sP208 Poster @ Cool Stars 23

Age Dependence of Occurrence Rate of Close-in Planets around Solar-Type Stars from Hierarchical Bayesian Inference

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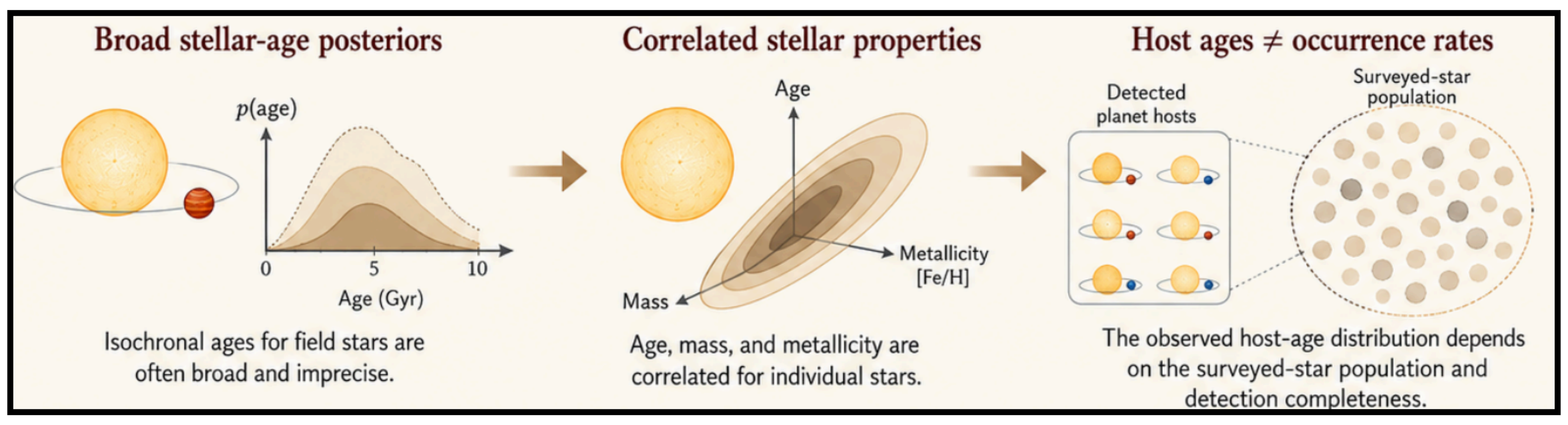
❶ Introduction

Why is the age distribution of planets around field stars difficult to infer?



Main-sequence stellar ages are uncertain, correlated with other stellar parameters, and the distribution of planet-host ages depends on the surveyed star population.
Challenge: observed planet-host ages cannot be directly interpreted as age dependence of planet occurrence rate.

Key difficulty

Field-star ages are uncertain and biased by selection.

For Sun-like stars on the main sequence, age estimates are typically broad and intertwined with mass and metallicity.
In addition, the survey observes a mixture of stars, not a single population at fixed age.

This work

We break this degeneracy with hierarchical Bayesian inference.

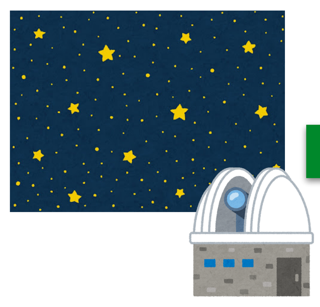
We jointly infer the surveyed-star population $p_\star(z|\alpha)$ and the planet-occurrence density $f(x|z,\gamma)$, while propagating stellar-posterior uncertainties and survey detection completeness.

$p_\star(z|\alpha)$ + $f(x|z,\gamma)$
population model + occurrence model

❷ What is inferred?

Stellar properties: $z = \{[\mathrm{Fe/H}], M_\star, t_\star, \dots\}$
Planet properties: $x = \{M_p \sin i, P, \dots\}$
Stellar population parameter: α
Planet occurrence parameter: γ

observation for each star



latent stellar properties z_j

stellar isochrone modeling

We jointly infer:

$p_\star(z|\alpha)$ surveyed-star population density

$f(x|z,\gamma)$ Planet-occurrence density at fixed stellar properties

❸ Core equations

D_j: stellar data for star j
H_j: detected planet set around star j

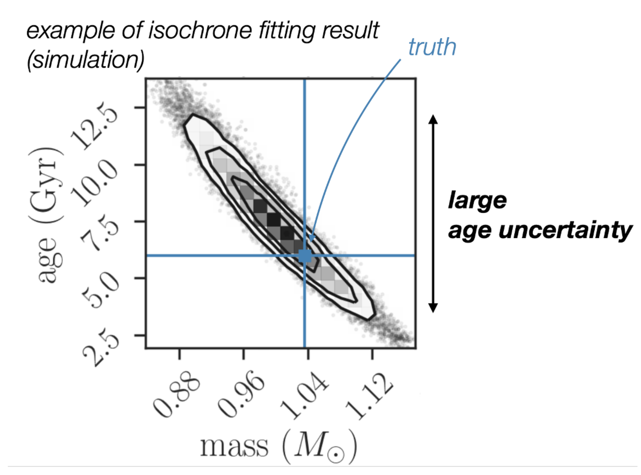
- planet occurrence density: $dn_p = f(x|z)\,dx$
- Number of planets per star (NPPS) in a planet domain: $n_p(z,\gamma) = \int_{\mathcal{P}} f(x|z,\gamma)\,dx$
- sample-averaged NPPS: $\bar{n}_p(\alpha,\gamma) = \int_\Sigma \int_{\mathcal{P}} f(x|z,\gamma)\,p_\star(z|\alpha)\,dx\,dz$
- hierarchical likelihood: $p(\alpha,\gamma|\{D_j,H_j\}) \propto p(\alpha,\gamma)\prod_{j=1}^{N_{\rm star}}\int p(D_j|z_j)p(H_j|z_j,\gamma)\,p_\star(z_j|\alpha)dz_j$

Expected planet detection for star j is $\Lambda_{p,j}(z_j,\gamma) = \int \eta_j(x) f(x|z_j,\gamma)dx$, where $\eta_j(x)$ is detection completeness.

Planet detections are modeled as an inhomogeneous Poisson point process.

❹ Why infer stellar population too?

- $f(x|z)$ is defined at fixed stellar properties, but the survey observes a mixture of stars with different z.
- Stellar properties are correlated, and their posteriors are broad and degenerate for main-sequence stars.



- **Without $p_\star(z)$, observed planet counts cannot be converted into NPPS as a function of stellar properties.**

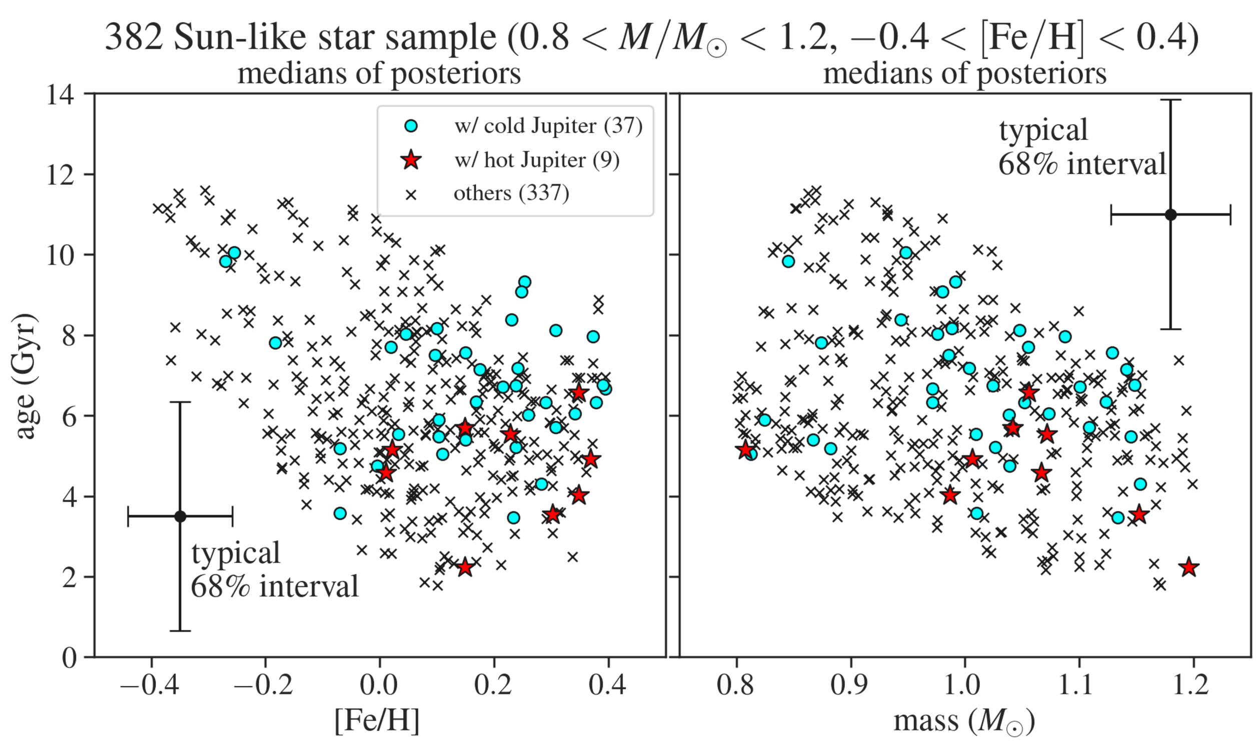
Planet-host ages alone do not measure occurrence rates. The surveyed-star inference is required for inferring the NPPS as a function of stellar parameters.

❺ Data

California Legacy Survey Sun-like Sample

- 382 Sun-like stars ($0.8 < M_\star/M_\odot < 1.2$, $|[\mathrm{Fe/H}]| < 0.4$)
- 9 Hot Jupiters ($1 < P_{\rm orb}/\mathrm{day} < 10$, $M_p \sin i = 0.3 - 10 M_{\rm Jup}$)
- 37 Cold Jupiters ($1 < P_{\rm orb}/\mathrm{yr} < 10$, $M_p \sin i = 0.3 - 10 M_{\rm Jup}$)

Stellar posteriors from isochrone fitting using spectroscopic parameters, Gaia DR3 parallaxes, and 2MASS K_s magnitudes.

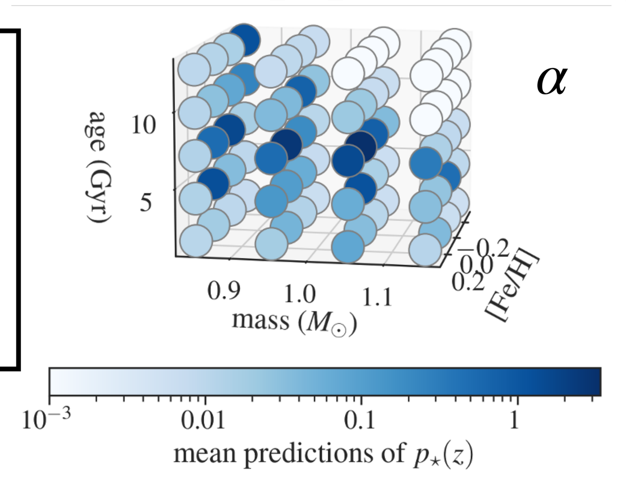


❻ Results

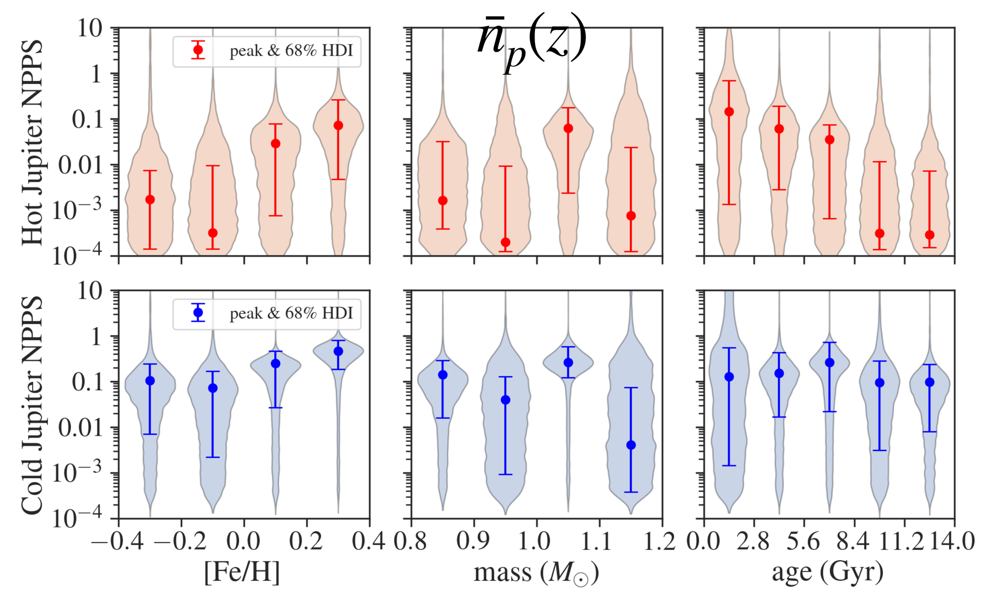
Main result

Sample-averaged NPPS: $\bar{n}_{\rm HJ} \simeq 4\,\%$, $\bar{n}_{\rm CJ} \simeq 18\,\%$
Hot Jupiter NPPS: increases with metallicity and decreases with stellar age.
Cold Jupiter NPPS: increases with metallicity but shows no age dependence.
Characteristic decline timescale: $\tau_{\rm HJ} \sim 1.4$ Gyr for exponential model.

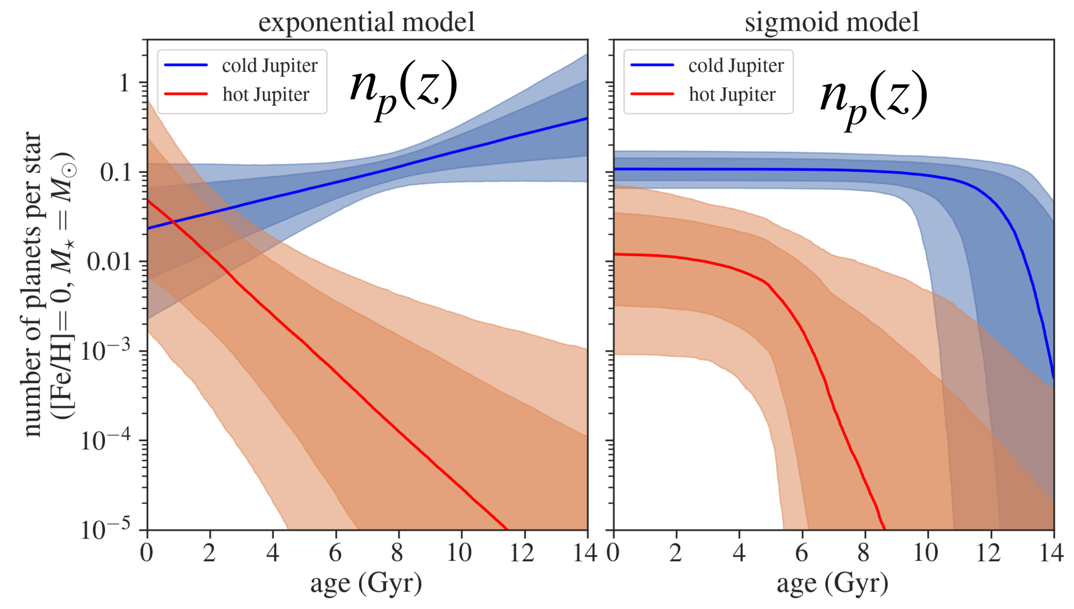
Stellar population



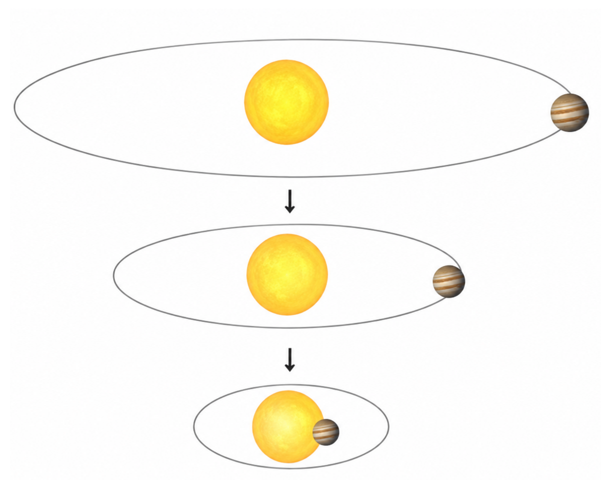
NPPS as a function of stellar properties



Age dependencies: model comparison



❼ Interpretation & Overview



If the decline of Hot Jupiter occurrence is caused by tidal orbital decay, the observed Gyr-scale decrease implies

$$Q'_\star \sim 10^6$$

for a Jupiter-mass planet on a $P_{\rm orb} \sim 3$ day orbit around a Sun-like star.
This is an order-of-magnitude population-level estimate.

- **Statistical framework**

The hierarchical model separates intrinsic planet occurrence from the distribution of surveyed stars and detection completeness. It converts heterogeneous survey catalogs into physically interpretable occurrence rates as functions of stellar and planetary properties.

- **Next applications**

The same framework is being extended to Kepler transiting planets, including super-Earths and sub-Neptunes. Future Gaia-calibrated Kepler, TESS/PLATO, RV, and Roman samples will test whether different planet populations evolve differently with stellar age and Galactic environment.

- **Details**

Miyazaki & Masuda (2023)
"Evidence That Occurrence Rate of Hot Jupiters around Sun-like Stars Decreases with Stellar Age"