INAF - Osservatorio Astrofisico di Torino

Structure and evolution of transiting giant planets: a Bayesian homogeneous determination of orbital and physical parameters

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Why a homogeneous determination of orbital and physical parameters of transiting giant planets?

- Eccentricities often fixed to zero in the discovery papers when found with low significance. However, in this way no uncertainties are provided and in some cases small but significant eccentricities can not be excluded

- RV data of some systems obtained with different instruments have never been combined to improve the orbital solution

- Jitter terms often not taken into account in the orbital fit ➪ underestimation of eccentricity uncertainties ➪ sometimes spurious eccentricities

- Previous homogeneous studies of orbital eccentricities of giant planets included only 65 systems (Pont+11, Husnoo+12) while ~250 giant transiting planets are known today.

Our sample: 211 giant transiting planets including 45 systems observed with HARPS-N@TNG

- Choice of the targets:
  - giant planets with $M_p > 0.1\ M_{Jup}$ (WASP, HATnet, CoRoT, Kepler, etc.)
  - planets with a precision on the mass better than 30%
  - planets published before 2014
  - planets in non-compact systems

- Collection of RV data from the literature:
  - datasets with number of observations $n_{meas} \geq 4$
  - Rossiter measurements were discarded and not included in the orbital fit

- New HARPS-N data for 45 systems:
  - HARPS-N $n_{meas} \geq 6$ for each system spread over 2.5 yr
  - RV precision ~2-5 m/s (exposure times ~ 15 min)

data collected within the Global Architecture of Planetary System (GAPS) consortium (80 nights/yr with HARPS-N during 2012-2015) with the aim of

- searching for planetary companions in wider orbits
- studying properties of giant planets (eccentricity, alignment, semi-major axis) in single and multiple systems (aiming at extending the investigation of Knutson+14)
- improving orbital parameters

Homogeneous determination of orbital and physical parameters through Bayesian analysis of RV data

- DE-MCMC (differential evolution Markov chain Monte Carlo) technique, that is the MCMC version of the DE genetic algorithm (e.g., TerBraak 2006, Eastman et al. 2013), to derive the posterior distributions of orbital parameters. The DE-MCMC guarantees optimal exploration of the parameter space and fast convergence through the automatic choice of step scales and orientations to sample the posterior distributions

- Free parameters: T_0, P, $e\cos\omega$, $e\sin\omega$, K, slope, and RV zero points V_r and jitter terms for each dataset ➪ up to 16 free parameters for the maximum number of datasets (5)

- Priors:

- gaussian on T_0 and P from photometry (most updated ephemeris from TEPCat)
- gaussian on occultation times from the ground and/or from space (e.g., Spitzer)
- uniform on V_r, e, and K
- modified Jeffrey's priors on jitter terms

- Method: a number of chains equal to twice the number of free parameters are run simultaneously; the analysis stops when convergence and well mixing of the chains are achieved according to Ford (2006): $\hat{R} < 1.01$ and $T_z > 1000$

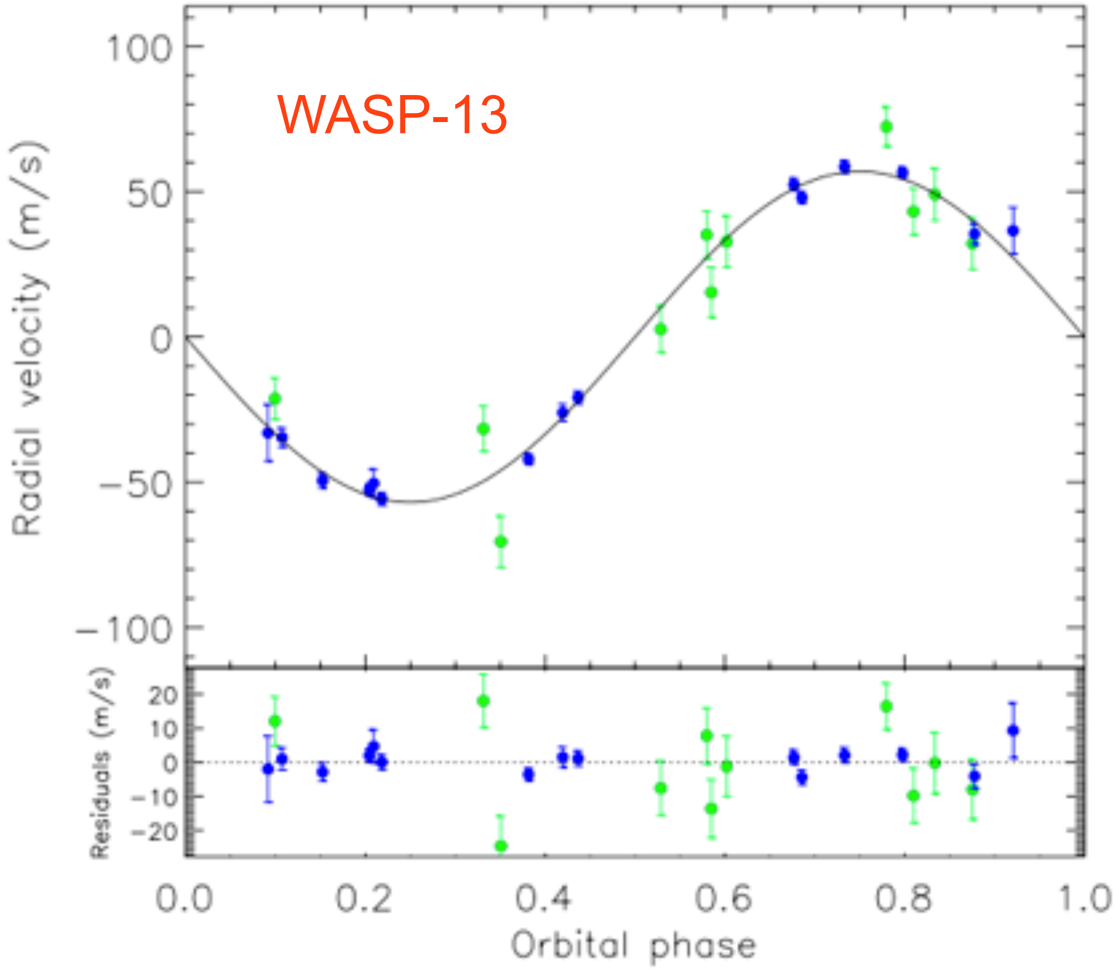
- Physical planet parameters (M_p, ρ_p, $\log g_p$) from our orbital parameters (K and e) and the most updated values of M_s, i, R_p, P taken from the literature.

First results (I): eccentricities

- Two new significant eccentricities not reported in the literature

- Four significant eccentricities in the literature consistent with *e*=0

- Uncertainties on eccentricities for a few systems observed with HARPS-N reduced by a factor of ~3-10



blue circles: HARPS-N data

green circles: literature measurements

First results (II): long-term trends and outer companions

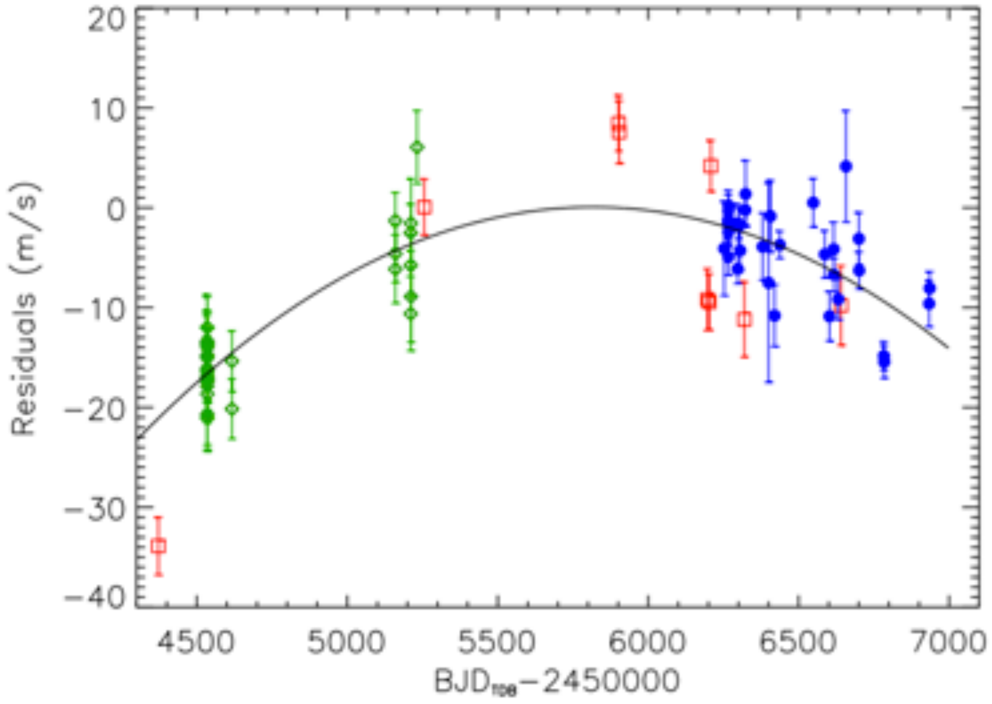
- Different or inverted slopes for three long-term trends known in the literature (curvatures due to an outer companion or activity cycles)

Ex.: XO-2N (see Damasso, Biazzo, Bonomo et al. 2015) although, unlike Knutson et al. (2014), we attribute its curvature to an activity cycle rather than a long-period companion.

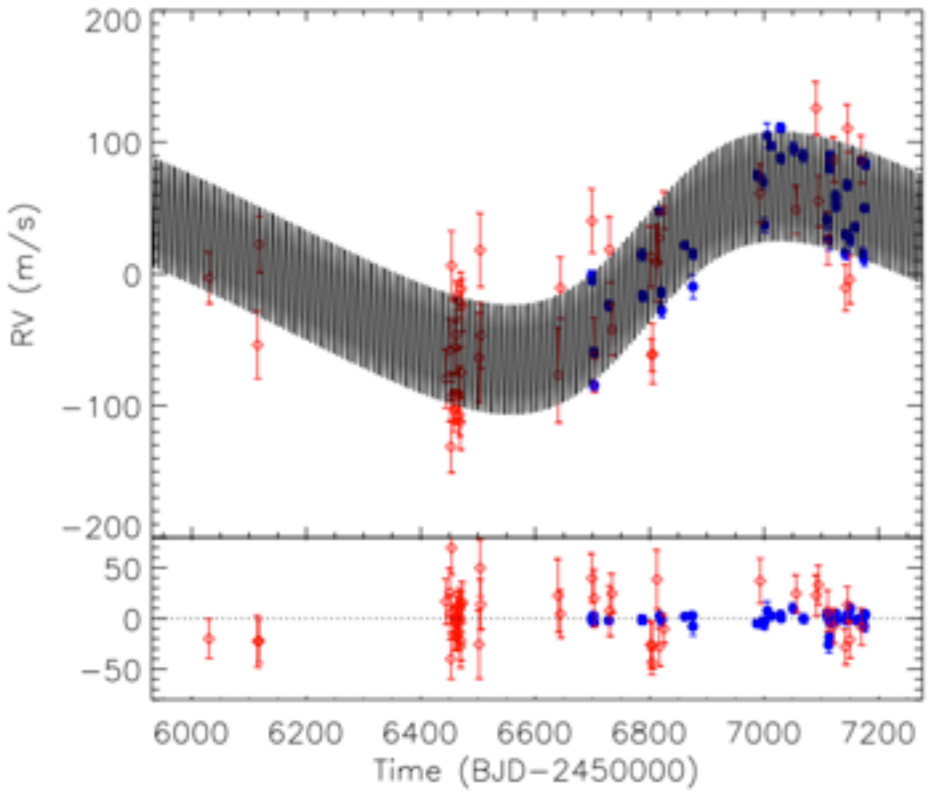
- Two long-term trends with the same slope as reported in the literature

- No slope for two long-term trends reported in the literature (still consistent with presence of trends if we are sampling the maximum of the curvature)

XO-2N curvature (Damasso+15)



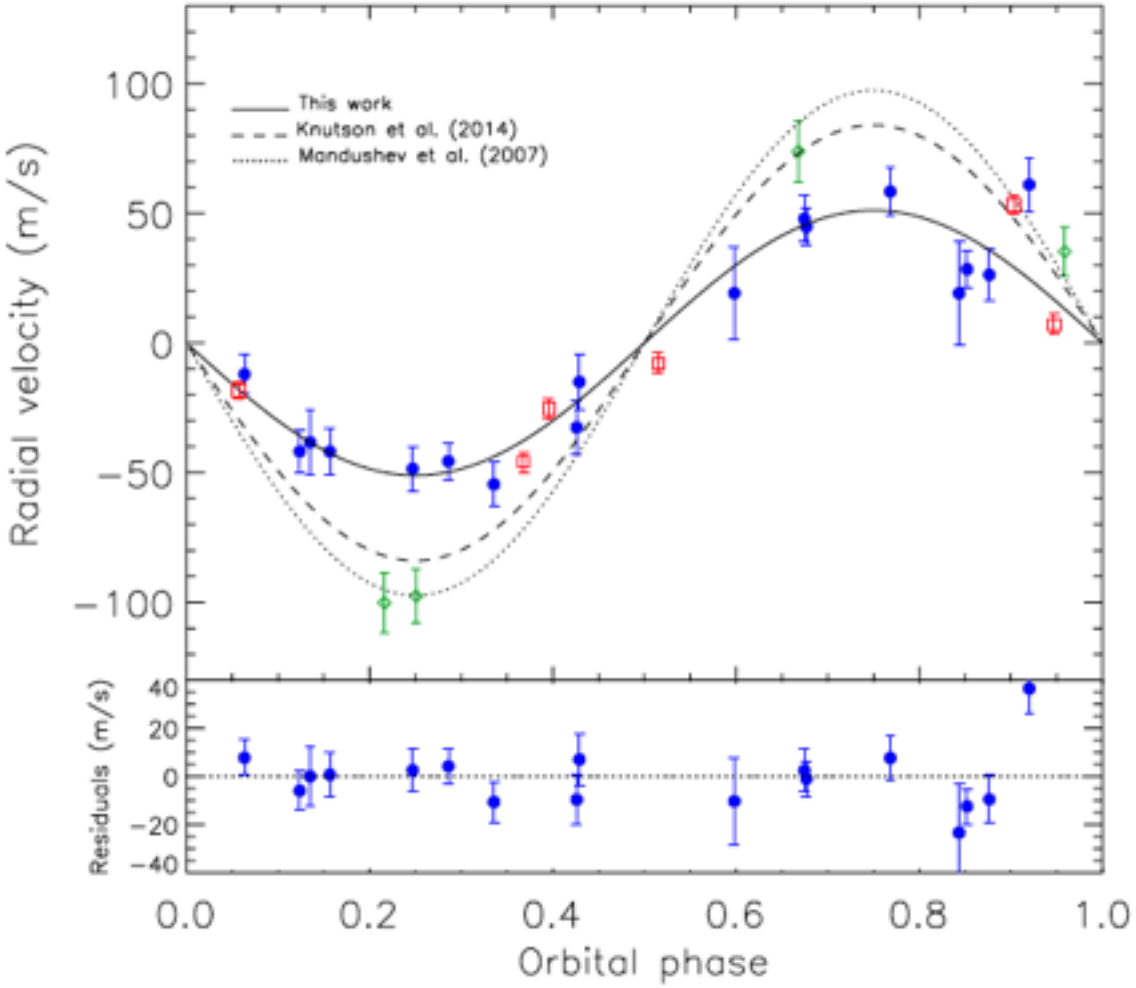
blue circles:	HARPS-N data
green diamonds:	SUBARU data
red squares:	HIRES data



- One new long-period companion characterized with a HARPS-N/TRES coordinated RV campaign (Damasso et al., in prep.)

blue circles:	HARPS-N data
red diamonds:	TRES data

A surprise:
the curious case of TrES-4b



We found a RV semi-amplitude $K=51\pm3$ m/s that is significantly lower than $K=97\pm7$ m/s reported in the literature (Sozzetti, Bonomo et al. 2015)

⇩

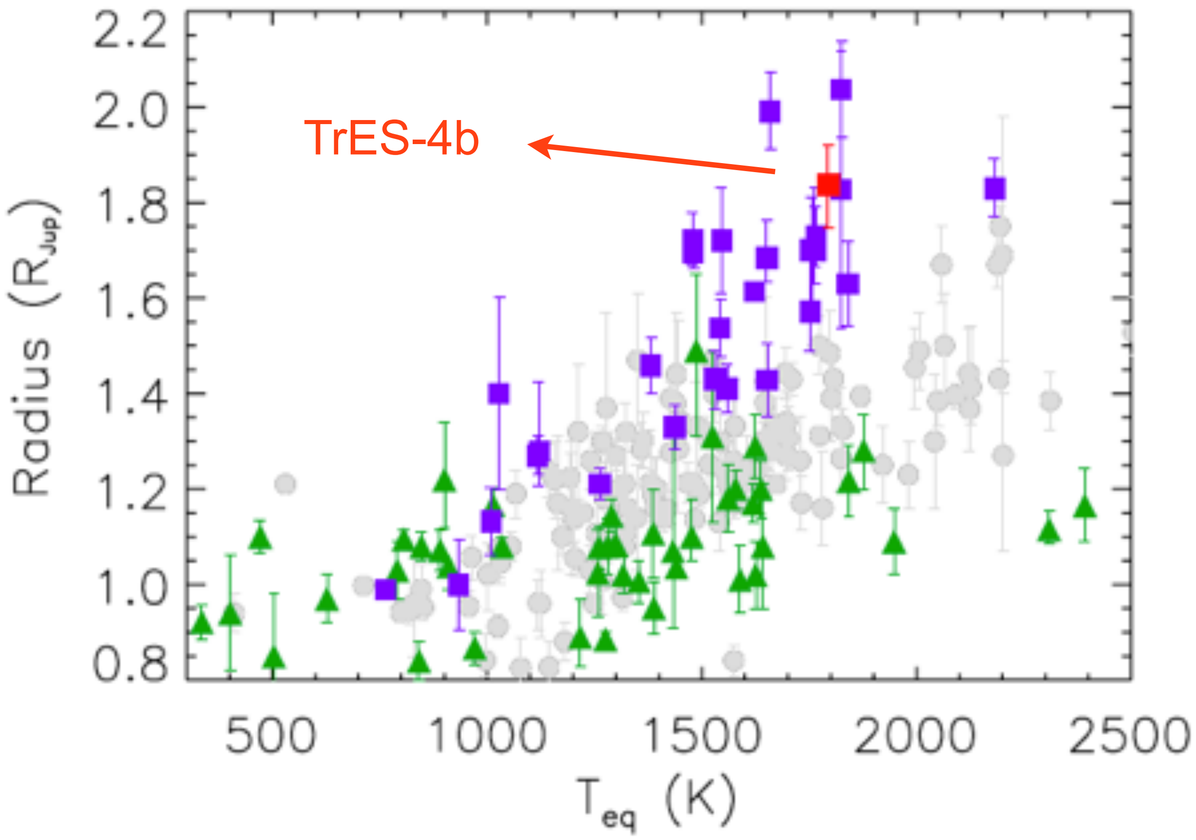
$M_p=0.494\pm0.035\ \mathrm{M_{Jup}}$ vs $M_p=0.84\pm0.10\ \mathrm{M_{Jup}}$

blue circles:	HARPS-N data (Sozzetti+15)
green diamonds:	HIRES data (Mandushev+07)
red squares:	HIRES data (Knutson+14)

The reason of the discrepancy is not clear. In any case, TrES-4b turned out to be the hot Jupiter with the second lowest-density known: $\rho_p=0.099\pm0.015$ g cm^{-3} !!

purple squares:	$\rho_p \leq 0.25$ g cm^{-3}
grey circles:	$0.25 < \rho_p < 1.50$ g cm^{-3}
green triangles:	$\rho_p \geq 1.50$ g cm^{-3}

(Sozzetti, Bonomo et al. 2015)



Tidal interactions and the orbital evolution of hot Jupiters

Close-in giant planets can not form where they are now. How do they get there?

- disk migration ➪ circular orbits and spin-orbit alignments (unless the primordial disk was misaligned)

- high-eccentricity migration [i.e. multi-body interactions involving *planet-planet scattering* or *Kozai interactions* (perturbations by an outer stellar or planetary companion in an inclined orbit), followed by tidal dissipation at periastron]

➪ circular (eccentric) orbits of short-period (long-period) planets, both spin-orbit alignments and misalignments, and $a \gtrsim 2\, a_R$

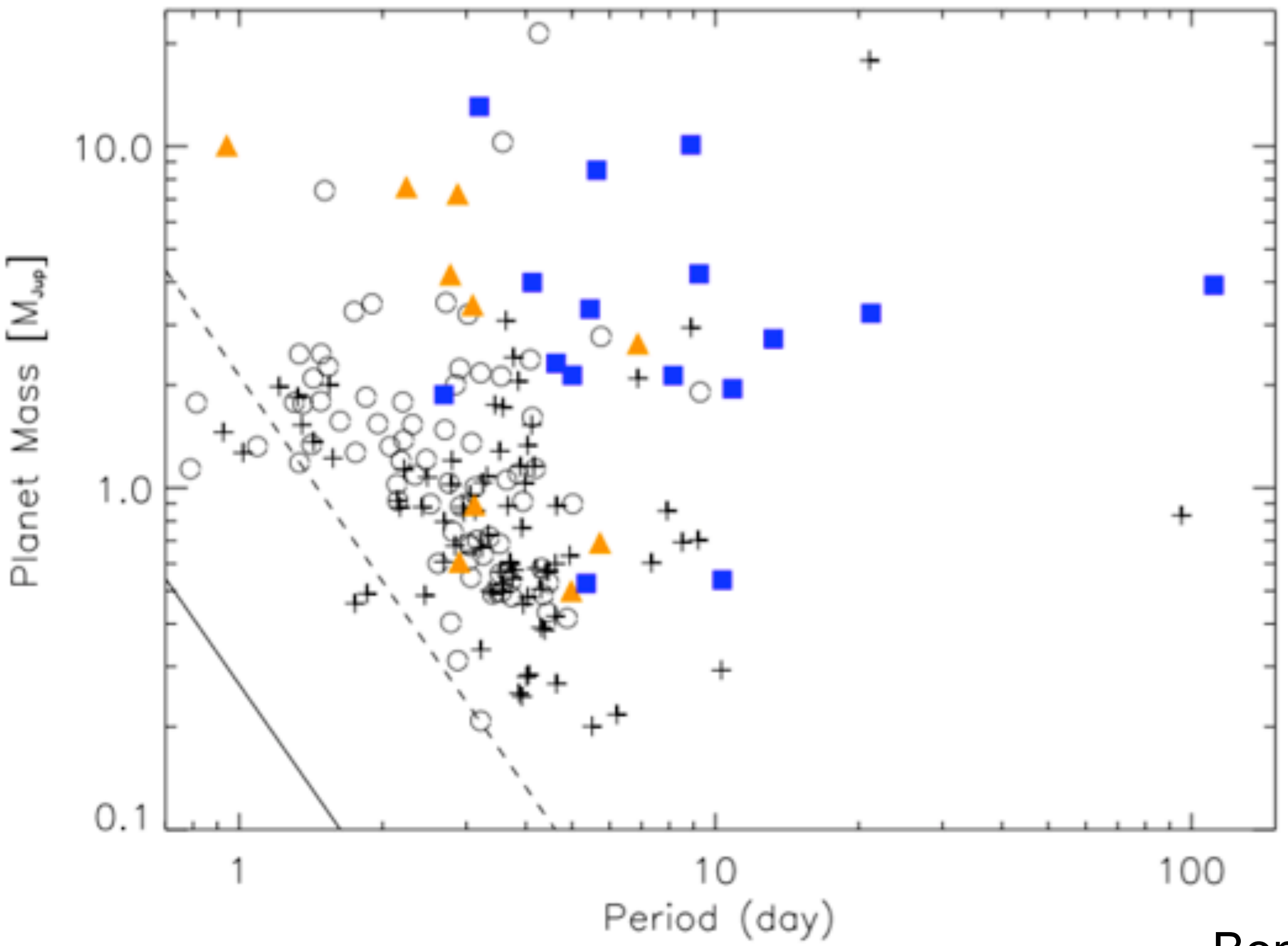
a_R is the Roche limit, i.e. the critical separation where the planet fills its Roche lobe:

$$a_R = 2.16\, R_p\, (M_s/M_p)^{1/3}$$

tidal dissipation at periastron: a↓ and e↓

See, e.g., Faber et al. (2005), Ford & Rasio (2006), Pont et al. (2011), Valsecchi & Rasio (2014)

The mass-period diagram



- empty circles: well-determined circular orbits ($\sigma_e < 0.05$)

- cross: orbits compatible with e=0 but with large uncertainties ($\sigma_e > 0.05$)

- orange triangles: $e < 0.1$

- blue squares: $e > 0.1$

- solid line: $a = a_R$

- dashed line: $a = 2\ a_R$

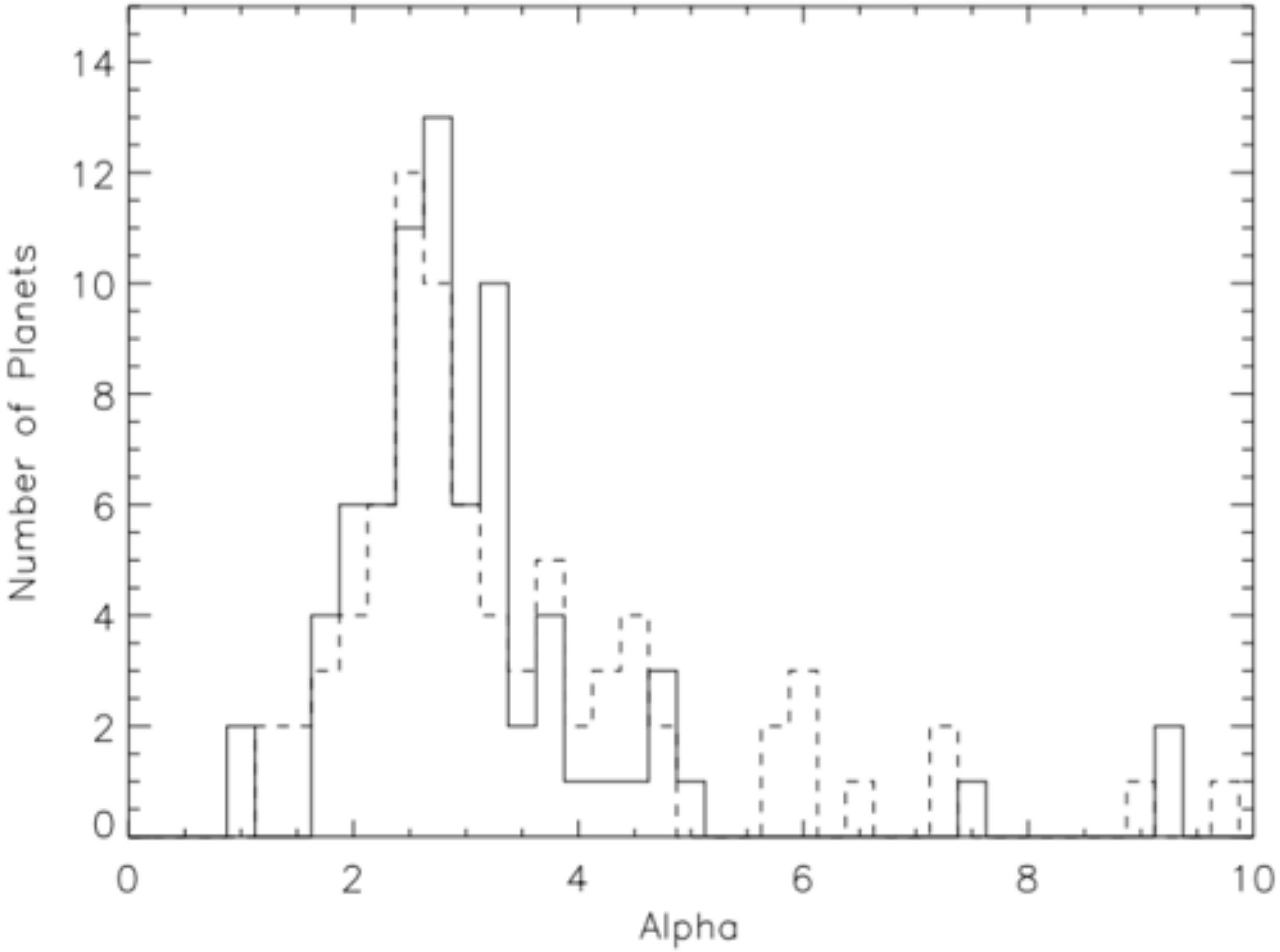
Bonomo et al., in prep.

Confirmation of previous trends seen with a much smaller sample (e.g., Pont et al. 2011):

- $M_p < 1\ M_{Jup}$: planets stop at $a \gtrsim 2\ a_R$ (circularization radius)
- $M_p \sim 1\text{-}2\ M_{Jup}$: a few planets can move closer to the host star ($a_R < a < 2\ a_R$)
- $M_p \gtrsim 4\ M_{Jup}$: dearth of close-in (circular) planets: they rise tides in the star strong enough for angular momentum exchange and tidal decay till they end up in the star.

The α distribution

Bonomo et al., in prep.



$\alpha = a / a_R$

a: semi-major axis
a_R: Roche limit

- solid line: planets with well-determined circular orbits ($\sigma_e < 0.05$)

- dashed line: planets whose orbits are compatible with e=0 but with large uncertainties ($\sigma_e > 0.05$)

The orbital radius of the vast majority of circular planets is $a \gtrsim 2\ a_R$, with a distribution which peaks at $\alpha = 2.75$.

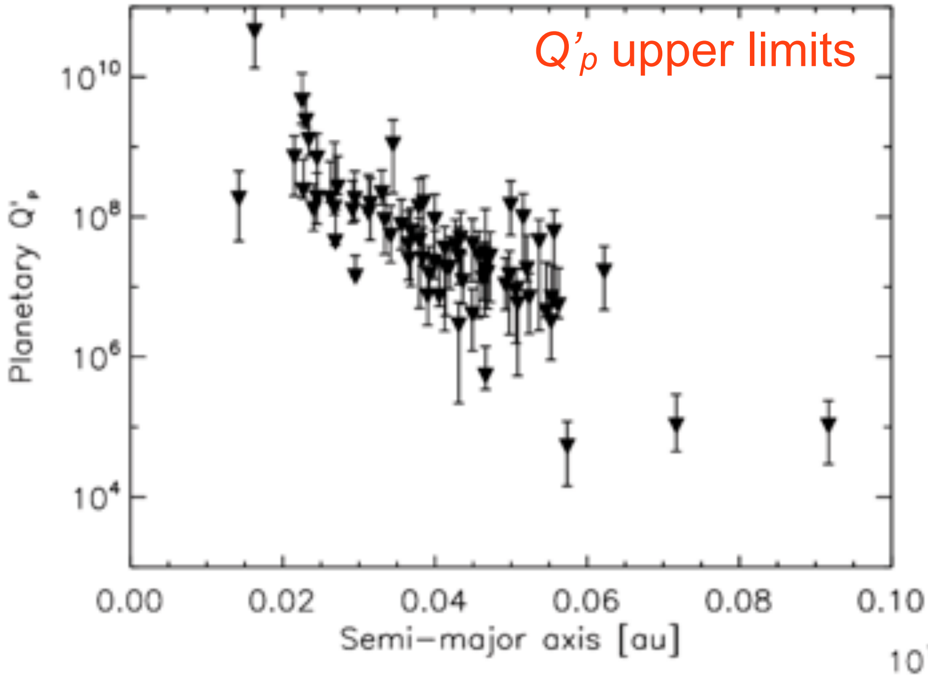
This favours the high-eccentricity migration scenario against the disk-migration scenario

Estimating planetary and stellar modified tidal quality factors

$Q'_p = 3Q / 2k_2$, where Q is the tidal quality factor and k_2 the Love number.
Q'_p is a parameterization of the response of the planet's interior to tidal perturbation. It is related to planet internal structures: the higher Q'_p, the lower the internal tidal dissipation.

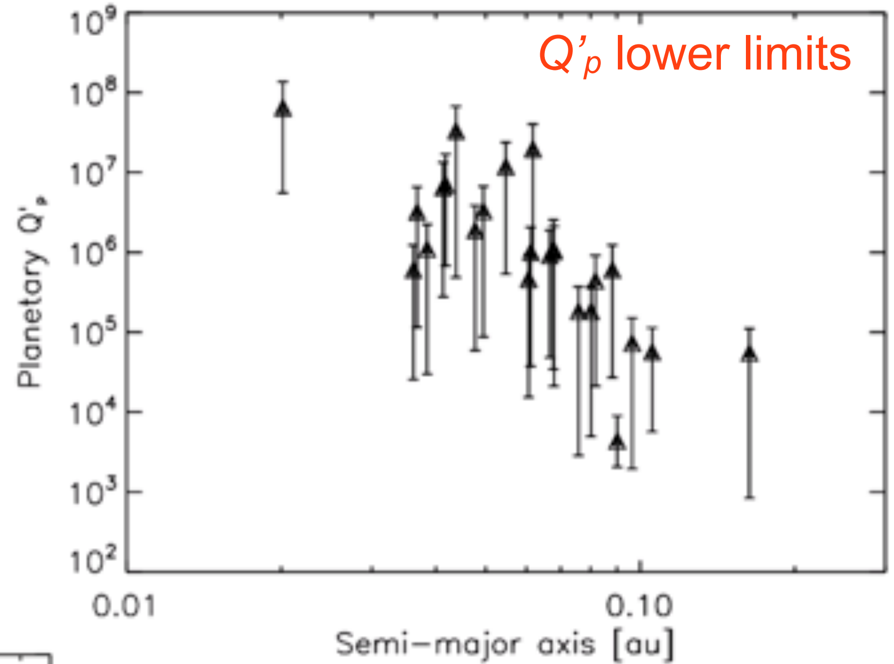
- circular orbit $\tau_{circ} < \tau_{age}$ ⇨ upper limits on Q'_p
- eccentric orbit $\tau_{circ} > \tau_{age}$ ⇨ lower limits on Q'_p & Q'_s

(see Matsumura et al. 2008)

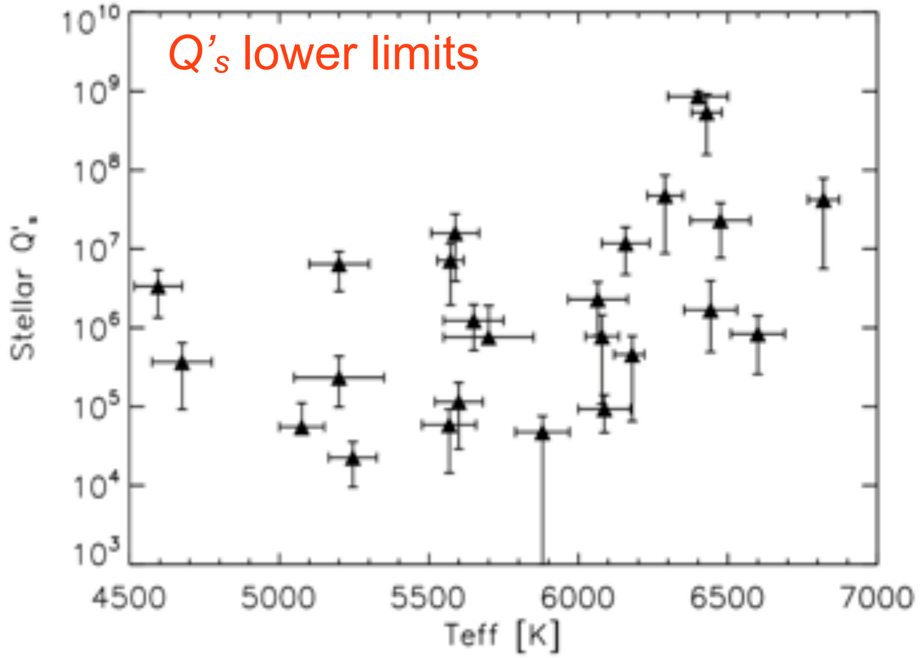


$10^4 \lesssim Q'_p \lesssim 10^9$

$Q'_p \uparrow$ for $a \downarrow$



Bonomo et al., in prep.



$Q'_s \uparrow$ for $T_{eff} \gtrsim 6200$ K

Summary and conclusions

▸ homogeneous Bayesian DE-MCMC determination of orbital and physical parameters of 211 giant planets including 45 systems observed with HARPS-N@TNG

▸ orbital eccentricities: two new significant eccentricity; four significant eccentricities reported in the literature consistent with $e=0$; uncertainties in some cases reduced by a factor of 3-10

▸ trend/companions: 1 new long-period planet, 3 trends with different/inverted slopes, no slope for 2 reported trends (still compatible with curvature)

▸ mass-period diagram and $\alpha=a/a_R$ distribution favour the high-eccentricity migration scenario rather than the disk-migration scenario

▸ new upper and lower limits to Q'_p and Q'_s : low tidal dissipation rates (high Q'_p) are required to explain the closest hot Jupiters

▸ ~33% (~12%) of eccentric (clearly circular) giant planets in our sample have an outer companion detected in RVs

Perspectives

▸ continuation of HARPS-N RV monitoring to unveil long-term trends and characterize outer companions

▸ properties of giant planets (eccentricity, alignment, semi-major axis) in single and multiple systems, by taking detection limits into account and extending the investigation of Knutson+14