Rocky, Icy, or Gaseous Planet?

The Effect of Stellar Companions

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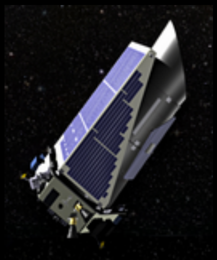
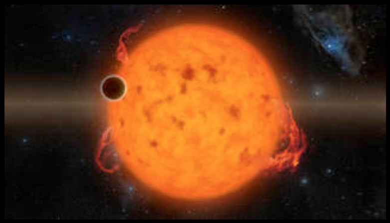
image credit: NASA/JPL-Caltech

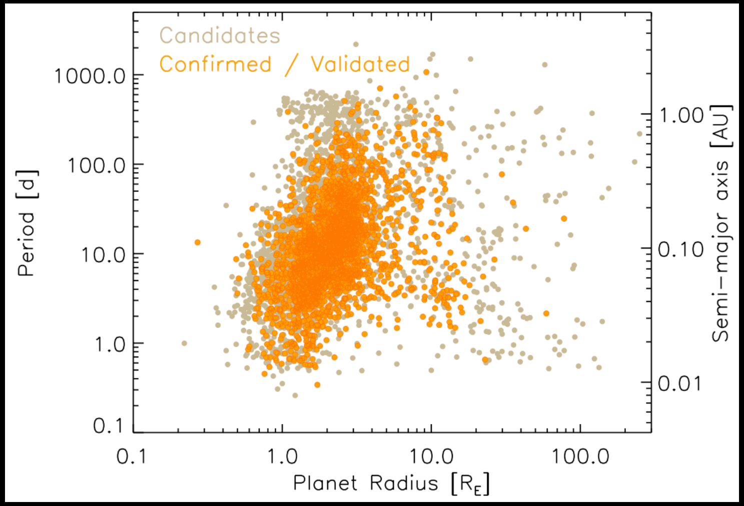
The Search for Earth-Like Planets

Kepler mission:

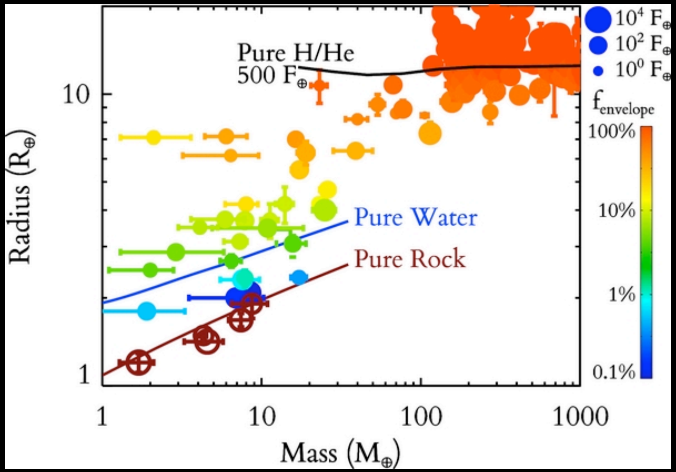
- ➢ 4496 planets or planet candidates around 3411 stars (~1/2 confirmed/validated);
- ➢ 2213 planets with $R < 2\ R_{Earth}$
  $\Longrightarrow$ small planets are very common





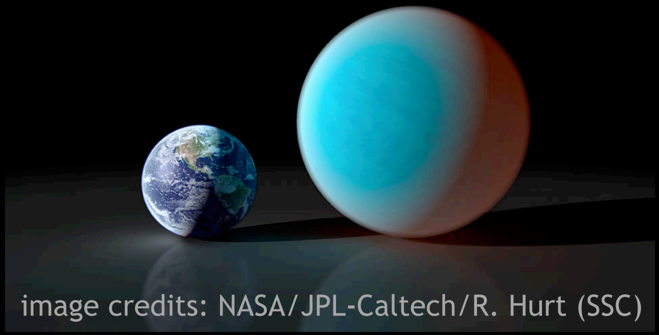


radius + mass $\Longrightarrow$ planet composition



planet radius vs. mass for transiting planets with measured masses

(Lopez & Fortney 2014)



Effect of Stellar Companions

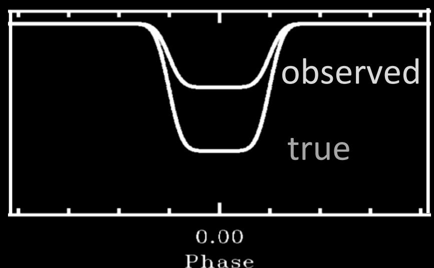
radius of transiting planet depends on stellar radius:

⟶ one star: $\delta = \left(\frac{R_p}{R_*}\right)^2$ transit depth

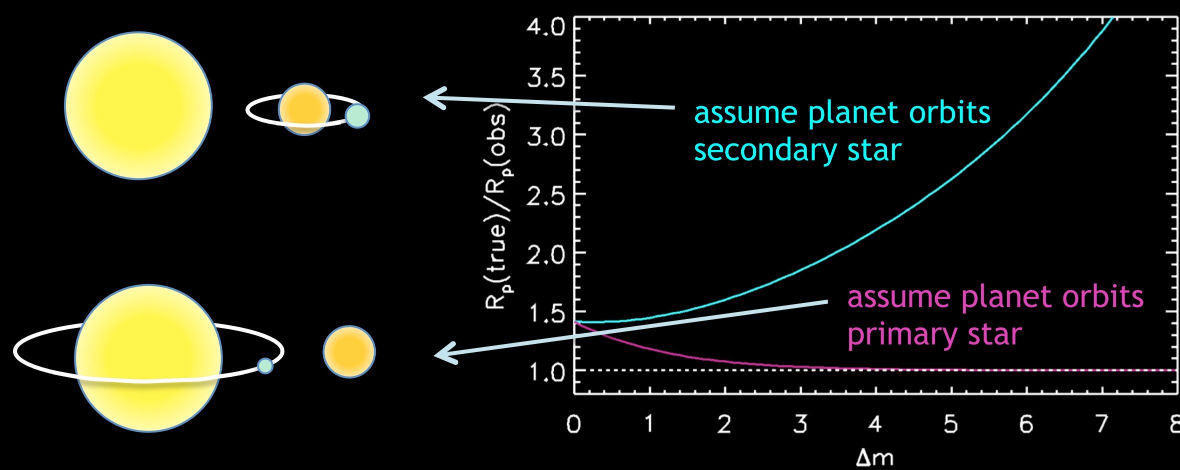
if companions are present and planet transits star t:

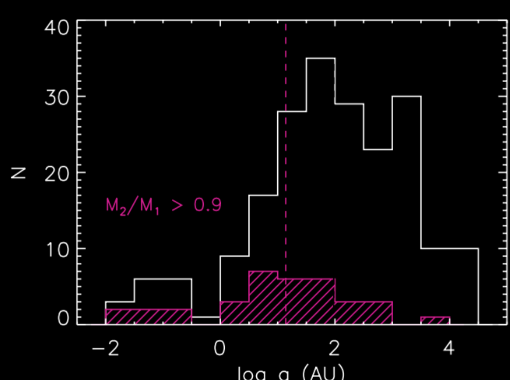
$\delta = \left(\frac{F_t}{F_{total}}\right)\left(\frac{R_p}{R_{t*}}\right)^2$ observed transit depth $\Longrightarrow$ $\frac{R_p(true)}{R_p(obs)} = \left(\frac{R_{t*}}{R_{1*}}\right)\sqrt{\frac{F_{total}}{F_t}}$

$\Longrightarrow$ planet radii are underestimated



(Ciardi et al. 2015)





➢ ~50% of stars in the solar neighborhood have stellar companions

➢ ~15% of stars have ~equal-mass, close (<100 AU) companions

(Raghavan et al. 2010)

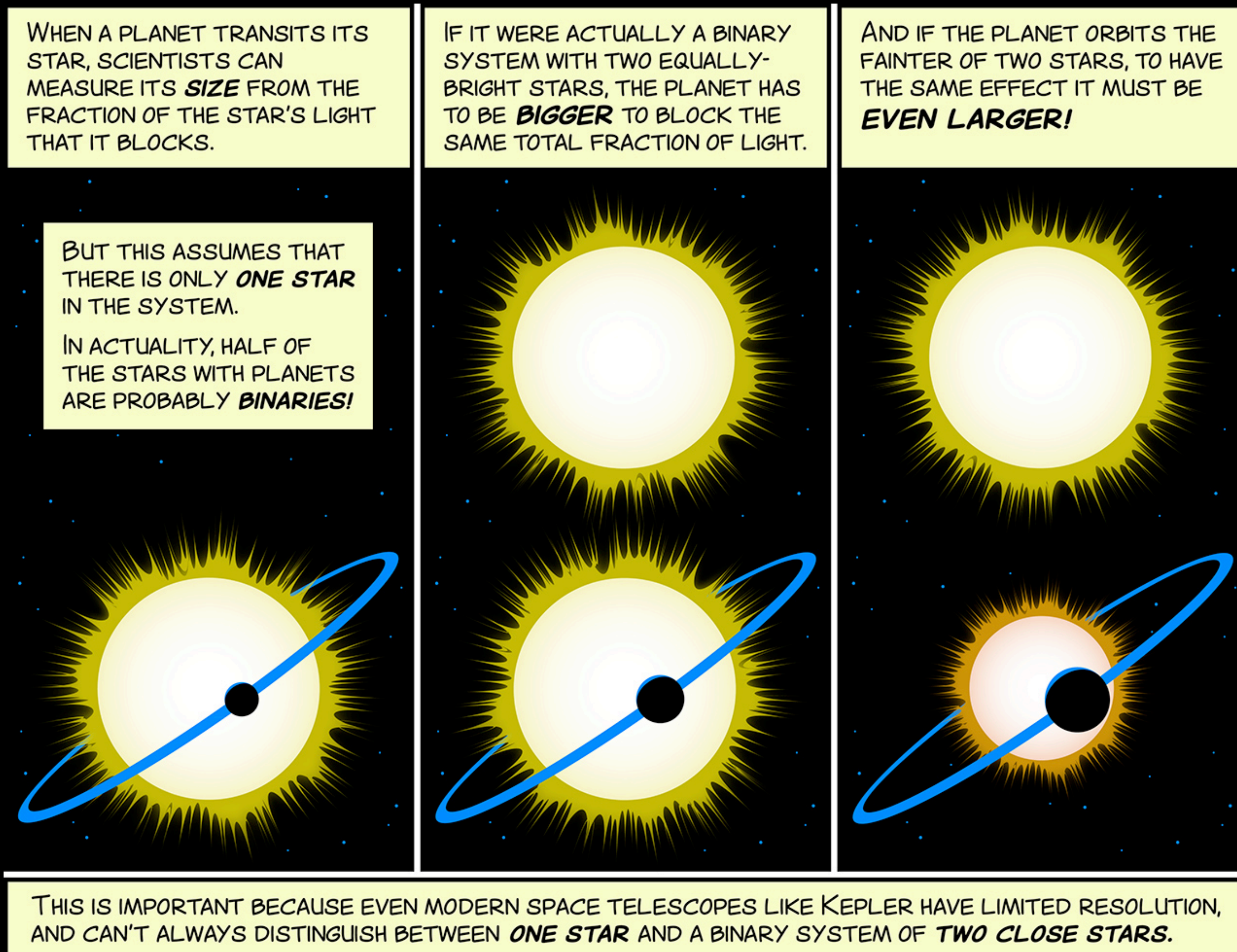


image credit: NASA/JPL-Caltech/T. Pyle (SSC)

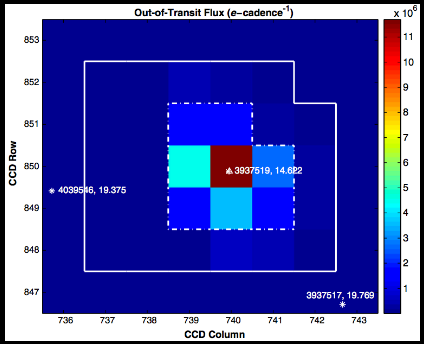
Finding Stellar Companions of Kepler Stars

- ✧ Kepler: 4” pixels, ~12” apertures
  - → can find circumbinary planets around eclipsing binaries
  - → cannot resolve close binaries (<1”-2”)
    - → measure combined light curve

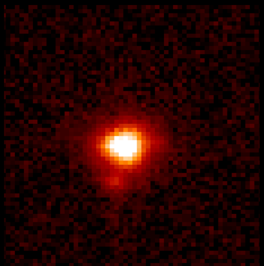
- ✧ UKIRT J-band survey of the Kepler field: spatial resolution of 0.8”-0.9”

- ✧ Kepler Follow-Up Observation Program: high-resolution imaging of KOI host stars (adaptive optics, Robo-AO, speckle interferometry, lucky imaging, HST), 2009-2015
  - → sub-arcsecond resolution
  - → Kepler targets: median distance of 800 pc ⟹ 0.1” = 80 AU

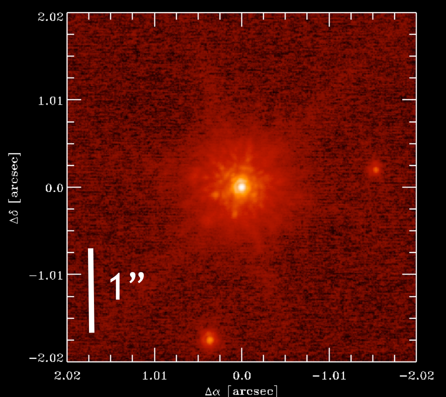
KOI 221 (Kepler-495 b):



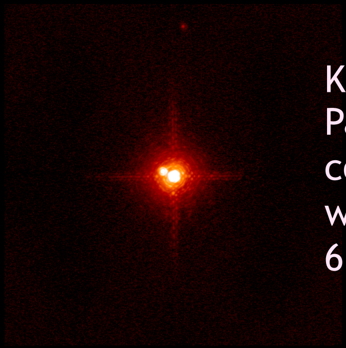
Kepler pixels
(Bryson et al. 2013)



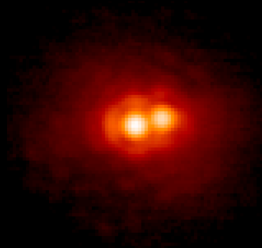
UKIRT J-band image



Keck/NIRC2 K-band image

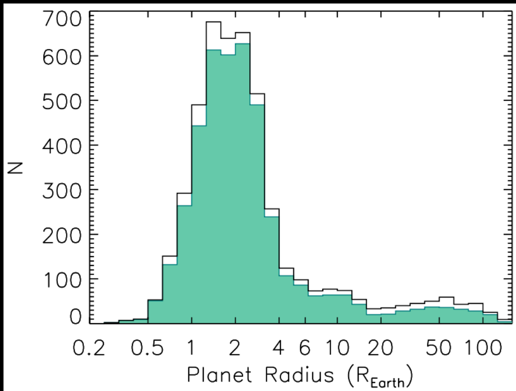


KOI 1119, K-band, Palomar; companions at 0.47” with Δm=2.42 and at 6.23” with Δm=7.65



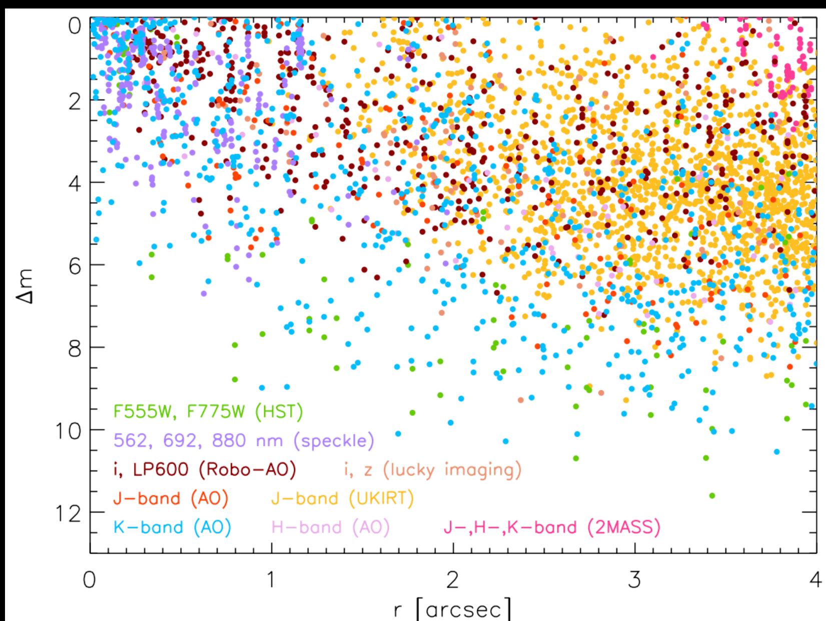
KOI 5545, K-band, Keck; companion at 0.08” with Δm=0.38

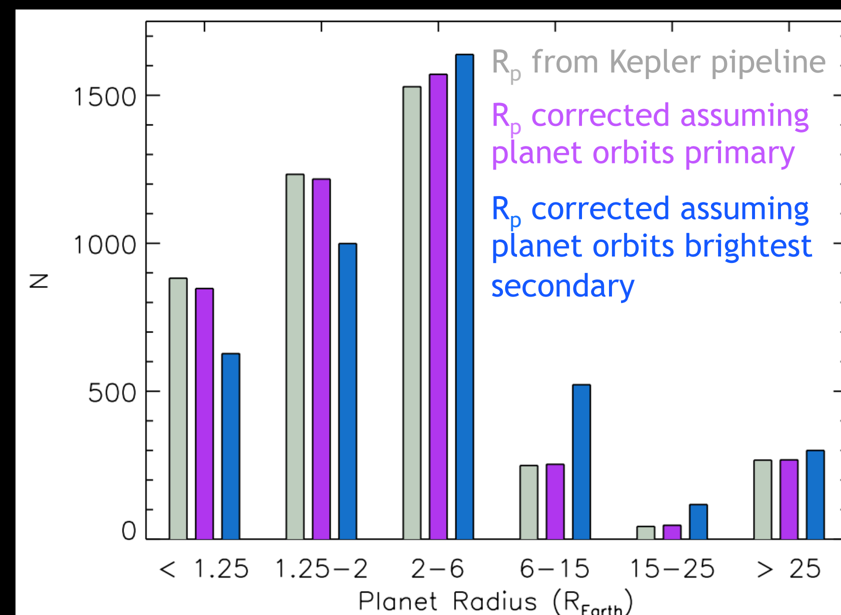
Correcting the Radii of Kepler Planets



last KOI table used for follow-up observations (Q1-Q17 DR24):
3665 stars with 4706 candidate or confirmed planets
→ 87% of planet host stars have high-resolution images (especially from Robo-AO)

Adams et al. (2012,2013), Cartier et al. (2015), Baranec et al. (2016), Cartier et al. (2015), Dressing et al. (2014), Everett et al. (2012,2015), Furlan et al. (2017), Gilliland et al. (2015), Horch et al. (2012), Kraus et al. (2016), Law et al. (2014), Lillo-Box et al. (2012,2014), Wang et al. (2015abc), Ziegler et al. (2017)





2297 companions within 4” around 1903 stars

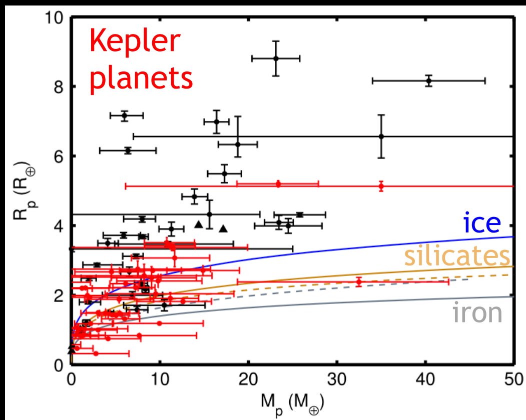
(Furlan et al. 2017a)

from observations (limited by sensitivity and resolution):
~30% of Kepler stars have companions within 4” (actual fraction: ~40%-50%)

Planet Mass-Radius Diagrams

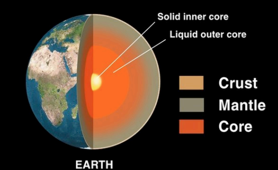
transit depth ⟹ planet radius

radial velocity (or transit timing variations) ⟹ planet mass



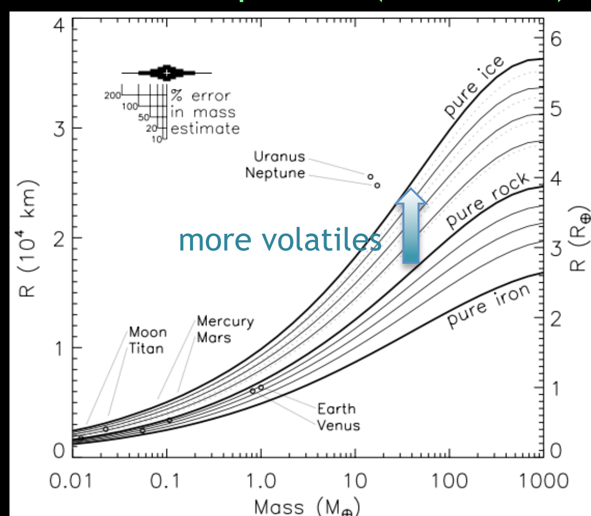
(Rogers 2015)

planet bulk density (composition)



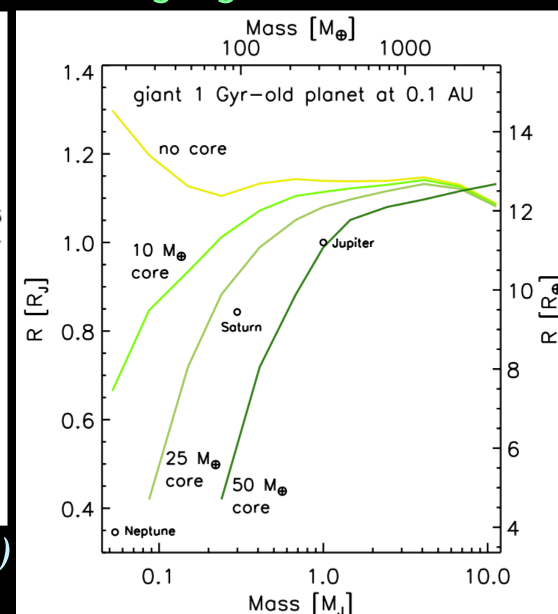
Models for different planetary compositions

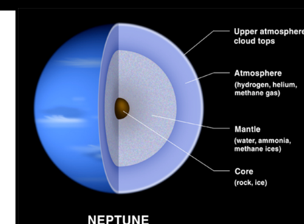
solid planets (rock & ice):

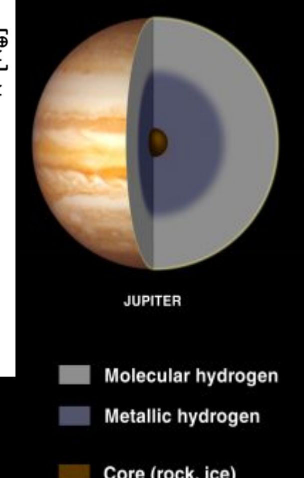


(Fortney et al. 2007)

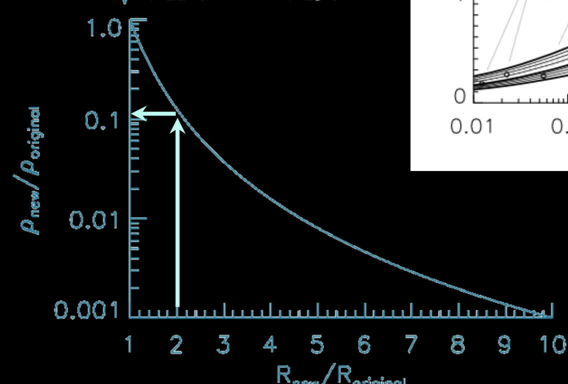
gas giants:







$$\Delta\rho/\rho \approx \sqrt{\left(\frac{\Delta M}{M}\right)^2 + 9\left(\frac{\Delta R}{R}\right)^2}$$

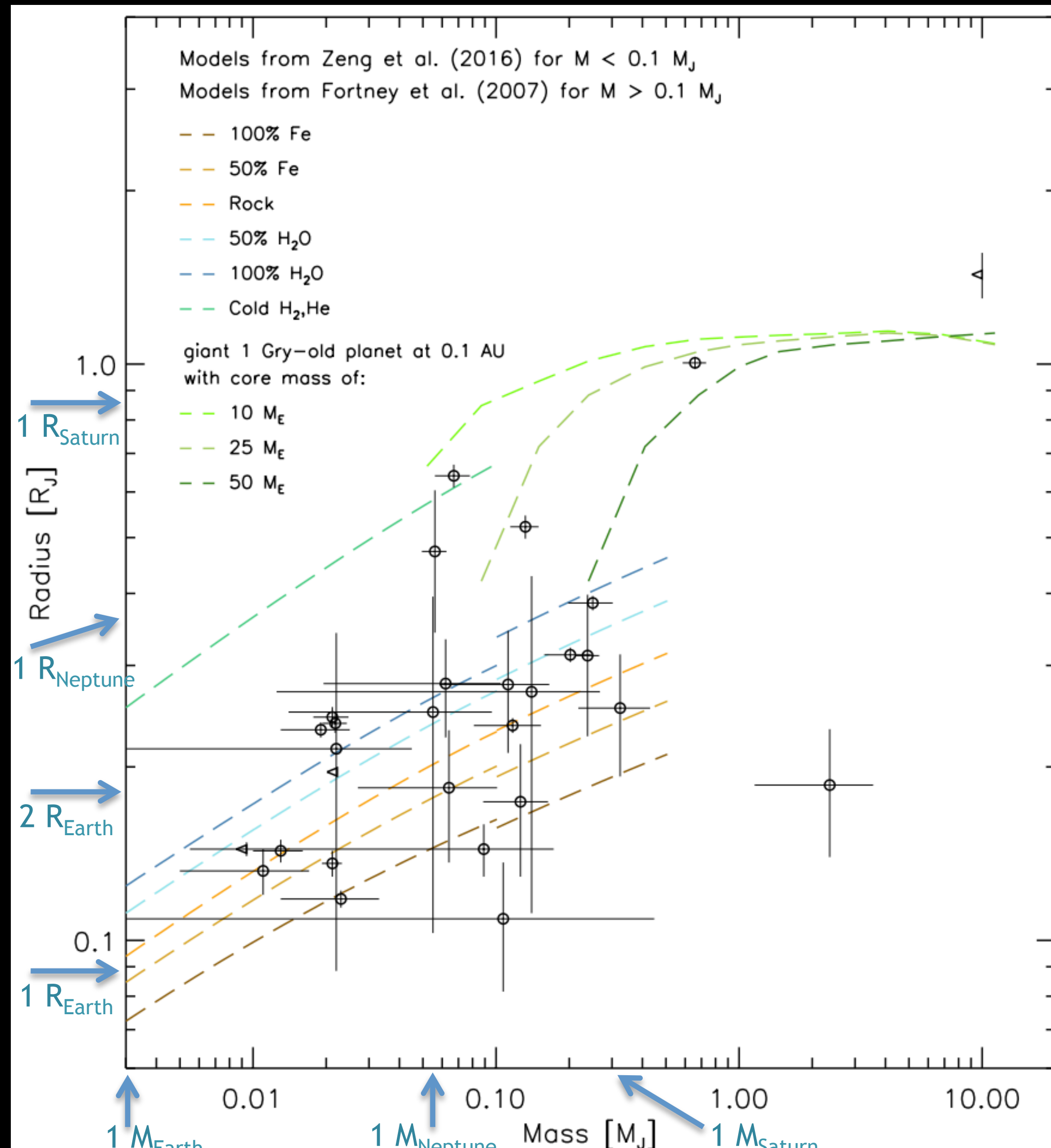


larger planet ⟹ more volatiles
(water, ices, gases)

Kepler Planets: Mass-Radius Diagram

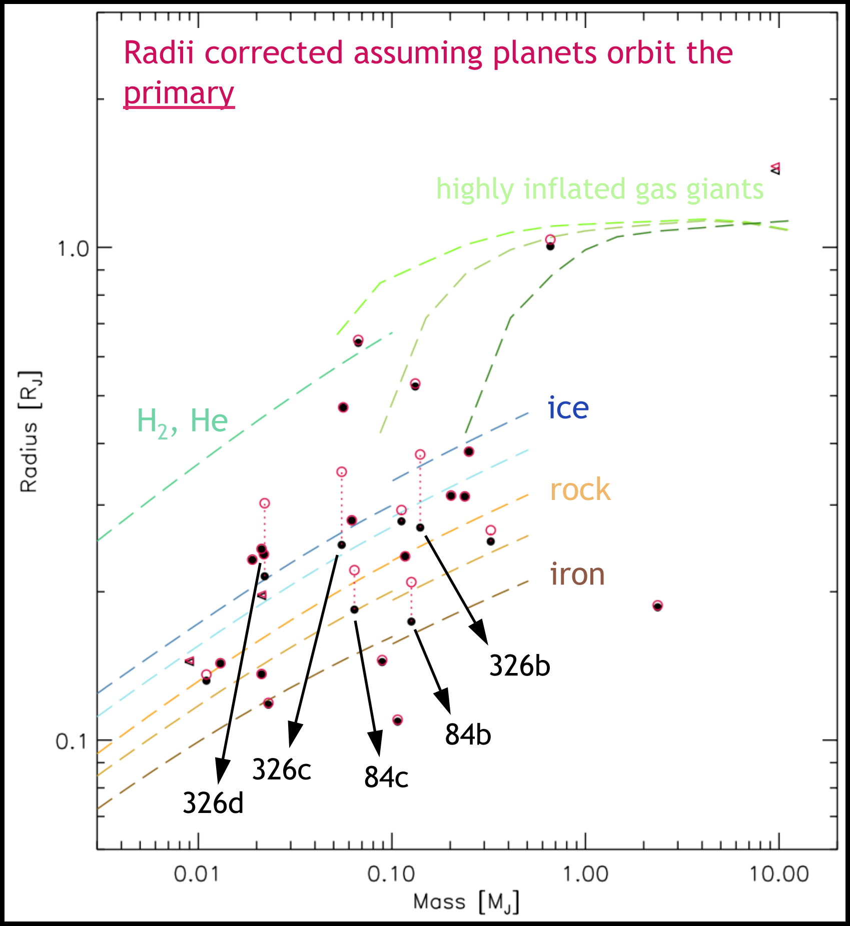
29 confirmed Kepler planets (orbiting 15 stars) with

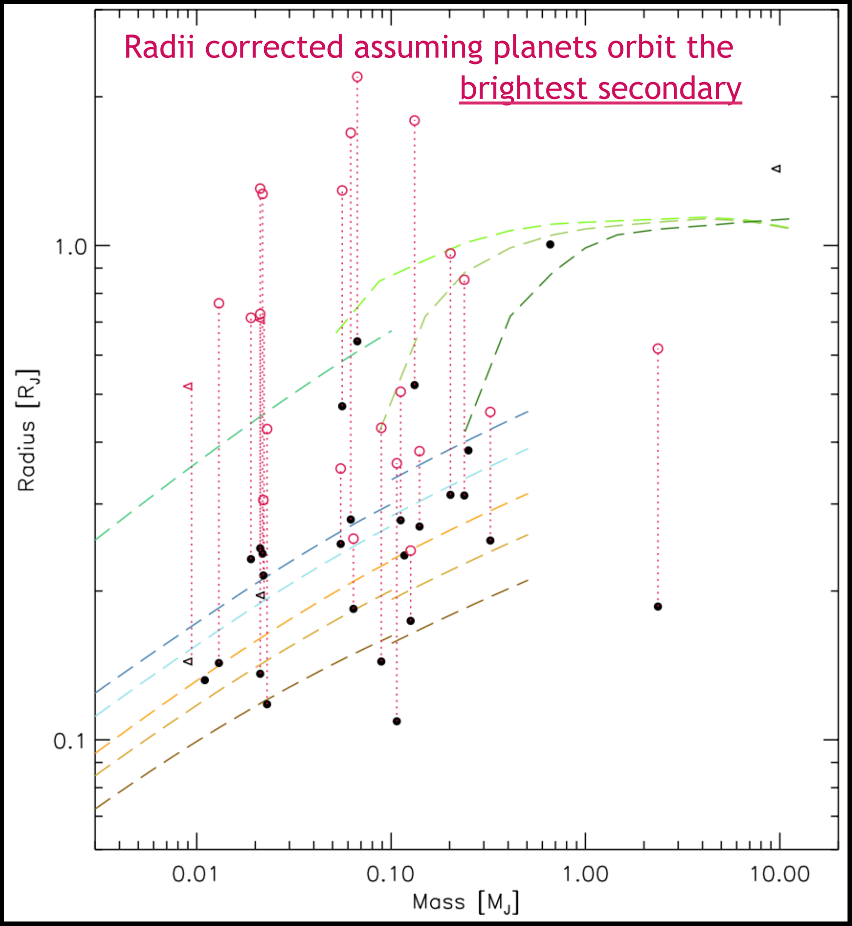
- measured radius and mass (including mass upper limits)
- detected companion star within 2”
- companion star not excluded to be the planet host (e.g. from RV, centroid analysis)
- flux dilution by companion star not yet accounted for in derived planet parameters



(Furlan & Howell 2017)

Kepler Planets: Revised Mass-Radius Diagram



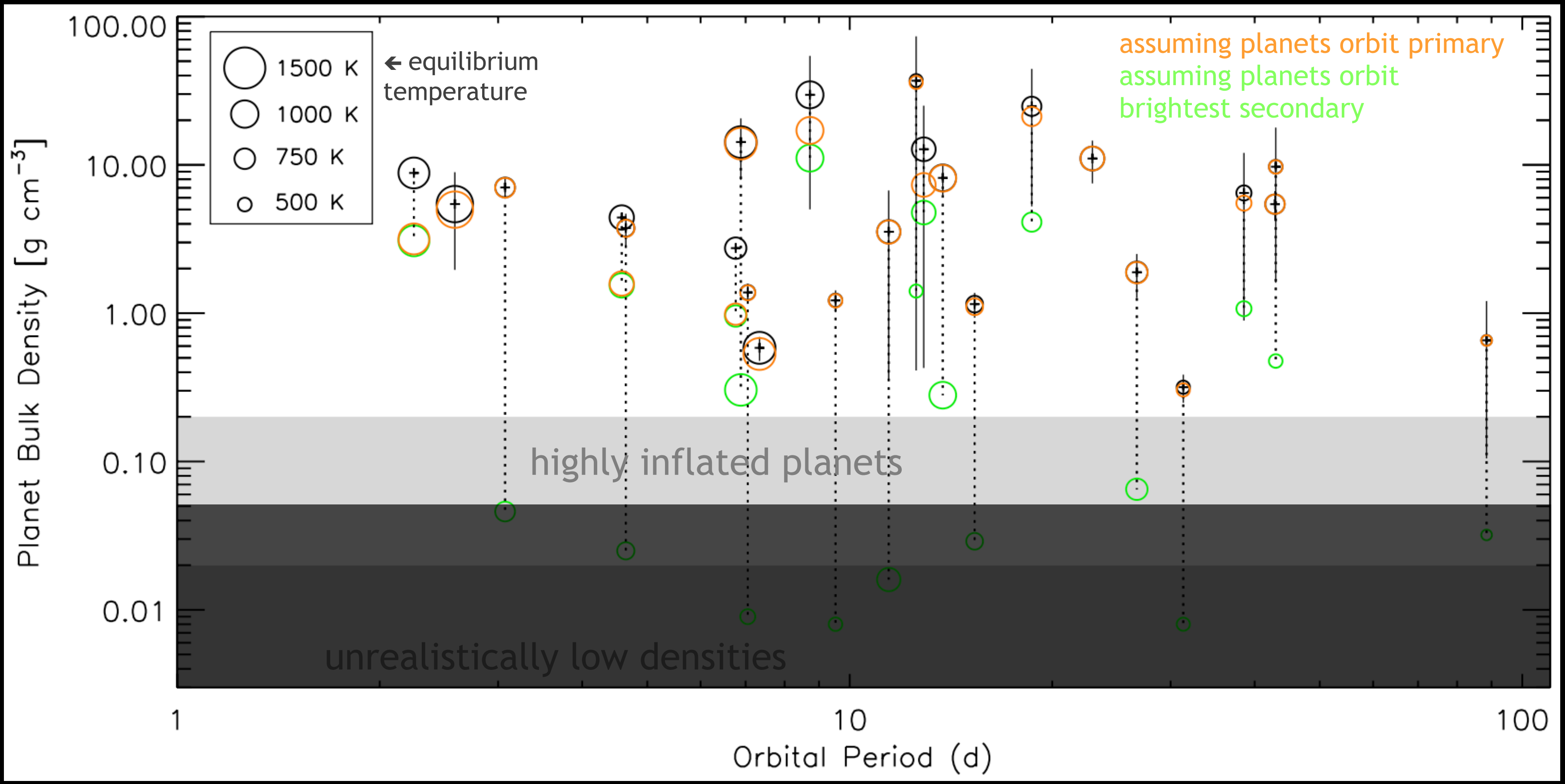


- most planets: small (< 1%) increase in radius ⇒ 1%-2% decrease in density
- largest change for planets around stars with ~ equal-brightness companion:
  ➞ up factor of 2.8 decrease in density

- decrease in density by 1-2 orders of magnitude
- most planets would have unrealistically low densities ➞ highly inflated atmospheres or massive H/He envelopes

Kepler Planets: Revised Densities

Planet bulk densities change due to the presence of a stellar companion



⟹ 15 planets in 7 planetary systems could orbit either the primary or companion star

(assuming companion star is bound to primary)

Conclusions

✧ rocky, icy or gaseous planet? ➞ also look for stellar companions

✧ stellar companion ⟹ transit depth dilution
⟹ upward revision of planetary radii
⟹ decrease of planet bulk density (even if planet orbits primary)
➞ rocky planet becomes more volatile-rich

✧ ~50% of stars have companions ⟹ follow-up observations (high-resolution imaging, radial velocity measurements) of stars with transiting planets are crucial!
➞ ground-based transit surveys, and K2, TESS, PLATO missions: reliably identify truly Earth-like planets

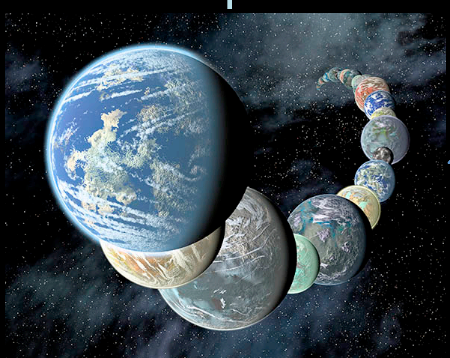
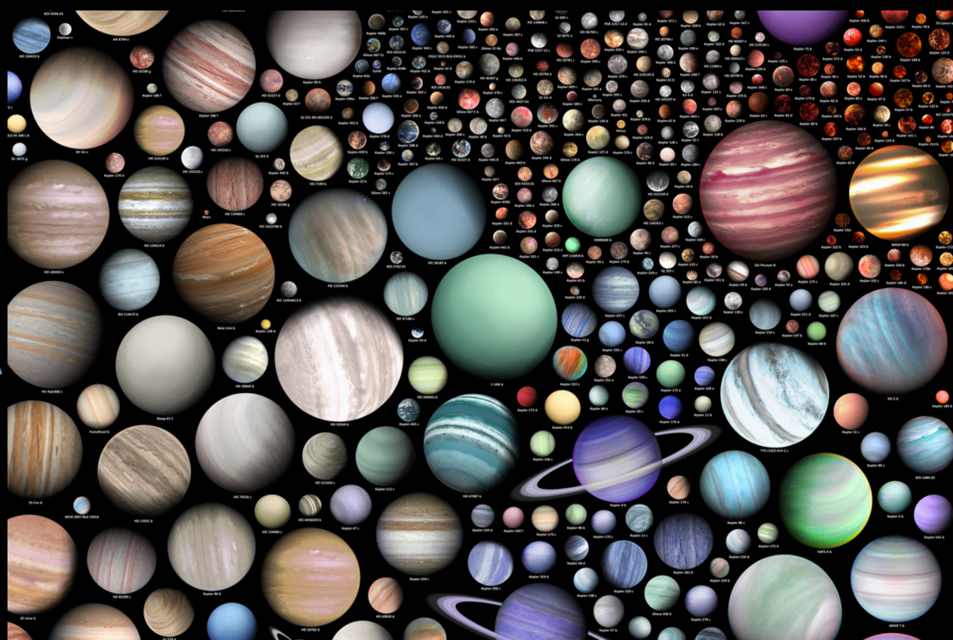


image credit: NASA/JPL-Caltech/R. Hurt (SSC)



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