

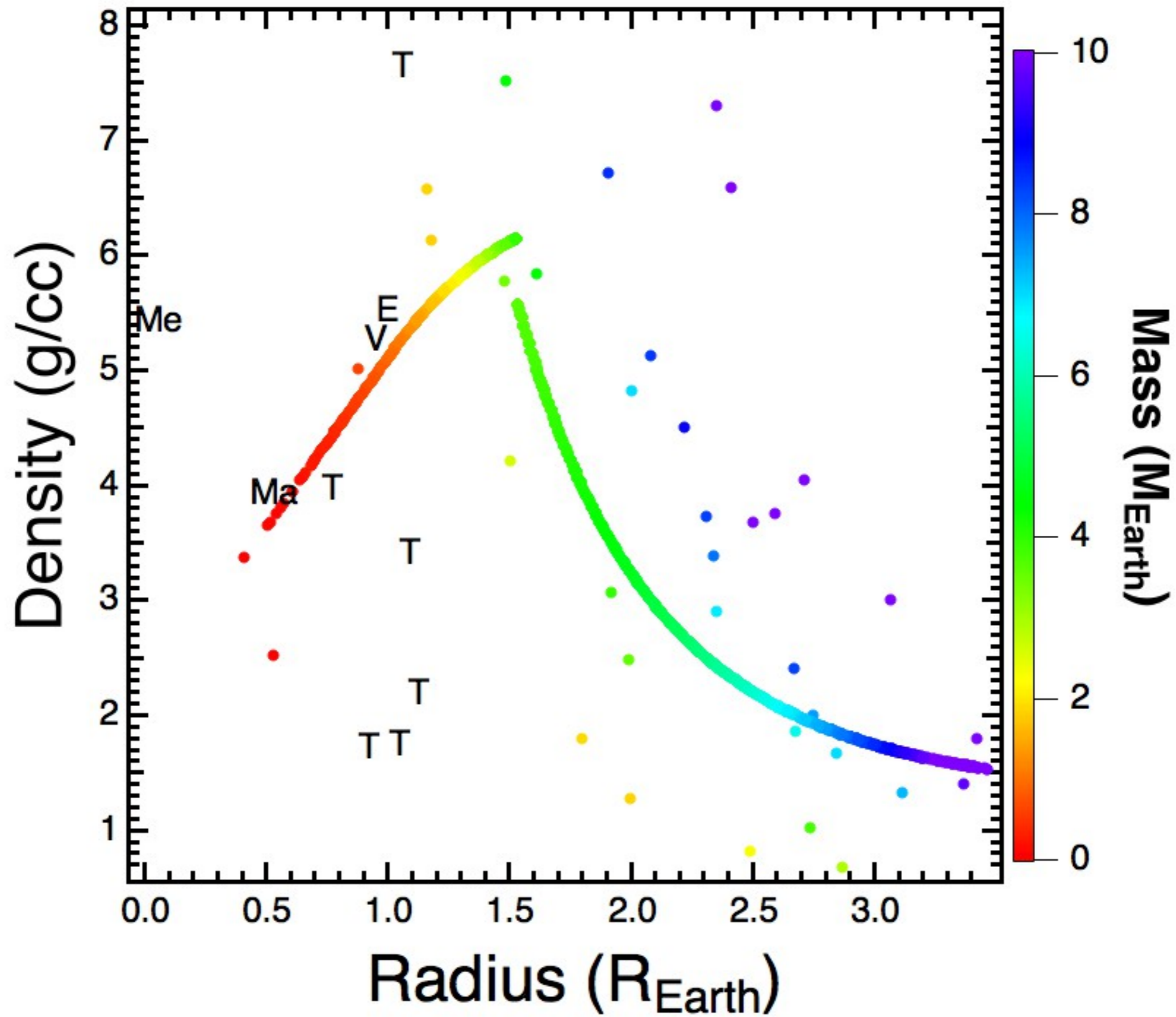
# Density is not Destiny: Characterizing Exoplanet Geology from Stellar Compositional Abundances

Cayman Unterborn  
Exploration Fellow

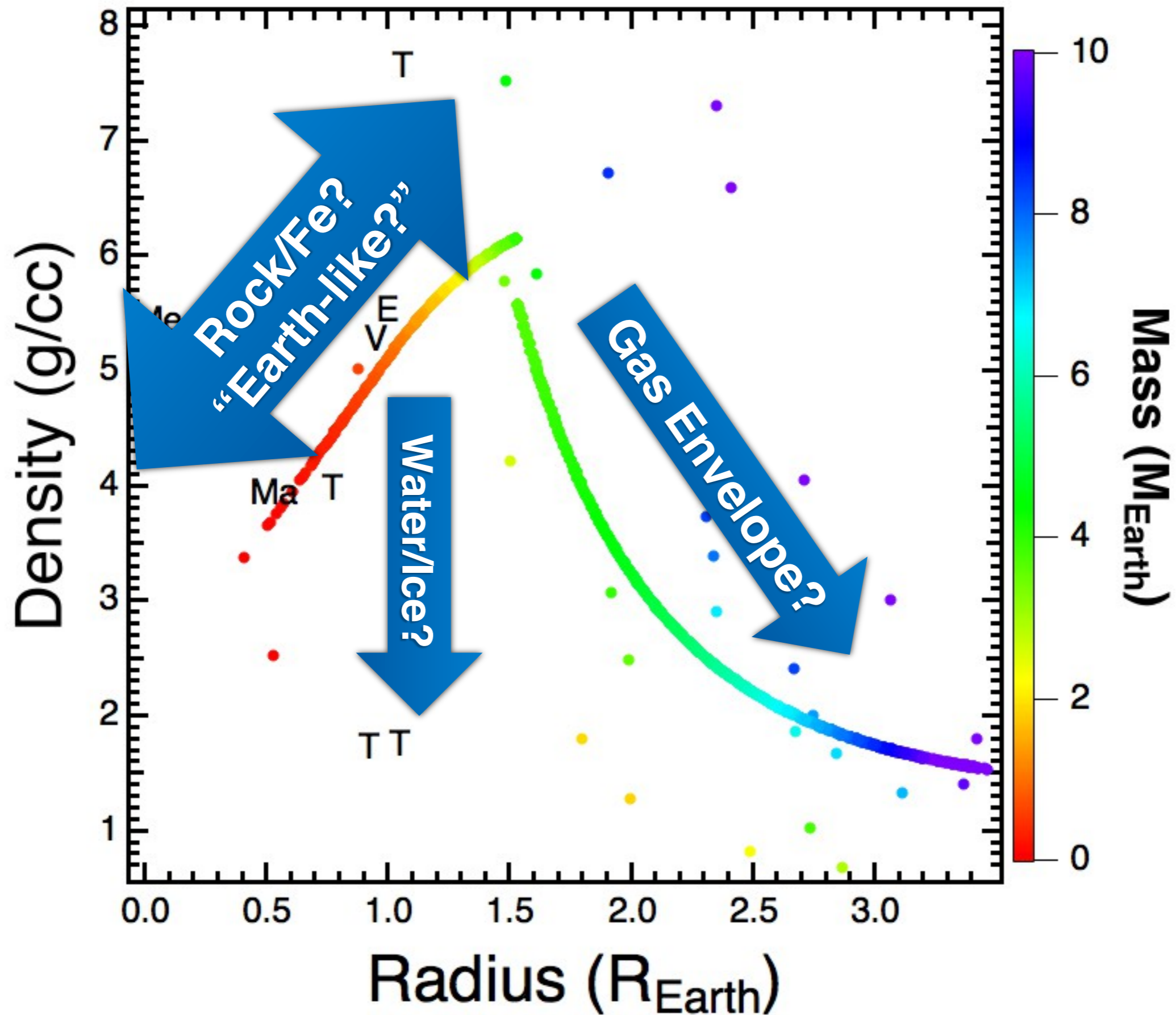
School of Earth And Space Exploration  
Arizona State University  
Cayman.Unterborn@asu.edu

Scott Hull, Jennifer Johnson, Wendy Panero (The Ohio State University)  
Johanna Teske (Carnegie Institute of Science)  
Lars Stixrude (University College London)  
Natalie Hinkel (Vanderbilt)  
Steve Desch, Alejandro Lorenzo (ASU)





Adapted from [exoplanets.org](http://exoplanets.org);  
Wang et al., 2017



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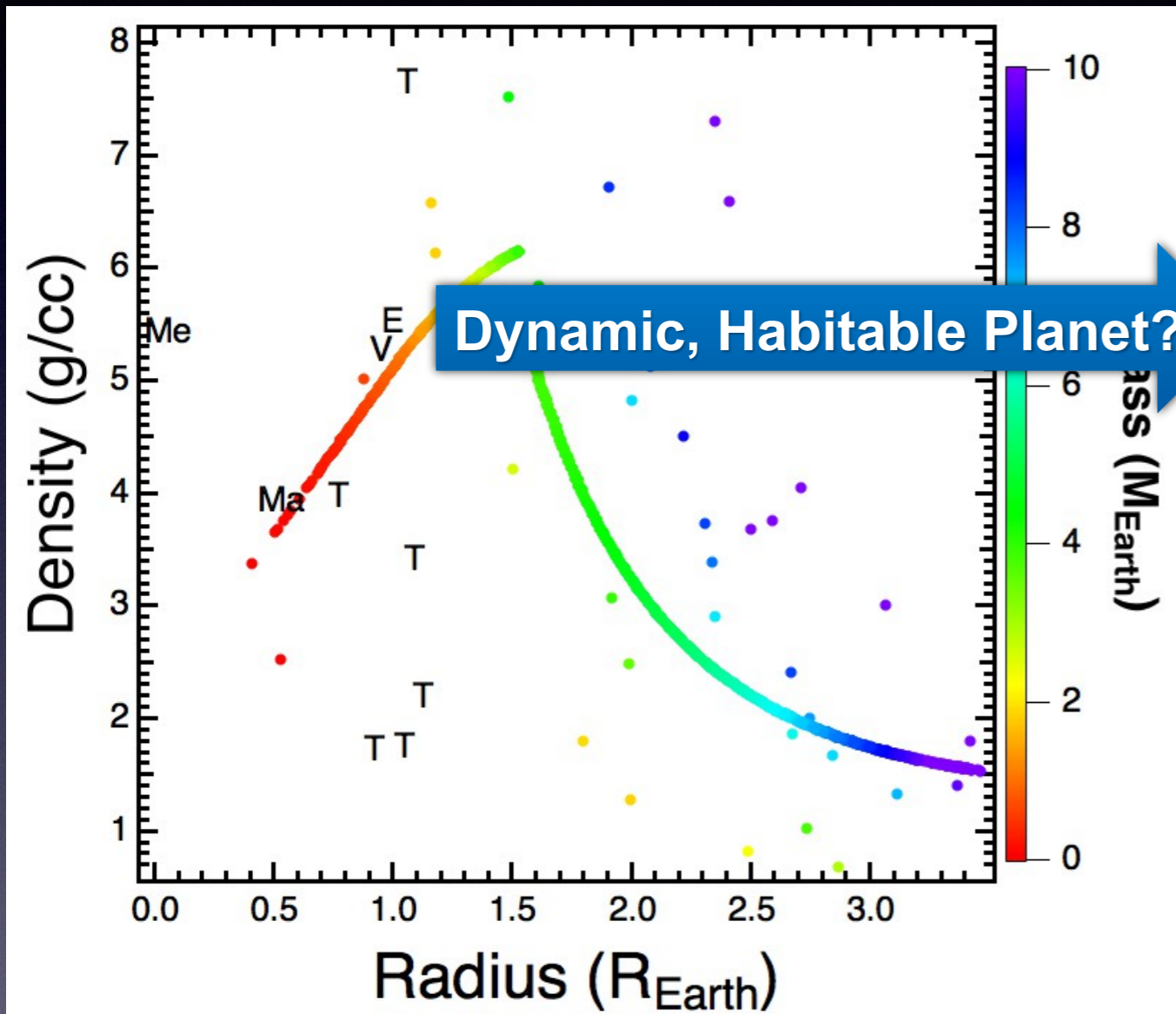


“Earth-like” means much more  
than a:

- 1 Earth mass
- 1 Earth radius
- 1 Earth density  
planet



# What is “Earth-like”?



Adapted from exoplanets.org;  
Wang et al., 2017

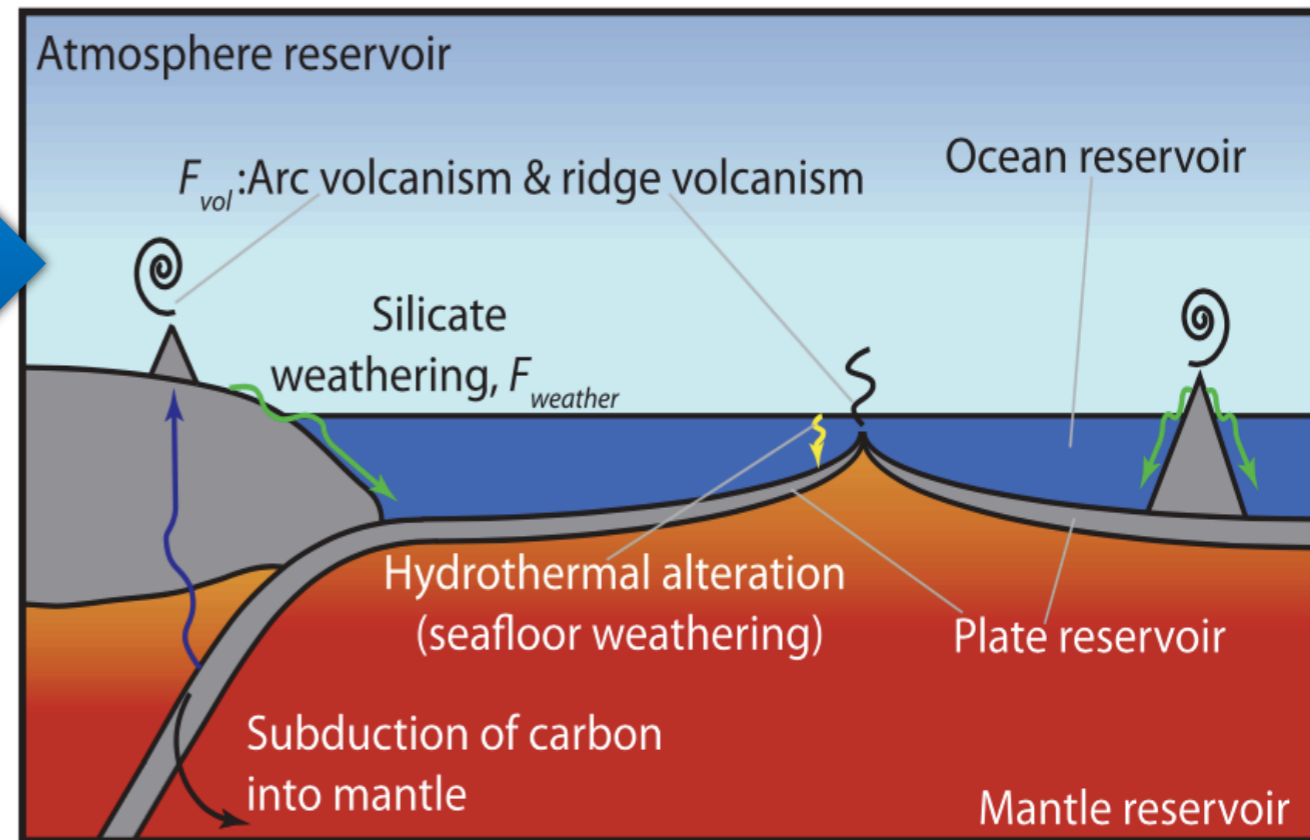
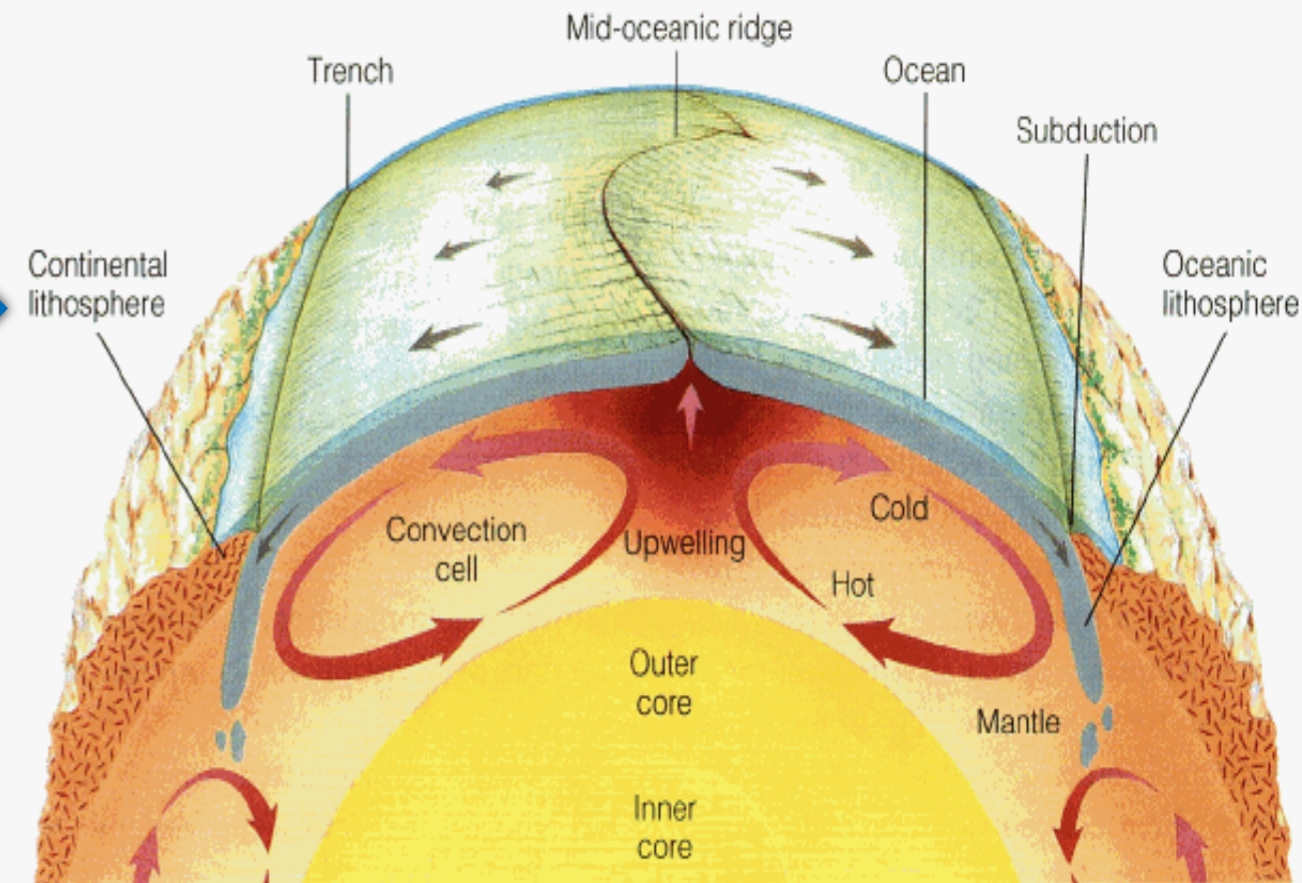
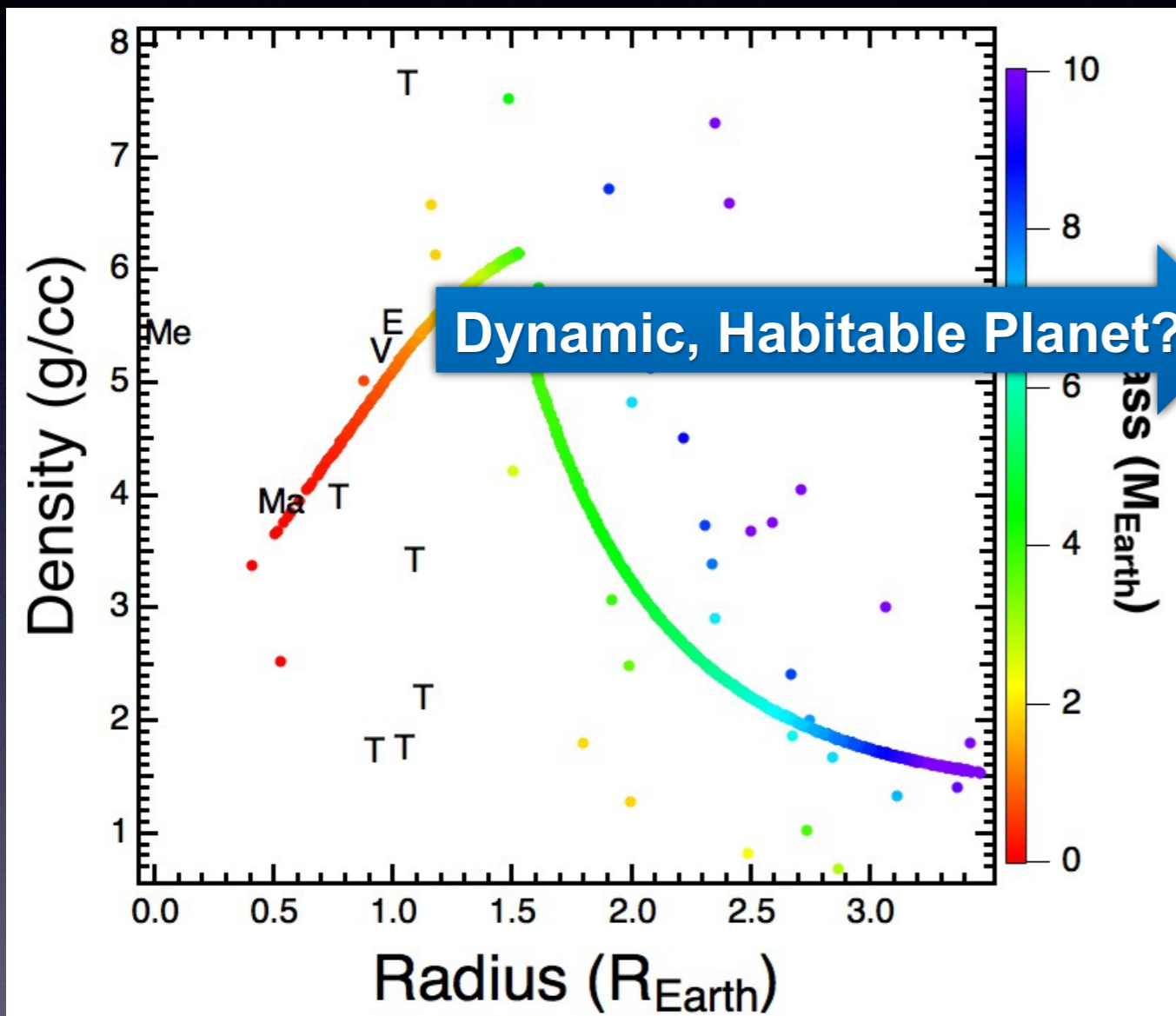


Figure 4. Schematic diagram of the global carbon cycle after *Foley* [2015].

Foley & Driscoll 2016



# What is “Earth-like”?

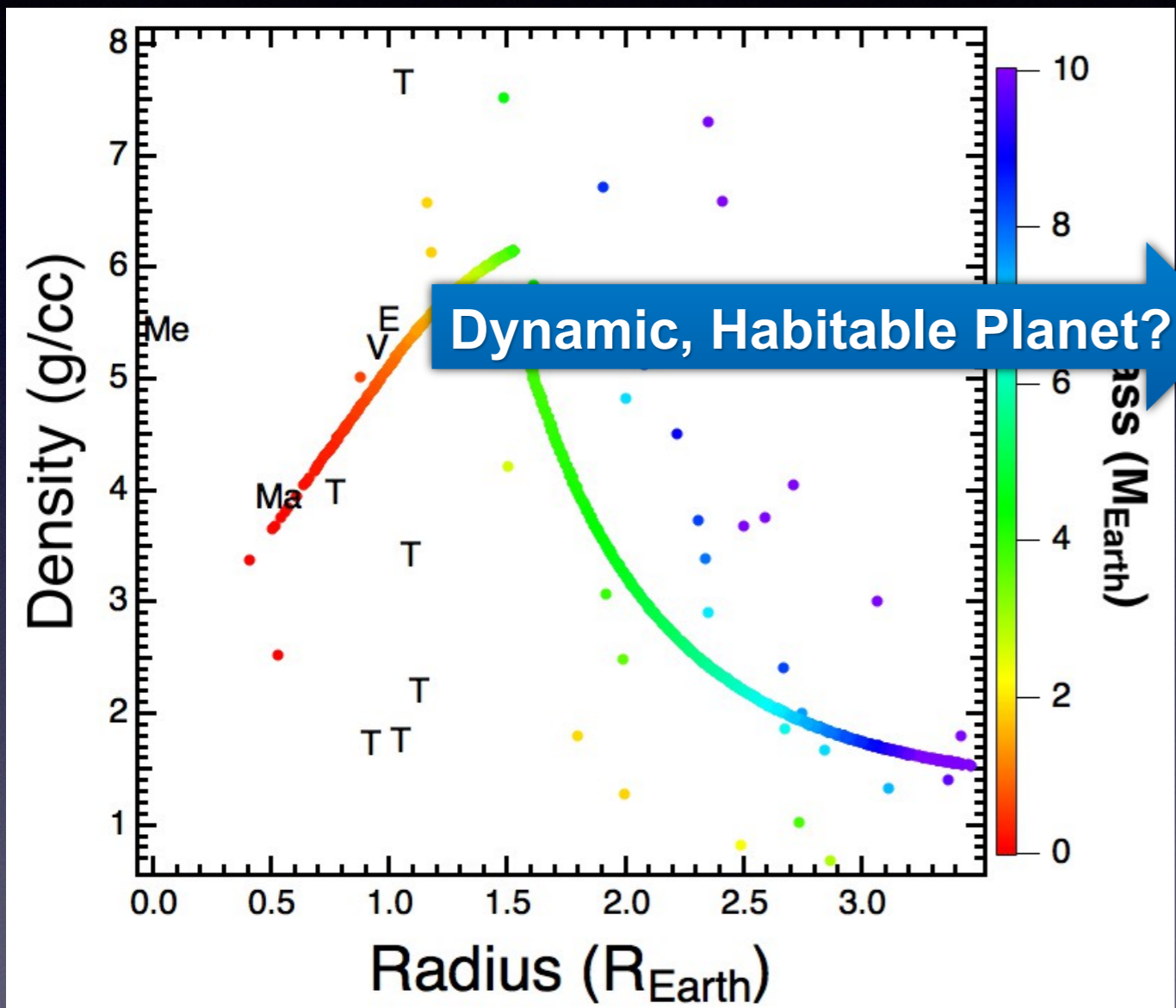


SERC

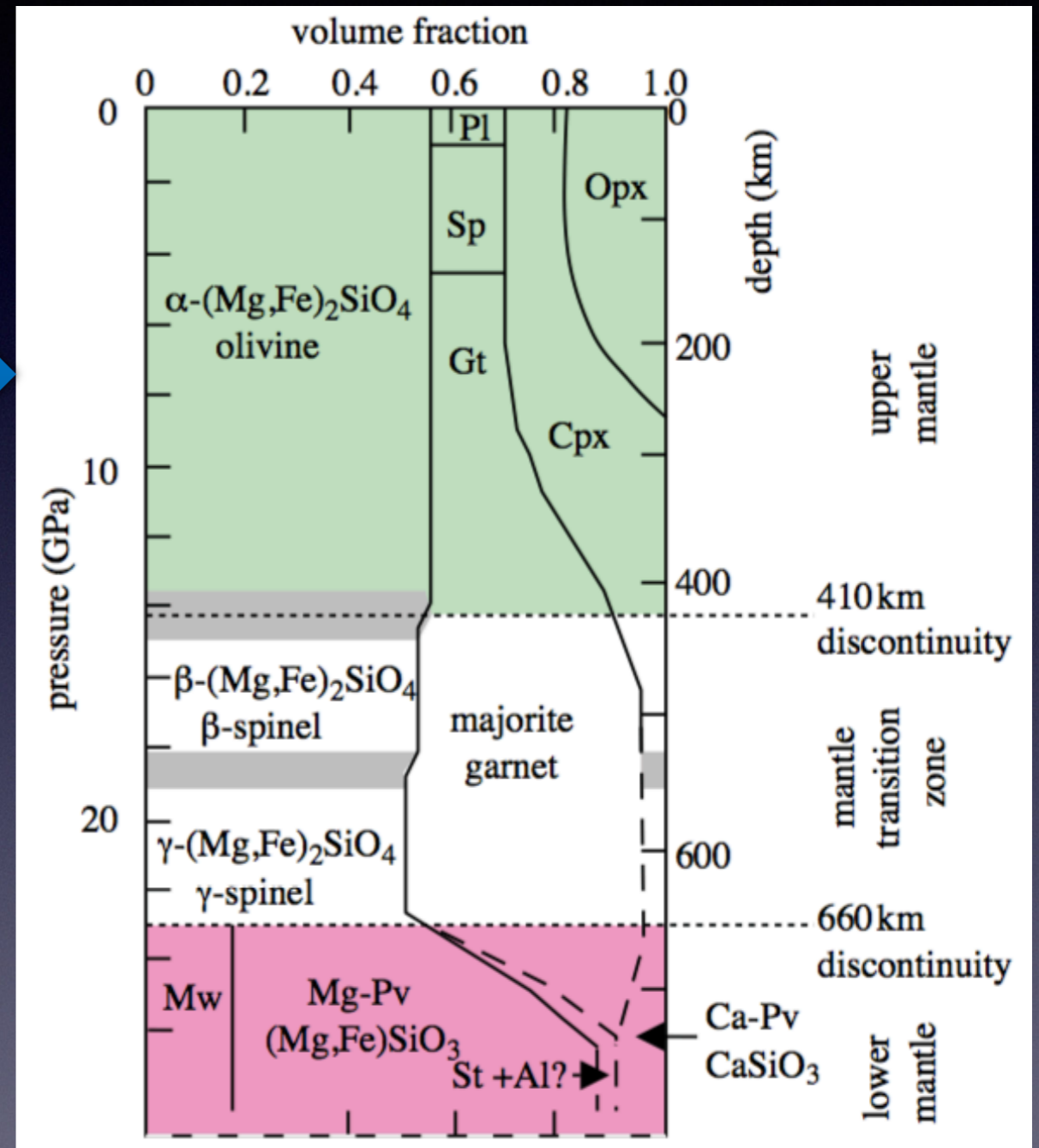
Adapted from exoplanets.org;  
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# What is “Earth-like”?

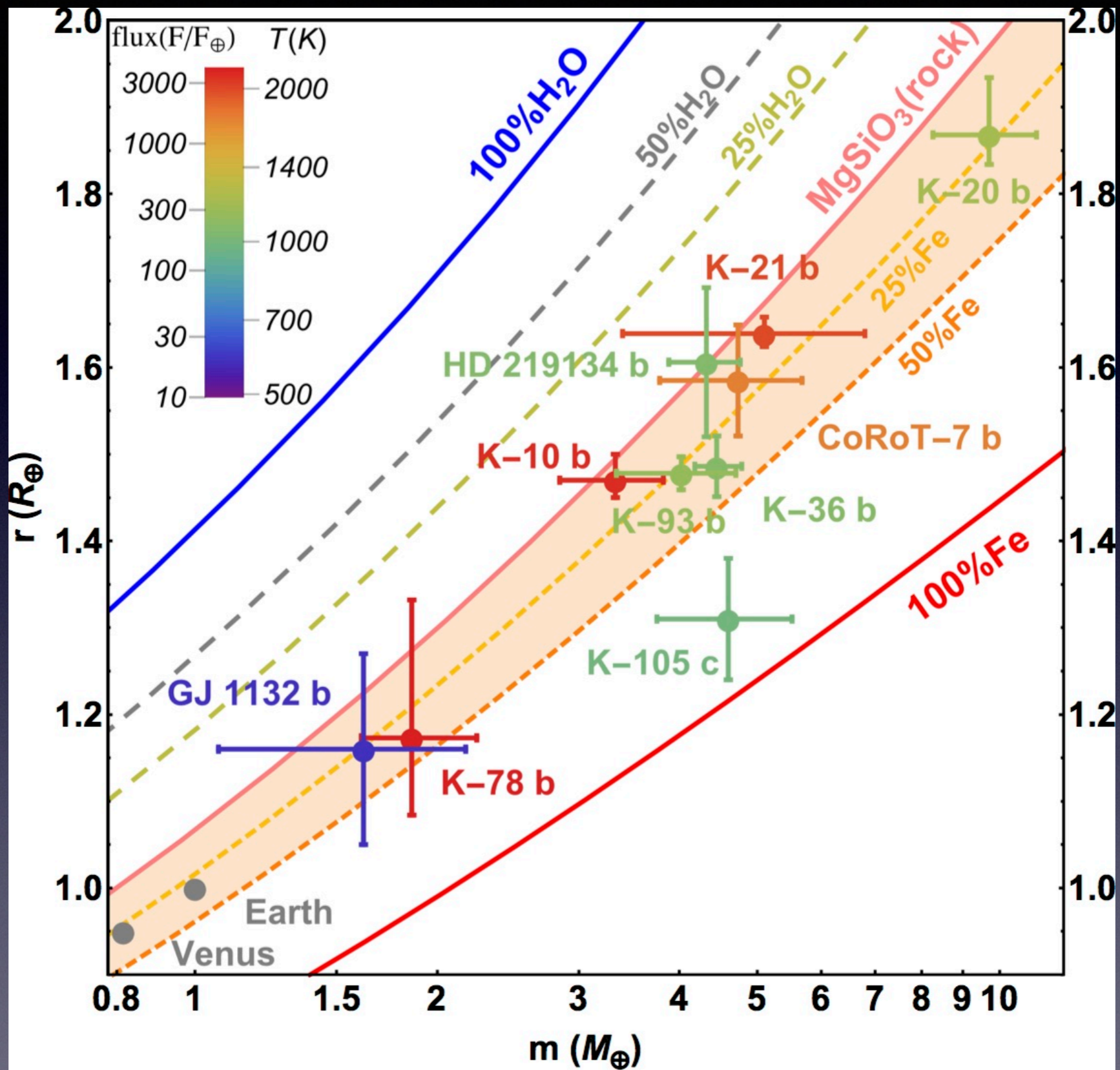


Adapted from exoplanets.org;  
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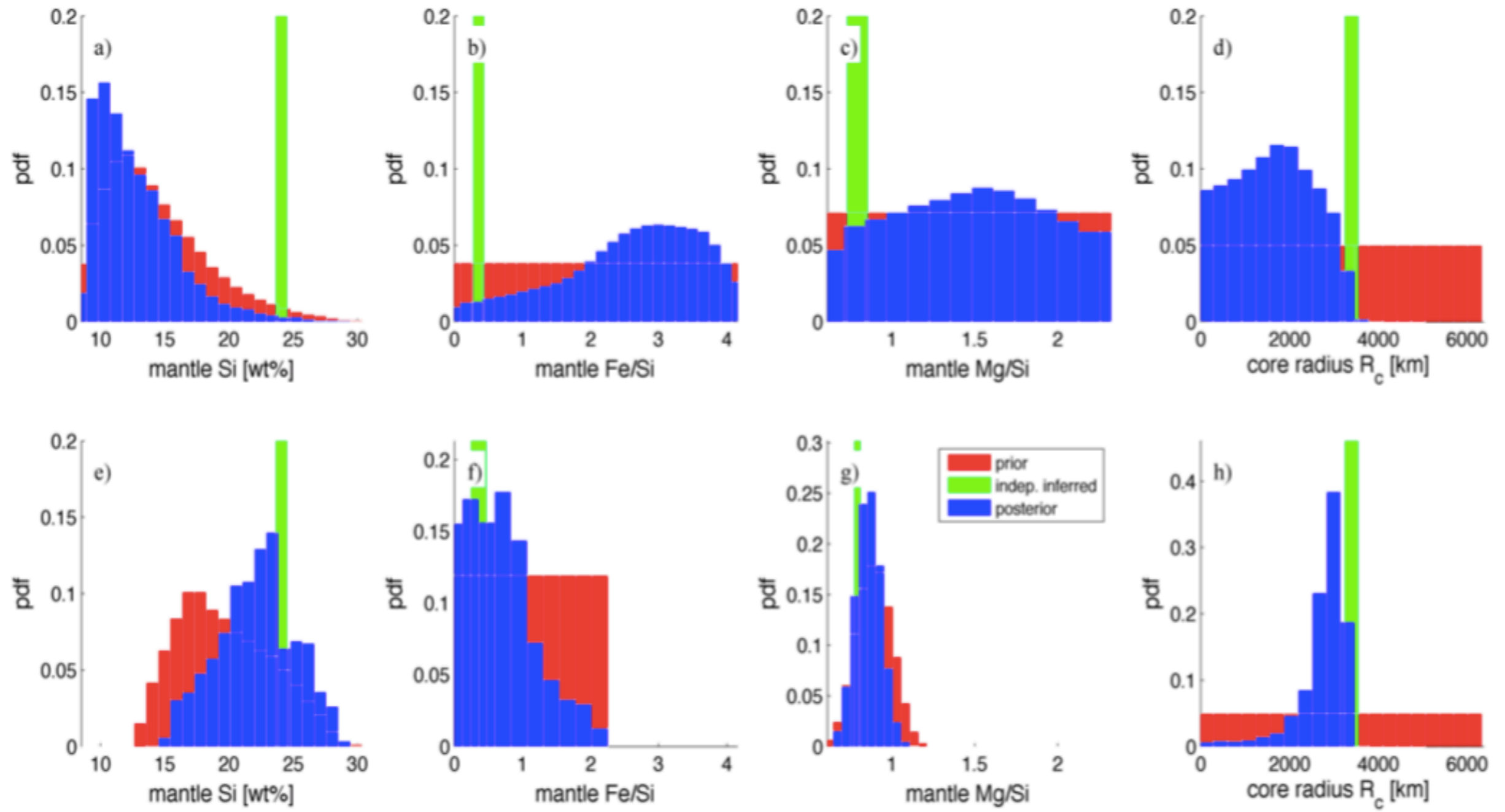
Bovolo, 2005



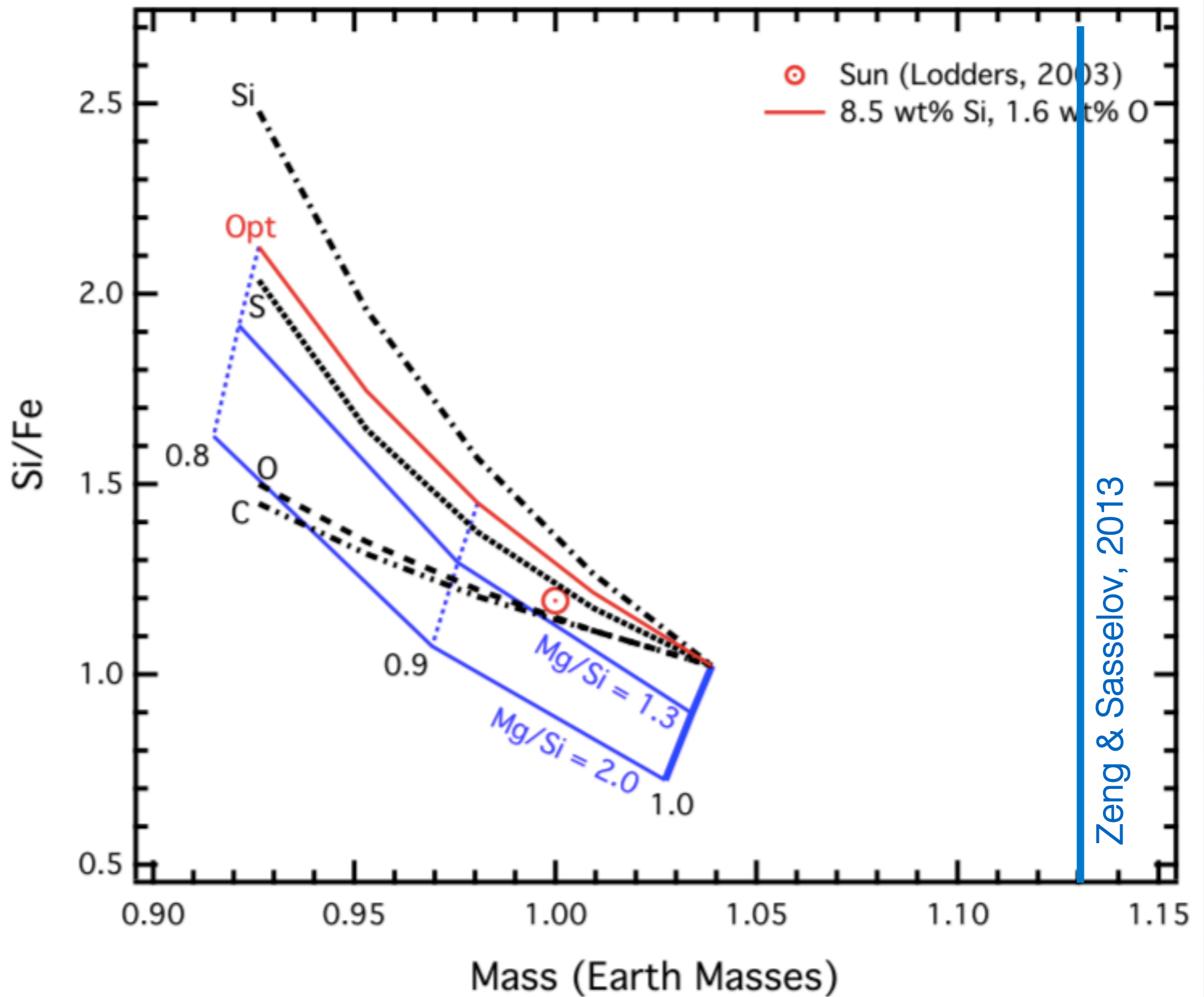


Zeng et al., 2016



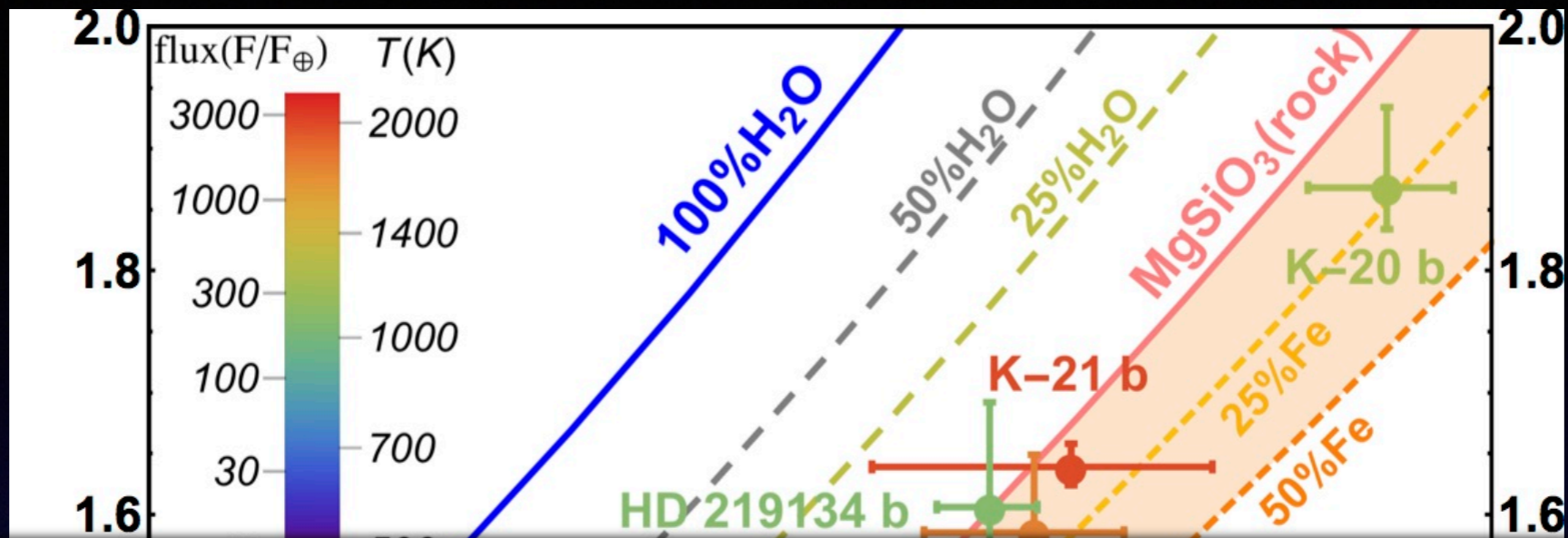




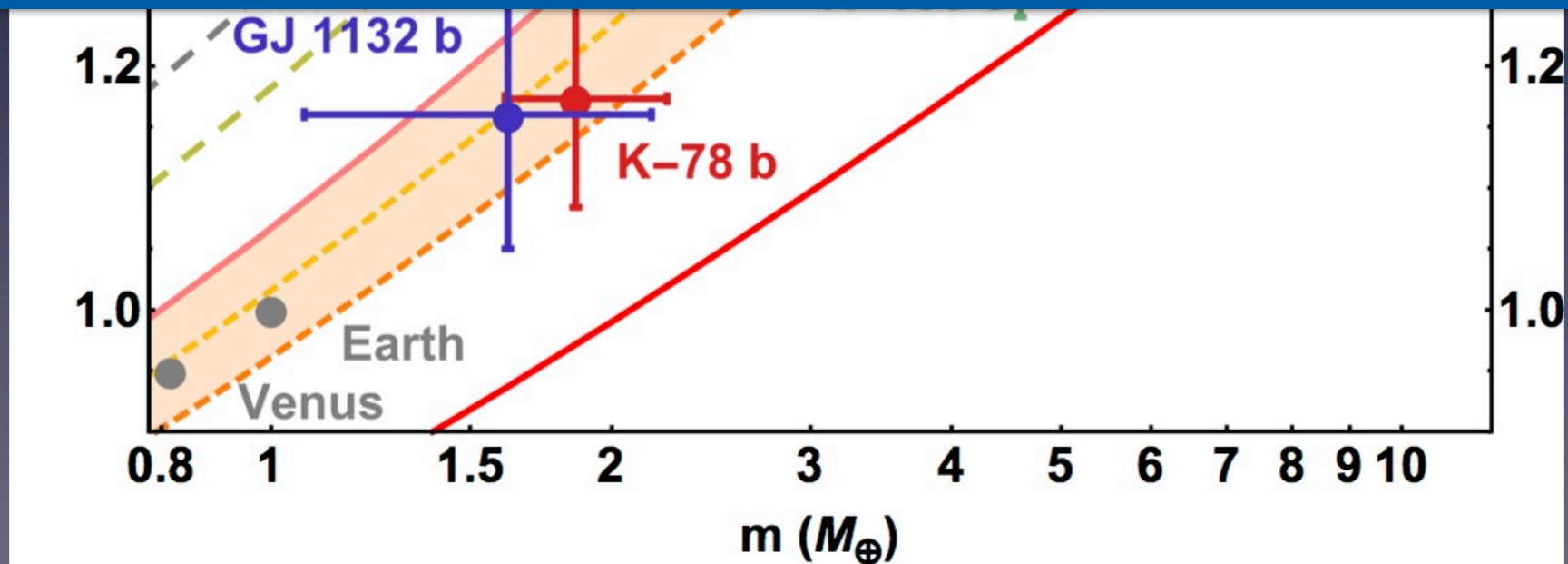


Zeng & Sasselov, 2013





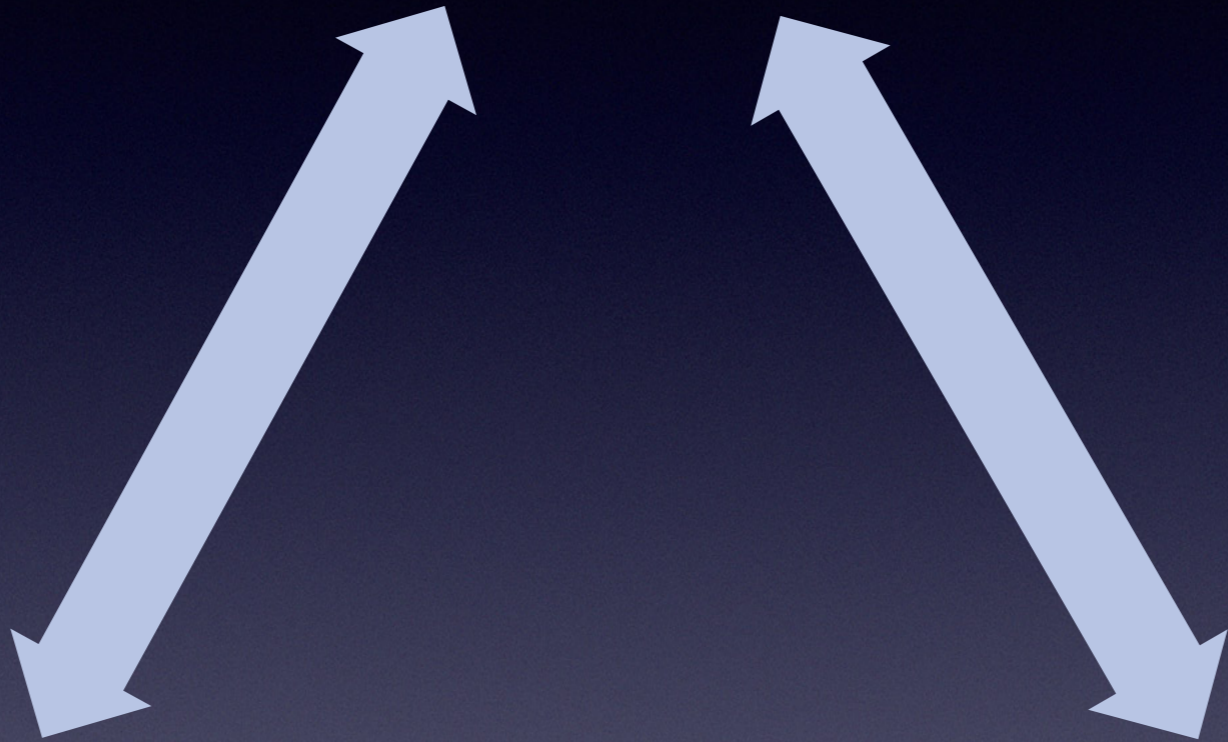
M-R tells you rocky/not rocky  
 $\pm$  all of the rock, all of the water



Zeng et al., 2016



Host/Planet  
Composition



Mass

Radius

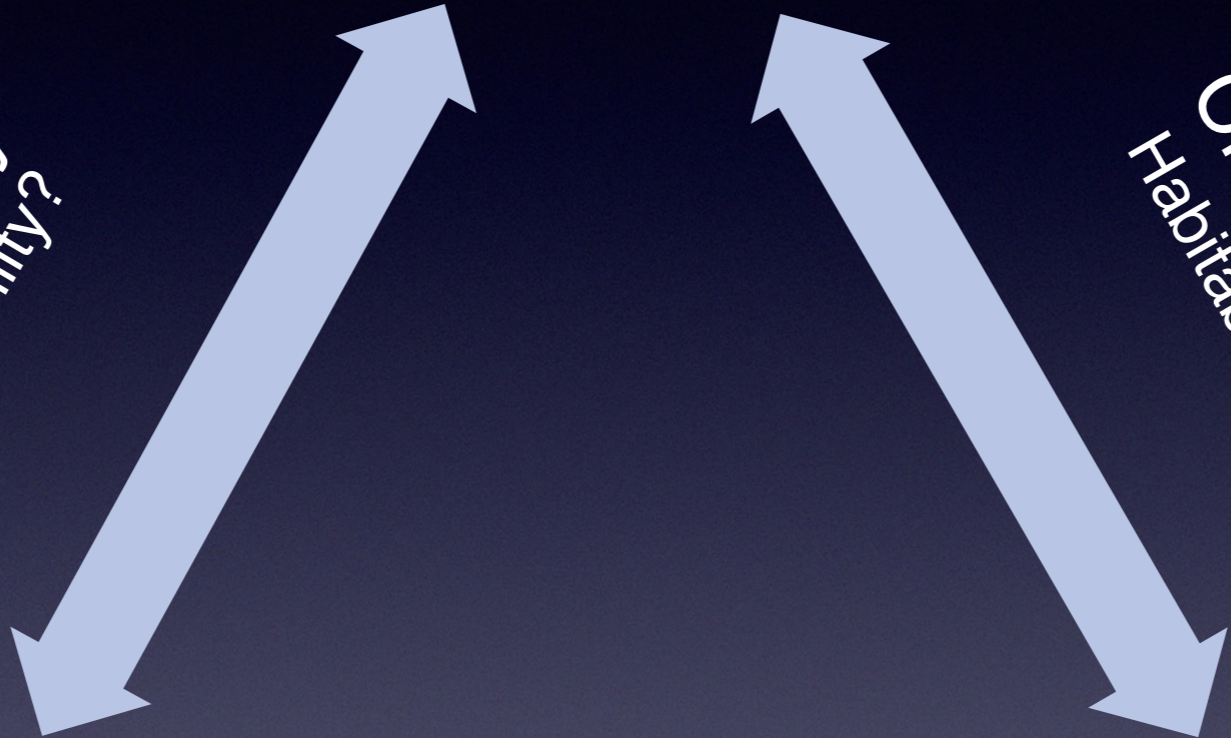
Degenerate Compositions  
Rocky or Not Rocky  
Core Size



Host/Planet  
Composition

Mineralogy  
Core Size  
Chemistry  
Habitability?

Mineralogy  
Core Size  
Chemistry  
Habitability?



Mass

Radius

Degenerate Compositions  
Rocky or Not Rocky  
Core Size



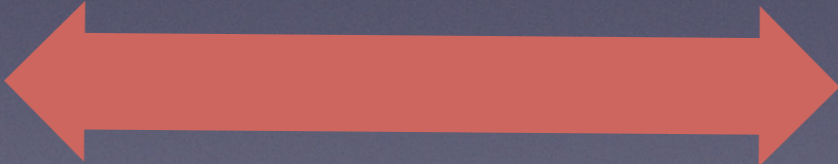
Host/Planet  
Composition

Mineralogy  
Core Size  
Chemistry  
Habitability?



Mineralogy  
Core Size  
Chemistry  
Habitability?

Mass



Radius

Degenerate Compositions  
Rocky or Not Rocky  
Core Size

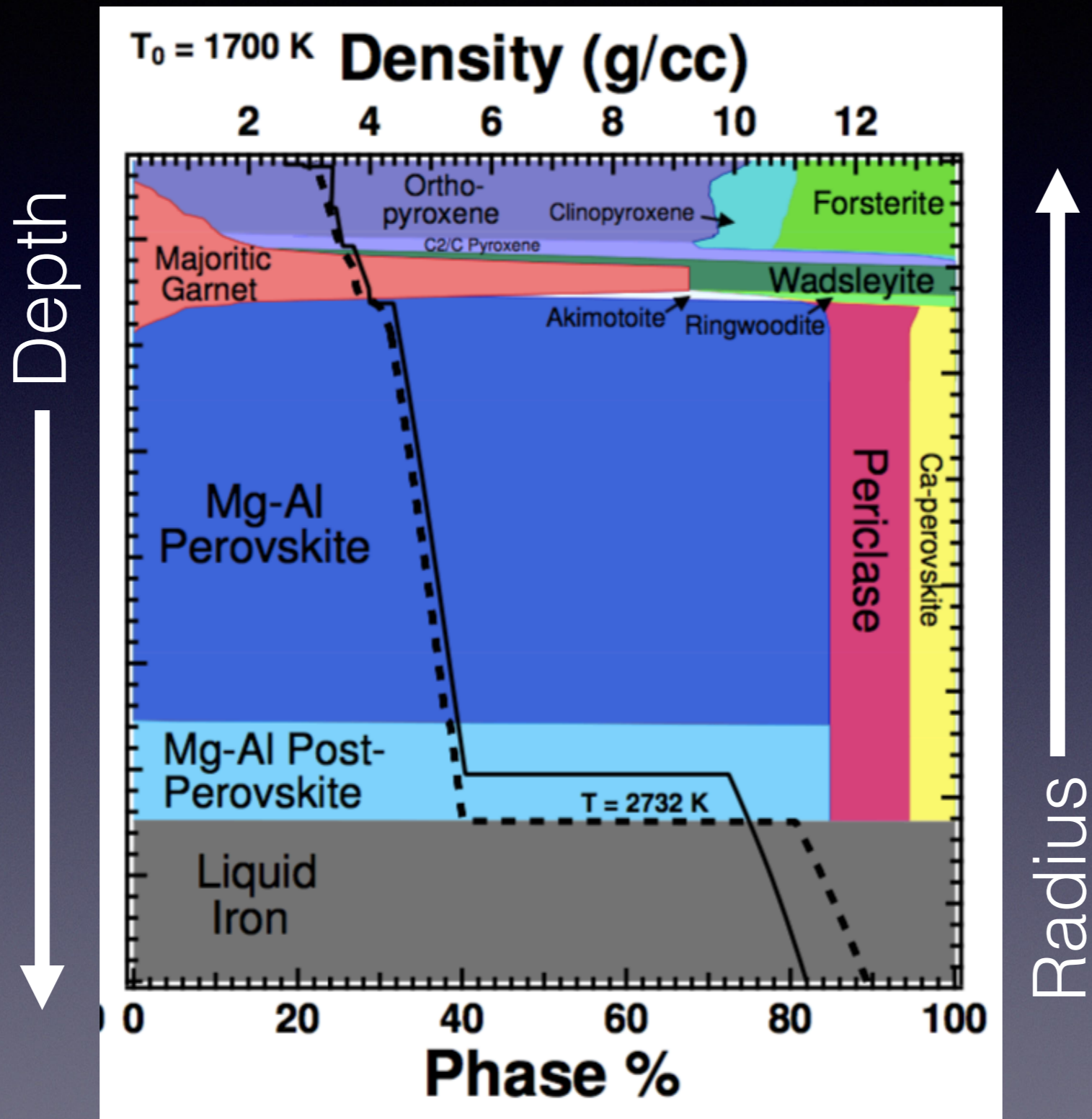


# ExoPlex

- Mass-Radius-Composition Calculator
- Mg, Si, Fe, Ca and Al (Na soon)
- Utilizes the PerPlex Gibbs Energy Minimization Software to calculate phase equilibria (Connely et al., 2009)  
At a P and T in planet, what is the stable composition?
- Self-consistently calculates mantle mineralogy, core size, adiabatic temperature and density profiles while preserving elemental ratios
- Includes IAPWS Water phase diagrams for water/ice
- Gasses soon!



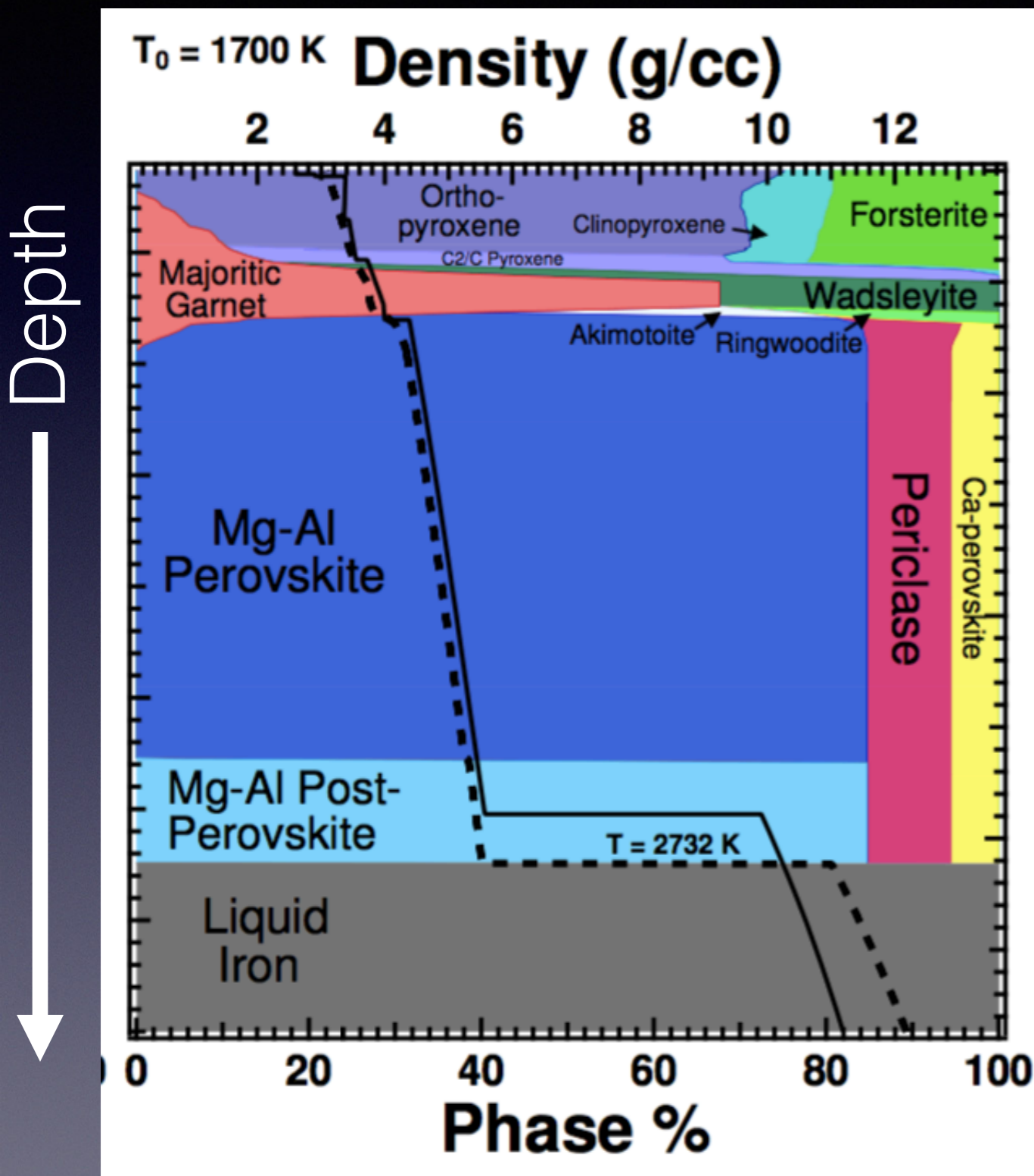
# 1 Earth-Radius “Solar” Planet



Hinkel & Unterborn, *in review*  
<https://arxiv.org/abs/1709.08630>



# Star to Stone?



Mg, Fe, Si, Al, Ca:  
All refractory Elements (C/O < 0.8). Condense first.

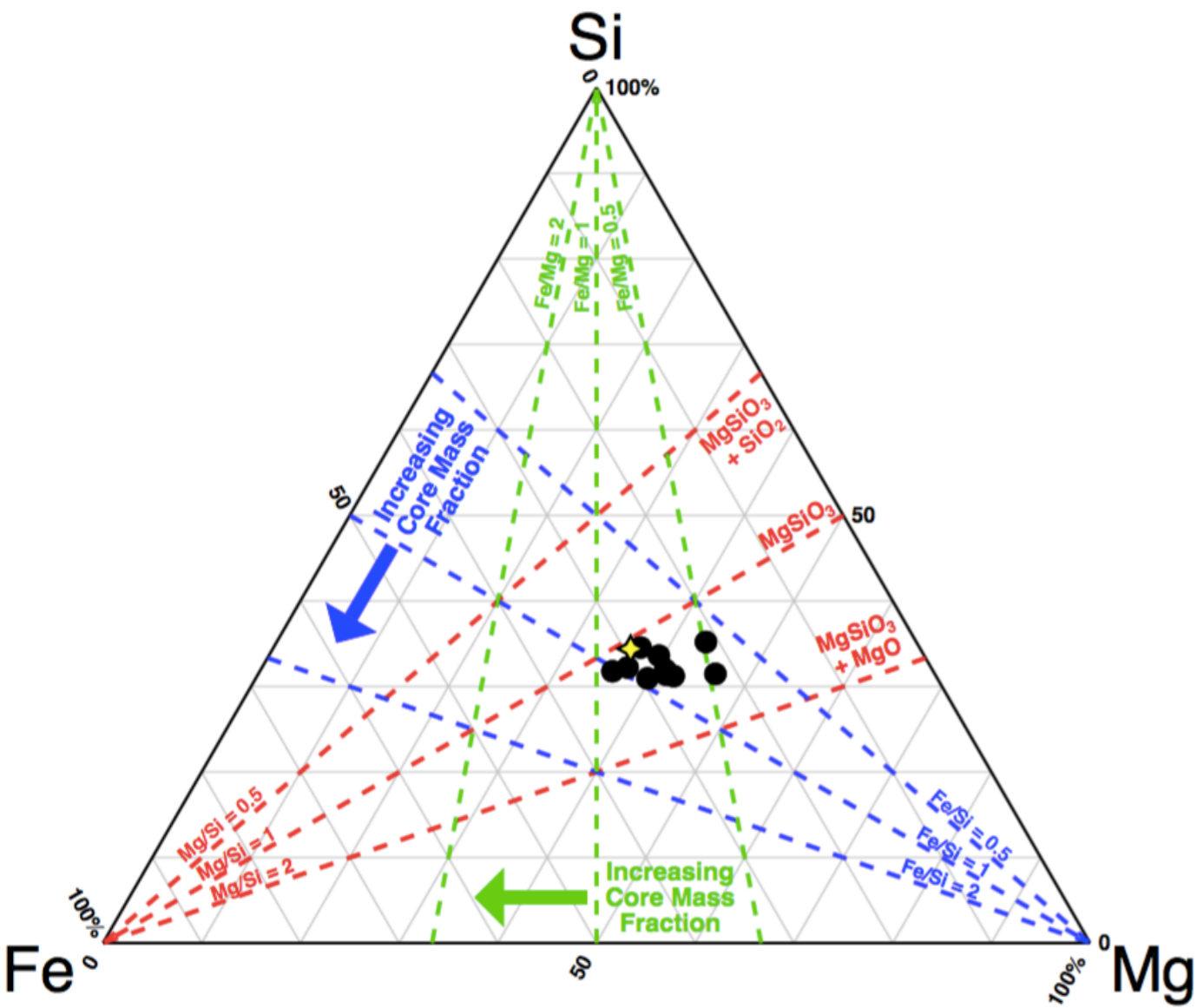
Mg, Fe, Si, O:  
95% of the Earth's atoms  
93% of Earth's mass  
(McDonough, 2003)

O is *somewhat* refractory:  
~23% is condensed in  
rocks in disk (Lodders, 2003;  
Unterborn & Panero, 2017)

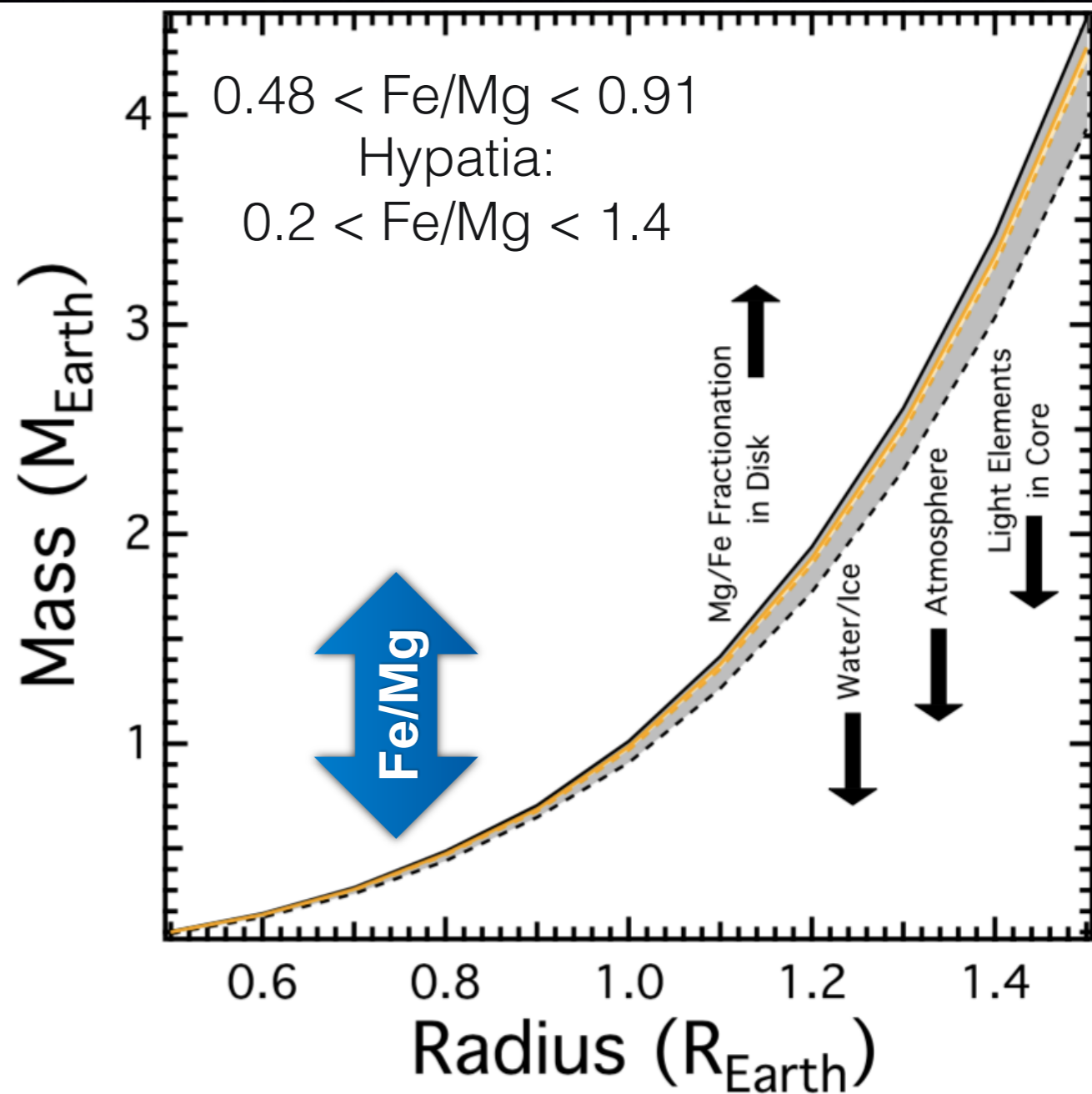
Mixing changes refractory  
ratios very little, ~10% (Bond  
et al., 2010a, b)



# ExoPlex



Hinkel & Unterborn, *in review*  
<https://arxiv.org/abs/1709.08630>



Unterborn & Hinkel, *in prep*  
 Full Grid: Lorenzo, Unterborn & Desch,  
*in prep*



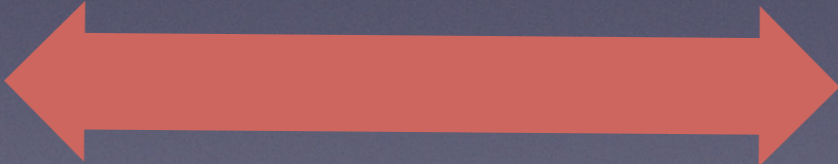
Host  
Composition

Mineralogy  
Core Size  
Chemistry  
Habitability?



Mineralogy  
Core Size  
Chemistry  
Habitability?

Mass



Radius

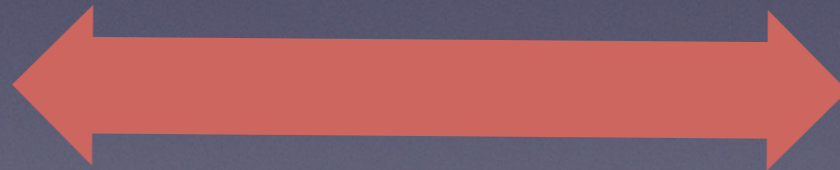
Degenerate Compositions  
Rocky or Not Rocky  
Core Size



Host  
Composition

Stellar Composition + Radius or  
Mass = Maximum Planet Mass or  
Radius  
+ Geochemistry!

Mass

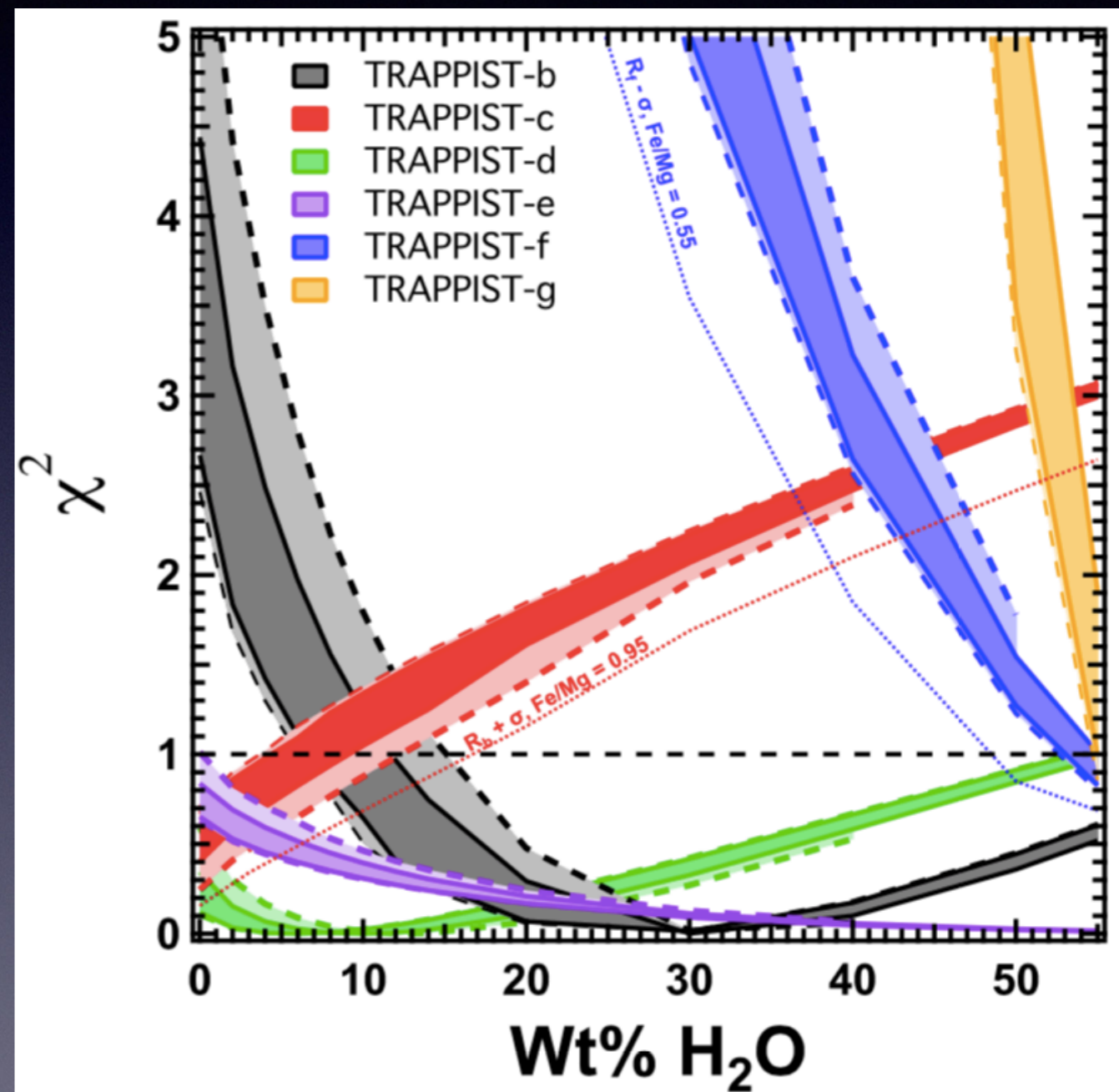
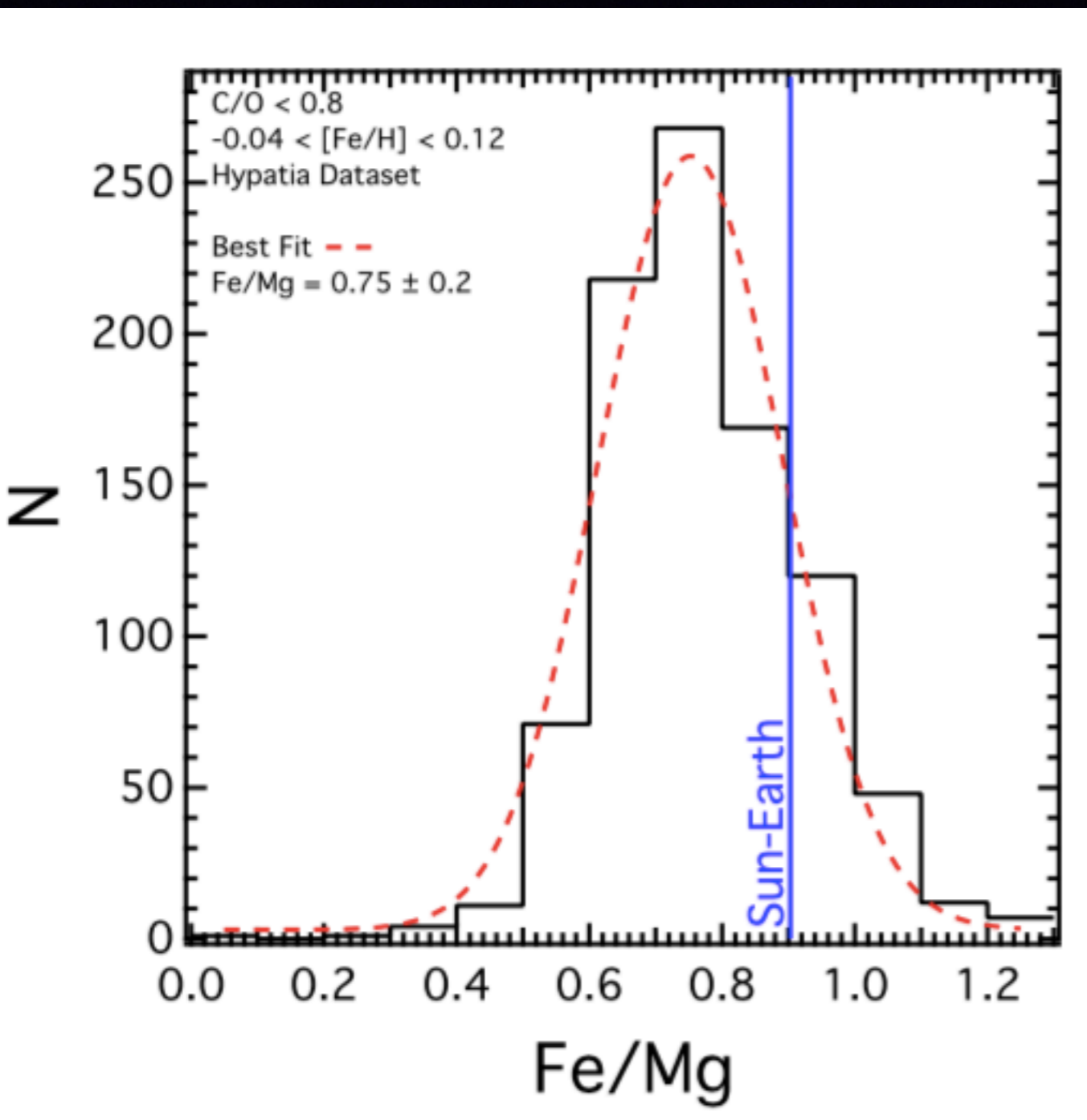


Radius

Degenerate Compositions  
Rocky or Not Rocky  
Core Size

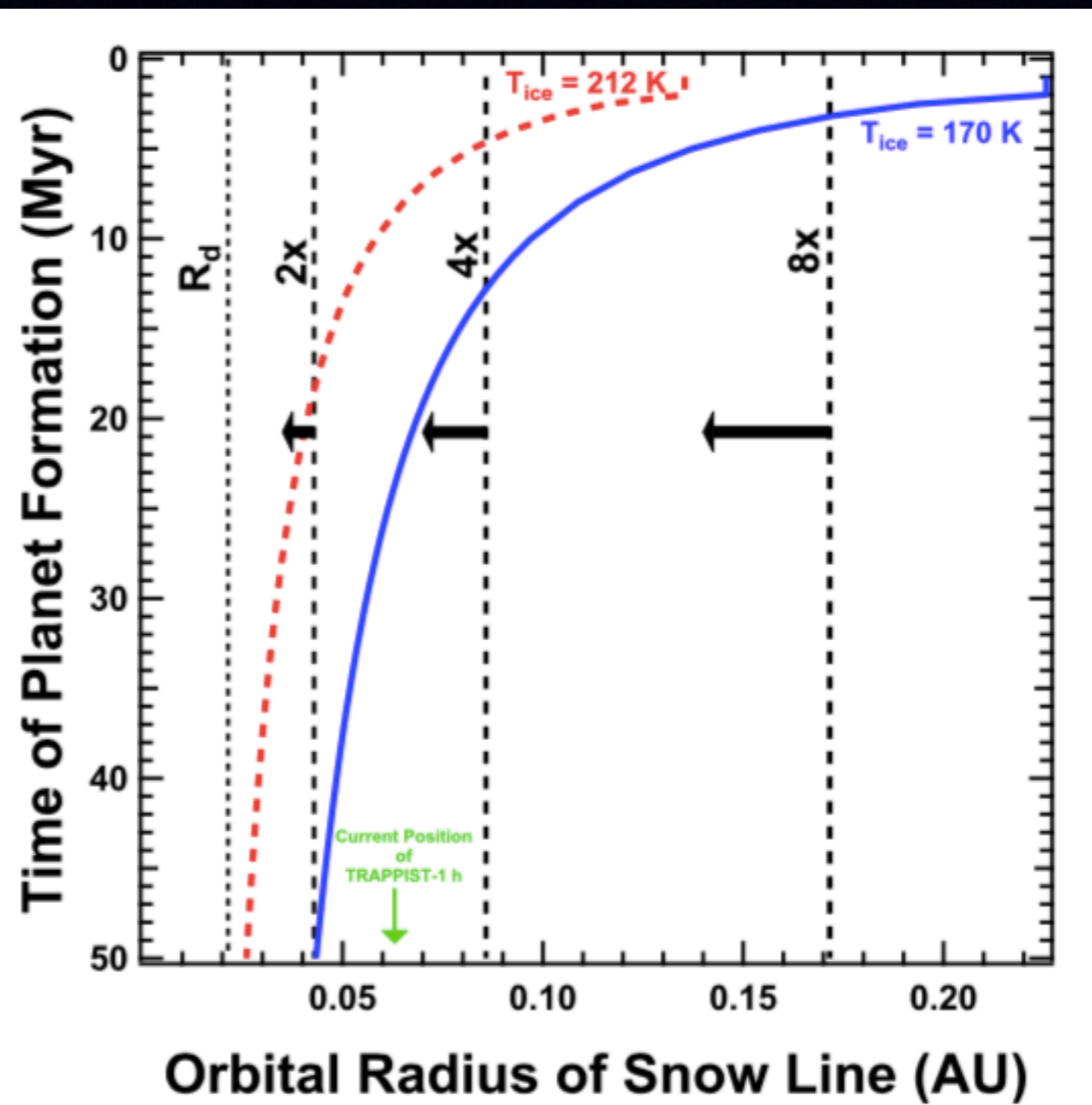
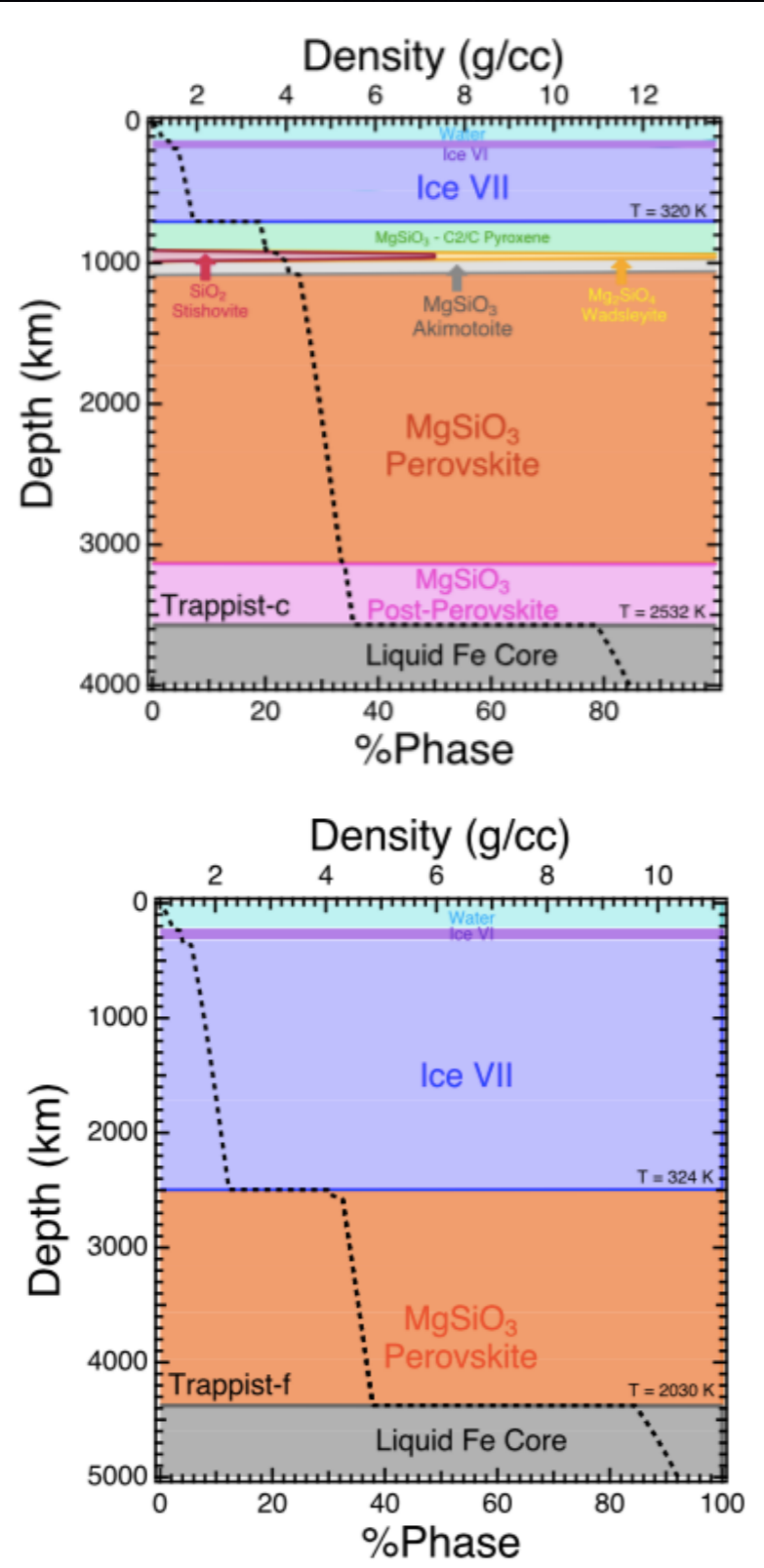


# TRAPPIST-1





# Composition → Migration



Unterborn et al., *in revision*  
<https://arxiv.org/abs/1706.02689>

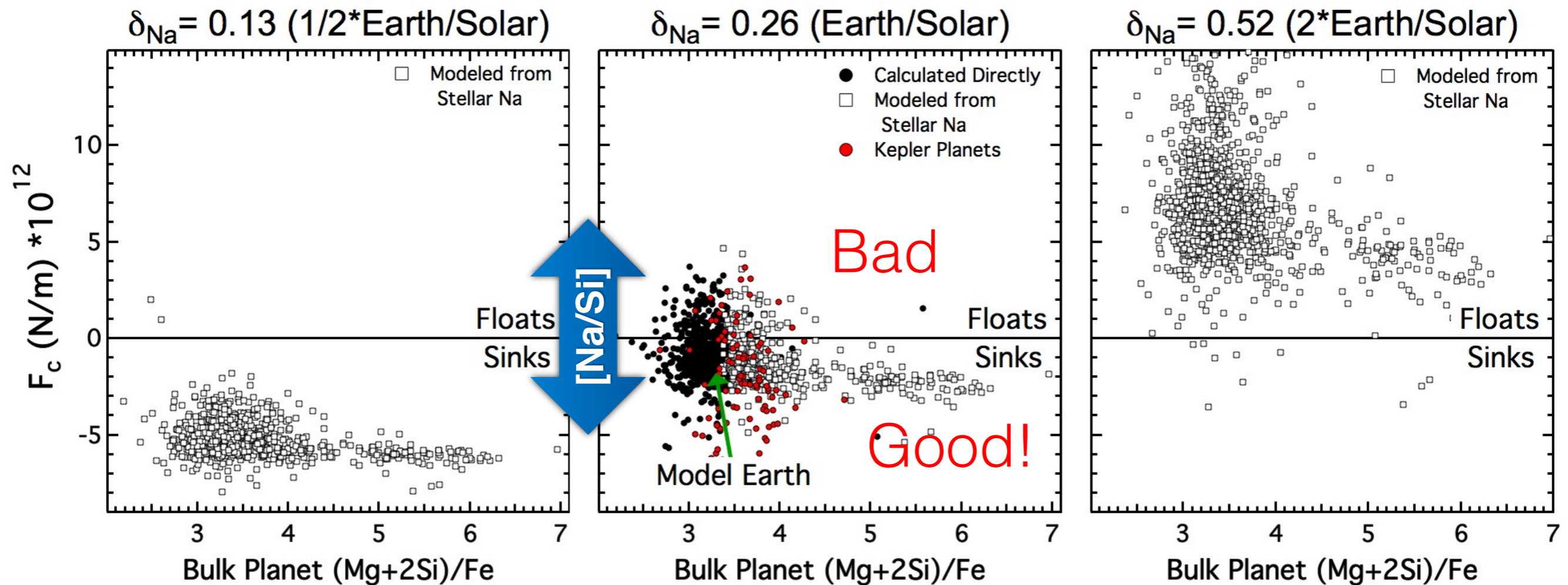


# Na, Crustal Composition, Tectonics, Volatility

Less

Earth/Sun

More



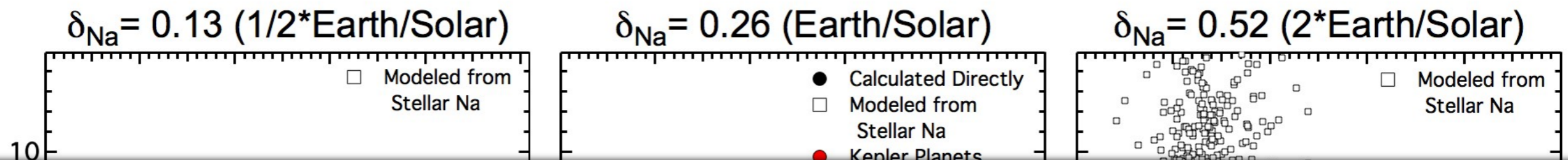


# Na, Crustal Composition, Tectonics, Volatility

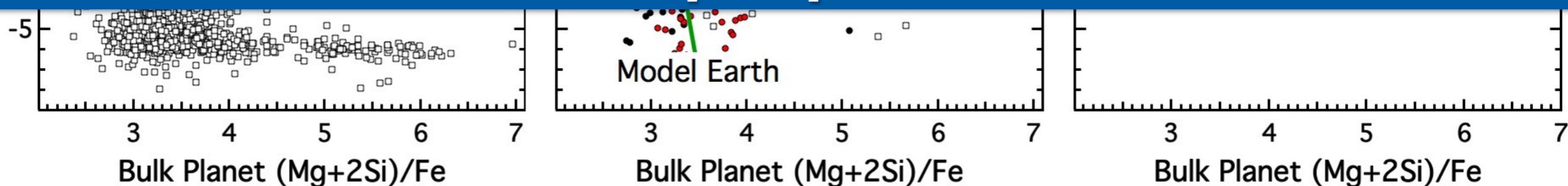
Less

Earth/Sun

More



Na as important as water?  
Si too! See paper for more



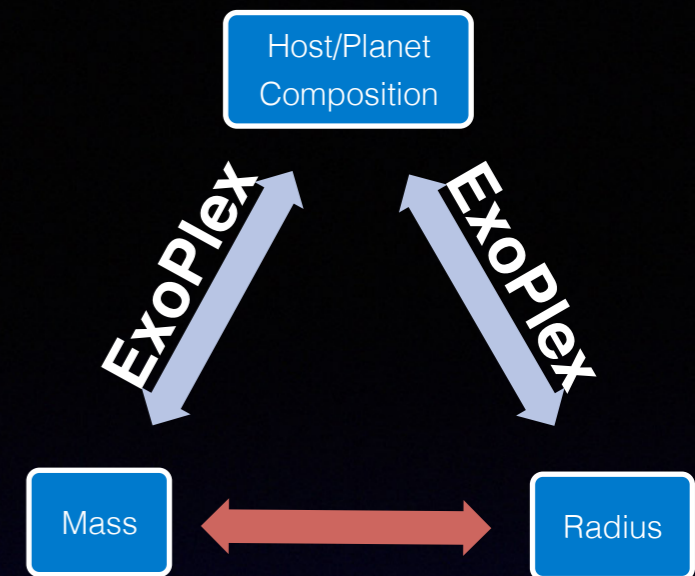


# And Many More

- Mg/Si affects mantle phase ratios (dynamics?)
- Fe/Mg affects relative core size (mag field?)
- Al/Mg, Ca/Mg, Na/Mg affect melting of rock
- C can play a role in geodynamics, geochemistry,
  - mag field (Unterborn et al., ApJ, 2014)
- Radionuclides U, Th, K are a main driver of mantle convection. U and Th are refractory!  
(Unterborn et al., ApJ, 2015)



# Conclusion



- Host star composition is an observable for terrestrial exoplanets
- Roughly sets upper limit on mass for terrestrial planet given radius and comp.
- Terrestrial planet composition affects melting, dynamics, tectonics, mantle water storage, geochemical cycling, climate and thus habitability
- “Earth-like” is not Earth-like (E. Tasker et al., 2017, Nat. Astro)
- Must update definition to include the *behavior* of exoplanets (Habitability too)
- Full ExoPlex Grid of Mass-Radius-Composition Forthcoming
- Preliminary code is available at [github.com/CaymanUnterborn](https://github.com/CaymanUnterborn)
- Geoscience has lots to do. New experiments and models are vital.
- Cross pollinate with geoscience! Planets are an interdisciplinary problems that require an interdisciplinary approach to solve them