Glimpsing the Distribution of Exoplanet Bulk Compositions

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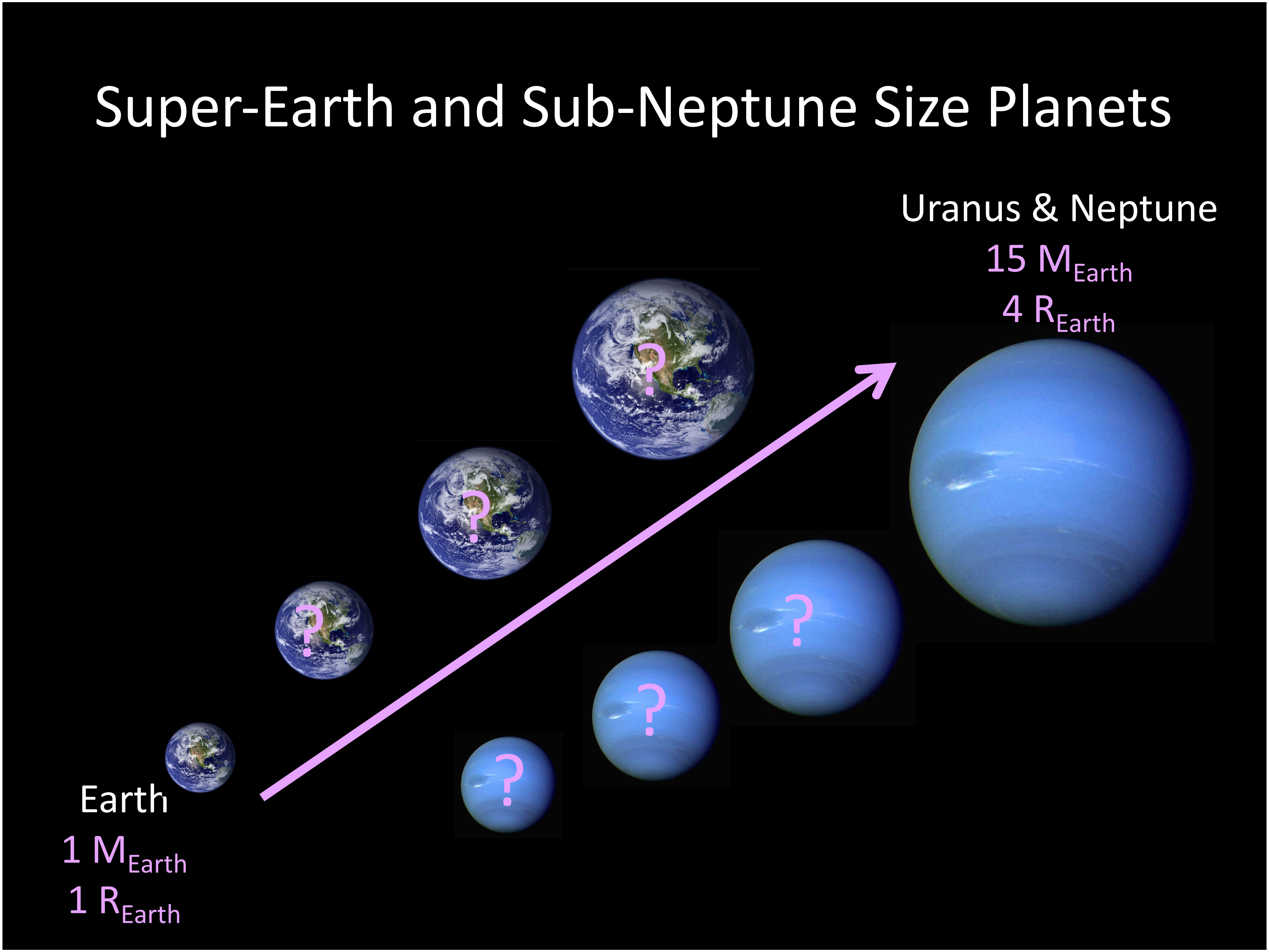
MIRA Volatiles – October 16, 2017

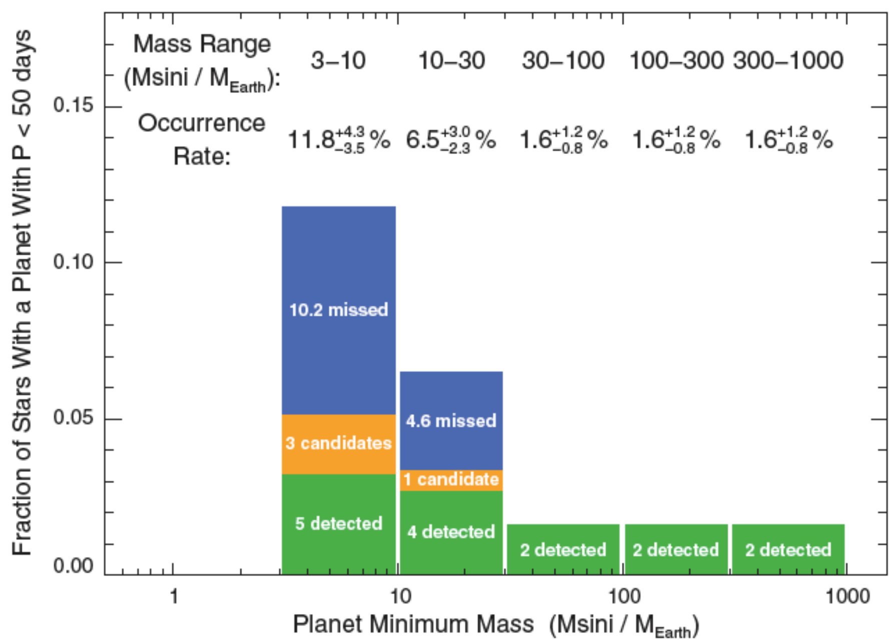

Super-Earth and Sub-Neptune Size Planets
Uranus & Neptune
15 M_{Earth}
4 R_{Earth}
?
?
?
?
?
?
Earth
1 M_{Earth}
1 R_{Earth}

Sub-Neptune size/mass planets are common!

Microlensing:

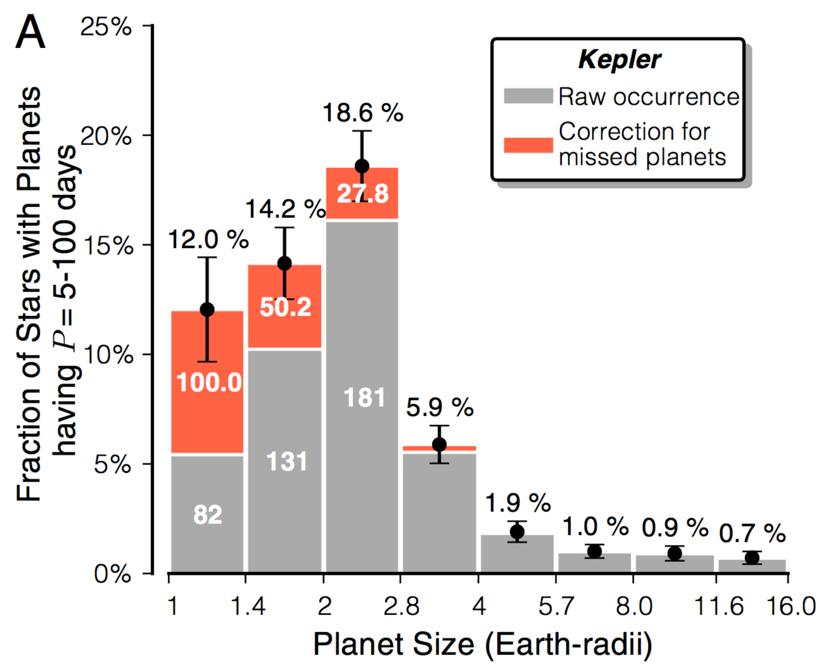
- Beyond the snow-line, Neptune-mass planets are at least three times more common than Jupiters at the 95% confidence level. Sumi et al. (2010)
- 62±36% of stars have a 5-10 M_{Earth} planet at 0.5-10 AU. Cassan et al. (2012)

Radial Velocity:

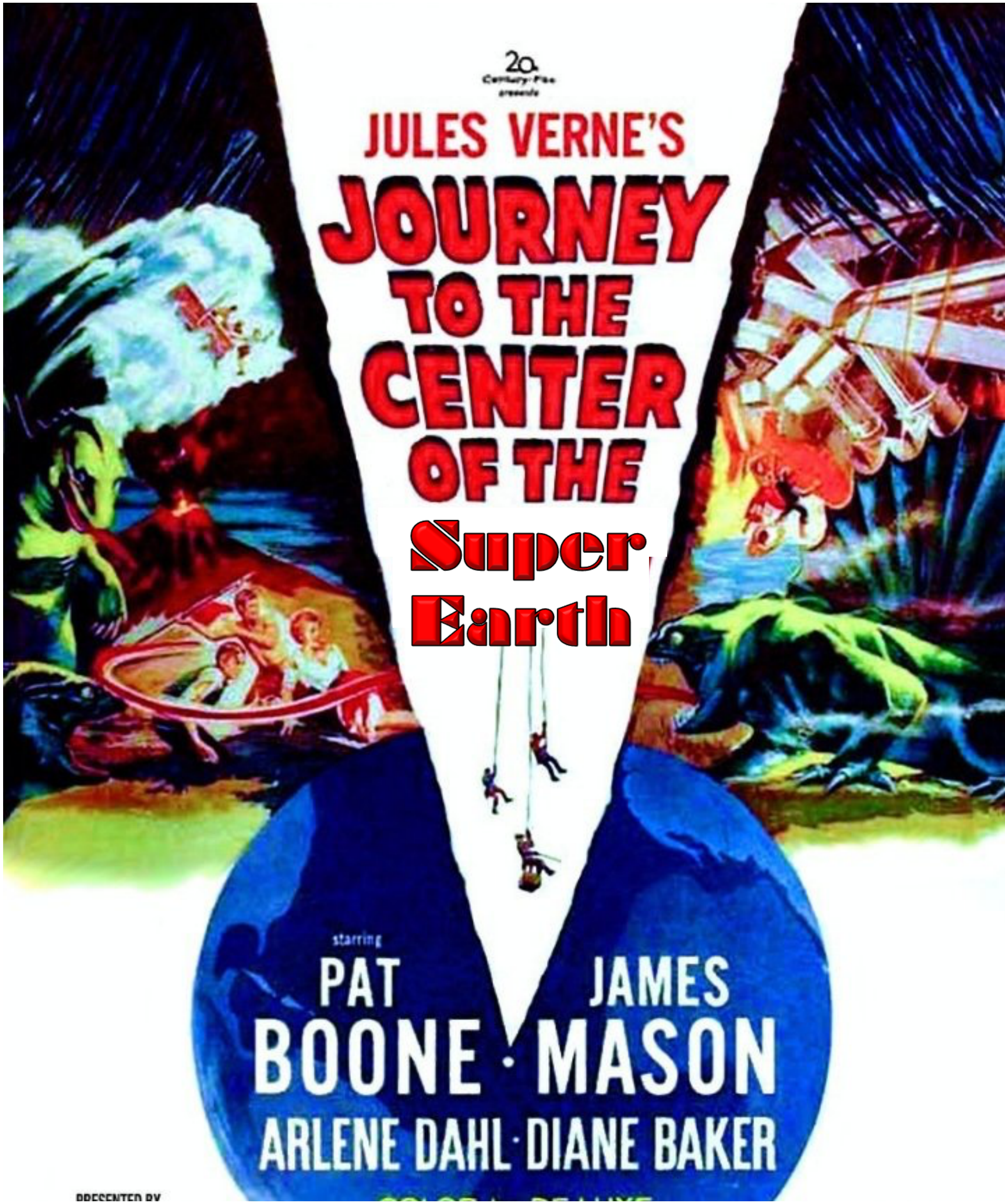


Howard et al (2010)

Transits:

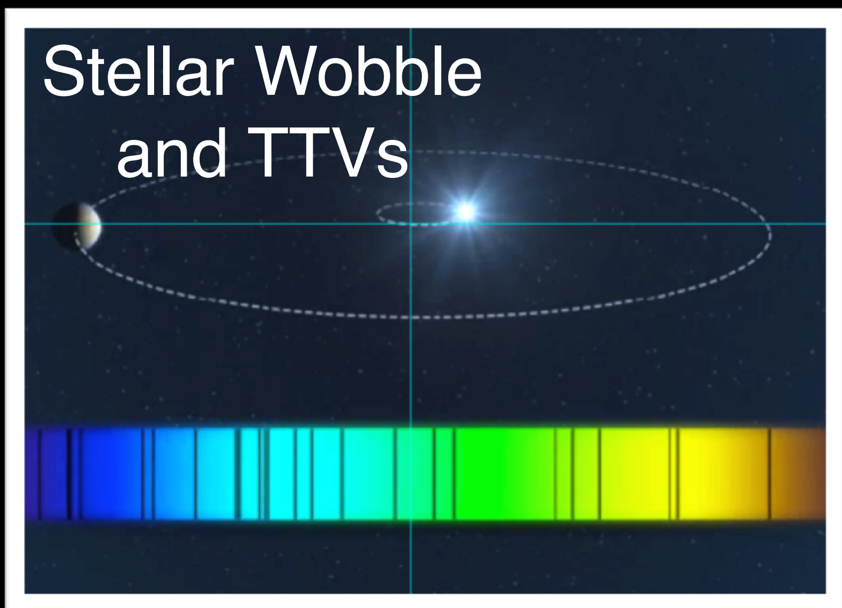


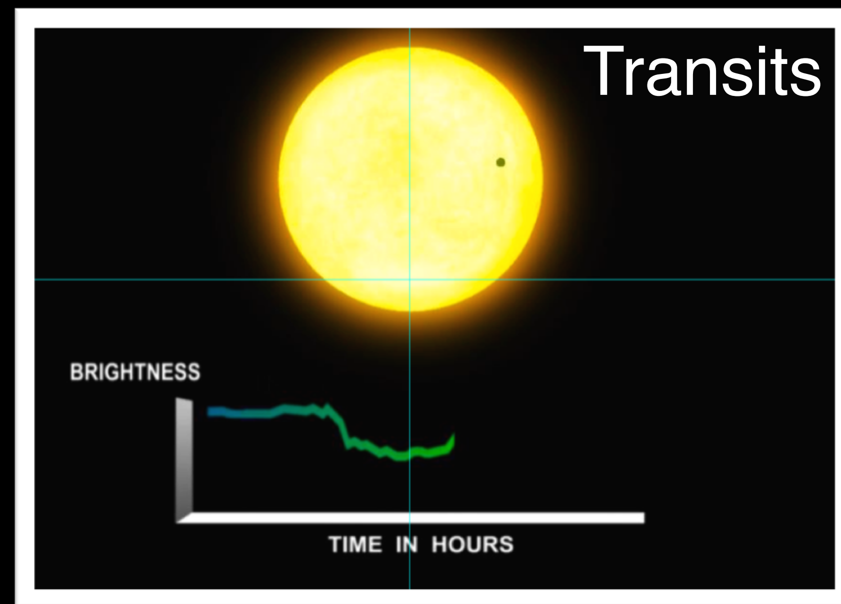
Petigura et al. (2013)



- Review Planet Interior Structure and Evolution Models
- Highlight Recent Empirical Insights Into Low-Mass Planet Evolution and Formation Histories
- Future Prospects

Planets Detected both Dynamically and in Transit are Valuable!



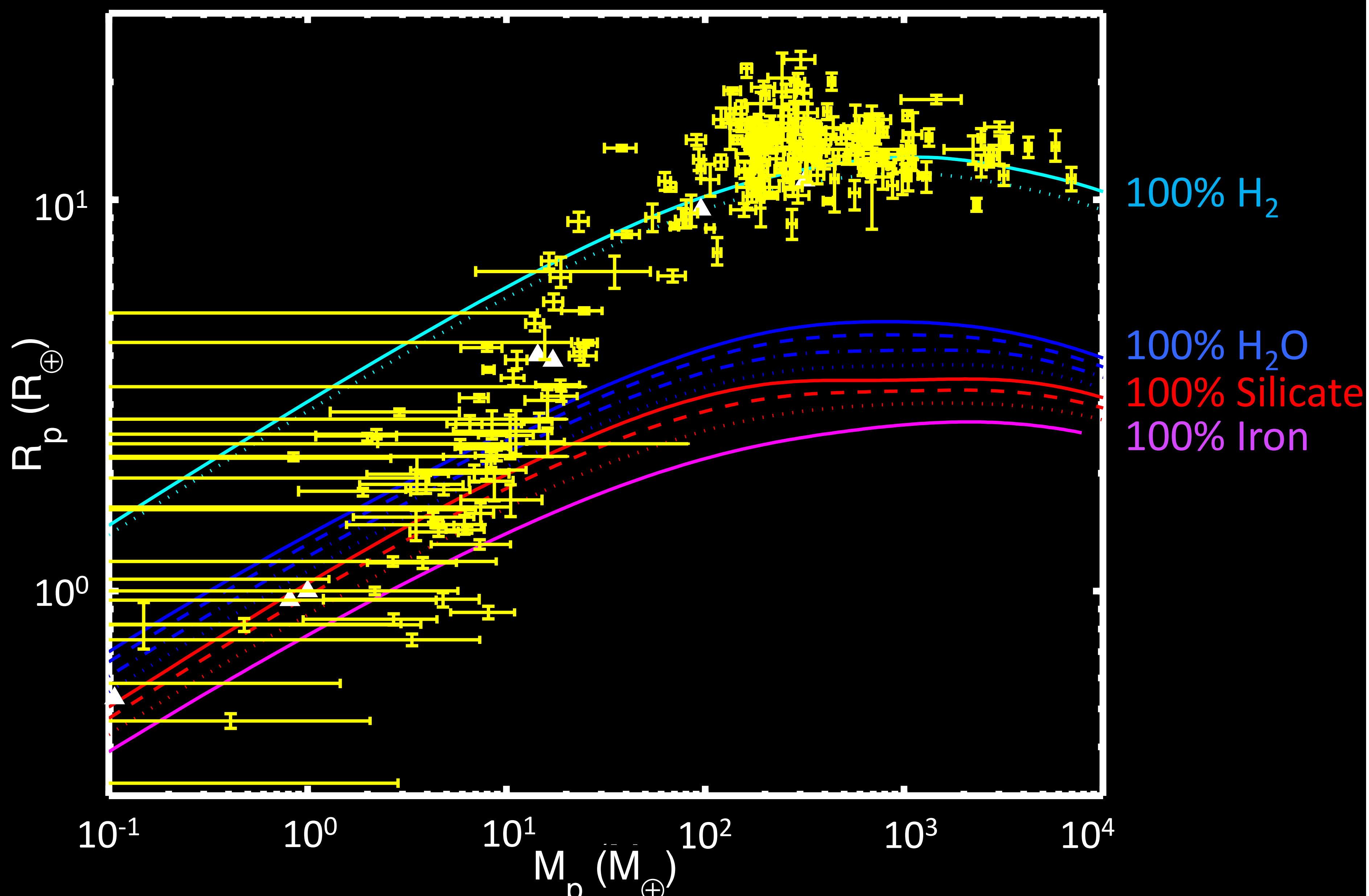


Planet Mass

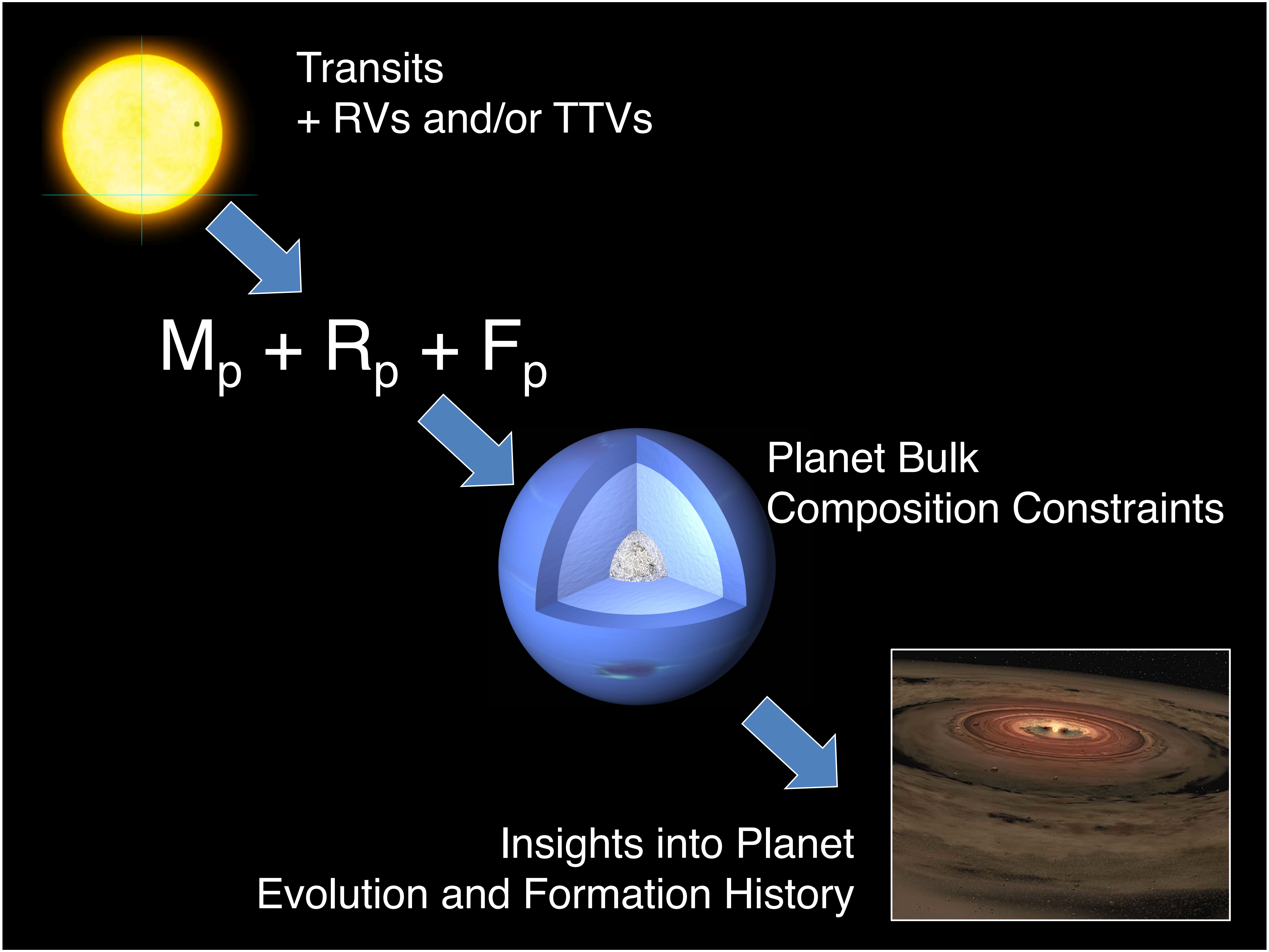
Planet Radius

Planet Density

Planet Mass-Radius Measurements



Seager et al. (2007) M-R Relations

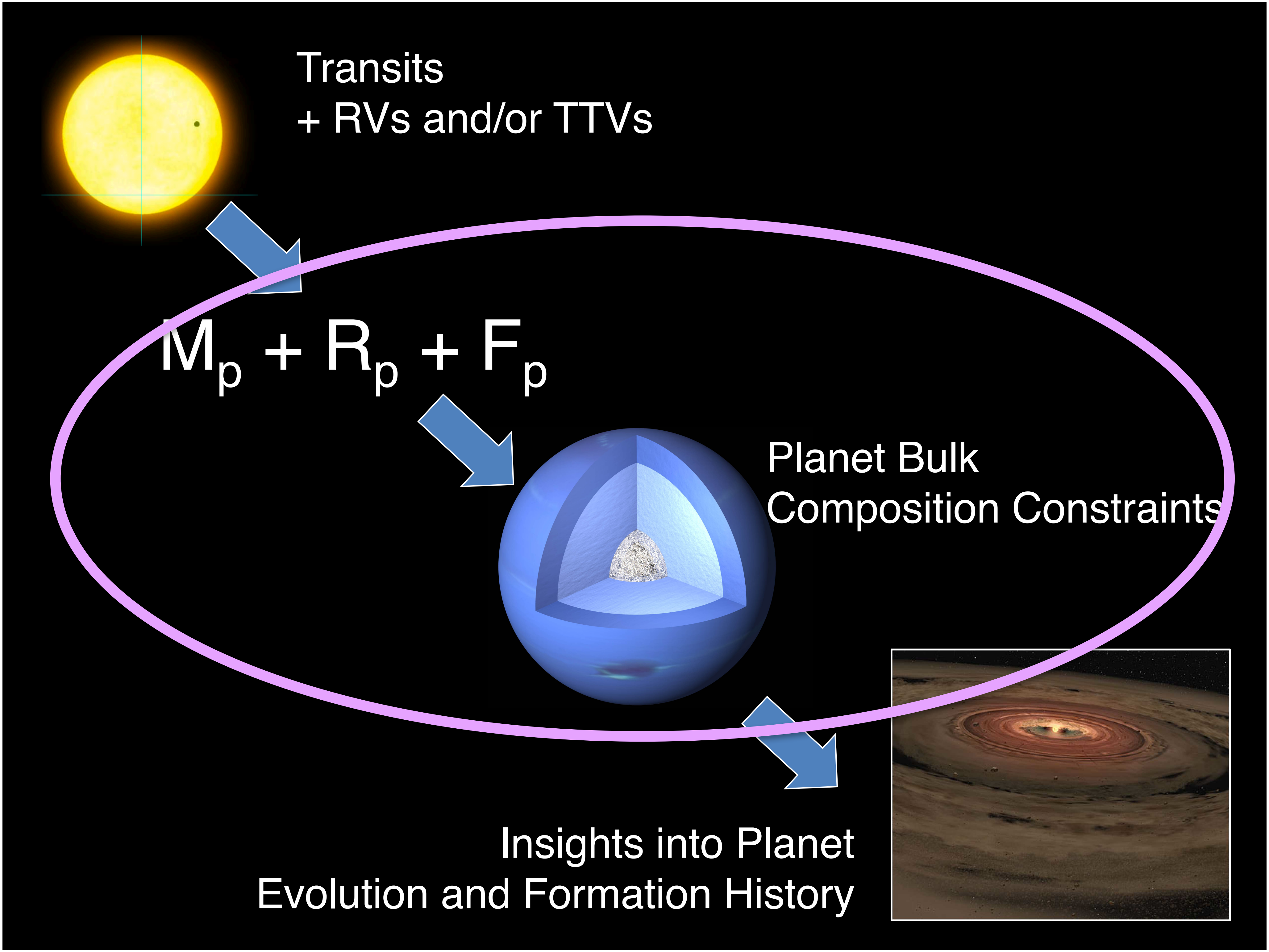

Transits
+ RVs and/or TTVs
$M_p + R_p + F_p$
Planet Bulk
Composition Constraints
Insights into Planet
Evolution and Formation History

Exoplanet Challenges

- (Typically) Fewer Observables than for Solar System planets
- (Typically) Exoplanet parameters are more uncertain than Solar System parameters
- Degeneracies in interpreting observables
- Selection effects and biases
- Disentangling the effect of formation v. evolution

Exoplanet Opportunities

- Large numbers sample the statistical outcomes of planet formation
- Large numbers, sample extreme outliers; individual planets that push the boundaries of understanding
- Trends and correlations to reveal insights into planet formation process
- Clustering may reveal distinct planet formation pathways


Transits
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$M_p + R_p + F_p$
Planet Bulk
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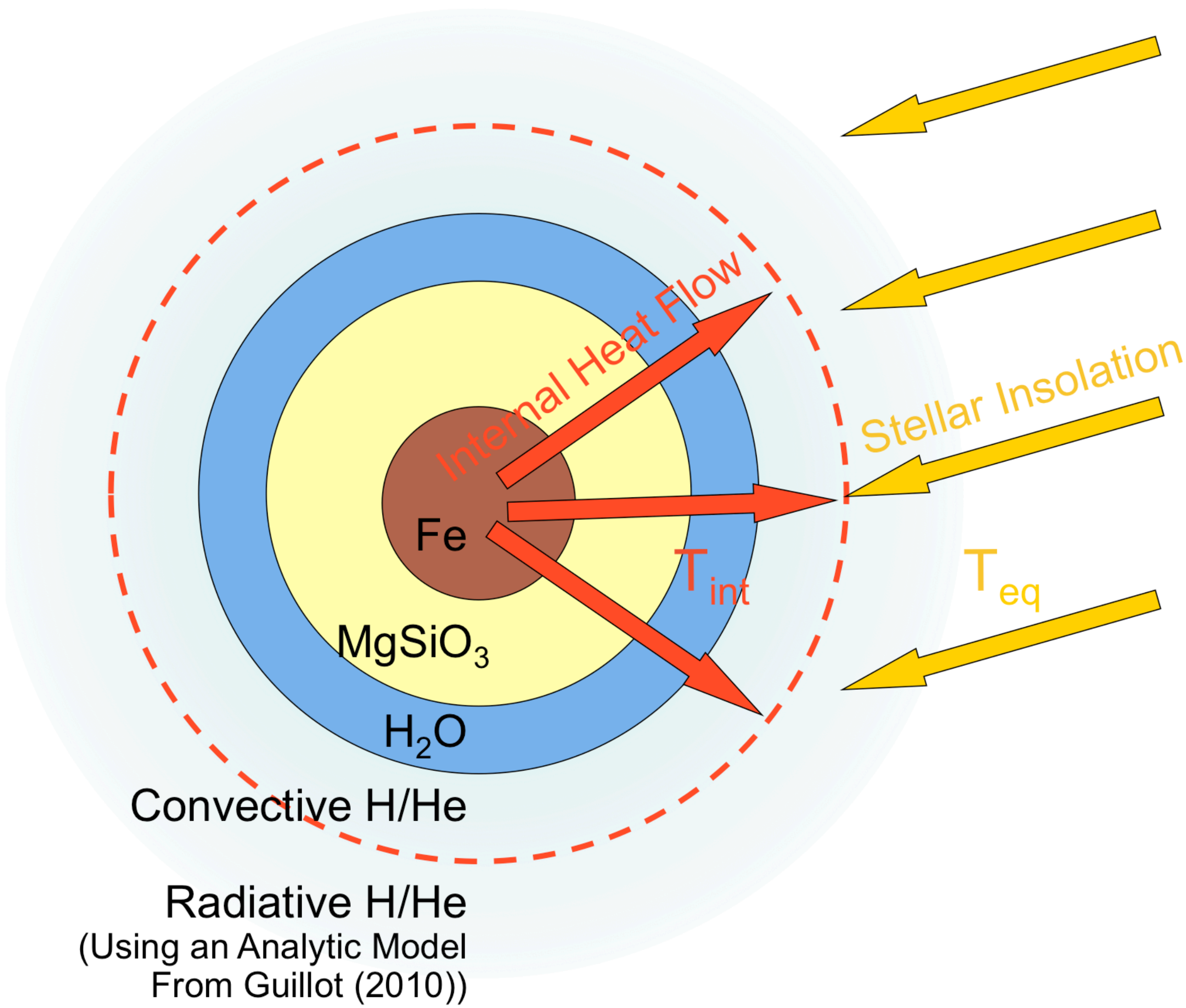
Model Overview

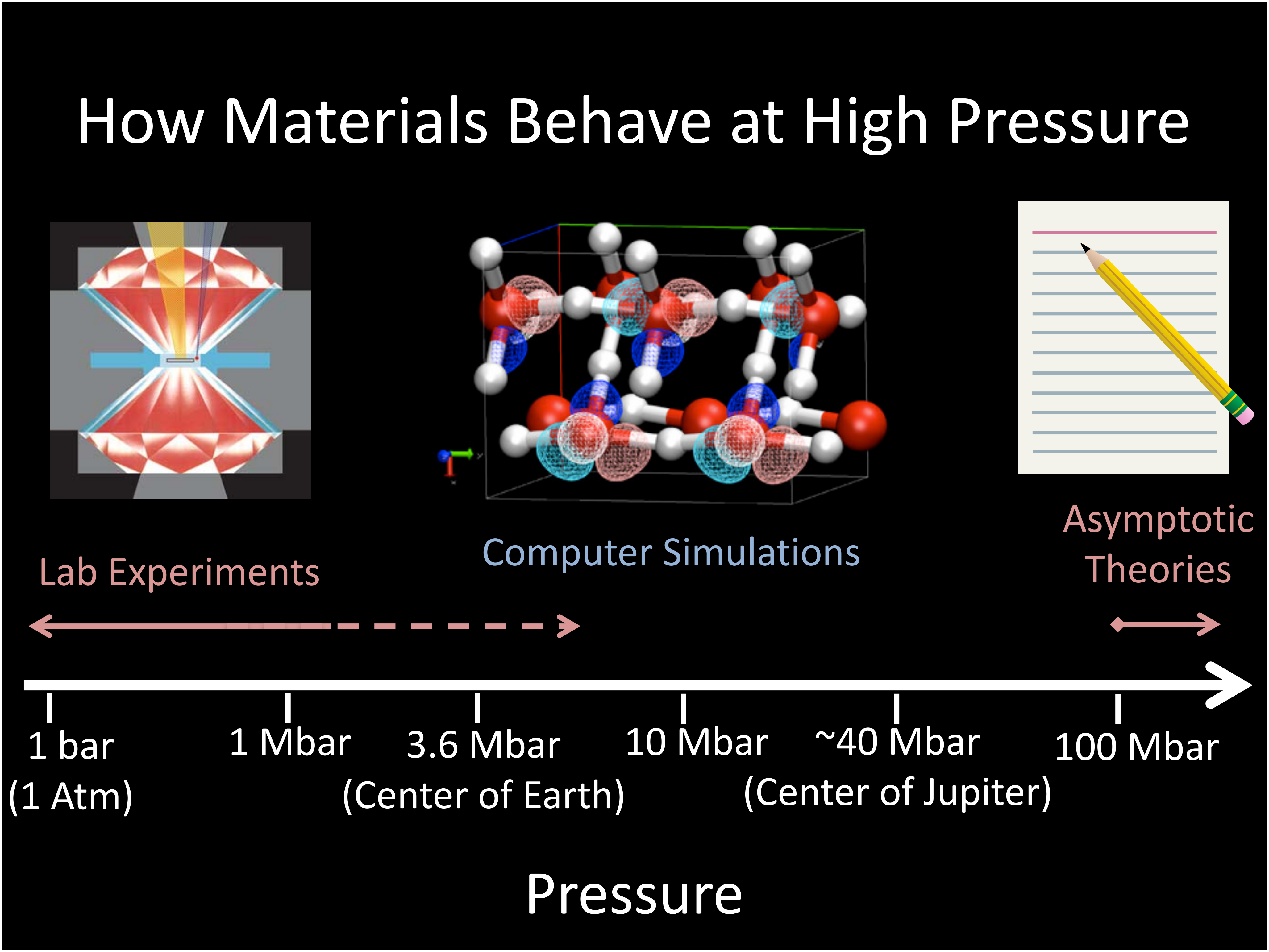


$$\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho}$$

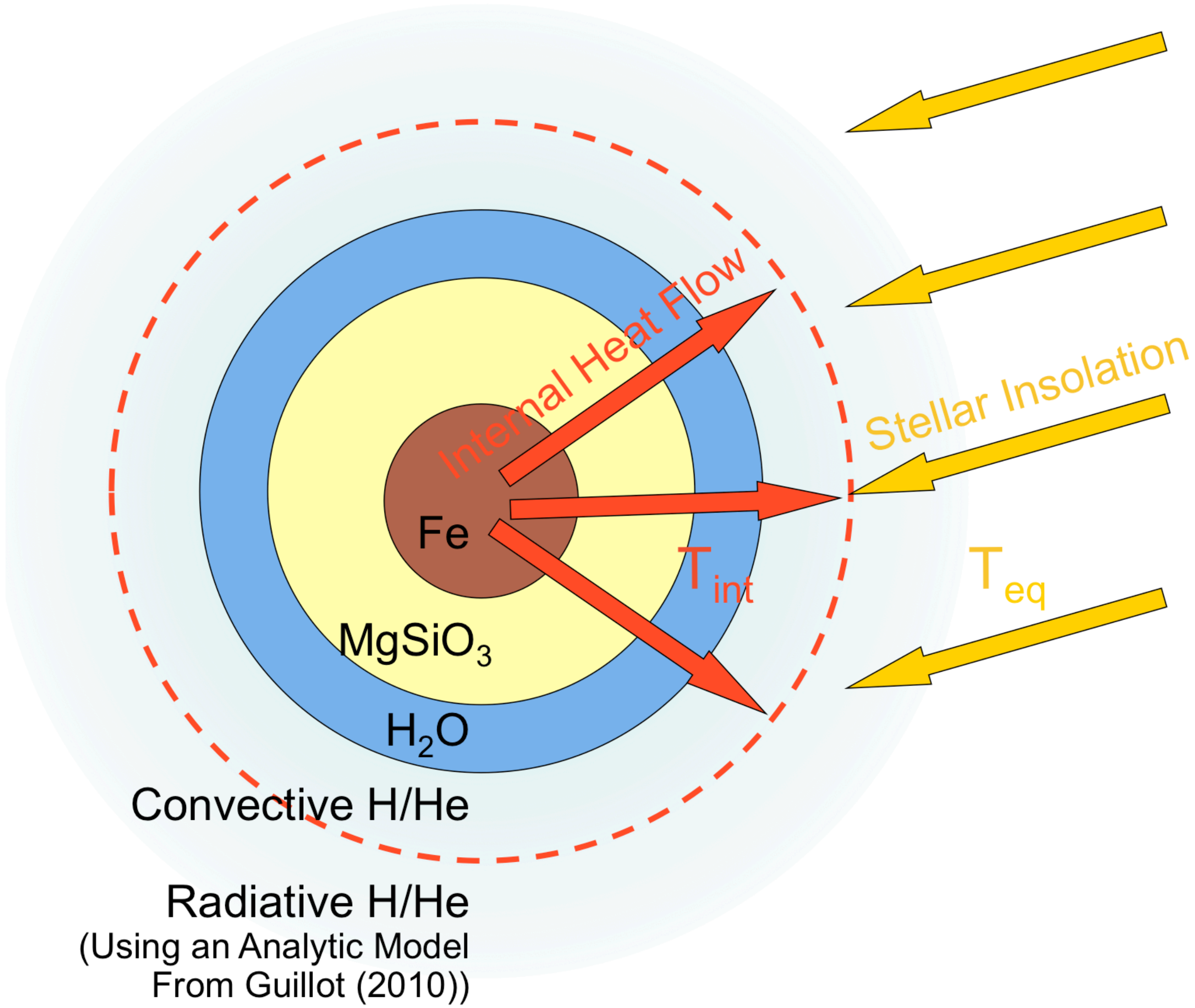
$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$$

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

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


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



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

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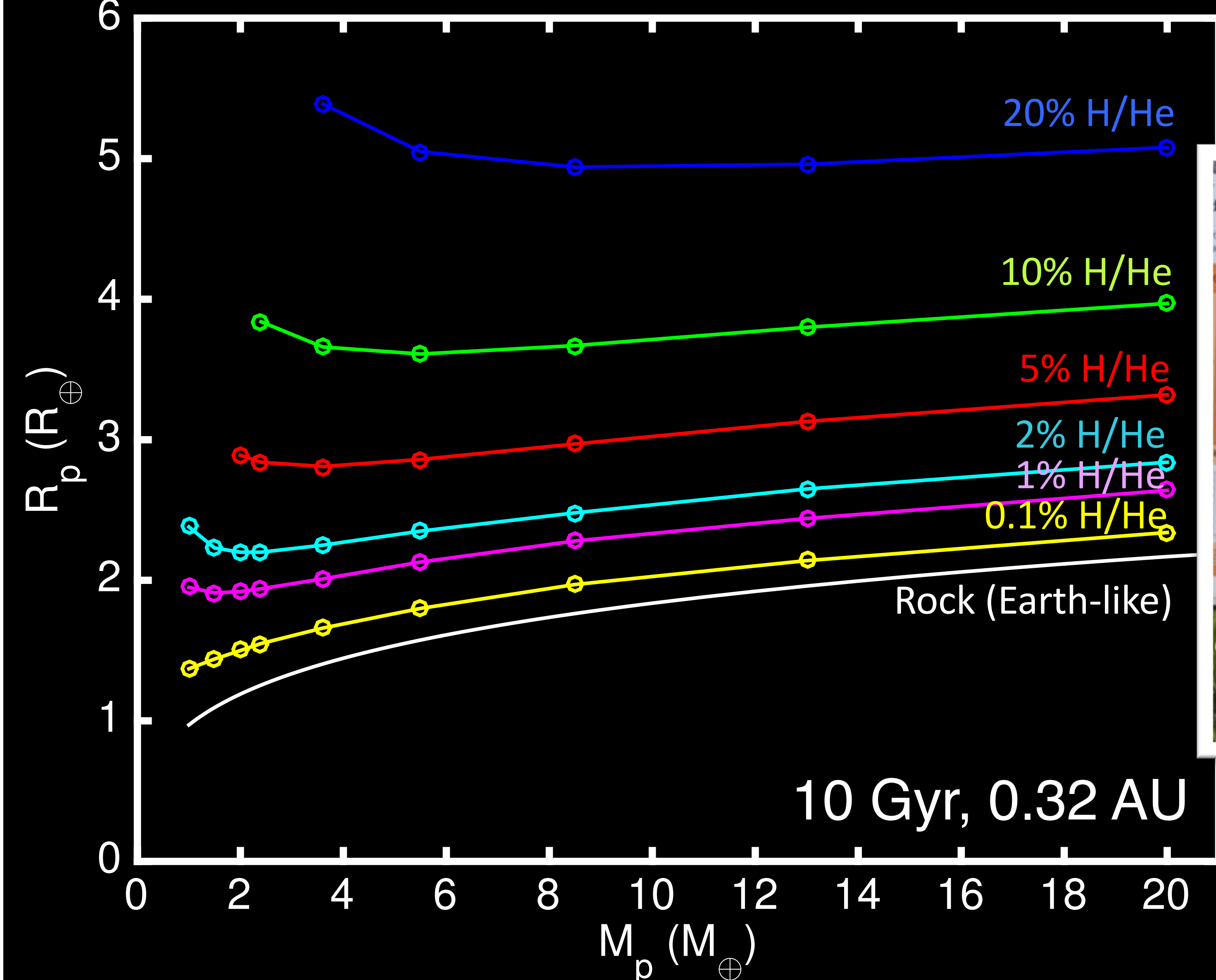
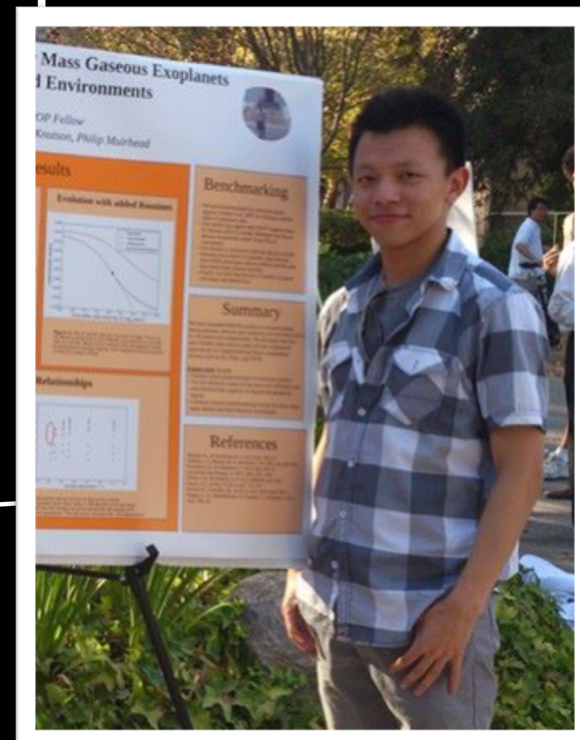
Extending MESA to Model Low-Mass planets with H/He envelopes

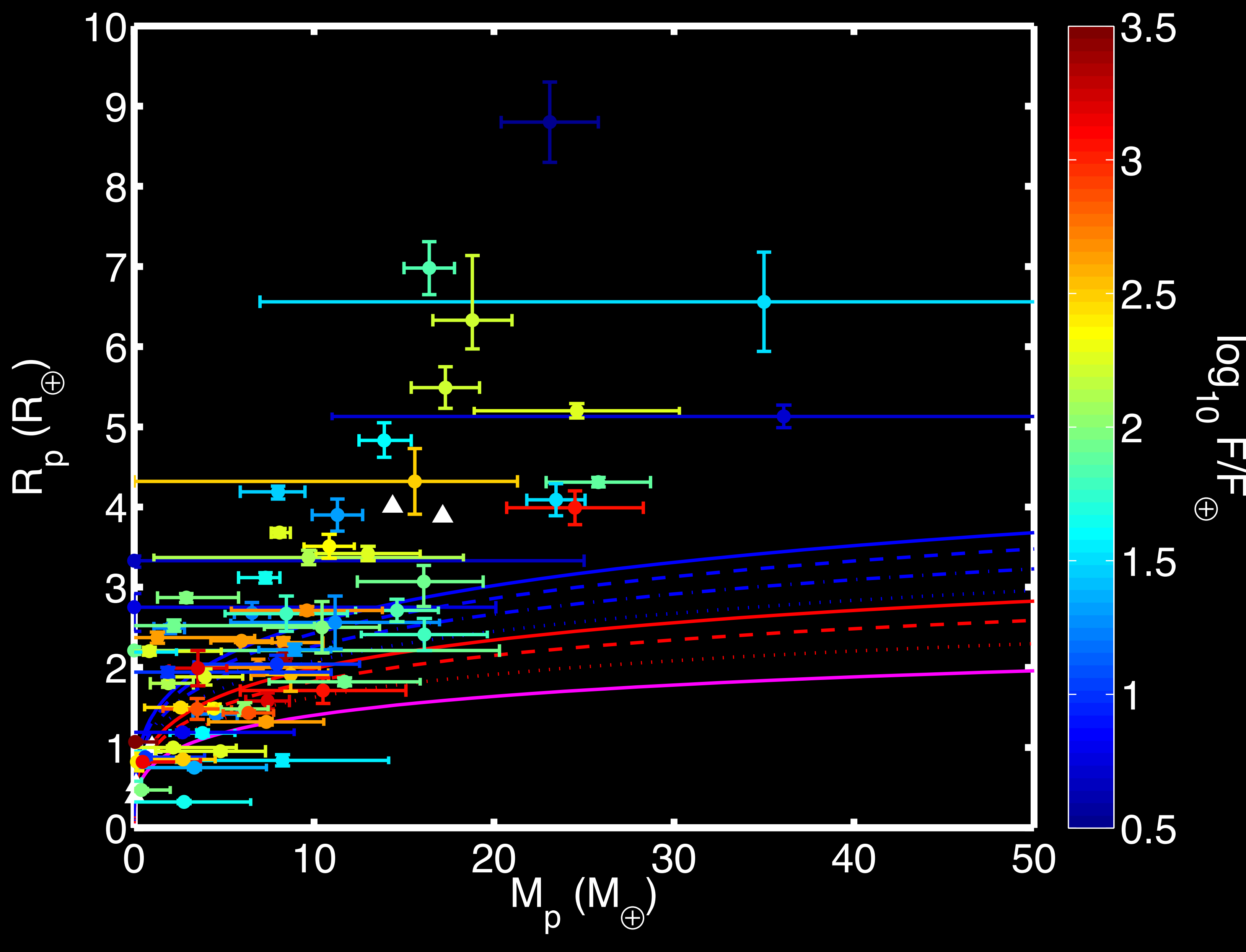




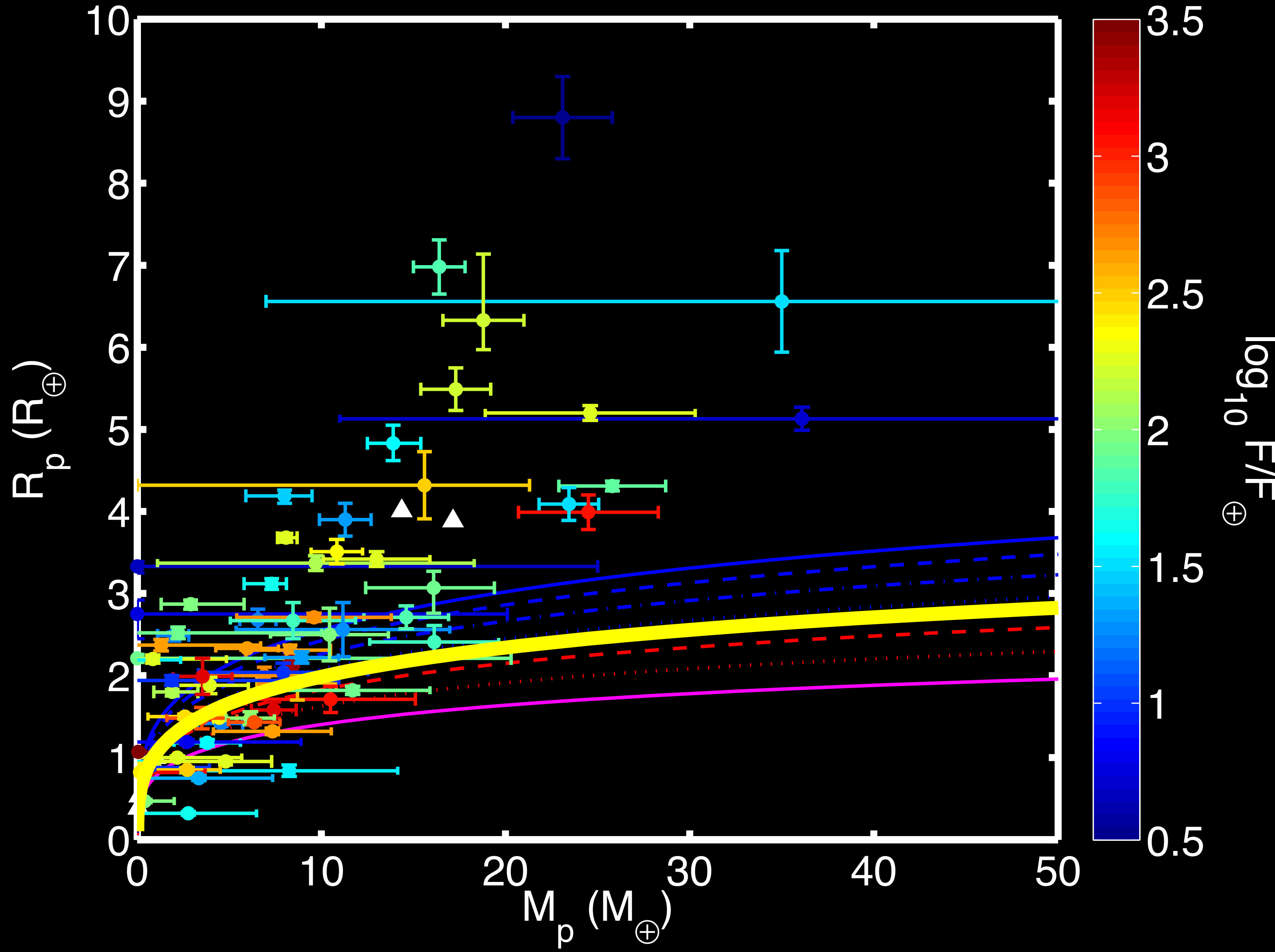
BU UROP Howard Chen

Chen & Rogers (2016)

Sample of Small Planet M-R



Which Planets Are Rocky?



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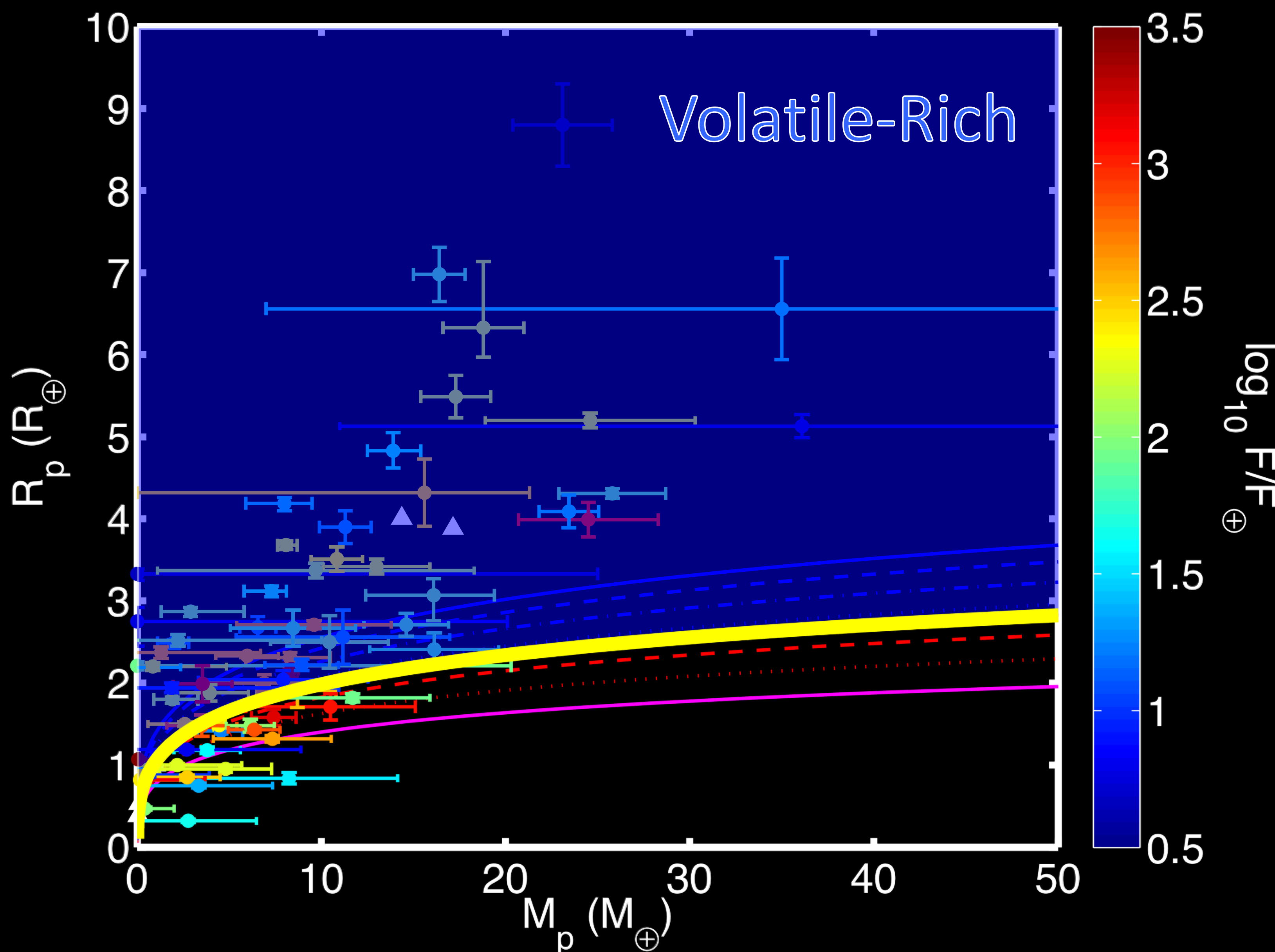

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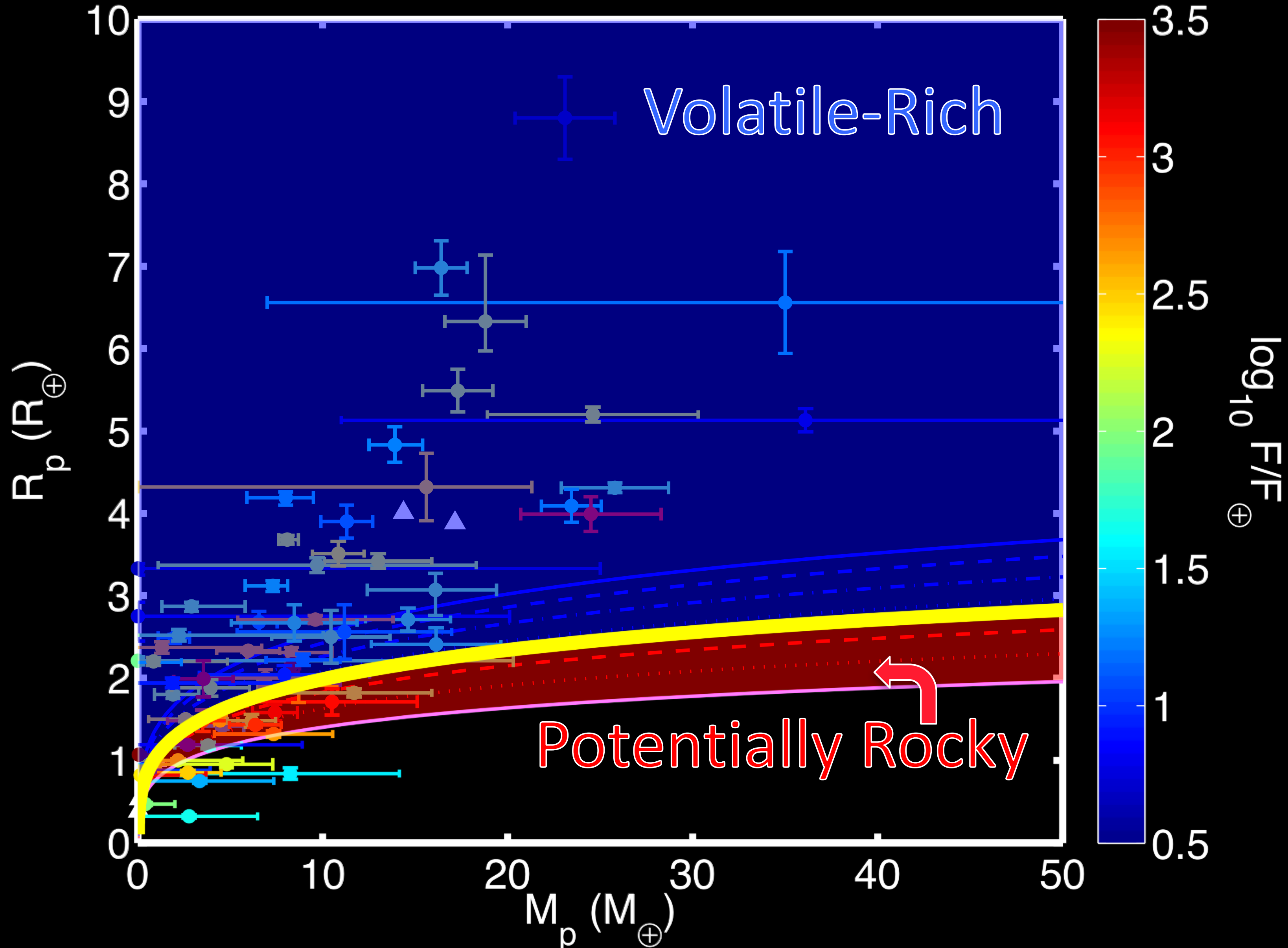
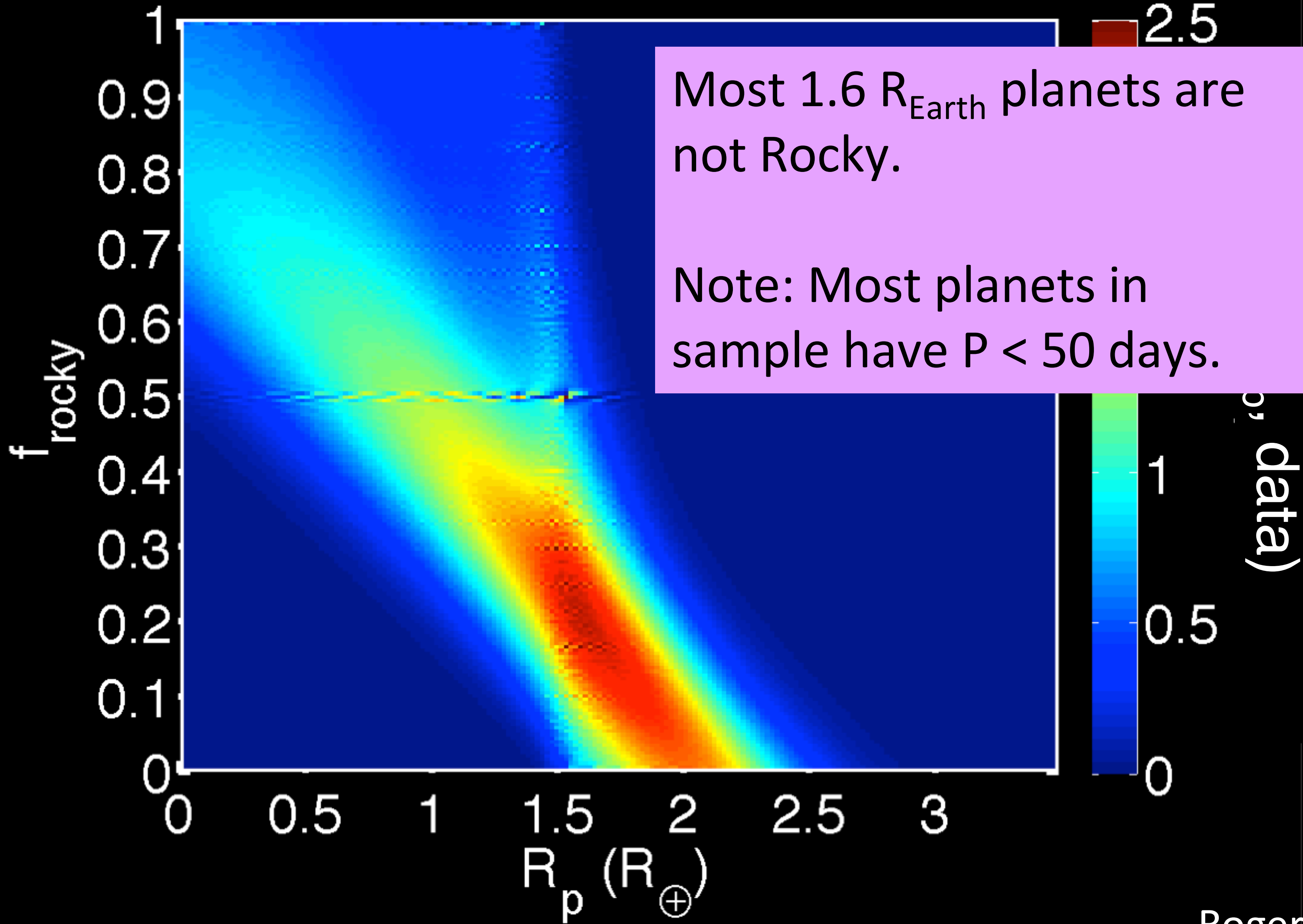


Abundance of Low Density planets Constrains Fraction of Planets in Underlying Population that are Rocky, $f_{rocky}(R_p)$

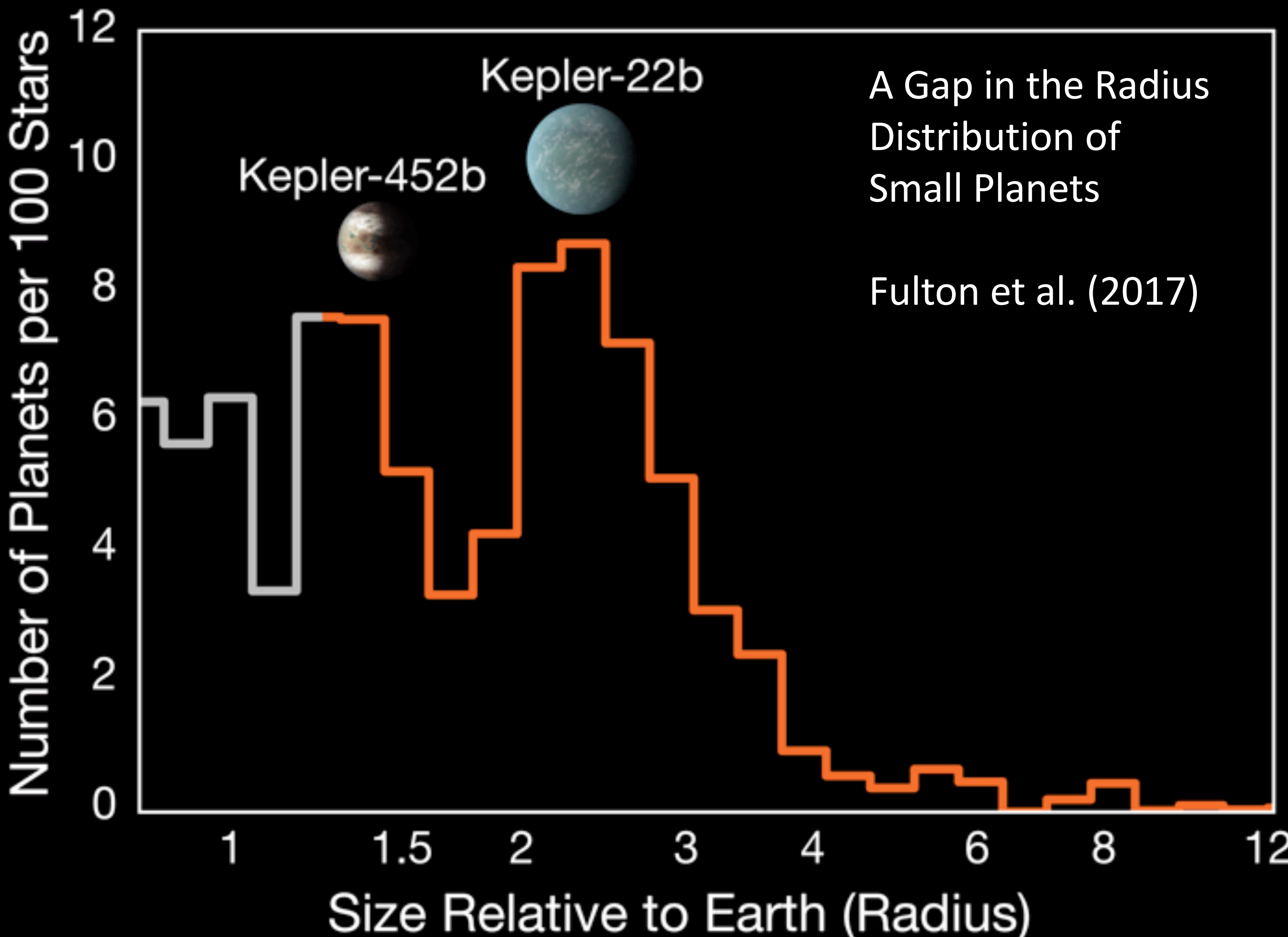


Most 1.6 R_{Earth} planets are not Rocky.

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

Rogers (2015)

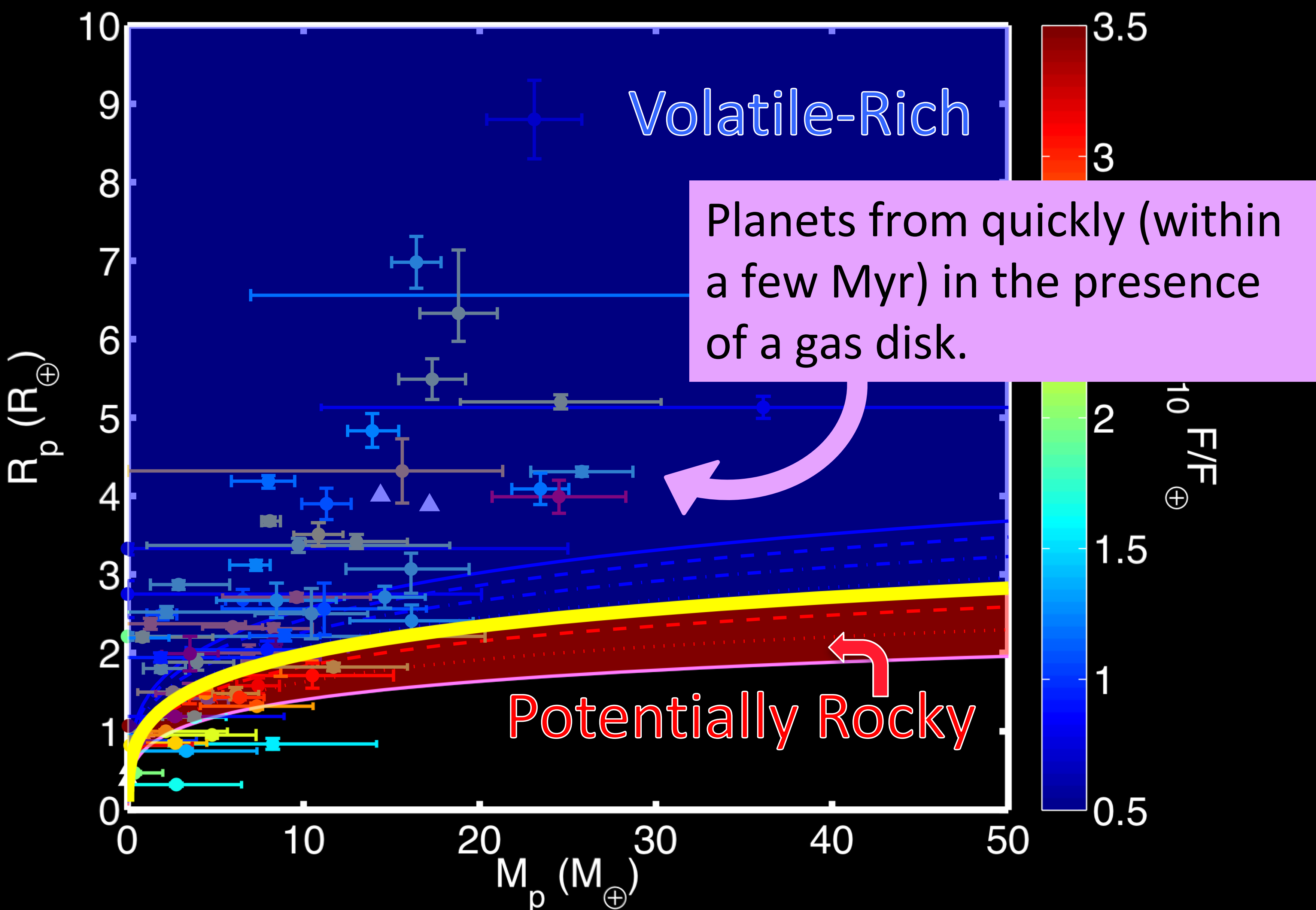
Mind the Exoplanet Gap



A Gap in the Radius Distribution of Small Planets

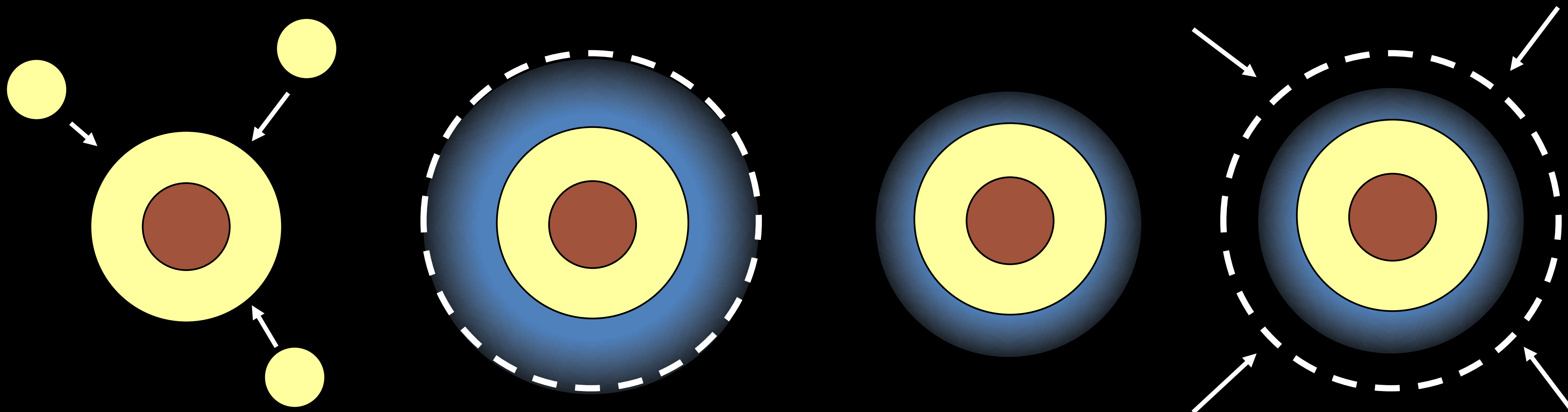
Fulton et al. (2017)

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

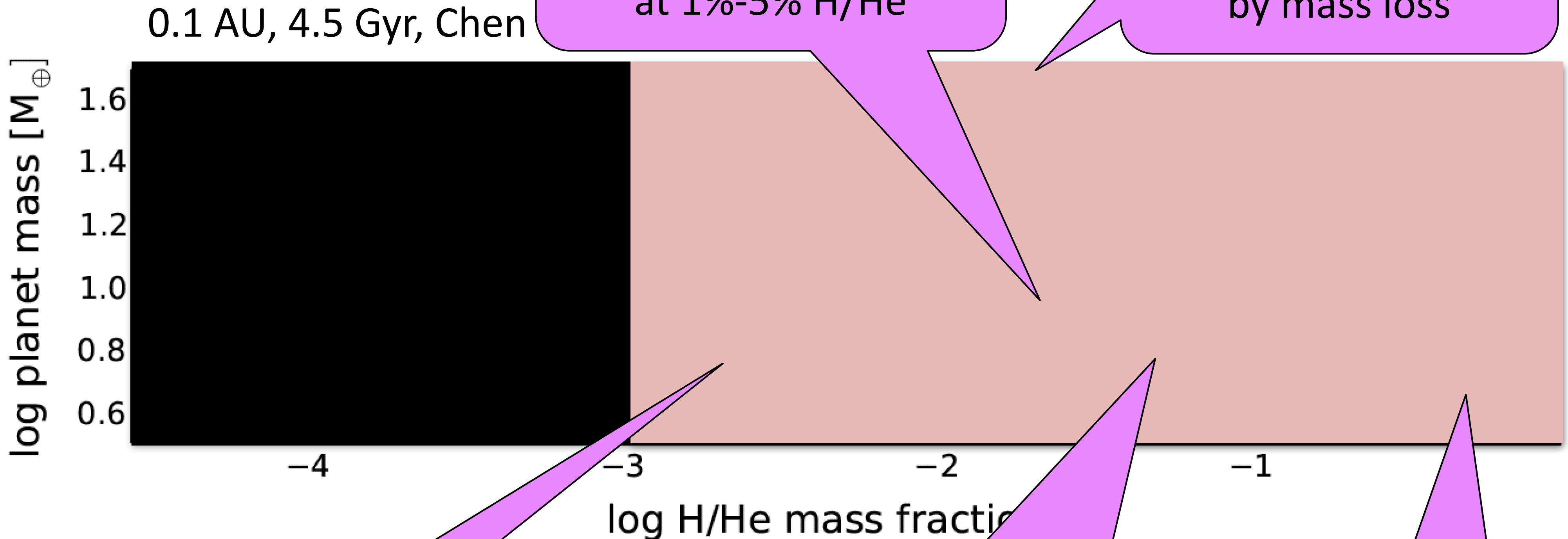
Ambient gas refills the Hill sphere

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

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

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

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

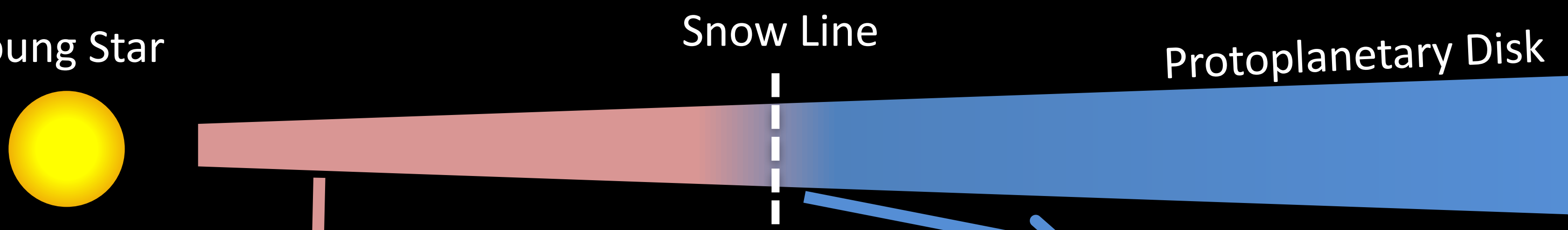
Low M_p planets quickly lose low M_{env} envelopes

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)

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), Izidoro + (2017)

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

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

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

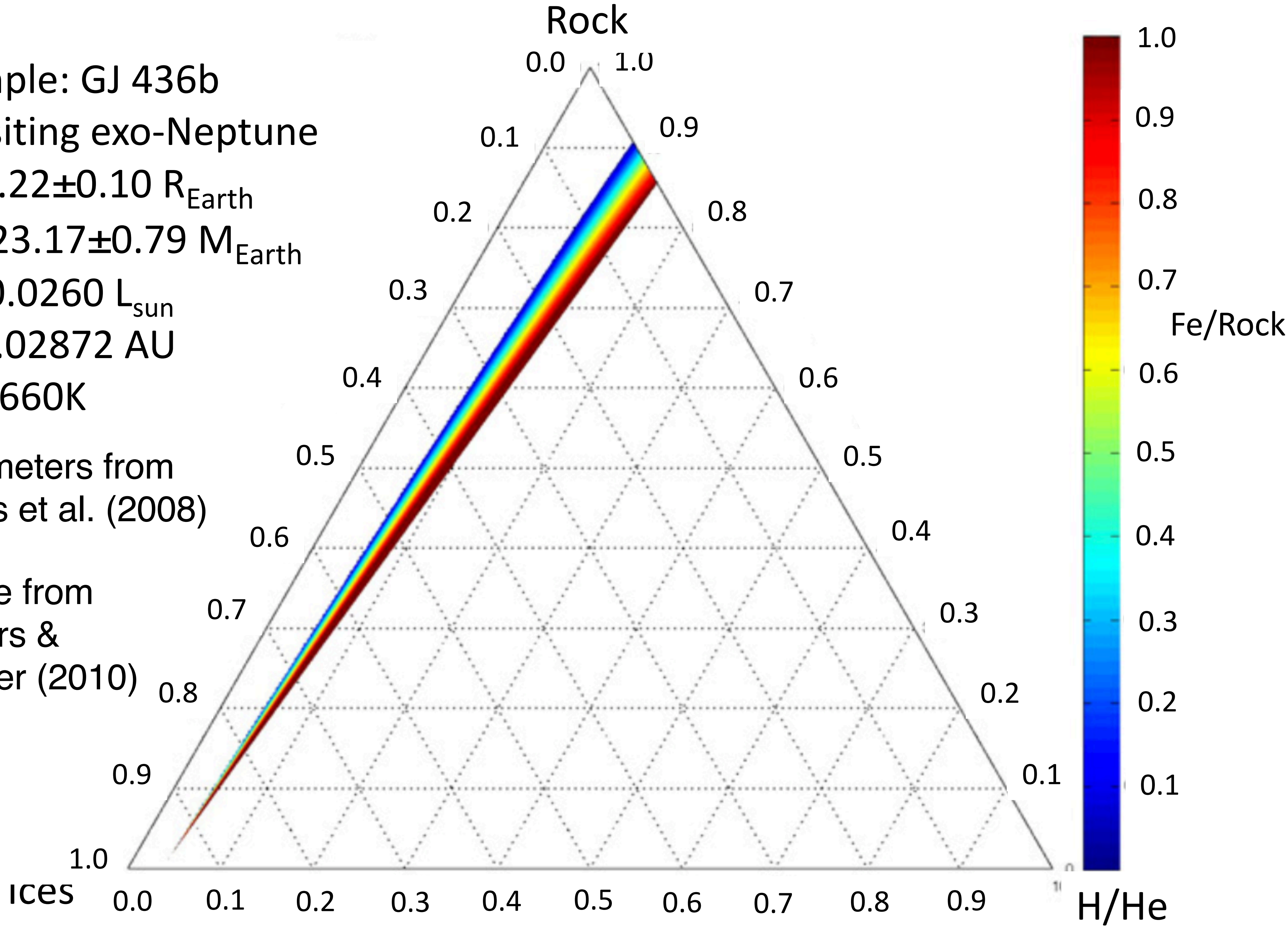
$L_* = 0.0260\ L_{sun}$

$a = 0.02872$ AU

$T_{eq} \sim 660$K

Parameters from Torres et al. (2008)

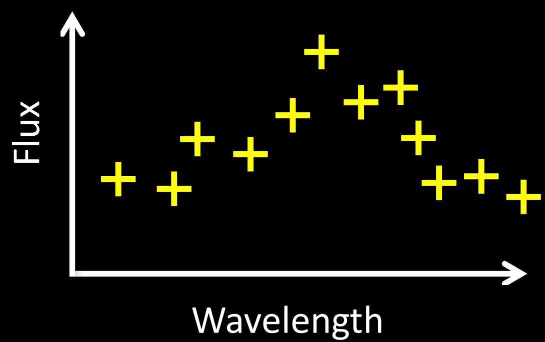
Figure from Rogers & Seager (2010)



Searching for Water in Distant Worlds

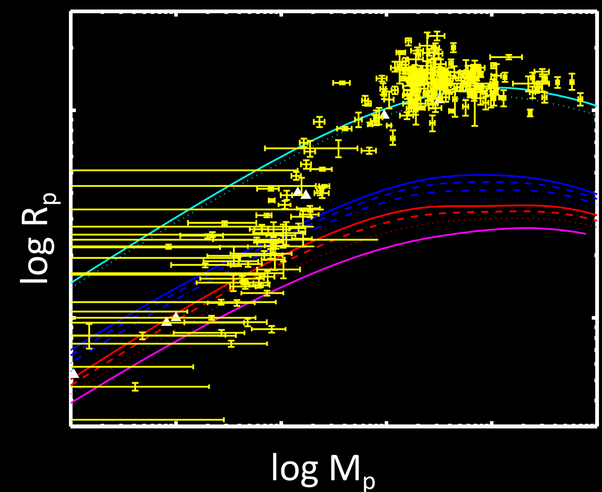
Potential future approaches to constrain the bulk water content of distant exoplanets:

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.

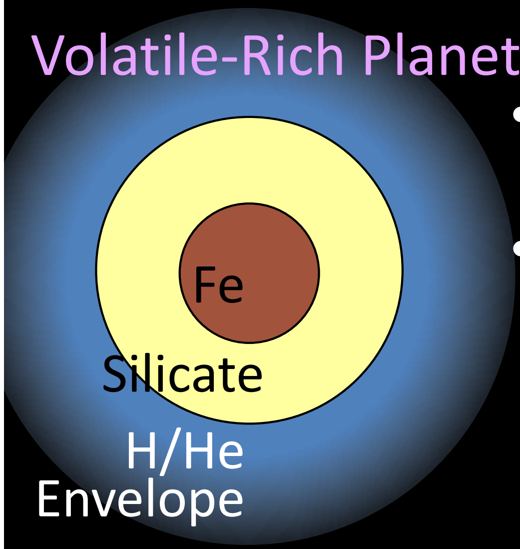
Population Statistics



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.

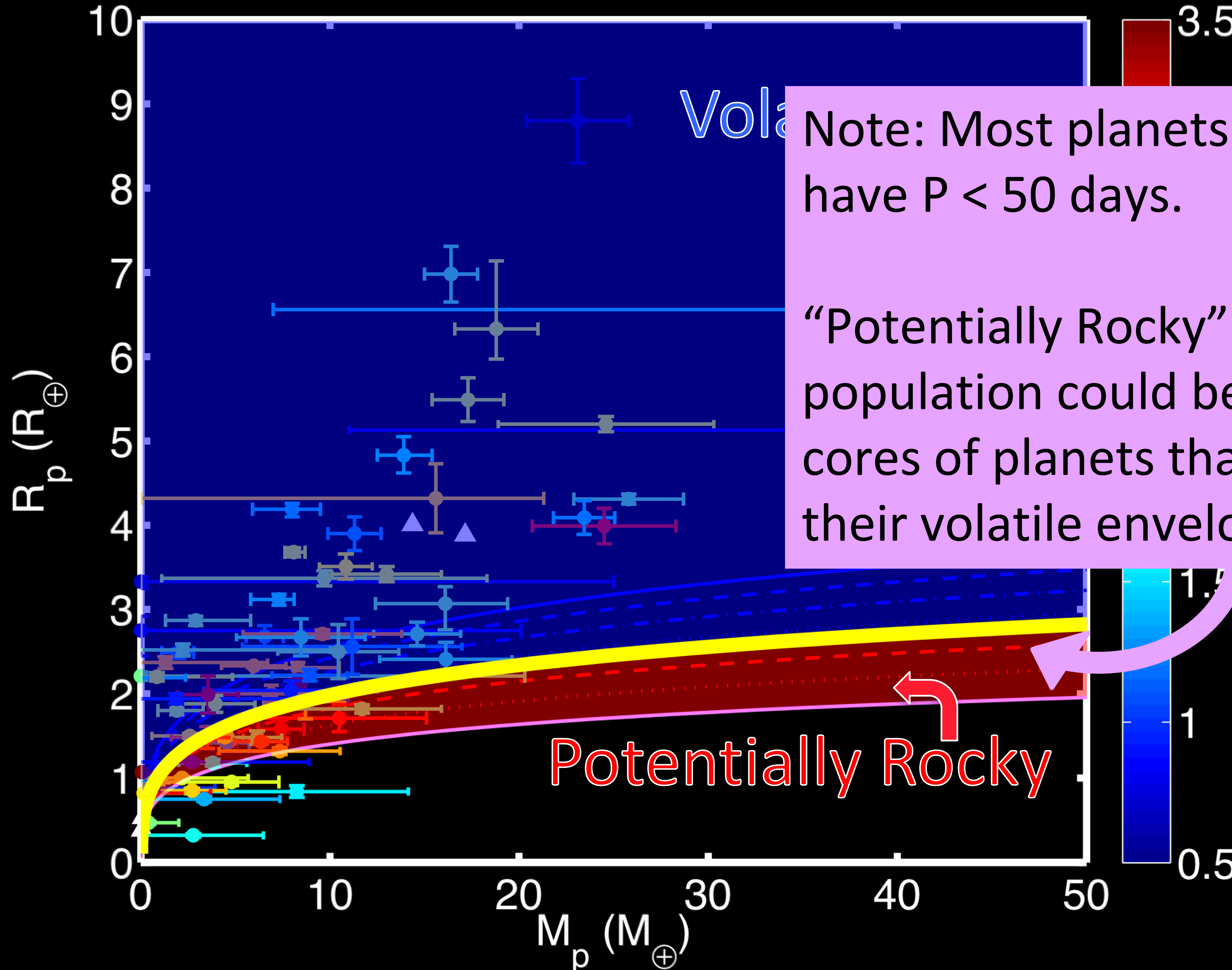
Empirical Insights Into Low-Mass Planet Interior Structure, Formation and Evolution

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.
  - Ongoing debate whether heavy-element embryos form in situ or migrate from beyond the snow-line

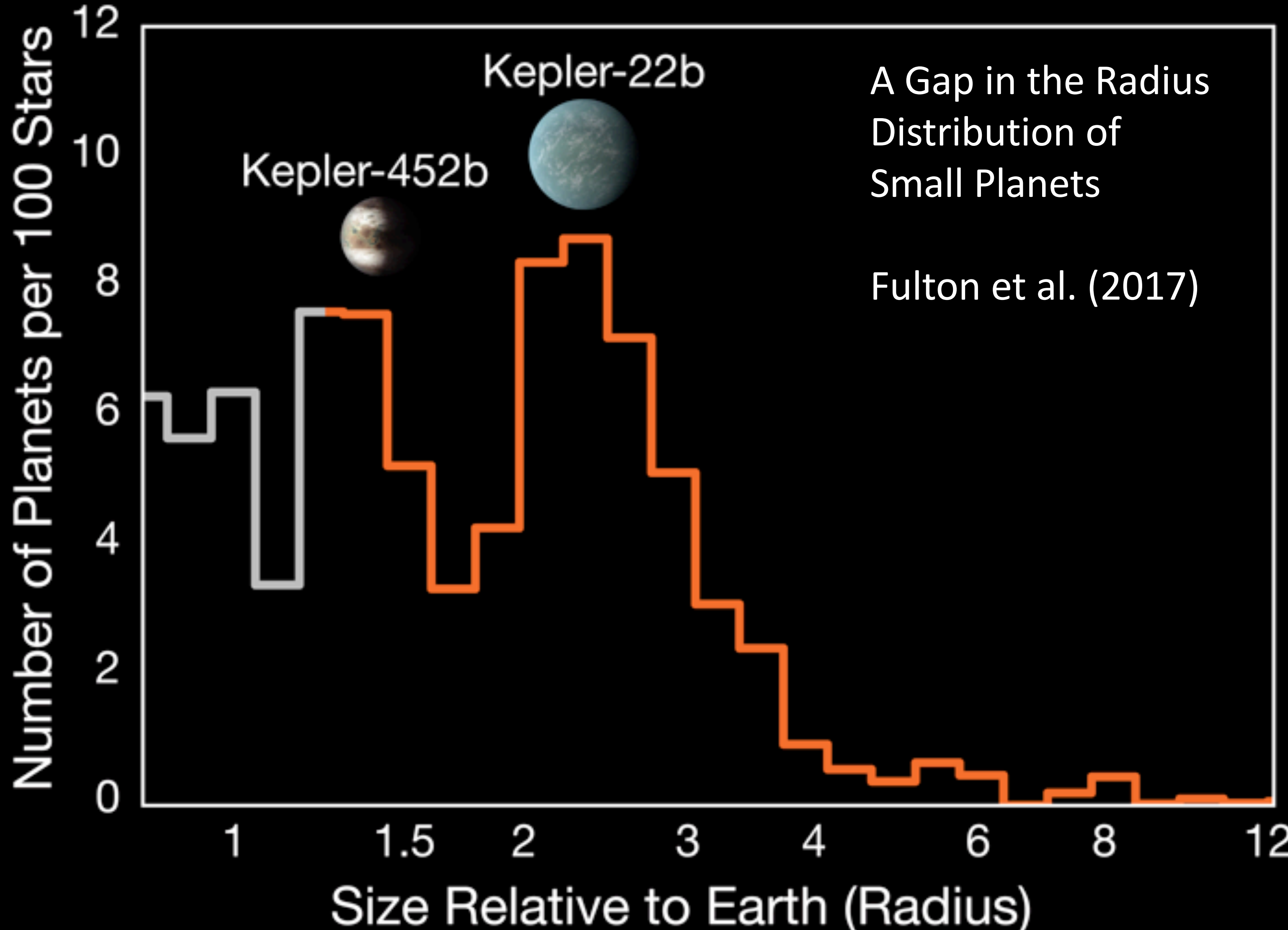
Which Planets Are Rocky?



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

"Potentially Rocky" population could be remnant cores of planets that lost their volatile envelopes.

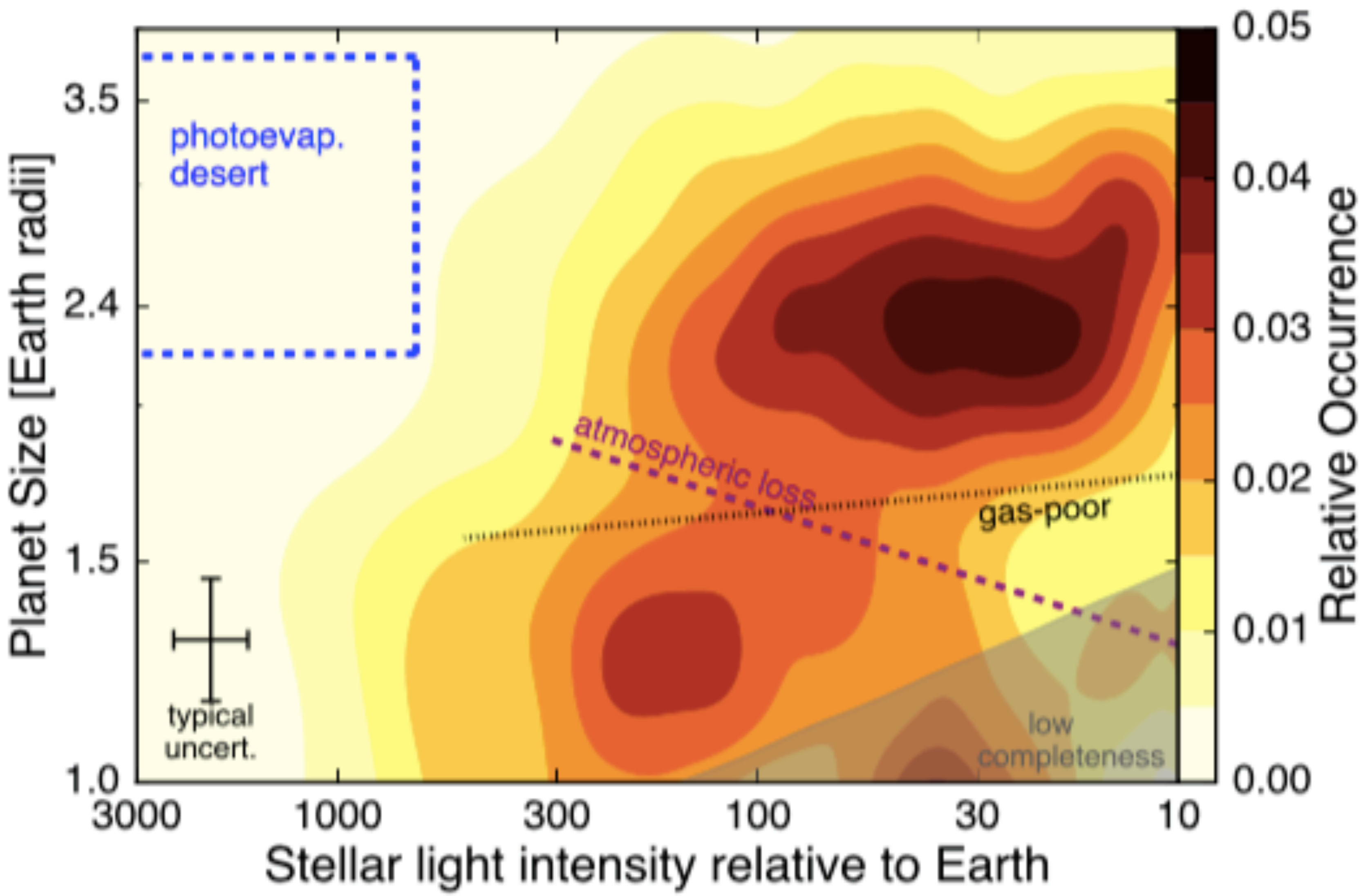
Mind the Exoplanet Gap



A Gap in the Radius Distribution of Small Planets

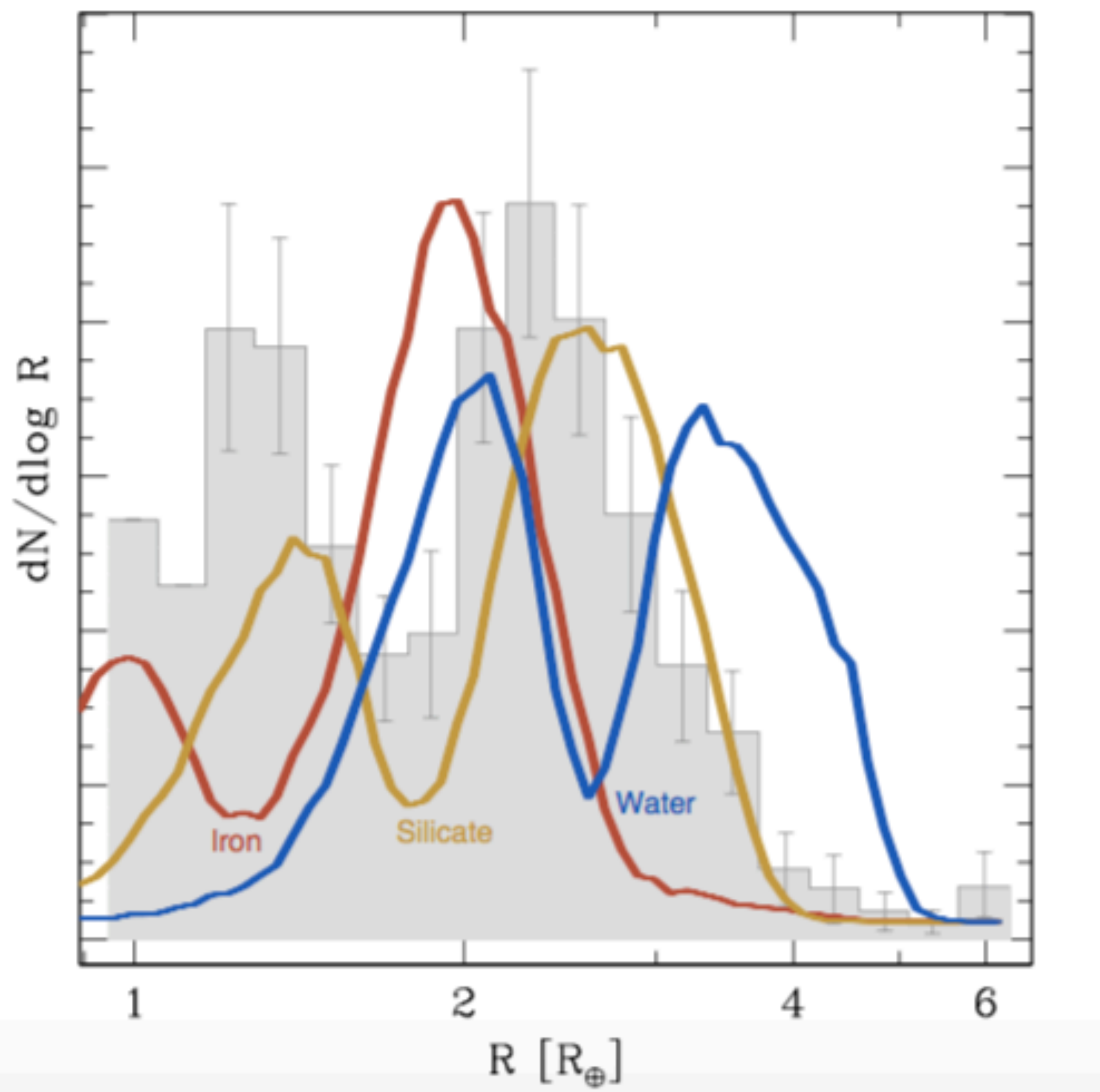
Fulton et al. (2017)

“Evaporated Cores” or “Inherently Rocky”?



Rogers (2015), Lopez & Rice (2016), Fulton et al. (2017)

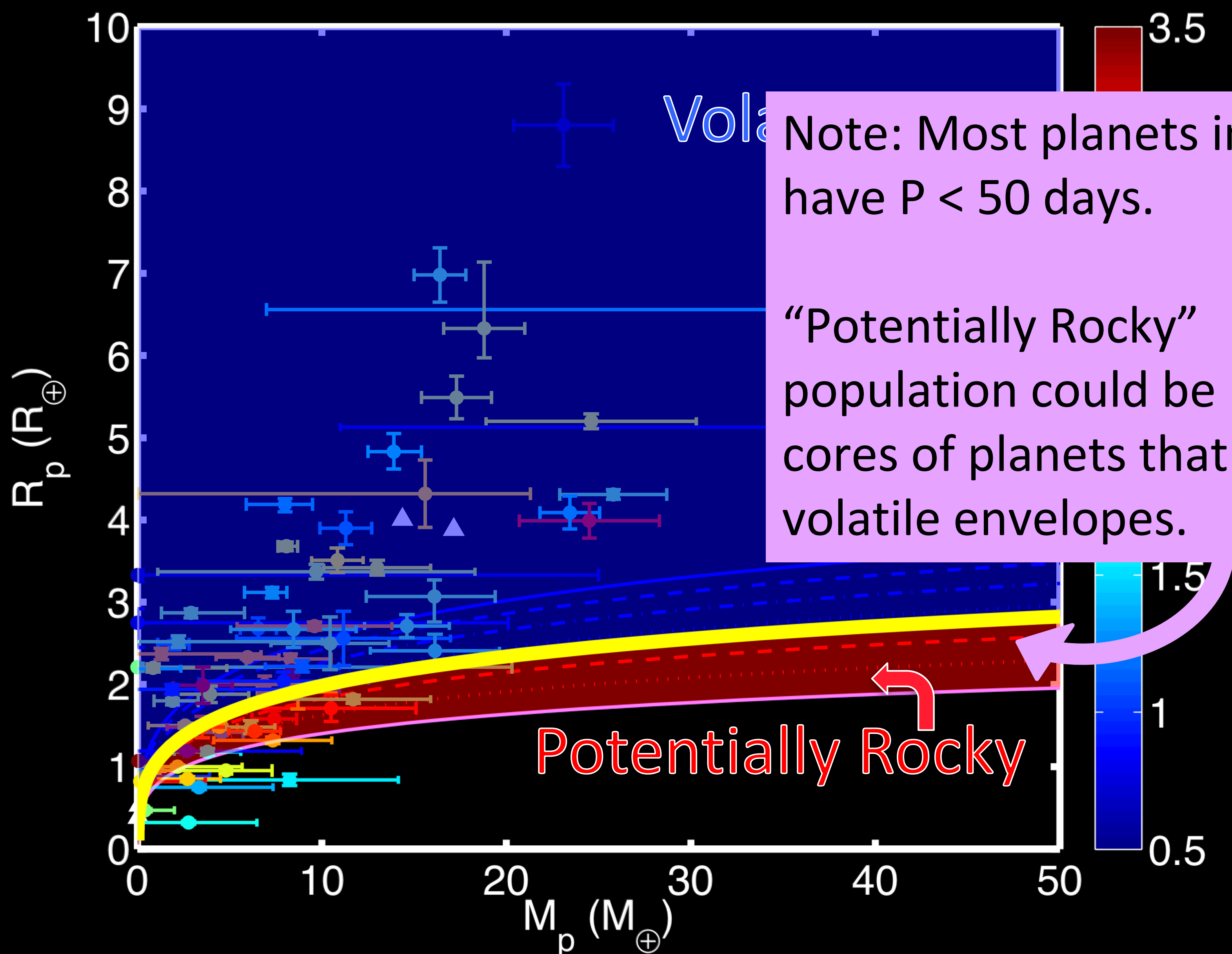
Leveraging Planet Mass Loss to Constrain Heavy-Element Interior Compositions



Owen & Wu (2017)

(see also Jin & Mordasini 2017)

Which Planets Are Rocky?



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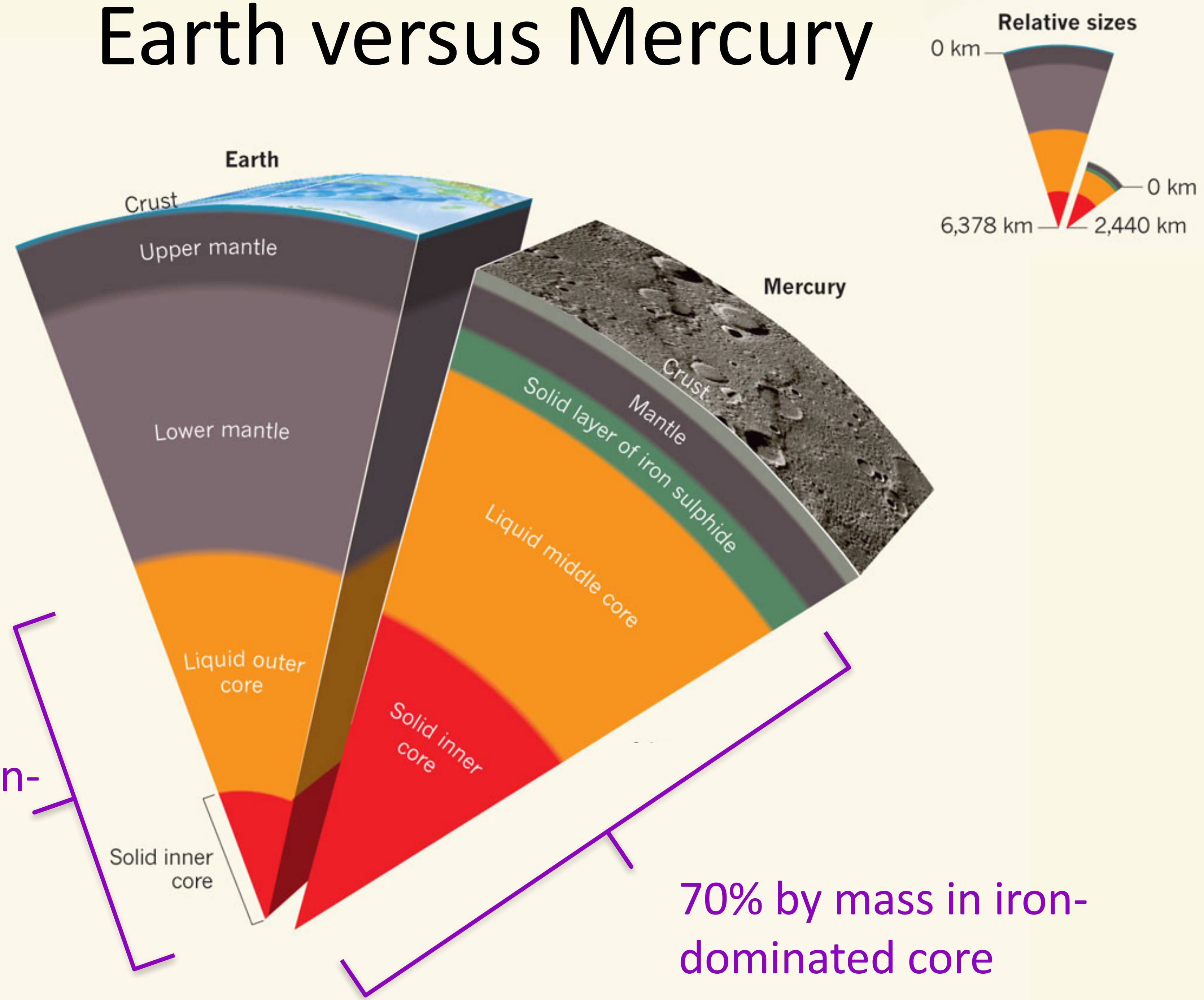
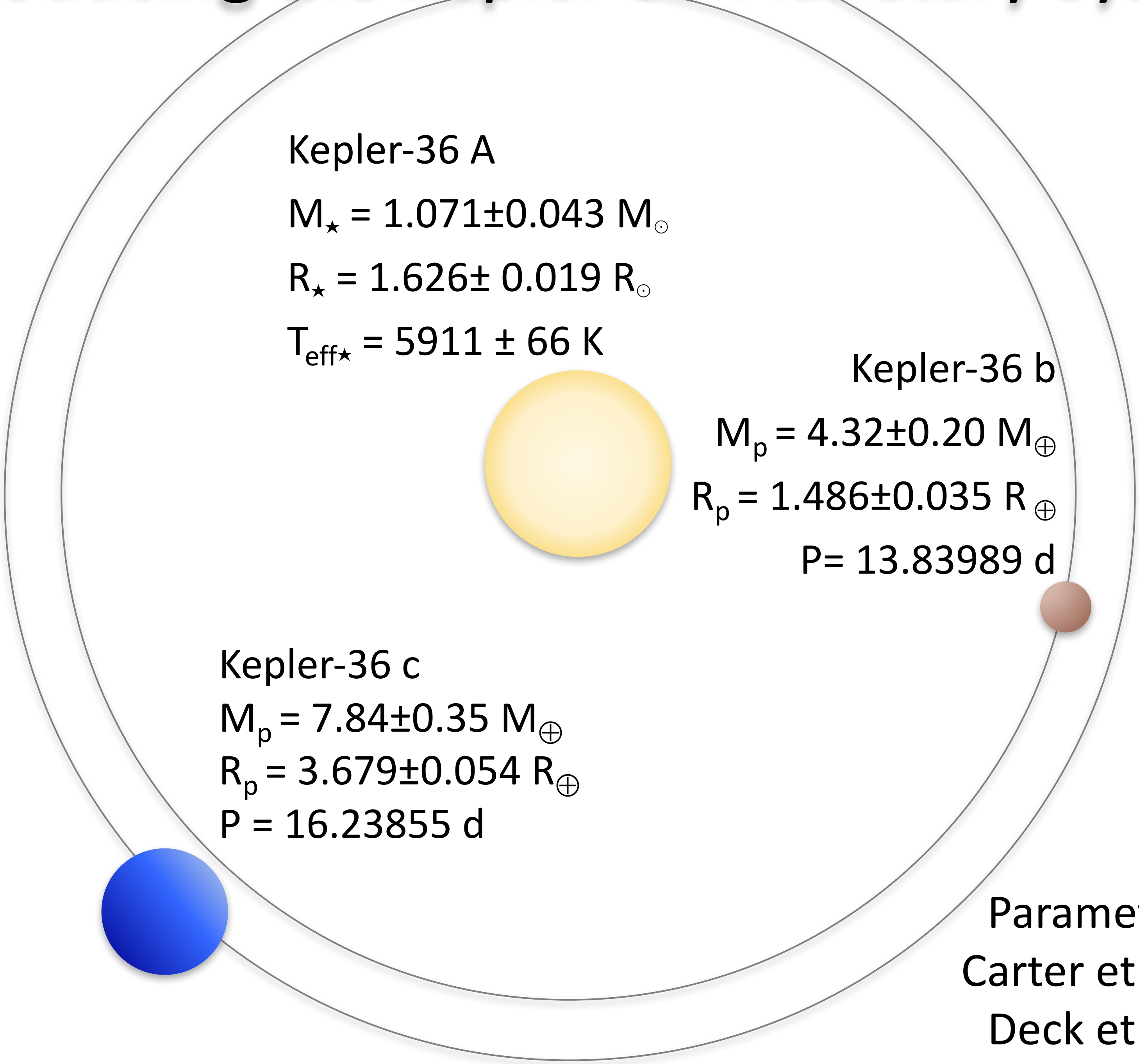
Earth versus Mercury



32.5% by mass in iron-dominated core

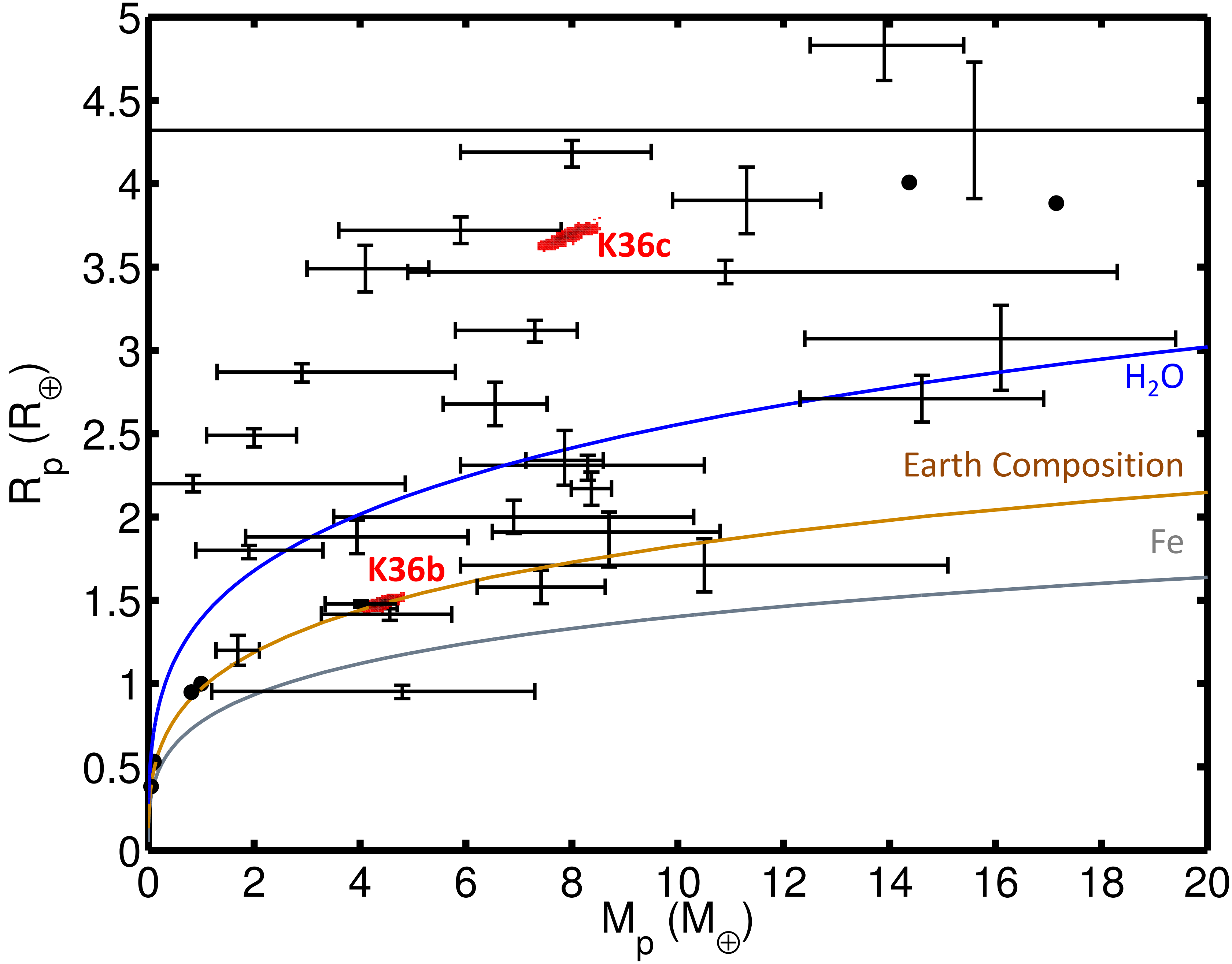
70% by mass in iron-dominated core

Introducing the Kepler-36 Planetary System

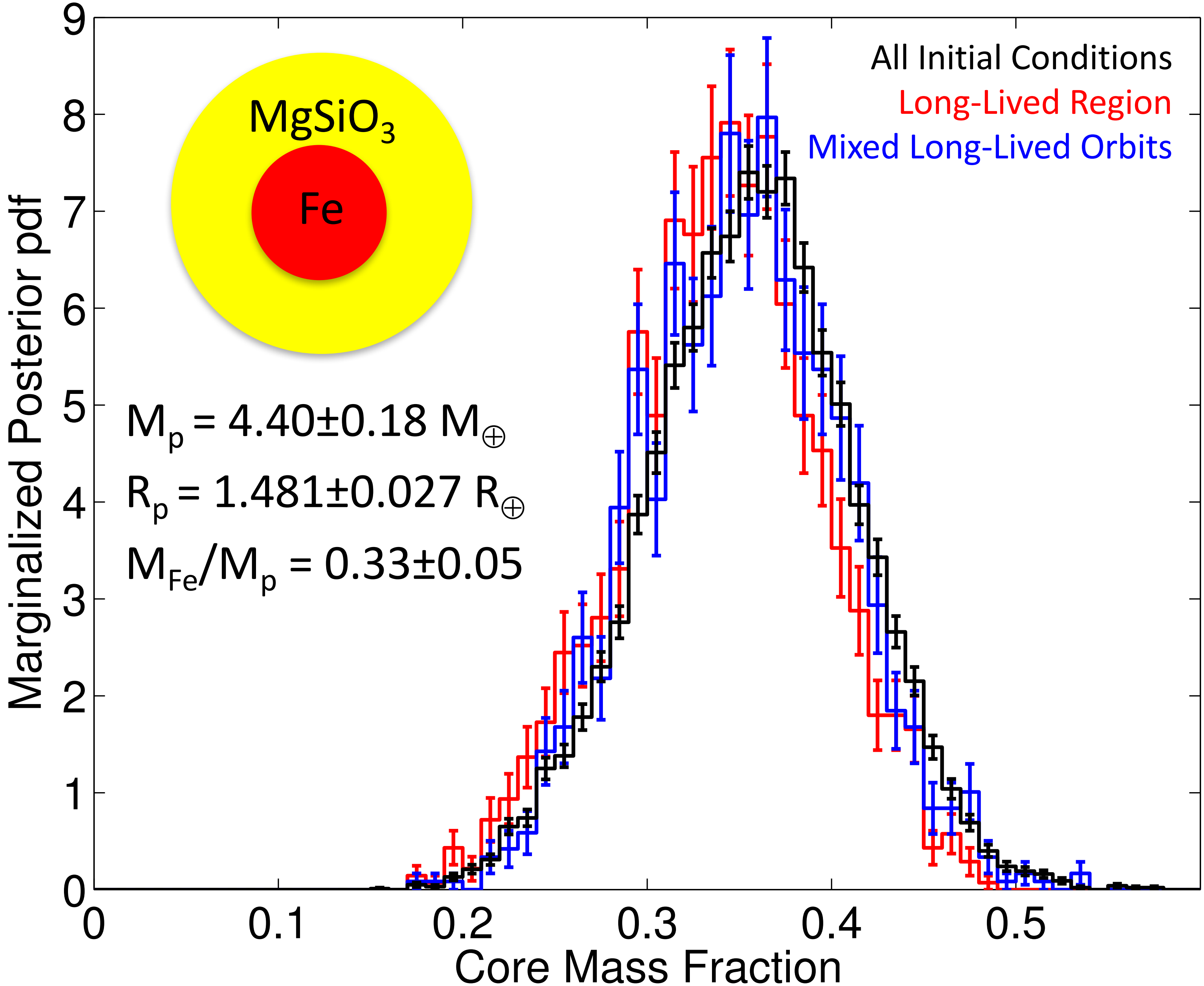


Parameters from:
Carter et al. (2012)
Deck et al. (2012)

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



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

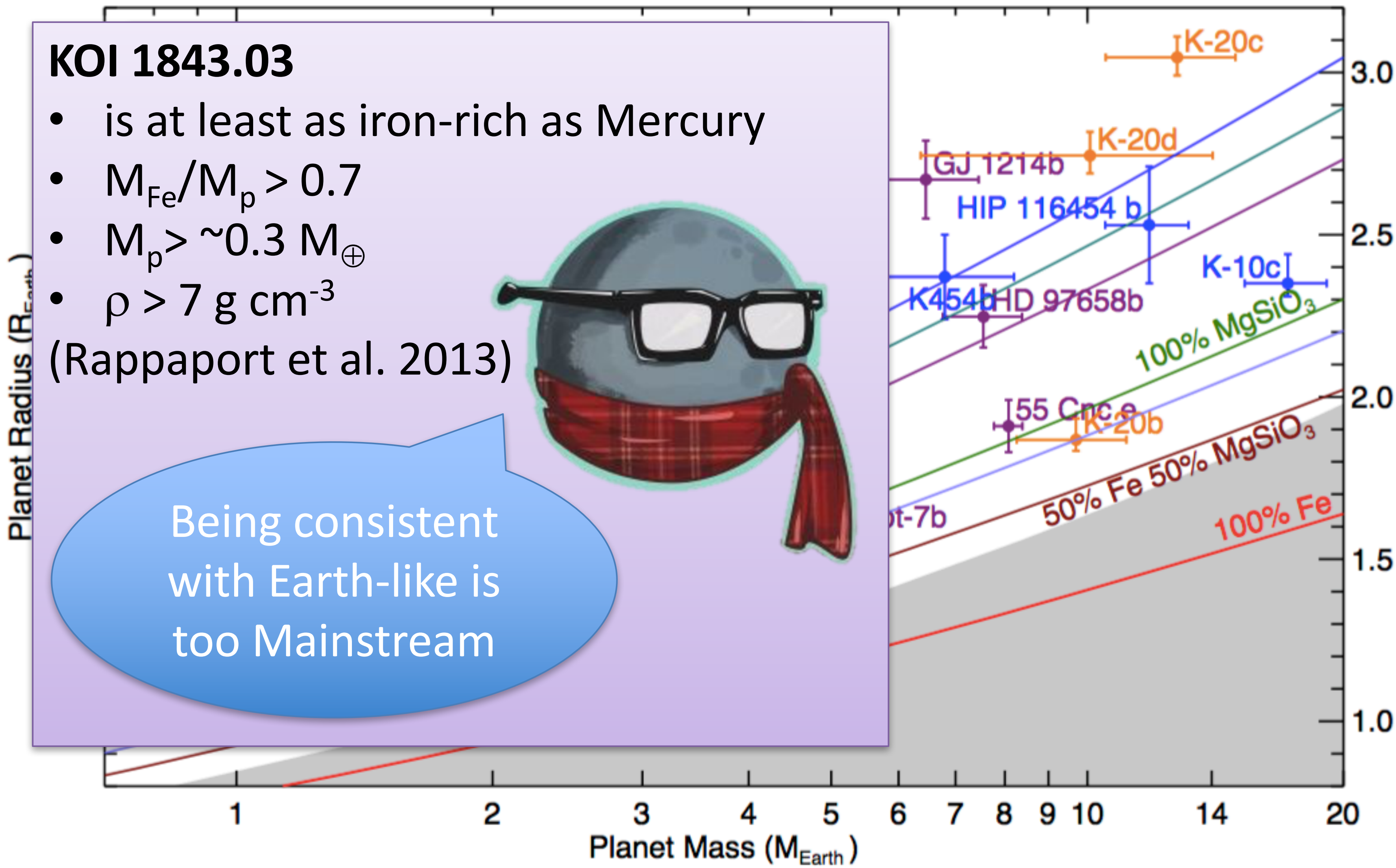


Rocky Exoplanets (with with σ_M/M_p<20%) also Consistent with Earth-like Bulk Compositions

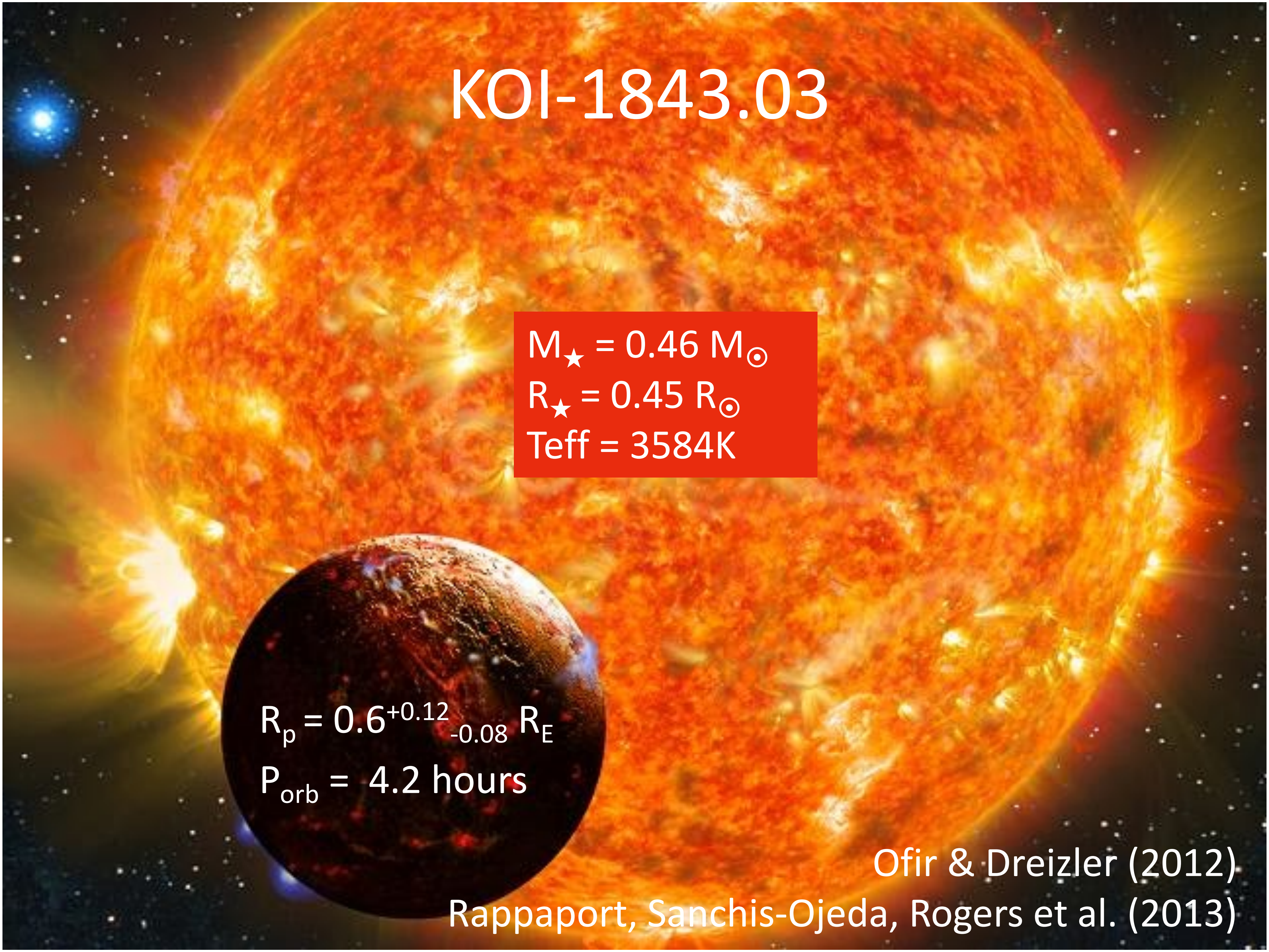
KOI 1843.03

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

(Rappaport et al. 2013)

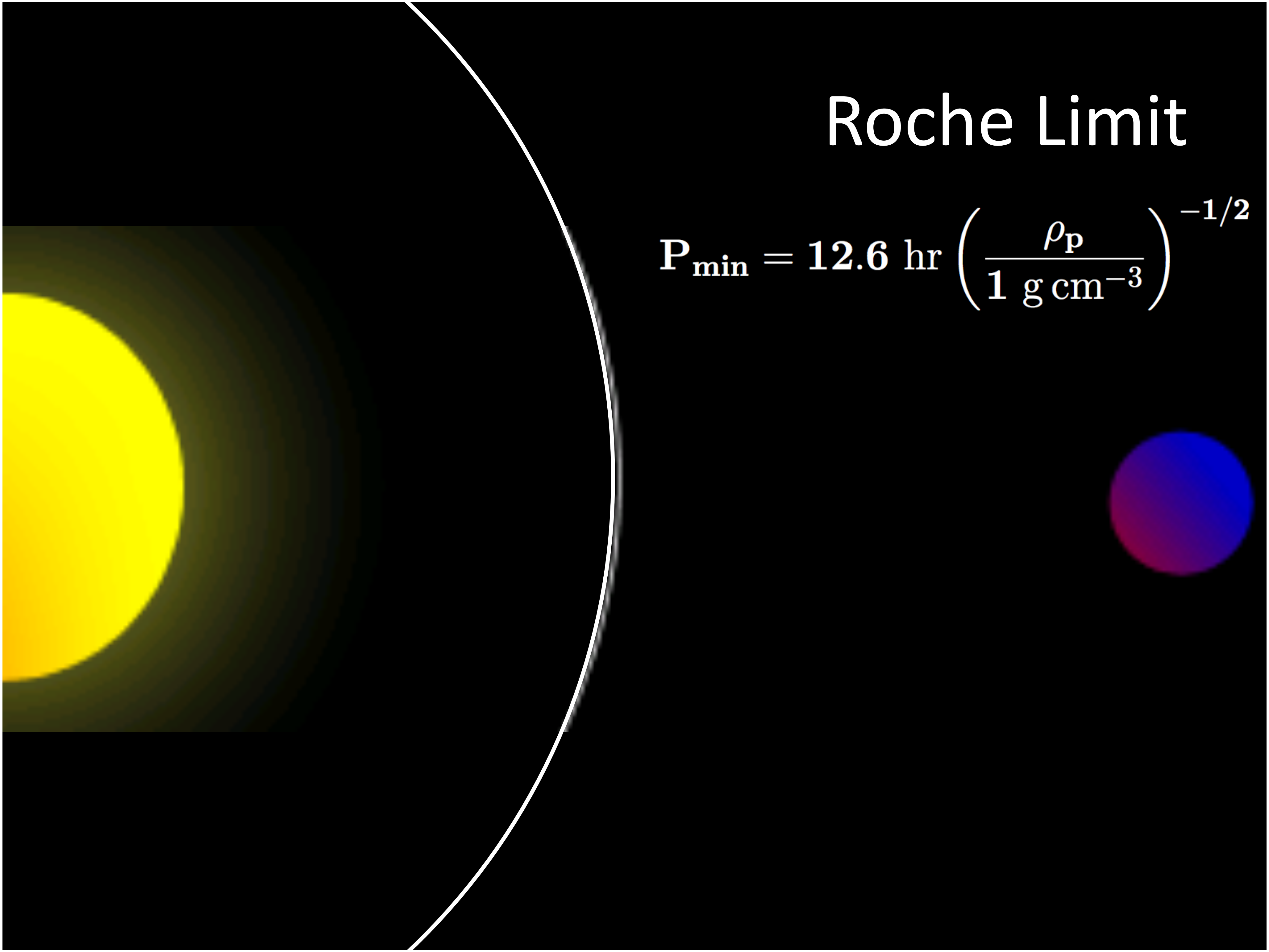


Dessing et al. (2015), Zeng & Sasselov (2016), Buchhave et al. (2016)


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

$$\mathbf{P_{min}} = \mathbf{12.6}\ \mathrm{hr}\left(\frac{\rho_{\mathbf{p}}}{\mathbf{1}\ \mathrm{g\,cm^{-3}}}\right)^{-\mathbf{1/2}}$$



Roche Limit

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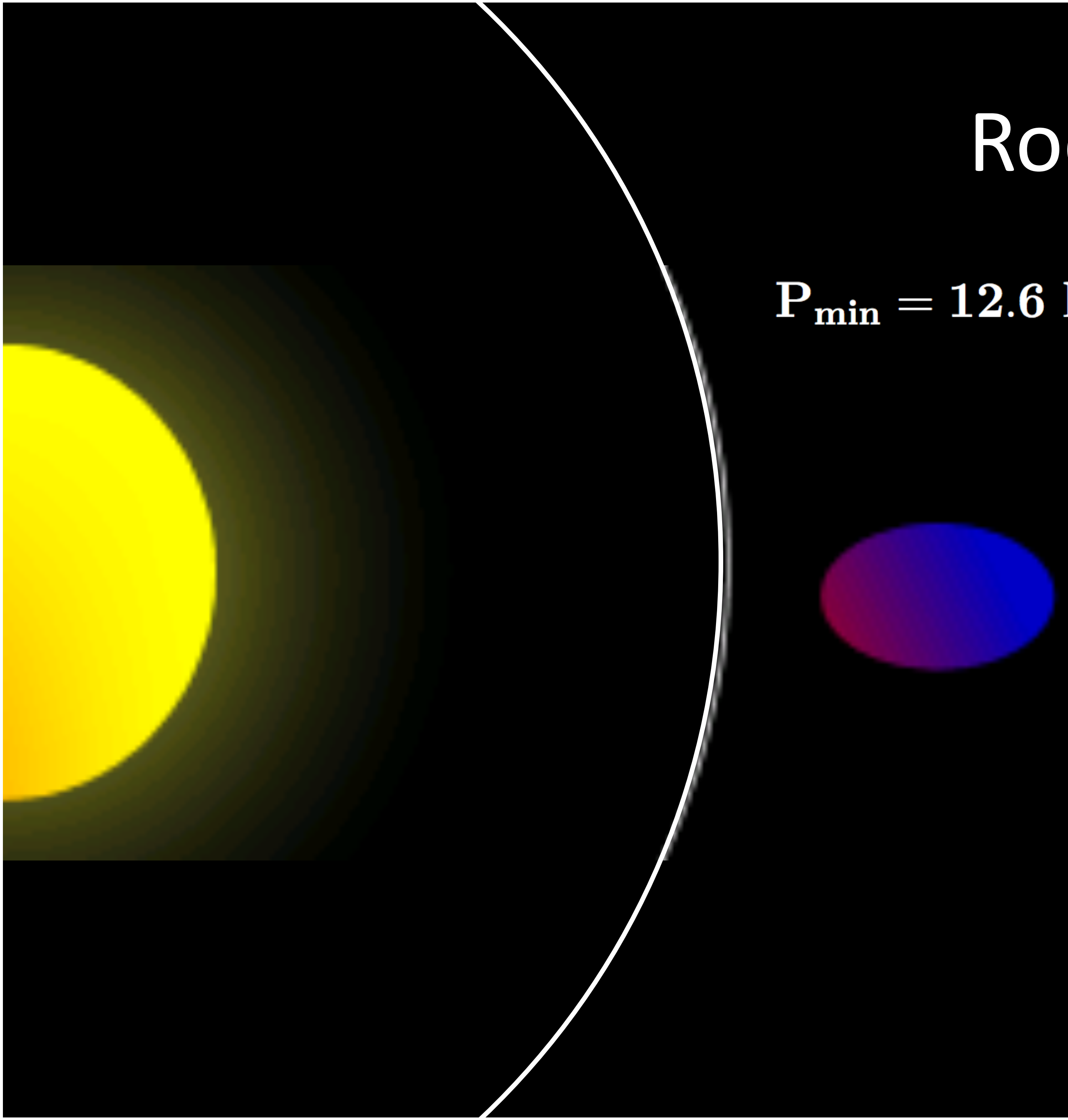
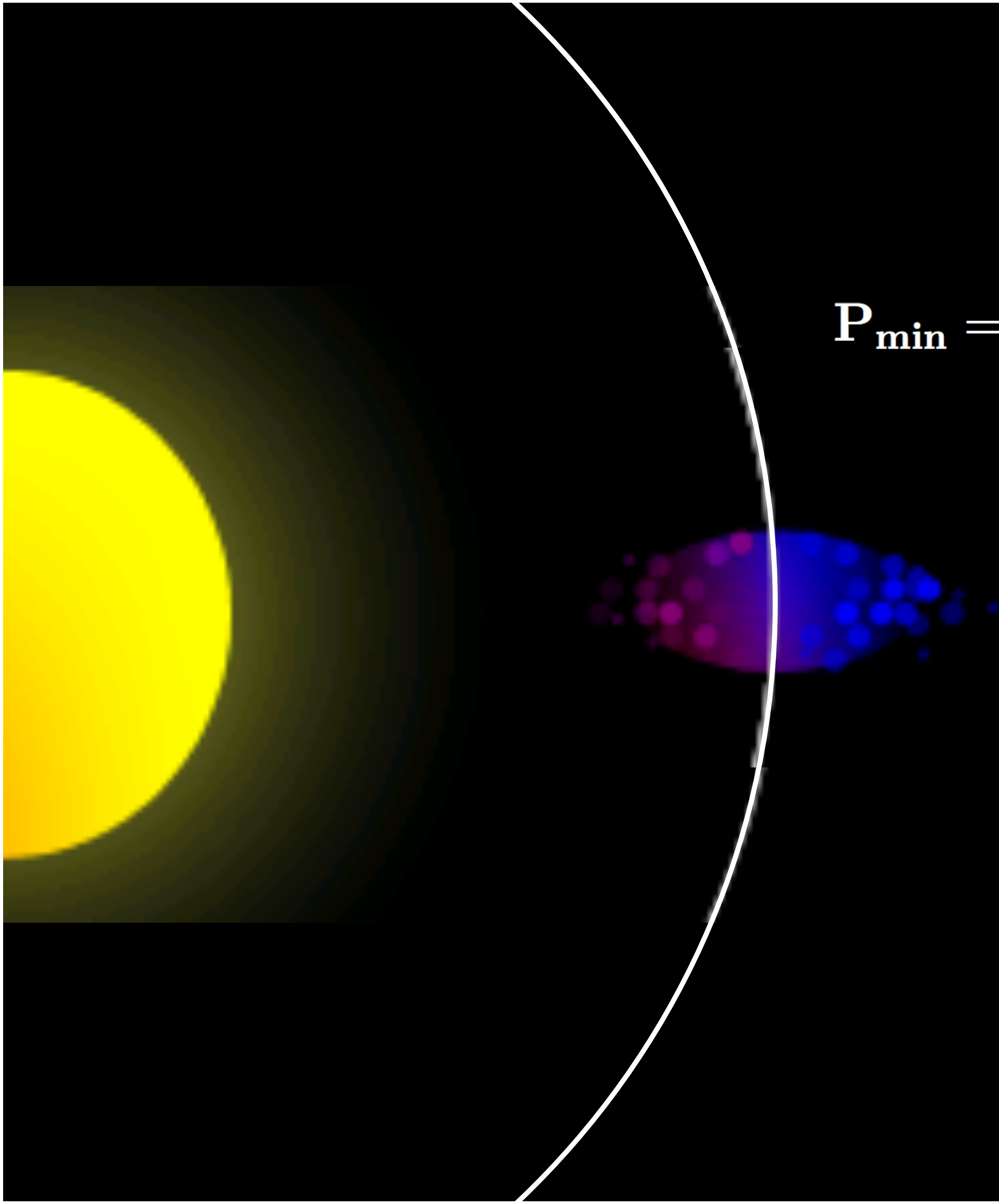


Roche Limit

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



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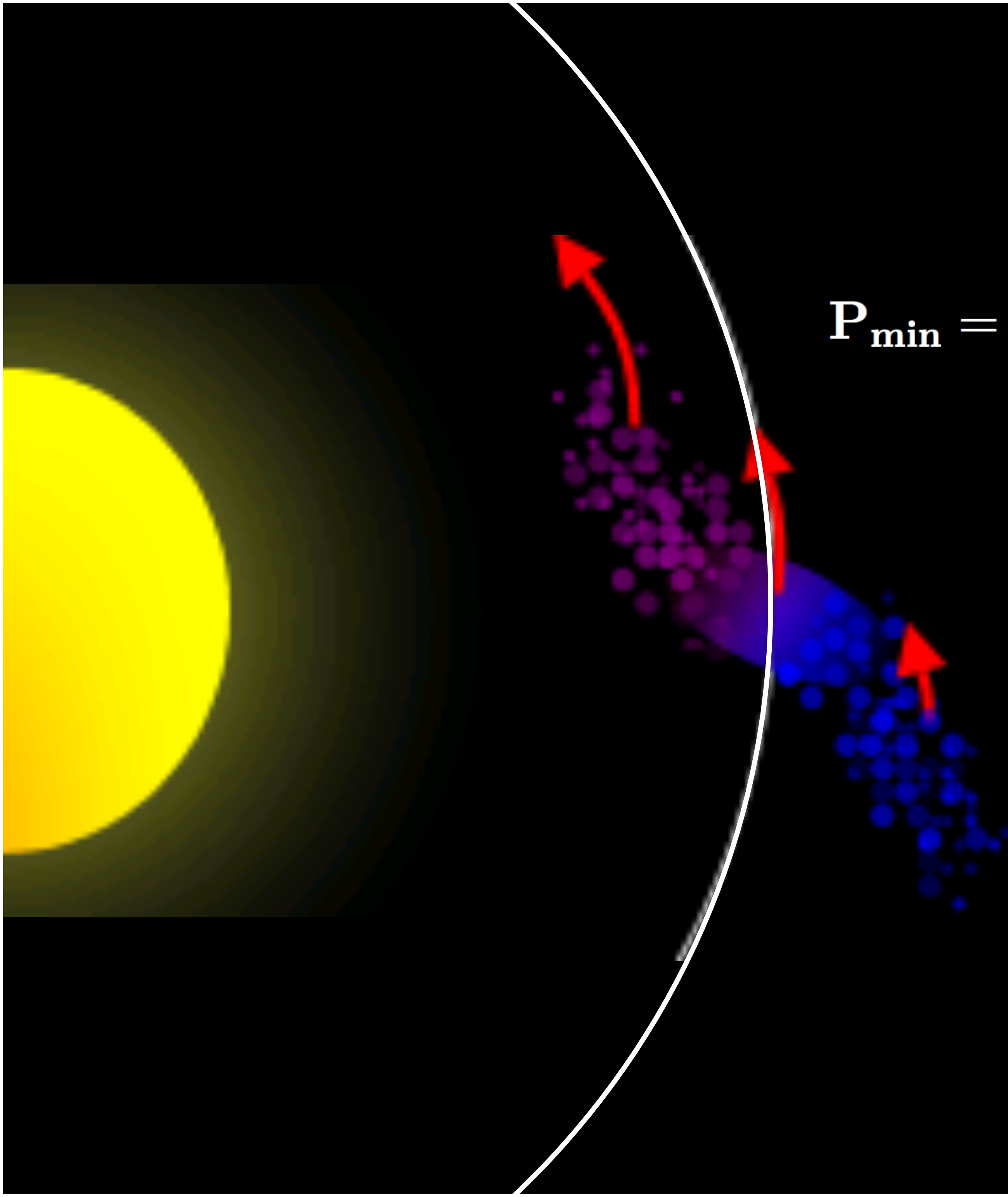

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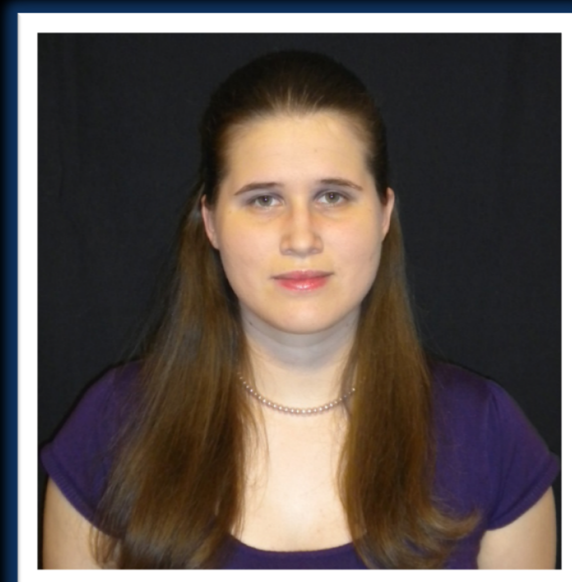
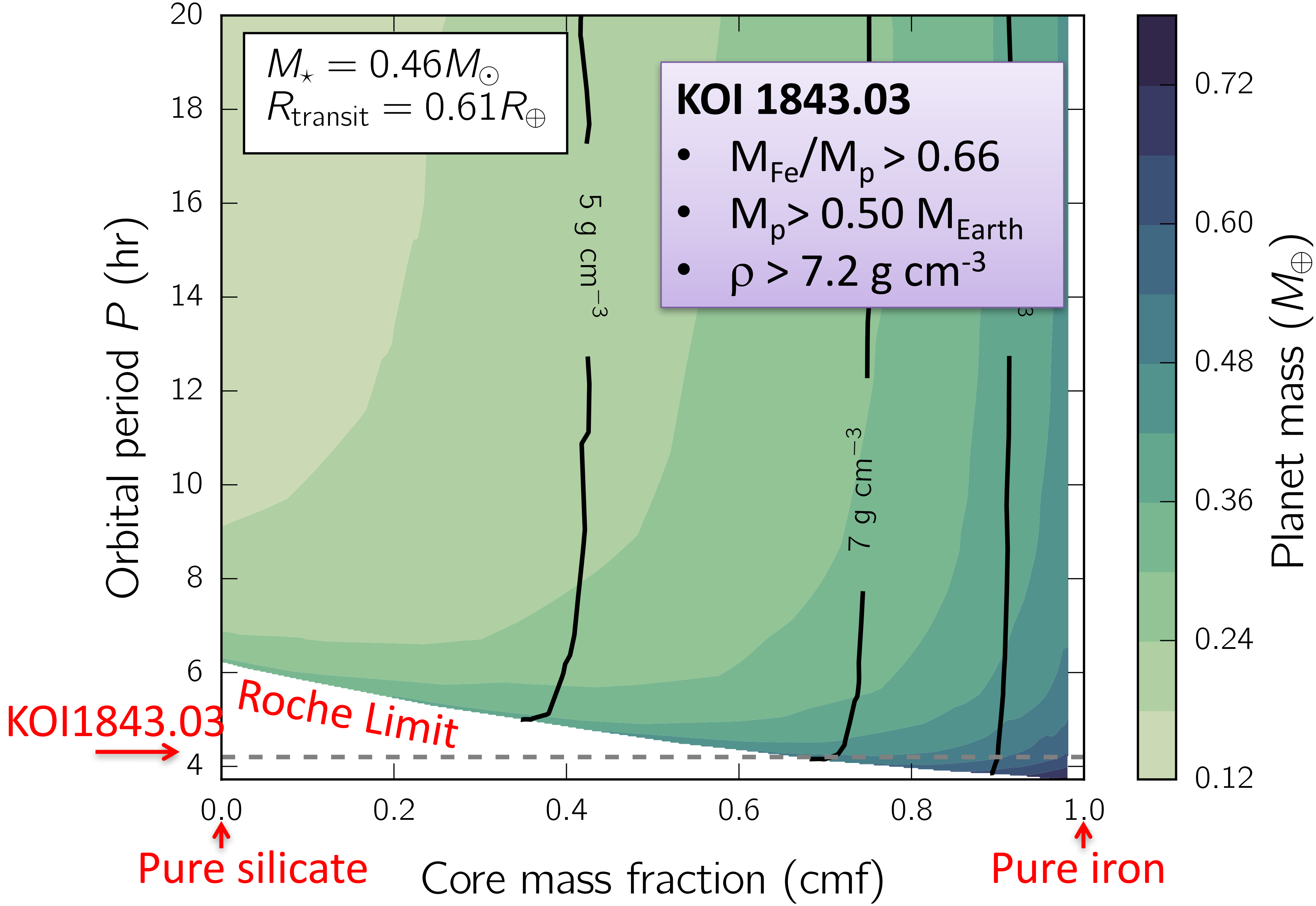


Ellen Price
Harvard Grad Student

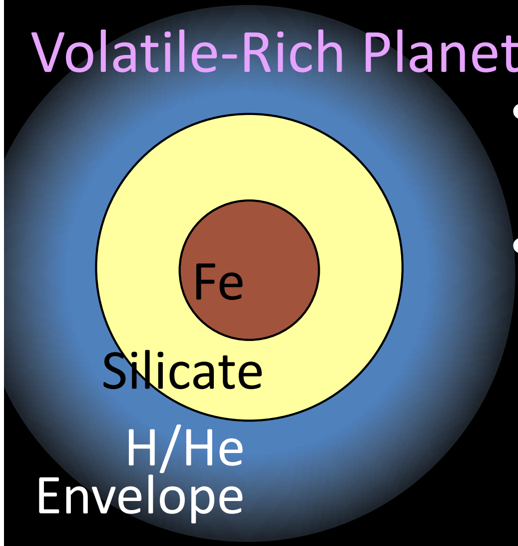
Revised Constraints on the Properties of KOI-1843.03



Price & Rogers (to be submitted)

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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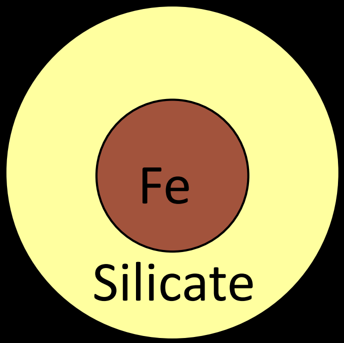
Rocky Planets

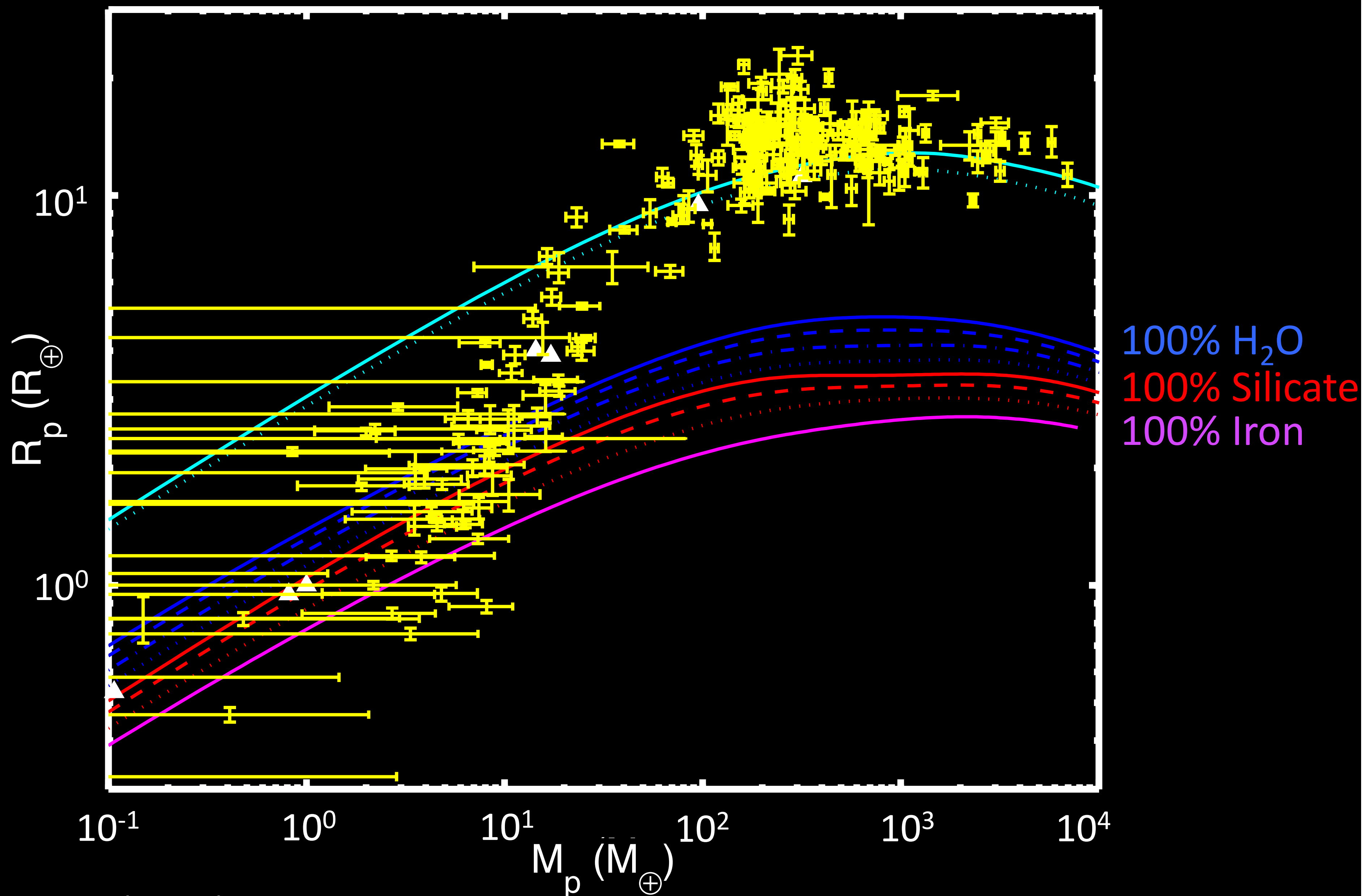


- Most rocky planets with measured M-R (including Kepler-36b) are consistent with an Earth-like composition.
  - KOI-1843.03 is Fe-enhanced exo-Mercury
- Rocky planets with M-R measurements could be remnant cores of planets that lost their volatile envelopes.

Upcoming space-based surveys will discover many transiting planets around bright stars!

Many Precision RV Spectrographs Under Development:
e.g., SHREK (Keck), SPIRou (CFHT), MAROON-X (Magellan), HPF (HET), CARMENES (Calar Alto), Espresso (VLT), EXPRES, G-CLEF (GMT)

Planet Mass-Radius Measurements



Seager et al. (2007) M-R Relations