The Orbital Dynamics of Small Stars and their Exoplanets

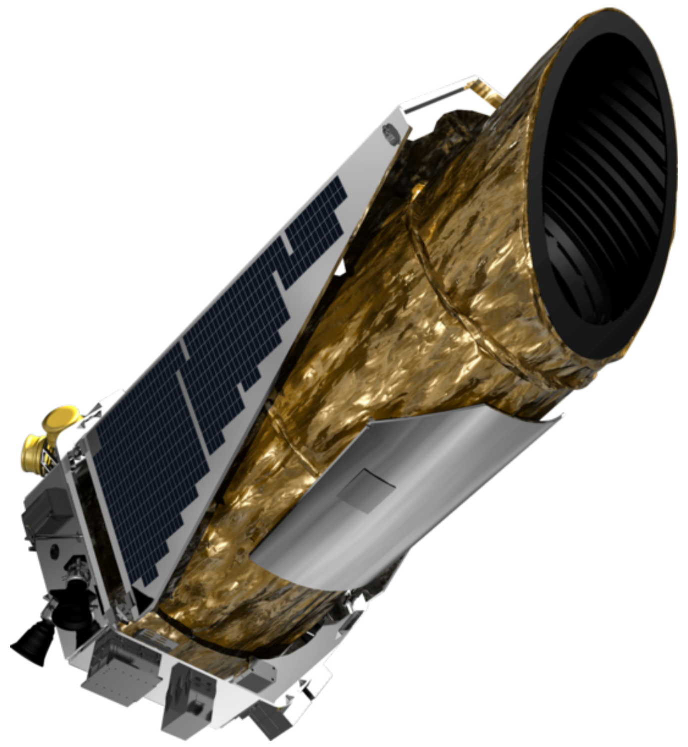
Sheila Sagear

Ph.D. Candidate @ the University of Florida

Advisor: Sarah Ballard

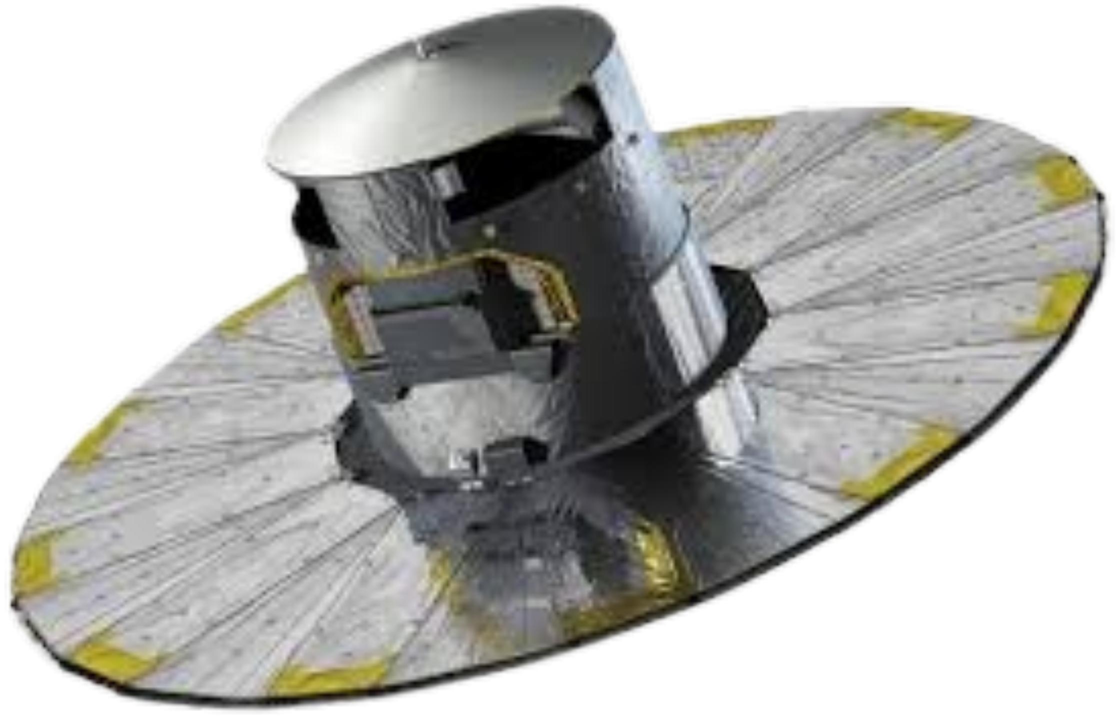
Exoplanet demographics

There is a LOT of exoplanet data.



Kepler/K2

TESS



Gaia

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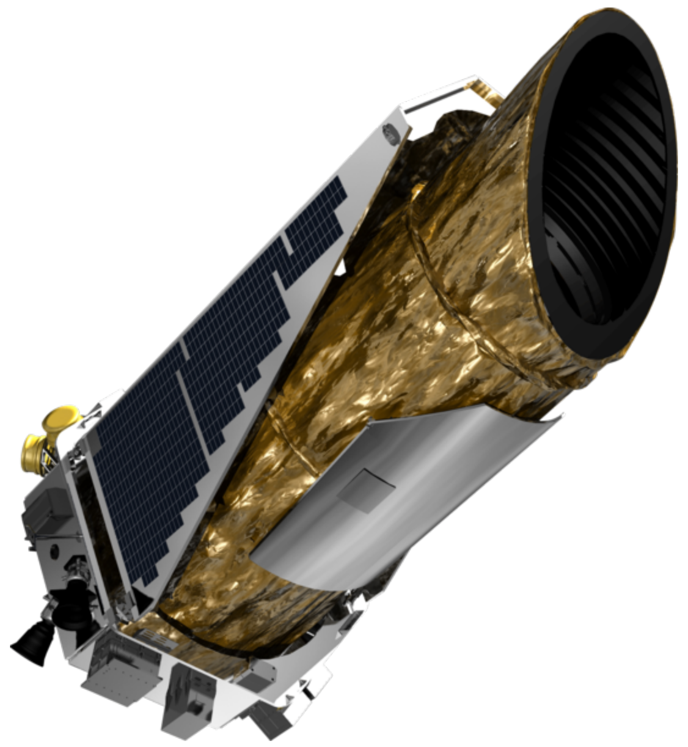

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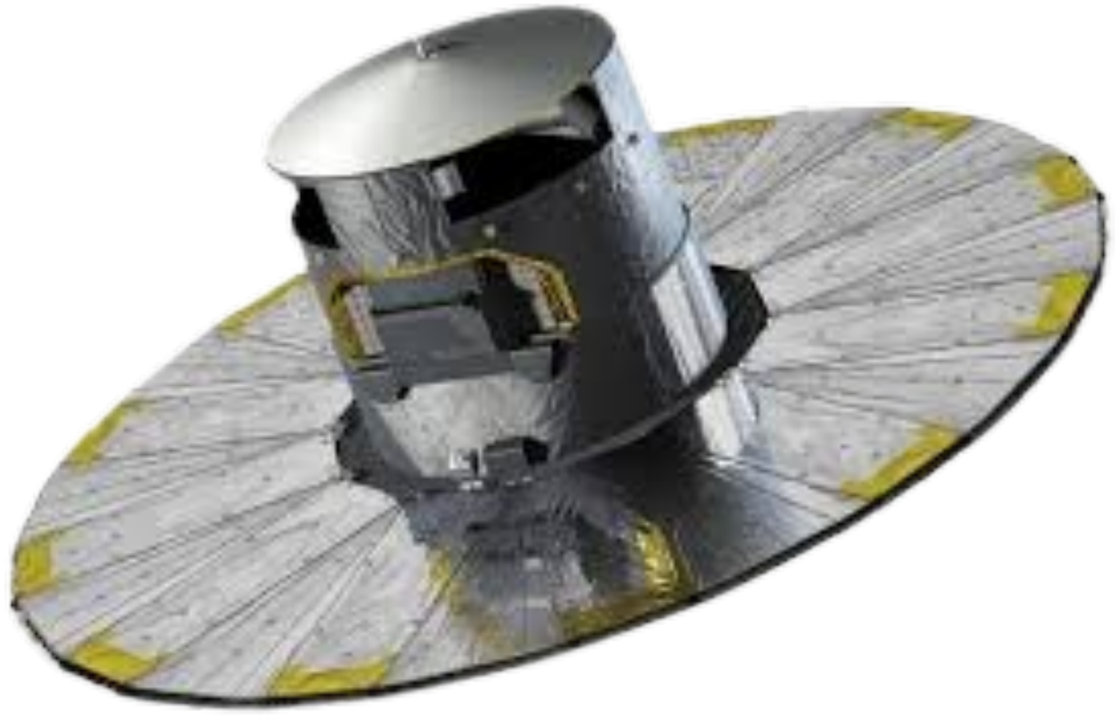
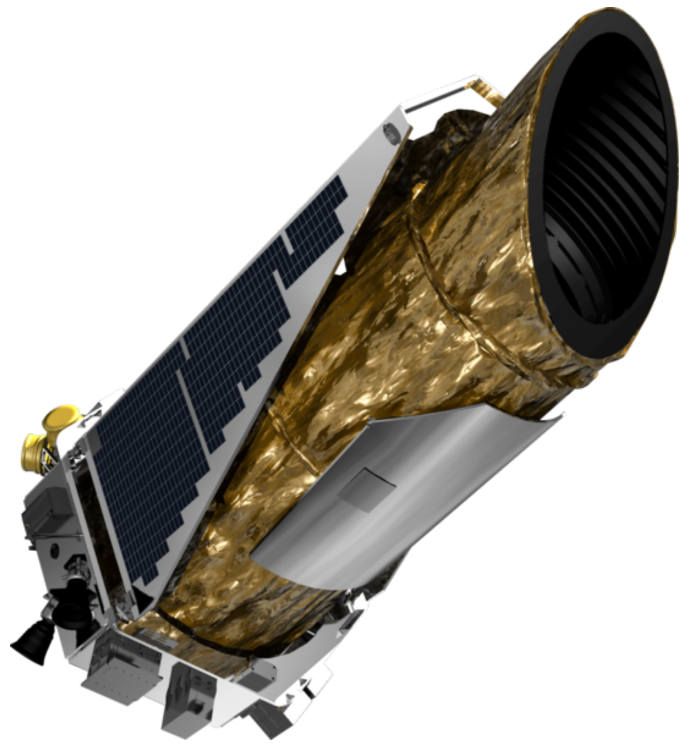


Gaia

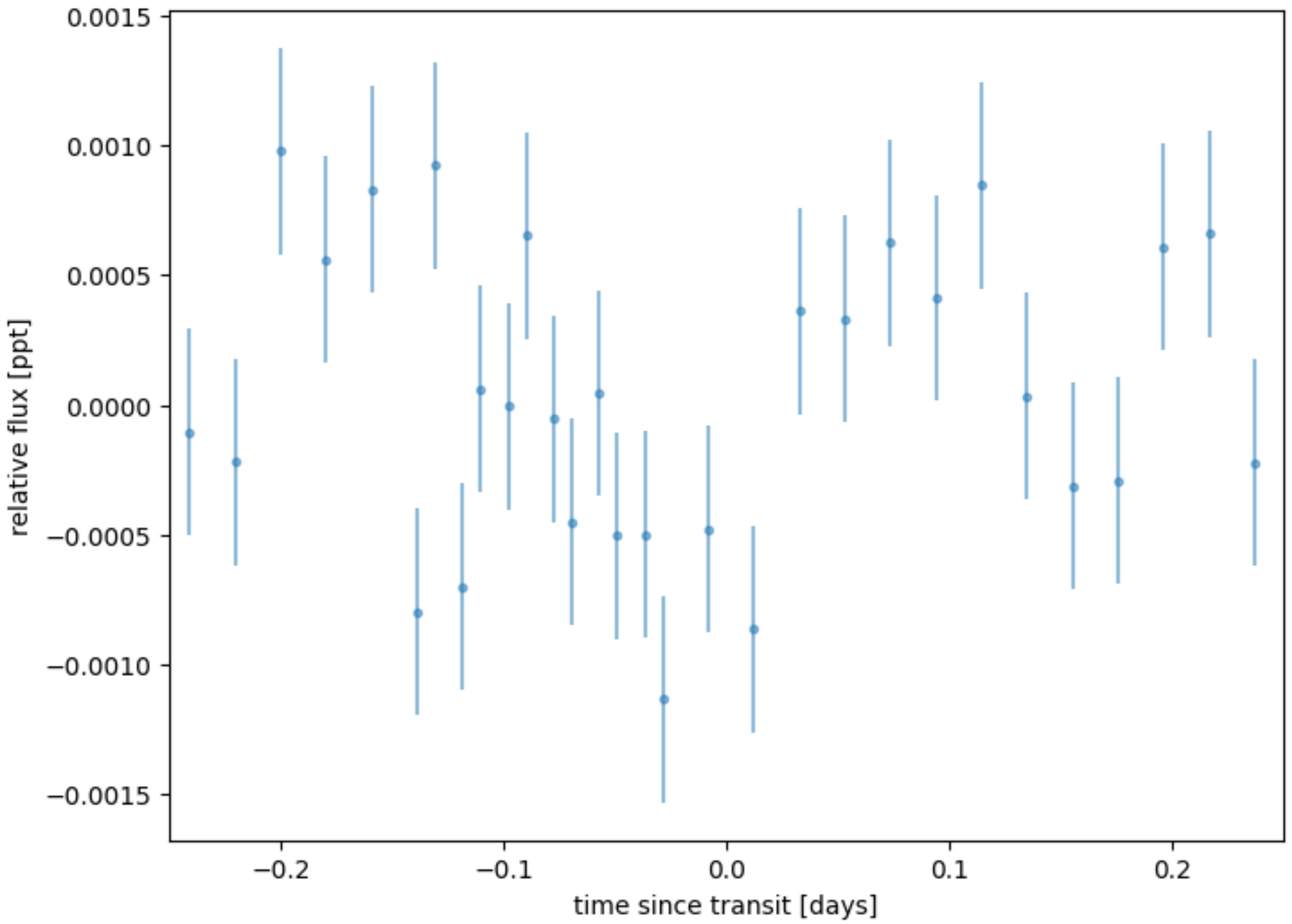
stellar parameters, kinematic measurements, and
thousands upon thousands of transit light curves

Exoplanet demographics



However, the precision of these data varies…

One transit of Kepler-42b



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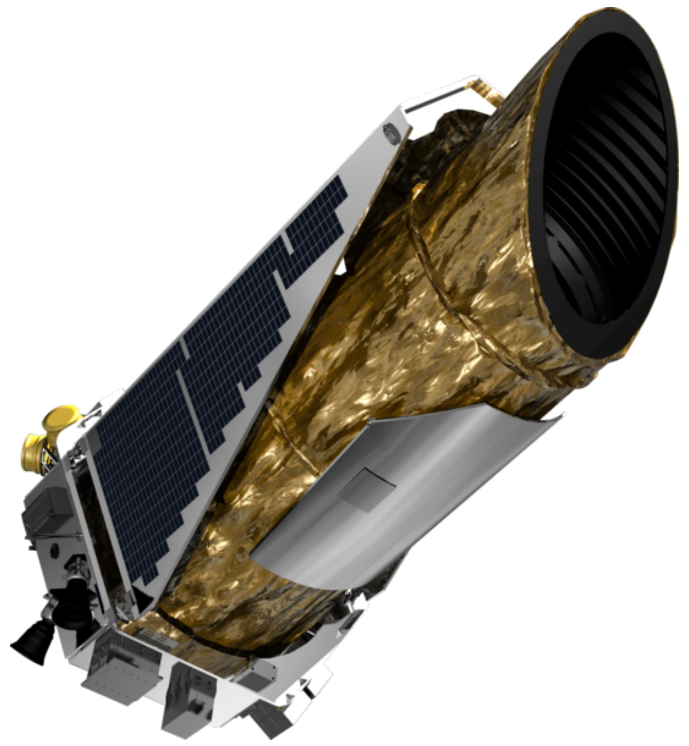

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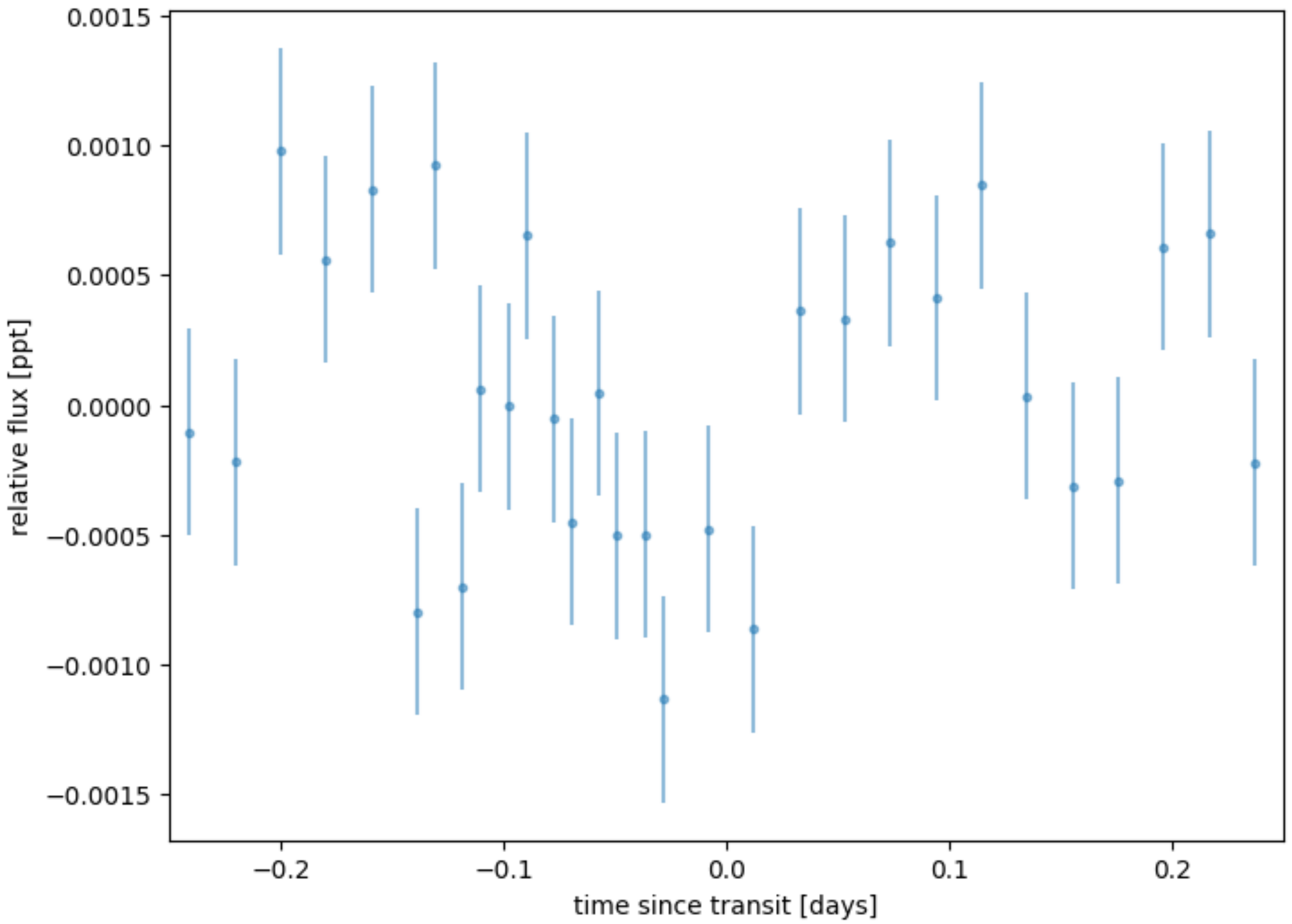
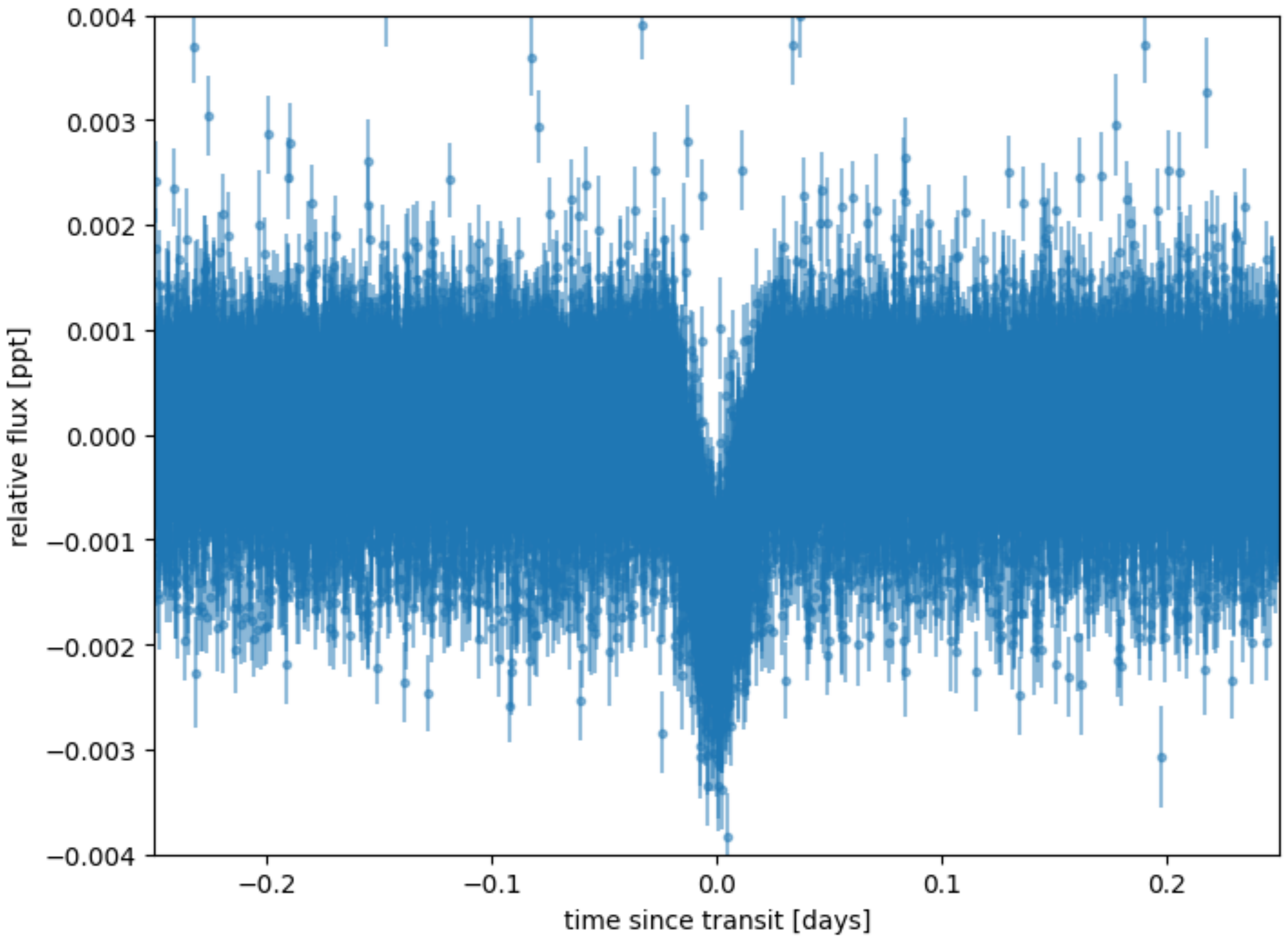
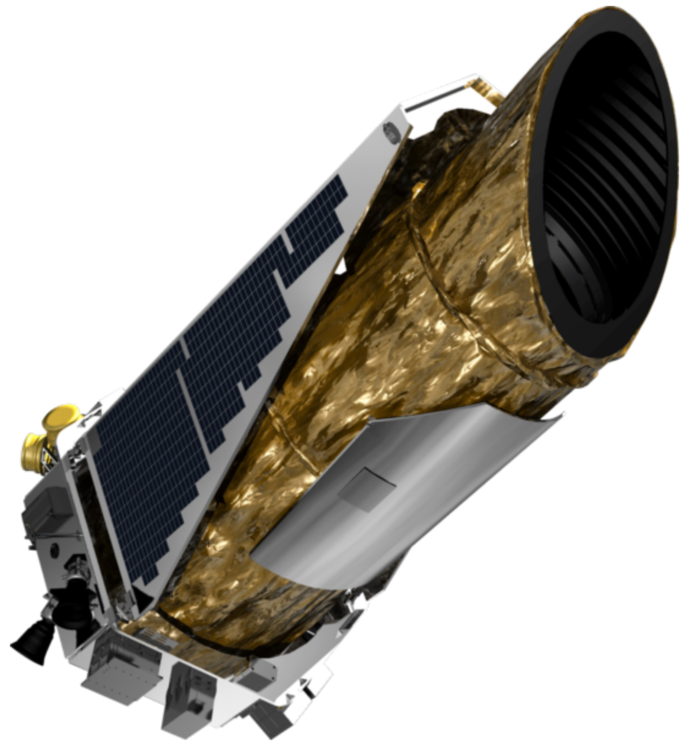


Combined transits of Kepler-42b over several years



Exoplanet demographics



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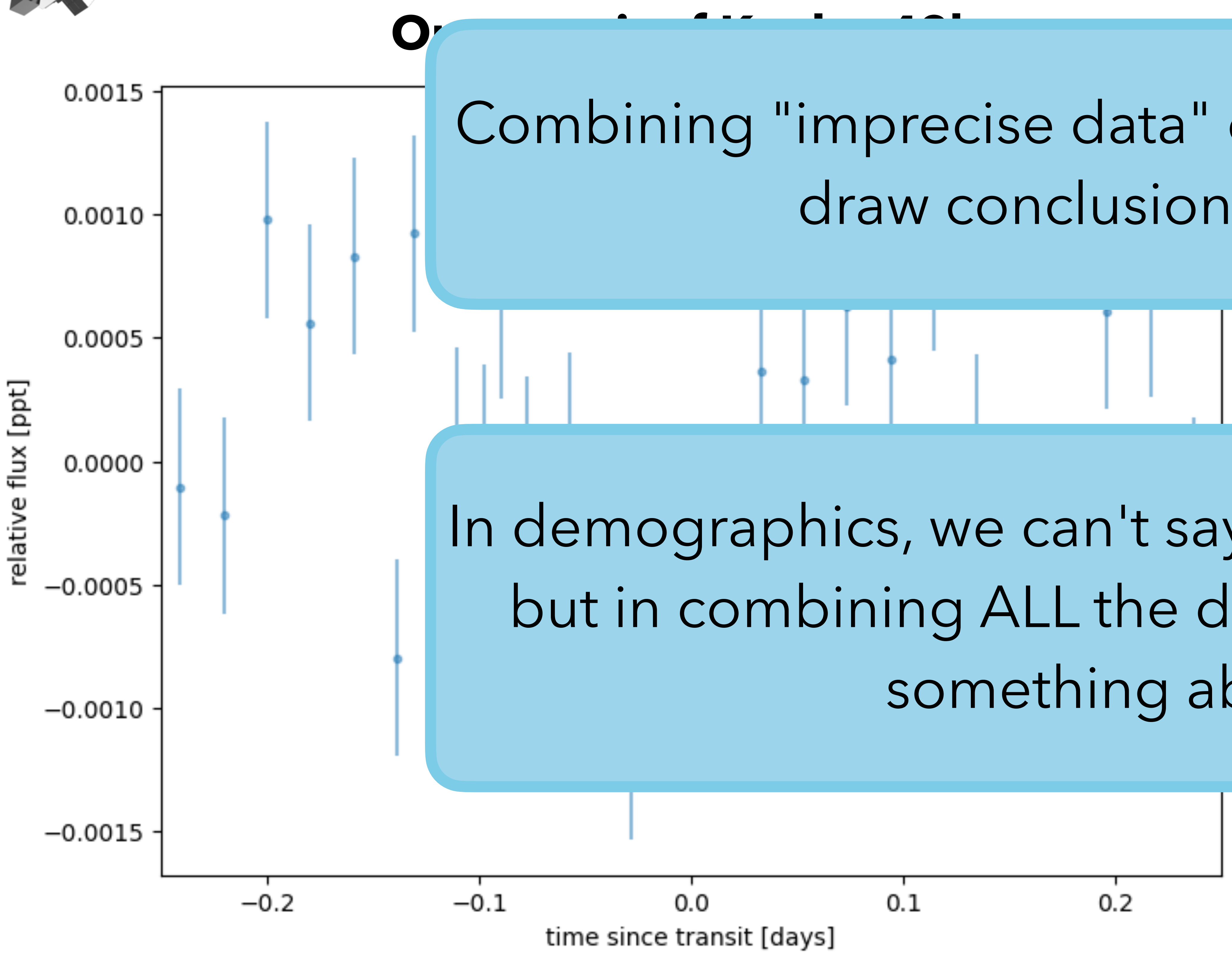

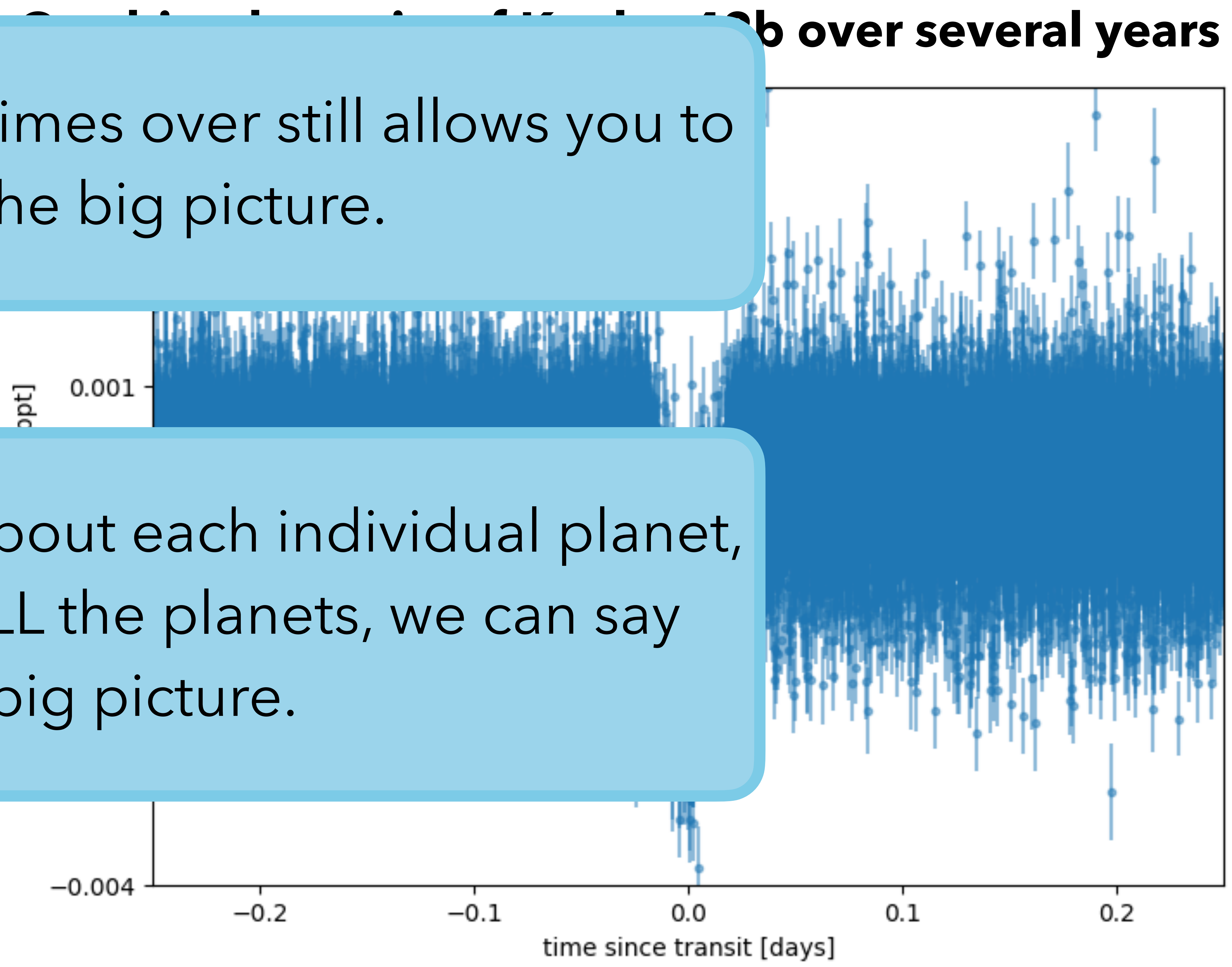

Combining "imprecise data" enough times over still allows you to draw conclusions about the big picture.

In demographics, we can't say much about each individual planet, but in combining ALL the data for ALL the planets, we can say something about the big picture.

What can orbits tell us?

A planet's orbital dynamical state is a signature of its formation and evolution, and gives us clues about its climate and potential for habitability.

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We often assume that planets form in stationary isolation—but that isn't true.
How might planetary systems be affected by their Galactic environment?

In order to answer this question, we need to understand planetary orbital dynamics and stellar/Galactic dynamics.

The Orbital Dynamics of Small Stars and their Exoplanets

1. The orbital eccentricity distribution for M dwarf planets

2. The eccentricity–radius relation for M dwarf planets

3. Dynamical stellar ages using *Gaia* kinematics

4. The impact of Galactic dynamics on planetary dynamics

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Why M dwarf planets?

- M dwarfs ($M < 1M_{\odot}$; $T_{eff} < 4000K$) have emerged as the ***predominant exoplanet hosts***:
  - They are abundant
  - They often host small, rocky planets

1. The orbital eccentricity distribution for M dwarf planets

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Why eccentricities?

- Eccentricity influences planets' tidal heating and variable insolation
- This is particularly important for M dwarf planets, with close-in orbits and narrow habitable zones

1. The orbital eccentricity distribution for M dwarf planets

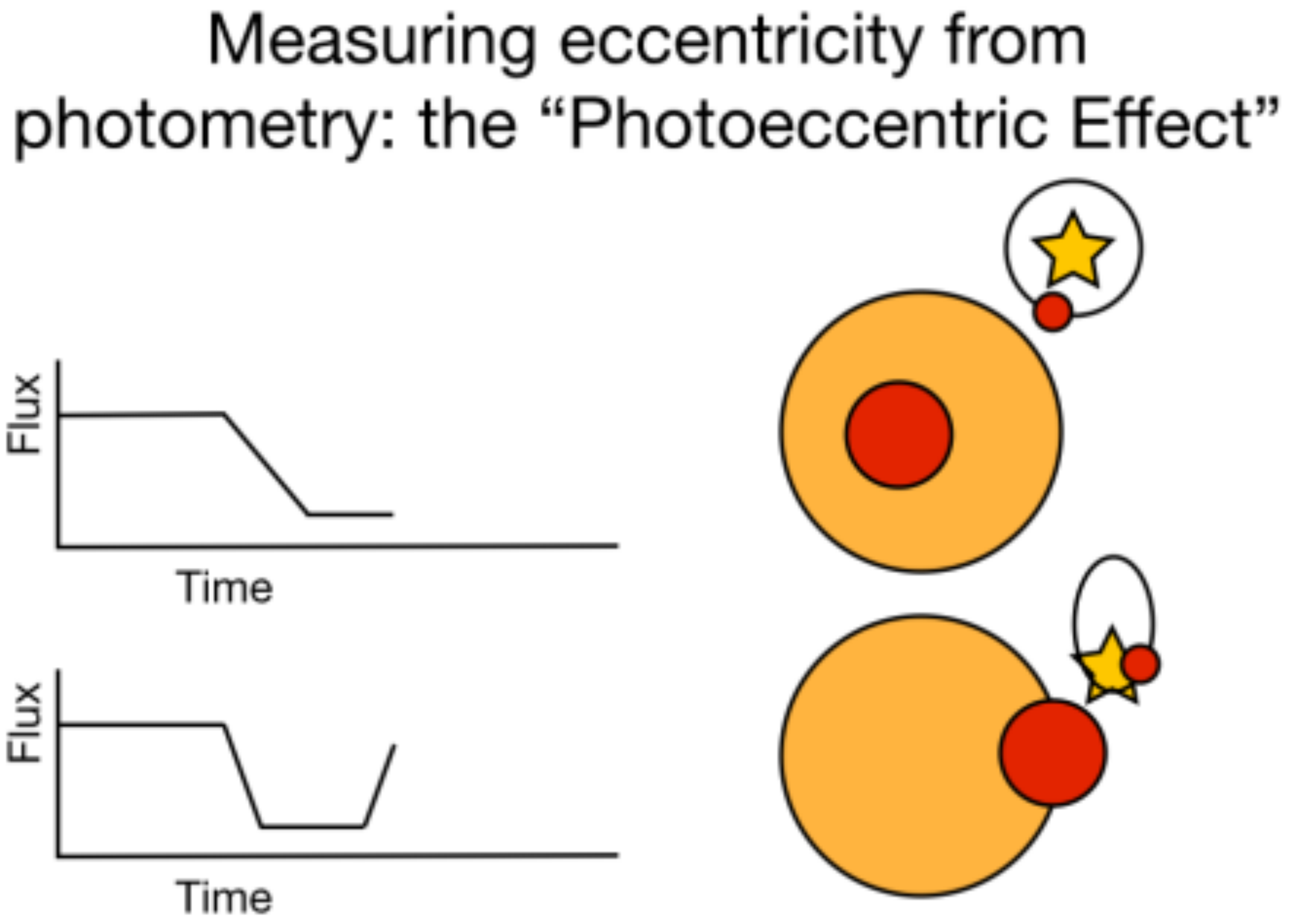
The problem: Transit light curves are abundant, but not well-suited for drawing out precise dynamical information.

We take advantage of the abundance of data by combining individual, **imprecise** dynamical measurements to come to a demographic conclusion.

1. The orbital eccentricity distribution for M dwarf planets

Transit light curves are not designed to give us precise dynamical information about individual planets (i.e. eccentricities).

But we *can* indirectly measure eccentricities by measuring the velocity of the transiting planet via the transit duration. (Dawson & Johnson 2012)



Credit: Rebecca Dawson

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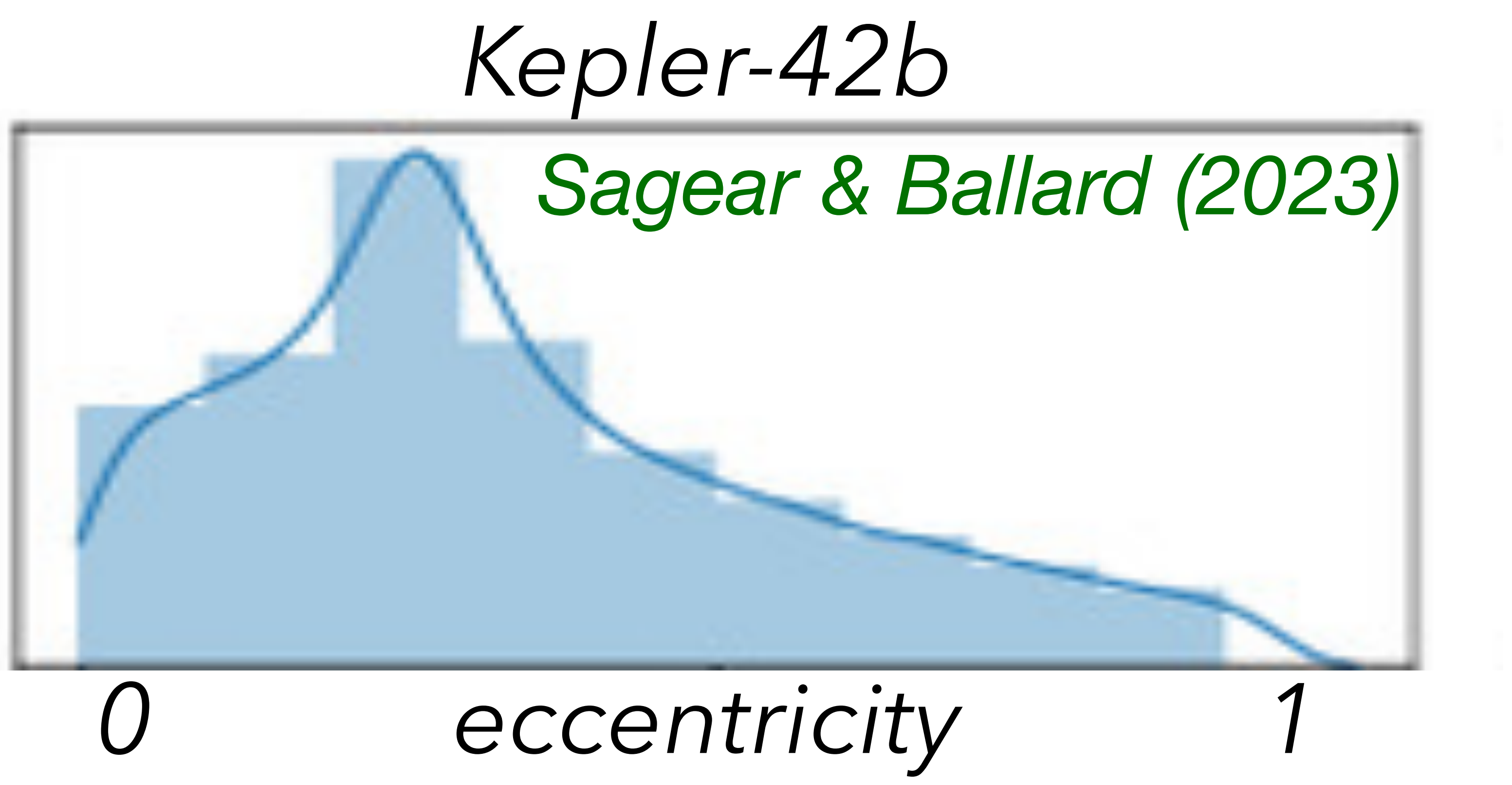
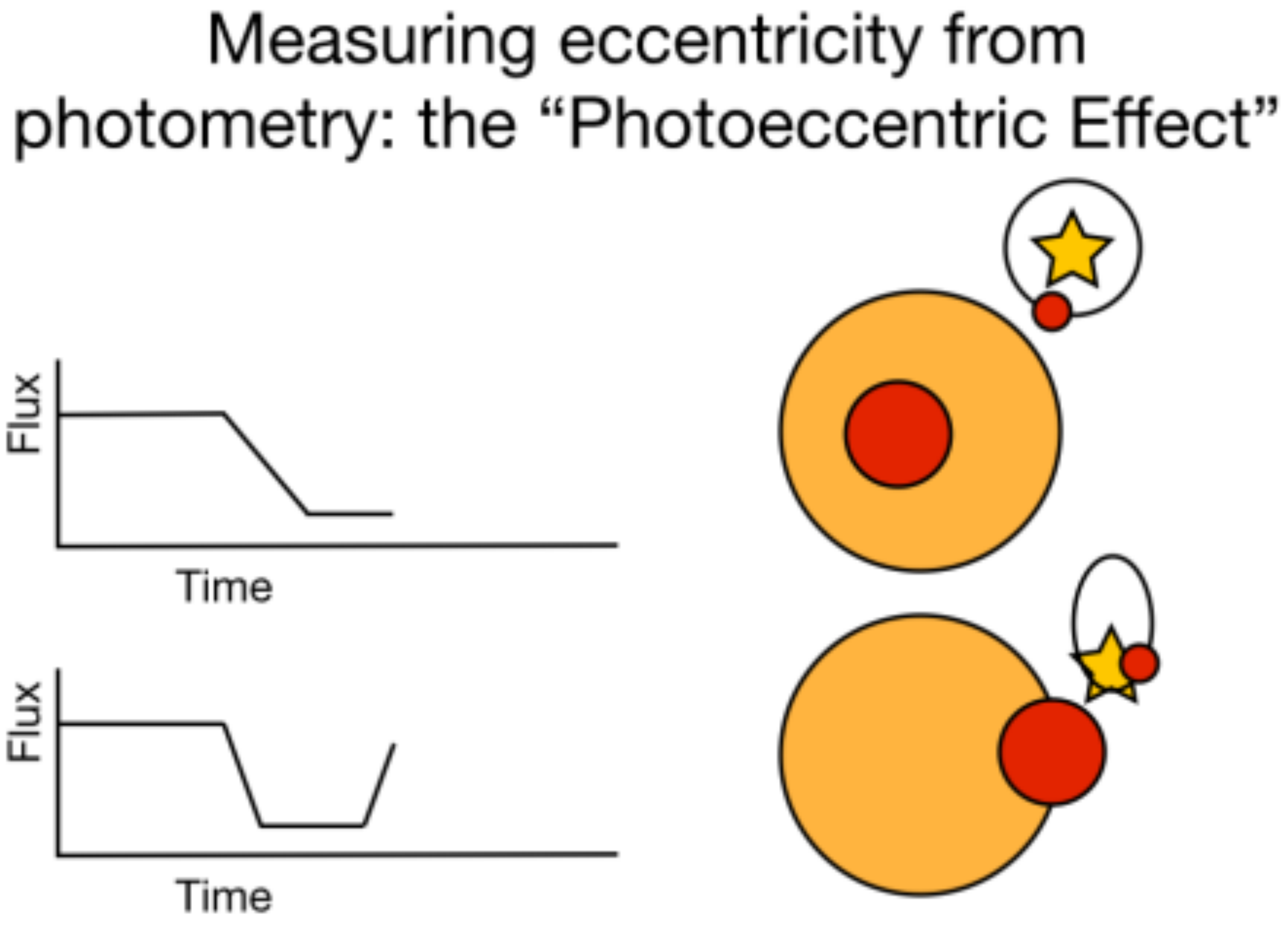
The "photoeccentric effect" gives us wide eccentricity posteriors, but *SO MANY* of them.





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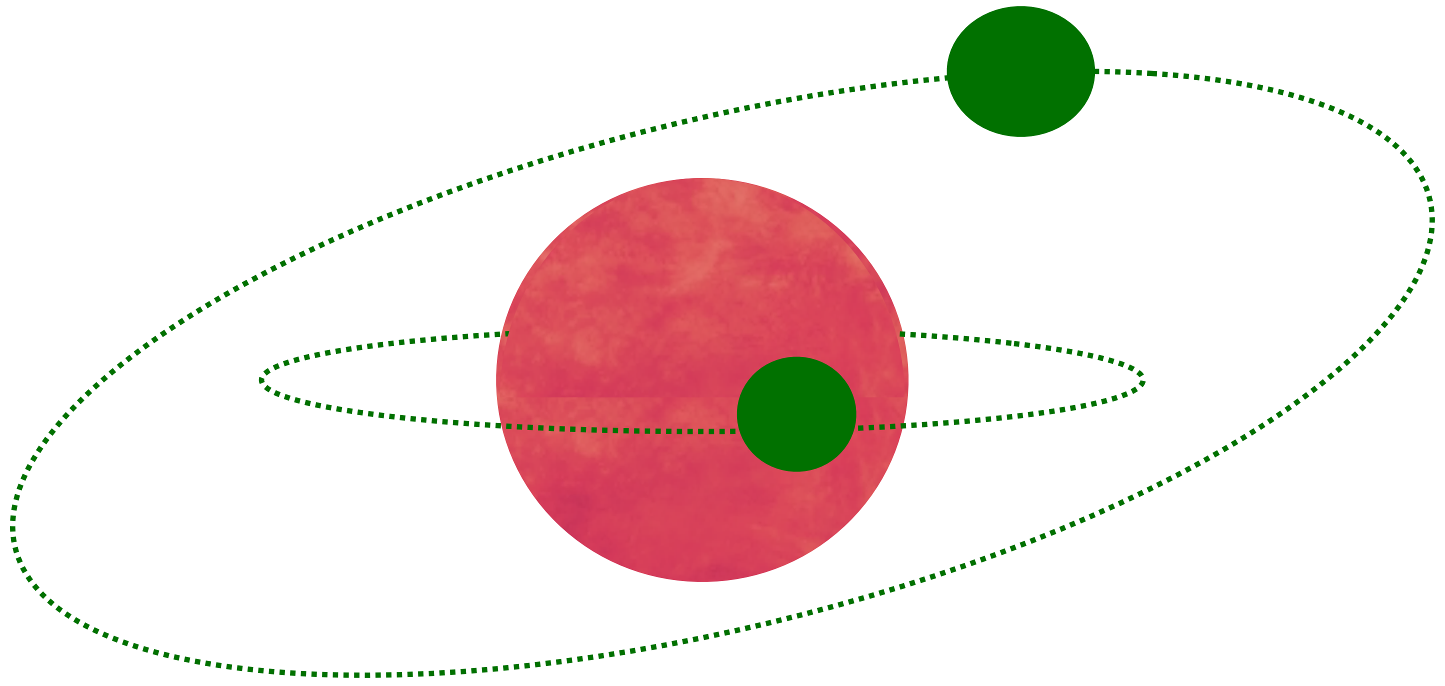
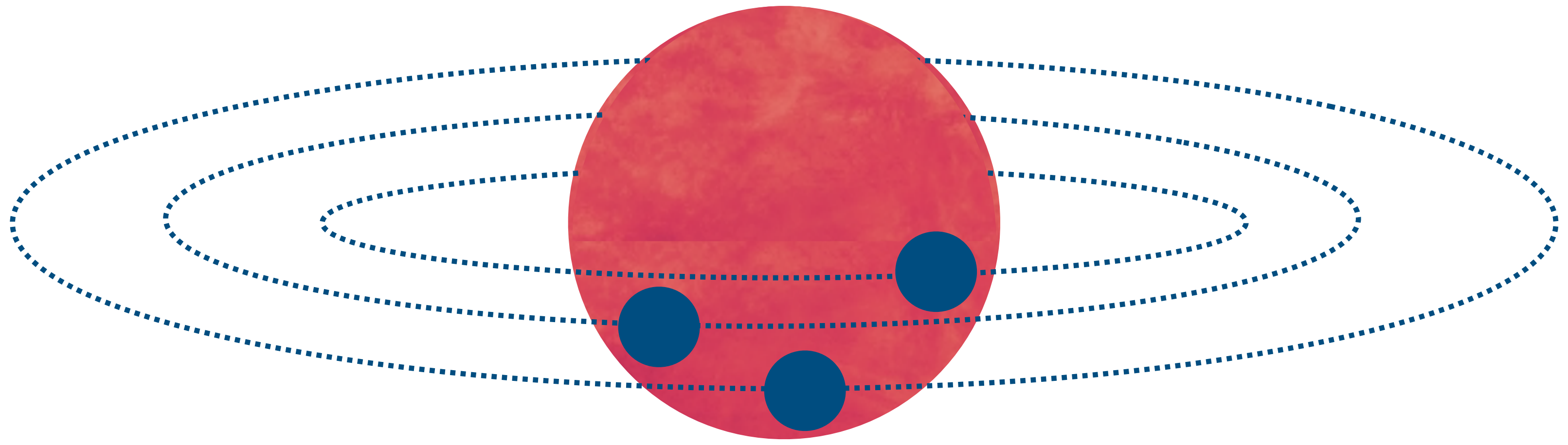
1. The orbital eccentricity distribution for M dwarf planets

"Singles" vs. "Multis"

- ***Single-transit*** systems have one planet that transits the star, from our point of view.
  - There could be more planets that we just can't see!



- ***Multi-transit*** systems have more than one transiting planet.



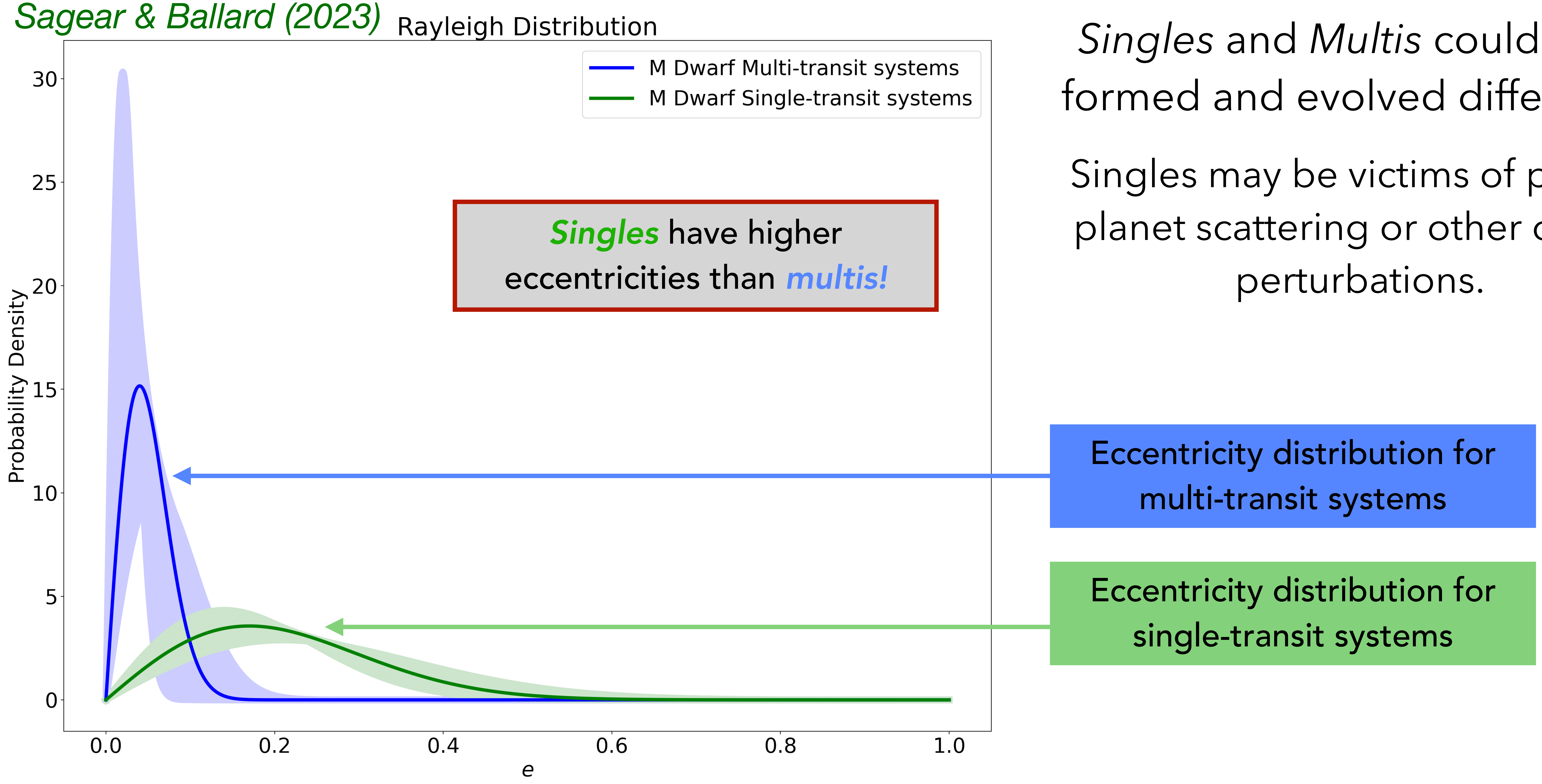
There are several observable differences between these two populations.

1. The orbital eccentricity distribution for M dwarf planets

Sagear & Ballard (2023)

One of these differences is their eccentricity distributions.

Sagear & Ballard (2023)



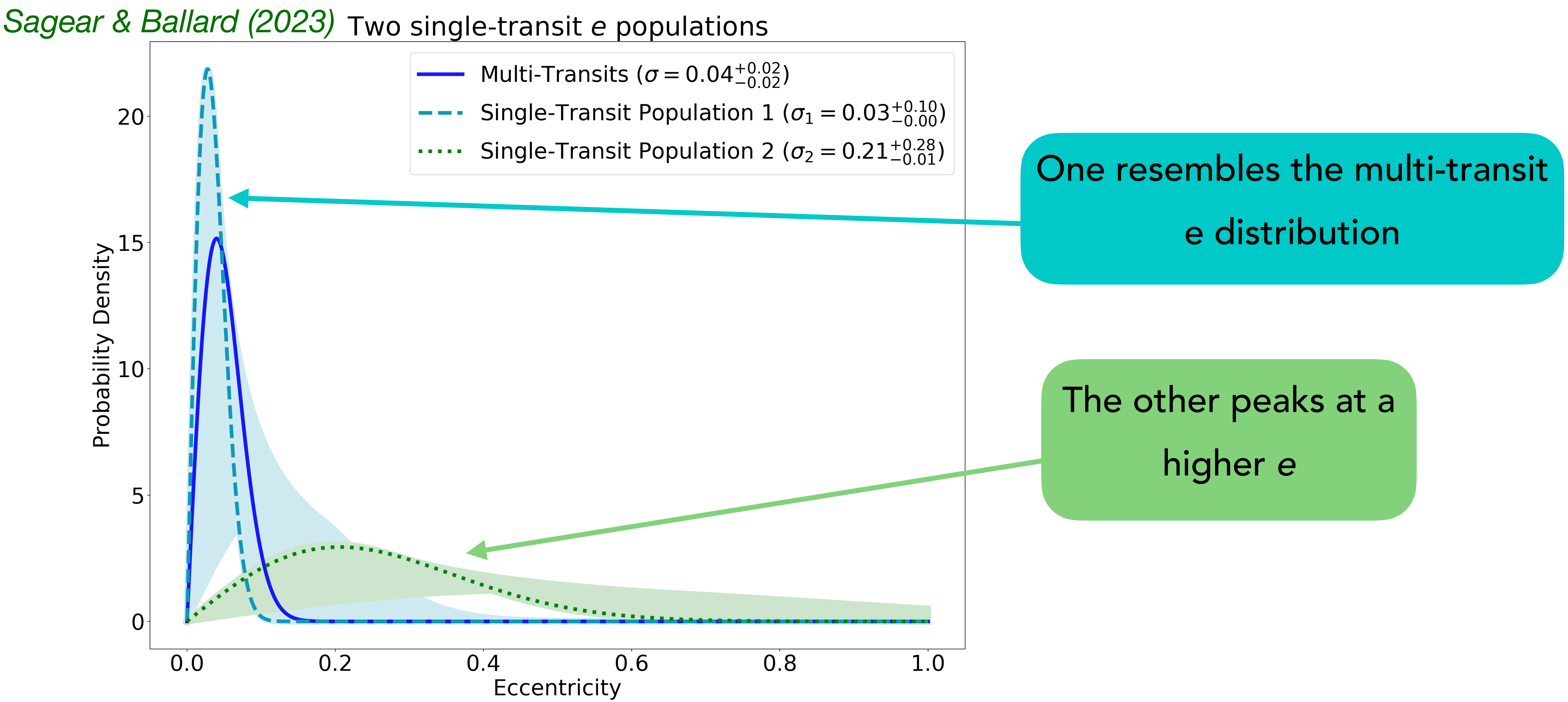
Singles and *Multis* could have formed and evolved differently.

Singles may be victims of planet-planet scattering or other orbital perturbations.

1. The orbital eccentricity distribution for M dwarf planets

Sagear & Ballard (2023)

There are two distinct populations within the Singles:



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Different late-stage planet evolution mechanisms imprint differently on eccentricities. For example...

- Planet-planet scattering or giant impacts may excite eccentricity
- Disk-driven migration, inelastic mergers may quench eccentricity
- Mass-loss driven by stellar luminosity (e.g. photoevaporation) may have no effect on eccentricity

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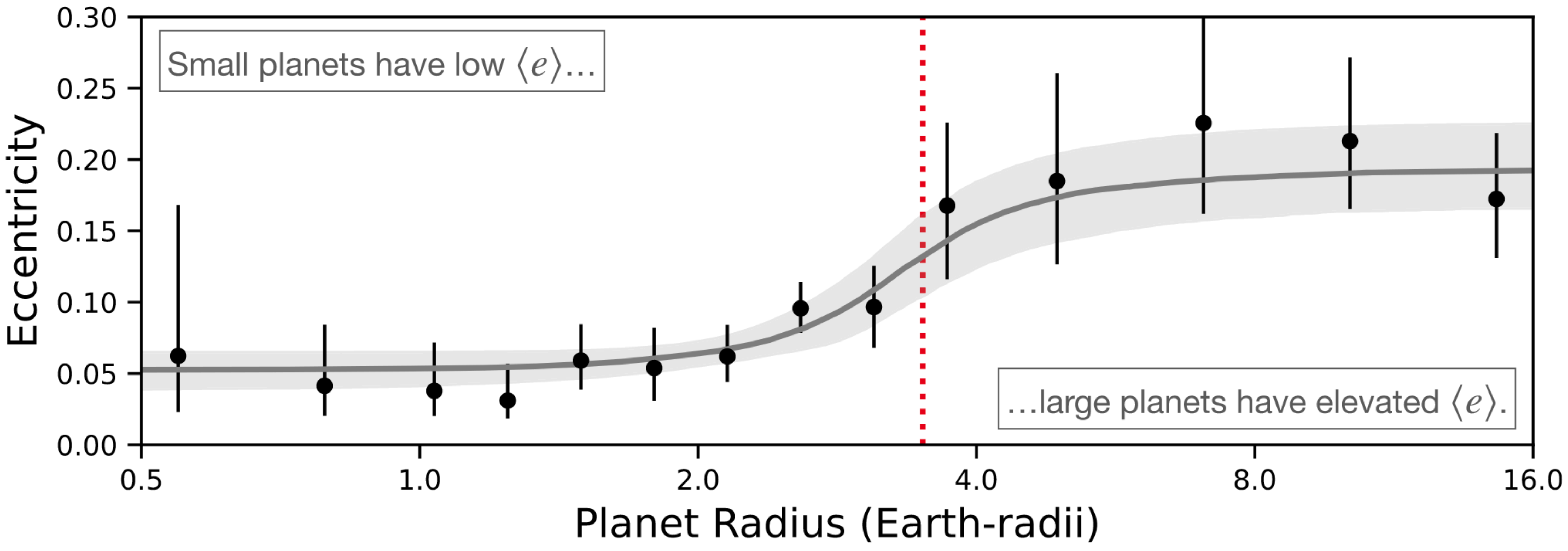
Which late-stage evolution mechanisms are dominant for M dwarf planets?

We investigate this by looking at the eccentricity--planet radius relation.

2. The eccentricity–radius relation for M dwarf planets

***Gilbert+ 2025:* Large planets orbiting *Sun-like stars* have elevated orbital eccentricities.**



What about planets around M dwarfs?

2. The eccentricity–radius relation for M dwarf planets

arXiv:2507.07169

Kepler transit light curves

+ TESS transit light curves

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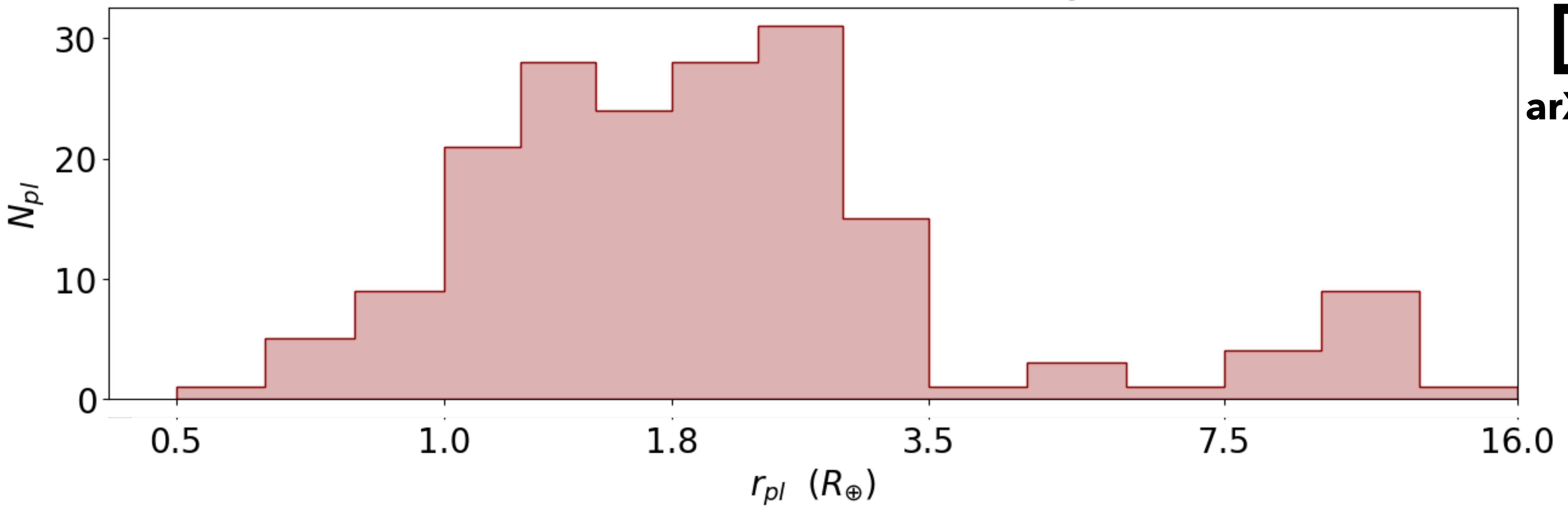
Large planets orbiting M dwarfs are rare...

Sagear+ (in review)



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And require higher stellar metallicities.

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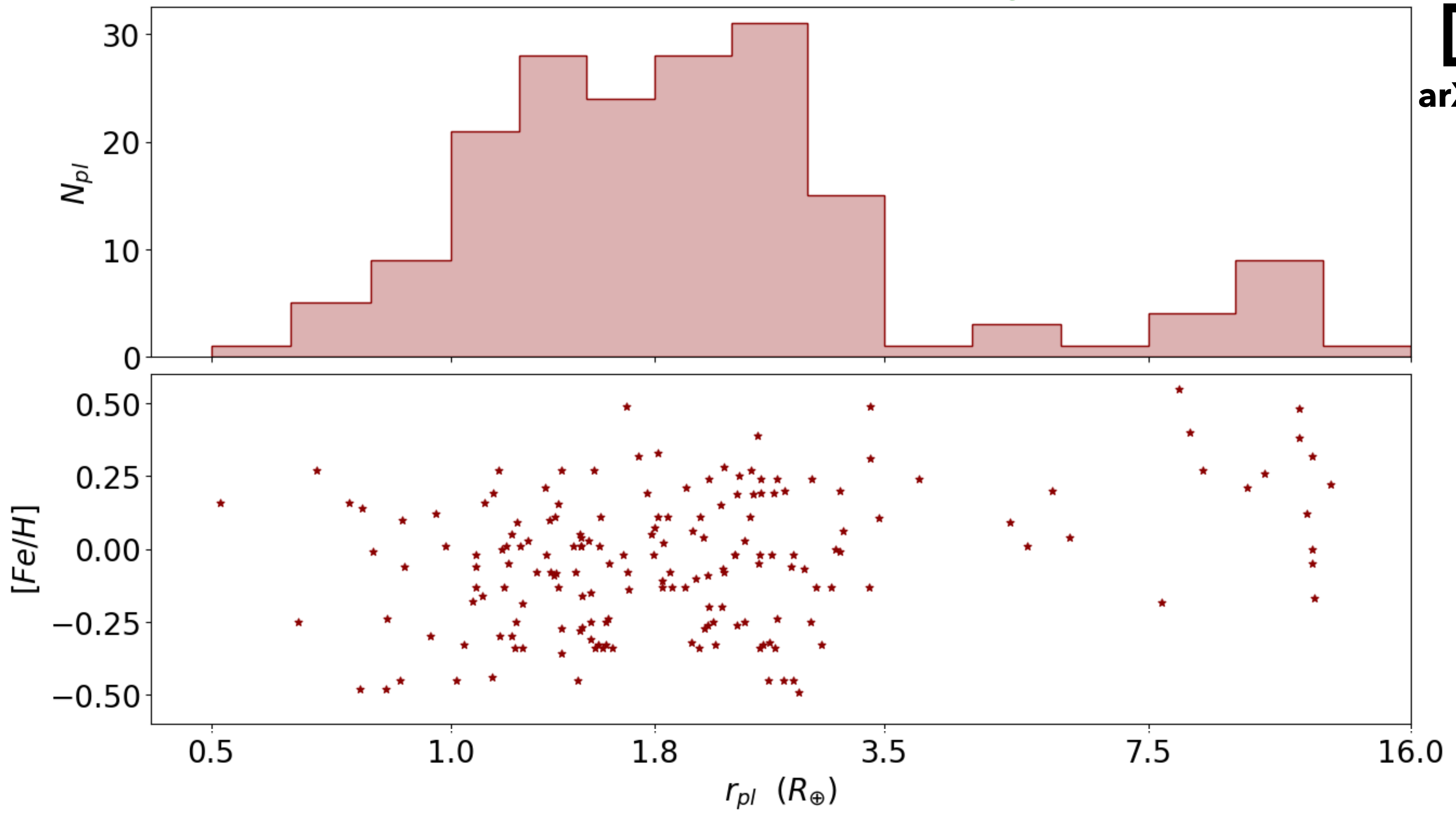

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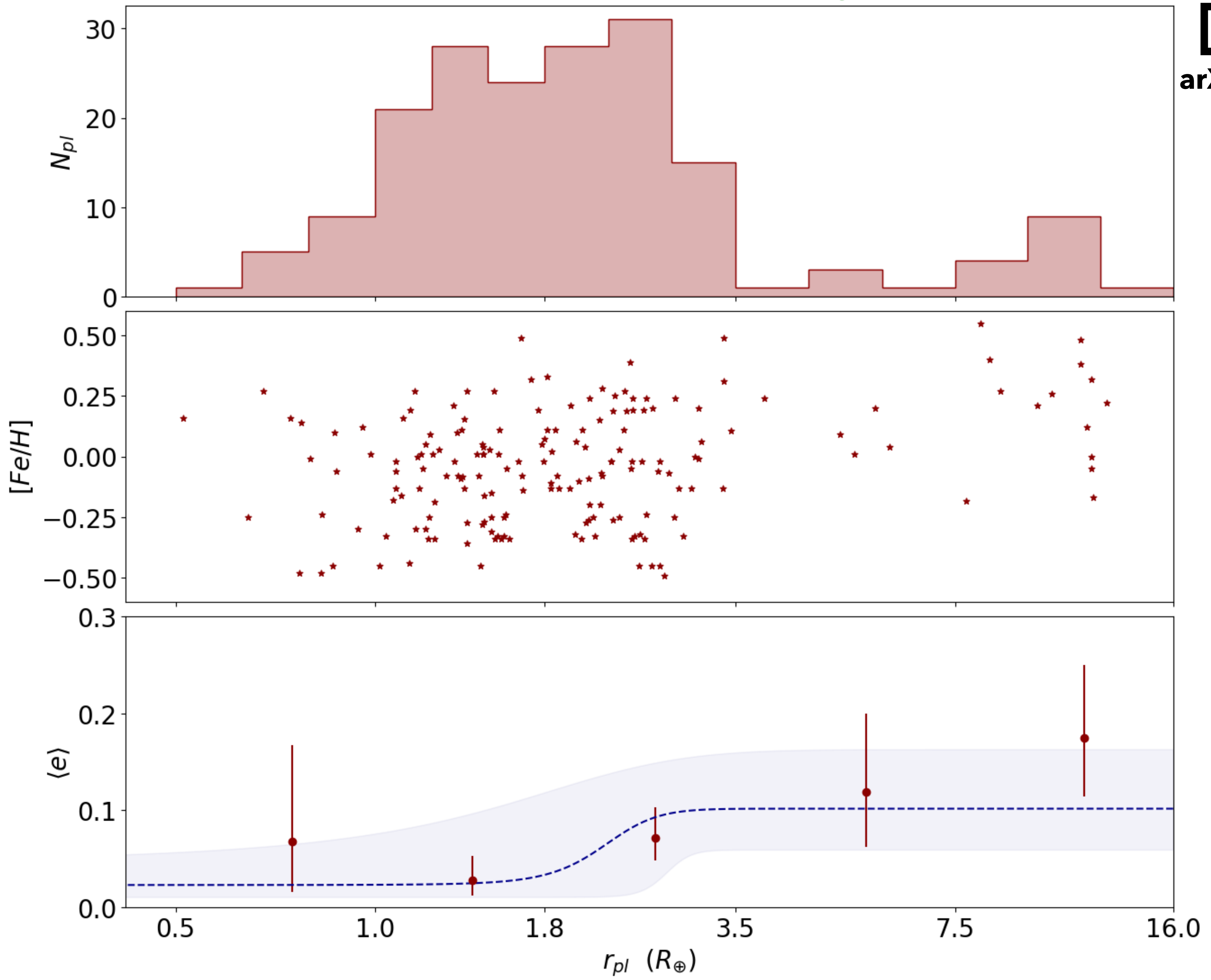

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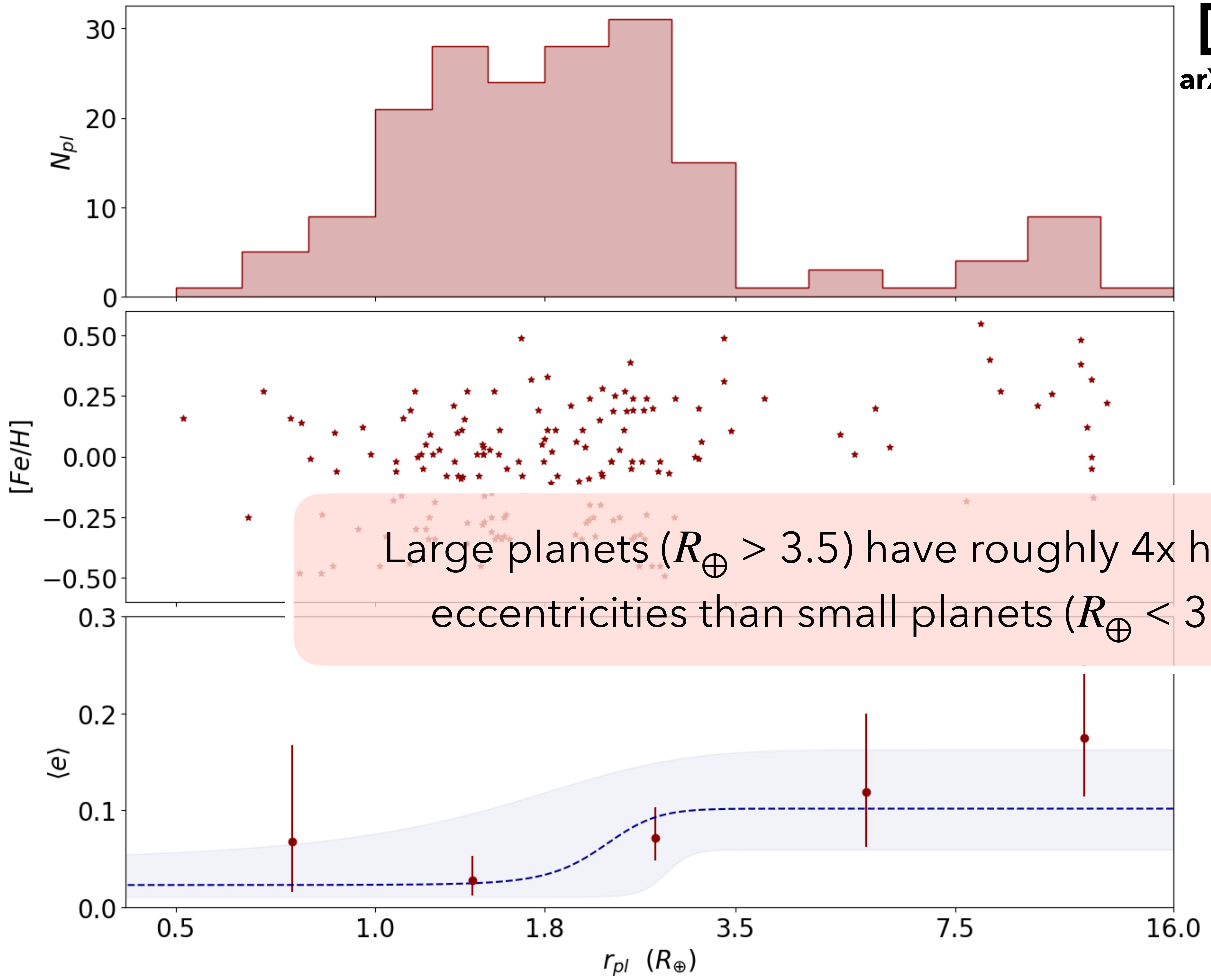

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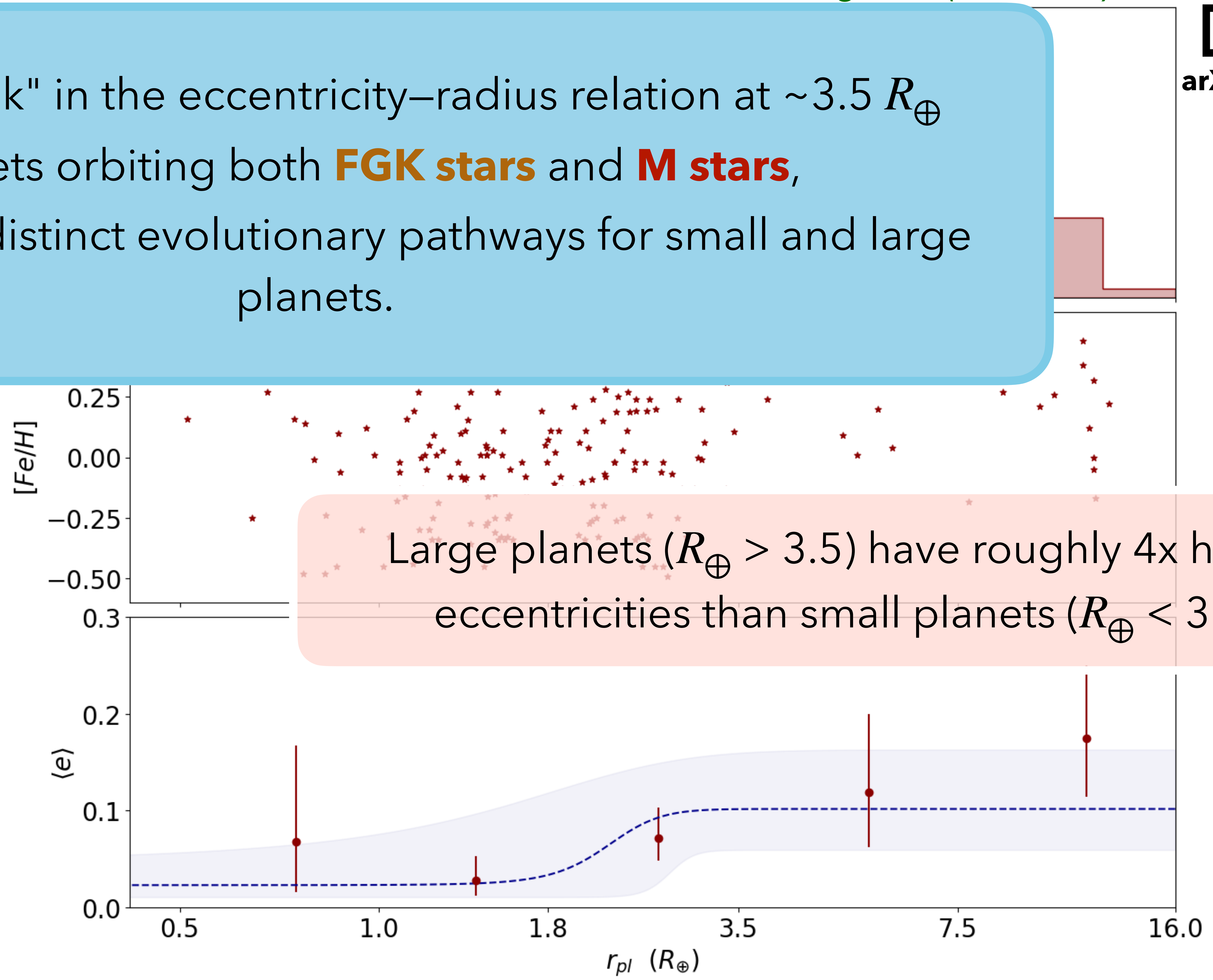
There is a "break" in the eccentricity–radius relation at ~3.5 $R_{\oplus}$ for planets orbiting both **FGK stars** and **M stars**, suggesting two distinct evolutionary pathways for small and large planets.



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M dwarf ages are difficult to constrain, since isochrone ages aren't reliable for low masses.

But a star's Galactic orbit relies primarily on the gravitational potential distribution of the Milky Way.

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Sagear+ (2024)

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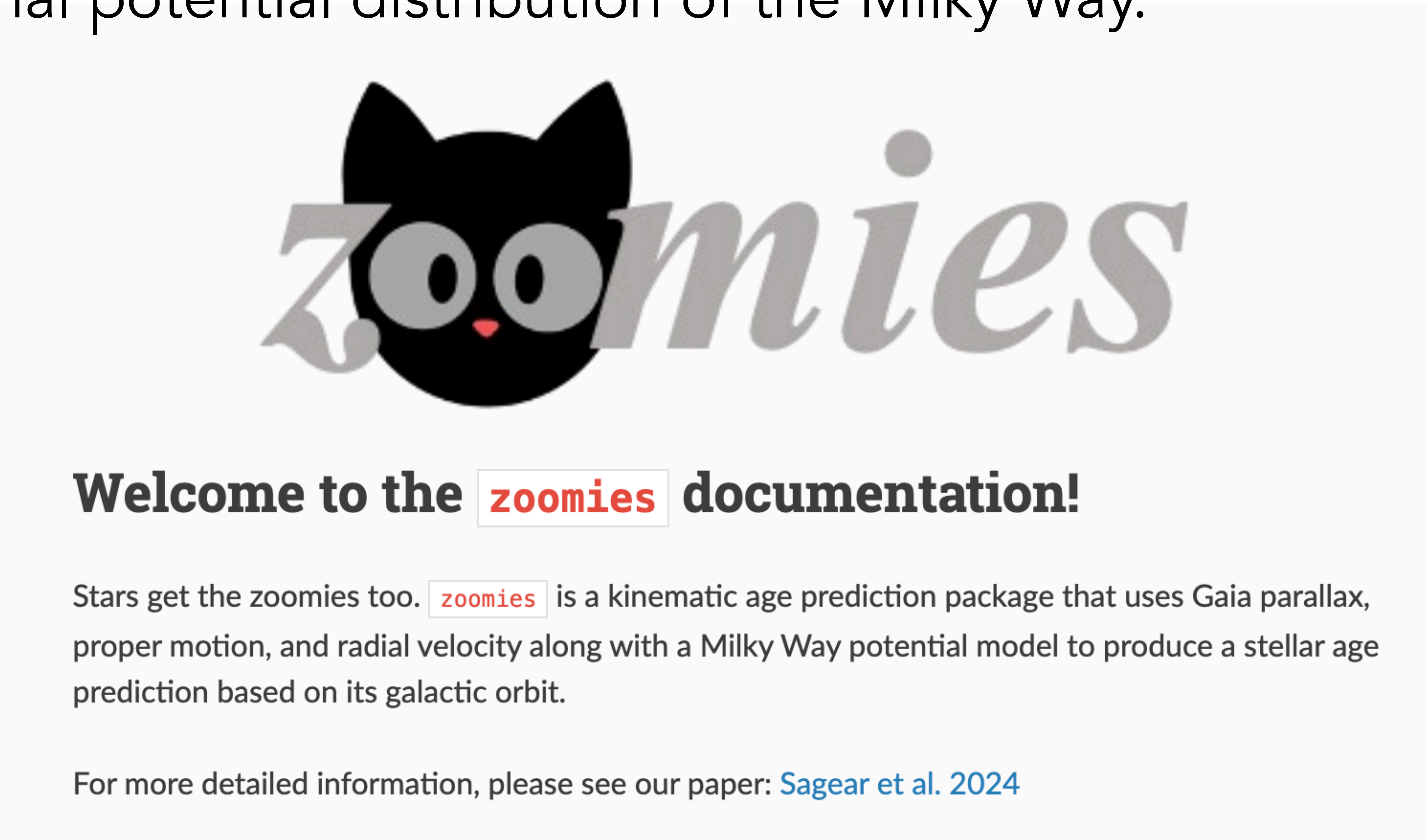
M dwarf ages are difficult to constrain, since isochrone ages aren't reliable for low masses.

But a star's Galactic orbit relies primarily on the gravitational potential distribution of the Milky Way.

I developed a software package to generate stellar age estimates with *Gaia* kinematics
(great for stars where isochrone ages are unreliable!).



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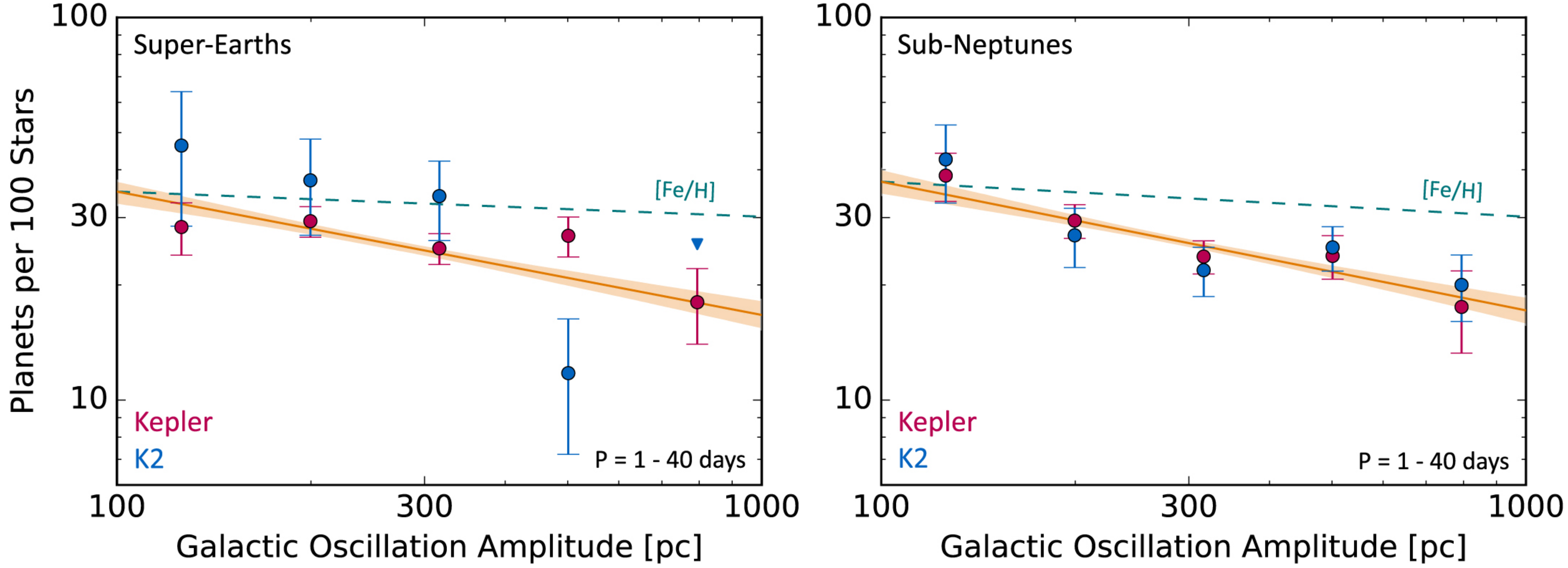
Planets seem to know where they are in the Galaxy.

Zink+ 23 (and *Lam+ submitted.)*: The planet occurrence rate appears to decrease with Galactic amplitude.

Zink et al. 2023



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What physical mechanisms might link Galactic and planetary dynamics?

Schoettler+ 24, Charalambous+ 25: stellar flybys (on the order of 1000s of AU) could disrupt planetary orbits

Kaib+13, Stegmann+24: Wide binary orbits (and their planets) could be dynamically disrupted by Galactic tides

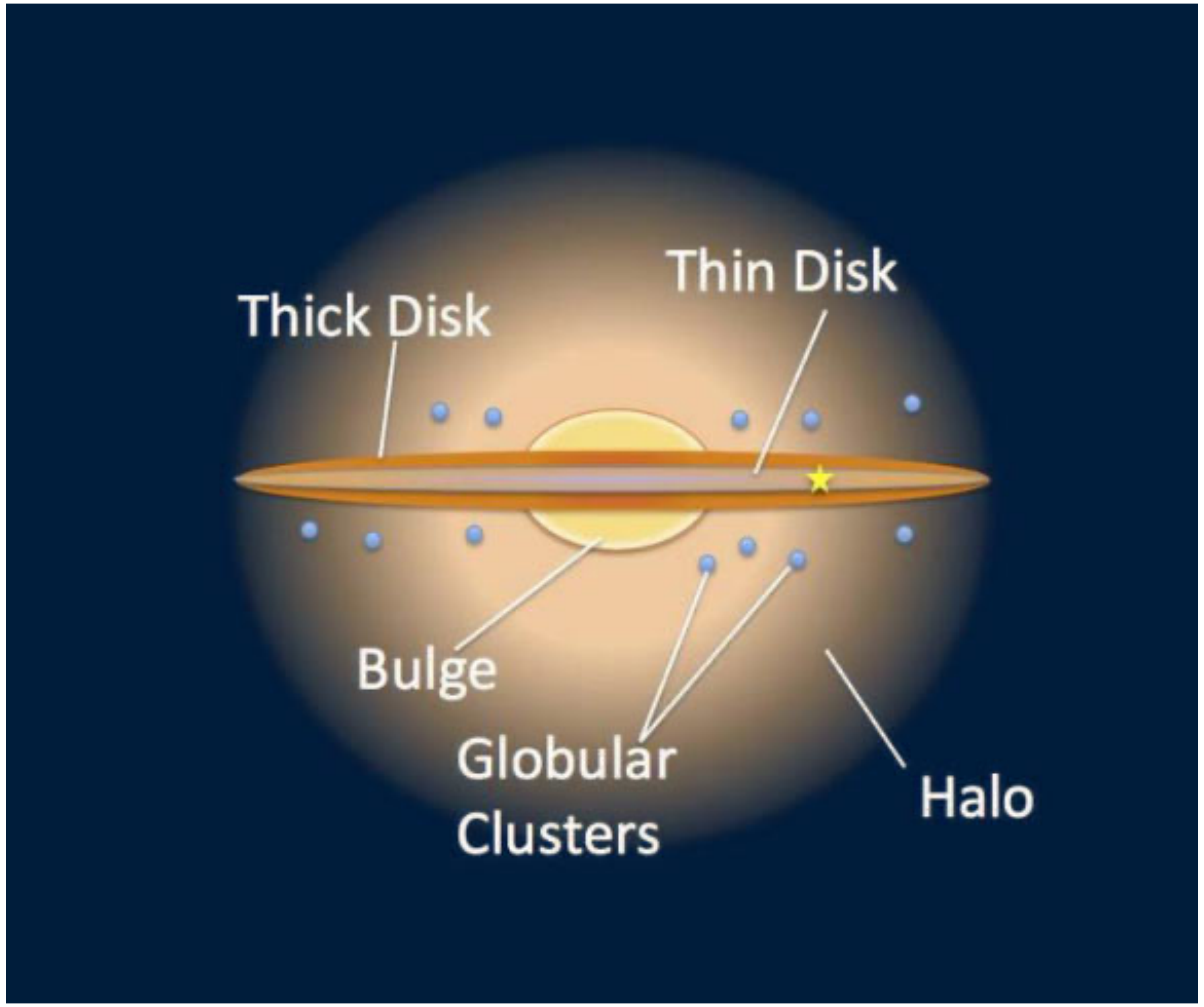
4. The impact of Galactic dynamics on planetary dynamics

Sagear+ (submitted) PDF

We can probe Galactic dynamical properties via kinematic disk association.

Thin disk: spiral arms, younger & metal-rich stars, less extreme vertical orbital excursions

Thick disk: older, metal-poor stars, more extreme vertical orbital excursions

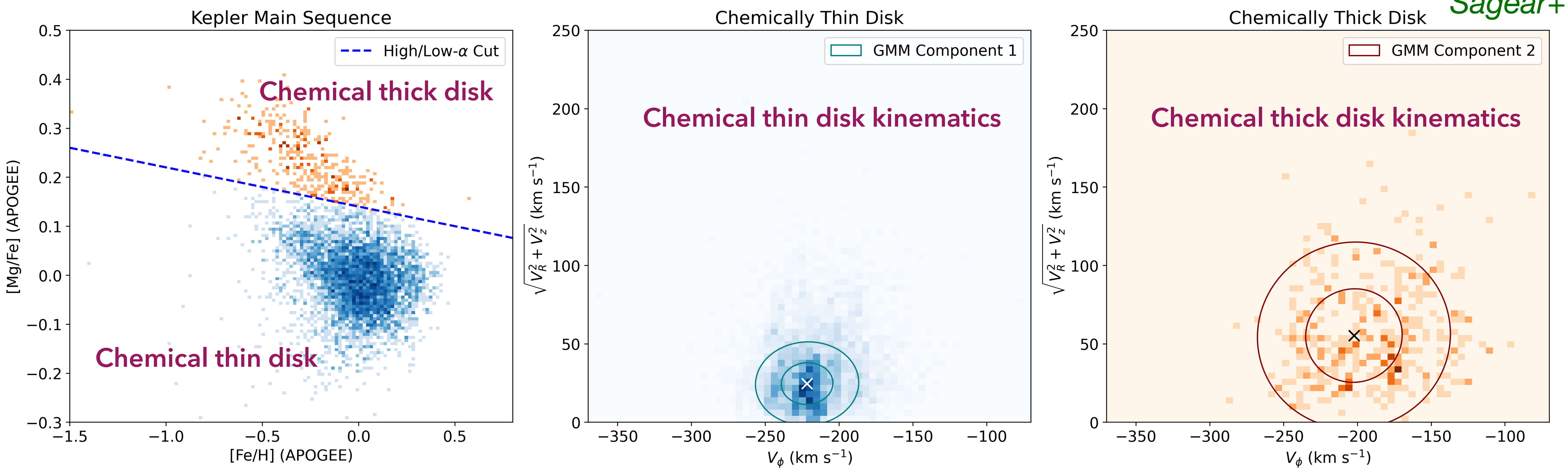


4. The impact of Galactic orbits on planetary dynamics

Robust "thin vs. thick disk" classifications rely on both ***stellar chemistry*** and ***kinematics***, but many Kepler planet hosts don't have reliable stellar abundances.

We calibrate a kinematic disk classification method on Kepler–APOGEE stellar abundances, then apply the kinematic portion to the rest of the Kepler sample.

Sagear+ (submitted)



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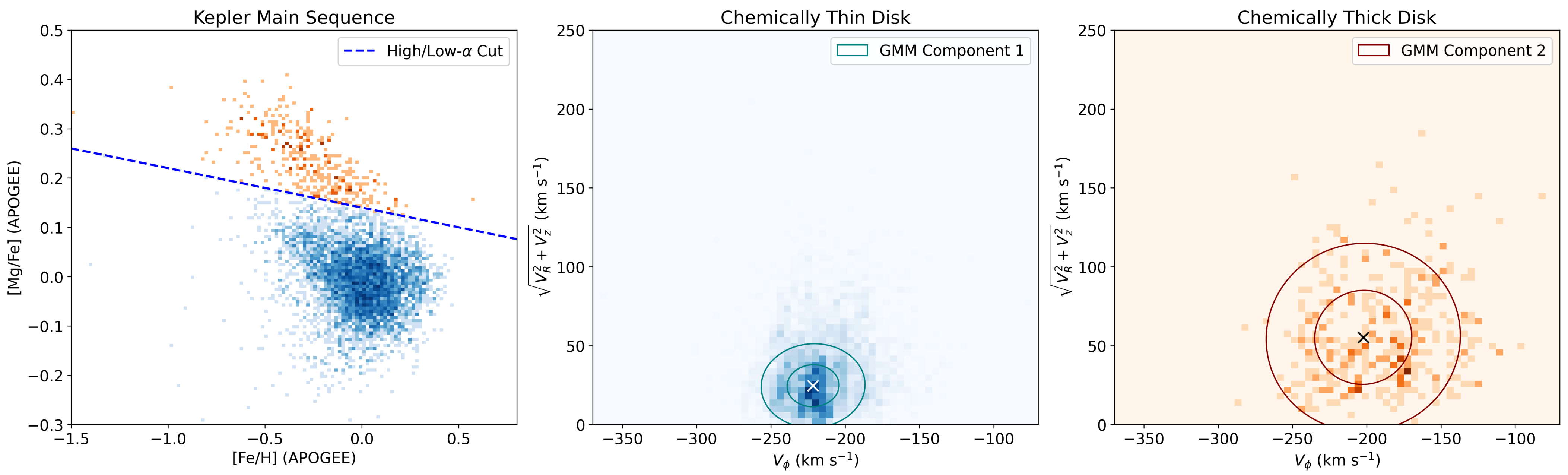

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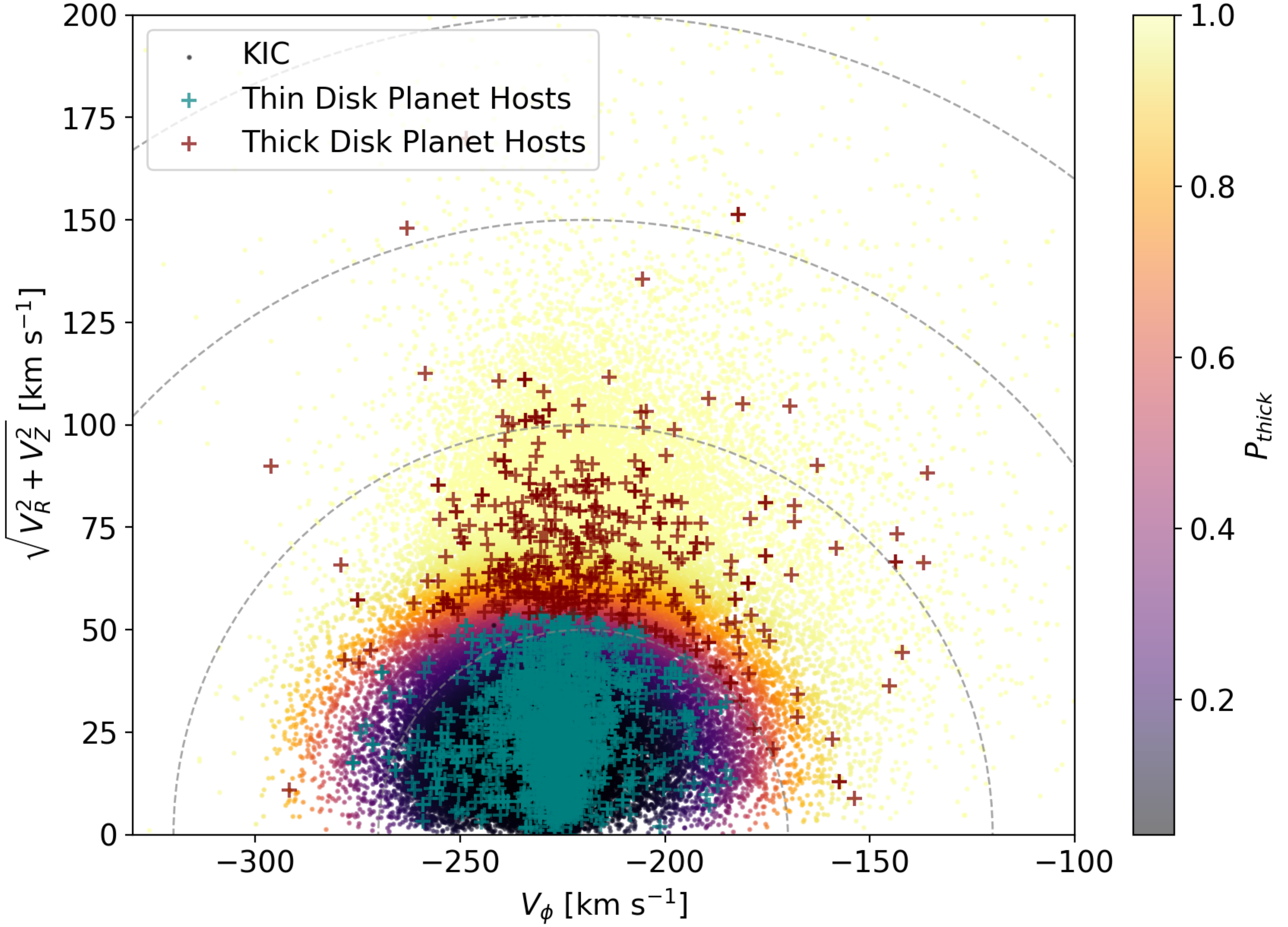

Toomre diagram (representation of relative Galactic kinematics) for our sample

4. The impact of Galactic dynamics on planetary dynamics

Sagear+ (submitted) PDF

We categorize Kepler planet hosts (based on Galactic kinematic information from *Gaia)* into kinematically "thick" and "thin" disk groups.

Toomre diagram (representation of relative Galactic kinematics) for our sample

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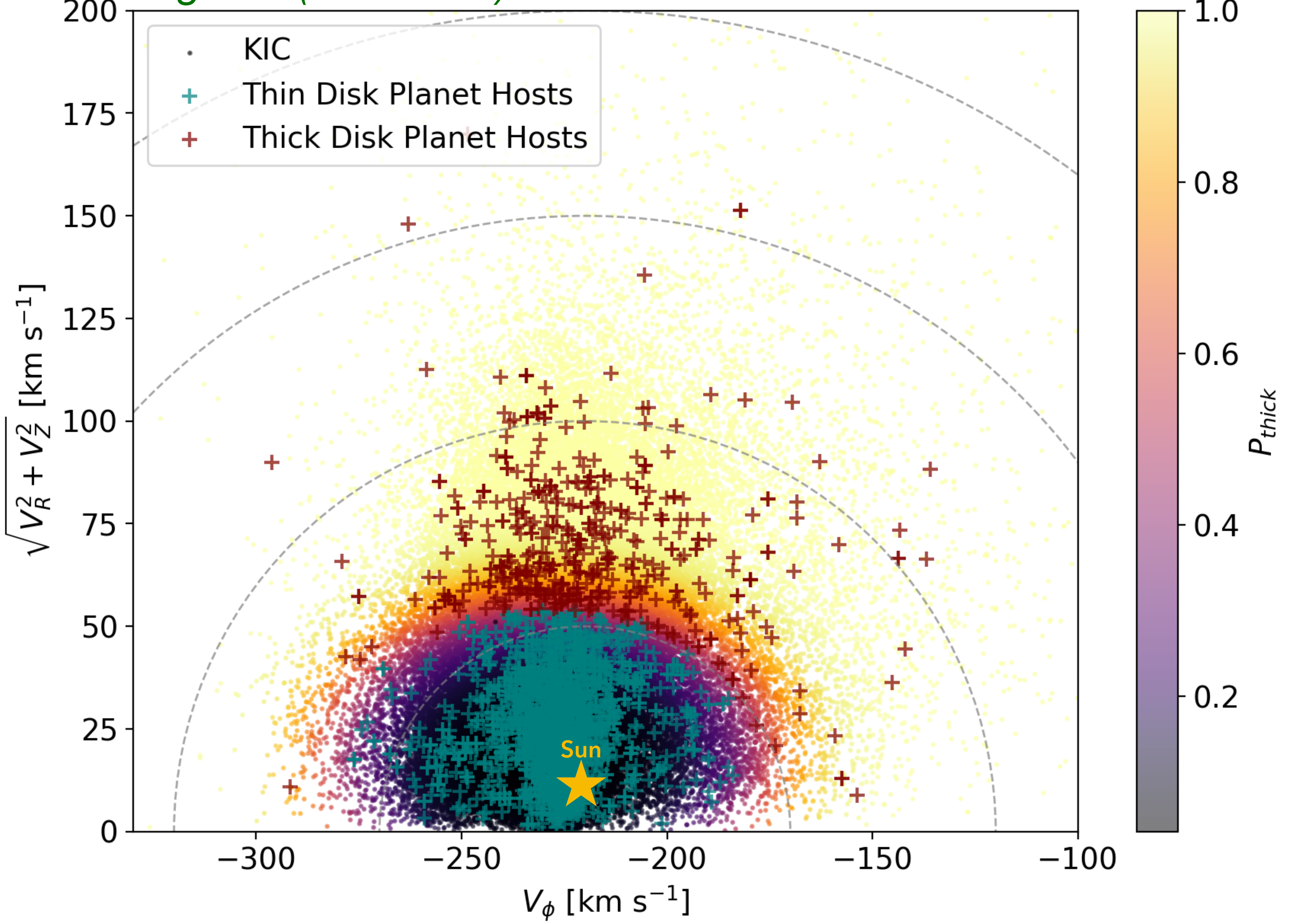

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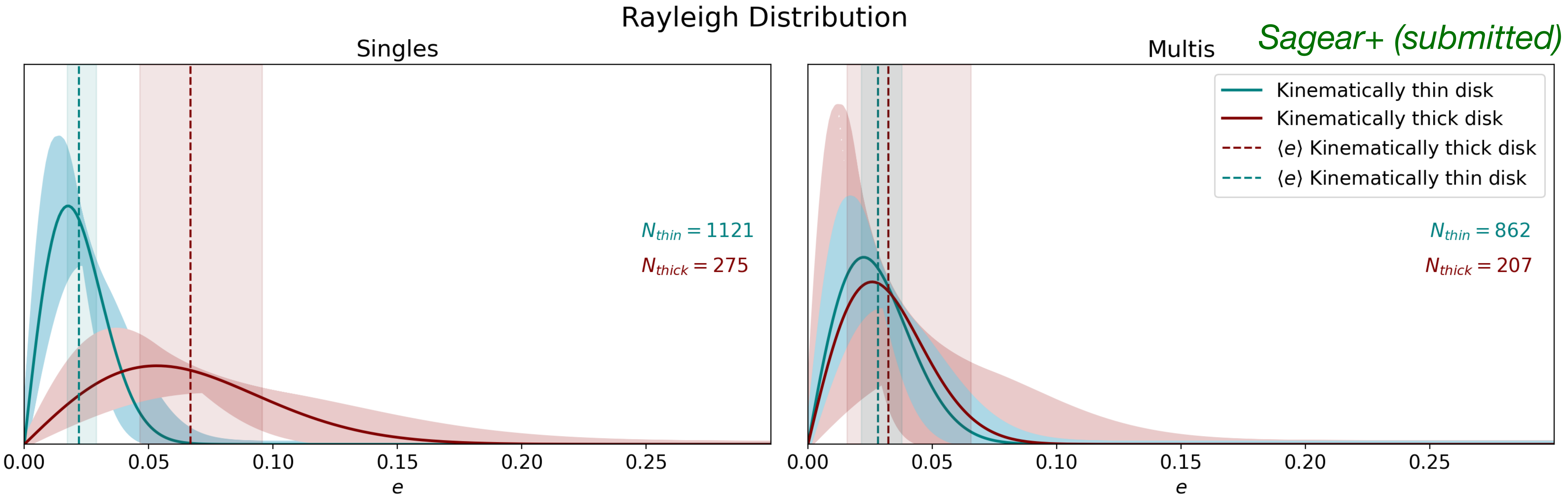
Sagear+ (submitted) PDF

Comparing the underlying orbital eccentricities of the thin vs. thick disk groups…

Single-transit planets in the thick disk are more eccentric than planets in the thin disk.



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Comparing the underlying orbital eccentricities of the thin vs. thick disk groups…

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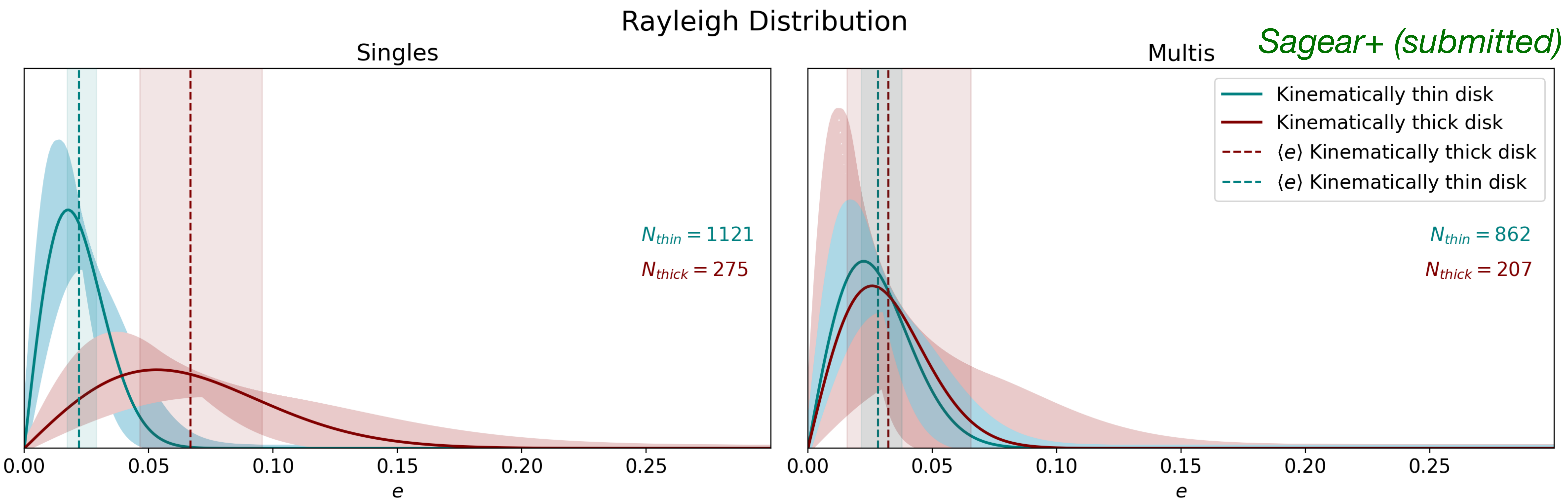
We know that large planets around metal-rich hosts tend to be more eccentric.
But to first order, this trend isn't fully explained by metallicity or planet radius alone.



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Can we better understand how stellar age trends with eccentricity?
Can we determine the likelihood of a stellar system to fly by another star throughout its lifetime?
What about the effect of wide binary disruption by the Galactic potential?

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What about the effect of wide binary disruption by the Galactic potential?

We are in a fantastic position to learn more about planet populations in the galaxy with
1. Galactic dynamical information for stellar hosts from *Gaia*,
2. planetary orbital eccentricities, and
3. *the power of demographics with hierarchical Bayesian inference.*