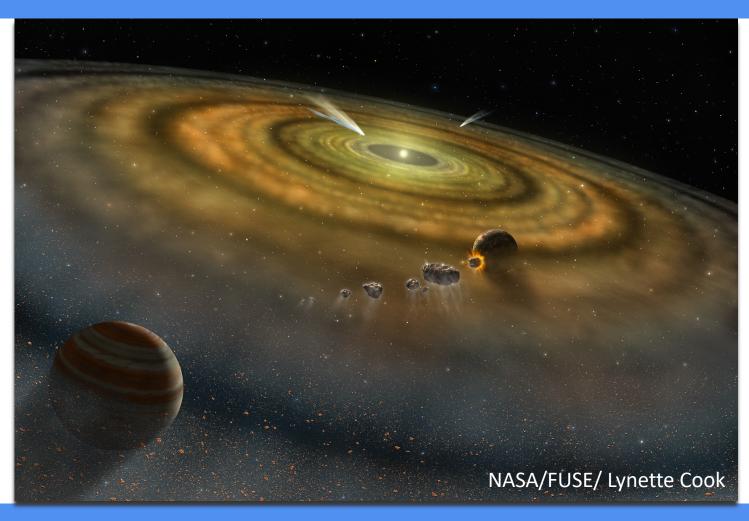
Planet Occurrence as a Function of Metallicity to Probe Planet Formation

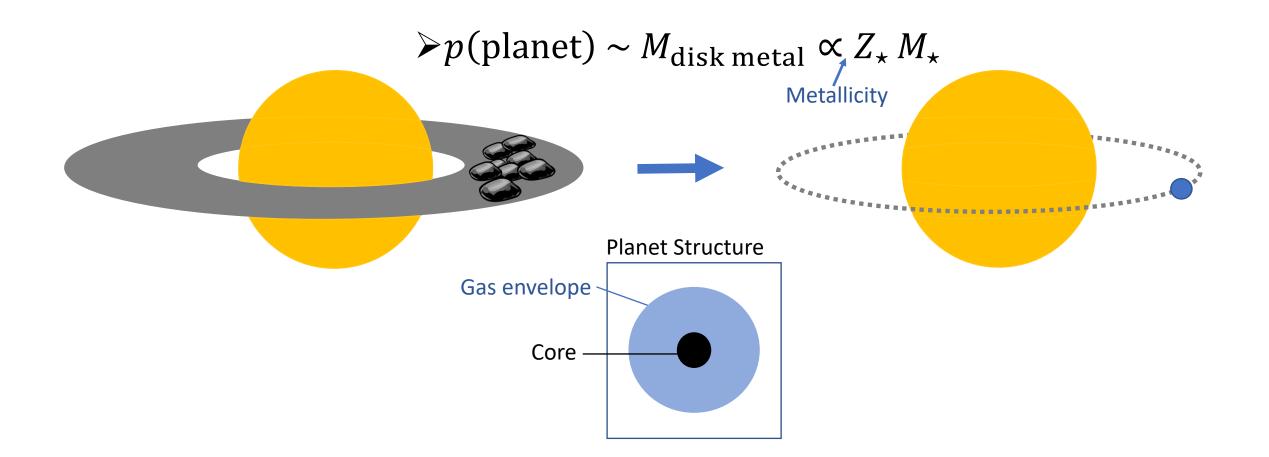
Cicero Lu, Kevin Schlaufman & Sihao Cheng (2020)

Johns Hopkins University

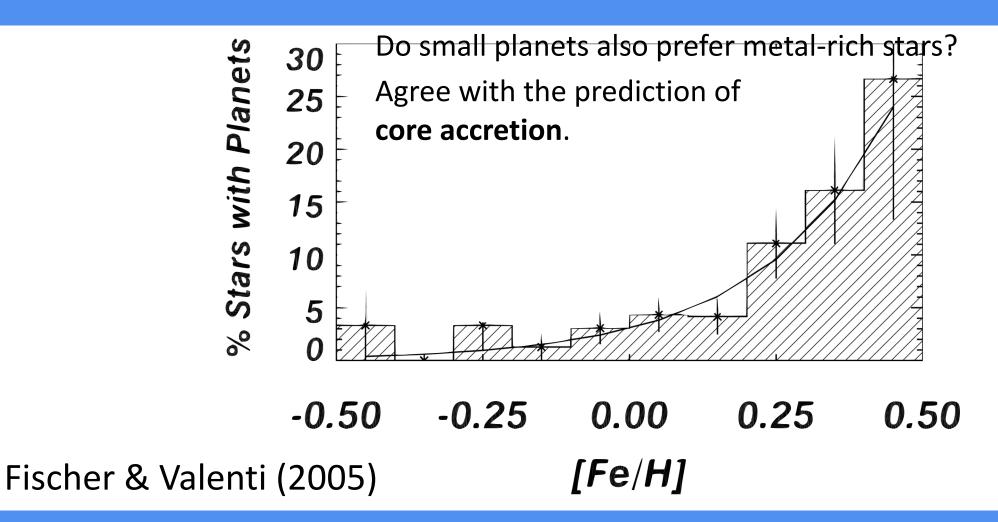
Core Accretion Model of Planet Formation



Core accretion

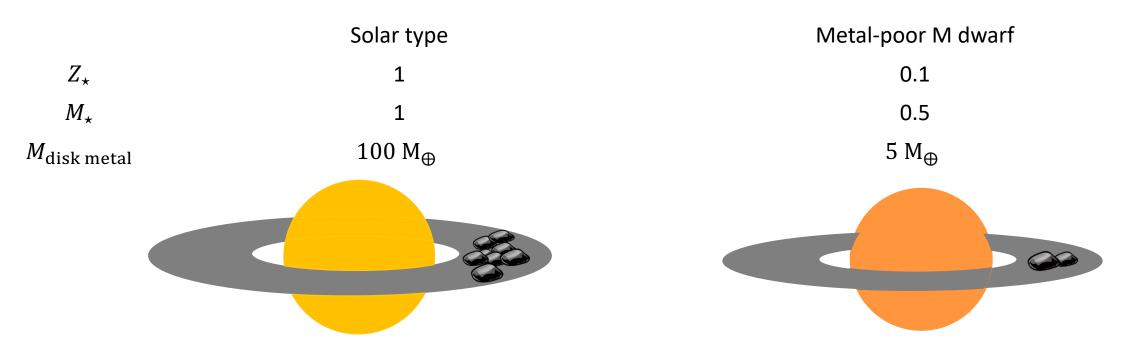


Giant planets prefer metal-rich stars.



Do small planets also prefer metal-rich stars?

$$\succ p(\text{planet}) \sim M_{\text{disk metal}} \propto Z_{\star} M_{\star}$$

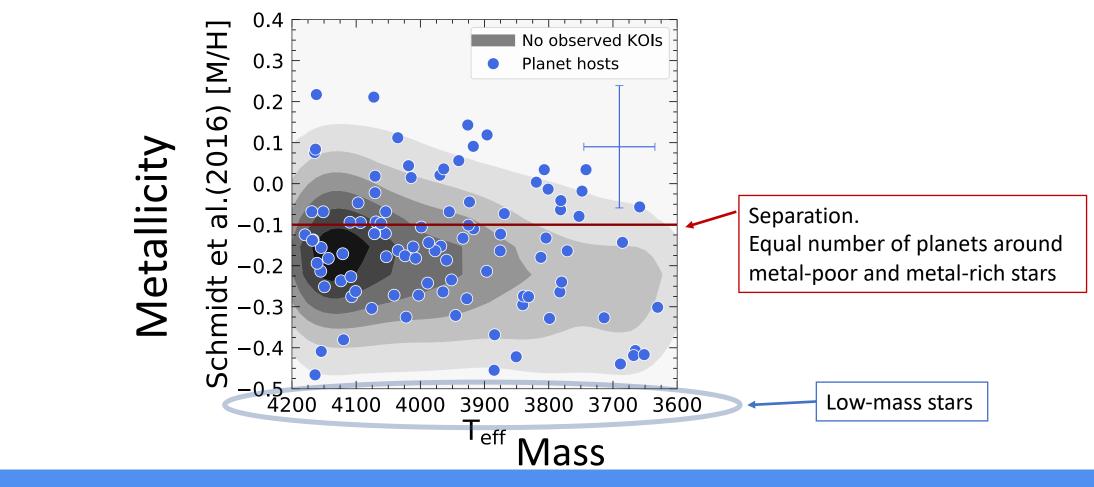


Scaling relations: Andrews et al. (2013, 2018); Gordon et al. (2003)

12/11/2020

CHEXO Talk - Cicero Lu

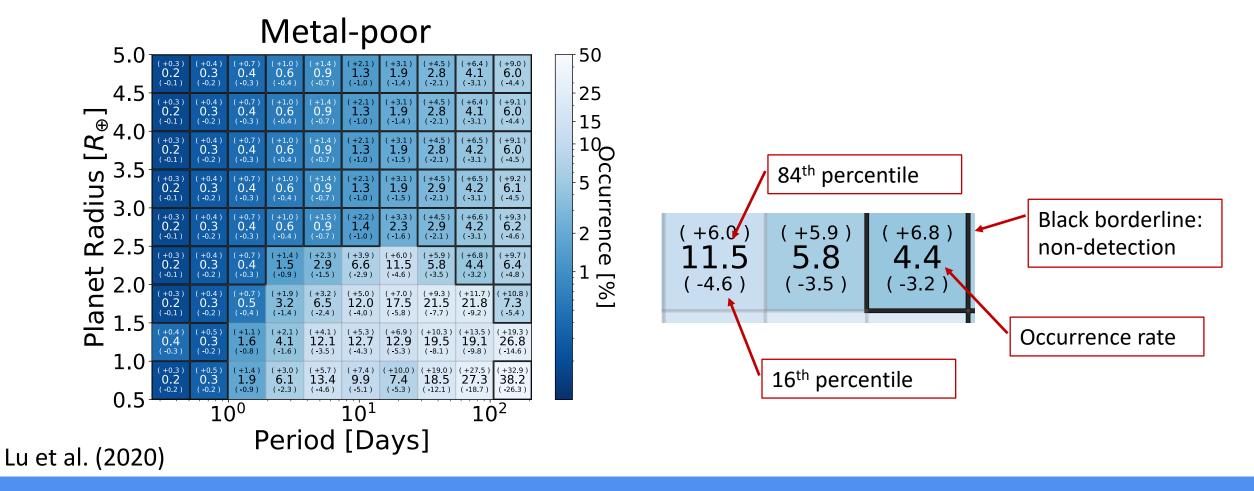
Separating metal-rich and metal-poor stars



12/11/2020

Lu et al. (2020)

Small Planet Occurrence Increases with Host Star Metallicity



12/11/2020

Small Planet Occurrence Increases with Host Star Metallicity

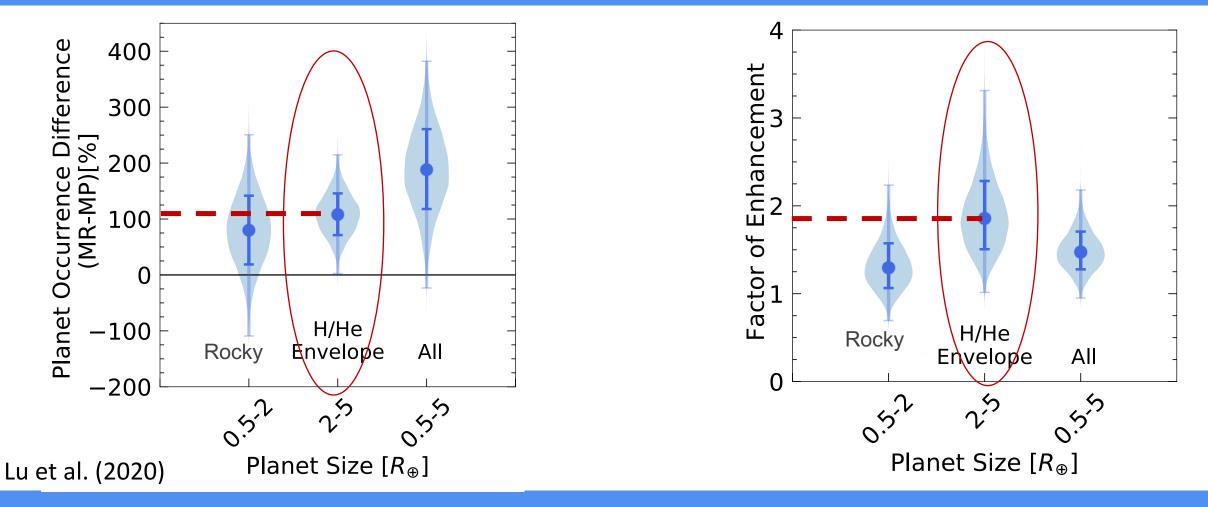
Metal-poor Metal-rich 5.0 5.0 50 50 (+6.4) 4.1 (-3.1) +0.5) (+4.5) 2.8 (-2.1) (+1.0) 0.6 (-0.5) (+1.8) **1.5** (1.0) (+2.2) 1.3 (-1.0) (+6.5) **4.2** (-3.1) $(^{+2.1})$ 1.3 $(^{-1.0})$ (+9.0) +12.5 **8.5** (+3.1) 1.9 (-1.4) 0.9 0.4 **2.0** (-1.5) **2.9** (2.2) 0.3 0.3 6.0 (4.5) 0.4 0.6 6.0 (-0.1) (-0.2) (-4.4) (-6.3) 4.5 4.5 25 25 (+1.6) **1.1** (-0.8) (+0.7 **0.4** (-0.3) (+1.0 **0.6** (-0.4) (+1.4) 0.9 (-0.7) (+3.1) **1.9** (-1.4) (+4.5) **2.8** (-2.1) (+6.4 **4.1** (-3.1) (+0.5 0.3 (-0.2) (+1.0) **0.6** (-0.5) (+2.2) **1.3** (-1.0) (+3.2) 2.0 (-1.5) (+4.6) **2.9** (-2.2) (+6.5) 4.2 (3.1) (+2.1) **1.3** (-1.0) (+9.1 [⊕4.0 3.5 3.0 2.5 [[⊕] 4.0 3.5 3.0 2.5 0.2 0.3 0.4 **6.0** 8.5 6.0 15 15 (-4.4)(-6.3) 4.0 ^{t 10}0 (+0.7) 0.4 (-0.3) (+1.0 0.6 (-0.4) (+0.5 0.3 (-0.2) (+1.0) **0.6** (-0.5) (+1.5) **0.9** (-0.7) (+0.3) 0.2 (-0.1) (+0.4) 0.3 (-0.2) (+1.4) 0.9 (-0.7) (+2.1) 1.3 (-1.0) (+3.1) **1.9** (-1.5) (+4.5) 2.8 (-2.1) (+6.5) **4.2** (-3.1) 10_{0} (+2.2) 1.3 (-1.0) (+3.2) 2.0 (-1.5) (+4.9) **3.6** (-2.5) (+6.5) 4.2 (-3.1) +10.6 +12.5 **8.5** 0.4 9.6 6.0 (-4.5)(-6.3) 5 2 1 (+0.3) 0.2 (-0.1) (+0.4) 0.3 (-0.2) (+0.7) 0.4 (-0.3) (+1.0) 0.6 (-0.4) (+2.1) **1.3** (-1.0) (+3.1) **1.9** (-1.5) (+4.5) **2.9** (2.1) (+0.5 0.3 (-0.2) (+1.0) 0.6 (-0.5) (+1.5) **0.9** (-0.7) (+2.2) 1.3 (-1.0) (+3.4) **2.4** (1.7) (+6.0) 6.2 (-3.7) (+6.5) 4.2 (-3.1) (+6.5 +11.0 +9.2) 0.9 **4.2** (3.1) 10.9 (-6.7) 0.4 8.6 6.1 (-4.5) (-6.3) 3.0 3.0 (+1.0) 0.6 (-0.5) (+1.5) 0.9 (-0.7) (+5.2) (+7.6)7.7 12.5 (-3.6) (-5.6)(+9.2 6.2 (-4.6) (+0.7 **0.4** (-0.3) (+1.0 0.6 (-0.4) (+4.5) **2.9** (-2.1) (+6.6) **4.2** (-3.1) +0.5) 0.3 (+6.7) 4.5 (-3.3) (+0.3) 0.2 (-0.1) (+0.4) 0.3 (-0.2) (+2.2) 1.4 (-1.0) (+3.3 **2.3** (-1.6) (+0.7) 0.4 (-0.3) (+2.2) +12.6 0.9 6.2 (4.6) 1.4 8.6 (-0.2 (-6.4) (+0.7 **0.4** (-0.3) (+6.0) **11.5** (-4.6) (+5.9) 5.8 (-3.5) (+1.3) 1.3 (0.8) (+1.5) 0.9 (-0.7) (+4.0) 6.8 (-2.9) (+6.9) 17.5 (-5.7) (+7 8) **13 5** (5 9) $^{(\ +10.2\)}_{(\ 7.5\)}$ $(+0.3) \\ 0.2 \\ (-0.1)$ (+0.4) 0.3 (-0.2) (+1.4) 1.5 (-0.9) (+23) **2.9** (-1.5) (+3.9) **6.6** (-2.9) (+12.0 +12.9 (+6.8 +9.7) Blanet I 1.5 Planet 1.5 **4 4** (-3.2) 13.9 6.4 0.3 0.4 8.9 (-0.2) (-6.6 (-4.8)(+0.3) 0.2 (-0.1) (+0.4) 0.3 (-0.2) (+0.7) 0.5 (-0.4) (+1.9) 3.2 (-1.4) (+3.2) 6.5 (-2.4) (+5.0) **12.0** (-4.0) (+93) **21.5** (77) (+11.7) 21.8 (-9.2) (+1.2) 0.9 (-0.6) (+2.4) 3.1 (-1.6) (+4.5) 9.0 (-3.4) (+6.5) **14.3** (-5.2) (+8.3) 15.6 (-6.4) ${\overset{(}{\underset{(}}{\overset{+10.5}{16.4}}}_{(-7.7\,)}$ (+13.3) 17.8 (-9.4) (+7.0) **17.5** +10.8 (+0.8) **0.6** (+14.4) 10.0[°] 73 0.3 (-5.8) (+2.1) 4.1 (-1.6) (+2.9) **5.0** (2.1) (+0.5) 0.3 (-0.2) (+1.1) **1.6** (-0.8) $\begin{array}{c} (+2.1) & (+4.1) \\ \textbf{4.1} & \textbf{12.1} \\ (-1.6) & (-3.5) \end{array}$ $\begin{smallmatrix} (+13.5 \\ 19.1 \\ (9.8) \end{smallmatrix} (\begin{smallmatrix} +19.3 \\ +19.3 \\ (+19.3 \\ +14.6 \end{smallmatrix})$ (+4.6) 9.1 (-3.5) (+17.3 **22.7** (12.5 (+5.3) **12.7** (-4.3) ${\overset{(}_{}^{}+10.3\,)}\atop{\overset{(}_{}-8.1\,)}$ +1.2) (+4.8) 5.3 (-3.0) (+8.6) (+12.2) +21.8 12.9 0.3 0.4 2.0 13.2 17.116.9 (-0.3) (-6.2) (-8.7) (-12.4) (-5.3) 1.0 1.0 (+0.5) 0.3 (-0.2) $\begin{array}{cccc} (+3.0) & (+5.7) & (+7.4) \\ \textbf{6.1} & \textbf{13.4} & \textbf{9.9} \\ (-2.3) & (-4.6) & (-5.1) \end{array}$ $\begin{array}{c} (+10.0) & (+19.0) & (+27.5) \\ \hline 7.4 & 18.5 & 27.3 \\ (-5.3) & (-12.1) & (-18.7) \\ \end{array} \\ \begin{array}{c} (+32.9) \\ 38.2 \\ (-26.3) \end{array}$
 (+1.8)
 (+4.5)
 (+7.8)
 (+12.4)
 (+19.3)
 (+26.1)
 (+33.0)
 (+34.4)

 1.8
 8.9
 15.6
 20.9
 45.7
 43.5
 35.1
 44.7

 (-1.1)
 (-3.4)
 (-6.1)
 (-9.5)
 (-18.4)
 (-23.7)
 (-24.8)
 (-30.8)
(+1.4) **1.9** (-0.9) (+1.3) (+1.8) ^{+0.3}) 0.2 **1.9** 0.3 0.5 0.5 100 100 10² 10^{1} 10^{2} 10^{1} Period [Days] Period [Days] Lu et al. (2020)

ccurrence [%]

Small planet occurrence rises linearly with metallicity



Using planet occurrence to distinguish models of planet formation

Planetesimal accretion:

- slow
- uses ~30% of all solids

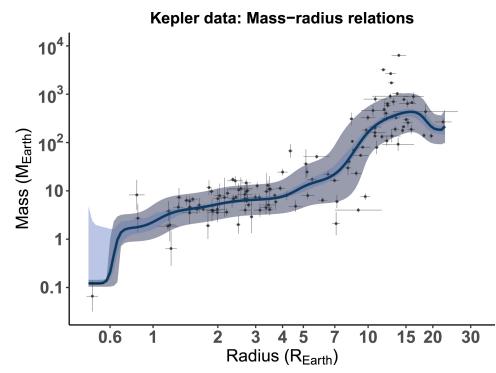
Pebble accretion:

- Fast but wasteful
- uses ~10% of all solids

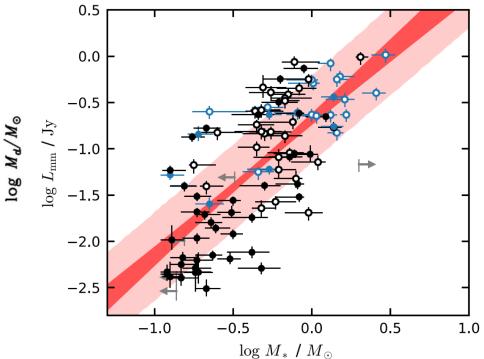
(Lin et al. 2019)

Estimate planet formation efficiency from Kepler data

Planet formation efficiency = Mass in planets/ Solids mass in the Disk



We convert sizes of planets into masses using Mass-radius relation (Ning et al. 2018 ; Kanodia et al. 2019) with *MRExo*.



Andrews et al. (2013, 2018) shows that the disk mass to is linear, with a typical disk-to-star mass ratio of ~0.5%, with which we obtain the disk mass from. We estimate the mass of solids in the disk with stellar metallicity, because metallicity is a proxy of fraction of solids in the disk.

The small planets in the Kepler field favor the planetesimal accretion model.

Sample	Expected Mass in Planets	Expected Mass in Disks
	(M_\oplus)	(M_\oplus)
Metal-poor	$16.5\substack{+0.6 \\ -1.8}$	14
Metal-rich	$24.5\substack{+0.9 \\ -2.5}$	28
Complete	$13.9\substack{+0.5\\-1.2}$	20

Our results shows that planet formation efficiency exceeds 50%. Therefore, we favor planetesimal accretion model.

Alternatively, the disks in the Kepler field can be more massive than that of the solar neighborhood.

Caveats:

Kepler data is limited to planets with periods less than 200 days. If more long-period planets exist, then the planet formation efficiency can change.



- We found that for small planets with radii between 2 to 5 Earth radii, their occurrence increases linearly with stellar metallicity.
- We investigated the planet formation efficiency to constrain planet formation model. We found that the small planets in the Kepler field favors the planetesimal accretion.