# Structure, Formation, and Evolution of Low-Mass Planets

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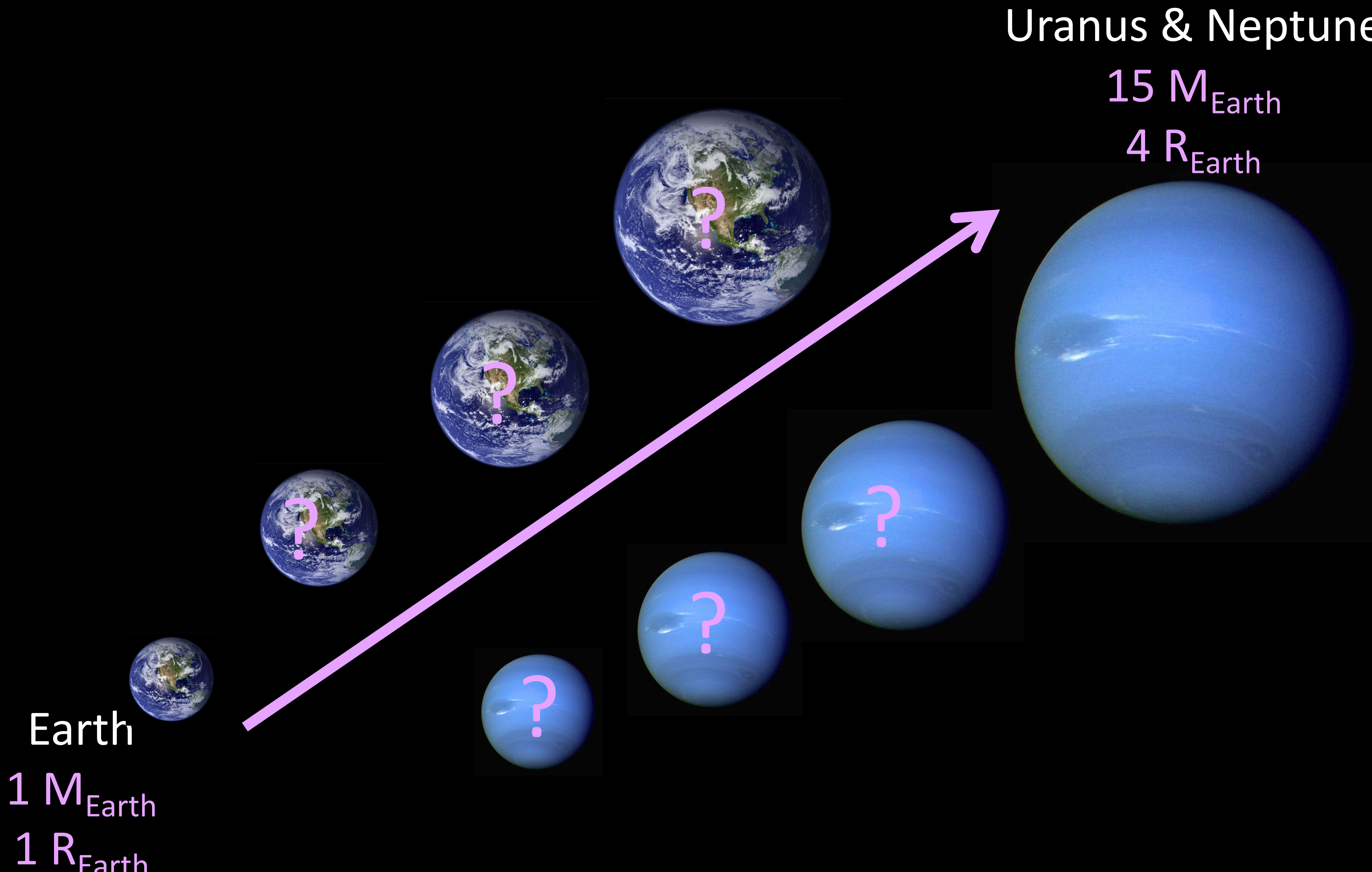
# Super-Earth and Sub-Neptune Planets

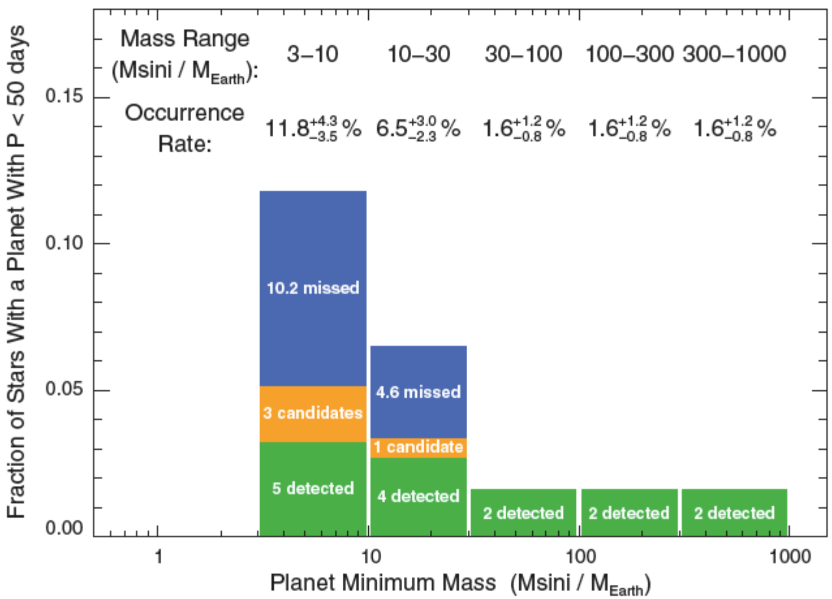


# Sub-Neptune size/mass planets are common!

## Microlensing:

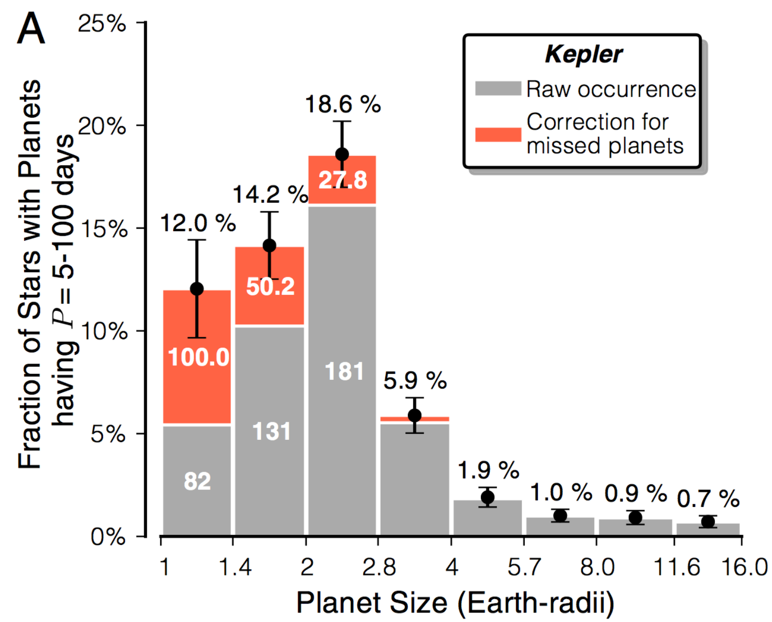
- Beyond the snow-line, Neptune-mass planets are at least three times more common than Jupiters at the 95% confidence level. Sumi et al. (2010)
- 62±36% of stars have a 5-10 $M_{Earth}$ planet at 0.5-10 AU. Cassan et al. (2012)

## Radial Velocity:




Howard et al (2010)

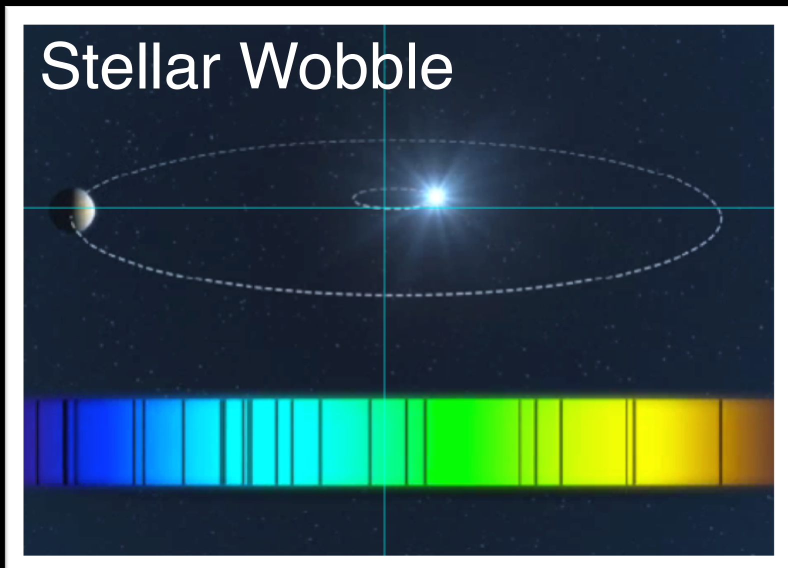
## Transits:

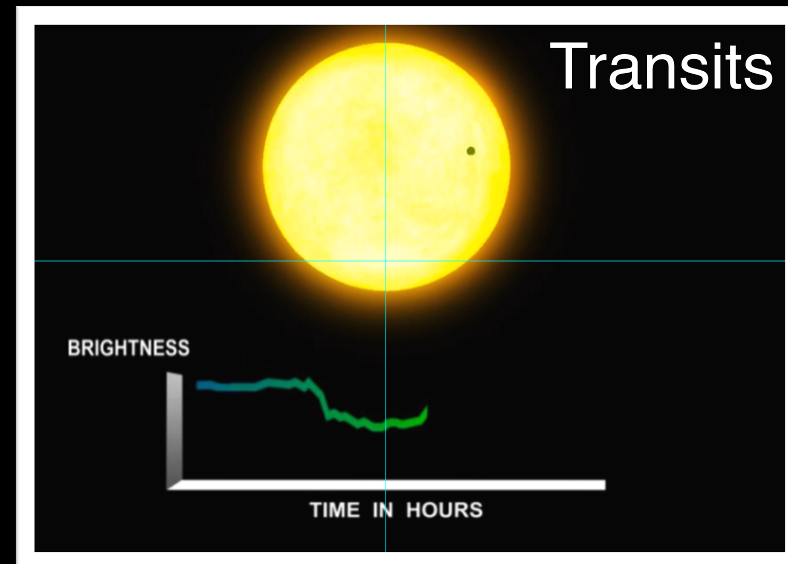



Petigura et al. (2013)


- Review Planet Interior Structure and Evolution Models
- Highlight Recent Empirical Insights Into Low-Mass Planet Evolution and Formation Histories
- Implications for Microlensing Surveys

# Planets Detected both Dynamically and in Transit are Valuable!



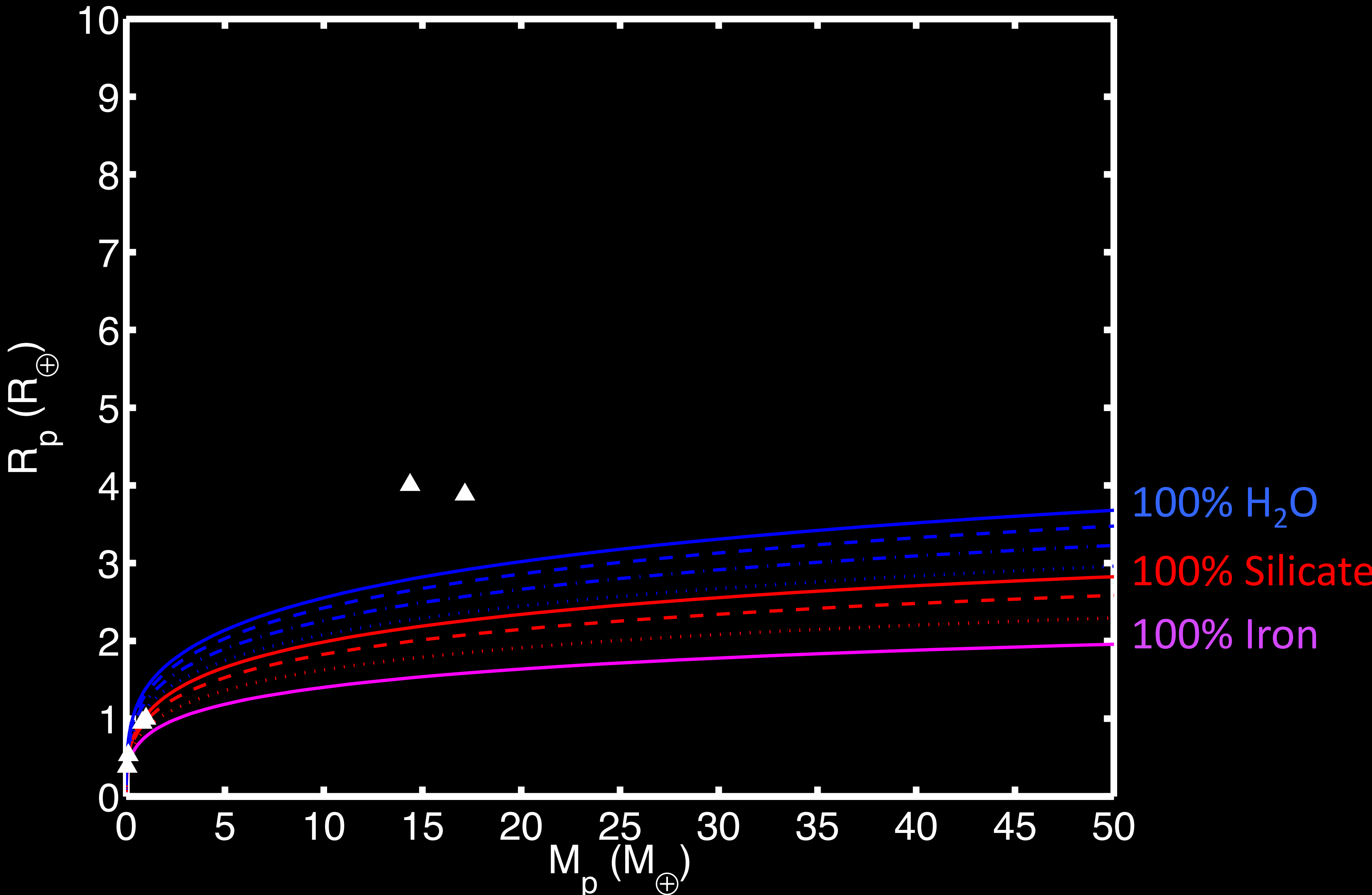




Planet Mass

Planet Radius

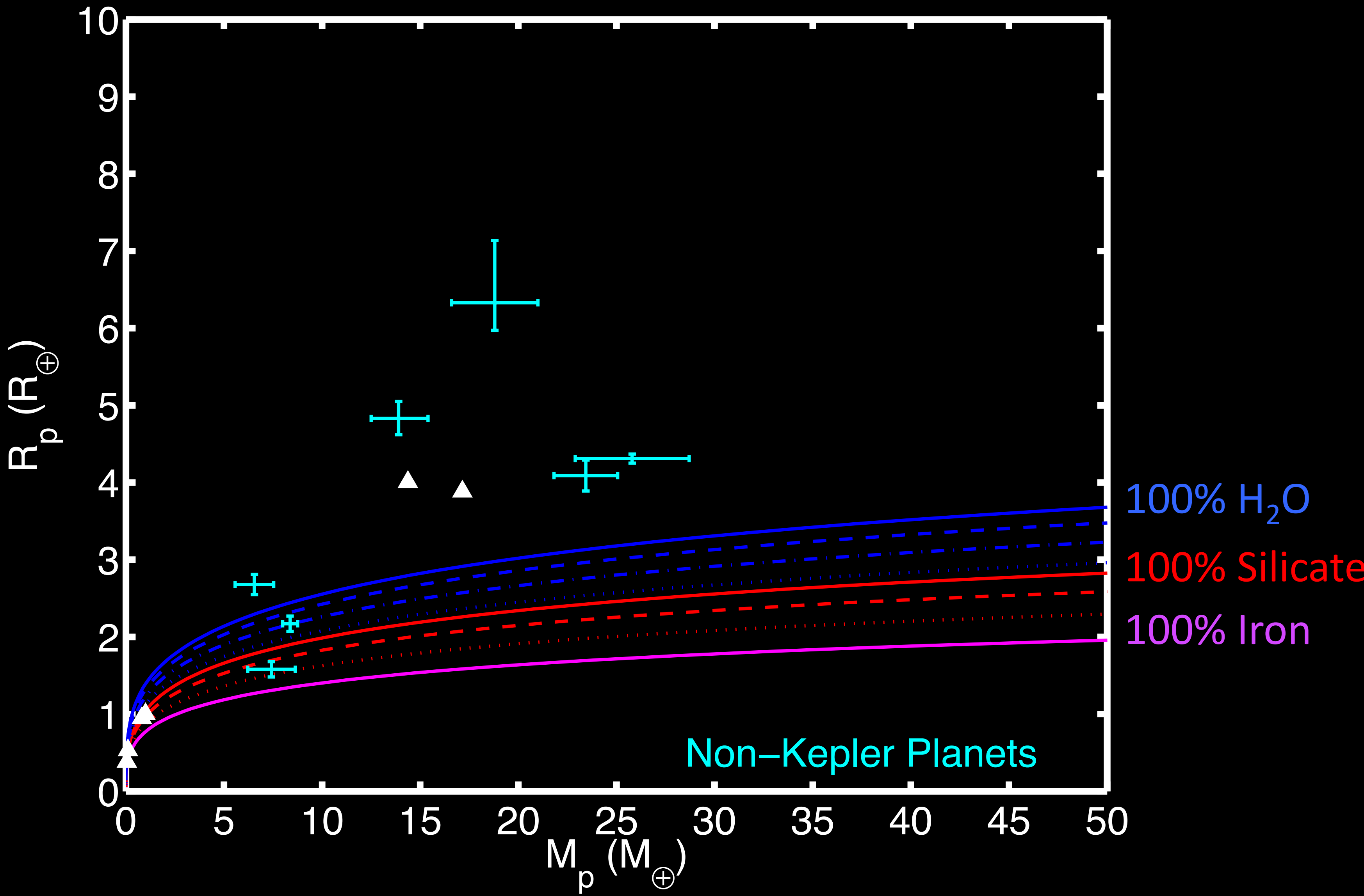
Planet Density

# Ten Years Ago



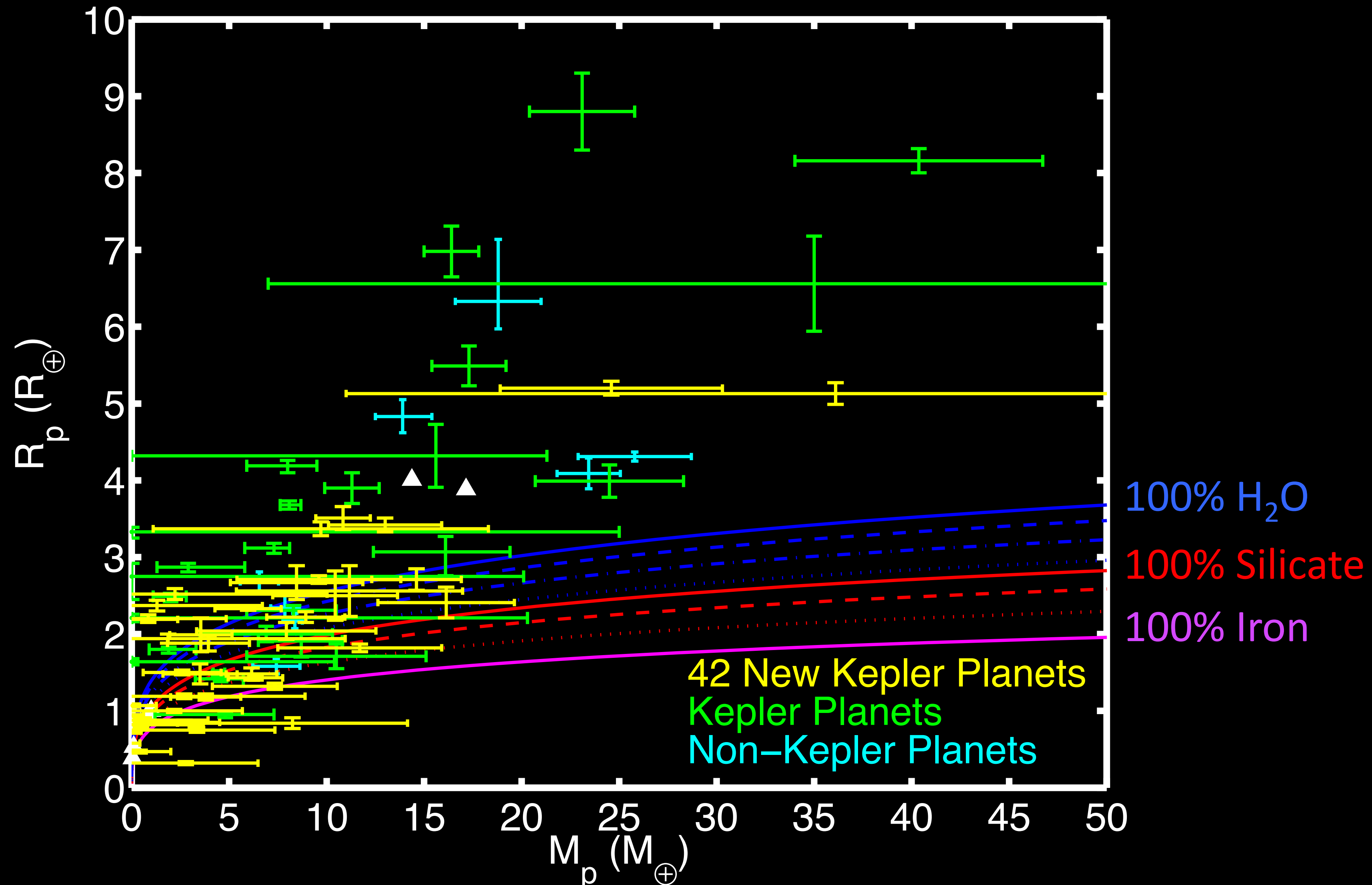

Seager et al. (2007) M-R Relations

# Non-*Kepler* Planets




Seager et al. (2007) M-R Relations

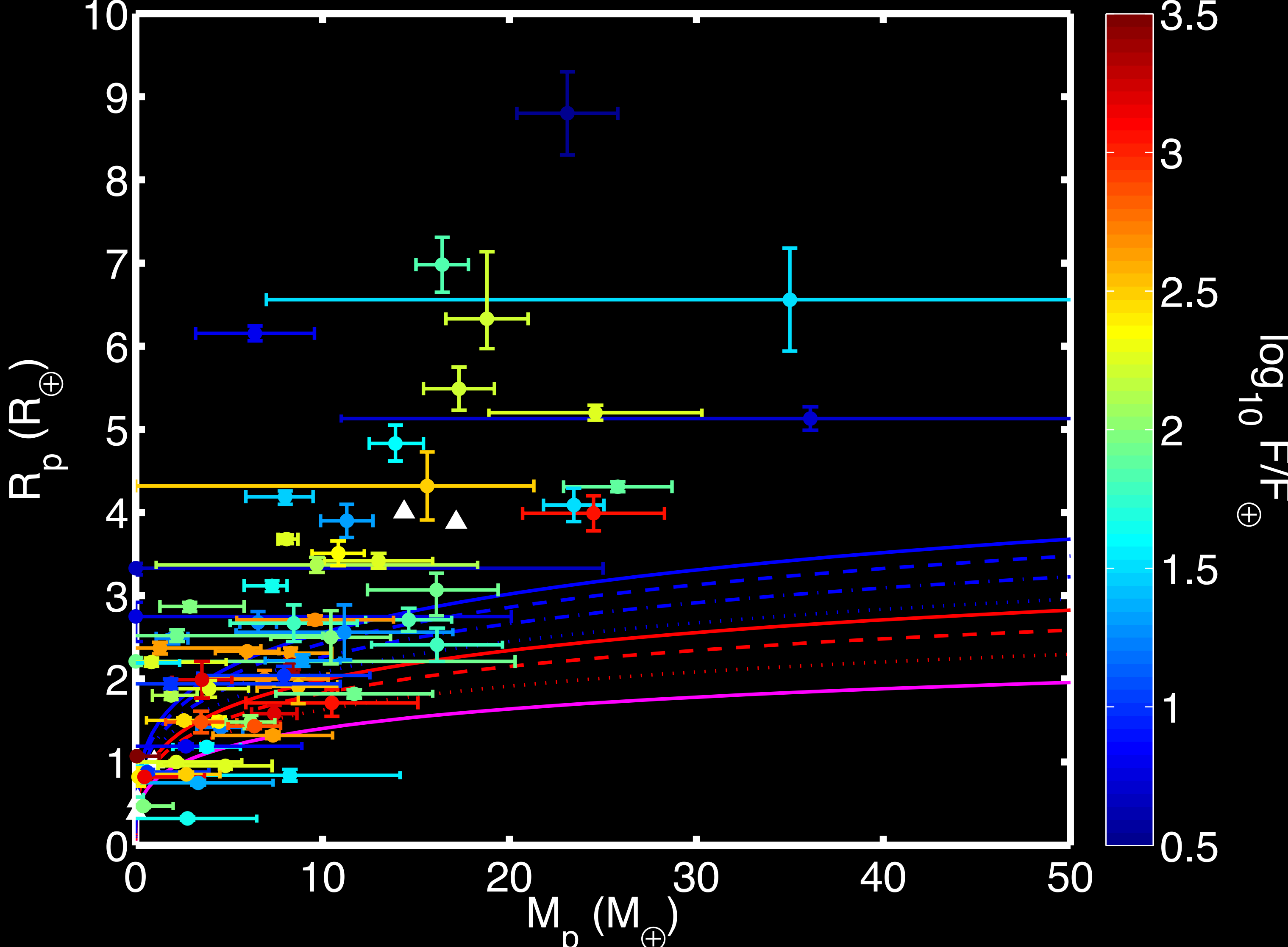
# New *Kepler* Planet Masses from Keck RVs




Seager et al. (2007) M-R Relations

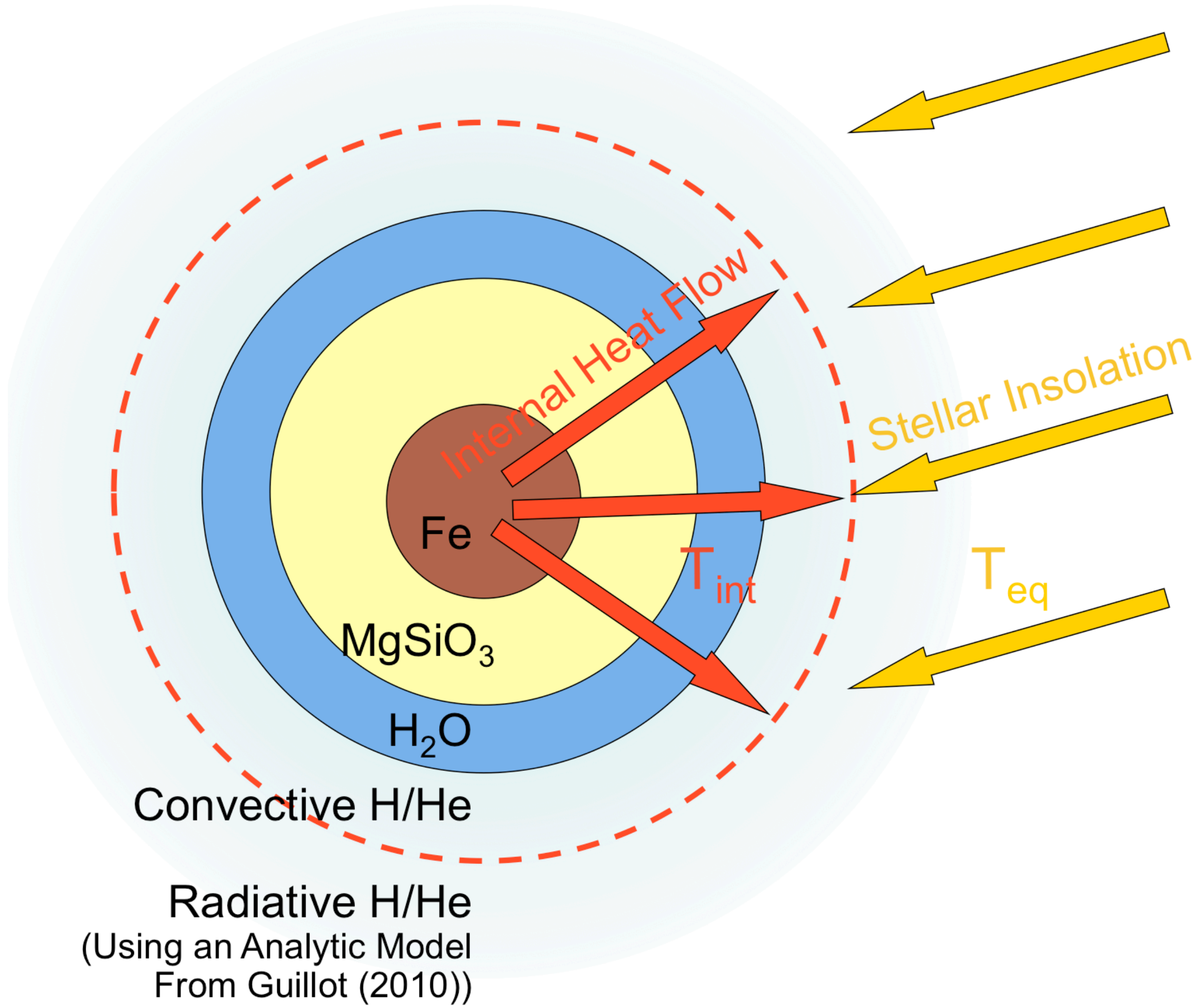
Marcy et al. (2014)

# Adding Incident Flux Dimension




Seager et al. (2007) M-R Relations

# Model Overview



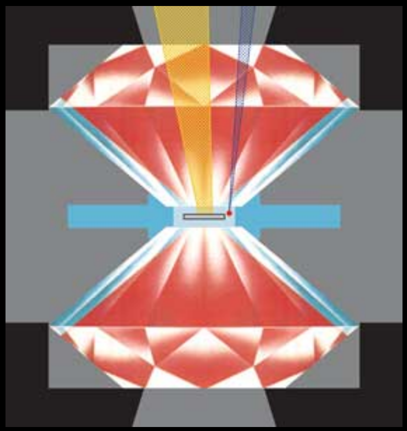

$$\frac{\mathrm{d}r}{\mathrm{d}m} = \frac{1}{4\pi r^2 \rho}$$

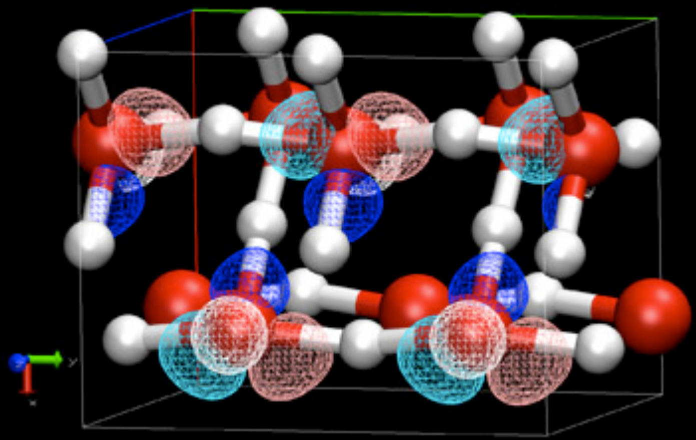
$$\frac{\mathrm{d}P}{\mathrm{d}m} = -\frac{Gm}{4\pi r^4}$$

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

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

# How Materials Behave at High Pressure





Lab Experiments

Computer Simulations

Asymptotic Theories

1 bar (1 Atm)

1 Mbar

3.6 Mbar (Center of Earth)

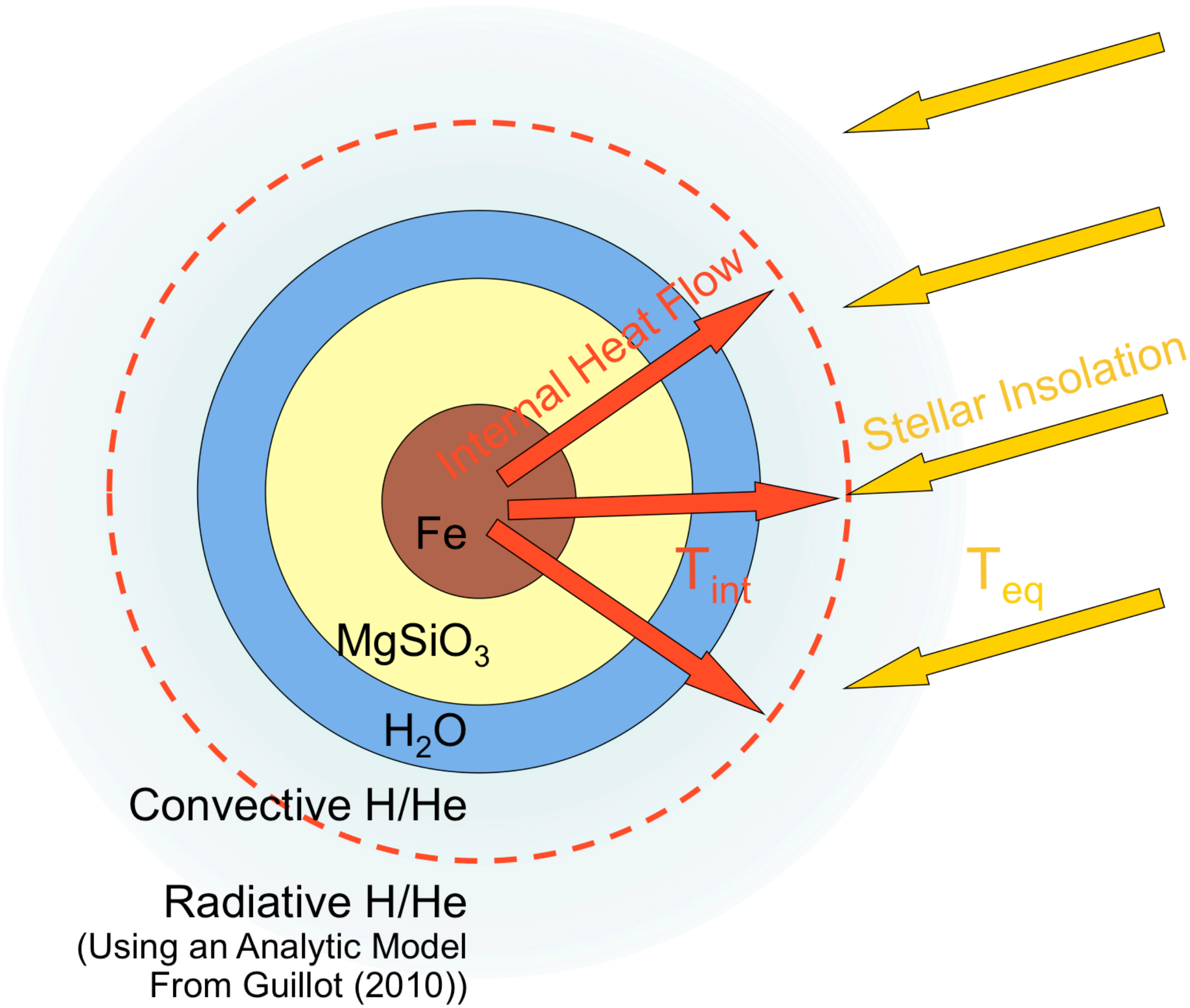
10 Mbar

~40 Mbar (Center of Jupiter)

100 Mbar

Pressure

# Model Overview



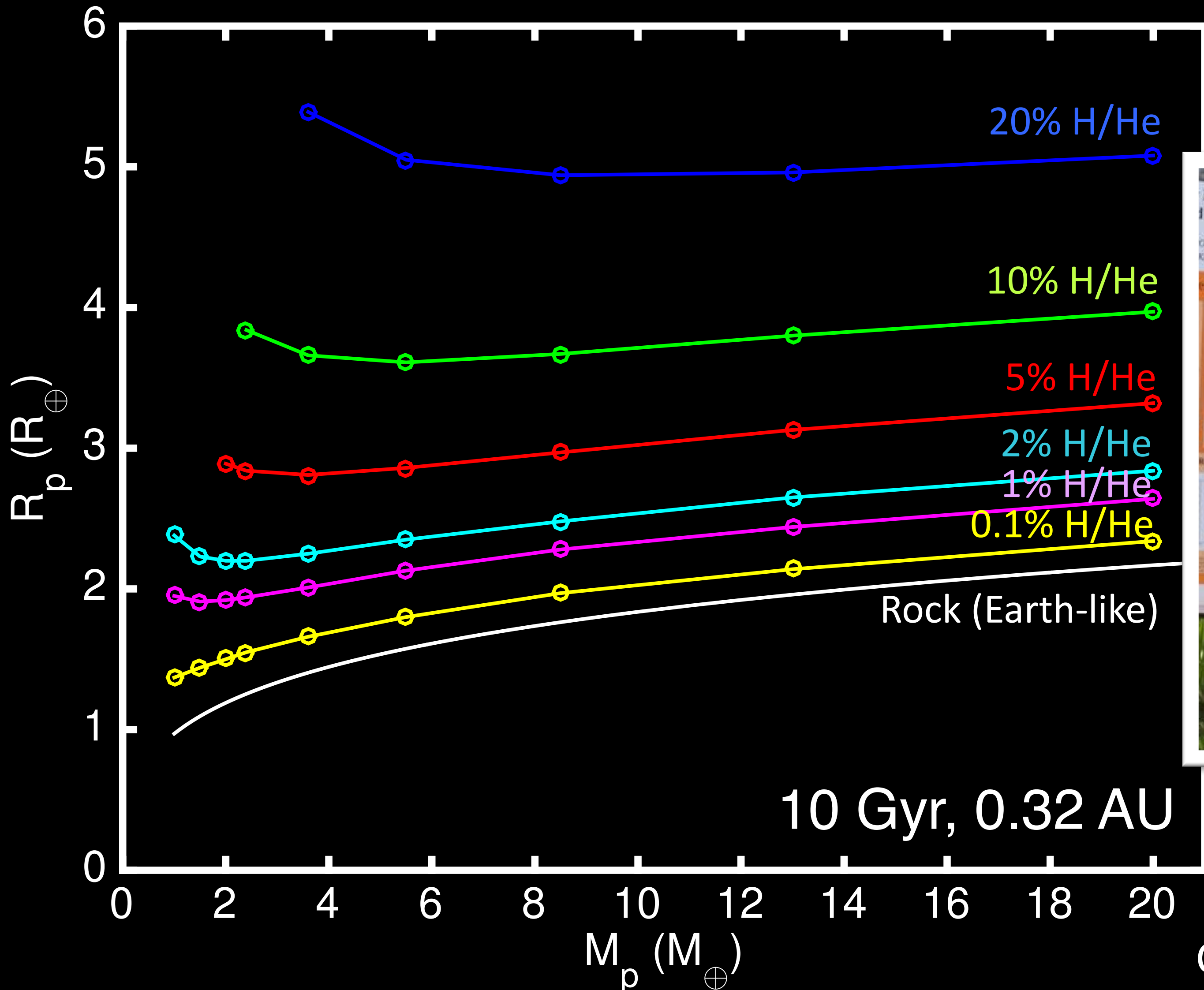

$$\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho}$$

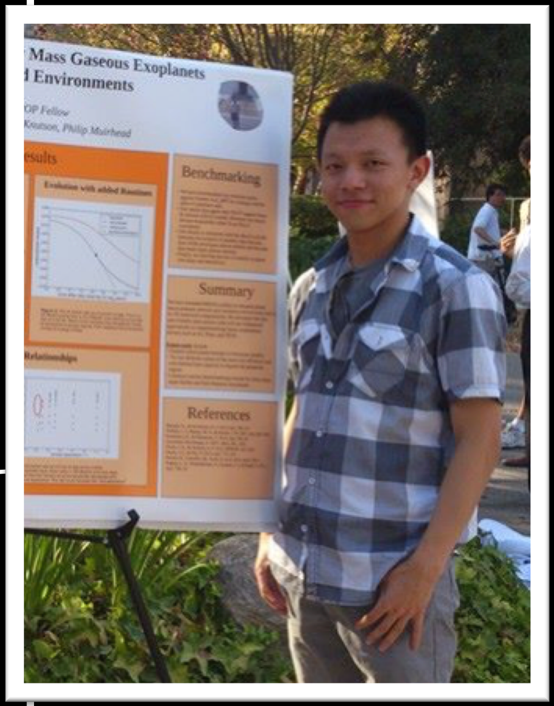
$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$$

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

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

# Extending MESA to Model Low-Mass planets with H/He envelopes

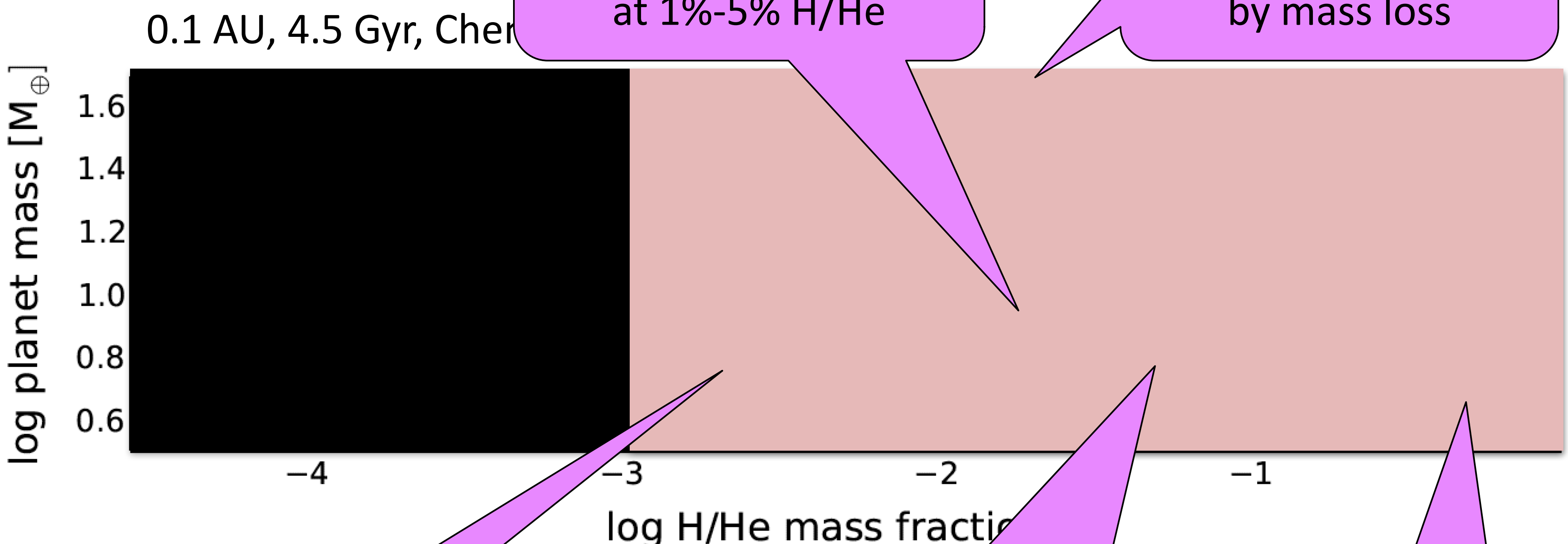



BU UROP Howard Chen

Chen & Rogers (in press)

# Mass Loss Sculpts Close-In Planet Populations




Envelope mass-loss timescale maximized at 1%-5% H/He

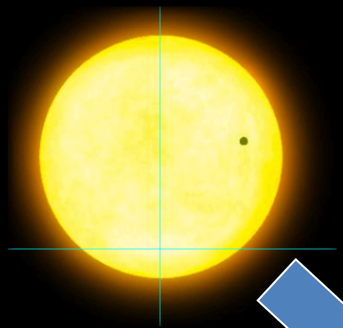
High-Mass planets not strongly affected by mass loss

Low $M_p$ planets quickly lose low $M_{env}$ envelopes

Higher $M_{env}/M_p$ have higher $R_p$ and higher cross-section to ionizing radiation

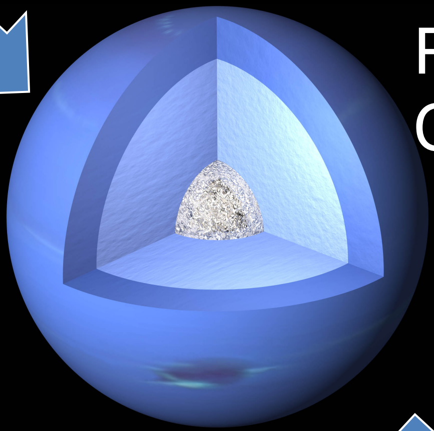
Unbound Configurations

(e.g., Lopez & Fortney 2014, Owen & Wu 2013, Howe et al. 2014)

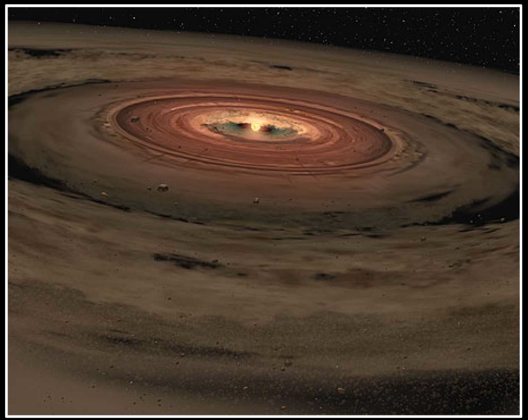


Transits
+ RVs and/or TTVs

$M_p + R_p + F_p$

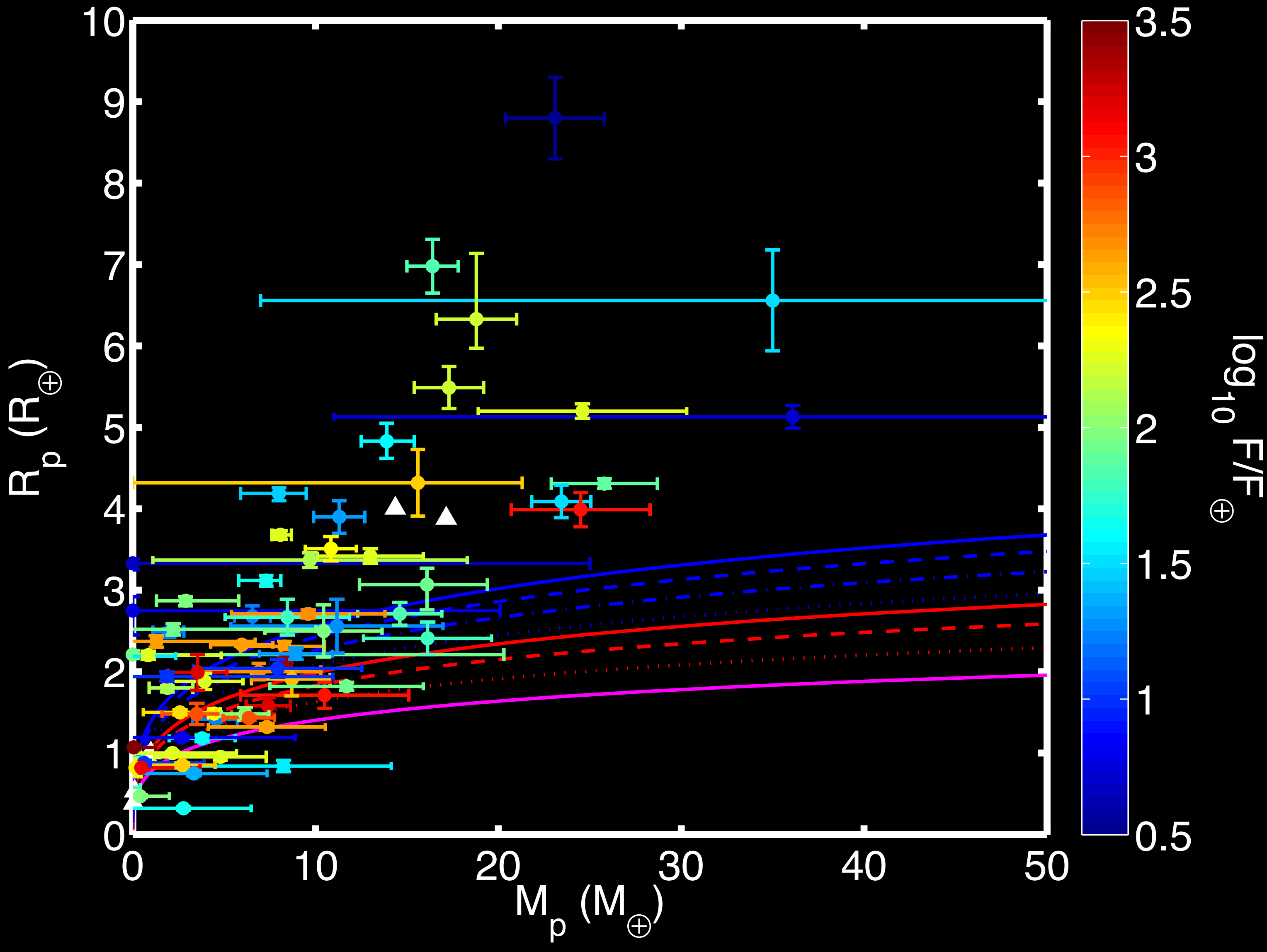


Planet Bulk
Composition Constraints

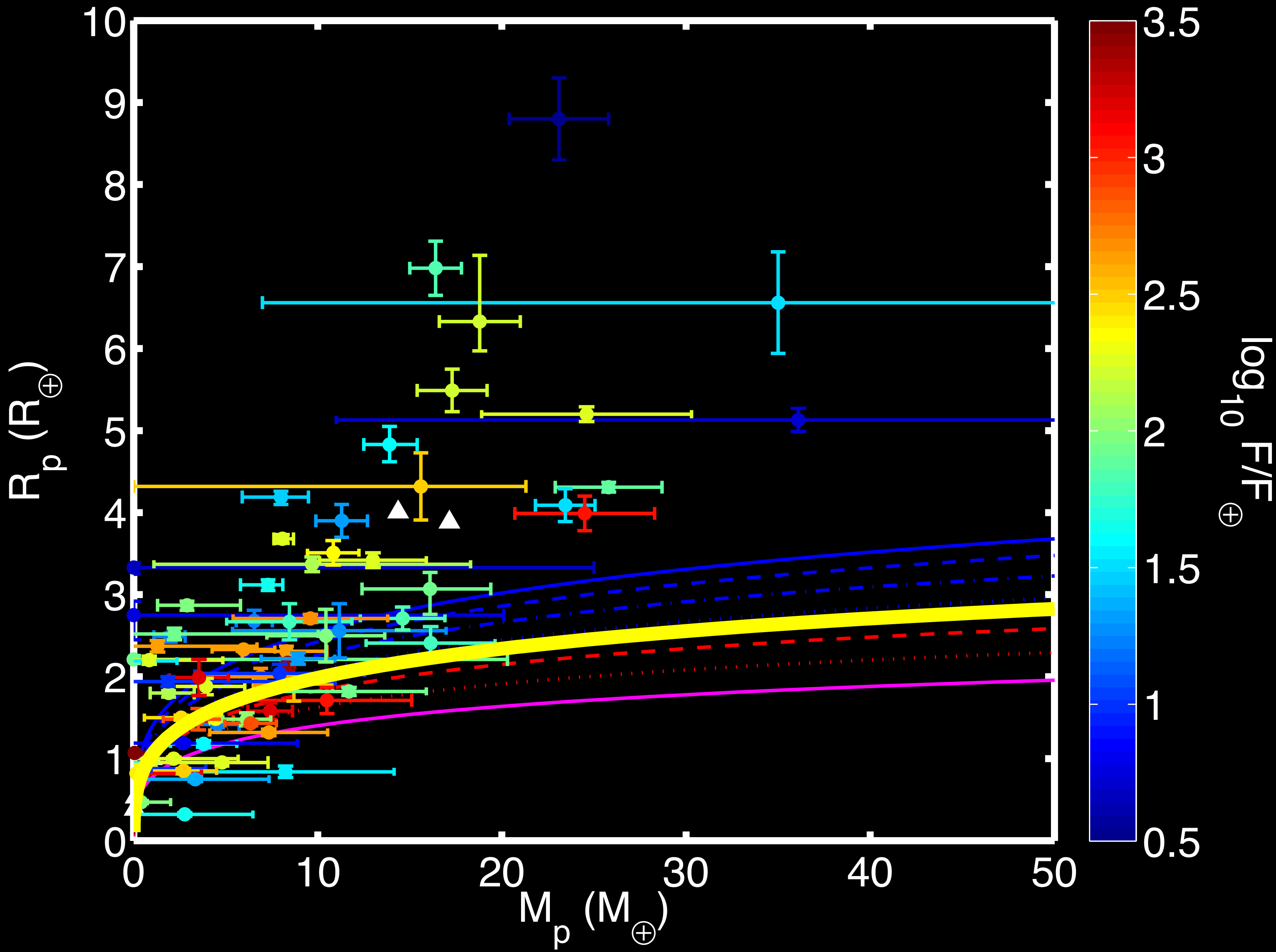


Insights into Planet
Evolution and Formation History

# Sample of Small Planet M-R



# Which Planets Are Rocky?



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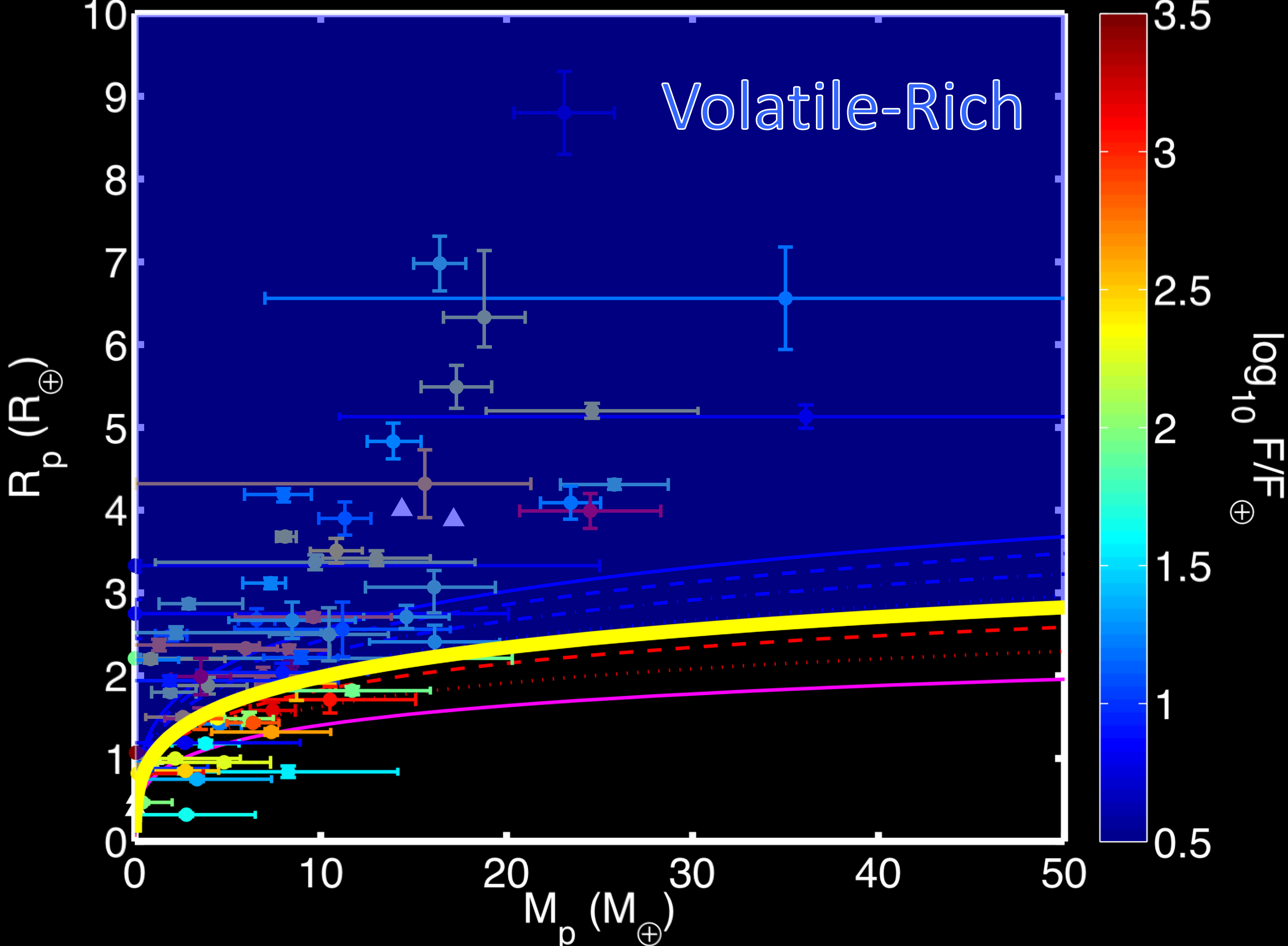

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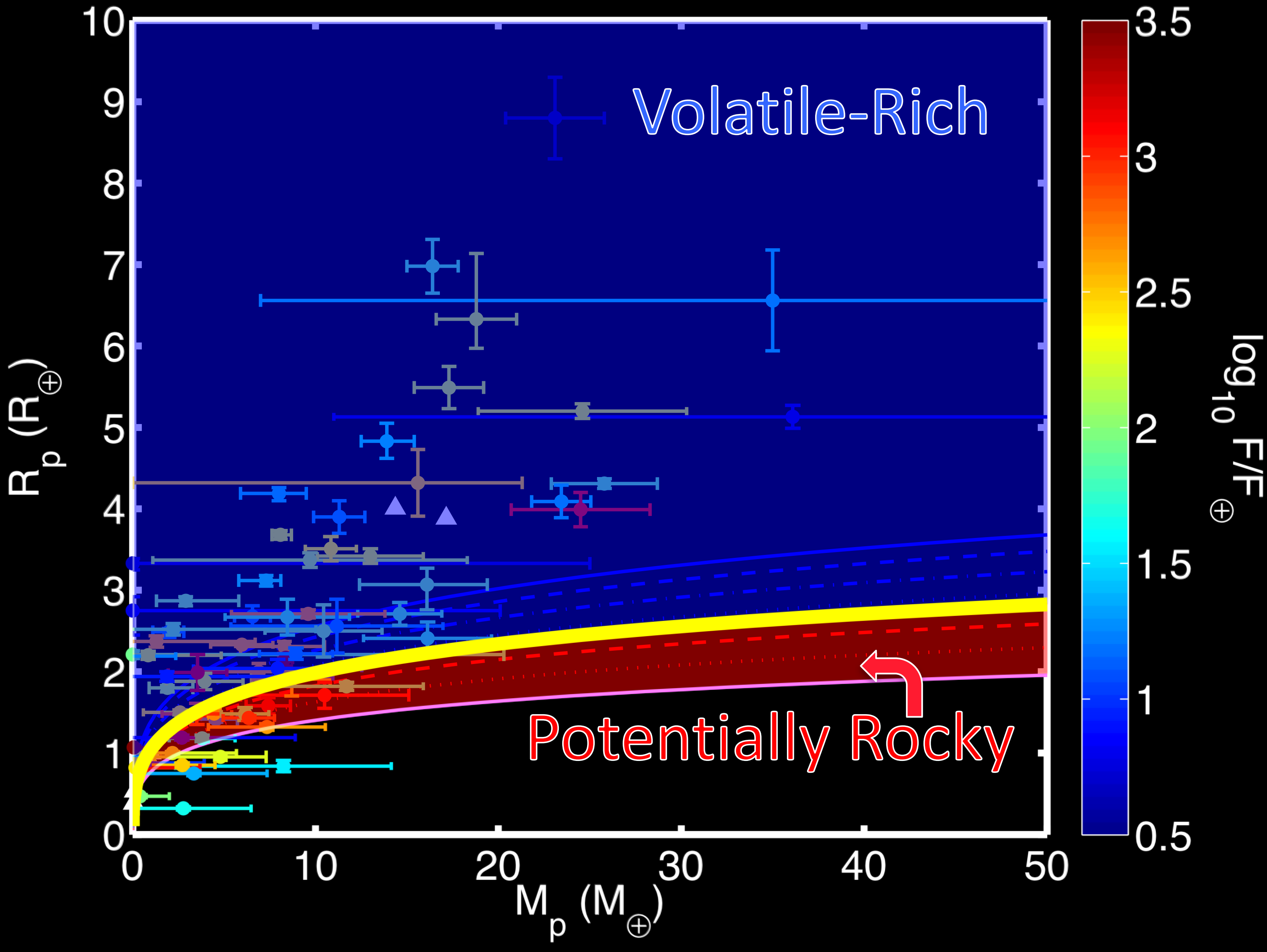
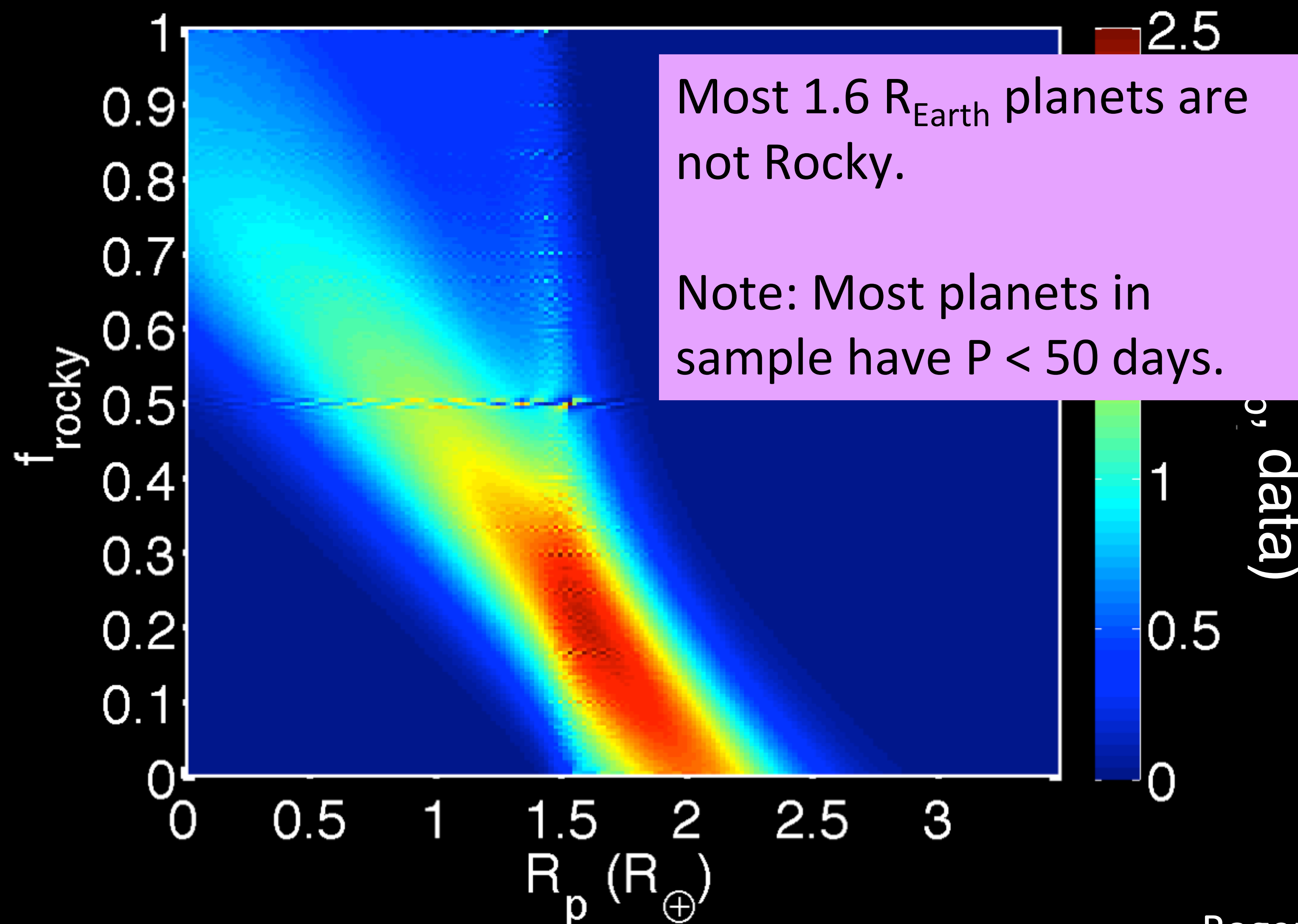


# Abundance of Low Density planets Constrains Fraction of Planets in Underlying Population that are Rocky, $f_{rocky}(R_p)$

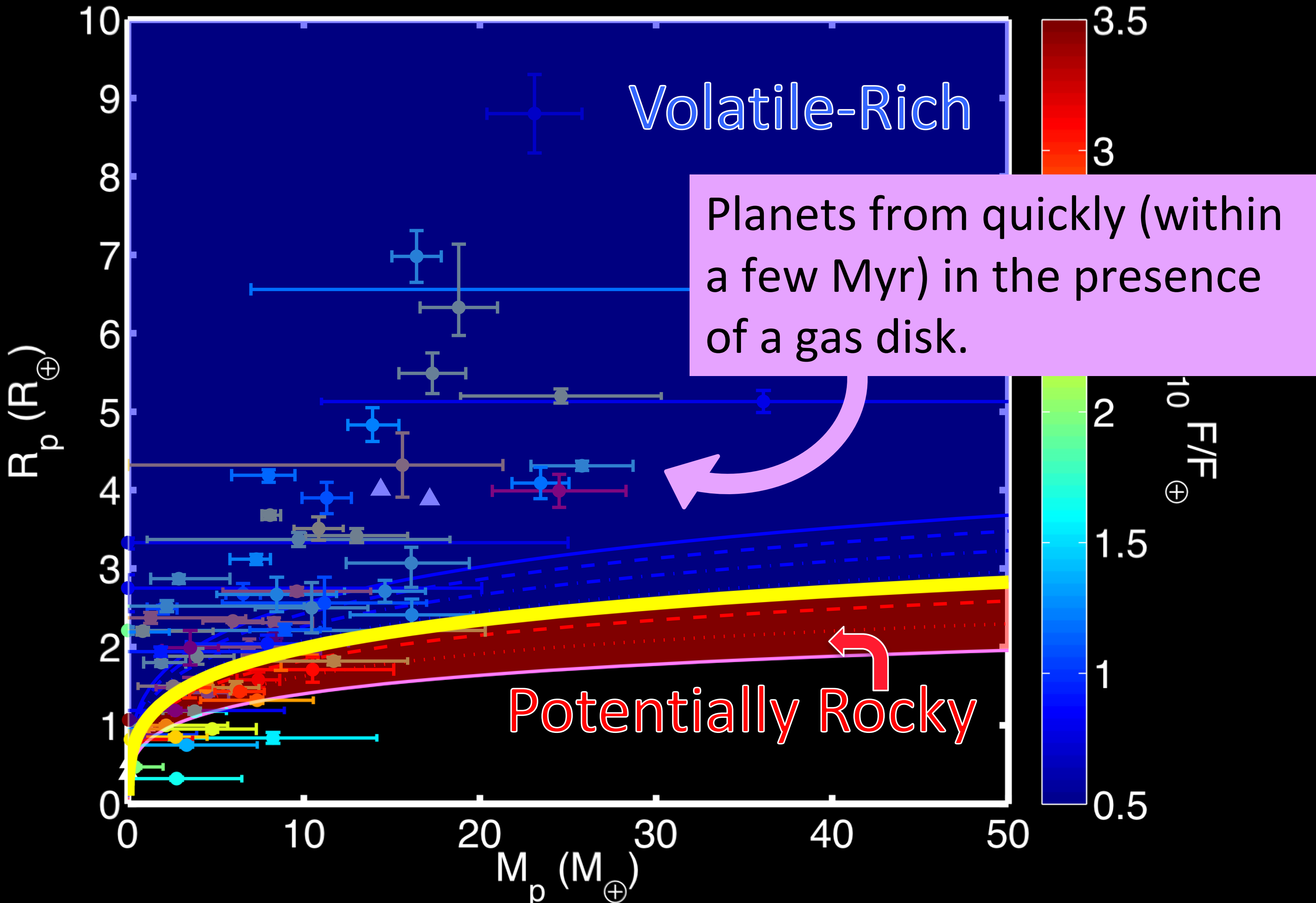



Most 1.6 $R_{Earth}$ planets are not Rocky.

Note: Most planets in sample have P < 50 days.

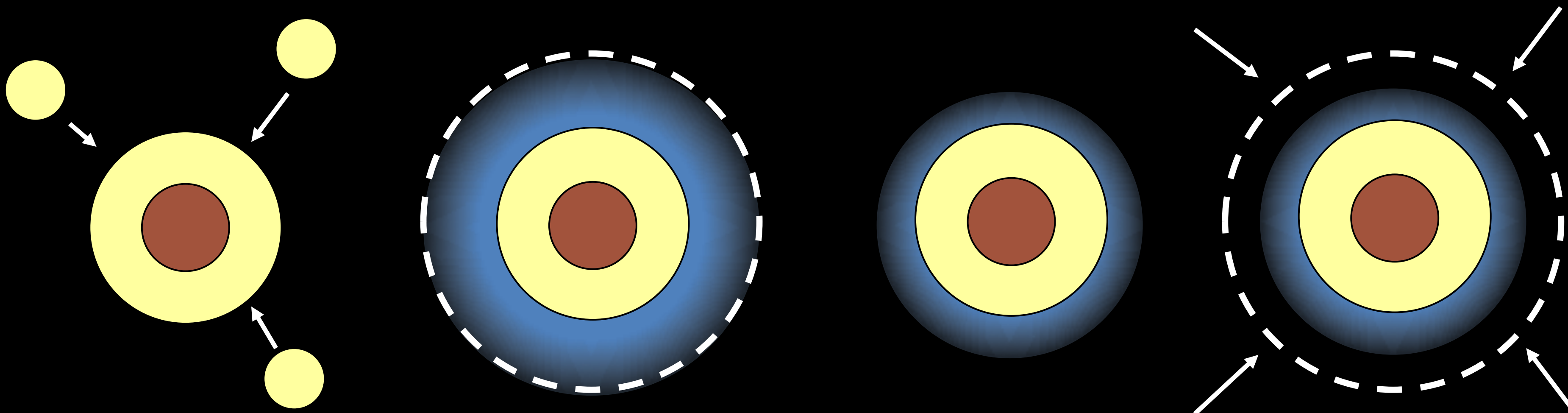
Rogers (2015)

# Which Planets Are Rocky?



# Earth-Mass Cores in Gas Disk Will Accrete H/He

(e.g., Rogers et al. 2011, Piso & Youdin 2014, Lee et al. 2014, Inamdar & Schlichting 2015)



Core Forms via solid coagulation

Accretes gas out to smaller of Hill and Bondi radii

Atmosphere cools and shrinks

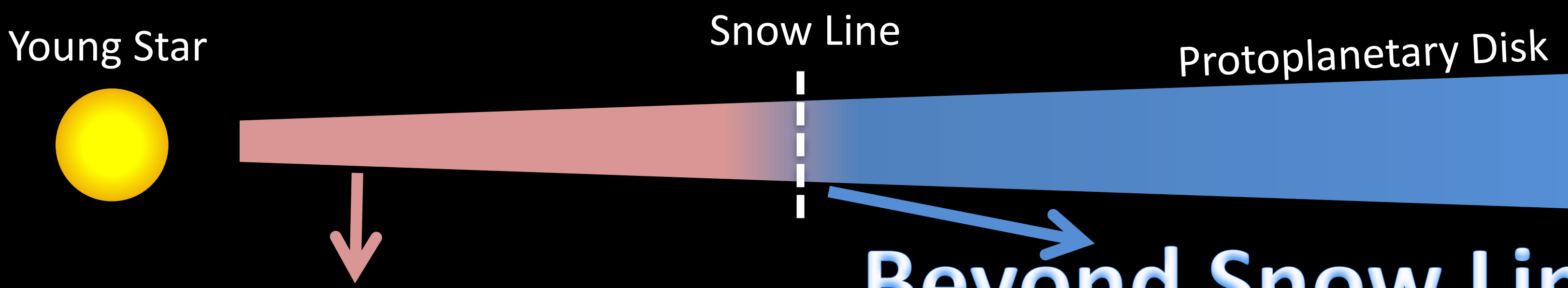
Ambient gas refills the Hill sphere

$$\Delta M/\dot{M} \sim \Delta t_{\rm cool} \sim |\Delta E|/L$$

$$\Delta t_{\rm cool} \sim {\rm Myr} \gg \Delta t_{\rm hydrostatic} \sim {\rm day}$$

If $M_{atm} \sim M_{core}$ , while the gas disk is still present, Run-away Gas accretion begins

# There are competing theories for how these close-in sub-Neptune-size planets formed




## In Situ

e.g., Hansen & Murray, (2012), Chiang & Laughlin (2013), Bodenheimer & Lissauer (2014), Lee & Chiang (2016) , Batygin et al. (2016)

Rocky Heavy Element Interior
(Trace Amounts of Water)

## Beyond Snow Line + Inward Migration

e.g., Terquem & Papaloizou (2007), Cresswell & Nelson (2008), Rogers et al. (2011), Chatterjee & Ford (2015), Inamdar & Schlichting (2015)

Ice-Rock Heavy Element Interior

**The bulk water content of a planet is a tracer of formation location**

# Range of Compositions Consistent with Planet $M_p$ and $R_p$

Example: GJ 436b

Transiting exo-Neptune

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

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

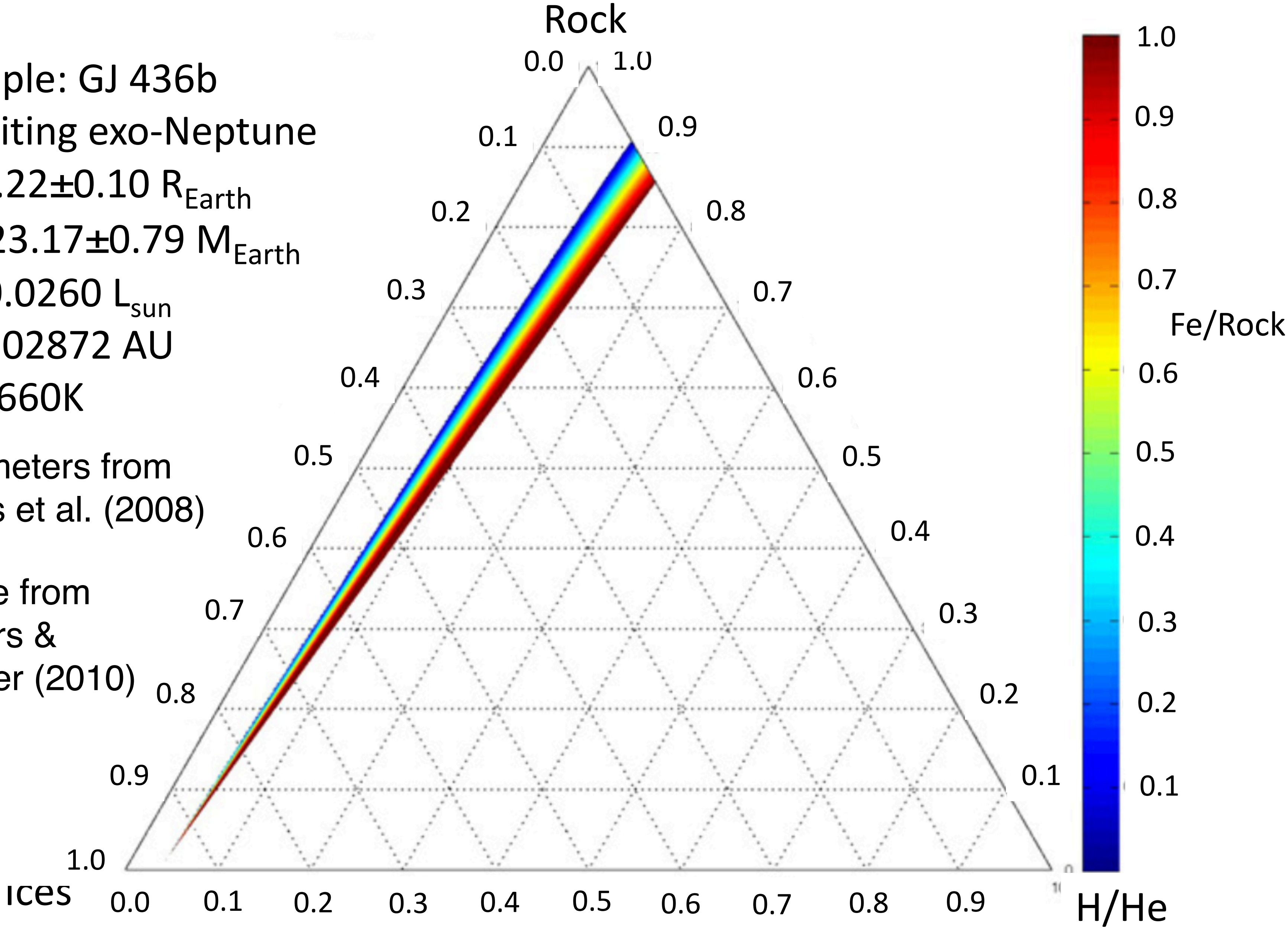
$L_* = 0.0260\ L_{sun}$

$a = 0.02872$ AU

$T_{eq} \sim 660$K

Parameters from Torres et al. (2008)

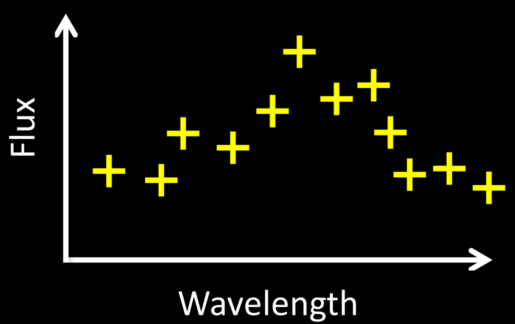
Figure from Rogers & Seager (2010)



# Searching for Water in Distant Worlds

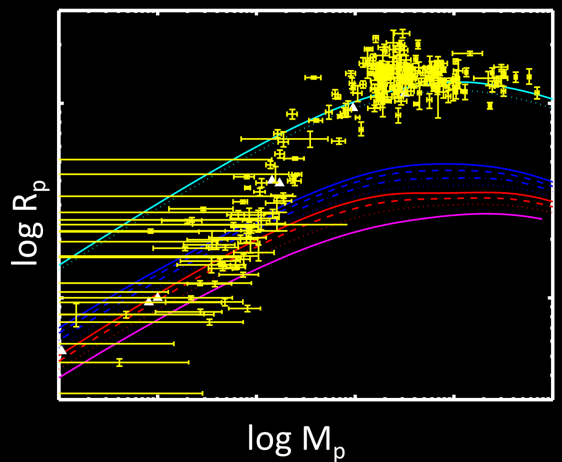
Potential future approaches to constrain the bulk water content of distant exoplanets:

## Atmospheric Spectra



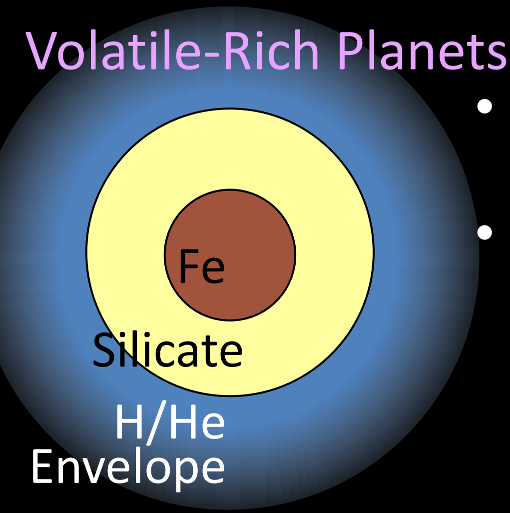

Study the planet interior-atmosphere connection to identify atmospheric abundance patterns that could be used as robust indicators of water in the deep interior.

## Population Statistics




Consider large numbers of observed exoplanets to identify sub-populations and trends in the planet $M_p$-$R_p$ distribution, breaking some of the degeneracies in exoplanet compositions.

# Empirical Insights Into Low-Mass Planet Interior Structure, Formation and Evolution

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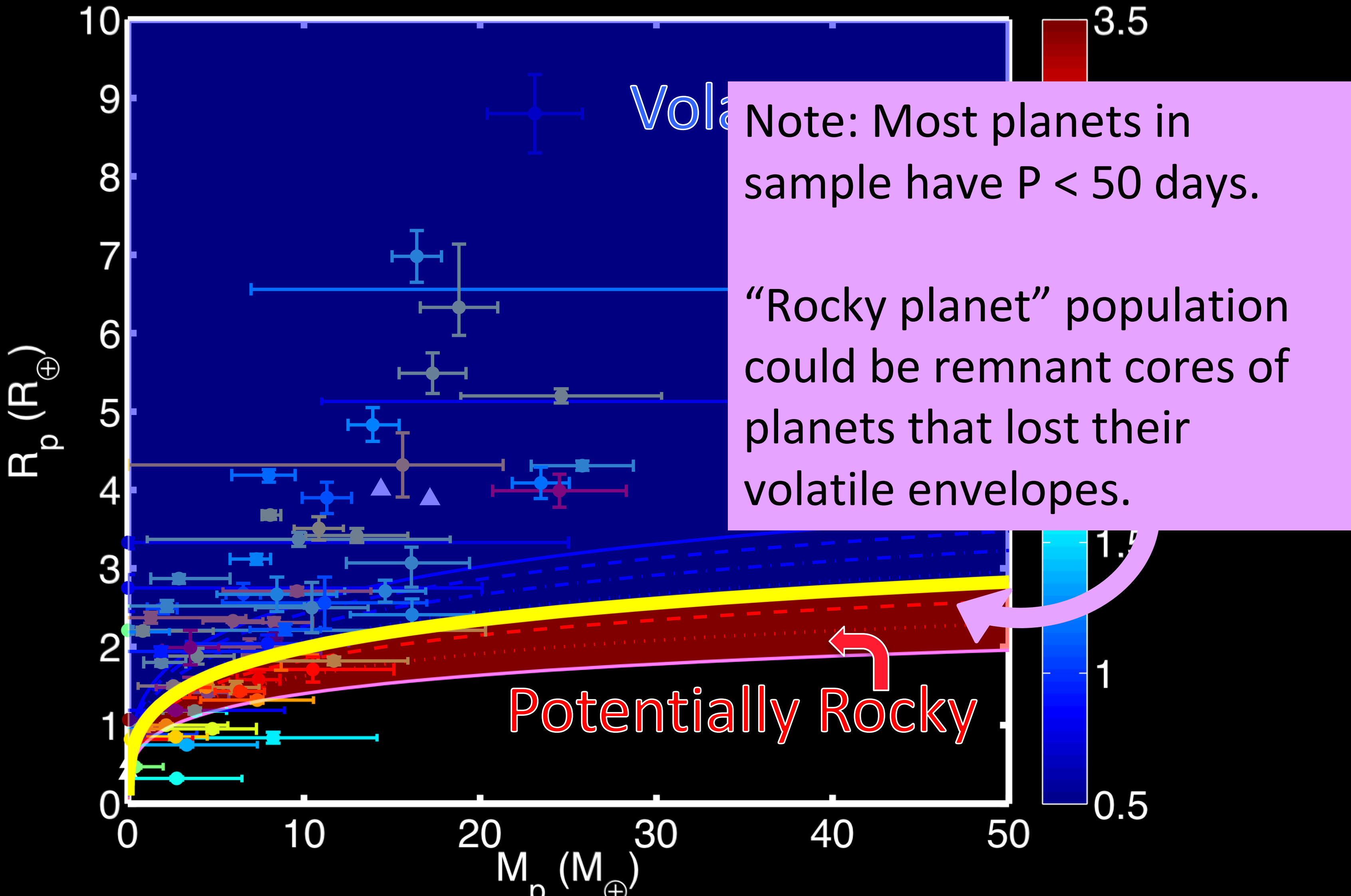
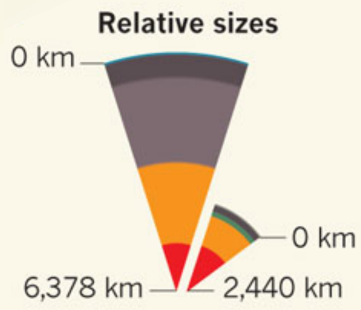
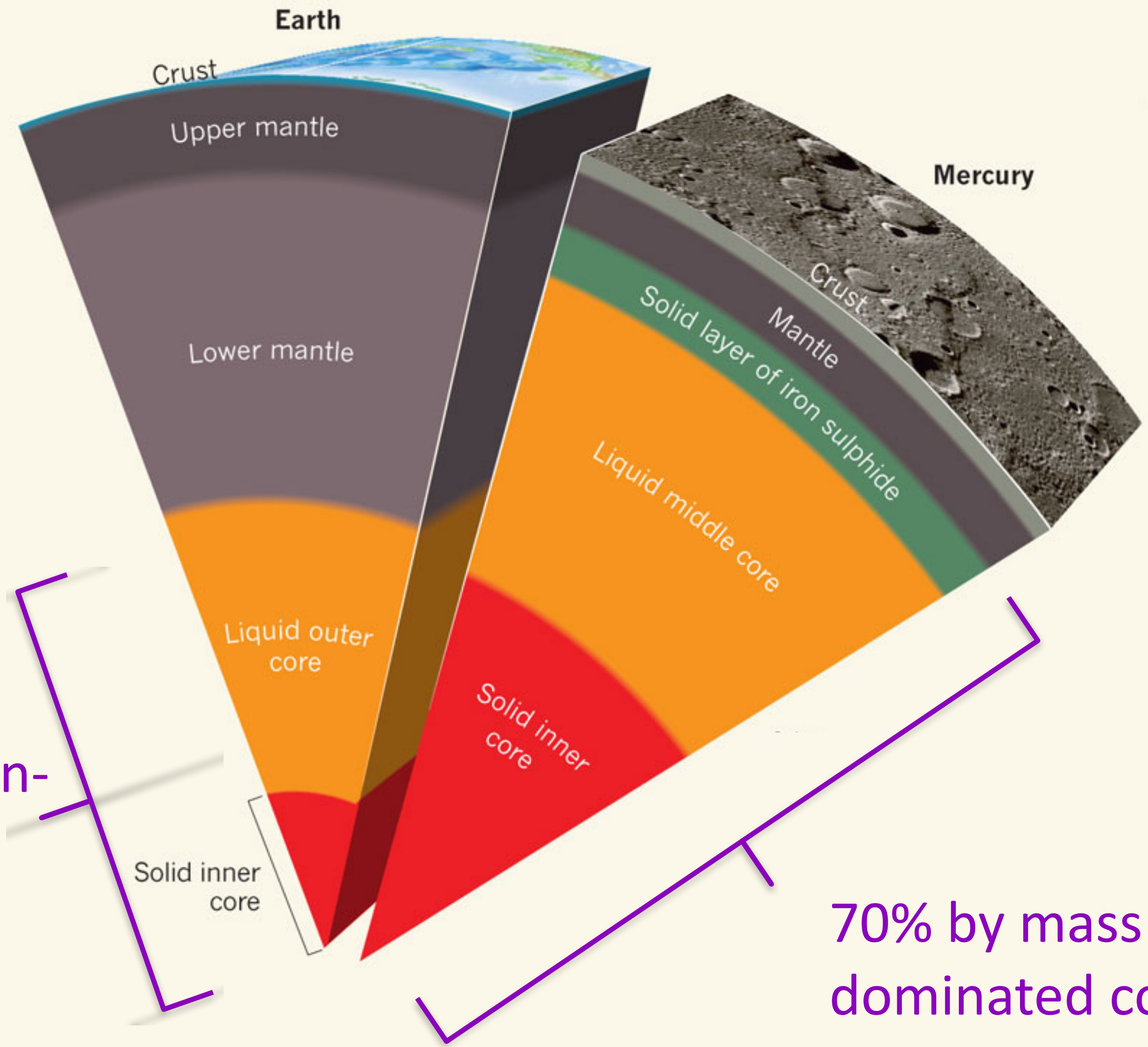


# Earth versus Mercury

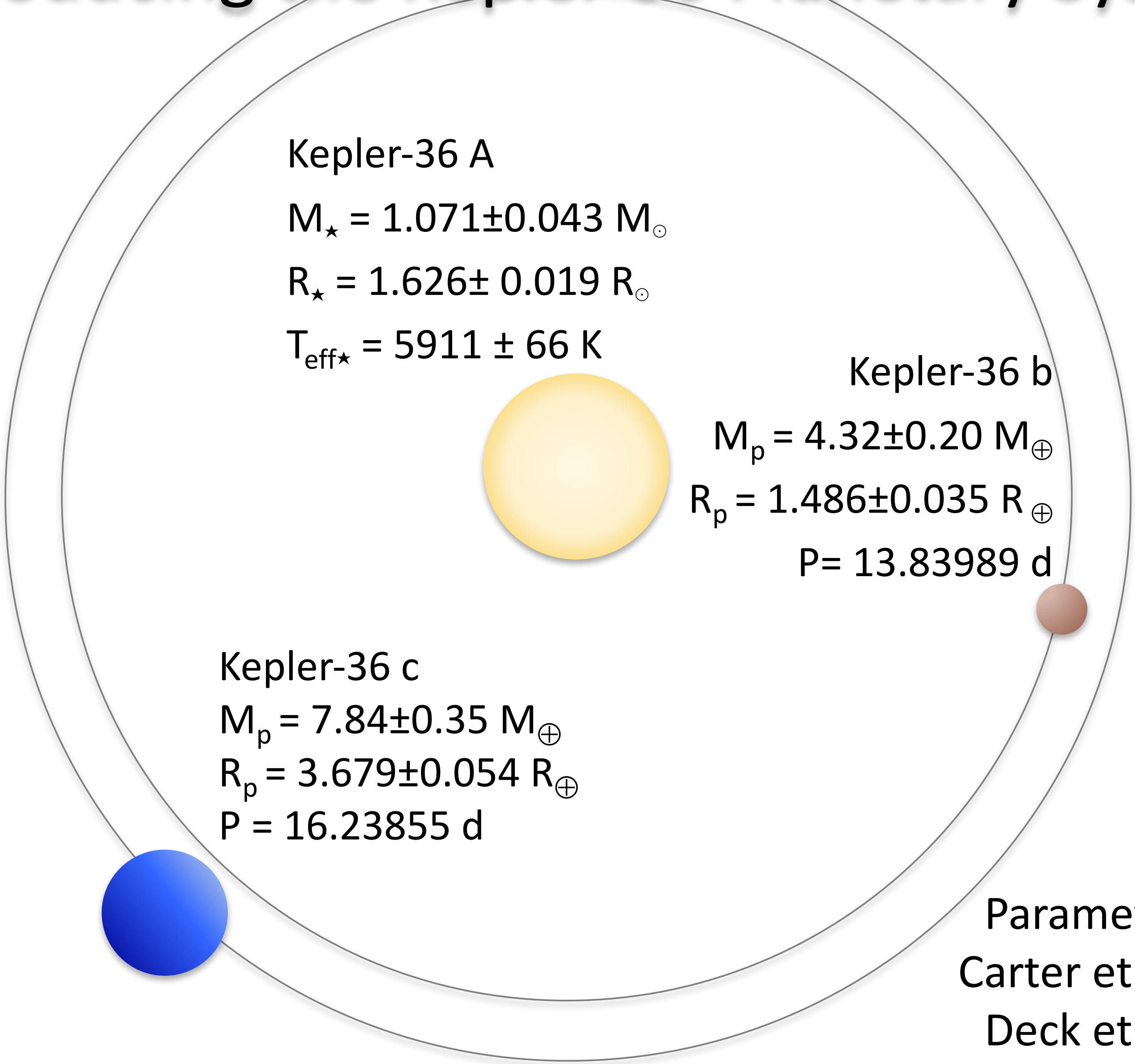



32.5% by mass in iron-dominated core

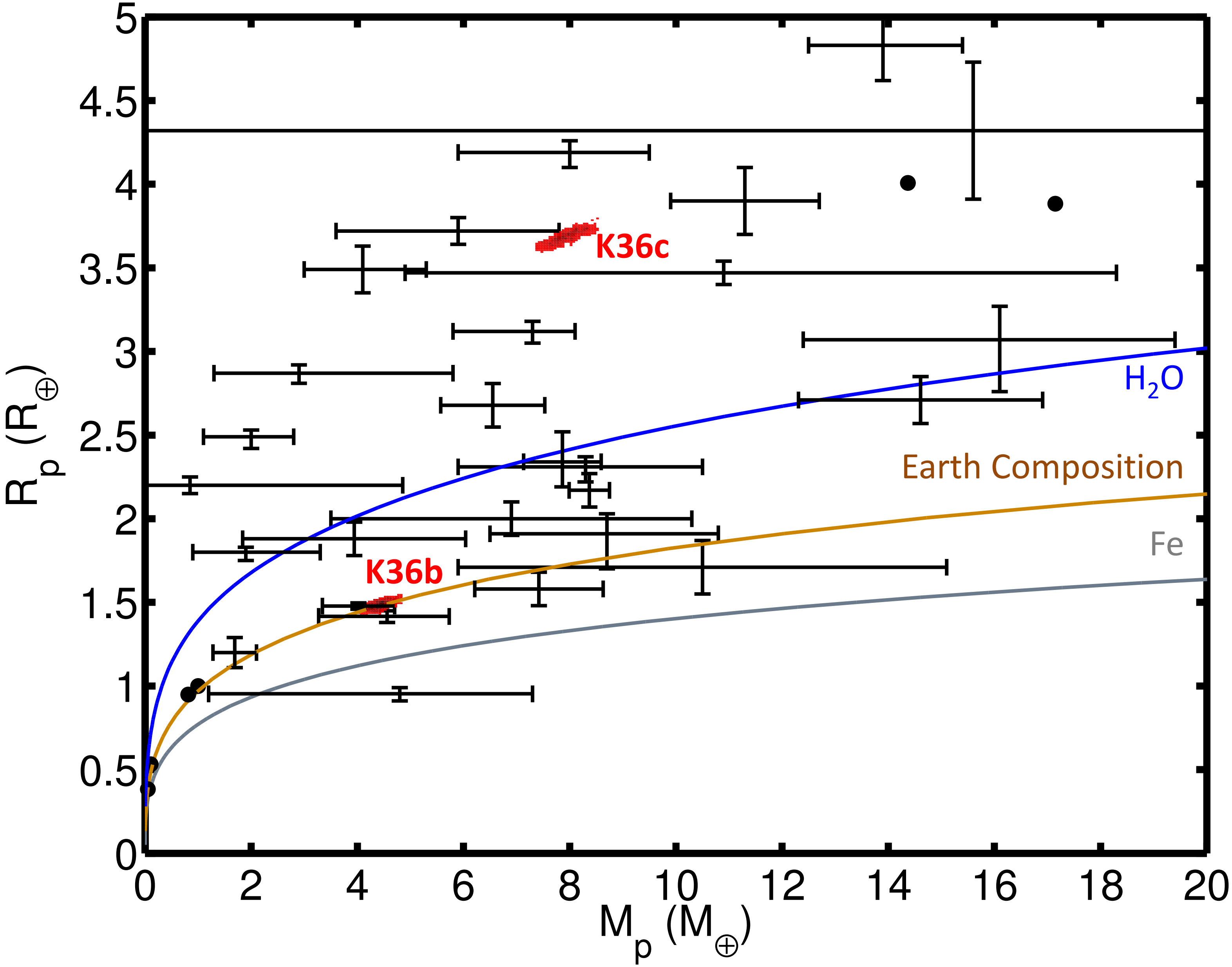
70% by mass in iron-dominated core

# Introducing the Kepler-36 Planetary System

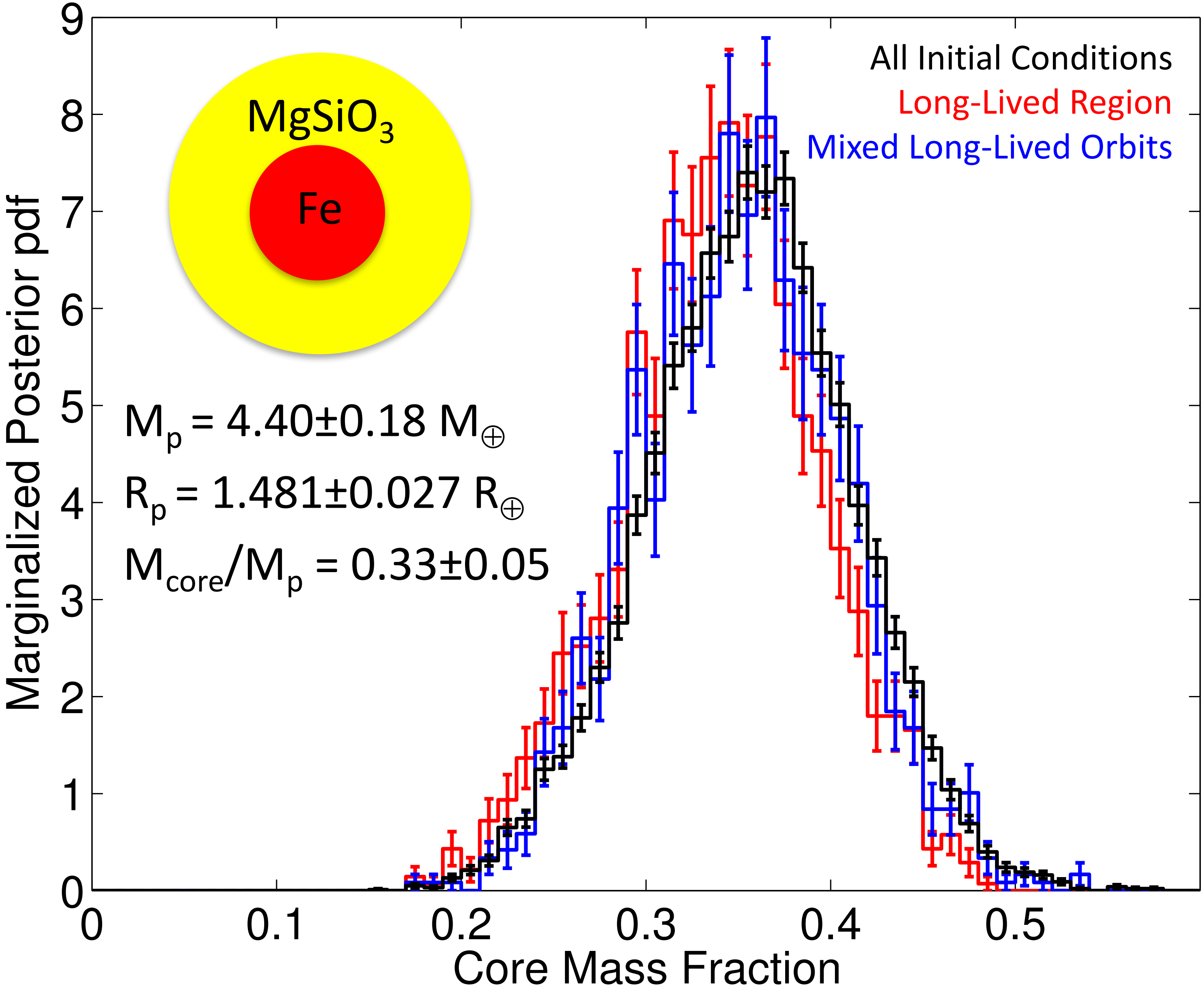



Parameters from:
Carter et al. (2012)
Deck et al. (2012)

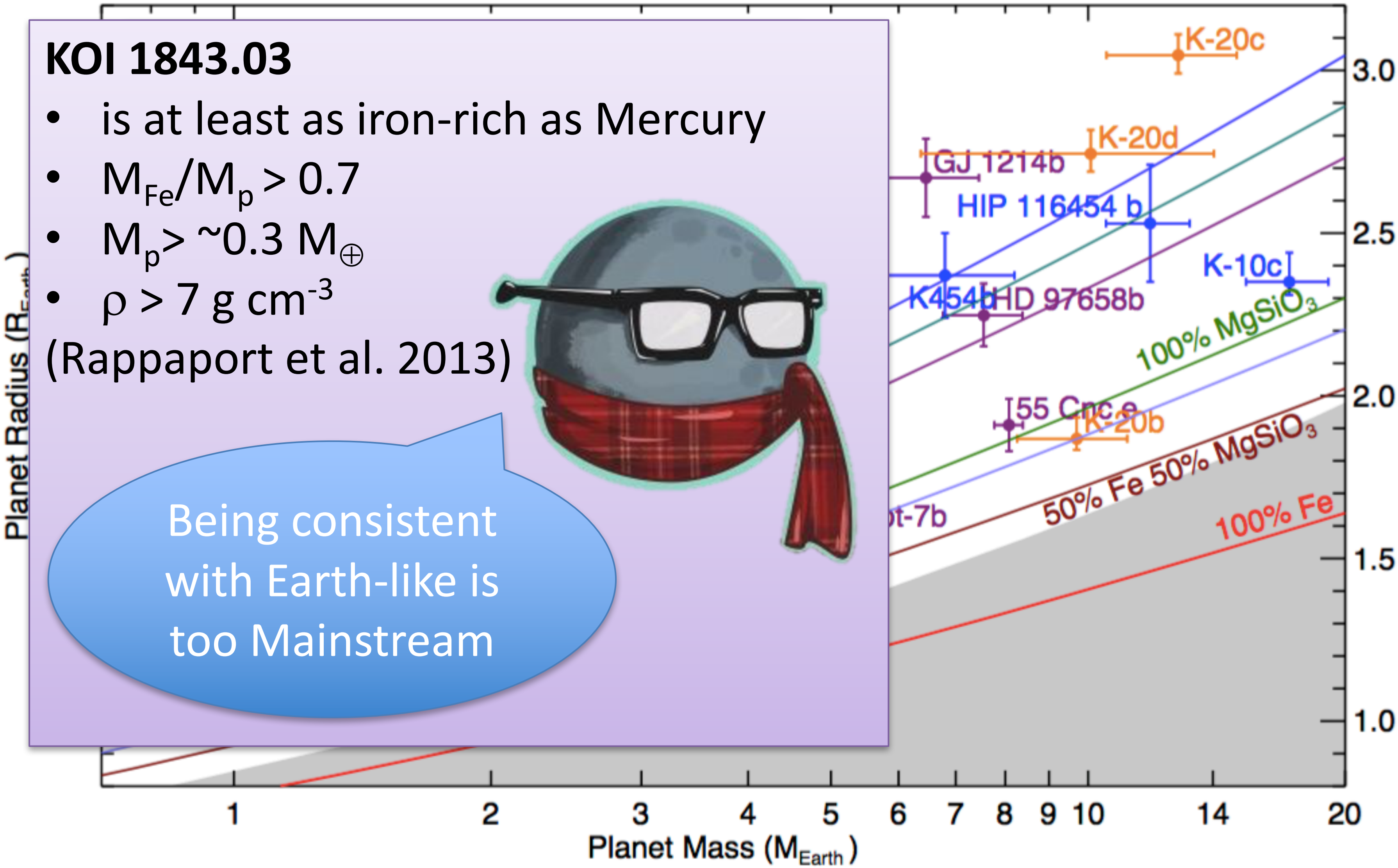
# Kepler-36 b Mass Measured within 4.2%, Radius Measured within 1.8%



# Kepler-36 b is Consistent with an Earth-like Composition



# Rocky Exoplanets (with with $\sigma_M/M_p$<20%) also Consistent with Earth-like Bulk Compositions




**KOI 1843.03**

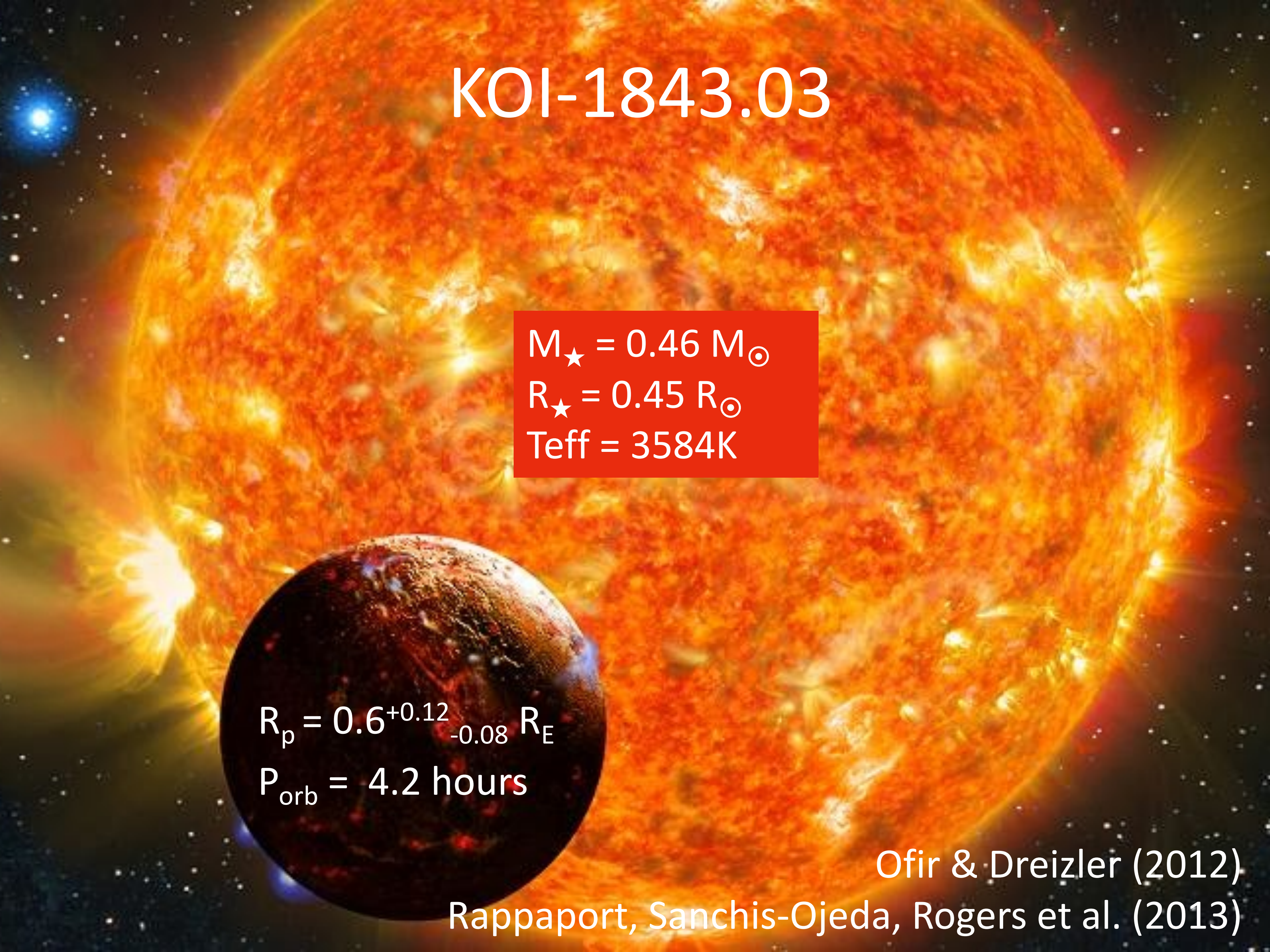
- is at least as iron-rich as Mercury
- $M_{Fe}/M_p > 0.7$
- $M_p > \sim 0.3\ M_\oplus$
- $\rho > 7$ g cm$^{-3}$

(Rappaport et al. 2013)

Being consistent with Earth-like is too Mainstream

Dessing et al. (2015), Zeng & Sasselov (2016), Buchhave et al. (2016)

# KOI-1843.03



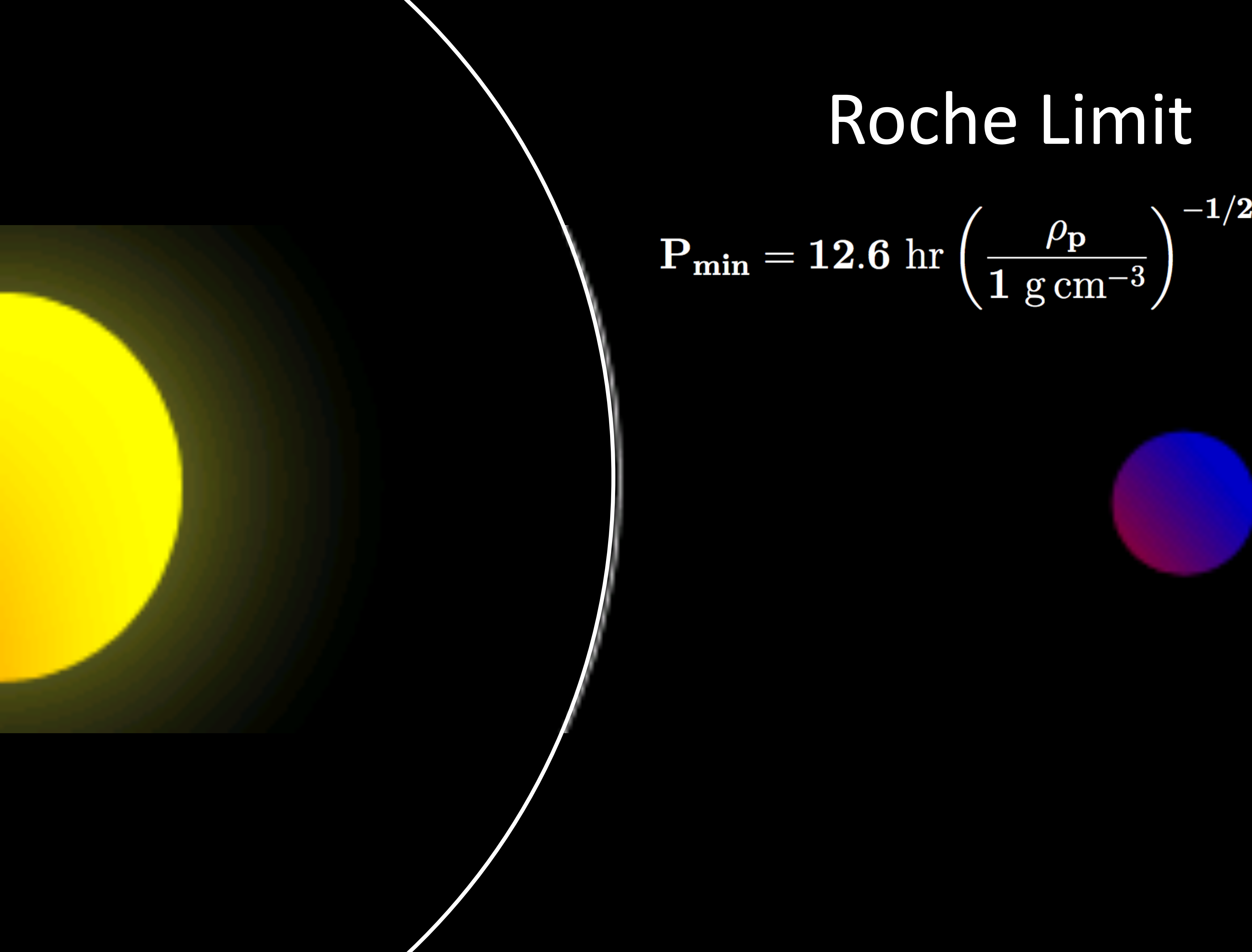
$M_\star = 0.46\ M_\odot$
$R_\star = 0.45\ R_\odot$
Teff = 3584K

$R_p = 0.6^{+0.12}_{-0.08}\ R_E$
$P_{orb} =\ 4.2$ hours

Ofir & Dreizler (2012)
Rappaport, Sanchis-Ojeda, Rogers et al. (2013)

# Roche Limit

$$P_{min} = 12.6 \text{ hr} \left( \frac{\rho_p}{1 \text{ g cm}^{-3}} \right)^{-1/2}$$



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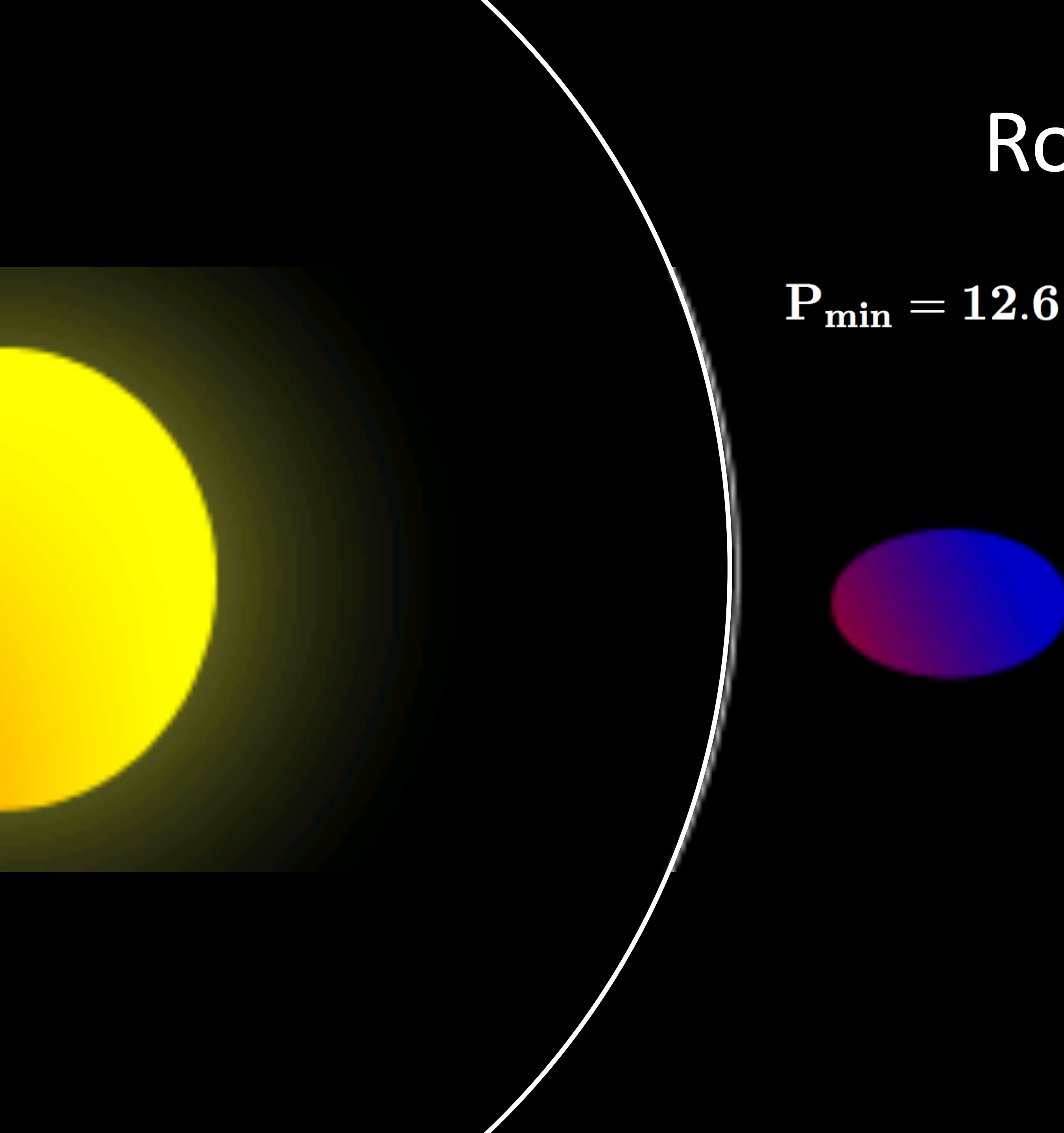

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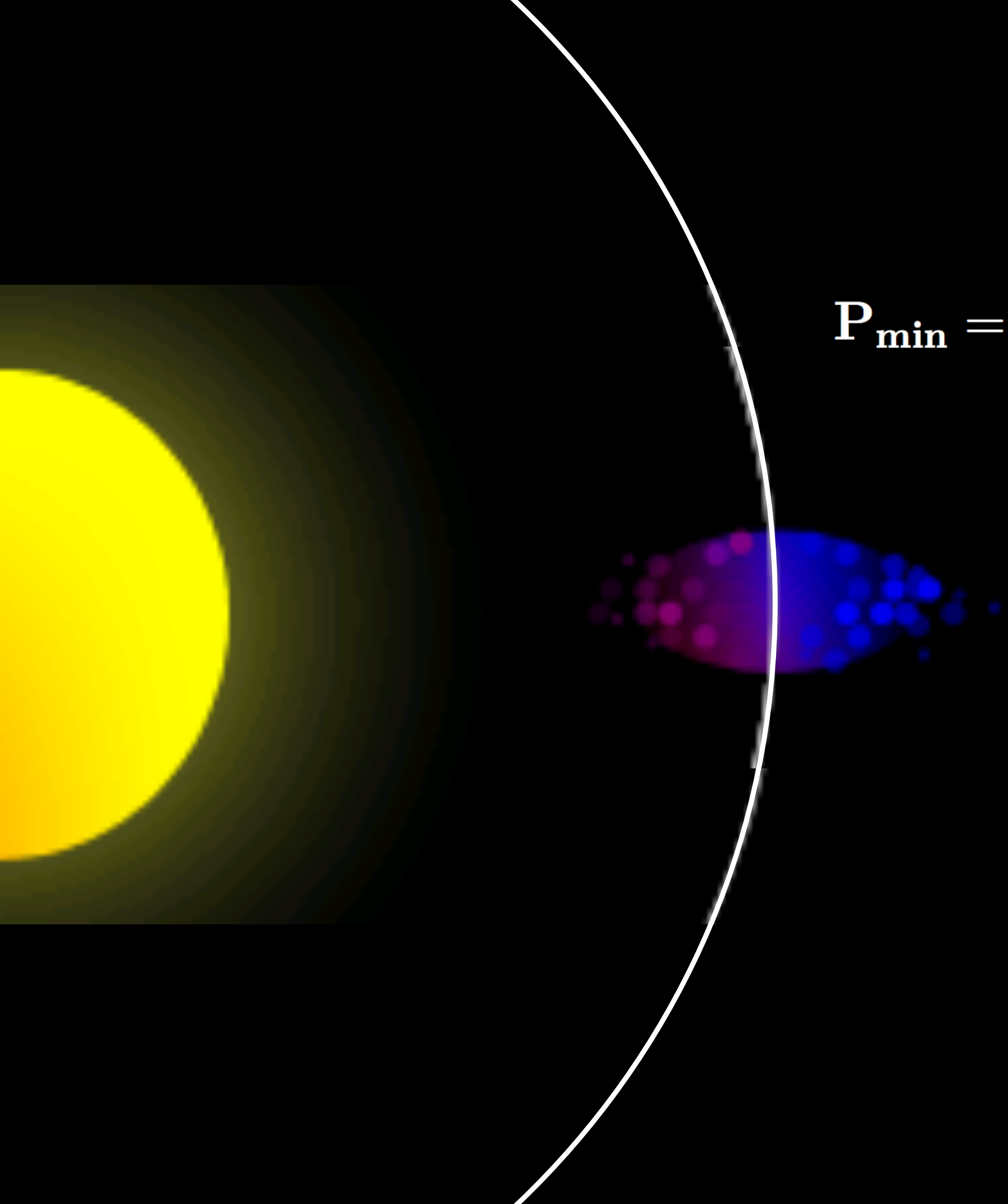

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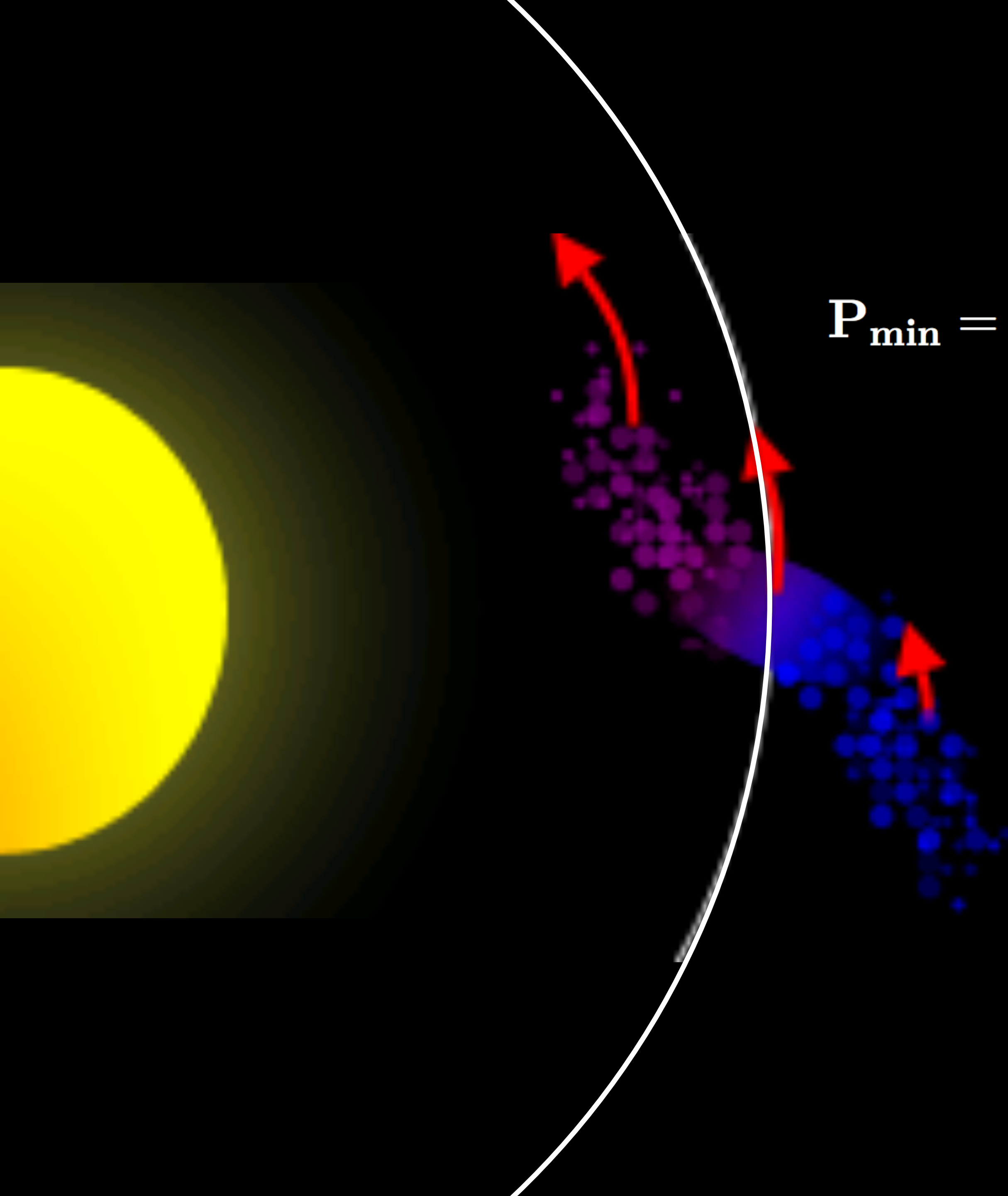
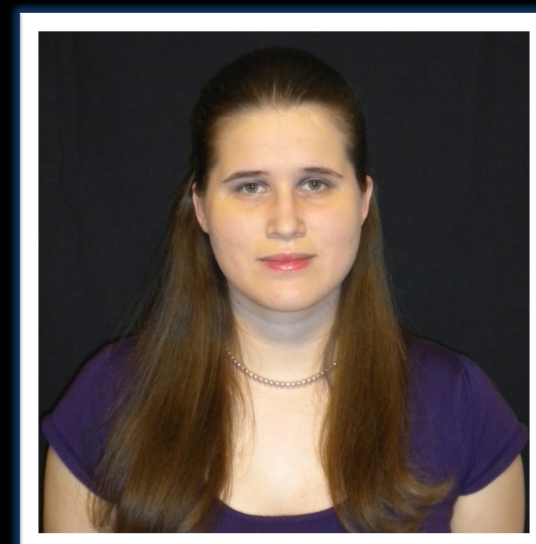
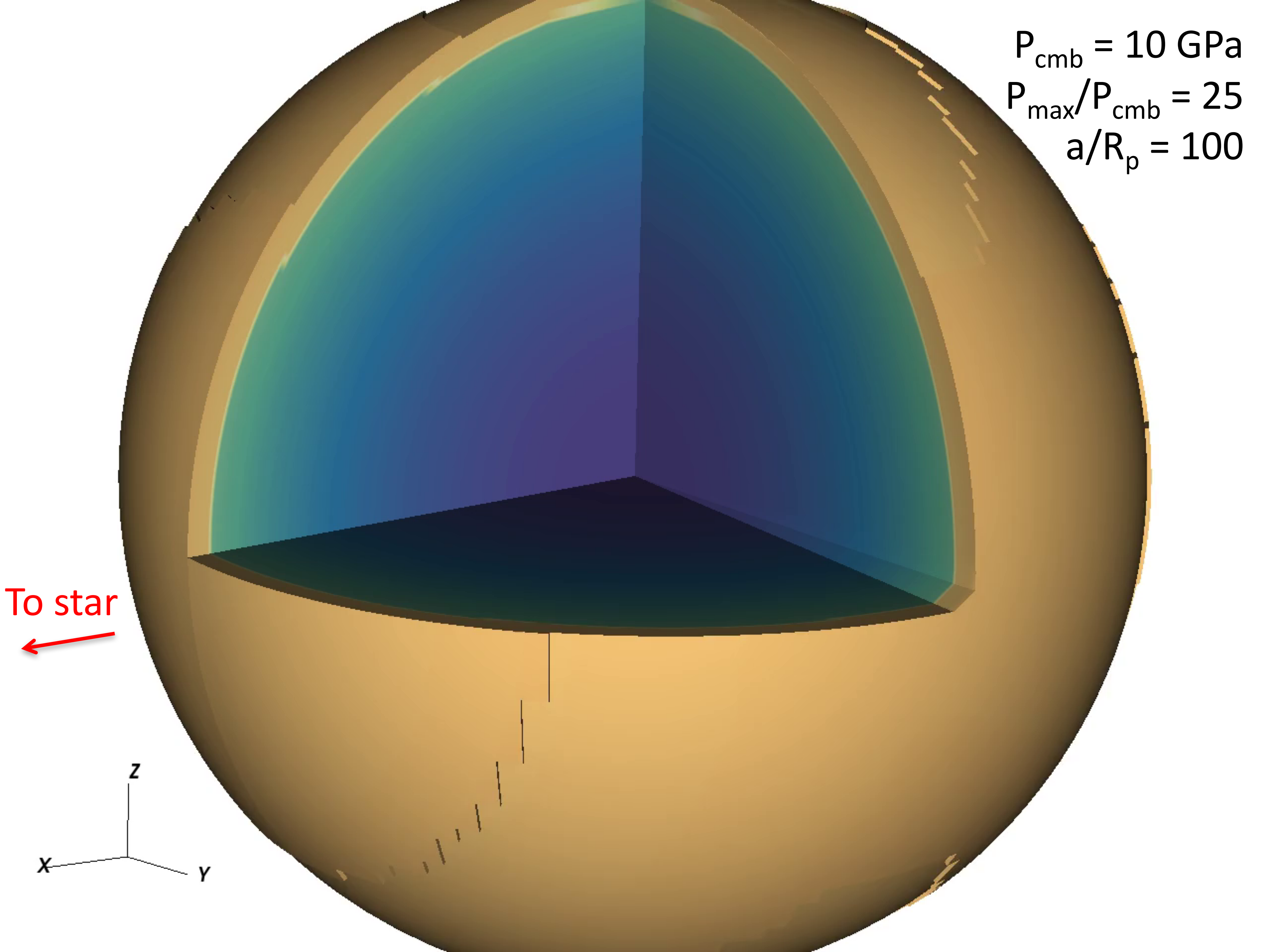


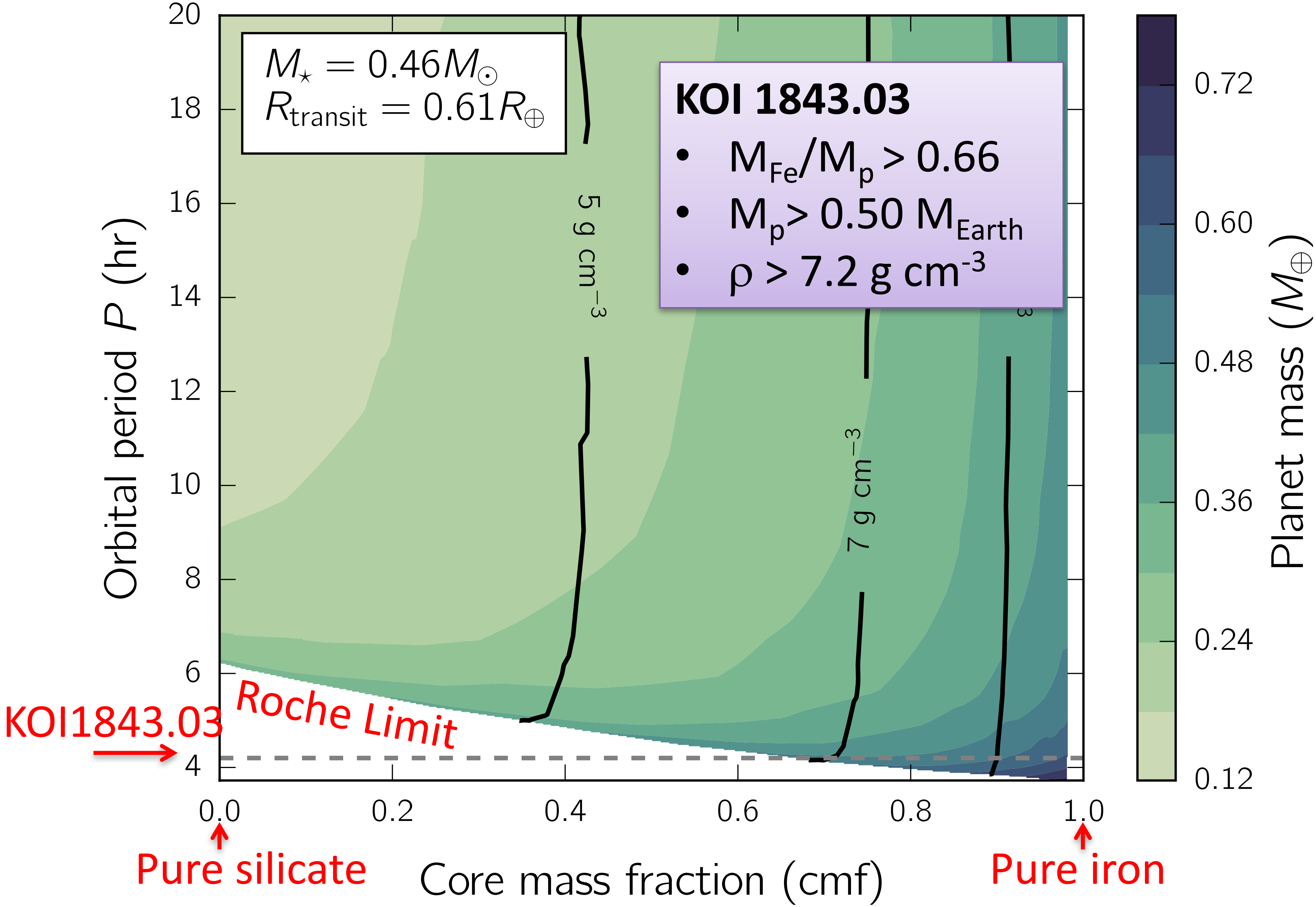


Ellen Price
Harvard Grad Student



P_cmb = 10 GPa
P_max/P_cmb = 25
a/R_p = 100
To star
Z
X
Y

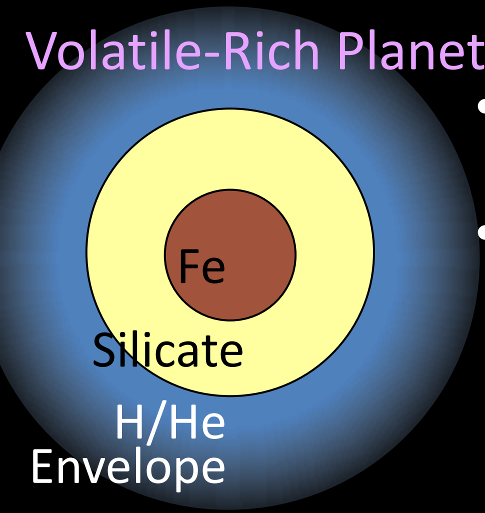
# Revised Constraints on the Properties of KOI-1843.03




Price & Rogers (in prep)

# Empirical Insights Into Low-Mass Planet Interior Structure, Formation and Evolution

## Volatile-Rich Planets




- Most 1.6 $R_{earth}$ planets have voluminous volatile envelopes.
- Abundant population of close-in low-mass low-density planets formed quickly (within a few Myr) in the presence of a gas disk.
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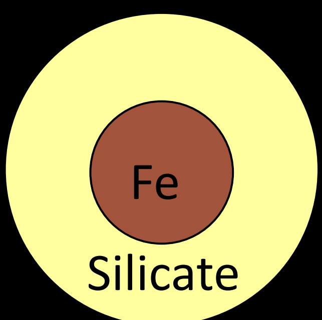
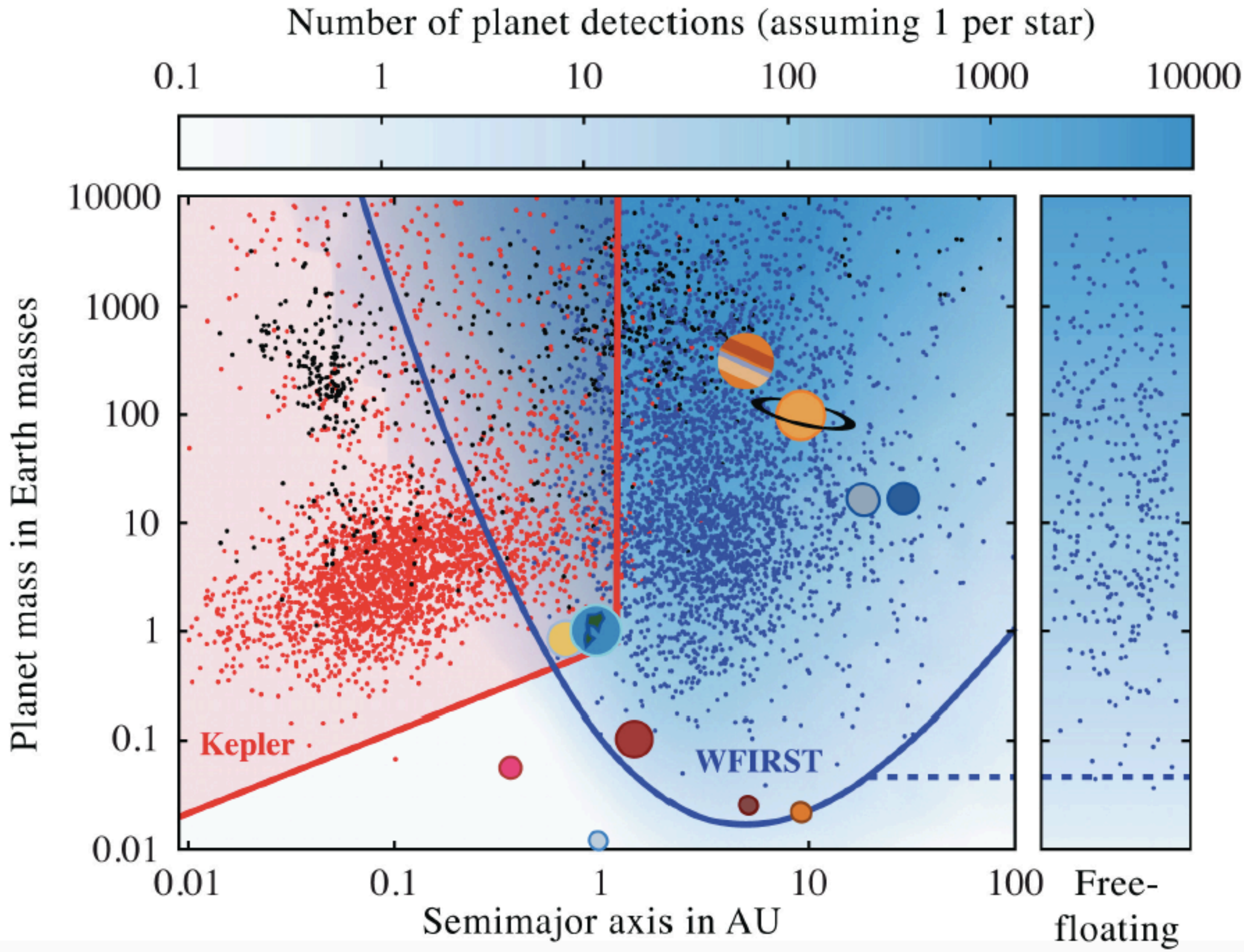
## Rocky Planets




- Most rocky planets with measured M-R (including Kepler-36b) are consistent with an Earth-like composition.
  - KOI-1843.03 is Fe-enhanced exo-Mercury
- Rocky planets with M-R measurements could be remnant cores of planets that lost their volatile envelopes.

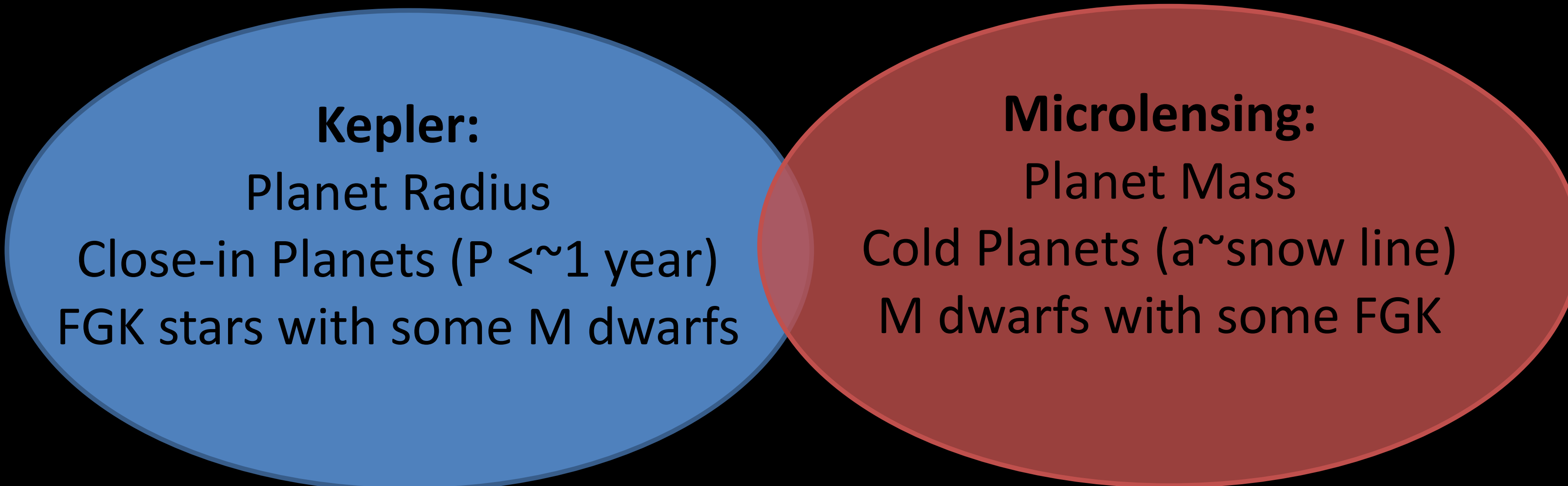
# Microlensing: Completing the Exoplanet Census



# Combining/Comparing Kepler and Microlensing Statistics

Poster: Andrew Neil

Talk: Angie Wolfgang




Need: Probabilistic $M_p$-Composition-$R_p$-Insolation-$M_*$ distribution

A Universal probabilistic M-R relation is insufficient because:

- Less irradiated volatile envelopes are smaller
- Composition trends due to evolution (e.g., mass loss)
- Composition trends due to formation

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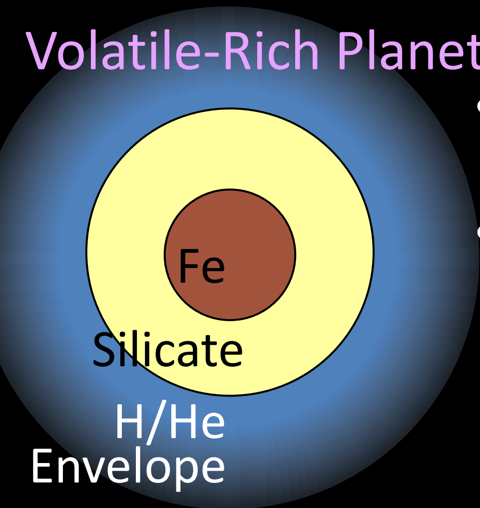
## Volatile-Rich Planets

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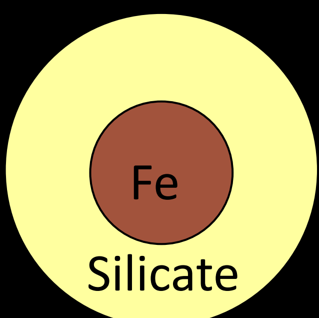
## Rocky Planets




- Most rocky planets with measured M-R (including Kepler-36b) are consistent with an Earth-like composition.
  - KOI-1843.03 is Fe-enhanced exo-Mercury
- Rocky planets with M-R measurements could be remnant cores of planets that lost their volatile envelopes.