Many Kepler Planets Have Distant Companions

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**Intrinsic** architecture of inner planetary System

- 30% of Sun-like stars have Kepler planets.
- Each system has on average 3 planets within 1 AU.
- Fewer-planet systems are dynamically hotter.
- Multi-planet systems are not always coplanar.
- No Kepler dichotomy.
- Our solar systems fits "well" in this picture.


(see Xie et al. 2016; Van Eylen et al. 2018 for e part)
Go beyond 1 AU

Kepler planets (30%)

(Data from NASA Exoplanet Archive)
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The outer companion dominates the mass and angular momentum budget.

(Data from NASA Exoplanet Archive)
Super Earth-cold Jupiter relations

22 from Kepler (triangles) + 39 from RV (squares)

Cold Jupiters →
Super Earths

Zhu & Wu, 2018, AJ, 156, 92
(see also Bryan et al. 2019)
Super Earth-cold Jupiter relations

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- 1/3 of Kepler systems have cold Jupiter companions.
  - >50%, if \([Fe/H]>0\).

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$P(SE|CJ) = \frac{P(SE)}{P(CJ)} P(CJ|SE) \approx 100\%$

- Cold Jupiters (almost) always have inner super Earth companions!

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(Un)Popularity of Solar system

- Solar system has no super Earth (70%).
- Solar system has a cold Jupiter (10%).
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\[ P(\text{no SE, CJ}) = [1 - P(\text{SE|CJ})] \times P(\text{CJ}) \approx 1\% \]
TESS discovers a super Earth in pi Mensae system

10$M_J$
3 AU
$e = 0.6$

5$M_{\oplus}$
6 d

Huang et al., (2018)
(see also Gandolfi et al. 2018)
TESS + Gaia

- TESS
  - 1000s of close-in small planets (e.g., Sullivan+15)

- Gaia
  - 1000s of cold giants (Perryman+14)

- TESS+Gaia provides ~1000 of multi-planet systems
Super Earth & cold Jupiter show strong correlations
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- Formation
  - They do not compete for building blocks.
  - Cold Jupiters require more stringent conditions.
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- **Formation**
  - They do not compete for building blocks.
  - Cold Jupiters require more stringent conditions.

- **Evolution**

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1/3 of Kepler systems have cold Jupiter companions, but what about the other 2/3?
1/3 of Kepler systems have cold Jupiter companions, what about the other 2/3?

(see Miranda Herman's talk tomorrow)
Cold giant planets:
Elephant in the room?

- Most Kepler-like planetary systems have outer giant planets.
- Almost all cold giant planets have inner small planets.
- Cold planets play important roles in the formation and evolution of the inner system.

Kepler planets (30%)

Cold Jupiters (~10%)

Cold Neptunes

Zhu et al. (2018)
Zhu & Wu (2018)
Herman, Zhu, & Wu (2019)