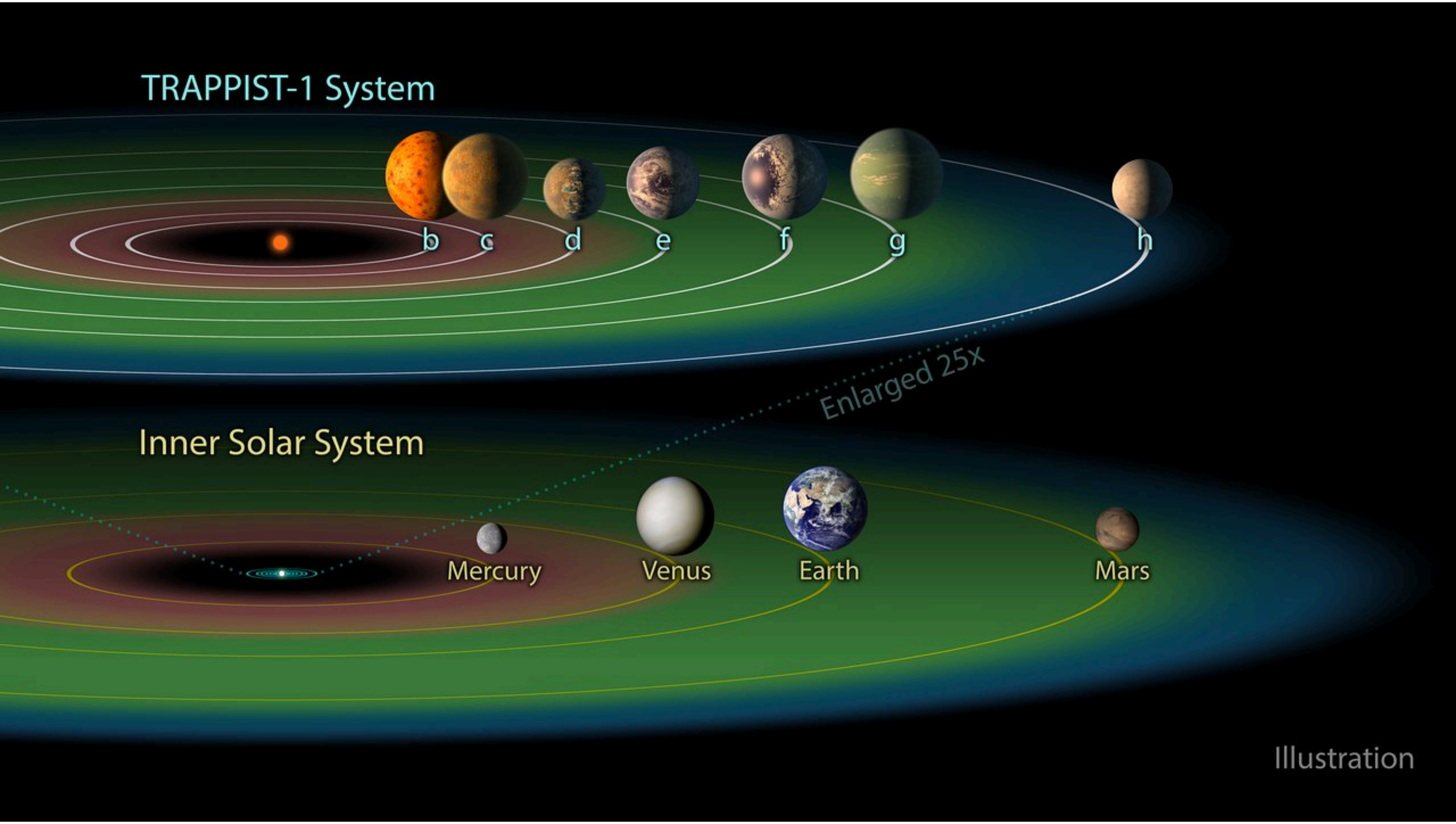


Rocky planets in the habitable zone around red dwarfs (75% of stars in the Galaxy) should have a permanent dayside and nightside

Example: GJ 1214b
(Charbonneau et al., Nature 2009;
Bean et al., Nature 2010)

→Exoplanet phase curves can test this prediction

Visualization: CfA/David Aguilar


TRAPPIST-1 System
b
c
d
e
f
g
h
Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars
Illustration

HIGH XUV FLUX SUSTAINED FOR LONG PERIOD FOR SMALL STARS

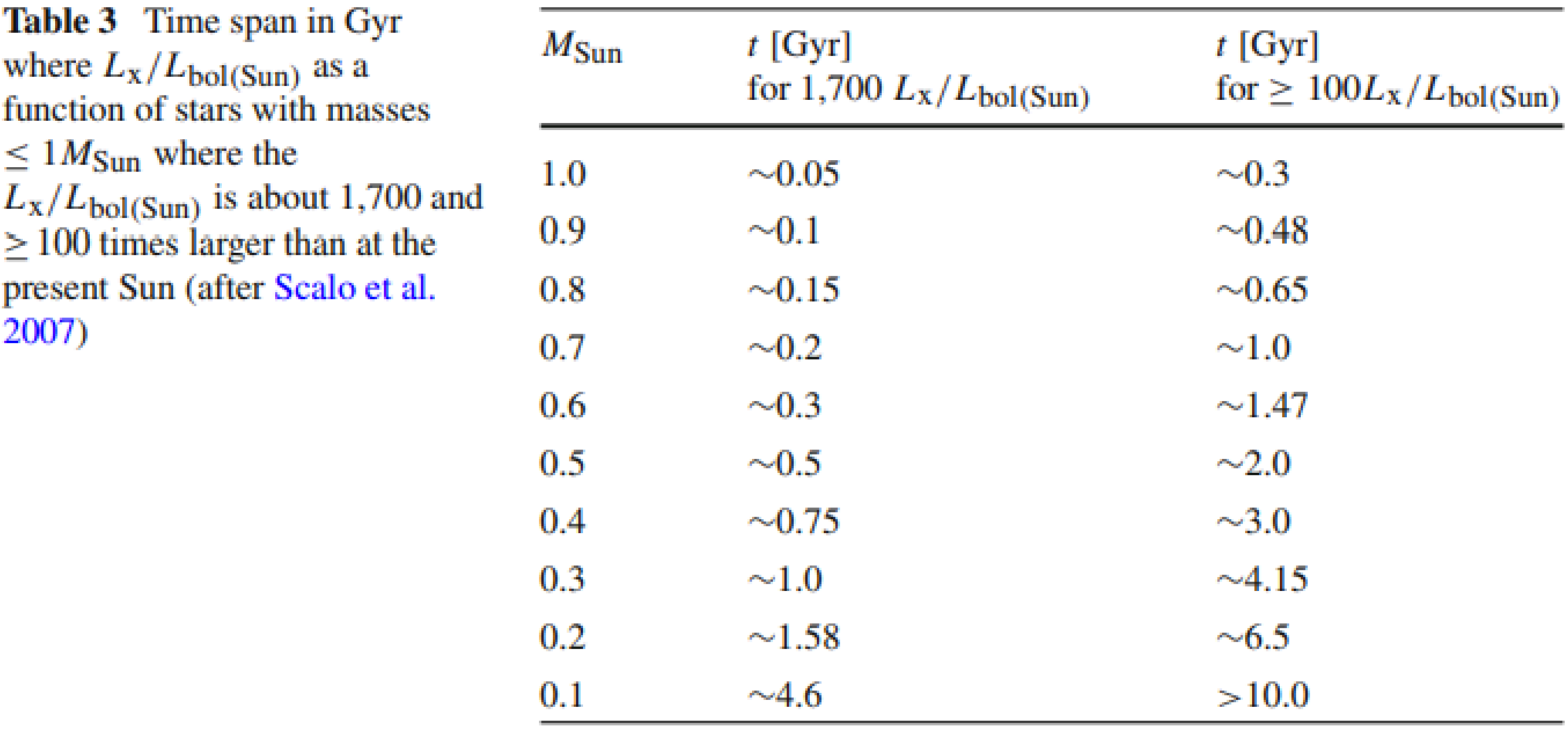
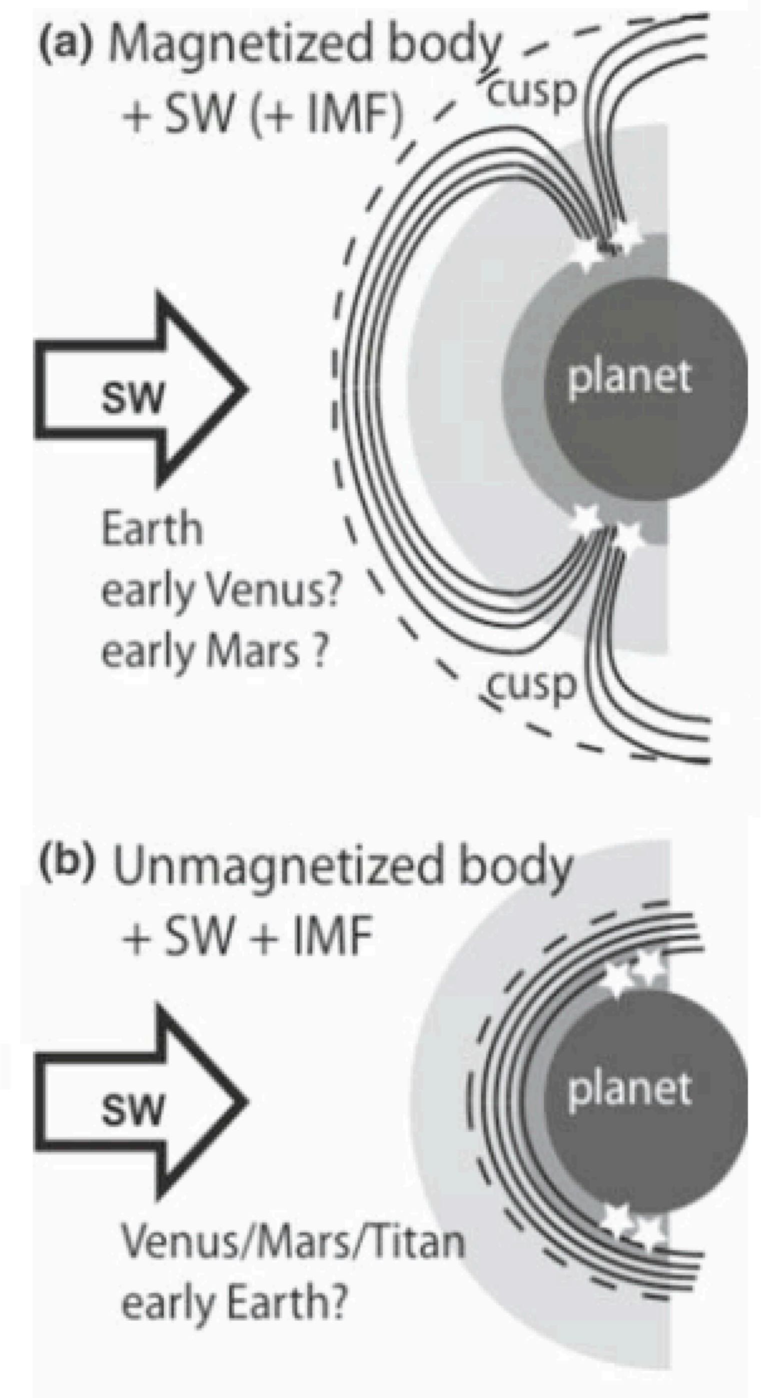


Table 3 Time span in Gyr where $L_x/L_{bol(Sun)}$ as a function of stars with masses $\leq 1 M_{Sun}$ where the $L_x/L_{bol(Sun)}$ is about 1,700 and ≥ 100 times larger than at the present Sun (after Scalo et al. 2007)

M_{Sun}	t [Gyr] for 1,700 $L_x/L_{bol(Sun)}$	t [Gyr] for $\geq 100 L_x/L_{bol(Sun)}$
1.0	~0.05	~0.3
0.9	~0.1	~0.48
0.8	~0.15	~0.65
0.7	~0.2	~1.0
0.6	~0.3	~1.47
0.5	~0.5	~2.0
0.4	~0.75	~3.0
0.3	~1.0	~4.15
0.2	~1.58	~6.5
0.1	~4.6	>10.0

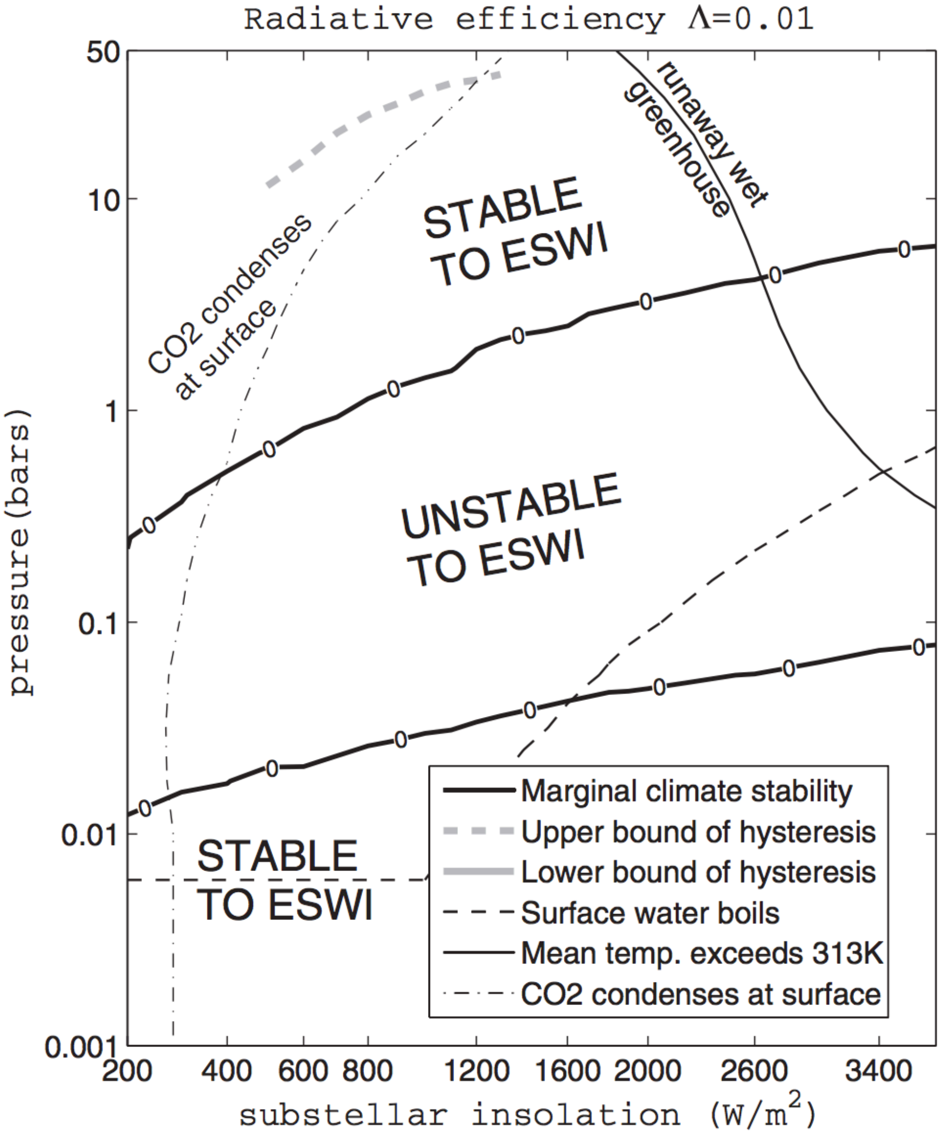
Lammer et al. 2009 Space Science Reviews

STRONGER STELLAR WIND → STRONGER NONTHERMAL ATMOSPHERIC ESCPAE



ADDITIONAL PROBLEMS FOR HABITABILITY FOR PLANETS ORBITING M-STARS

Enhanced Substellar Weathering Instability



Tarter et al. Astrobiology 2007

Kite et al. ApJ 2011

Exoplanet habitability

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THE M-STAR OPPORTUNITY

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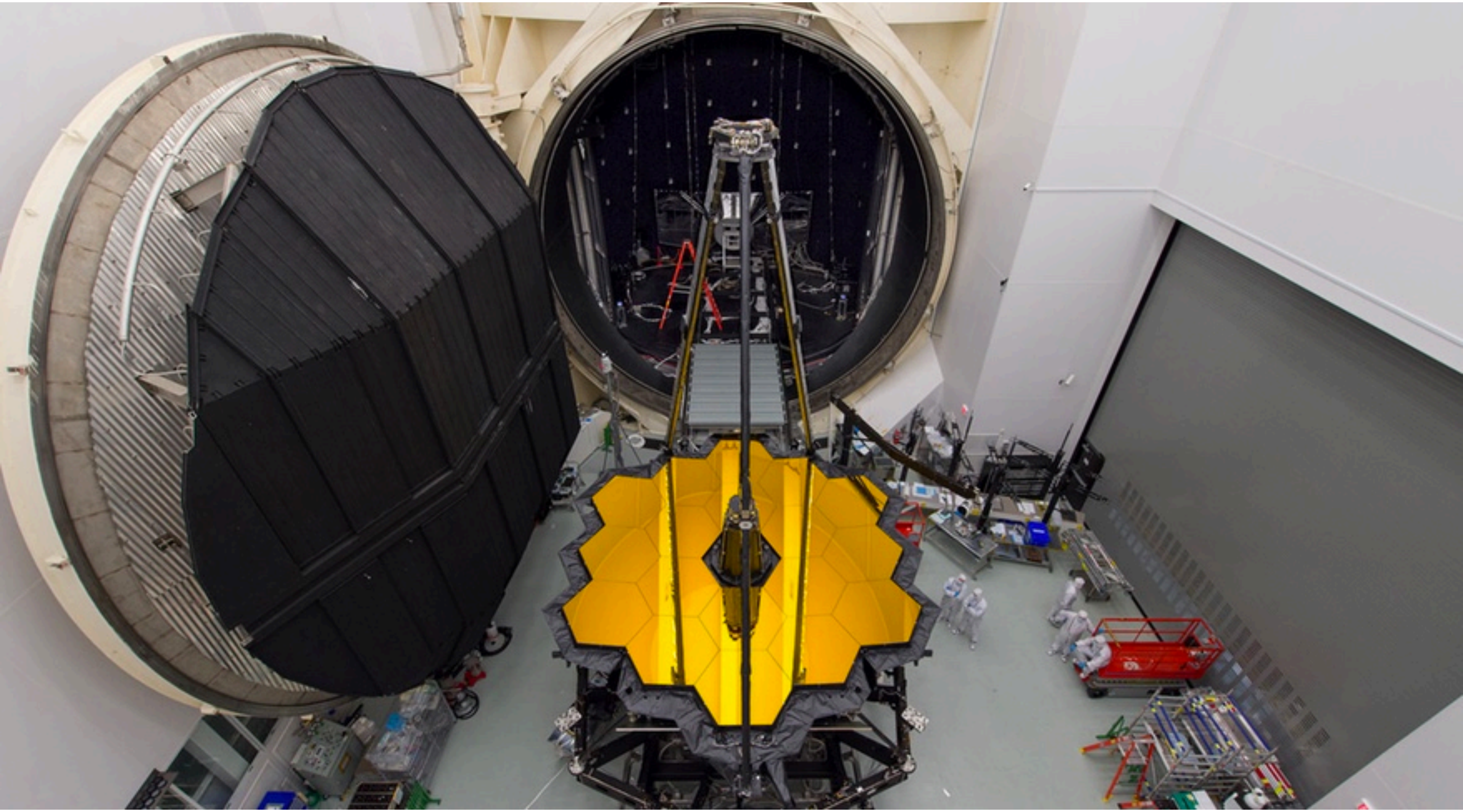
FUTURE MISSIONS

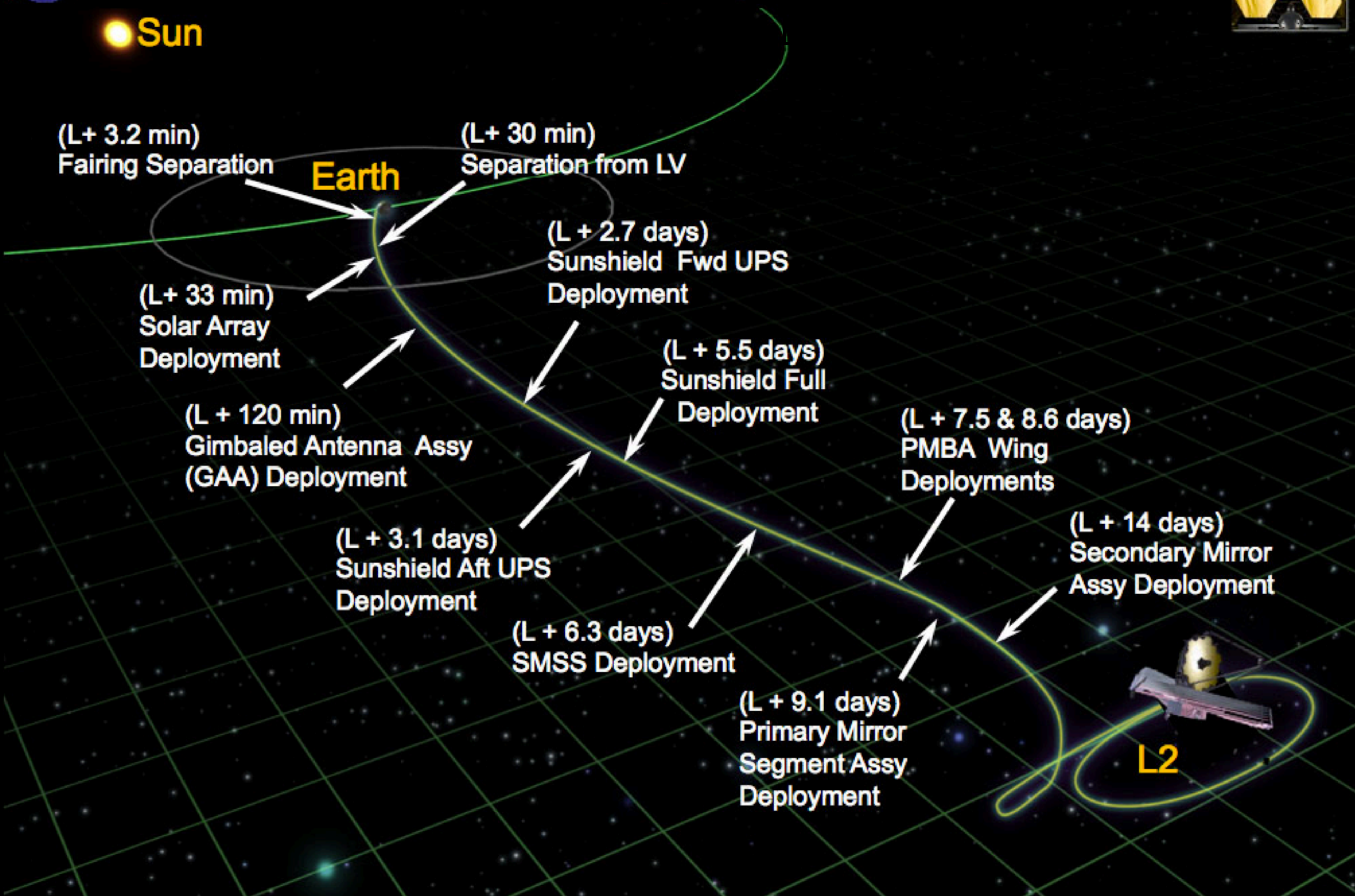
What’s next

Hubble Space Telescope

JWST



JWST Launch/Deployment Timeline



(L+ 3.2 min)
Fairing Separation

(L+ 30 min)
Separation from LV

(L+ 33 min)
Solar Array
Deployment

(L + 120 min)
Gimbaled Antenna Assy
(GAA) Deployment

(L + 2.7 days)
Sunshield Fwd UPS
Deployment

(L + 3.1 days)
Sunshield Aft UPS
Deployment

(L + 5.5 days)
Sunshield Full
Deployment

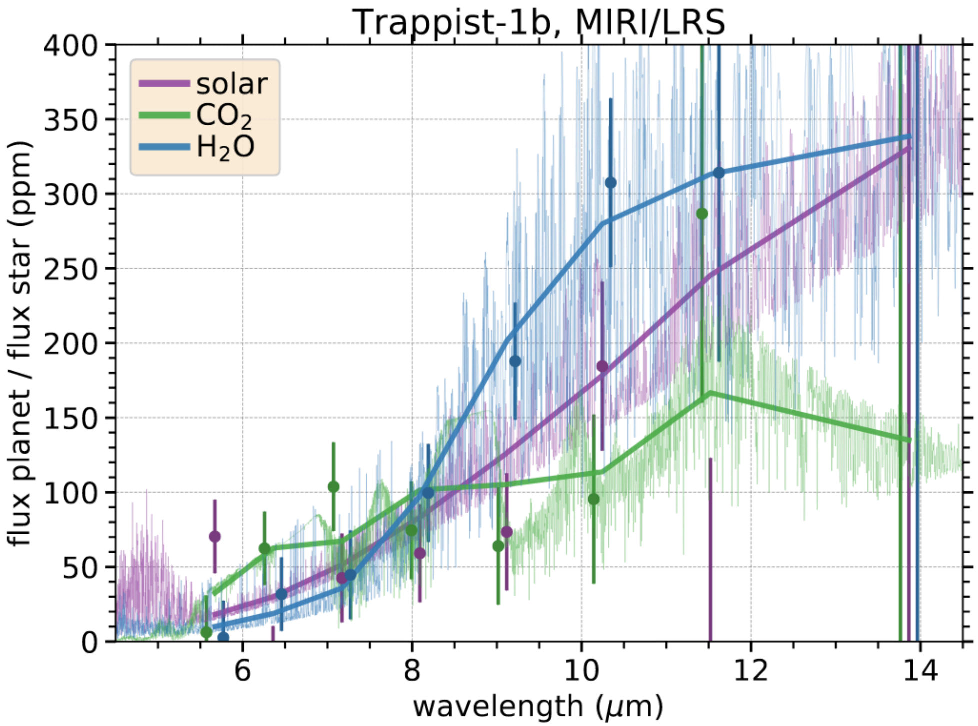
(L + 6.3 days)
SMSS Deployment

(L + 7.5 & 8.6 days)
PMBA Wing
Deployments

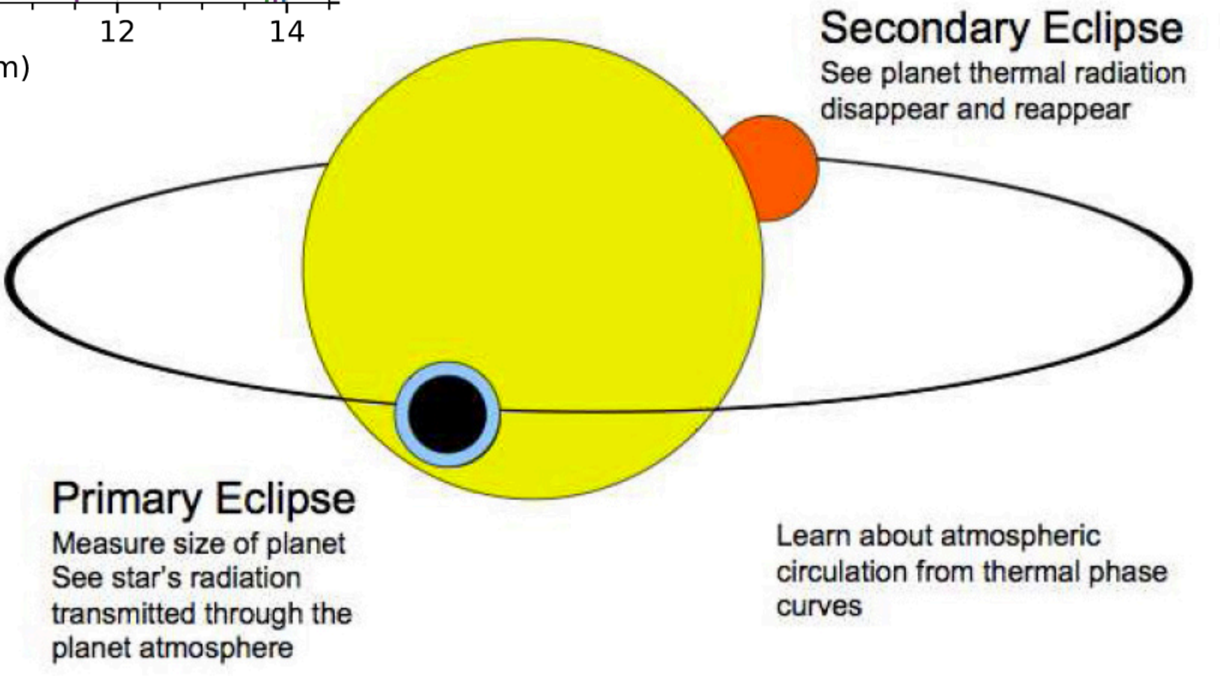
(L + 9.1 days)
Primary Mirror
Segment Assy
Deployment

(L + 14 days)
Secondary Mirror
Assy Deployment

Simulated secondary eclipse spectra



Malik et al. in review



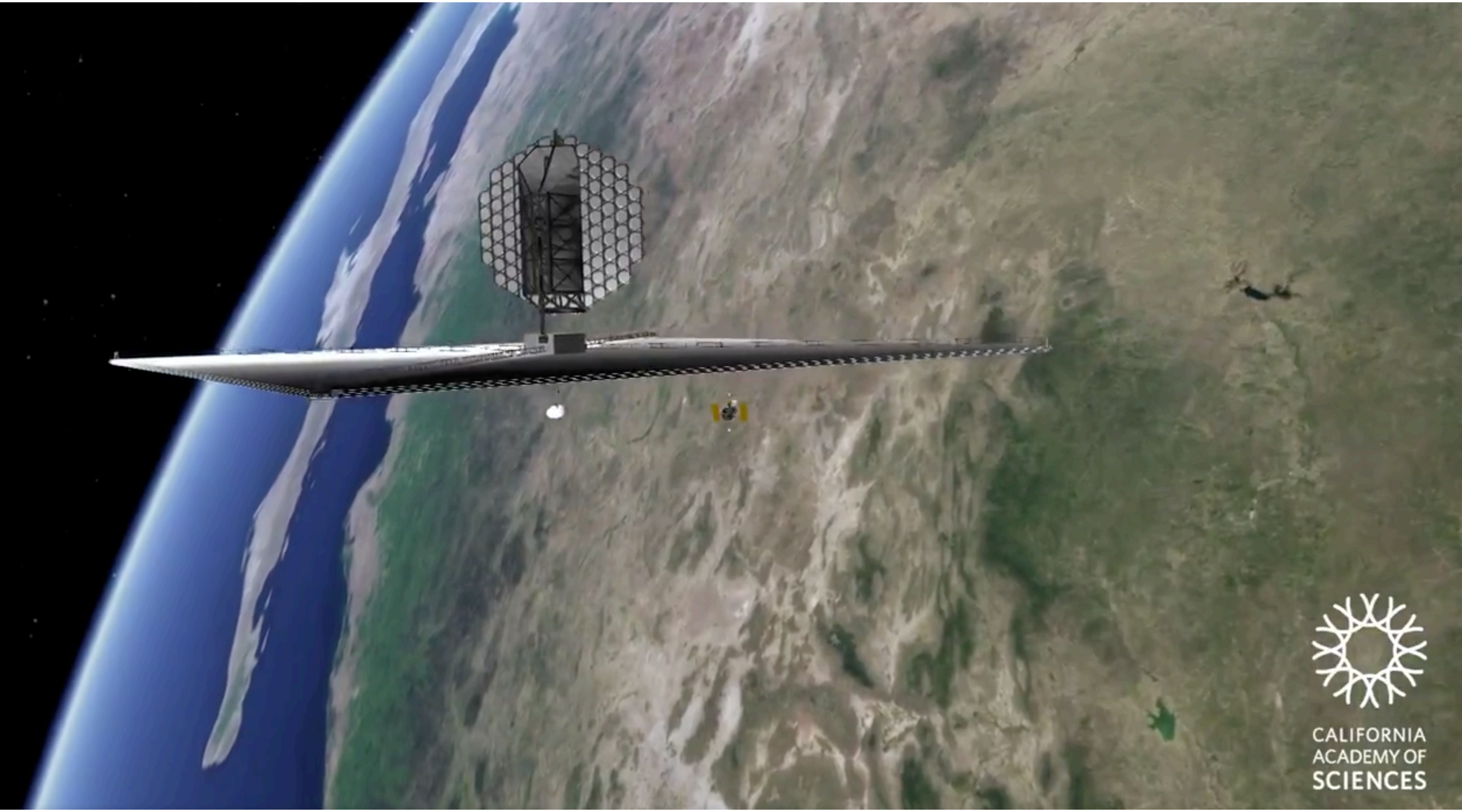
Secondary Eclipse

See planet thermal radiation disappear and reappear

Primary Eclipse

Measure size of planet
See star's radiation transmitted through the planet atmosphere

Learn about atmospheric circulation from thermal phase curves



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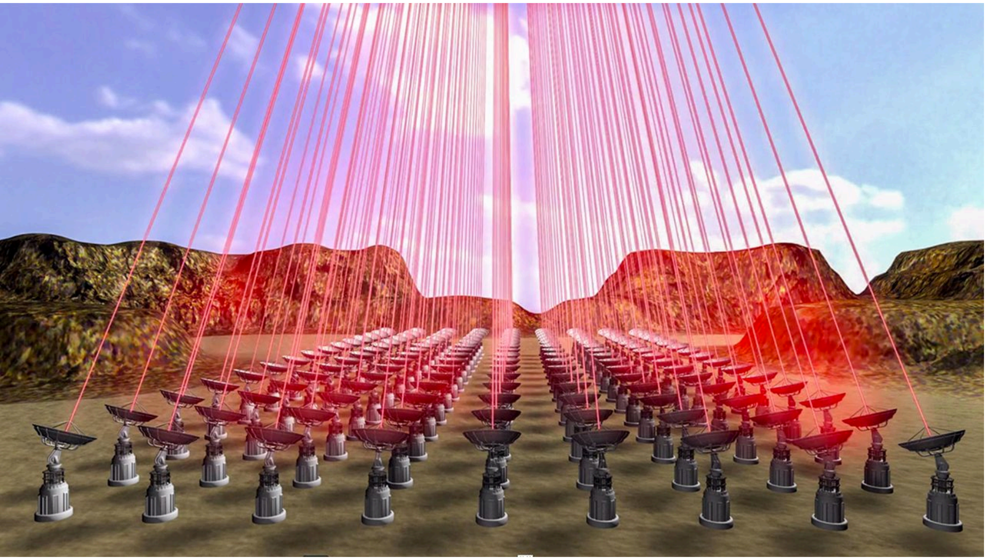
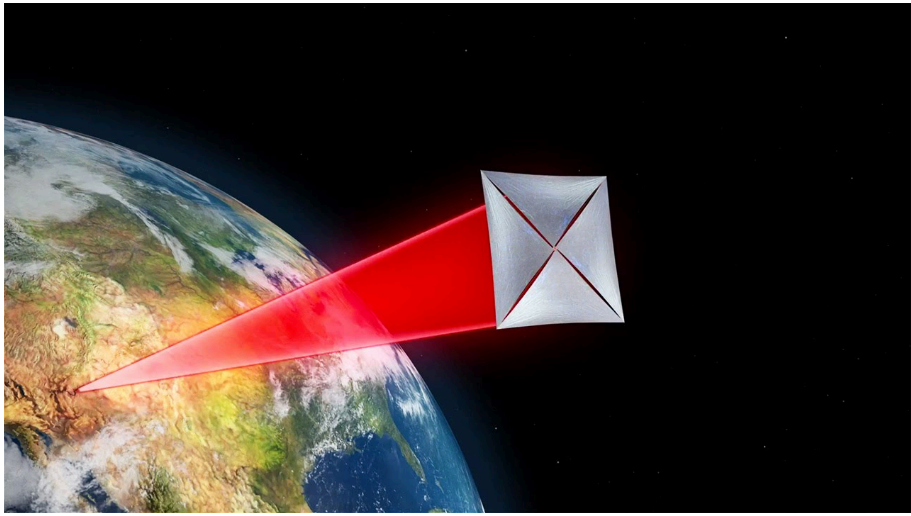
INTERSTELLAR MISSIONS?

- Current distance record: Voyager 1 @ 0.8 light-days
- No interstellar missions have been funded
- The technology for an interstellar mission does not currently exist
- Breakthrough Starshot is a philanthropically-funded technology development project for a laser-accelerated interstellar lightsail





50-70GW power, 0.1 gram payload, 5000g acceleration, 0.2c cruise speed

Exoplanet habitability

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FUTURE MISSIONS