Factors Affecting the Nature and Identification of Planetary Habitability

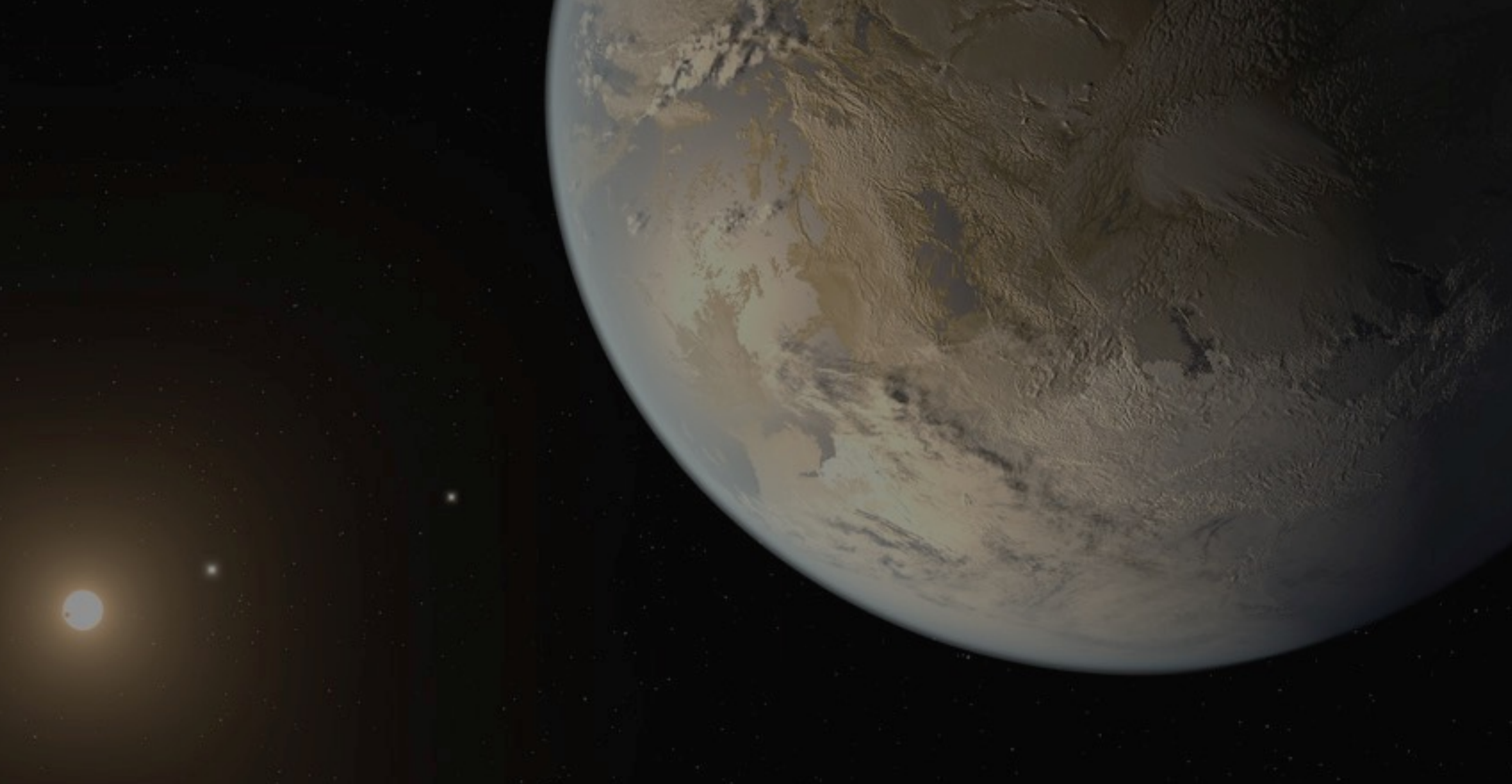
vpl

Victoria Meadows and the
NAI Virtual Planetary Laboratory Team

The University of Washington, California Institute of Technology, Jet Propulsion Laboratory, Pennsylvania State University, NASA Goddard Space Flight Center, University of Maryland, NASA Goddard Institute for Space Studies, University of Chicago, Weber State University, Princeton University, Laboratoire d'Astrophysique – Bordeaux, NASA Ames Research Center, Stanford University, Rice University, Washington University at Saint Louis, Yale University, Australian Center for Astrobiology.

Habitability

- Habitability is a measure of an environment's potential to support life.



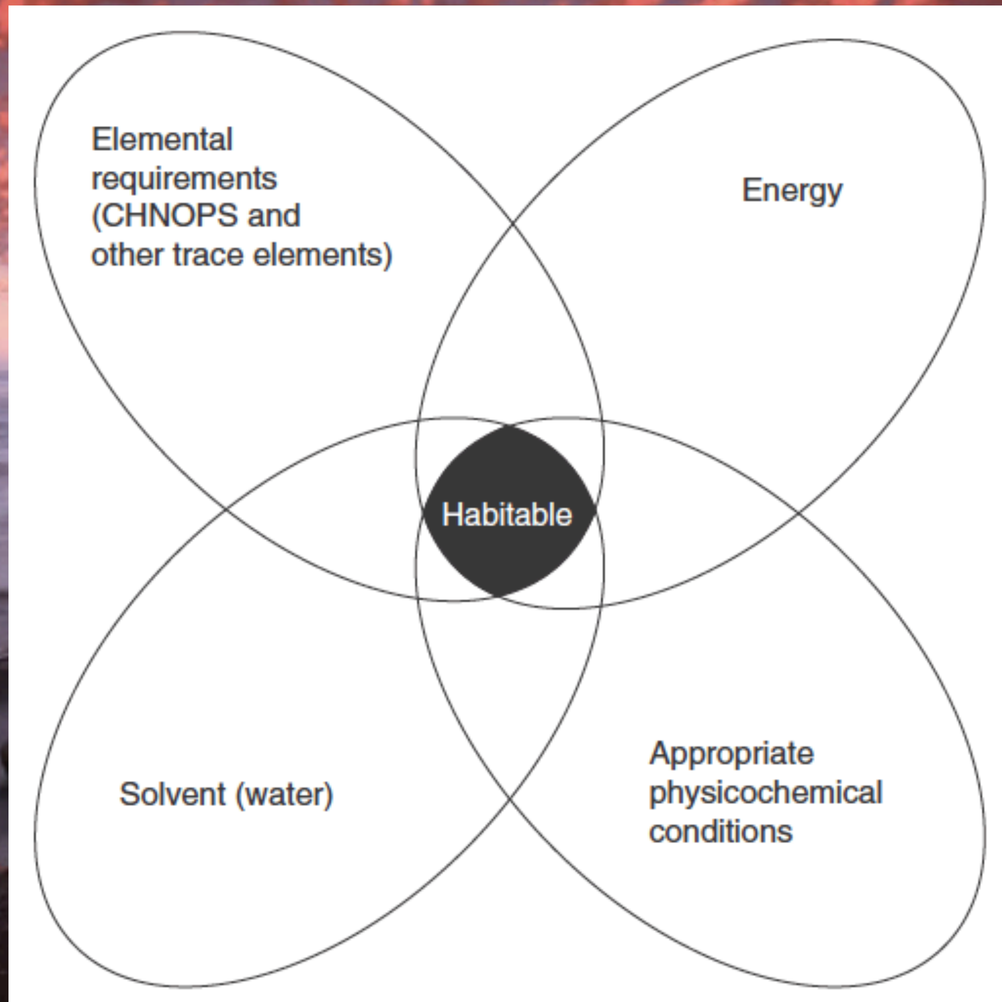
Why is the Study of Habitability Important?

- Habitability increases the probability that life, a planetary process, may be operating in the planetary environment.
  - This can make a target more desirable, and will improve interpretation of our data.

- Broader definitions of habitability help inform the possible distribution of life elsewhere.

- Narrower definitions of planetary habitability provide practical tools to inform mission design and help prioritize targets.

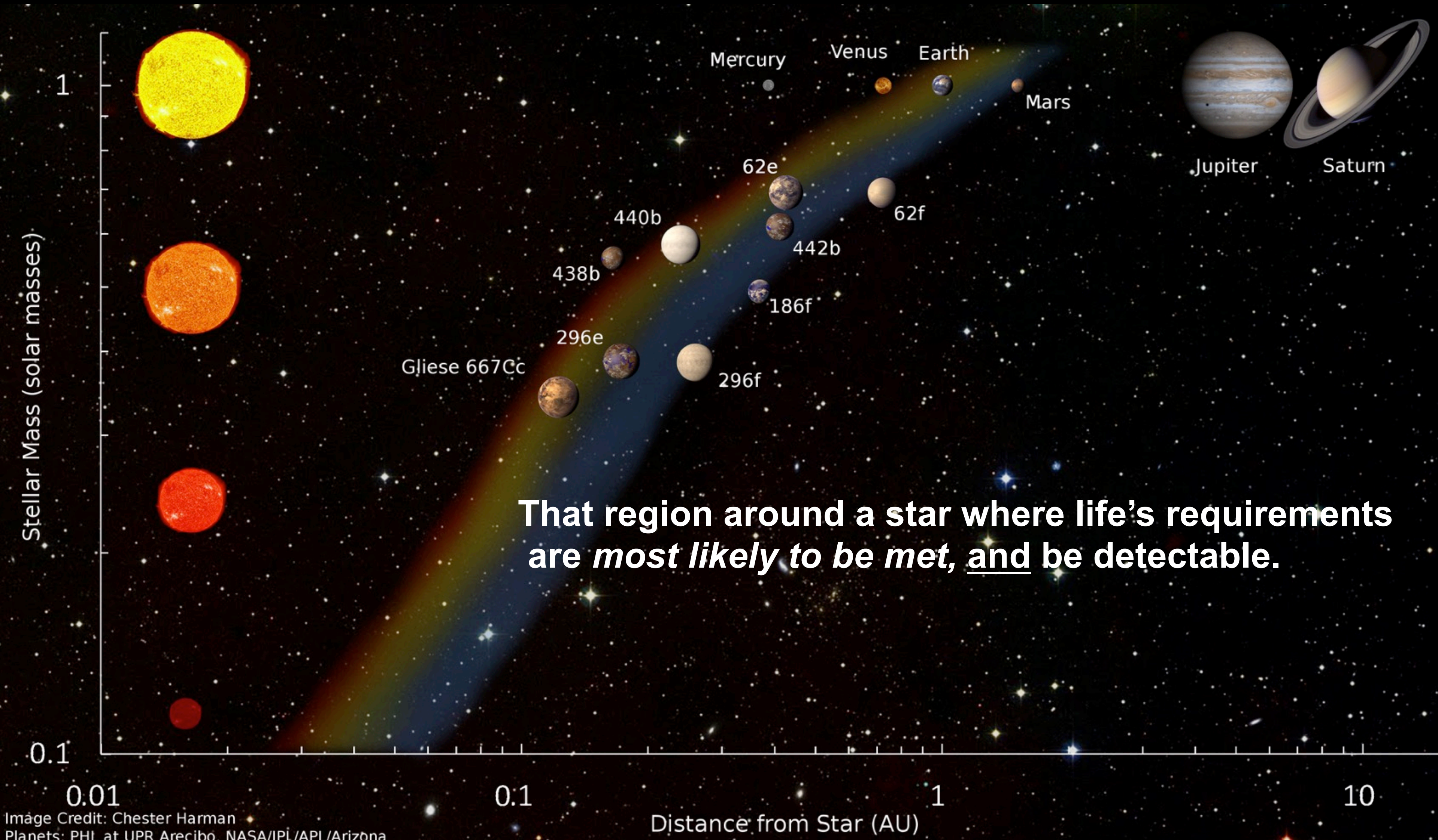
Life’s Requirements



Cockell et al., 2016; After Hoehler et al., 2007

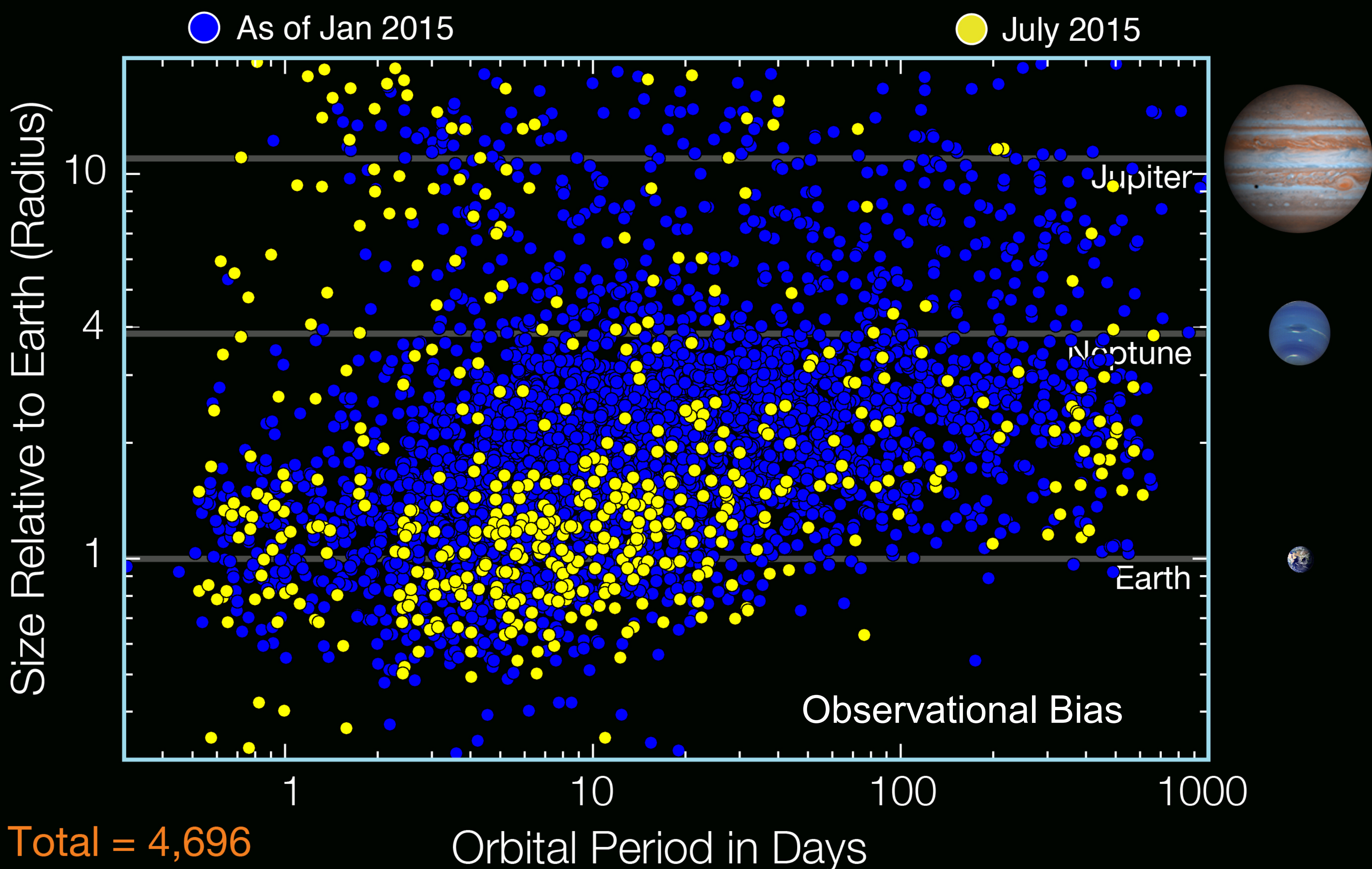
Photo: Frans Lanting

The Surface Liquid Water Habitable Zone



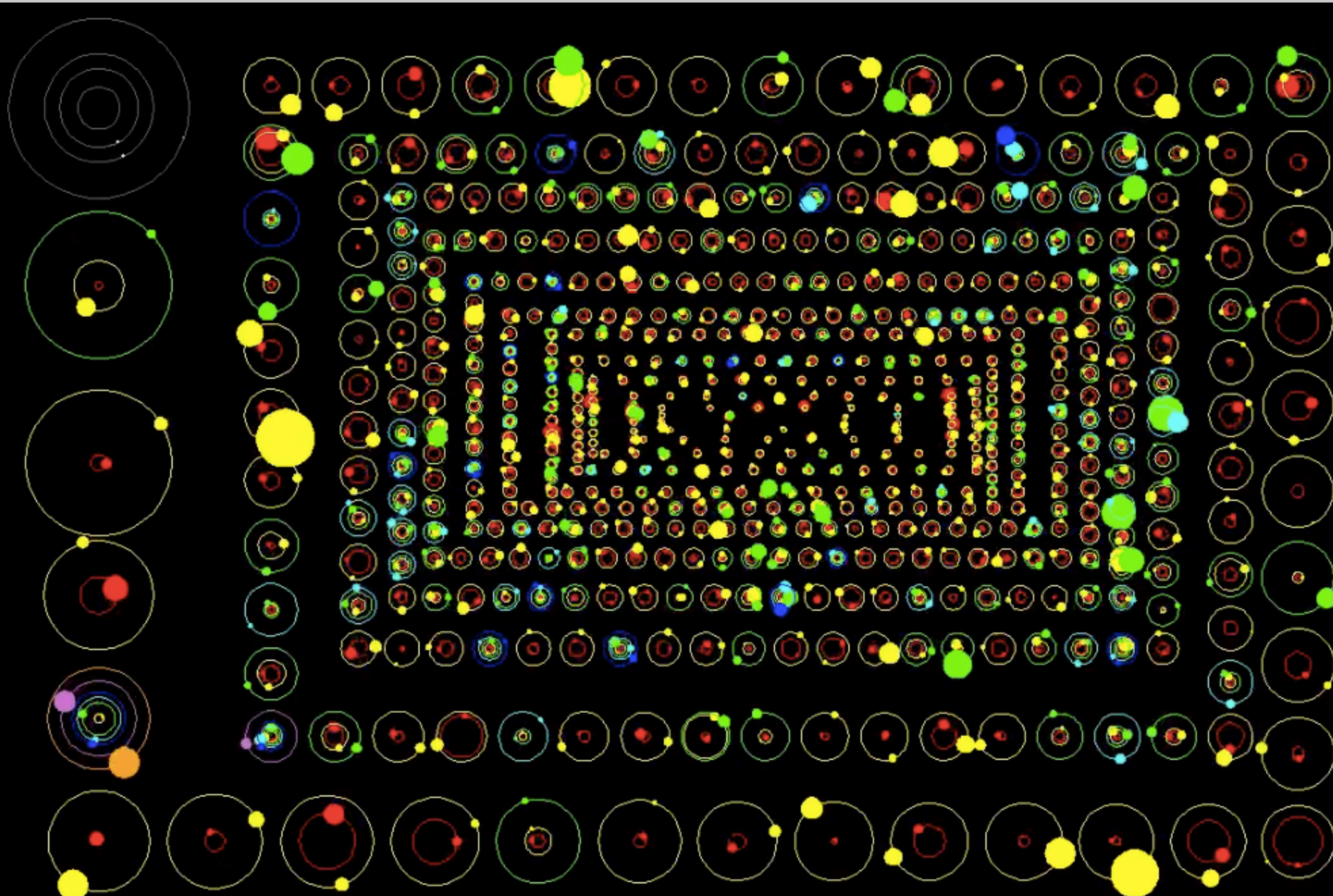
That region around a star where life's requirements are *most likely to be met,* <u>and</u> be detectable.

A Multitude of Worlds

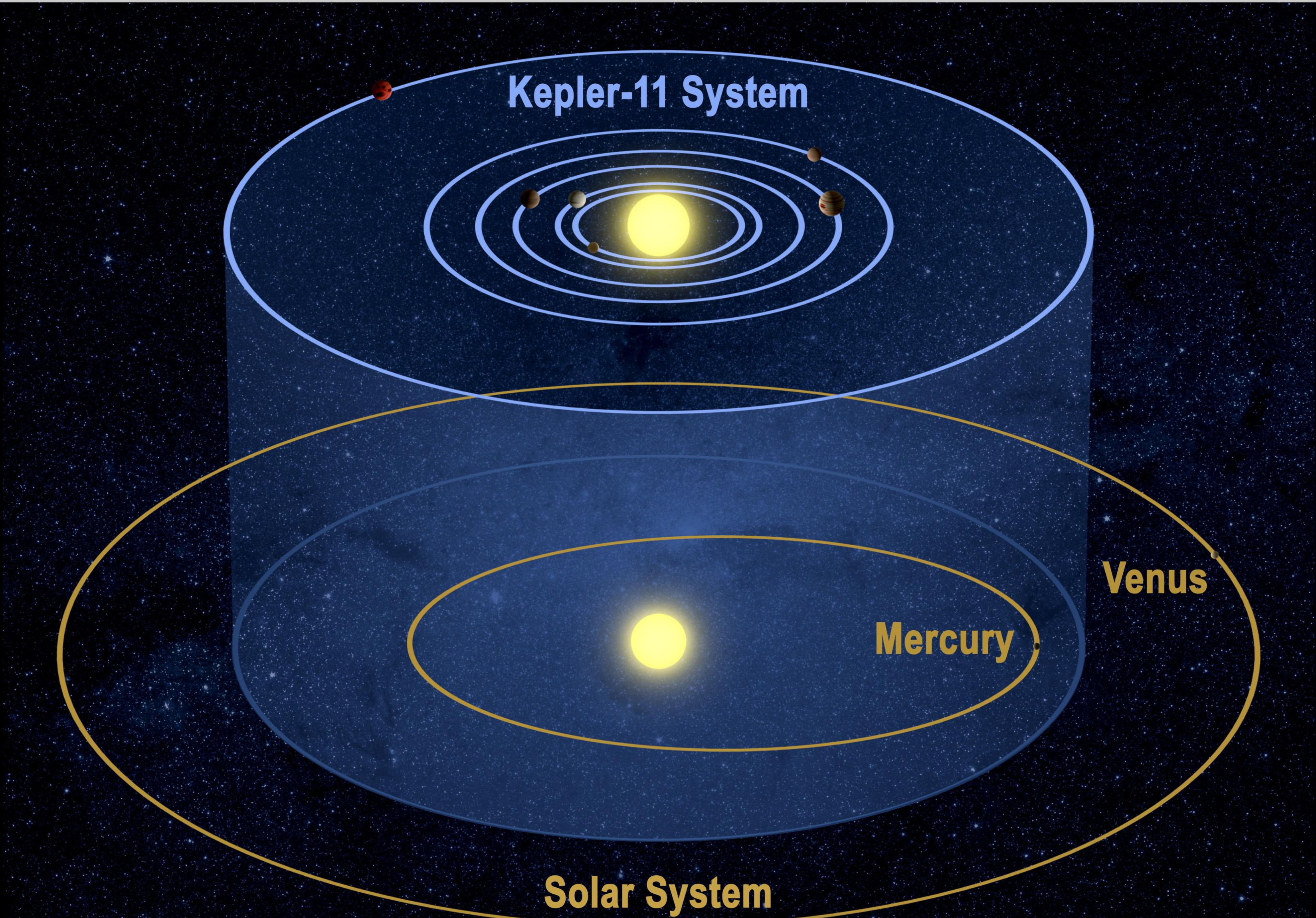


Many unlike planets in our own Solar System

Planetary System Architectures



Planets May Form In Crowded Systems

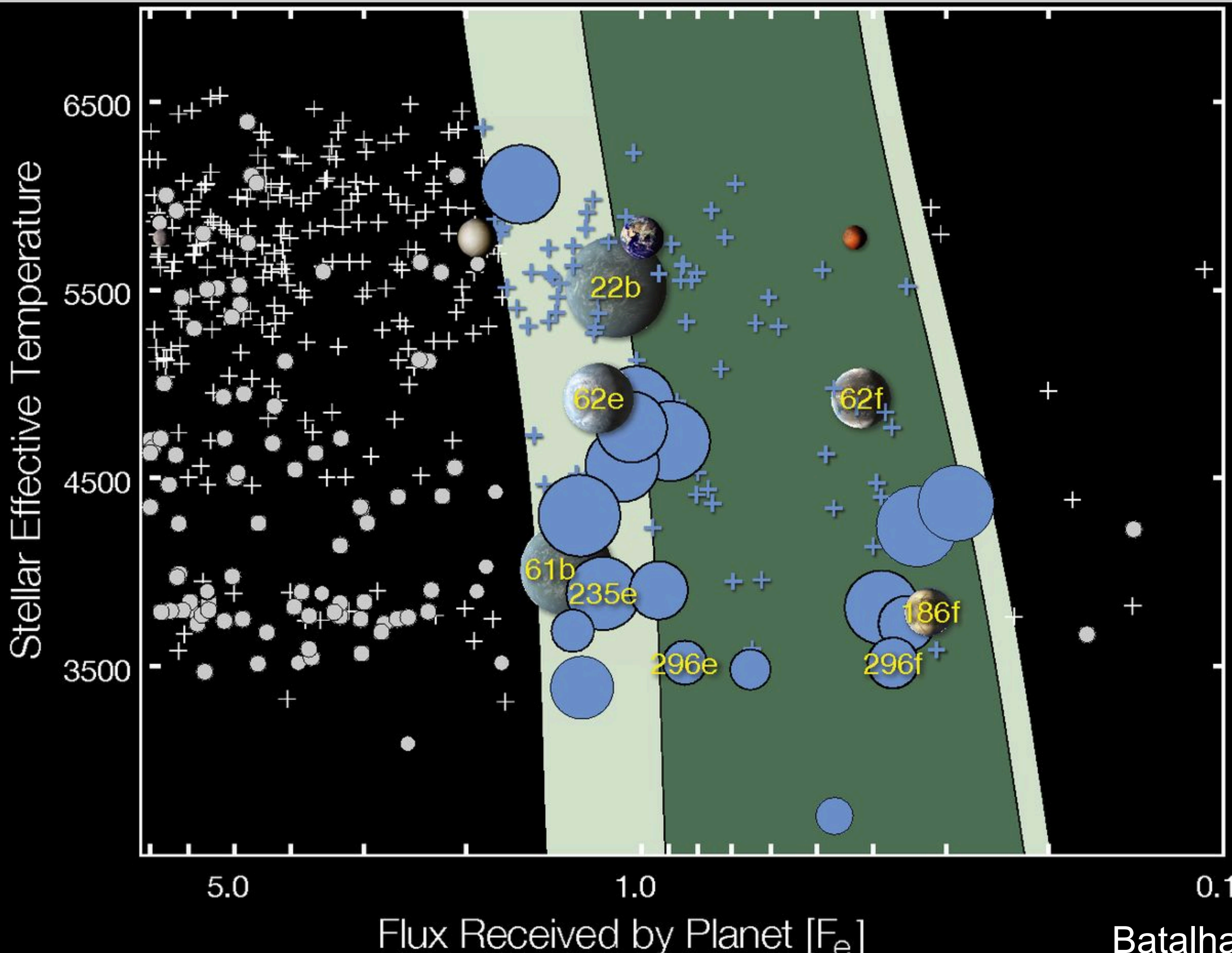


Where the influence of other planets may be higher

Planets Orbiting Binary Stars

- 19 confirmed systems of circumbinary planets.
- Terrestrial planets could form in ~50-60% of all binary systems. (Quintana & Lissauer, 2007)

Habitable Zone Planets Have Been Found



Batalha, 2014

Potentially Habitable Planets are Abundant and Nearby

For M dwarf stars, the HZ terrestrial planet occurrence rate may be as high as 0.8 per star ***(Morton&Swift, 2014***)

Even a more conservative estimate of 0.24 HZ terrestrials per M dwarf predicts that the nearest HZ terrestrial is **within 8.4 light years** ***(Dressing and Charbonneau, 2015)***

Now we just have to find it!
…and observe it with JWST or ELTs.

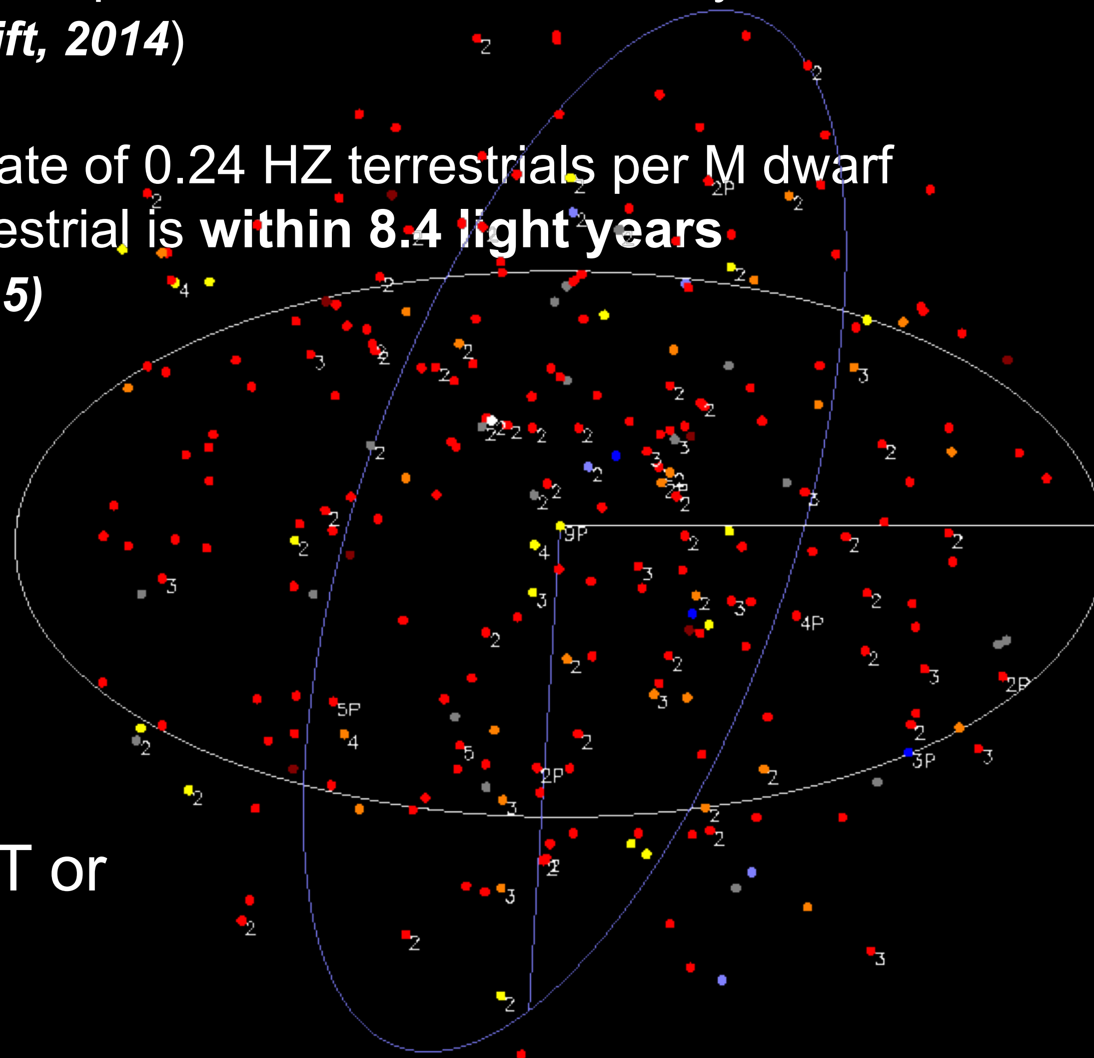


Image: Riedel, Henry, & RECONS group

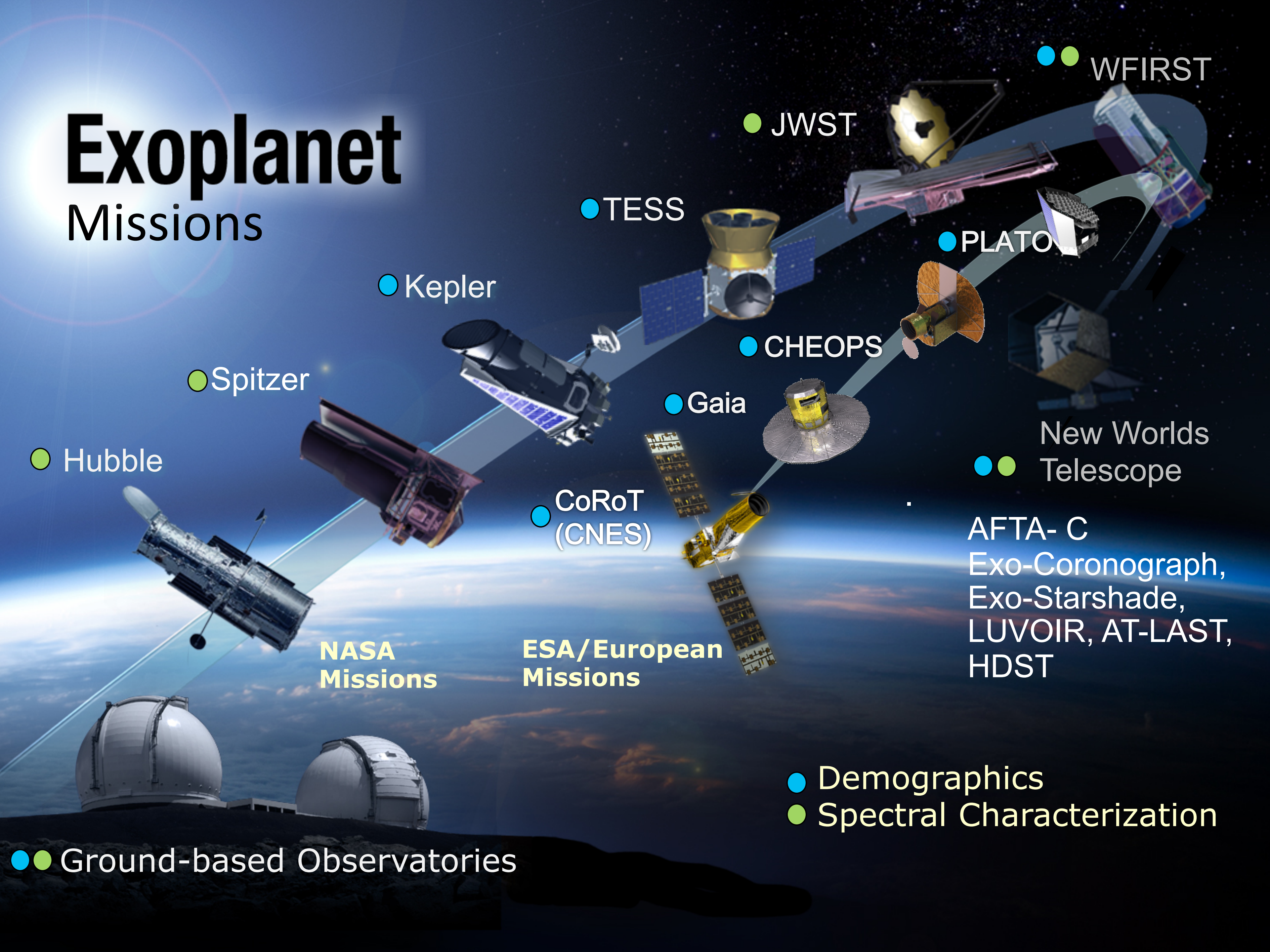
The Habitability of M Dwarf Planets

The majority of environments for life in the Universe might orbit M dwarfs

M dwarf planets provide our first opportunity to search for life beyond the Solar System.

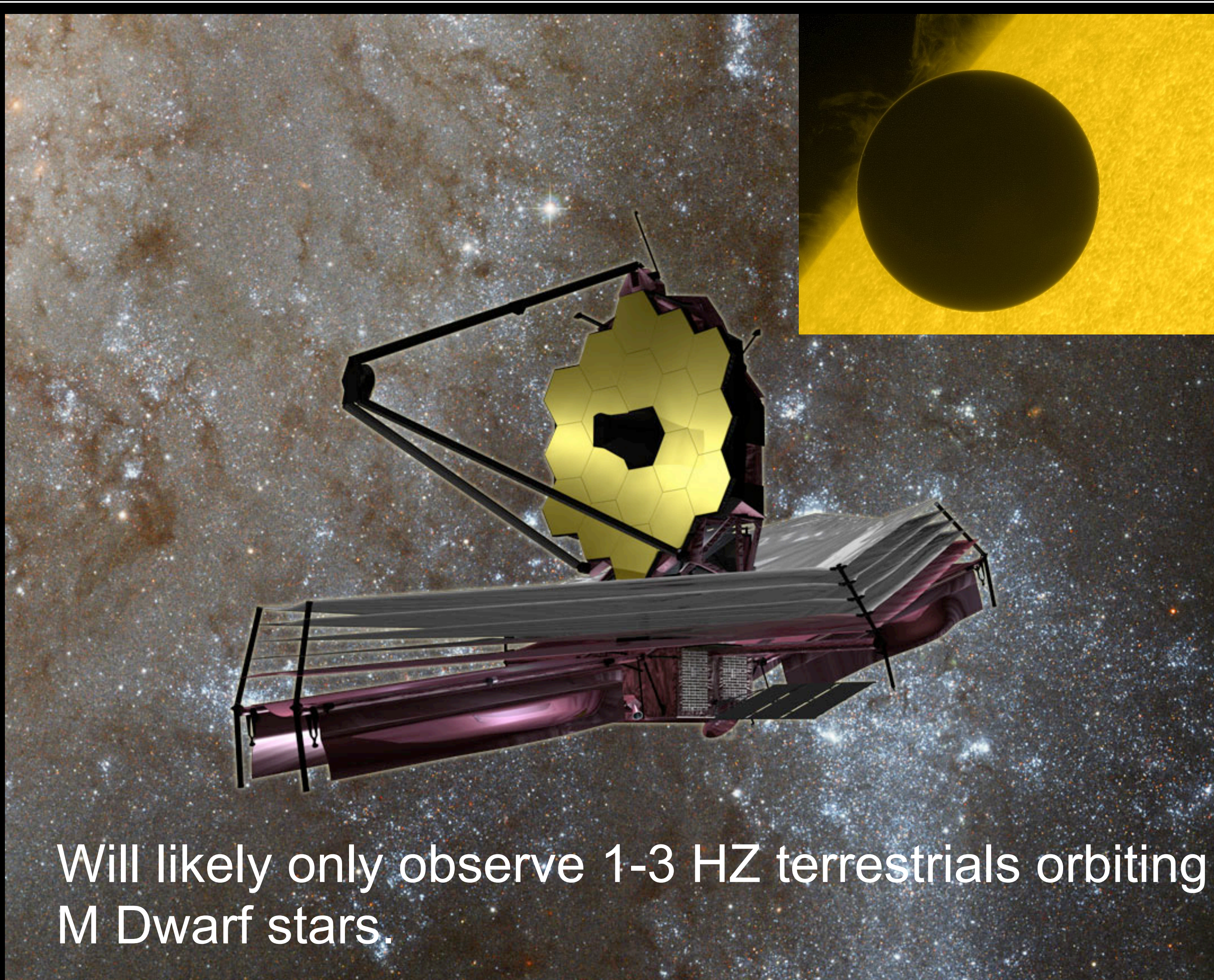
M dwarf planets often exist in very different planetary architectures and interact differently with their parent star

To better understand planetary habitability, we have to also understand the factors affecting the habitability of terrestrial planets *that do not orbit Sun-like stars*.



Exoplanet
Missions
WFIRST
JWST
TESS
PLATO
Kepler
CHEOPS
Spitzer
Gaia
New Worlds
Telescope
Hubble
CoRoT
(CNES)
AFTA- C
Exo-Coronograph,
Exo-Starshade,
LUVOIR, AT-LAST,
HDST
NASA
Missions
ESA/European
Missions
Demographics
Spectral Characterization
Ground-based Observatories

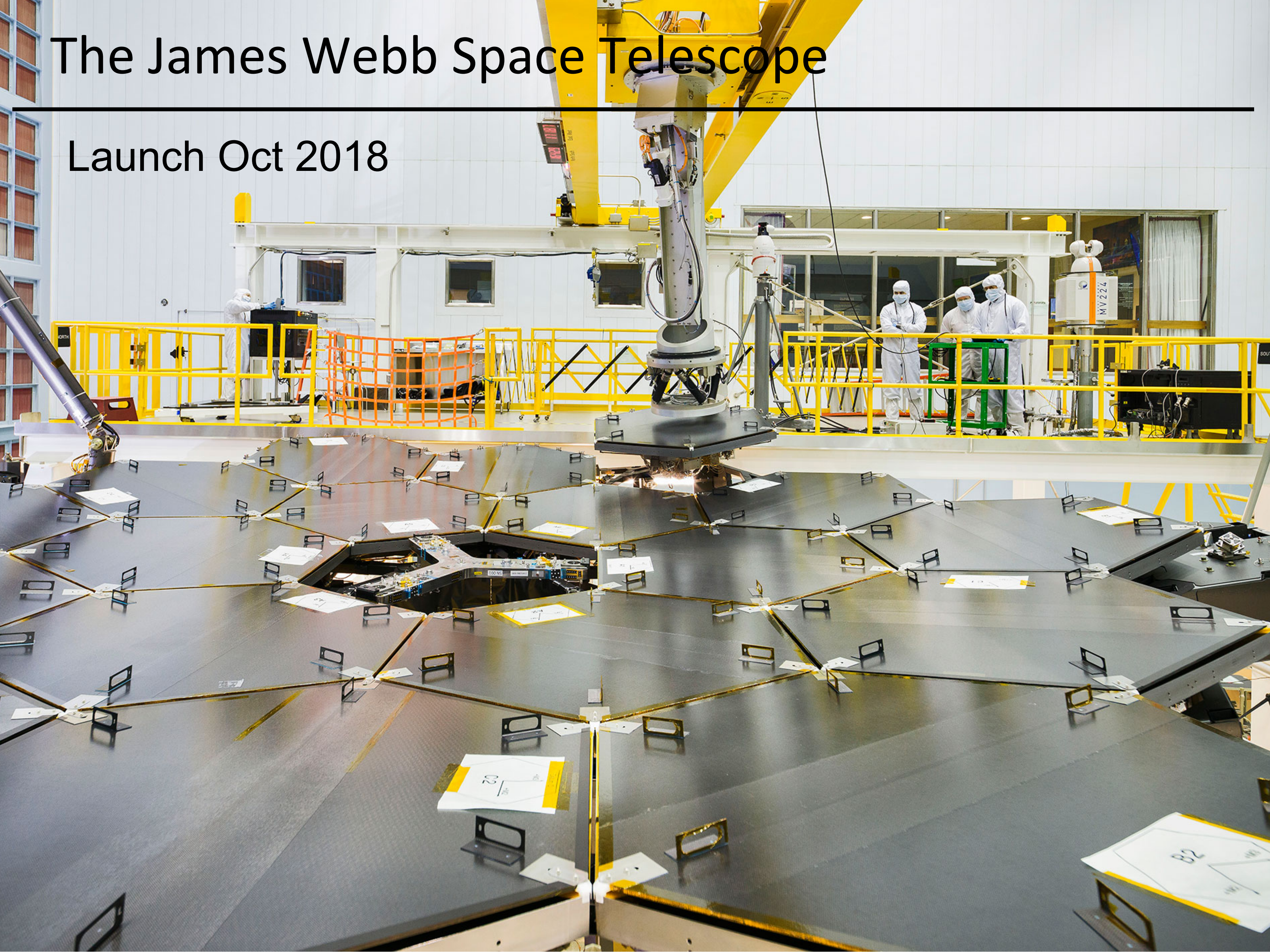
JWST: Our First Chance to Take Spectra of HZ Planets



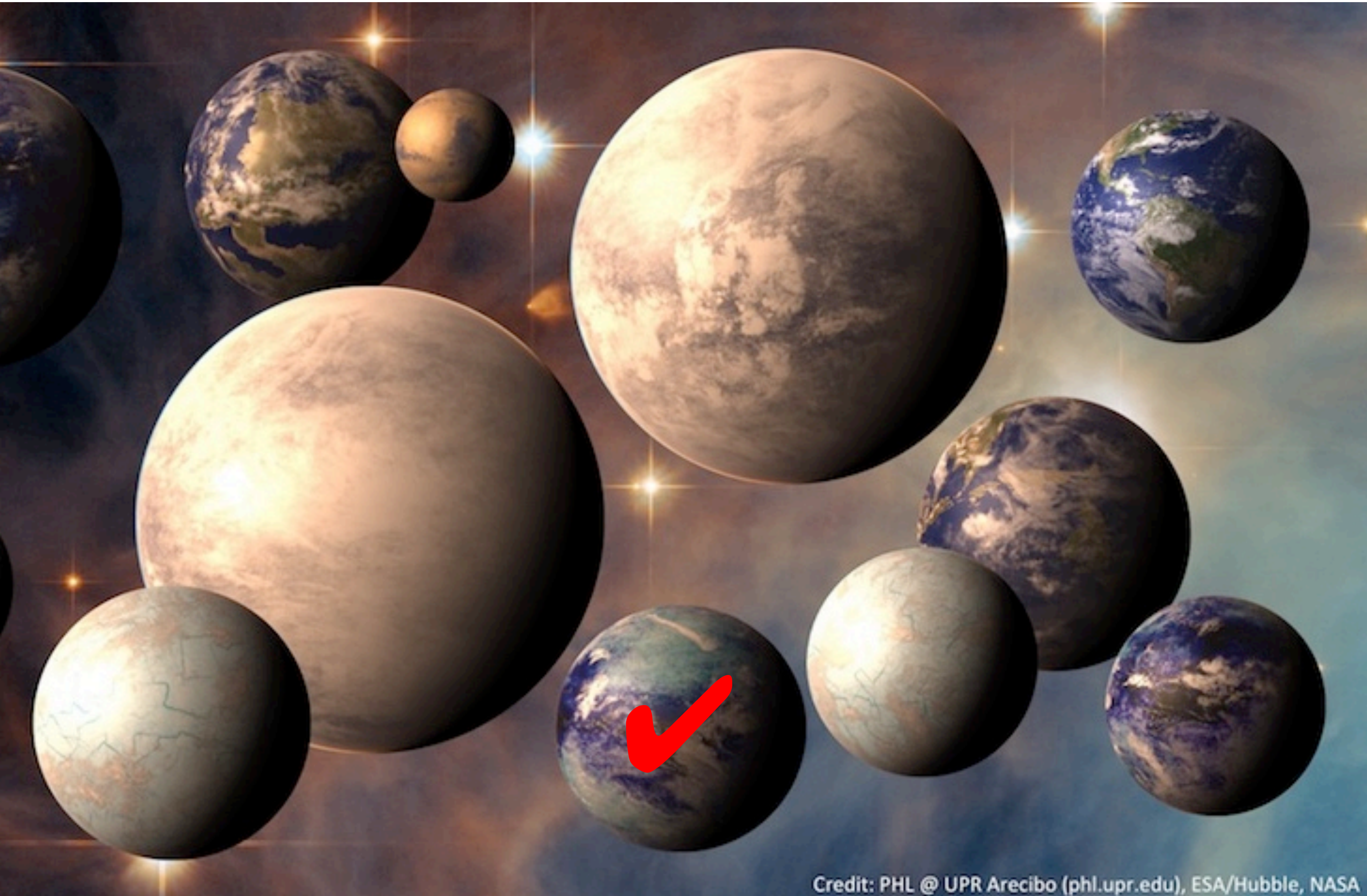
Will likely only observe 1-3 HZ terrestrials orbiting M Dwarf stars.

The James Webb Space Telescope

Launch Oct 2018

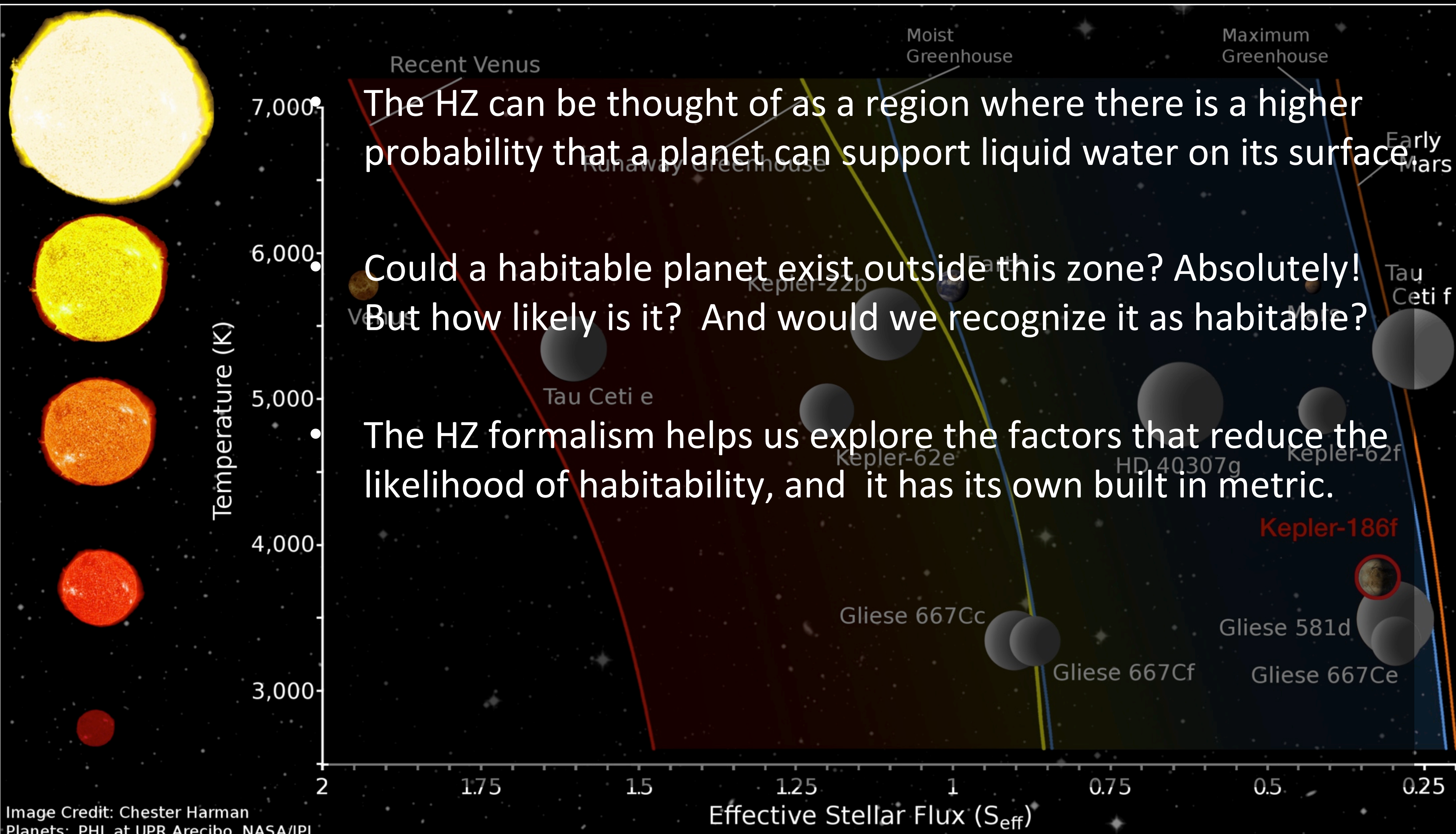


How should we pick the right planet to study?

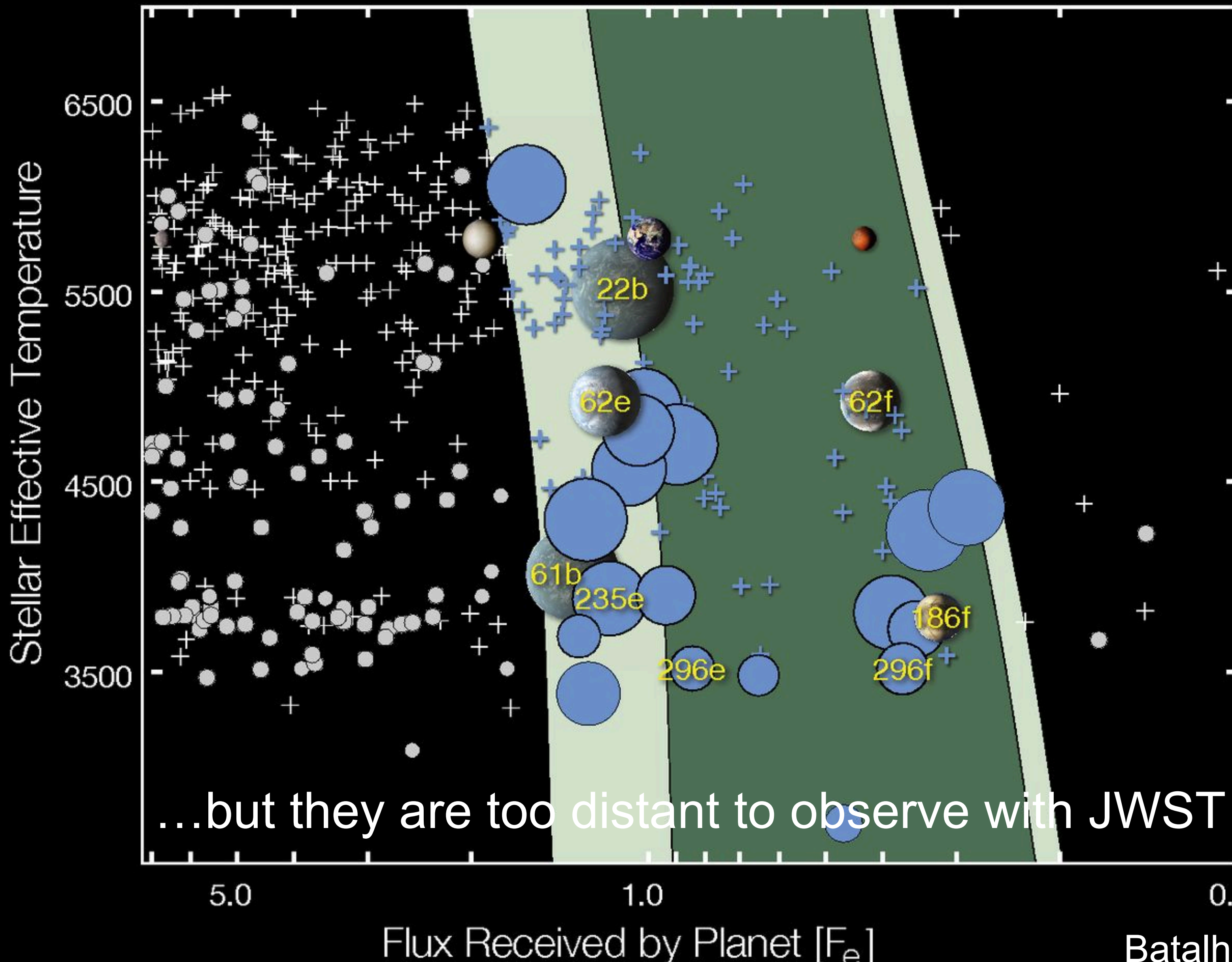


This Is Our First Sorting Device

- The HZ can be thought of as a region where there is a higher probability that a planet can support liquid water on its surface.
- Could a habitable planet exist outside this zone? Absolutely! But how likely is it? And would we recognize it as habitable?
- The HZ formalism helps us explore the factors that reduce the likelihood of habitability, and it has its own built in metric.

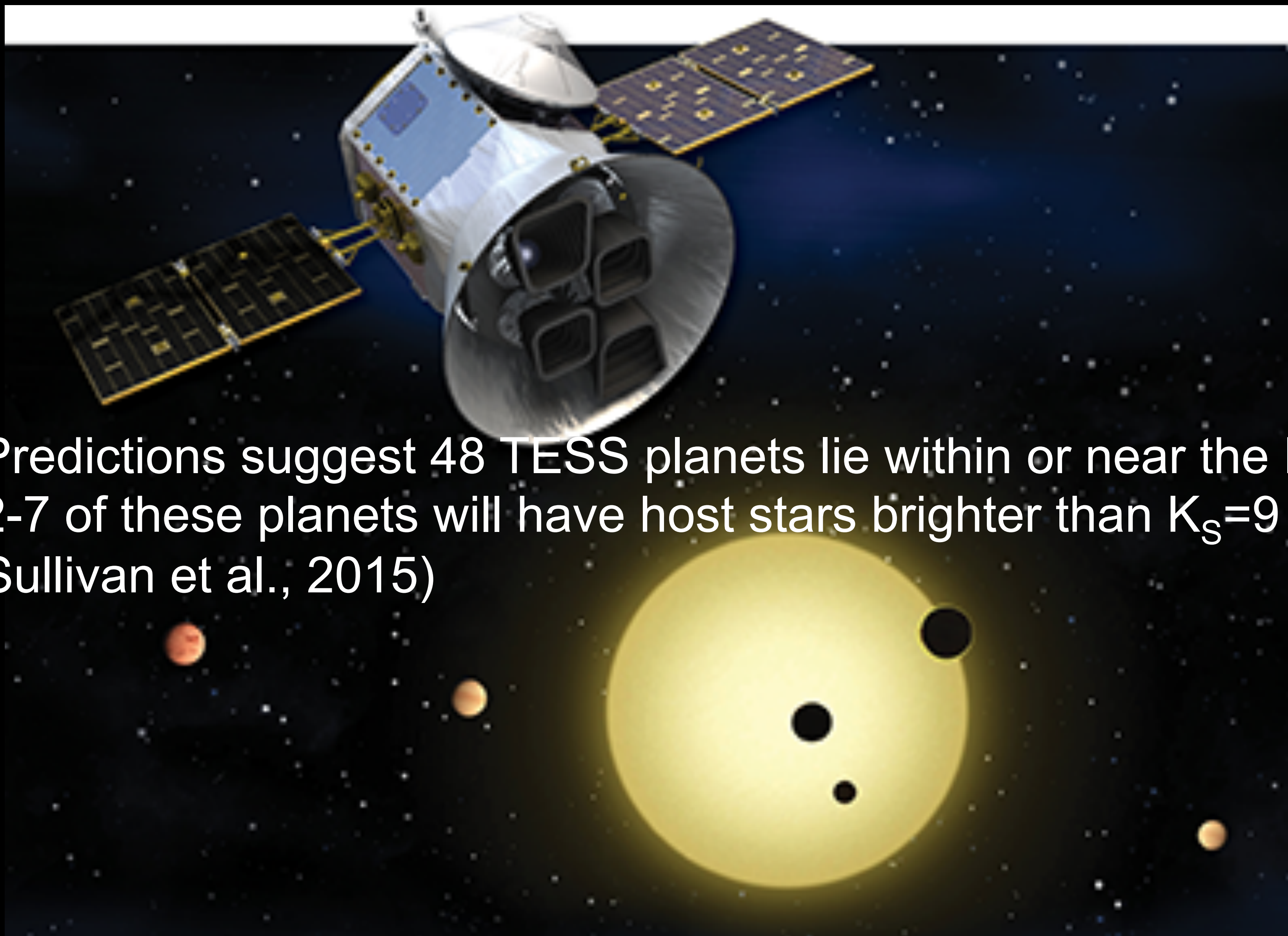


Kepler Has Found Many Planets Within the HZ



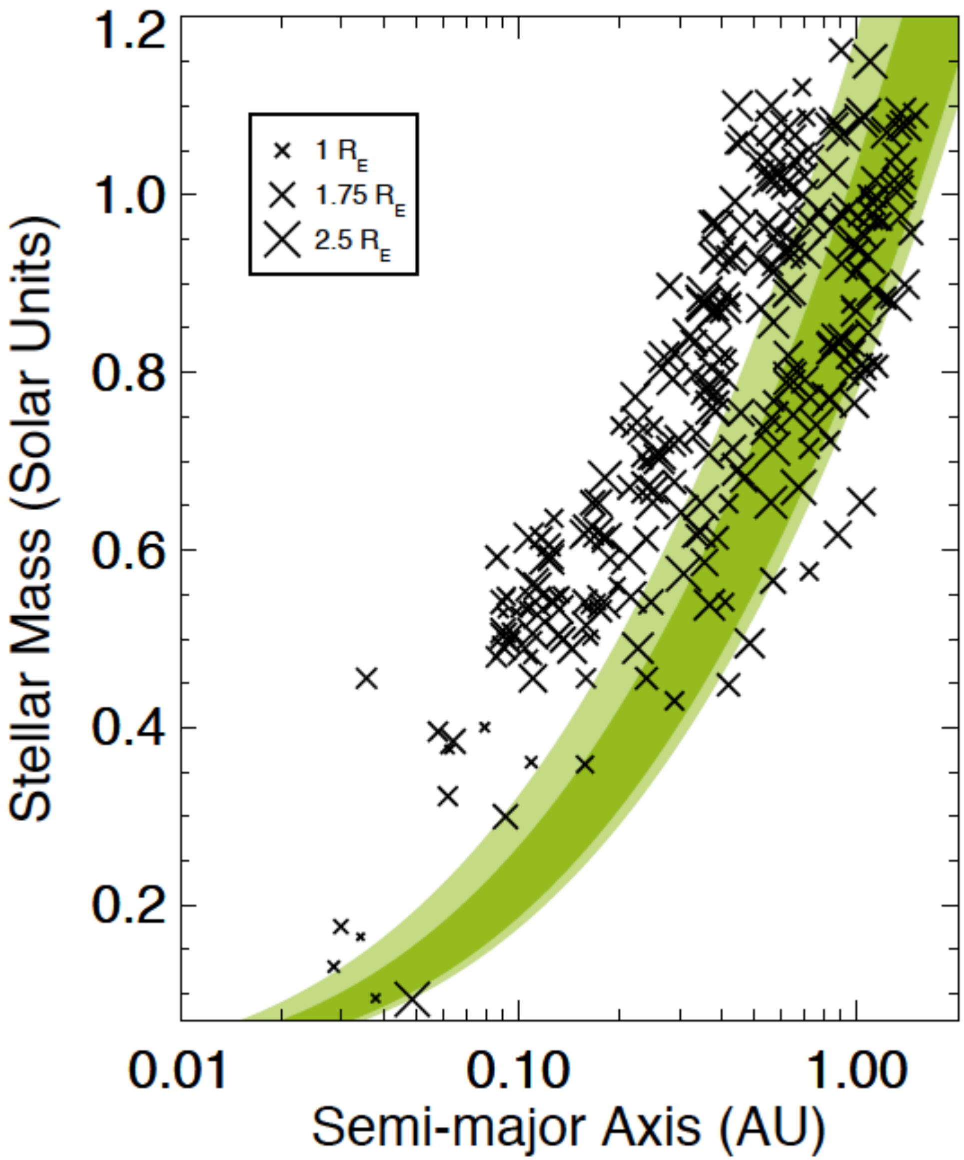
Batalha, 2014

TESS will most likely find JWST targets



- Predictions suggest 48 TESS planets lie within or near the HZ
- 2-7 of these planets will have host stars brighter than K_S=9 (Sullivan et al., 2015)

The "Problem" with the HZ

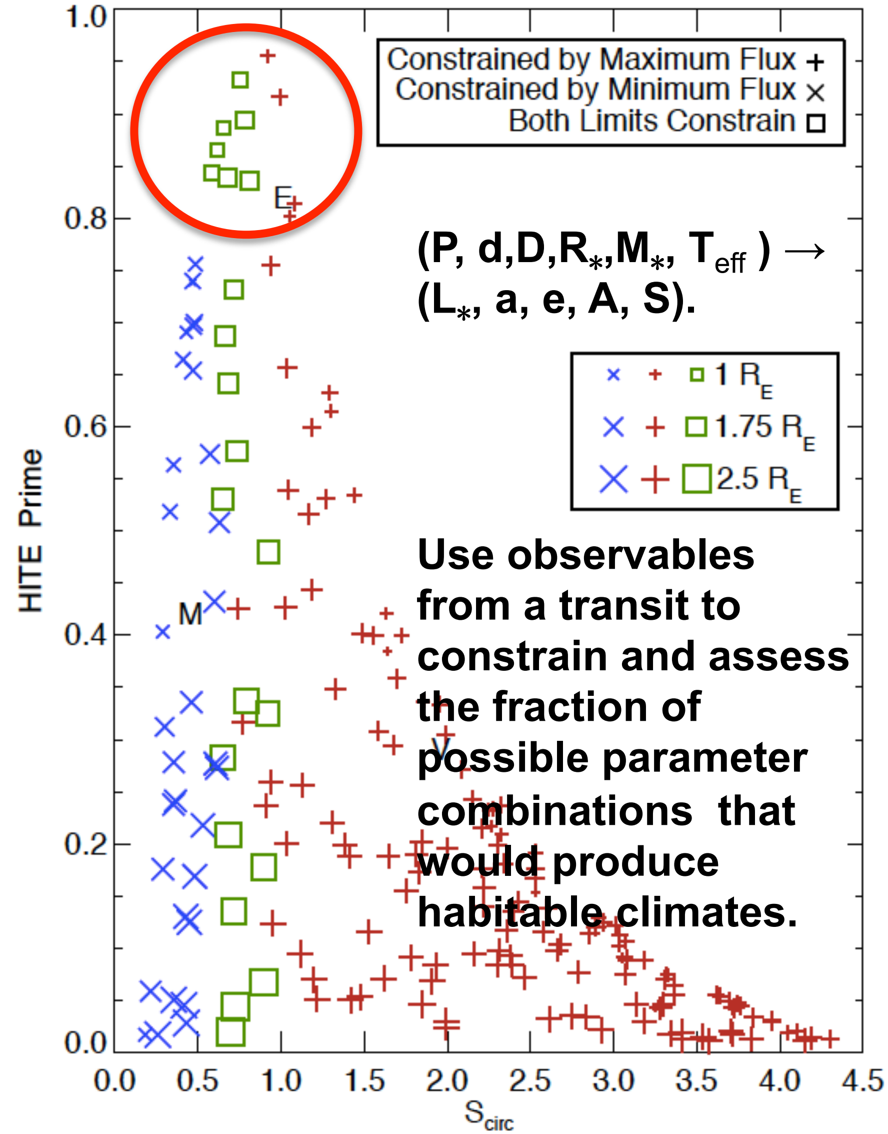


- Habitability becomes a binary assessment.
- This initial assessment does not take into account the many other factors that can affect habitability.
  - E.g. the nature and evolution of the planet and planetary system.

The Habitability Index

- The Habitability Index for transiting exoplanets uses observables from a transit to constrain and assess the fraction of possible parameter combinations that would produce habitable climates

- Serves as an initial framework for a larger, more comprehensive Habitability Index.

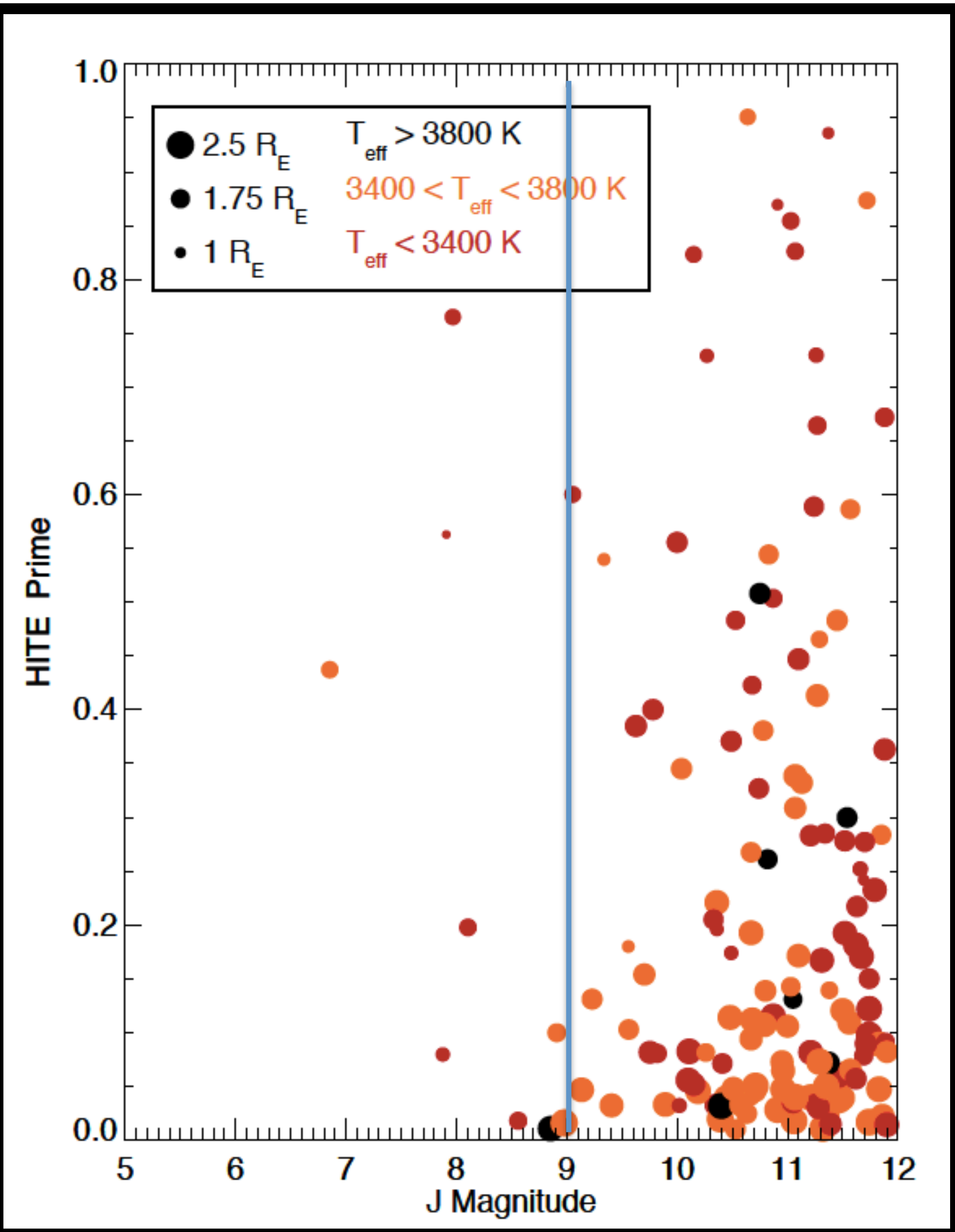


Barnes, Meadows & Evans, 2015

Habitability Index for TESS Planets

From Barnes, Meadows & Evans, (2015)

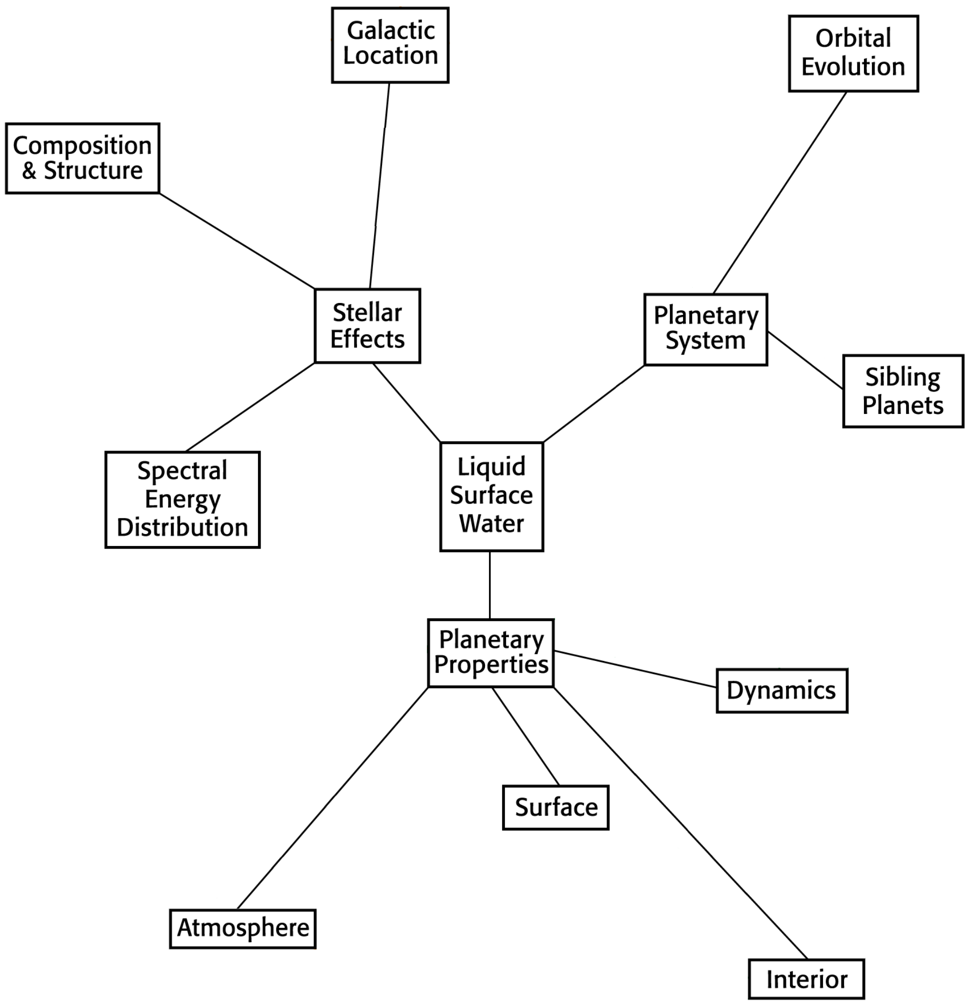
Based on a the Sullivan et al. (2015) study to predict the exoplanet yield from TESS.



Our Fundamental Requirement

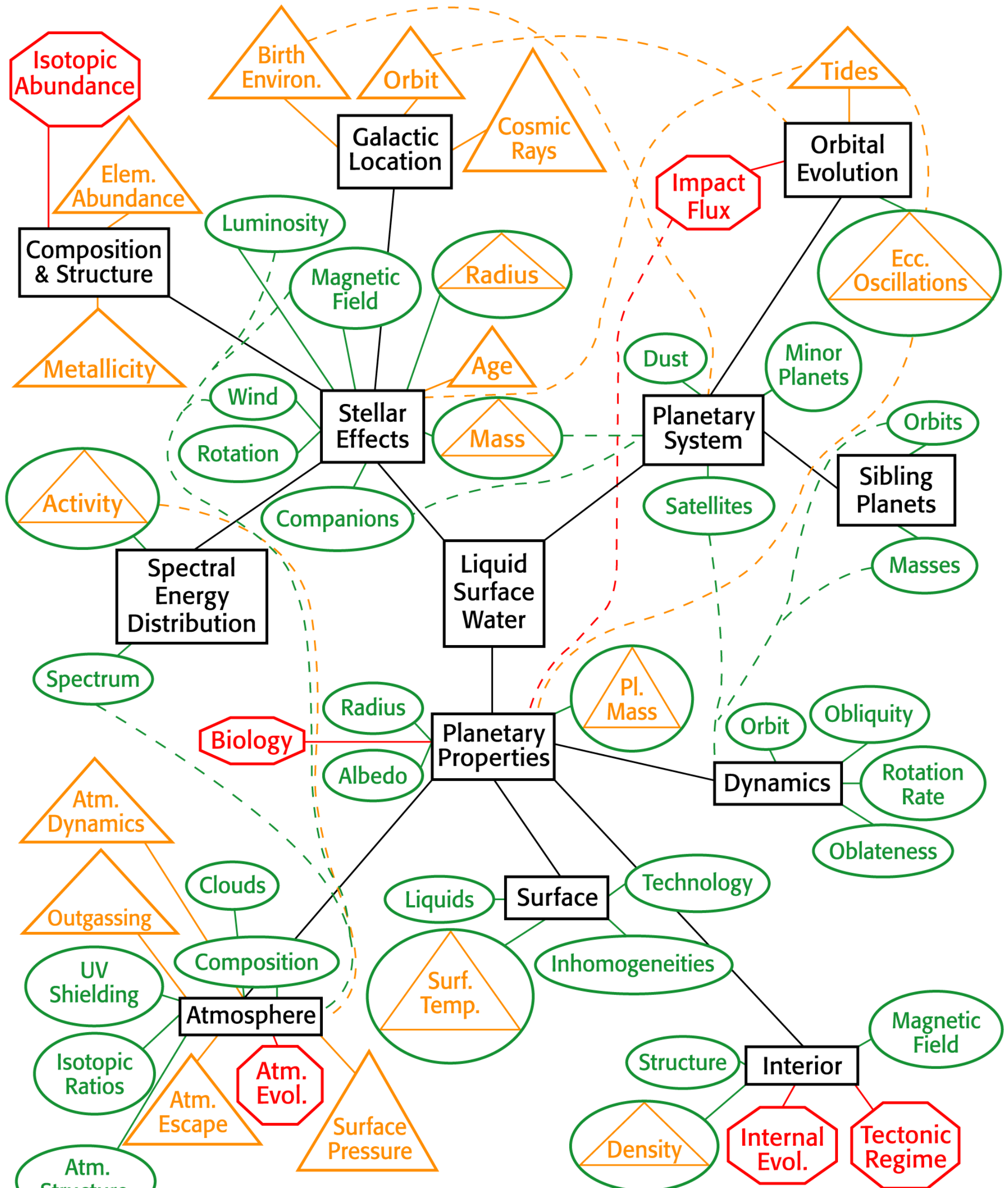
Liquid
Surface
Water

Factors Affecting Habitability



- Habitability is an outcome of the interactions between a planet, its star, and its planetary system.
- These interactions modify the planet's environment and evolution and can increase or decrease the probability that life's requirements will be met.

Planets are Hard!



Meadows, Barnes et al., in prep

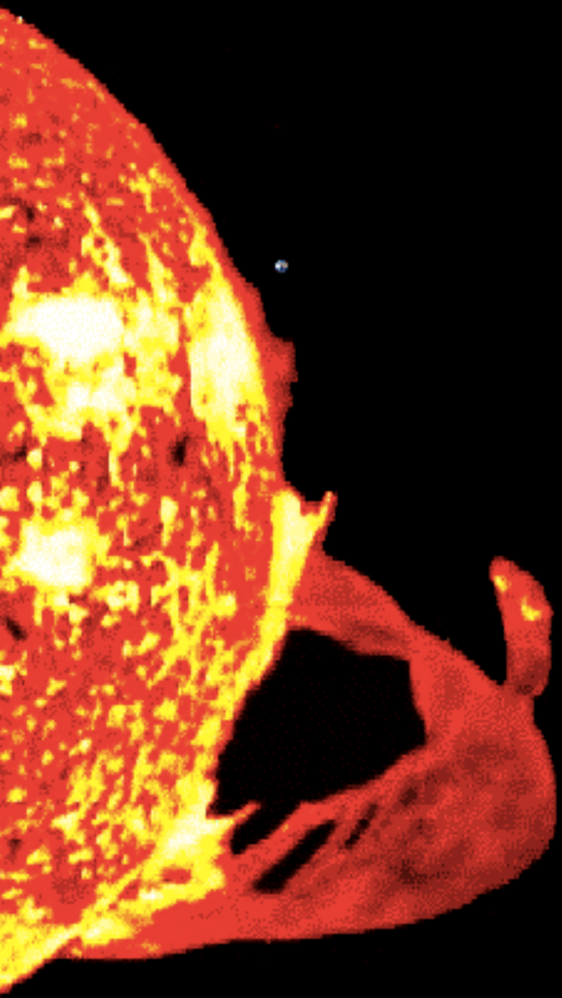
Habitability Assessment is a multiparameter, interdisciplinary process.

As a community, we want understand the interplay of these many influences on habitability.

Habitability evolves over time and its interpretation requires knowledge of planetary system age and history.

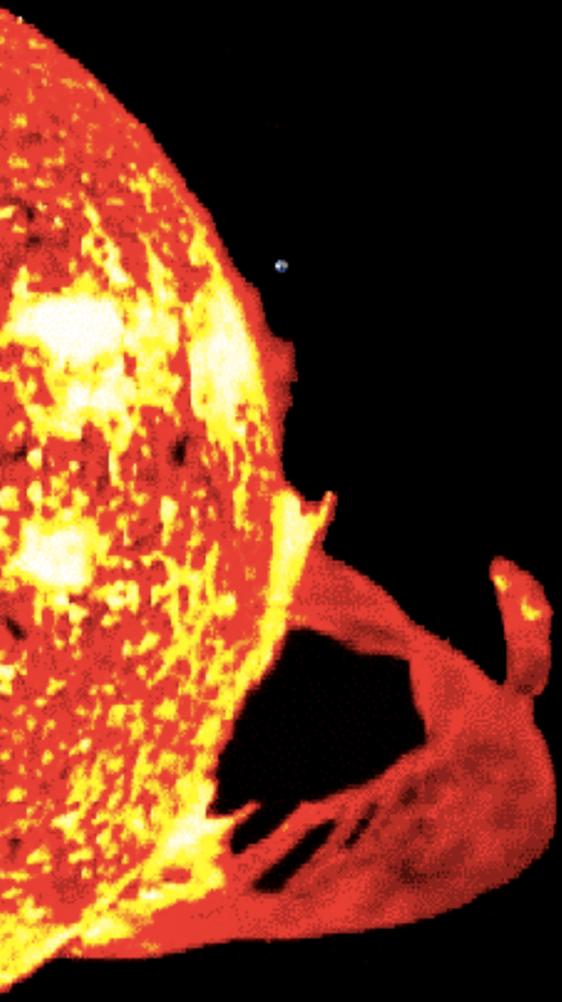
Determination of a planet's "Habitability Factor" will allow ranking of targets for follow-up.

The Host Star



- Radiation
  - Affects climate via changes to atmospheric/surface absorption
  - Stellar activity affects atmospheric composition and loss, surface radiation
- Gravity
  - Tidal Energy
  - Orbital Evolution

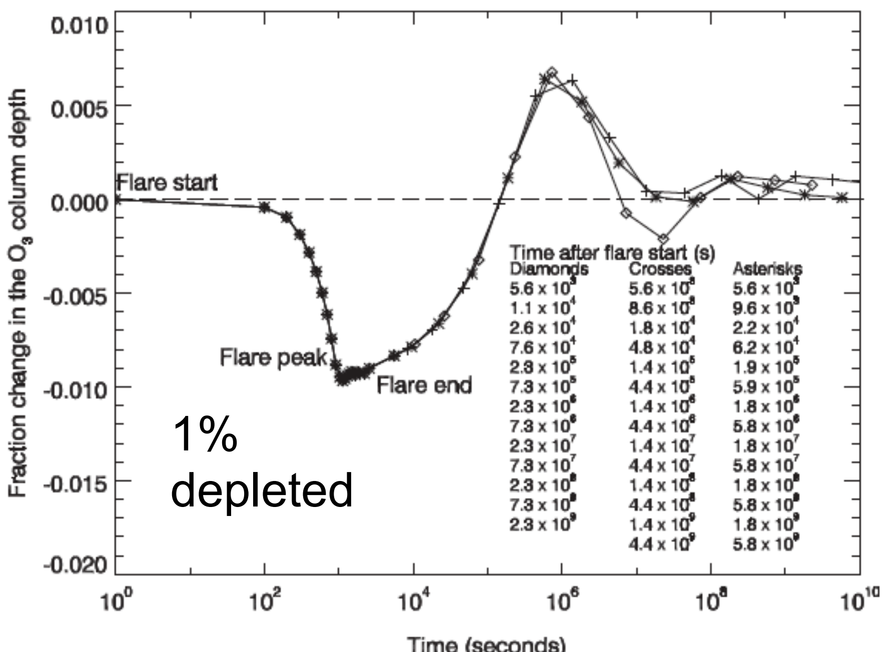
M Dwarf Planets: Radiative Effects

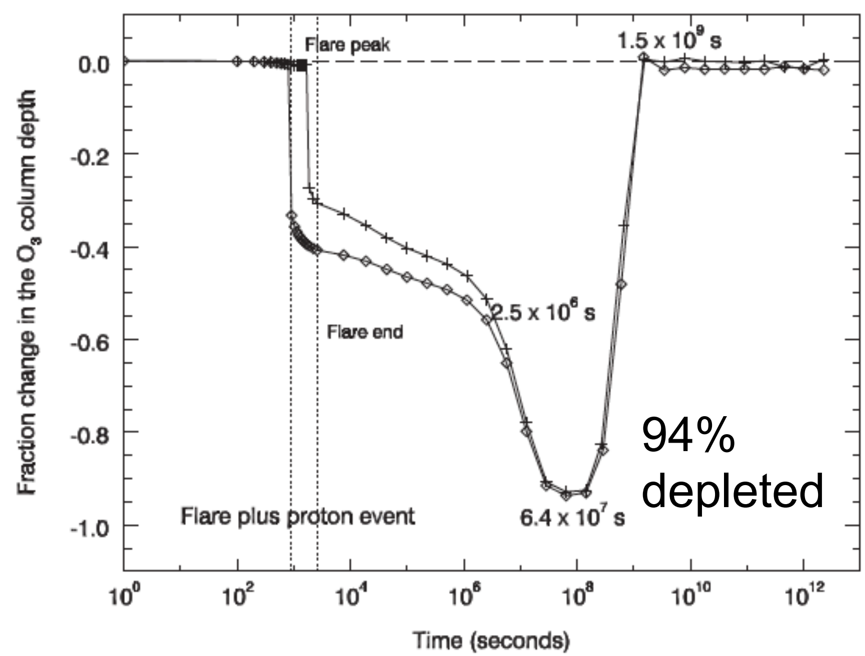


- Spectrum of starlight
  - Affects climate via changes to atmospheric/surface absorption
  - Photochemistry
- Stellar Activity
  - Photochemistry
  - Surface UV fluxes
- Stellar Evolution
  - Extended Pre-Main Sequence

Stellar Activity and Ozone Depletion: UV vs Protons

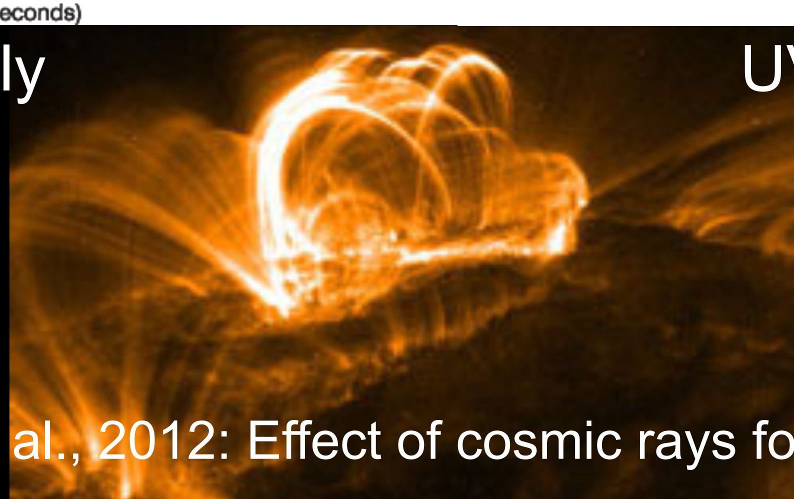
Segura, Walkowicz et al., 2010





UV only

UV and Protons



Proton induced NO chemistry is very effective at destroying O_3

See also Grenfell et al., 2012: Effect of cosmic rays for M dwarf planets

UV Fluxes at the Planetary Surface

Table 2. Ultraviolet Integrated Flux in W m^{-2} for Selected Times Before, During, and After the UV Flare with a Proton Event Included

	UVA		*UVB*		*UVC*	
	(3150–4000 Å)		*(2800–3150 Å)*		*(<2800Å)*	
	TOA	*Surface*	*TOA*	*Surface*	*TOA*	*Surface*
Earth	102.36	118.45	17.23	2.55	6.73	2.13×10^{-14}
AD Leo planet						
Quiescence ($t = 0$ s)	2.60	2.97	0.20	0.01	2.76	2.13×10^{-14}
Flare start ($t = 100$ s)	10.89	11.59	5.34	0.21	43.10	1.93×10^{-14}
Flare peak ($t = 915$ s)	112.17	120.77	45.43	3.15	368.76	1.93×10^{-14}
After flare ($t = 7.6\times10^3$ s)	2.60	3.00	0.20	0.02	2.76	1.93×10^{-14}
After flare ($t = 1.3\times10^7$ s)	2.60	3.02	0.20	0.04	2.76	2.52×10^{-10}
After flare ($t = 6.4\times10^7$ s)	2.60	3.03	0.20	0.06	2.76	5.85×10^{-5}
After flare ($t = 1.4\times10^8$ s)	2.60	3.03	0.20	0.06	2.76	3.38×10^{-5}
After flare ($t = 6.0\times10^8$ s)	2.60	3.00	0.20	0.02	2.76	1.93×10^{-14}

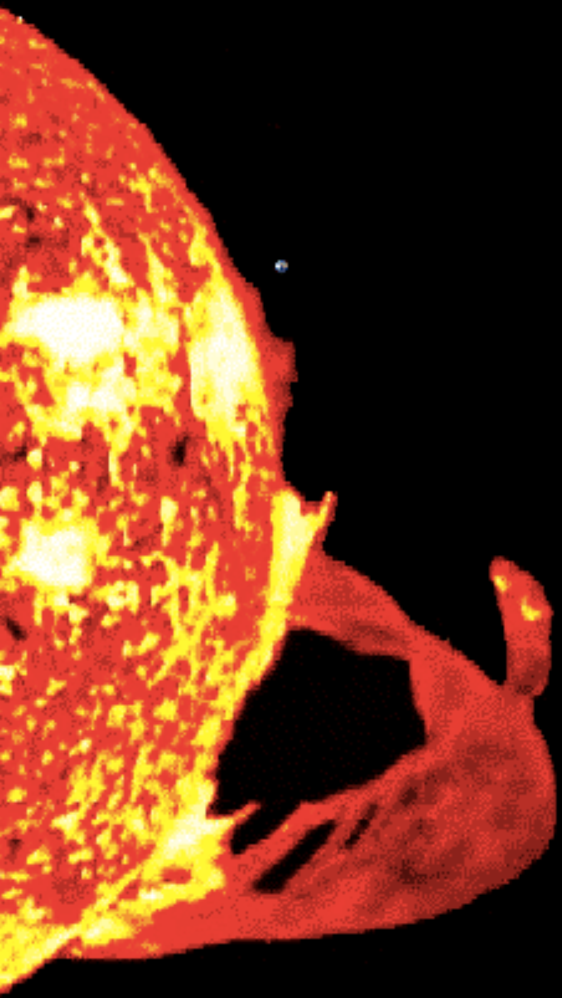
Earth values are shown for comparison. TOA, top of the atmosphere.

Segura et al., 2010

At the flare peak, the UV dose rate for DNA damage is ~19% larger than that on Earth, and for less than 100 seconds.

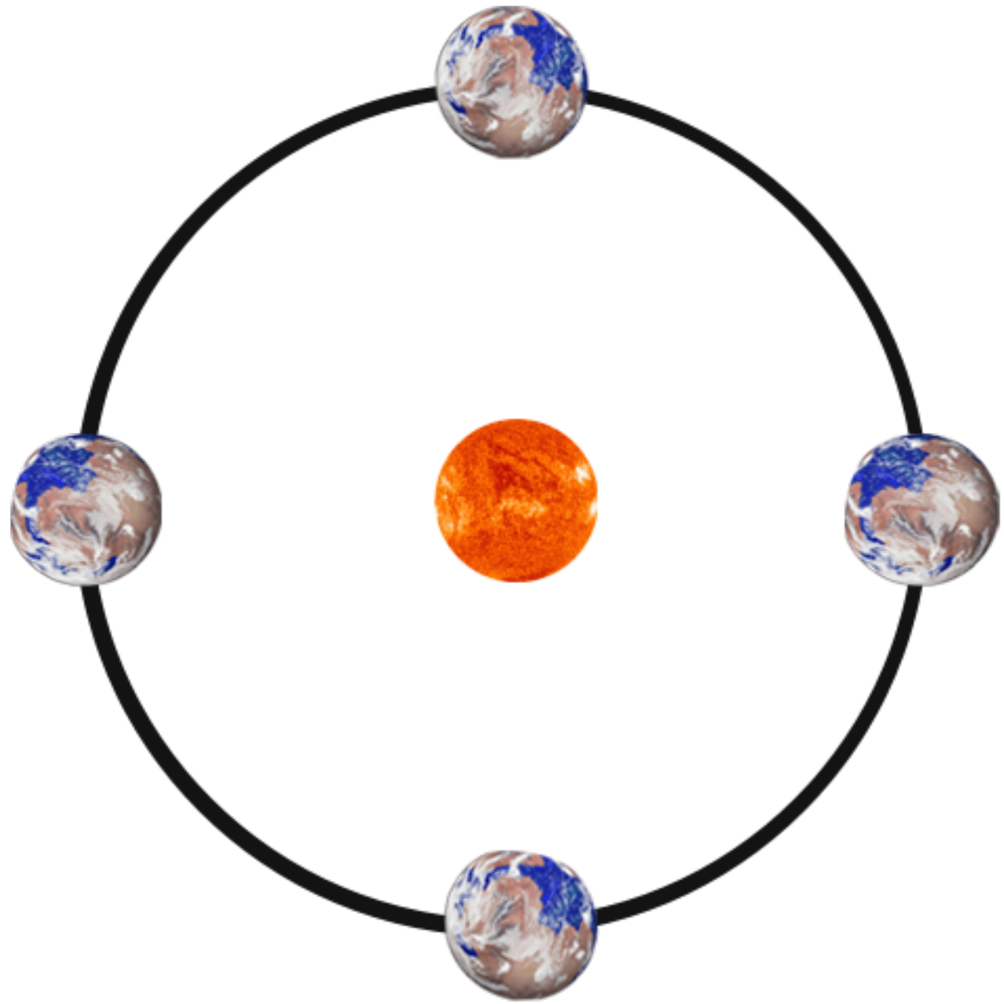
Initial Conclusion: Flares may not present a significant hazard for M dwarf planets, especially for planets with magnetic fields (e.g. Lopez-Morales et al., 2011)

M Dwarf Planets: Gravitational Effects

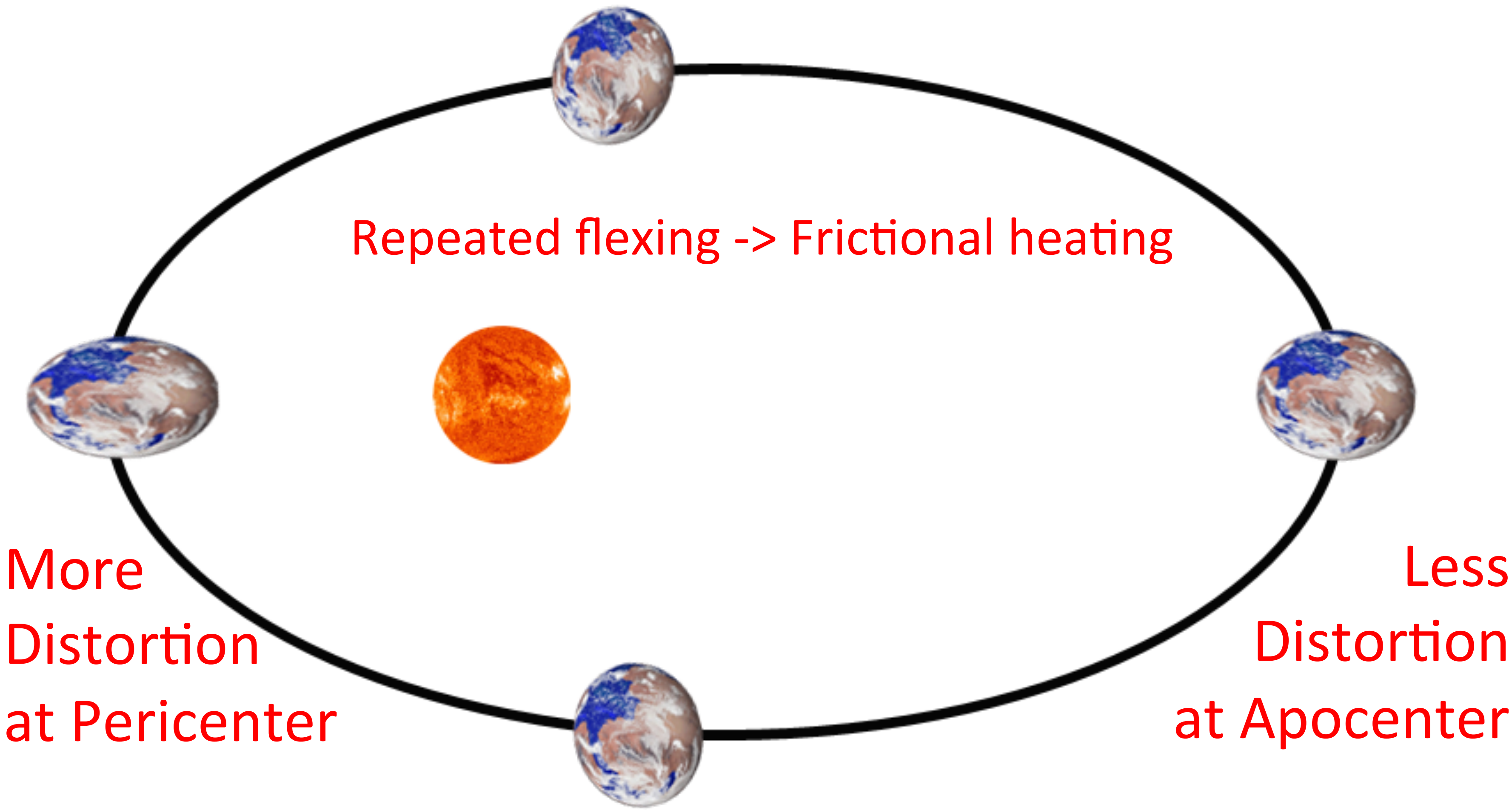


- Tidal Locking
  - Circularization
  - Climate effects
- Tidal Effects
  - Tidal Habitable Zone
  - Tidal Venuses
  - Loss of magnetic field

An Orbit with No Tides



Tidal Heating



Many orbits will circularize but it may take billions of years
Mutual gravitational perturbations may sustain tidal heating indefinitely.

Tidal Heating In The Solar System

Tvashtar from *New Horizons*

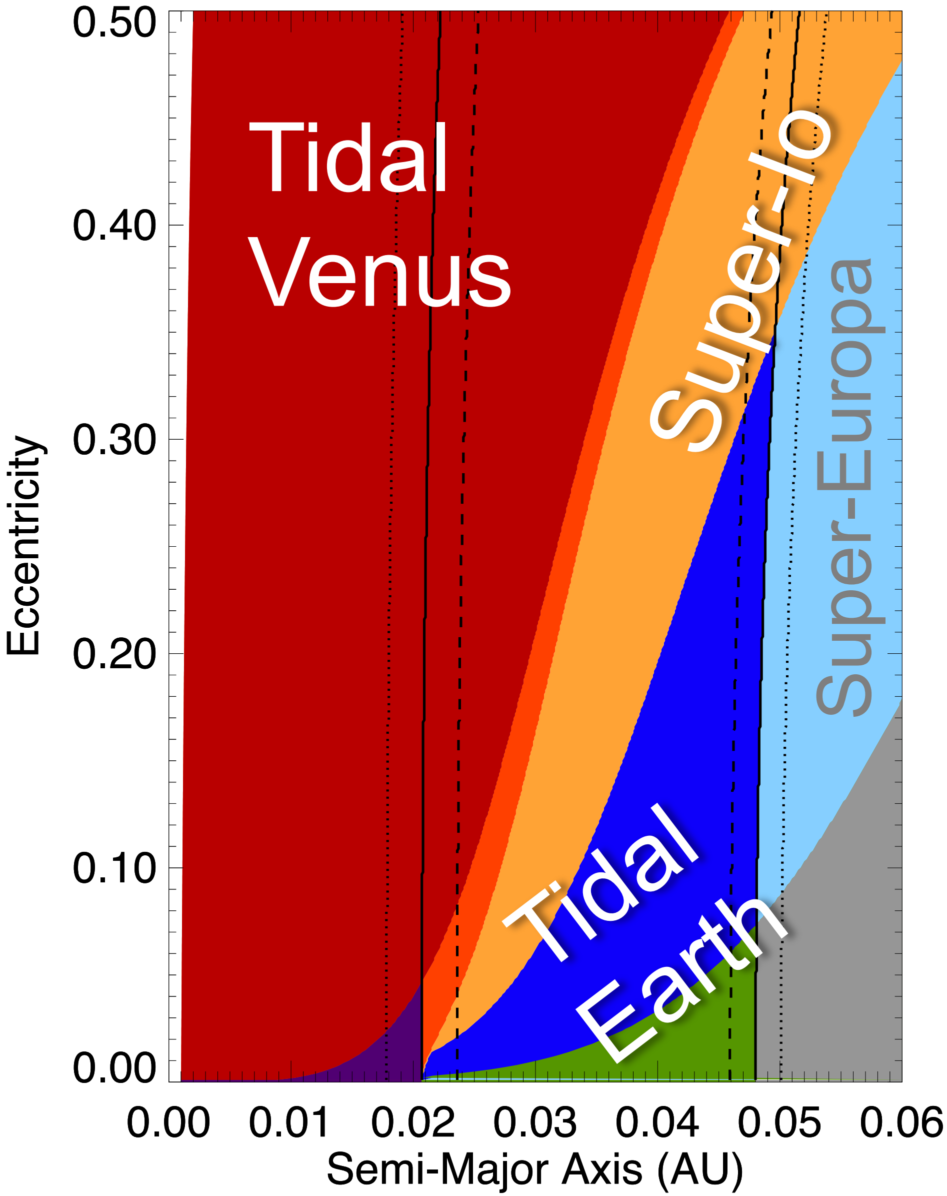
Io's Surface Flux = 2 W/m^2

Earth's = 0.08 W/m^2

Tectonics requires > 0.04

Runaway Greenhouse > 300

Tidal Energy Could Drive Climate

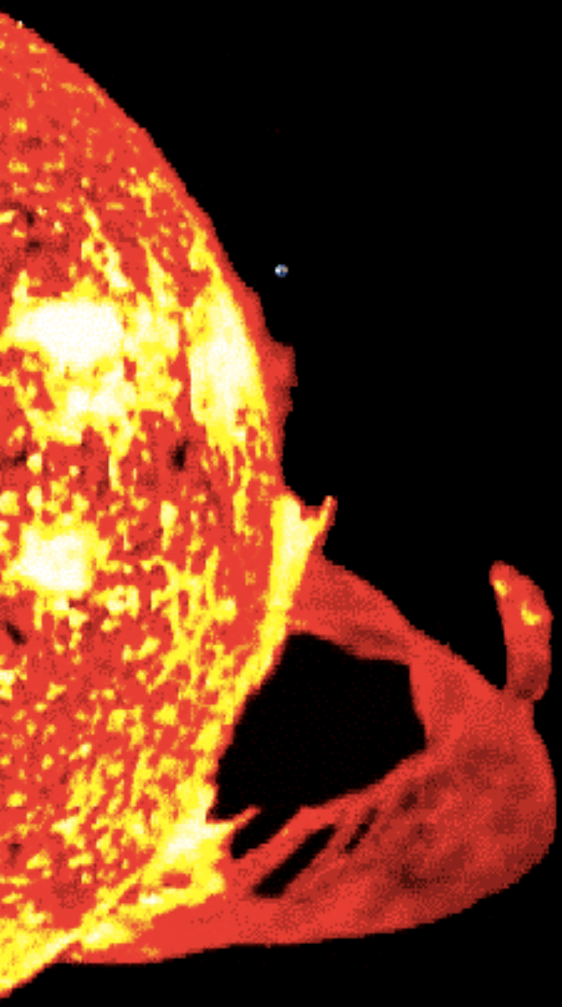


1 M_{Earth} orbiting 0.1 M_{sun} with modern Earth's tidal Q

Ecc. damps in > 10^8 -- 10^9 yrs, or could be maintained by a planetary perturber.

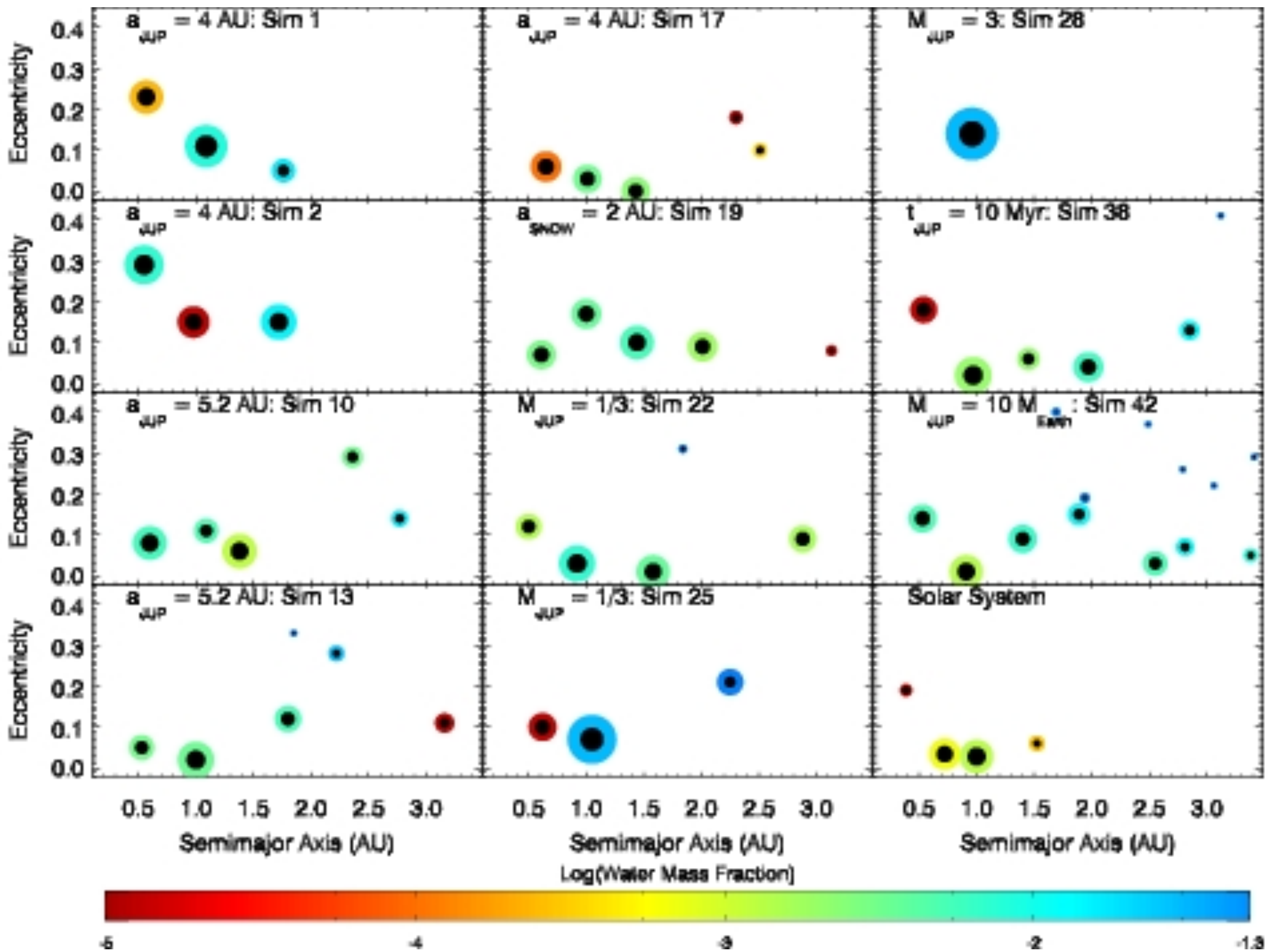
Barnes, Mullins, Goldblatt, Meadows, Kasting, Heller, 2013, *Astrobiology*, 13(3), 225-250.

Stellar and Planetary System Evolution



- Volatile Delivery
- Orbital Evolution
- Impacts
- Atmospheric Loss
- Compositional Changes

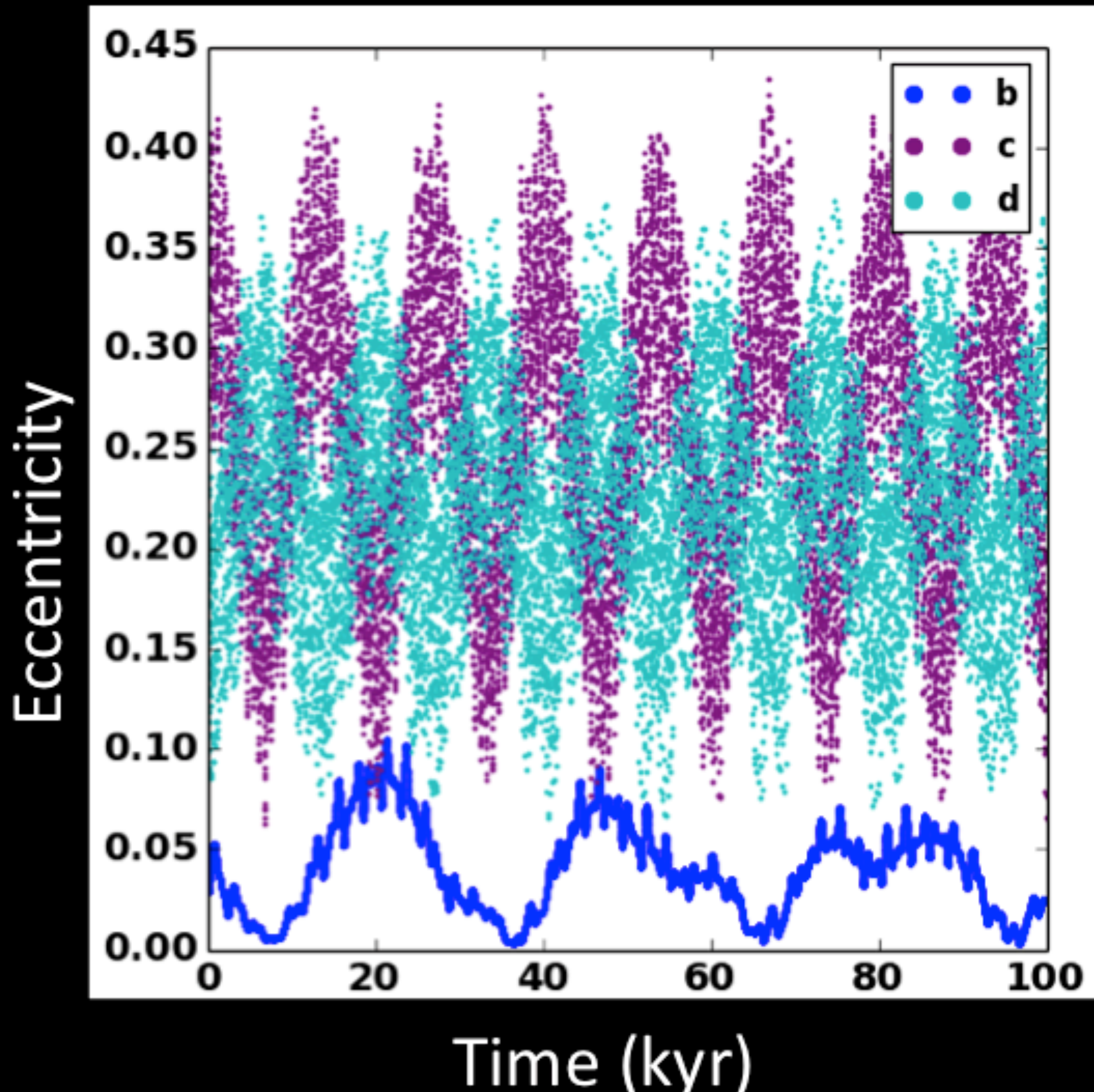
Planetary Architecture Affects Water Delivery



Raymond, Quinn & Lunine 2004

•Water-poor inner planets are often, but not always, formed
•Initial composition depends sensitively on the Jovians

Sibling Planets Can Drive Eccentricity Variations



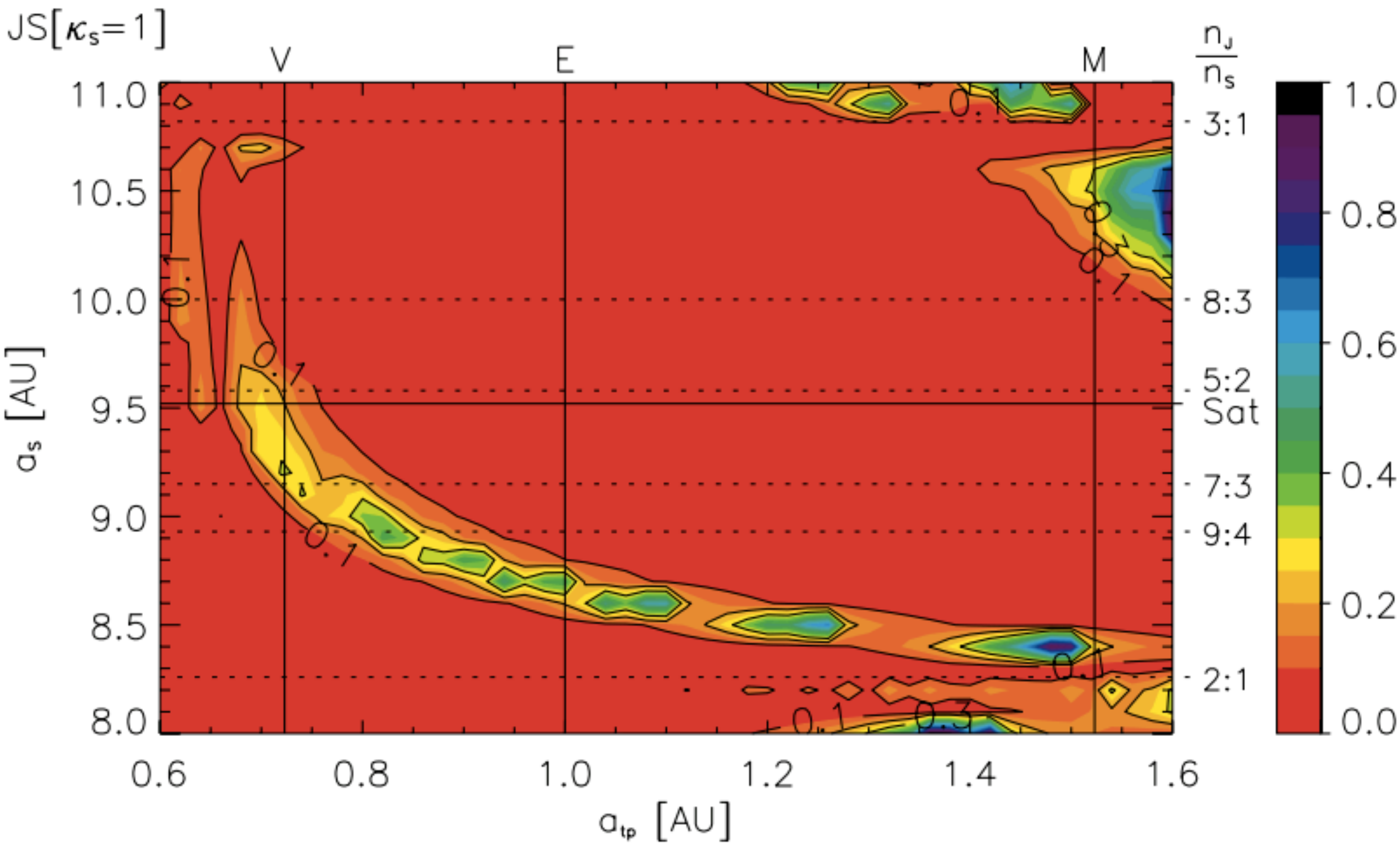
Upsilon Andromeda planets c and d are on orbits that are mutually inclined by 30 degrees.

They induce a periodic eccentricity change on planet b and could maintain periods of non-zero eccentricity long past the tidal circularization time scale.

See also van Laerhoven et al. (2014).

Deitrick et al., 2015; See talk here on obliquity evolution & climate

Position of Jovians Affects Terrestrial Eccentricity

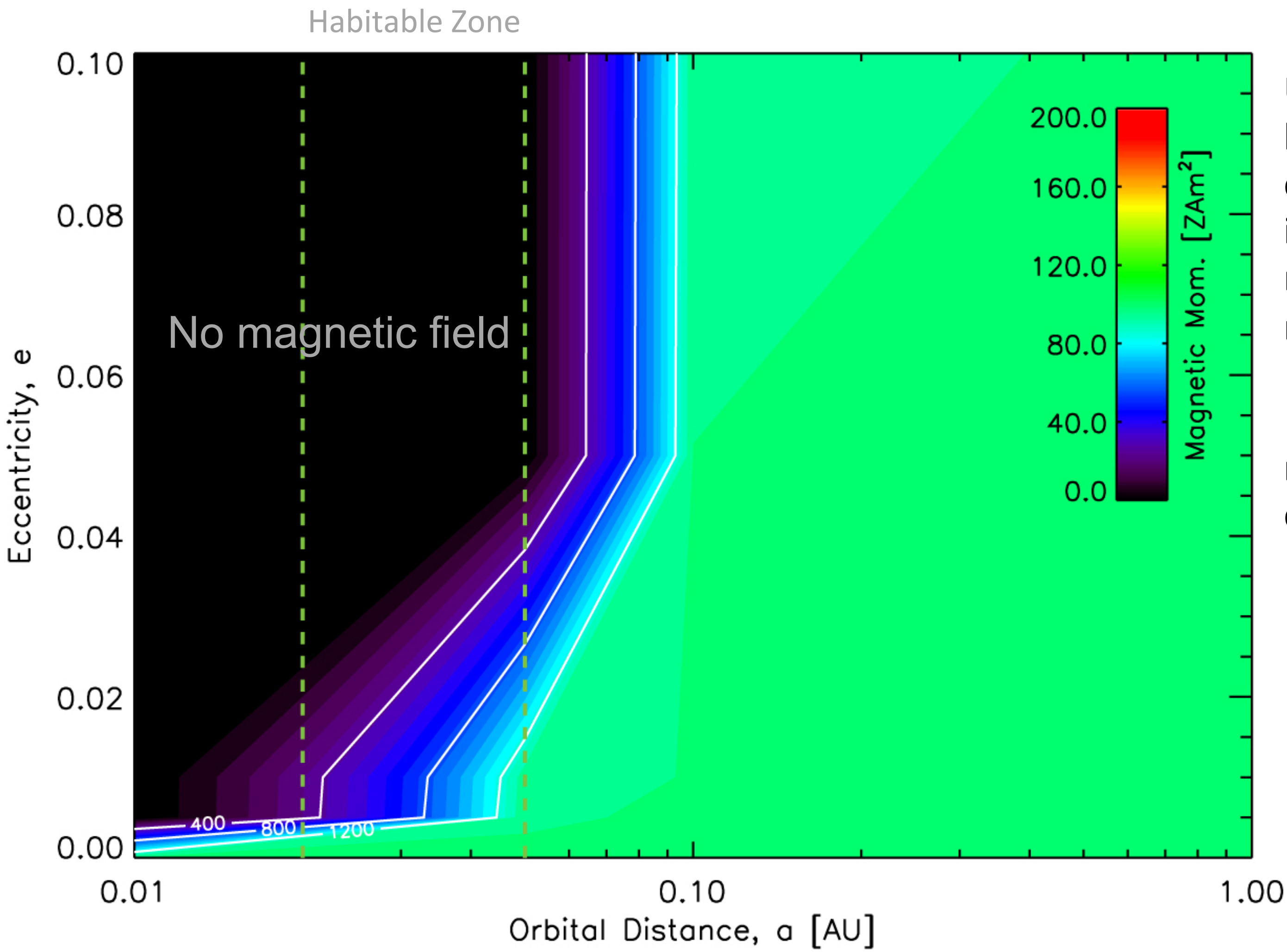


If Saturn were ~0.8AU closer than its current position the maximum eccentricity of Earth could be significantly higher.

Pilat-Lohinger et al., 2008

Tidal Heating Can Disrupt Planetary Magnetic Fields

M_{star}=0.1M_{sun} , t=4.5 Gyr, stagnant lid

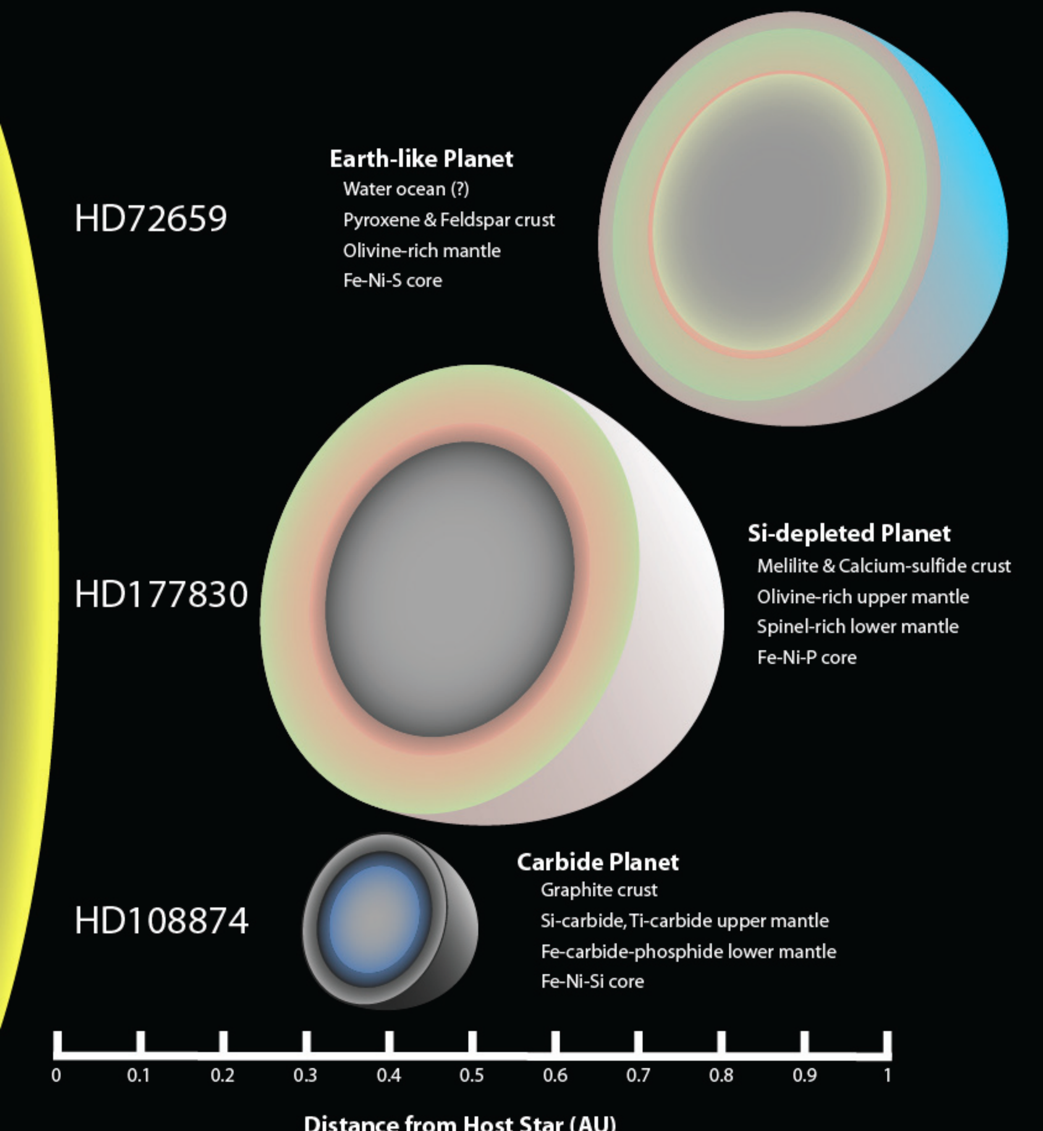


Under a stagnant lid, tidal heating in the mantle disrupts convection and inhibits the dynamo, reducing the magnetic moment.

At 4.5 Gyr, *e < 0.01* required to maintain dynamo

Driscoll & Barnes, 2015

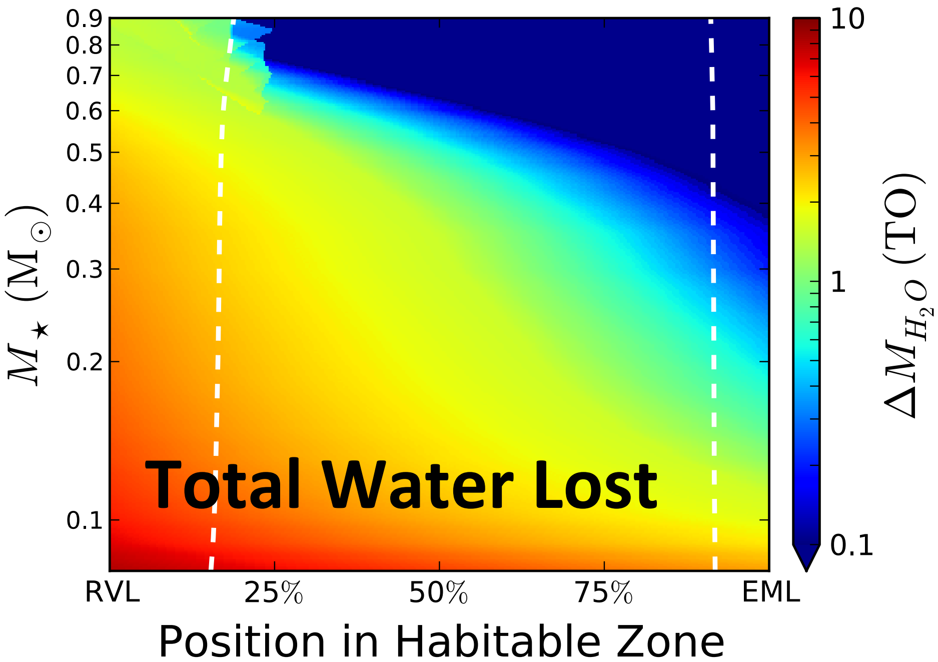
Initial Planetary Composition Affects Habitability



Bond, Lauretta and O'Brien, 2010

- Depends on abundance and composition of materials in the protoplanetary disk
- Delivery and maintenance of (SPONCH) and volatiles depends on disk composition and evolution, planet-star interactions, as well as intrinsic planetary properties.
- Terrestrial planets with very different composition will likely differ in many properties.
  - Tectonics and volcanism
  - Secondary outgassed atmospheres

Early Atmospheric Loss for M Dwarf Planets

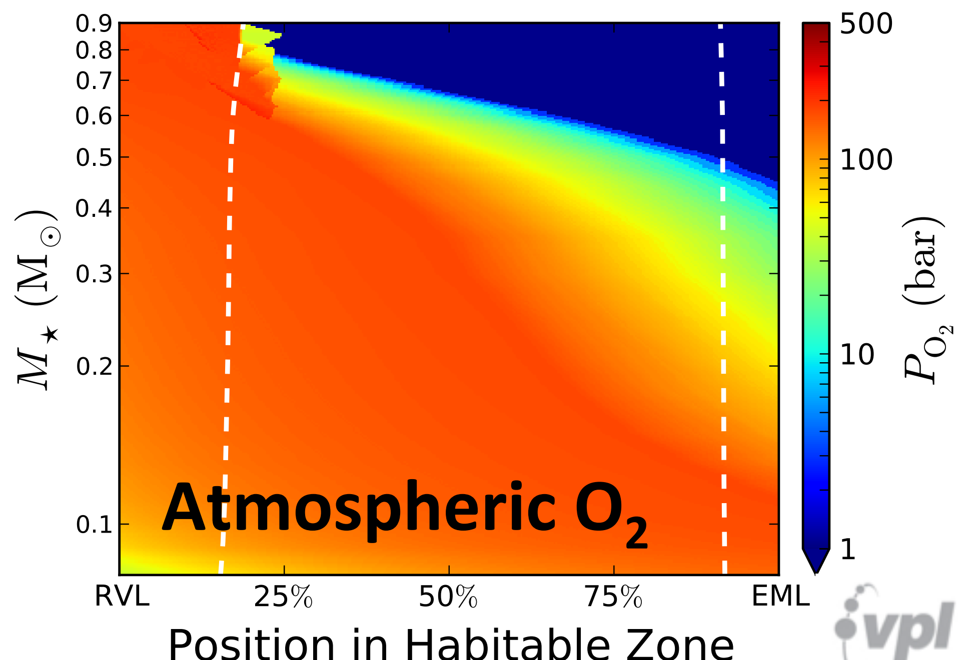


During the Pre-MS of M dwarfs terrestrial planets can lose several Earth oceans of water via hydrodynamic escape during the PMS phase of M dwarfs.

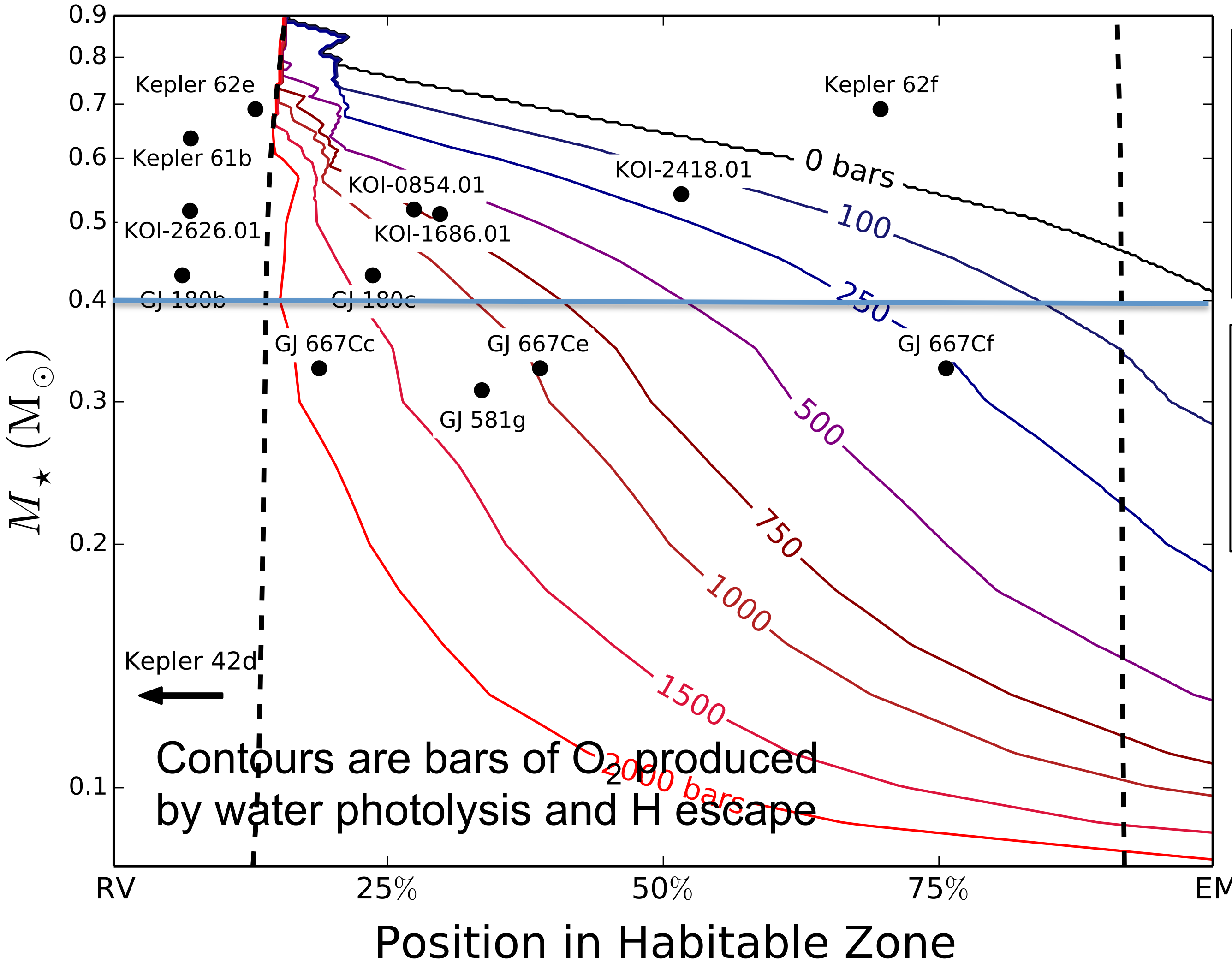
Luger & Barnes (2015)

Depending on surface sinks, up to several hundreds of bars of photolytically-produced O_2 can potentially build up in the atmospheres of these planets.

Luger & Barnes (2015)



This Effect Stronger for Later Type Stars

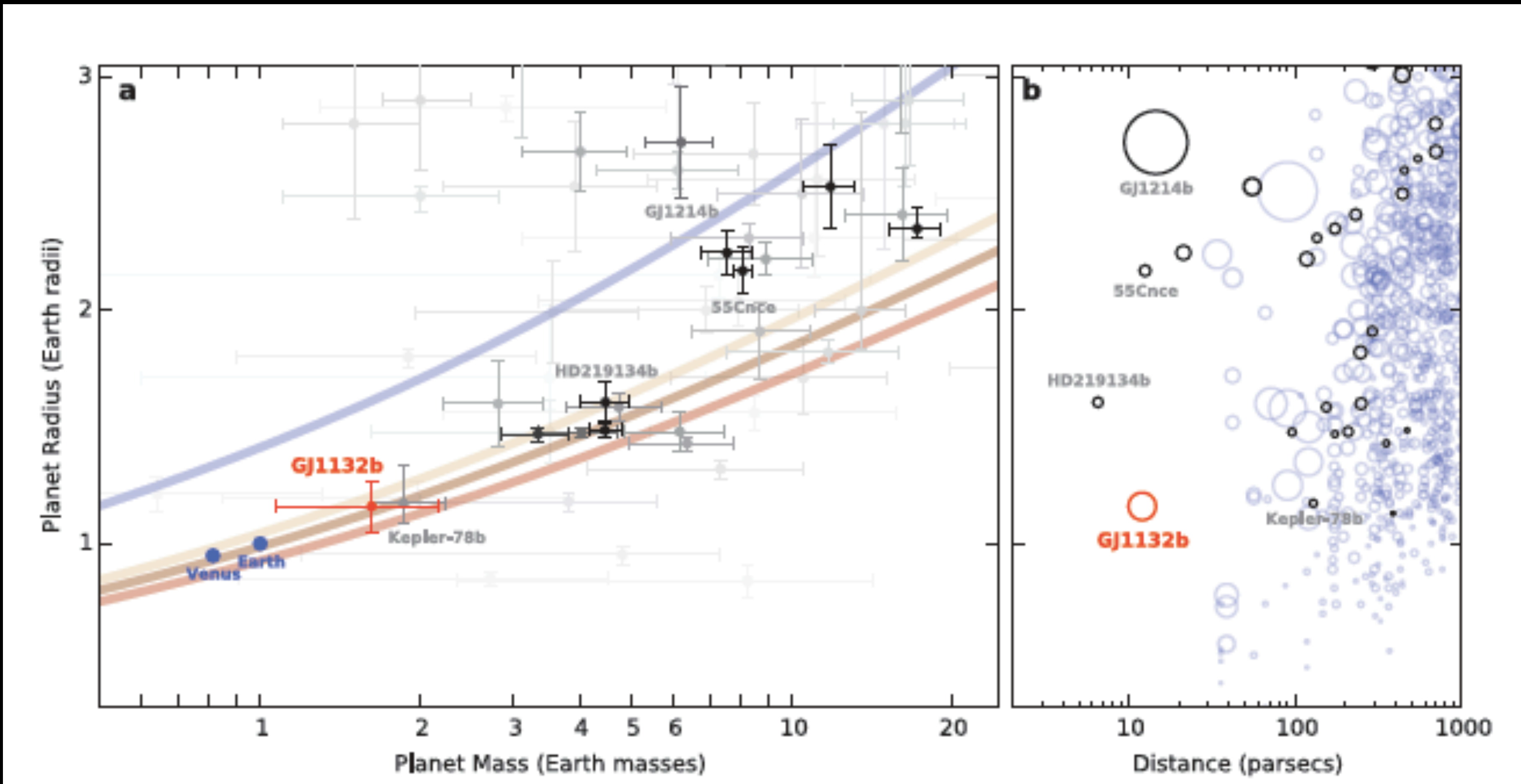


This extra pre-MS luminosity can last for up to a billion years and could dessicate planets formed in the habitable zone of low mass stars within the first 100 Myr

THE PUNCHLINE: Planets orbiting stars above a stellar mass of ~ 0.4 are less likely to experience this phenomenon, especially towards the outer edge of the HZ.

Luger and Barnes, 2015

GJ1132b – A SuperVenus

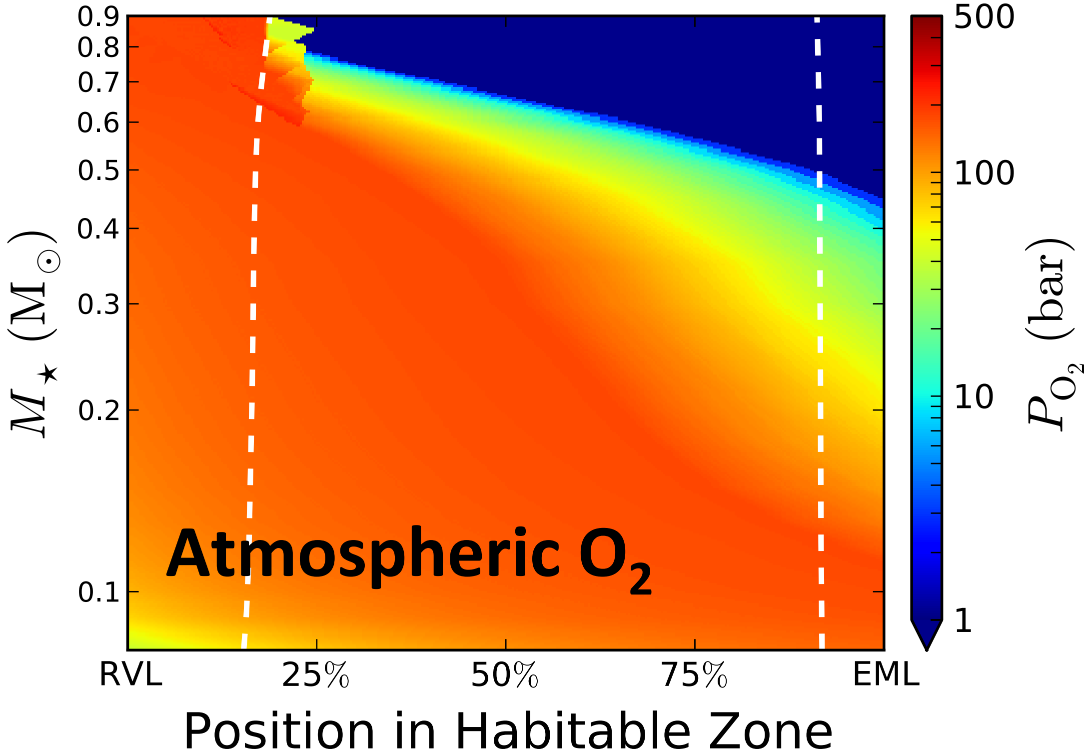


Berta-Thompson et al., 2015

Planet parameters	
Radius of planet, R_p	$1.16 \pm 0.11\, R_\oplus$
Mass of planet, M_p	$1.62 \pm 0.55\, M_\oplus$
Density of planet, ρ_p	$6.0 \pm 2.5\, g\, cm^{-3}$

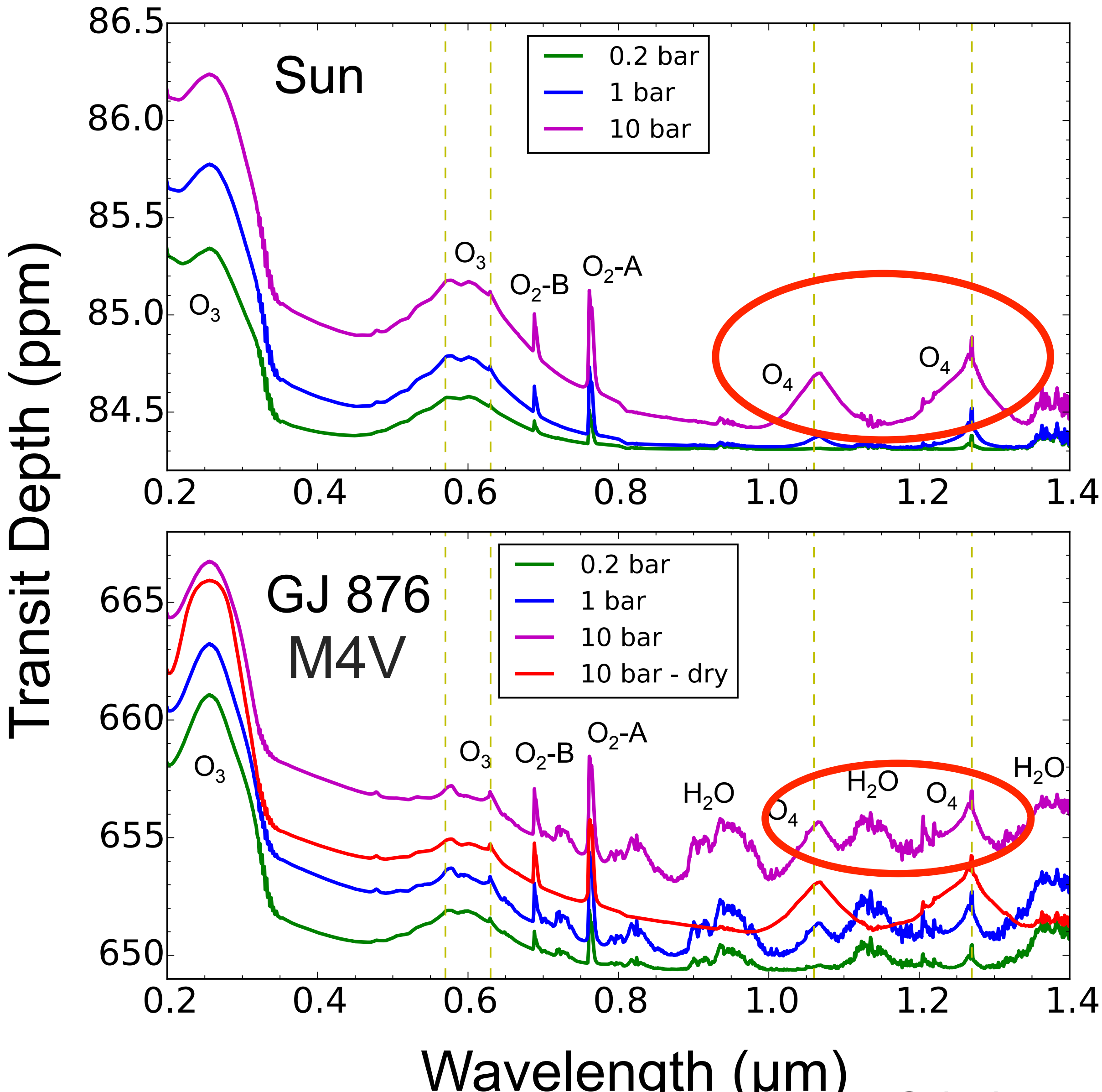
12pc distant

Uninhabitable Planets Will Be Valuable Test Cases



If a hot Earth has abundant O_2 then we know that the abiotic formation mechanism is viable, which may be a concern for false positive O_2 in the HZ

Massive O_2 atmospheres may have O_4 features



Schwieterman et al., in review

Open Issues for Planetary Habitability

- How common are terrestrial planets?
- What are their plausible atmospheric compositions and physical properties?
- How habitable are planets orbiting M dwarfs?
- Can super-Earths be habitable?
- Do terrestrial planets form with and retain dense atmospheres? Or lose them completely?
- What can uninhabitable planets tell us about planetary evolution and habitability?

- This is a vibrant, important field, and there are many other questions to be answered !

Assessing Planetary Habitability

- Understanding Habitability is crucial for target selection and data interpretation for the highest priority targets for future exoplanet characterization missions.

- Habitability is strongly affected by the stellar-planet-planetary system interplay. We need to:
  - Identify factors affecting habitabilty
  - Quantify their relative impact on habitability
  - Determine interdependencies.

- We also need to move beyond the HZ concept and develop an interdisciplinary, multi-parameter Habitability Index for assessing potential targets.

The Virtual Planetary Laboratory

PI: Victoria Meadows (UW)

With Thanks To…

Eric Agol (UW)
Rika Anderson (NAI-NPP/WHOI)
John Armstrong (Weber State)
Jeremy Bailey (UNSW)
Giada Arney (UW)
Rory Barnes (UW)
John Baross (UW)
Cecelia Bitz (UW)
Bob Blankenship (WUStL)
Linda Brown (NASA-JPL/Caltech)
Roger Buick (UW)
David Catling (UW)
Benjamin Charnay (NAI-NPP/UW)
Mark Claire (U. St. Andrews)
David Crisp (NASA-JPL/Caltech)
Pan Conrad (NASA-GSFC)
Russell Deitrick (UW)
L. Drake Deming (U. Maryland)
Feng Ding (U. Chicago)
Shawn Domagal-Goldman (NASA-GSFC)
Peter Driscoll (CIW)
Peter Gao (Caltech)
Colin Goldblatt (U. Victoria)
Chester (Sonny) Harman (PSU)
Suzanne Hawley (UW)
Tori Hoehler (NASA-Ames)
Jim Kasting (PSU)
Nancy Kiang (NASA-GISS)
Ravi Kopparapu (PSU)
Monika Kress (SJSU)
Andrew Lincowski (UW)
Rodrigo Luger (UW)
Jacob Lustig-Yaeger (UW)
Amit Misra (UW)
Niki Parenteau (NASA-Ames)
Ray Pierrehumbert (U. Chicago)
Tom Quinn (UW)
Sean Raymond (Lab. Astrophysique de Bordeaux)
Tyler Robinson (Sagan Fellow – UC Santa Cruz)
Eddie Schwieterman (UW)
Antigona Segura (UNAM)
Janet Seifert (Rice U.)
Holly Sheets (U. Maryland)
Aomawa Shields (NSF/UCLA/Harvard)
Norm Sleep (Stanford)
Eva Stüeken (UW)
Lucianne Walkowicz (Adler Planetarium)
Robin Wordsworth (Harvard)
Yuk Yung (Caltech)
Kevin Zahnle (NASA-Ames)