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Characterization and occurrence rate of cold Jupiters to assess their impact on the formation of small and terrestrial inner planets.

The crucial role of GaiaNIR

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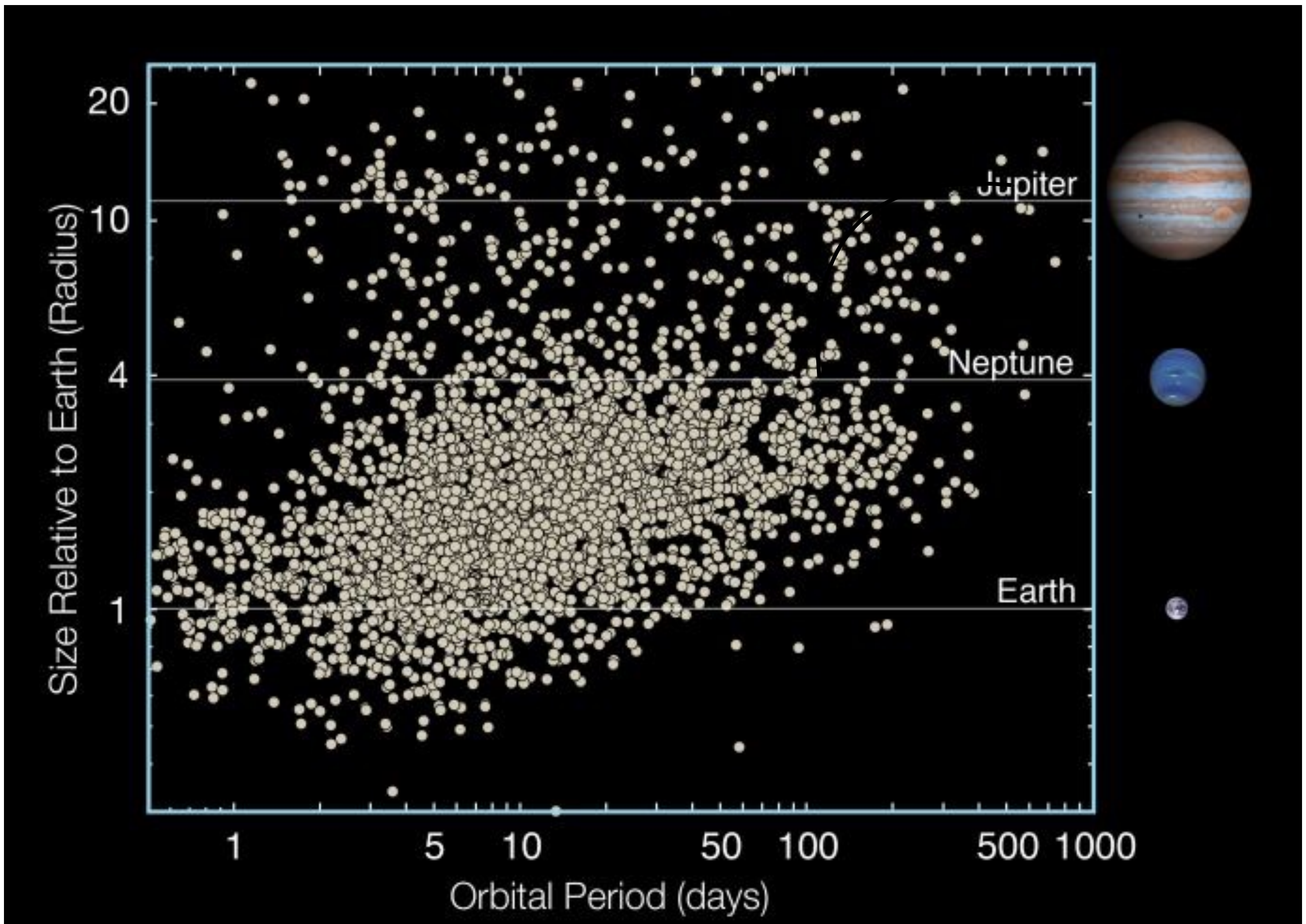
the HARPS-N/GTO Consortium

Gaia-NIR: next generation astrometric mission
Bologna - 17/18 January 2024

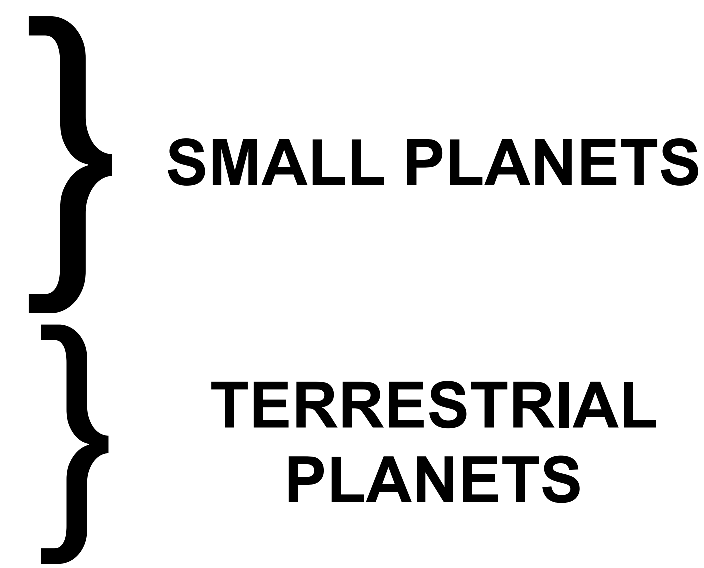
Scientific Context - The R_p-P diagram

- About 75% of the ~5500 exoplanets known to date have been discovered through the transit method
- Small planets (SPs) with $1\ R_\oplus < R_p < 4\ R_\oplus$ and $P < 100$ d are very abundant in the Milky Way

Kepler validated planets

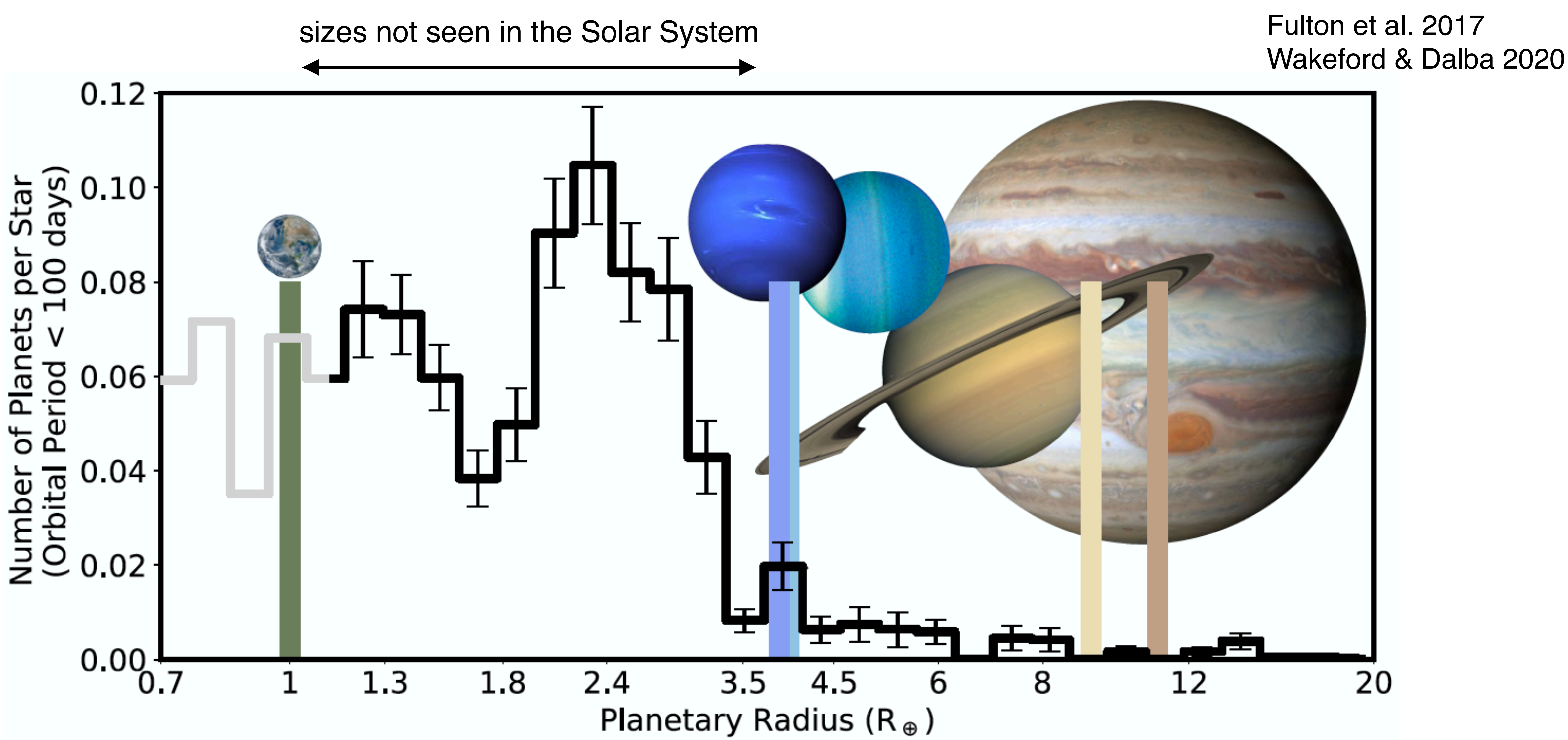


courtesy of Kepler team



Scientific Context - Planet frequency vs R_p

- By correcting for the transit probability, it is possible to derive planet occurrence rates as a function of the planet radius



- ~50% of FGK dwarfs host at least one small planet with P < 100 d, but small planets are absent in the Solar System (e.g. Petigura et al. 2013, Mulders et al. 2015)

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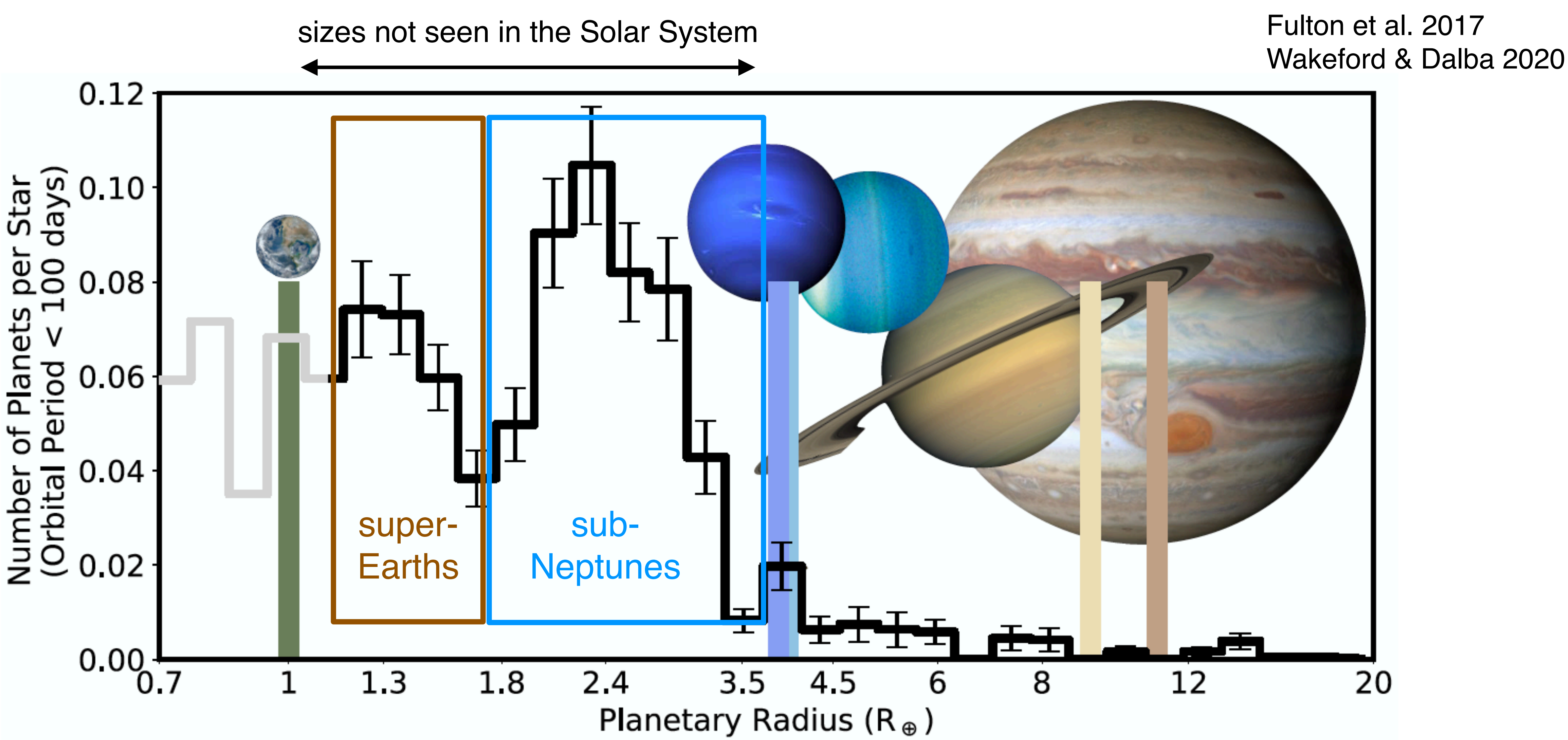

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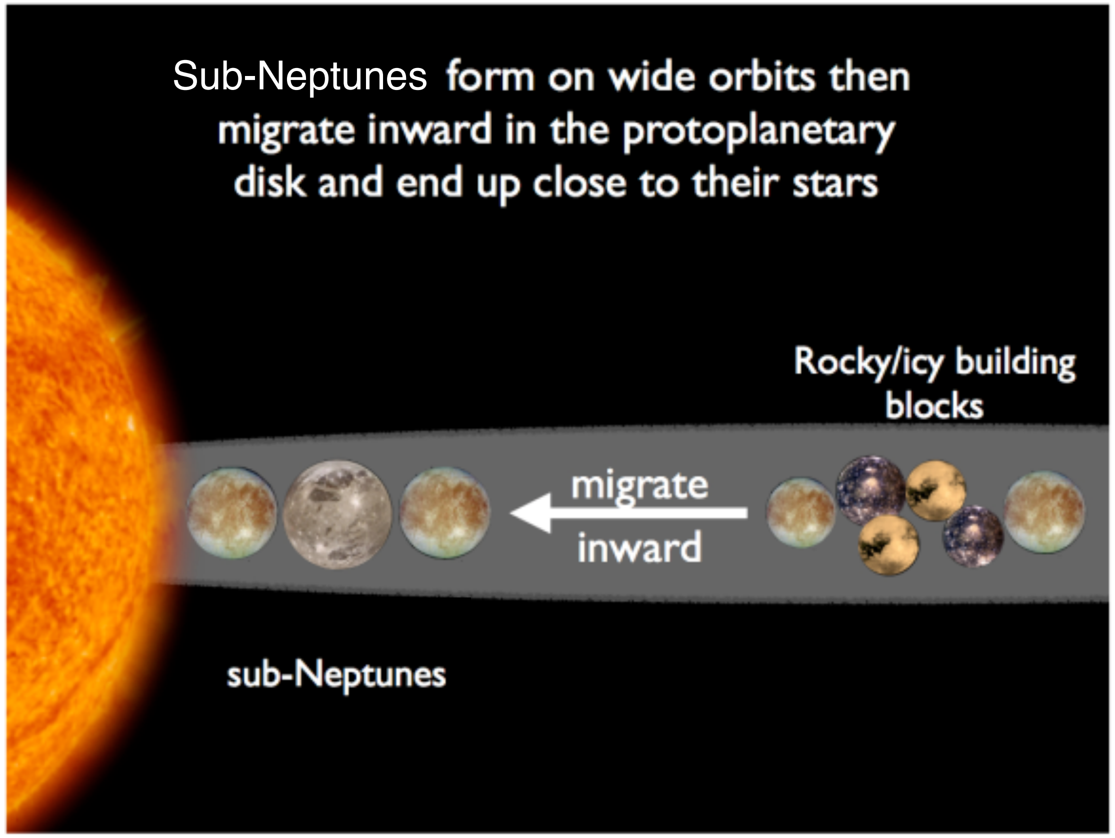
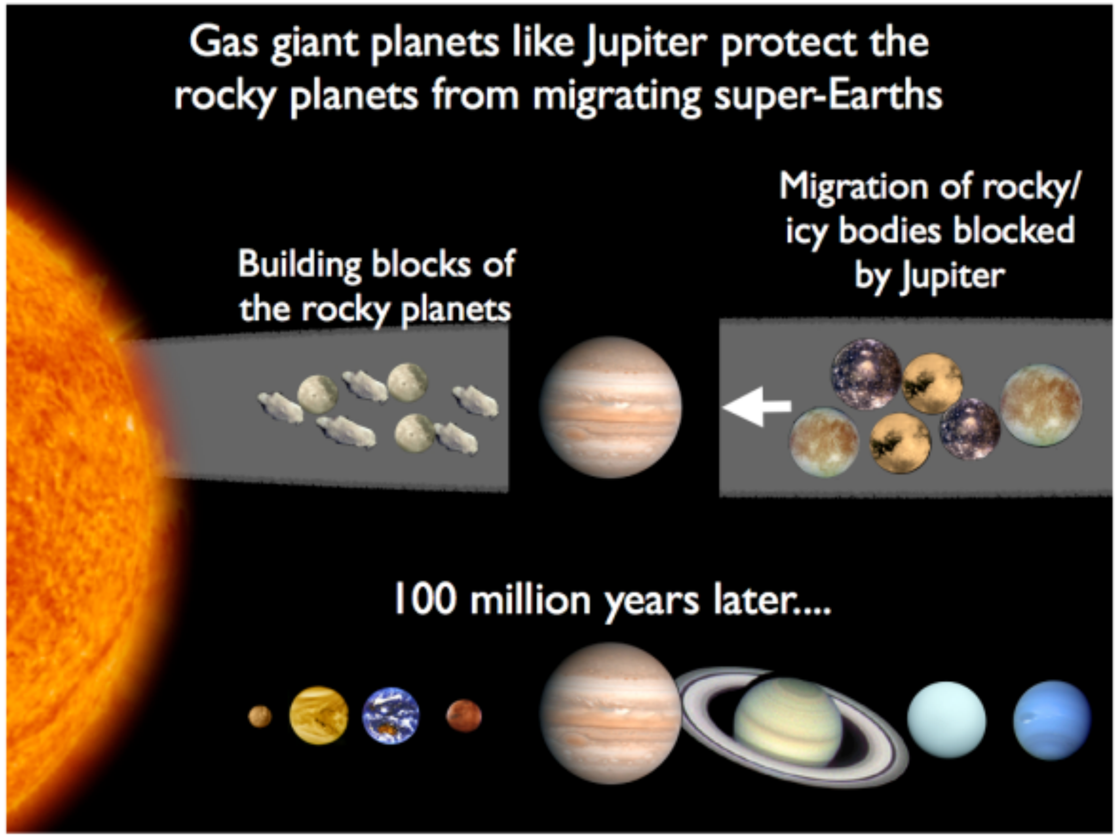
Theoretical SP vs CJ anti-correlation and the lack of small planets in the Solar System





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)

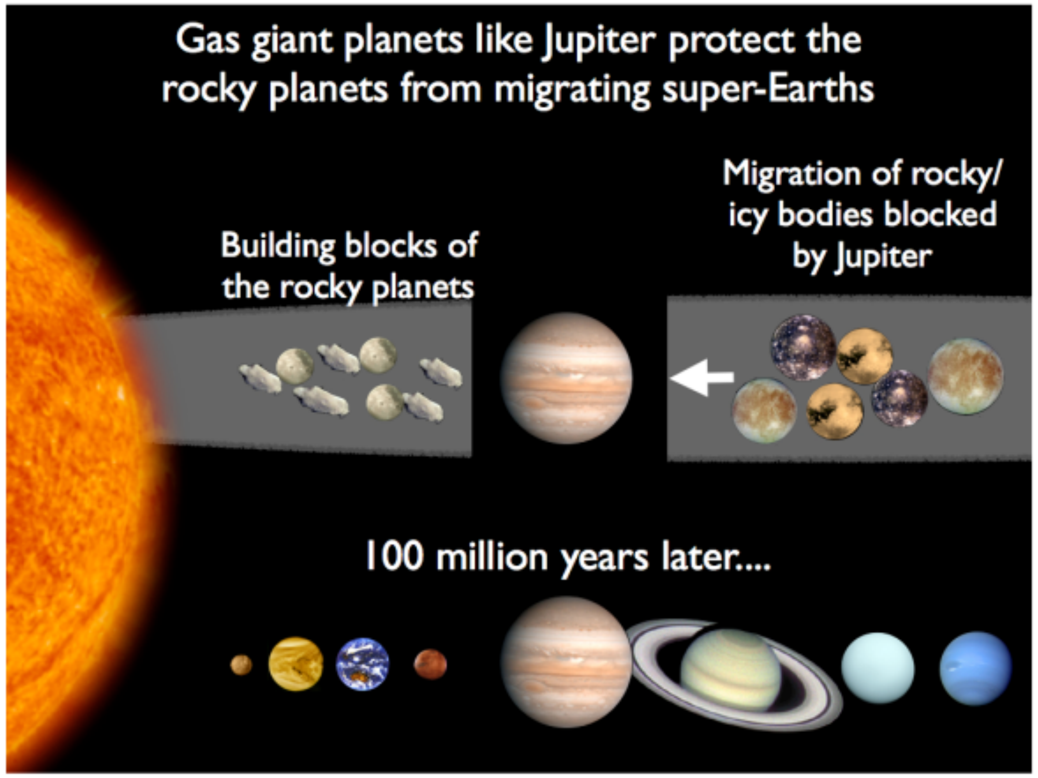
Theoretical SP vs CJ anti-correlation and the lack of small planets in the Solar System

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

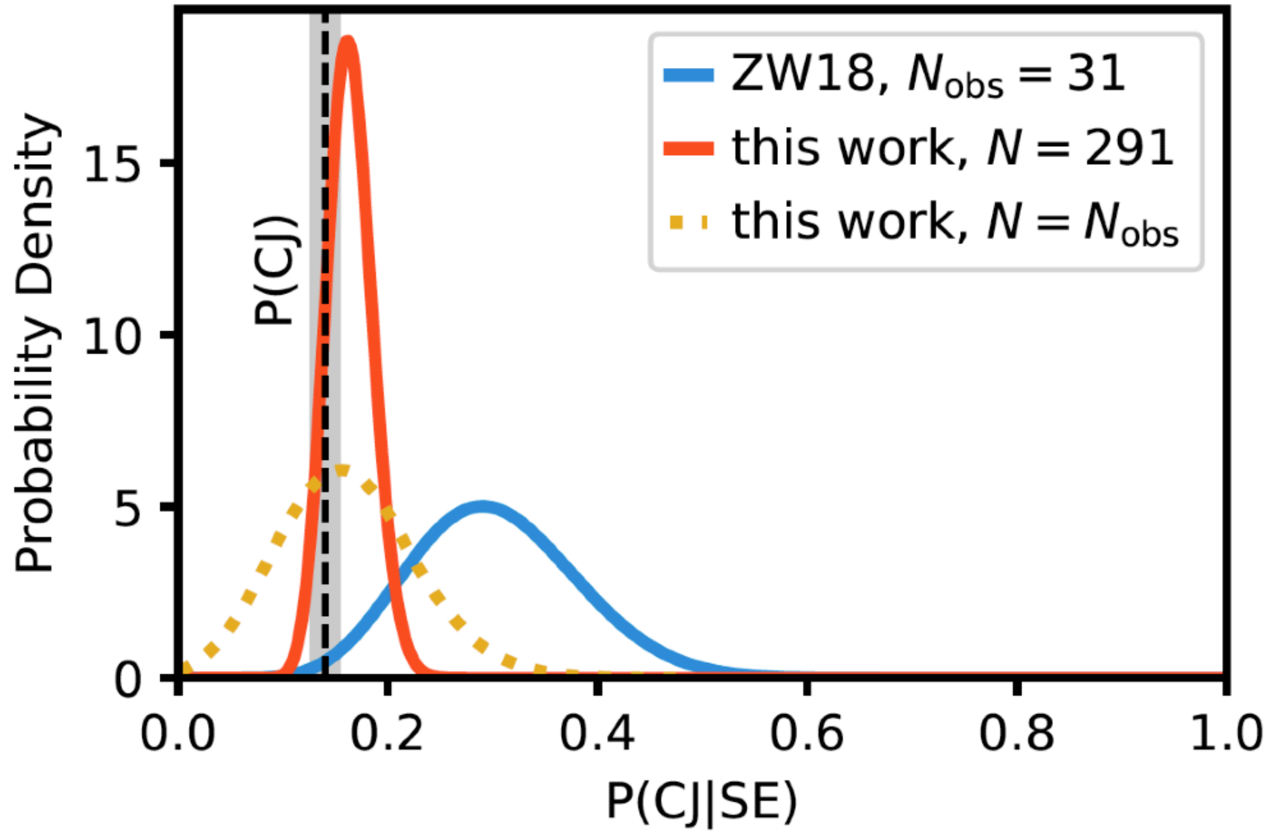


Izidoro et al. 2015

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)

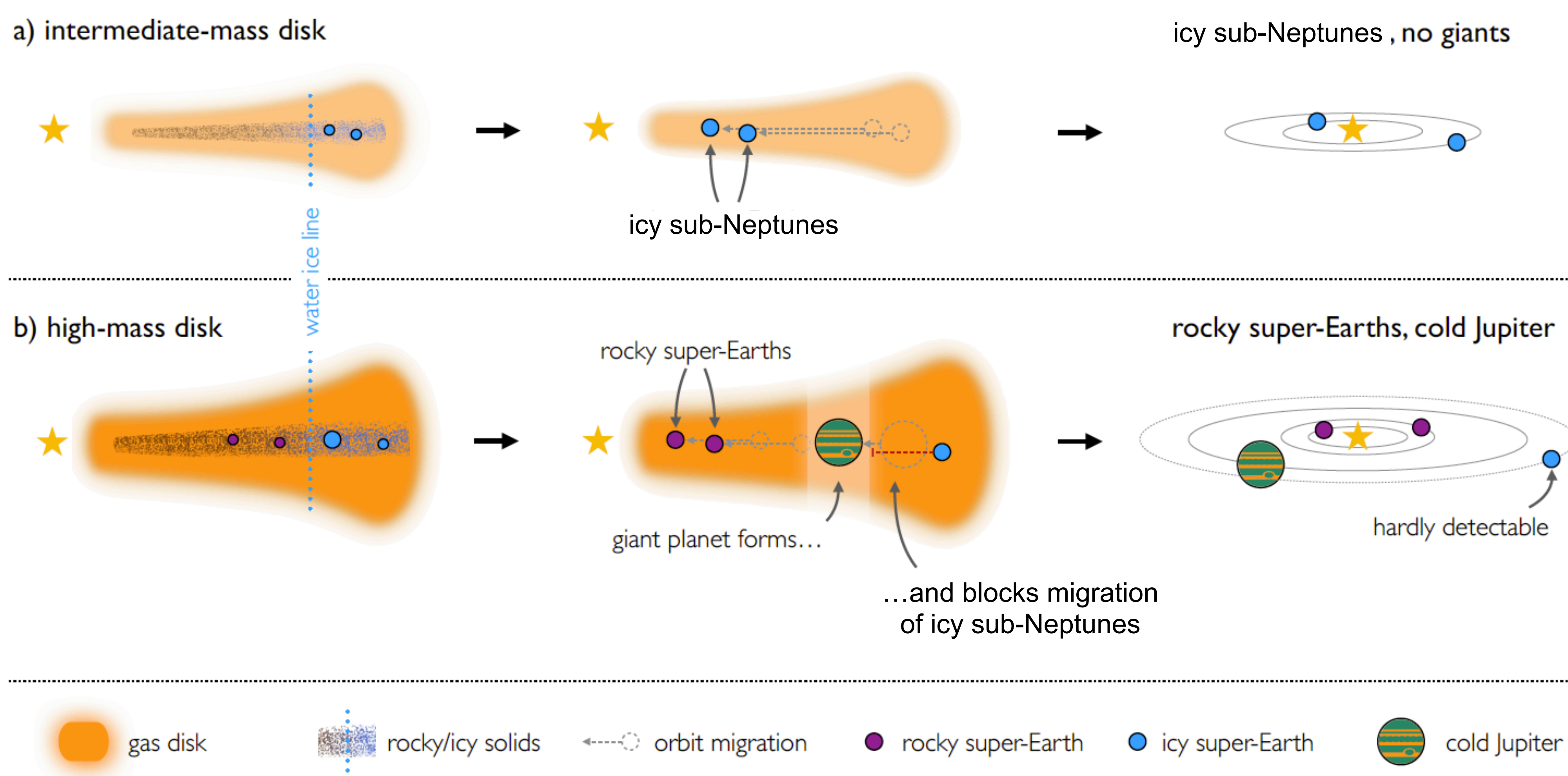
Cold Jupiters (CJs) should be rare in planetary systems with inner small planets



Theoretical weak (or no) SP vs CJ correlation

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

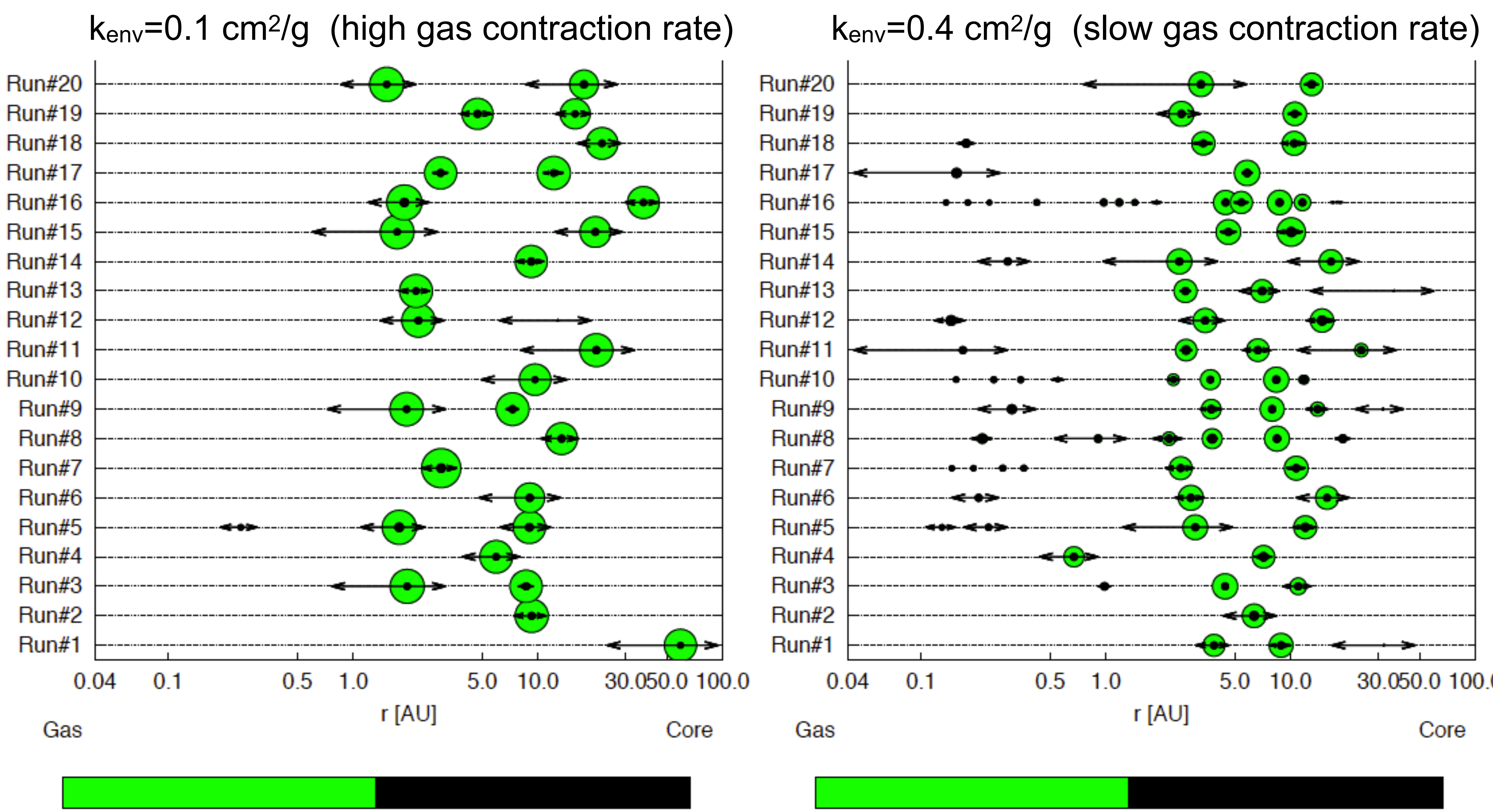
Strong architecture-composition link



Theoretical SP vs CJ correlation

Less efficient gas contraction rates allow for a more efficient formation of systems with inner SPs and 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

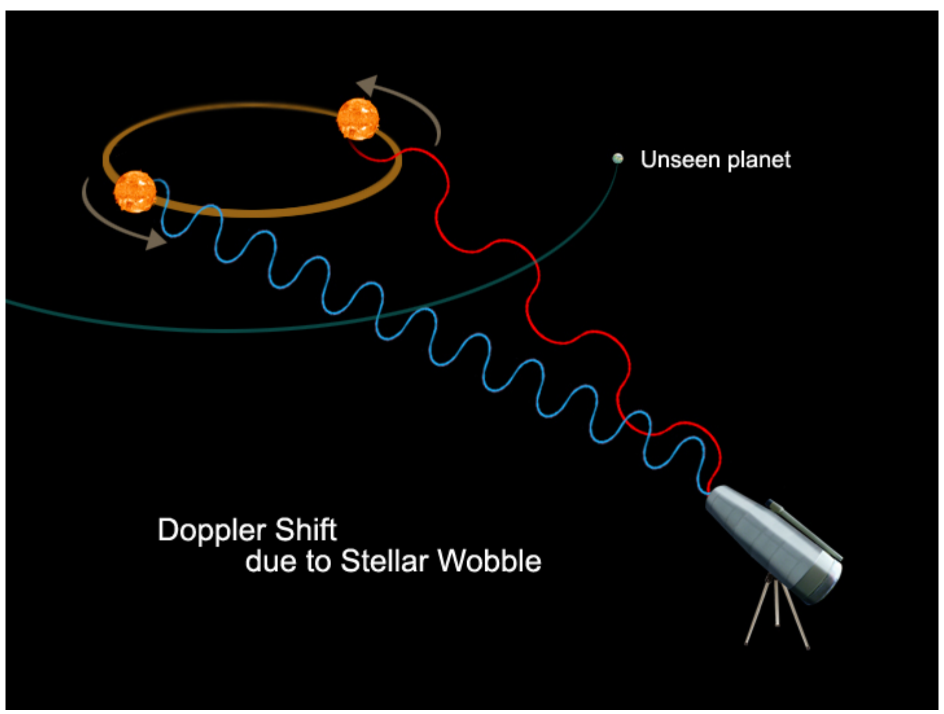


Testing theoretical scenarios

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).

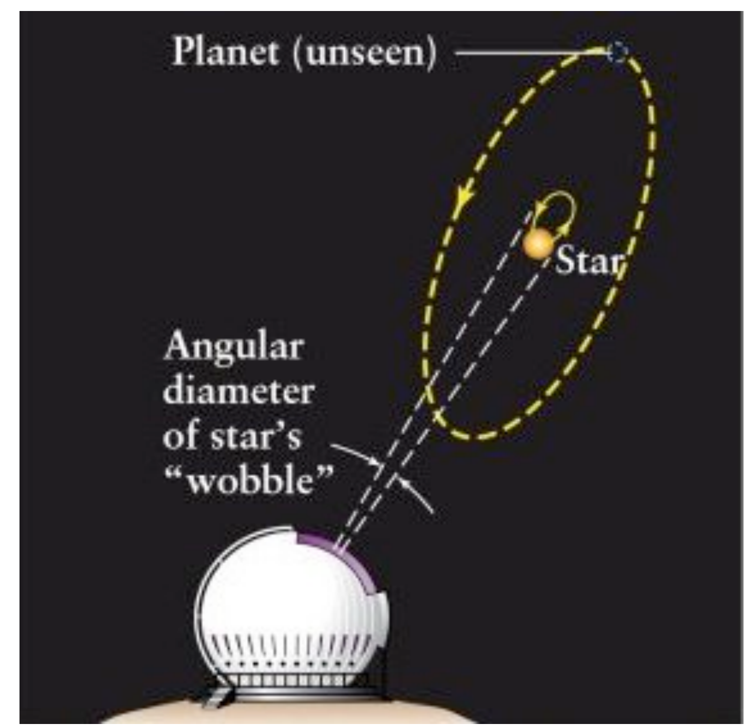
Can we test these theoretical predictions? How?

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 astrometric missions:
Gaia and GaiaNIR

The HARPS-N/GTO (2012-2022) radial-velocity survey

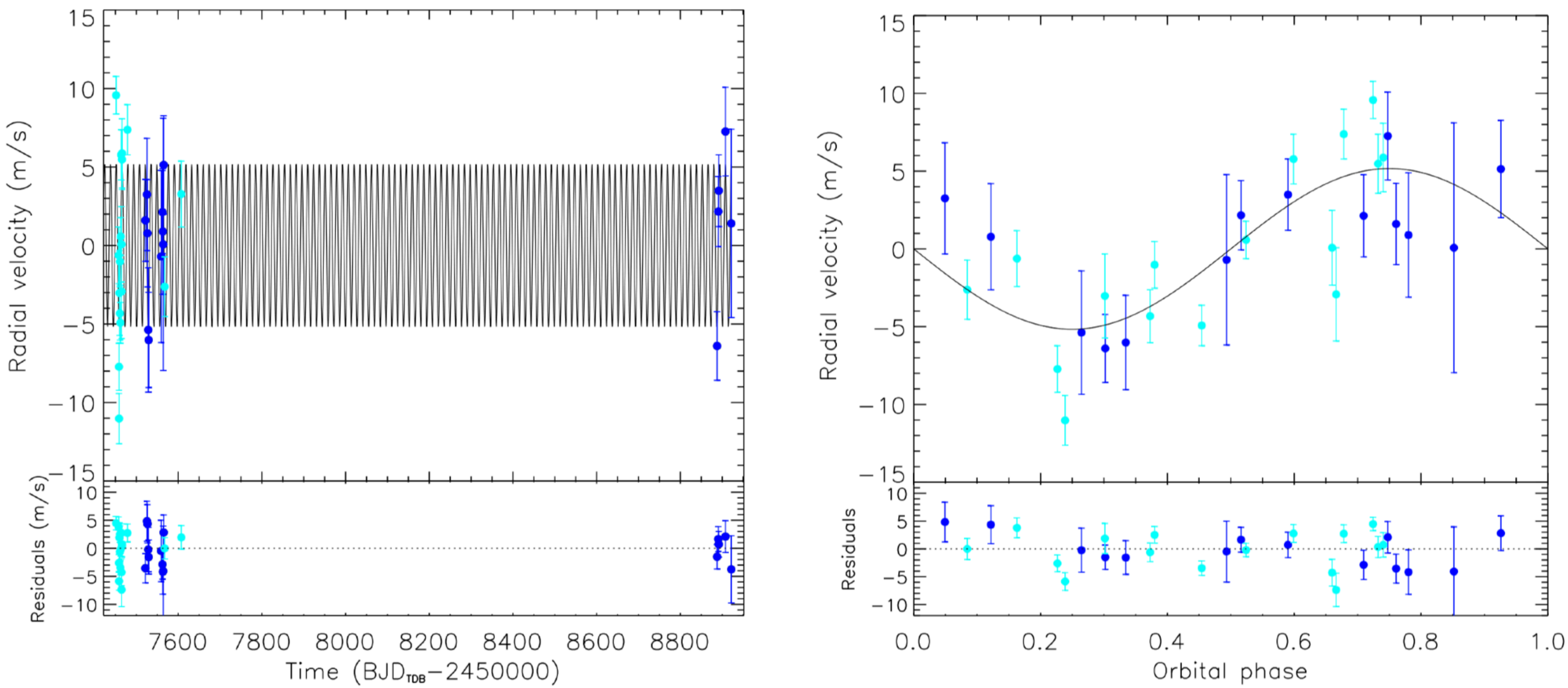
About 40 Kepler and K2 systems were monitored to i) determine the masses/densities of the small transiting planets and ii) search for outer cold Jupiters.

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

Bonomo et al. 2023

K2-110

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



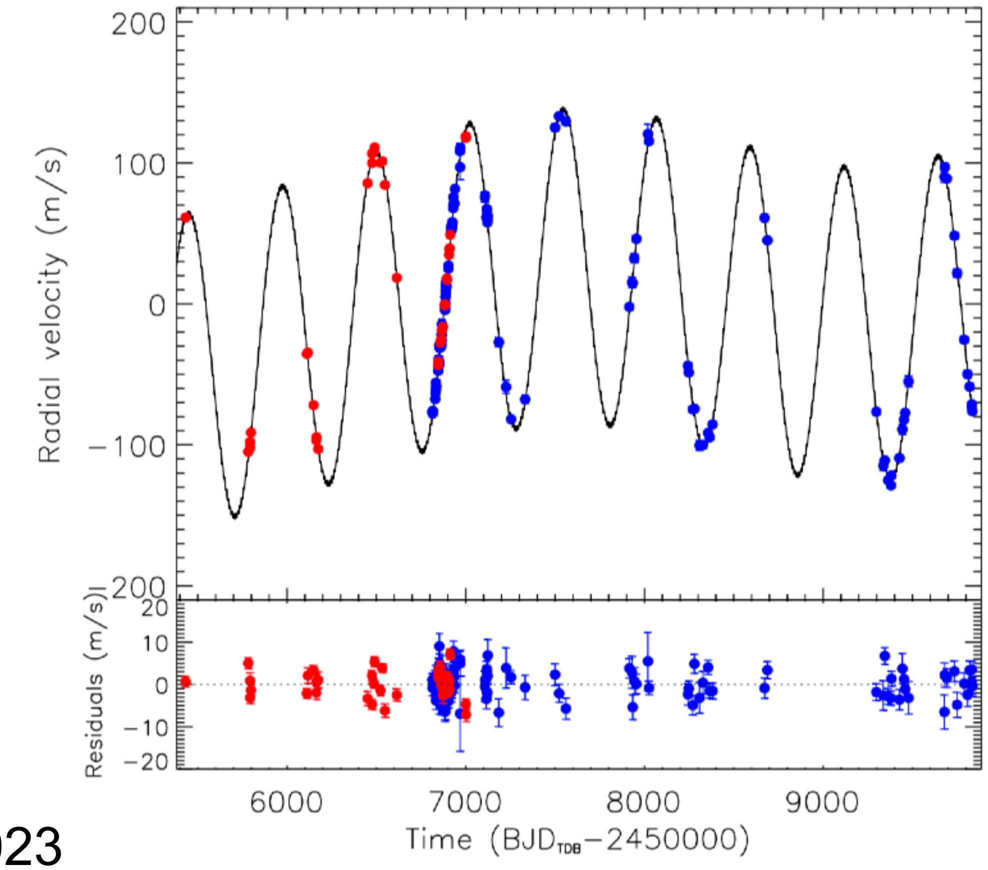
Blue circles: HARPS-N data; Light blue circles: HARPS data

The HARPS-N/GTO (2012-2022) radial-velocity survey

Two cold Jupiters in the Kepler-454 system

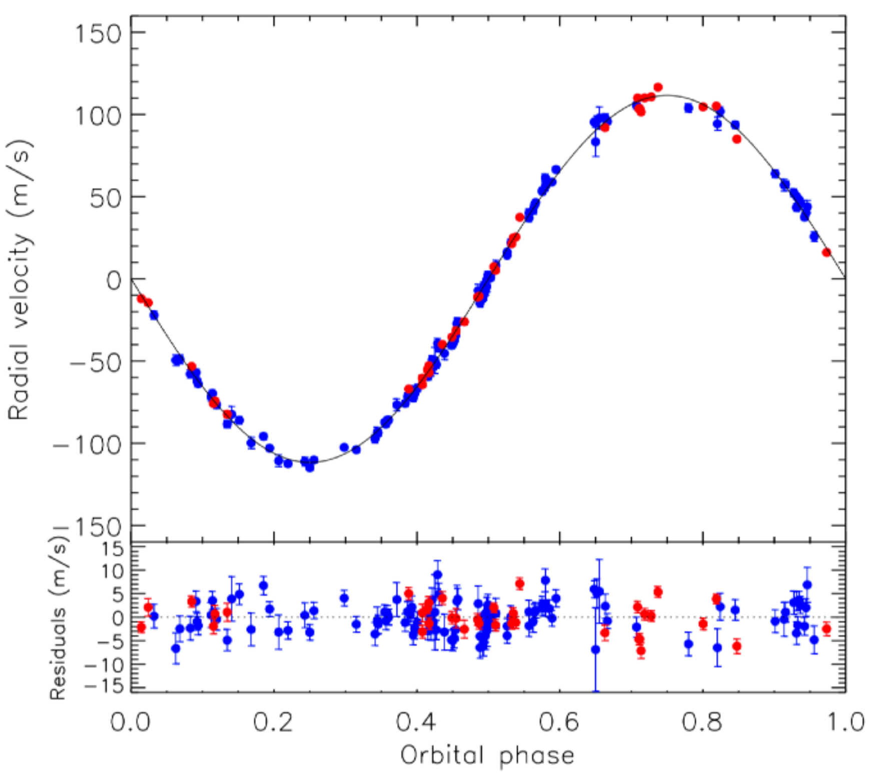
Kepler-454

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

Bonomo et al. 2023

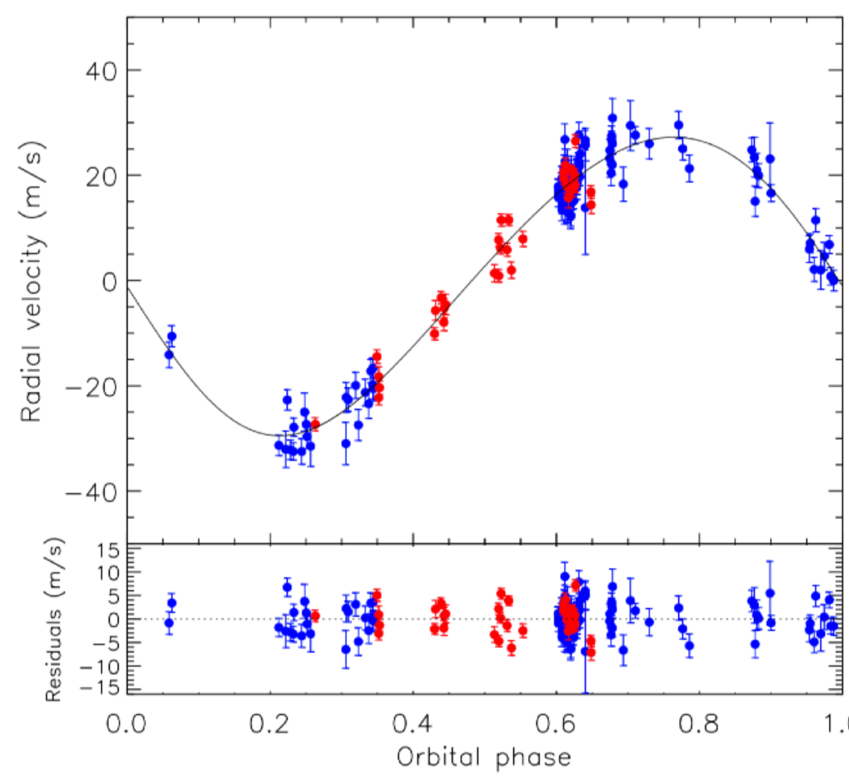


P_c = 524 d

a_c = 1.3 AU

e_c < 0.005

M_c = 4.51 M_{Jup}



P_d = 4070 d

a_d = 5.1 AU

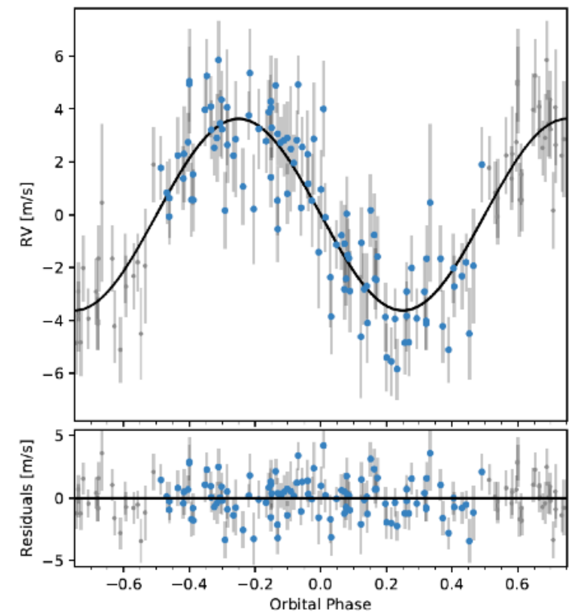
e_d = 0.09

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

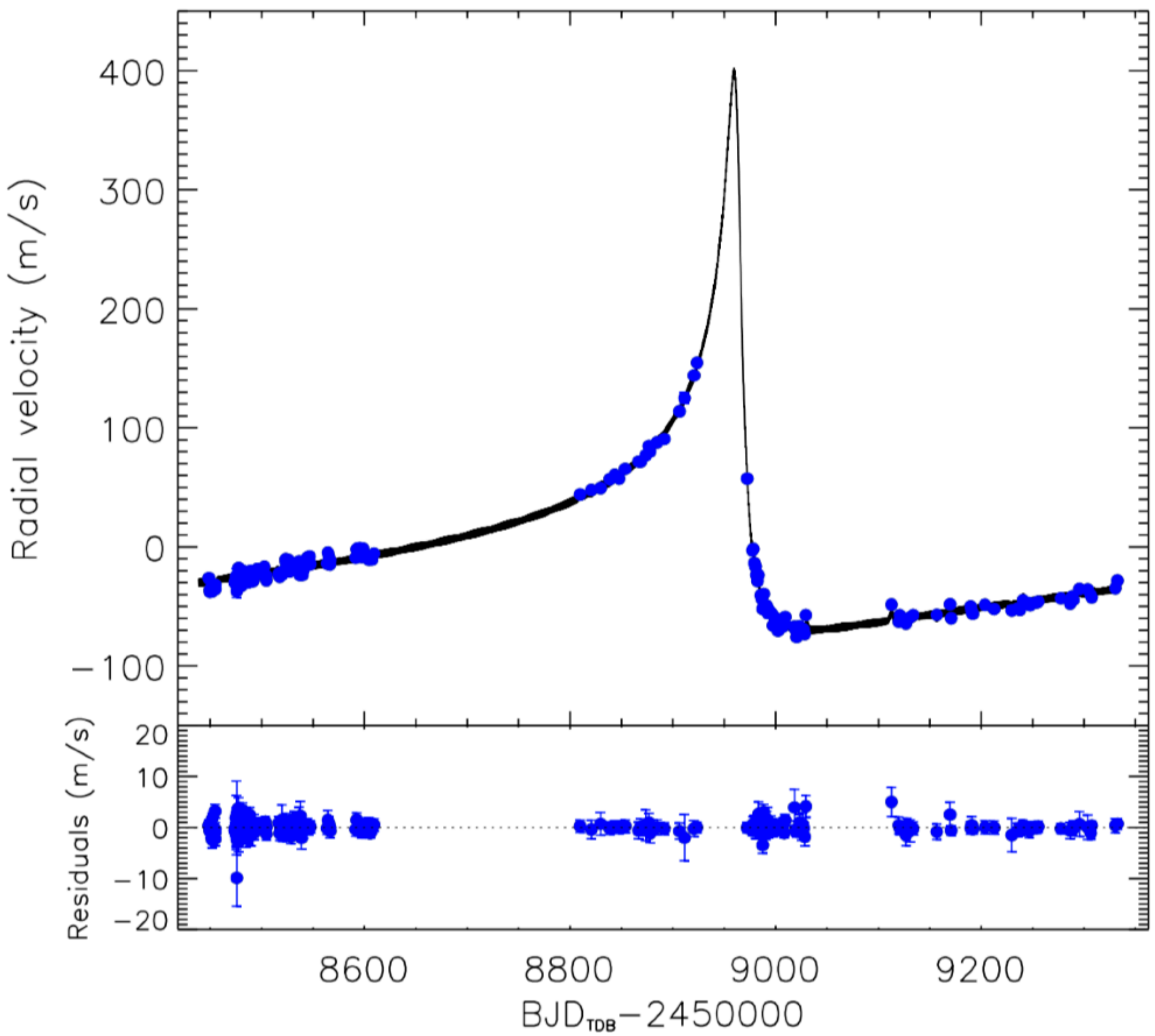
K2-312

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

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).

Independent confirmations of our results by Van Zandt+2023 (TESS-Keck survey, ~35 systems) and Weiss+2024 (Kepler-Keck survey, ~60 systems)

The crucial role of Gaia and GaiaNIR

- A few thousands (Gaia DR4) to several thousands (Gaia DR5) of CJs at intermediate separations (1-5 AU) will be found by Gaia (e.g., Sozzetti+2014, Perryman+2014, Sozzetti+2018).

- GaiaNIR, possibly in combination with Gaia, will play a crucial role to find CJs at larger separations (5-10 AU), where the RV sensitivity decreases substantially.

- For comparison, homogeneous RV surveys are limited to the detection of ~40-100 CJs (e.g., Wittenmyer+2020, Rosenthal+2022)

The crucial role of Gaia and GaiaNIR - Perspectives

- Bigger sample of transiting systems with sensitivity to the presence of CJs (including brighter host stars found by PLATO, see Nascimbeni's talk) ➪ more accurate and precise $f_{CJ|SP}$

- More accurate and precise f_{CJ} to be compared with $f_{CJ|SP}$ and thus distinguish between the different theoretical predictions (SP vs CJ anti-correlation or no correlation)

- True masses of CJs previously found with RVs (see Pinamonti's talk)

- More in-depth studies of $f_{CJ|SP}$ as a function of

  - *small planet composition* (icy vs rocky/dry planets) to possibly distinguish between different formation scenarios (Izidoro+2015, Lambrechts+2019, Schleker+2021)

  - *small planet multiplicity*: CJs should be even rarer in multiple systems than in single systems

  - *giant planet multiplicity*: systems with multiple CJs should even more rarely host inner small planets (stronger dynamical barrier and/or reduction of inward pebble flux).