Planet Occurrence Rates in HZ: the HARPS sample analysis and a Path Toward Habitable Zone Refinement ..

.. in era of PLATO

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IPAG - CNRS

Demographics of Exoplanets - a review of Occurrence Rates, focus on Habitable Zone

Context:

- **Occurrence rates**
- **Habitable Zone**

Occurrence in HZ:

- Transit surveys
- RV surveys
- Parameters dependance

Occurrence rates: definition

Sample:
- Largest (as possible)
- Without bias (as possible)

Computation:
- Detectability sensitivity
- Planets detections

Planetary systems occurrence
= planetary systems per star

Exoplanet occurrence
= planets per star

Average multiplicity
= planets per planetary systems

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Planetary systems occurrence
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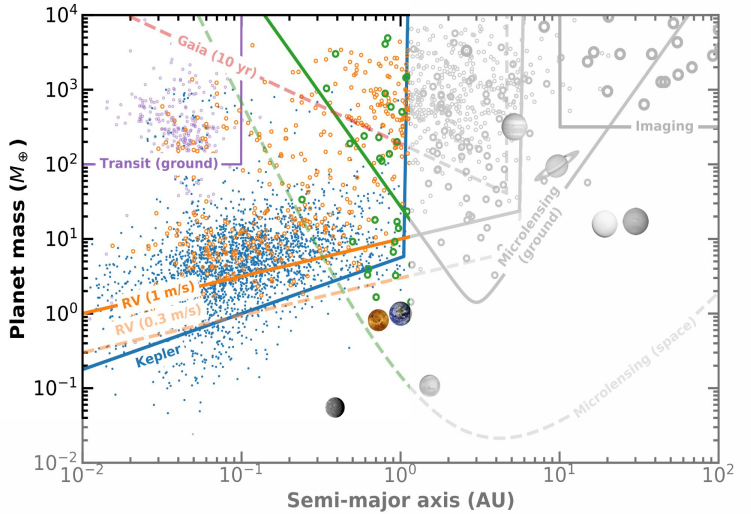
Occurrence rates: methods

Transit:

- \+ Size of sample
- \+ Sensitivity short periods
- \+ Homogeneous time series
- \+ Sampling of obs
- \- Detections = candidates
- \- Sensitivity long periods (> 100d)

Surveys/Instruments:

- \- TESS
- \- Kepler



Dressing et al. 2013 - Kepler
Dressing et al. 2015 - Kepler (early-M)
Ment et al. 2023 - TESS (late-M)
Beleznay et al. 2022 (AFG)
Kovas et al. 2018 - Ground Transit WTS (early-M)
Gan et al. 2023 - TESS (early-M)
Santerne et al. 2012 - CoRot (FGK)
Santerne et al. 2012b - Kepler (F5-K5)

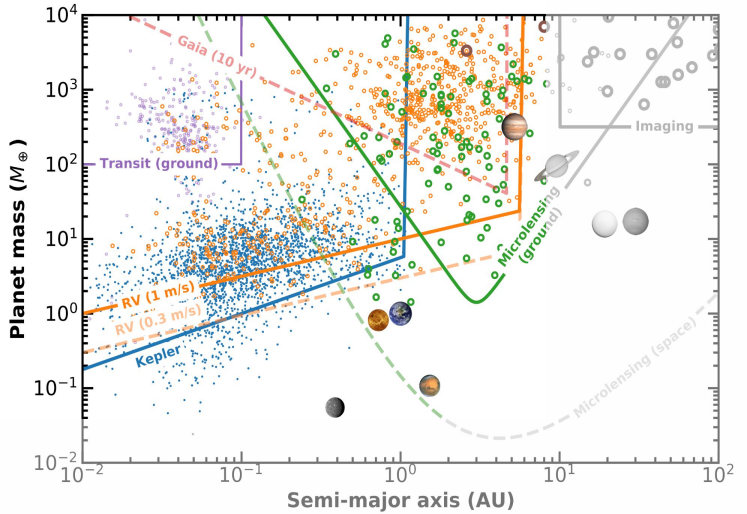
Occurrence rates: methods

Radial Velocity:

- \+ Sensitivity very long periods (20 years !)
- \+ Sensitivity short periods
- \+ Detections
- \- Size of sample
- \- Sampling of obs
- \- Completeness
- \- Inhomogeneous time series

Instruments/surveys:

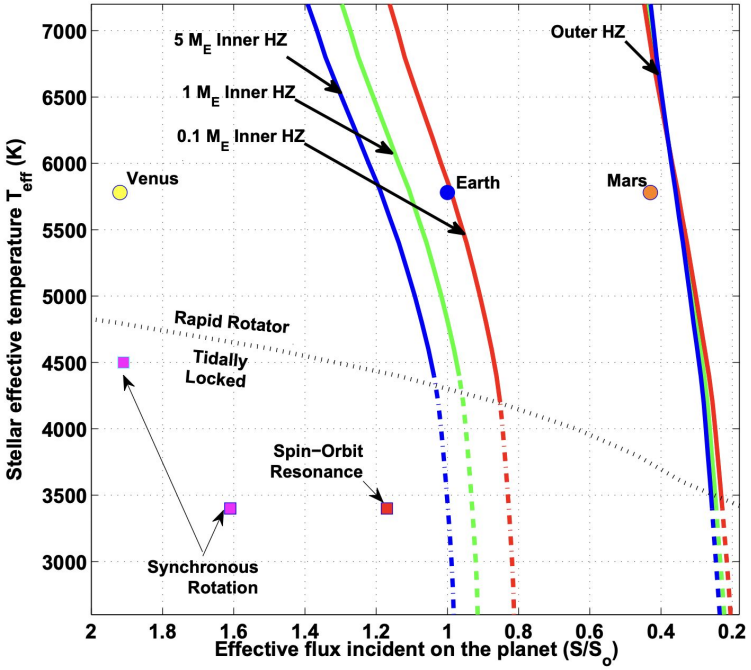
- \- HARPS / HARPS-N
- \- CARMENES
- \- SOPHIE
- \- HIRES



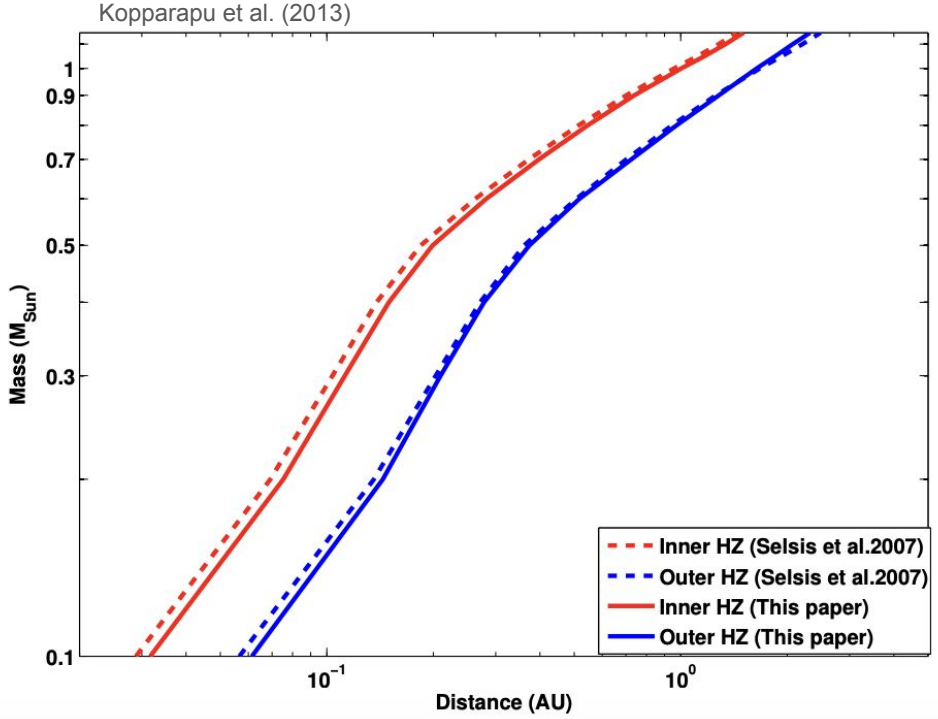
Pinamonti et al. 2023 - HARPS -N (early-M)
Sabotta et al. 2021 - CARMENES (M)
Mayor et al. 2011 - CORALIE + HARPS (FGKM)
Bonfils et al. 2013 - HARPS (M)
Mignon et al. 2025 - HARPS (M)
Ribas et al. 2023 - CARMENES (M)
Borgniet et al. 2017 - HARPS + SOPHIE (AF young)
Grandjean et al. 2020 - HARPS (AF young)

Focus on Habitable Zone

Kopparapu et al. (2014)

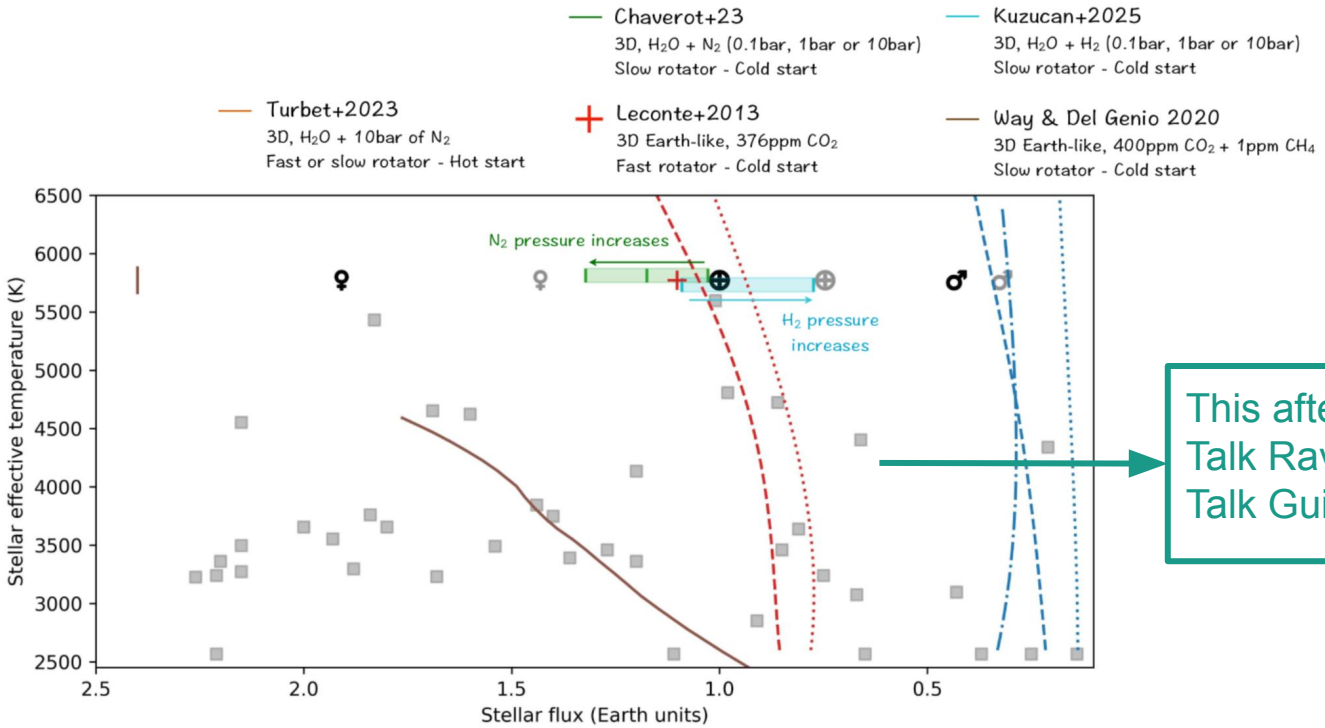


Kopparapu et al. (2013)



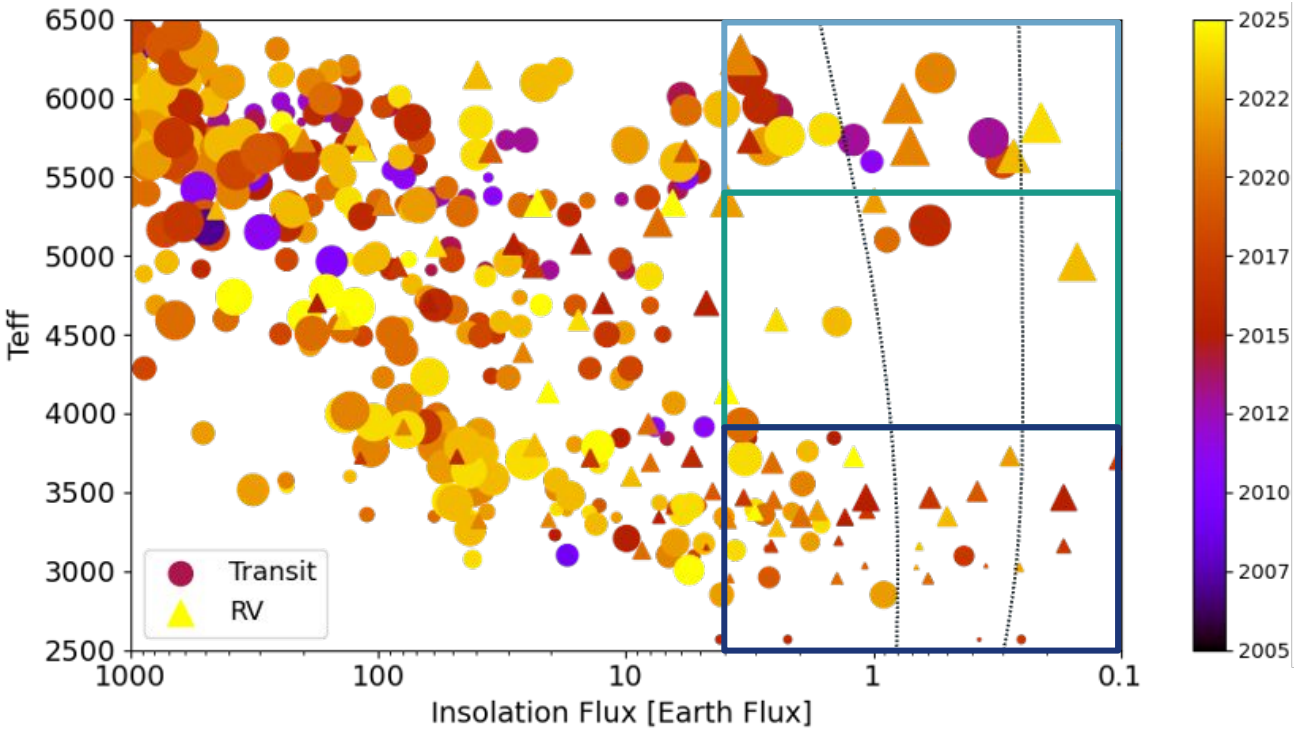
Kasting et al. 1993
Kopparapu et al. 2013
Selsis et al. 2007
Kopparapu et al. 2014

Focus on Habitable Zone



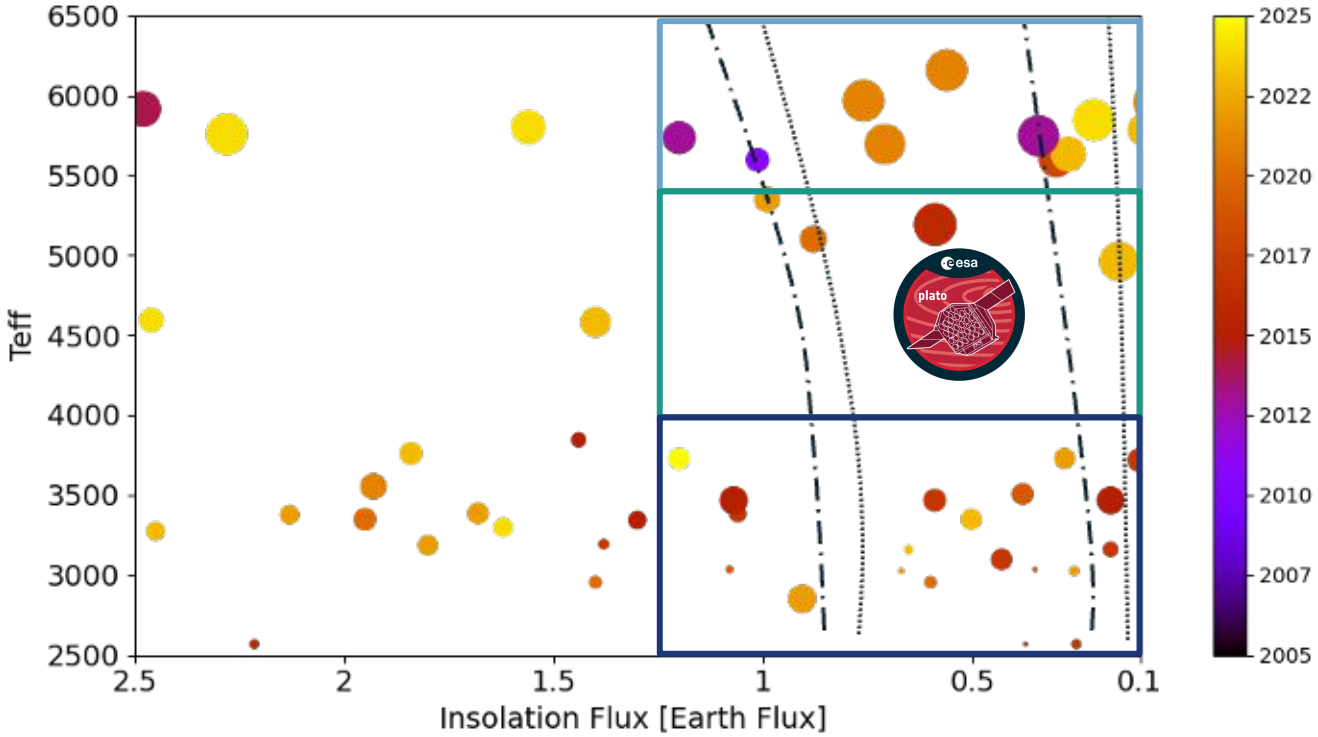
This afternoon:
Talk Ravi Kumar Kopparapu
Talk Guillaume Chaverot

Detectability in the HZ



- Only Giant planets detectable
  - ≠ HZ
- Only Giant planets detectable but rare!
  - ≠ HZ
- Earth-like and Super-Earth-like planets detectable in HZ

Detectability in the HZ



- Only Giant planets detectable
  - ≠ HZ
  - **Challenging PLATO domain**
- Only Giant planets detectable but rare
  - ≠ HZ
  - **PLATO domain**
- Earth-like and Super-Earth-like planets detectable in HZ

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Context:

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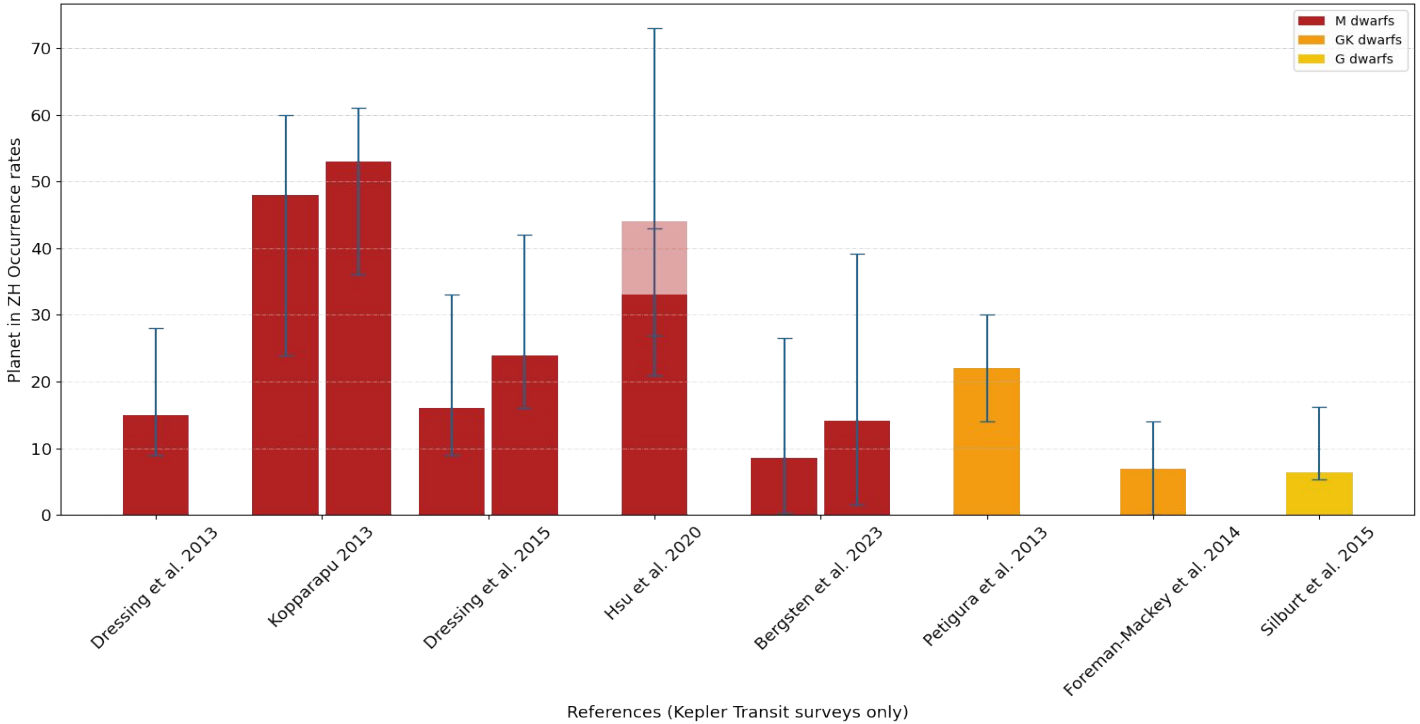
- Habitable Zone

Occurrence in HZ:

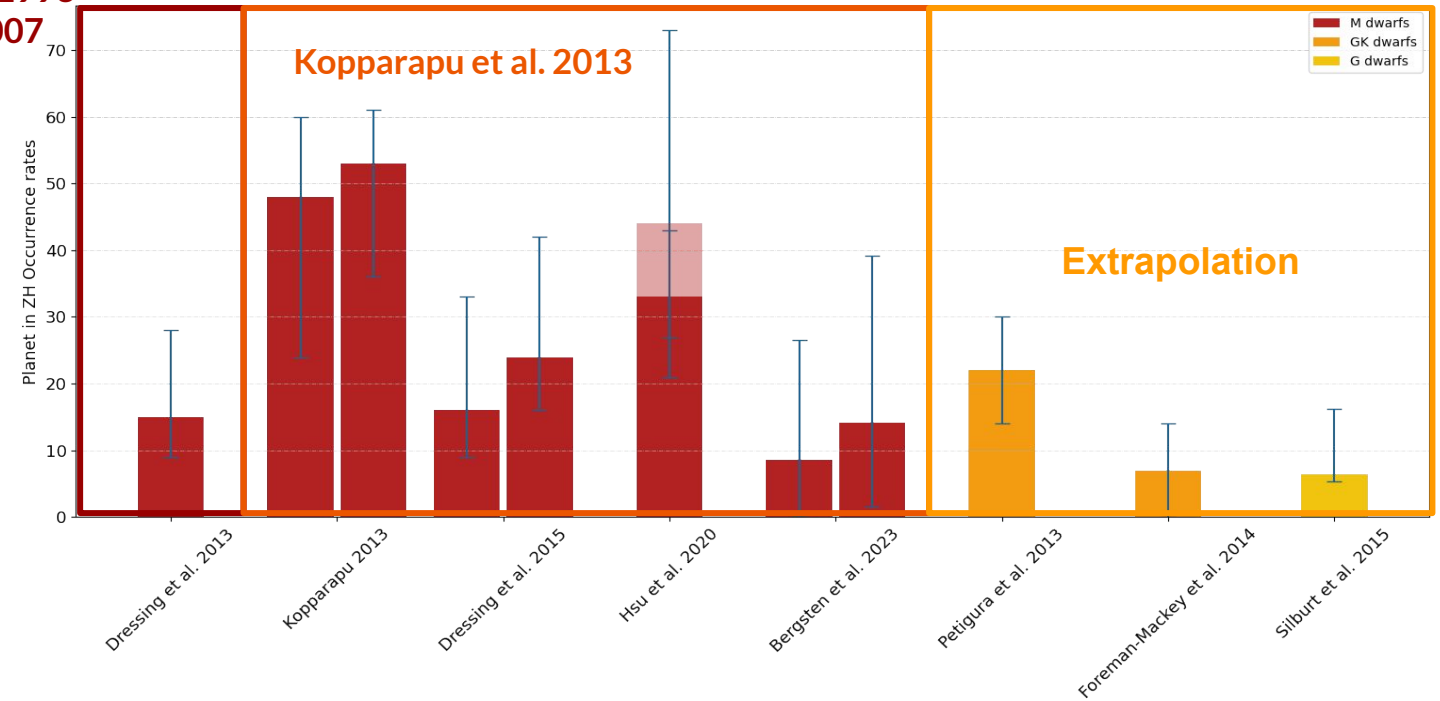
- **Transit surveys**
- **RV surveys**
- **Parameters dependance**

Occurrence Rates in HZ determined by Transit



Occurrence Rates in HZ determined by Transit

Kasting et al. 1993
Selsis et al. 2007

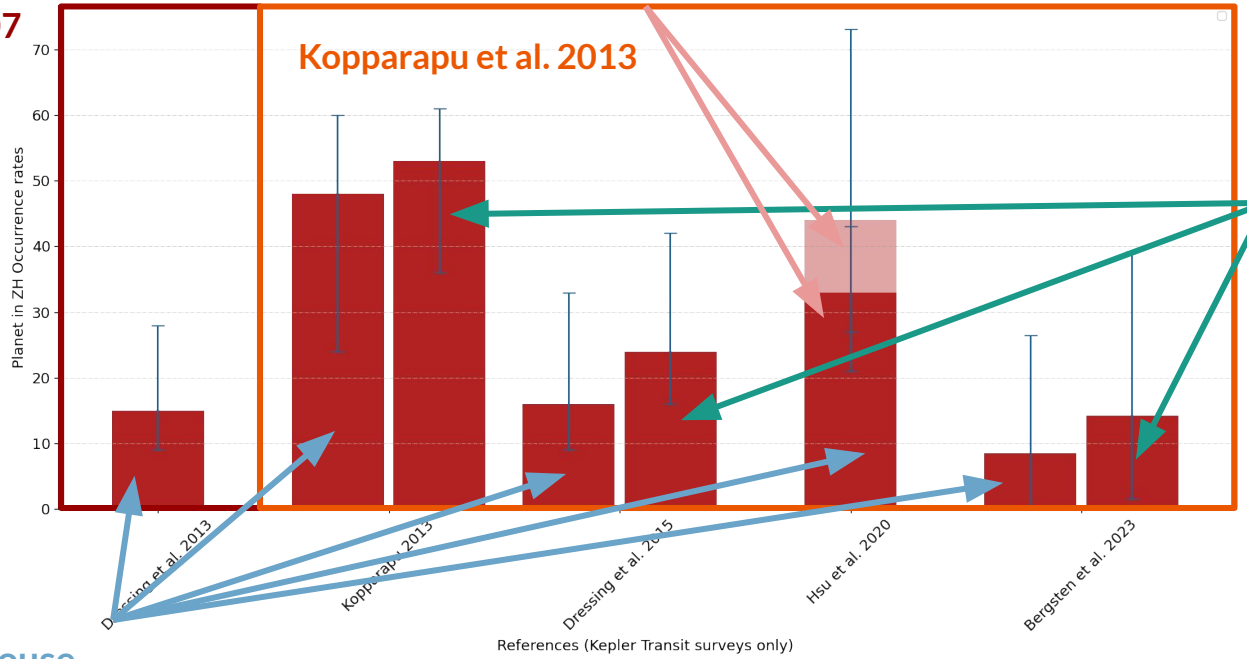


Occurrence Rates in HZ determined by Transit

Kasting et al. 1993
Selsis et al. 2007

Model dependant

Kopparapu et al. 2013

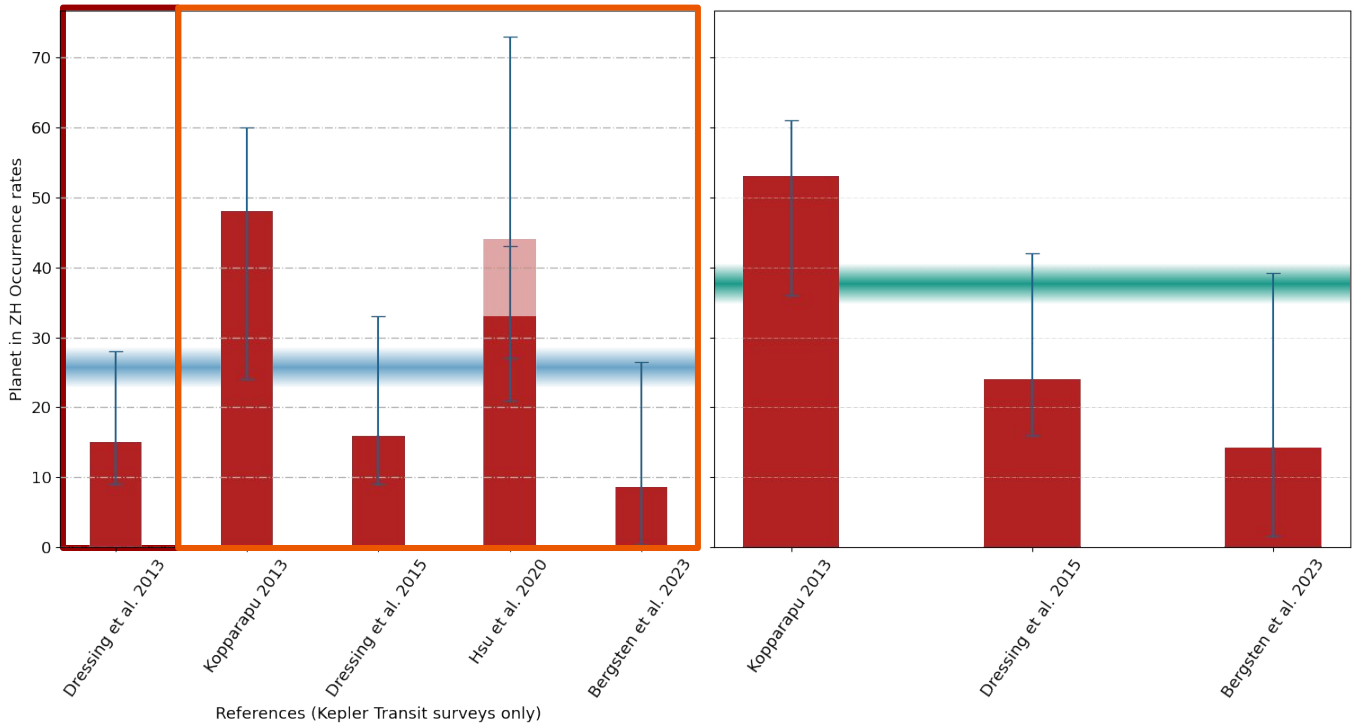


"Optimistics":
Recent Venus
- Early Mars

"Conservative":
Moist Greenhouse
- Maximum Greenhouse

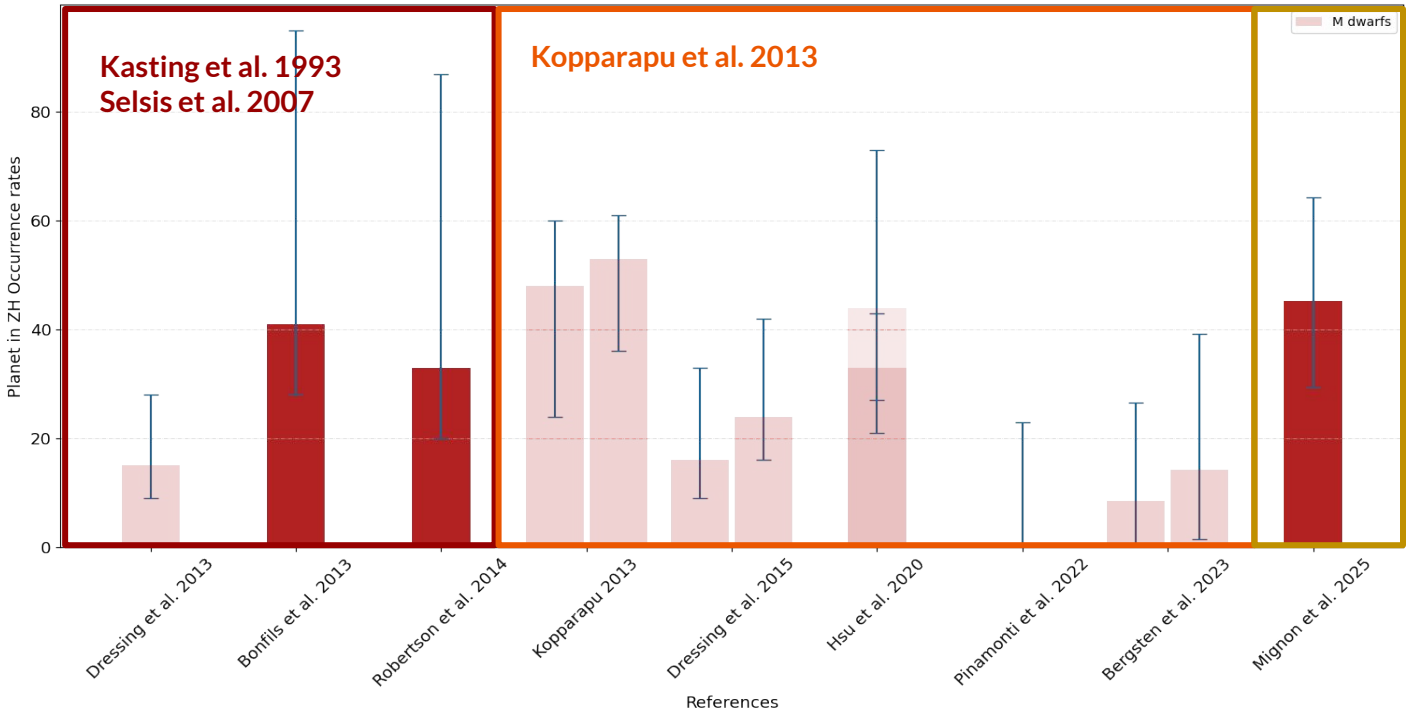
Occurrence Rates in HZ determined by Transit

Conservative Habitable Zone Occurrence: ~26%



Optimistic Habitable Zone Occurrence: ~37%

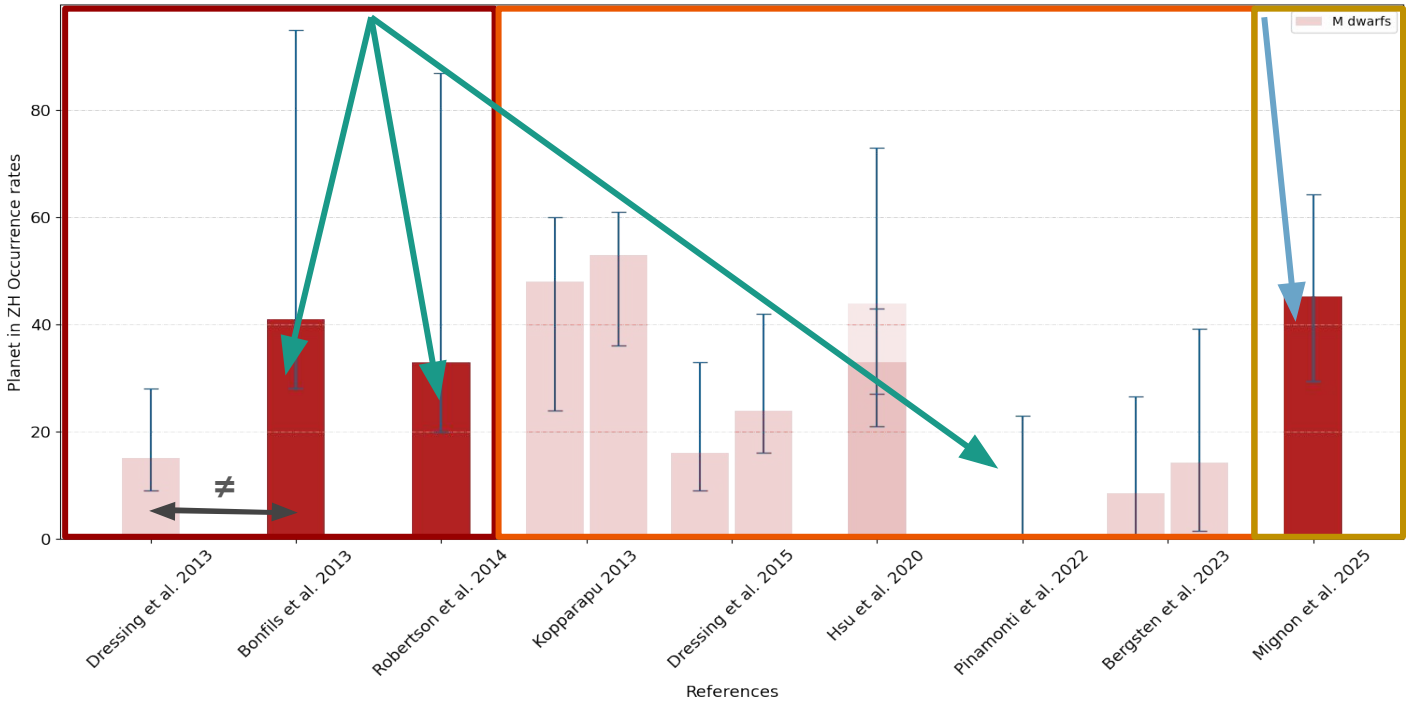
Occurrence Rates in HZ determined by RV



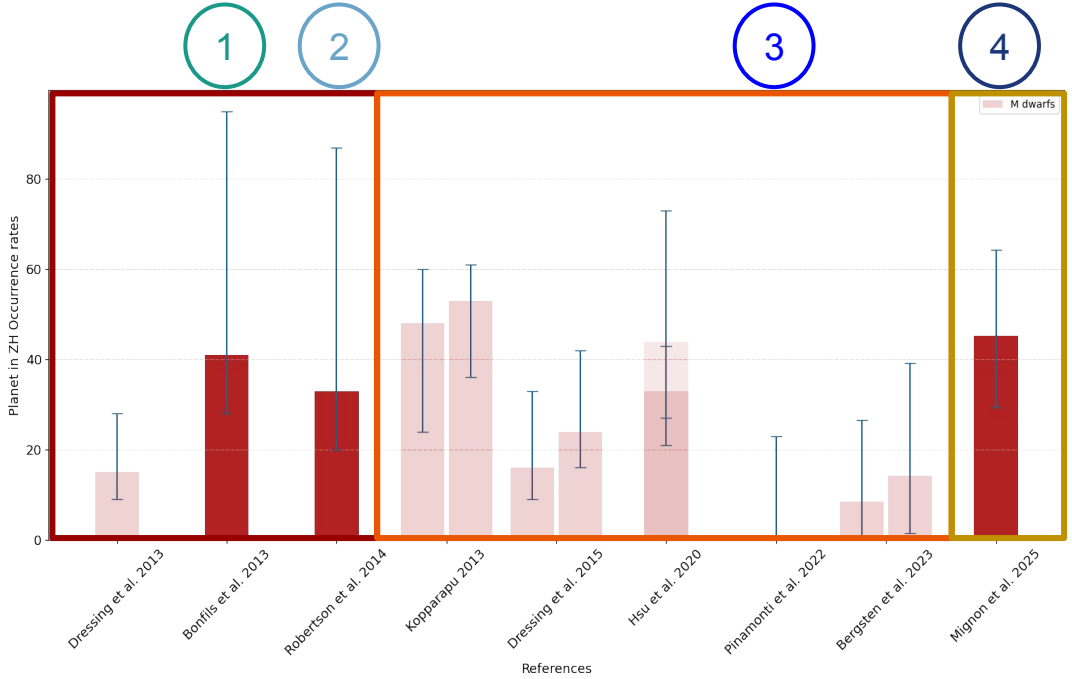
Kopparapu et al., 2014
1 Mearth inner limit

Occurrence Rates in HZ determined by RV

"Optimistics": Recent Venus - Early Mars "Conservative": Runaway Greenhouse - Maximum Greenhouse



Occurrence Rates in HZ determined by RV



1
- 102 late -M
- HARPS
- Nvisits > 3
- 2 planets in ZH (1 ruled-out)

2
- 102 mid-M
- HARPS
- Nvisits > 3
- 1 planet in ZH

3
- 56 early-M
- HARPS-N
- Nvisits > 10
- 0 planet in ZH
- GP applied

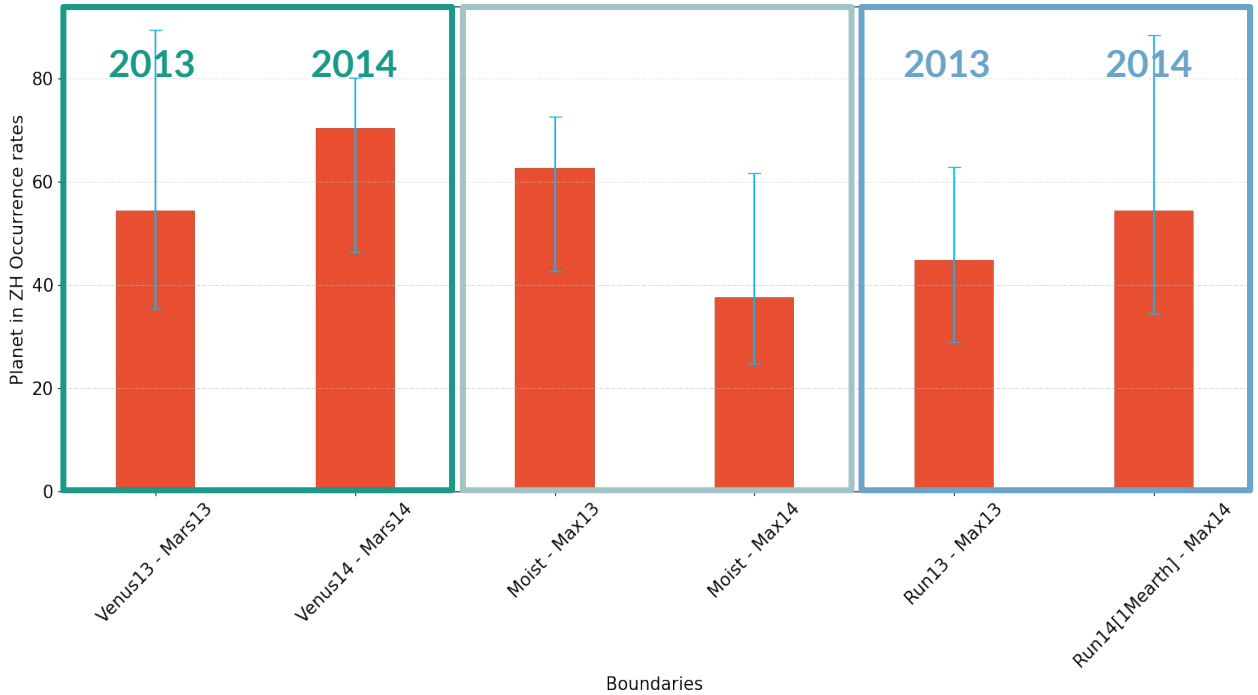
4
- 197 mid-M
- HARPS
- Nvisits > 3
- 4 planets in ZH

Occurrence Rates in HZ: inner and outer bounds

Focus on HARPS M dwarfs sample

"Conservative": MOIST Greenhouse (2013) - Maximum Greenhouse (both)

"Optimistics": Recent Venus - Early Mars

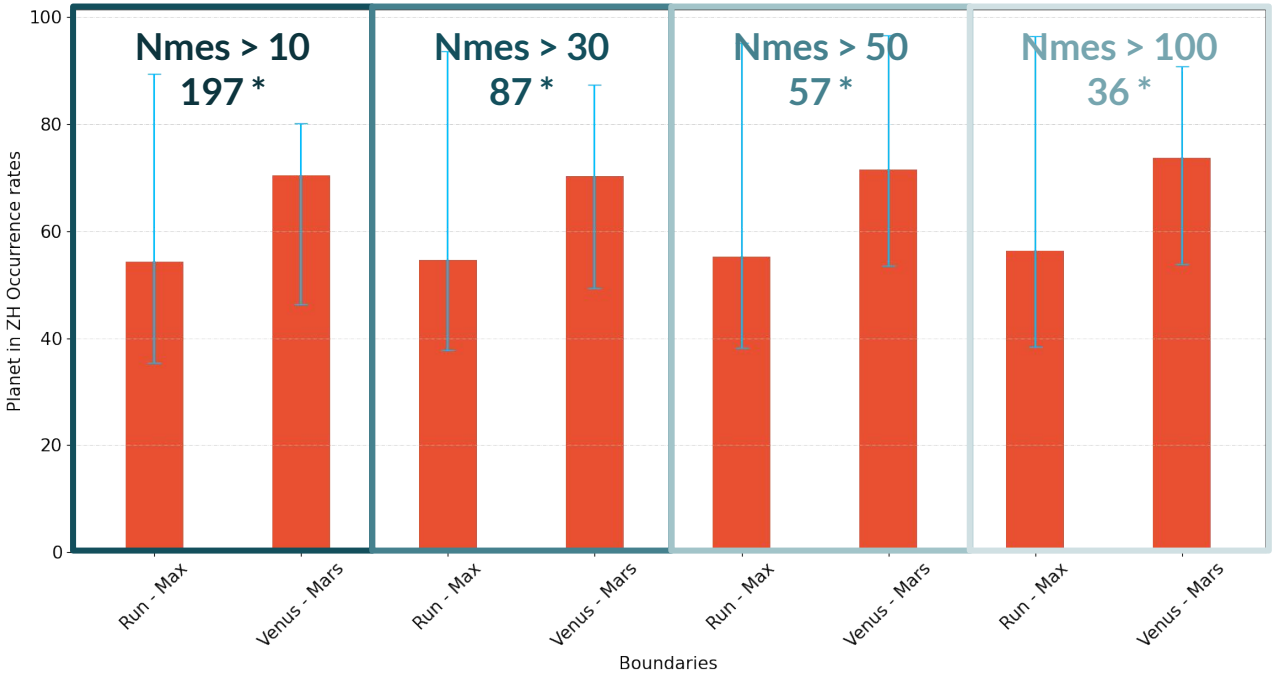


"Conservative": Runaway Greenhouse - Maximum Greenhouse

Chaverot et al., in prep
Mignon et al., in prep

Occurrence Rates in ZH: Sample dependance

Focus on HARPS M dwarfs sample



Minimum number of measurements = selection number of targets

All targets in HZ in the sub-sample of 36 M dwarfs observed > 100 = rates robust

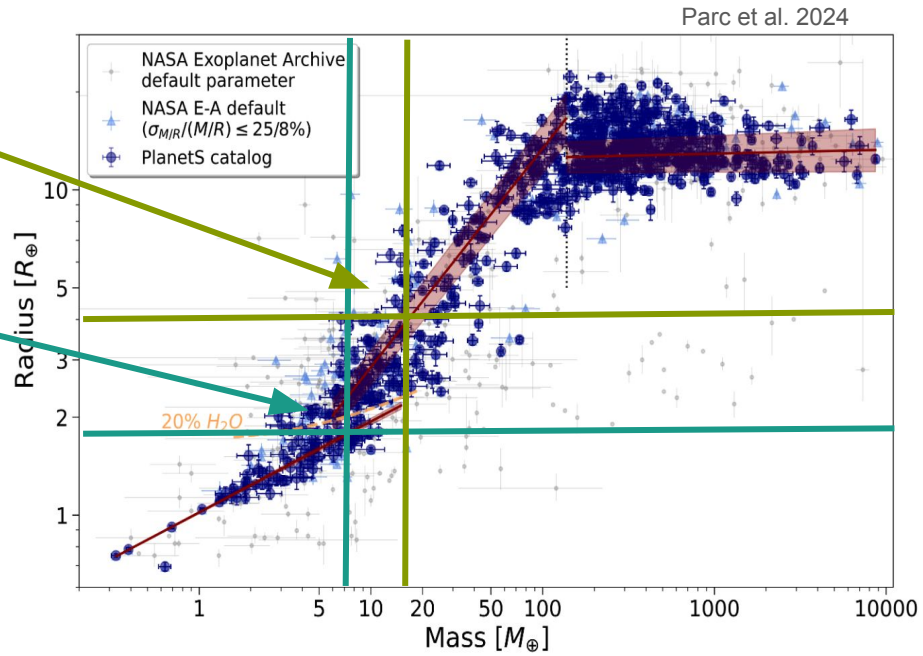
Chaverot et al., in prep
Mignon et al., in prep

Occurrence Rates in HZ: Mass of the planet

Occurrence rates of the HZ obtained in **RV** are computed in the **minimum mass** domain ranging from **1 to 10 Mearth**

Occurrence rates of the HZ obtained in **Transit** are computed in the **radius** domain ranging from **0.5 to ~1.5 Mearth**

Planetary real statistical mass domain limit:
mp.sin(i) = 10 Mearth -> real mp ~ 14 Mearth
mp.sin(i) = 5 Mearth -> real mp ~ 7 Mearth



Occurrence Rates in HZ: Mass of the planet

Occurrence rates of the HZ obtained in **RV**
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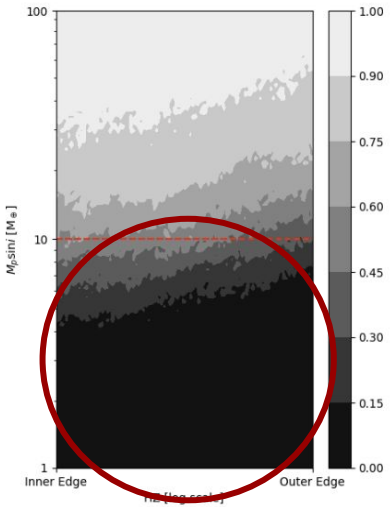
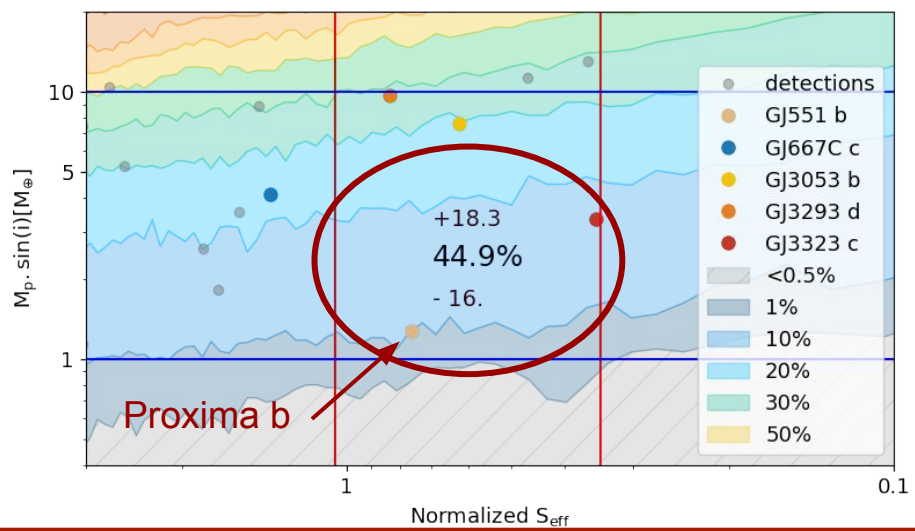
Planetary
mp.sin(i) =
mp.sin(i) =

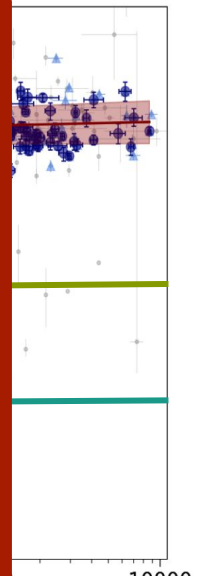
Pinamonti et al. 2022



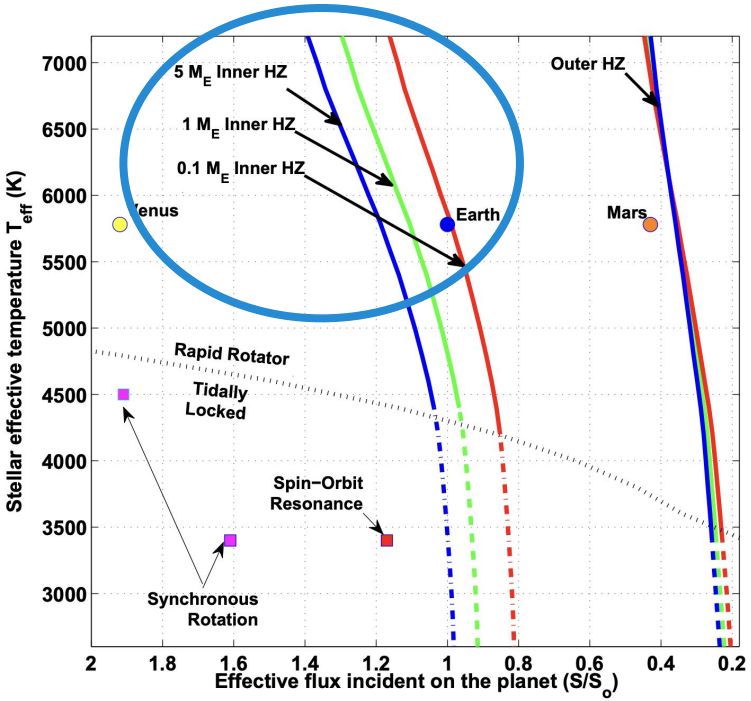
Mignon et al. 2025/ in prep



Parc et al. 2024



Occurrence Rates in HZ: Mass of the planet



Almost all occurrence rates in HZ obtained with inner bound **1 Mearth** from Kopparapu et al. 2013

HARPS M dwarfs sample, “conservative” HZ occurrence rate fully dominated by Proxima b (m.sini ~ 1 Mearth)
But **7 planets** in the “optimistic” HZ

Adjust the **inner limit** as a function of the planetary mass to verify the impact on occurrence rates obtained

Chaverot et al., in prep
Mignon et al., in prep

Conclusions

Occurrence rates around **GK dwarfs** = estimations and extrapolations

PLATO domain

Occurrence rates of planets in "**Conservative**" HZ around **M dwarfs** between **20% and 30%** considering "**Optimistic**" HZ between **40% and 50%** from Kepler sample analysis of M dwarfs

Influence of the Inner and outer bounds chosen is about **10% to 20%**

Statistical uncertainties are dominant

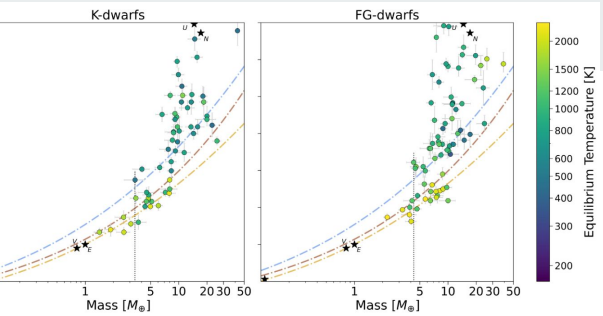
Comparison occurrence rates in HZ around M dwarfs obtained in **RV** and in **Transit**…

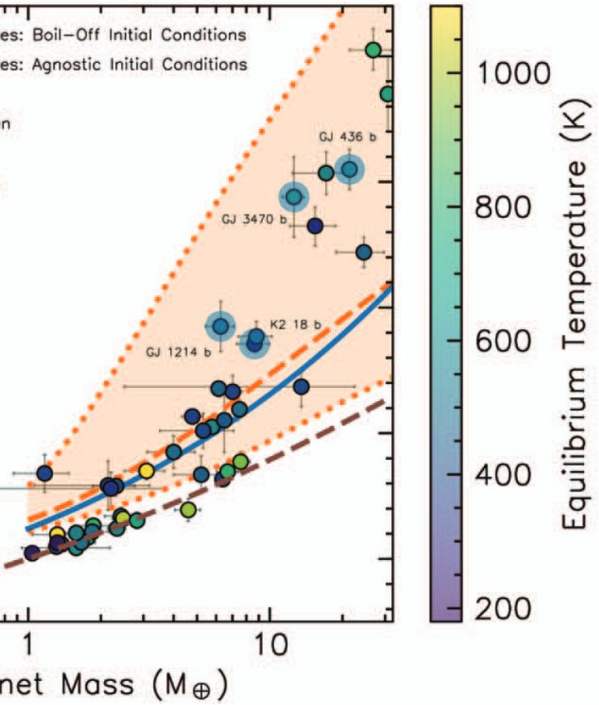
Mass domain ≠ Radius domain

Upper limits only (Massive M dwarfs) or very small number statistics (less massive) **in RV**

M dwarfs sample of Kepler quite massive

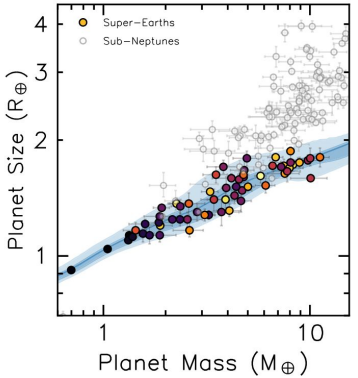
Thank you for you attention





Parc et al. (2024)

Parc et al. (2024)

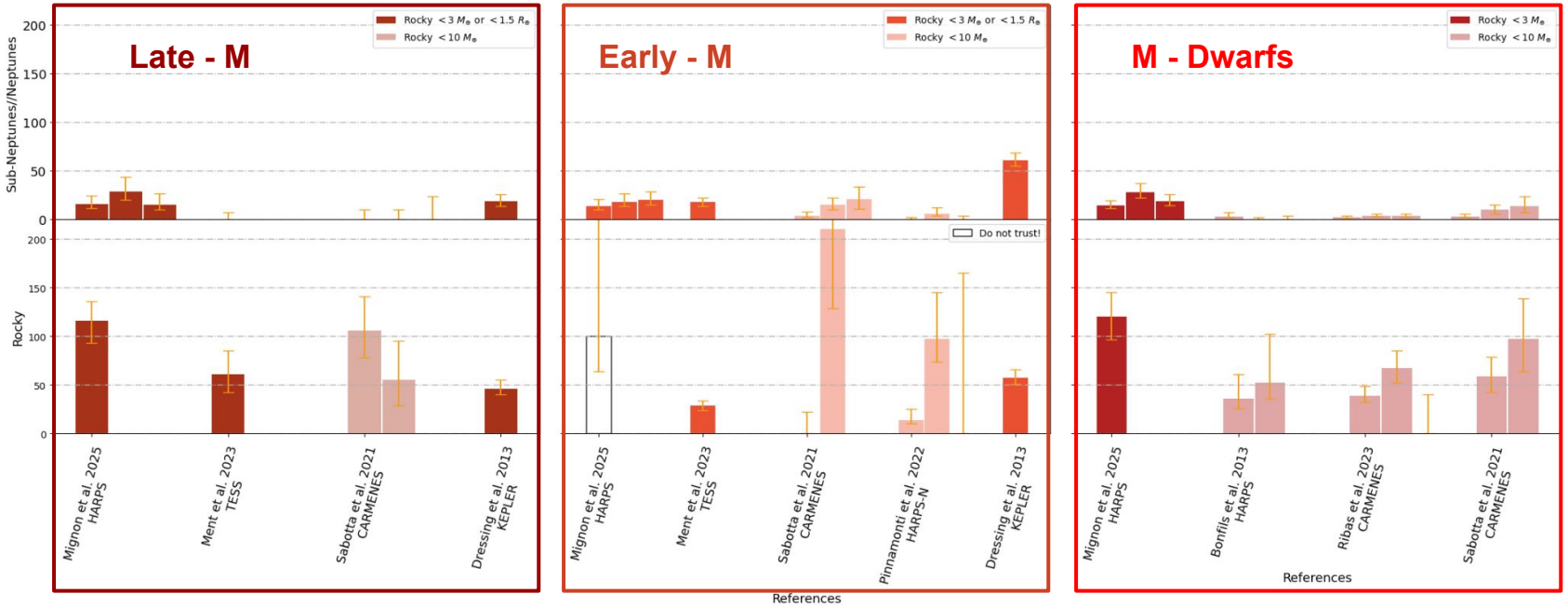


Rogers J. et al. (2023)

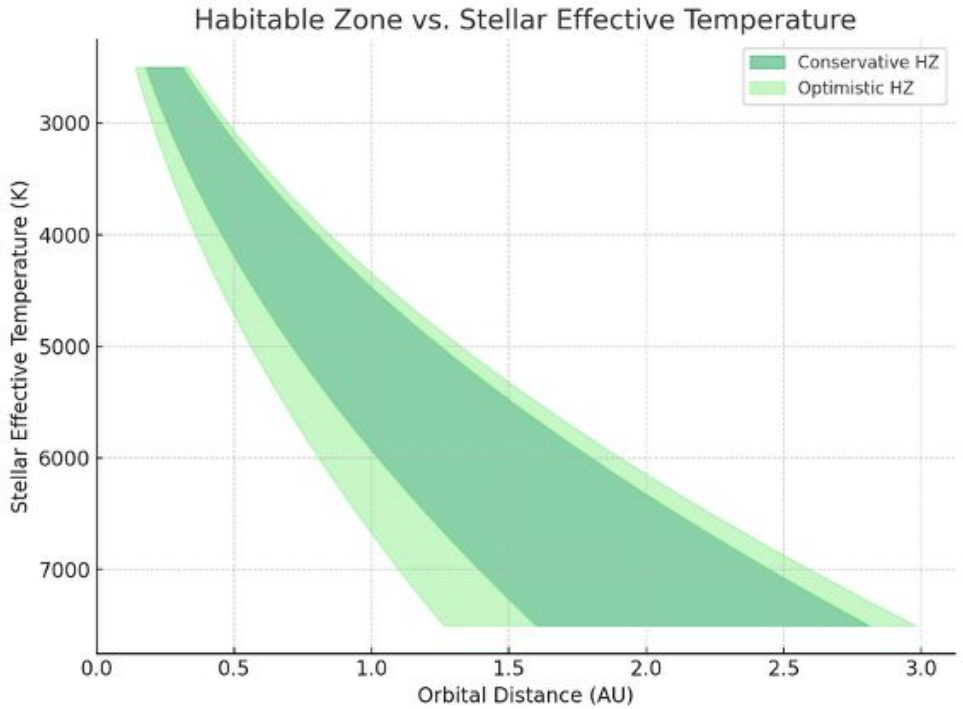
Rogers J. et al. (2025)

Occurrence rates: host star dependence

Rocky planets vs (Sub-Neptunes)/Neptunes



Focus on Habitable Zone



ChatGPT:

Here is a visual representation of the Habitable Zone (HZ) as a function of stellar effective temperature. The shaded green area shows the range of orbital distances where liquid water could potentially exist on a planet's surface—depending on the star's luminosity.

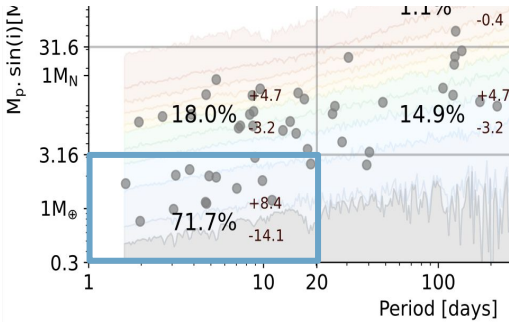
- The **inner edge** marks where a planet would enter a "moist greenhouse" state.
- The **outer edge** marks where a "maximum greenhouse" effect would still allow surface liquid water.

This diagram uses the conservative HZ limits defined by Kopparapu et al. (2013), and helps illustrate how the HZ shifts with hotter or cooler stars.

Occurrence rates: Systems and architecture

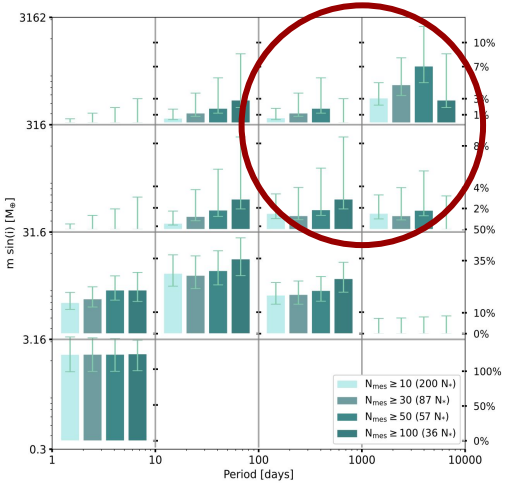
INNER systems:

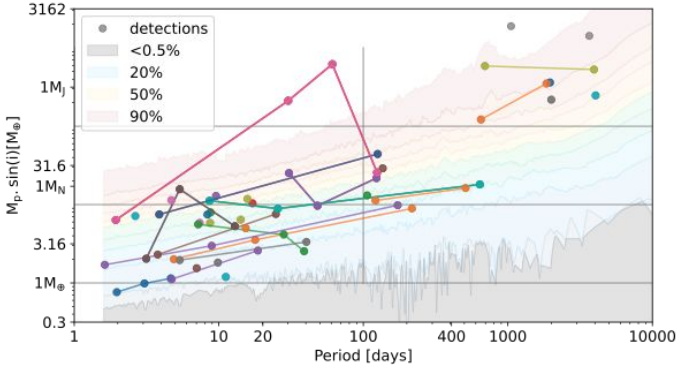
- 120% VS 70%
- M dwarfs without any
- Peas-in-a-pod !



OUTER systems:

- Nmes < 100 visits





INNER VS OUTER systems remains an open question…

-> GAIA DR4 + TESS + PLATO + RV follow up

Mignon et al. 2025 - HARPS (M)