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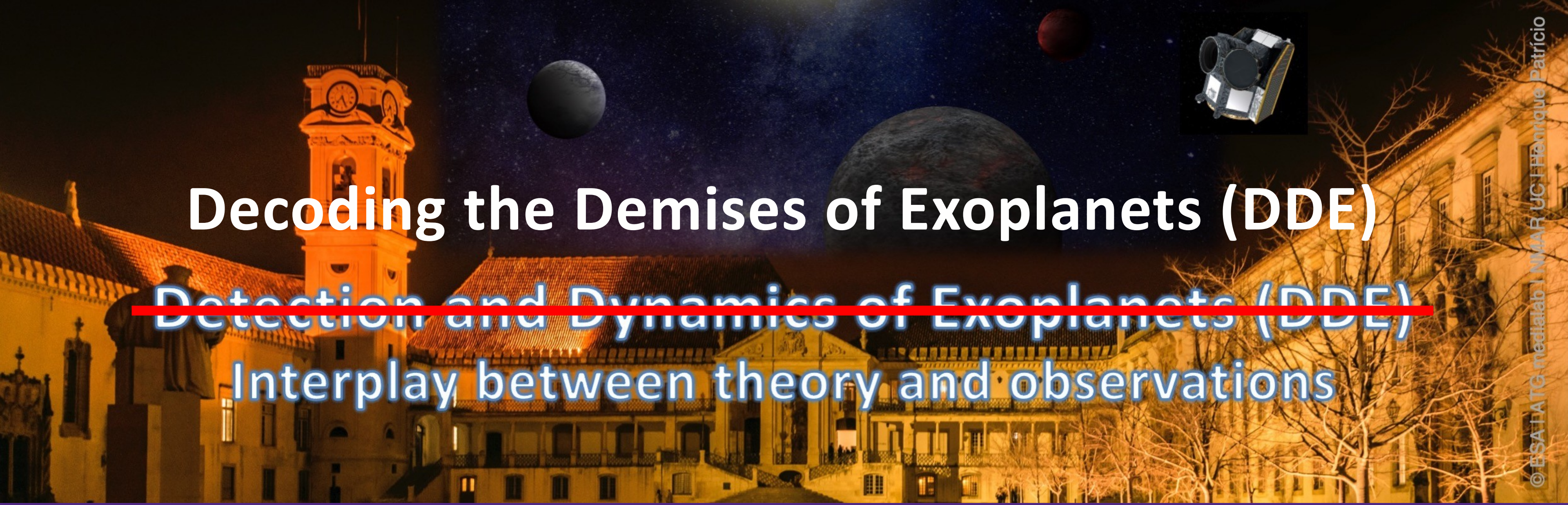
Tidal destruction of ultra-short-period planets

based on
O'Connor & Lai (2025), ApJL, 978, L26

Christopher E. O'Connor | Det. Dyn. Exoplanets @ U. Coimbra | 2025 July 10



Decoding the Demises of Exoplanets (DDE)

~~Detection and Dynamics of Exoplanets (DDE)~~

Interplay between theory and observations

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Some current problems of interest for me:

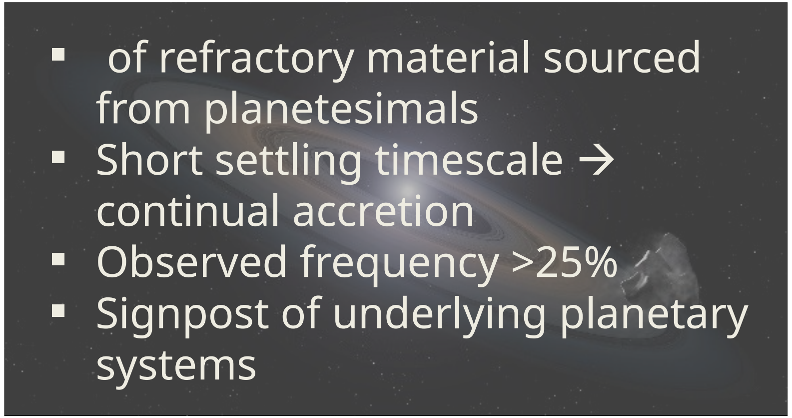
- Planetary/substellar engulfment events
- White dwarf pollution & exoplanets orbiting WDs
- Tidal interactions and disruption

Planetary metal pollution in stars

Pollution refractory metal enrichment attributed to recent accretion

White dwarfs

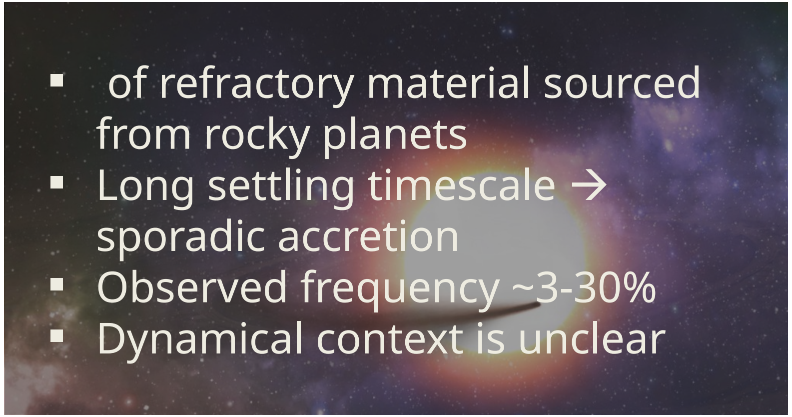
(e.g. Zuckerman+ 2003, 2010; Koester+ 2014; Xu+ 2019)



- of refractory material sourced from planetesimals
- Short settling timescale → continual accretion
- Observed frequency >25%
- Signpost of underlying planetary systems

Sun-like stars

(e.g. Spina+ 2021, Behmard+ 2023, Liu+ 2024)

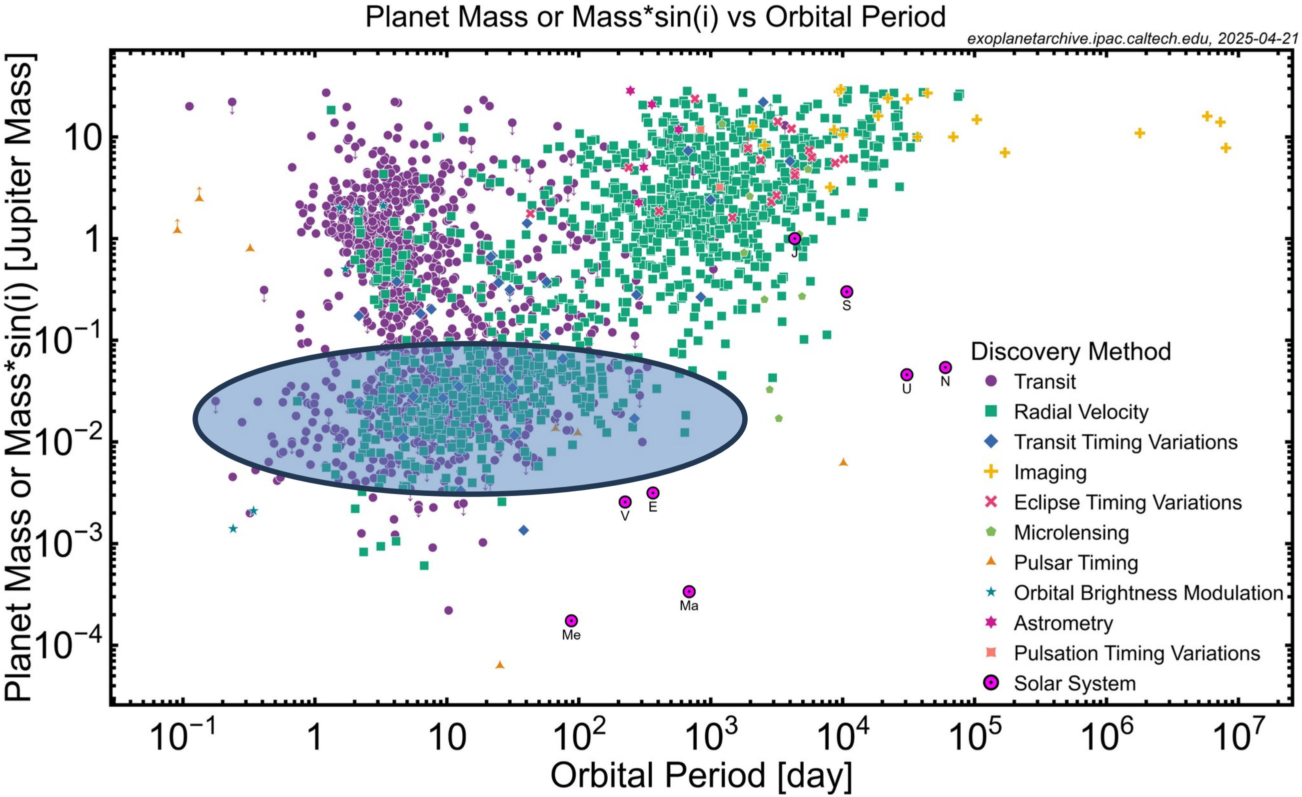


- of refractory material sourced from rocky planets
- Long settling timescale → sporadic accretion
- Observed frequency ~3-30%
- Dynamical context is unclear

Image: Maciej Szyszko

Rocky planets live in “Kepler-multi” systems

Only population abundant enough to be the main source of engulfed planets


Planet Mass or Mass*sin(i) vs Orbital Period

exoplanetarchive.ipac.caltech.edu, 2025-04-21

Routes to engulfment in “Kepler multis”

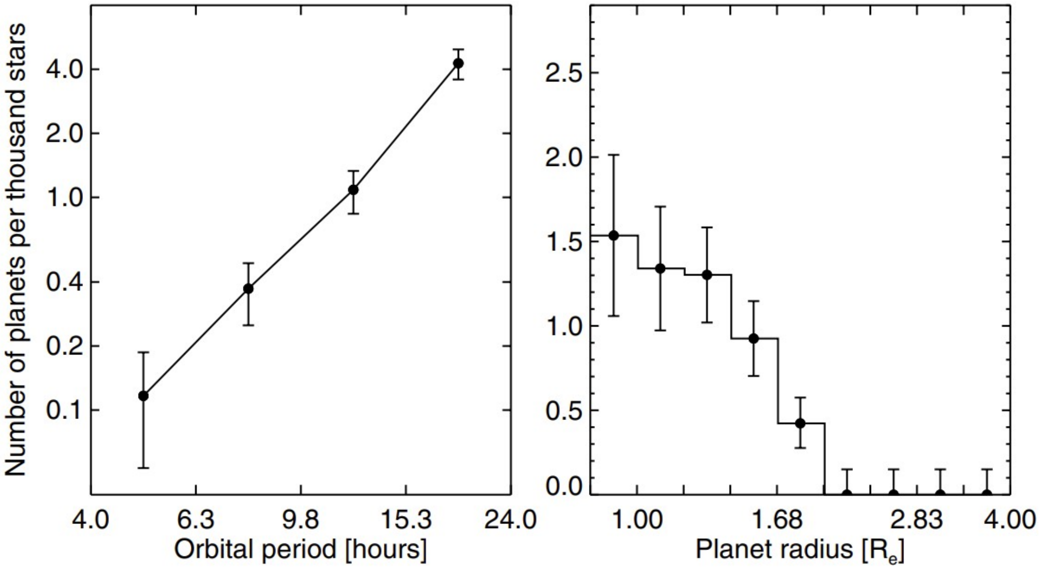
Violent dynamics

- Planet-planet scattering
- Secular driving (secular chaos, ZLK…)

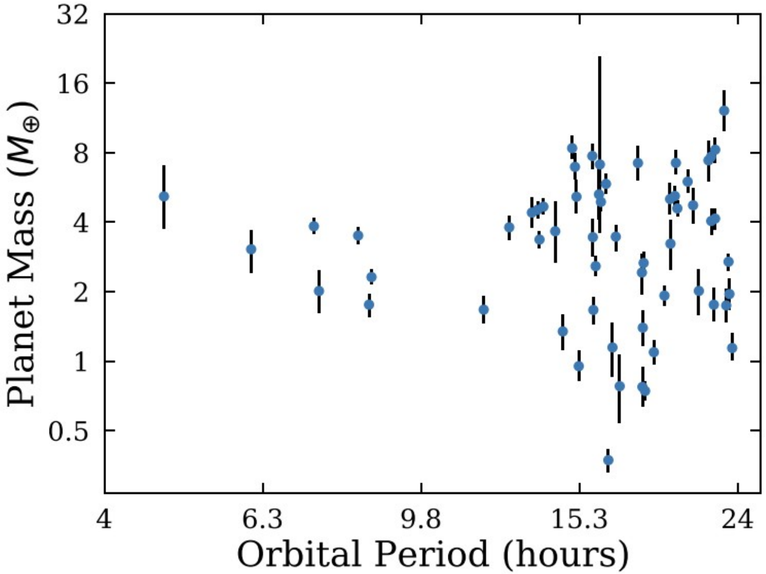
Tidal inspiral

- Implies a connection with **ultra-short-period planets**

USPs in 3 panels



Sanchis-Ojeda+ (2014)



Uzsoy+ (2021)

USPs formation, migration, and inspiral

Roche limit
few hours

1 day

Proto-USP
1-3 days

Companion planet(s)
4 days

Disruption/ engulfment

Tidal dissipation

Secular forcing

e.g. Petrovich et al. (2019), Pu & Lai (2019), Millholland & Spaulding (2020)

A (useful) toy model

We use a “population current” formalism (cf. Millholland+ 2024)

Key assumptions:

1. Each Kepler-multi system (occurrence fraction =) can produce 1 USP during its MS lifetime.
2. USP formation rate is described by a **source function** .
3. USP orbital decay occurs on a **characteristic lifetime** .

A (useful) toy model

[change of USP fraction] ~ [formation rate] – [destruction rate]

[change of pollution fraction] = [destruction rate]

A (useful) toy model

With and universal, solve subject to boundary values .
Relevant regime for USPs is .

$$y_u(t) = \frac{y_{p0}\Sigma_0\tau}{1-\Sigma_0\tau}\left(e^{-\Sigma_0 t} - e^{-t/\tau}\right),$$

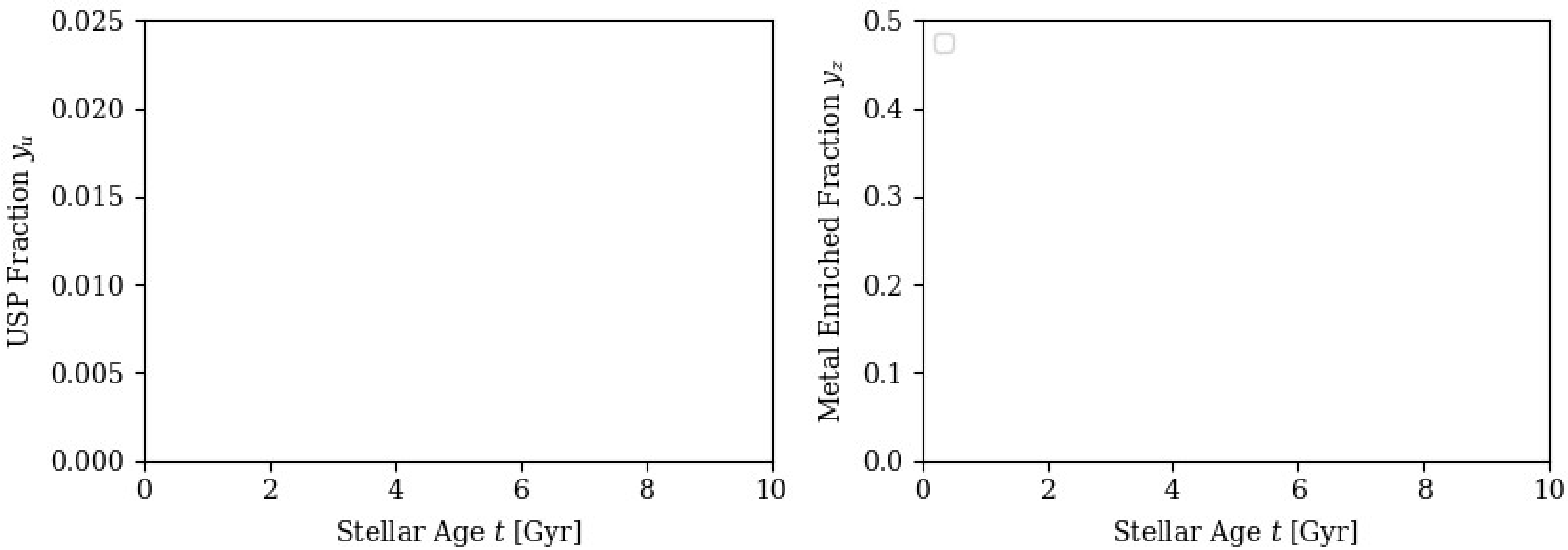
$$\max_t y_u(t) \sim y_{p0}\Sigma_0\tau \ll y_{p0}$$

$$y_z(t) = y_{p0}\left[1-\left(\frac{e^{-\Sigma_0 t} - \Sigma_0\tau e^{-t/\tau}}{1-\Sigma_0\tau}\right)\right].$$

$$\lim_{t\to\infty} y_z(t) = y_{p0}$$

Example solutions

Assumed Kepler-multi abundance $y_{p0} = 0.5$



Example solutions

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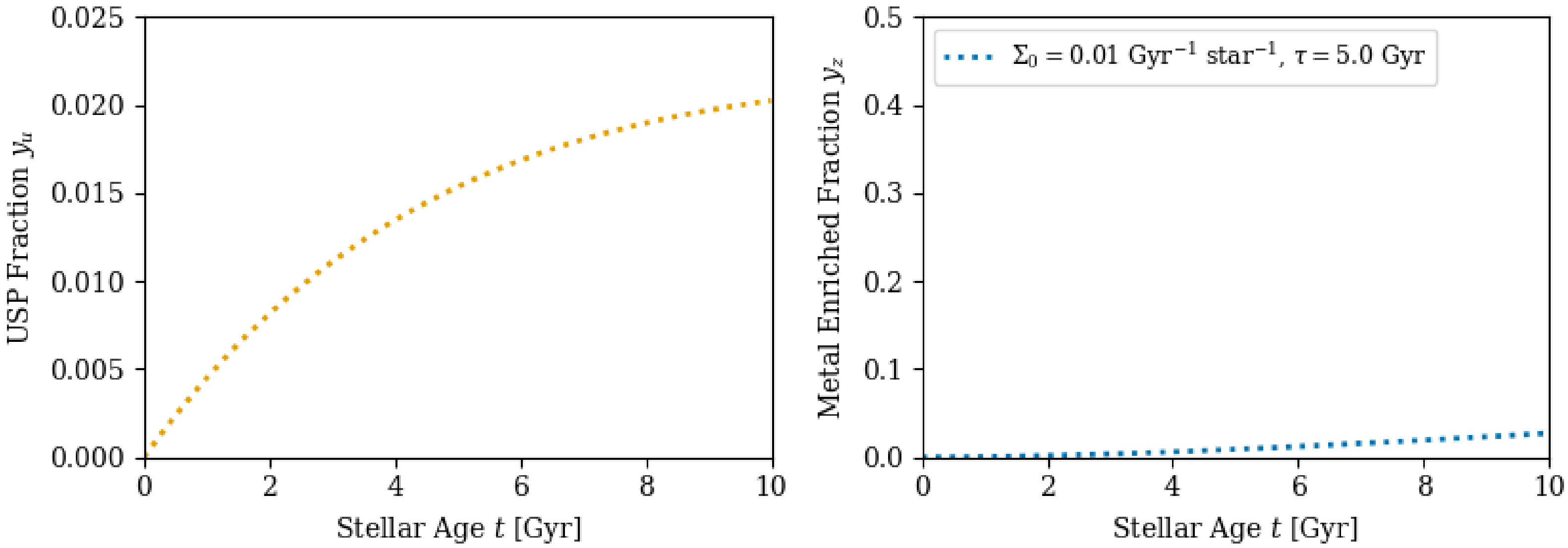
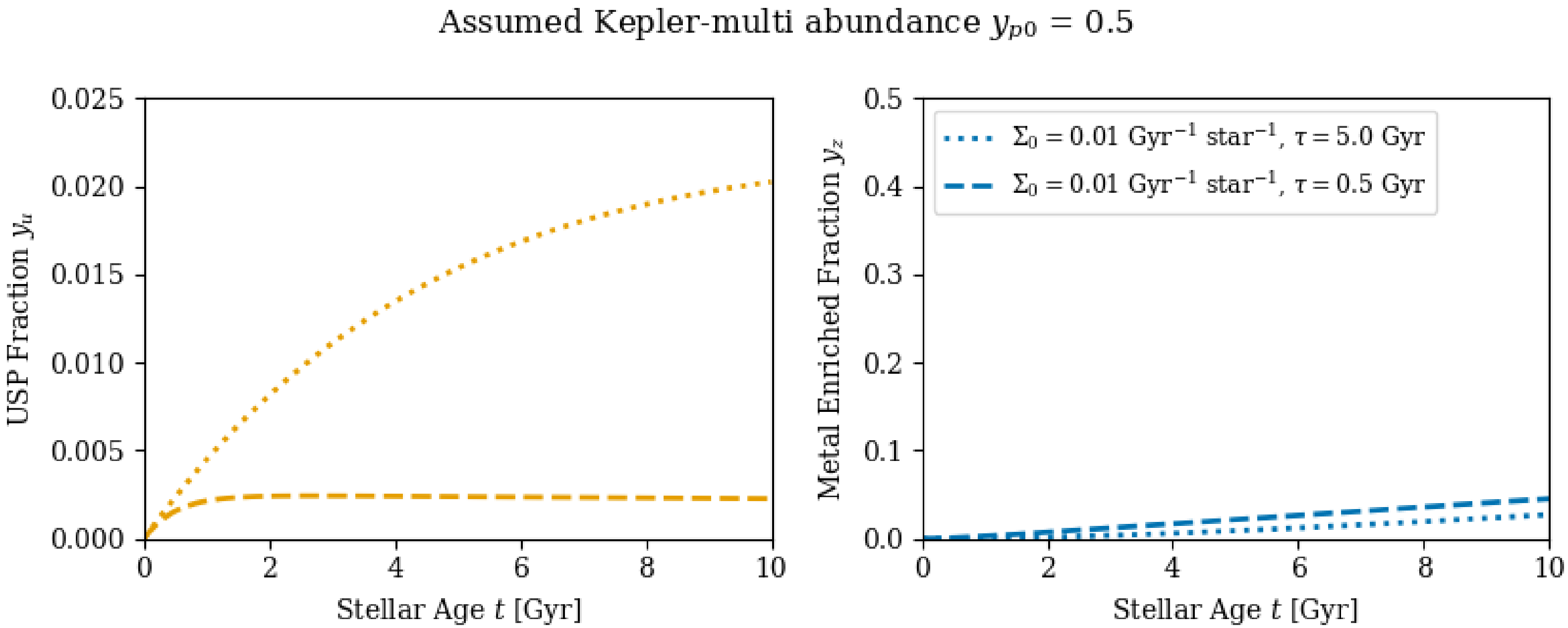


Example solutions



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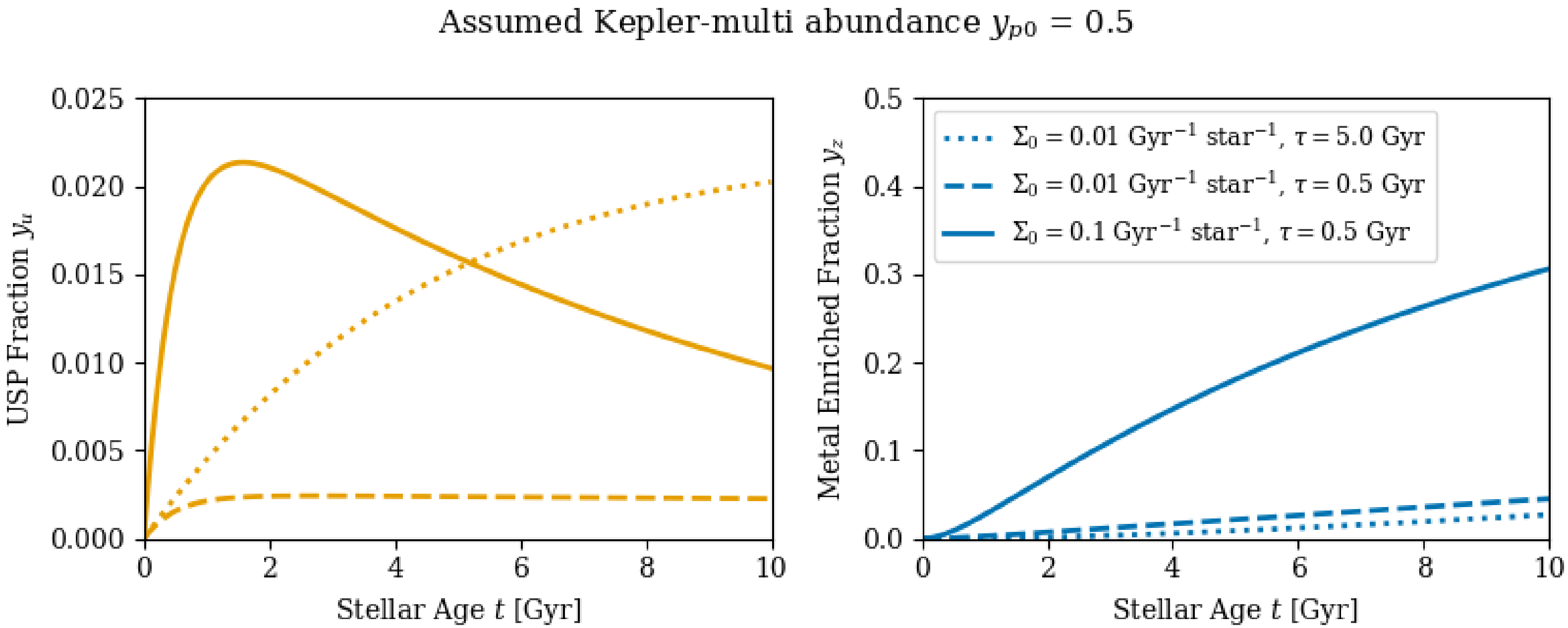
Example solutions



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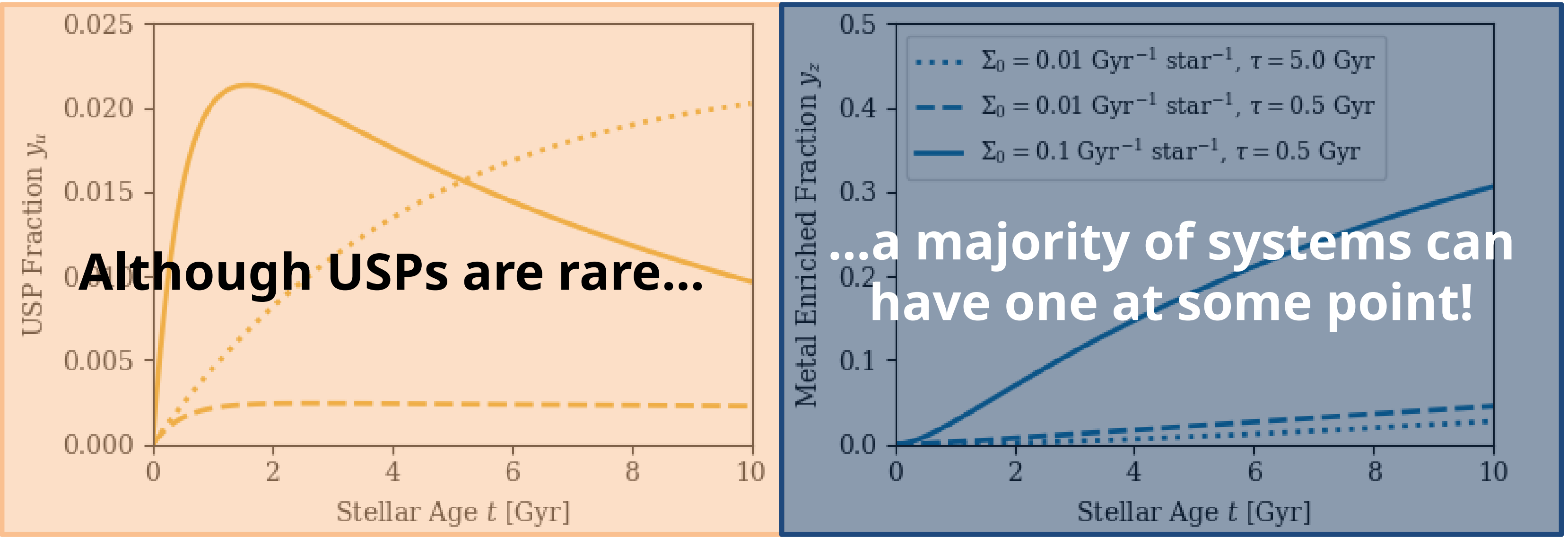
Example solutions

Assumed Kepler-multi abundance $y_{p0} = 0.5$



Although USPs are rare…

…a majority of systems can have one at some point!

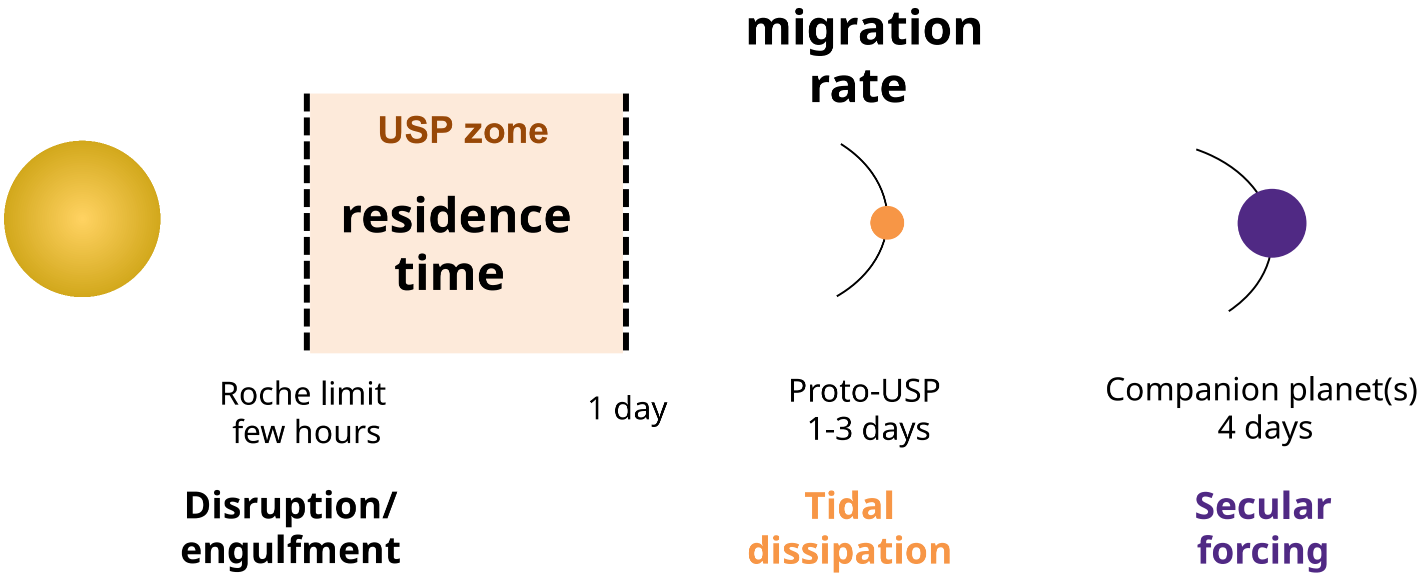
Model inversions

Adopt G-dwarf occurrence fractions (Sanchis-Ojeda+ 2014) and . Given an **observational estimate** of , we can solve for and .

Source		(Gyr^{-1} star^{-1})	(Gyr)
Spina+ (2021)	0.27	0.19	0.11
Behmard+ (2023)	0.029	0.014	0.78
Liu+ (2024)	0.077	0.037	**0.32**

Are these results **astrophysically reasonable?**

Recall: interpretation of and



migration rate

USP zone

residence time

Roche limit
few hours

1 day

Proto-USP
1-3 days

Companion planet(s)
4 days

Disruption/ engulfment

Tidal dissipation

Secular forcing

Planetary tidal dissipation determines

$$\Sigma_0 \sim \left|\frac{\dot{a}_1}{a_1}\right| \approx 0.08\,\overset{\checkmark}{\mathrm{Gyr}^{-1}}\,\mathrm{star}^{-1}\boxed{\left(\frac{k_{2,1}\Delta t_{\mathrm{L},1}}{100\ \mathrm{s}}\right)} \times \left(\frac{R_1}{R_\oplus}\right)^5\left(\frac{m_1}{M_\oplus}\right)^{-1}\left(\frac{e_1}{0.01}\right)^2 \times \left(\frac{M_\star}{M_\odot}\right)^{-2/3}\left(\frac{P_{1i}}{2\ \mathrm{day}}\right)^{-16/3}.$$

rocky planet values

For eccentricity tides (Petrovich+ 2019, Pu & Lai 2019)

Obliquity tides yield similar result (Millholland & Spaulding 2018)

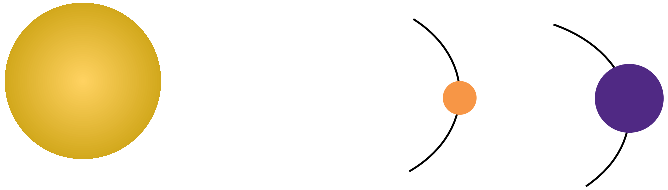
Stellar tides cannot provide 1 Gyr

Most tidal theories predict 10 Gyr.
(e.g. Hamer & Schlaufman 2019; Ma & Fuller 2021)

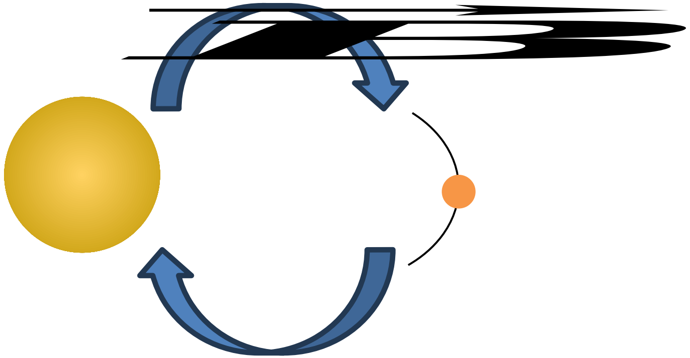
What can provide extra dissipation?

- Continued secular coupling (e.g. Lai & Pu 2019)
- Magnetic drag (e.g. Lee & Owen 2025)

Continued forcing?



Magnetic drag?



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Observational cross-checks

USP host stars should have ages consistent with the Galactic field ☑
(cf. Hamer & Schlaufman 2019)

If USPs produce pollution in Sun-like stars:

- Pollution should **correlate** with compact KM occurrence. ?
- Pollution should ***anti-*correlate** with USP occurrence in KMs. ?

Expected correlations w/ stellar type are unclear. ?

Summary

Metal pollution in Sun-like stars may be linked with USPs. If so, we may conclude that:

I. Most KM systems temporarily host a USP.

II. The observed USPs are short-lived (< 1 Gyr), requiring dissipation beyond stellar tides alone.

III. Chemical evidence can probe dynamical evolution around MS stars, not just WDs!

Scan to read our paper:

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