Hot Jupiters, cold kinematics:

High phase space densities of host stars reflect an age bias

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ABSTRACT

Context. The birth environments of planetary systems are thought to influence planet formation and orbital evolution through external photoevaporation and stellar flybys. Recent work has claimed observational support for this, in the form of a correlation between the properties of planetary systems and the local Galactic phase space density of the host star. In particular, hot Jupiters are overwhelmingly present around stars in regions of high phase space density, which may reflect a formation environment with high stellar density.

Aims. We aim to investigate whether the high phase space density may have a Galactic kinematic origin: hot Jupiter hosts may be biased towards being young and therefore kinematically cold, because tidal inspiral leads to the destruction of the planets on gigayear timescales, and the velocity dispersion of stars in the Galaxy increases on similar timescales.

Methods. We used 6D positions and kinematics from *Gaia* for the hot Jupiter hosts and their neighbours, and we constructed distributions of the phase space density. We investigated correlations between the stars' local phase space density and peculiar velocity.

Results. We find a strong anti-correlation between the phase space density and the host star's peculiar velocity with respect to the Local Standard of Rest. Therefore, most stars in 'high-density' regions are kinematically cold, which may be caused by the aforementioned bias towards detecting hot Jupiters around young stars before the planets' tidal destruction.

Conclusions. We do not find evidence in the data for hot Jupiter hosts preferentially being in phase space overdensities compared to other stars of similar kinematics, nor therefore for their originating in birth environments of high stellar density.

Key words. Planetary systems — open clusters and associations — Planet–star interactions — Stars: kinematics and dynamics — Galaxy: disc — Solar neighbourhood

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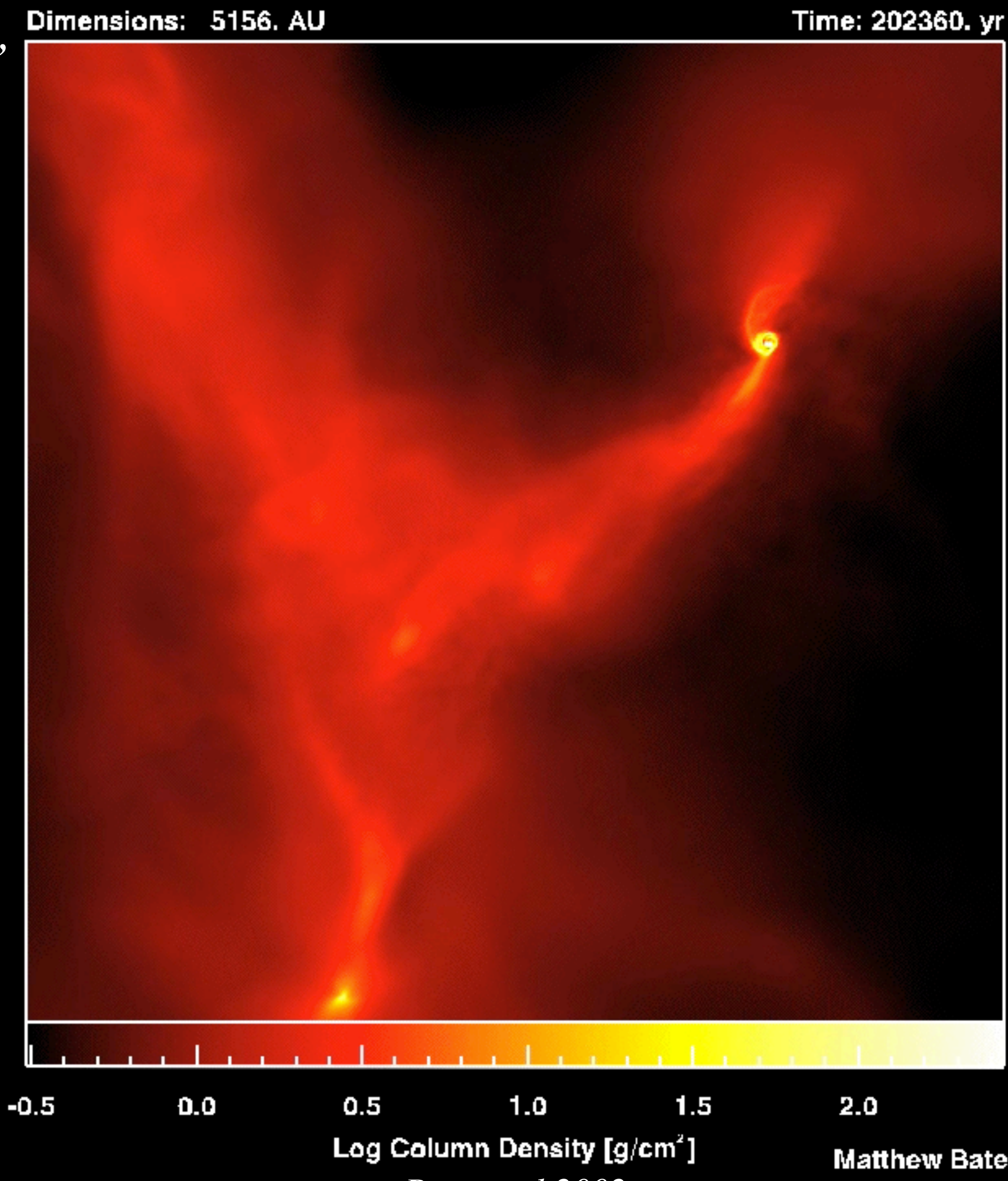
Observed planetary systems depend on the host stars' properties

- Stellar metallicity and heavy element composition sets amount and composition of material available for planet formation (*cf*. Vardan Adibekyan's talk, Tom Wilson's talk)
- Planetary systems can change as stars age (*cf*. Andrea Bonfanti's talk)
- Different stars form in regions of different density, and planet formation and system evolution can be affected by this

Stellar birth environment is expected to have an impact on forming planetary systems

- Dynamical effects of flybys/encounters (see, *e.g.*, de la Fuente Marcos & de la Fuente Marcos 1997, Laughlin & Adams 1998, Malmberg *et al*. 2007, Li, Mustill & Davies 2019, 2020a,b):
  - Truncating discs
  - Unbinding planets
  - Pumping up eccentricities/inclinations of planets
  - Capture of planets from other stars
  - Exchange into binaries
- Photoevaporation from nearby massive stars (see, *e.g.*, Winter *et al*. 2018)
  - Truncation of disc lifetime
- **These effects should be more significant for denser formation environments (*e.g.,* massive clusters *versus* loose associations)**



Bate et al 2002

Can we directly observe the impact of formation environment on planetary systems?

- Most stars leave their birth environment on timescales of 10s–100s Myr and disperse into the Galactic field
- Young stars pose a challenge for planet searches because of their high activity (but note a few discoveries, *e.g.*, via ZEIT [K2] and THYME [TESS] surveys, TOI-2076 [Hugh Osborn's talk])
- Observation of older open clusters suggests Hot Jupiters may be more common around open cluster stars than field stars
  - M67 (~4–5 Gyr): Brucalassi *et al*. 2016
  - Præsepe (~600 Myr): Quinn *et al*. 2012
- But in general, statistics are not great

Stellar clustering shapes the architecture of planetary systems

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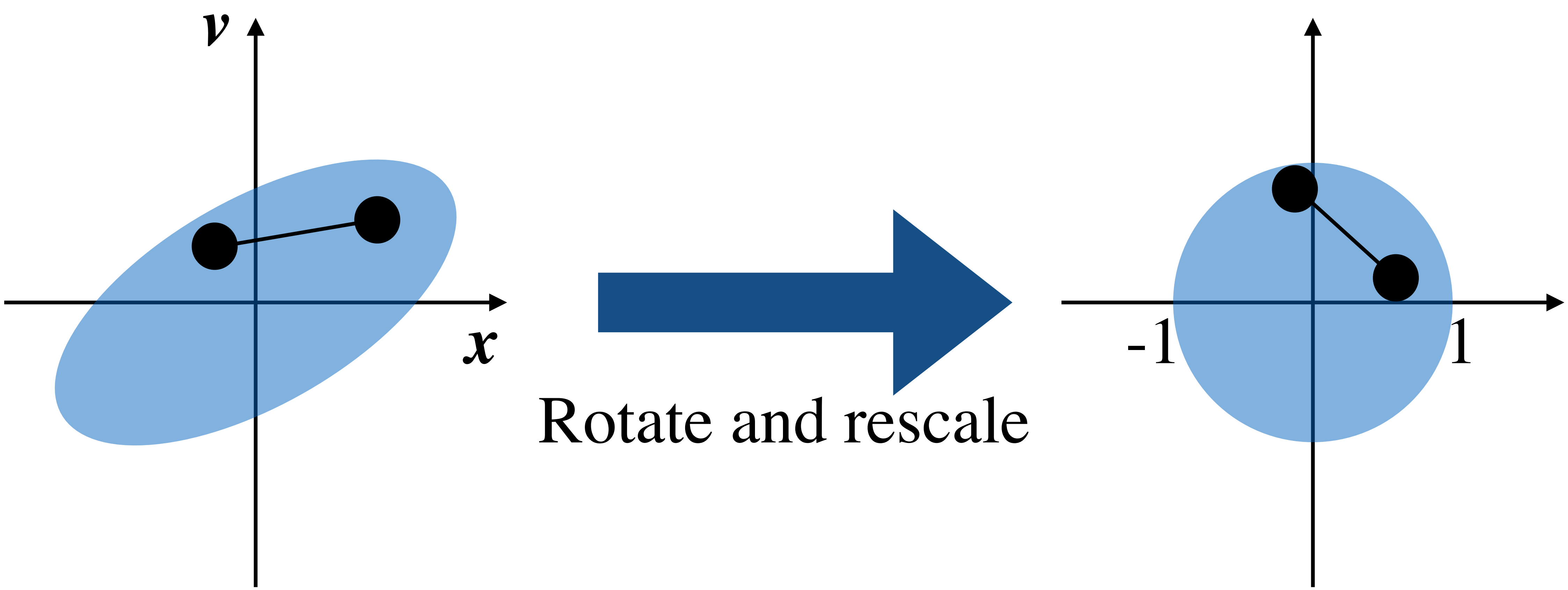
Planet formation is generally described in terms of a system containing the host star and a protoplanetary disk[1–3], of which the internal properties (for example, mass and metallicity) determine the properties of the resulting planetary system[4]. However, (proto)planetary systems are predicted[5,6] and observed[7,8] to be affected by the spatially clustered stellar formation environment, through either dynamical star–star interactions or external photoevaporation by nearby massive stars[9]. It is challenging to quantify how the architecture of planetary sysems is affected by these environmental processes, because stellar groups spatially disperse within less than a billion years[10], well below the ages of most known exoplanets. Here we identify old, co-moving stellar groups around exoplanet host stars in the astrometric data from the Gaia satellite[11,12] and demonstrate that the architecture of planetary systems exhibits a strong dependence on local stellar clustering in position-velocity phase space. After controlling for host stellar age, mass, metallicity and distance from the star, we obtain highly significant differences (with p values of 10^{-5} to 10^{-2}) in planetary system properties between phase space overdensities (composed of a greater number of co-moving stars than unstructured space) and the field. The median semi-major axis and orbital period of planets in phase space overdensities are 0.087 astronomical units and 9.6 days, respectively, compared to 0.81 astronomical units and 154 days, respectively, for planets around field stars. 'Hot Jupiters' (massive, short-period exoplanets) predominantly exist in stellar phase space overdensities, strongly suggesting that their extreme orbits originate from environmental perturbations rather than internal migration[13,14] or planet–planet scattering[15,16]. Our findings reveal that stellar clustering is a key factor setting the architectures of planetary systems.

Extremely interesting indirect approach! Assume present-day density relates to density at birth

Winter *et al.*, *Nature*, **586,** 528

Determining phase space density

- Stars live in the Galaxy in 6-dimensional phase space: three spatial coordinates and three velocity coordinates
- *Physical* proximity to nearby stars isn't sufficient to measure density: need to include velocity
- We have the relevant astrometric and RV data from *Gaia!*
- Use the *Mahalanobis distance*, which non-dimensionalises and normalises all 6 components

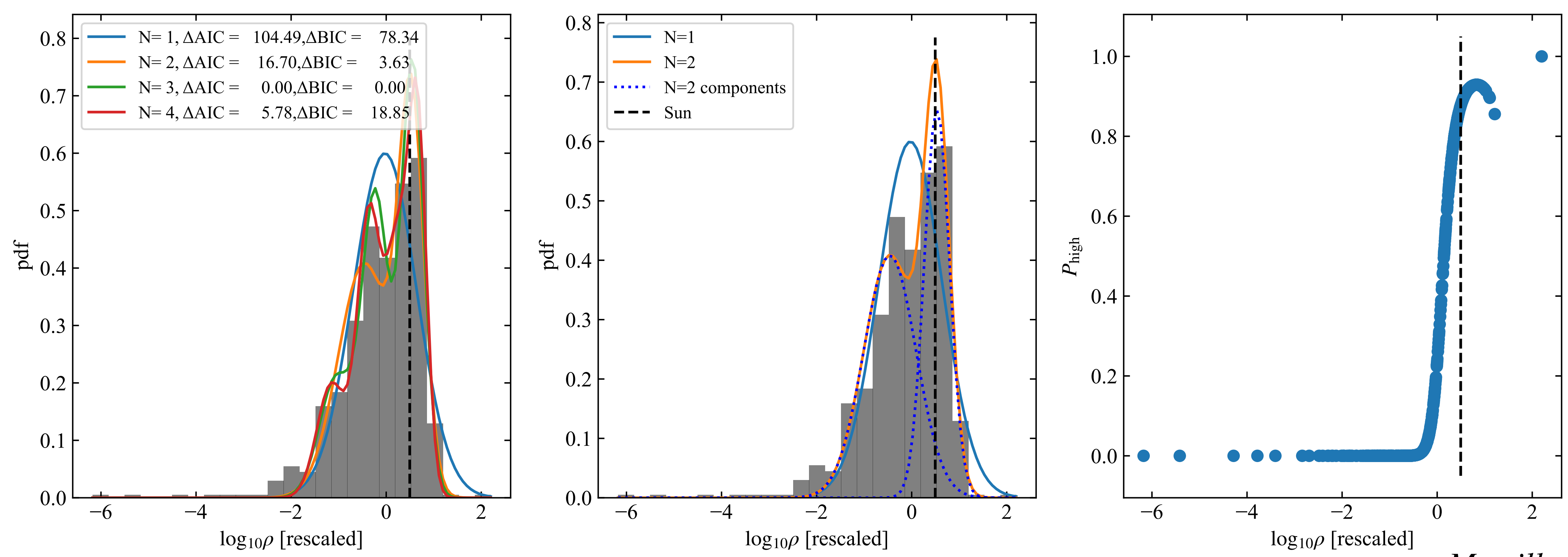


Determining phase space density

- Method of Winter *et al:* for each exoplanet host:
  - Measure the Mahalanobis distance to all other stars with 6D *Gaia* data within 40pc of the host,
  - Find the distance to the 20th nearest neighbour
  - Invert the volume of the sphere of this radius to get a local density
  - Repeat this for 600 randomly-drawn stars within 40pc of the host to get a local distribution of the density
  - Verify that it can't be fit by a single lognormal (justifying division into "field" and "overdensity") by Gaussian Mixture Modelling
  - Assign the star to the high- or low-density population, if sufficiently probable ($P > 0.84$)

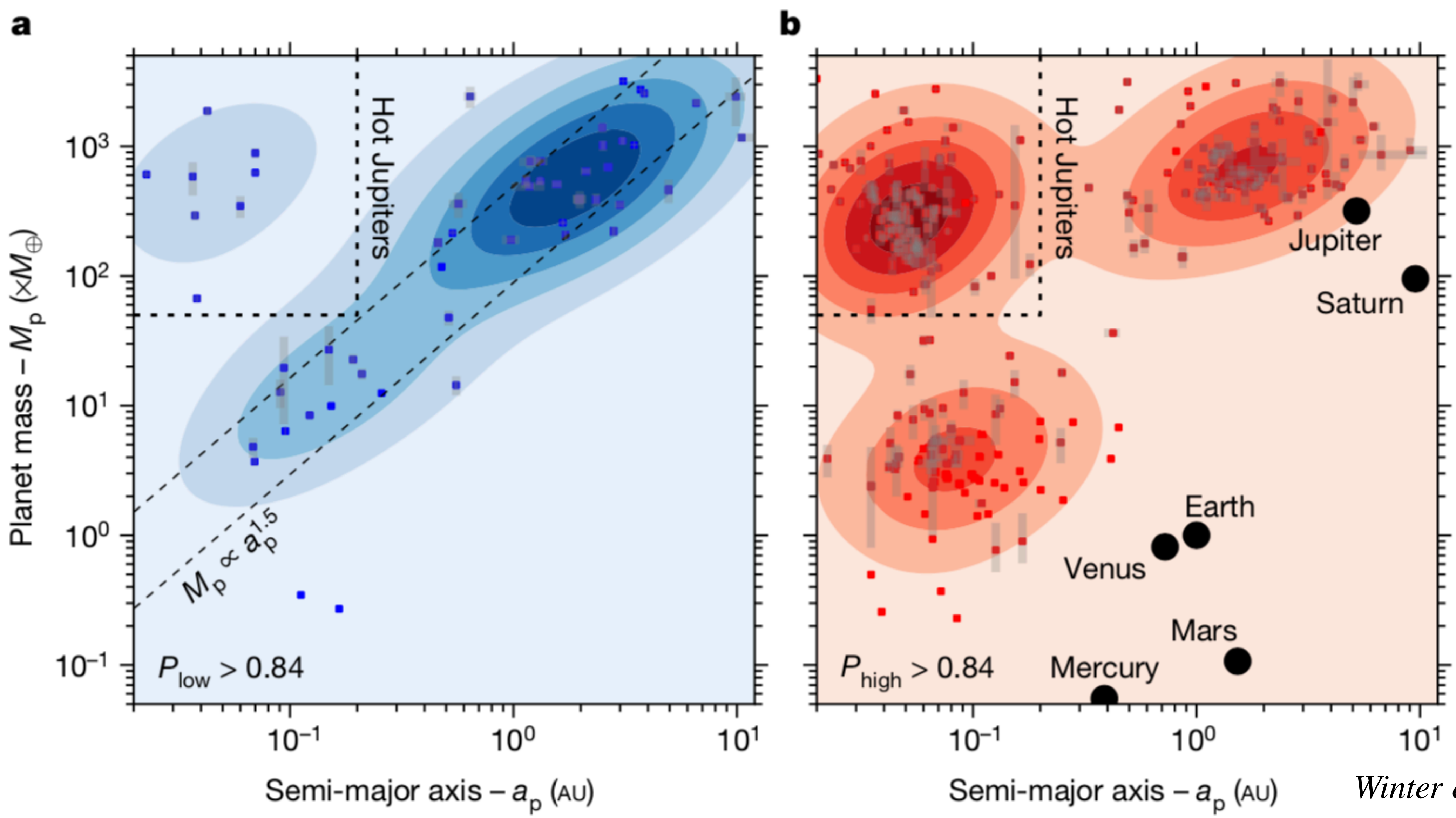
Determining phase space density

- Most distributions indeed break down into more than one population
- Actually more than two are sometimes the best fit: more a continuum than a bimodality?
- We stick to a 2-component fit



Mustill et al 2022

Winter *et al*. main result:



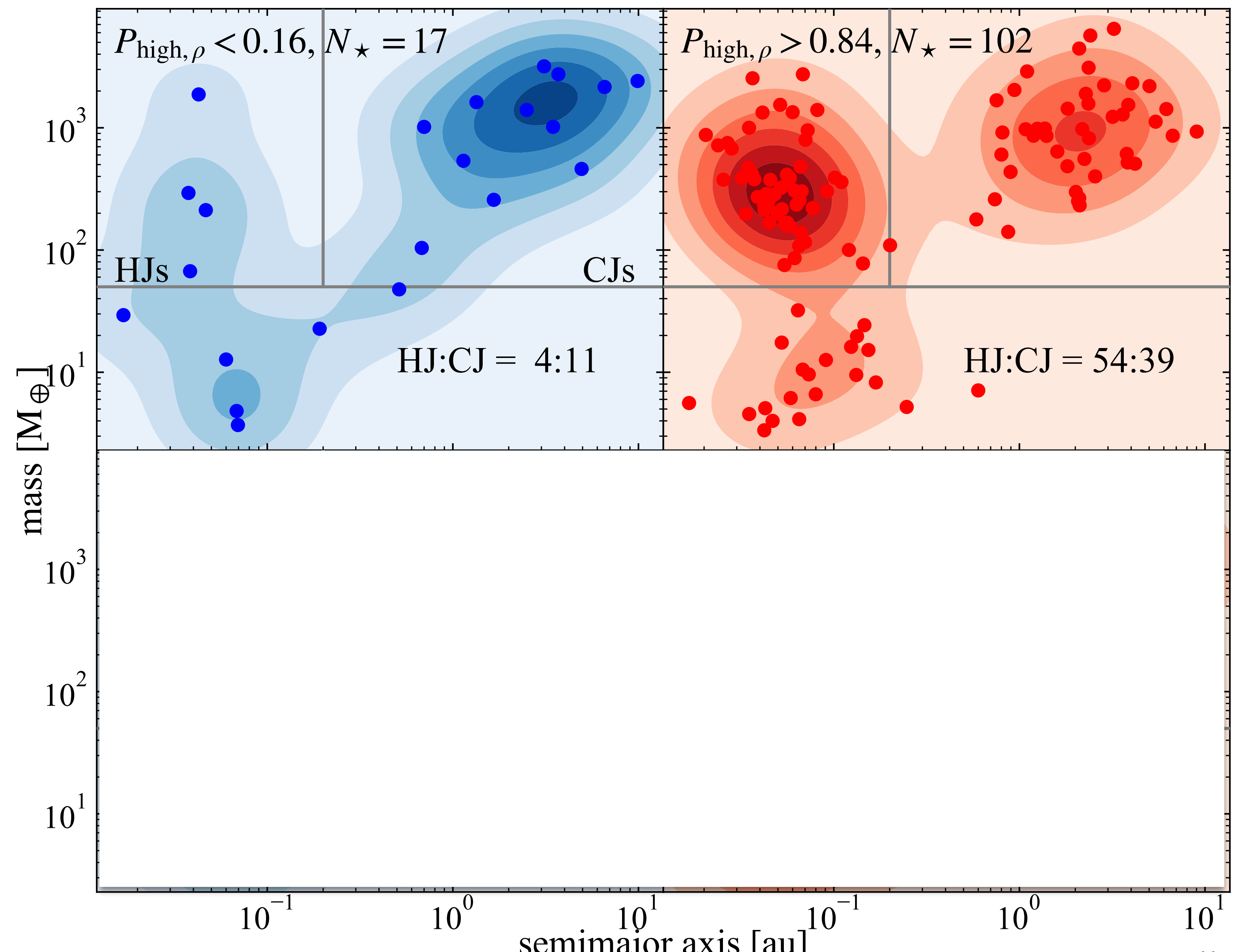
Winter et al 2020

- High-density hosts have more hot Jupiters, more close-in super-Earths, [more abundant altogether…]

We focus on explaining the Hot Jupiter difference

Reproducing Winter *et al* results

- *Gaia* EDR3 *vs* DR2; some updates to the Exoplanet Archive
- The Hot Jupiters are indeed found preferentially orbiting stars in the high-density component of phase space



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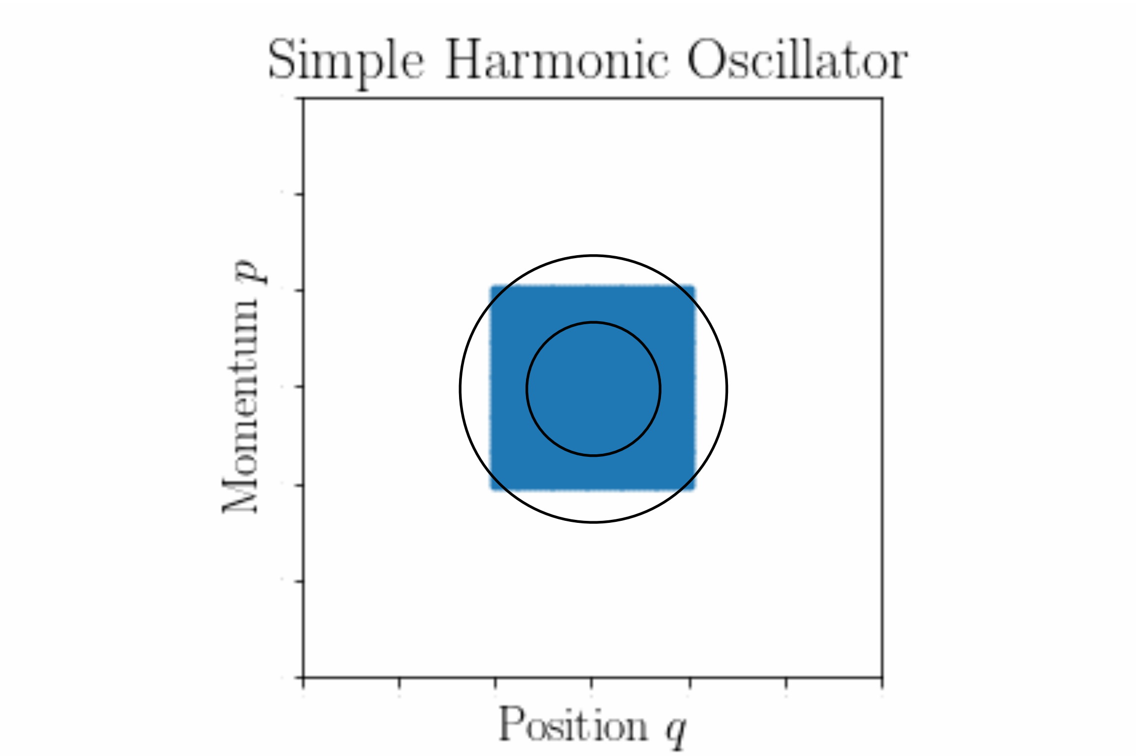
What does the phase space density mean physically?

- Interpretation 1: preserves some "memory" of the density of the formation environment
- Liouville's Theorem in Hamiltonian Mechanics says that phase space density is conserved along trajectories



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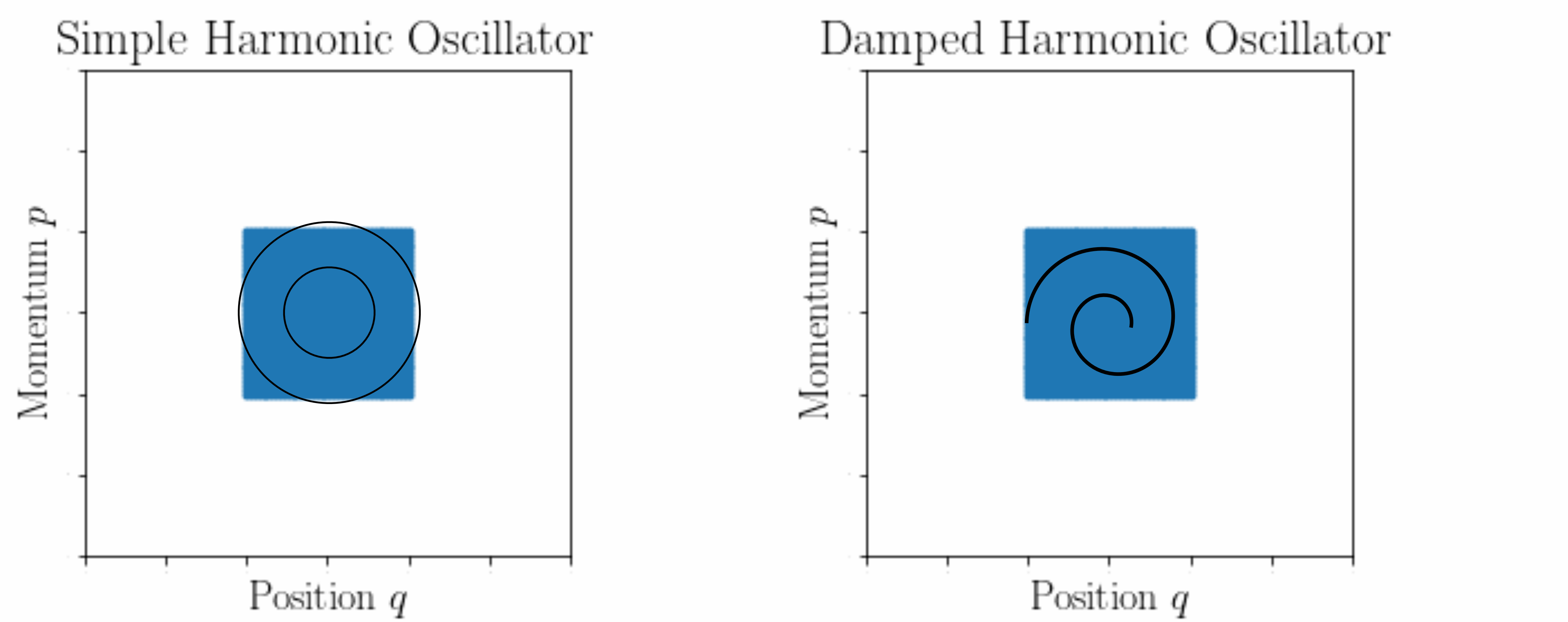
What does the phase space density mean physically?

- Interpretation 1: preserves some “memory” of the density of the formation environment
- BUT this doesn’t apply to stars in the Galaxy: the potential is time-dependent and velocities can change impulsively
- Also issues with sampling the density distribution



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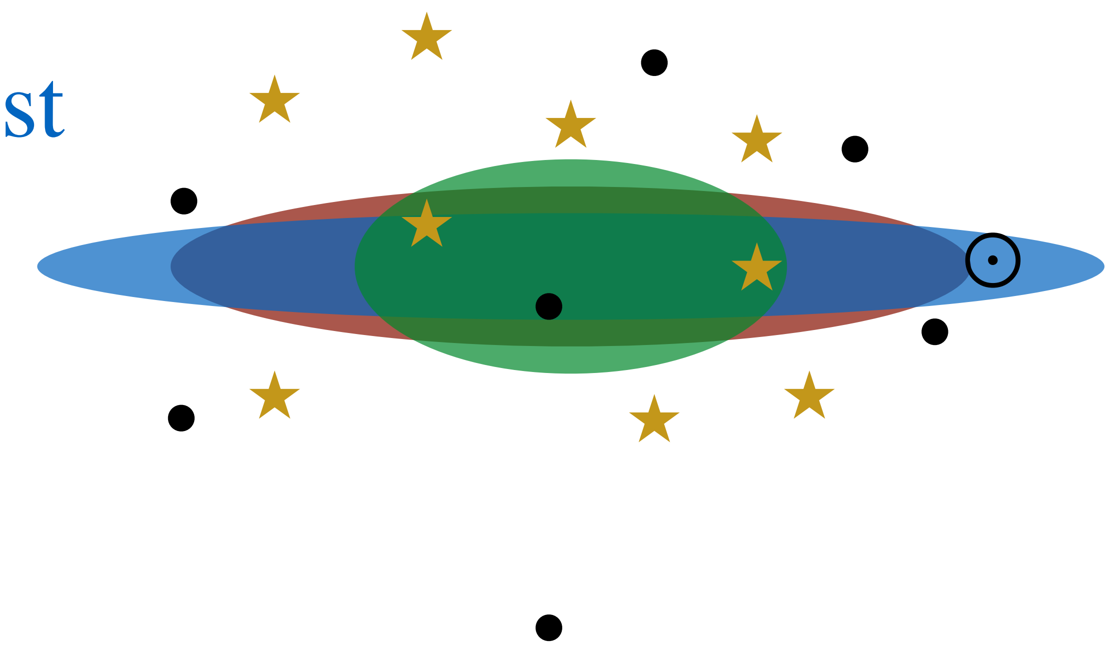
What does the phase space density mean physically?

- Interpretation 1: preserves some “memory” of the density of the formation environment
- If this interpretation is true, it suggests that Hot Jupiters overwhelmingly arise from stars in dense clusters
- This would make sense if
  - Most Hot Jupiters form through high-eccentricity migration
  - Close encounters and/or change into binaries in the dense cluster provide the necessary dynamical trigger

What does the phase space density mean physically?

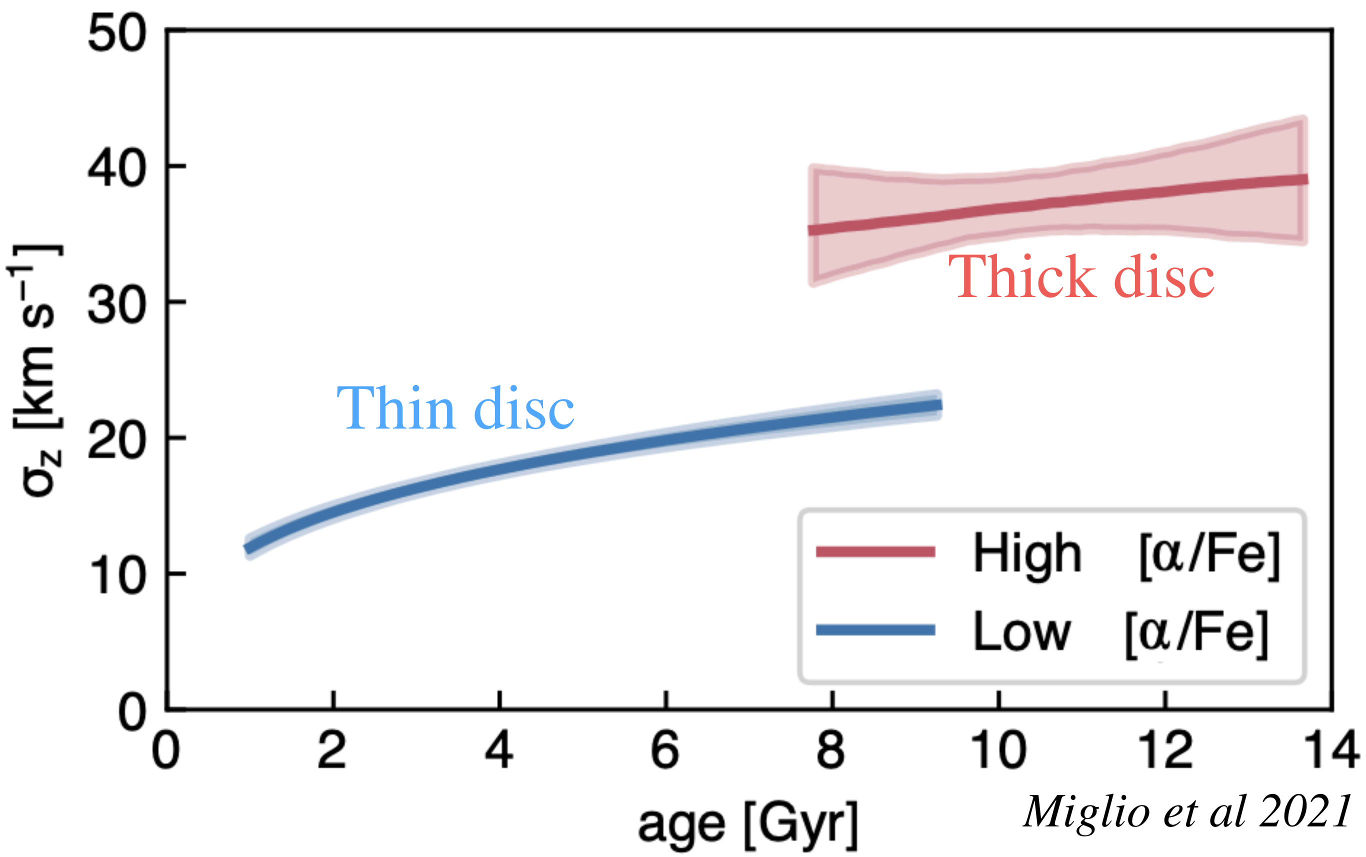
- Interpretation 2: simply relates to present-day Galactic kinematics
- Recall that the Galaxy has several components…
  - a central bar
  - a "thin disc" of stars, gas and dust
  - a "thick disc" of older stars
  - a stellar halo
  - a dark matter halo



- Most stars in the Solar neighbourhood belong to the thin disc, some to the thick disc, a few to the halo

What does the phase space density mean physically?

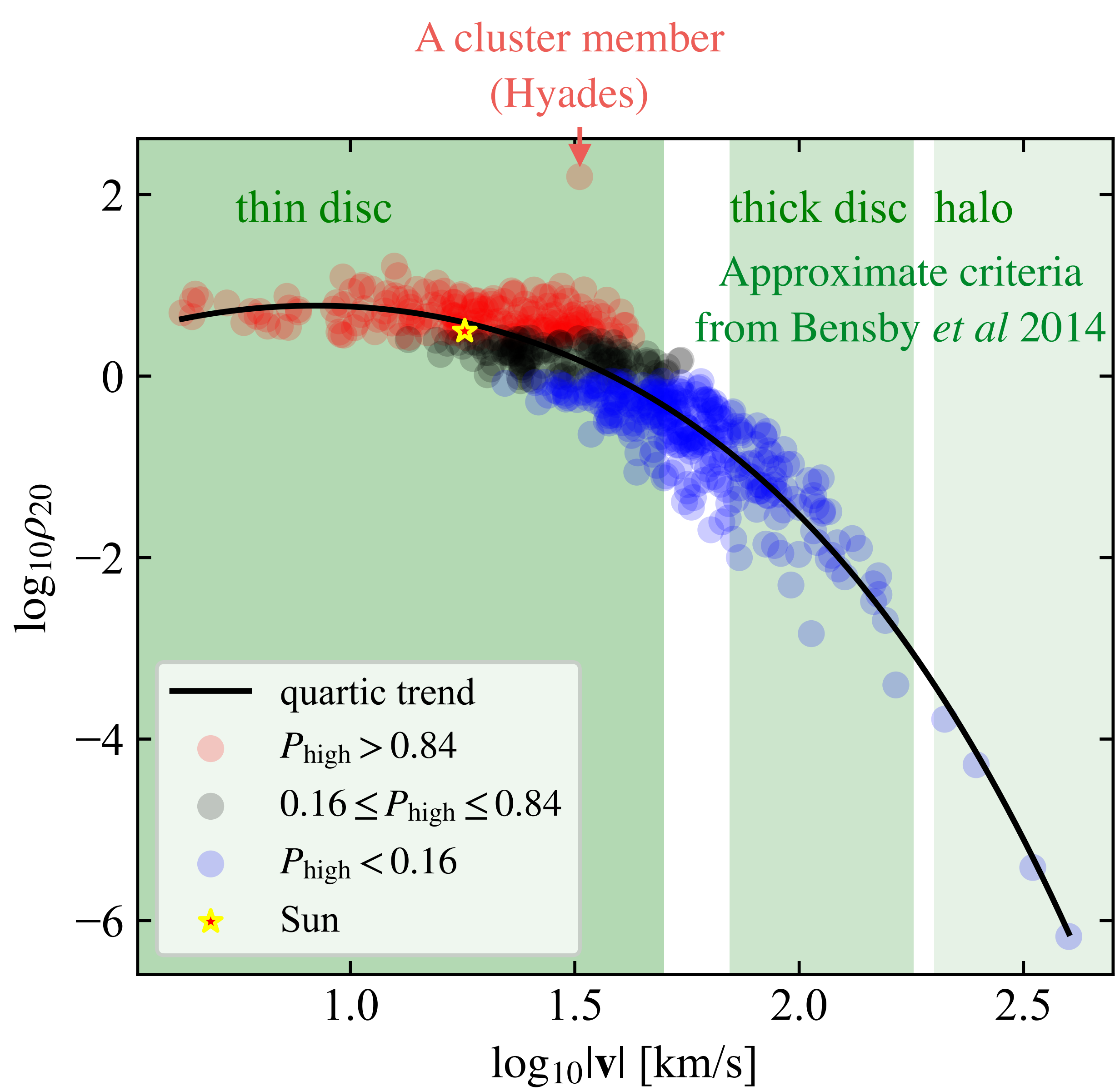
- Interpretation 2: simply relates to present-day large-scale Galactic kinematics
- With *Gaia* kinematics, we can measure a star's *peculiar velocity:* its velocity with respect to the Local Standard of Rest (circular orbit in the Galactic midplane)
- The velocity dispersion of stellar populations increases with time, and the thick disc has a higher dispersion than the thin disc



Miglio et al 2021

What does the phase space density mean physically?

- For field stars, the phase space density is primarily determined by the star's peculiar velocity w.r.t. to the LSR

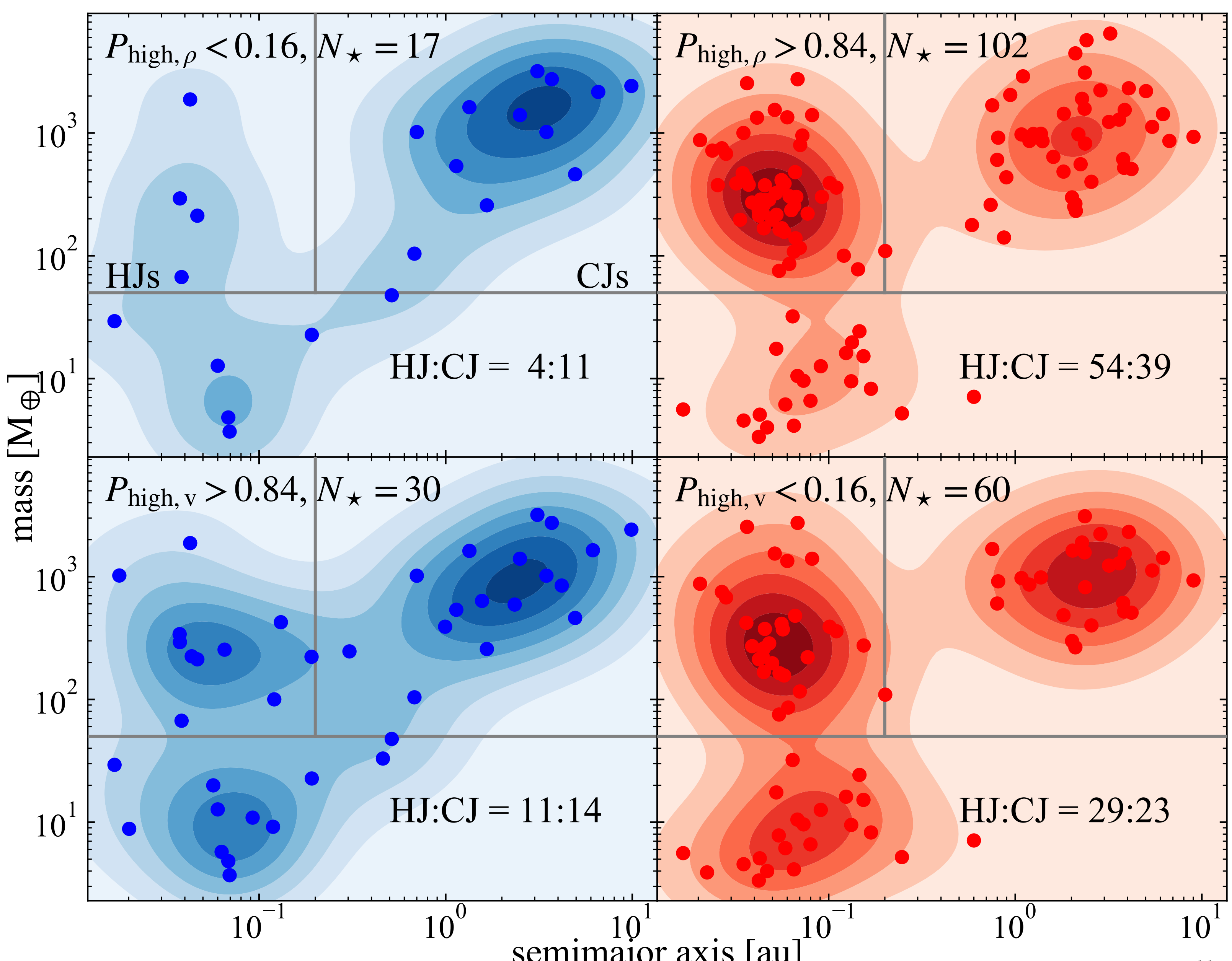


Peculiar velocity

Mustill et al 2022

Hot Jupiter overabundance persists when cutting in velocity

- More Hot Jupiter hosts orbiting low-velocity stars



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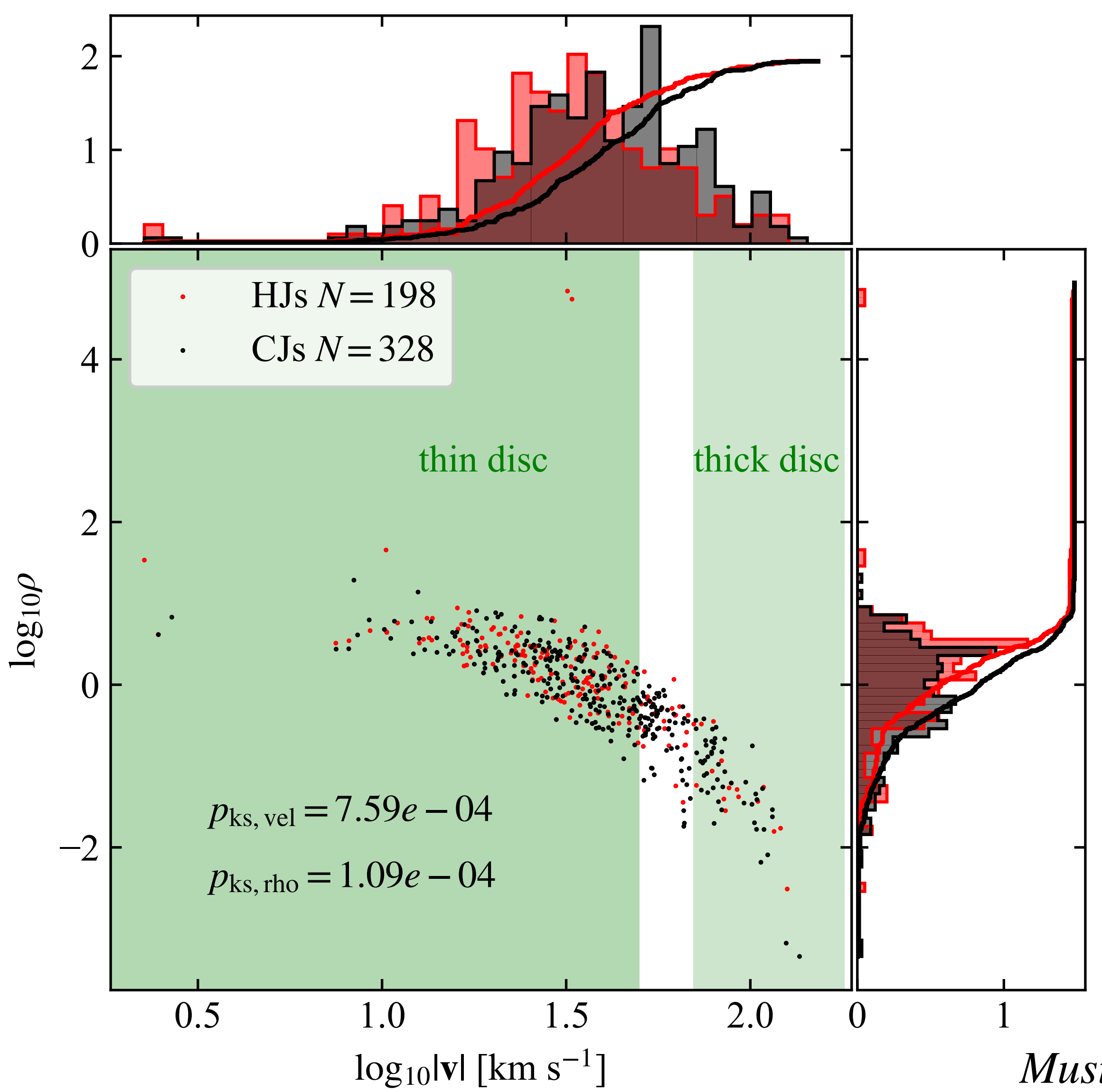
Hot Jupiter overabundance persists when cutting in velocity

- Interpretation 2:
- More Hot Jupiters orbiting low-velocity stars
- This makes sense as low-velocity stars are on average younger, with "heating" happening on timescales of a few Gyr
- Hot Jupiters spiral in to their host stars under tidal forces on timescales also of a few Gyr
- Therefore, the host stars of Hot Jupiters are biased towards being young (Collier Cameron & Jardine 2018) and therefore kinematically cold (Hamer & Schlaufman 2019)
- Cold Jupiters, on wider orbits, do not suffer from this age bias and the stars are therefore on average kinematically hotter

Hot Jupiter overabundance persists when cutting in velocity



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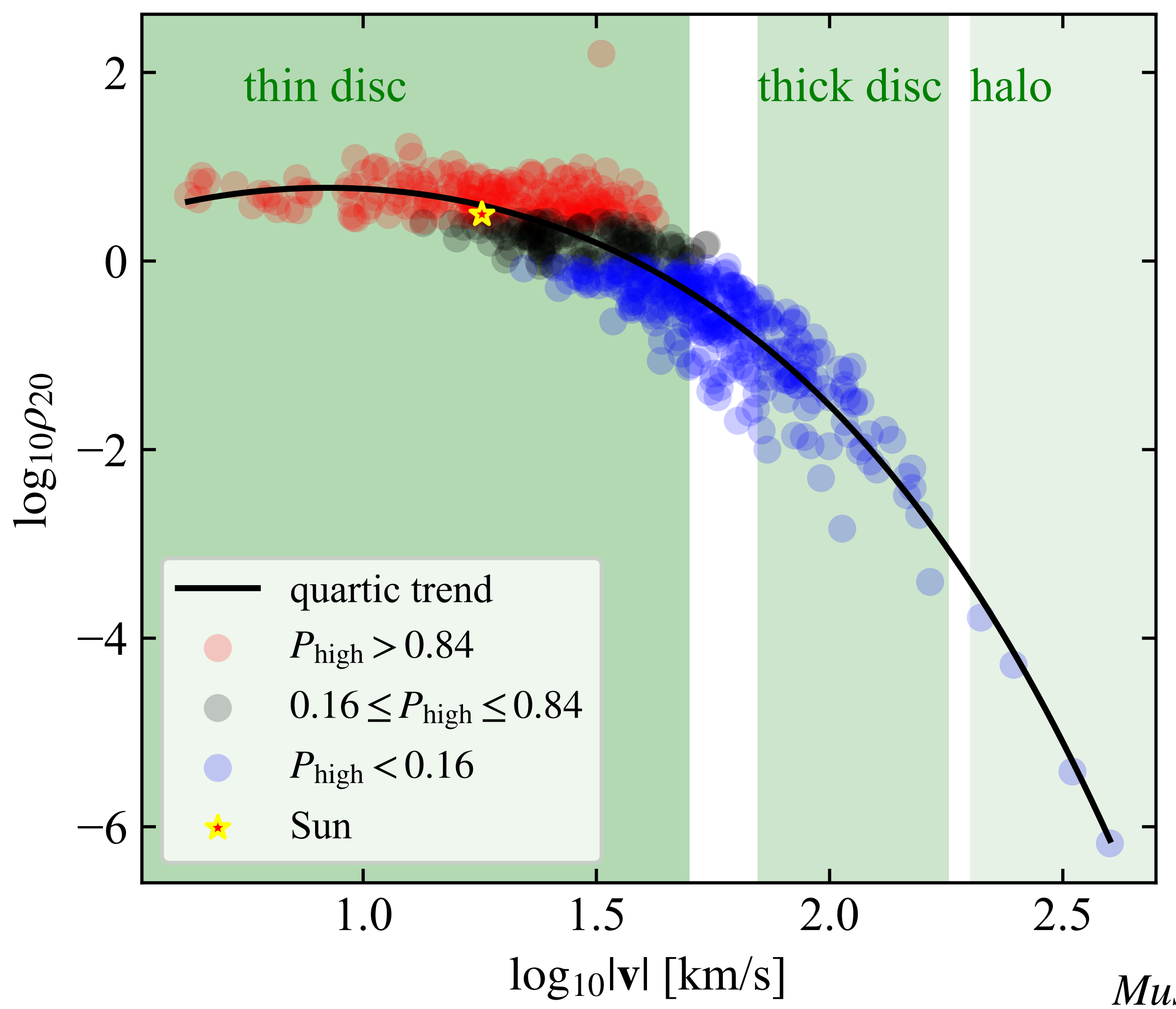
Is there anything when the velocity trend is removed?

- Are Hot Jupiter hosts in high-density regions, given their low peculiar velocities?



Peculiar velocity

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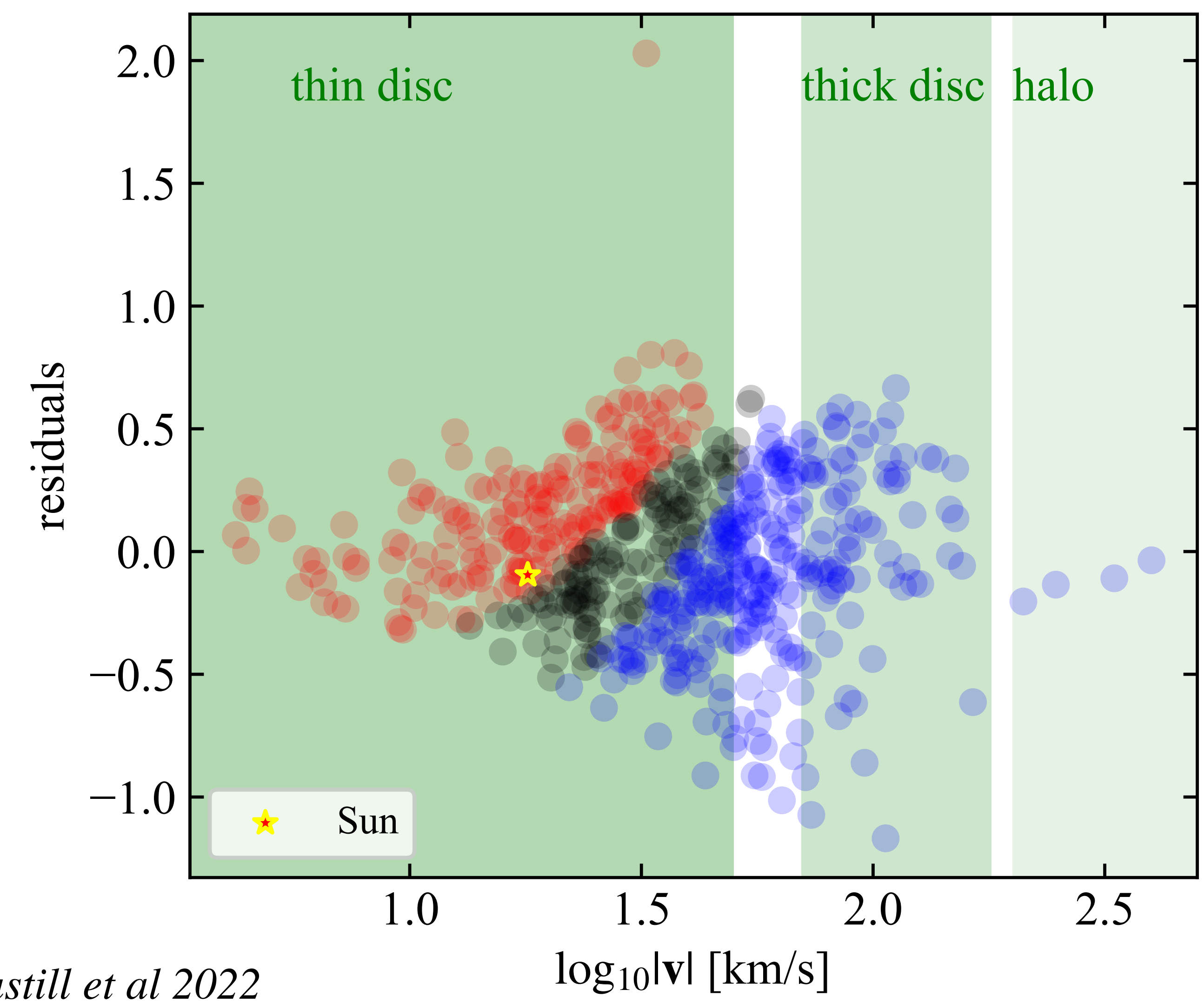
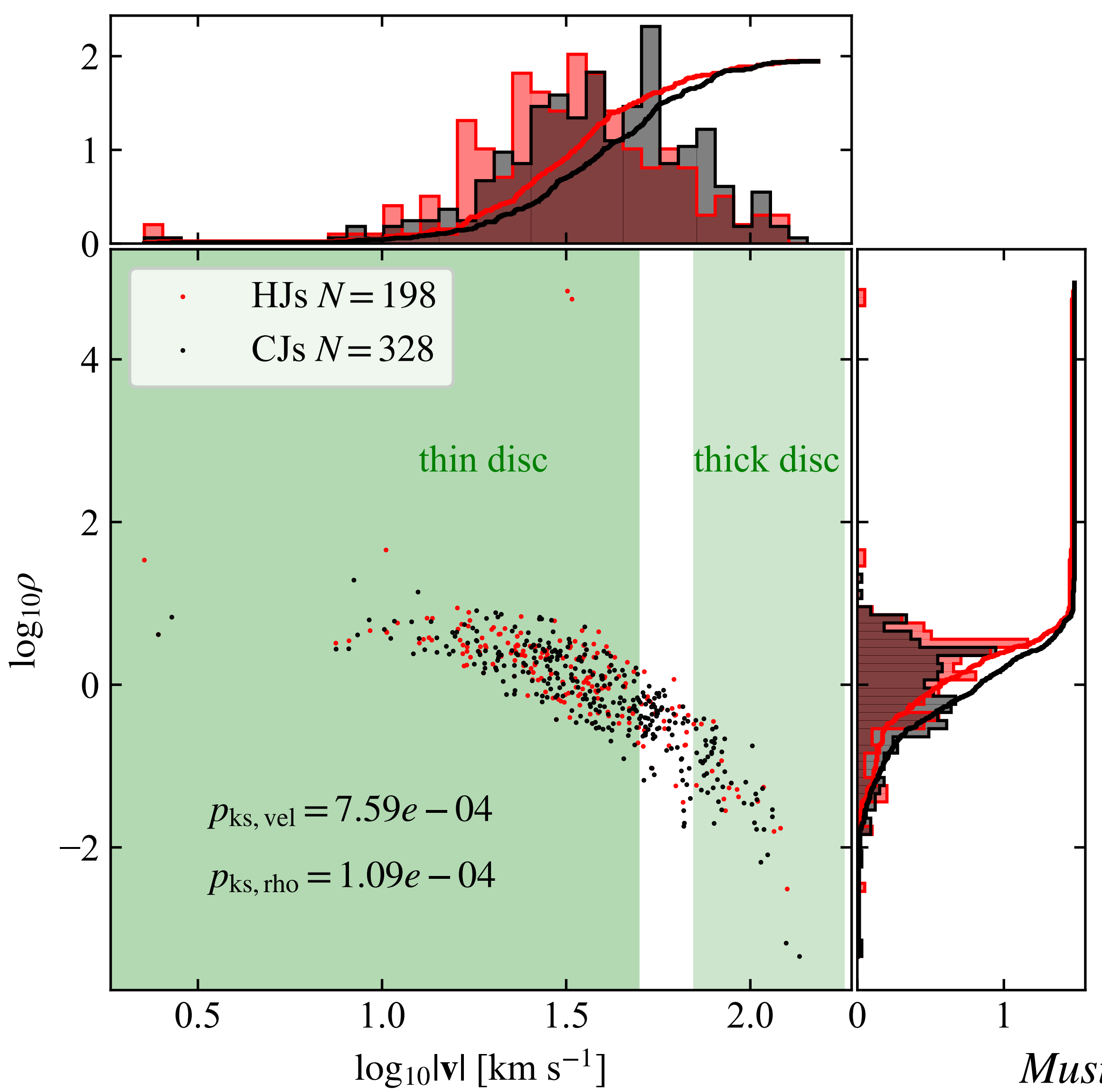
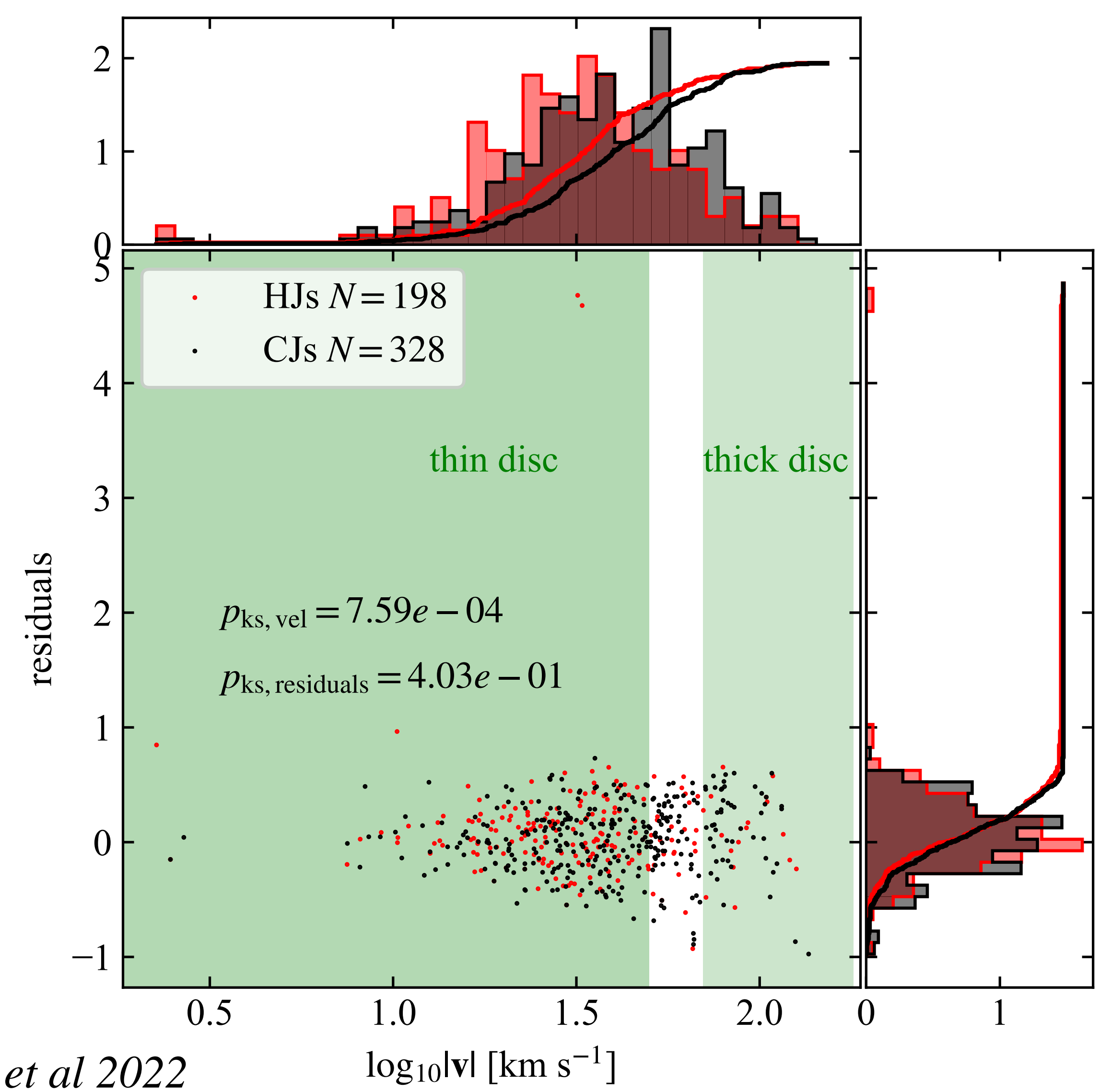


Peculiar velocity

Is there anything when the velocity trend is removed?

- There is no difference in the distribution of residuals
- This means that, if the density of the birth environment (a) matters for HJ formation and (b) determines some of the scatter in the $v - \rho$ relation…we see no evidence of it





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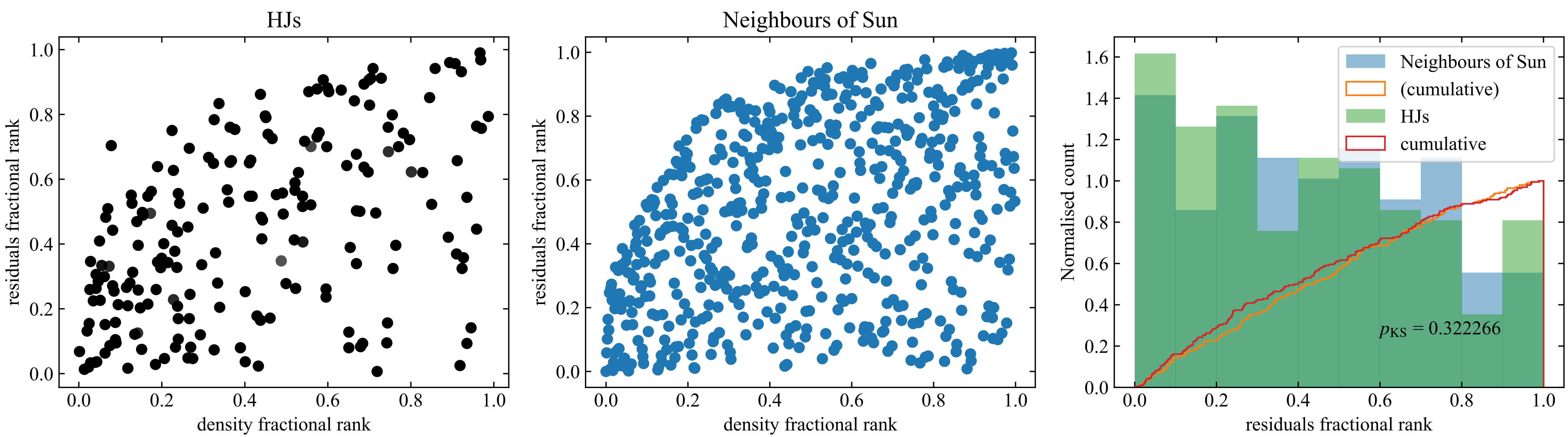
Is there anything when the velocity trend is removed?

- We also performed another comparison, comparing each HJ host to a neighbour of the Sun chosen to have a similar density, and comparing the residuals…again, no difference



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Conclusions

- The Winter *et al*. phase space classification is primarily determined by stellar peculiar velocity, and is hence an age proxy
- In particular, Hot Jupiter hosts, more common in “high density” regions of phase space, are lower velocity and hence younger
- This is naturally explained as a result of an age bias arising from tidal destruction of Hot Jupiters
- NB: doesn’t prove that formation environment has no effect on planet formation/evolution…only that this method doesn’t provide evidence
- There are other differences between the samples found by Winter *et al*. and follow-on papers…these should also be looked at in light of age bias

Final thoughts

- Studying planetary systems in their Galactic context is an exciting frontier (*cf* talks by Tom Wilson, Gaia Lacedelli)
- Formation environment, age, stellar metallicity, stellar elemental abundances must all be disentangled
- We look forward to *CHEOPS*, *TESS &c* characterising the systems of host stars of a range of stellar populations
- Accurate characterisation of the host stars is also extremely important (see Adibekyan *et al* 2021, A&A)
- In the future, we will get reliable ages from *PLATO* to help disentangle matters further
- If you use a mathematical/statistical[/machine learning] tool…do please stop and think about the underlying physics!

Thank you 🙂