Hot Jupiters,
Cold Kinematics?

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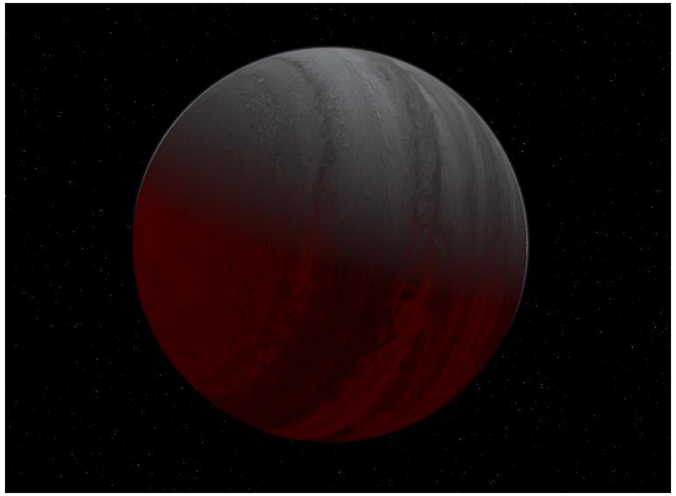
Student Seminar

2022.10.21

Content

- Hot Jupiters & Their (possible) Origins
- Stellar Environment: Is the host an *over-density star* or *field star*?
- The Correlation between *Hot Jupiters Occurence* and *Over-density Stars*
- Origin of overdensity: Age Bias
- Origin of overdensity: from Galactic-Dynamical Perturbations
- Environment Affect on Hot Jupiter Distribution
- Future Tests

Hot Jupiters (HJ)

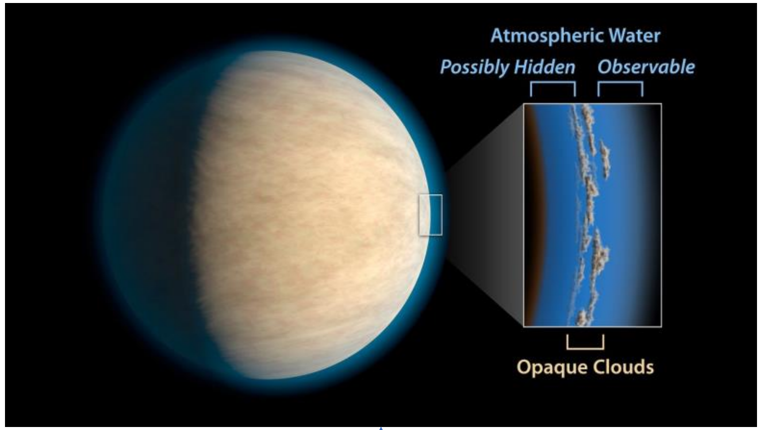


- What is hot jupiter?
- Why are they important?

- physically similar to Jupiter
  - large mass: 0.36–11.8 Jupiter masses
  - gas giant
- very short orbital periods
  - 1.3–111 Earth days
- "hot": high surface-atmosphere temperatures
- low density
- usually be tidally locked

Artist concept (from Wikipedia)

Hot Jupiters (HJ)



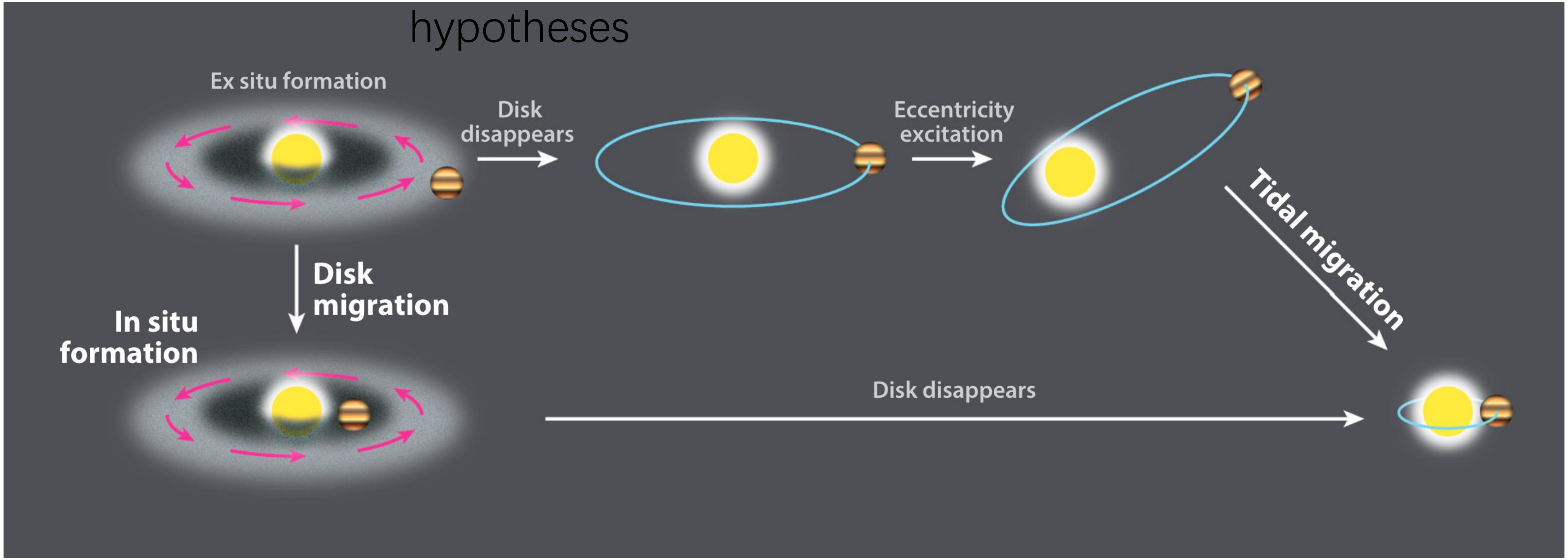
- What is hot jupiter?
- Why are they important?

- The first detected exoplanet *orbiting main-sequence star*: 51 Pegasi b (Mayor & Queloz 1995)
  - radial-velocity method
    - large mass + low orbit → easy to detect!
  - P ~ 4 days
    - orbits 10 times closer to its star than Mercury to the Sun
- hidden water
- ……
- mysterious origin

Artwork (Credit: ESA / NASA and JPL-Caltech)

The Origin of Hot Jupiters: Overview

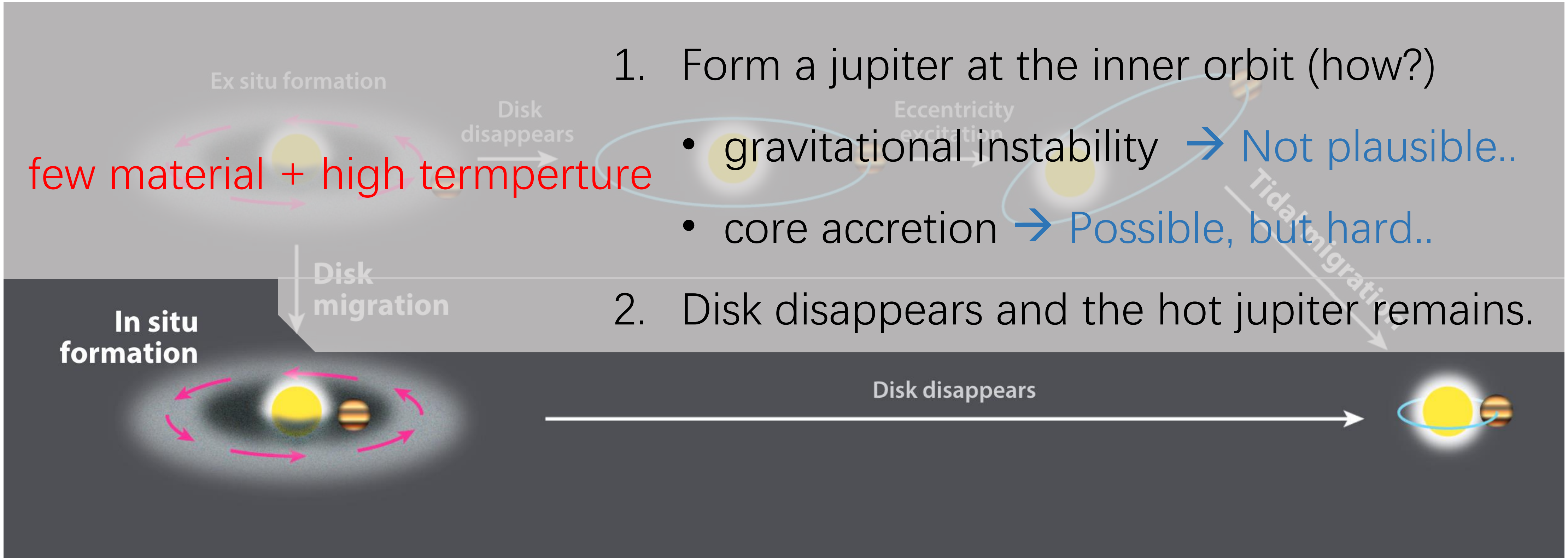
3 classes of hot Jupiter creation hypotheses



(Dawson and Johnson, 2018)

The Origin of Hot Jupiters: In situ formation

Not likely work



few material + high termperture

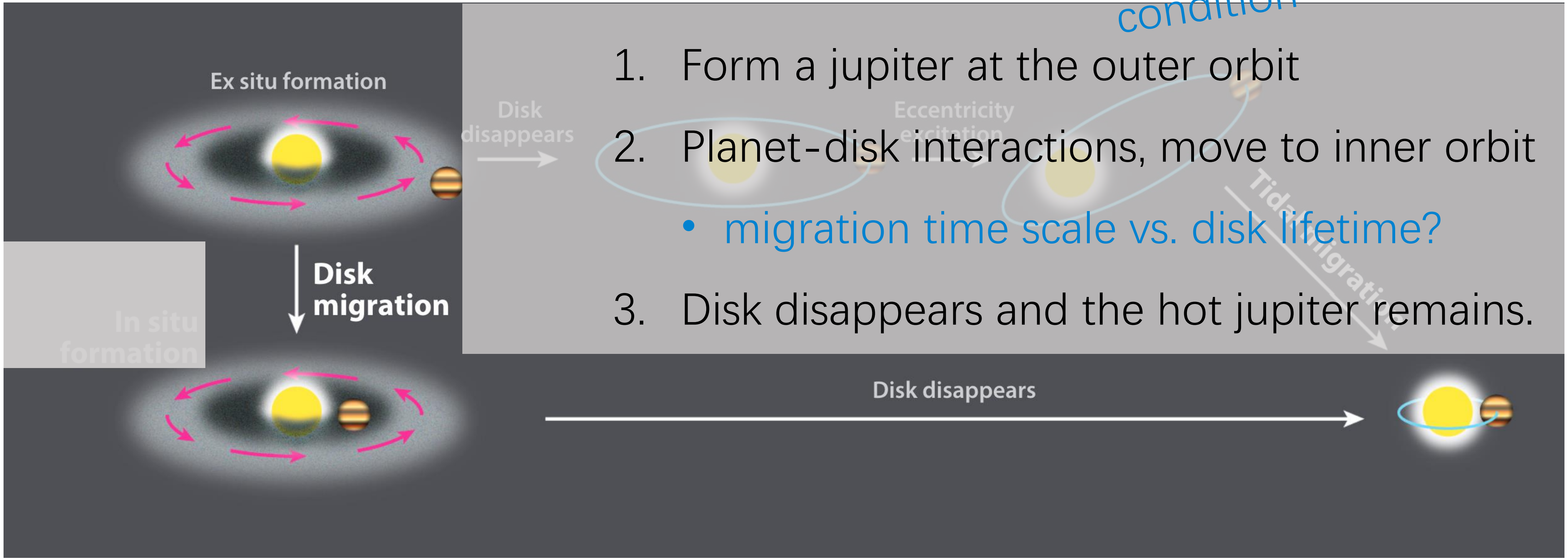
1. Form a jupiter at the inner orbit (how?)
   - gravitational instability → Not plausible..
   - core accretion → Possible, but hard..
2. Disk disappears and the hot jupiter remains.

(Dawson and Johnson, 2018)

The Origin of Hot Jupiters: Disk migration

cold jupiter to hot jupiter (before disk disappears) sensitive to disk condition

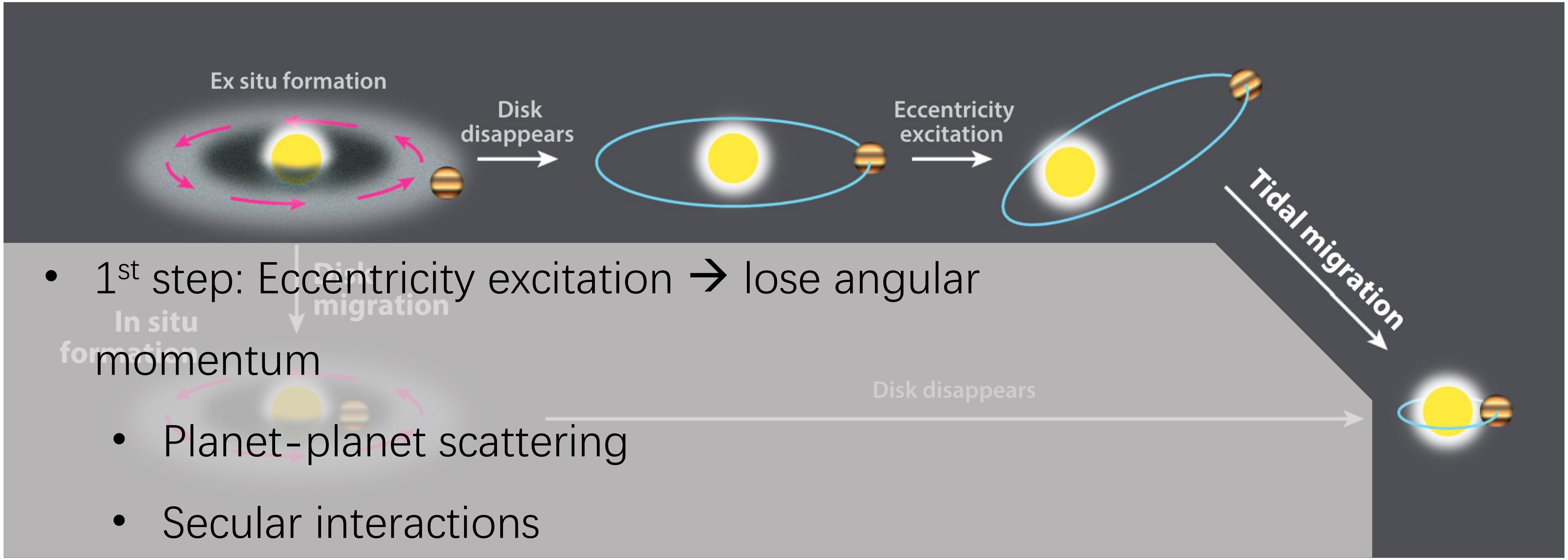
1. Form a jupiter at the outer orbit
2. Planet-disk interactions, move to inner orbit
   - migration time scale vs. disk lifetime?
3. Disk disappears and the hot jupiter remains.



(Dawson and Johnson, 2018)

The Origin of Hot Jupiters: Tidal migration

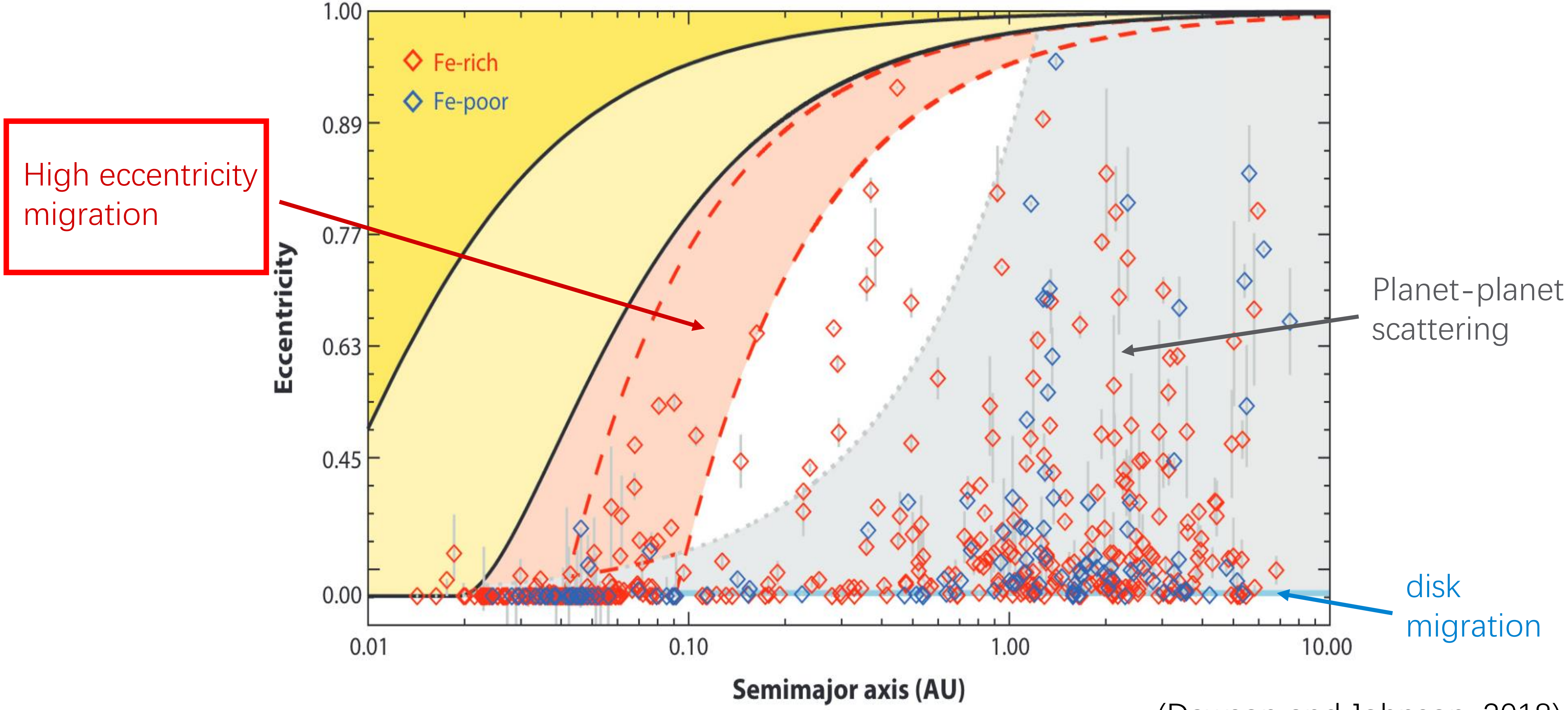
cold jupiter to hot jupiter (after disk disappears)



- 1st step: Eccentricity excitation → lose angular momentum
  - Planet-planet scattering
  - Secular interactions
- 2nd step: Tidal dissipation → lose energy

(Dawson and Johnson, 2018)

The Origin of Hot Jupiters: Observational Hint



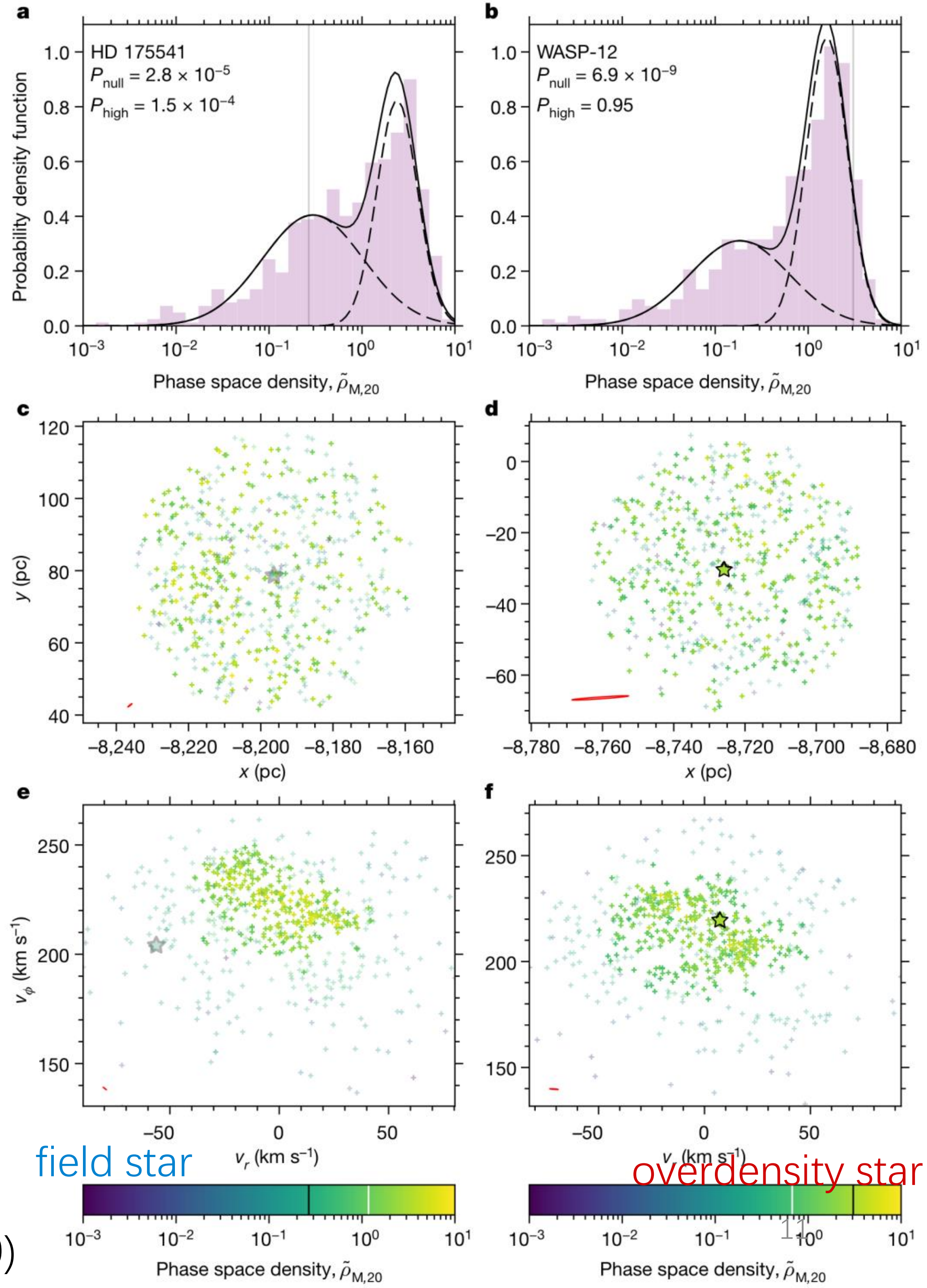
(Dawson and Johnson, 2018)

Over-density Stars

stellar clustering in --

6D phase space = 3D position + 3D velocity

- phase space distance
- calculate the **phase space density** of 600 randomly drawn stars around the host star.
- define ‘overdensity host’ with PDF.



(Winter et al., 2020)

Cold Kinematics

stellar clustering in --

6D phase space = 3D position + 3D velocity

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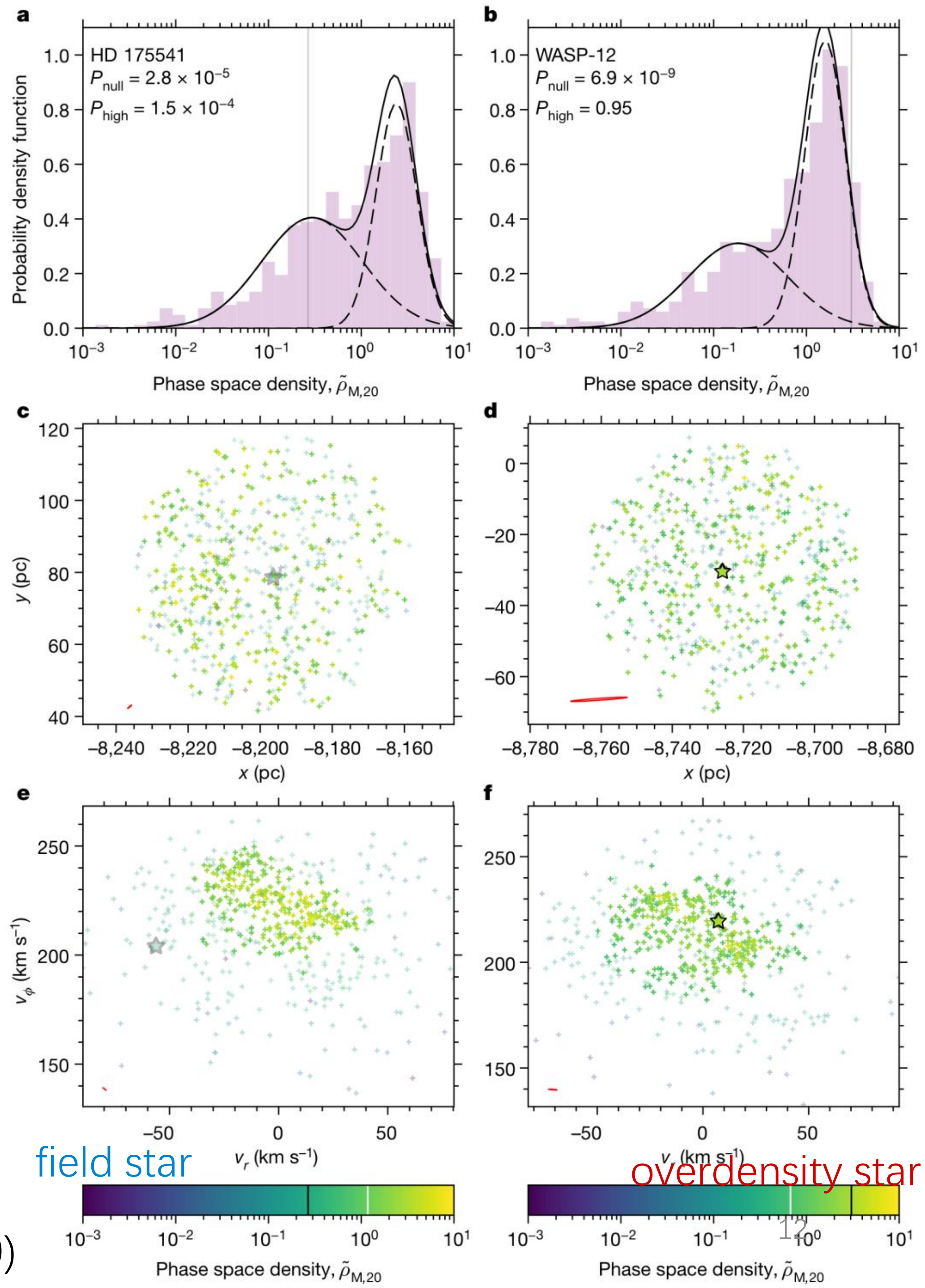
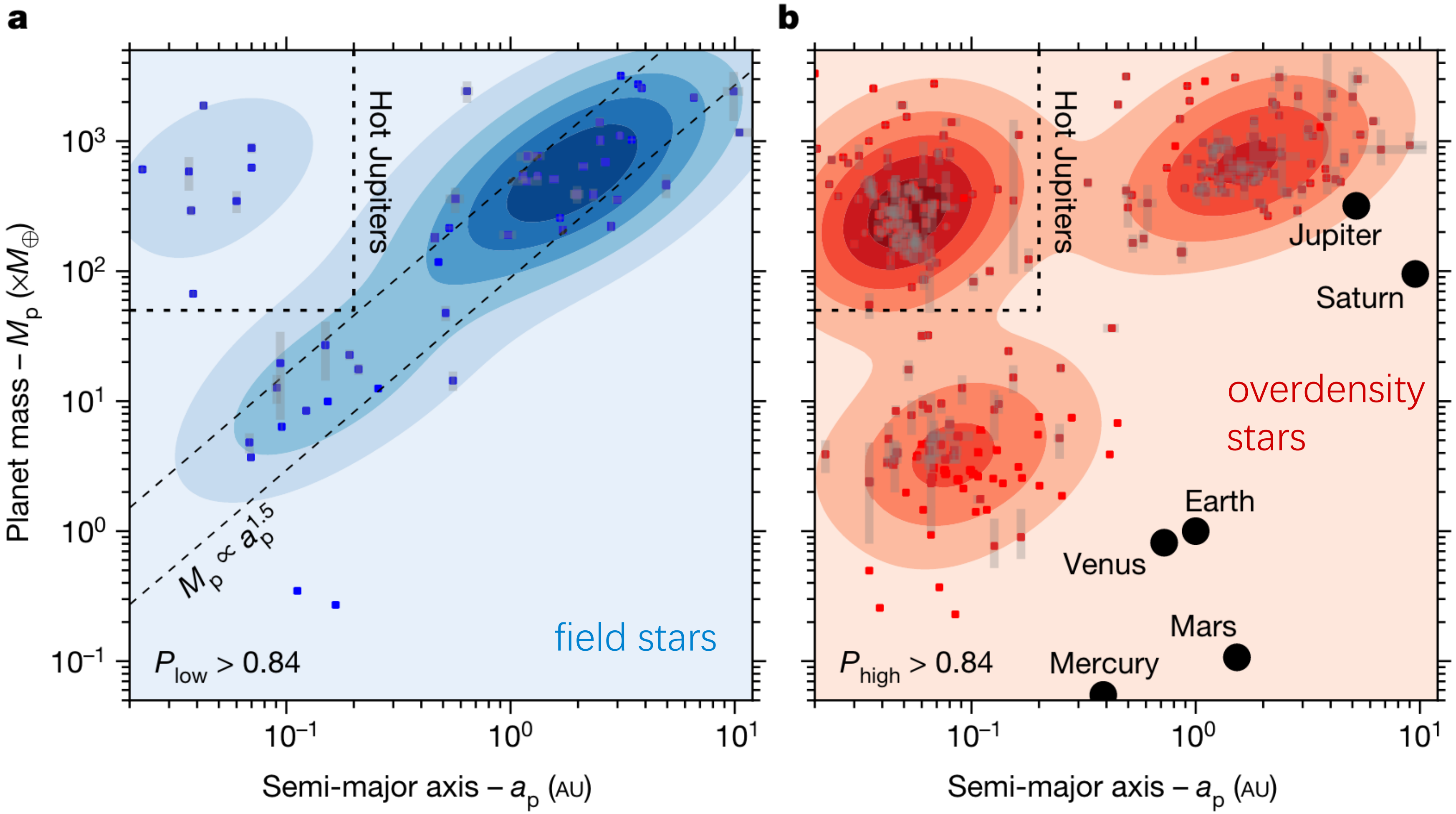


(Winter et al., 2020)

The Correlation between Hot Jupiters and Overdensity Stars

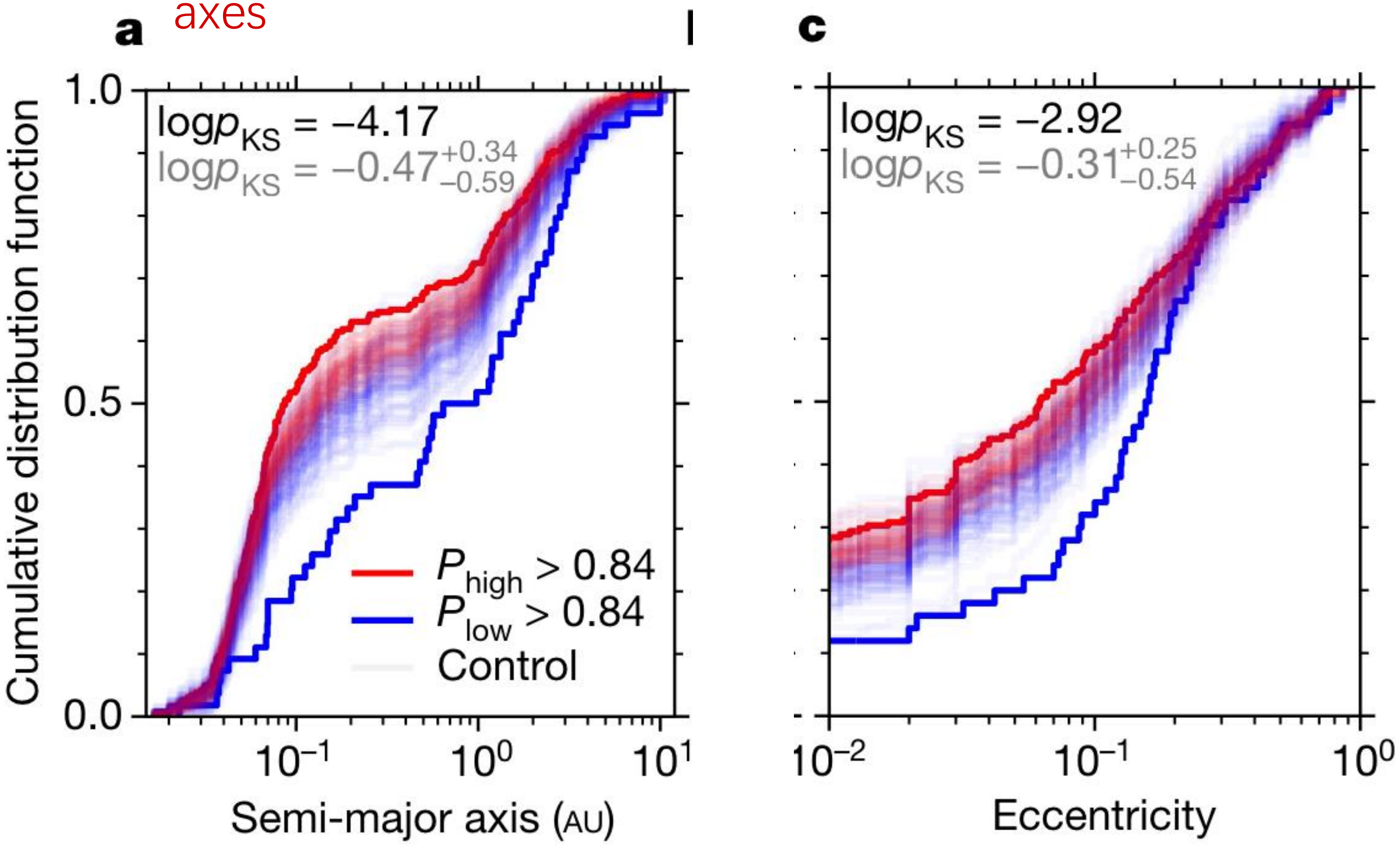


(Winter et al., 2020)

Statistical Analysis

smaller semi-major axes

smaller eccentricities



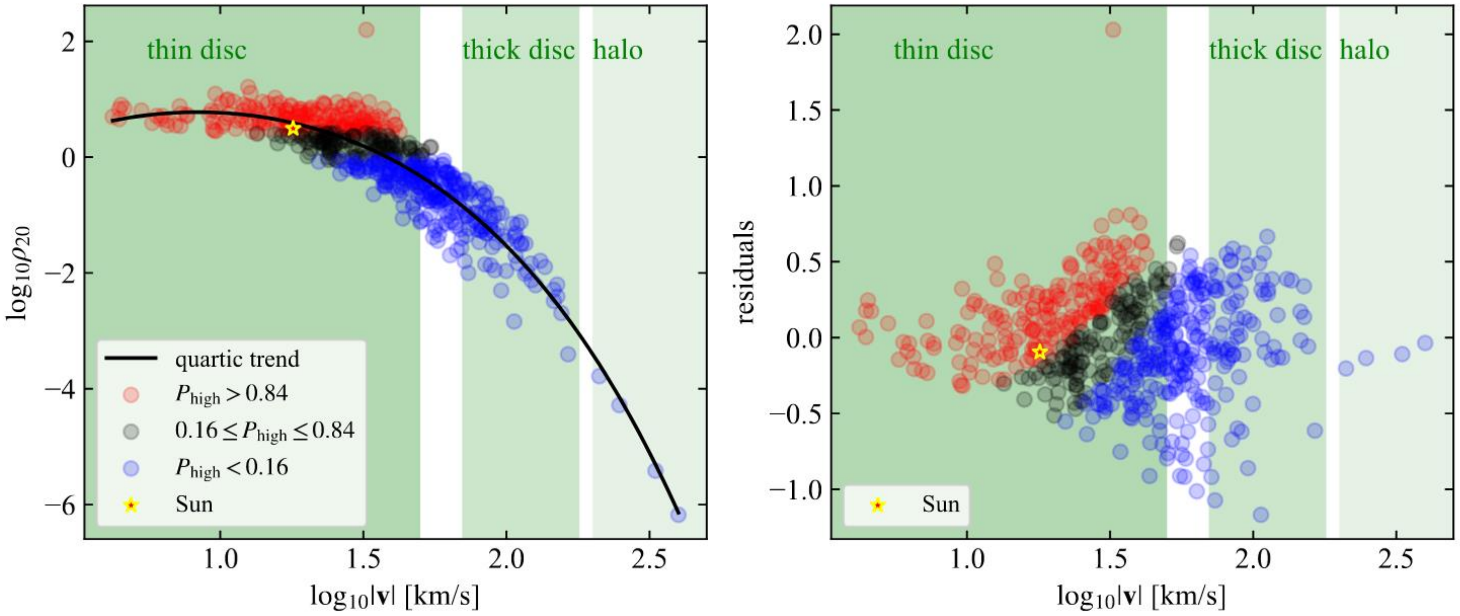
(Winter et al., 2020)

Age Bias

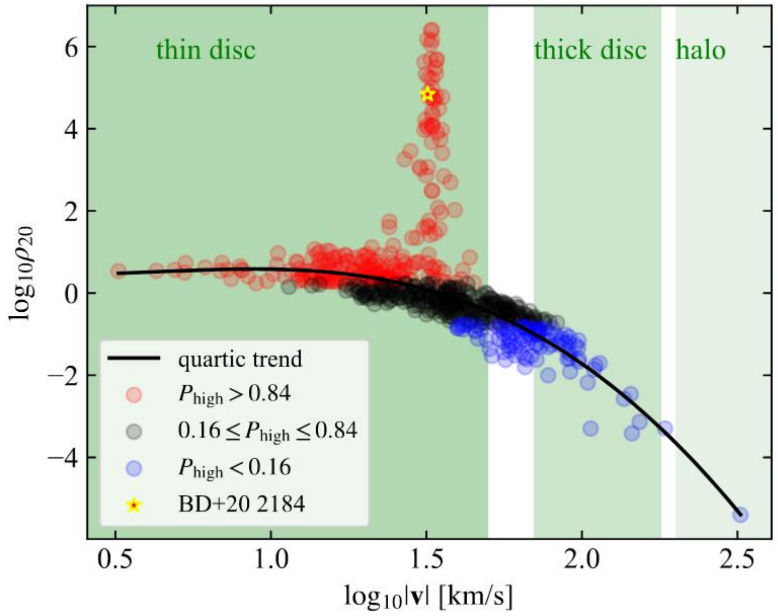
- Motivation: tidal inspiral leads to the destruction of the planets in ~Gyr

Peculiar Velocity <-> Age

- A Quartic Component reflect <u>Kinematically Cold</u> / <u>Young</u>



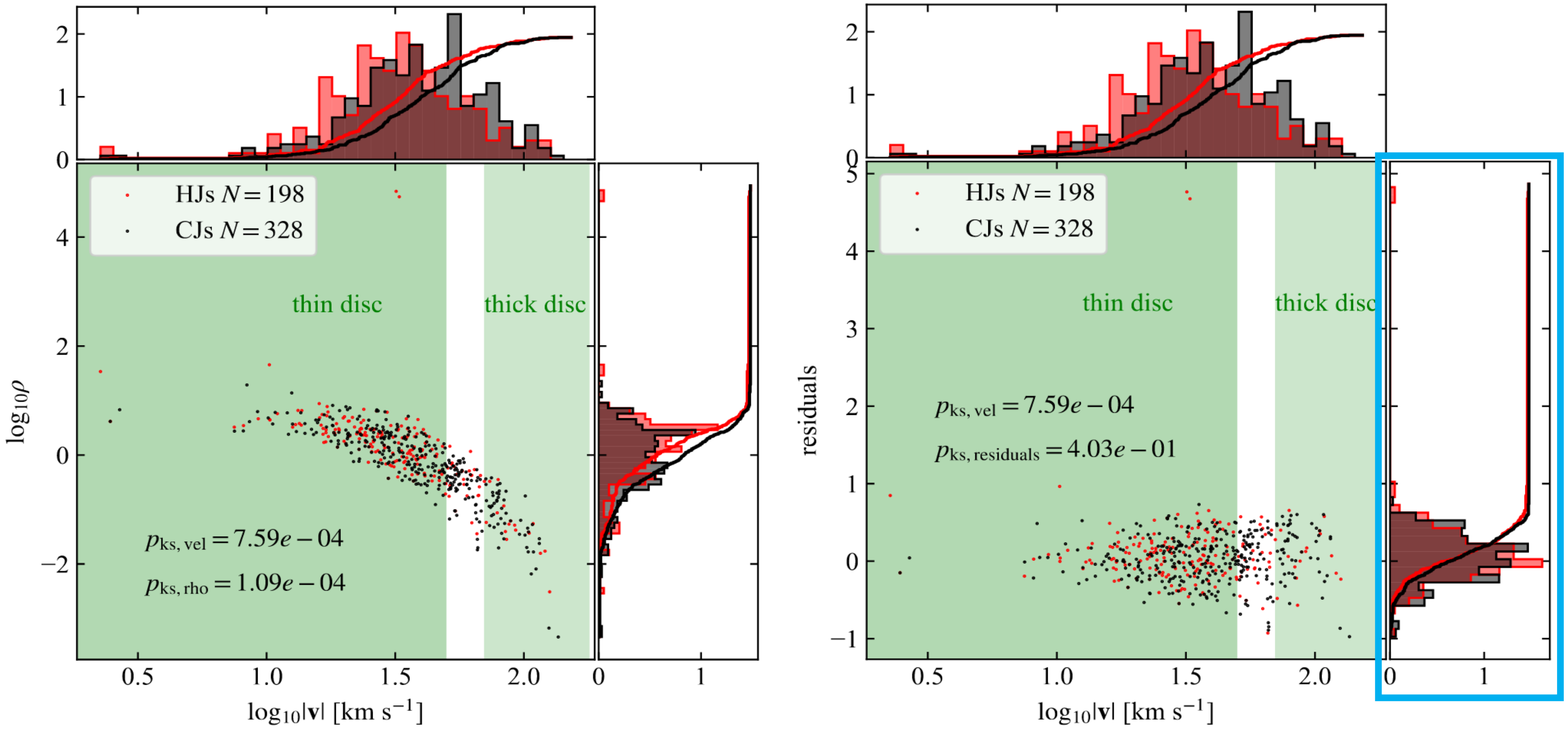
False Overdensity
eg: our Sun



True Overdensity

(Mustill et al., 2022)

Age Bias: difference dispear after detrend..



(Mustill et al., 2022)

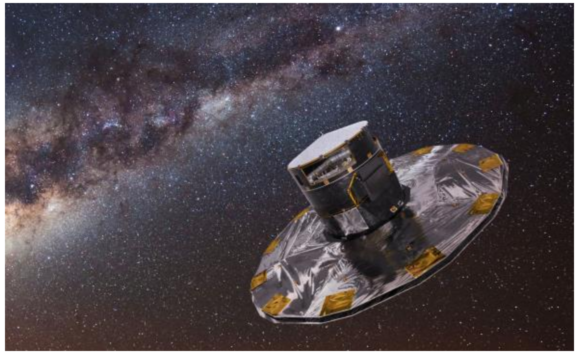
Take Home Message

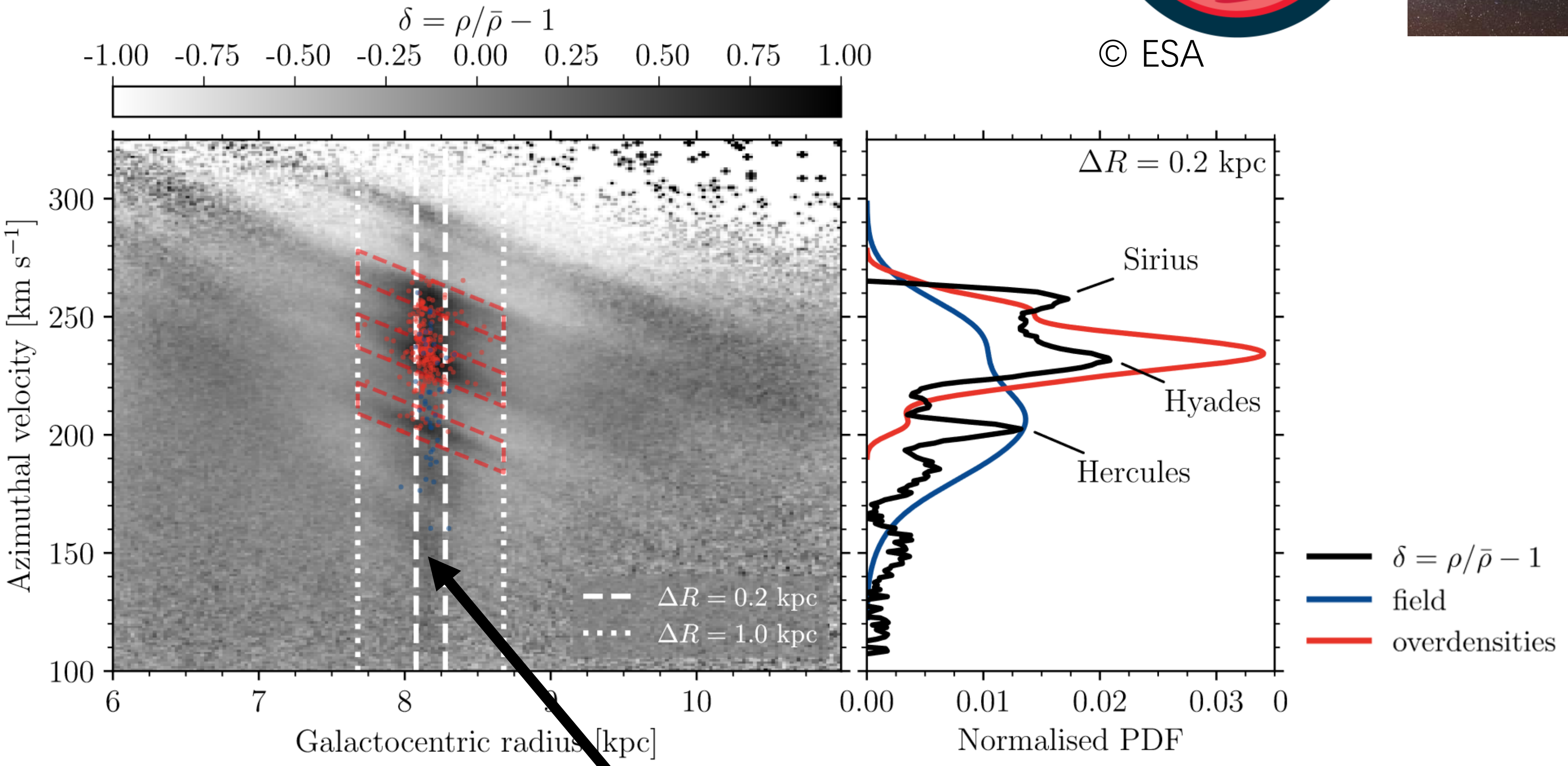
- Hot jupiters: Jupiter-like exoplanets (large mass) with very short orbital periods / near to the host stars
- Relatively easy to detect by radial-velocity or transit method
- Very mestrous origins, CANNOT be single channel
- Winter et al., 2020 finds a correlation between hot jupiters and overdensity stars, indicating the environment of host star may shape the architercture of planetary system.
- Mustill et al., 2022 argues the correlation maybe just an age bias because most ‘over-density stars’ are kinematically cold, and young.

Content

- Origin of Hot Jupiters
- Correlation between Hot Jupiter occurrence and stellar clustering
- Origin of overdensity: Age bias
- Cold Kinematics from Galactic-Dynamical Perturbations
- Mechanisms: How stellar overdensity affect hot Jupiter distribution
- Future tests

Ripples in $\mathbf{R} - V_{\phi}$ plane

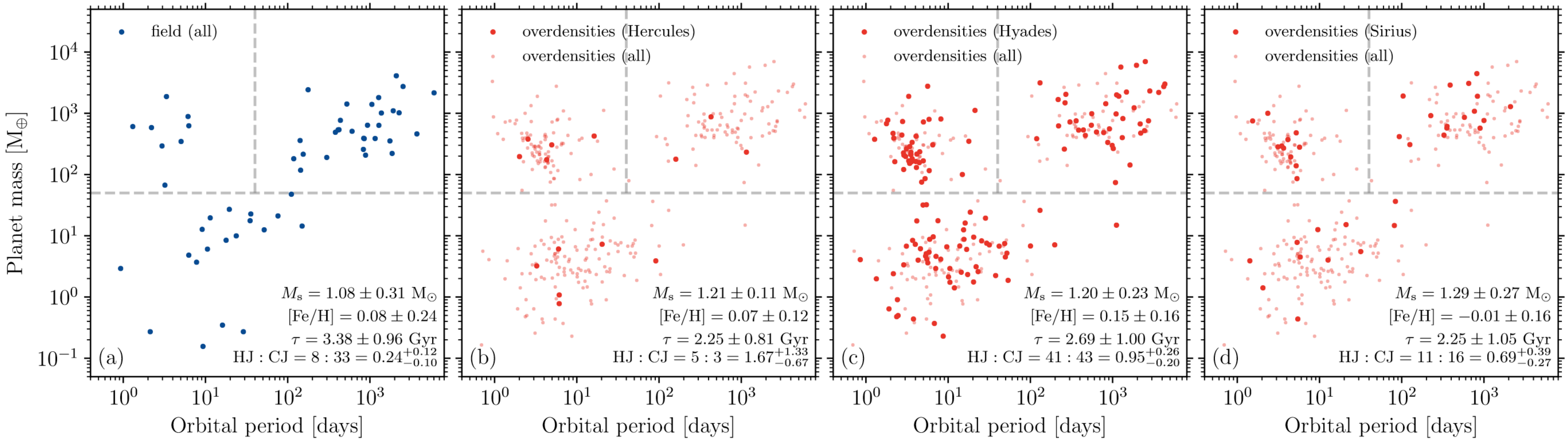




Strongly biased by solar position

Kruijssen et al, ApJ, 2021

Overdensities of different groups



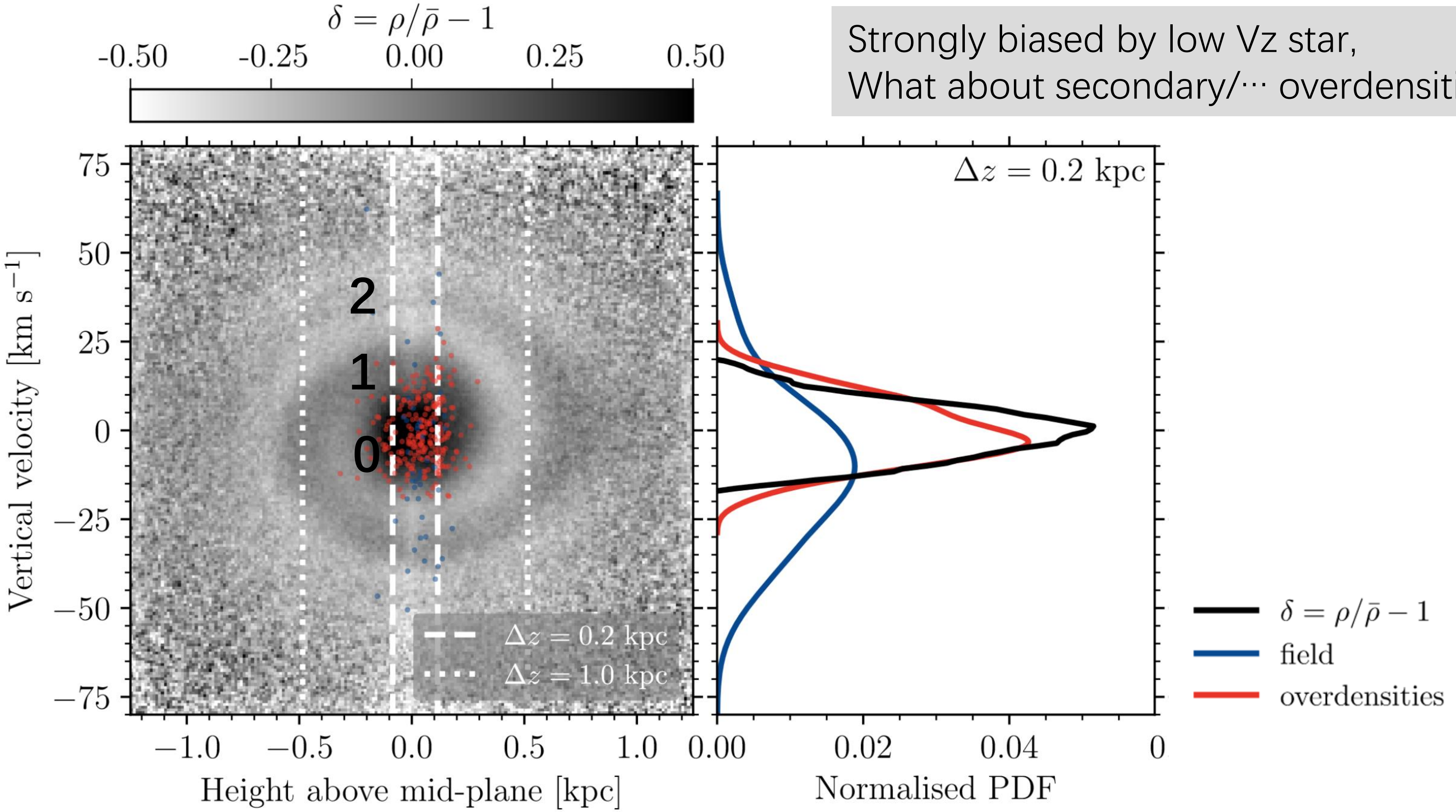
(HJ:CJ) / (HJ:CJ) ~ 7 **(HJ:CJ) / (HJ:CJ) ~ 4** **(HJ:CJ) / (HJ:CJ) ~ 3**

overdensity **field**

Kruijssen et al, ApJ, 2021

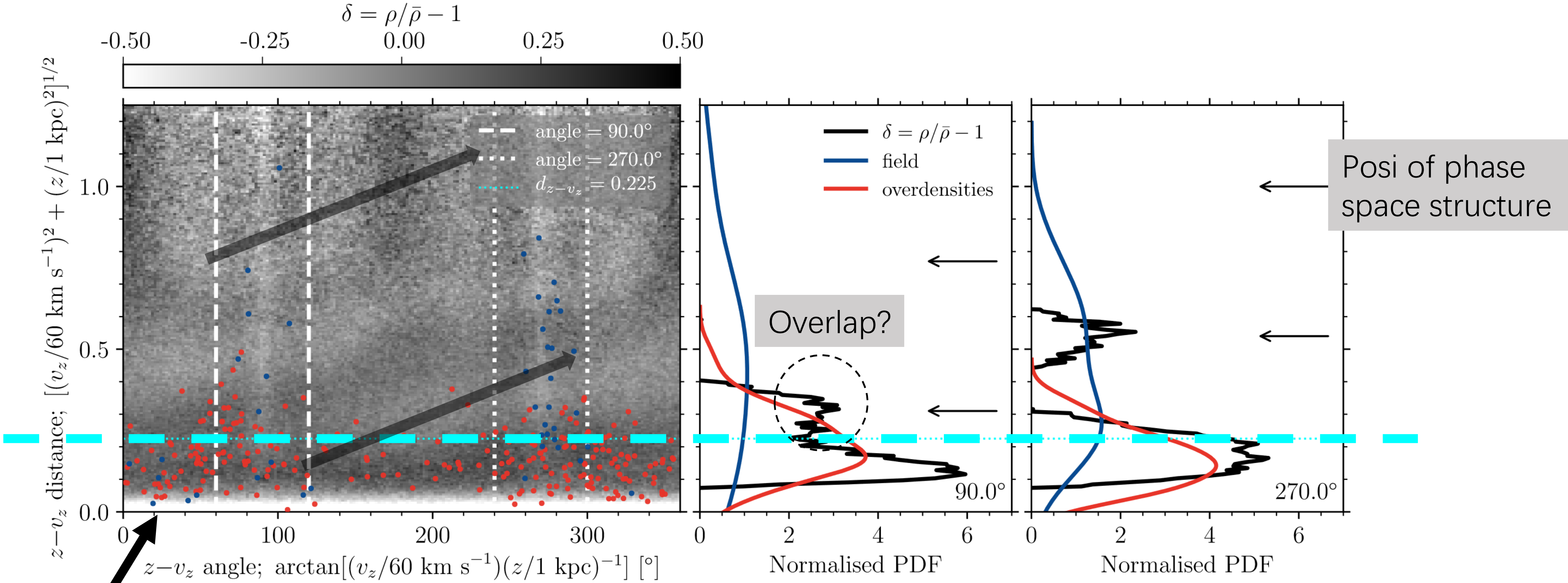
Spirals in $\mathbf{Z} - V_z$ plane

Strongly biased by low Vz star,
What about secondary/⋯ overdensities?



Kruijssen et al, ApJ, 2021

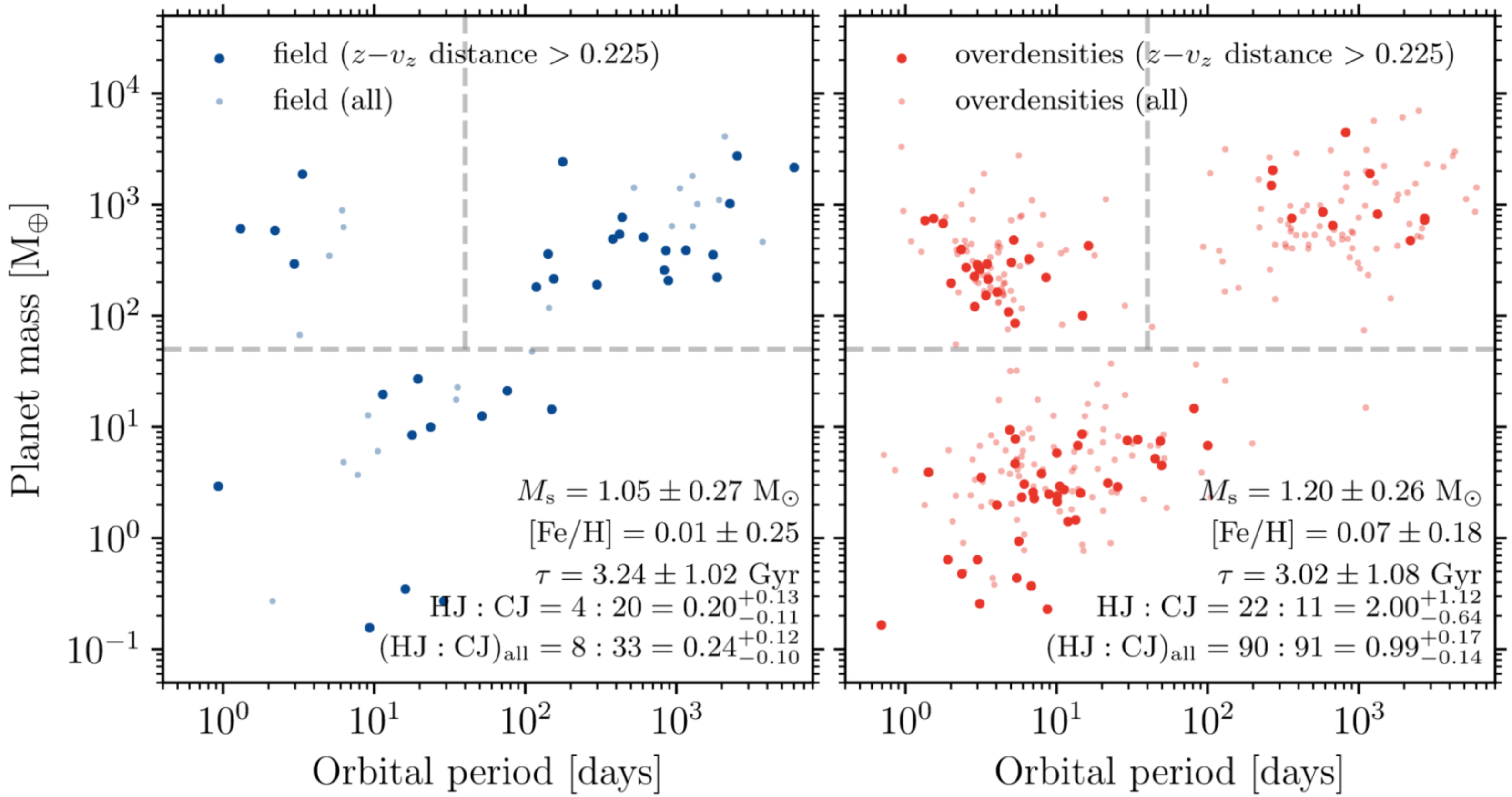
Spirals in $Z - V_z$ plane:



Strongly biased by either low v or vz.
Abandon them!

Kruijssen et al, ApJ, 2021

Examine host stars with highest vz



	(HJ:CJ) / (HJ:CJ)
High vz	10
All	4

Even higher contrast for stars with **high vz**.

Interpretations:

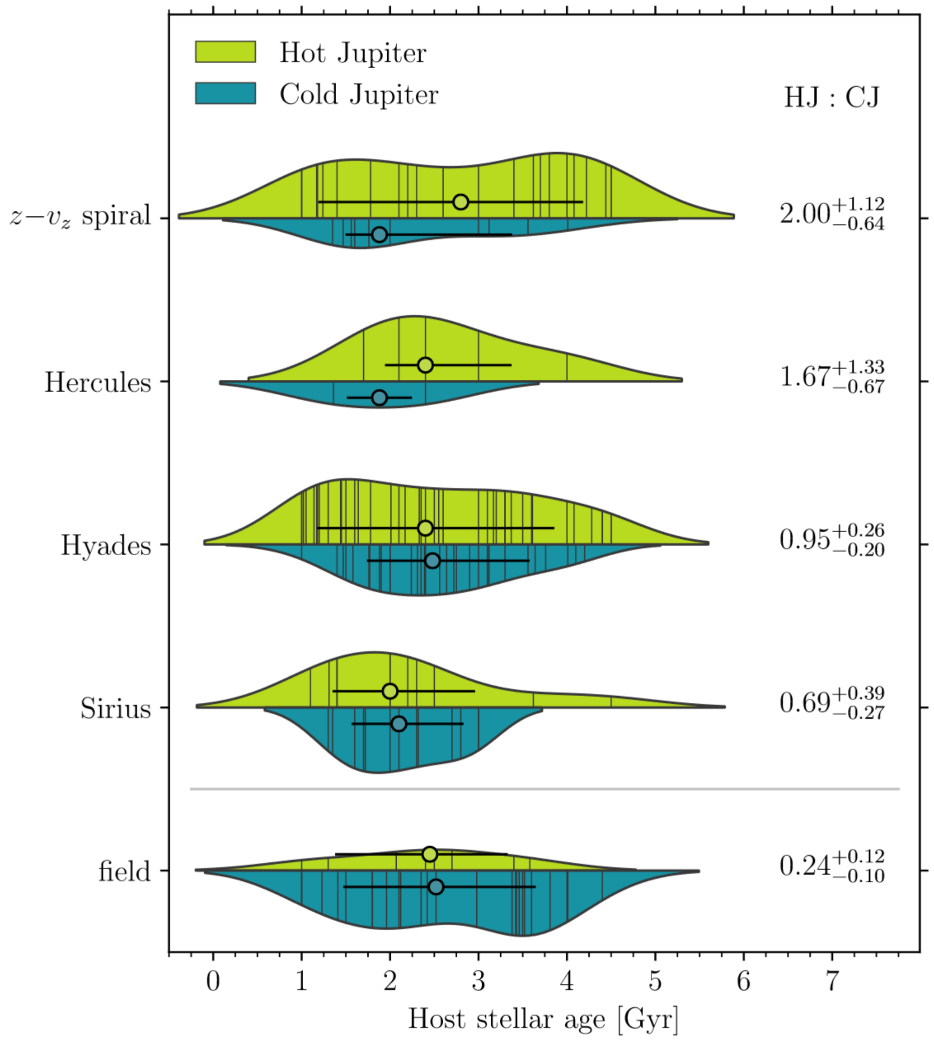
Elder stars (×)

Comoving group(√)

Disfavor age-biased theory:
Age bias may contribute but can not fully explain overdensity.

Kruijssen et al, ApJ, 2021

Origin of overdensity: Age biased?



Kruijssen et al, ApJ, 2021

(Against Mustill+ 2021):
Age evolution of HJ:CJ ratio seems increasing with age, more HJs are **created** rather than **destroyed**.

What about a larger sample with more accurate age determination in the future?

Finer age bins to reveal the clear trend.

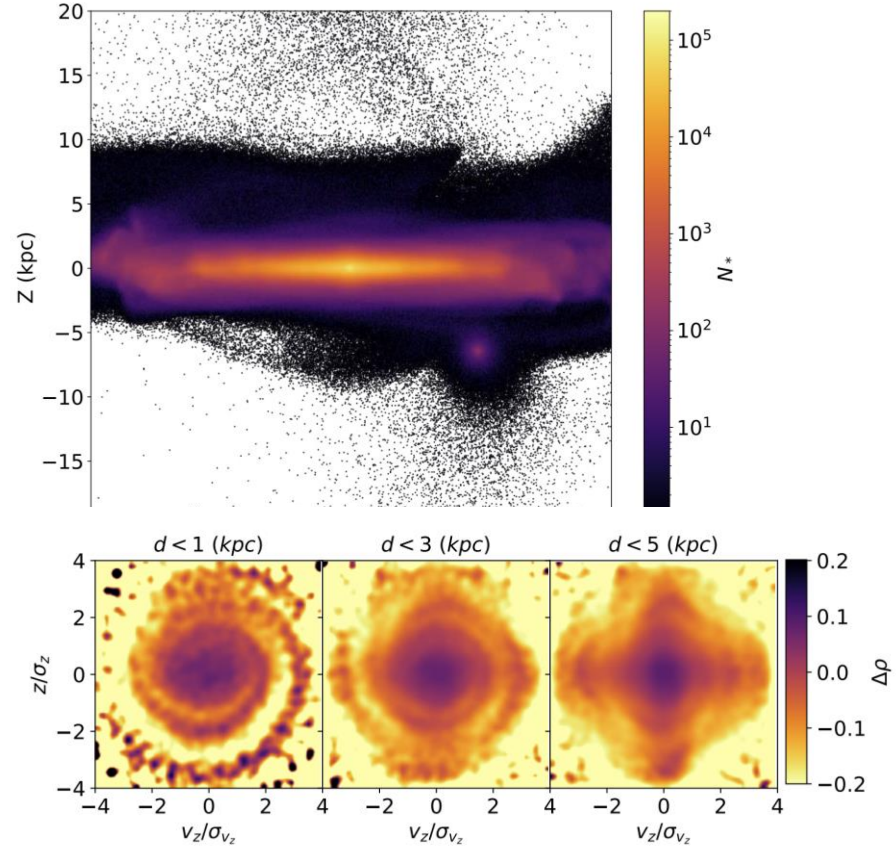
Multiple physical origins of phase space overdensities

- Remnants of birth environment:

Position clustering disperse in Gyrs and comoving feature remains as remnants.

- Generated by galactic dynamics

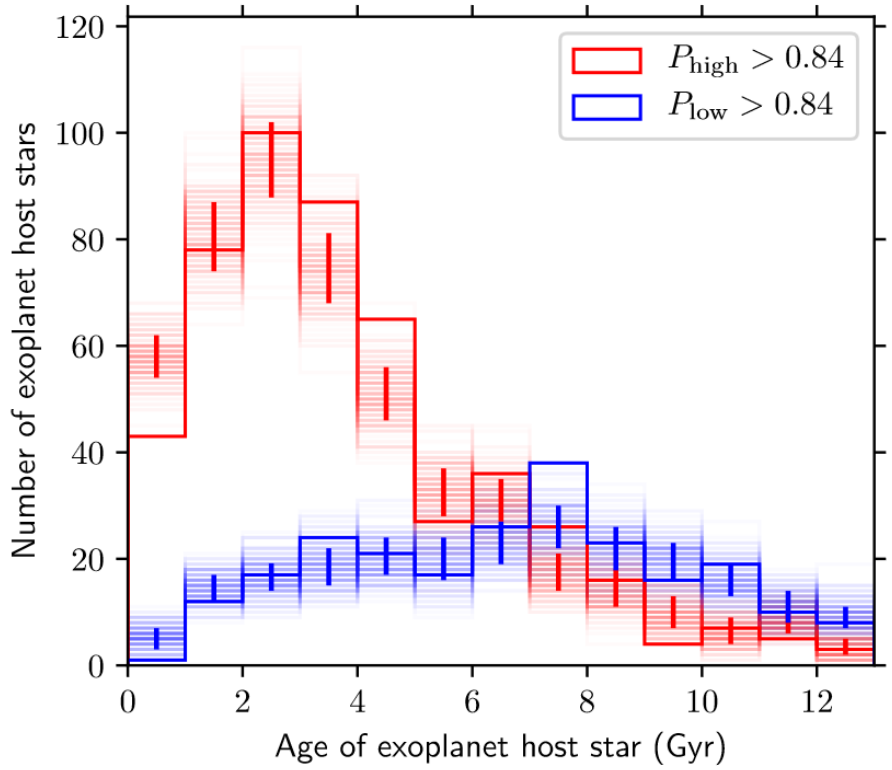
Resonances driven by bar or spiral arms-> ridges in R_vphi plane ->Hercules (bar age: ~8 Gyrs)
Satellite galaxy passages –> bending waves -> phase space spirals in z-vz plane and ripples in R-vphi plane. -> Sirius (live for several Gyrs in numerical simulations.)



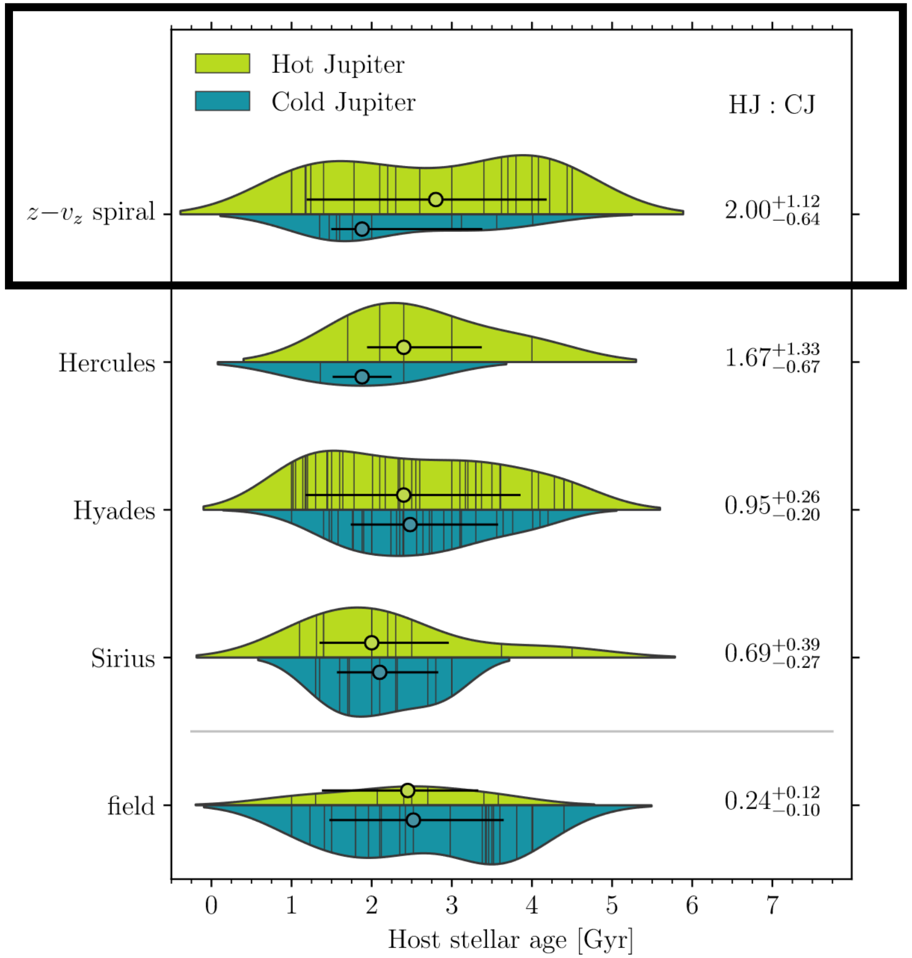
Hunt et al, 2021, MNRAS

1e9 Particle simulation of merger of a **Sagittarius**-like dwarf galaxy

Pros and Cons



Winter et al, Nature, 2020



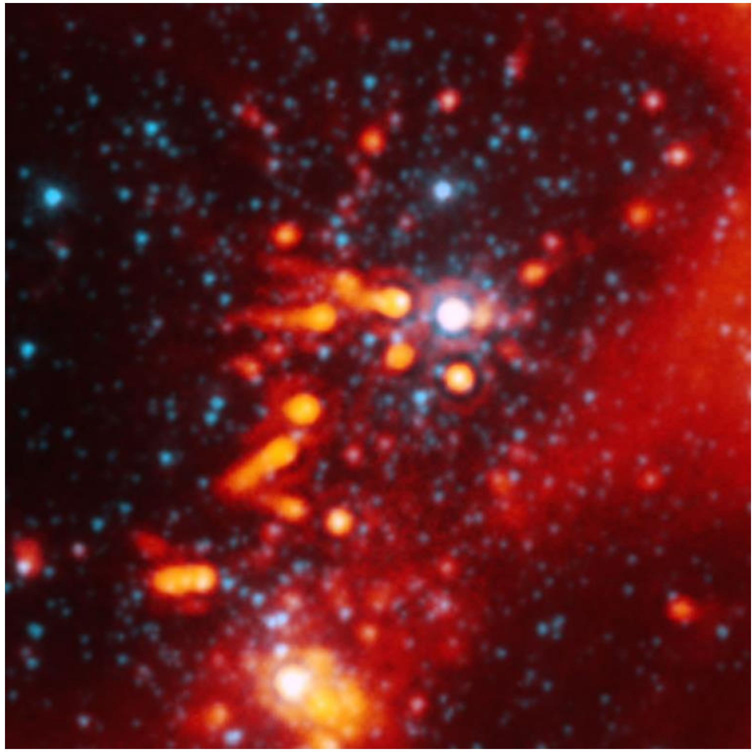
Kruijssen et al, ApJ, 2021

Dynamical heating has a typical timescale of 4.5Gyrs in Milky Way the fraction of exoplanetary systems in overdensities drops precipitously at ages > 5 Gyr

For Z-vz spirals, age distribution quite flat. Overdensities spreads at all time.

“Correlation does not imply causation.”

How stellar overdensity affect hot Jupiter distribution: During the formation process


Ionized protoplanetary disk
©Spizer Space Telescope

Higher Photoevaporation:
- disk disperse quicker
  ->planet grows smaller -> migration speed slower
  ->disk migration stops earlier
- More Hot Jupiters not destroyed by the star.

Chemical enrichment in stellar clusters:

- 26Al, heat the disk, change disk snowline dramatically. Largely influence planet formation position, speed etc.

How stellar overdensity affect hot Jupiter distribution: after disk dispersal

Close encounters:

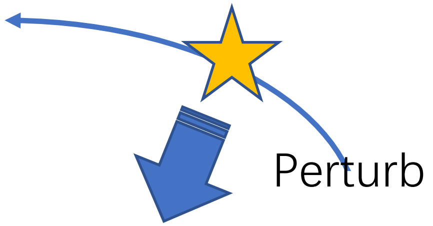
- **Farther planets easier perturbed**.

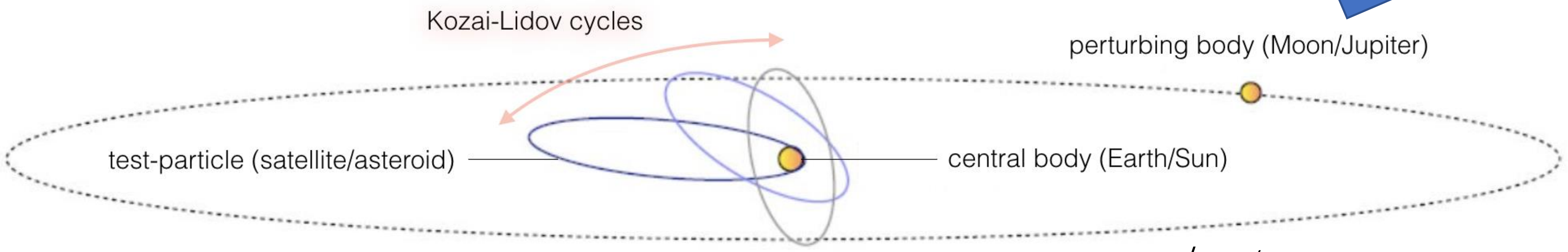
How exactly it works matters:

- The demanded **stellar density**. (excite in-spiral migration or kicks out to become rouge planets?; Short timescale)
- The initial configuration of planetary systems.
- Star flyby excite/strengthen **other secular perturbation**. E.g., it perturbs an outer companian and excite eccentric Kozai-Lidov resonance for a inner Jupiter. (Rodet+ 2021)

To perturb planets at 1AU >1e4 /pc^3, typically the core of globular clusters

Proxima Centauri ~ 1.3pc





planetary.org

How stellar overdensity affect hot Jupiter distribution: galactic perturbation

Clusters are enhanced near spirals or ridges of interstellar medium.

- The large scale phase space overdensity in galaxies supply birth place for massive clusters.

Galactic tides from disk or ISM.

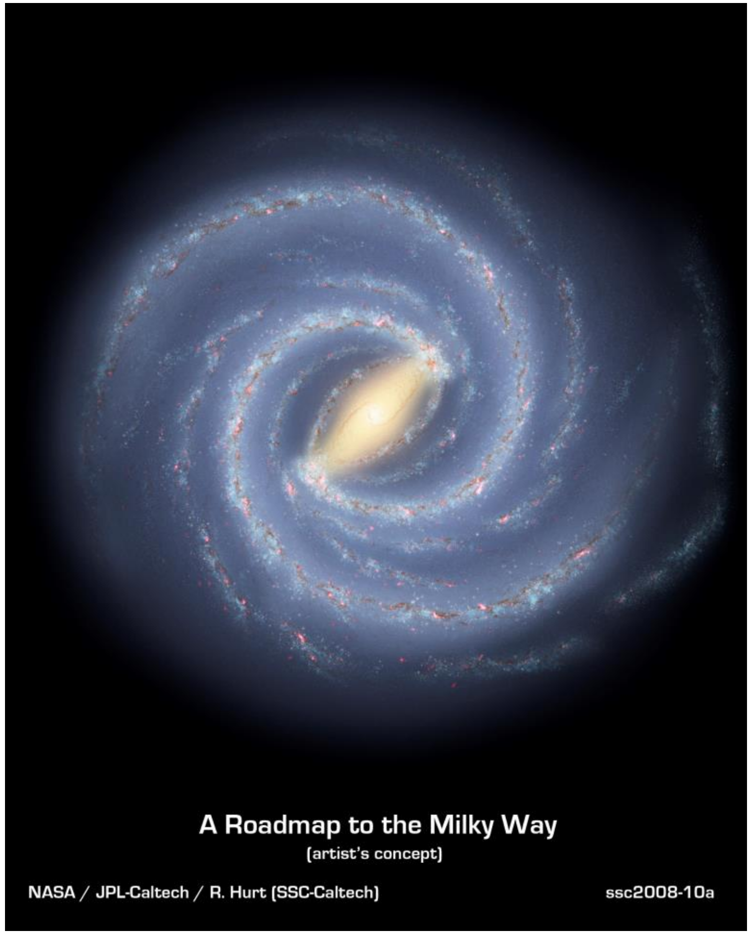
- Seen in binary system simulations.

Tides influence the binary orbit secularly.
(Kaib+ 2013)

Mixing of satellite and host galaxy stellar components

- **(Aha, Really?**

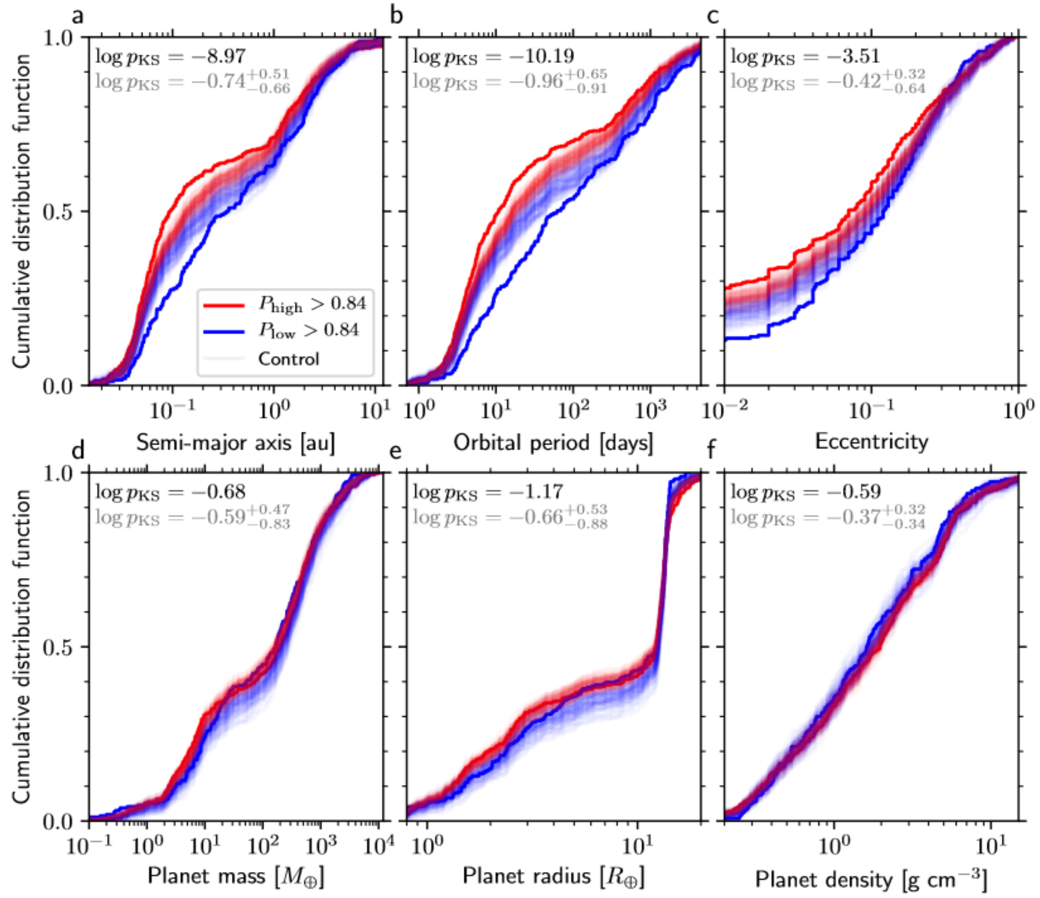
Seems harder if only velocity space is perturbed?



How stellar overdensity affect hot Jupiter distribution: observational constraints

- Eccentricity distribution.
- Planet mass distribution.

- Consistency of statistics: Can it jointly fits the observational data for other low mass planet?



Winter et al, Nature, 2020

Future tests

Distinguish the origin of overdensity:

- Larger & better sample to improve statistical confidence and reveal clear trend on stellar/planetary parameters.
- Obtaining accurate ages of exoplanet host stars and their parent overdensities (simulations?). -> when it operates (at birth/ late time)

Detailed study of the mechanism to influence planetary system.

- Does stellar perturbation tends to destroy Hot Jupiter or create Hot Jupiter? How efficient it operates?

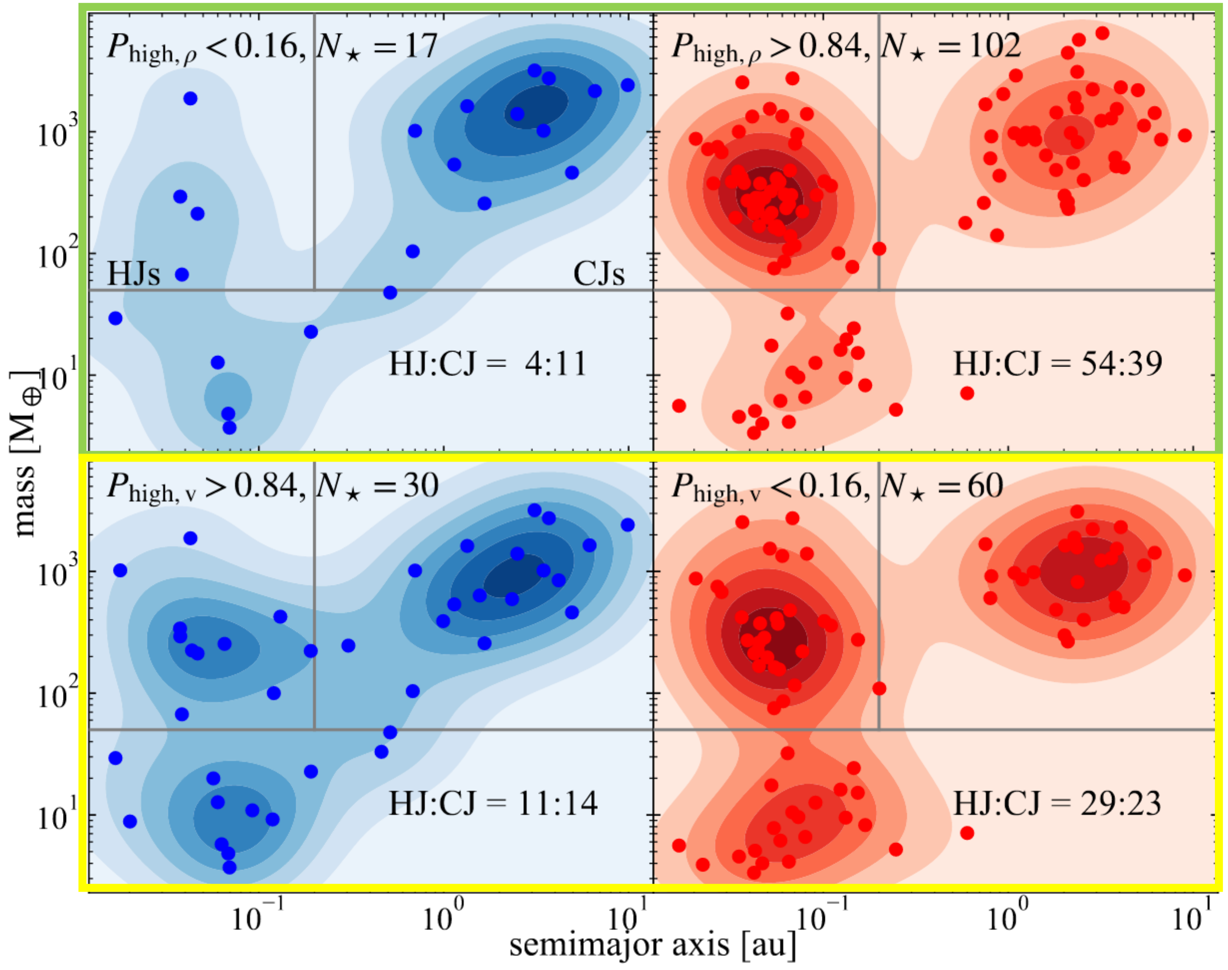
Take home messages

- The origin of phase space overdensities (cold kinematics) could be remnants of birth environments, galactic perturbation of late time or age biased, while the last is not favored.

- The detailed mechanisms for phase space overdensities to influence planetary system are diverse. Further investigation could potentially reveal the formation channel of Hot Jupiters.

Backup slides

Age Bias



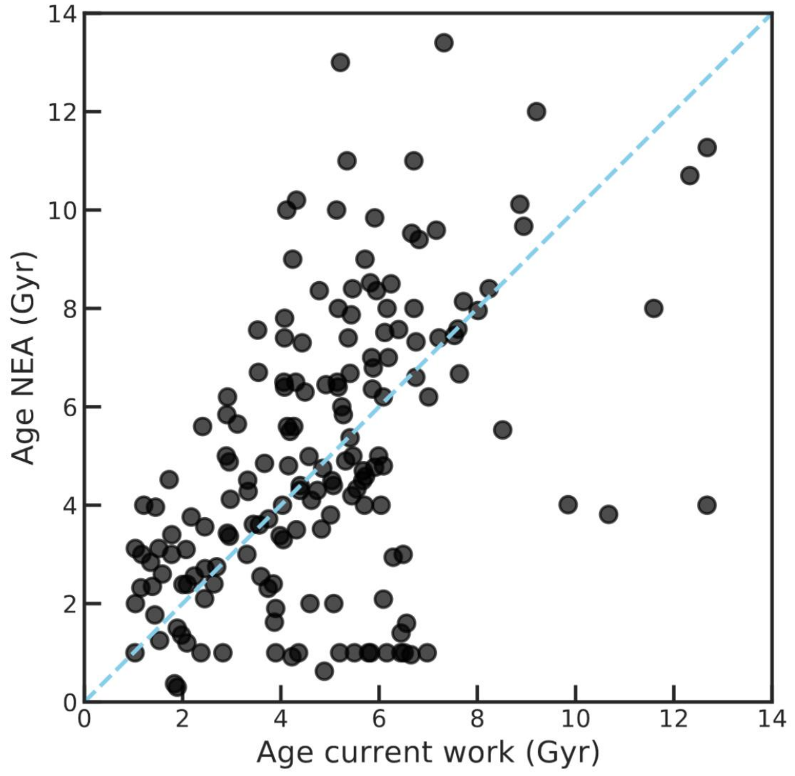
- reproduce by peculiar velocity

phase space density high → more HJ

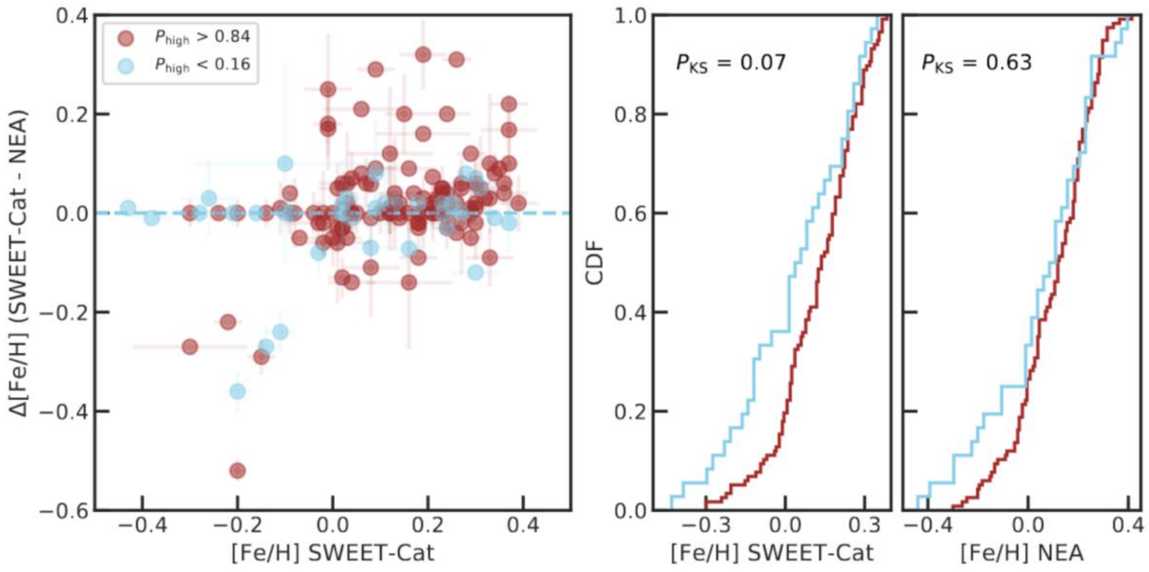
peculiar velocity low → more HJ

(Mustill et al., 2022)

Importance of homogeneity of stellar parameters



Ages determined from isochrone lines in HR diagram.

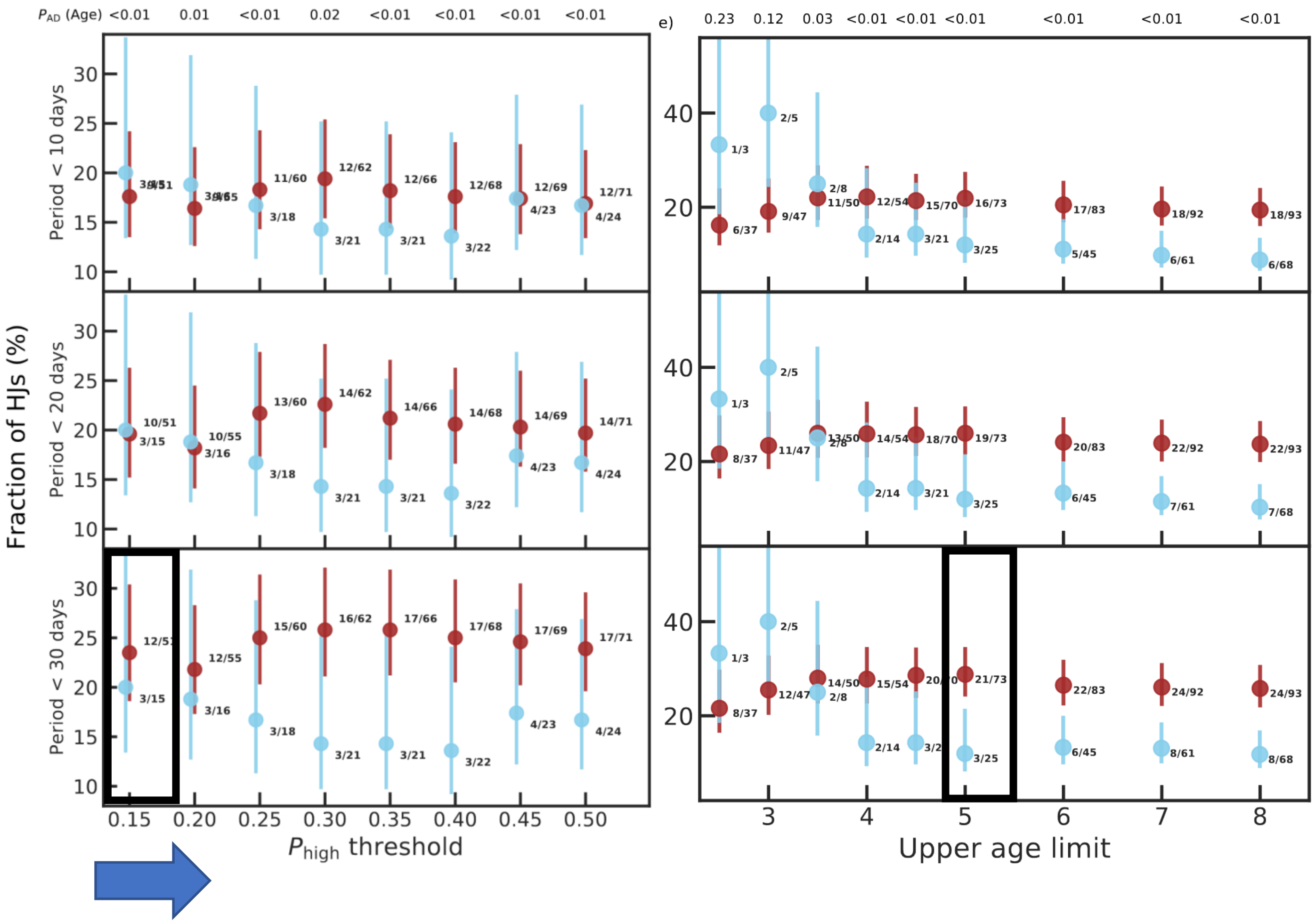


Using different methods to derive stellar properties leads to discrepancies in the results.

They use a sample with **homogeneously** determined stellar parameters (SWEET-Cat)

Adibekyan et al, A&A, 2021

Ambiguous results in small sample



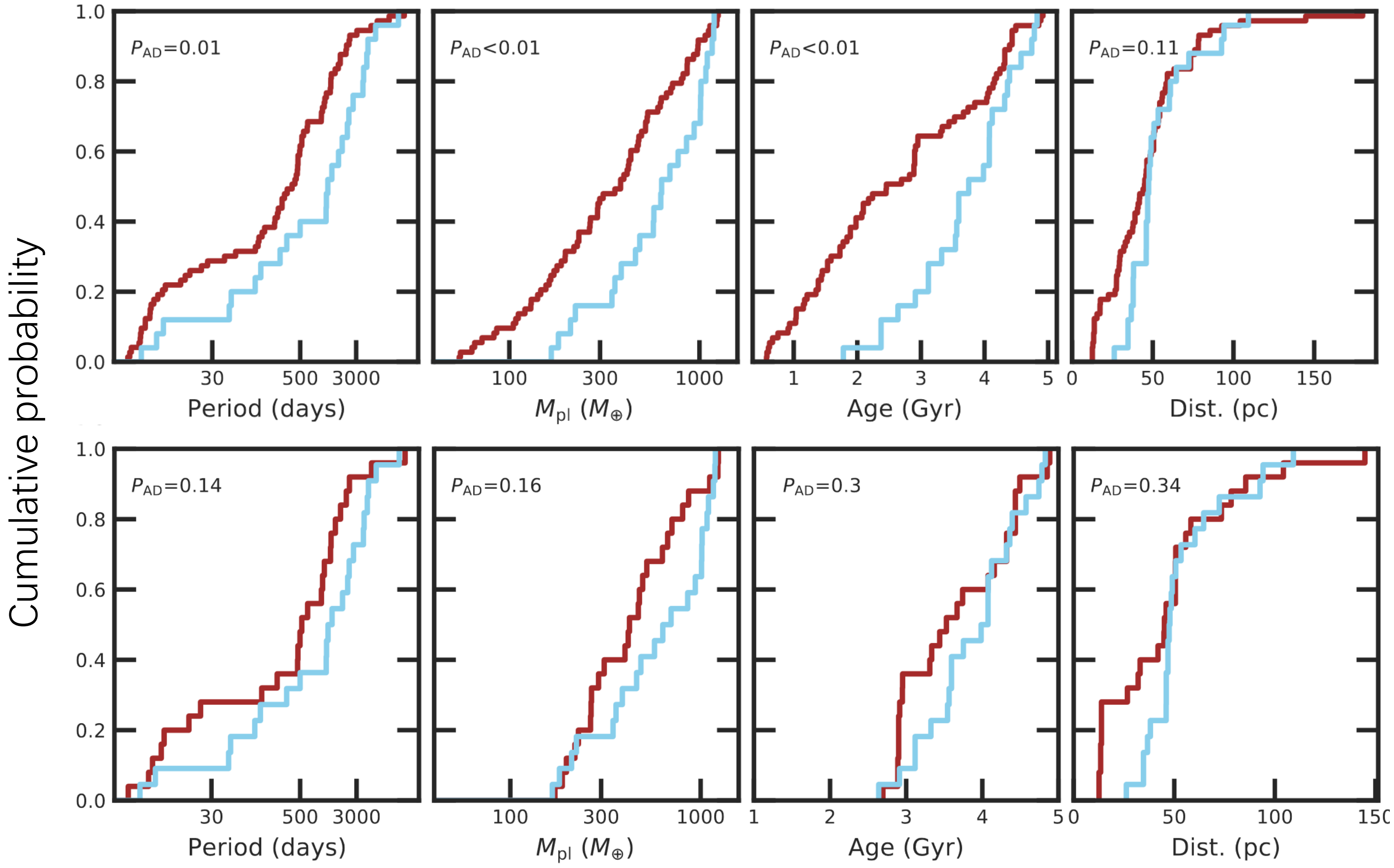
Loose constraints on overdensity criterion.

Adibekyan et al, A&A, 2021

Fiducial sample:
AGE: (1-5 Gyr)
$P_{high} = 0.84$
$(N_{overdensity}, N_{field})$=**(52, 15)**
(HJ:CJ) / (HJ:CJ) ~ 1.2

Extended sample:
AGE: (0.5-5 Gyr)
$P_{high} = 0.7$
$(N_{overdensity}, N_{field})$=(73, 25)
(HJ:CJ) / (HJ:CJ) ~ 2.4

Ambiguous results in small sample



Adibekyan et al, A&A, 2021

0.5-5 Gyr

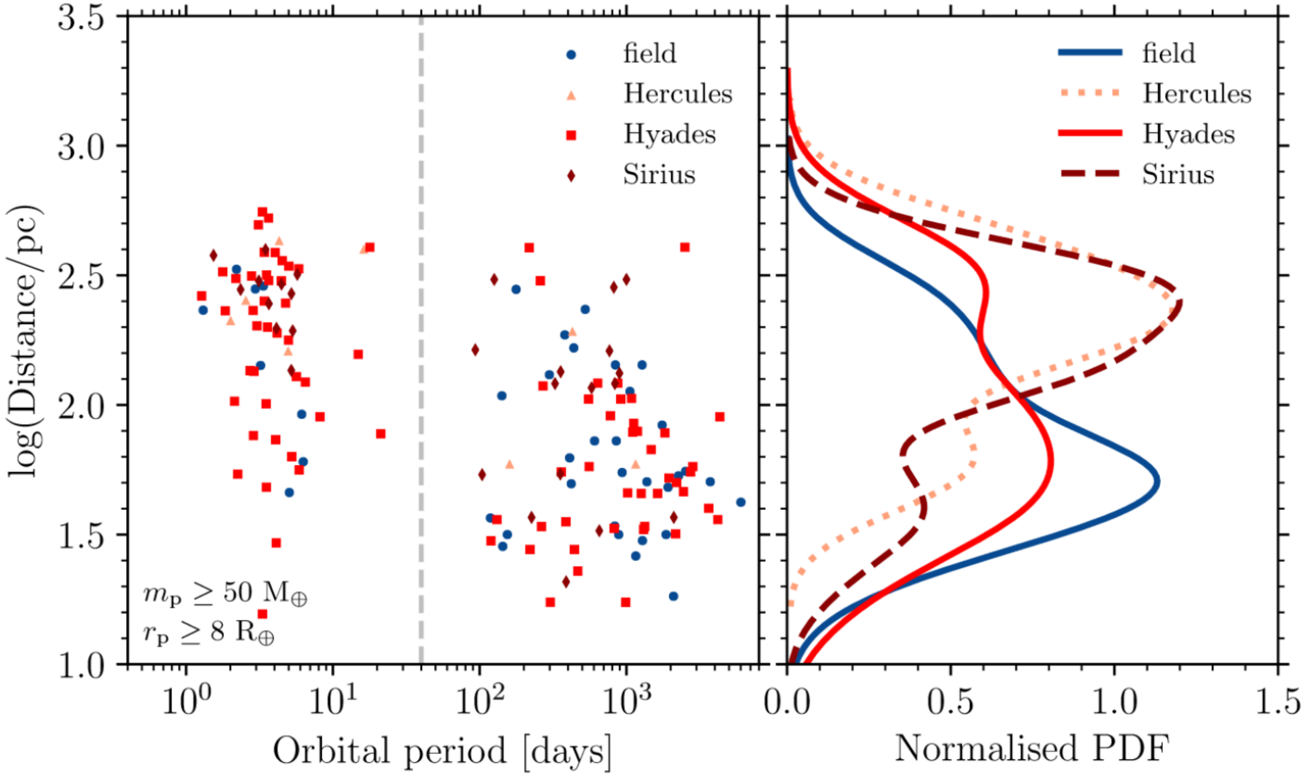
Significant difference in Period?
But also in T_eff, Age, planet mass.

2.5-5 Gyr

Tuning the sample cannot help…

Distance biased?

R-Vphi plane for example,



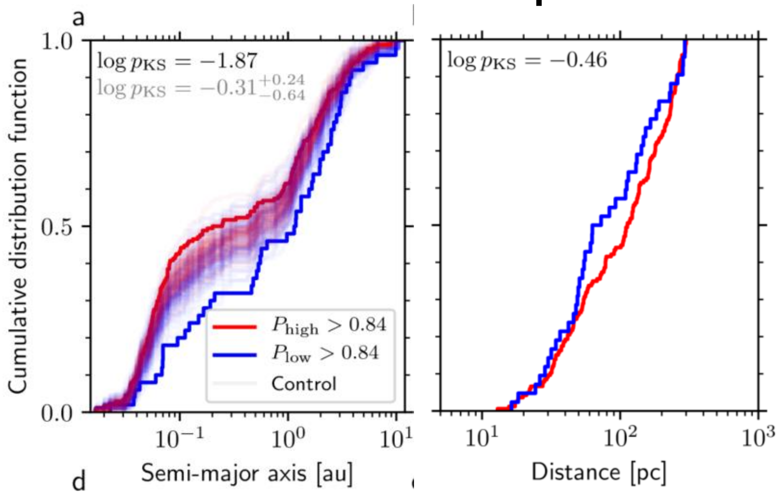
Kruijssen et al, ApJ, 2021

Correct for detectability?

CJ harder to detect than HJ using RV and transit.

Larger distance -> More HJ tend to be detected.

For D < 300 pc

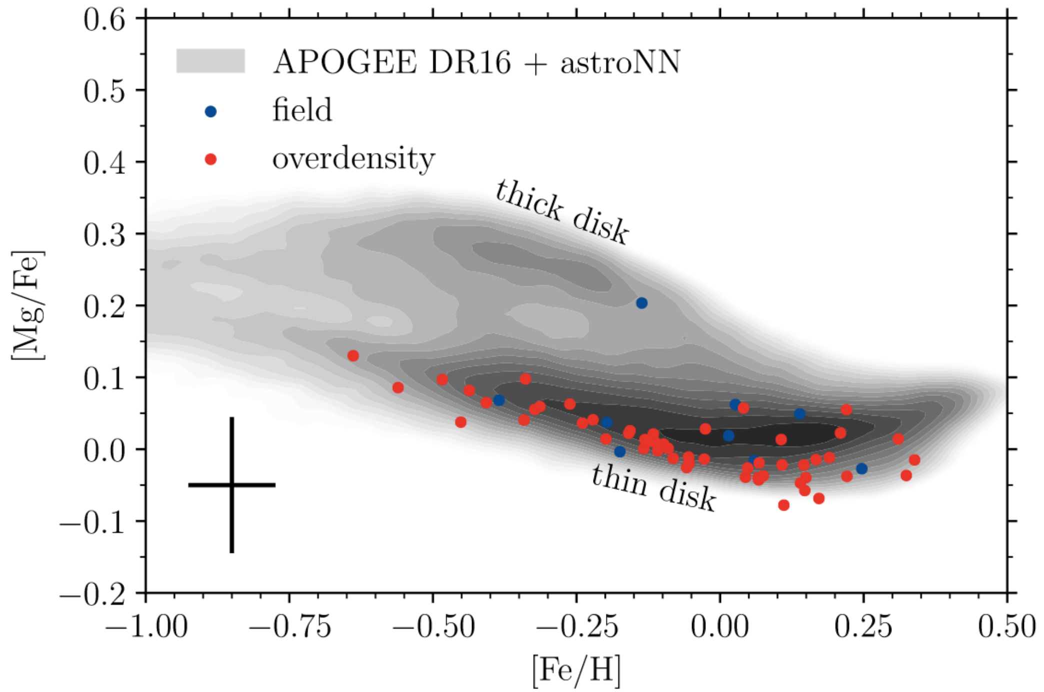


Winter et al, Nature, 2020

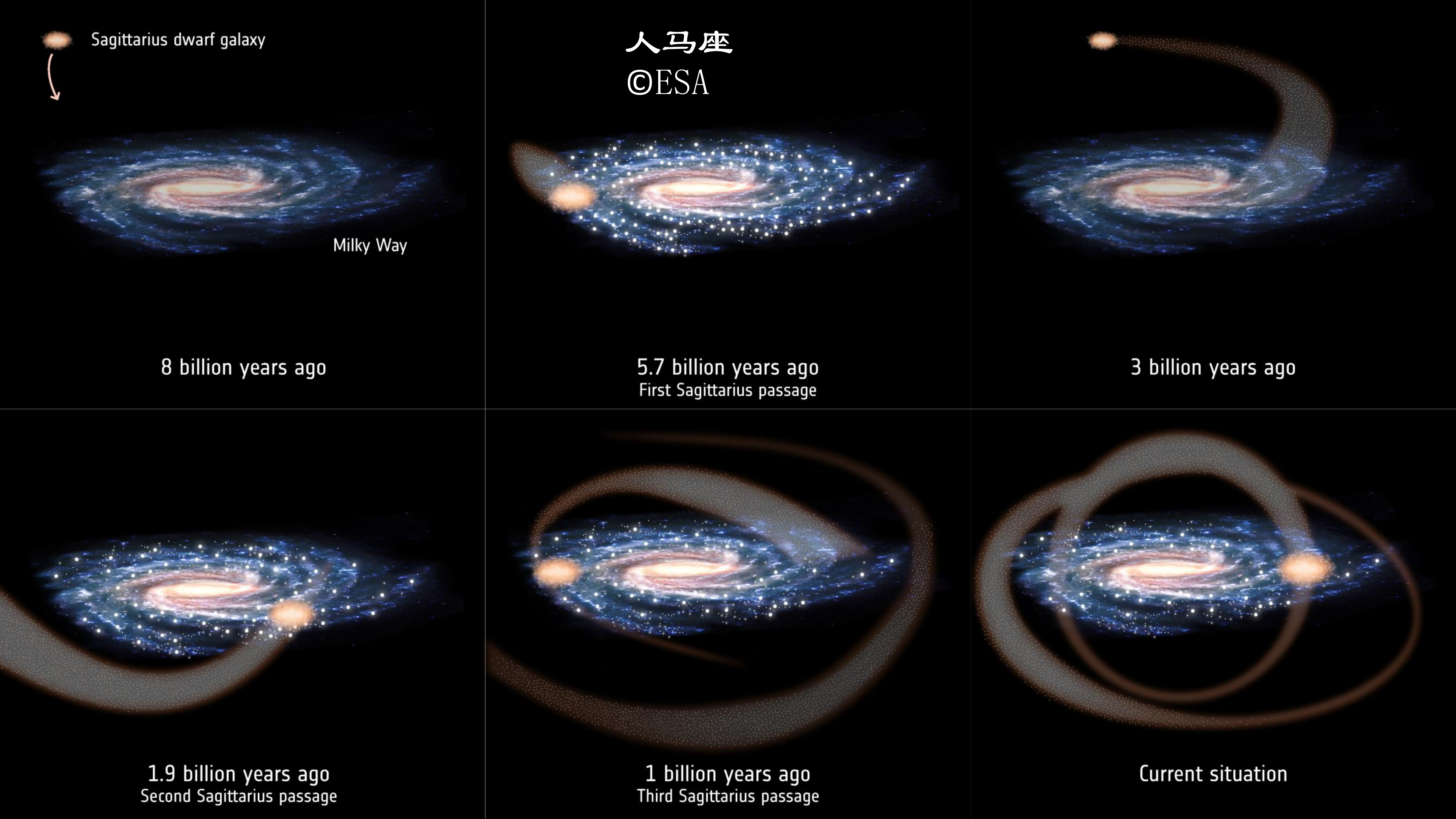
Distance indistinguishable, population difference persists

Thin disk v.s. Thick disk

- (Against Mustill+ 2021):



Kruijssen et al, ApJ, 2021


人马座
©ESA
Sagittarius dwarf galaxy
Milky Way
8 billion years ago
5.7 billion years ago
First Sagittarius passage
3 billion years ago
1.9 billion years ago
Second Sagittarius passage
1 billion years ago
Third Sagittarius passage
Current situation

Background question

Hot Jupiter, what is tidal inspiral ?

How to determine stellar ages：

Isochrone: HR diagram (metallicity, mass)

As Membership in star cluster.

Rotational rate.