Predicting Earth-like-planets-hosting systems

Jeanne Davoult - DLR

PLATO-ESP2025: Planets throughout the Habitable Zone

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Diversity and correlations in exoplanet demographic and architecture

- Positive relation between stellar metallicity/mass and giant planets

e.g. Santos+2001, Johnson+2010, Bonfils+2013

Diversity and correlations in exoplanet demographic and architecture

- Positive relation between stellar metallicity/mass and giant planets
- Lower-mass planets (Super-Earths, Mini-Neptune) are more common than giant planets

e.g. Mayor+2011, Mulders+2015

Diversity and correlations in exoplanet demographic and architecture

- Positive relation between stellar metallicity/mass and giant planets
- Lower-mass planets (Super-Earths, Mini-Neptune) are more common than giant planets
- Abundance of packed and regular inner systems

  ➔ Peas-in-Pod architecture

e.g. Lissauer+2011, Millholland+2017, Weiss+2018

Diversity and correlations in exoplanet demographic and architecture

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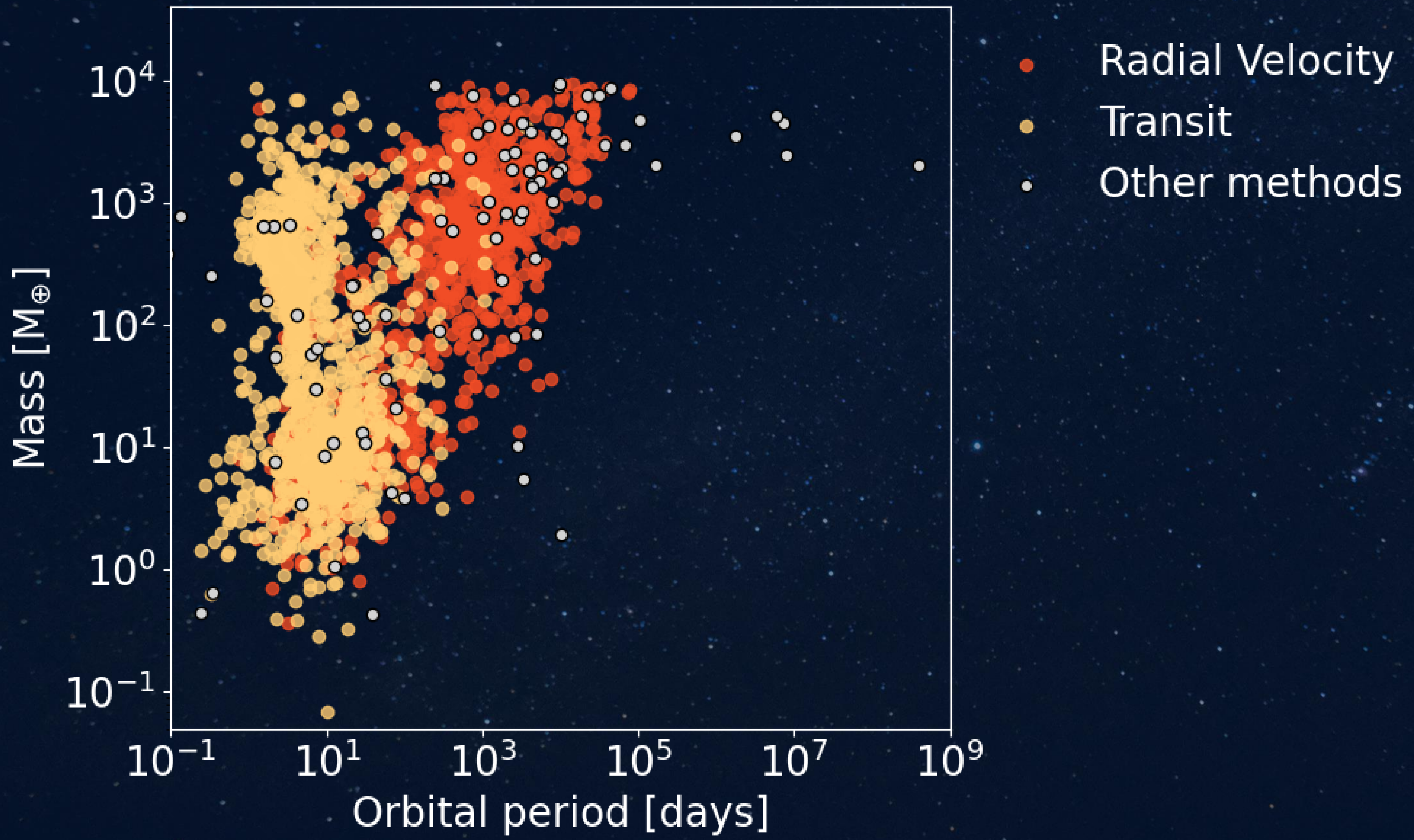
  ➔ Peas-in-Pod architecture

- Correlation between outer giant planets and inner terrestrial planets

  ➔ linked with the metallicity

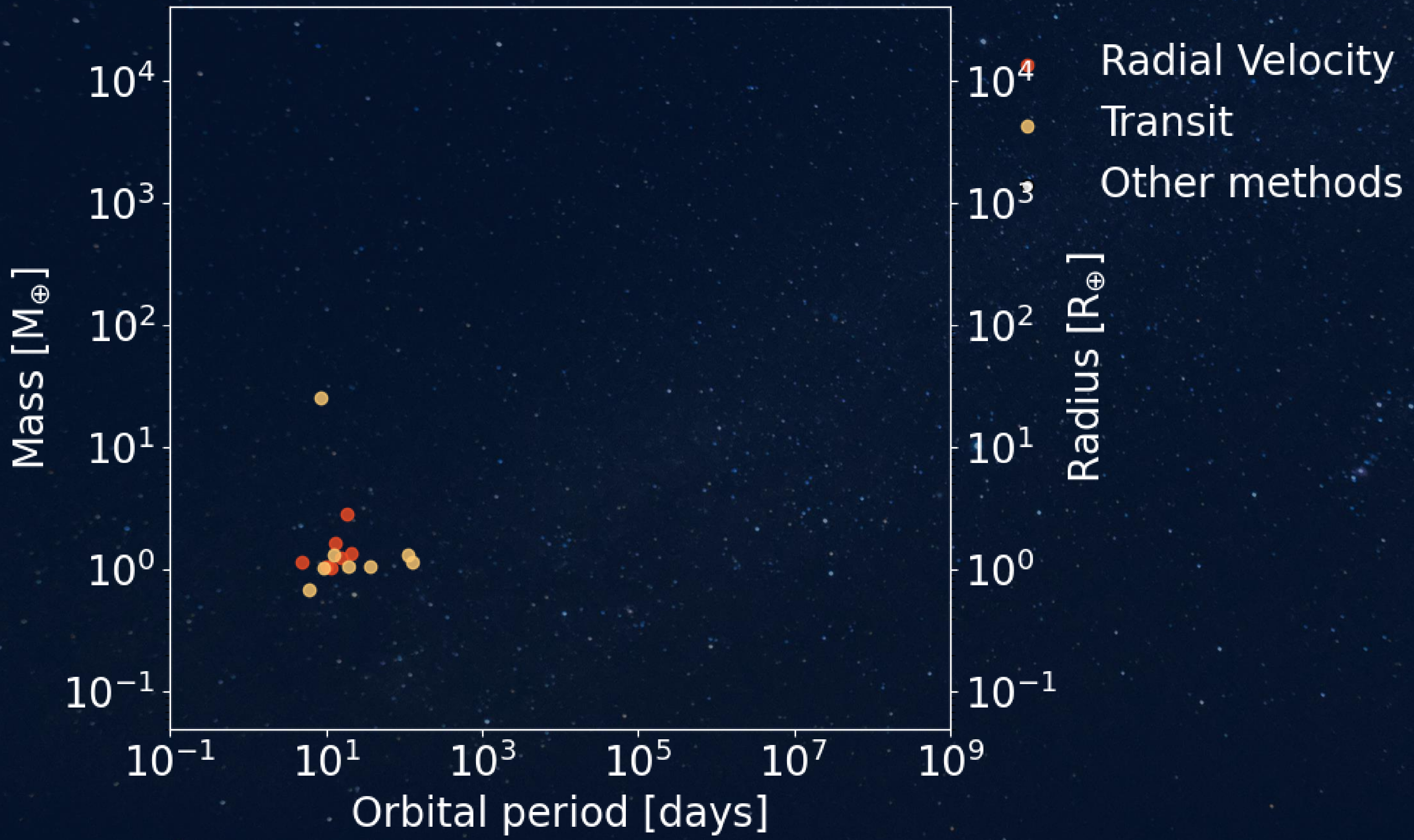
e.g. Zhu&wu2018, Bryan+2019

Exoplanet demographic



Earth-like: 0.5 < Rp < 1.5 Rearth OR 0.5 < Mp < 3 Mearth
0.25 < Sp < 1.1 Searth

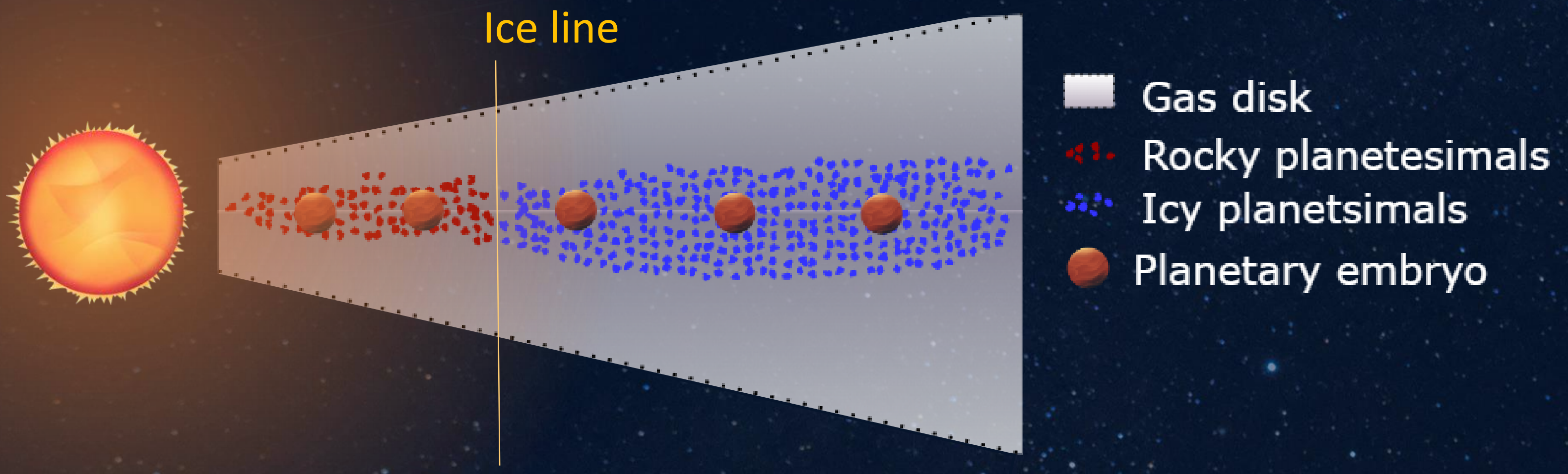
Exoplanet demographic



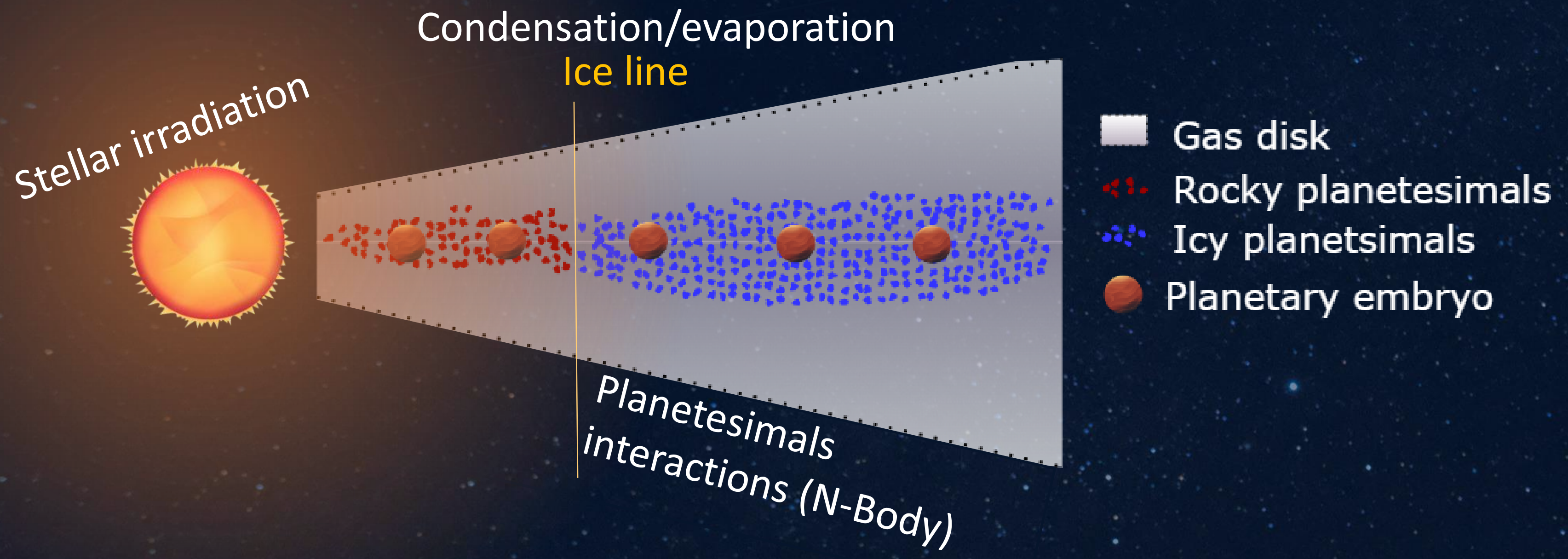
The Bern model

A population synthesis model for the formation and evolution of planetary systems

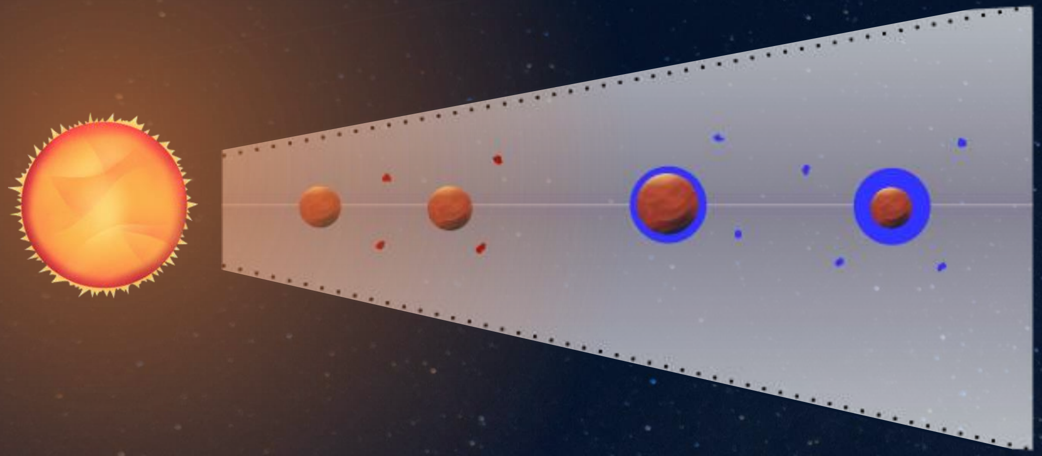
The Bern model



The Bern model



The Bern model



Core accretion paradigm: solid and gas accretion

The Bern model

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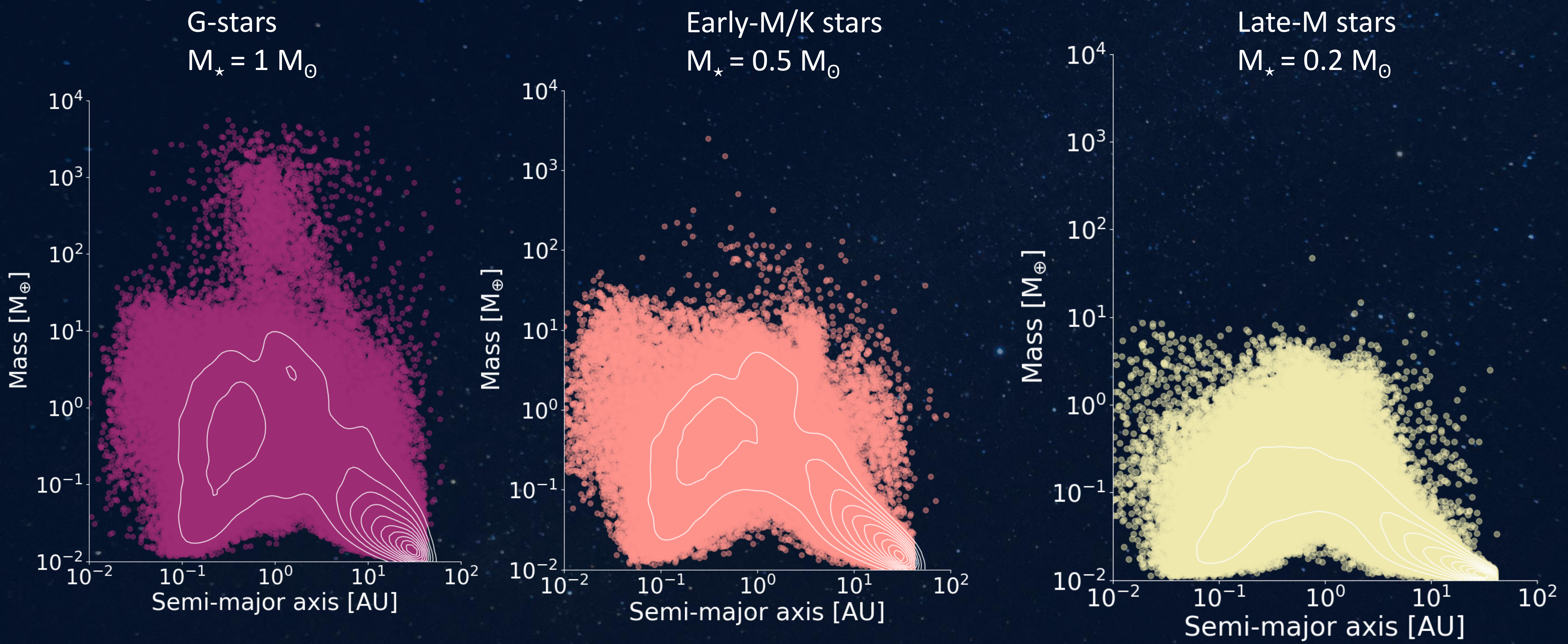
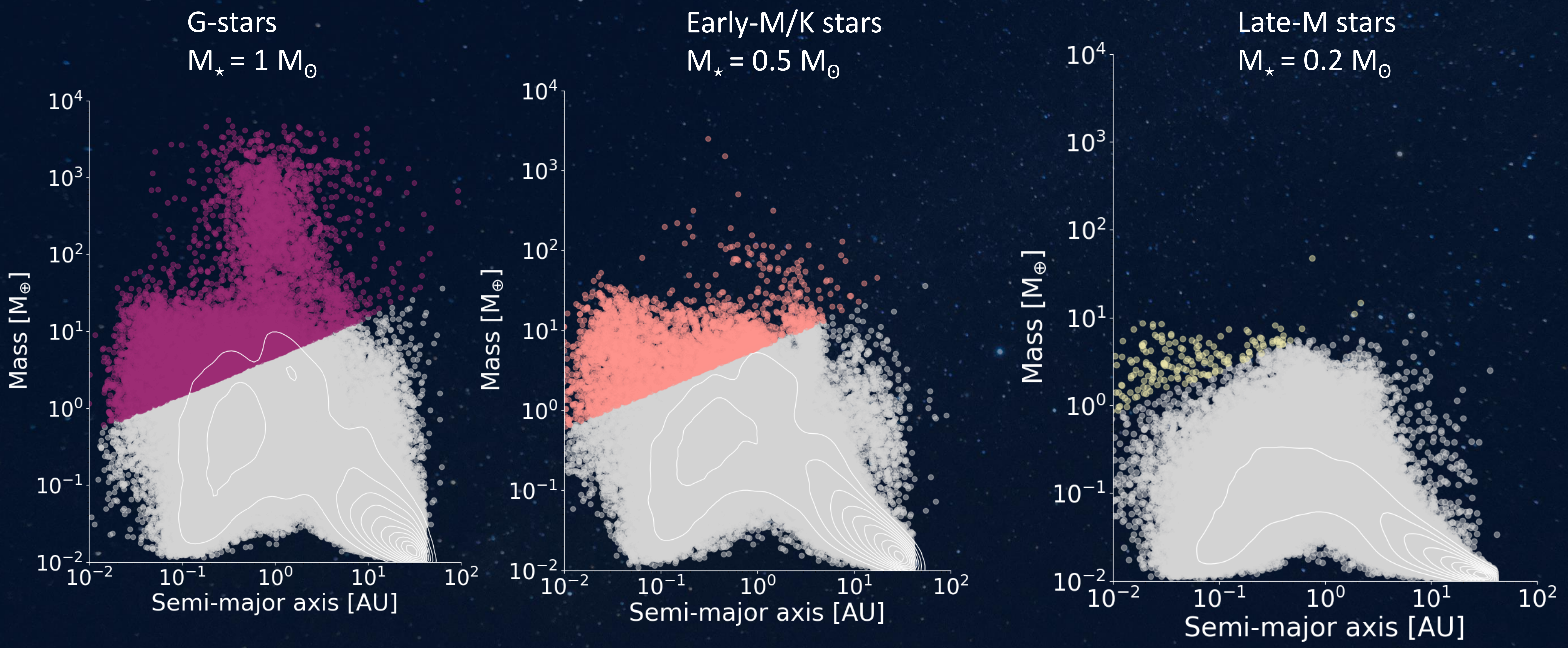
The Bern model

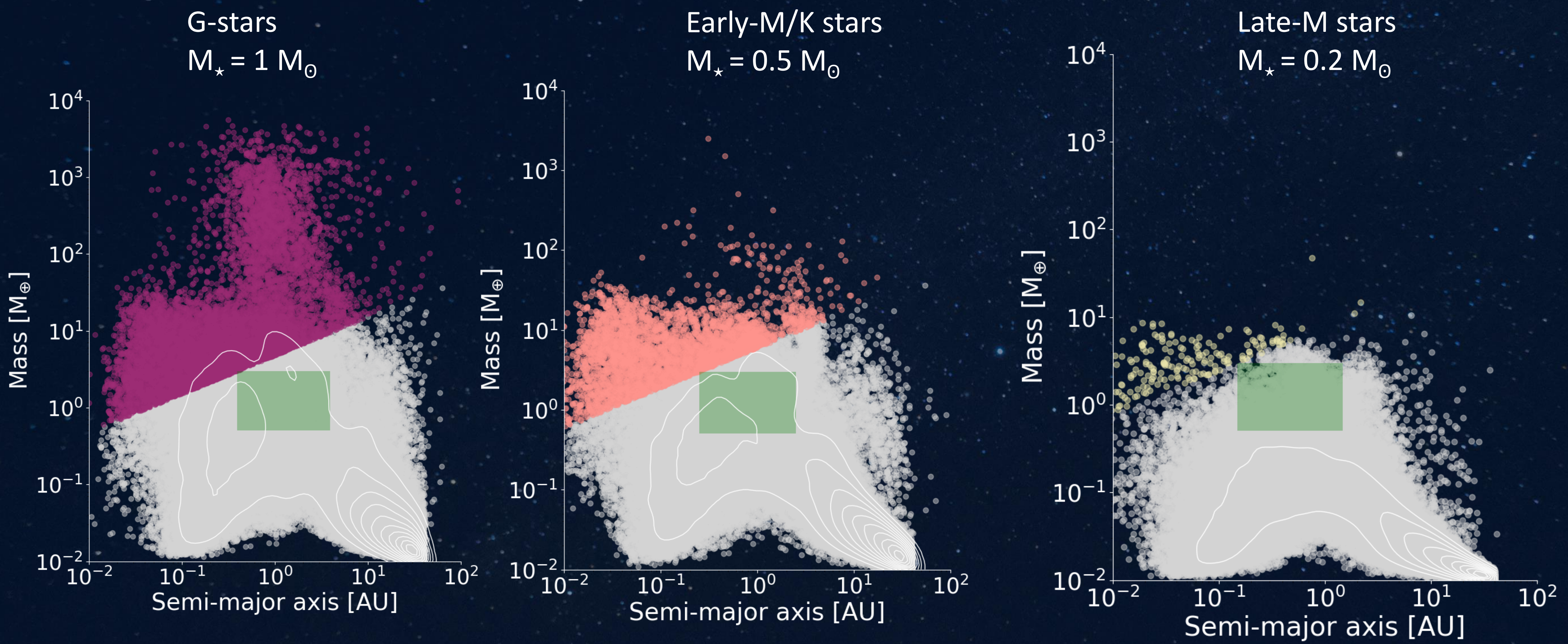
Populations of synthetic planetary systems



Populations of synthetic planetary systems

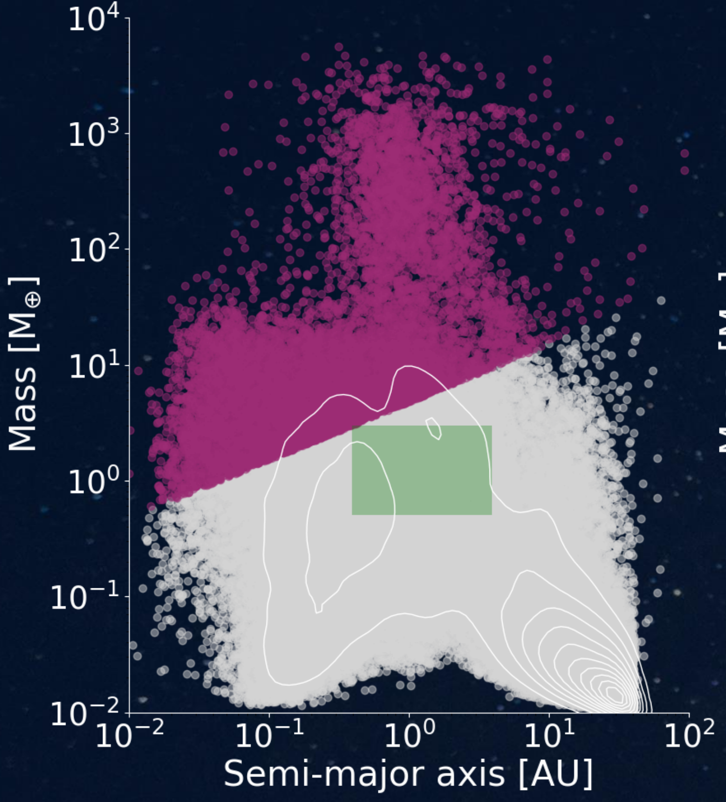


Populations of synthetic planetary systems



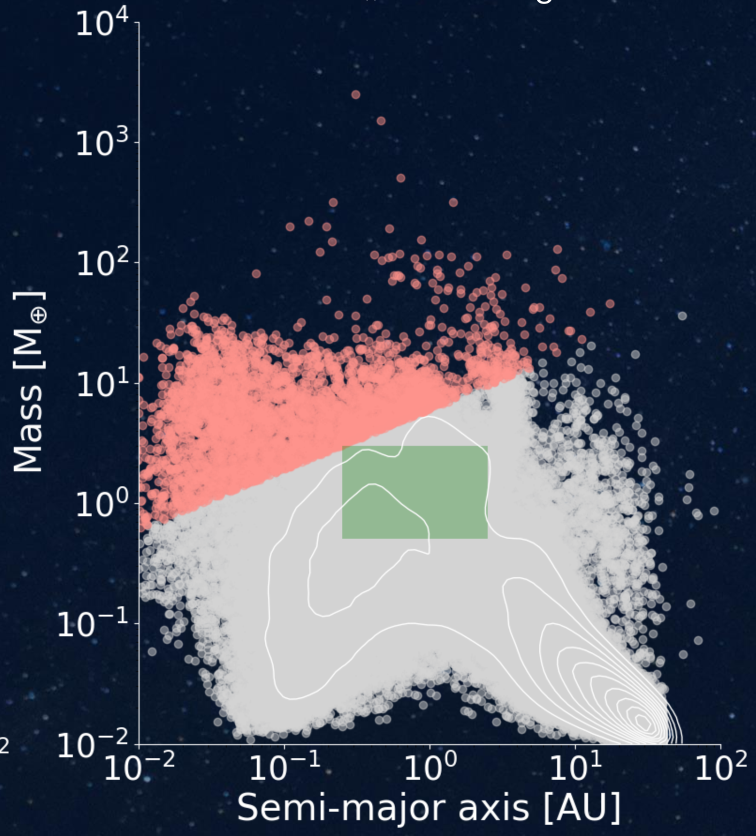
Populations of synthetic planetary systems

G-stars
$M_\star = 1\ M_\odot$



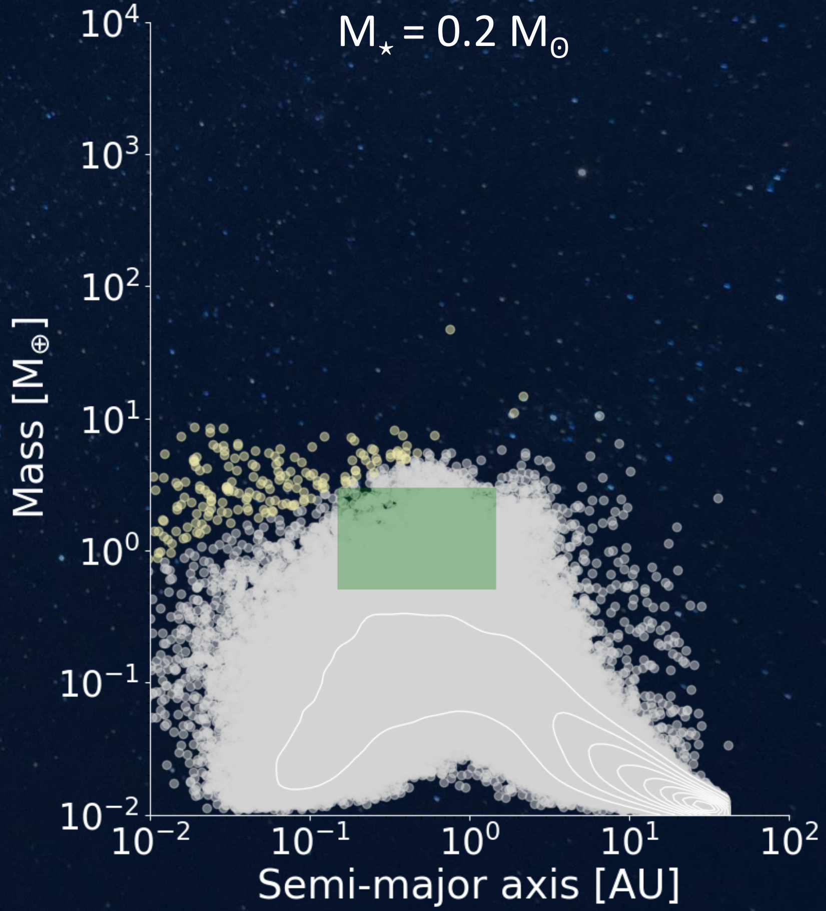
$\eta_{syst,ELP} = 0.6$

Early-M/K stars
$M_\star = 0.5\ M_\odot$



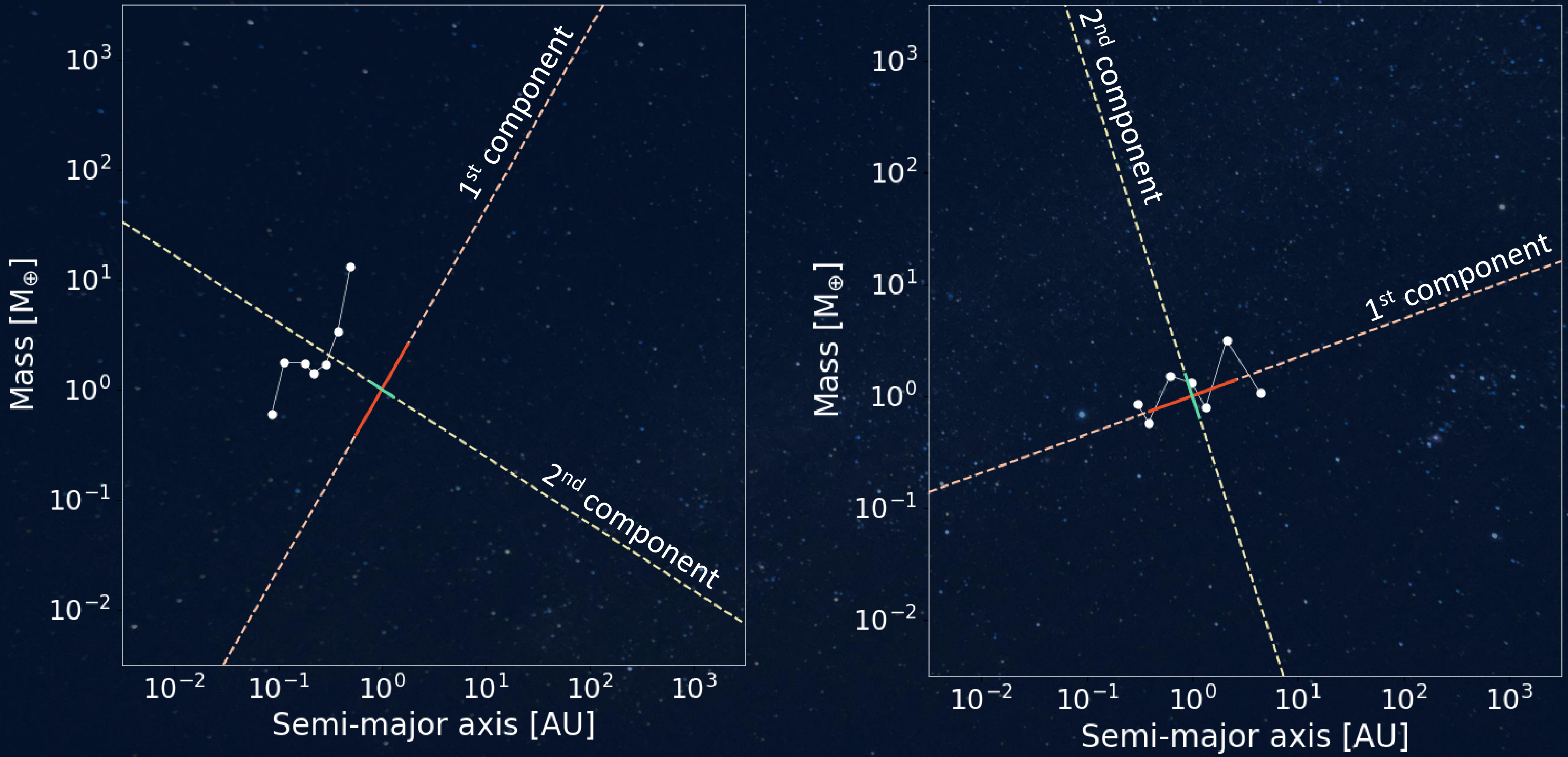
$\eta_{syst,ELP} = 0.74$

Late-M stars
$M_\star = 0.2\ M_\odot$



$\eta_{syst,ELP} = 0.4$

Principal component analysis (PCA)



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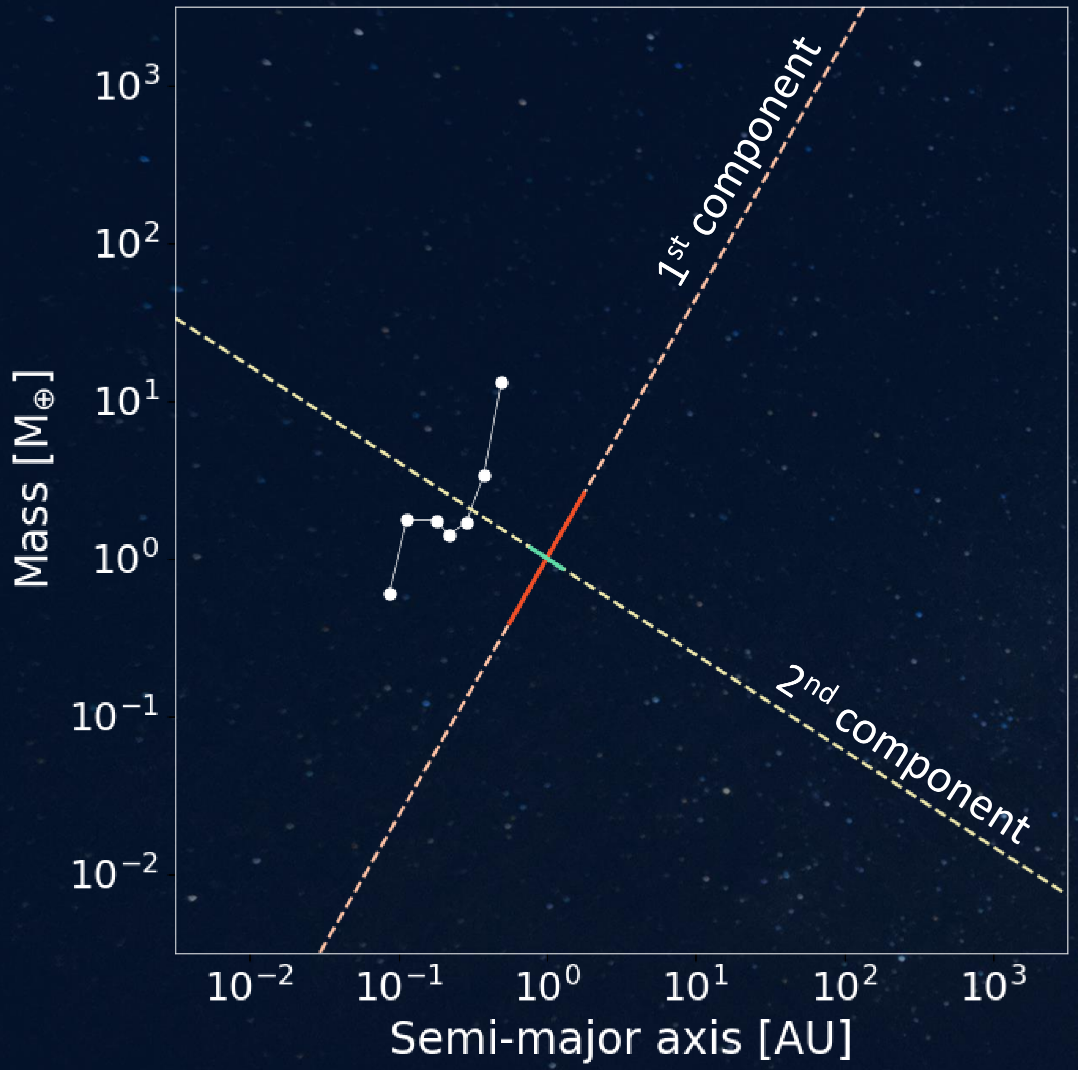
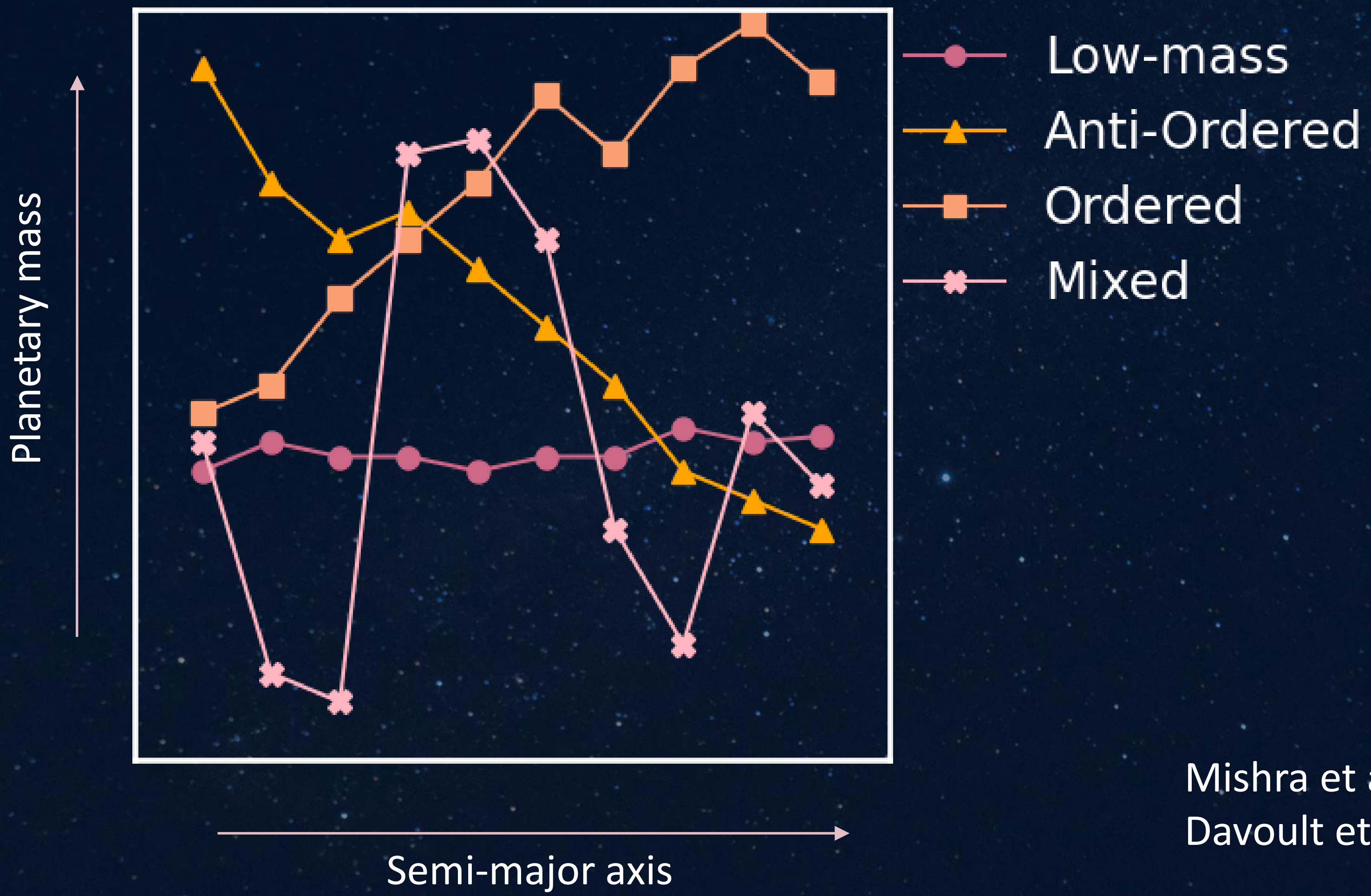


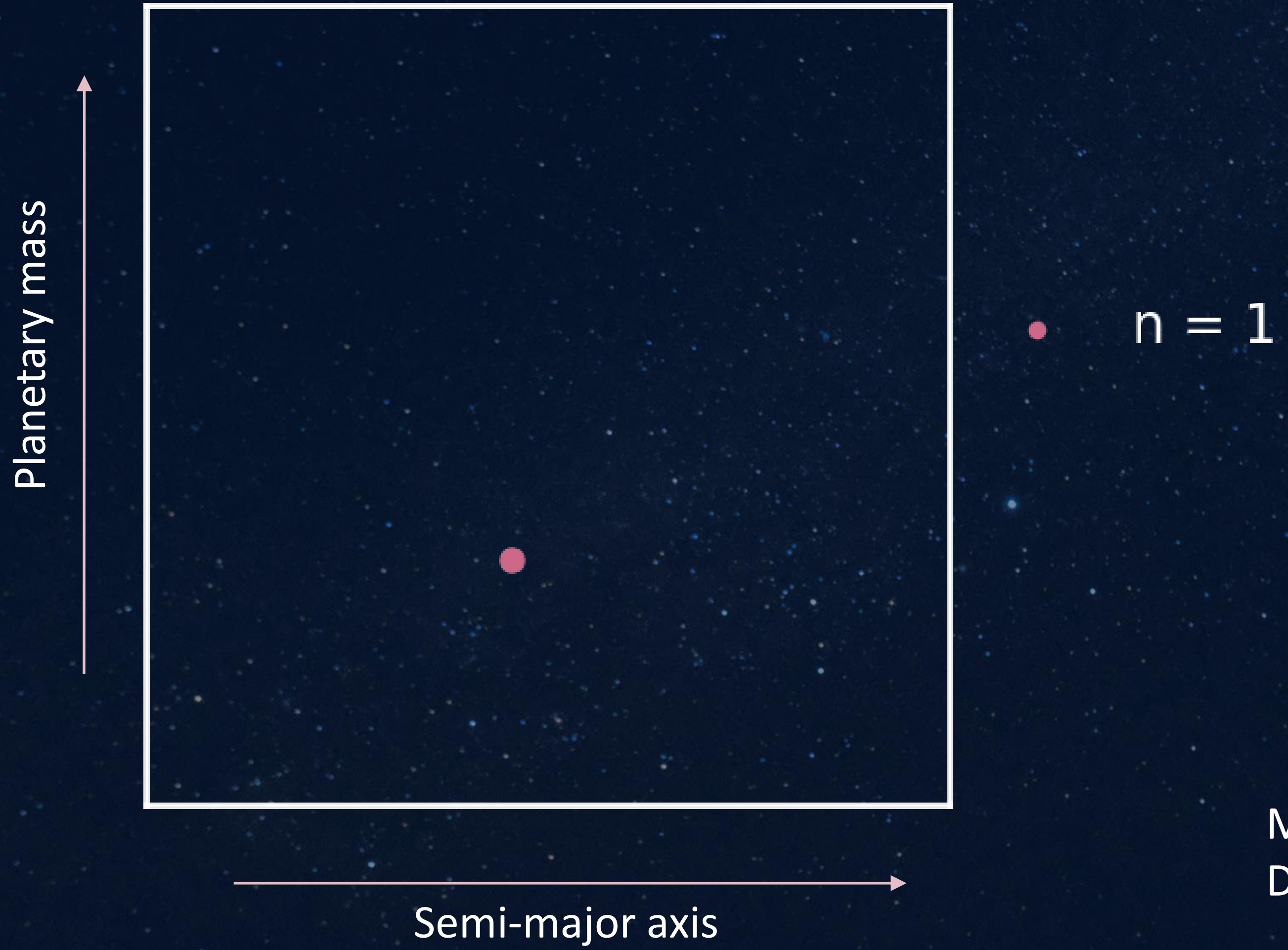
- Slope of the 1st Component: $S(C_1)$
- Variance of the 2nd Component: $V(C_2)$
- Mass of the most massive planet
- Total number of planets in the system

System architecture



Mishra et al. (2023)
Davoult et al. (2024)

System architecture



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Davoult et al. (2024)

Profile of ELP-hosting systems – Davoult et al. (2024)

	$M_\star = 1\ M_\odot$	$M_\star = 0.5\ M_\odot$	$M_\star = 0.2\ M_\odot$
Low-mass	$R_{IDP} < 2.5\ R_\oplus$ → 55.8% $R_{IDP} > 2.5\ R_\oplus$ → 88% $P_{IDP} < 10$ days → 38% $P_{IDP} > 10$ days → 83%	$R_{IDP} < 2.75\ R_\oplus$ → 64% $R_{IDP} > 2.75\ R_\oplus$ → 95% $P_{IDP} < 10$ days → 60% $P_{IDP} > 10$ days → 79%	88%
Anti-Ordered	$M_{IDP} < 100\ M_\oplus$ → 38% $M_{IDP} > 100\ M_\oplus$ → 6% $R_{IDP} < 10\ R_\oplus$ → 34% $R_{IDP} > 10\ R_\oplus$ → 5%	N.A.	N.A.
Ordered	$M_{IDP} < 10\ M_\oplus$ → 31% $M_{IDP} > 10\ M_\oplus$ → 7% $R_{IDP} < 6\ R_\oplus$ → 30% $R_{IDP} > 6\ R_\oplus$ → 3%	$M_{IDP} < 10\ M_\oplus$ → 50% $M_{IDP} > 10\ M_\oplus$ → 22% $R_{IDP} < 2\ R_\oplus$ → 50% $R_{IDP} > 2\ R_\oplus$ → 34%	N.A.
Mixed	$M_{IDP} < 10\ M_\oplus$ → 32% $M_{IDP} > 10\ M_\oplus$ → 13% $R_{IDP} < 2.5\ R_\oplus$ → 27% $R_{IDP} > 2.5\ R_\oplus$ → 8%	N.A.	N.A.
n = 1	$M_{IDP} < 100\ M_\oplus$ → 95% $M_{IDP} > 100\ M_\oplus$ → 4% $R_{IDP} < 8\ R_\oplus$ → 95% $R_{IDP} > 8\ R_\oplus$ → 8% $P_{IDP} < 30$ days → 37% $R_{IDP} > 30$ days → 91%	$M_{IDP} < 10\ M_\oplus$ → 93% $M_{IDP} > 10\ M_\oplus$ → 90% $R_{IDP} < 2.75\ R_\oplus$ → 75% $R_{IDP} > 2.75\ R_\oplus$ → 97% $P_{IDP} < 10$ days → 50% $P_{IDP} > 10$ days → 96%	94%

- IDP = Innermost Detectable Planet
- N.A. : Not Applicable

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Earth-like planet Predictor – Davoult et al. (2025)

A Machine Learning approach

- $M_\star$
- Architecture
- $M_{IDP}, R_{IDP}, P_{IDP}$

➔ Correlated with ELPs

Random Forest

Decision Tree
max_depth = 5

x500

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➔

Performance metrics:

- Precision score = $\frac{TP}{TP+FP}$
- Recall score = $\frac{TP}{TP+FN}$

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➔

Voting rate threshold	Precision score
> 70%	0.85
> 80%	0.98
> 90%	0.99

Earth-like planet Predictor: 44 results

G stars

Systems	Voting rates
HD 103949	96%
HD 42618	95%
HD 85390	93%
HIP 41378	**97%**
Kepler-22	92%
Kepler-538	96%
KMT-2021-BLG-0171L	94%

K stars

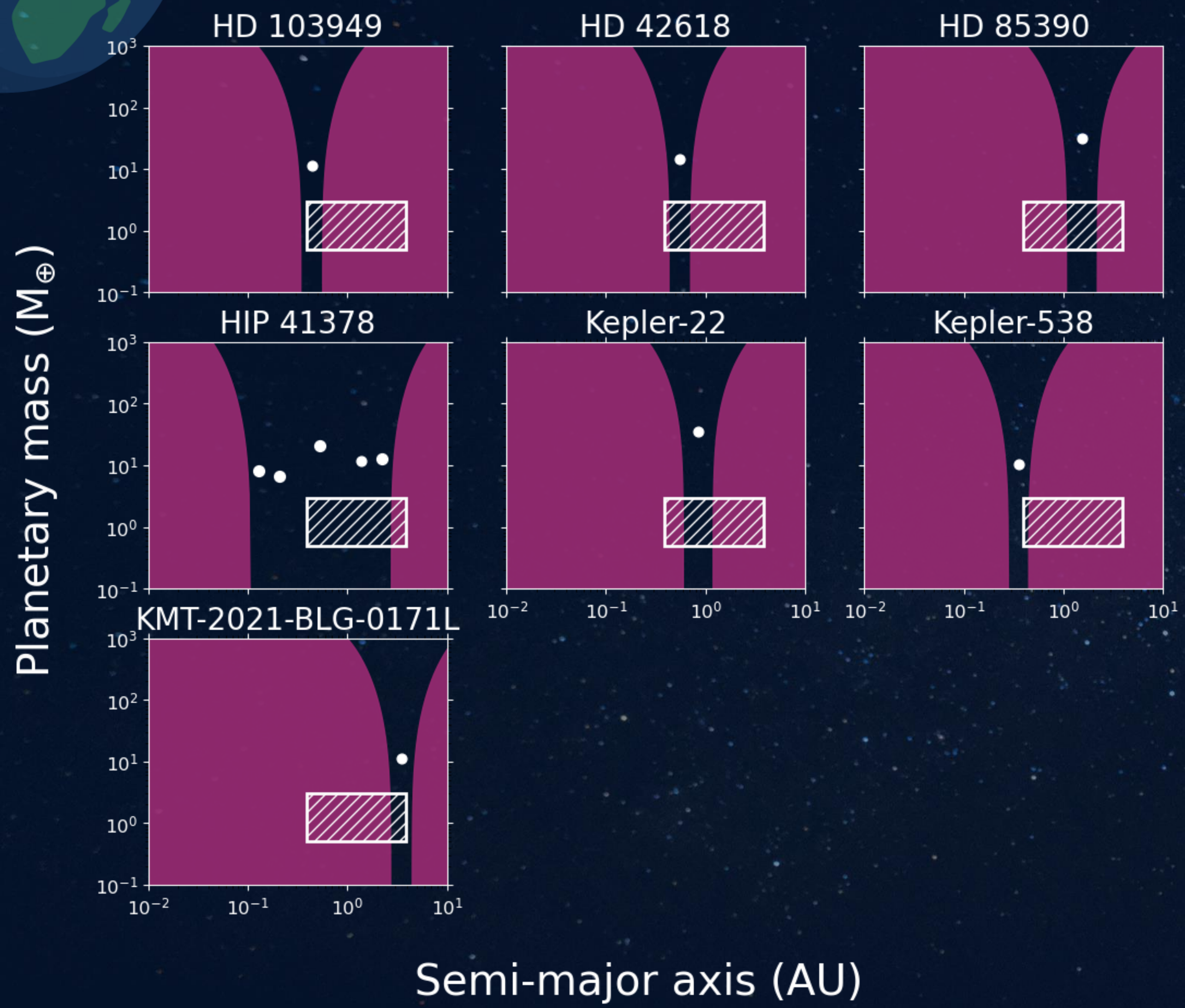
Systems	Voting rates
OGLE-2017-BLG-1691L	**97%**
GJ 685	92%
Gl 514	95%
HD 147379	96%
HD 211970	92%
HIP 71135	95%
K2-286	94%
KMT-2022-BLG-0440L	**98%**
KMT-2022-BLG-0475	92%
OGLE-2007-BLG-368L	96%
OGLE-2015-BLG-0966L	96%
OGLE-2015-BLG-1670L	96%
OGLE-2018-BLG-0506	96%
OGLE-2018-BLG-0516	95%
OGLE-2018-BLG-1126	96%
OGLE-2018-BLG-1185	96%
TCP J050742+244755	**97%**
TOI-1231	91%
TOI-2285	91%

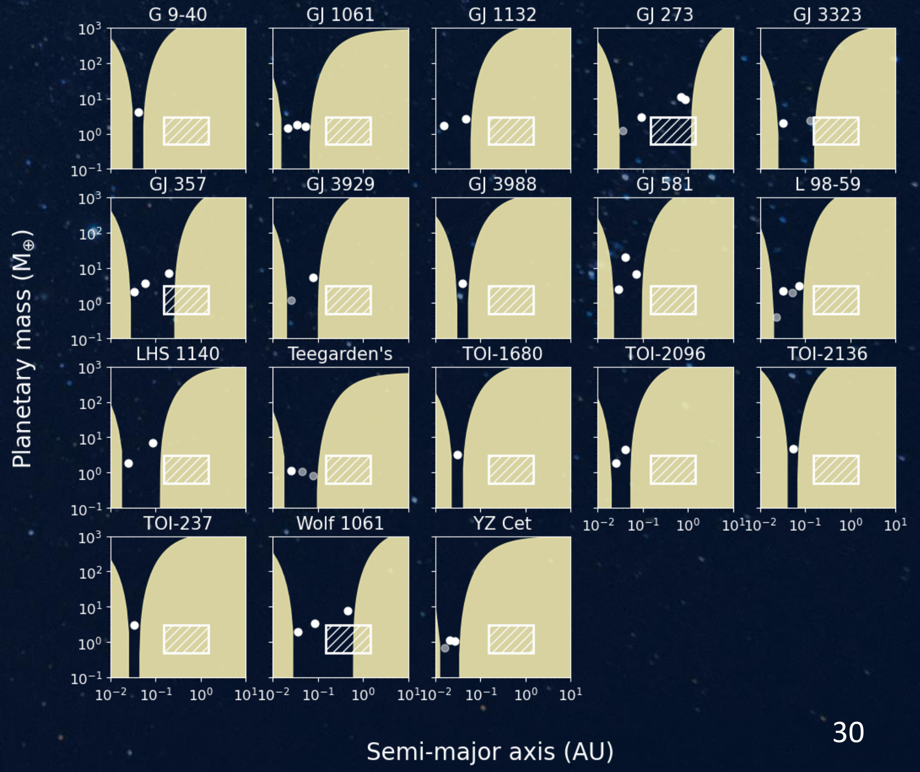
M-stars

Systems	Voting rates
G 9-40	91%
GJ 1061	**98%**
GJ 1132	94%
GJ 273	92%
GJ 3323	95%
GJ 357	**98%**
GJ 3929	91%
GJ 3988	91%
GJ 581	**98%**
L 98-59	**98%**
LHS 1140	95%
Teegarden's	95%
TOI-1680	91%
TOI-2096	**98%**
TOI-2136	91%
TOI-237	92%
Wolf 1061	**98%**
YZ Cet	**98%**

Stability criterion from Fabrycky+2014, Chen+2024

Earth-like planet Predictor: G stars





Take-away messages

- In the Bern model, we found correlations between the presence of Earth-like planets and observable properties of their systems such as their architecture, the mass, radius and period of the innermost detectable planet

- A Machine Learning model with very high performance during the training phase identified 44 systems as the most likely to host an Earth-like planet, and a study of their stability confirmed this possibility

- But one of the caveat of these studies, is how we deal with observational bias which is something I address in upcoming works (**Eltschinger, Davoult et al. (in prep.)** for RV with HARPS or ESPRESSO and **Davoult et al. (in prep.)** for photometry with PLATO)

- PLATO will populate an unreachable region of planet demographic so far, allowing a better comparison between models and data