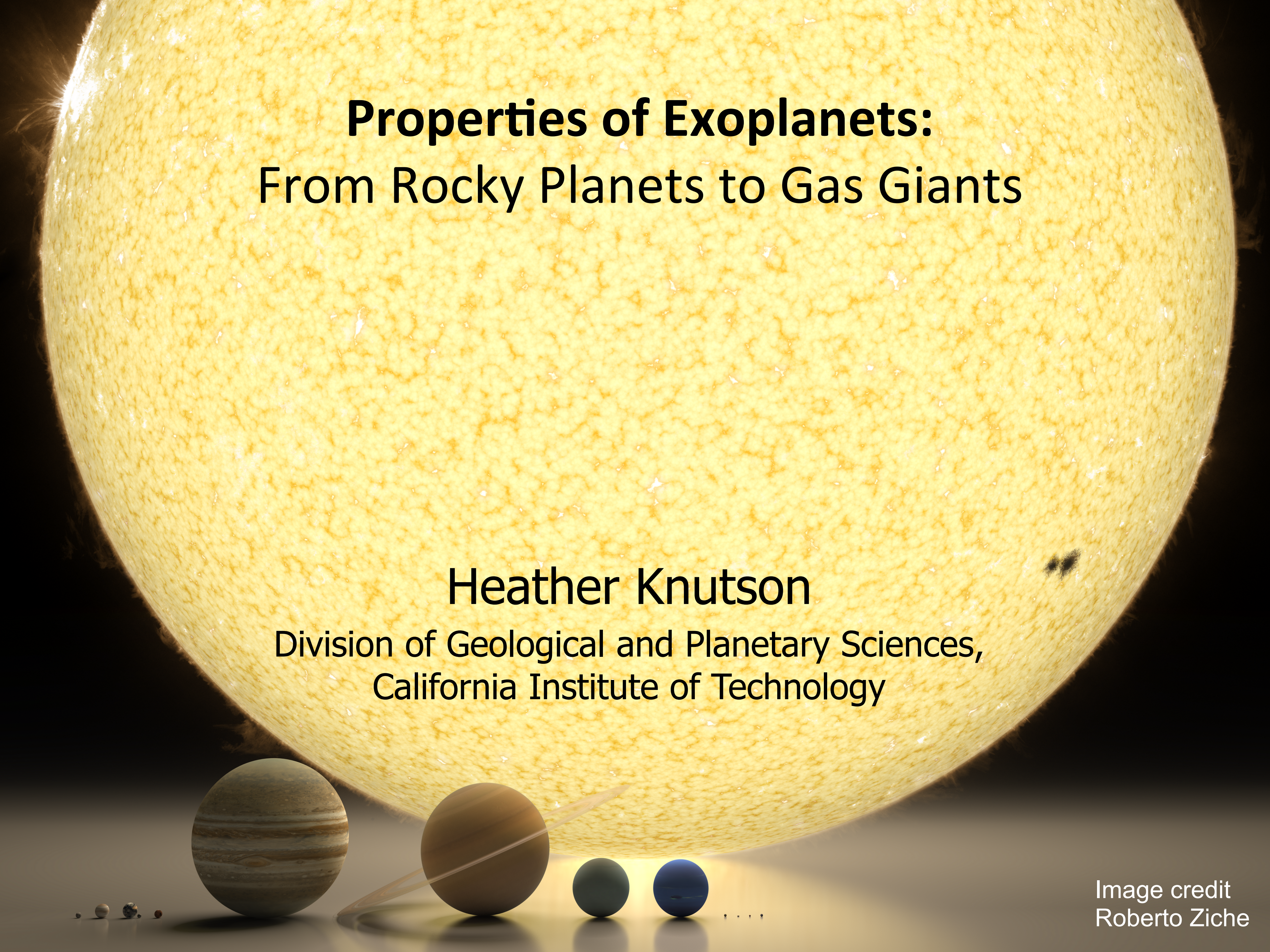


Properties of Exoplanets:

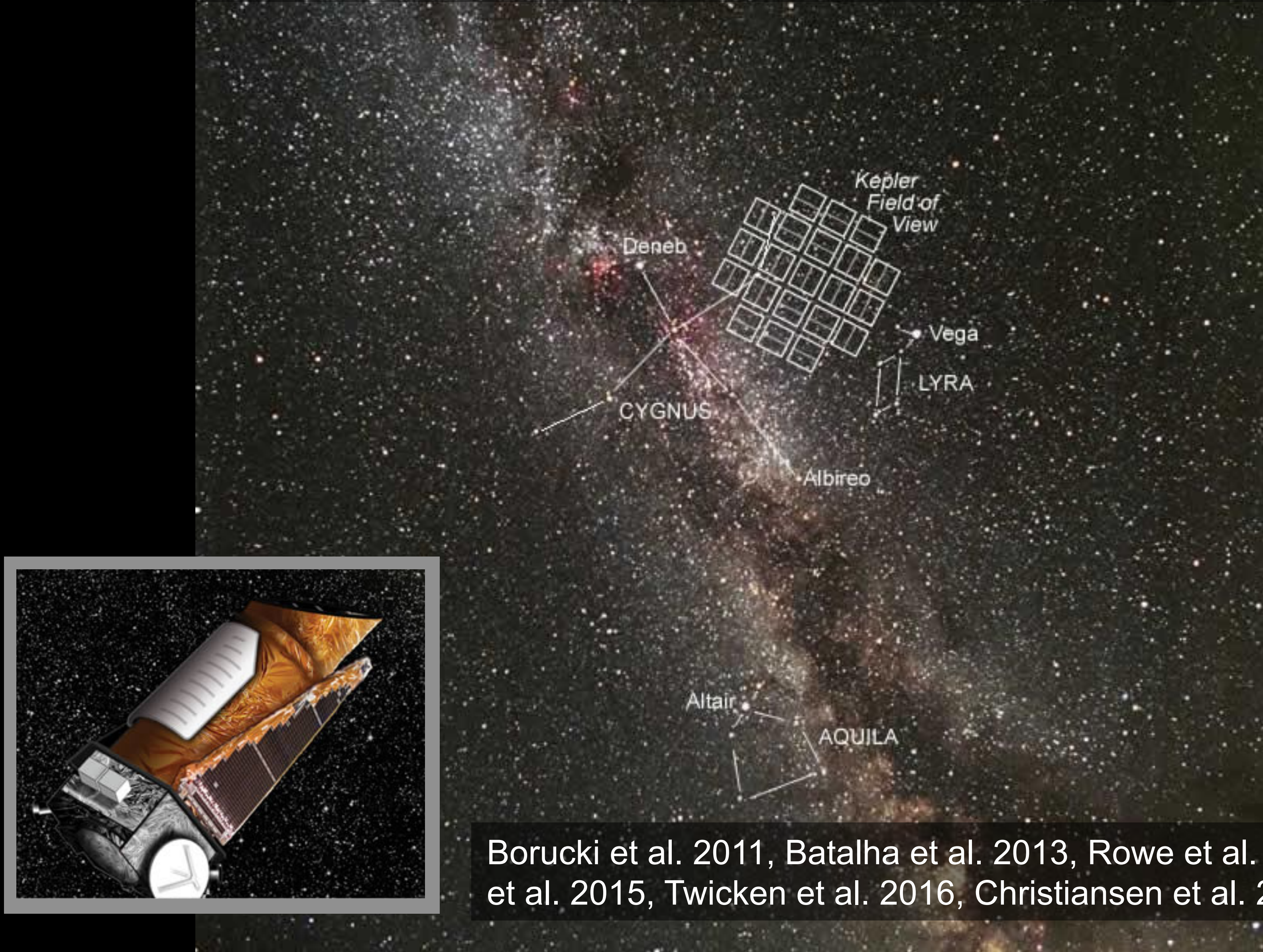
From Rocky Planets to Gas Giants

Heather Knutson

Division of Geological and Planetary Sciences,
California Institute of Technology

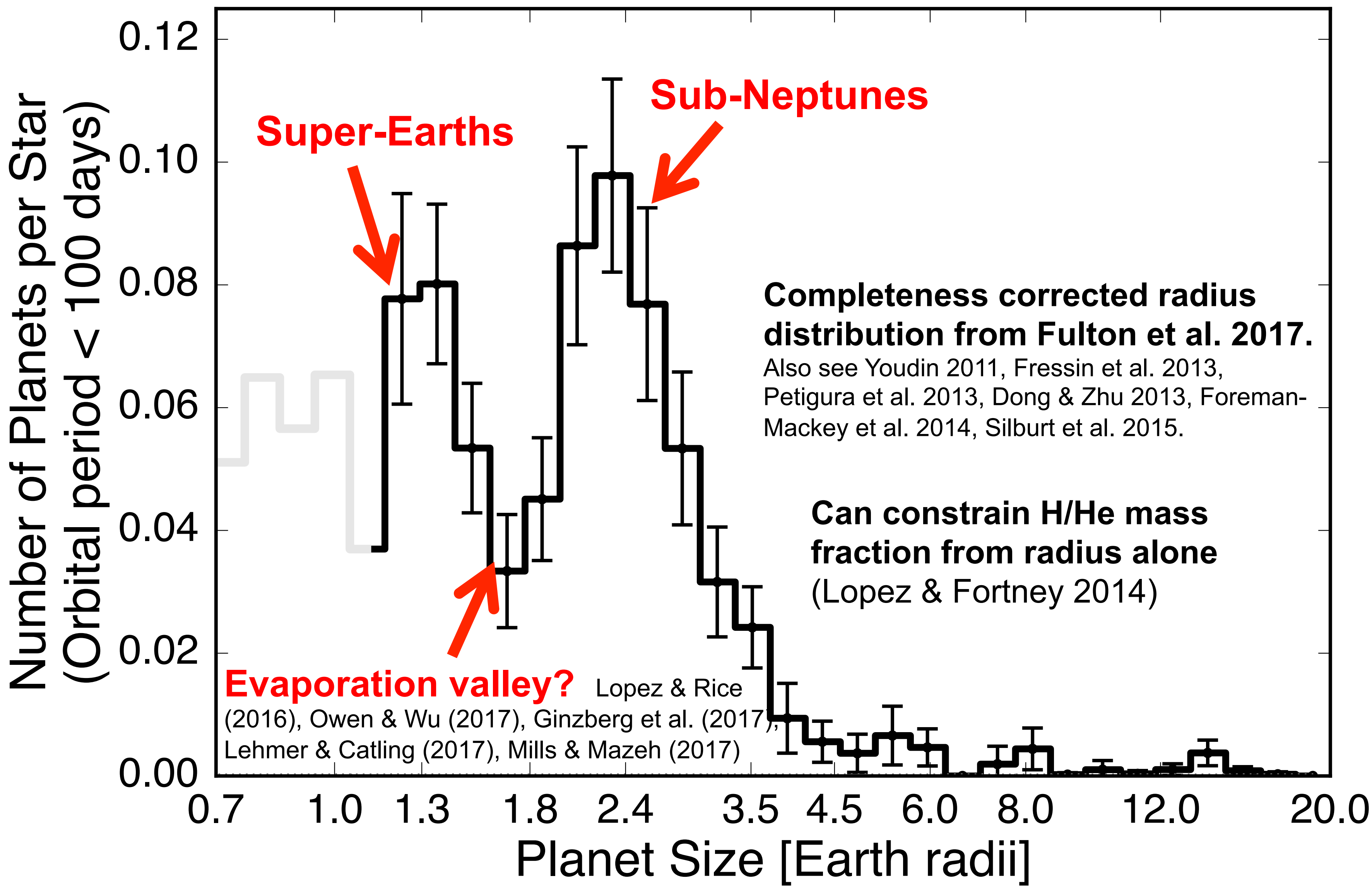
Image credit
Roberto Ziche

The Kepler Telescope searched ~150,000 FGKM stars for evidence of transiting planets…

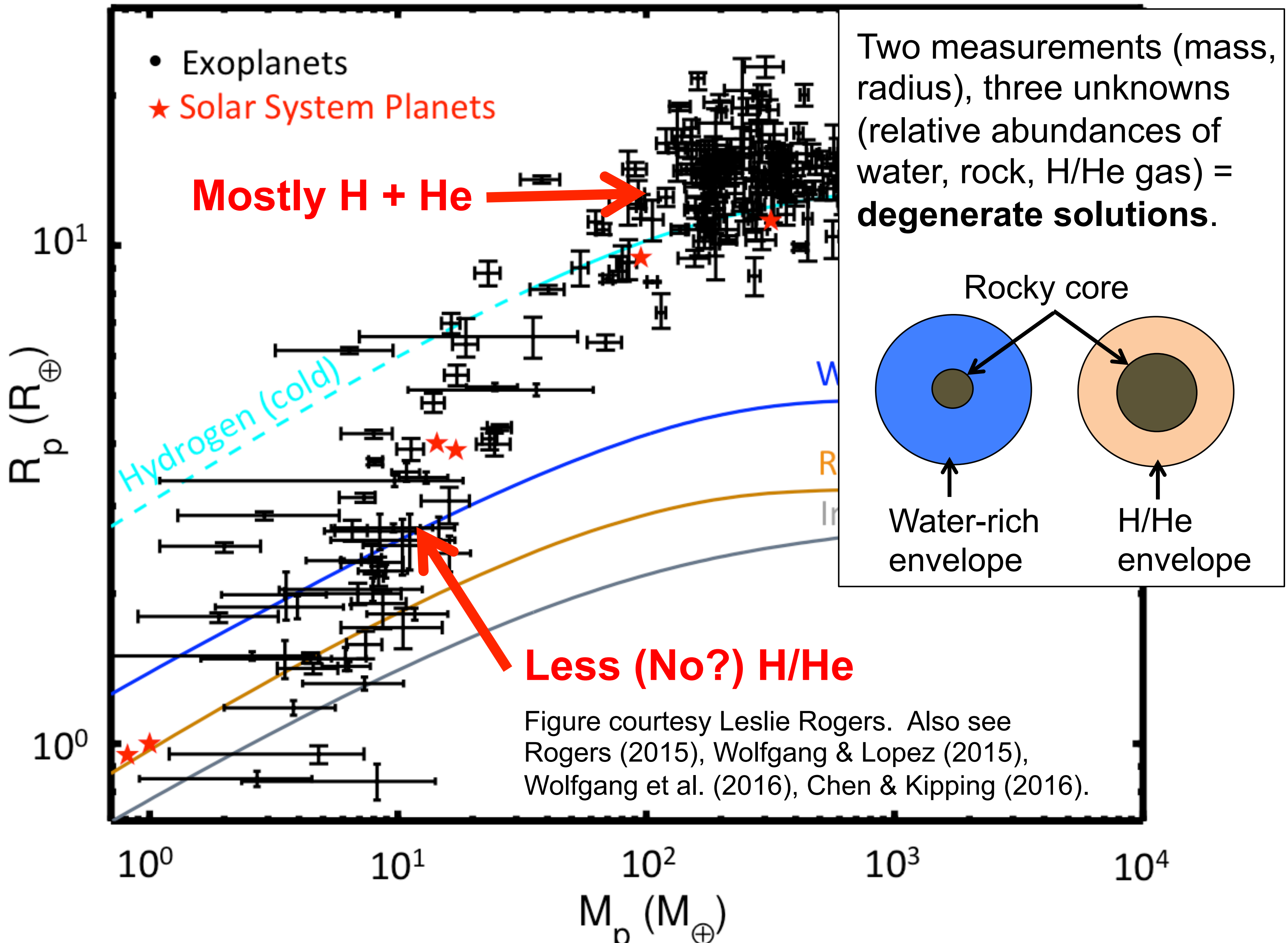


Borucki et al. 2011, Batalha et al. 2013, Rowe et al. 2015, Mullally et al. 2015, Twicken et al. 2016, Christiansen et al. 2016

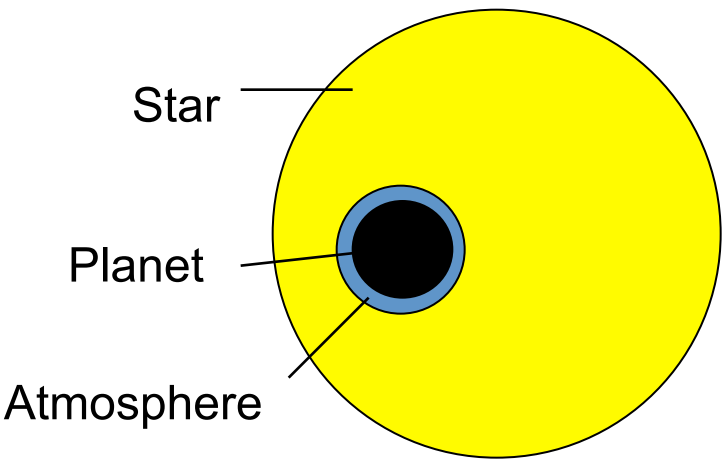
… and detected more than 5,000 planets and planet candidates.



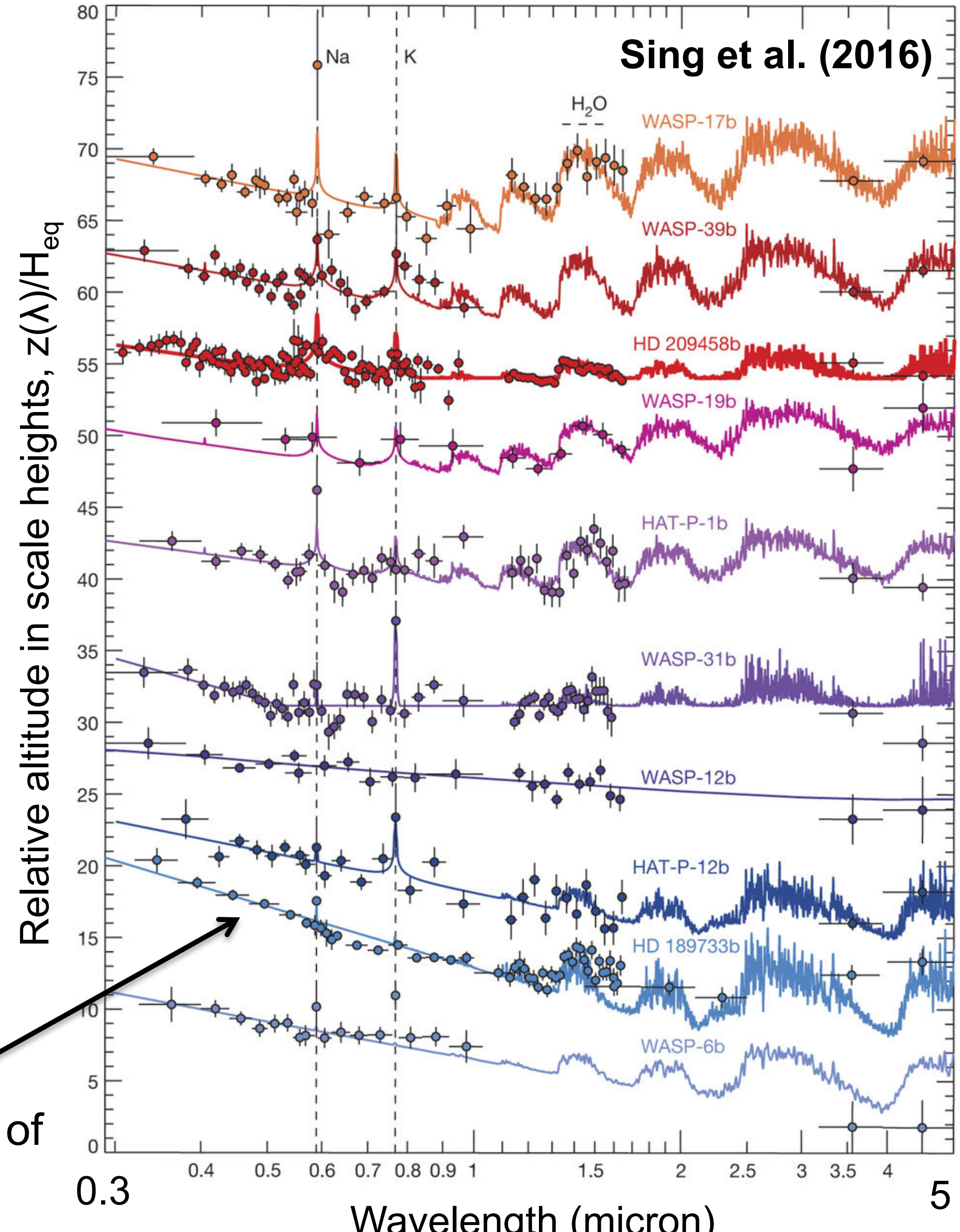
Mass measurements for ~200 planets



Studied the atmospheric compositions of a few dozen planets (not very well).



Clouds **attenuate expected absorption features** in majority of planets observed to date



Possible Trend in Atmospheric Metallicity, But Significant Diversity at Lower Masses

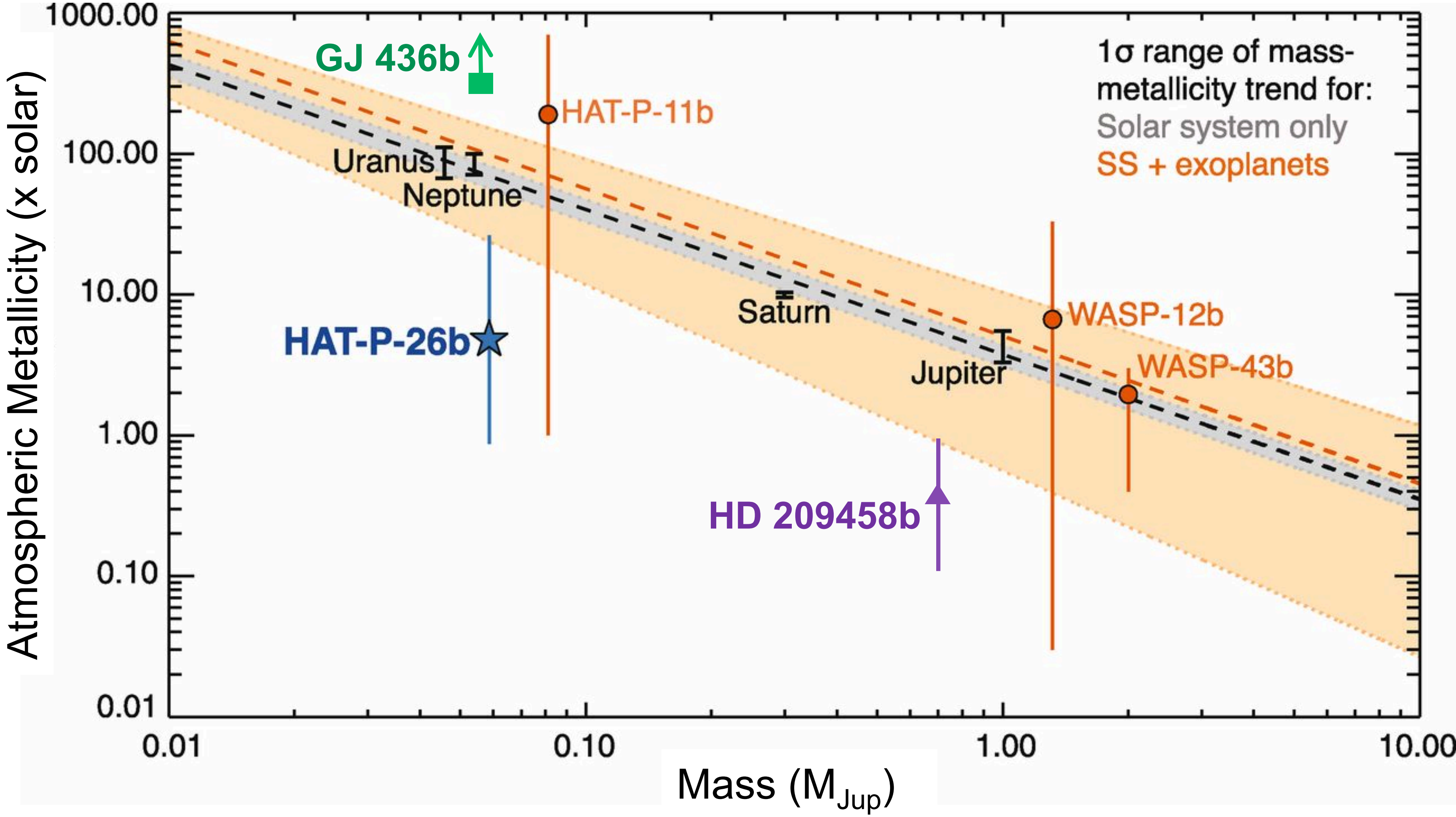
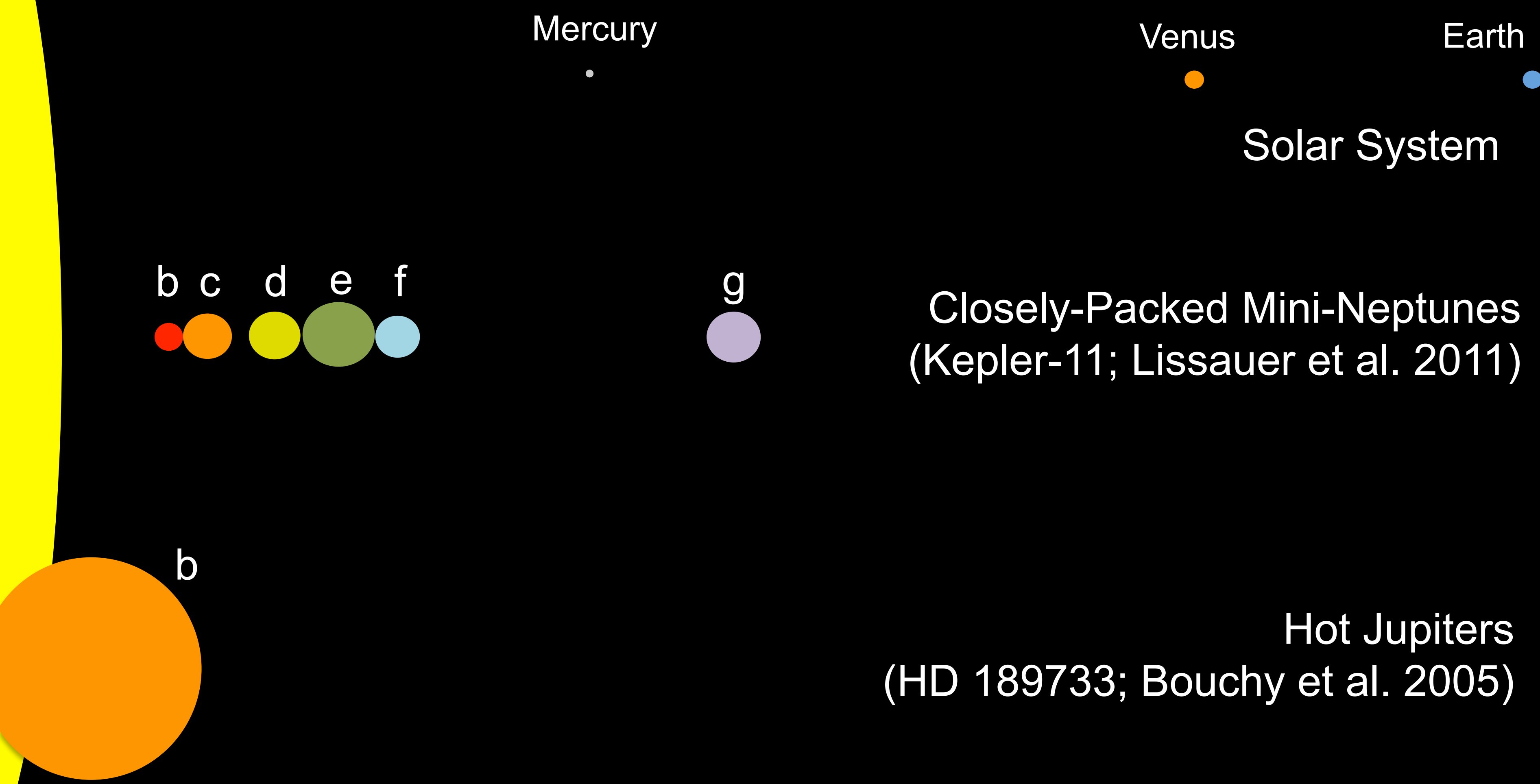


Figure adapted from Wakeford et al. (2017). GJ 436b measurement from Morley et al. (2017), HD 209458b from Brogi et al. (2017)

Cataloging the Diversity of (Exo)planetary System Architectures

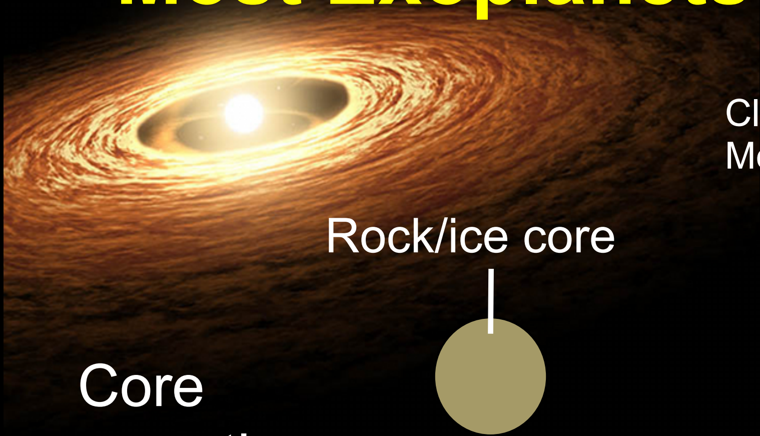


Want to go from stamp collecting -> storytelling.

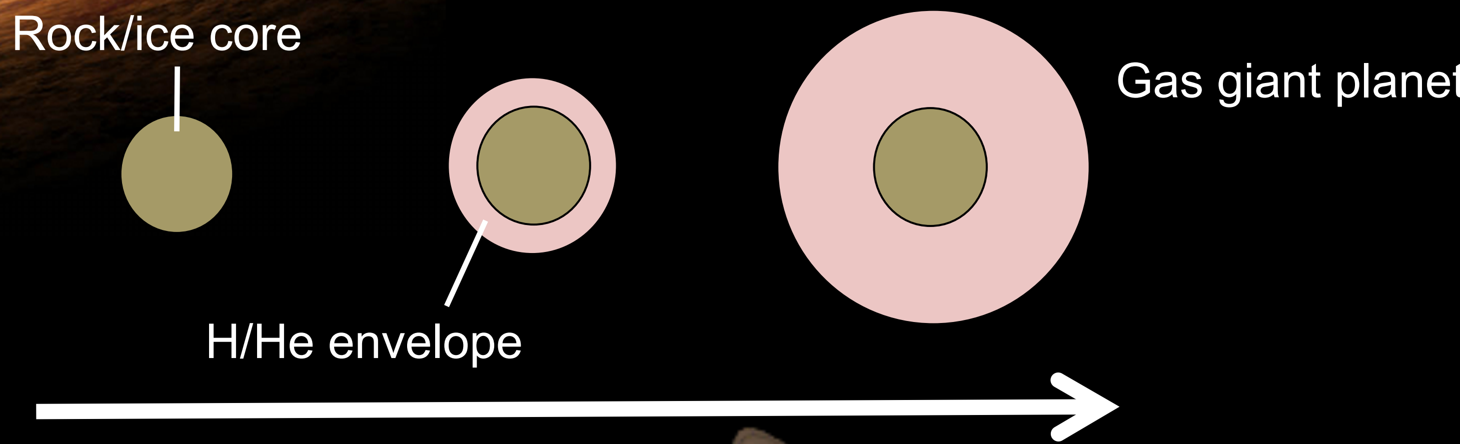
(radii to scale + distances to scale)

The Story So Far:
Most Exoplanets Formed Via Core Accretion

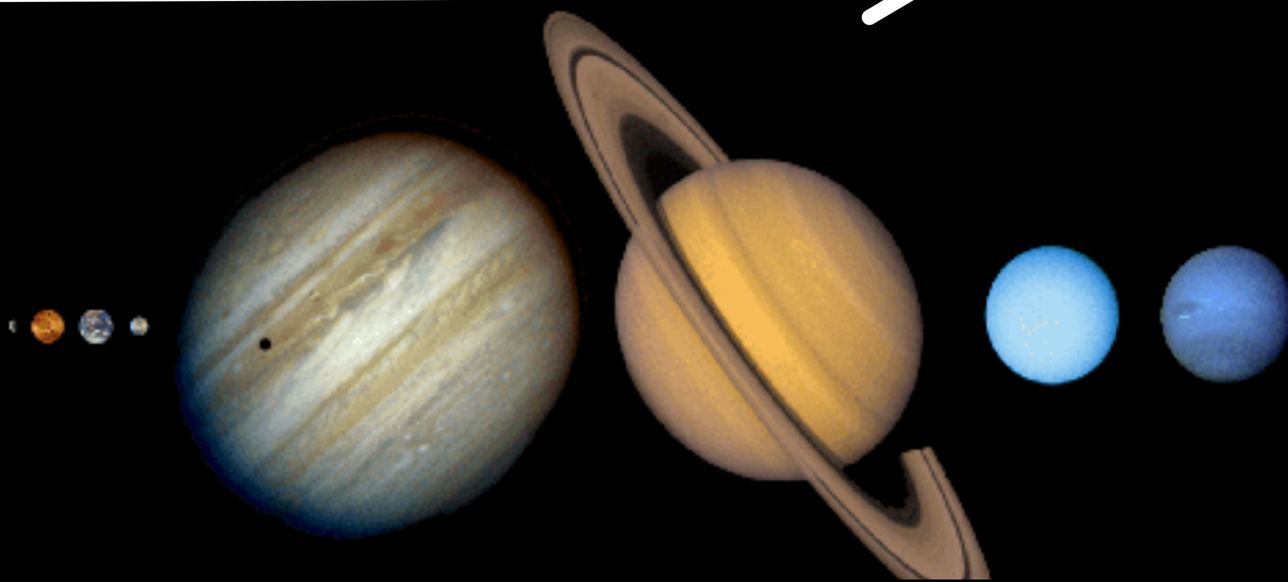
Classic: Pollack et al. 1996
Modern: Youdin & Goodman (2005), Lambrechts & Johansen (2012)



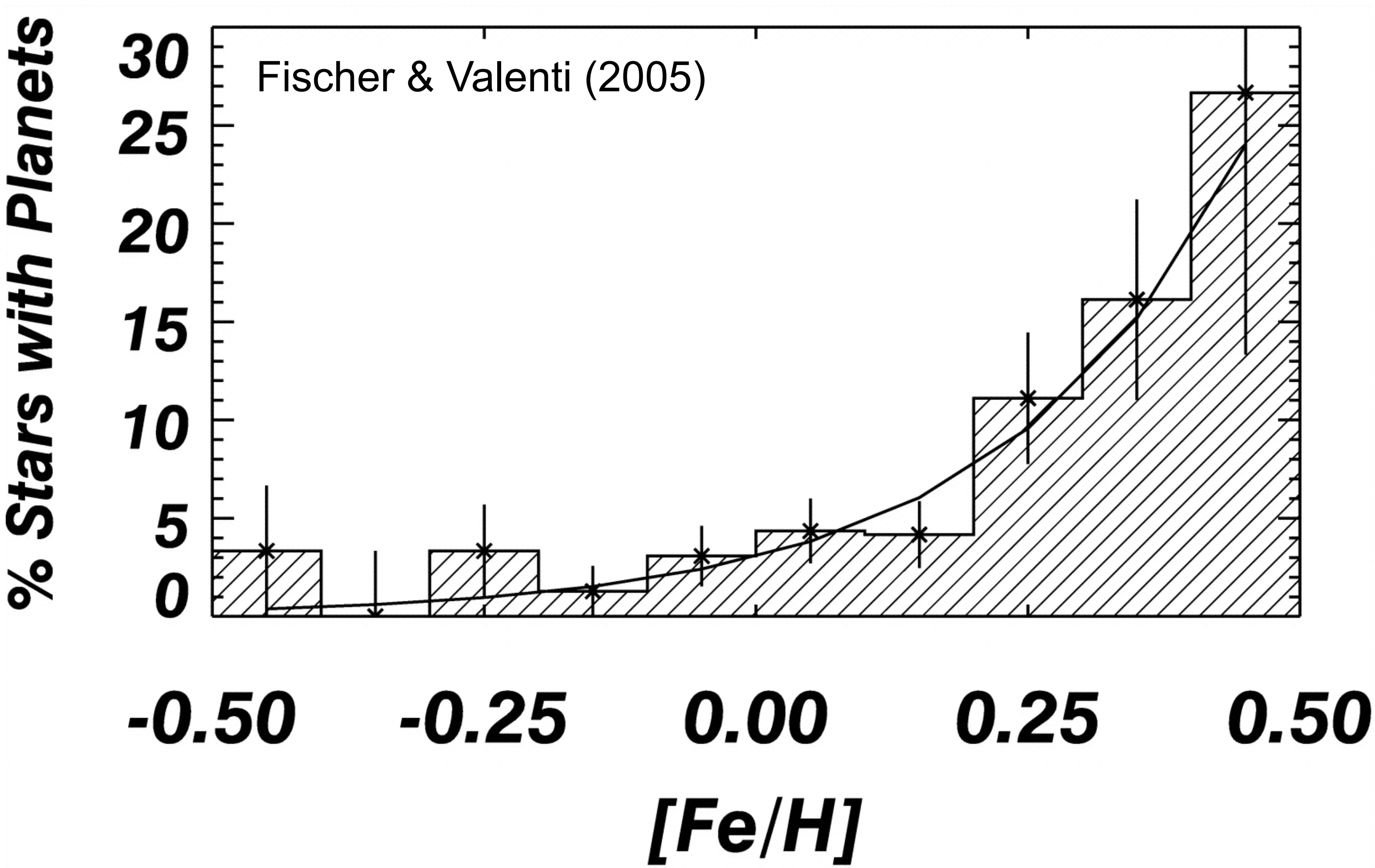
Core accretion model:



Final compositions, architectures:

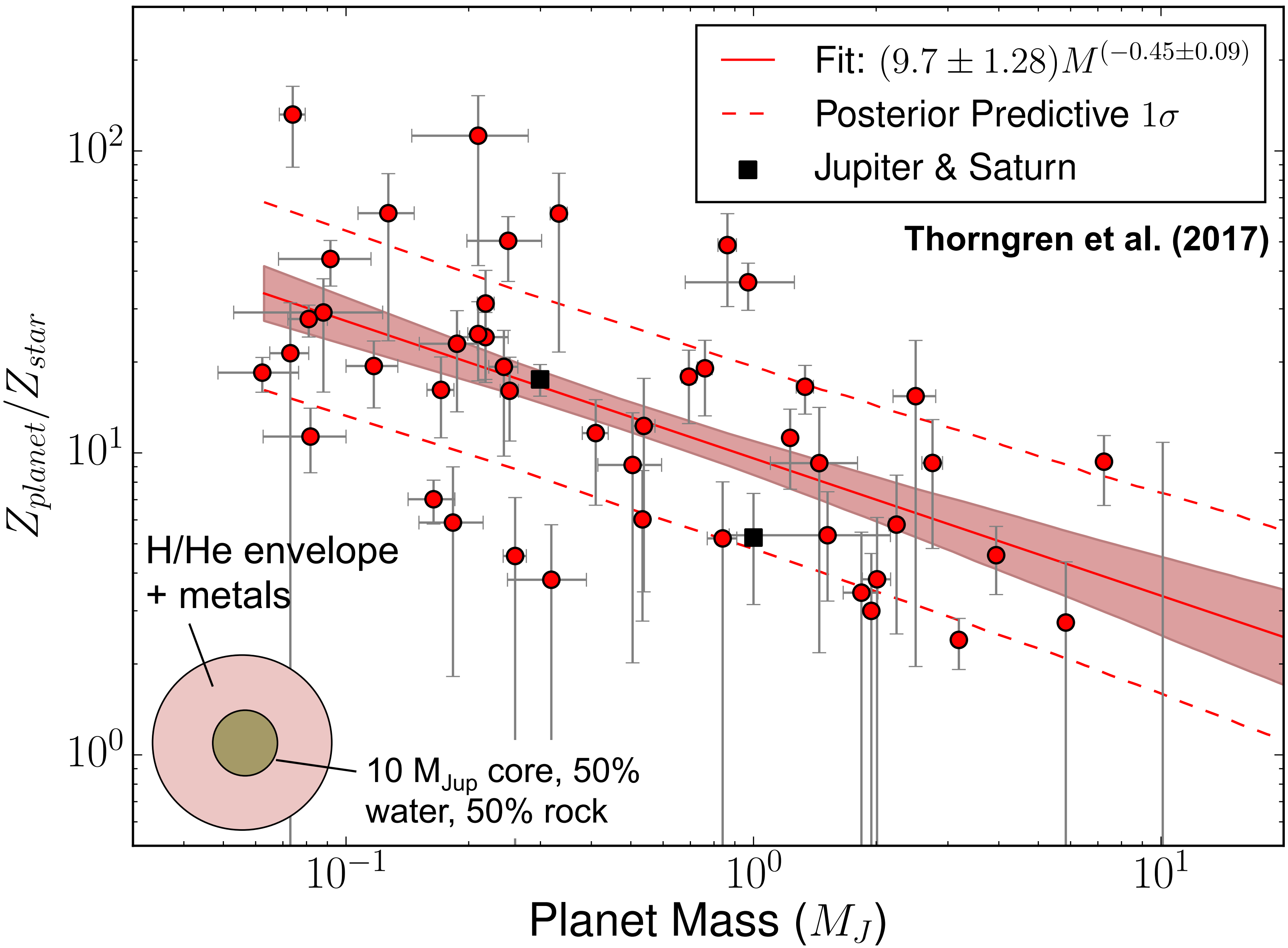


Evidence for Core Accretion: Gas Giant Planets Are More Common Around Metal-Rich Stars

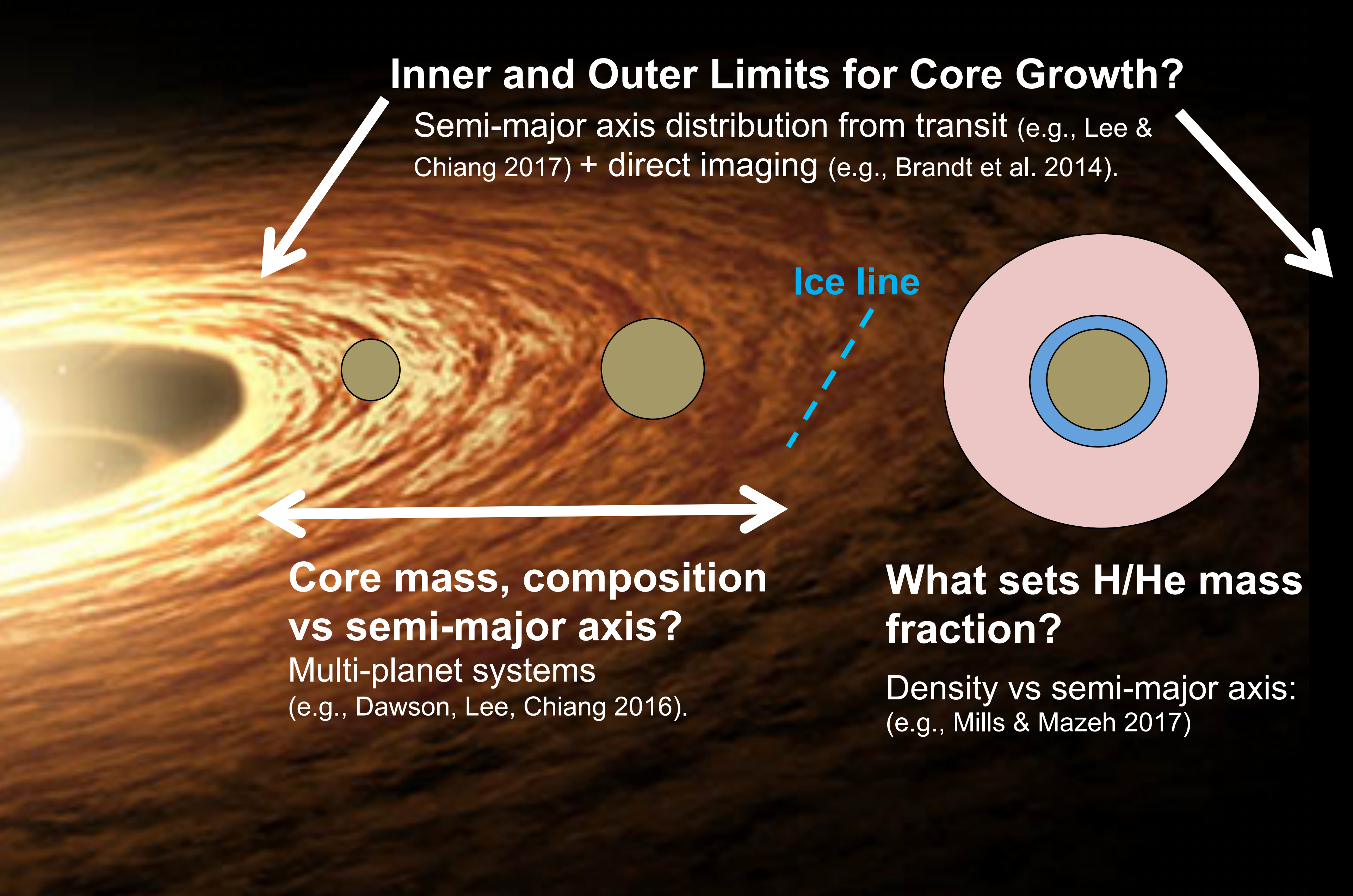


Small planets are controversial:
Wang & Fischer (2013)< Buchhave & Latham (2015), Zhu et al. (2016)

Evidence for Core Accretion: Gas Giant Planets Have Enhanced Metallicities



Big Questions for the Core Accretion Model



The Story So Far: Planets Migrate, Sometimes Large Distances

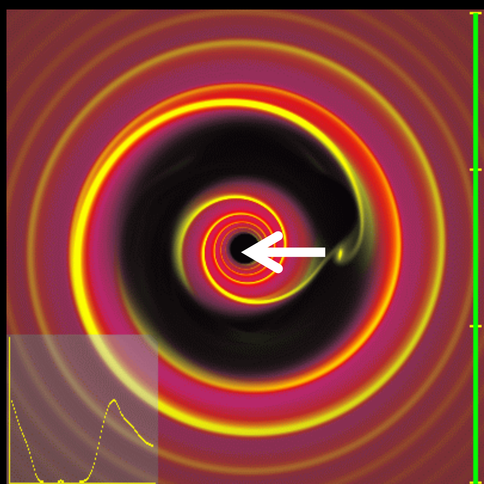
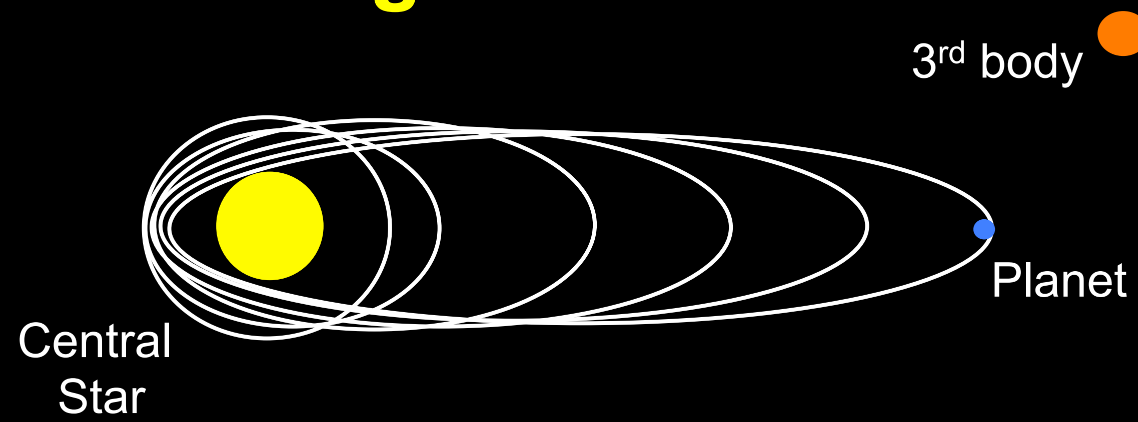


Image credit: P. Armitage

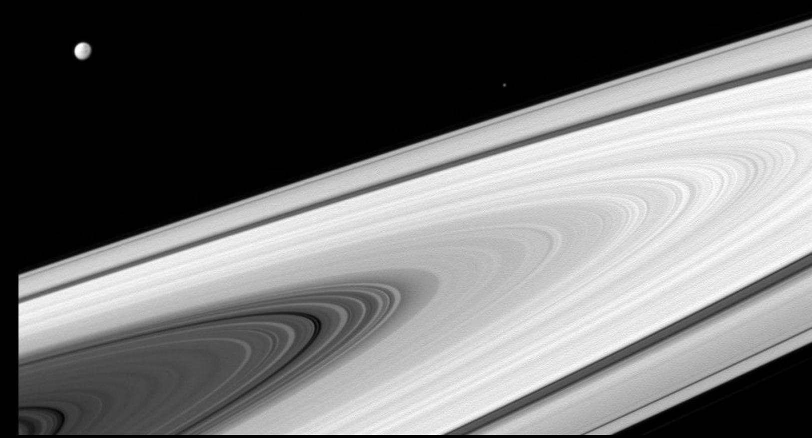
Disk Migration

Smooth convergent migration leads to orbital resonances. Examples include: GJ 876, Kepler-223, Kepler-36, Neptune + Kuiper belt, Saturn's rings + moons.

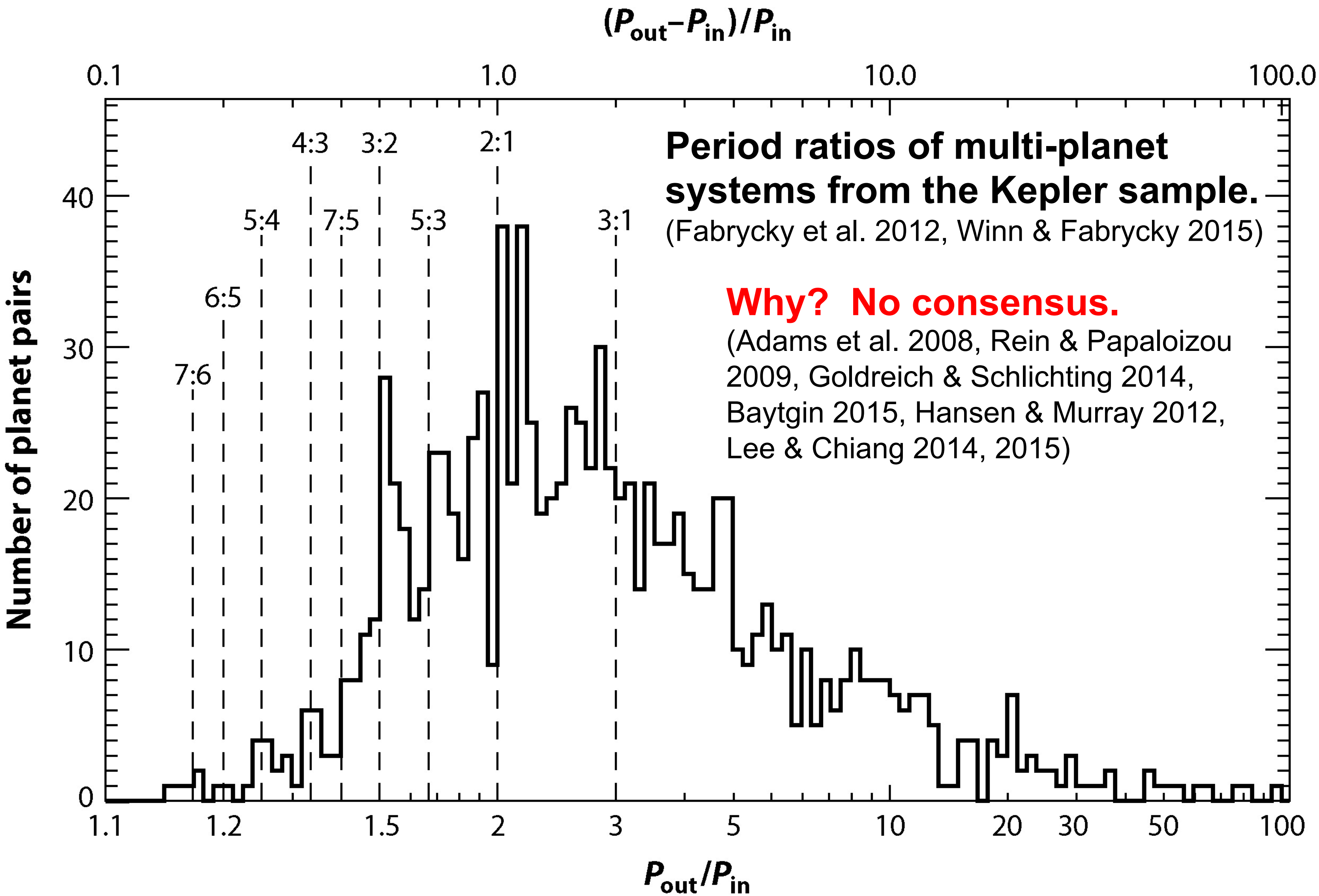


High Eccentricity Migration

Key evidence: population of exoplanets on highly eccentric and/or inclined orbits in multi-body systems.



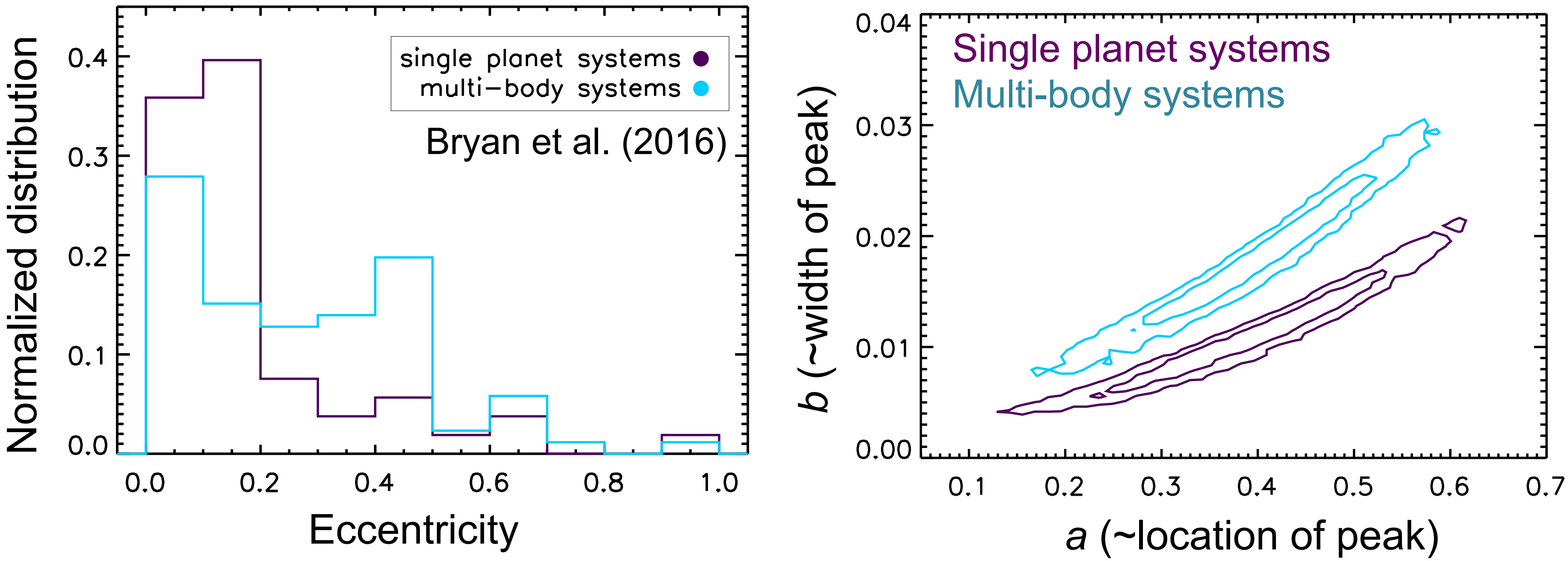
Orbital Resonances Exist, But Are Less Frequent Than One Might Expect



Period ratios of multi-planet systems from the Kepler sample.
(Fabrycky et al. 2012, Winn & Fabrycky 2015)

Why? No consensus.
(Adams et al. 2008, Rein & Papaloizou 2009, Goldreich & Schlichting 2014, Baytgin 2015, Hansen & Murray 2012, Lee & Chiang 2014, 2015)

Planet-Planet Interactions Excite Orbital Eccentricities of Widely Spaced Planets



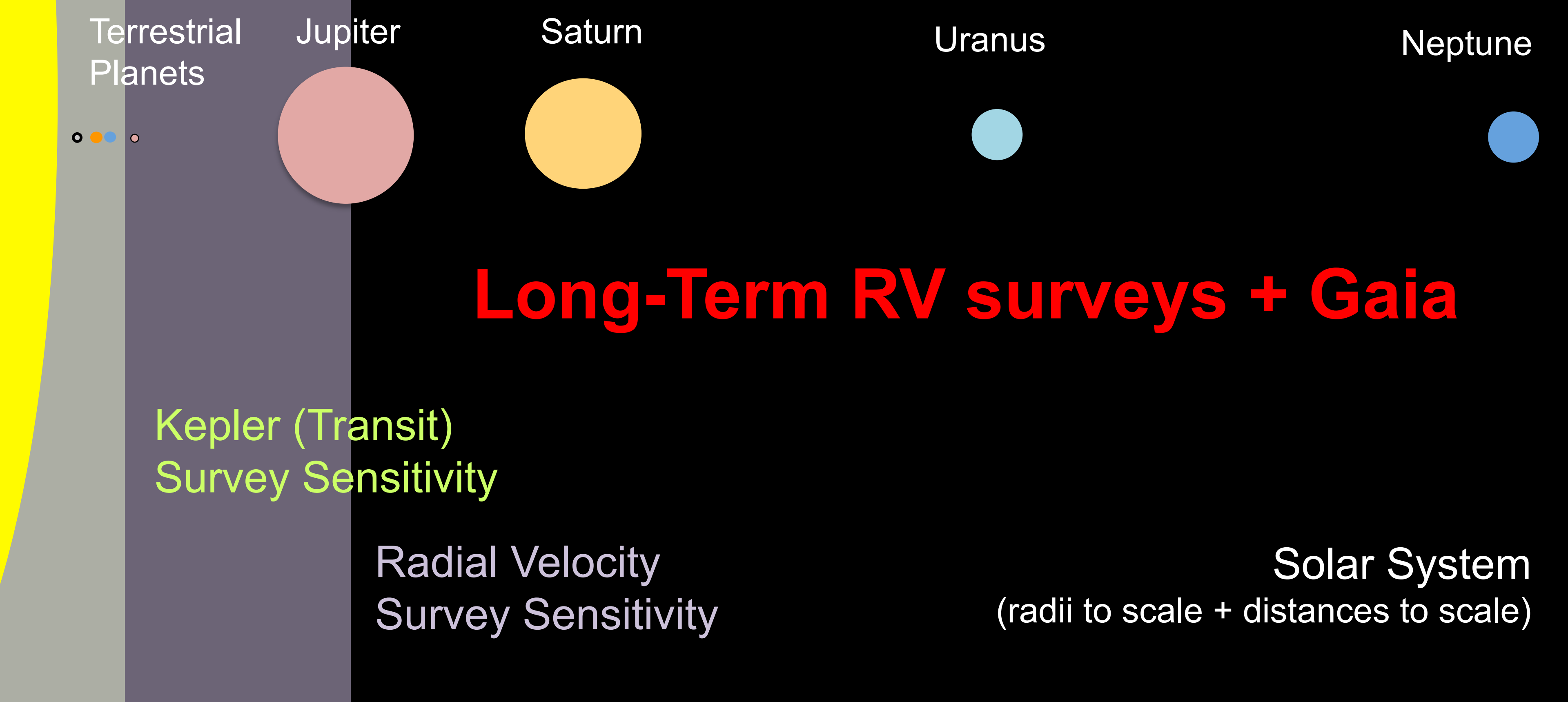
Fit posterior probability distributions for inner planet eccentricities with a beta distribution (Kipping et al. 2013):

$$P(e) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} e^{a-1}(1-e)^{b-1}$$

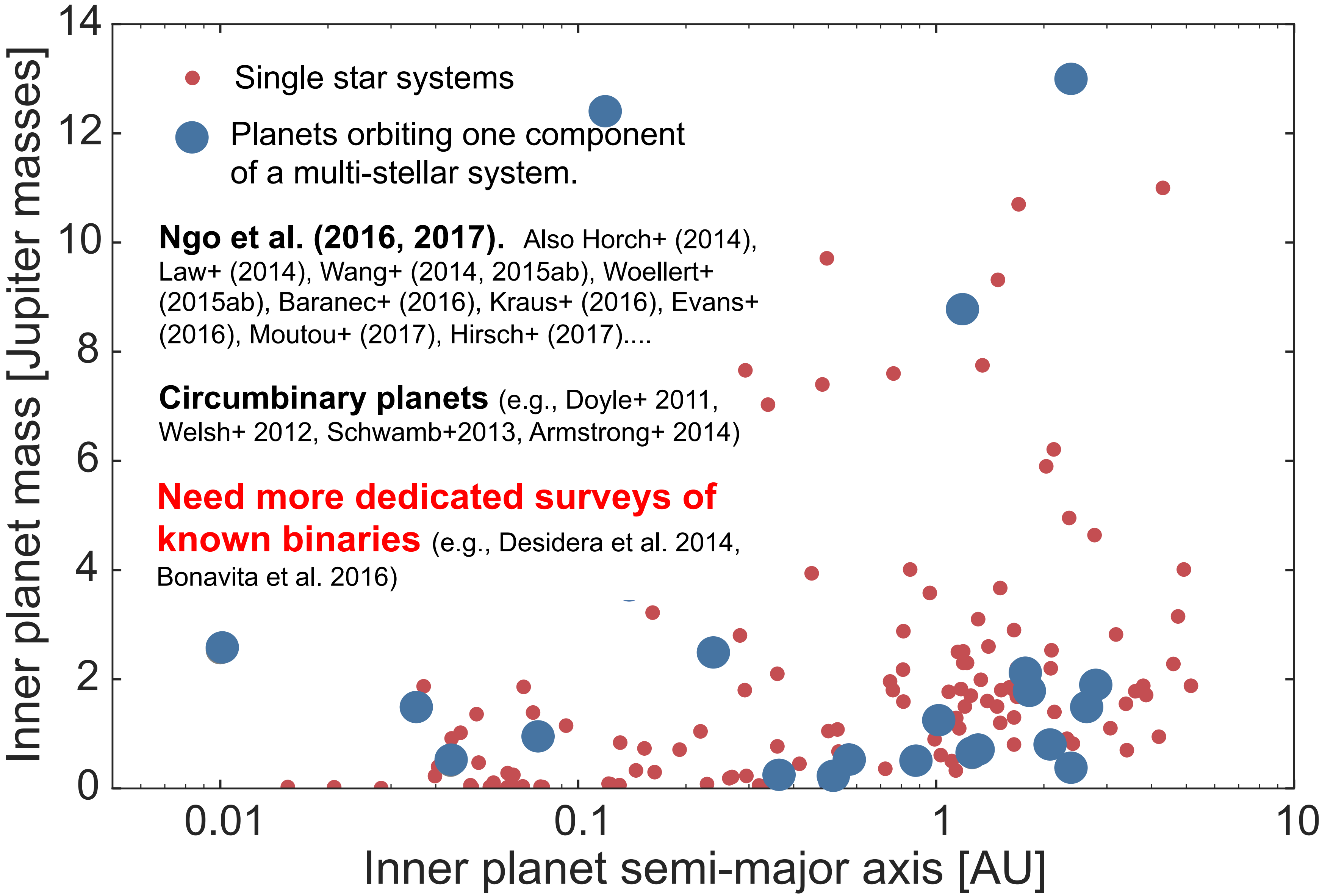
Studies based on short-period Kepler systems (Limbach & Turner 2014, Xie et al. 2016) reached the **opposite conclusion.** Dynamical instabilities?

We have a huge blind spot in our understanding of exoplanetary systems.

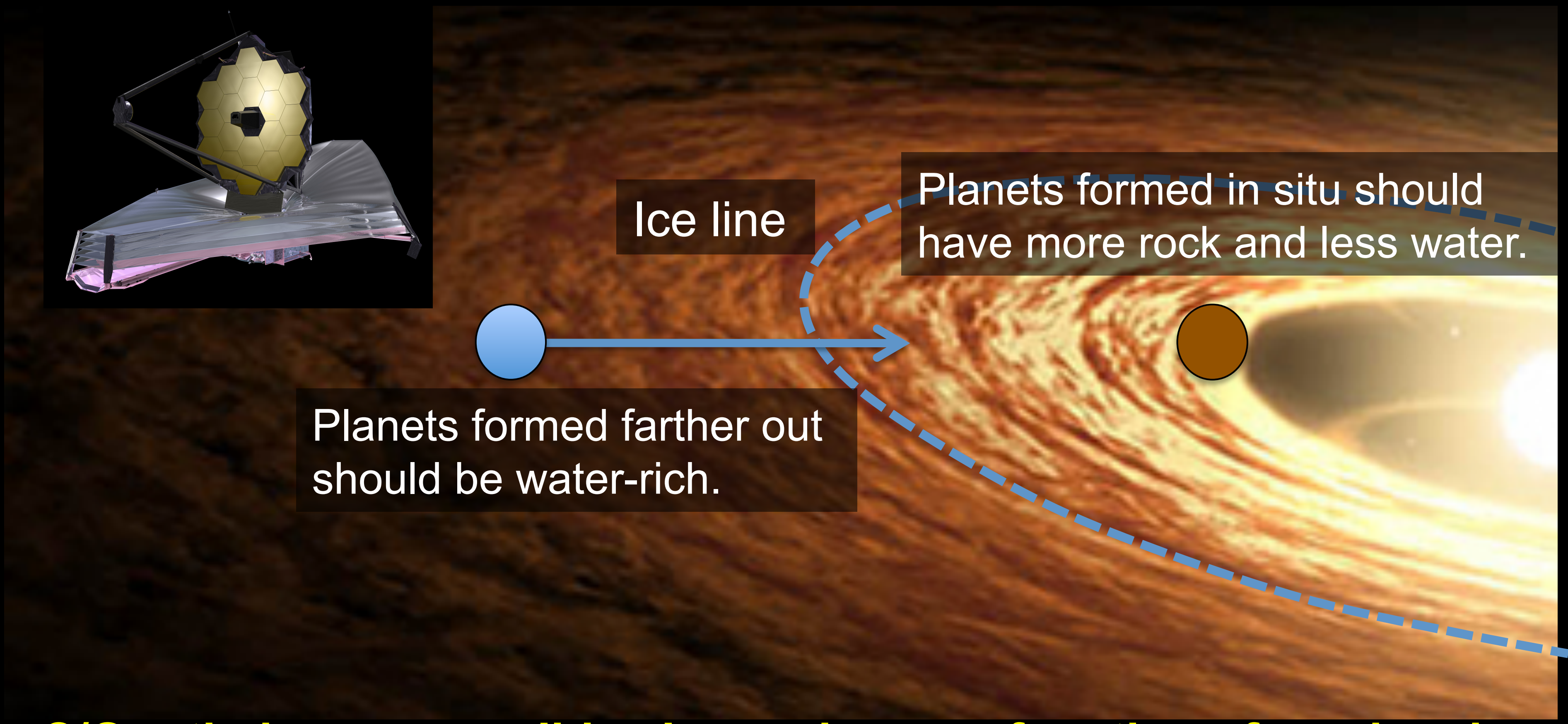
Control dynamical evolution of solar system, flow of materials to inner disk.



Another Blind Spot: Stellar Binaries



Bulk, Atmospheric Compositions Can Help Constrain Formation Locations.



C/O ratio in gas vs solids also varies as a function of semi-major axis (Oberg et al. 2011, Madhusudhan et al. 2014, Cridland et al. 2016, Oberg & Bergin 2016, Ali-Dib 2017, Piso et al. 2017), **but accreting atmospheres may also incorporate some solids** (Espinoza et al. 2016).

Trappist-1: An Important Case Study for Formation, Migration Models (Gillon et al. 2016, 2017)

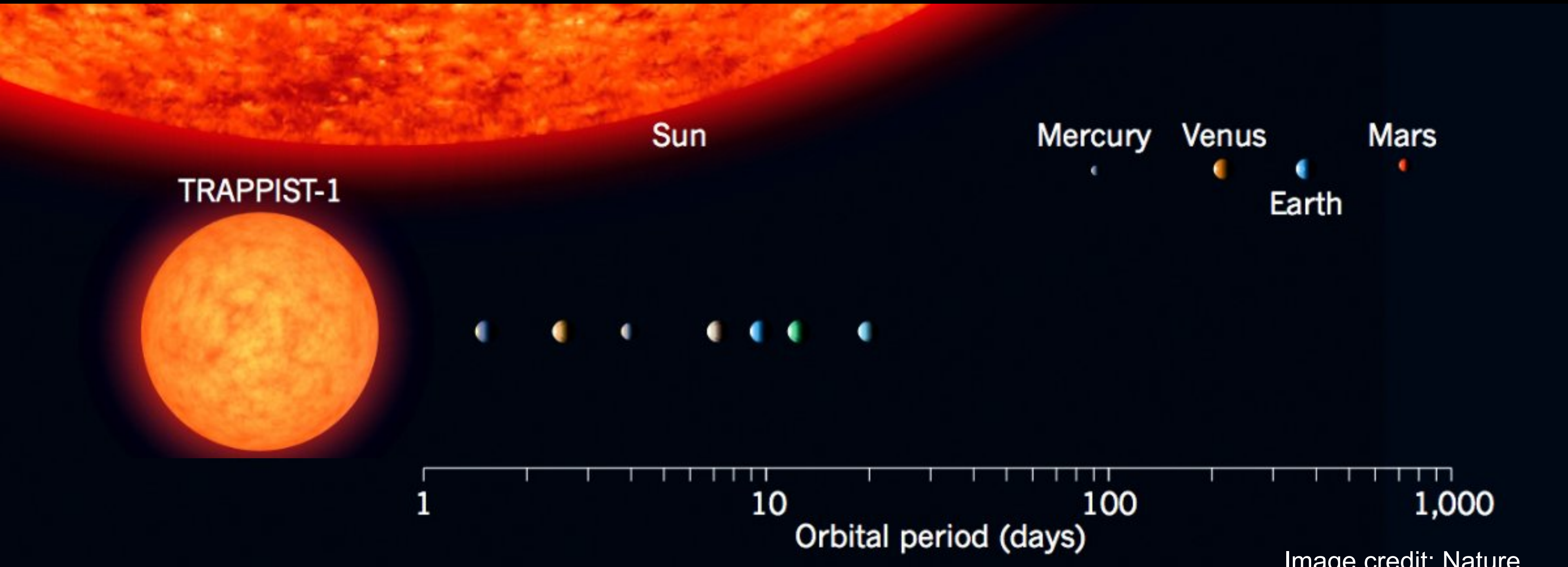
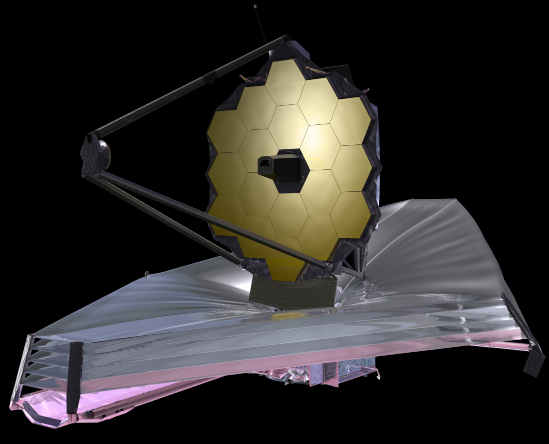


Image credit: Nature

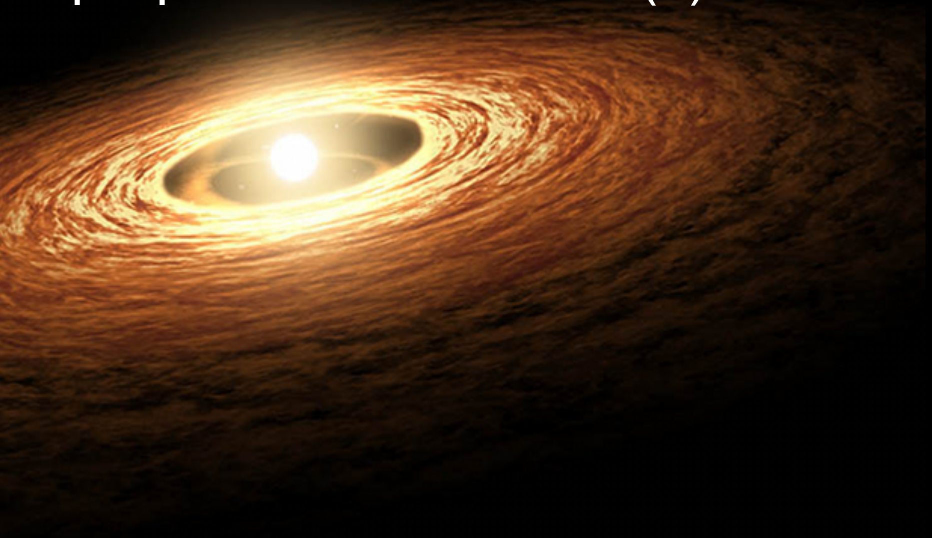


Inner three planets look rocky, outer four planets have more volatiles (Wang et al. 2017).

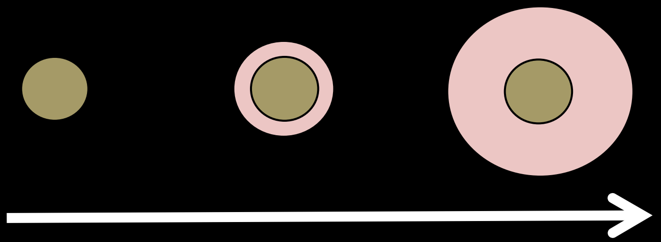
Dynamically delicate system constrains past migration (Tamayo et al. 2017)

Conclusion: The Life Story of Planetary Systems

Initial disk conditions,
properties of host star(s)



Masses, compositions of
newly formed planets



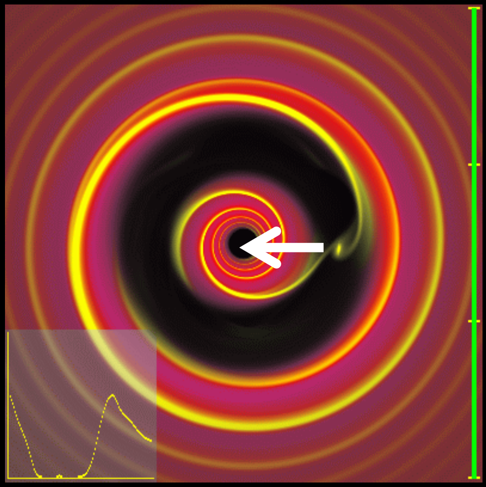
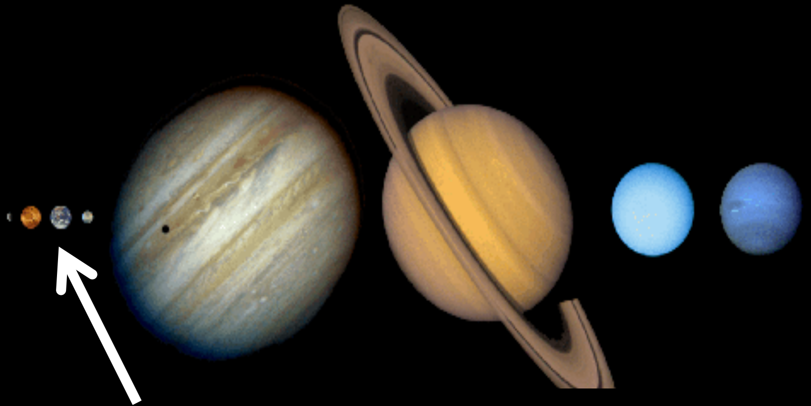


Image credit: P. Armitage

Dynamical
evolution +

Atmospheric
mass loss

Final architectures



Other Earths?