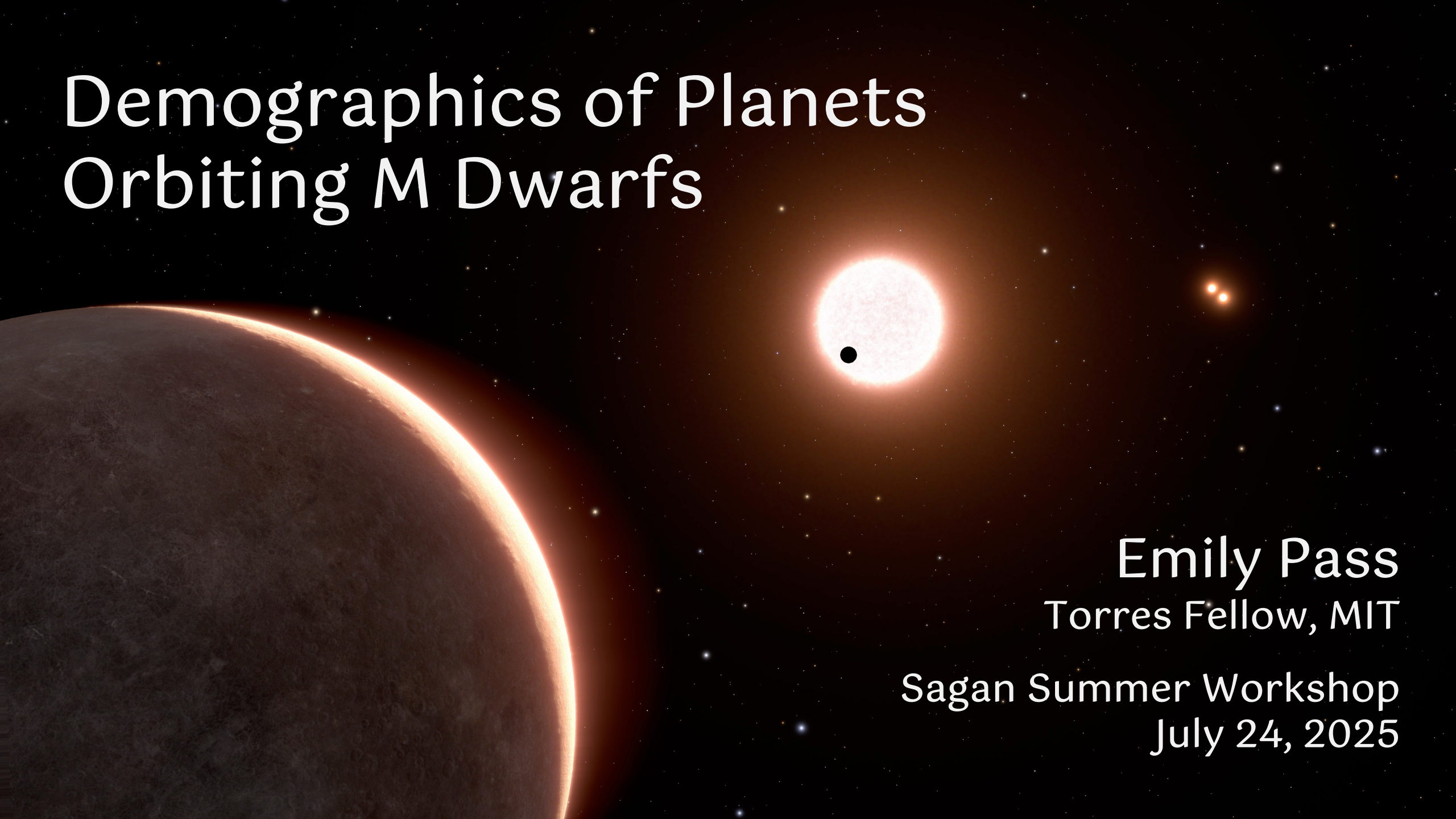
Demographics of Planets Orbiting M Dwarfs

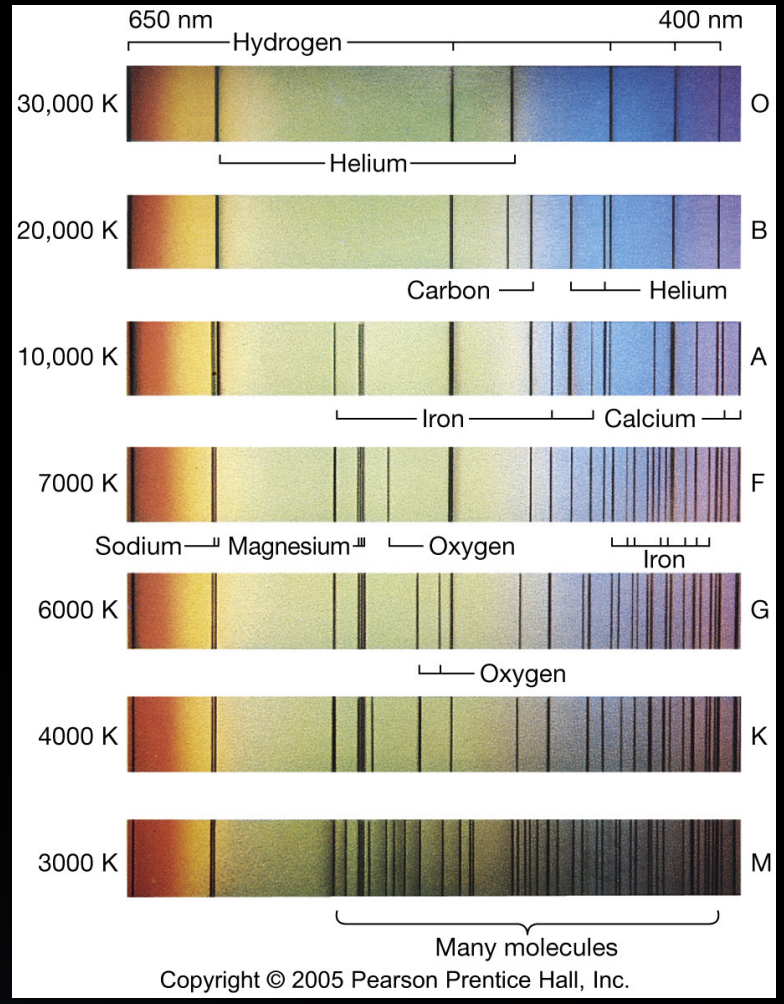


Emily Pass
Torres Fellow, MIT

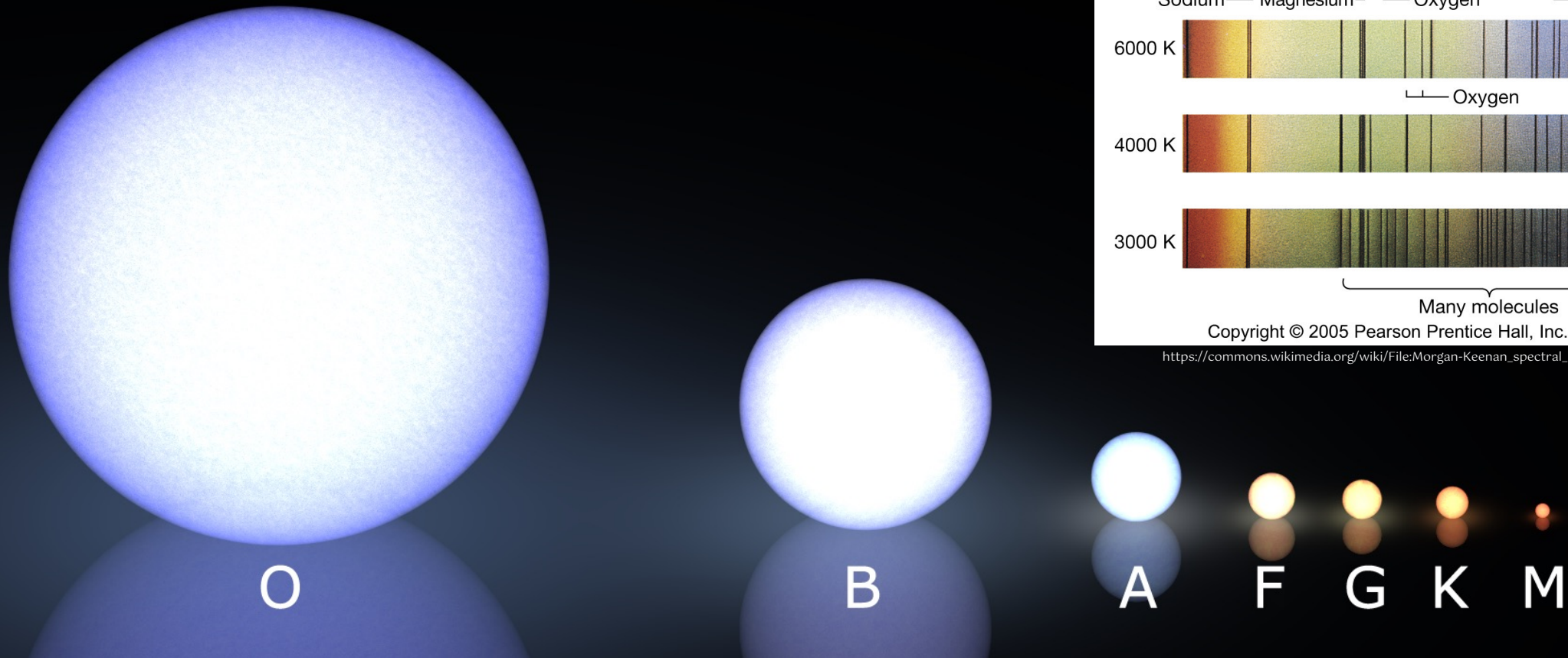
Sagan Summer Workshop
July 24, 2025

Q: What is an M dwarf?

A: The coolest stars in the spectral sequence



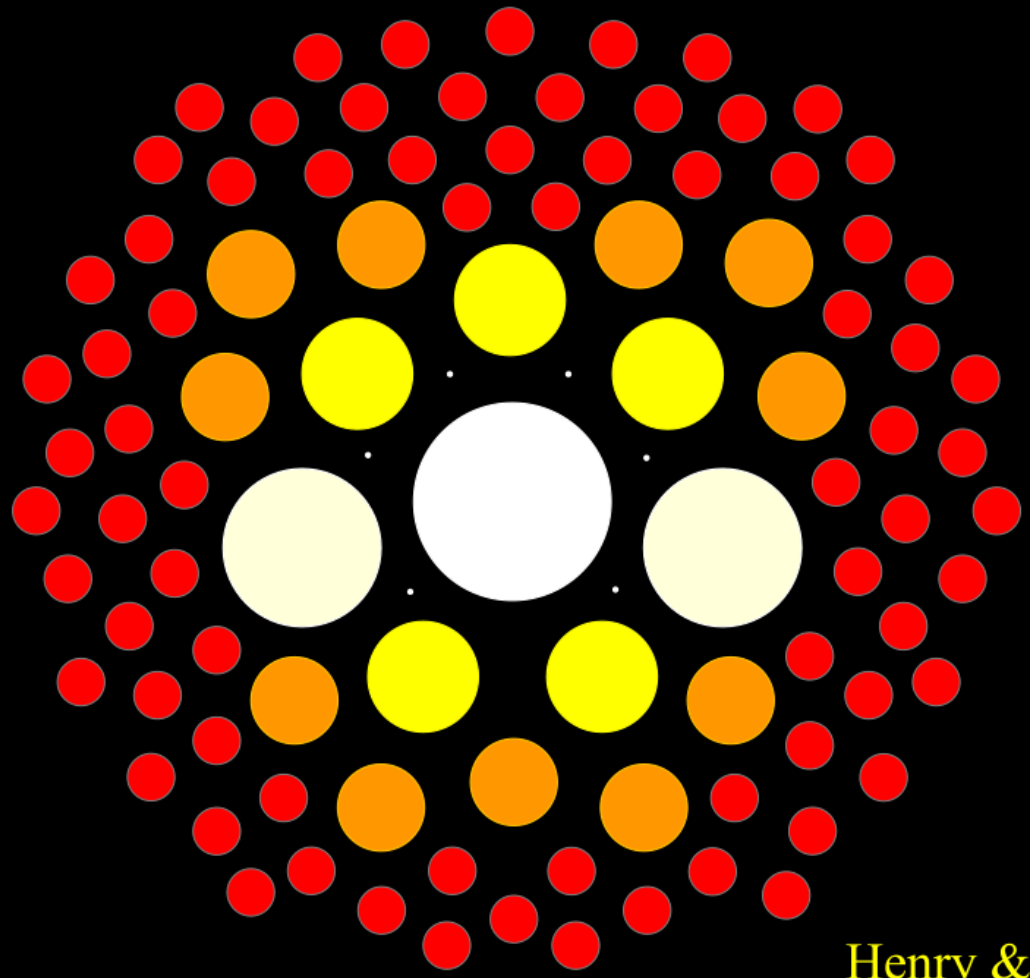
https://commons.wikimedia.org/wiki/File:Morgan-Keenan_spectral_classification.png



A: The majority of stars

100
dwarfs

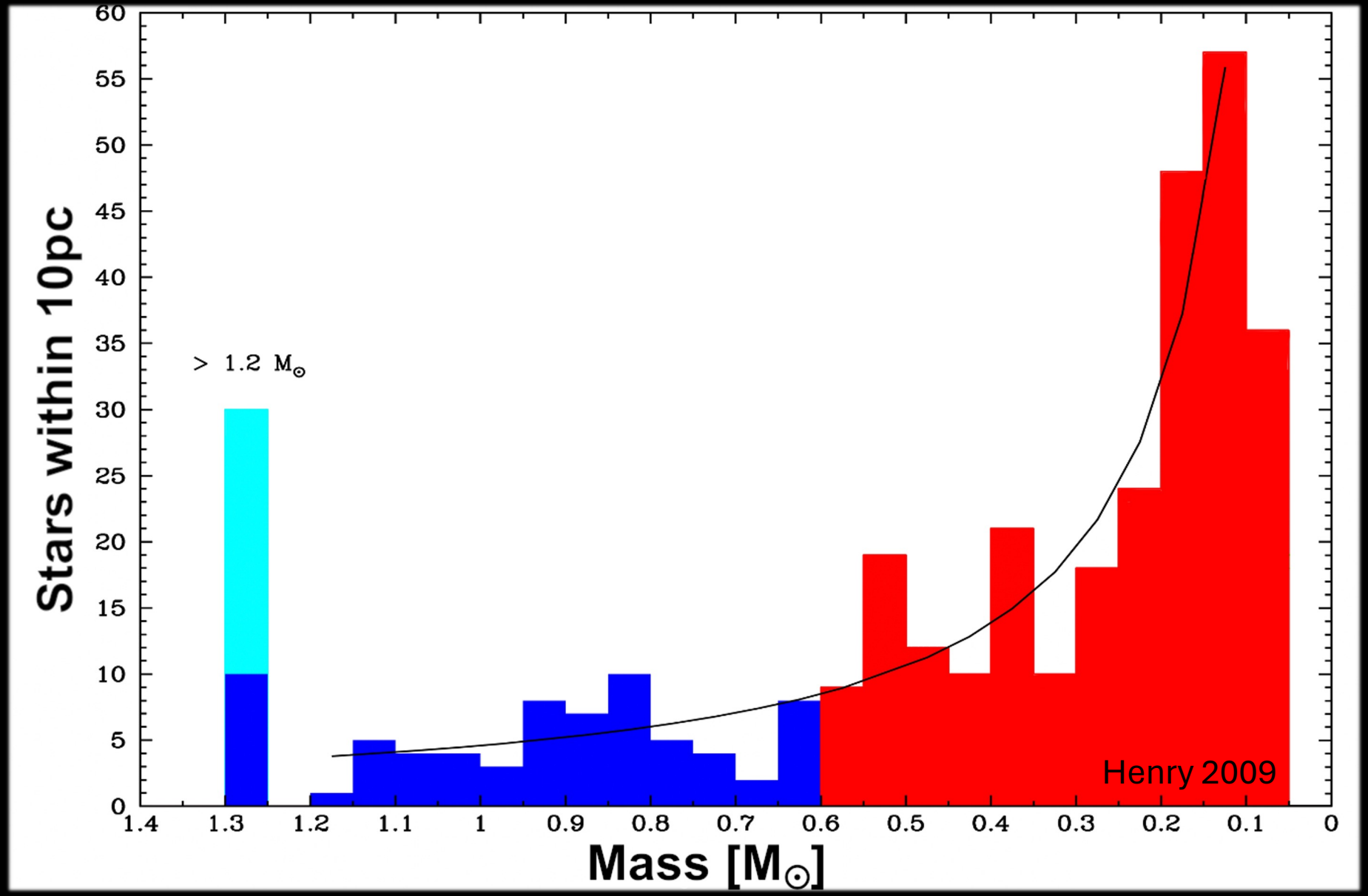
6 wd
1 A
2 F
5 G
11 K
75 M



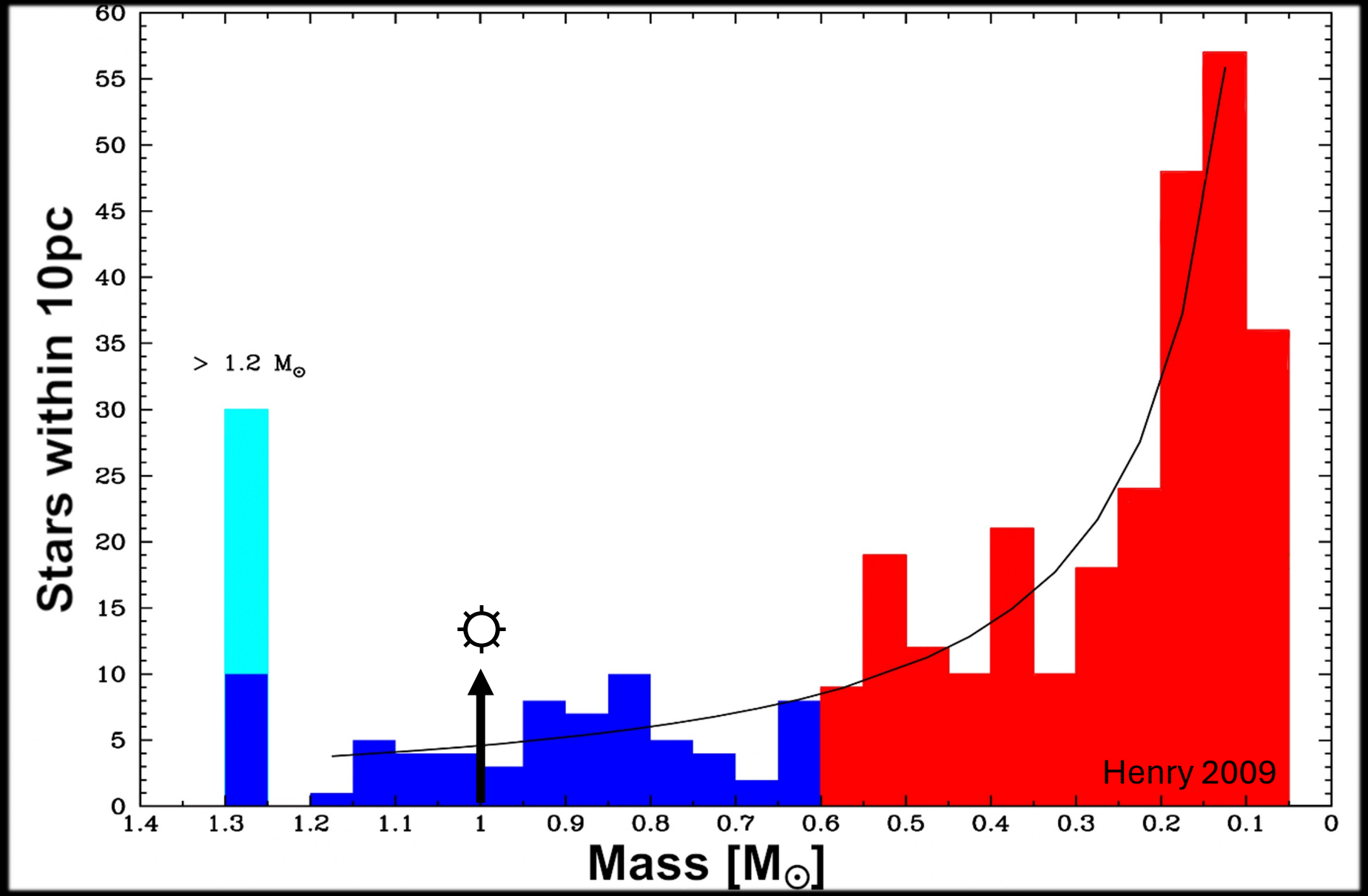
Henry & Jao

Annual Reviews 2024

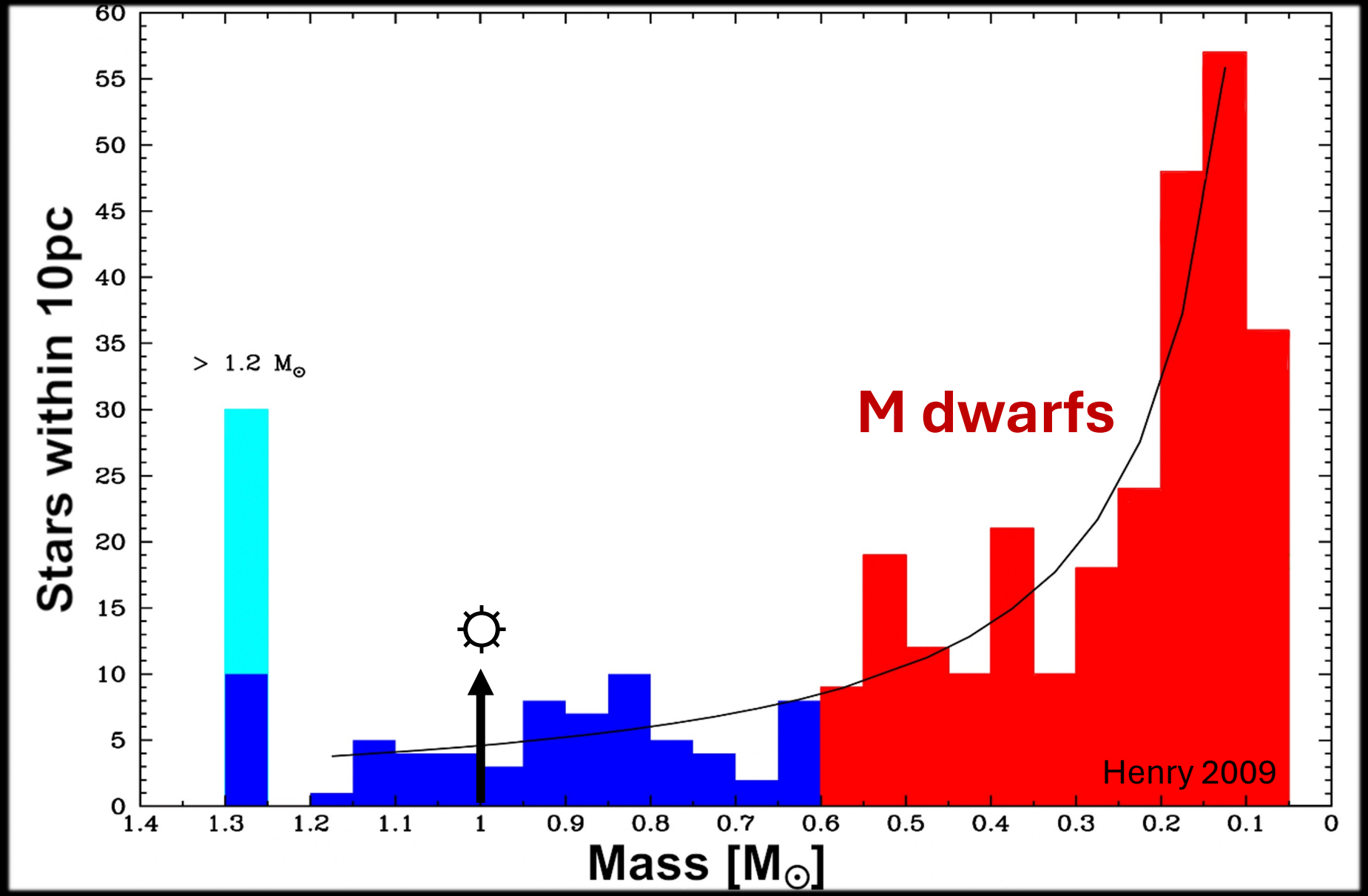
A: A diverse population



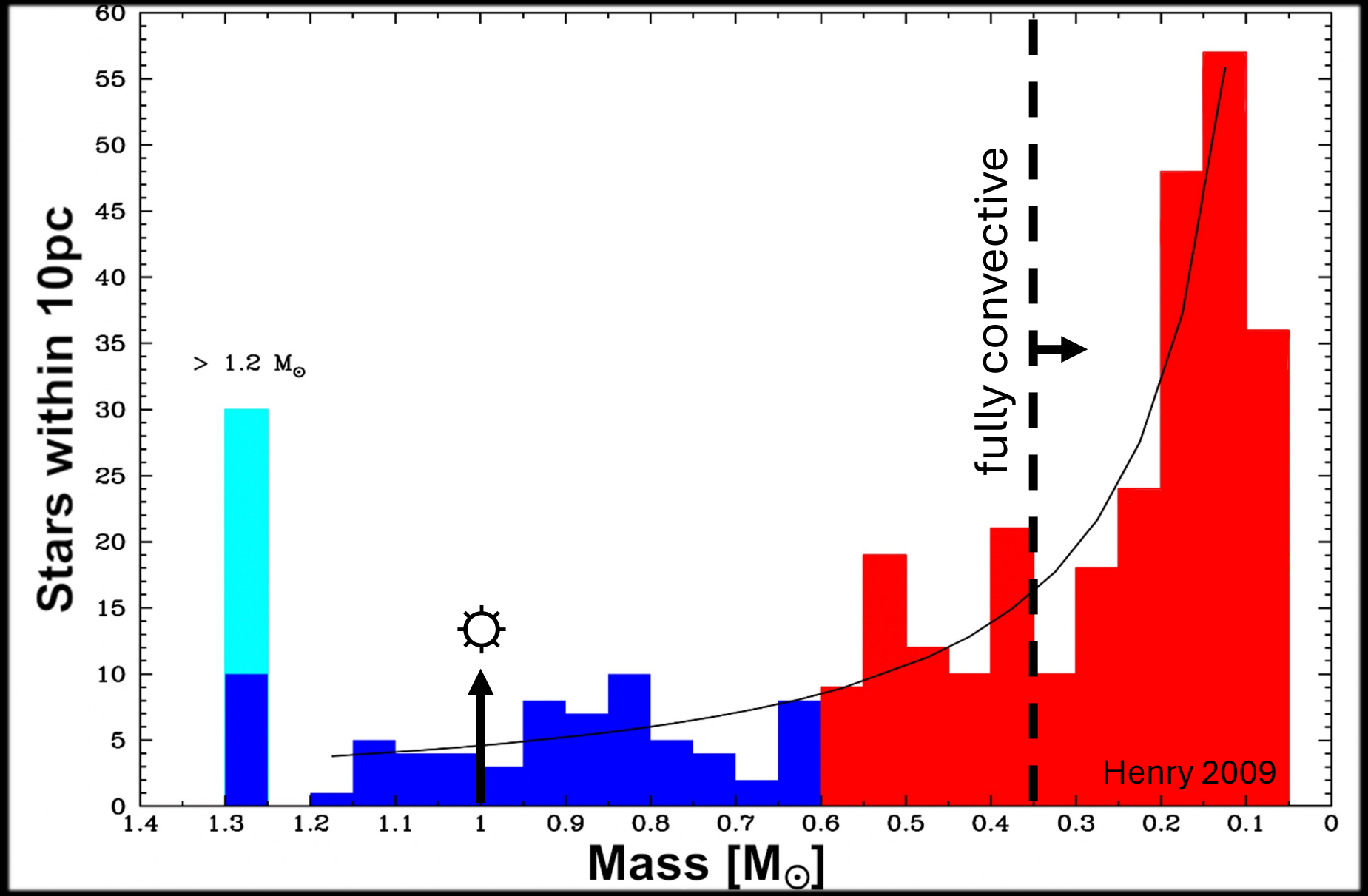
A: A diverse population



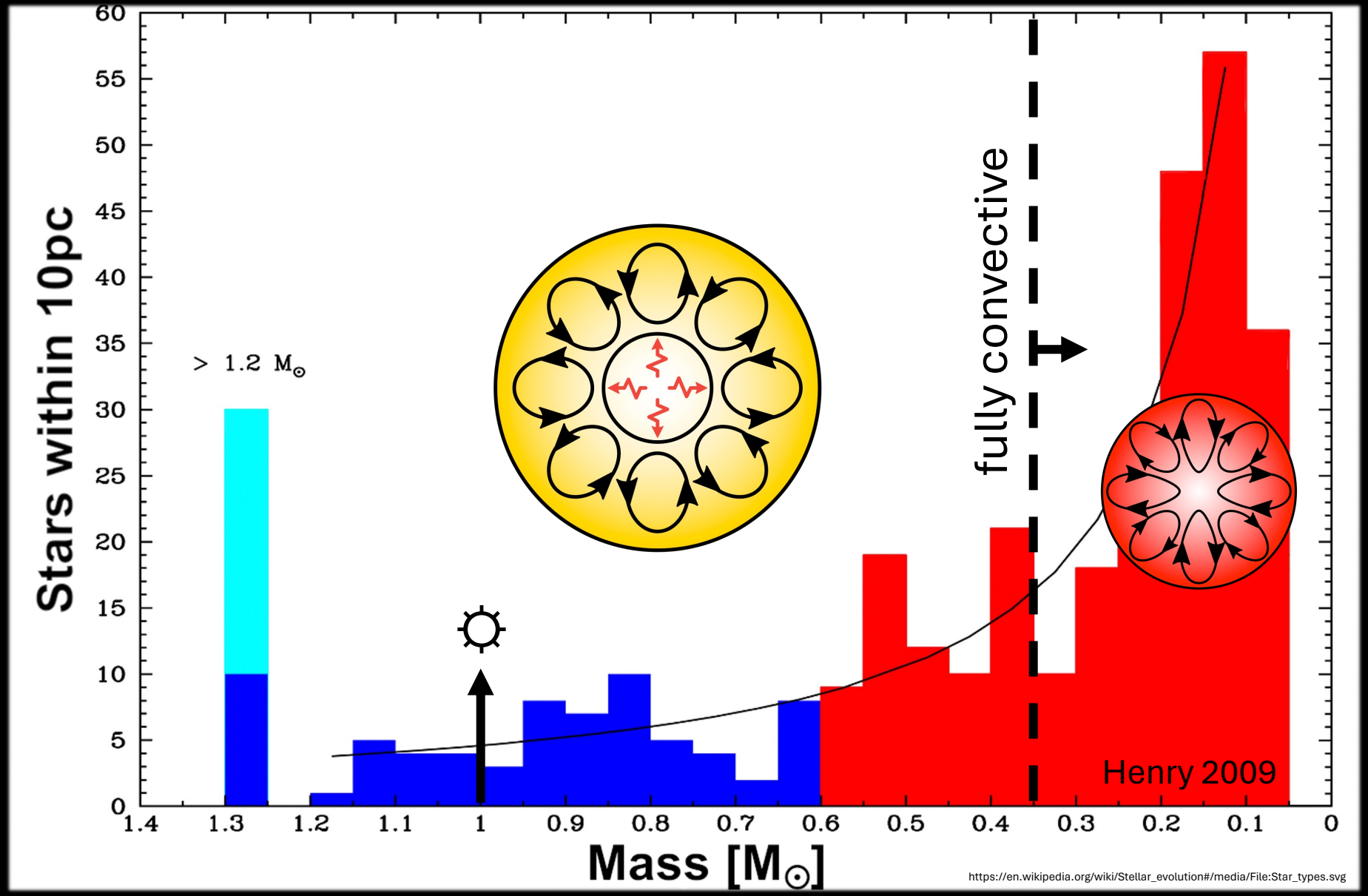
A: A diverse population



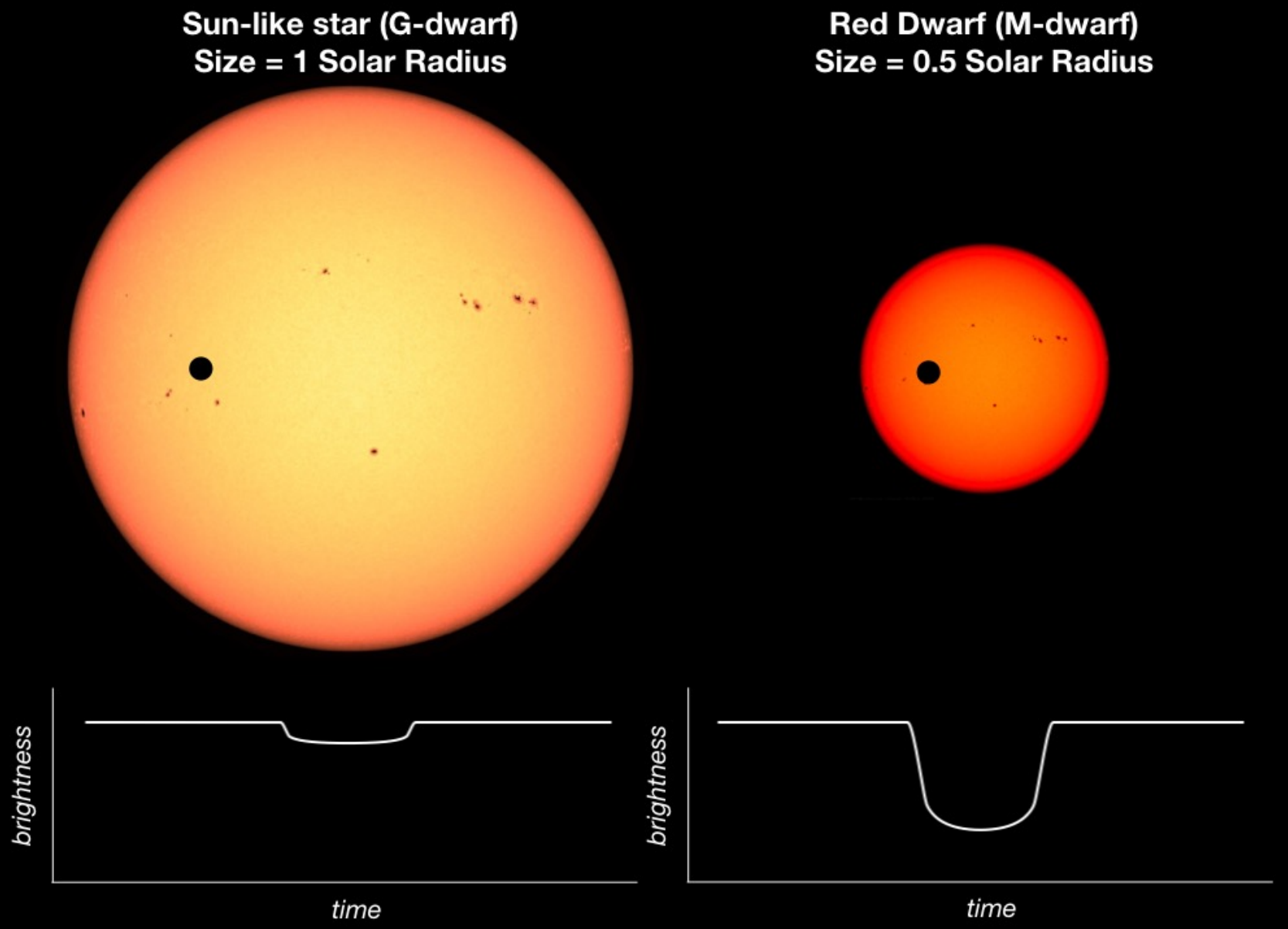
A: A diverse population



A: A diverse population

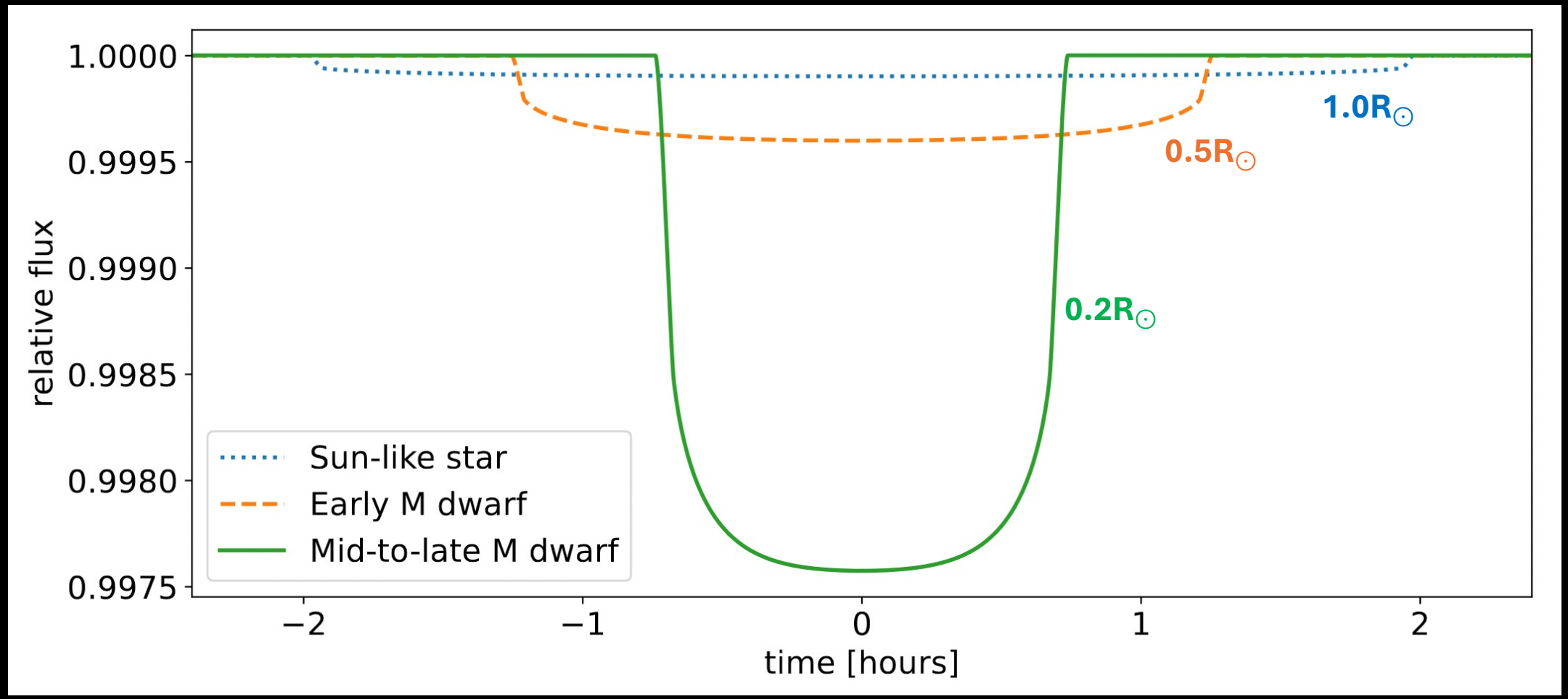


A: Ideal hosts for studying exoplanets

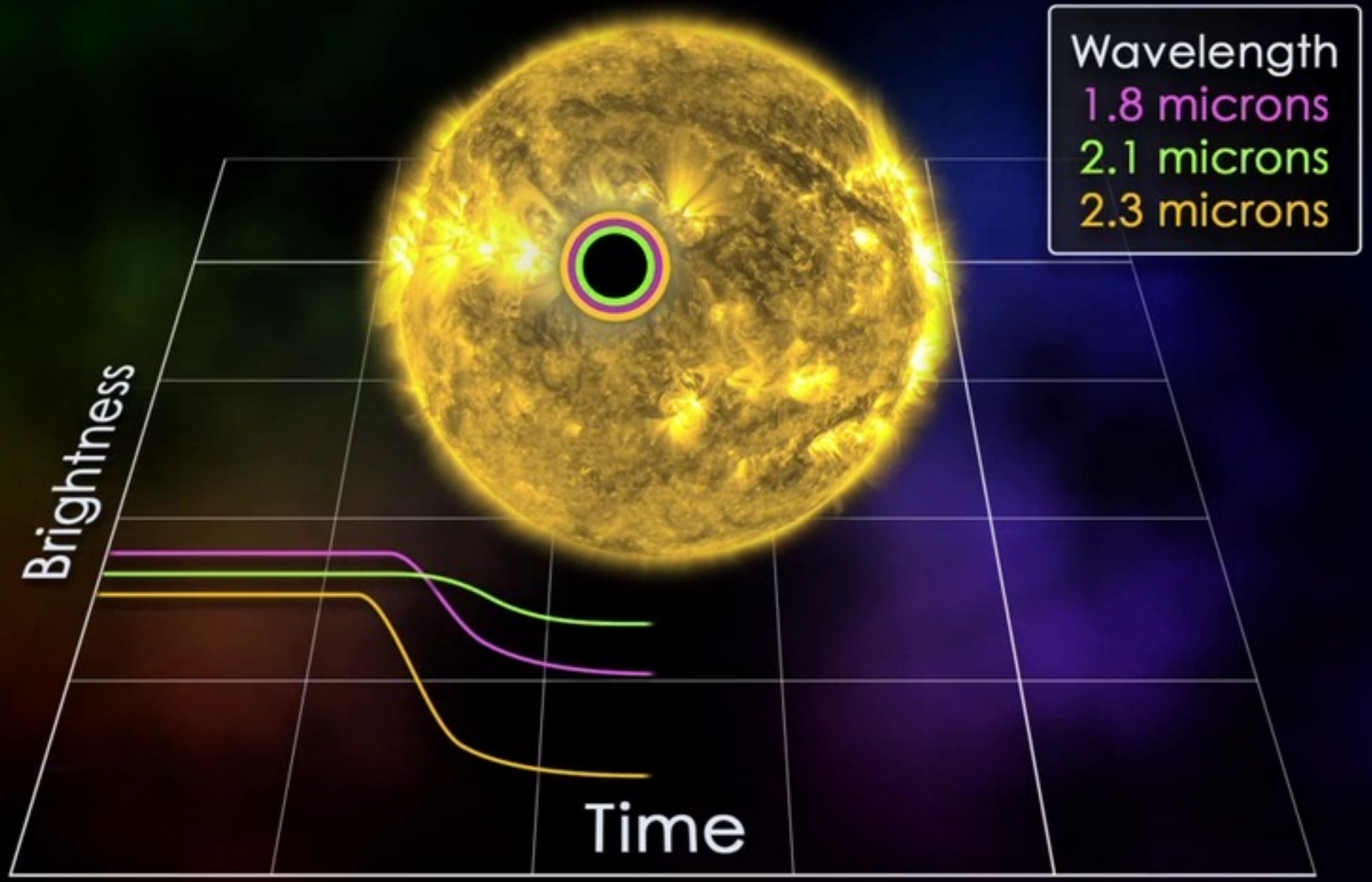


A. Vanderburg

A: Ideal hosts for studying exoplanets

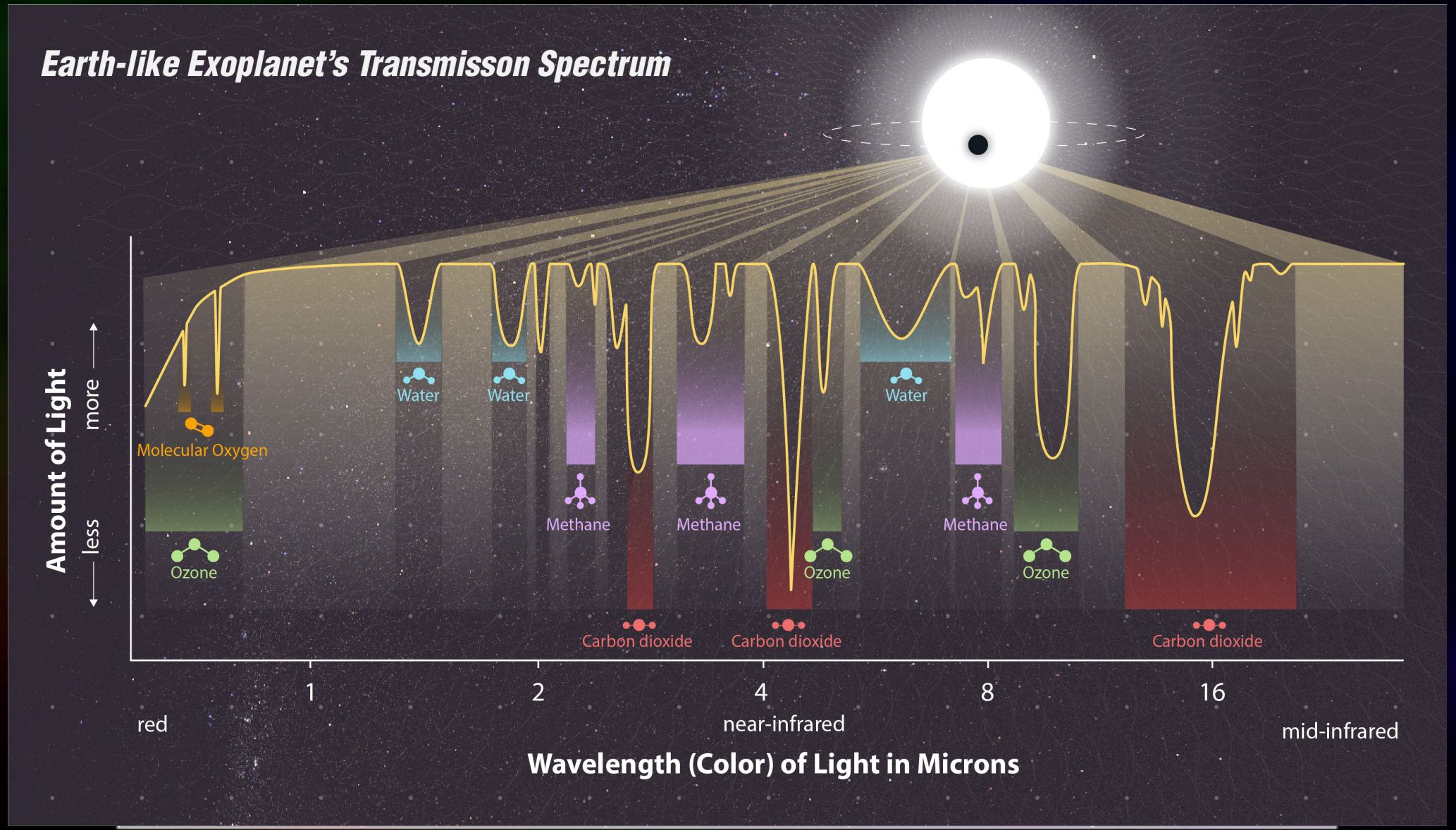


A: Ideal hosts for studying exoplanets



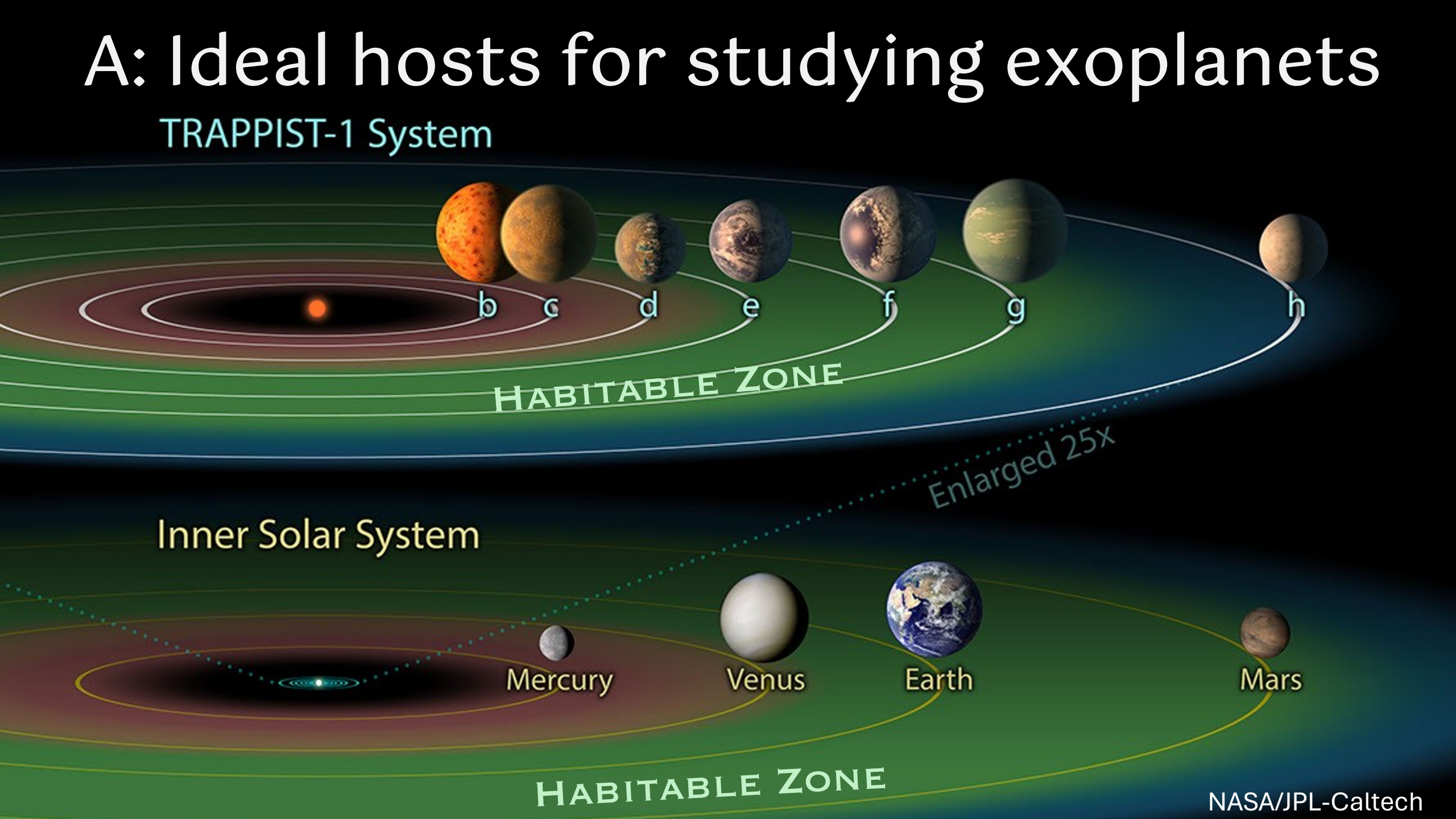
NASA

A: Ideal hosts for studying exoplanets

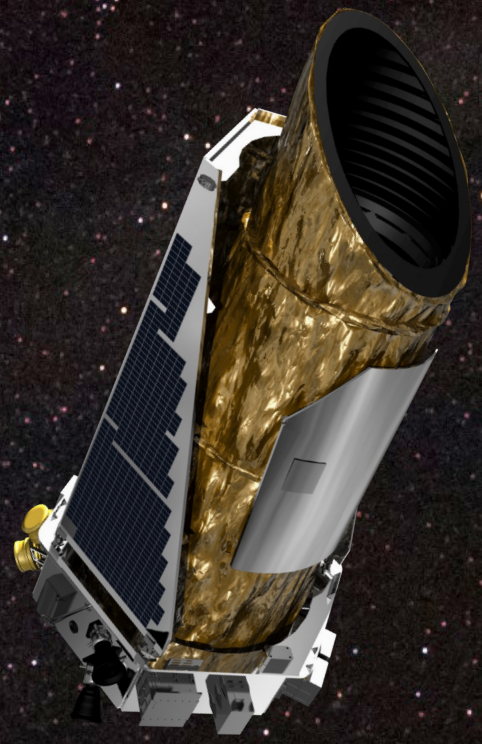


NASA

A: Ideal hosts for studying exoplanets

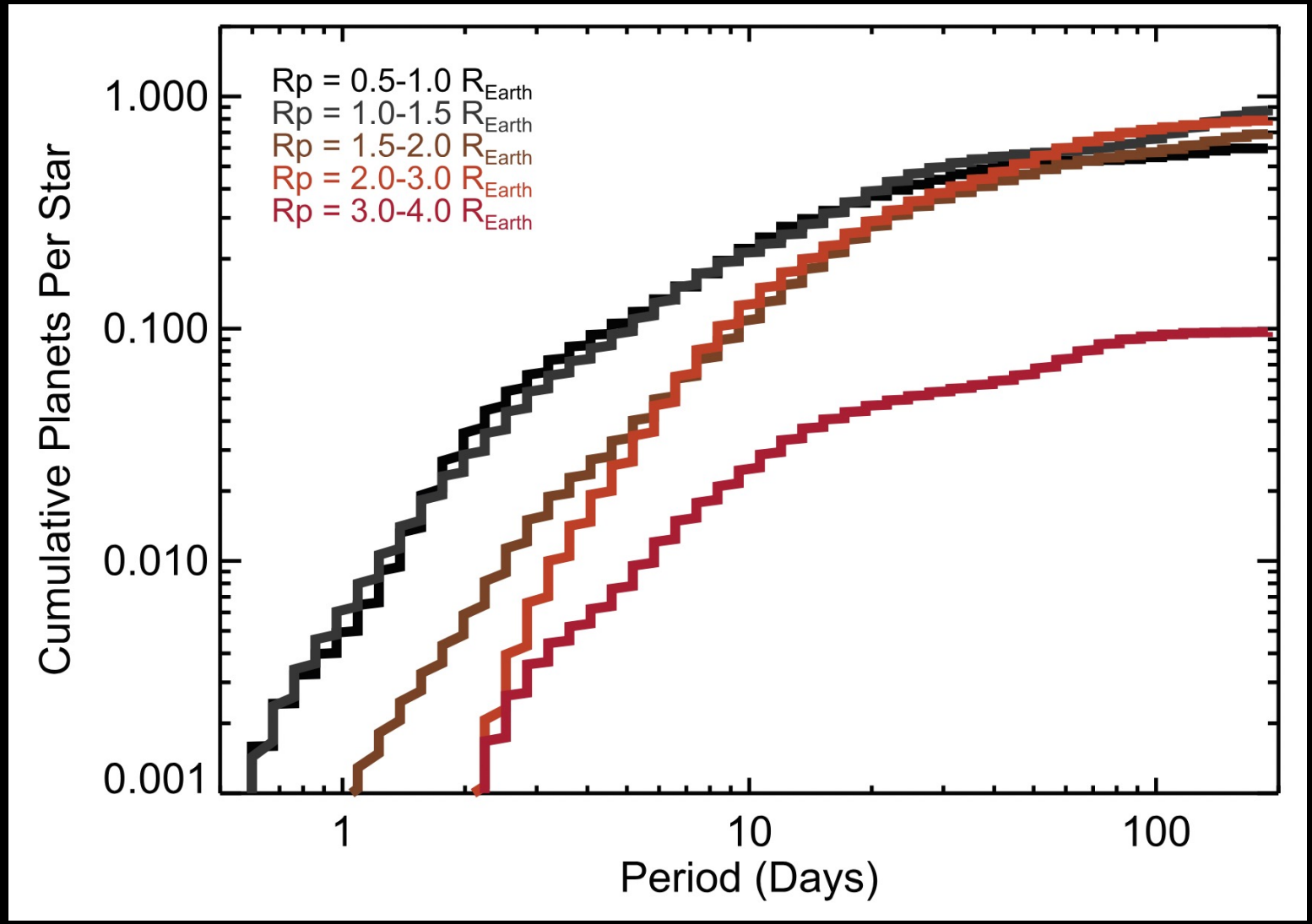


Demographics of M-dwarf planets in the Kepler Era



Dressing & Charbonneau 2015

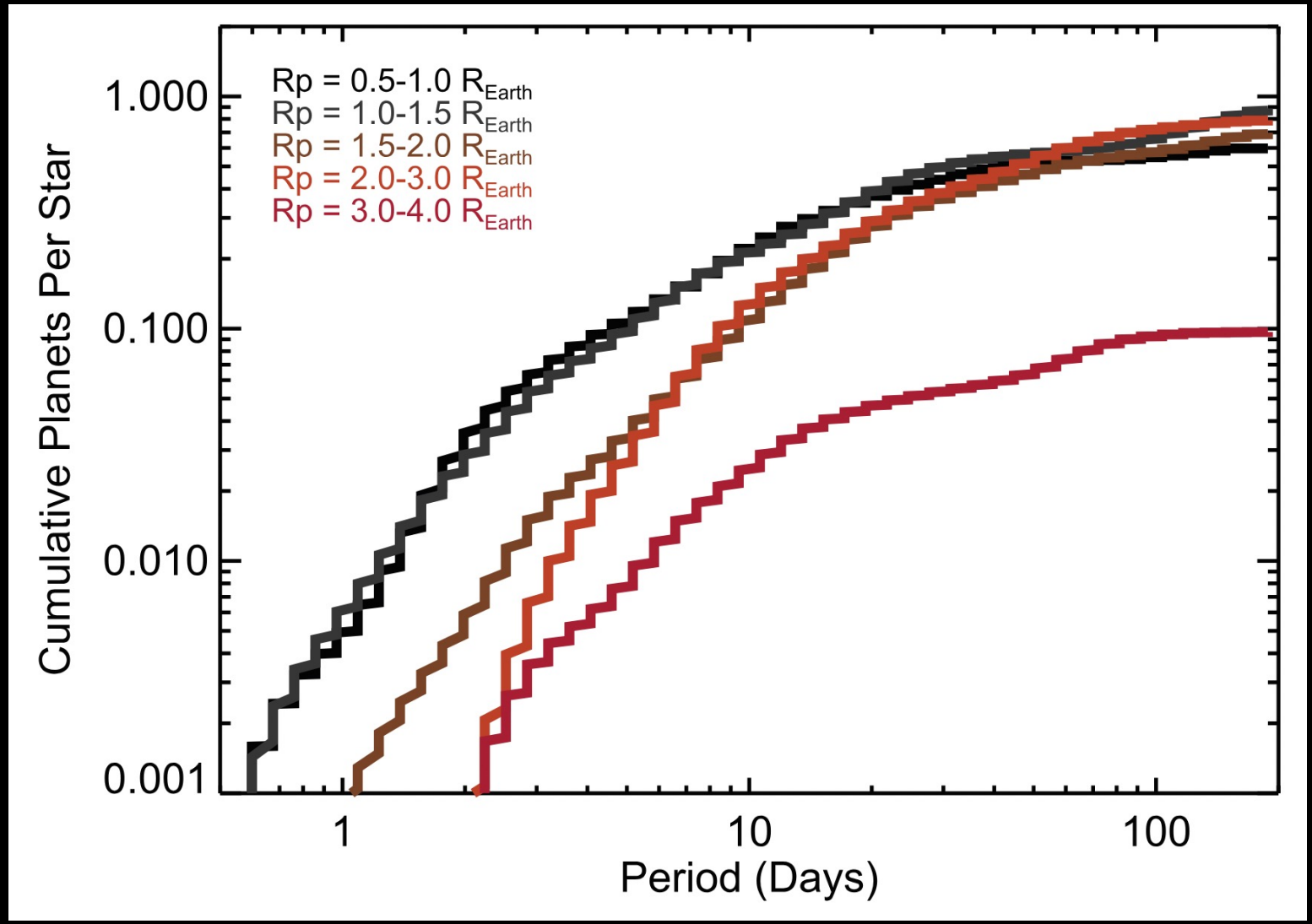
"For orbital periods shorter than 200 days and planet radii of 1–4 $R_\oplus$, we estimated a cumulative planet occurrence rate of 2.5 ± 0.2 planets per M dwarf"



Median $M_* = 0.50 M_\odot$

"For orbital periods shorter than 200 days and planet radii of 1–4 $R_\oplus$, we estimated a cumulative planet occurrence rate of 2.5 ± 0.2 planets per M dwarf"

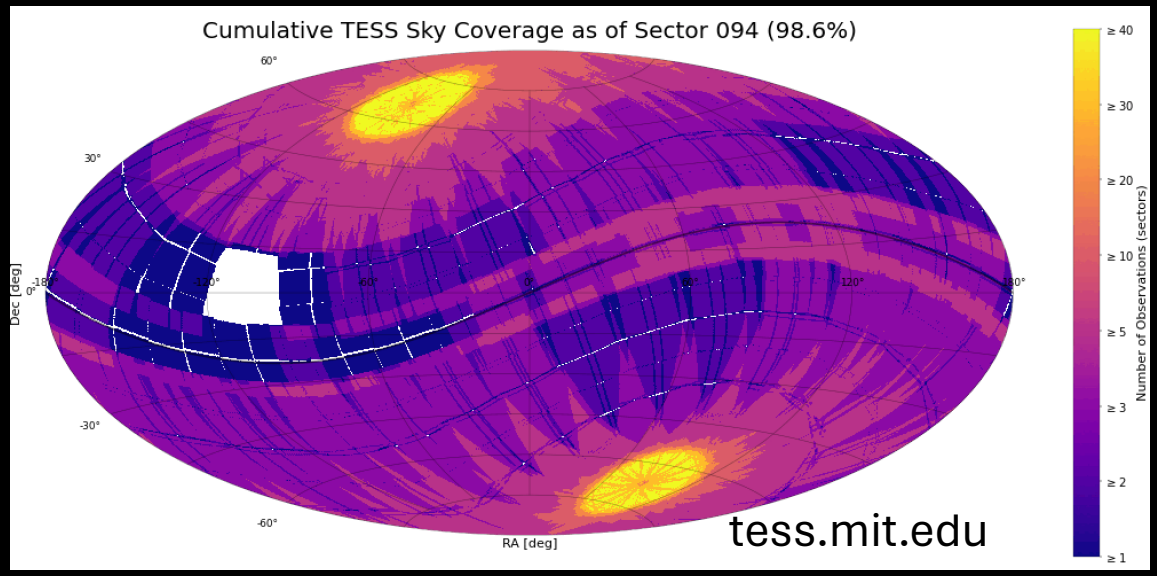
Dressing & Charbonneau 2015

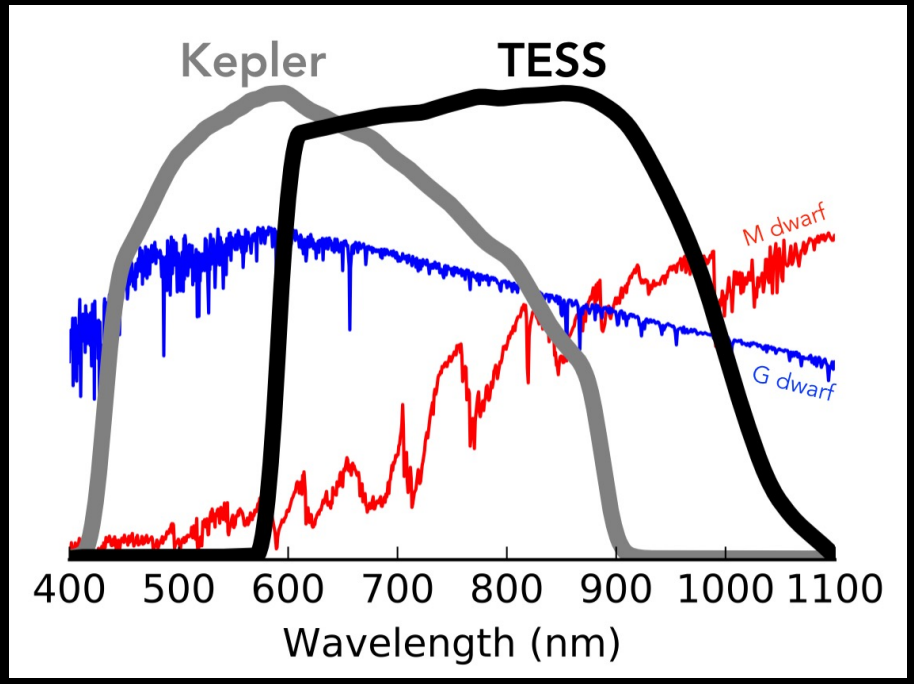


Demographics of M-dwarf planets in the TESS Era

How is TESS different?

- All-Sky
- Only 27-day sectors
- Redder bandpass



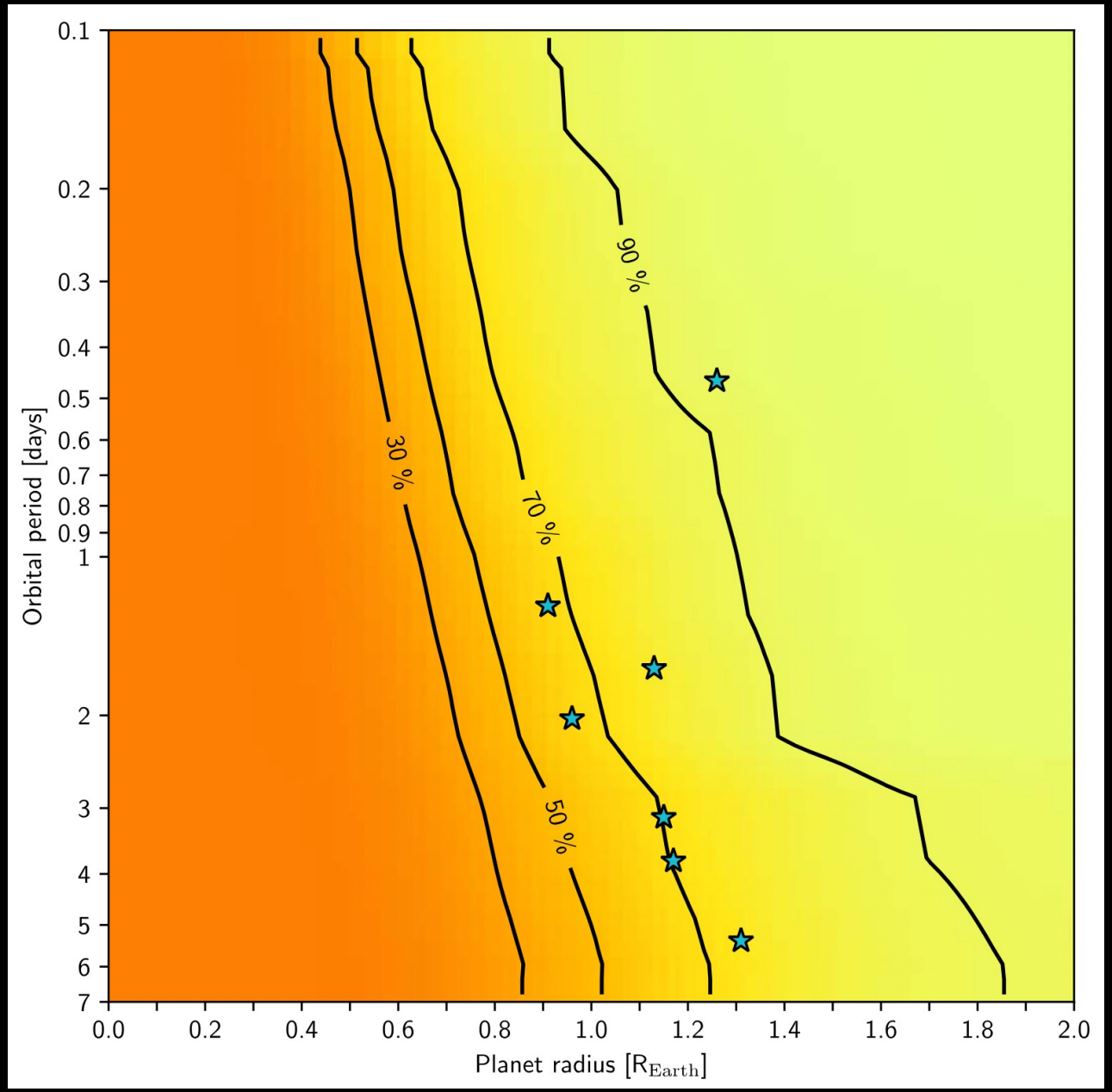


Z. Berta-Thompson with data from Sullivan et al. (2015)

Low-mass M dwarfs have far fewer Sub-Neptunes

Median $M_* = 0.17 M_\odot$

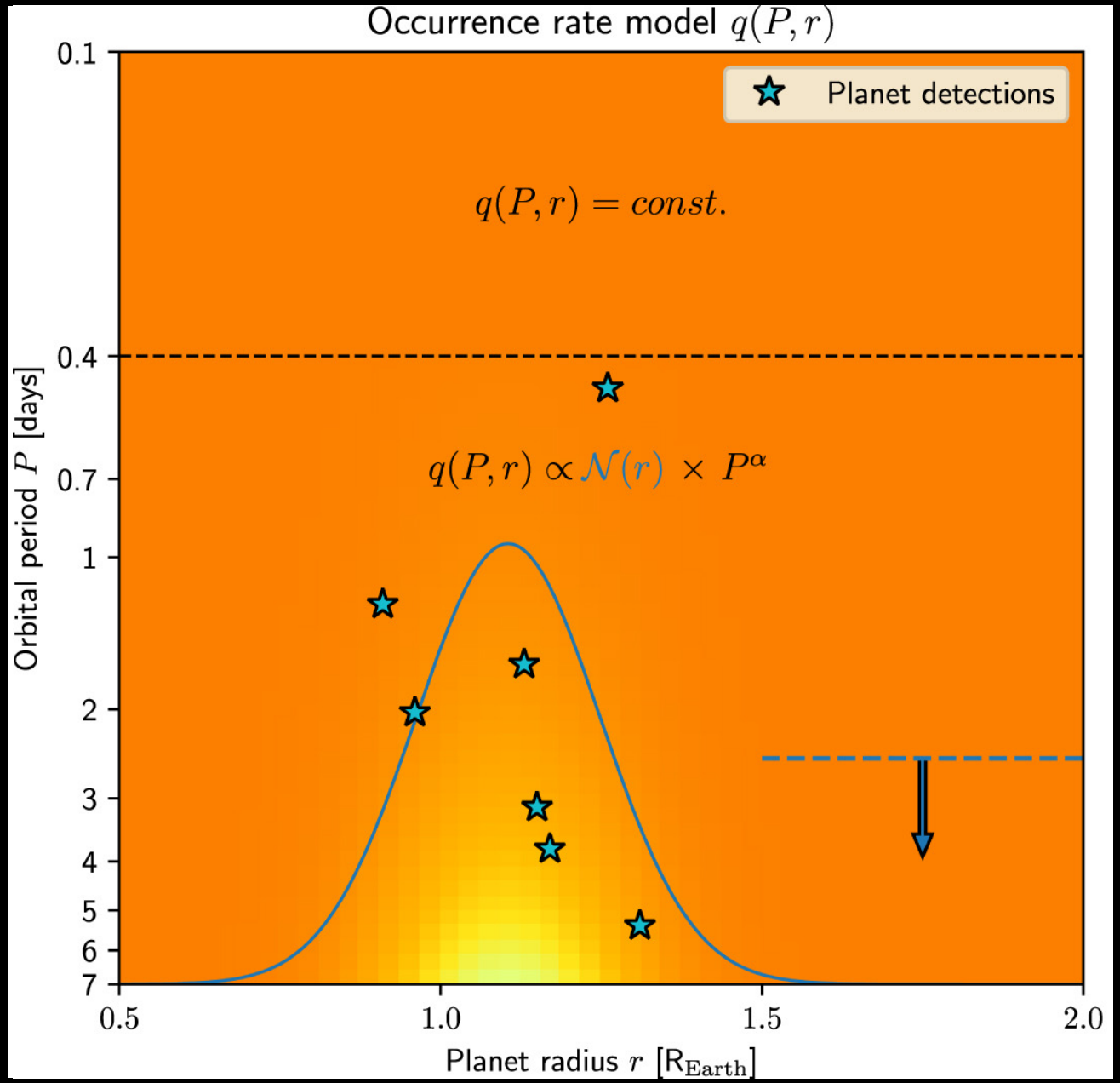
Ment & Charbonneau 2023



Low-mass M dwarfs have far fewer Sub-Neptunes

Median $M_* = 0.17 M_\odot$

Ment & Charbonneau 2023

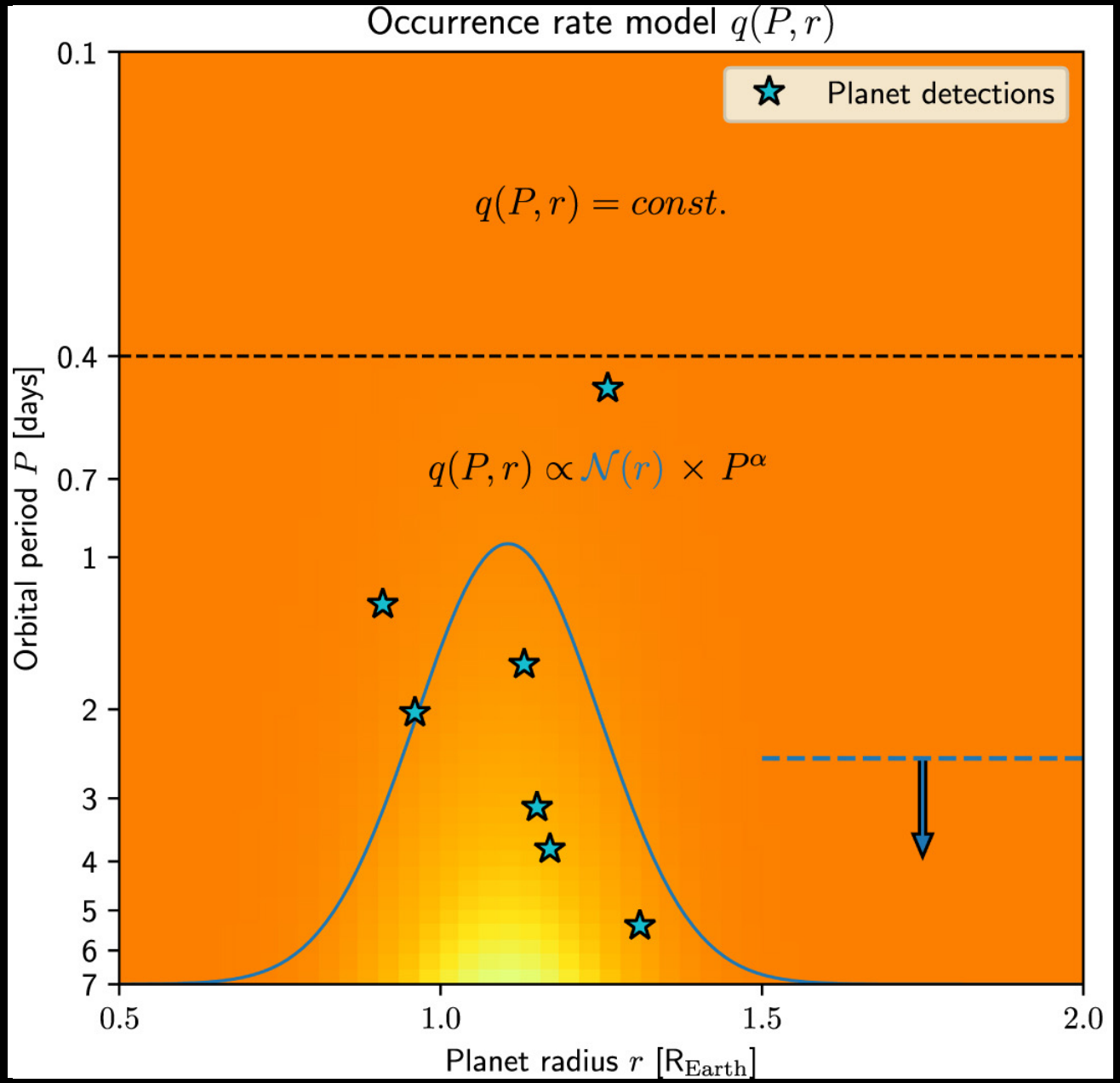


Low-mass M dwarfs have far fewer Sub-Neptunes

For insolations > $4S_{\oplus}$

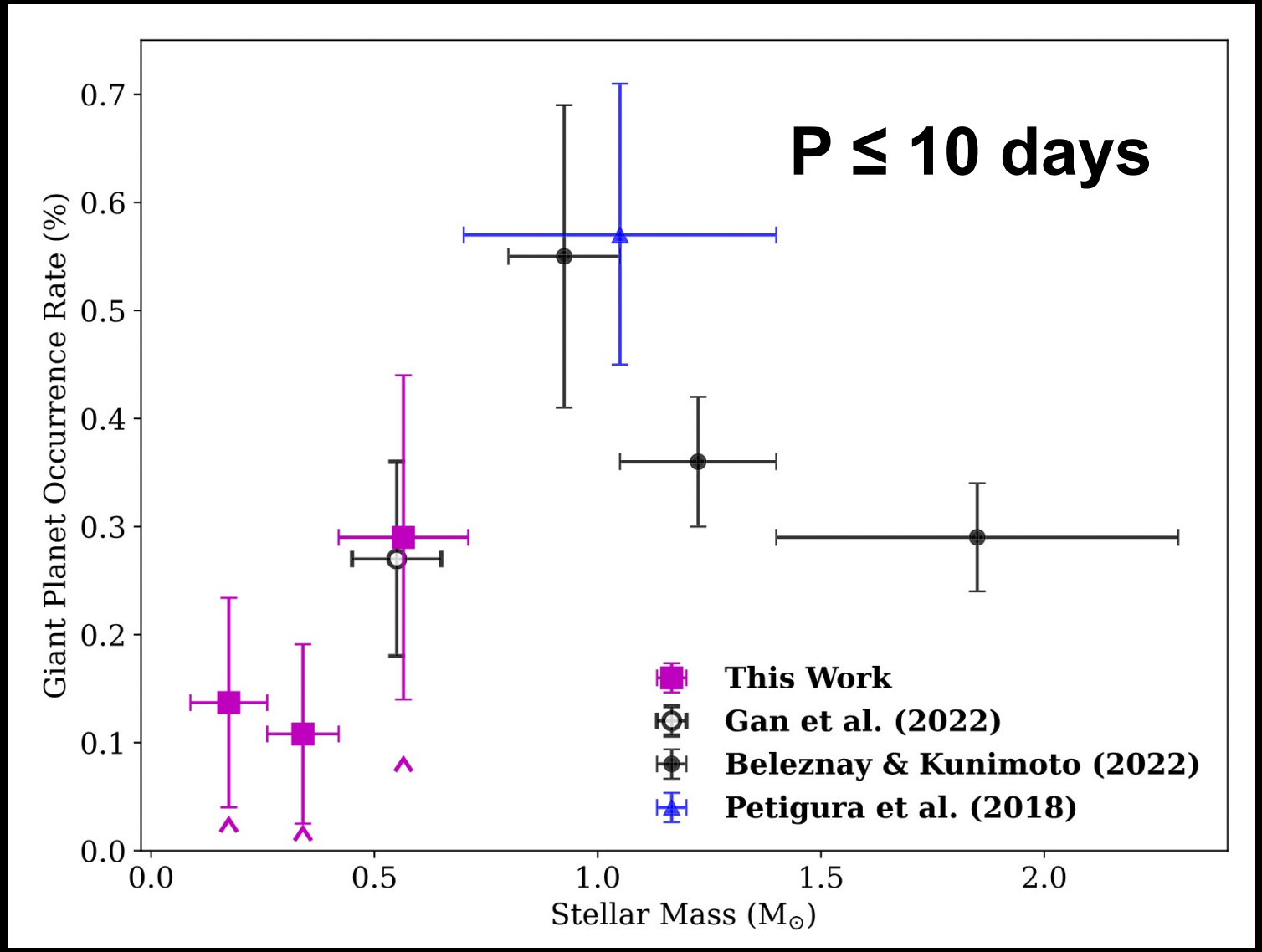
	Early M dwarfs	Mid-to-Late M dwarfs
Rocky ($R<1.5R_{\oplus}$)	0.48 ± 0.14	0.49 ± 0.17
Sub-Neptunes ($R>1.5R_{\oplus}$)	0.49 ± 0.10	≤ 0.06
Ratio	1 : 1	13 : 1

Ment & Charbonneau 2023



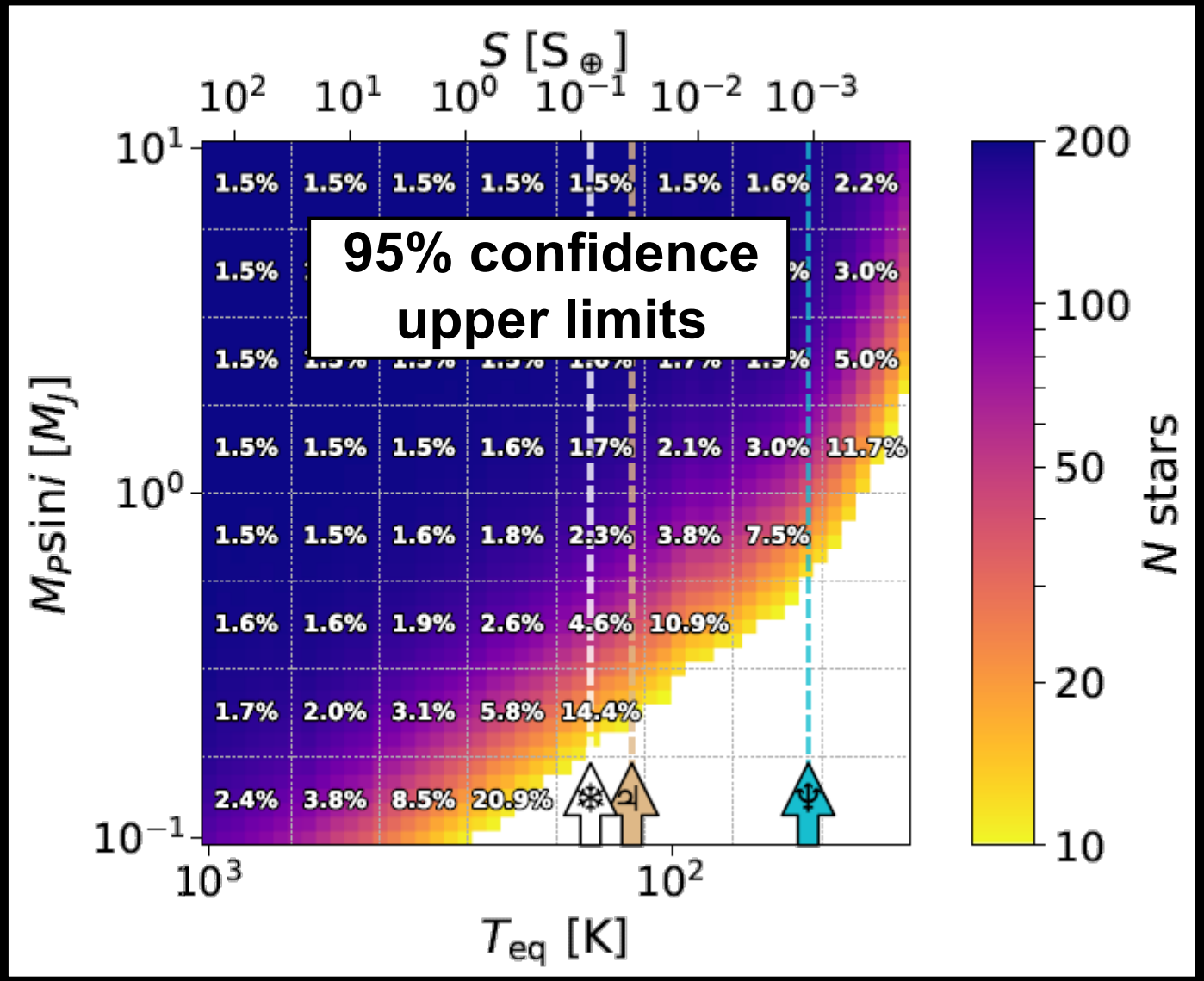
Bryant et al. 2023

Transits tell us that Hot Jupiters are rare for early Ms, and even rarer for late Ms



Pass et al. 2023

From RVs, we know that the same applies to Cold Jupiters



Terrestrial planets are common + giant planets are rare = M-dwarf system architectures are unlike ours

ESO/M. Kornmesser

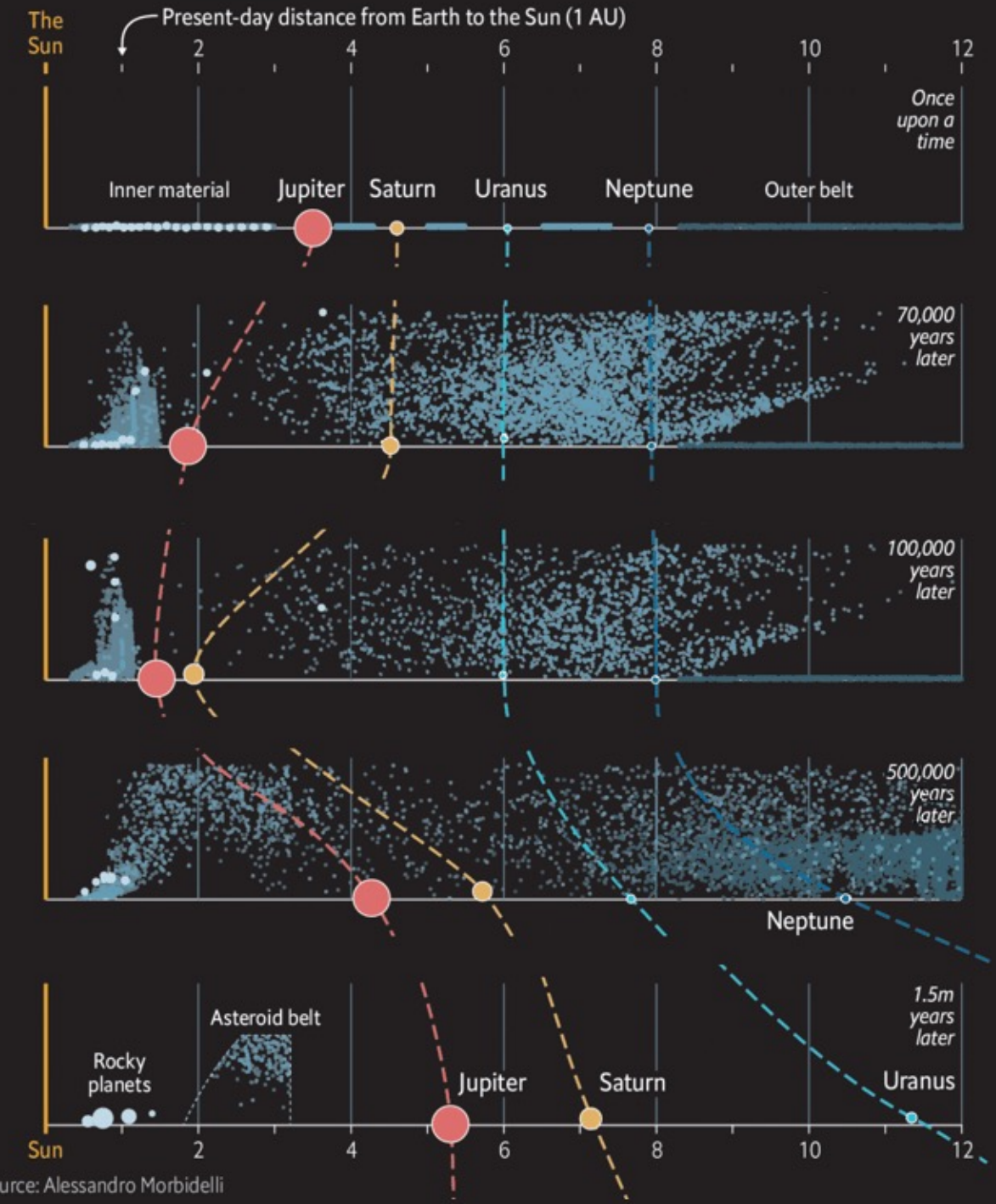
Terrestrial planets are common + giant planets are rare = M-dwarf system architectures are unlike ours

41% of Sun-like stars with an inner small planet have an outer Jovian (Rosenthal et al. 2022)

ESO/M. Kornmesser

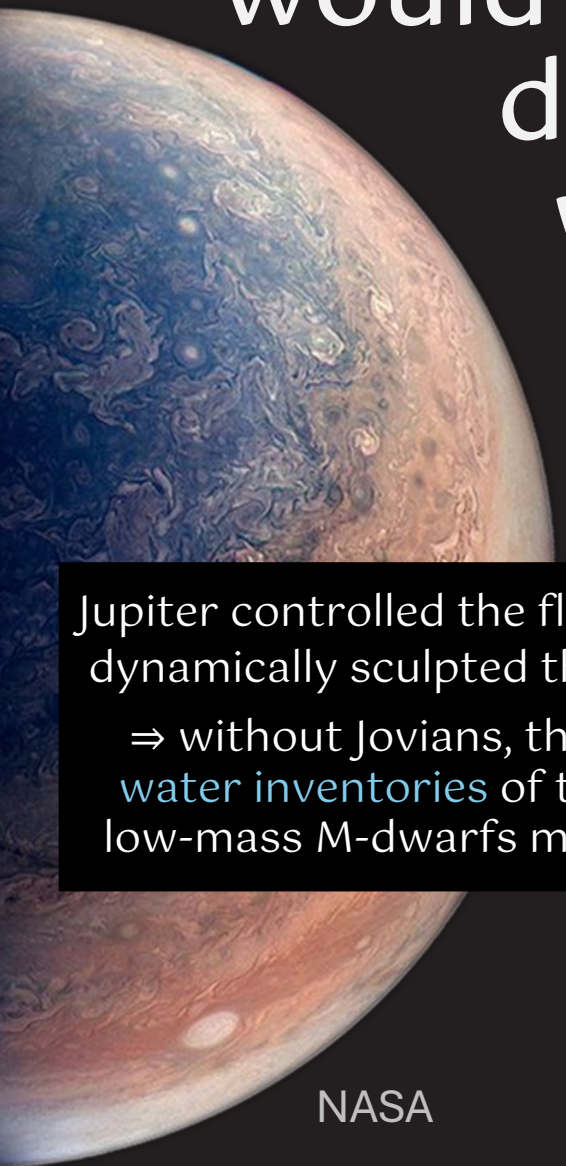
Our solar system would be very different without Jupiter

NASA



Source: Alessandro Morbidelli

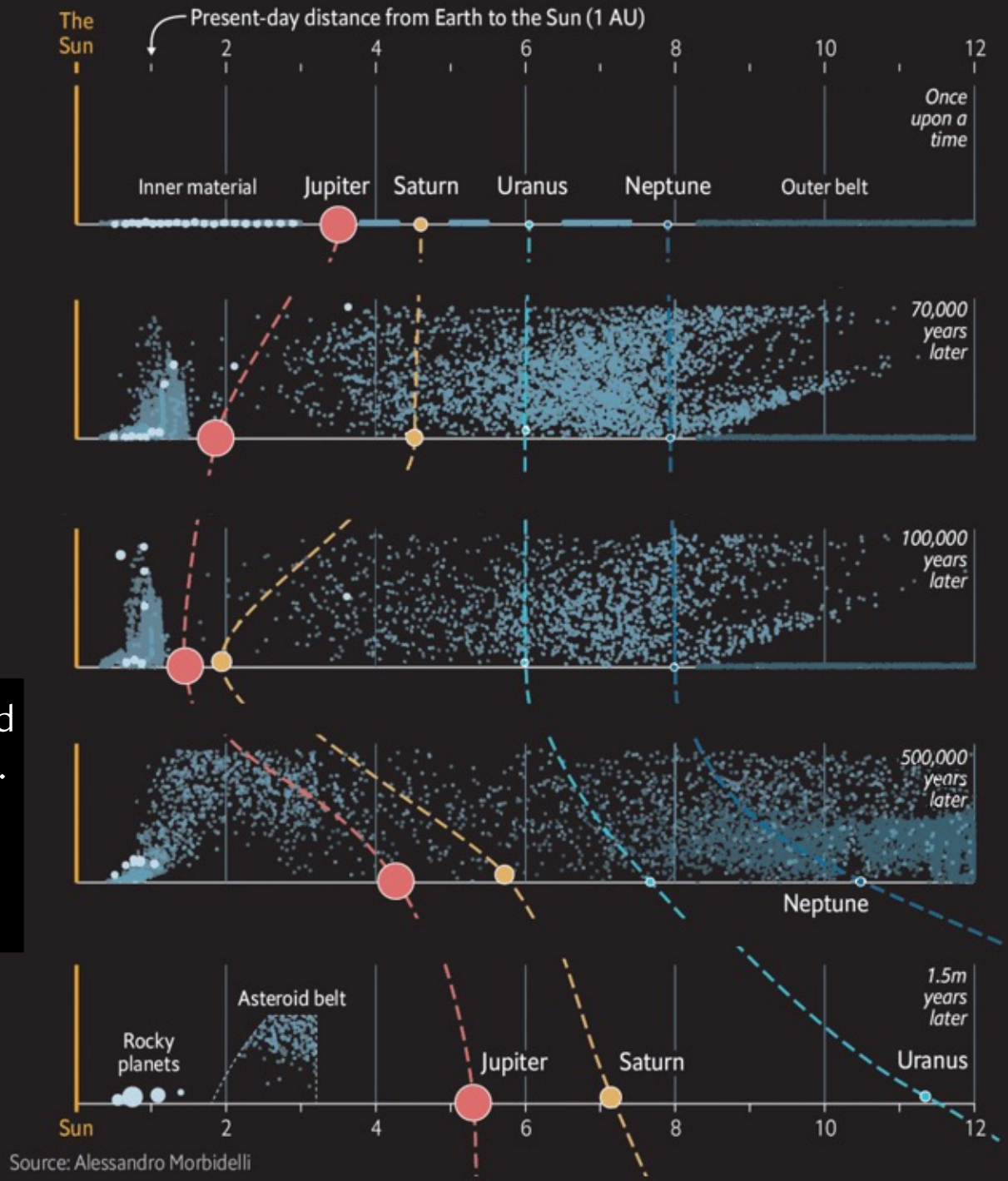
Our solar system would be very different without Jupiter



Jupiter controlled the flow of icy material and dynamically sculpted the inner solar system.

⇒ without Jovians, the compositions and water inventories of terrestrial planets of low-mass M-dwarfs may be quite different.

NASA



Source: Alessandro Morbidelli

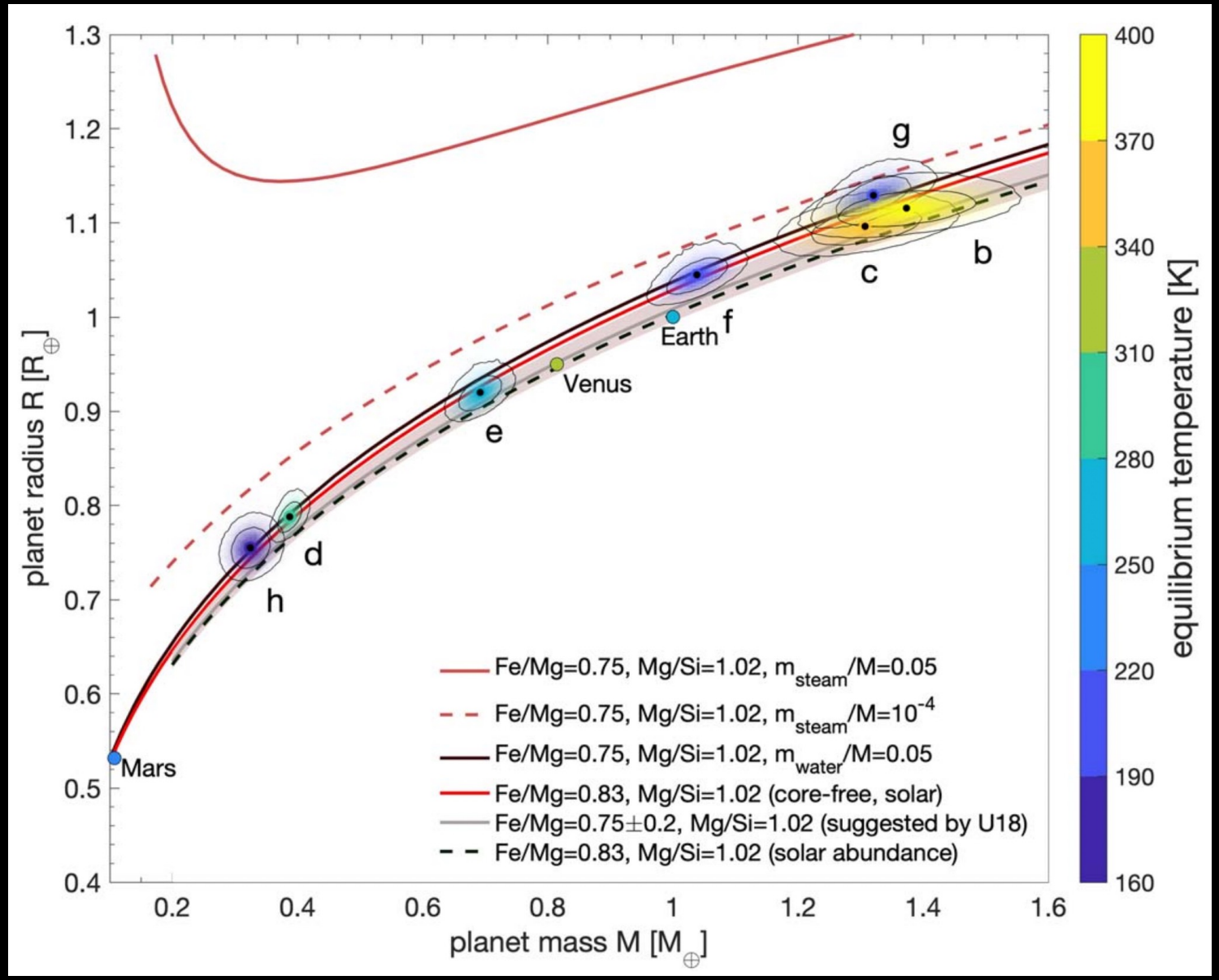
Demographics Beyond Occurrence Rates:

What are these planets made of?

TRAPPIST-1: It's all rocks

"... all seven planets' densities may be described with a single rocky mass–radius relation which is depleted in iron relative to Earth, with Fe 21 wt% versus 32 wt% for Earth, and otherwise Earth-like in composition"

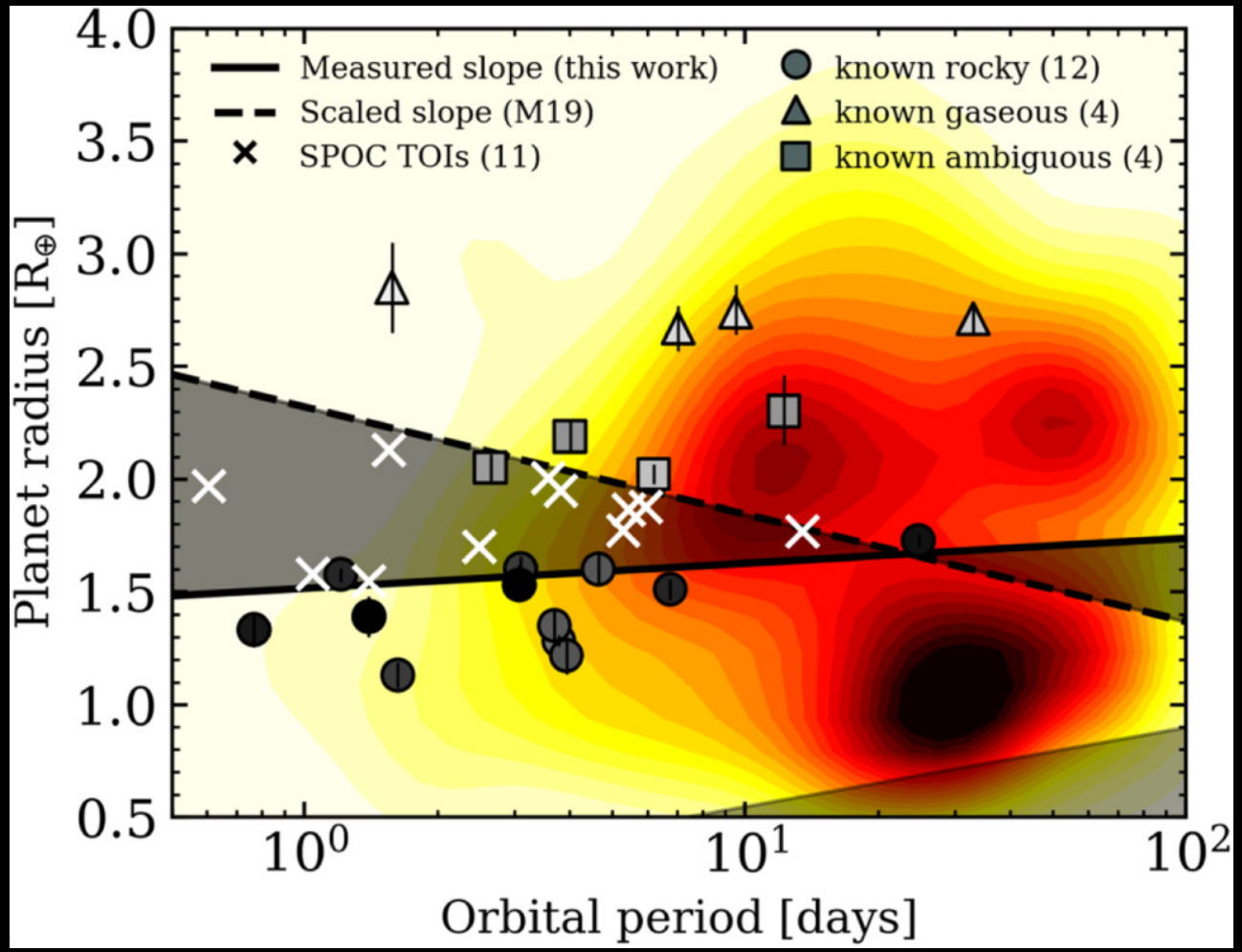
Agol et al. 2021



The slope of the radius valley is different for M dwarfs*

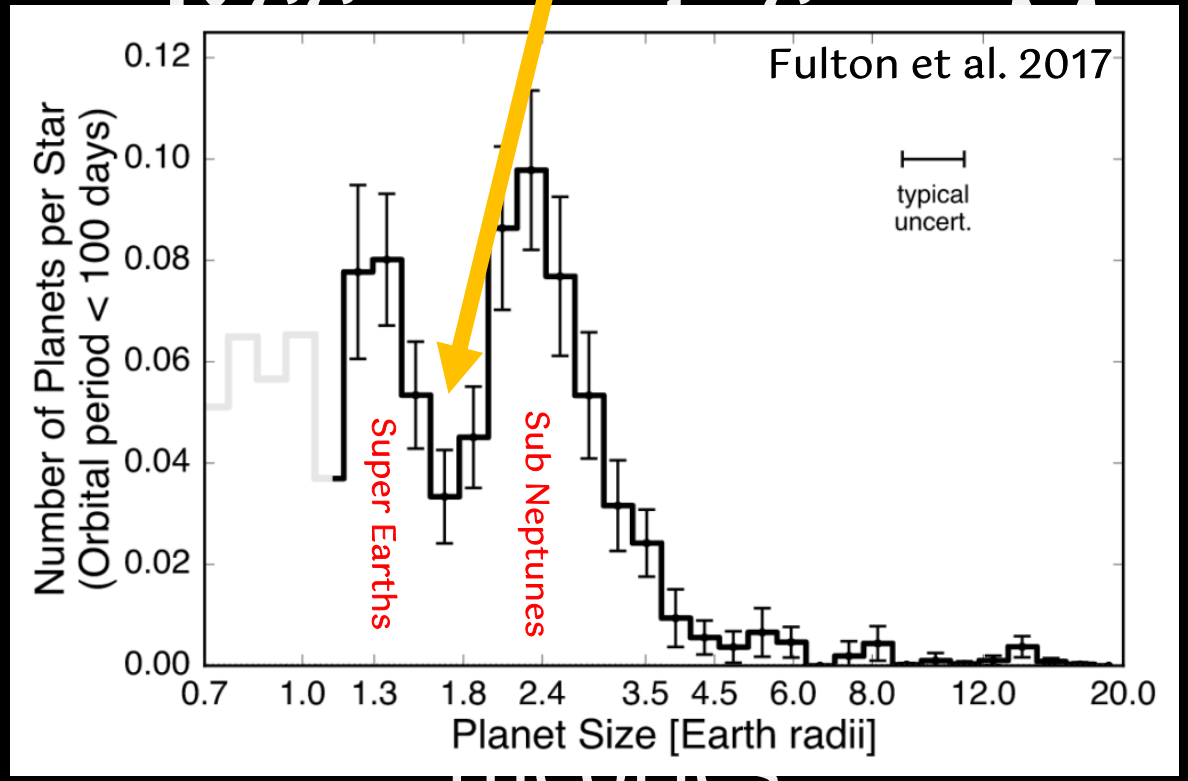
This has implications for atmospheric mass loss / planet formation theories

Cloutier & Menou 2020



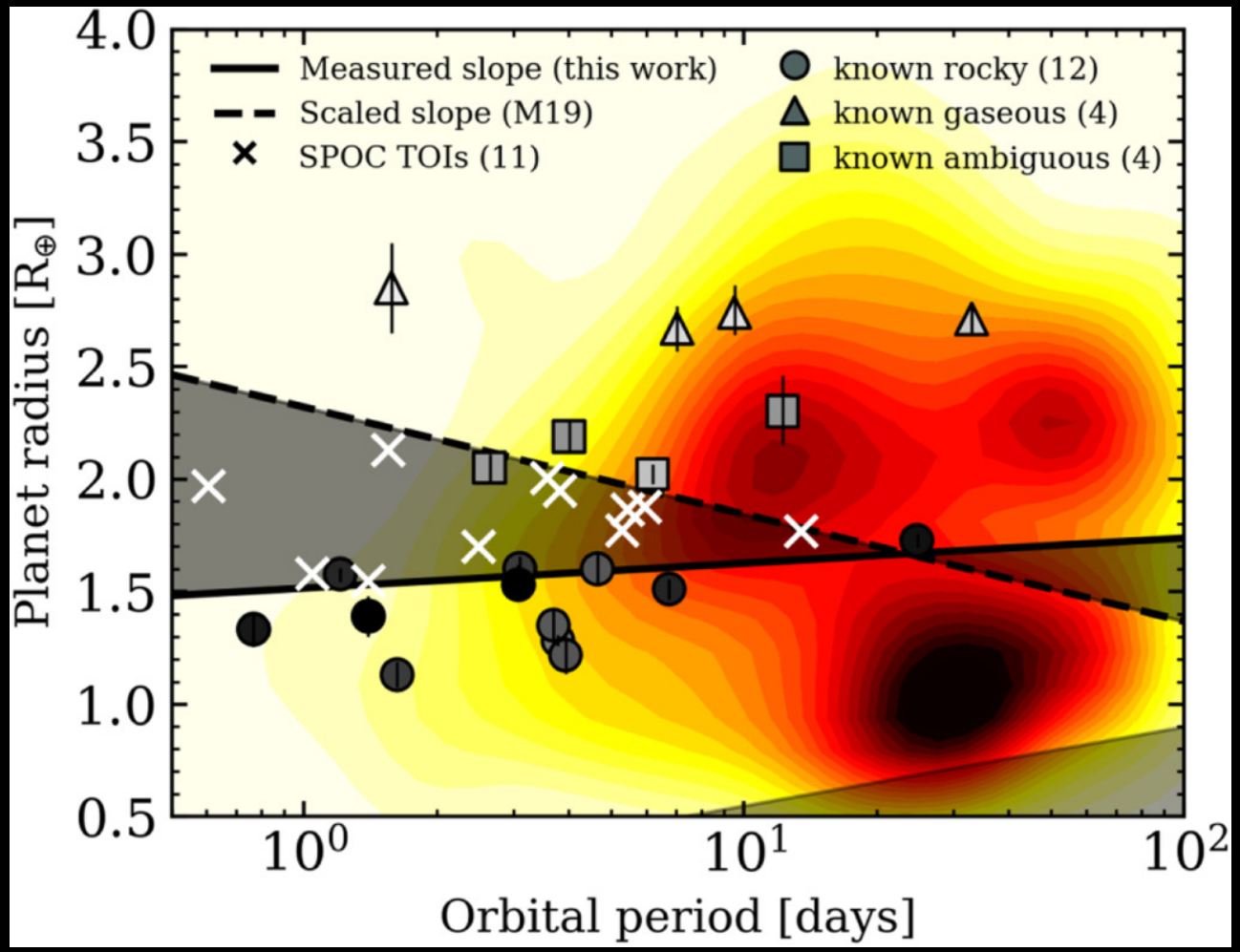
* From Kepler/K2, so these are early M dwarfs

The slope of the radius valley is



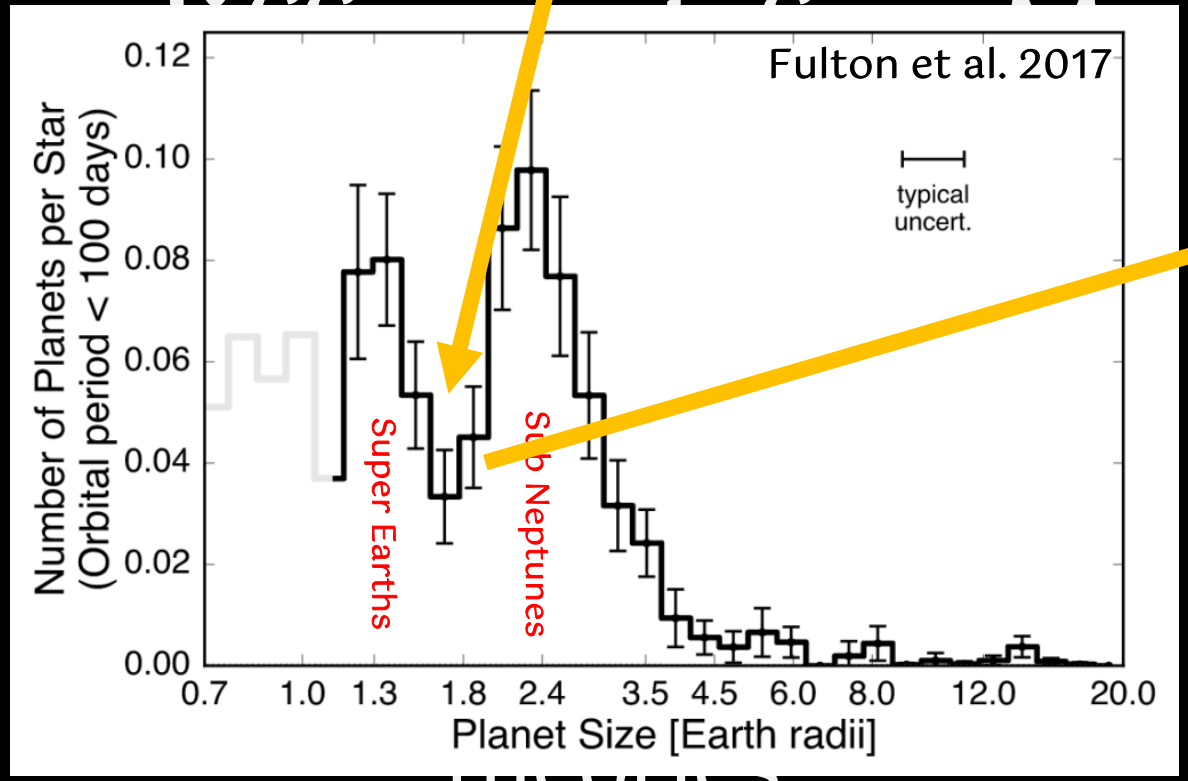
theories

Cloutier & Menou 2020



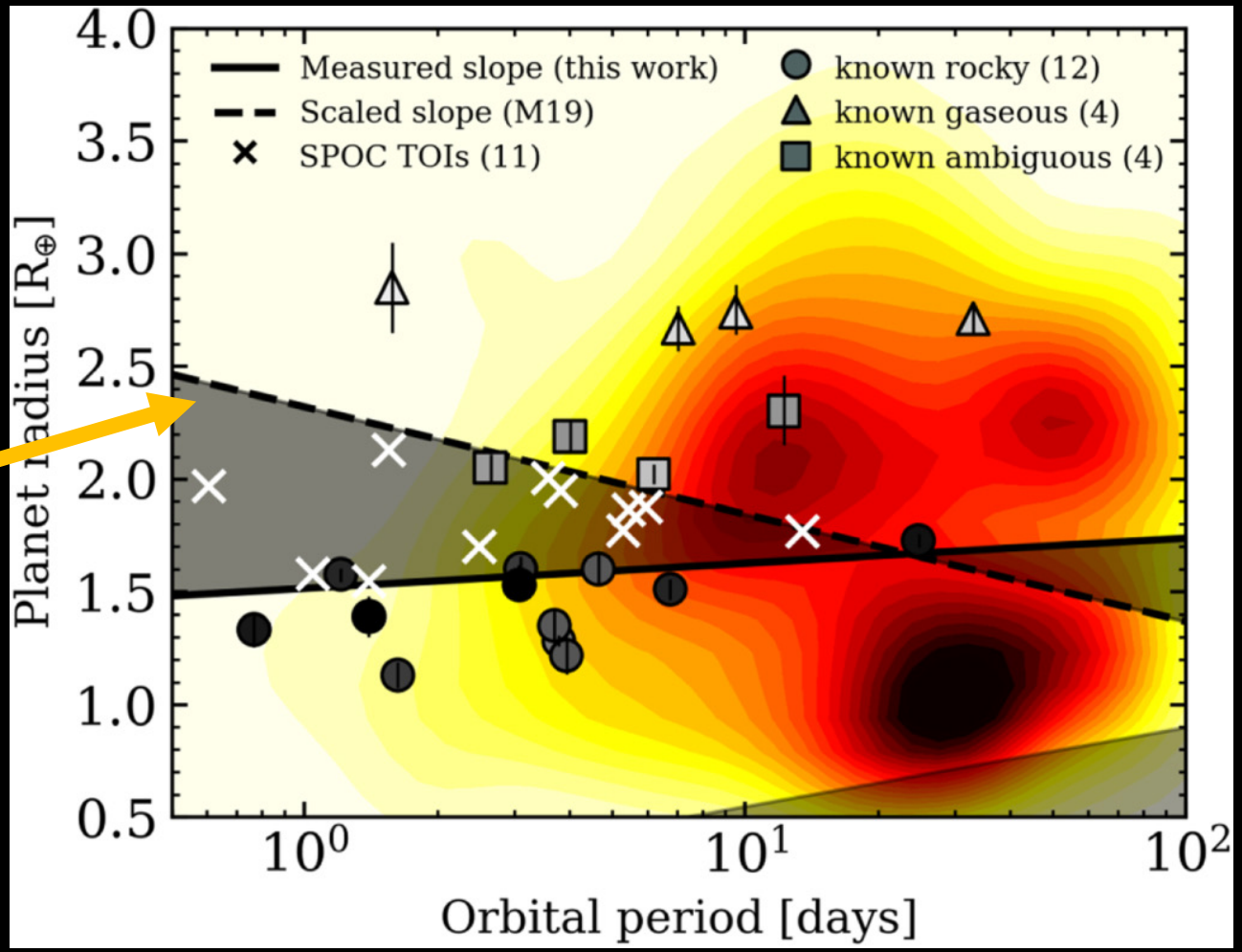
* From Kepler/K2, so these are early M dwarfs

The slope of the radius valley is



theories

Cloutier & Menou 2020

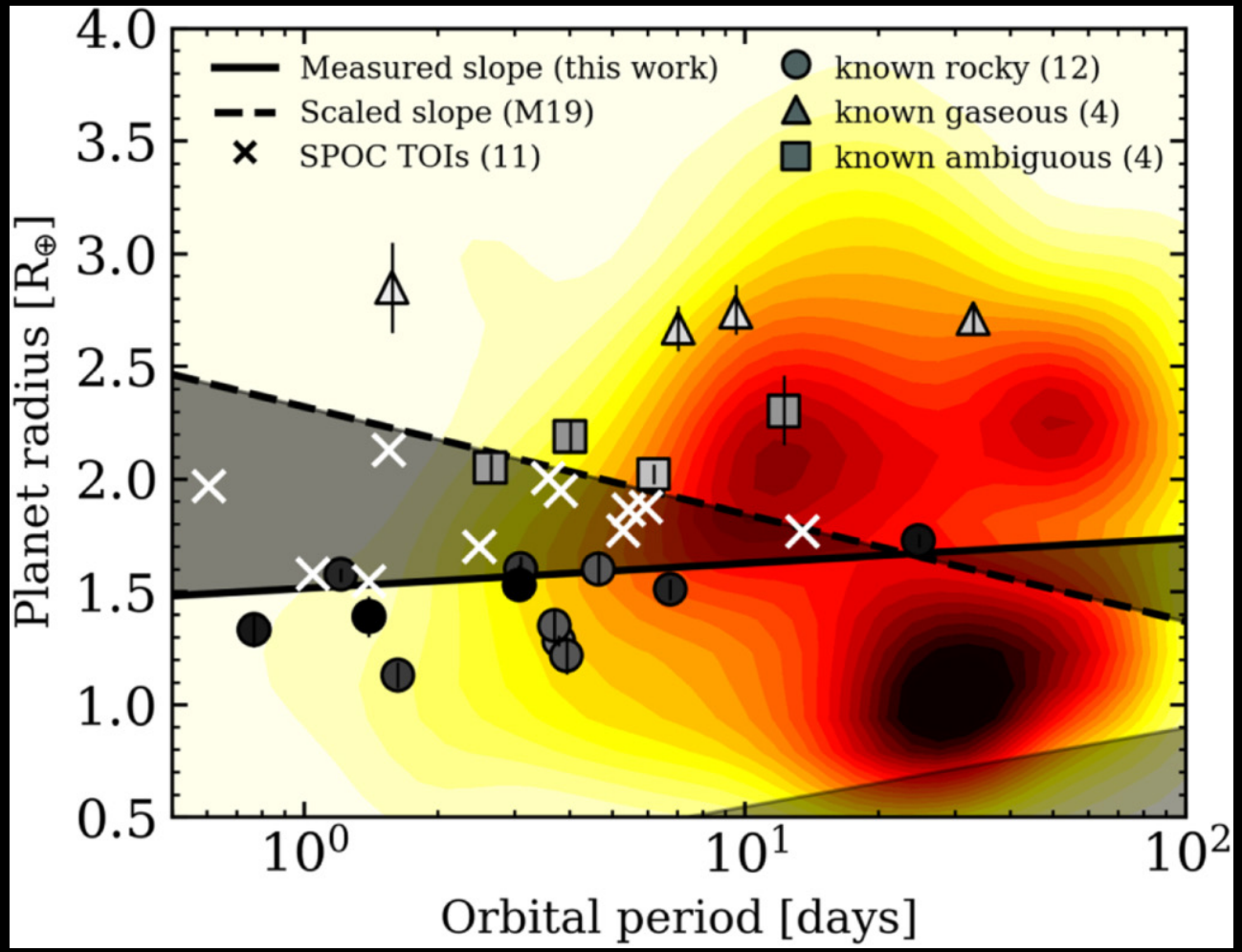


* From Kepler/K2, so these are early M dwarfs

The slope of the radius valley is different for M dwarfs*

This has implications for atmospheric mass loss / planet formation theories

Cloutier & Menou 2020



* From Kepler/K2, so these are early M dwarfs

What's Next? Demographics of Atmospheres

Rocky Worlds DDT Selects its First Targets

View all news >

September 19, 2024

The Rocky Worlds DDT Program will use JWST to search for atmospheres around a dozen nearby M-dwarf exoplanets while using HST to characterize activity in the host stars. Over the past month, community members have provided feedback on a provisional set of targets — the Targets Under Consideration (TUC) list. Based on that feedback, the Science Advisory Council (SAC), together with the Leads of the Core Implementation Team (CIT), have identified an initial set of targets for JWST MIRI 15 μm photometry:

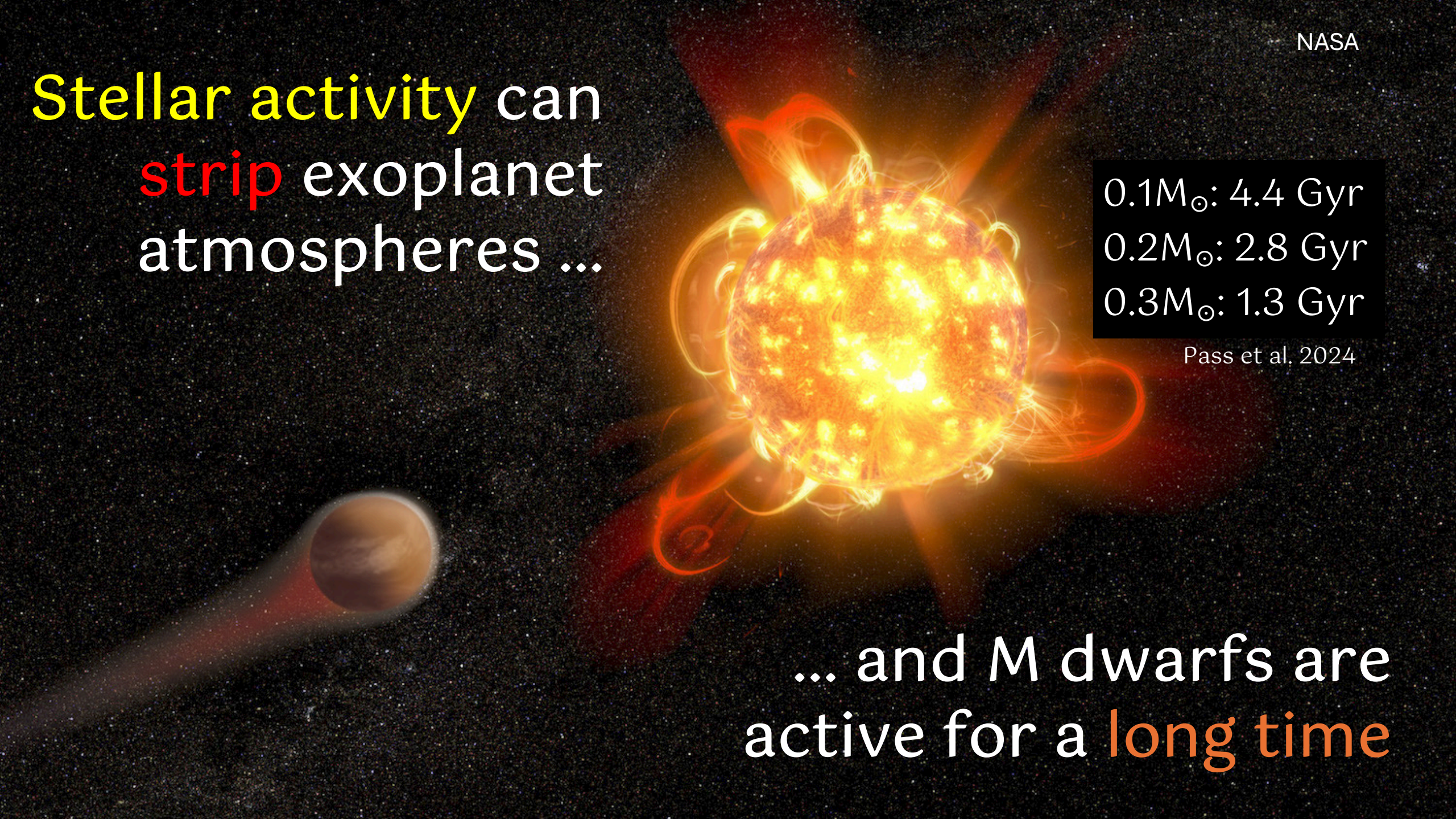
- LTT 1445 A c (11 eclipses)
- GJ 3929 b (15 eclipses)

Further targets will be selected after the results of the JWST Cycle 4 Call for Proposals are published in March 2025. Proposers may not apply for Cycle 4 Archival Research programs to analyze these data, as STScI cannot guarantee that all data will be in the archive when Cycle 4 begins. However, the SAC and CIT leads would like to encourage the community to consider JWST Cycle 4 proposals for complementary and supplementary observations of these targets or Theory programs. The standard JWST Duplication Policies apply. Additional exoplanet targets will be selected after the results from the Cycle 4 Telescope Allocation Committee are known. The DD program will be structured to avoid duplicating Cycle 4 General Observers programs.

We also highlight the importance of ancillary observations from ground and space-based facilities to better characterize these stellar systems and help prioritize future target selection. In particular, the following observations are critical for **all** targets in the TUC, specially those with high Priority Metrics and/or radii < 1.6 R_{Earth}:

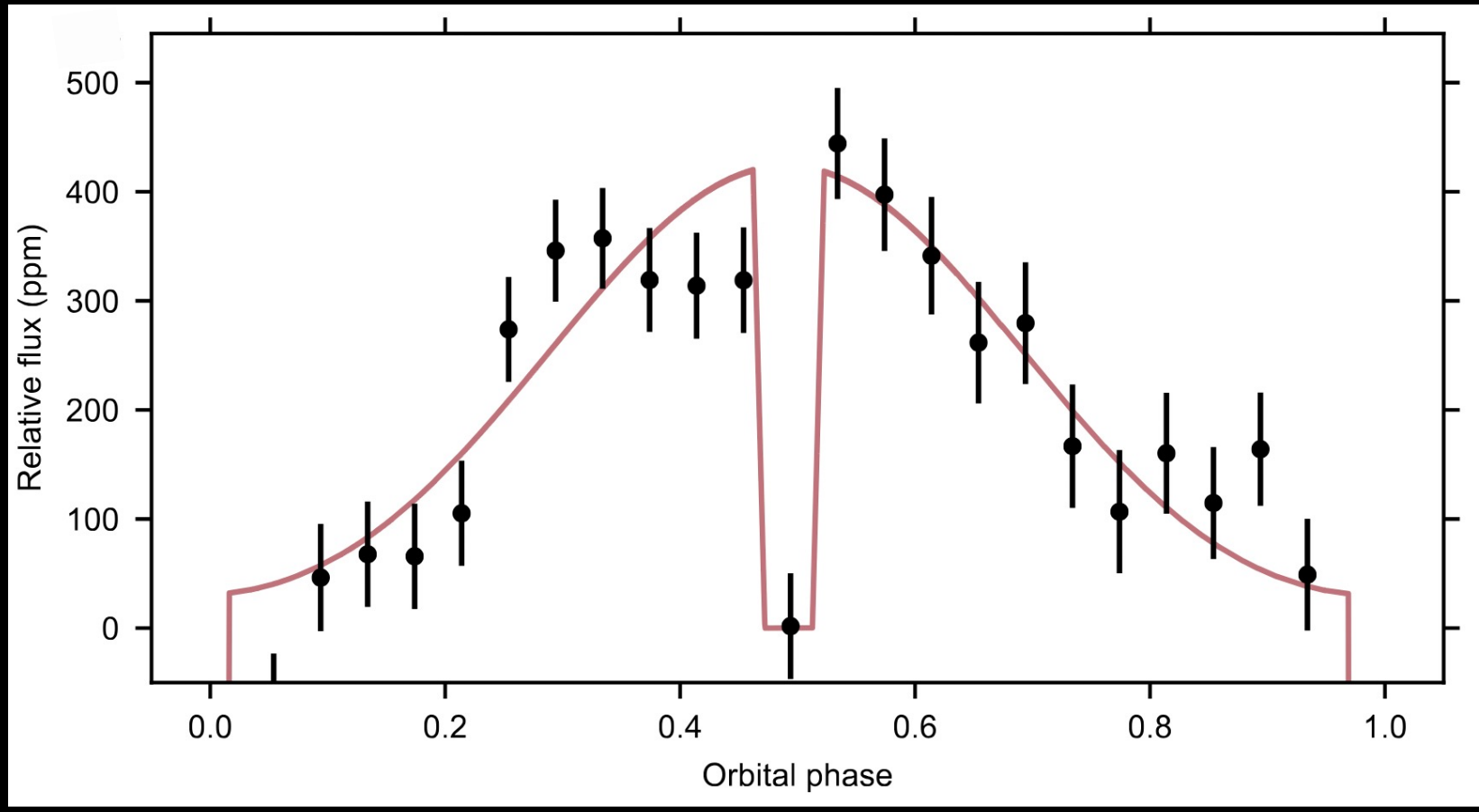
- **Precise radial-velocity monitoring:** This is crucial to constrain the rocky nature of the planets via their bulk density and the planetary escape velocity (mass), which is required to match targets against the “Cosmic Shoreline” (and to calculate the Priority Metric). In addition, they set important constraints


NASA
Stellar activity can strip exoplanet atmospheres ...
... and M dwarfs are active for a long time

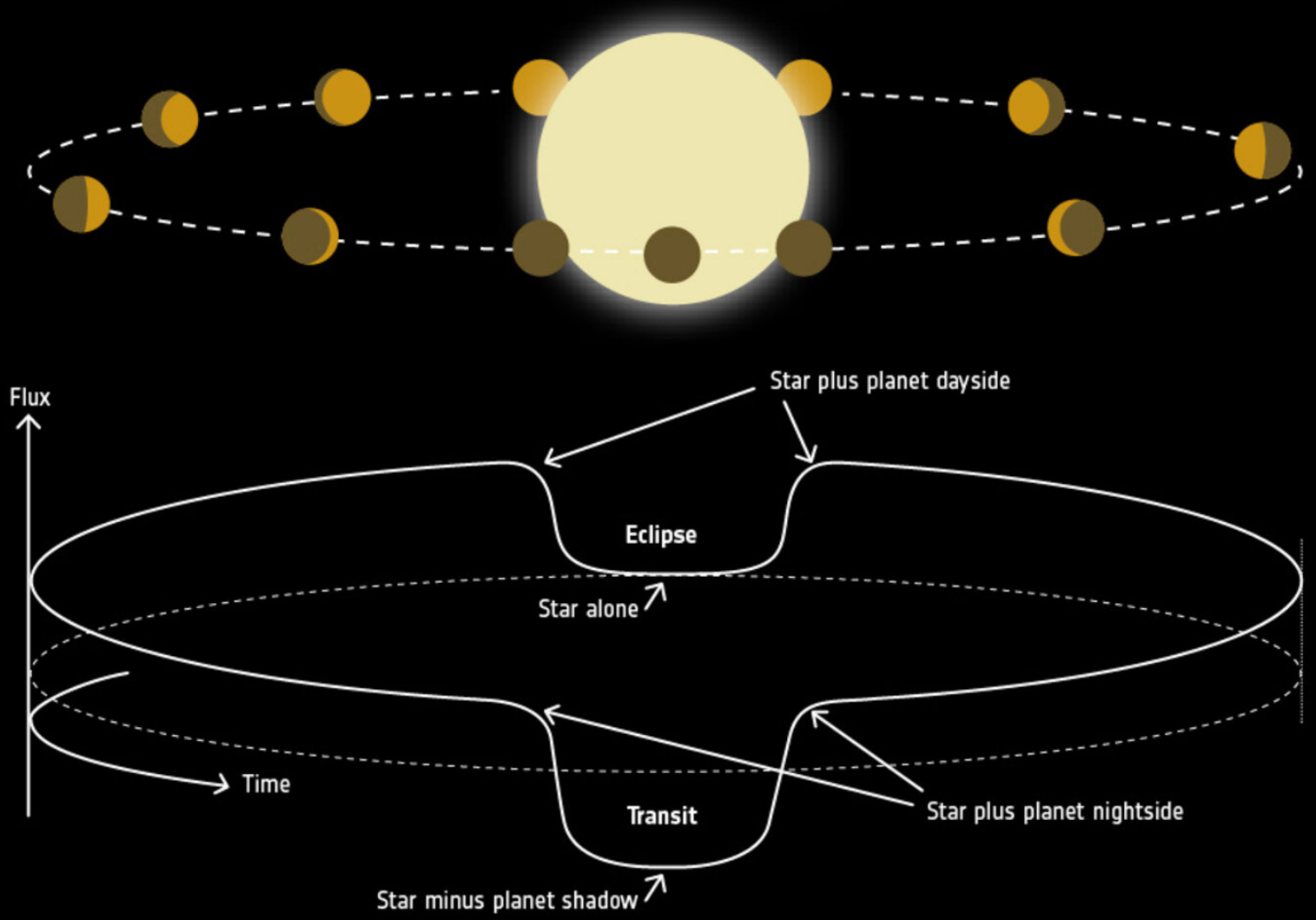

NASA
Stellar activity can strip exoplanet atmospheres ...
0.1M⊙: 4.4 Gyr
0.2M⊙: 2.8 Gyr
0.3M⊙: 1.3 Gyr
Pass et al. 2024
... and M dwarfs are active for a long time

Kreidberg et al. 2019

Are all M-dwarf planets bare rocks?



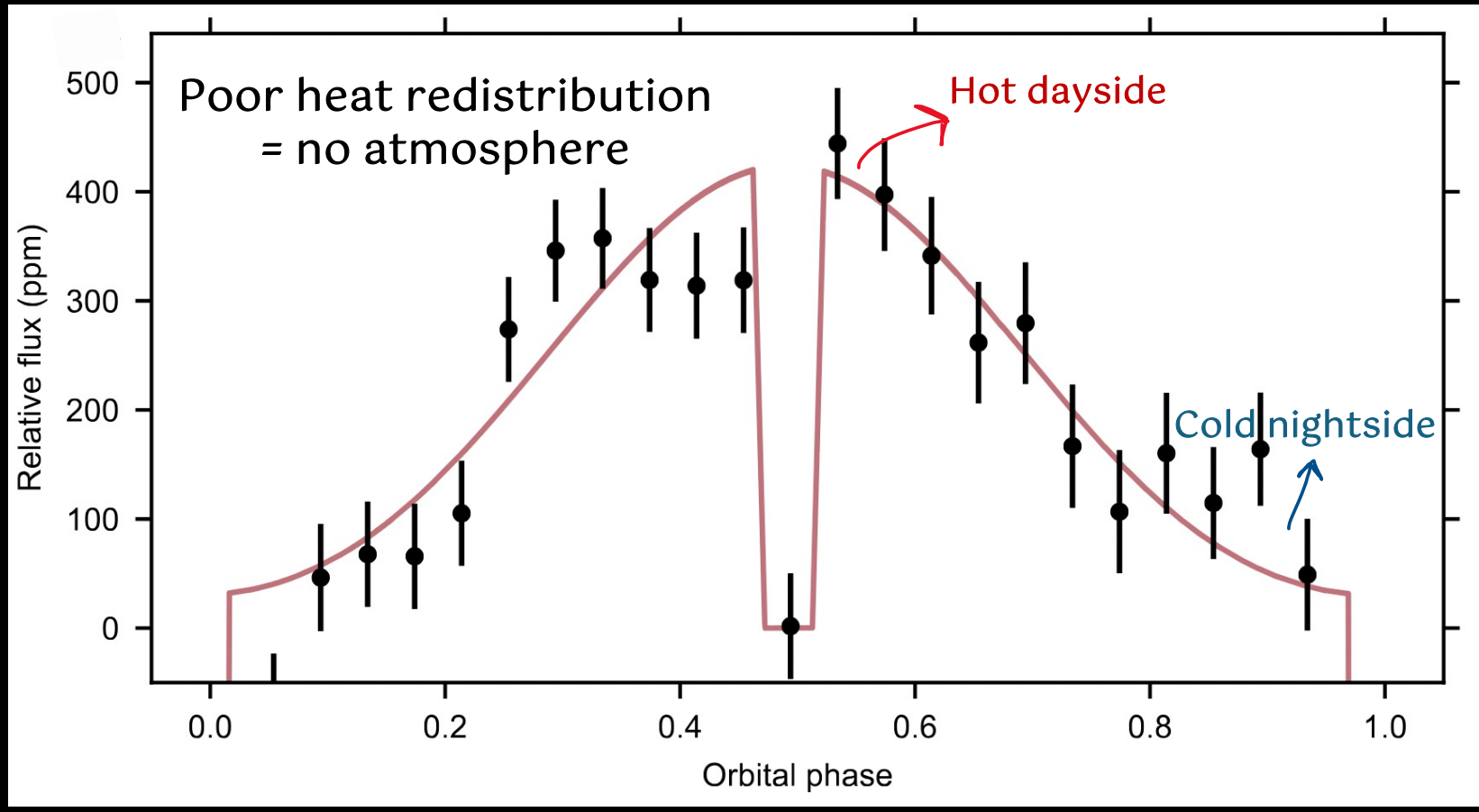
Spitzer phase curve of LHS 3844 b


Flux
Star plus planet dayside
Eclipse
Star alone
Time
Transit
Star plus planet nightside
Star minus planet shadow

ESA

Are all M-dwarf planets bare rocks?

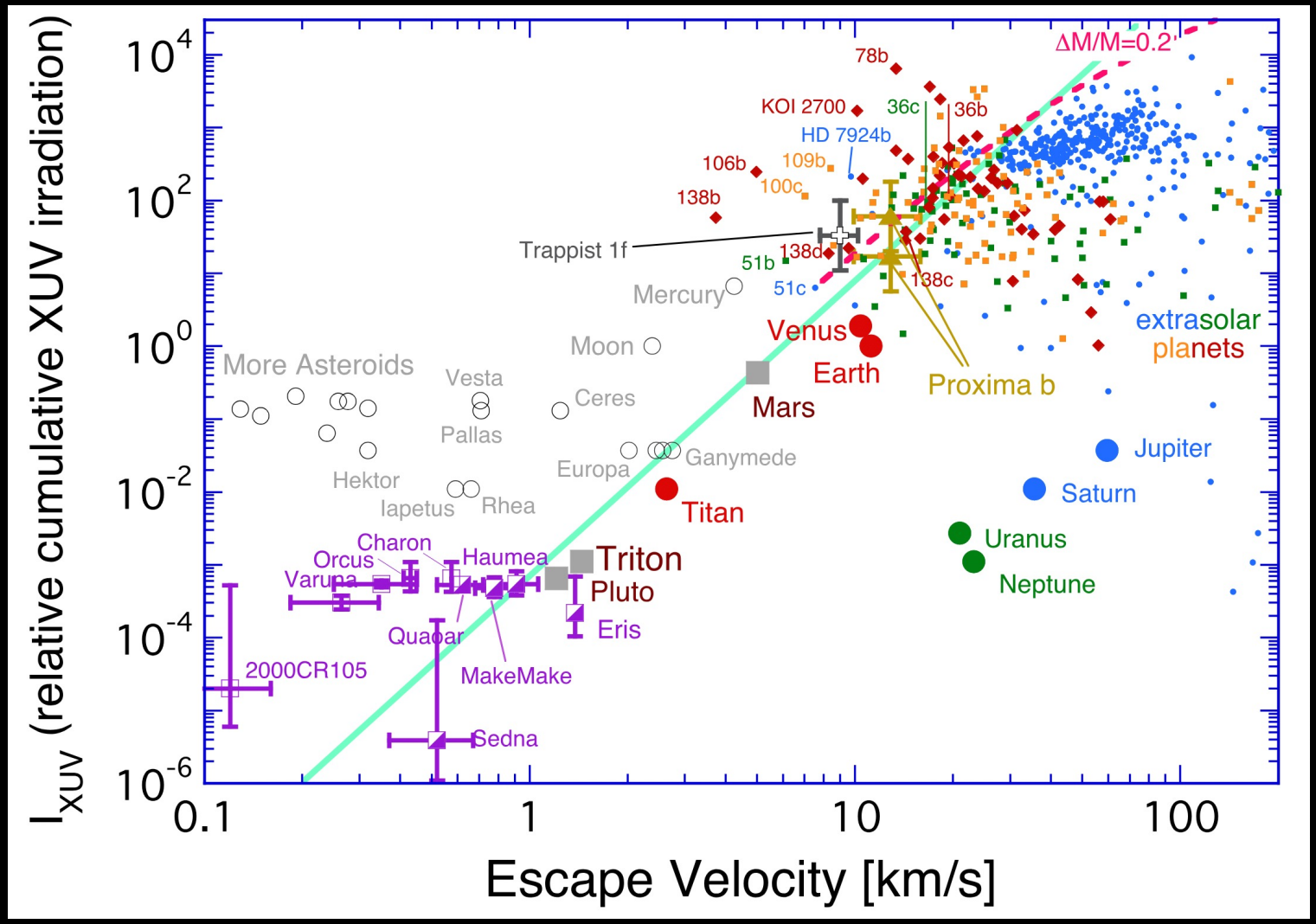
Kreidberg et al. 2019



Spitzer phase curve of LHS 3844 b

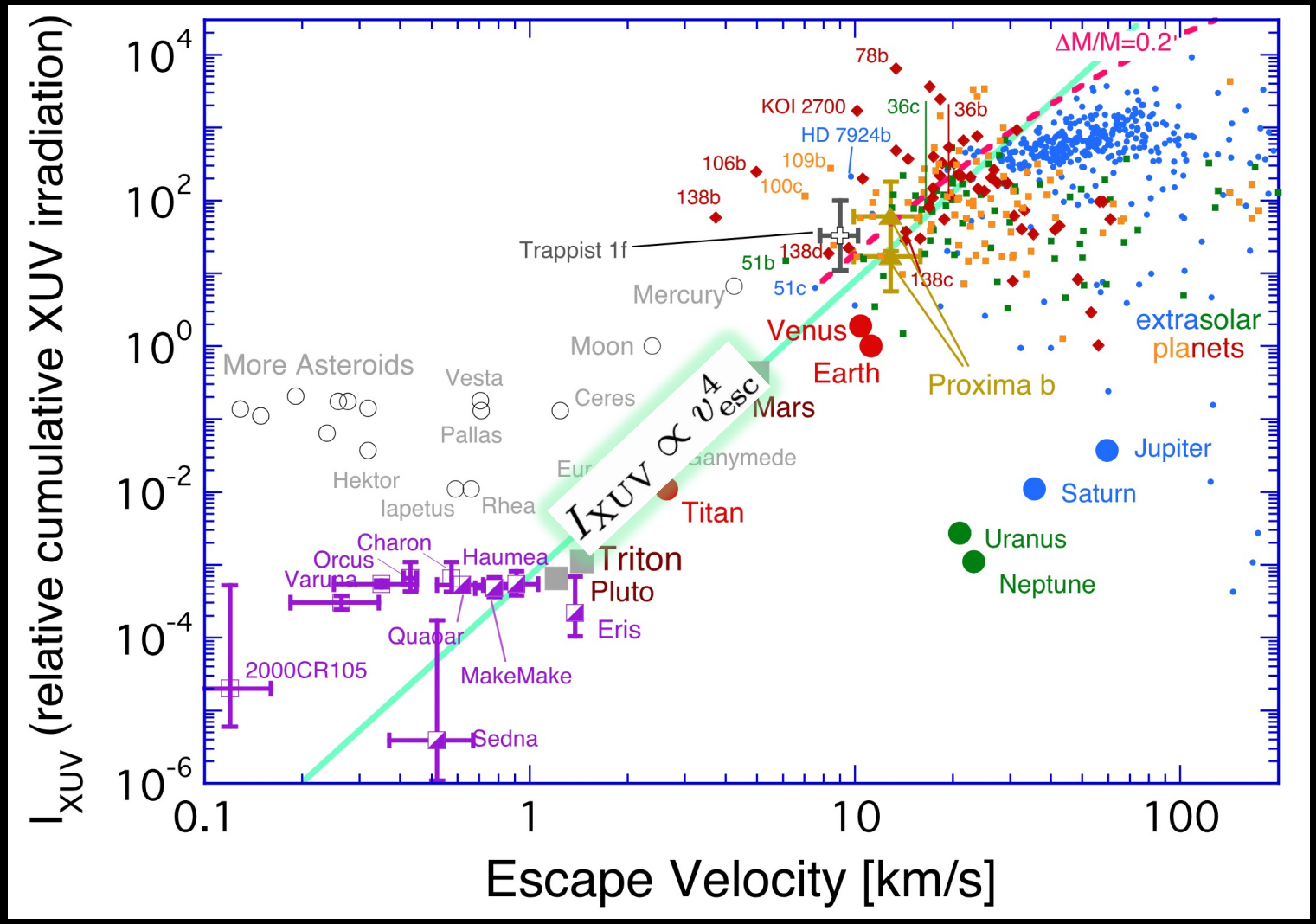
The Cosmic Shoreline approximates which planets can retain atmospheres

Zahnle & Catling 2017



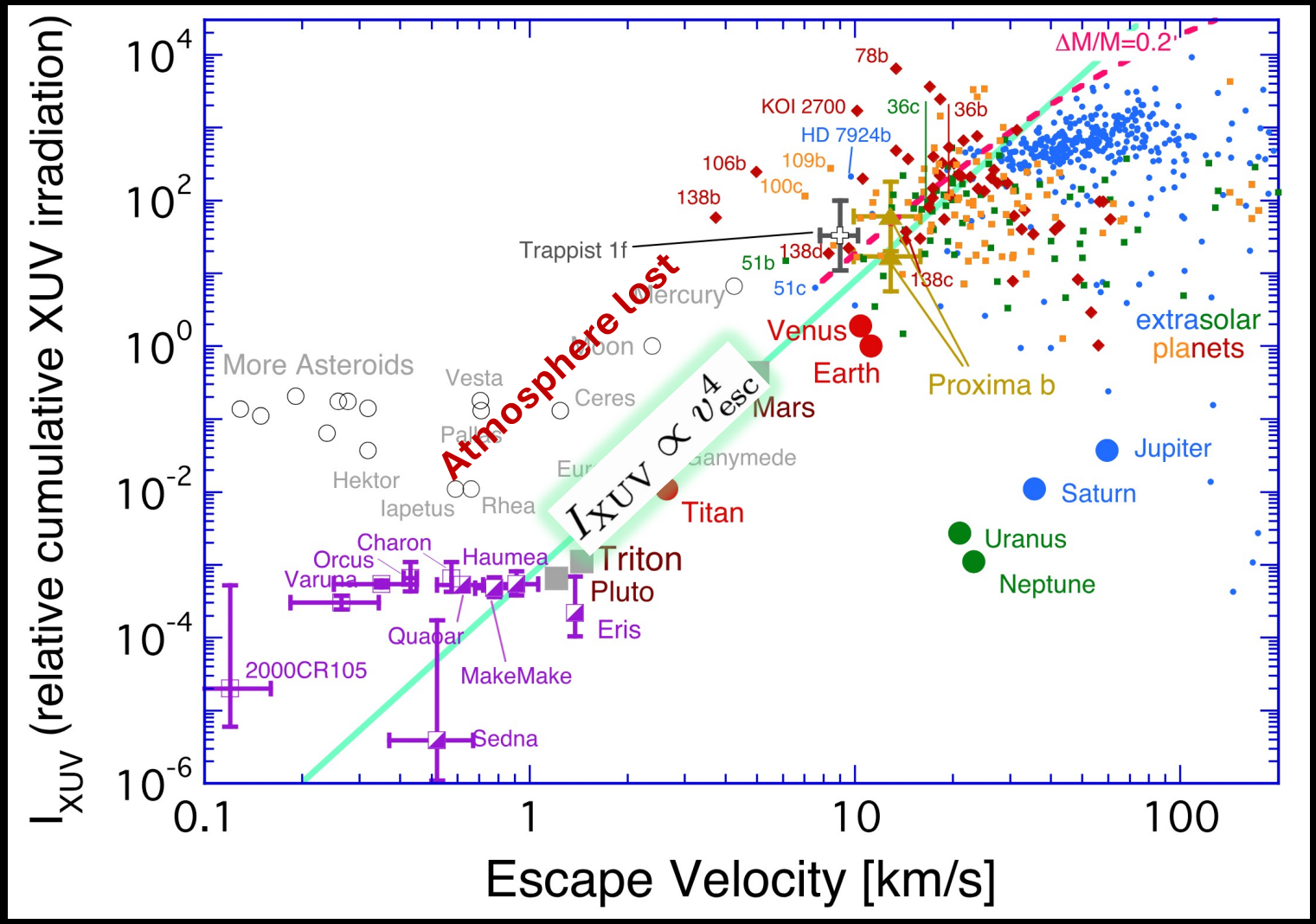
The Cosmic Shoreline approximates which planets can retain atmospheres

Zahnle & Catling 2017



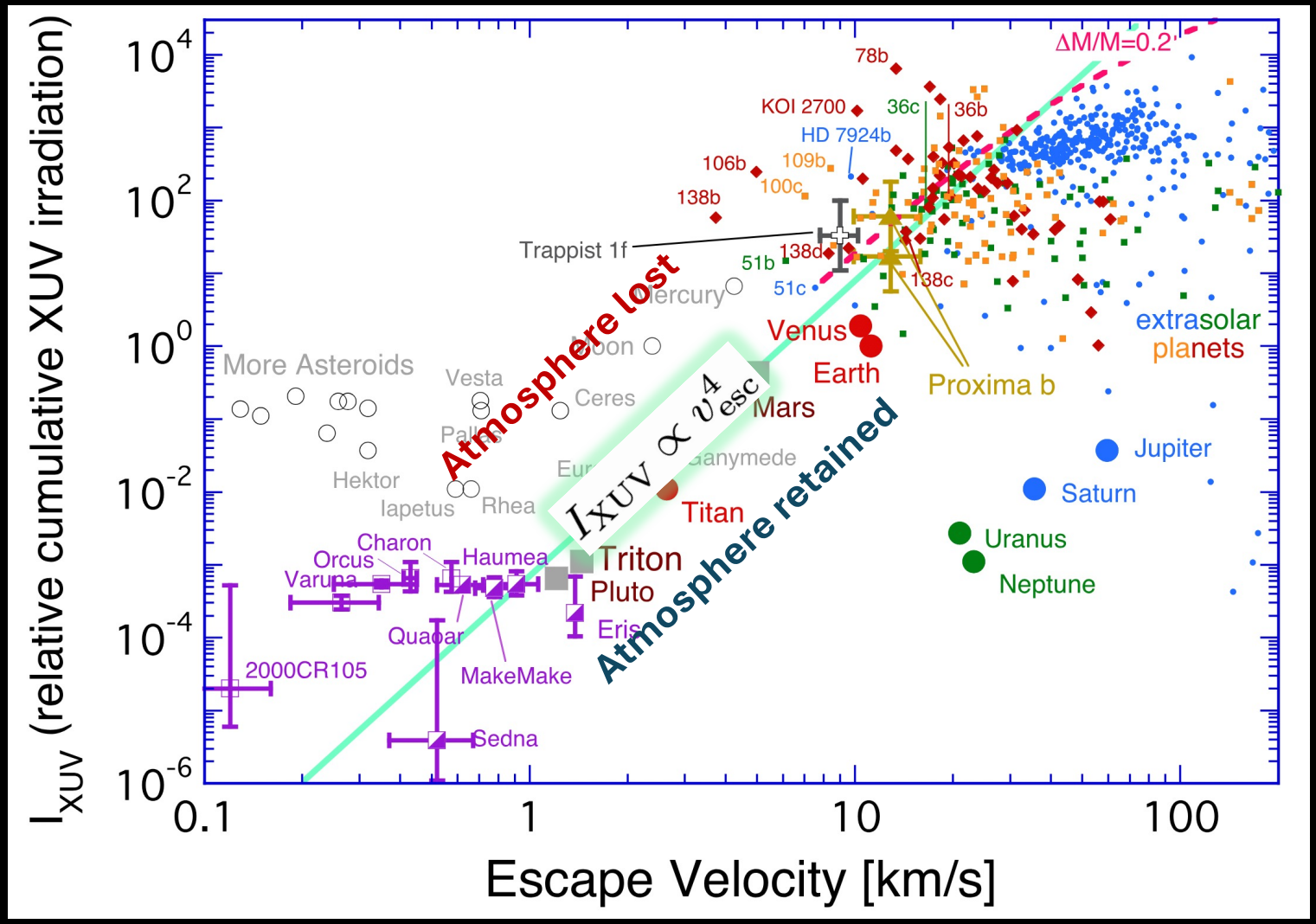
The Cosmic Shoreline approximates which planets can retain atmospheres

Zahnle & Catling 2017



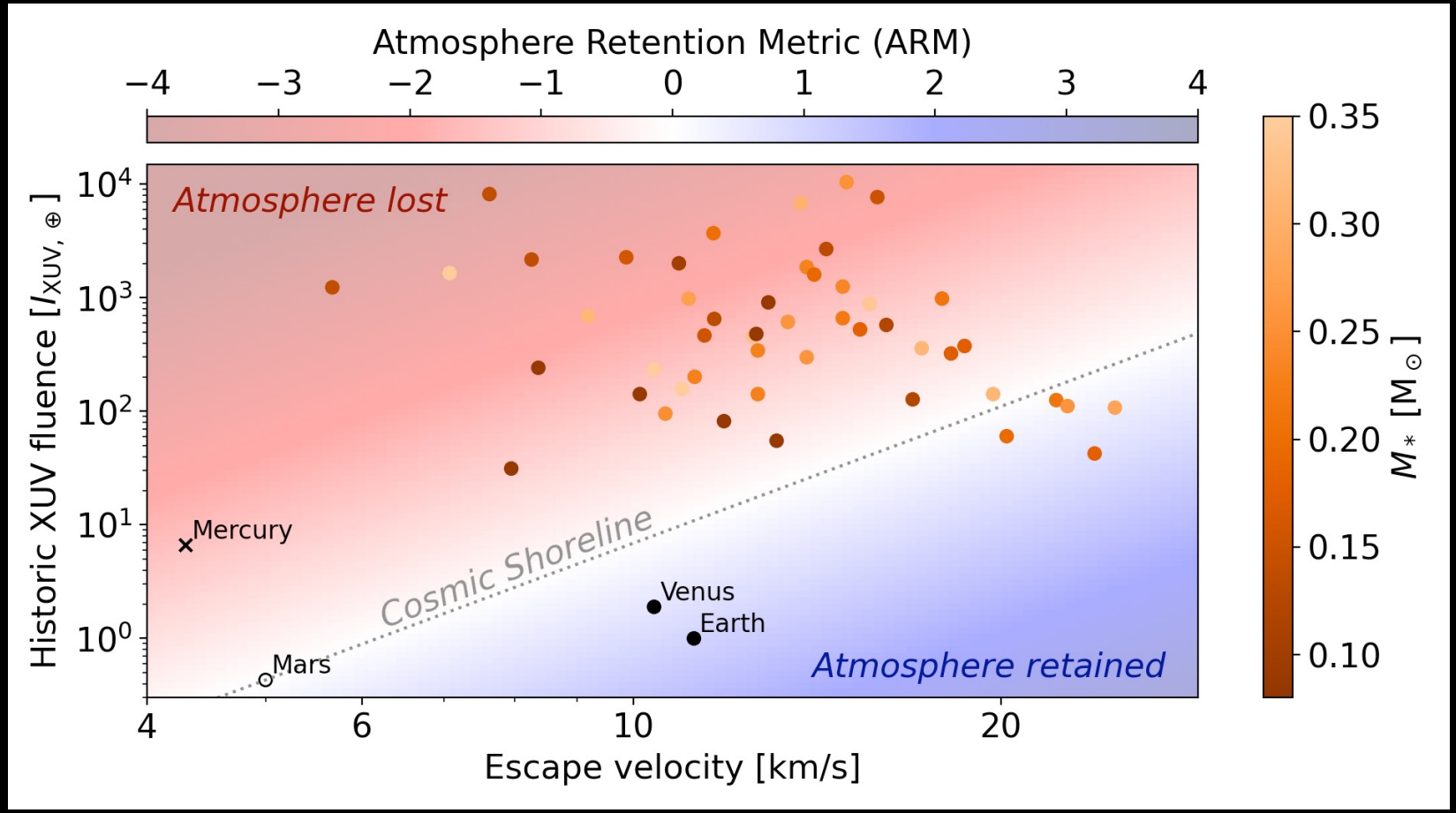
The Cosmic Shoreline approximates which planets can retain atmospheres

Zahnle & Catling 2017



For low-mass M dwarfs, this picture doesn't look too good...

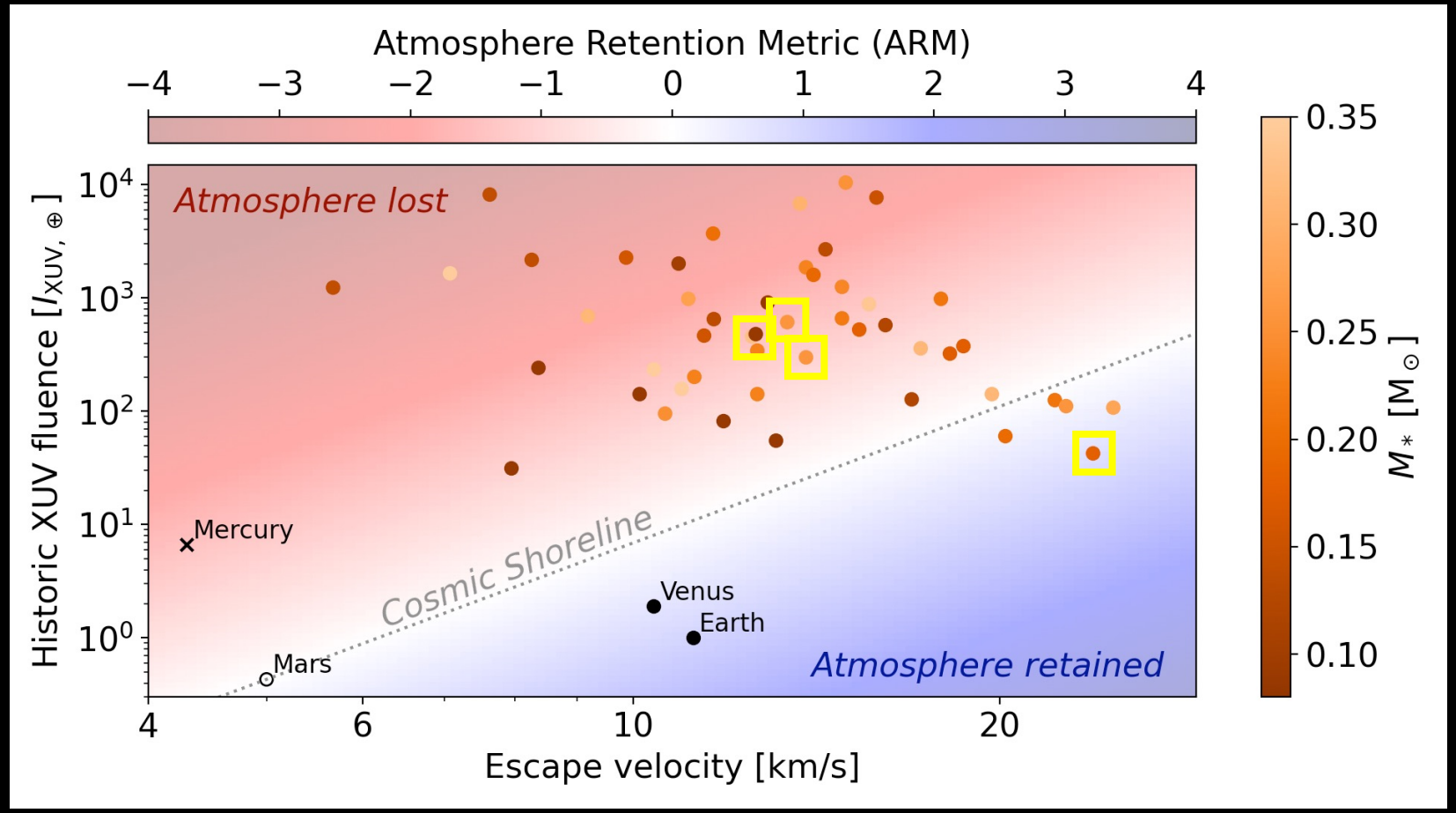
Pass et al. 2025



For low-mass M dwarfs, this picture doesn't look too good...

... but JWST will put this to the test!

Pass et al. 2025



Summary of M-dwarf planet demographics

Summary of M-dwarf planet demographics

- There is a big difference between early and late M dwarfs (in their internal structure, activity lifetimes, planet demographics, and more)

Summary of M-dwarf planet demographics

- There is a big difference between early and late M dwarfs (in their internal structure, activity lifetimes, planet demographics, and more)
- Small planets are abundant (on average, more than one per star)

Summary of M-dwarf planet demographics

- There is a big difference between early and late M dwarfs (in their internal structure, activity lifetimes, planet demographics, and more)
- Small planets are abundant (on average, more than one per star)
- Early and late M dwarfs have similar numbers of rocky planets on short orbits, but late M dwarfs have far fewer sub Neptunes

Summary of M-dwarf planet demographics

- There is a big difference between early and late M dwarfs (in their internal structure, activity lifetimes, planet demographics, and more)
- Small planets are abundant (on average, more than one per star)
- Early and late M dwarfs have similar numbers of rocky planets on short orbits, but late M dwarfs have far fewer sub Neptunes
- Giant planets are rare (and get rarer for late M dwarfs)

Summary of M-dwarf planet demographics

- There is a big difference between early and late M dwarfs (in their internal structure, activity lifetimes, planet demographics, and more)
- Small planets are abundant (on average, more than one per star)
- Early and late M dwarfs have similar numbers of rocky planets on short orbits, but late M dwarfs have far fewer sub Neptunes
- Giant planets are rare (and get rarer for late M dwarfs)
- Do M-dwarf rocky worlds have atmospheres? Time will tell.