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Understanding the formation of small planets by searching for their cold giant siblings.
The fundamental role of PLATO

A.S. Bonomo, L. Naponiello, E. Pezzetta, X. Dumusque, A. Mortier, L. Malavolta, A. Sozzetti, M. Damasso, M. Pinamonti, and
the HARPS-N Collaboration
(Astronomical Observatory of the University of Geneva, INAF & TNG/INAF, Harvard-Smithsonian CfA, Universities of Birmingham, Exeter, Padova, St. Andrews)

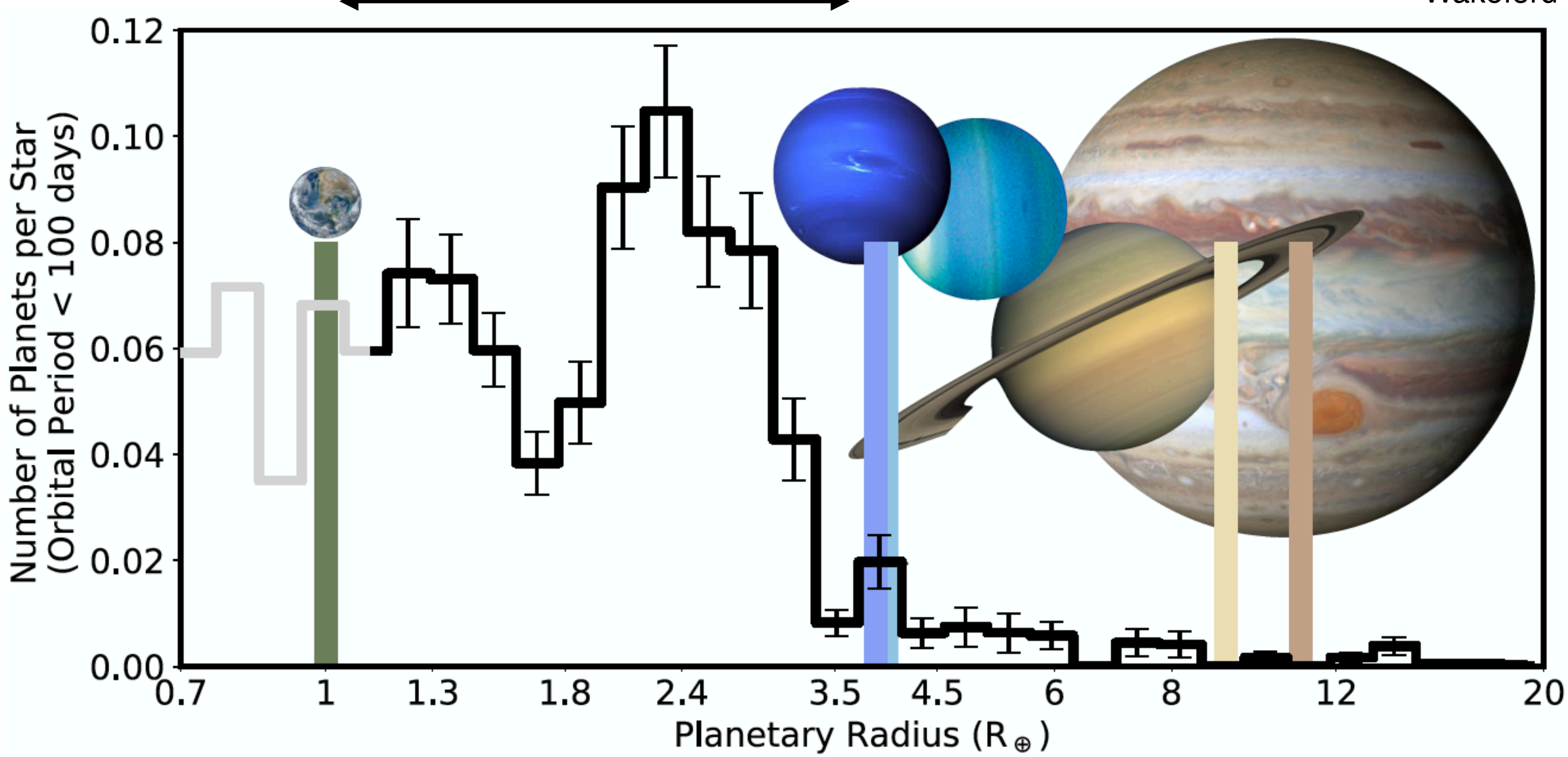
ESP2024: PLATO Planetary Systems - formation to observed architectures
Catania - 14-16 May 2024

Scientific Context - Planet frequency vs R_p

~50% of FGK dwarfs host at least one small planet ($1\ R_\oplus < R_p < 4\ R_\oplus$) with $P < 100$ d (e.g., Petigura et al. 2013), but small planets (SPs) are absent in the Solar System

sizes not seen in the Solar System

Fulton et al. 2017
Wakeford & Dalba 2020



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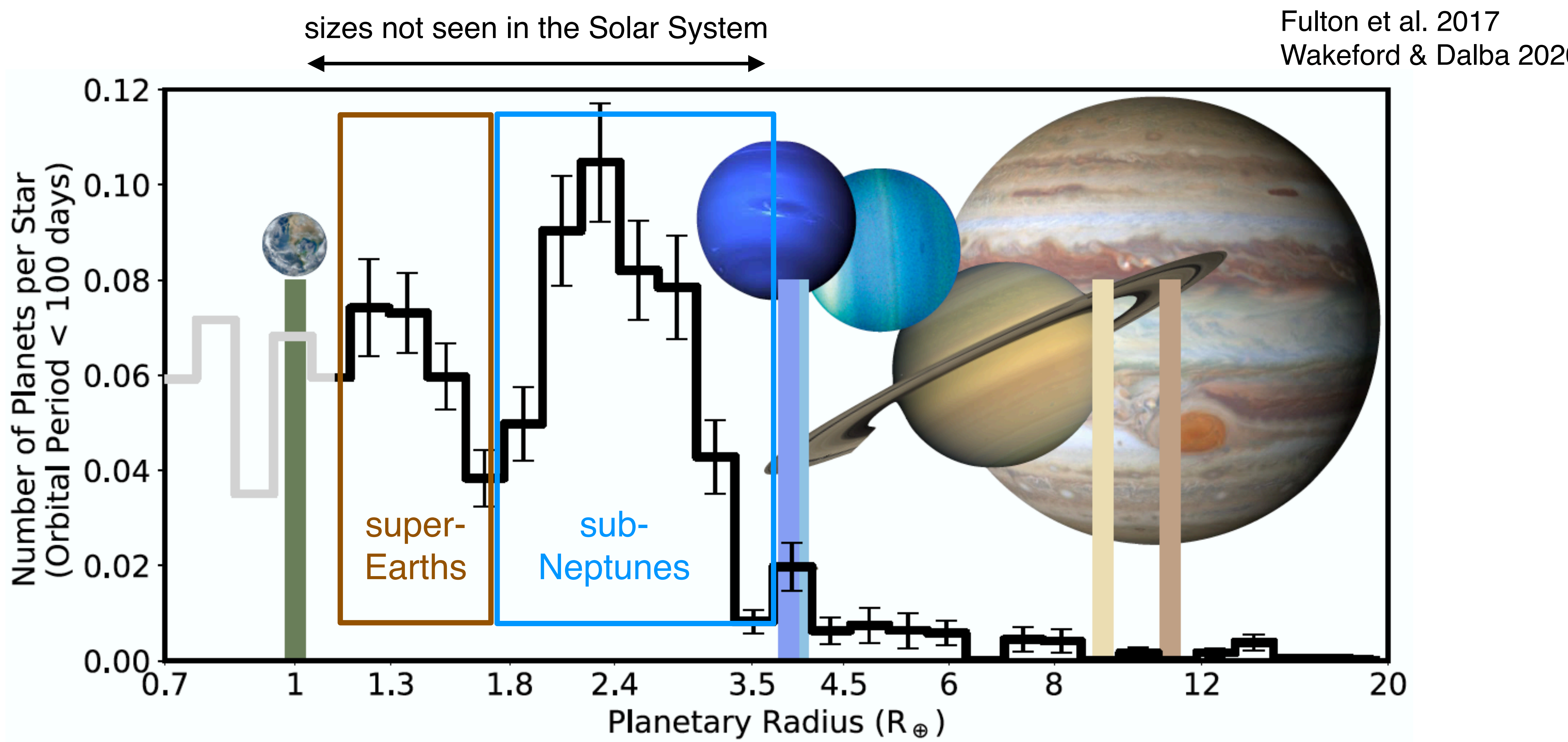
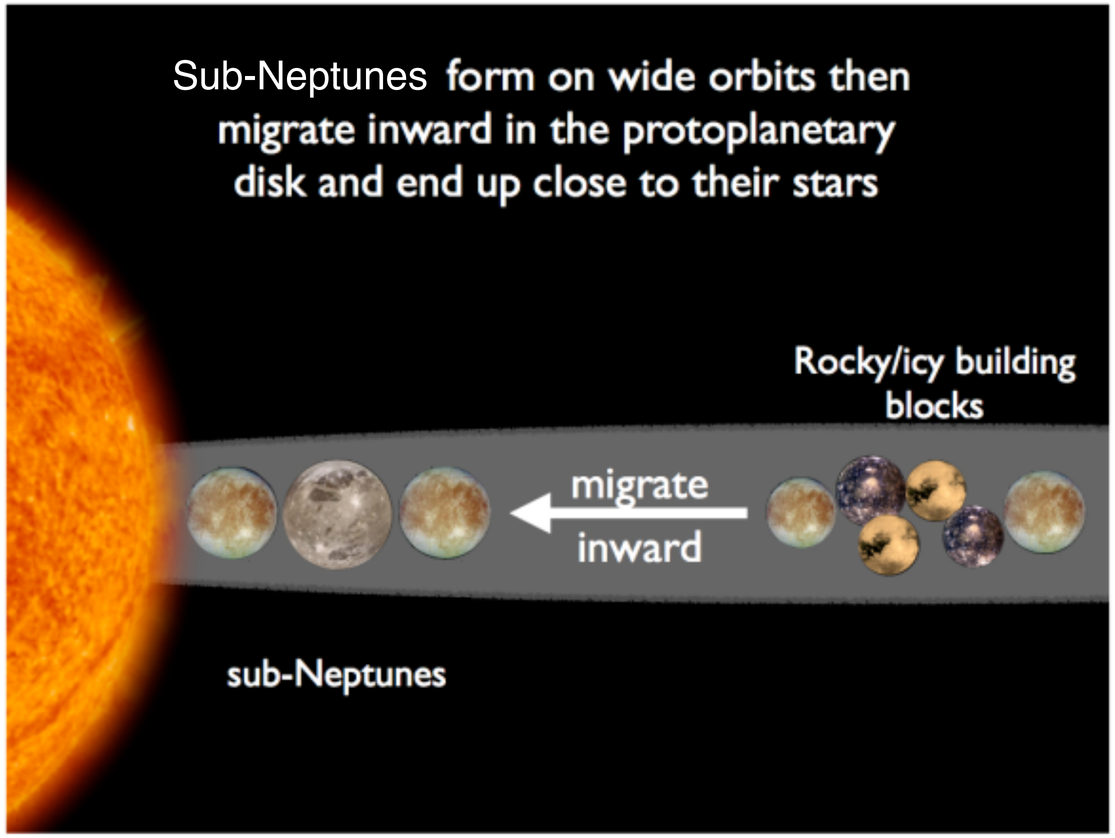
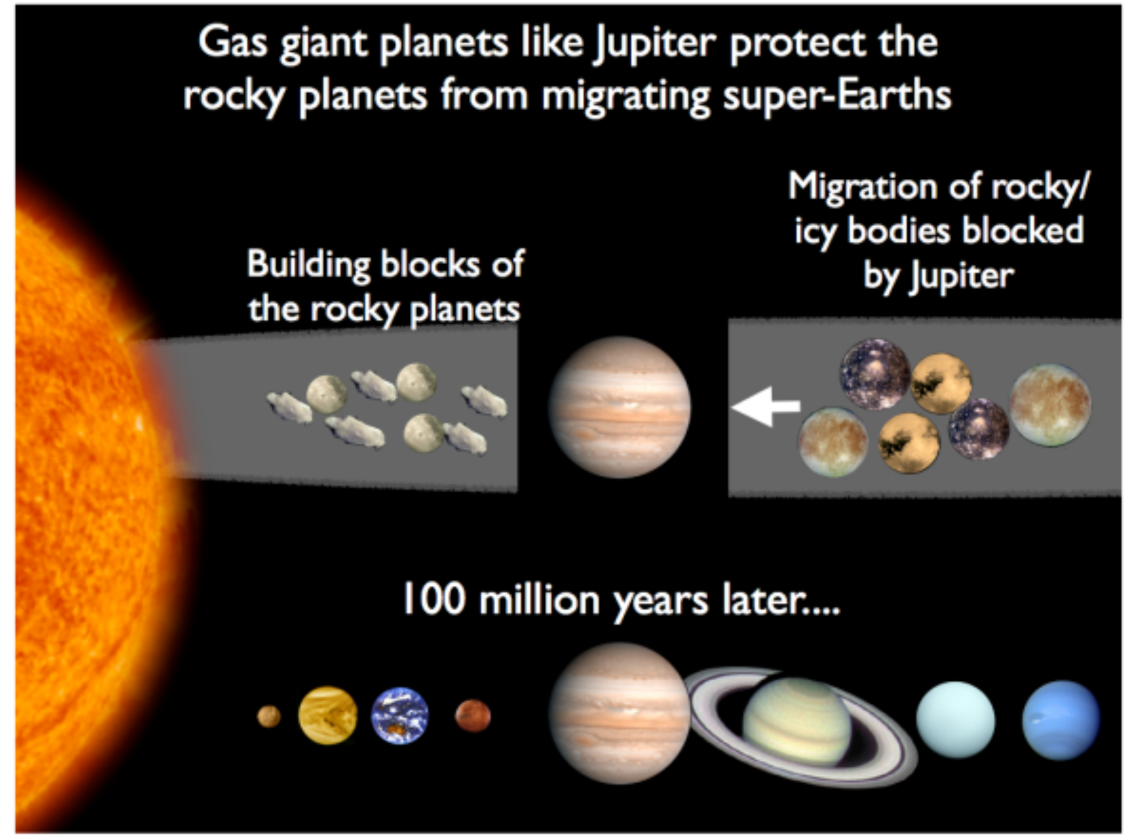


The radius valley seems to separate the populations of rocky super-Earths and non-rocky sub-Neptunes (there may be some mixing of the two populations)

Theoretical small planet (SP) vs cold Jupiters (CJ) anti-correlation and the lack of small planets in the Solar System





courtesy: S. Raymond

Cold Jupiters as dynamical barriers to sub-Neptune inward migration
(Izidoro et al. 2015)

- Jupiter may have prevented the icy-rocky nuclei of Saturn, Uranus and Neptune from migrating inward and thus becoming a compact system of sub-Neptunes like those observed by Kepler, K2 and TESS.

- It assumes sub-Neptunes form beyond the water snowline (~1-3 AU) and are thus ice-rich (with possible H/He envelopes)

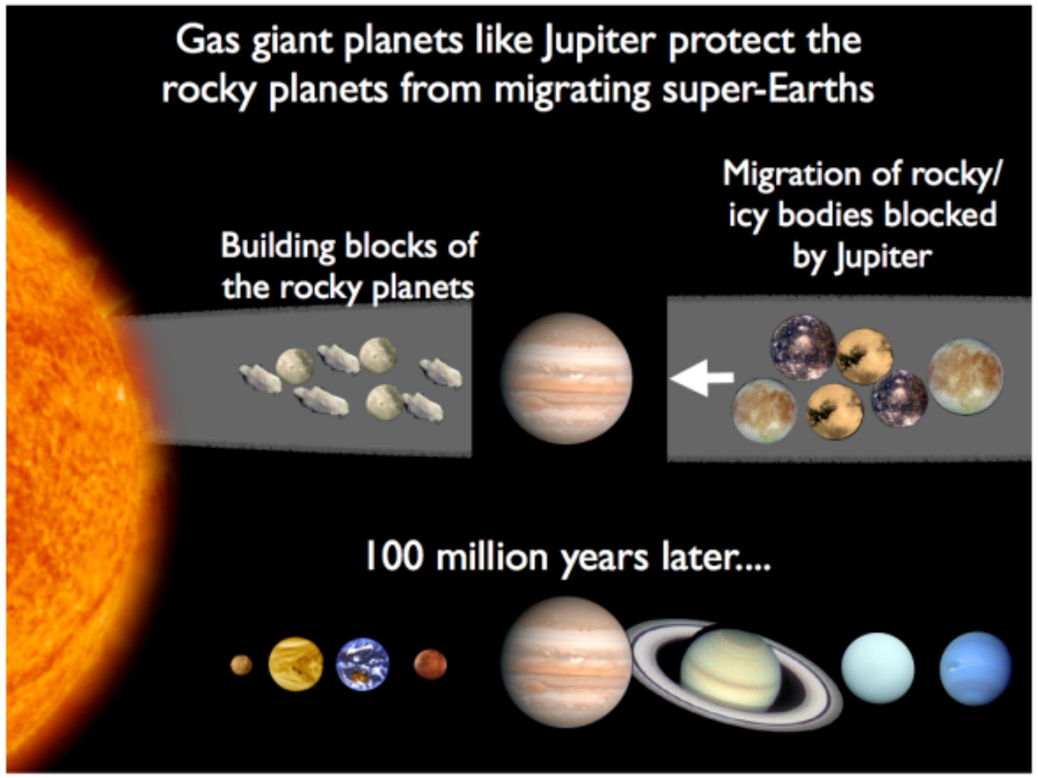
Theoretical SP vs CJ anti-correlation and the lack of small planets in the Solar System

courtesy: P. Armitage

Cold Jupiters as a hindrance to small-planet formation inside the water snowline
(Lambrechts et al. 2019)

- Jupiter may have opened a gap by reducing the inward flux of material (pebbles) required to form planets bigger than the terrestrial planets
- It assumes small planets form within the water snowline (~1-3 AU) and are thus dry (rocky with possible H/He envelopes)

Theoretical SP vs CJ anti-correlation and the lack of small planets in the Solar System

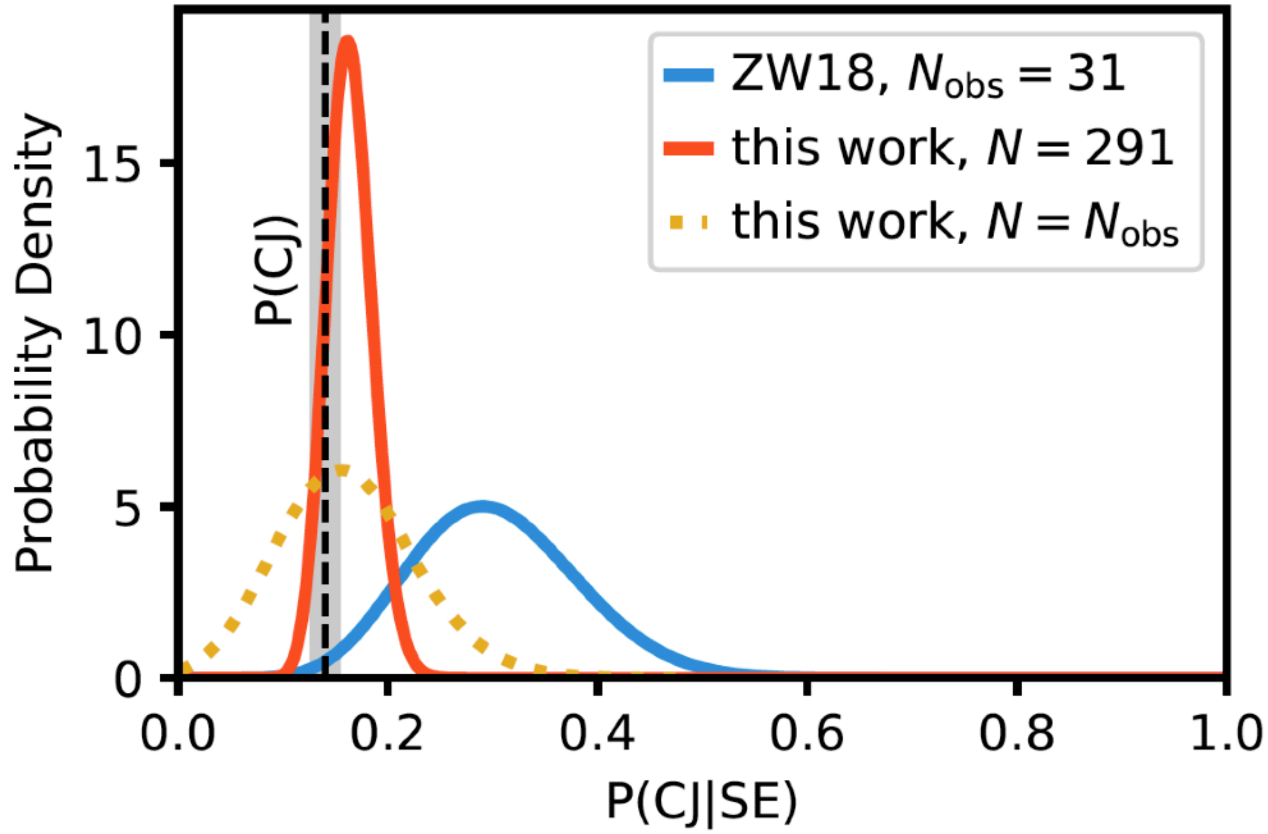


Izidoro et al. 2015

Lambrechts et al. 2019

Both the theoretical scenarios by Izidoro+ and Lambrechts+ predict an anti-correlation between the presence of short-period ($P < 100$ d) small planets ($1\ R_\oplus < R_p < 4\ R_\oplus$; $1\ M_\oplus < M_p < 20\ M_\oplus$) and cold Jupiters ($M_p$ = 0.3-13 M_{Jup} and a = 1-10 AU)

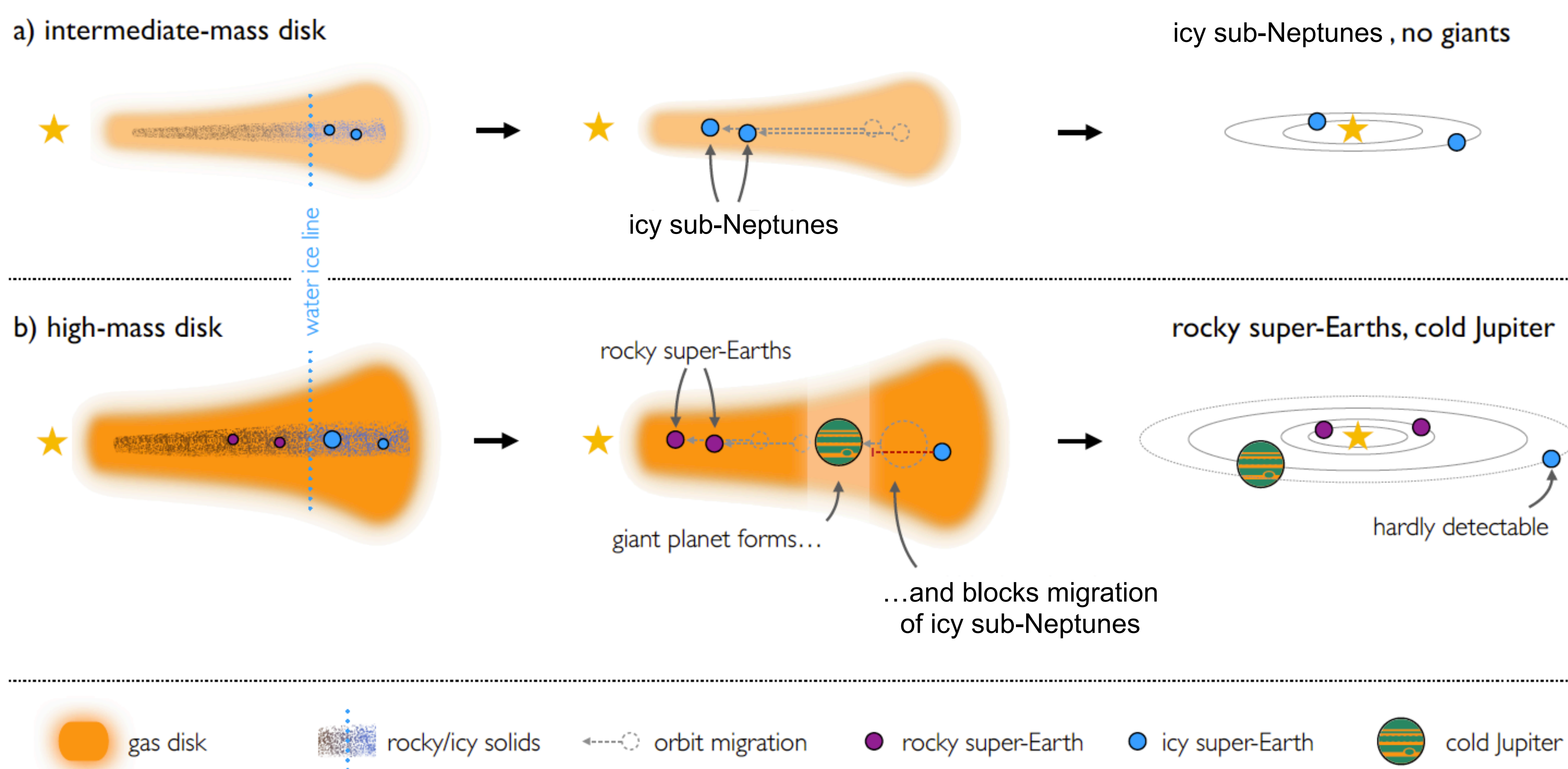
Cold Jupiters should be rare in planetary systems with inner small planets



Theoretical weak (or no) SP vs CJ correlation

Generation 3 Bern
Planet Population Synthesis
(Schlecker et al. 2021)

Strong architecture-composition link

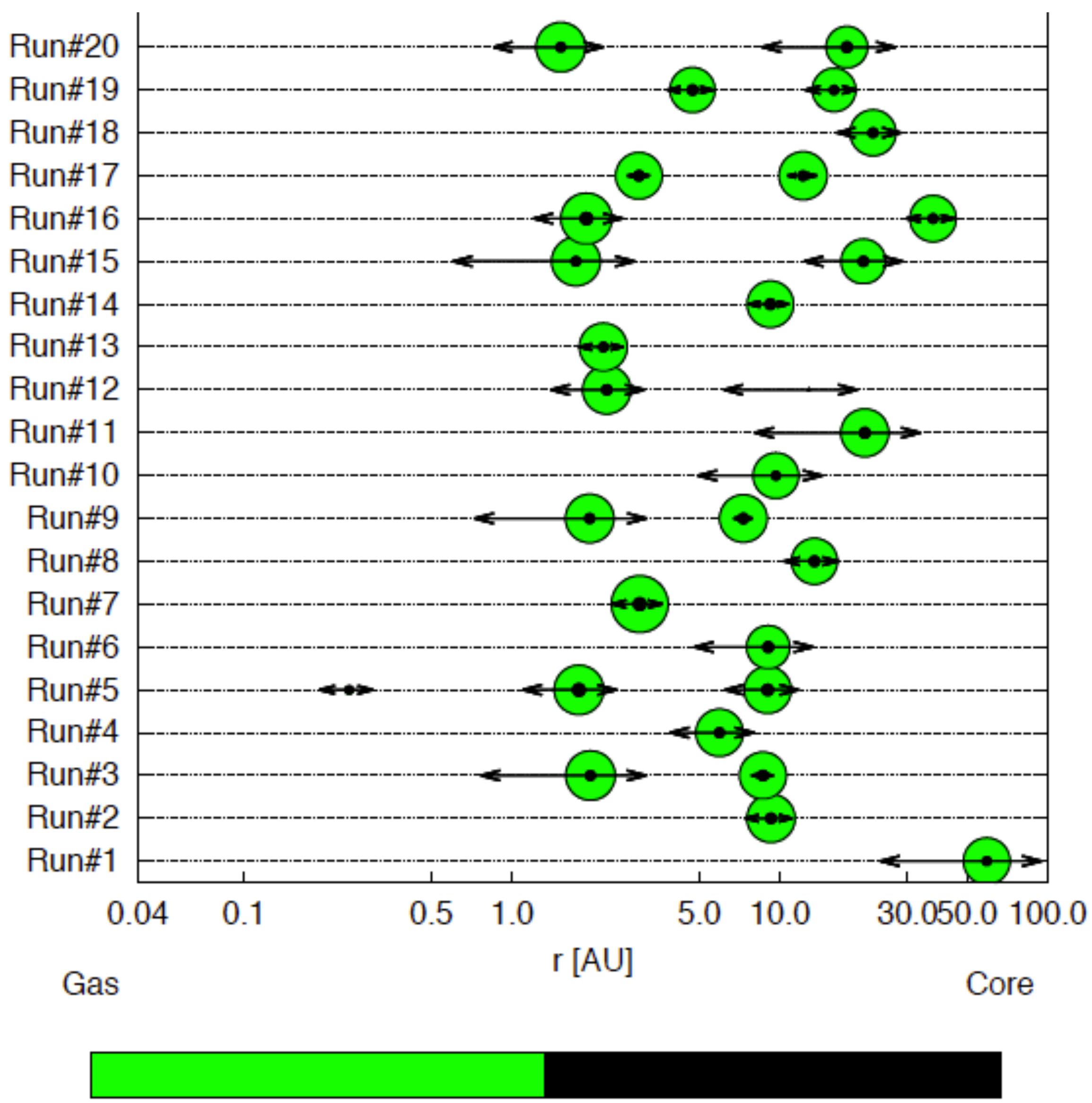


Theoretical SP vs CJ correlation

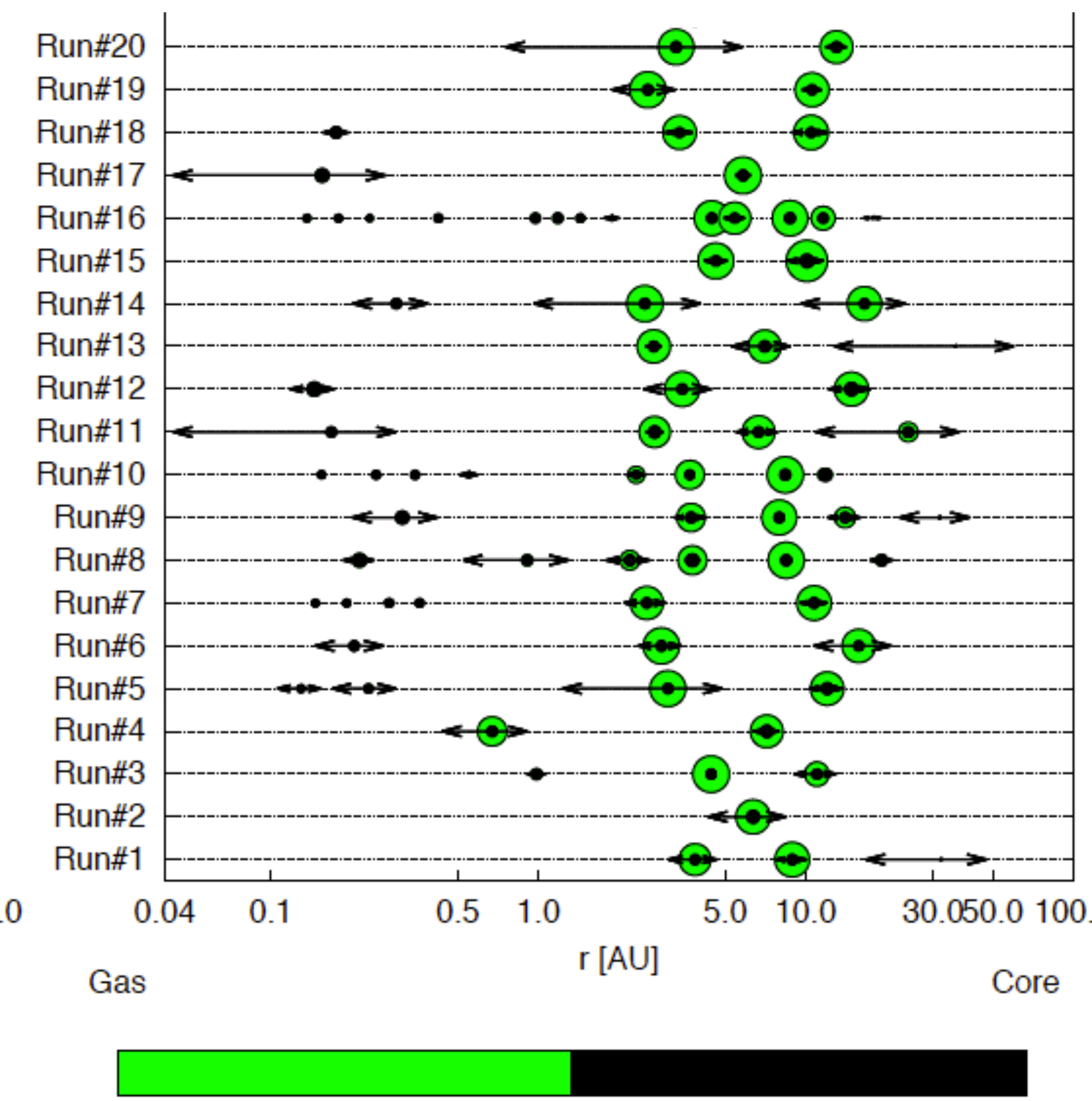
Less efficient gas contraction rates allow for a more efficient formation of systems with inner SPs and outer CJs: the cores that form in the inner disk are too small to effectively accrete large envelopes, and only cores growing in the outer disk can become giants. These outer giant planets are enough away not to necessarily destroy the inner systems of SPs.

Bitsch & Izidoro 2023

k_{env}=0.1 cm^2/g (high gas contraction rate)



k_{env}=0.4 cm^2/g (slow gas contraction rate)

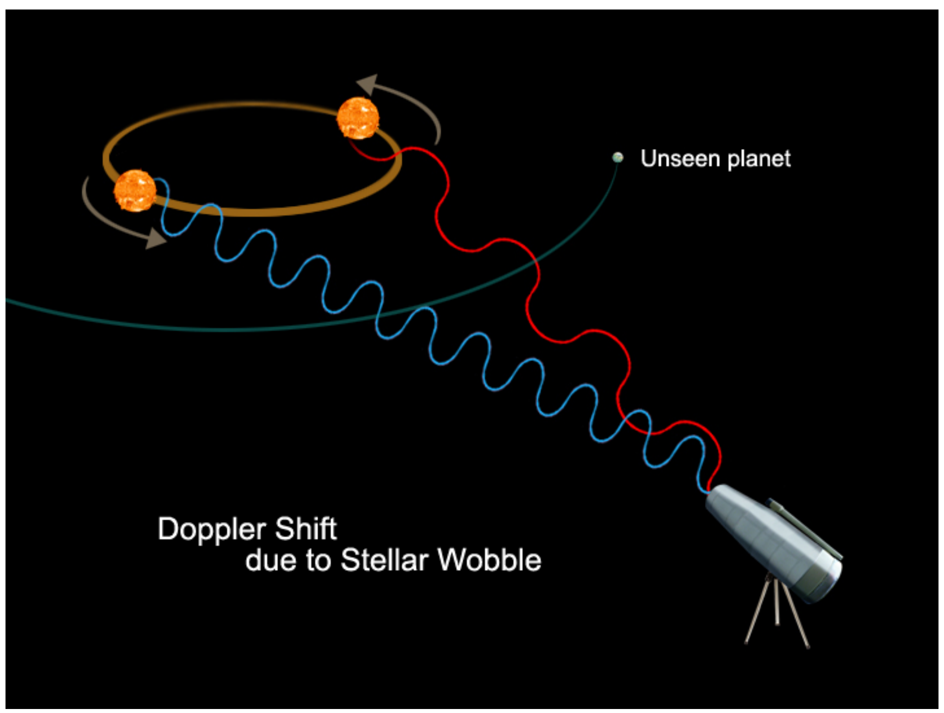


Testing theoretical scenarios

Theory can predict either ***anti-correlation*** (Izidoro+2015, Lambrechts+2019) or ***weak/no correlation*** (Schlecker+2021) or ***strong correlation*** (Bitsch & Izidoro 2023) between inner small planets and outer cold Jupiters (Jupiter and Saturn analogs).

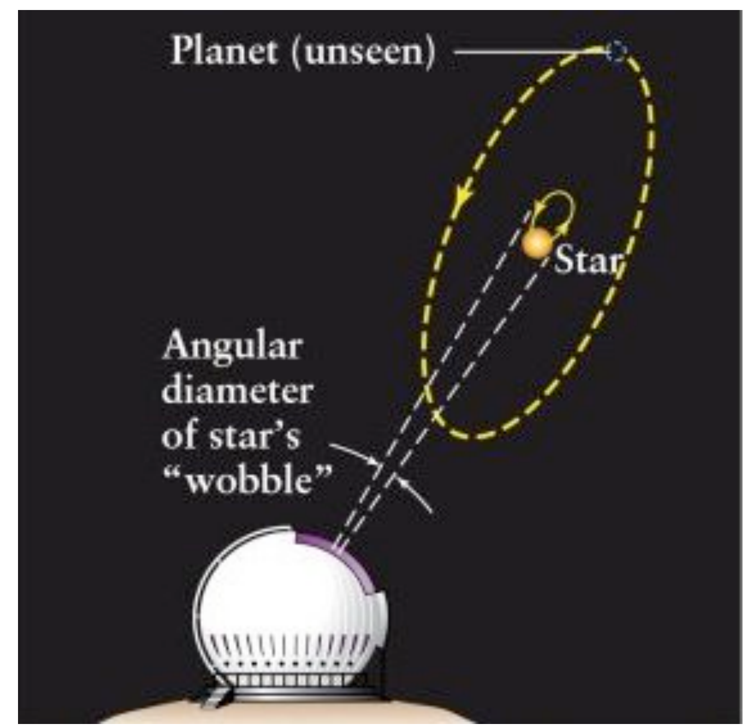
Can we test these theoretical predictions? How?

Radial-velocity (RV) long-term monitoring



Ground-based high-resolution spectrographs:
HARPS@ESO, HARPS-N@TNG, HIRES@Keck, CARMENES@CalarAlto, EXPRESS@LDT, ESPRESSO@VLT, etc.

Astrometric monitoring



Space-based astrometry (Gaia)

The HARPS-N/GTO radial-velocity survey (2012 -)

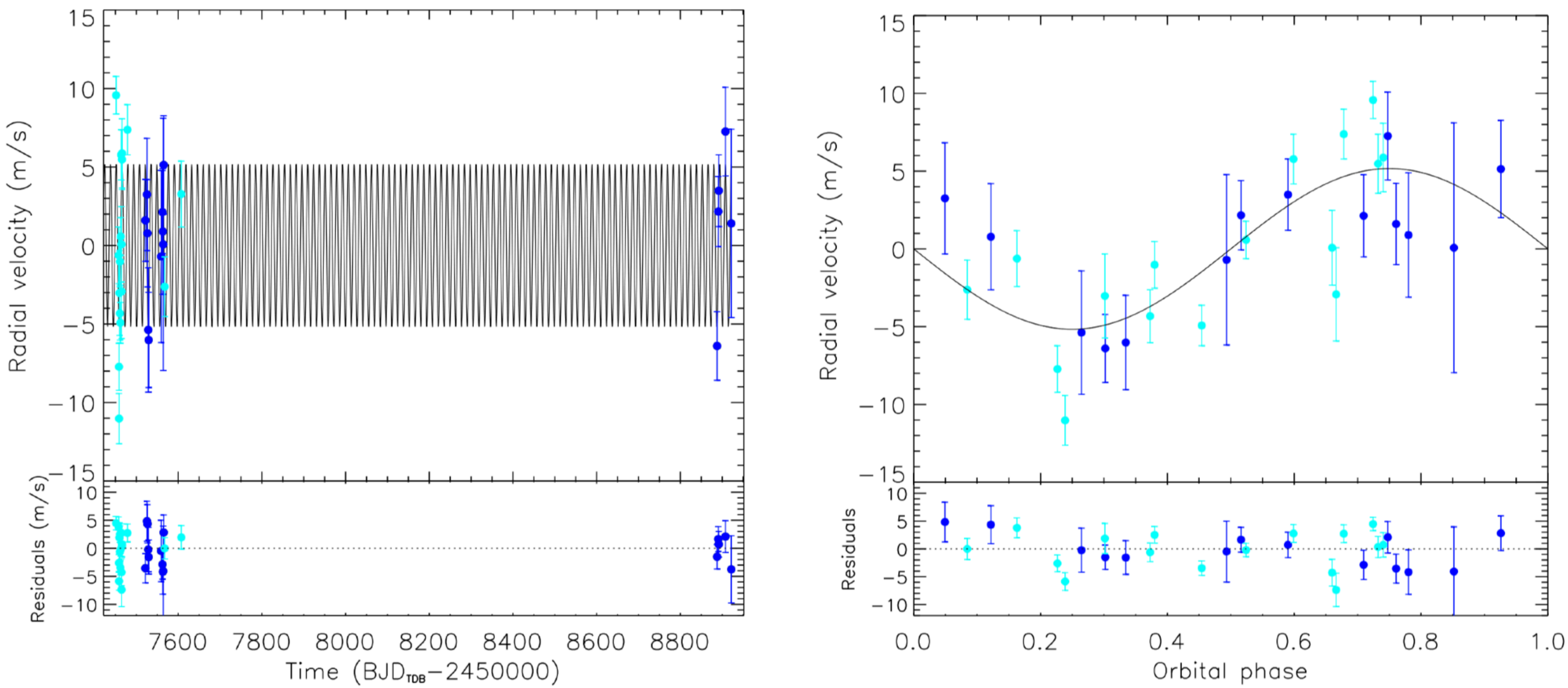
We monitored about 40 Kepler and K2 systems to i) determine the masses/densities of the small transiting planets (talk by A. Mortier) and ii) search for outer cold Jupiters.

The vast majority of those systems shows no evidence for cold Jupiters

Osborn et al. 2017
Bonomo et al. 2023

K2-110

P_b=13.9 d R_b=2.59 $R_\oplus$ ρ_b=5.0 g/cm^3

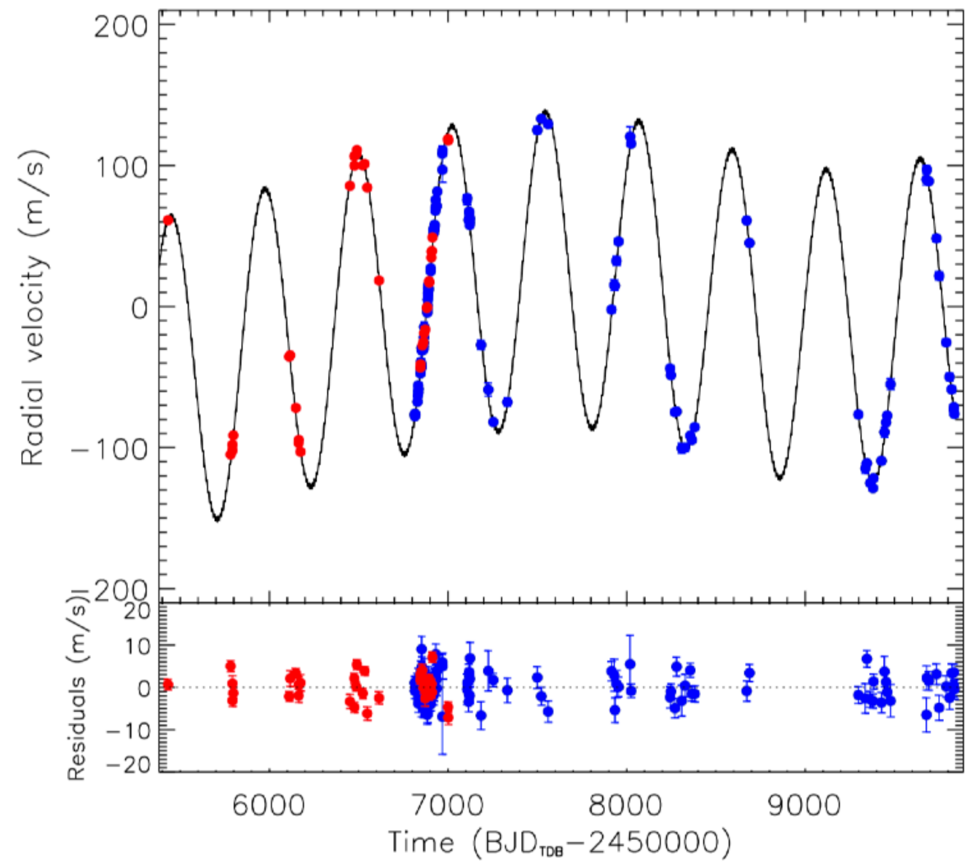


Blue circles: HARPS-N data; Light blue circles: HARPS data

The HARPS-N/GTO radial-velocity survey (2012 -)
Two cold Jupiters in the Kepler-454 system

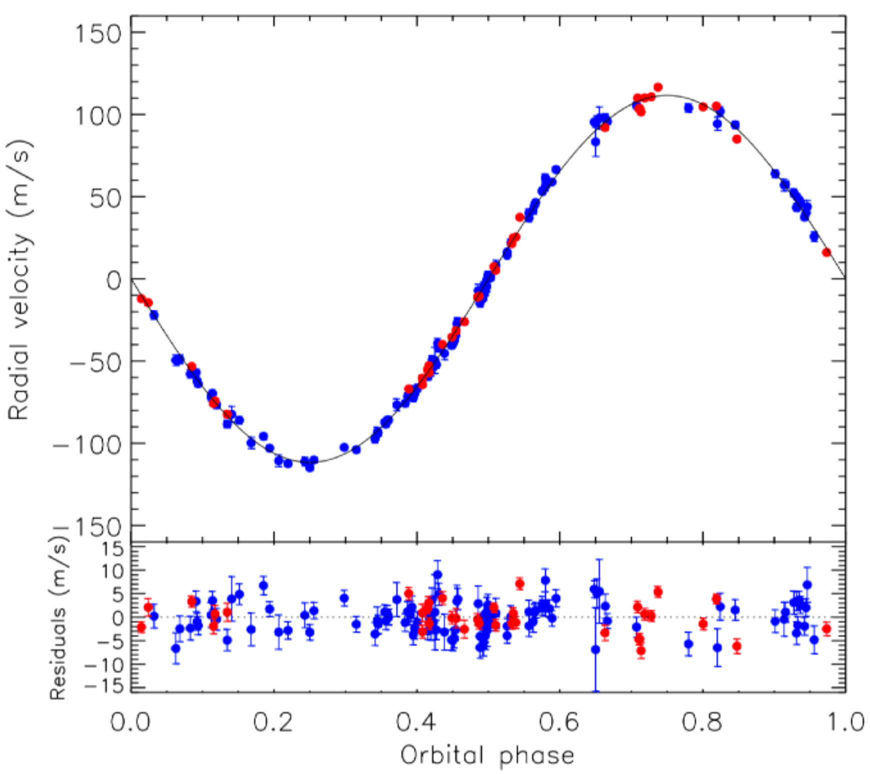
Kepler-454

P_b=10.6 d R_b=2.37 $R_\oplus$ ρ_b=2.2 g/cm^3



Blue circles: HARPS-N@TNG data
Red circles: HIRES@Keck data

Gettel et al. 2016
Bonomo et al. 2023

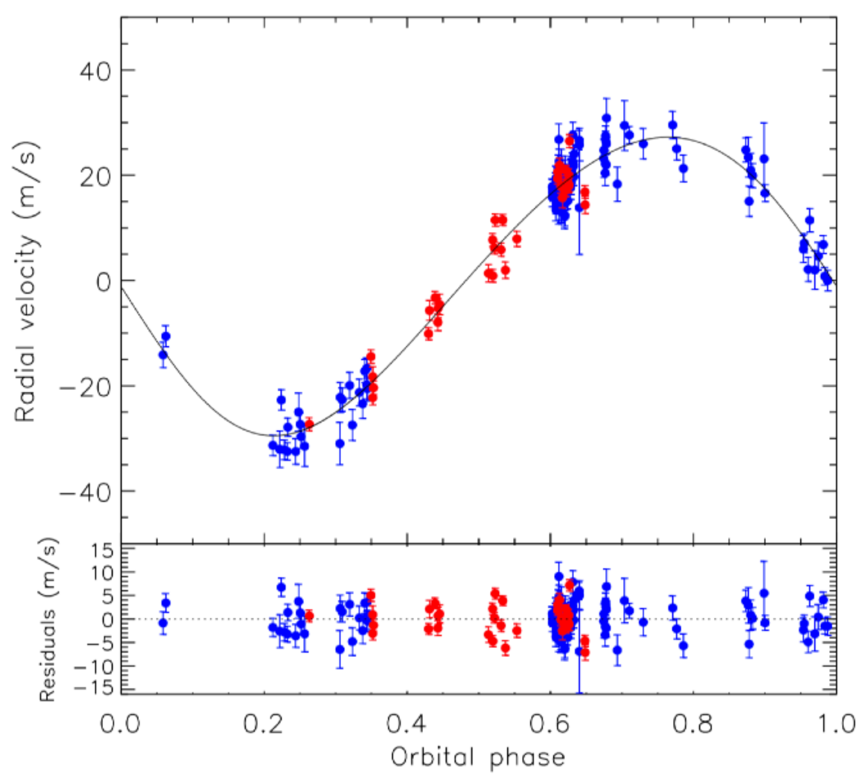


P_c = 524 d

a_c = 1.3 AU

e_c < 0.005

M_c = 4.51 M_{Jup}



P_d = 4070 d

a_d = 5.1 AU

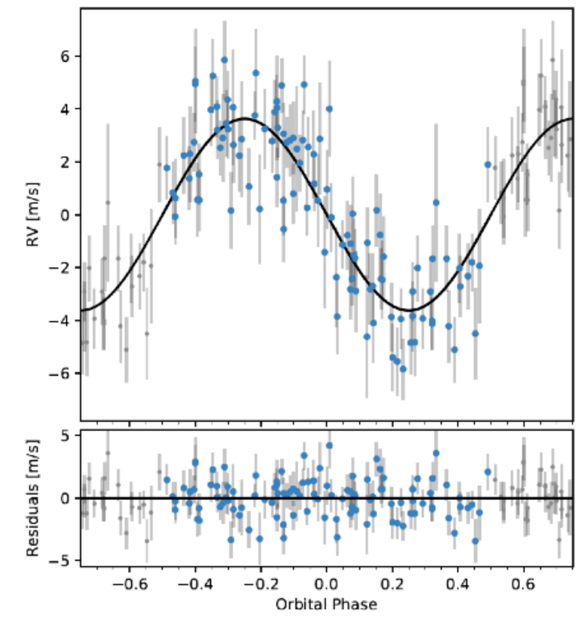
e_d = 0.09

M_c = 2.3 M_{Jup}

The HARPS-N/GTO (2012-2022) radial-velocity survey
A highly eccentric cold Jupiters in the K2-312 system

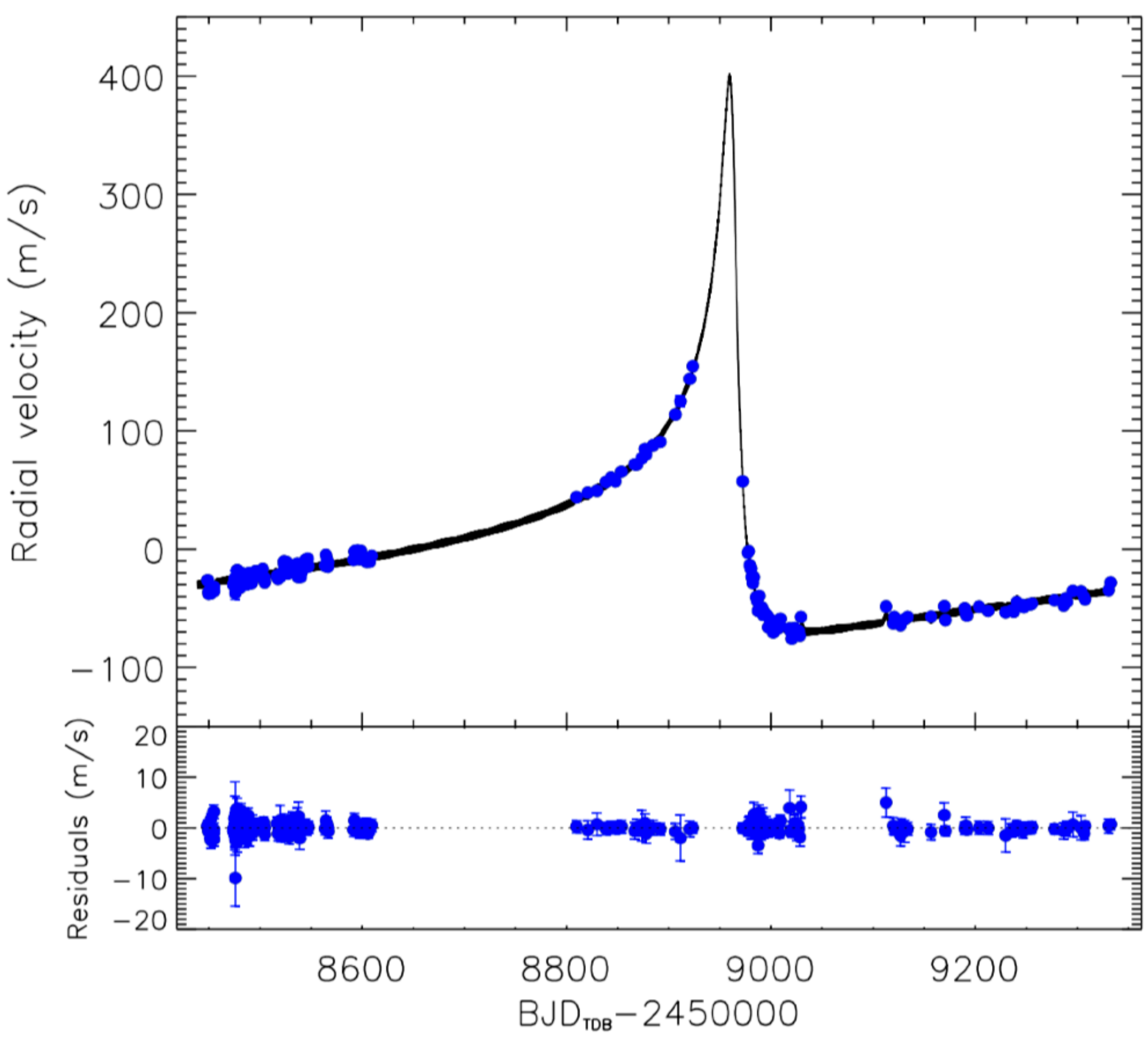
K2-312 (HD80653)

P_b=0.72 d R_b=1.61 $R_\oplus$ ρ_b=7.5 g/cm^3



Frustagli et al. 2020

Blue circles: HARPS-N@TNG data



P_c = 921 d

a_c = 2.0 AU

e_c = 0.85

M_c = 5.4 M_{Jup}

Bonomo et al. 2023

Occurrence rate of cold Jupiters in small planet systems

5 CJs in 3/37 Kepler and K2 systems

(Kepler-68, talk by L. Malavolta; Kepler-454; K2-312)

Survey sensitivity (or completeness) must be taken into account

f_{CJ}: frequency of cold Jupiters around solar-type stars, regardless of the presence or absence of small planets

$f_{CJ|SP}$: frequency of cold Jupiters around solar-type stars with small planets (RV follow-up of transiting systems)

Planetary Mass [M_{Jup}]	Orbital separation [AU]	$f_{CJ\|SP}[\%]$ from Keplerians	$f_{CJ\|SP}[\%]$ from Keplerians and trends	$f_{CJ}[\%]$ (Wittenmyer et al. 2020)	$f_{CJ\|SP}[\%]$ [1] (Bryan et al. 2019)
0.3-13	1-10	$9.3^{+7.7}_{-2.9}$	$12.3^{+8.1}_{-3.7}$	$20.2^{+6.3}_{-3.4}$	-
0.5-13	1-10	$8.8^{+7.4}_{-2.8}$	$11.8^{+7.7}_{-3.5}$	-	36^{+7}_{-6}
0.5-13	1-20	$8.3^{+7.0}_{-2.6}$	$11.1^{+7.4}_{-3.3}$	-	41^{+8}_{-7}

Zhu+2018, Bryan+2019: ***excess of cold Jupiters in small planet systems*** (limited samples and/or wrong interpretation of the origin of several linear trends in the RVs)

Bonomo+2023: ***no excess of cold Jupiters in small planet systems*** (possible SP-CJ anti-correlation uncertain due to the large uncertainties).

Similar occurrence rates can be estimated from the Kepler-Keck survey (~60 systems, Weiss+2024) and the TESS-Keck survey (~35 systems, Van Zandt+2023).

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This discrepancy cannot be explained by a difference in the average metallicity of the stellar samples:

<Fe/H> = -0.065 ± 0.011 dex   HARPS-N transit sample (Bonomo+2023)

<Fe/H> = -0.045 ± 0.009 dex   AAPS RV sample (Wittenmyer+2020)

<Fe/H> = -0.007 ± 0.010 dex   Bryan+2019 transit and RV sample

SP-CJ correlation at super-solar metallicities?

Bryan & Lee 2024 have recently reported a SP-CJ correlation only at super-solar metallicities from public RV data of 109 transiting + 75 RV systems with inner planets

B&L [Fe/H]>0	B&L [Fe/H]≤0	W20 [Fe/H]>0	W20 [Fe/H]≤0	σ [Fe/H]>0	σ [Fe/H]≤0
28.0 (+4.9 -4.6)%	4.5 (+2.6 -1.9)%	13.5 (+3.5 -3.0)%	6.4 (+2.9 -2.3)%	2.5σ	-0.5σ

If true, we should have found a SP-CJ correlation also at the average metallicities.

We are also working on the determination of $f_{CJ|SP}$ as a function of stellar metallicity. However, to that end we need

- homogeneous definitions of small-planet systems

- homogeneously derived completenesses for both the analyzed and the comparison samples

Conclusions and Perspectives I

- Our $f_{CJ|SP}$ disclaims previous findings of excess of Jupiter analogs in small planet systems. Too large uncertainties on $f_{CJ|SP}$ to draw any firm conclusion about a possible anti-correlation between inner SPs and outer CJs

- Need for enlarging (at least tripling) the sample with

i) the TESS systems observed with HARPS-N/GTO since 2019;

ii) the Kepler, K2 and TESS systems observed with facilities other than HARPS-N (HARPS-S, ESPRESSO, CARMENES, APF, HIRES, etc.)

- Need for enlarging the sample in the longer-term future with

III) the PLATO systems: ~2000 expected planets orbiting FGK dwarfs with $V \lesssim 11$ (~1200 of which with $R_p \lesssim 2\ R_\oplus$) compared to ~1400 known exoplanets (~400 in transit), (Matuszewski et al. 2023 with occurrence rates by Hsu et al. 2019)

Conclusions and Perspectives II

▸ **Compute more accurate/precise $f_{CJ|SP}$** (thanks to new PLATO systems and/or new PLATO planets in known systems) **as a function of**

- planet composition to check possible architecture-composition links (e.g., Izidoro+2015, Lambrechts+2019, Schlecker+2021)
- small planet multiplicity
  - cold Jupiters should be even rarer in multiple systems than in single systems, according to Izidoro+2015
  - lower multiplicity is expected in the presence of cold Jupiters (partial explanation for the Kepler dichotomy?)
- cold Jupiter multiplicity (systems with multiple cold Jupiters should even more rarely host inner small planets, according to Izidoro+2015 and Lambrecths+2019)
- stellar metallicity

▸ **Compute $f_{CJ|SP\text{-}HZ}$** (> a dozen of PLATO SPs in the HZ)**: role of Jupiter analogs for the habitability?** (e.g. trigger of heavy bombardment of water-rich asteroids, but also shielding from catastrophic impacts with asteroids?)