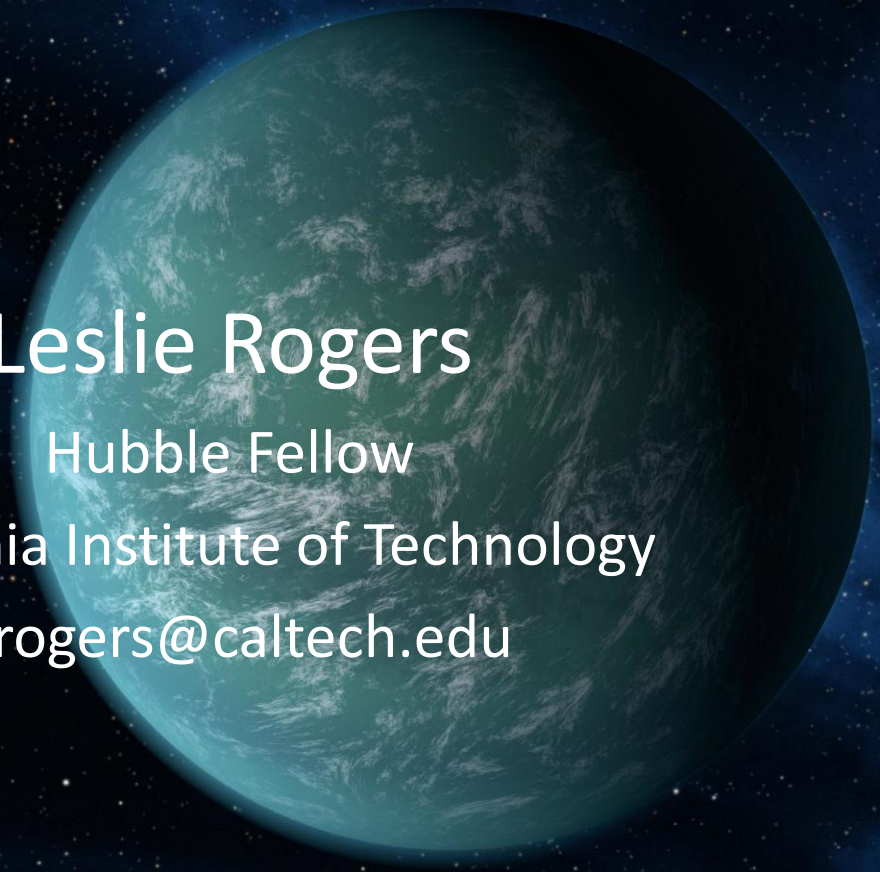
An Introduction to Super-Earth and Sub-Neptune Sized Planet Interiors



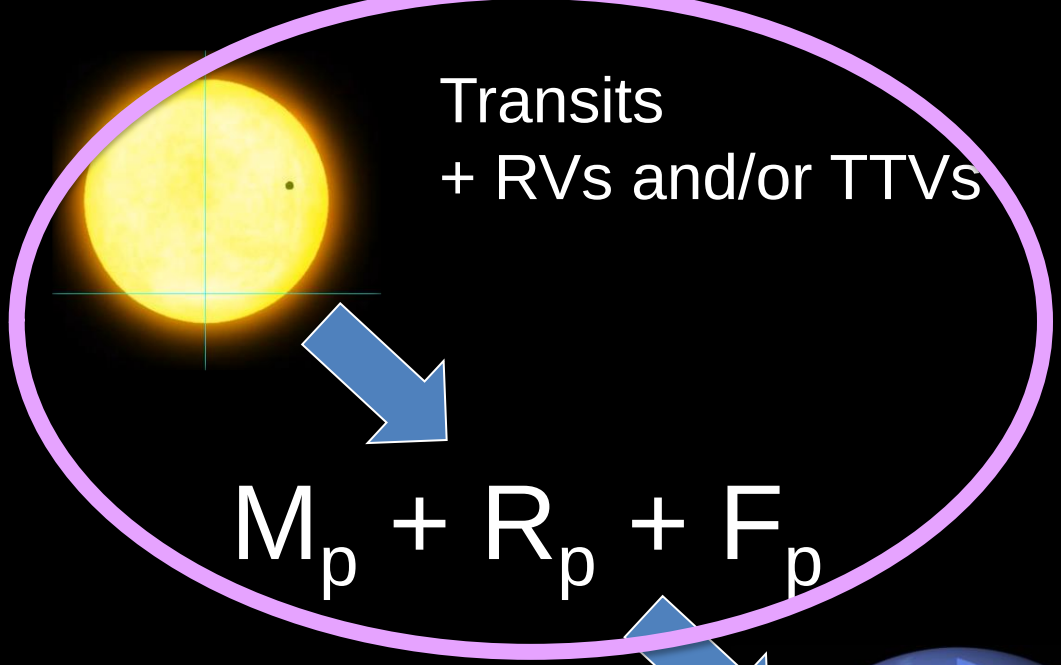
Leslie Rogers

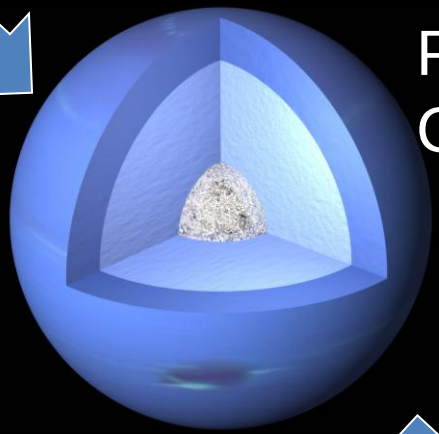
Hubble Fellow

California Institute of Technology

larogers@caltech.edu

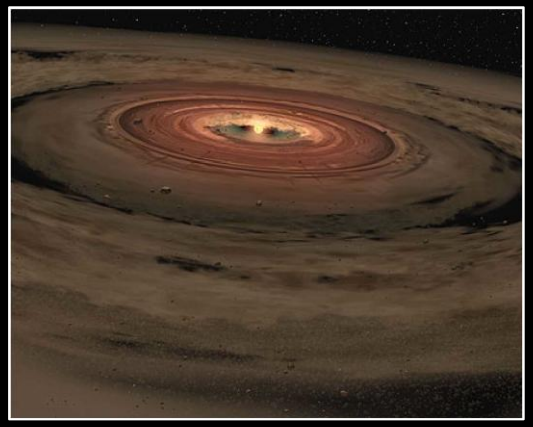
KITP Long Program – January 22, 2015

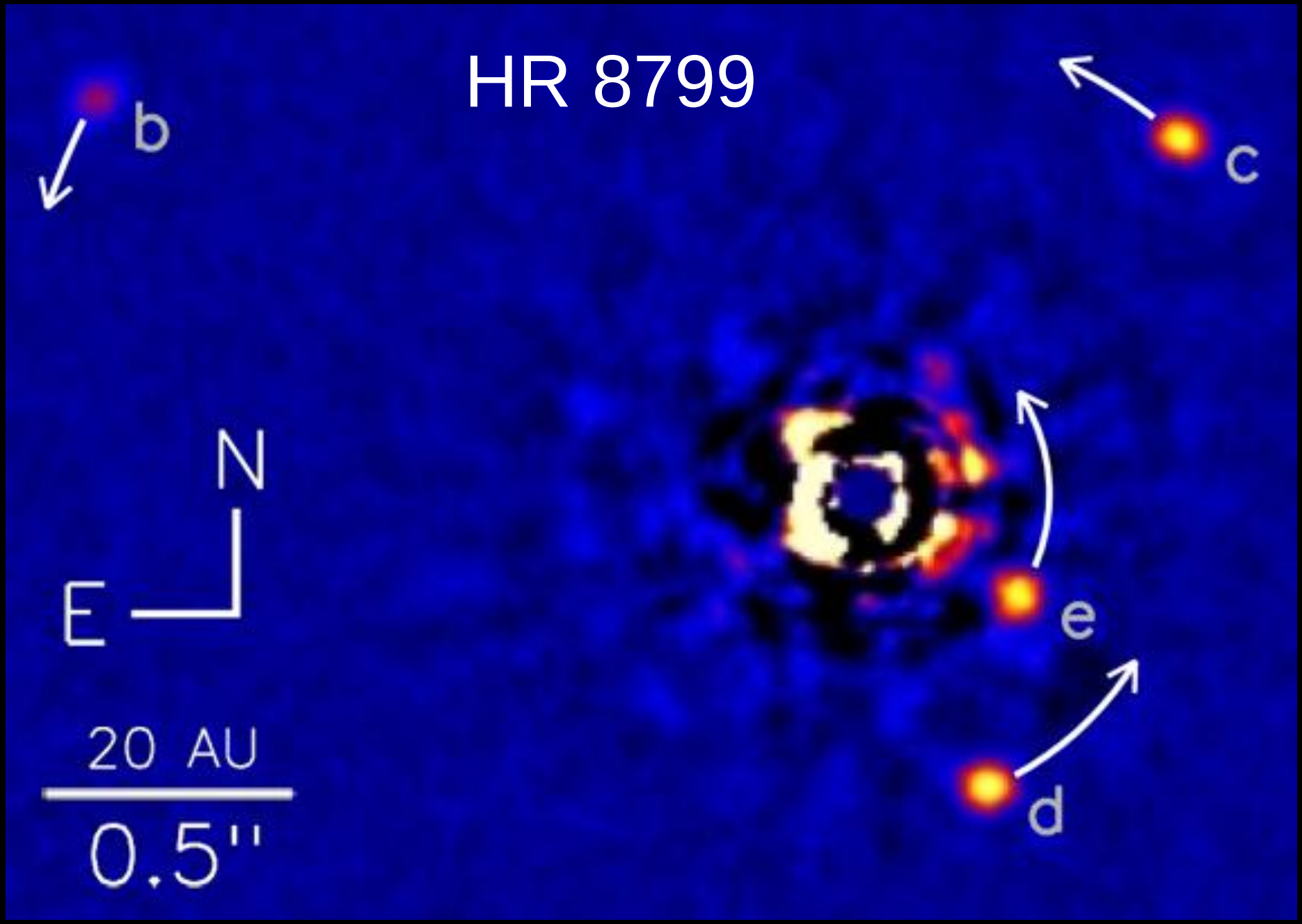




Planet Bulk
Composition Constraints

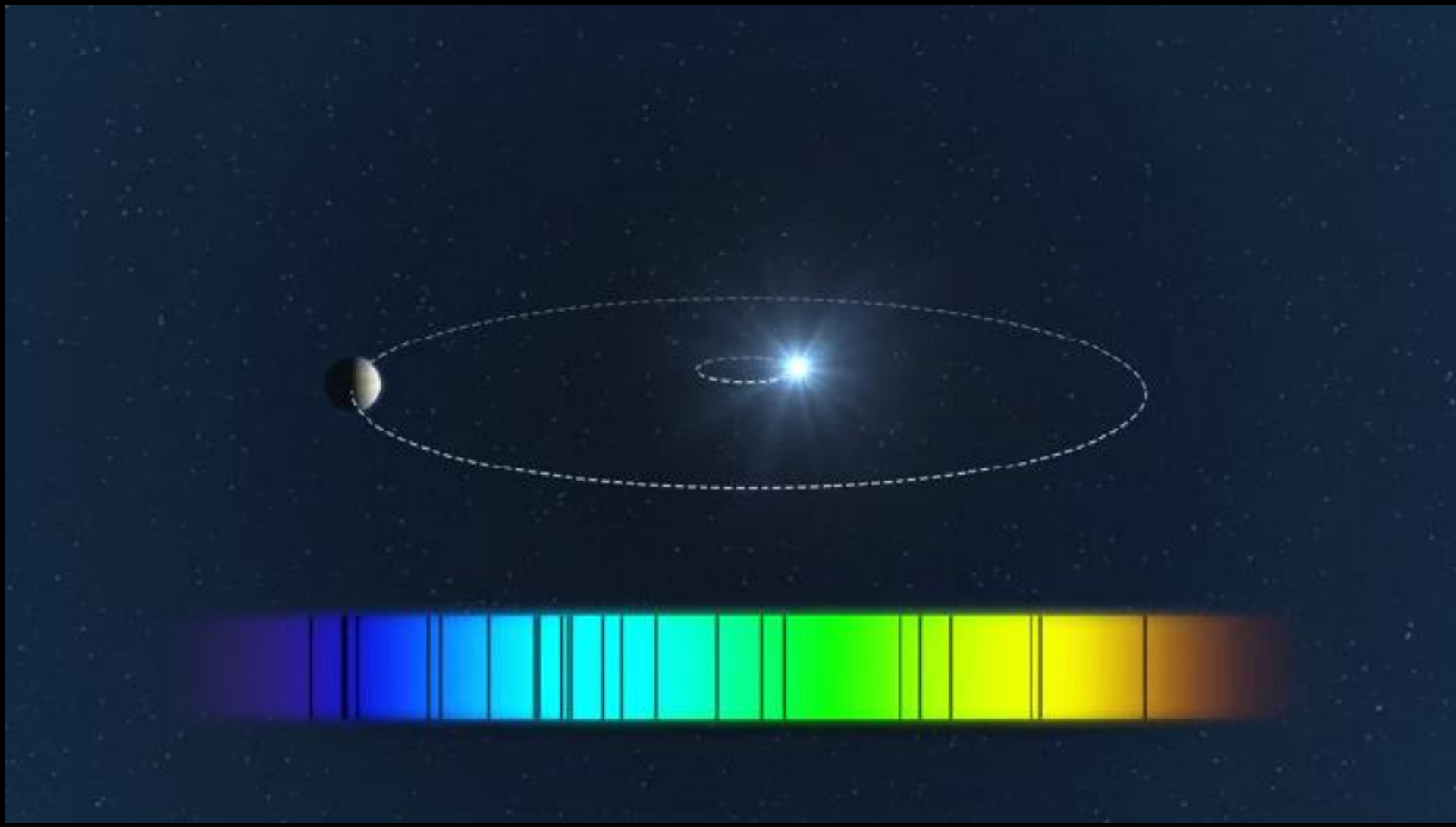
Insights into Planet
Evolution and Formation History



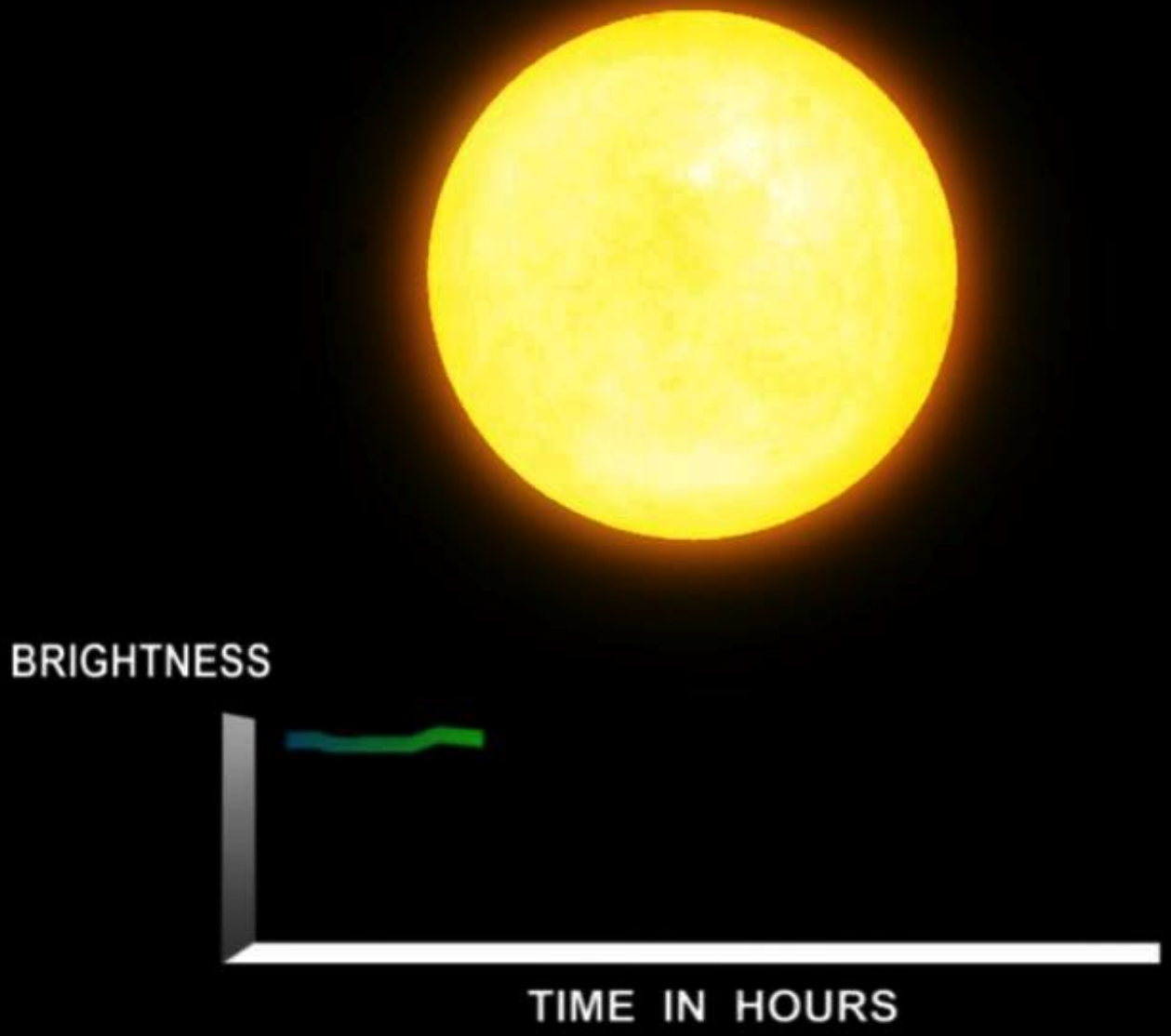


Marois et al. (2011)

Stellar Wobble



Transits



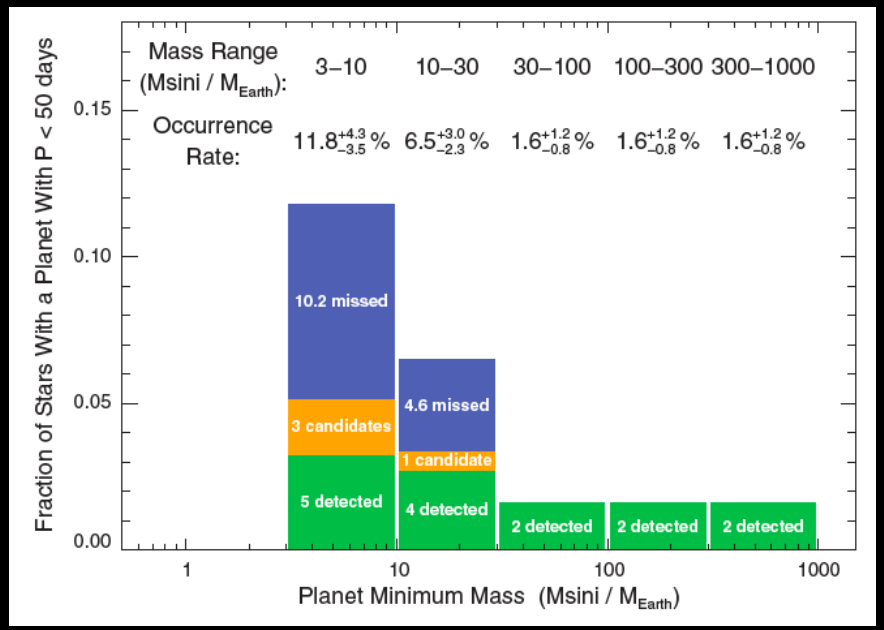
Kepler Mission

Neptunes are Common!

Microlensing:

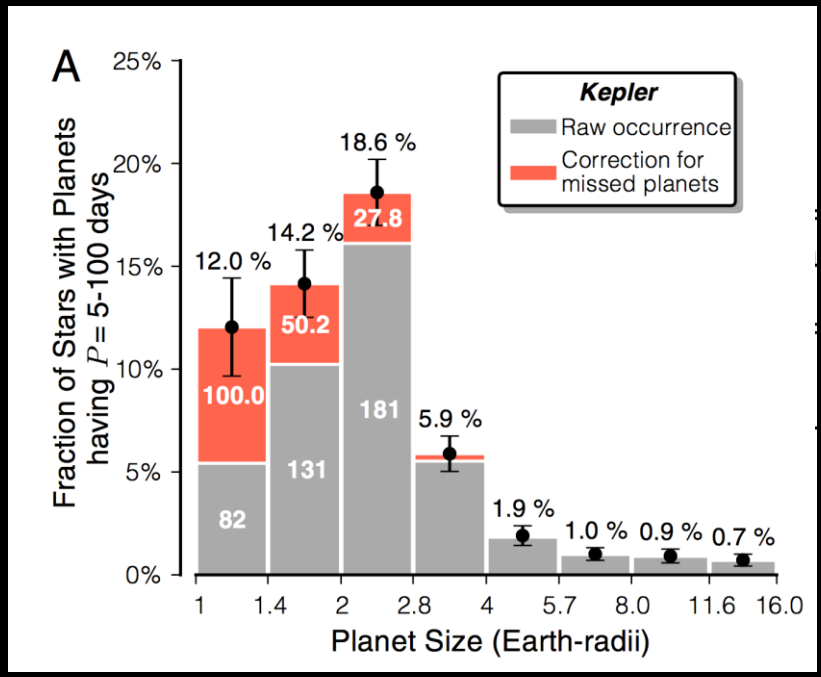
62±36% of stars have a 5-10 $M_\oplus$ planet at 0.5-10 AU.
Cassan et al. (2012)

Radial Velocity:



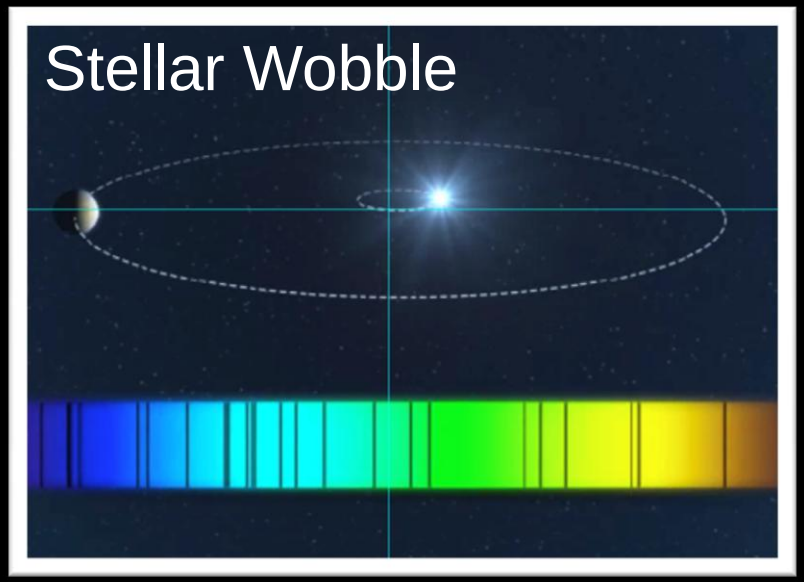
Howard et al (2010)

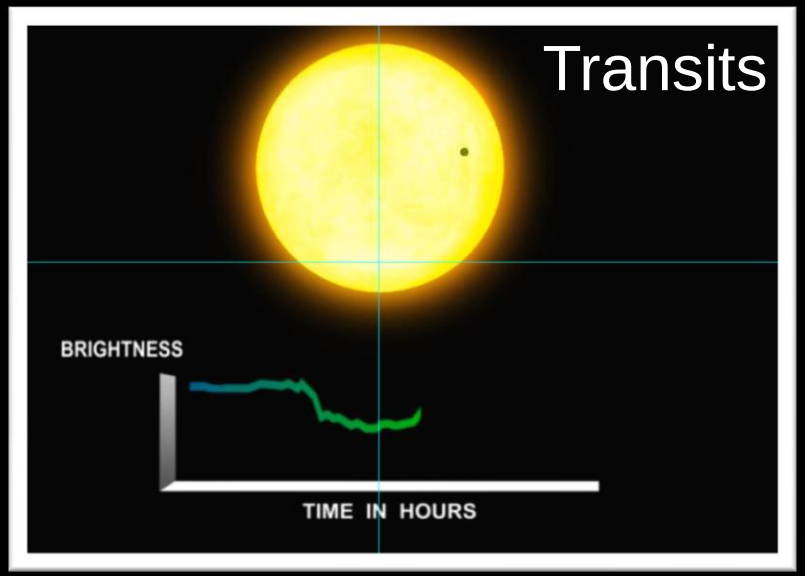
Transits:



Petigura et al. (2013)

Planets Detected both Dynamically and in Transit are Valuable!



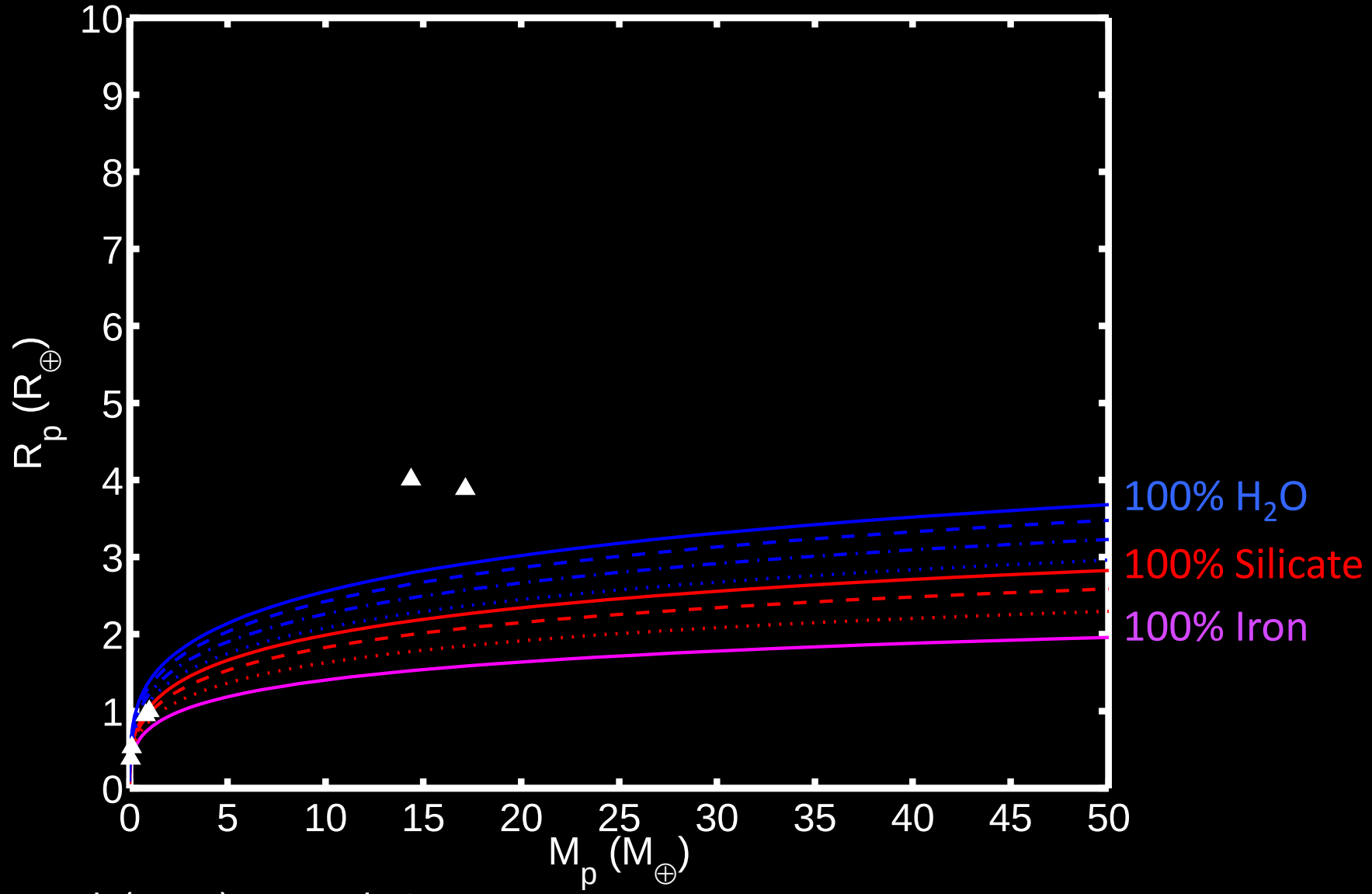


Planet Mass

Planet Radius

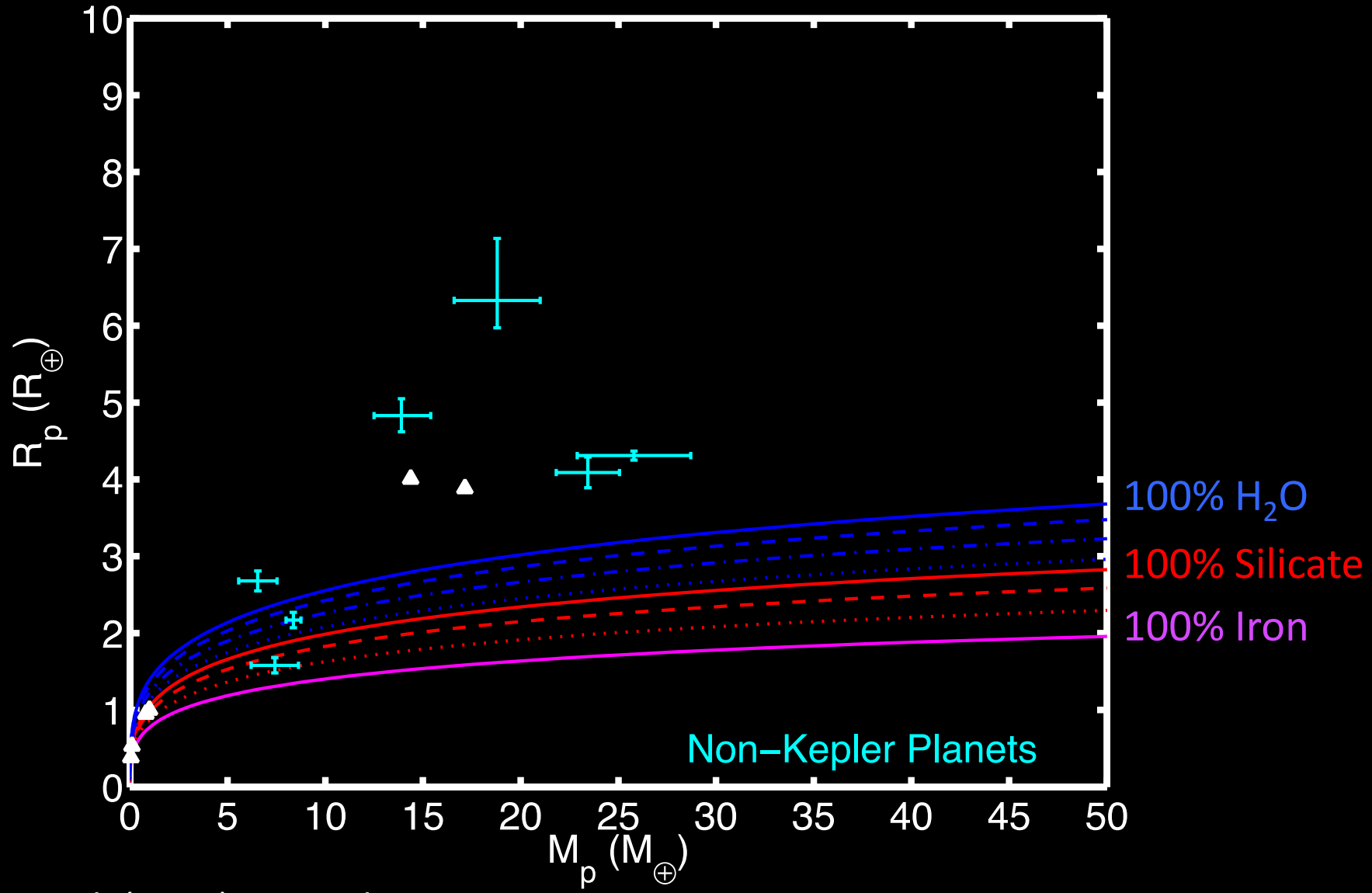
Planet Density

Seven Years Ago



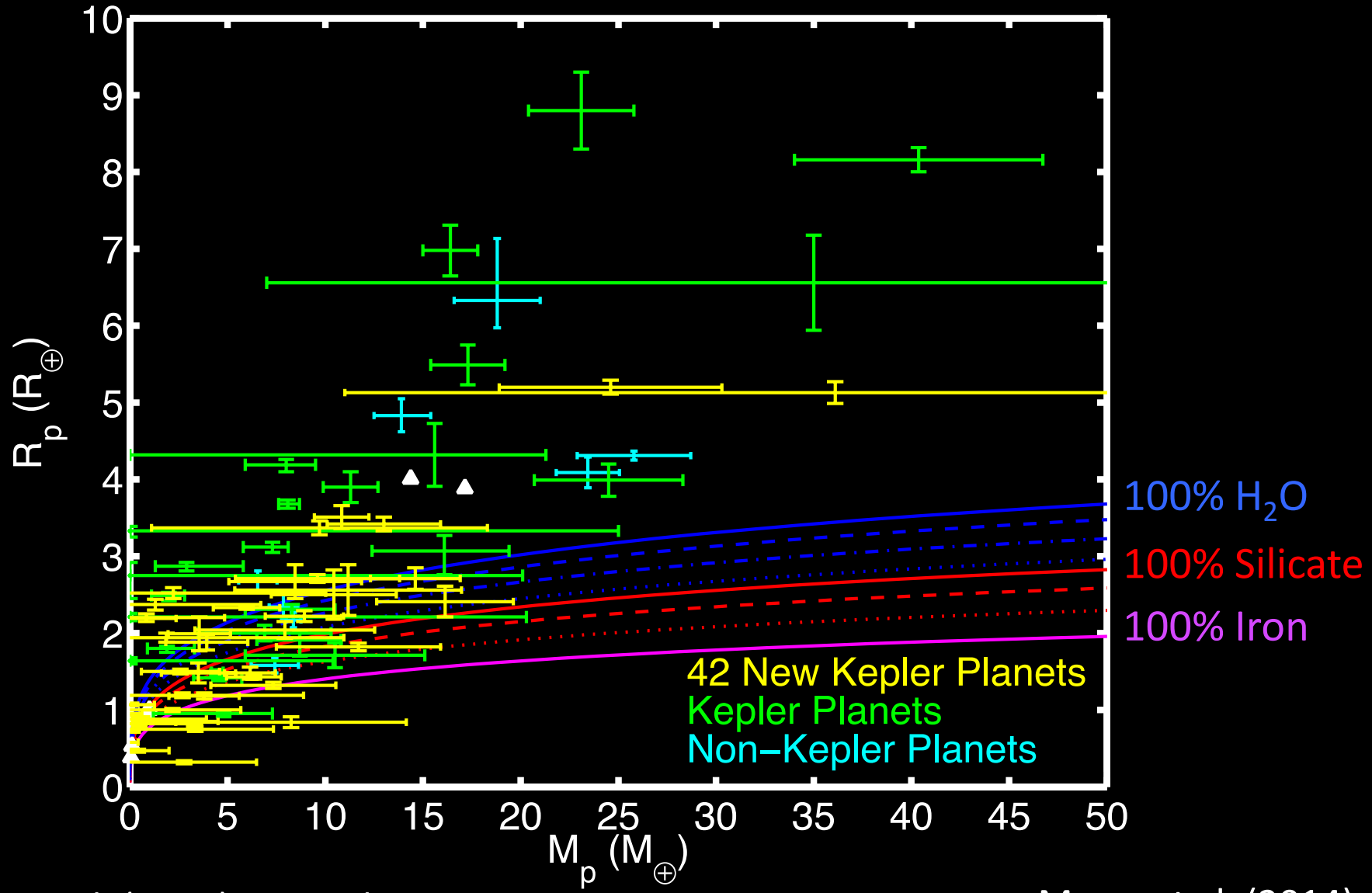
Seager et al. (2007) M-R Relations

Non-*Kepler* Planets



Seager et al. (2007) M-R Relations

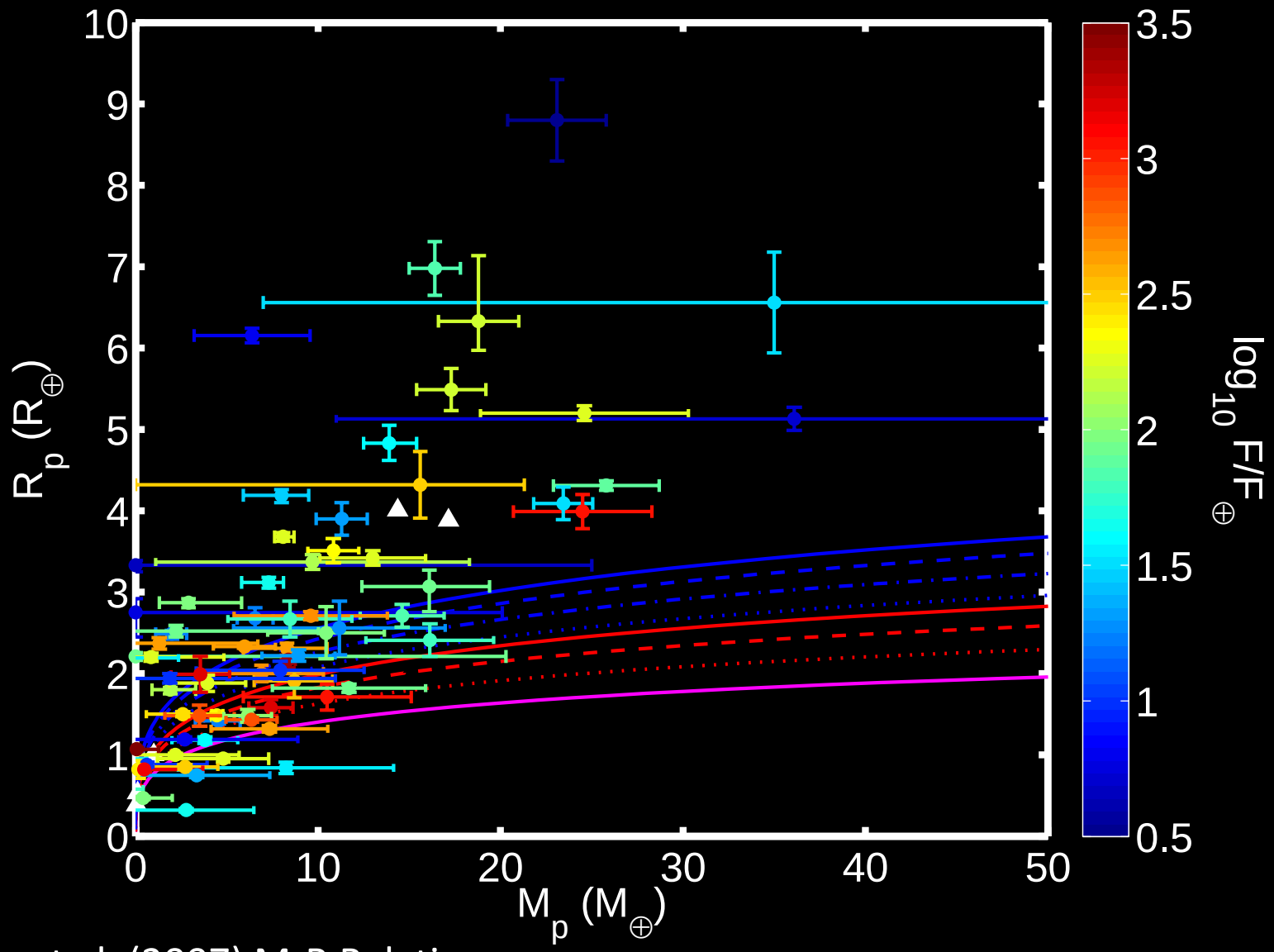
Accumulating a Statistical Sample of Planet M-R



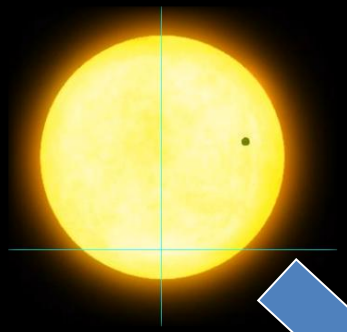
Seager et al. (2007) M-R Relations

Marcy et al. (2014)

Adding Incident Flux Dimension

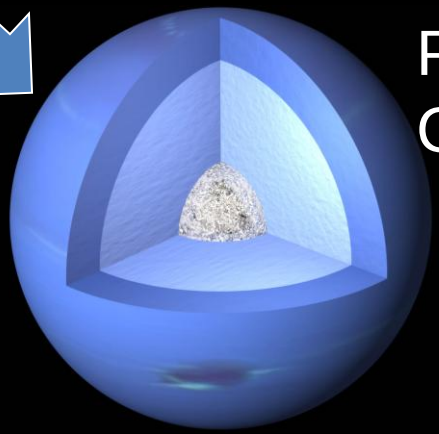


Seager et al. (2007) M-R Relations



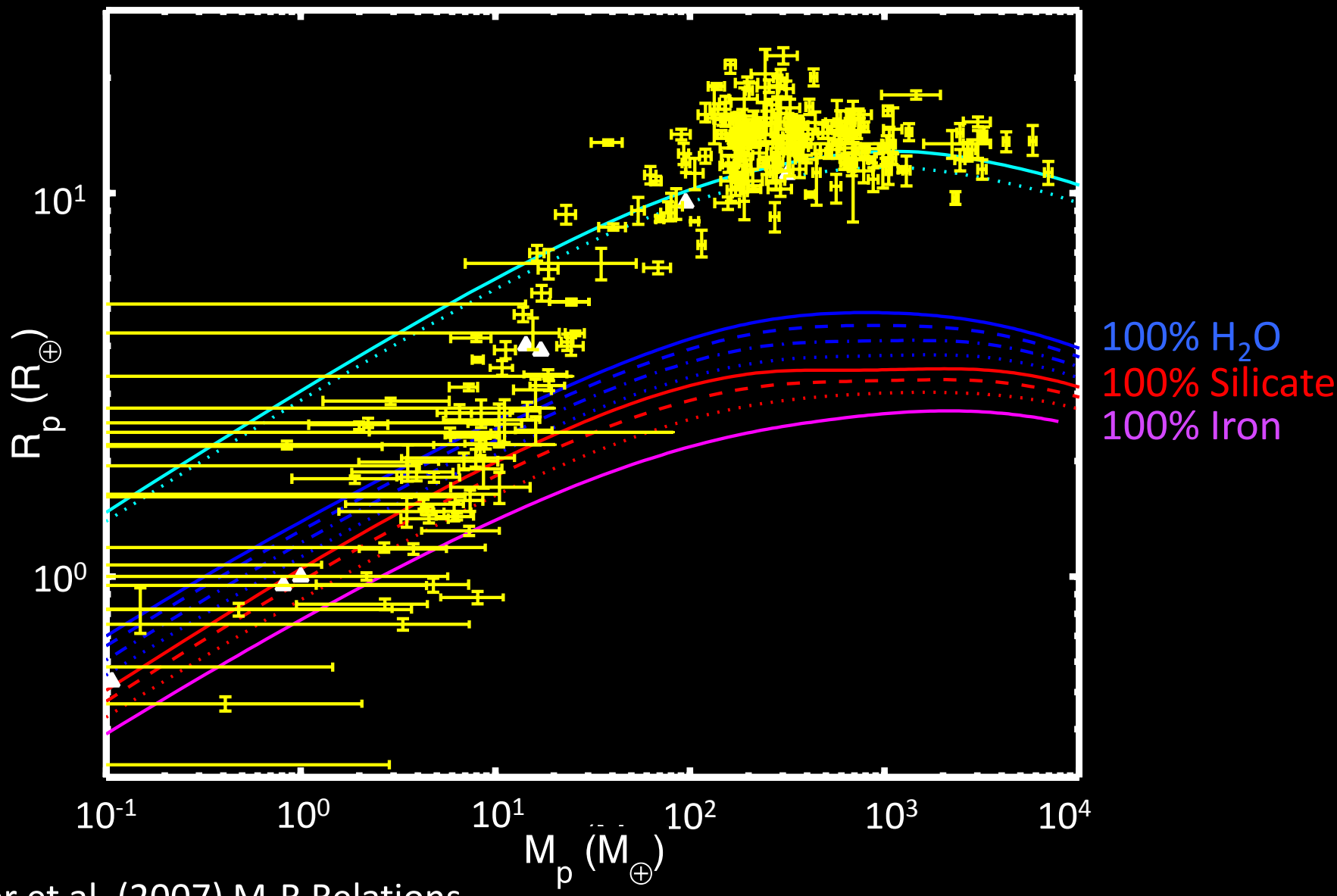
Transits
+ RVs and/or TTVs

$M_p + R_p + F_p$



Planet Bulk
Composition Constraints

Zooming Out On the Mass-Radius Diagram



Seager et al. (2007) M-R Relations

~30000 km -

1000 km -

200 km -

log Radius

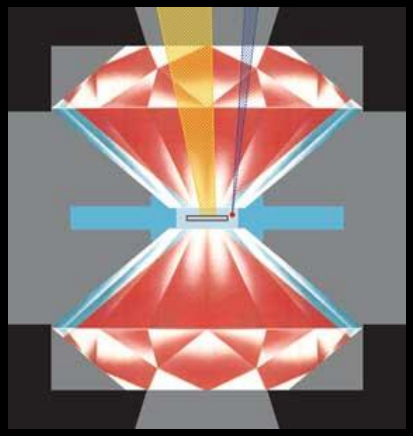
ρ ~ constant

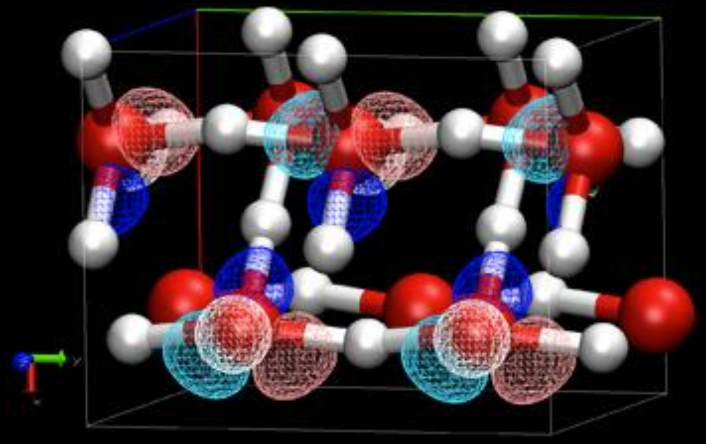
$R \sim M^{1/3}$

compression

log Mass

How Materials Behave at High Pressure





Lab Experiments

Computer Simulations

Asymptotic Theories

1 bar (1 Atm)

1 Mbar

3.6 Mbar (Center of Earth)

10 Mbar

~40 Mbar (Center of Jupiter)

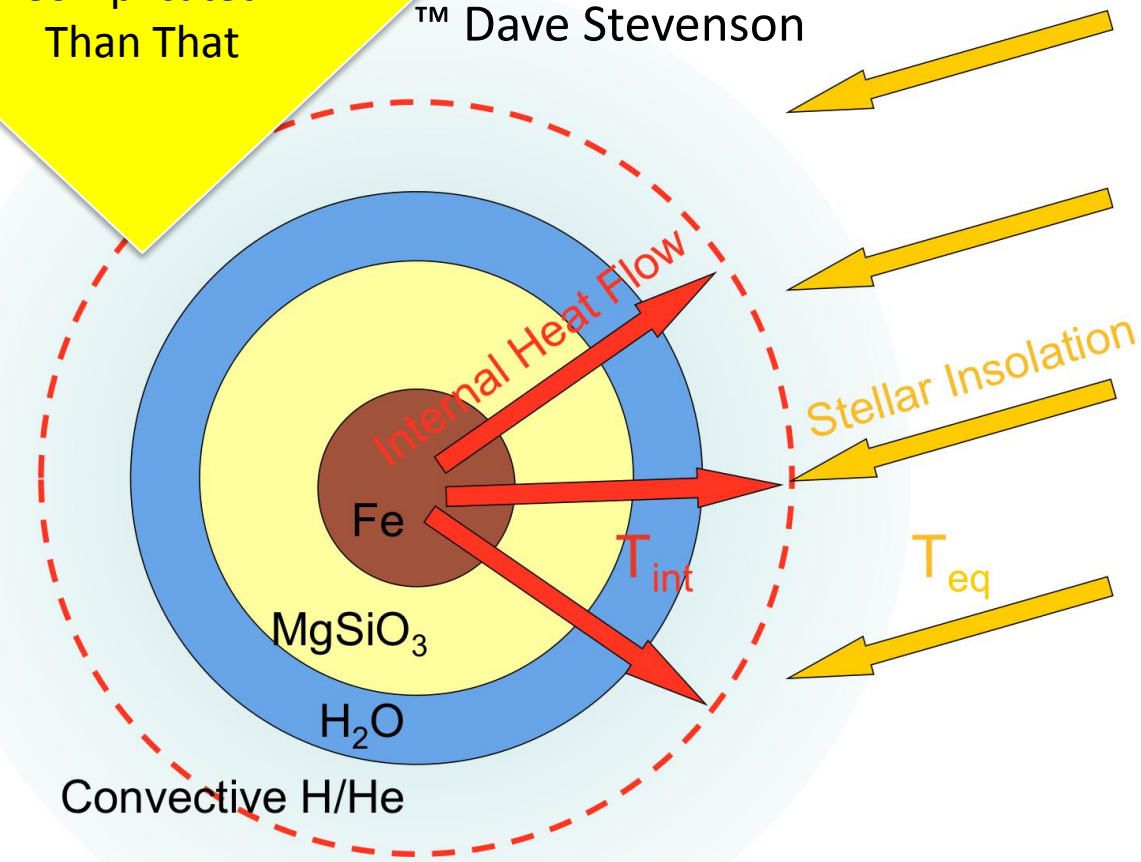
100 Mbar

Pressure

Model Overview

It's More Complicated Than That

™ Dave Stevenson



$$\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$$

$$\frac{d\tau}{dm} = \frac{\kappa}{4\pi r^2}$$

$$\rho = \rho(P, T)$$

Range of Compositions Consistent with Planet Mass and Radius

Example: GJ 436b

Transiting exo-Neptune

$R = 4.22 \pm 0.10\ R_{\oplus}$

$M = 23.17 \pm 0.79\ M_{\oplus}$

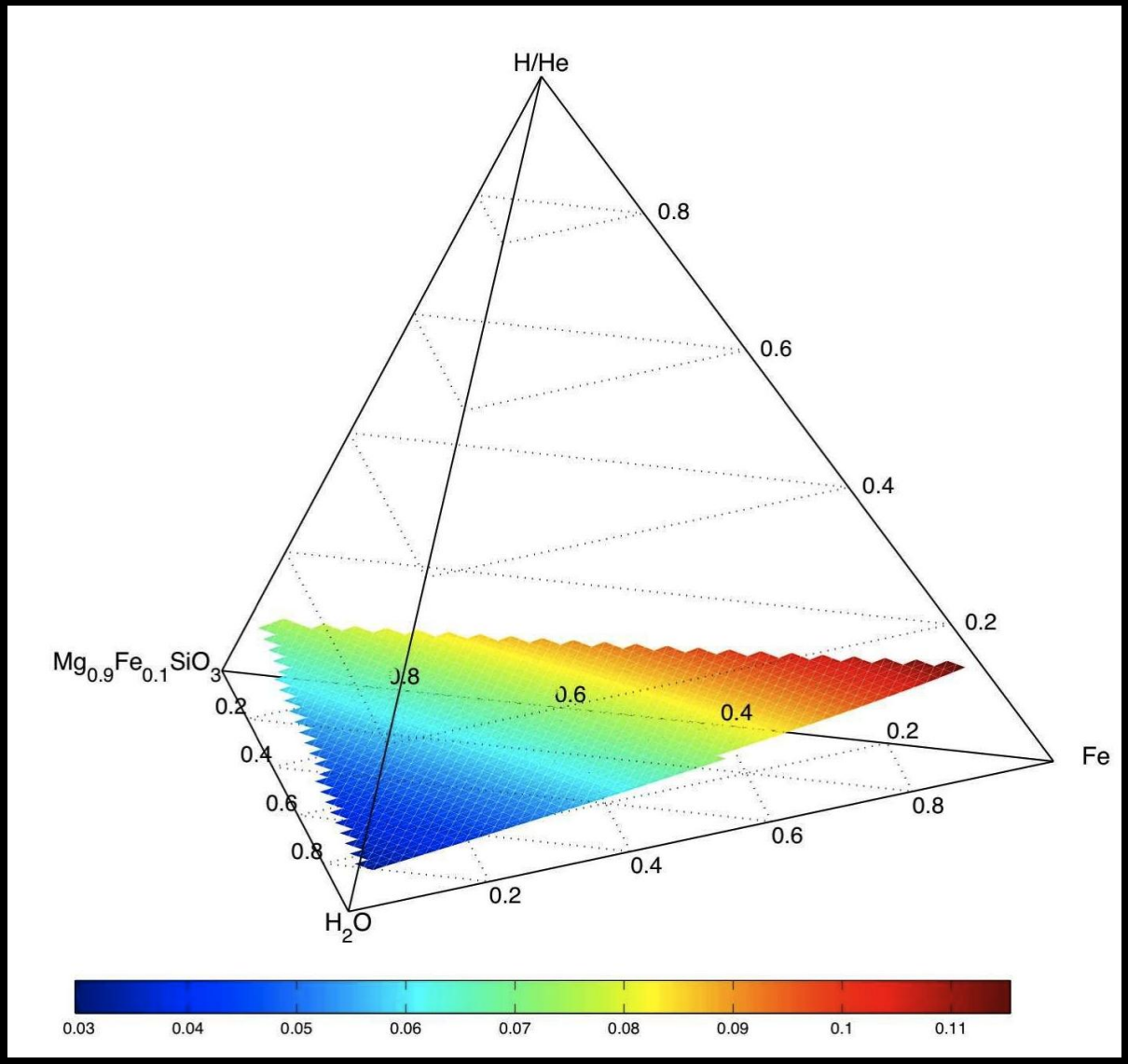
$L_* = 0.0260\ L_{sun}$

$a = 0.02872$ AU

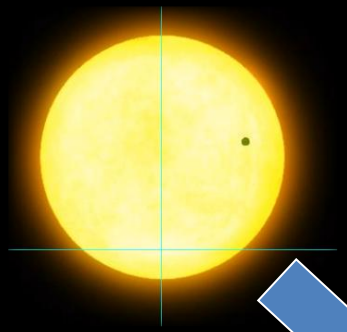
$T_{eq} \sim 660$K

Parameters from Torres et al. (2008)

Degeneracy in internal composition persists no matter how small the observational uncertainties

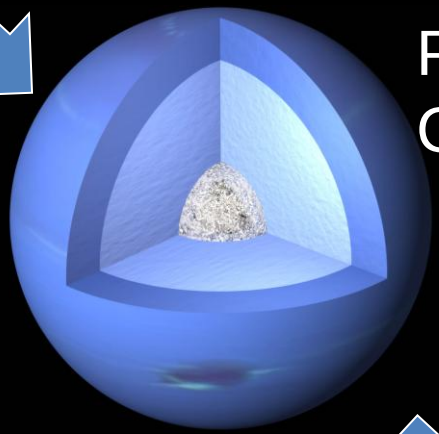


Rogers & Seager (2010a)



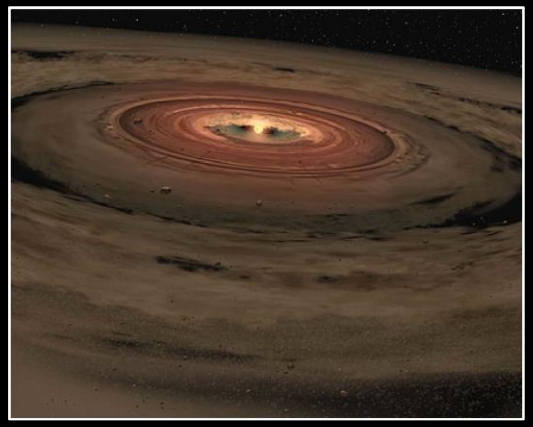
Transits
+ RVs and/or TTVs

$M_p + R_p + F_p$



Planet Bulk
Composition Constraints

Insights into Planet
Evolution and Formation History



Planet Formation Overview

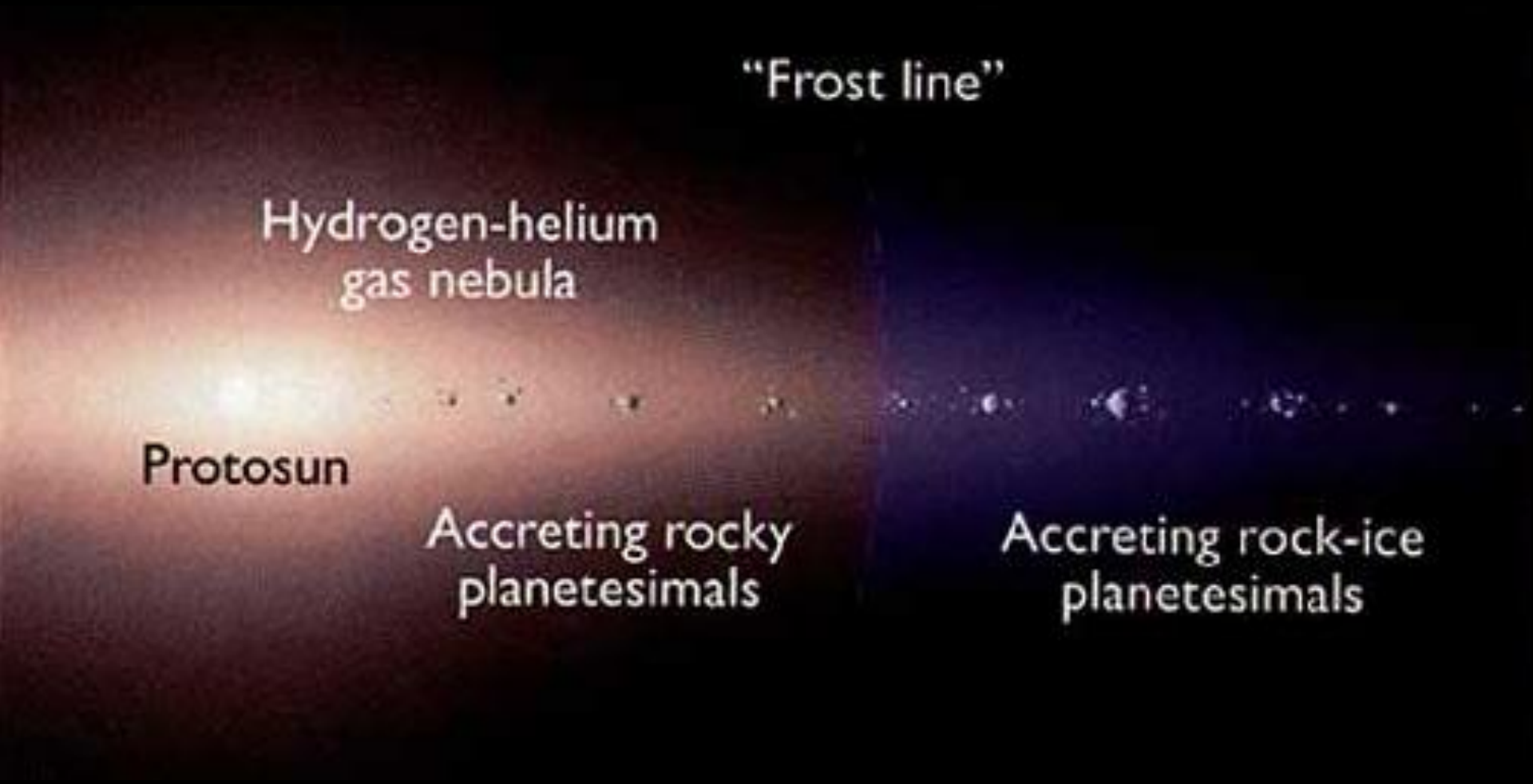


Figure Credit: Hubbard

Categories of Planetary Material

"Gas"

H, He, Noble Gasses

Don't Condense Anywhere in Disk

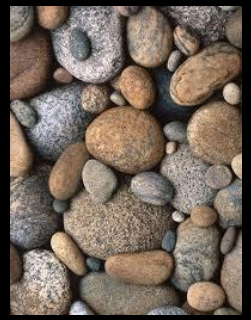
Weak Van der Waals Interactions

"Ices"

H_2O, NH_3, CH_4, CO, CO_2

Condense Beyond the Snowline

Van der Waals, Dipole Interactions & Hydrogen Bonding



"Rocks"

Silicates, Fe, Ni, Oxides

Most refractory material

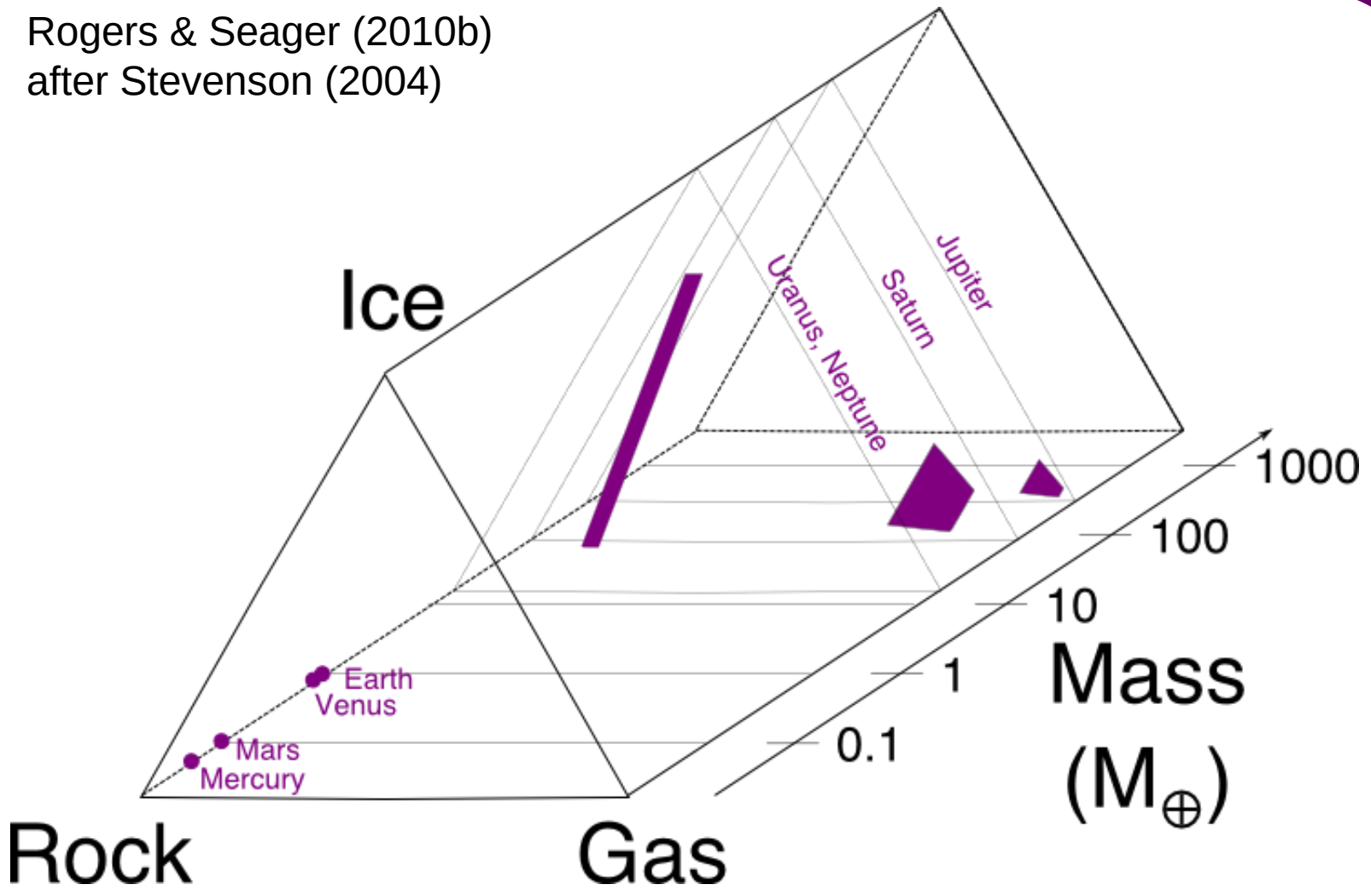
Covalent, Ionic, Metallic Bonding

Decreasing Volatility

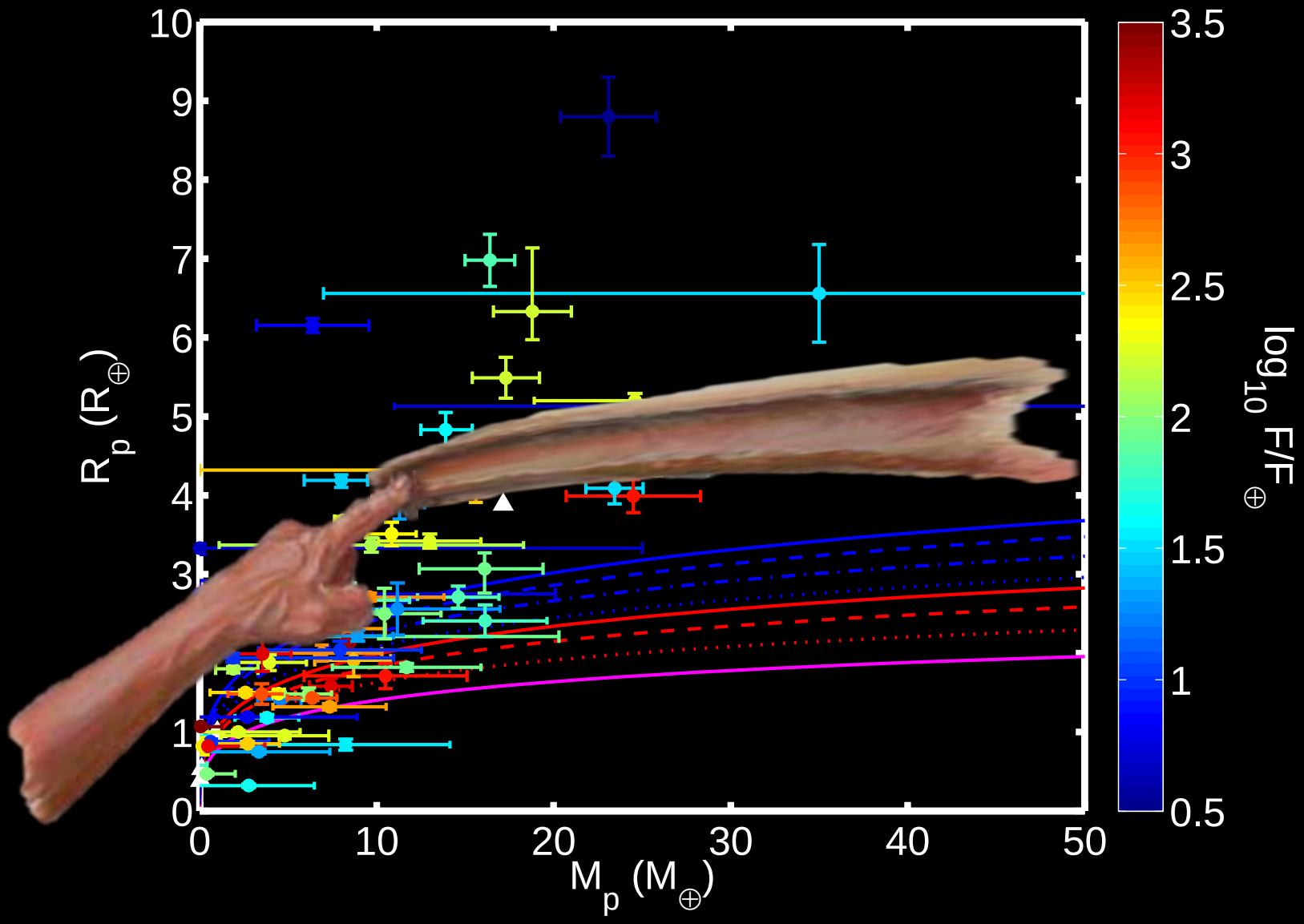
Increasing Density, Stiffness

Range of Initial Bulk Compositions

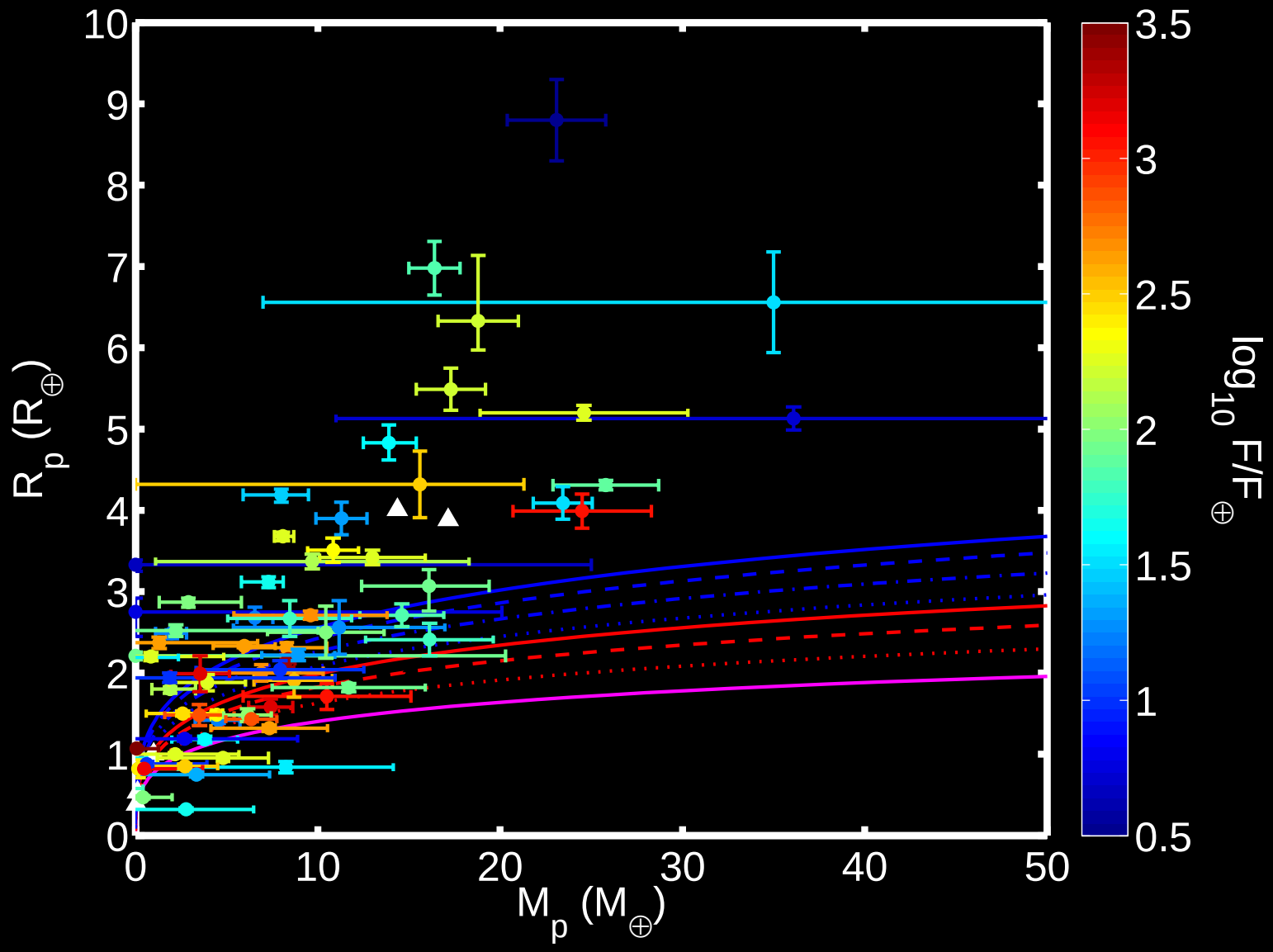
Rogers & Seager (2010b)
after Stevenson (2004)



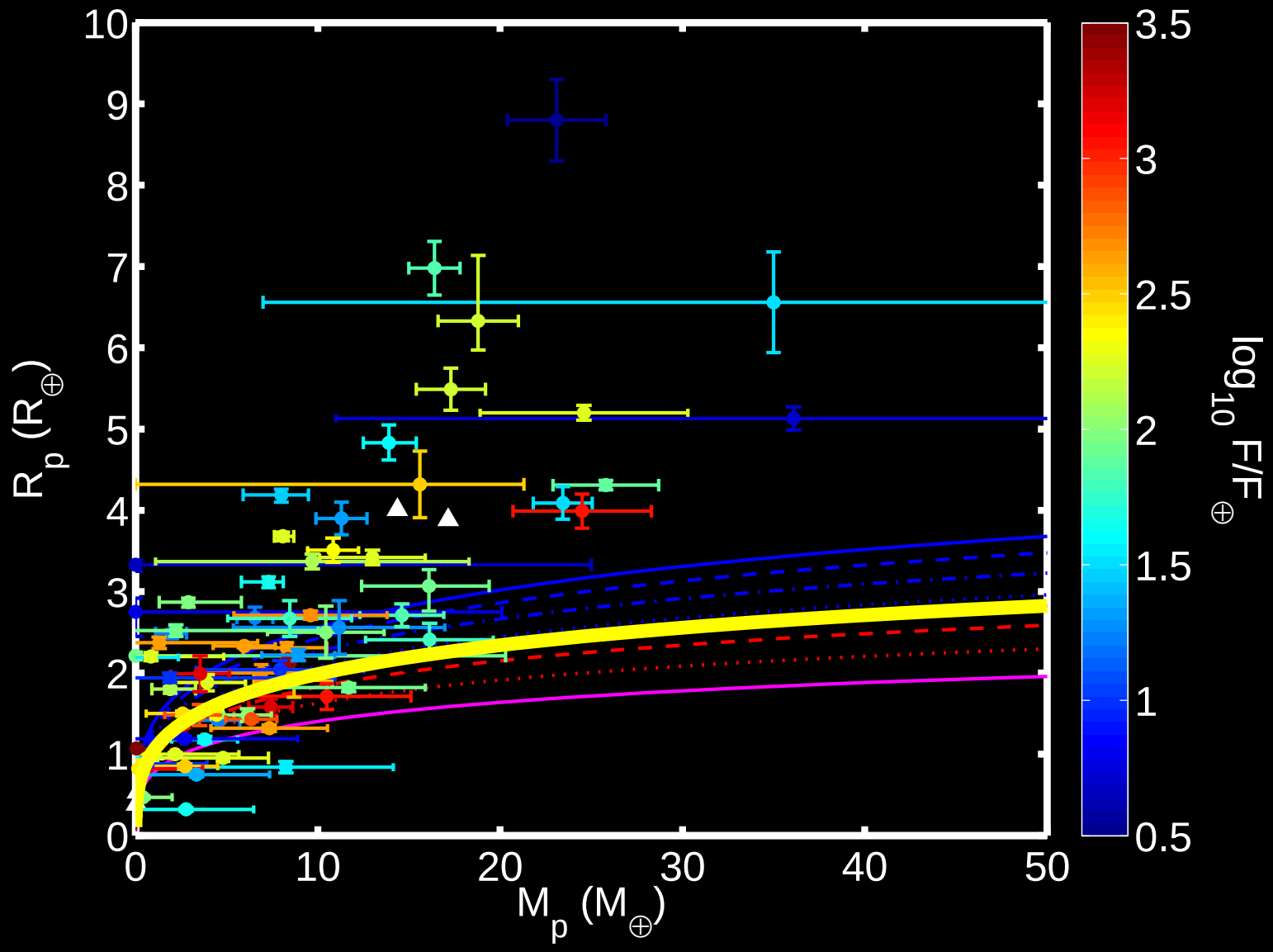
Distinguish Formation Scenarios with Limiting Composition M-R Relations



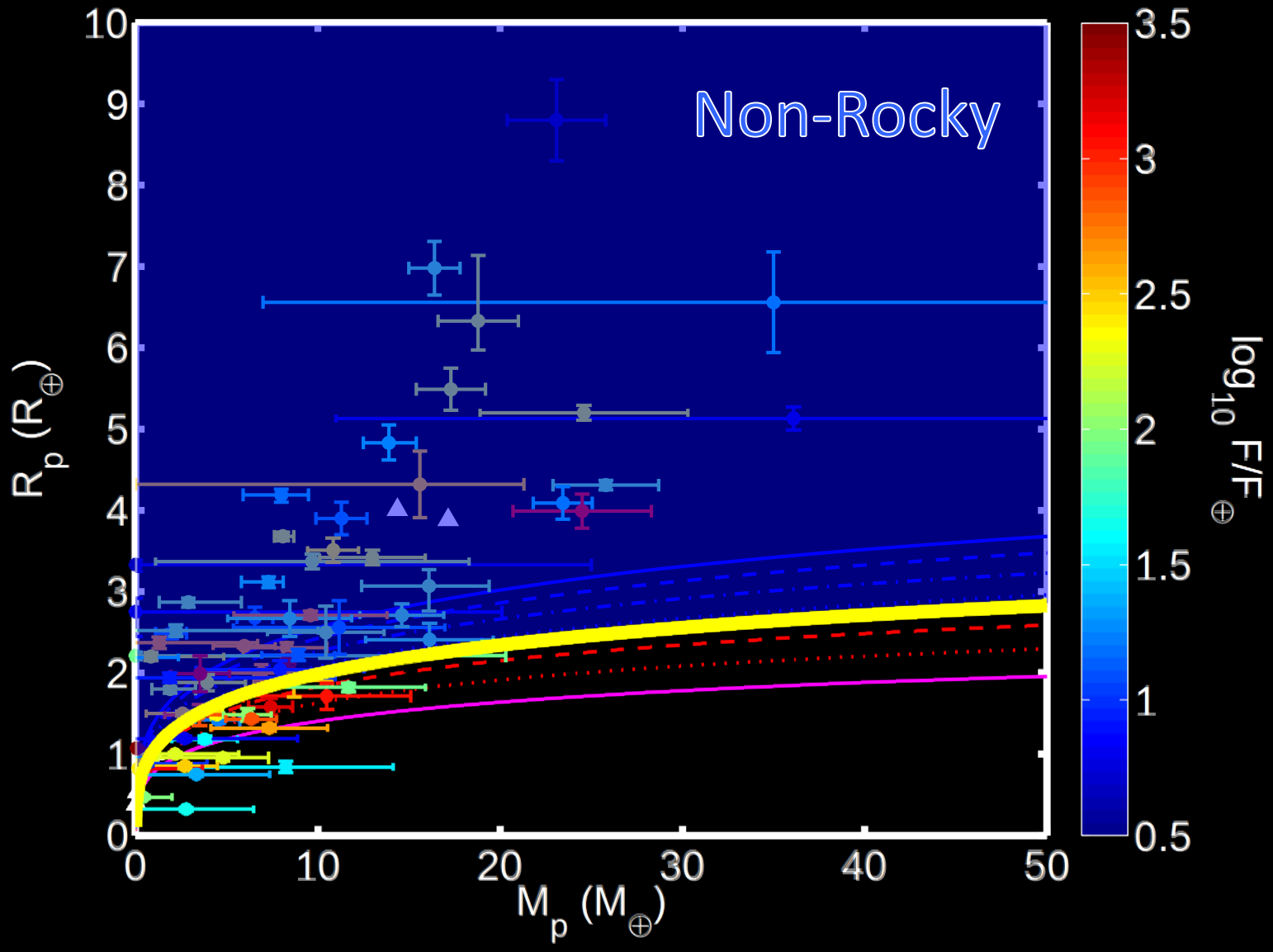
Which Planets Are Rocky?



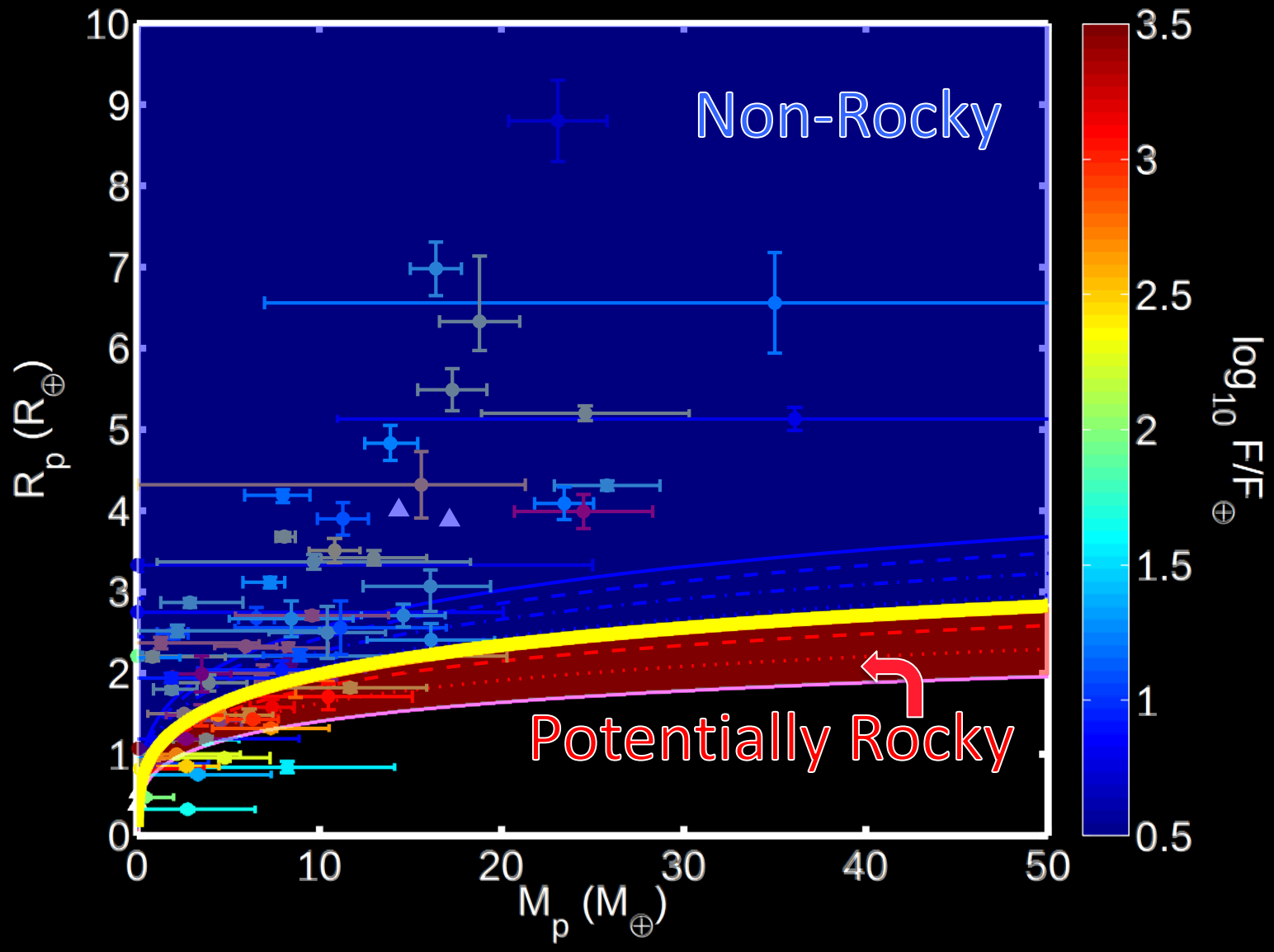
Which Planets Are Rocky?



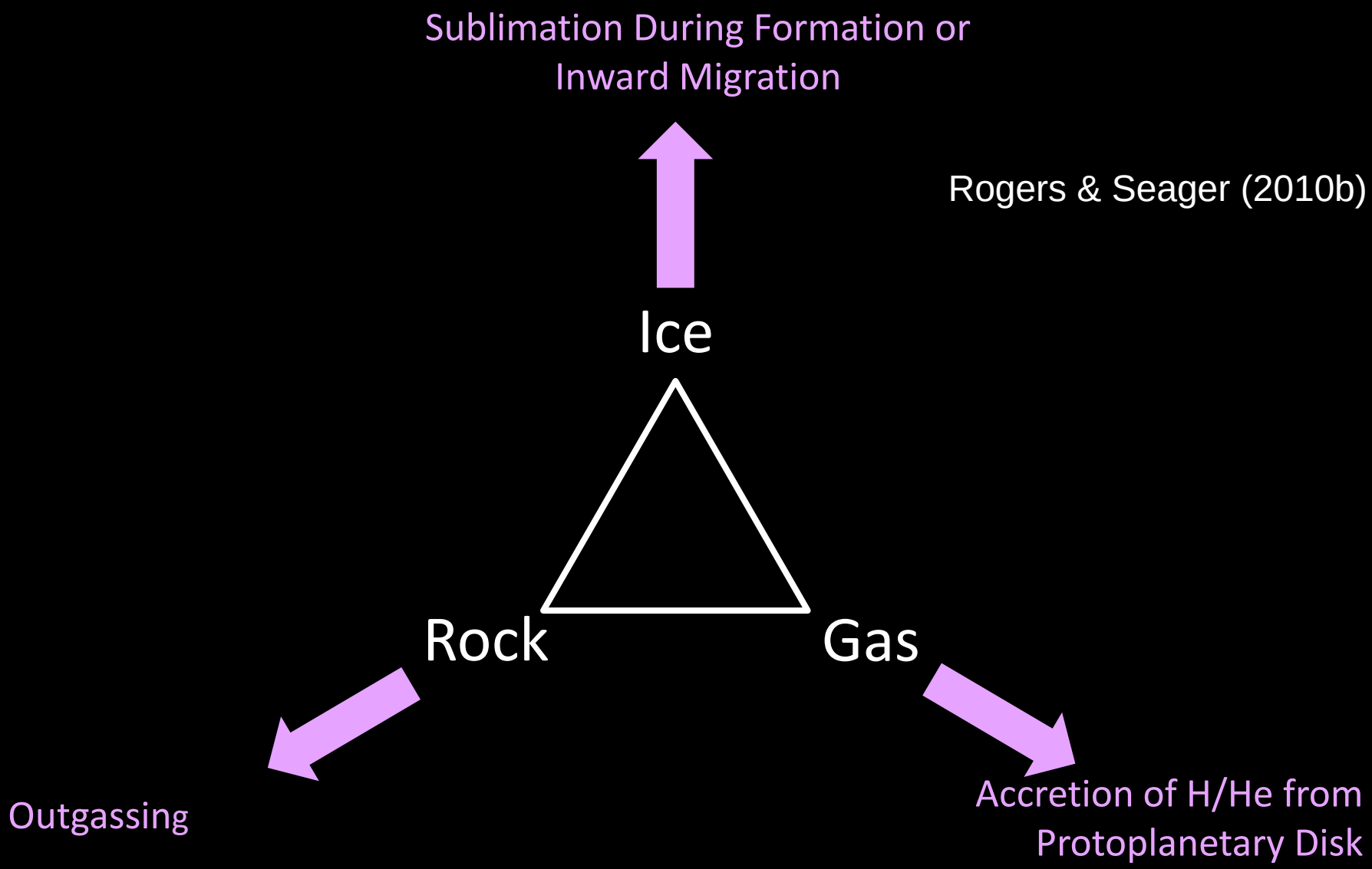
Which Planets Are Rocky?



Which Planets Are Rocky?

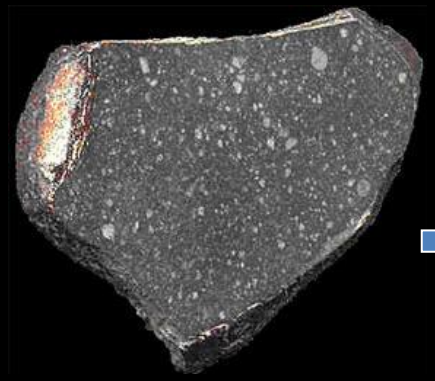


Gas Layer Sources



Outgassing of of Light Gases

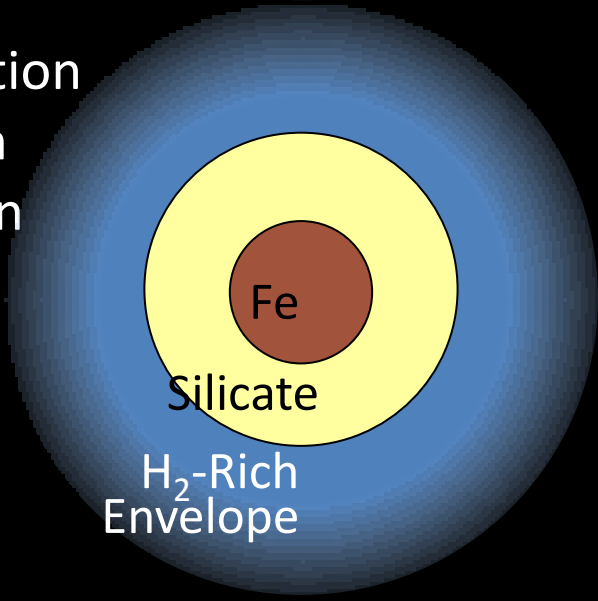
e.g. Elkins-Tanton & Seager (2008)



Primitive Materials

Water

Differentiation and Iron Oxidation



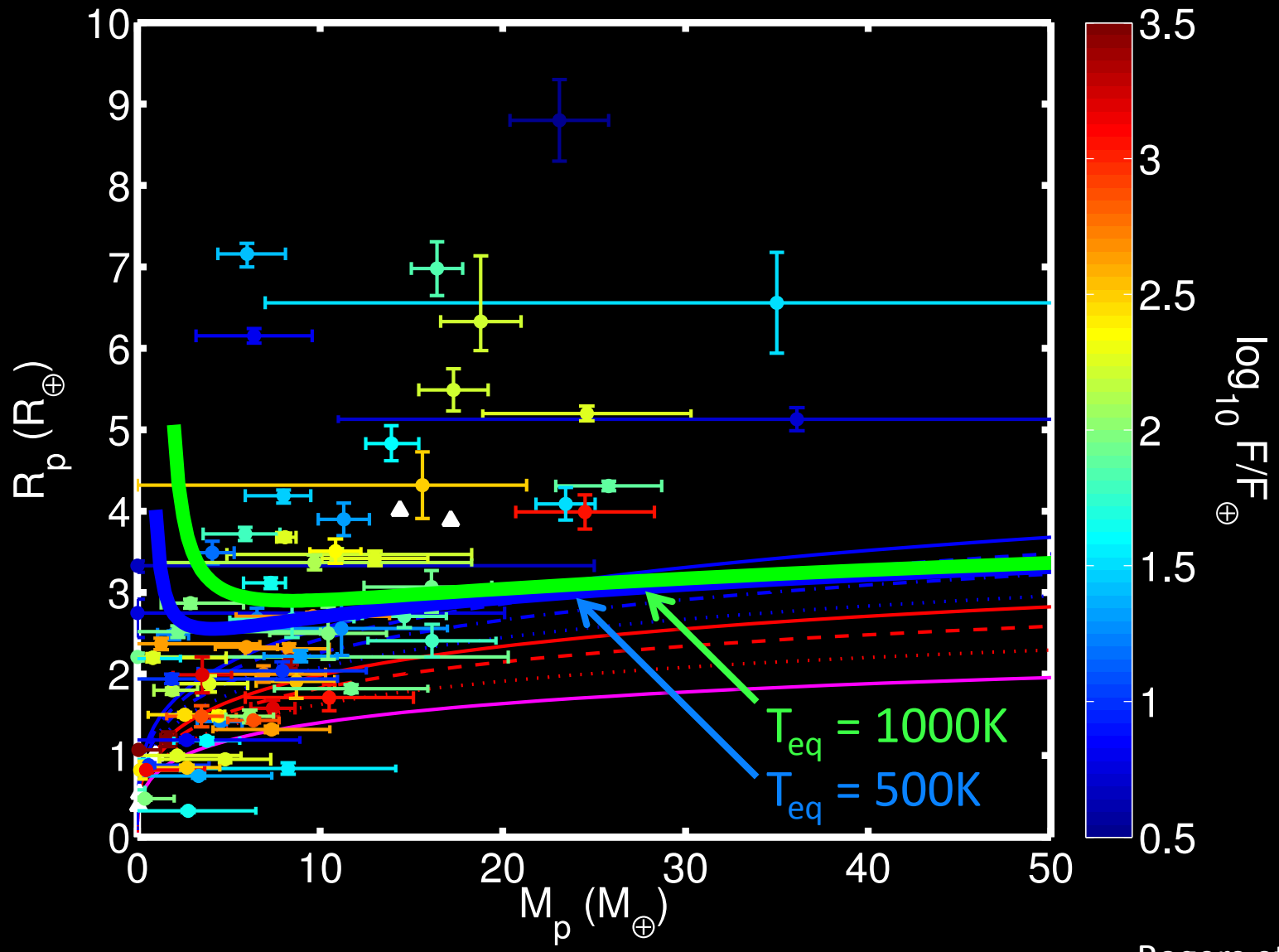
Model Parameters:

- Composition Primitive Material
- % Water Added
- % Oxidation
- % Gas Retention

Interior structure model consistently calculates R(M) accounting for:

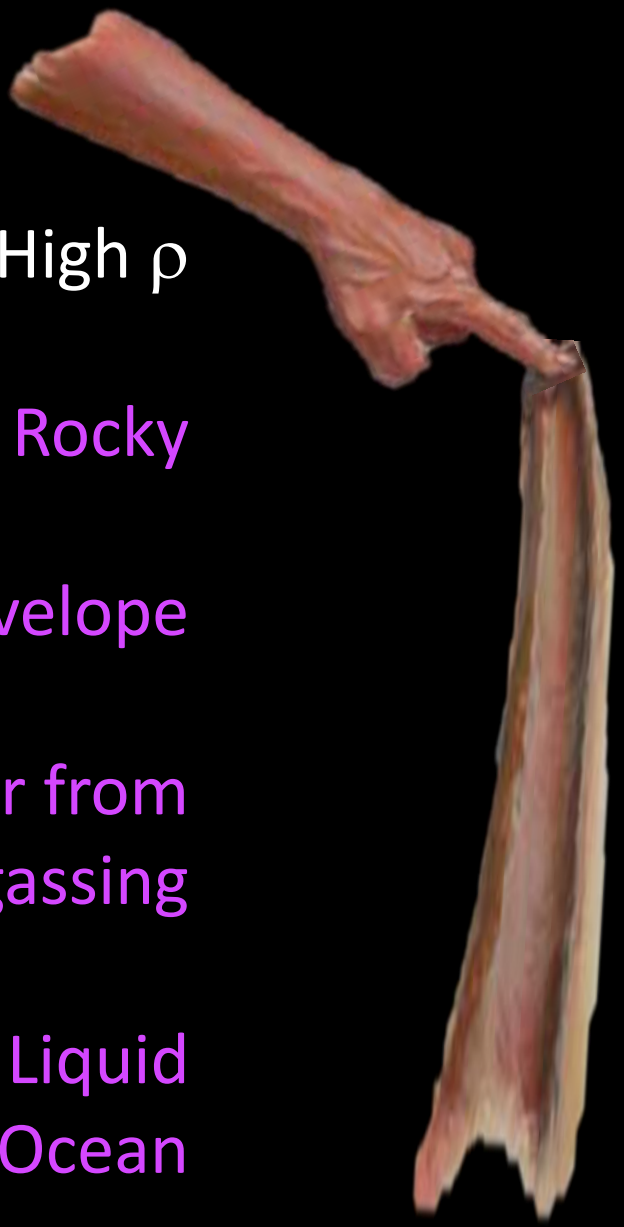
- core-silicate-gas mass fractions
- Mg/Si/Fe abundance of silicate
- radius contribution from gas layer

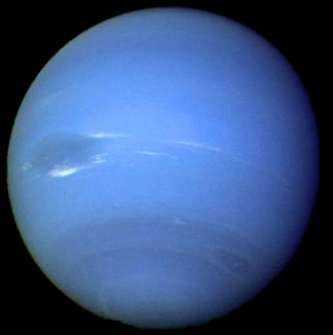
Which Planets Could Have Gas Envelopes Originating from Outgassing Alone?



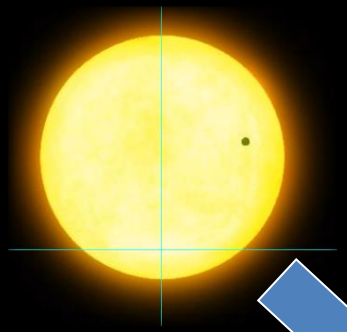
Rogers et al. (2011)

Limiting-composition M_p-R_p relations



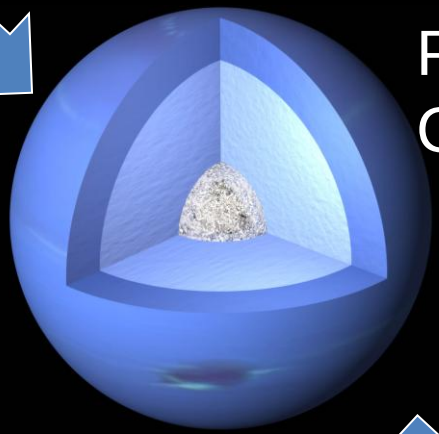


High ρ	Low ρ
Rocky	Volatile Rich
Water Envelope	Needs H/He
Gas Layer from Outgassing	Gas Mass too Large for Outgassing
Potential Liquid Water Ocean	Too Hot/Puffy for Water Ocean



Transits
+ RVs and/or TTVs

$M_p + R_p + F_p$



Planet Bulk
Composition Constraints

Insights into Planet
Evolution and Formation History