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Increasing Planet Formation in the Milky Way's Past Reproduces Present-Day Planet Occurrence Trend with Galactic Height

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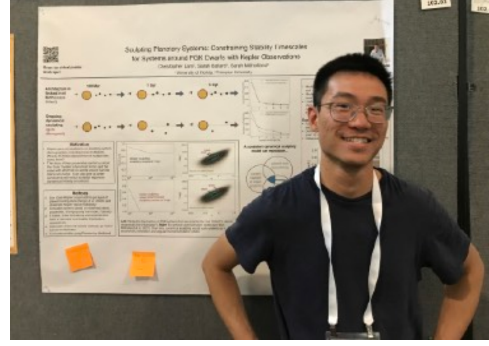
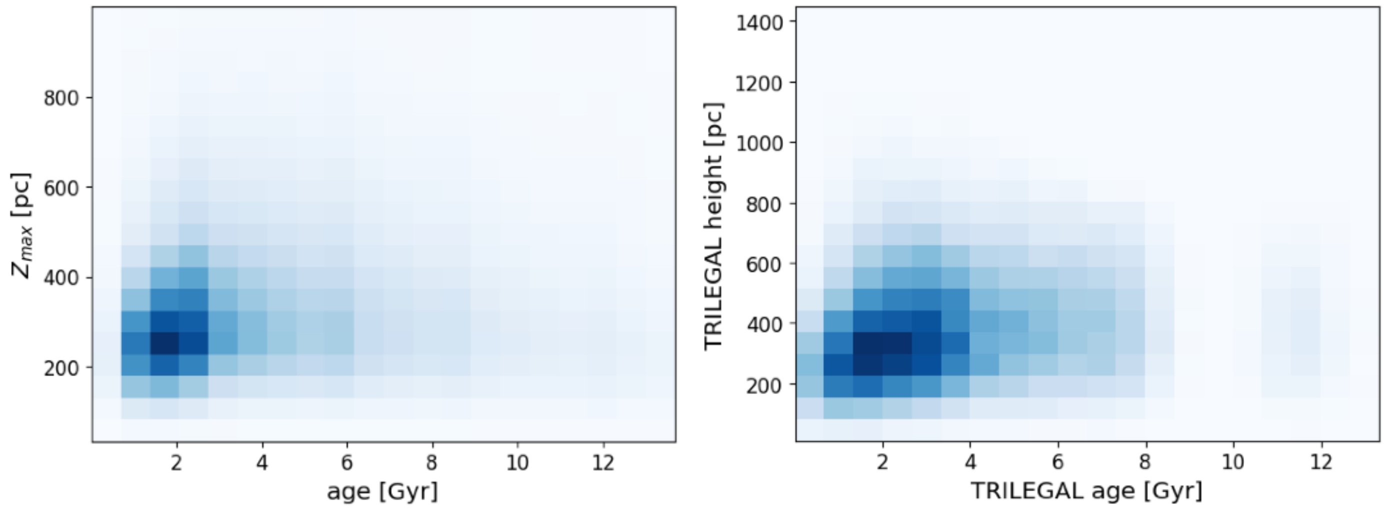


Motivation

- Planetary system formation and evolution have until recently been studied as a closed process, independent of the system's galactic context.
- Internal dynamical sculpting and the ISM metallicity gradient are insufficient to fully explain the observed *Kepler* trend between planet occurrence and galactic scale height (Lam+ 2024; Zink+ 2023).
- We probe whether some event in the Milky Way's past could have increased planet formation by forward modeling a single step increase in the planet host fraction at different time thresholds.



Left: Bootstrapping 30 times over the isochrone age, proper motion, radial velocity, and parallax uncertainties, we observe a positive trend between isochrone age and Z_{max}, as calculated by `gala` (Price-Whelan 2017).
Right: We show that a similar trend is exhibited by the TRILEGAL synthetic stellar dataset, which we use to verify our results against an idealized sample with much smaller age uncertainties.

Citations

Ballard 2024 arXiv.
Berger 2020a AJ 159 280.
Donlon 2019 ApJ 886 76.
Lam 2024 AJ 167 254.
Price-Whelan 2017 JOSS 2(18) 388.
Ruiz-Lara 2020 Nature 4 965.
Winter 2020 Nature 586 528.
Winter 2024 ApJL 972 L9.
Zink 2023 AJ 165 262.

Acknowledgments

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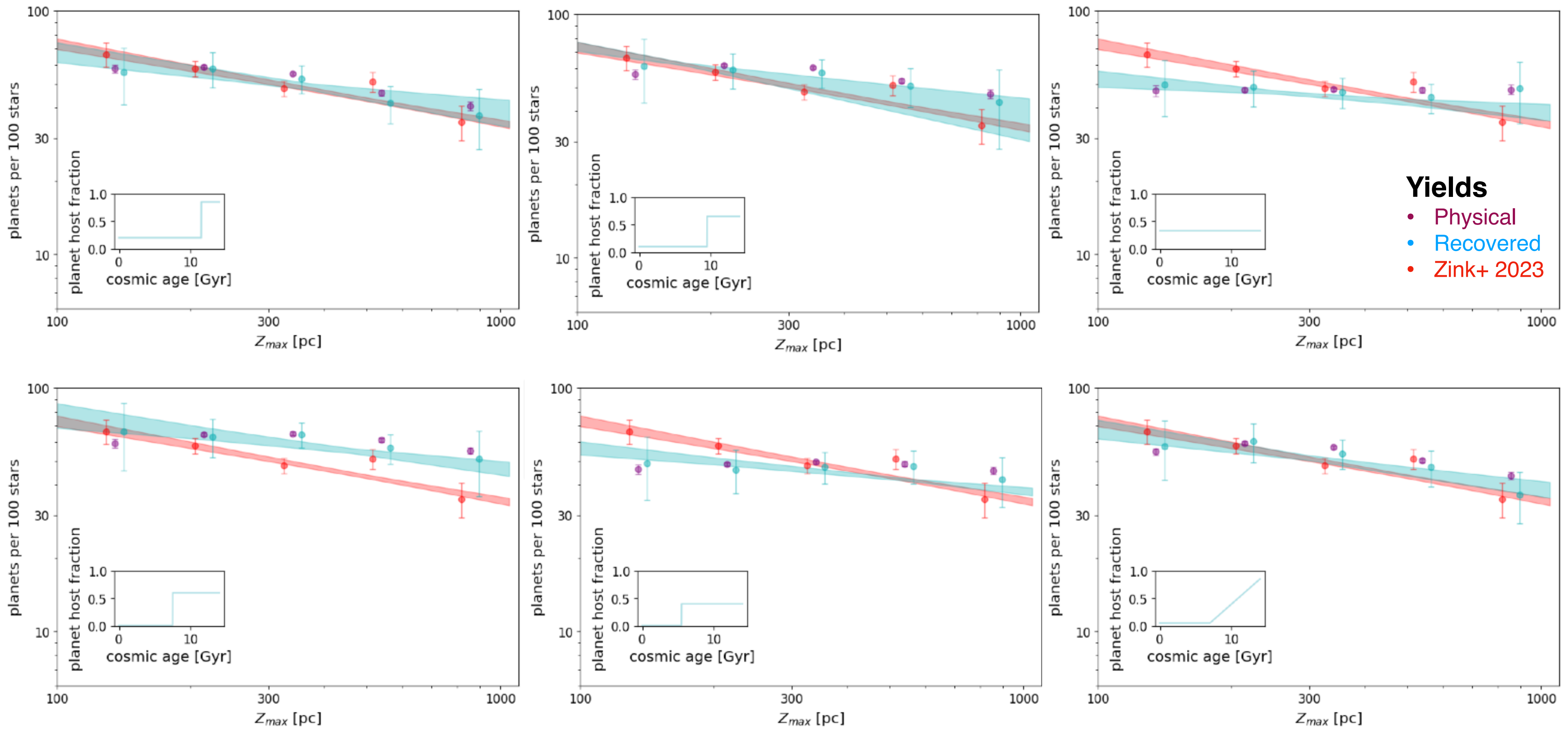
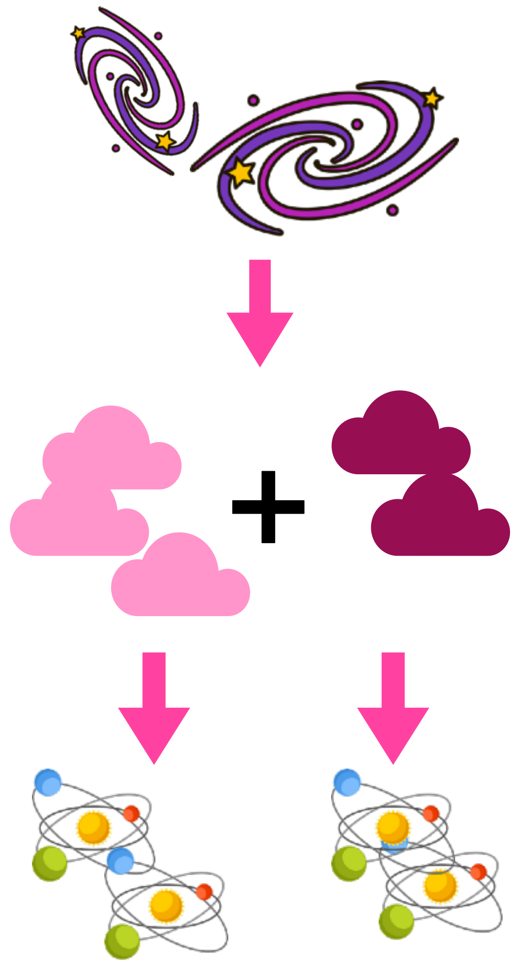


Planet occurrence versus Z_{max} for six different time-varying planet occurrence models, shown in insets. We consider only planets with period < 40 days and radius < 4 $R_\oplus$. All models are constrained to produce a present-day planet host fraction of 0.3 in order to maintain the correct normalization. **We find that some increase in planet host fraction must occur in order to match Zink+ 2023, and that if it is a step increase, then it must occur after the Milky Way was 7.5 Gyr old.**



Some galaxy-galaxy event occurs, eg. a merger.

Gas is injected into the Milky Way.

More favorable planet formation conditions results in a larger planet-host to non-planet-host ratio, which naturally increases the overall planet occurrence rate.

Methods: `psps`

`psps (planetary system population synthesis)` is a package for forward modeling exoplanet demographics. For our purposes, the recipe we followed was broadly as follows:

1. Starting with the Berger+ (2020a) *Gaia-Kepler* cross-match, assign each system a probability of hosting a planetary system, based on the models depicted to the left.
2. Paint on planet multiplicity, radius, period, mass, mutual inclination, and eccentricity using empirical distributions from the literature.
3. Calculate completeness map using ground truth for a portion of the simulations. Apply completeness map to go from physical (purple) to recovered (blue) yield.
4. Fit trend to estimate slope and compare to Zink+ 2023.
5. `psps` is modular and generalizable to other exoplanet demographic forward modeling questions! Git issues welcome!

Results & Discussion

1. Planet host fraction must increase at some point in the Milky Way's past in order to match the planet occurrence vs Z_{max} trend from Zink+ 2023. This could be a step or more gradual increase.
2. Step increase times prior to the Milky Way being 7.5 Gyr old cannot produce a match to Zink+ 2023. We cannot rule out any initializing timescales for the more gradual increase models.
3. The step increase times include some putative dynamical events in the Milky Way's past: the Virgo Radial Merger (Donlon+ 2019) and the Sagittarius dwarf galaxy second and third passages (Ruiz-Lara+ 2020).

What physical mechanisms could drive this trend (besides Galactic chemical evolution)?

ISM turbulence-driven infall (Winter+ 2024)? An evolving rate of close-in intact systems (Ballard 2024)? An evolving density of stellar birth environments (Winter+ 2020)? Changes in binarity (Chance+ in prep)? This question is extremely unconstrained and warrants further investigation into connecting the physical drivers of planet formation with Galactic scale processes!