Gas Giant Demographics

On giant planet occurrence rates, trends, and orbits

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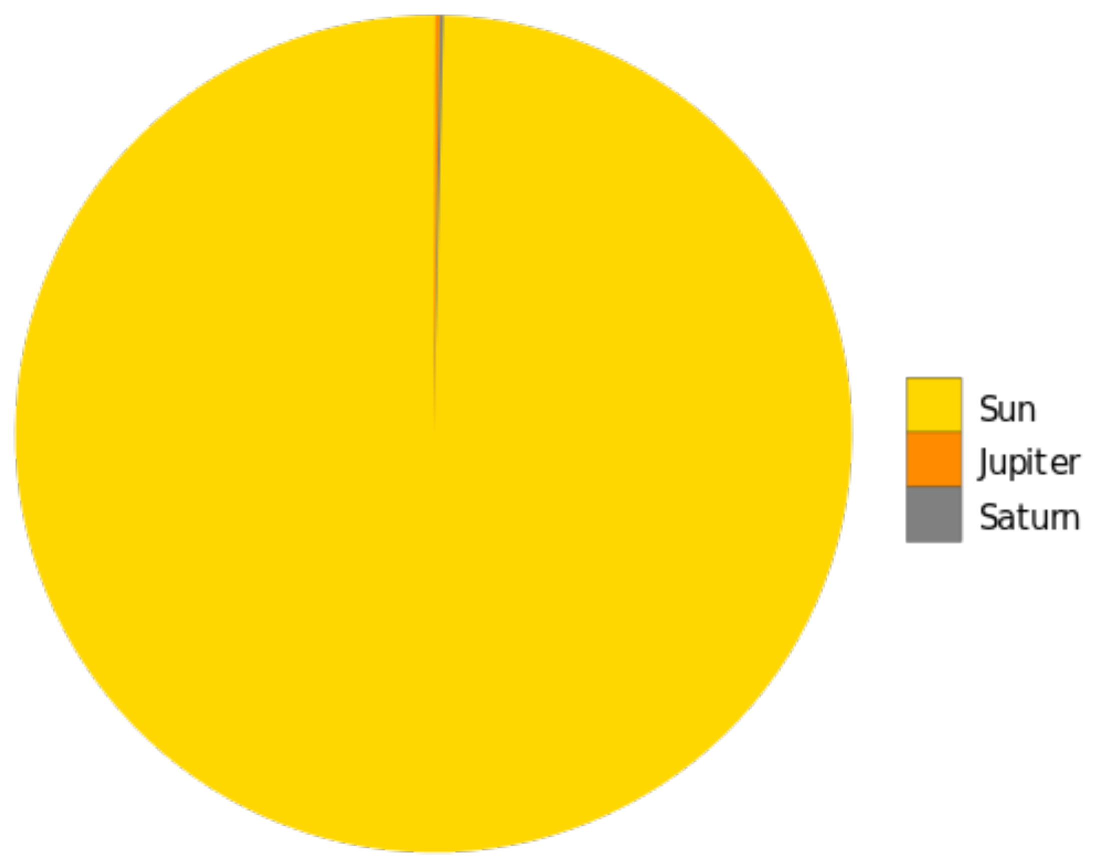
2025 Sagan Workshop — July 24, 2025

For this talk, I treat giant planets as > Saturn (0.3 M_{Jup})

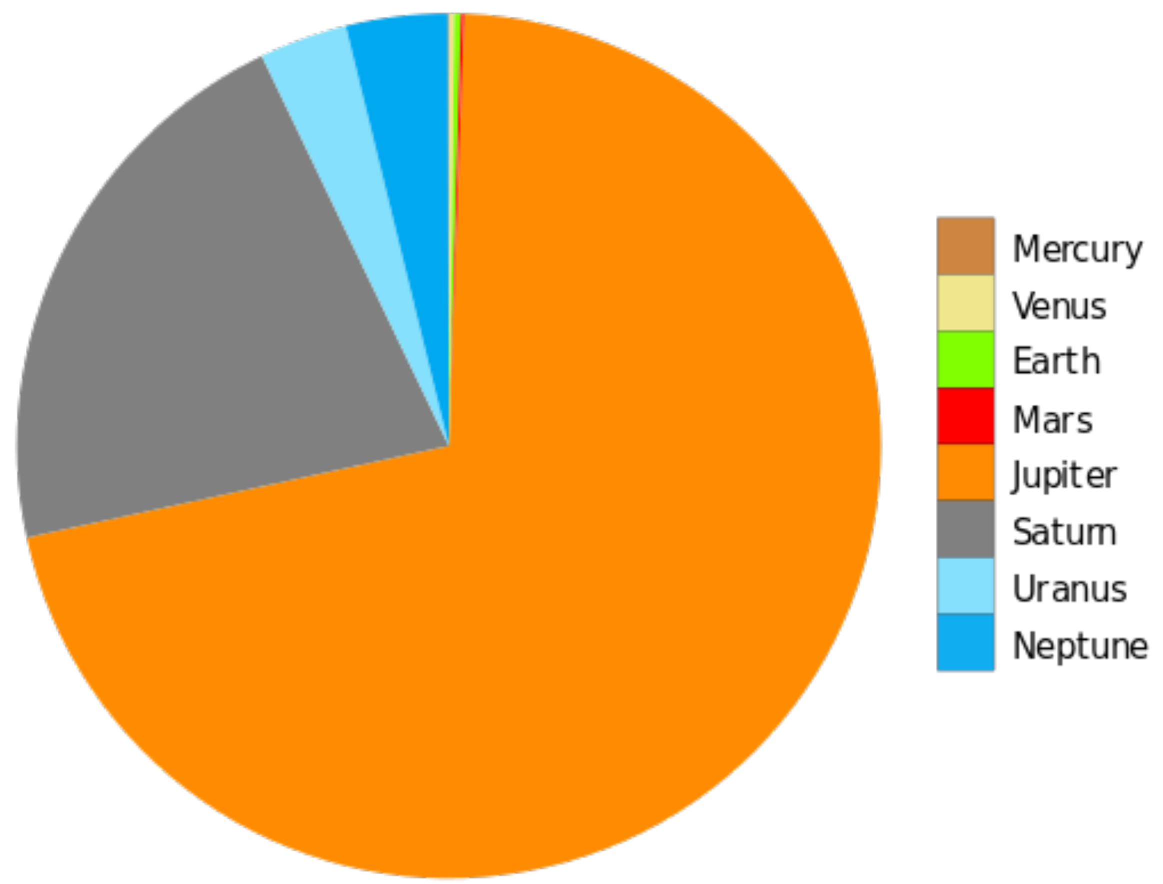
Giant planets dominate (nearly) everything in planetary systems

- **Mass budget**

Mass in the solar system



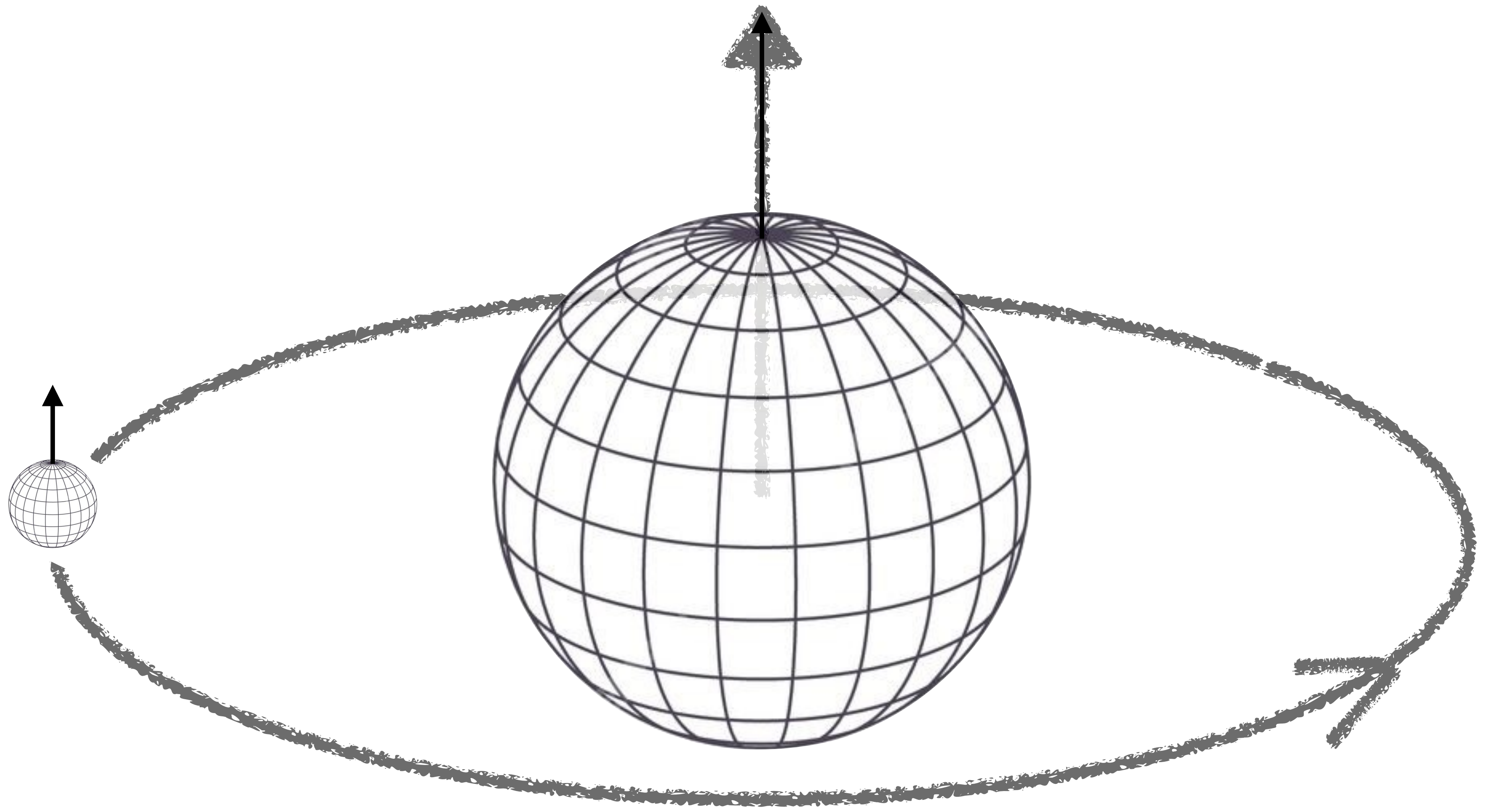
Mass of planets



Jupiter + Saturn: **~0.1%** **~92%**

Giant planets dominate (nearly) everything in planetary systems

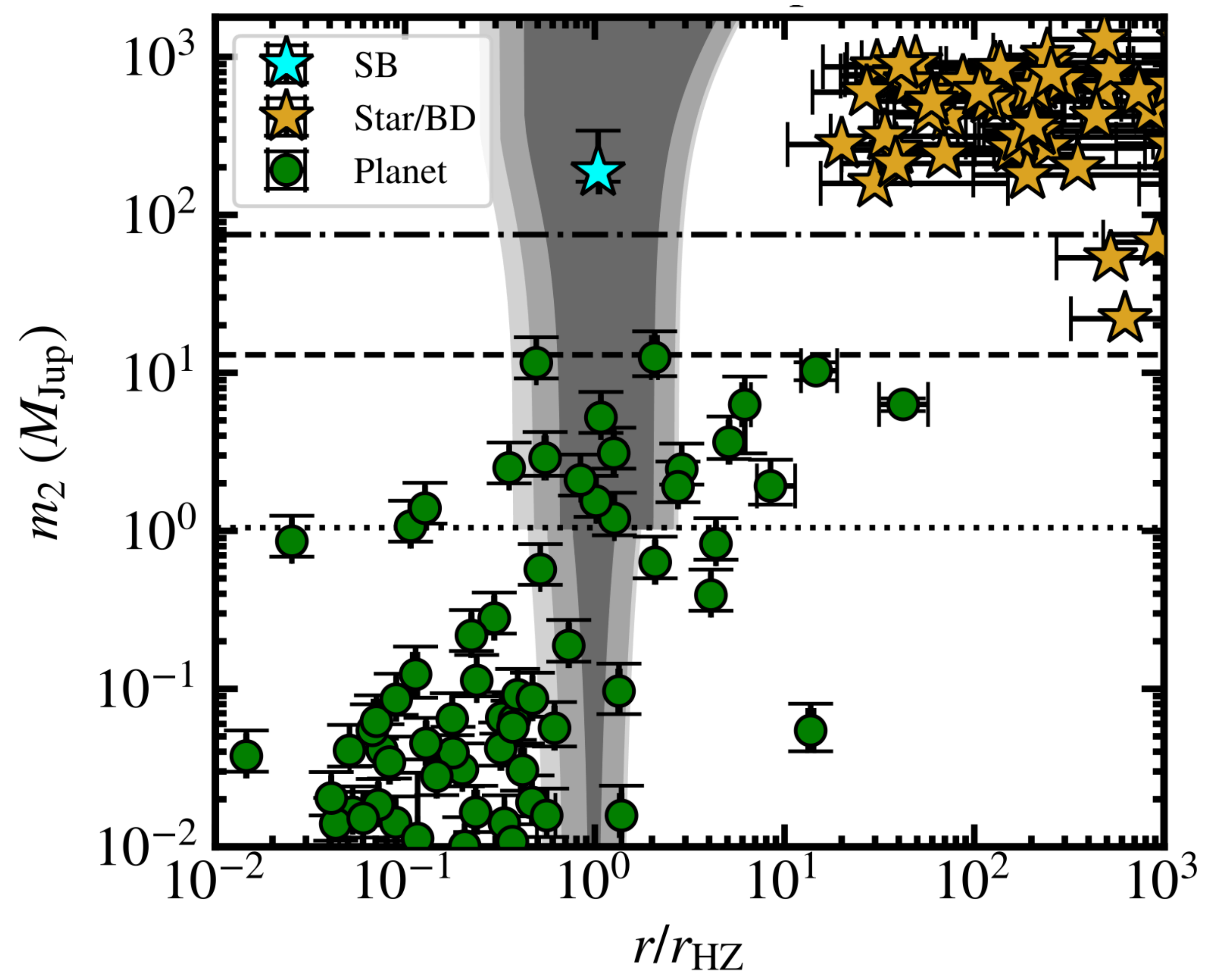
- Mass budget
- **Angular Momentum Budget**



$$\frac{L_{\text{Jupiter + Saturn}}}{L_{\text{SS}}} = \text{~87\%}$$

Giant planets dominate (nearly) everything in planetary systems

- Mass budget
- Angular Momentum Budget
- **Dynamics**



Habitable Zones

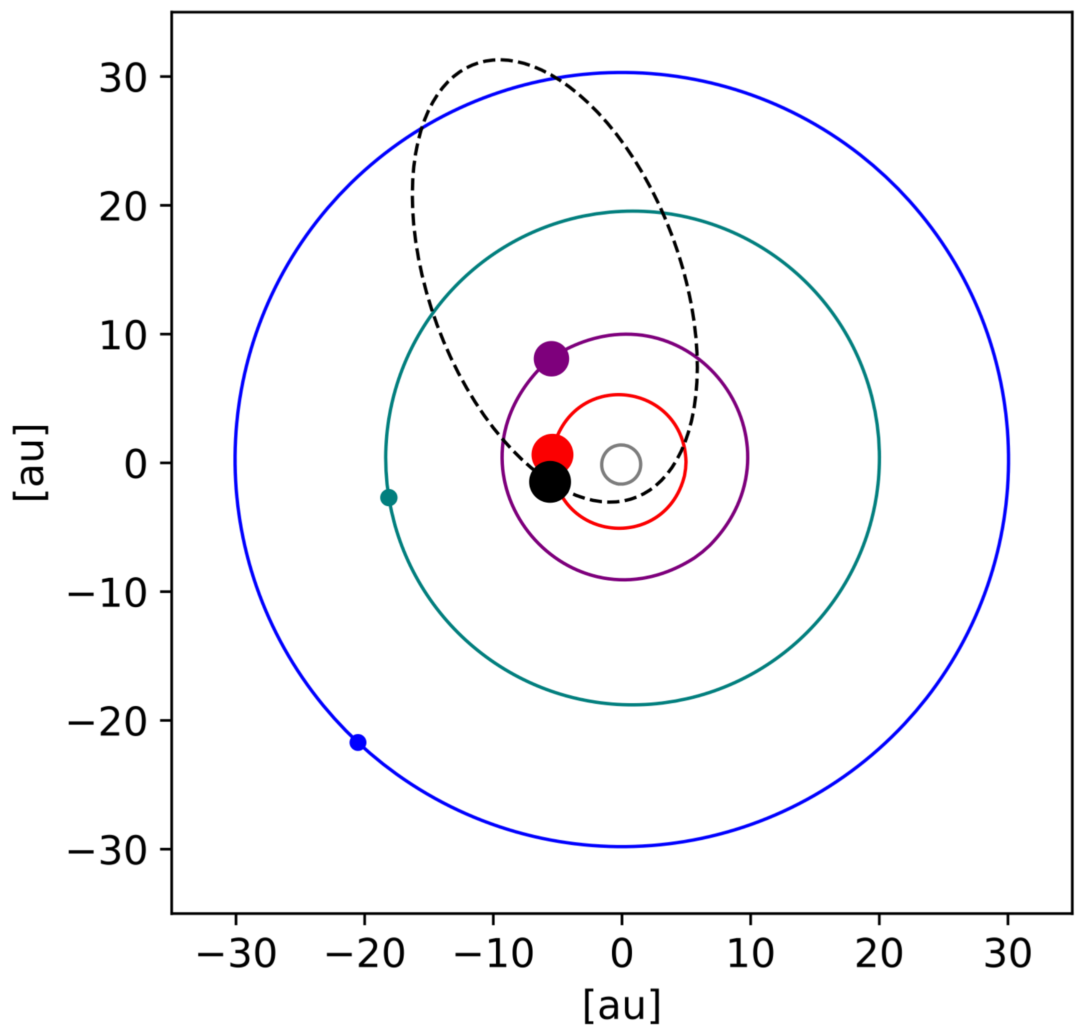
Dynamical impact on habitable zones of HWO precursor targets

Painter et al. 2025

Eccentricities

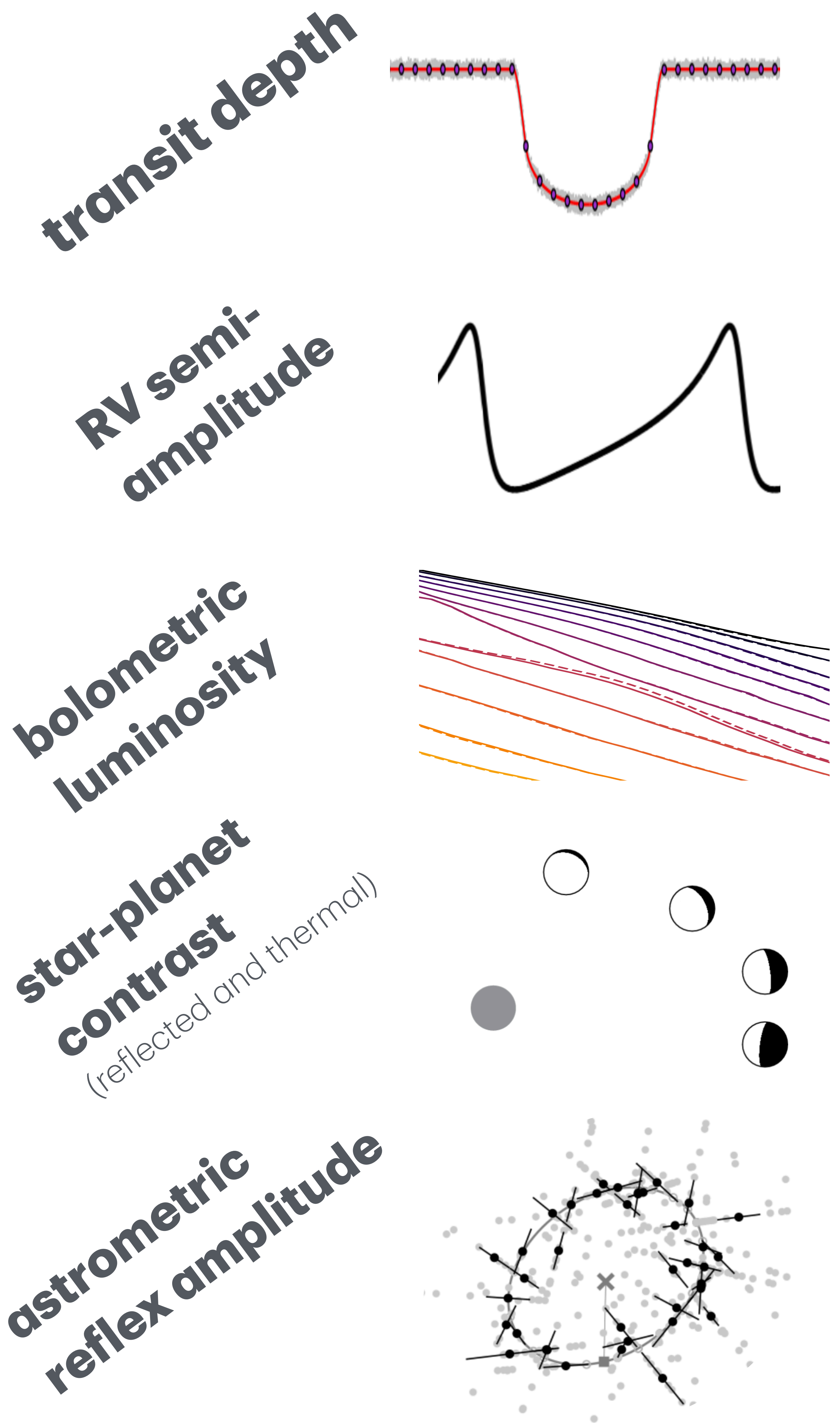
HR 5183 b, a highly eccentric (e=0.84) "wrecking ball"

Blunt et al. 2019



Giant planets dominate (nearly) everything in planetary systems

- Mass budget
- Angular Momentum Budget
- Dynamics
- **Detectability**



$$\delta \propto R_p^2$$

$$K \propto m_p$$

$$L_{\mathrm{bol}} \propto m_p^{5/2}$$

$$f_p / f_* \propto R_p^2$$

$$\theta \propto m_p$$

Demographics is a quilt

Transits

Wide-field surveys
Old (few Gyr) stars
Solar (Kepler), low-mass (TESS)
Distant (a few × 10^2 pc)

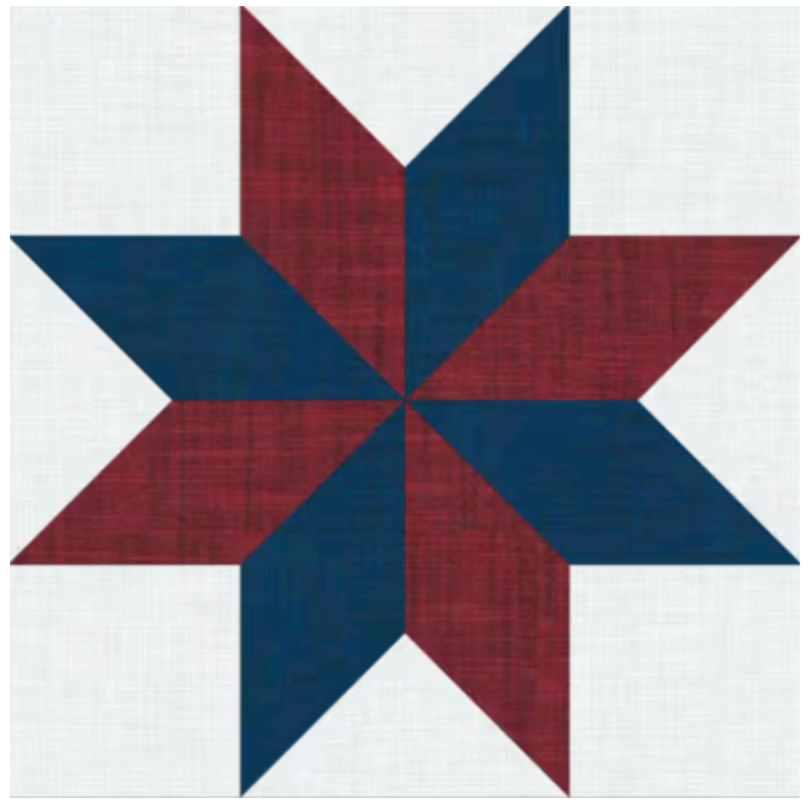
Planet size

RVs

Targeted surveys
Old (few Gyr) field stars
Traditionally Sun-like, low-mass
Nearby (<100 pc)

Planet minimum mass

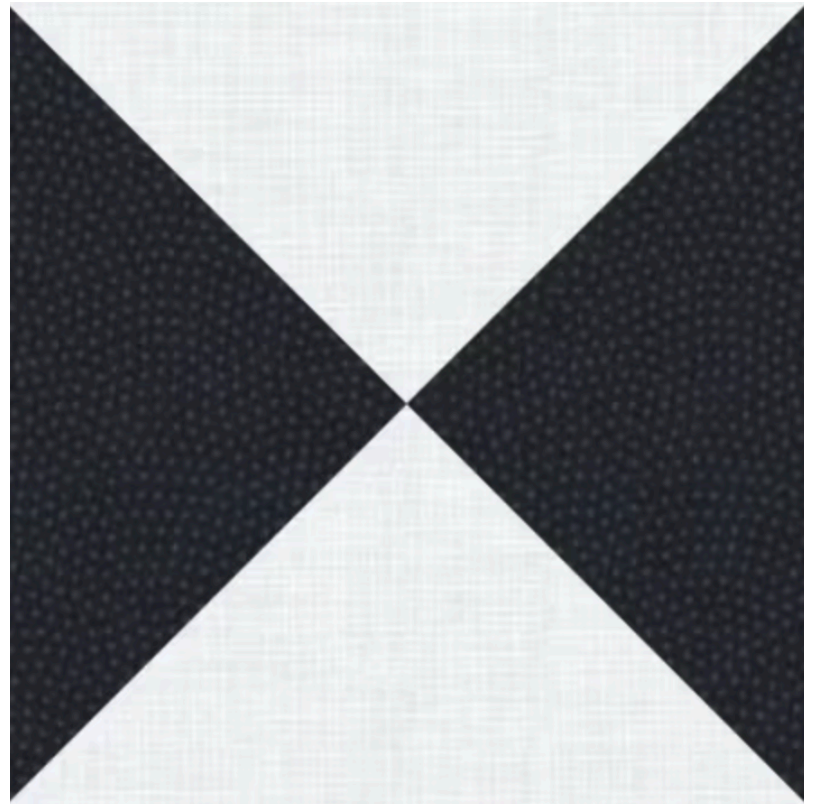
Microlensing



Wide-field surveys
Old (few Gyr) stars
Lower-mass stars
Distant (kpc scales)

Star-planet mass ratio

Direct Imaging*



Targeted surveys
Young (<200 Myr)
Sun-like, intermediate-mass stars
Nearby (<150 pc)

Planet luminosity

Why does this matter?

We may be ignoring potentially important effects like age, host mass, stellar multiplicity, metallicity, and birth environment

*in thermal emission

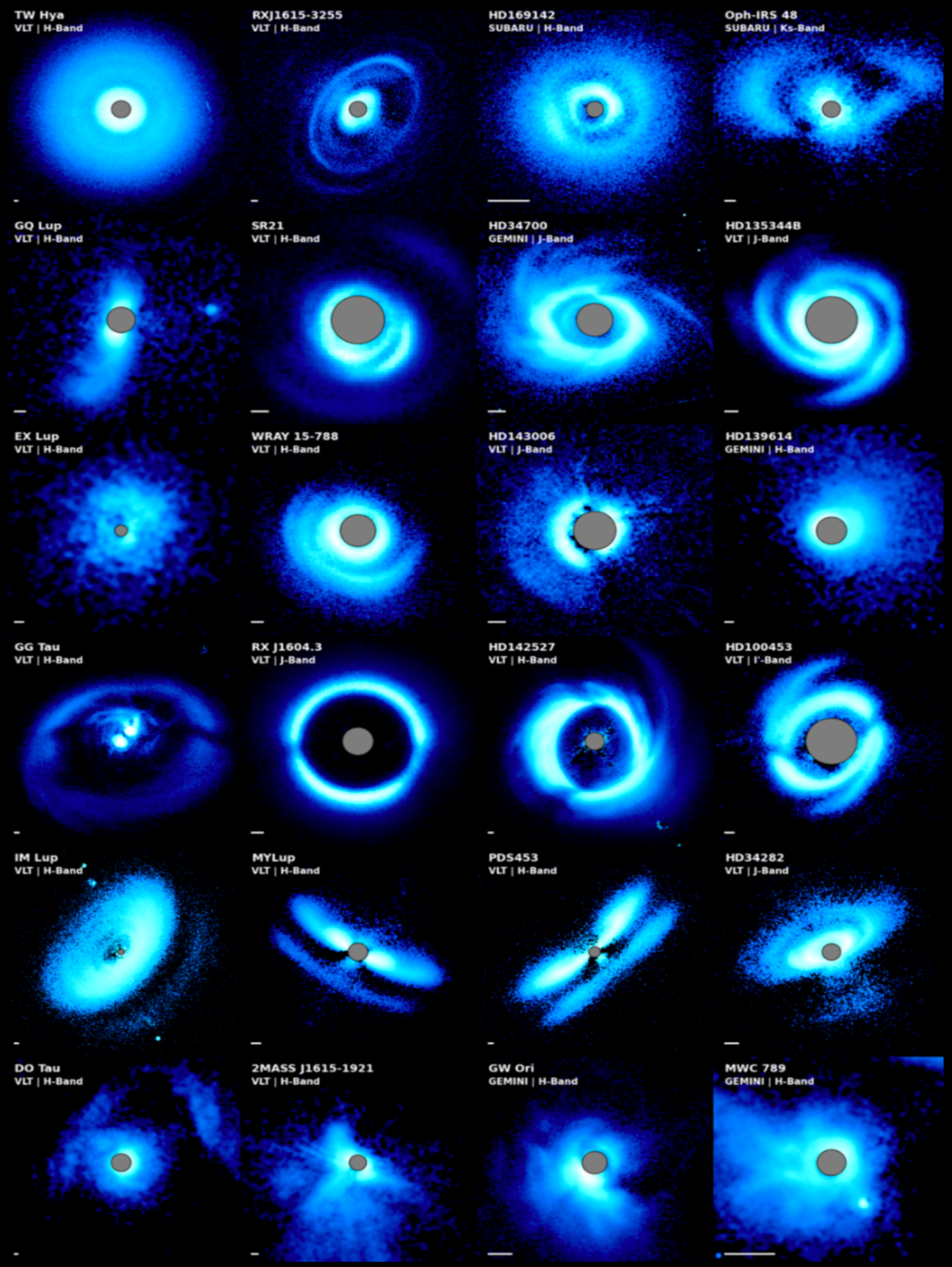
The Demographics of Wide-Separation Planets

B. Scott Gaudi

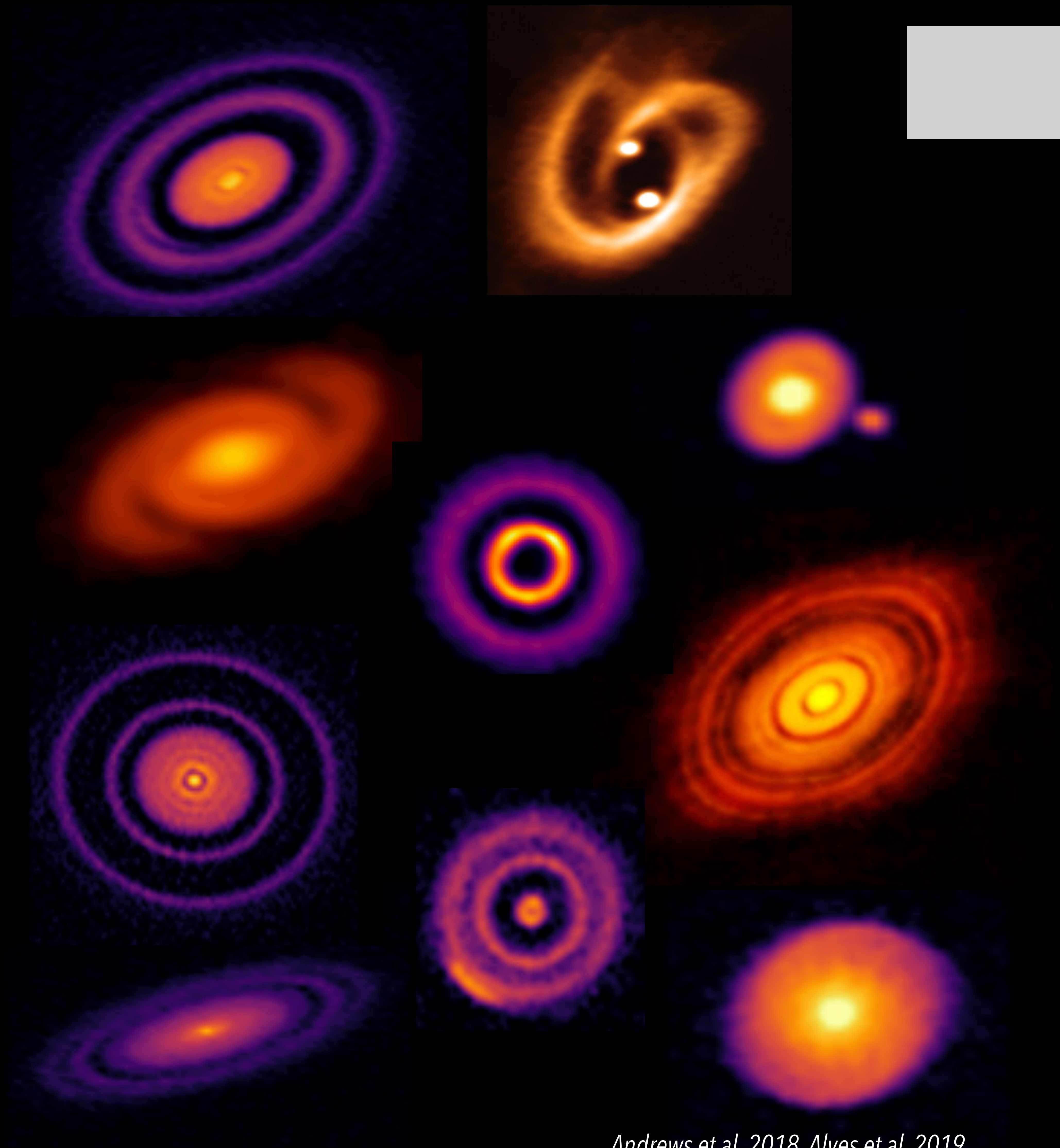
Abstract
I begin this review by first defining what is meant by exoplanet demographics, and then motivating why we would like as broad a picture of exoplanet demographics as possible. I then outline the methodology and pitfalls to measuring exoplanet demographics in practice. I next review the methods of detecting exoplanets, focusing on the ability of these methods to detect wide separation planets. For the purposes of this review, I define wide separation as separations beyond the “snow line” of the protoplanetary disk, which is at $\simeq$ 3au for a sunlike star. I note that this definition is somewhat arbitrary, and the practical boundary depends on the host star mass, planet mass and radius, and detection method. I review the approximate scaling relations for the signal-to-noise ratio for the detectability of exoplanets as a function of the relevant physical parameters, including the host star properties. I provide a broad overview of what has already been learned from the transit, radial velocity, direct imaging, and microlensing methods. I outline the challenges to synthesizing the demographics using different methods and discuss some preliminary first steps in this direction. Finally, I describe future prospects for providing a nearly complete statistical census of exoplanets.

Protoplanetary disks are remarkably diverse

They take on a wide range of masses, radii, and substructure



Benisty et al. 2023

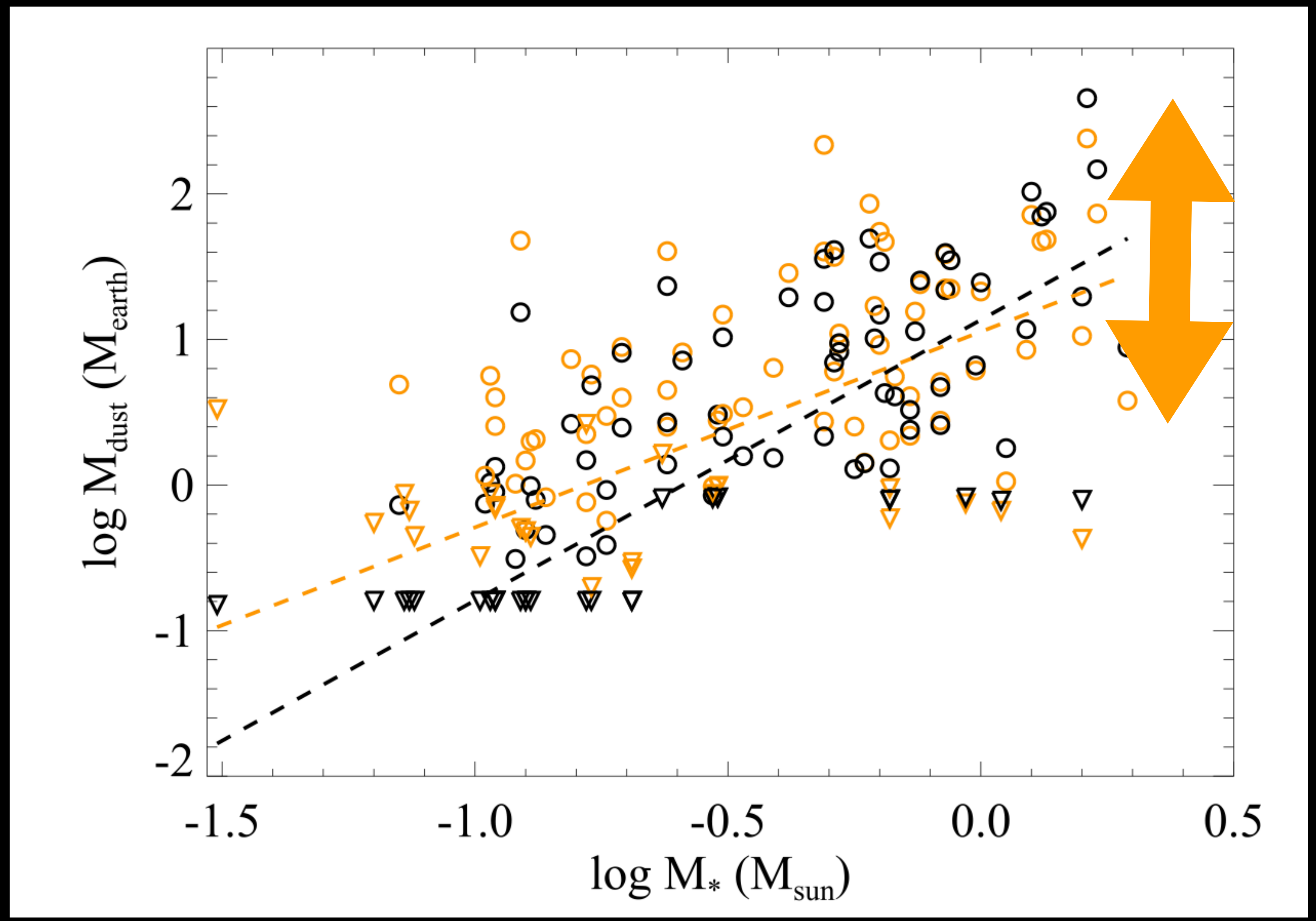


Andrews et al. 2018, Alves et al. 2019

Protoplanetary disks are remarkably diverse

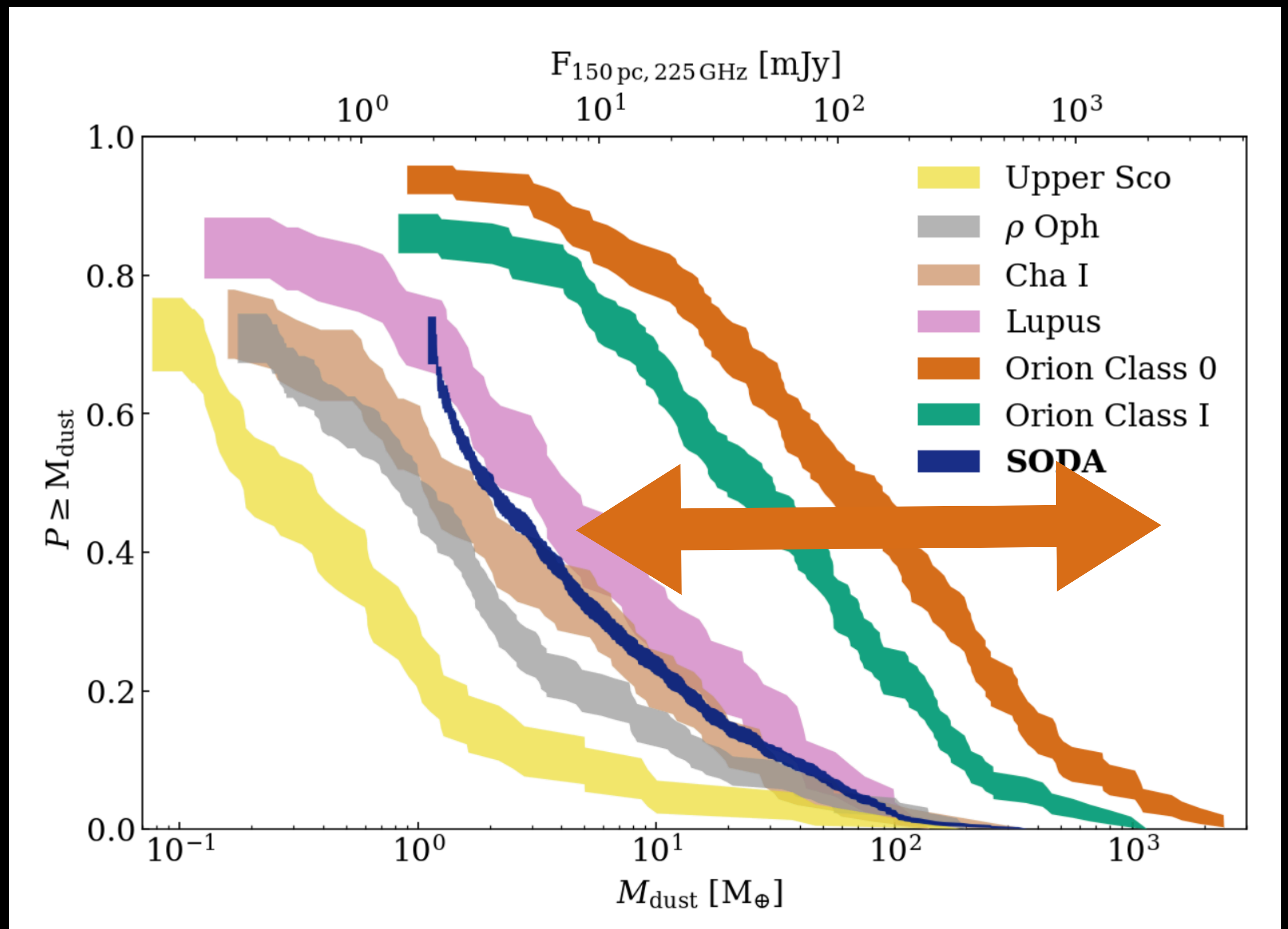
They take on a wide range of masses, radii, and substructure

Disk mass scales with host mass



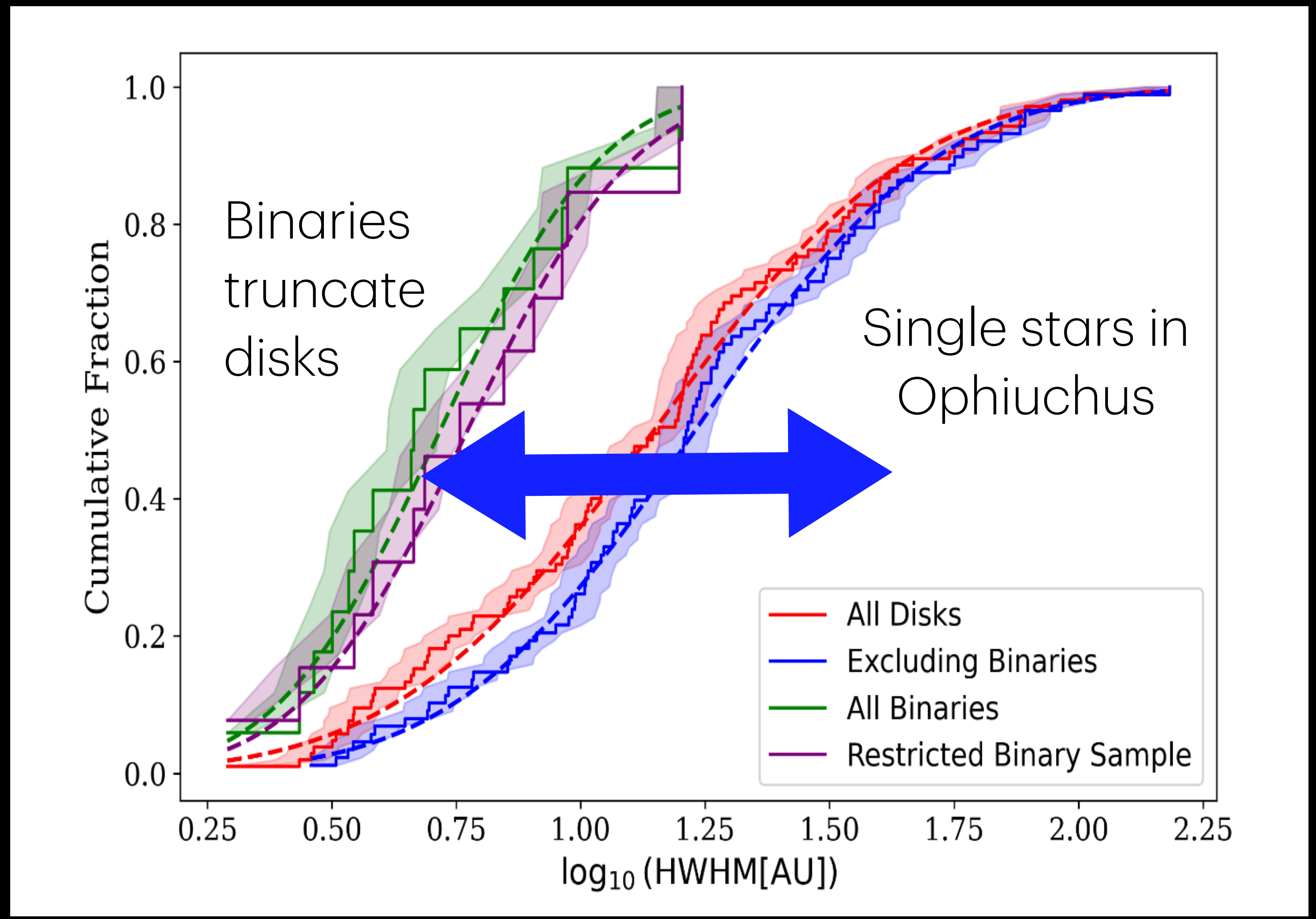
Pascucci et al. 2016

Large dynamic range for a given age



van Terwisga et al. 2022

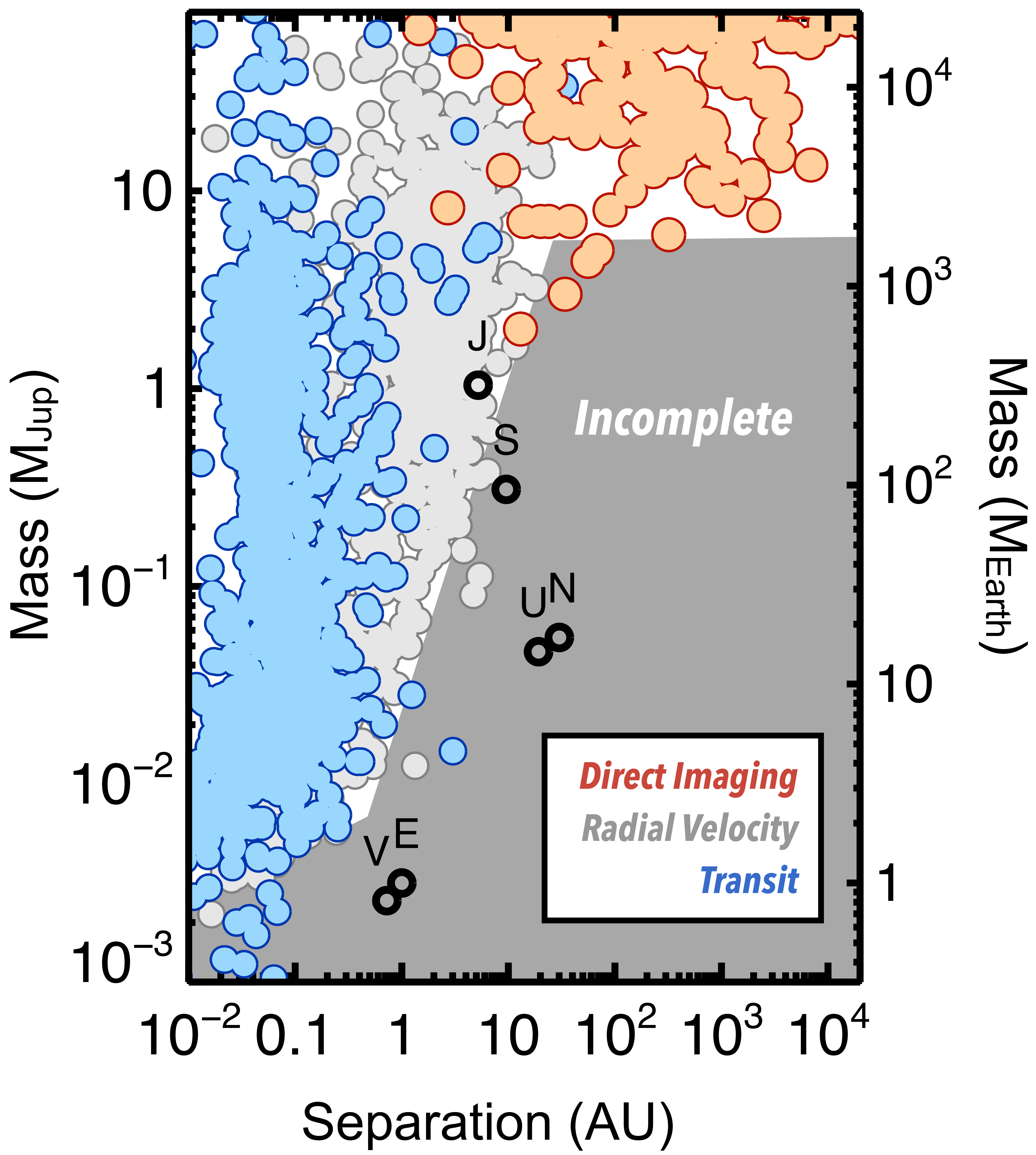
Wide range of disk sizes



Dasgupta et al. 2025

Planetary systems inherit this diversity

Only giant planets can currently be studied across the entire scale of protoplanetary disk sizes



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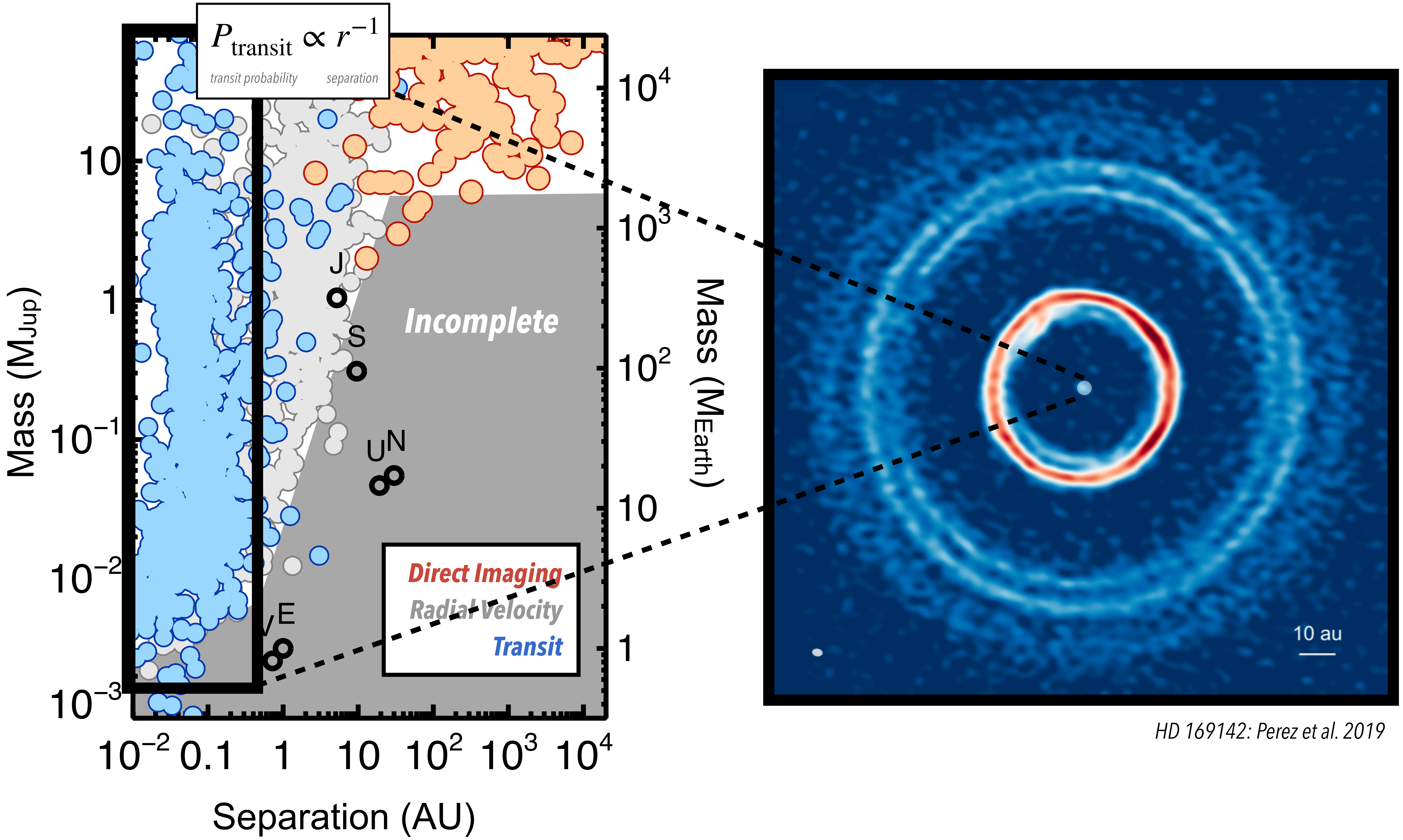

HD 169142: Perez et al. 2019

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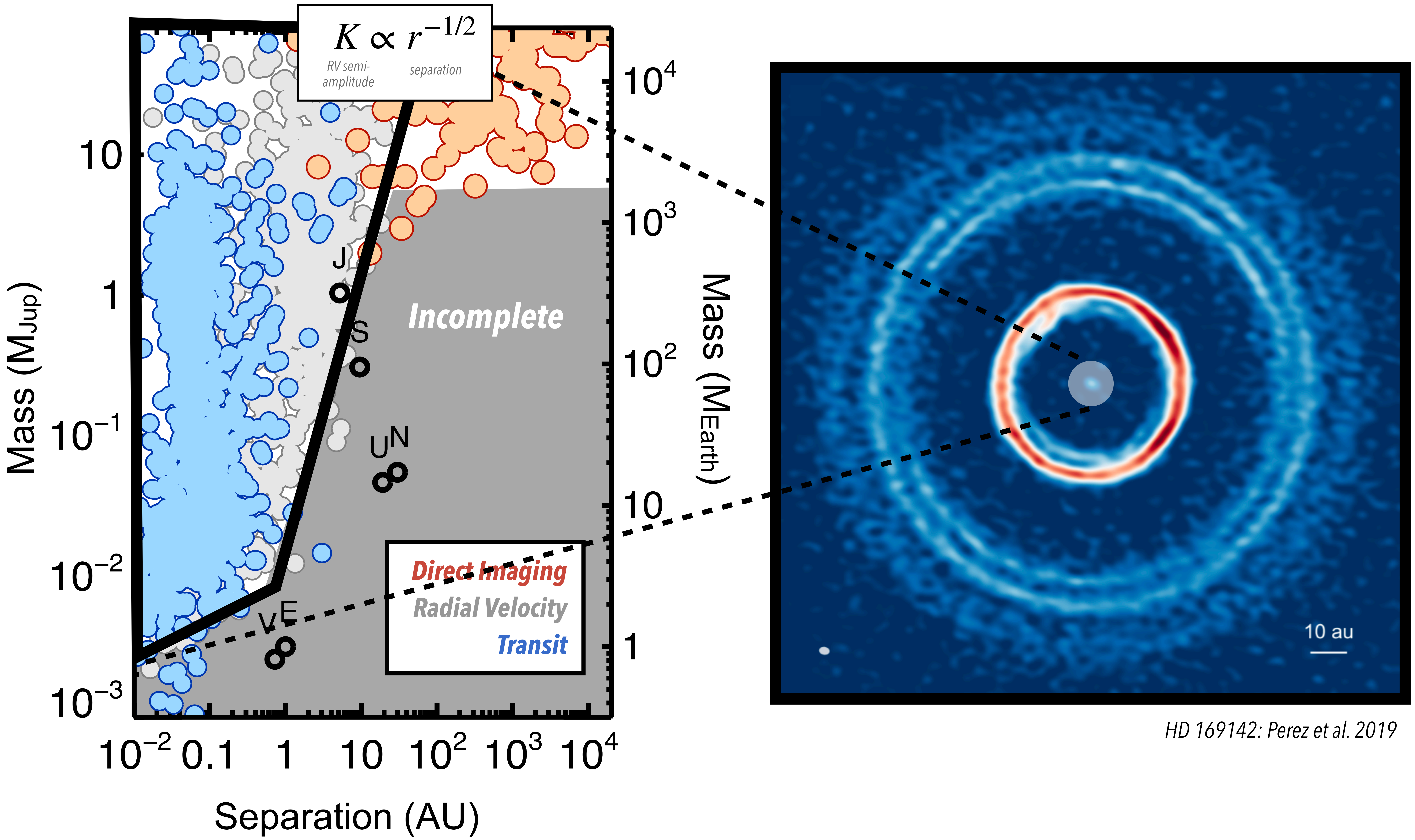

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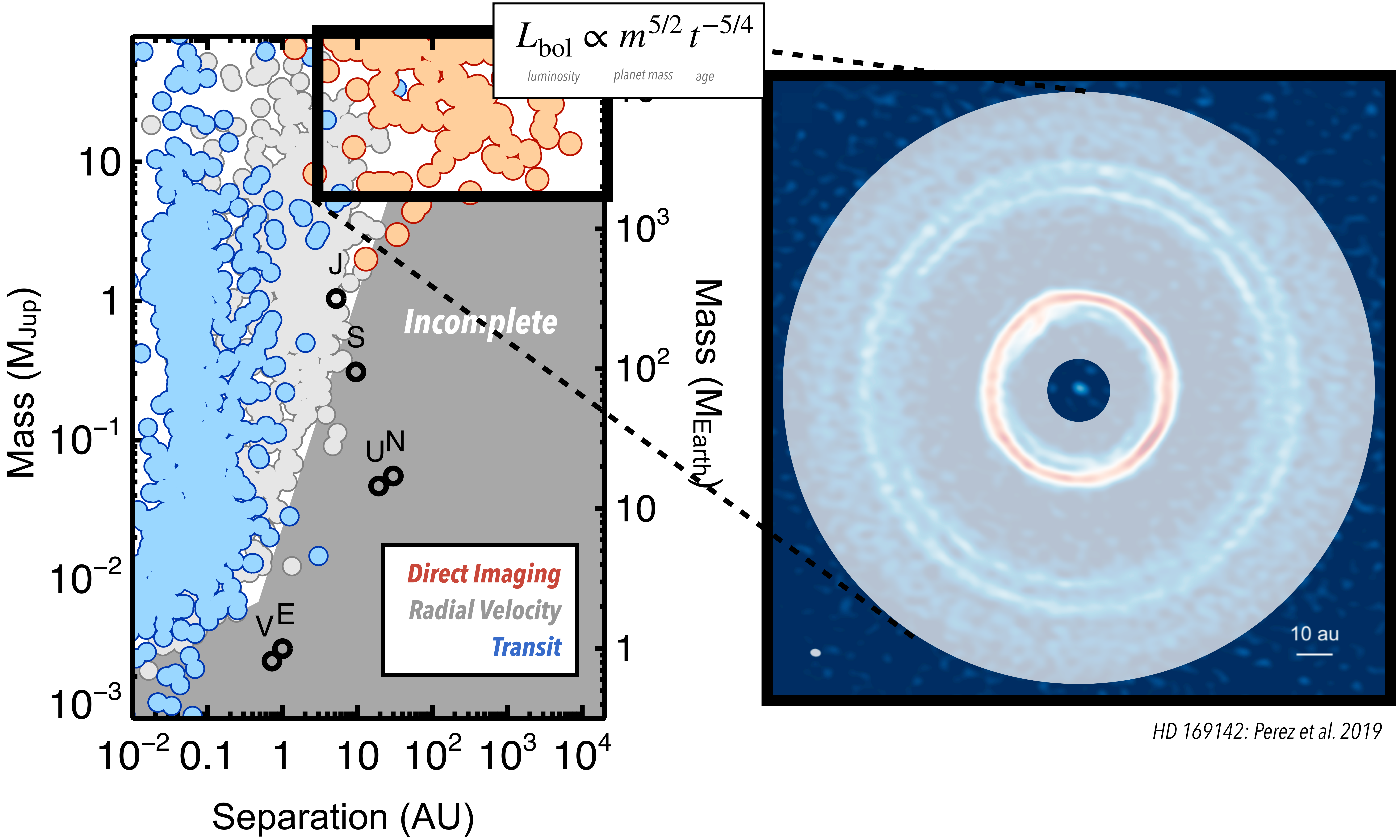

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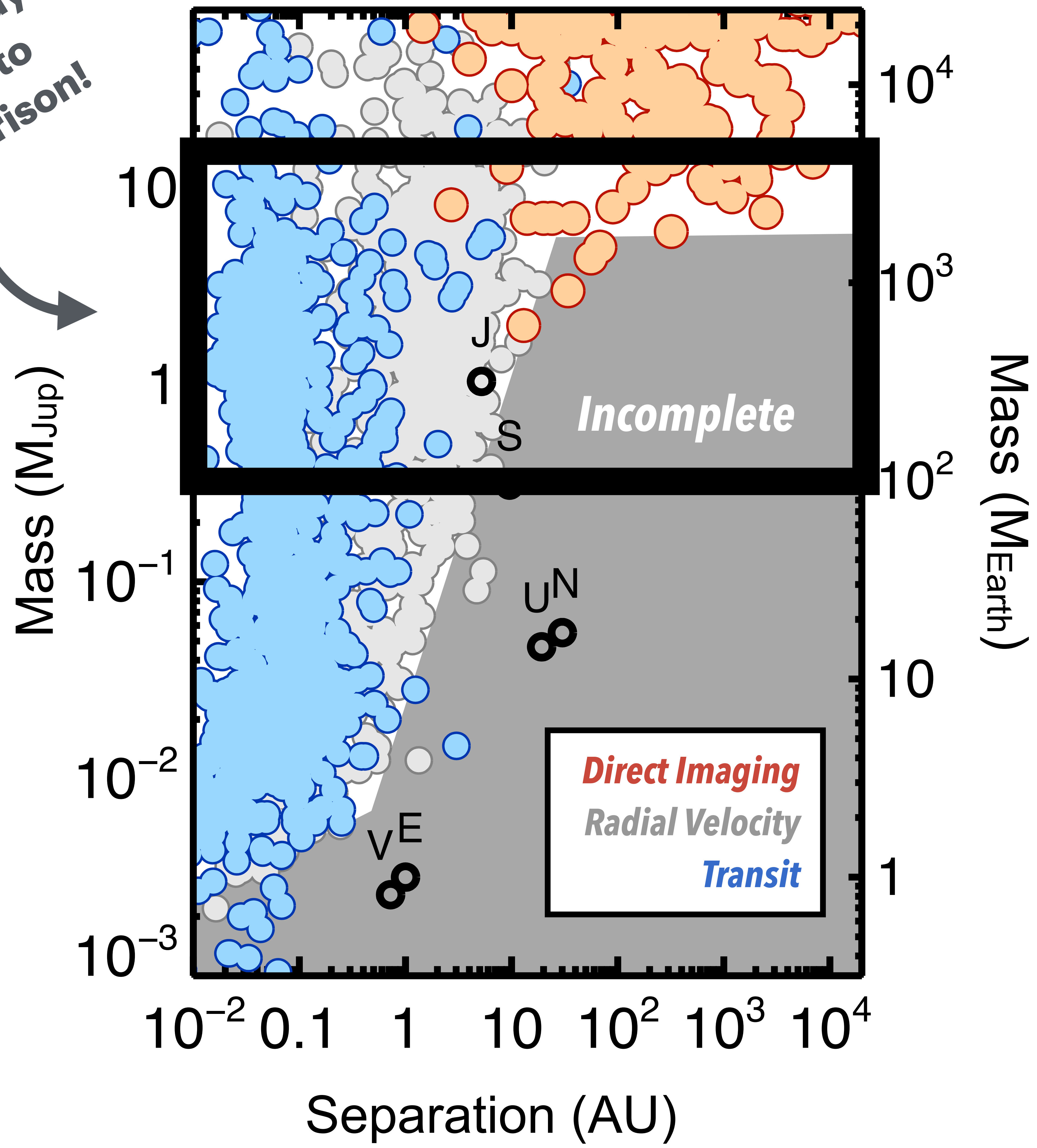
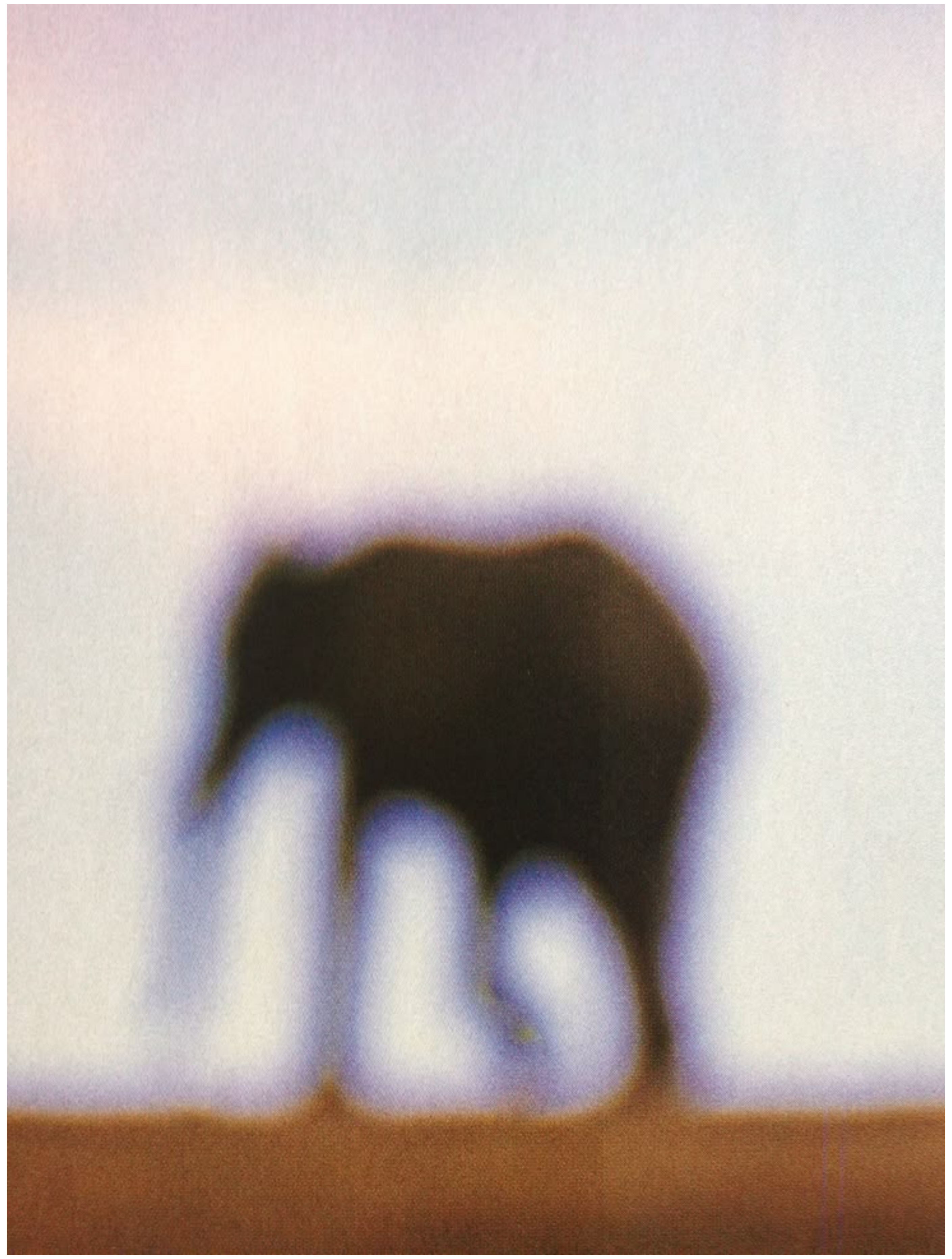
Parameter space we will cover today. Not an apples to apples comparison!





Imprints of planet formation and migration across space and time

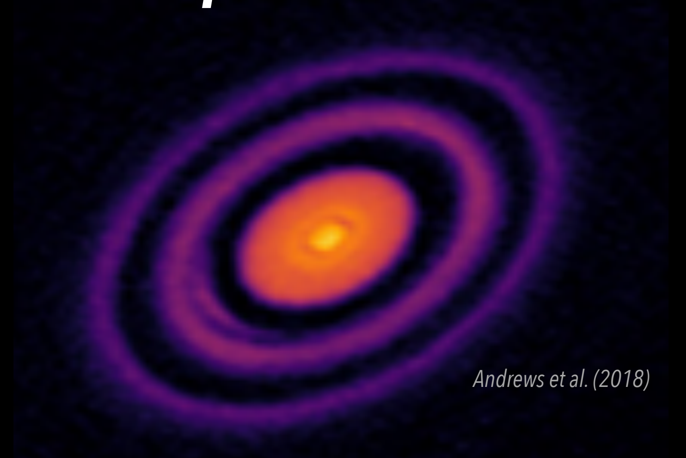
Demographics gives clues about how planetary systems form and evolve

Orbital Separation

~0.01-0.1 AU | ~0.1-1 AU | ~1-10 AU | ~10-100 AU | >100 AU

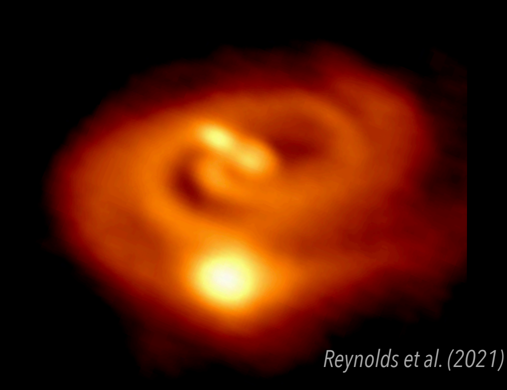
Formation $(\tau \lesssim 10^7 \text{ yr})$

Core/pebble accretion?



Pollack et al. 1996, Lambrechts & Johansen 2012

Disk instability?



e.g., Boss 1997, Kratter & Lodato 2016

Filament/core fragmentation?

e.g., Bate 2009, Offner et al. 2023

Dynamical Capture?

NASA, ESA, and Z. Levay (STScI)

e.g., Perets & Kouwenhoven 2012

Dynamics $(\tau \sim 10^{6-10} \text{ yr})$

Inward Migration

Disk migration, Planet scattering,
High-eccentricity migration

Outward Migration

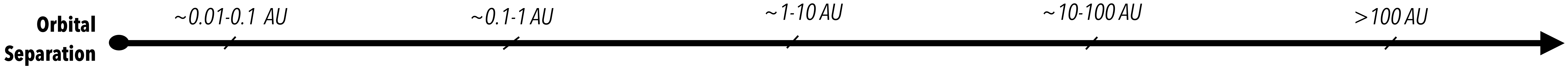
Planet scattering,
Resonant migration

How common are giant planets?

Occurrence rates across 5 orders of magnitude in separation for (largely) single, Sun-like stars

What are we marginalizing over?

M_*, [Fe/H], m_p, t, binarity, evolutionary phase, etc ...



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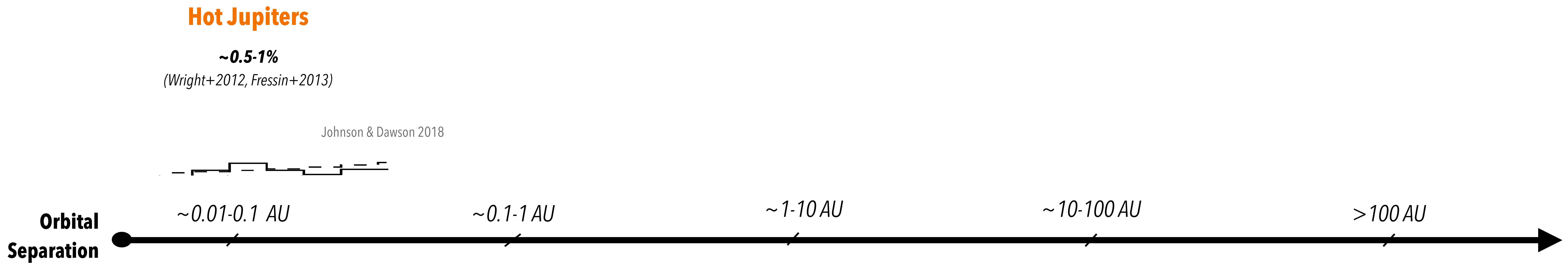

Hot Jupiters (P = 1-10 d)

- **Occurrence rates differ slightly between RV and transit surveys**
  - 1.2 ± 0.4% -> Wright et al. (2012) from RVs
  - 0.9 ± 0.4% -> Mayor et al. (2011) from RVs
  - 0.4 ± 0.1% -> Howard et al. (2012) from Kepler
  - 0.6 ± 0.1% -> Petigura et al. (2018) from Kepler
  - 1.0 ± 0.4% -> Beleznay & Kunimoto (2022), single stars from TESS

Reviews:

- **Dawson & Johnson 2018**
  Origins of Hot Jupiters
- **Fortney, Dawson, & Komacek 2021**
  Hot Jupiters: Origins, Structure, Atmospheres
- **Winn & Petigura 2024**
  Planet Occurrence: Doppler and Transit Surveys

Metallicity differences? Multiplicity?

See Guo et al. 2017, Moe & Kratter 2021

"...we should never lose too much sleep over 3σ discrepancies..."

— Winn & Petigura 2024

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Hot Jupiters

~0.5-1%

(Wright+2012, Fressin+2013)

Johnson & Dawson 2018

Orbital Separation — *~0.01-0.1 AU* — *~0.1-1 AU* — *~1-10 AU* — *~10-100 AU* — *>100 AU*

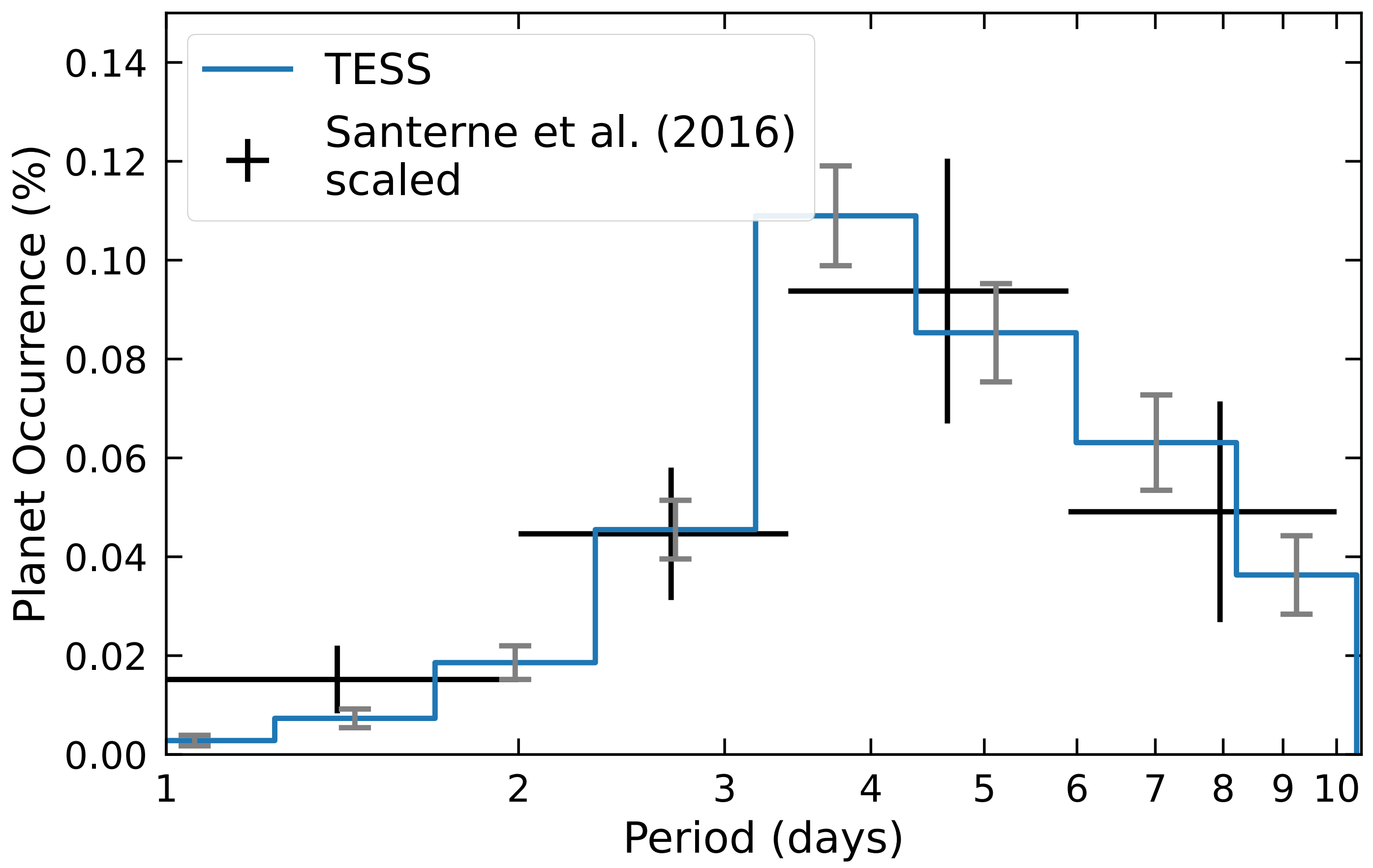
Hot Jupiters (P = 1-10 d)

- **The "few-day pile-up"**

  The incidence of hot Jupiters peaks at ~3-5 days.

  e.g., Udry et al. 2003, Butler et al. 2006

  ⟹ A signature of halted inward migration?



Yee et al., in prep.; see also Yee & Winn 2023

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Hot Jupiters (P = 1-10 d)

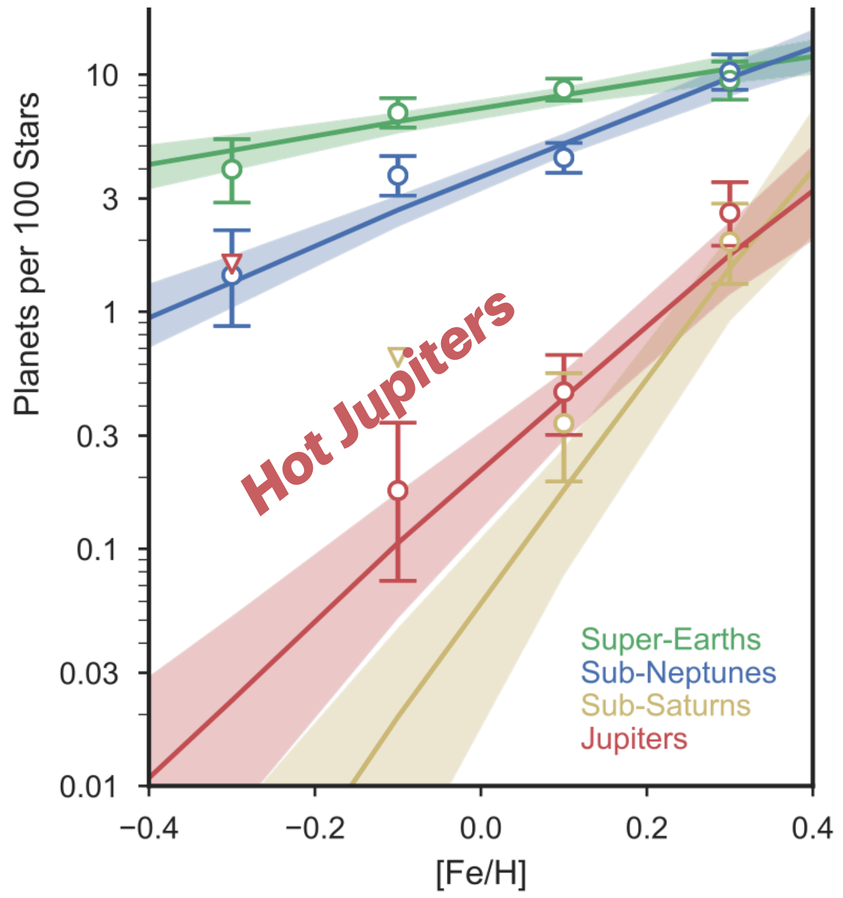
- **Steep dependence with stellar metallicity**

  Occurrence rate rises by a factor of ~10 over ~0.5 dex in metallicity.

  e.g., Guo et al. 2017, Petigura et al. 2018

$\Rightarrow$ A signature of planet-planet scattering?

Petigura et al. 2018



$$\frac{df}{d[\mathrm{Fe/H}]} \propto 10^{\beta[\mathrm{Fe/H}]}$$

$$\beta = 3.4^{+0.9}_{-0.8}$$

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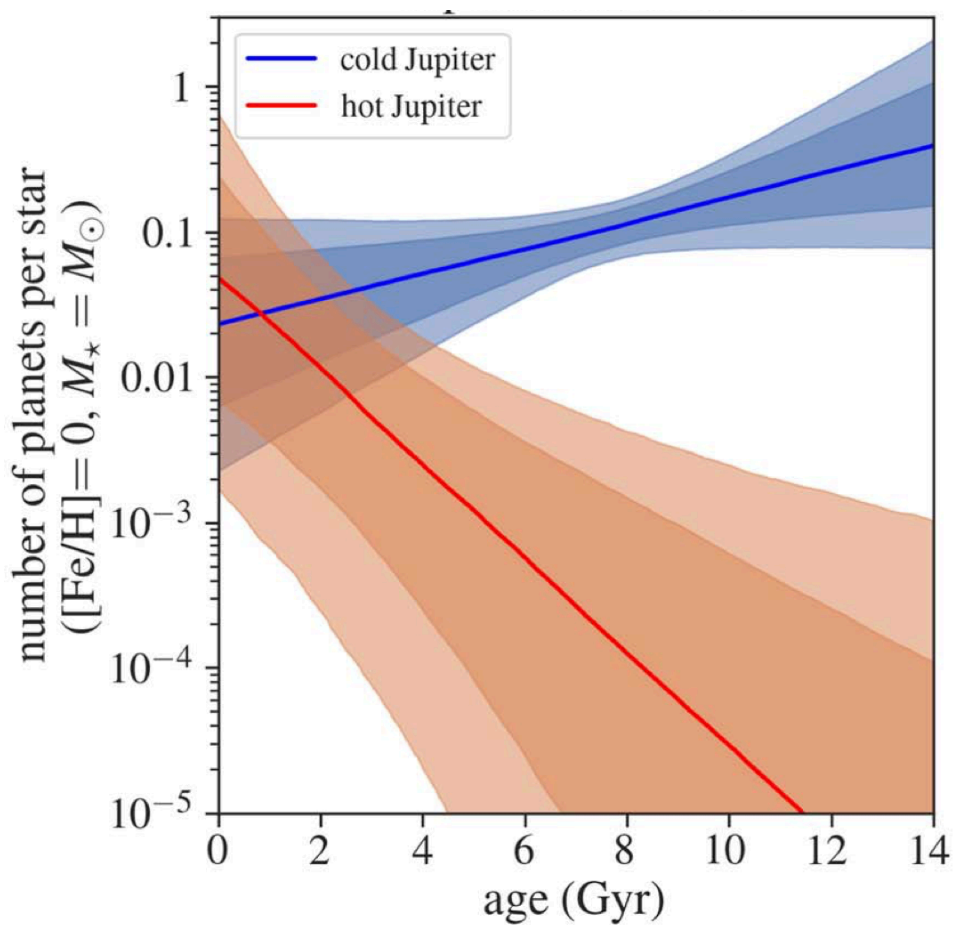
Hot Jupiters (P = 1-10 d)

- **Evolution over time?**

  Some signs that hot Jupiters are less common around older stars.

  e.g., Hamer & Schlaufman 2019, Miyazaki & Masuda 2023, Chen et al. 2023

$\Rightarrow$ A signature of tidal decay?



Miyazaki & Masuda 2023

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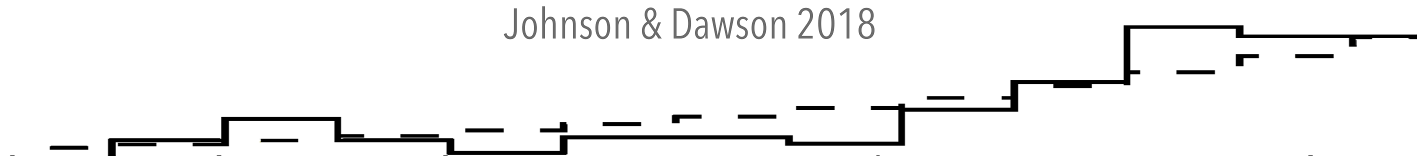
Warm Jupiters

~1-2%

(Cumming+2008)

Johnson & Dawson 2018



Orbital Separation

~0.01-0.1 AU — *~0.1-1 AU* — *~1-10 AU* — *~10-100 AU* — *>100 AU*

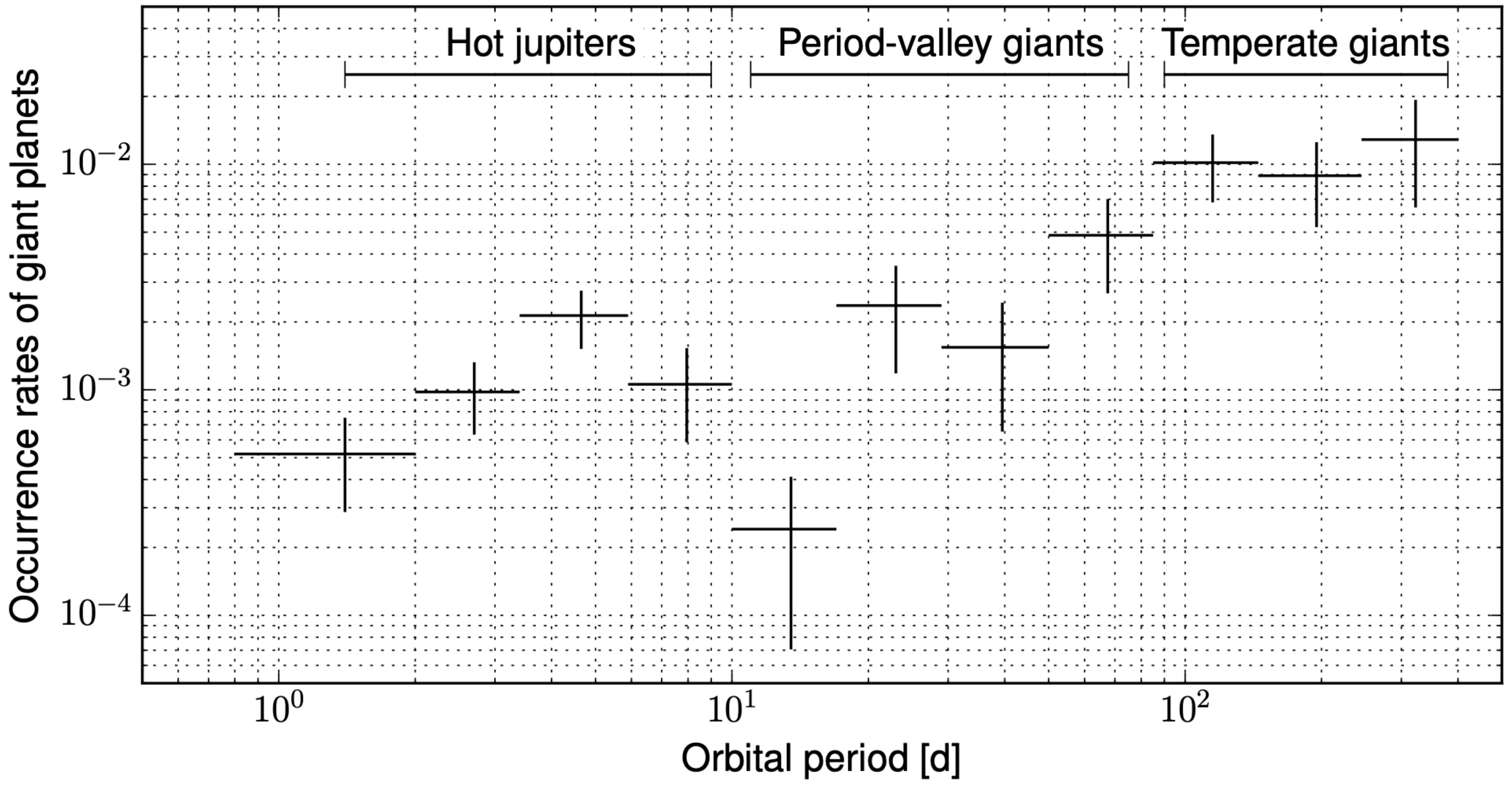
Warm Jupiters (P ~ 10-365 d)

- **Gradual rise out to ~1 AU**

Warm Jupiters are relatively rare. Their prevalence rises sharply near 1 AU.

e.g., Cumming et al. 2008,
Mayor et al. 2011,
Petigura et al. 2018,
Fulton et al. 2021

⇒ A signature of the water ice line?



Santerne et al. 2016

Reviews:

- **Udry & Santos 2007**
  Statistical Properties of Exoplanets
- **Winn & Fabrycky 2015**
  The Occurrence and Architecture of Exoplanetary Systems

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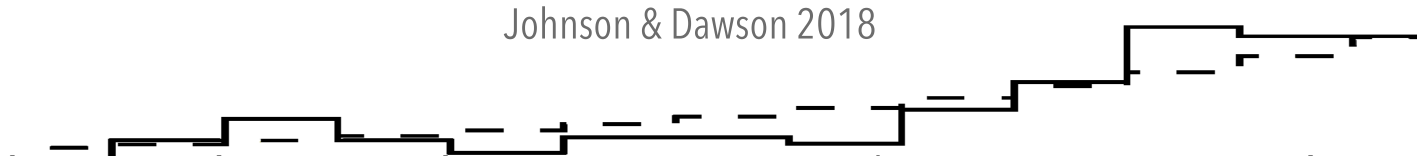

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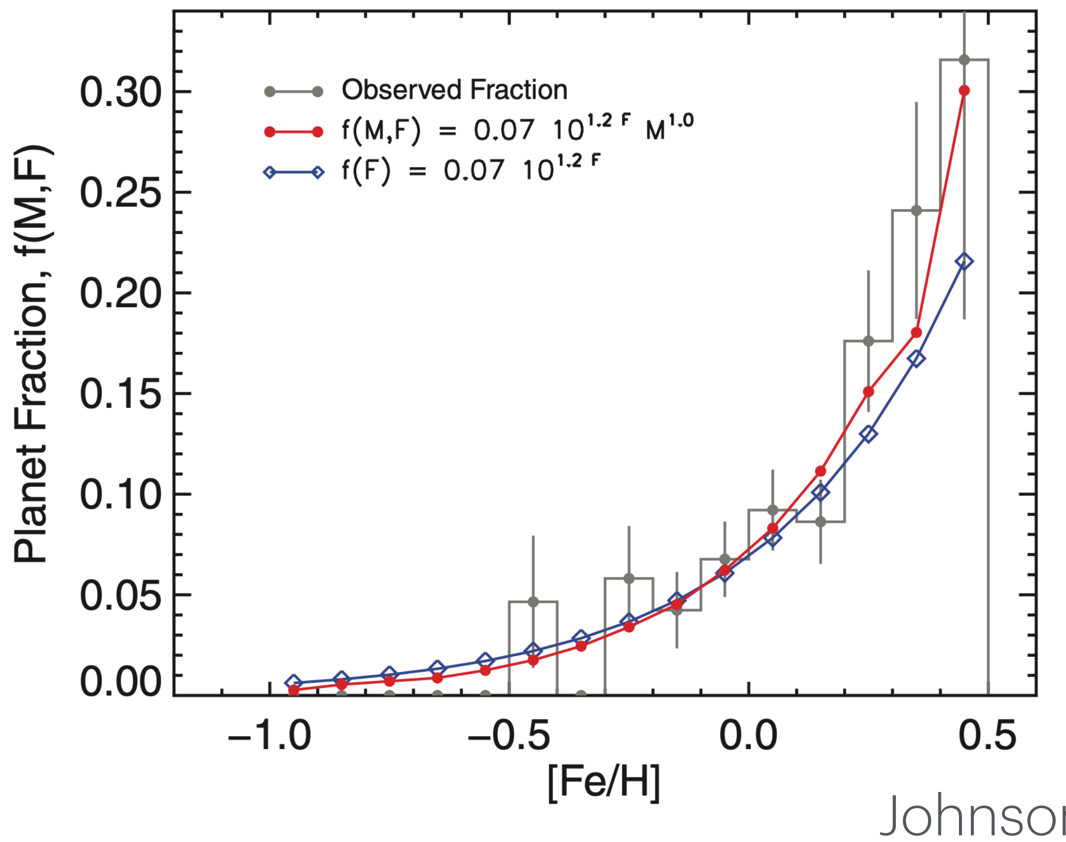
~0.01-0.1 AU | ~0.1-1 AU | ~1-10 AU | ~10-100 AU | >100 AU

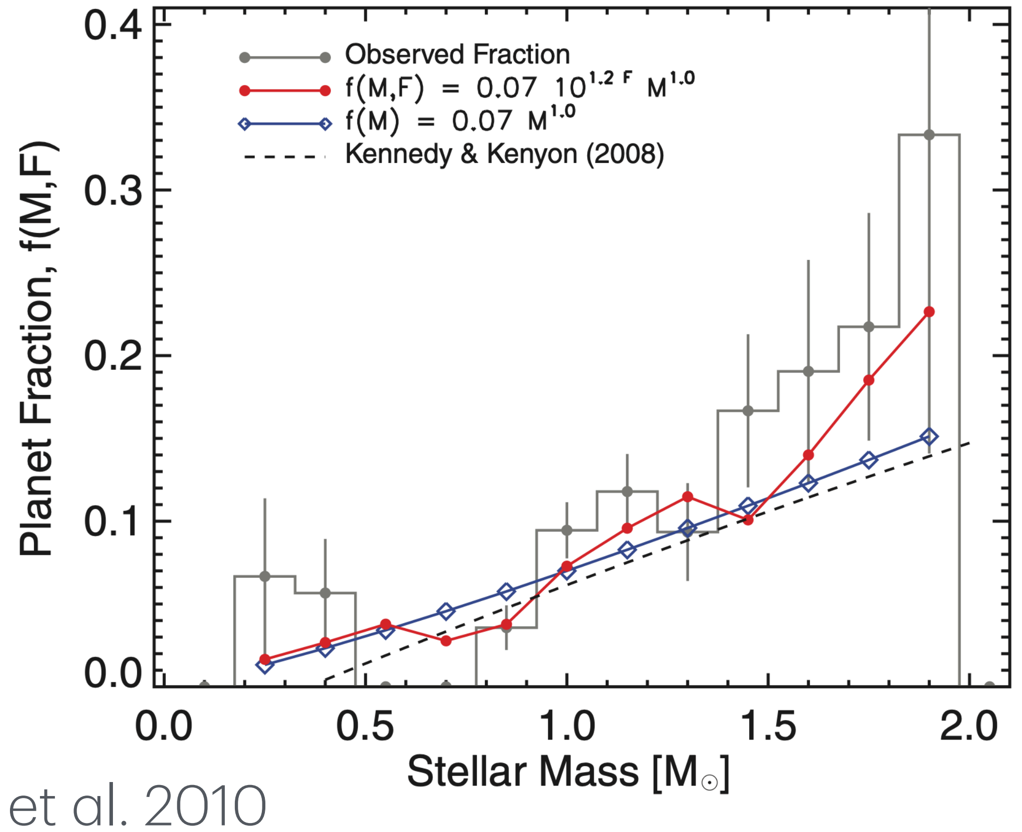
Warm Jupiters (P ~ 10-365 d)

- **Steep dependence with…** **stellar metallicity** and **stellar mass**

Giant planets are more prevalent around high-metallicity and high-mass stars. e.g., Santos et al. 2004, Fischer & Valenti 2005, Endl et al. 2006, Bowler et al. 2010, Johnson et al. 2010

⇒ A signature of more efficient core formation?





Johnson et al. 2010

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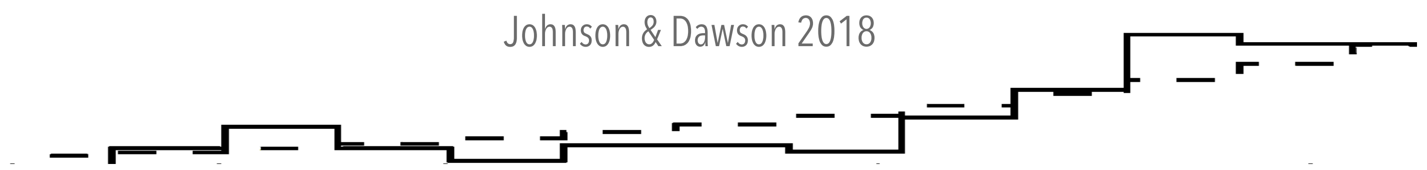

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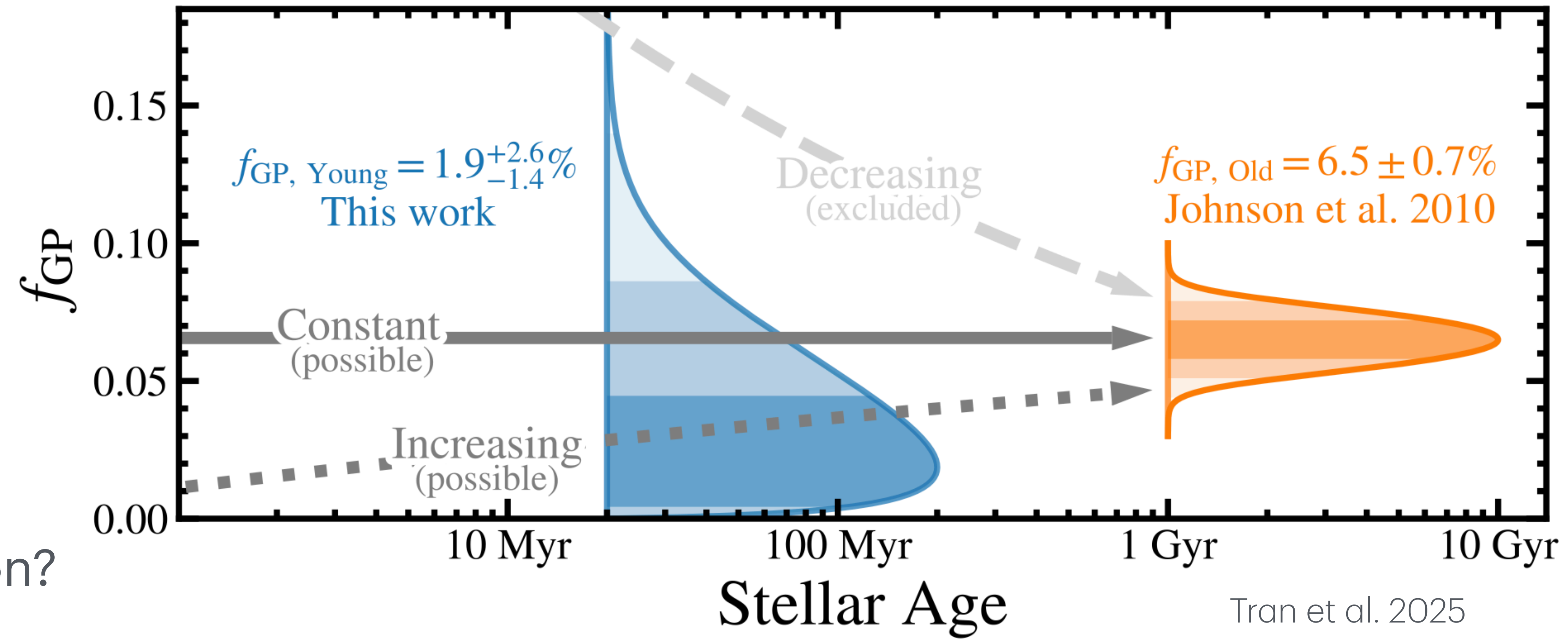
Warm Jupiters (P ~ 10-365 d)

- **Hints of increasing occurrence rate over time**

  RV surveys of young stars found lower frequencies compared to field stars.

  e.g., Grandjean et al. 2023, Tran et al. 2025

⇒ A signature of late inward migration?



Tran et al. 2025

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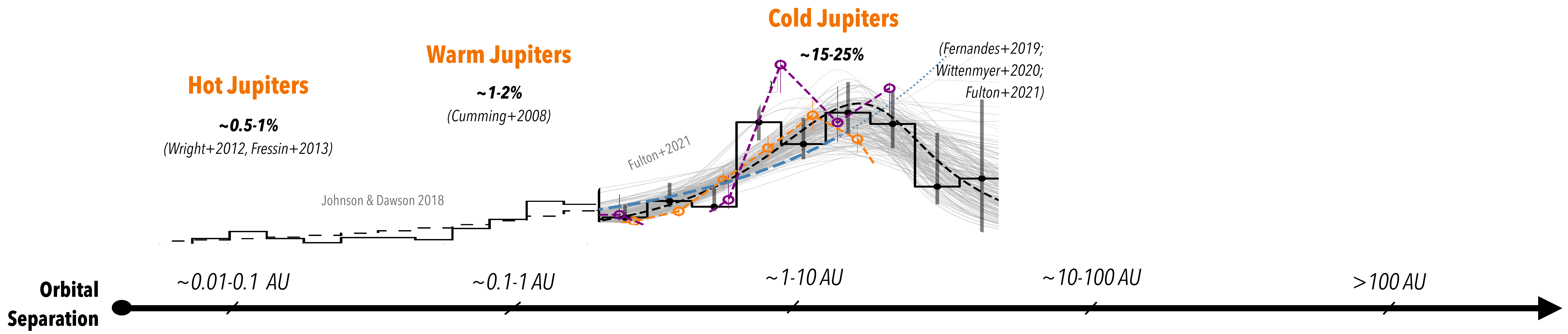
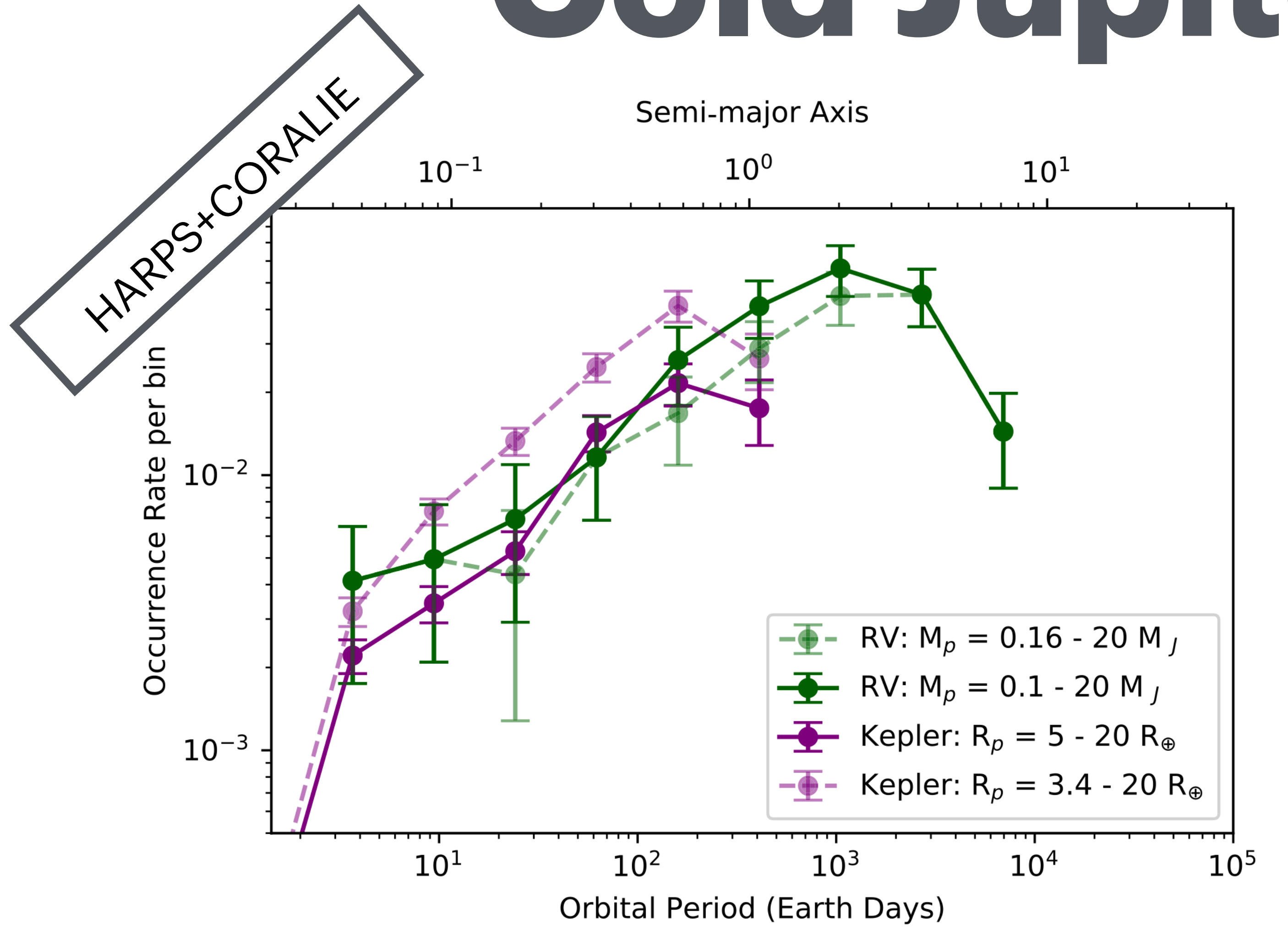


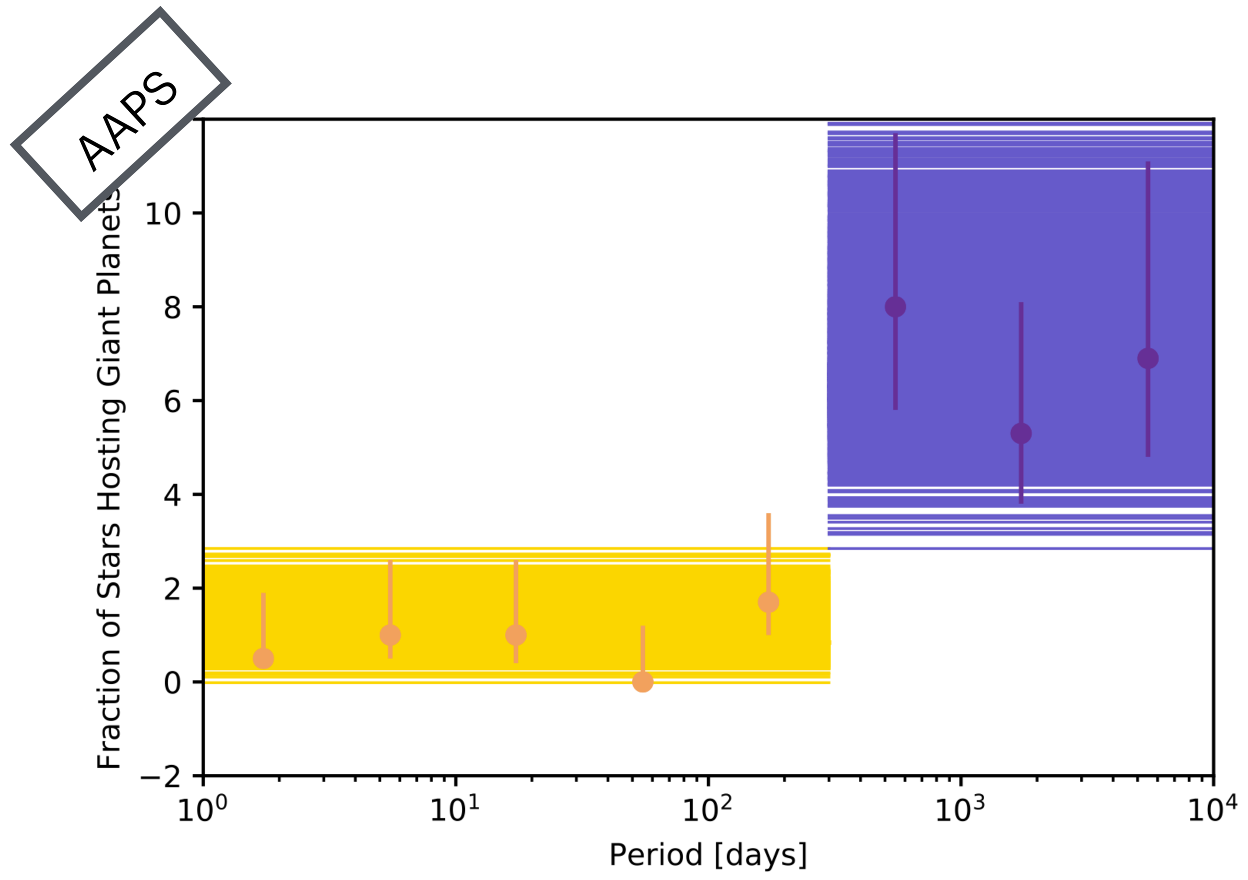
Cold Jupiters (a ~ 1-10 AU)

- **A peak in the giant planet distribution**

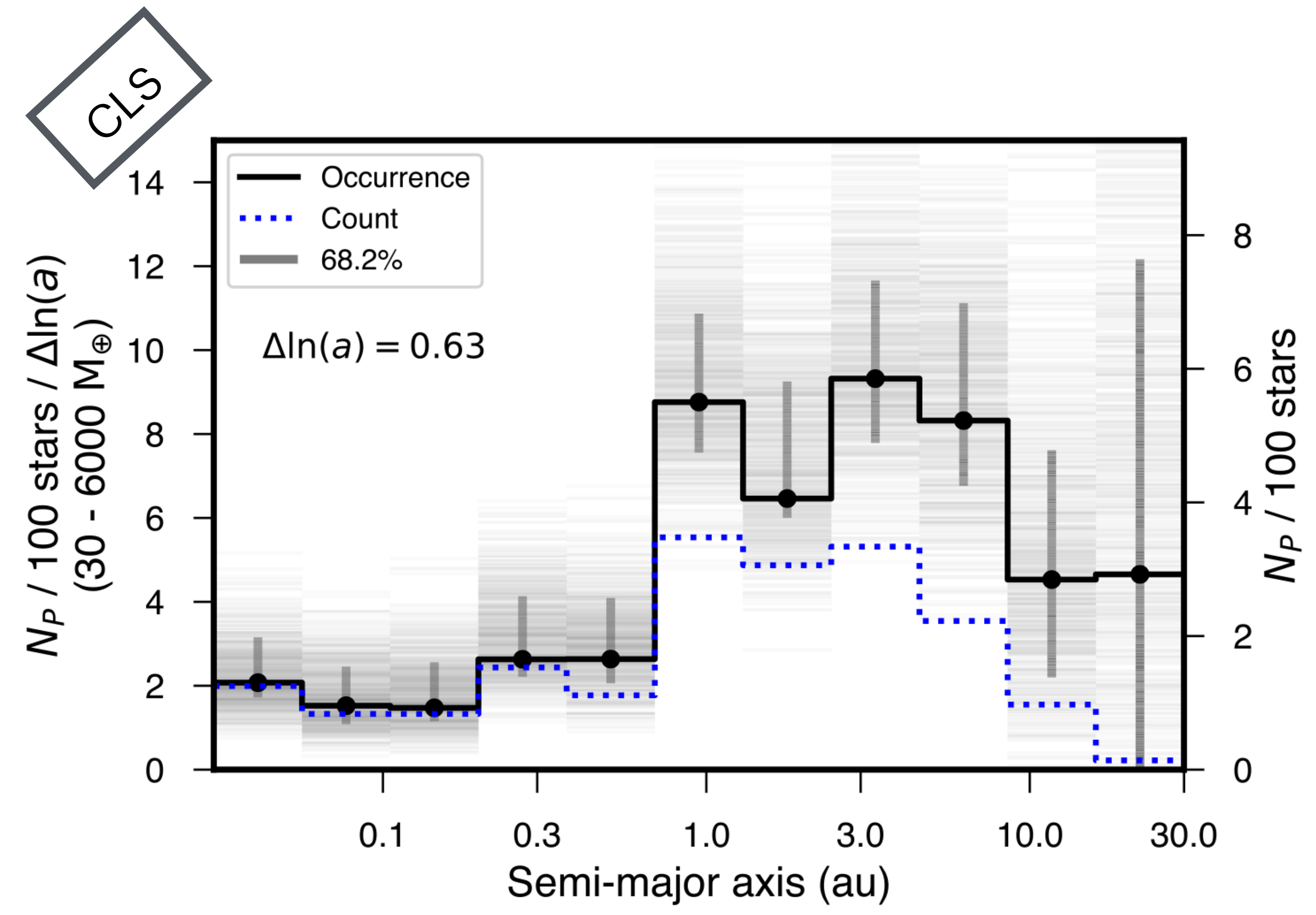
Giant planets are produced most readily at 1-10 AU



Fernandes et al. 2019



Wittenmyer et al. 2020



Fulton et al. 2021

How common are giant planets?

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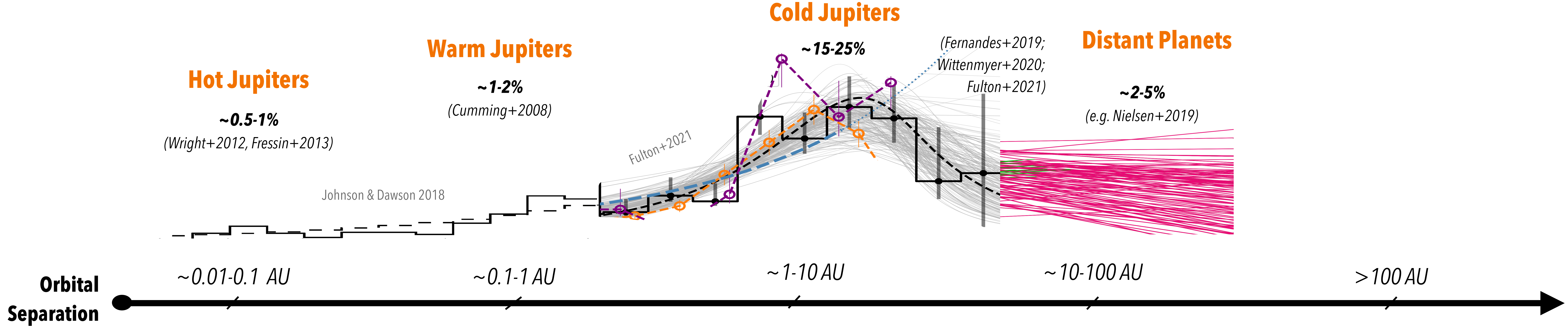
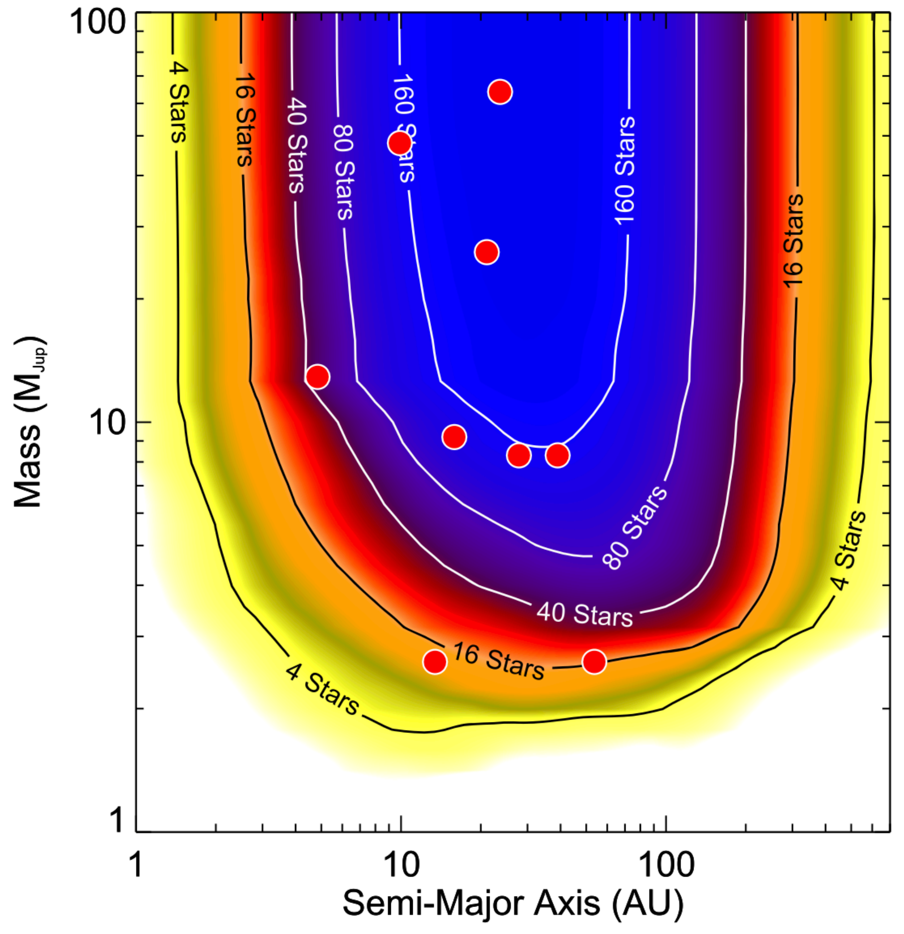


Distant Planets (a ~ 10–100 AU)

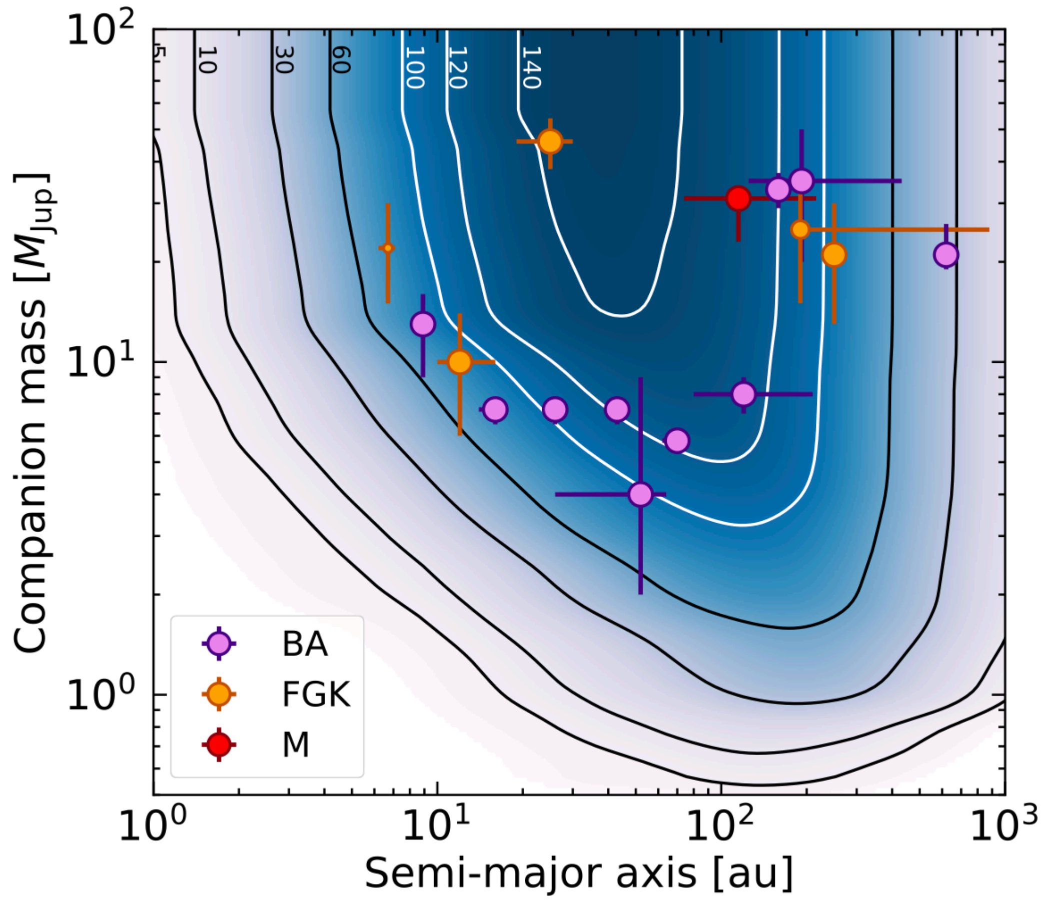
- **Occurrence rates fall with distance for massive planets**

Across all stellar masses:
2-5% for 5-13 M_{Jup} from 10-100 AU
(Nielsen et al. 2019, Vigan et al. 2022; Squicciarini et al. 2024)

Versus ~1% for 5-13 M_{Jup} from ~30-300 AU (e.g., Brandt et al. 2014, Bowler 2016)



Nielsen et al. 2019

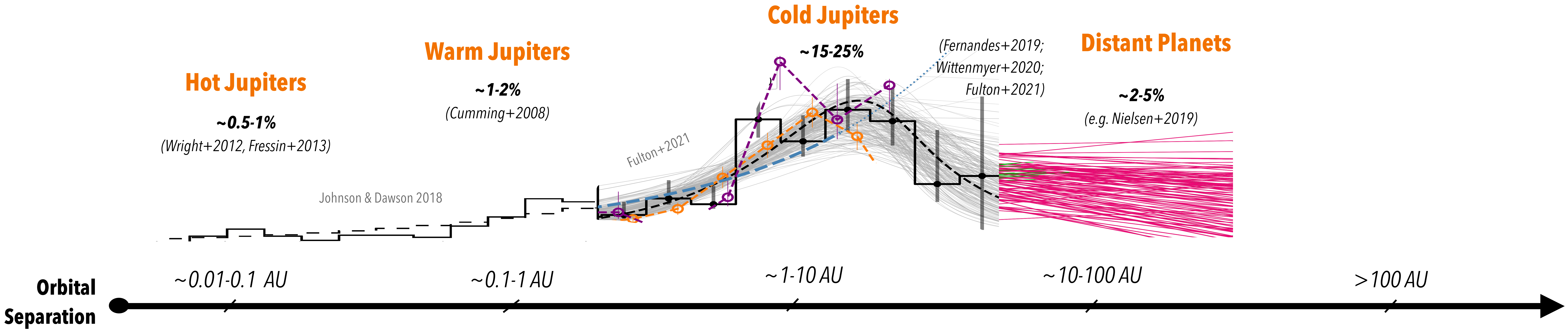


Vigan et al. 2021

Reviews:
- **Bowler 2016**
  Imaging Extrasolar Giant Planets
- **Bowler & Nielsen 2018**
  Occurrence Rates from Direct Imaging Surveys
- **Currie et al. 2023**
  Direct Imaging and Spectroscopy of Extrasolar Planets
- **Chauvin 2024**
  Direct Imaging of Exoplanets: Legacy and Prospects

How common are giant planets?

Occurrence rates across 5 orders of magnitude in separation for (largely) single, Sun-like stars



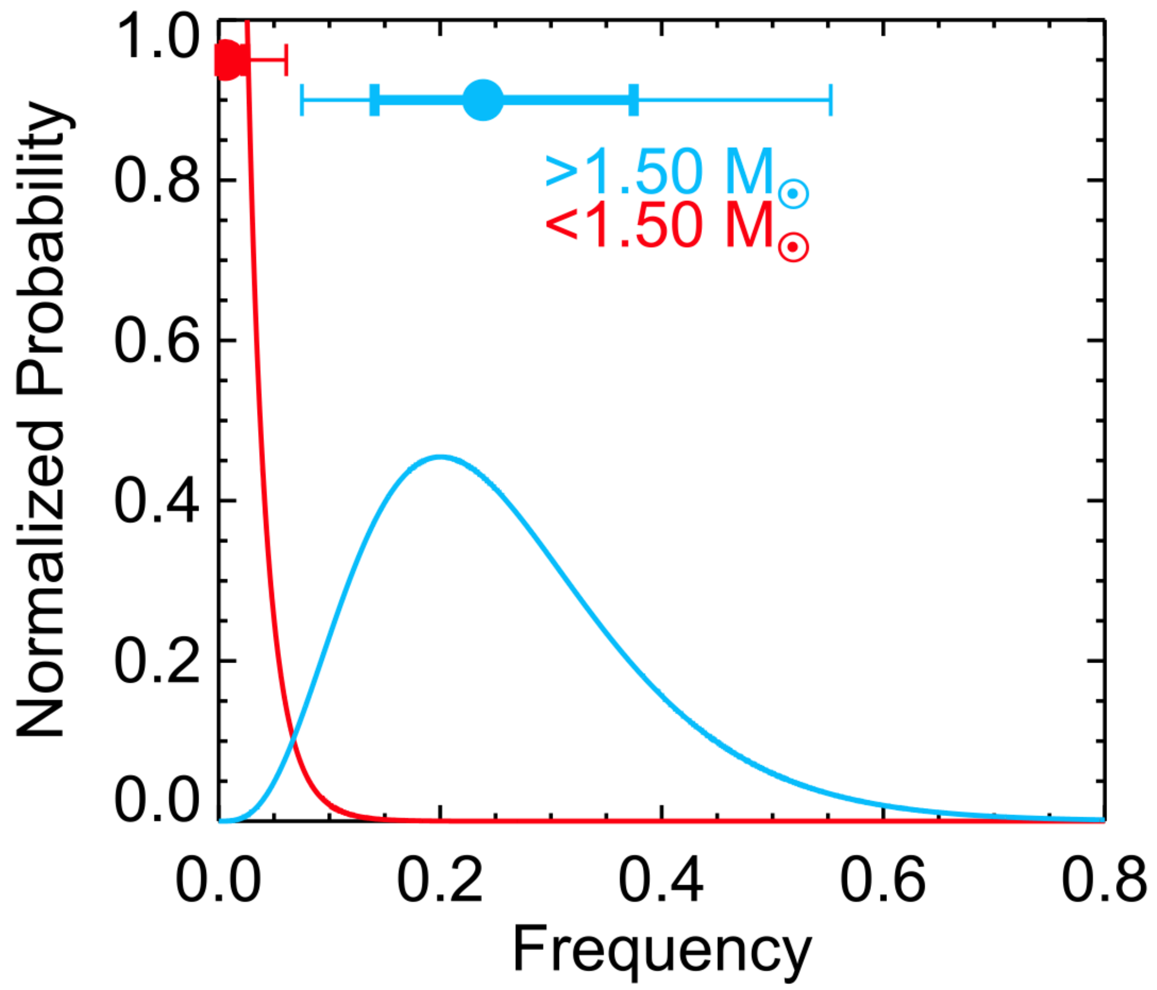
Distant Planets (a ~ 10–100 AU)

- **Occurrence rates scale with stellar host mass**

Most giant planets have been discovered around massive stars and reflects an intrinsic preference.

e.g., Nielsen et al. 2019, Vigan et al. 2021

⇒ Increased planet formation efficiency?



Reviews:

- **Bowler 2016**
  Imaging Extrasolar Giant Planets
- **Bowler & Nielsen 2018**
  Occurrence Rates from Direct Imaging Surveys
- **Currie et al. 2023**
  Direct Imaging and Spectroscopy of Extrasolar Planets
- **Chauvin 2024**
  Direct Imaging of Exoplanets: Legacy and Prospects

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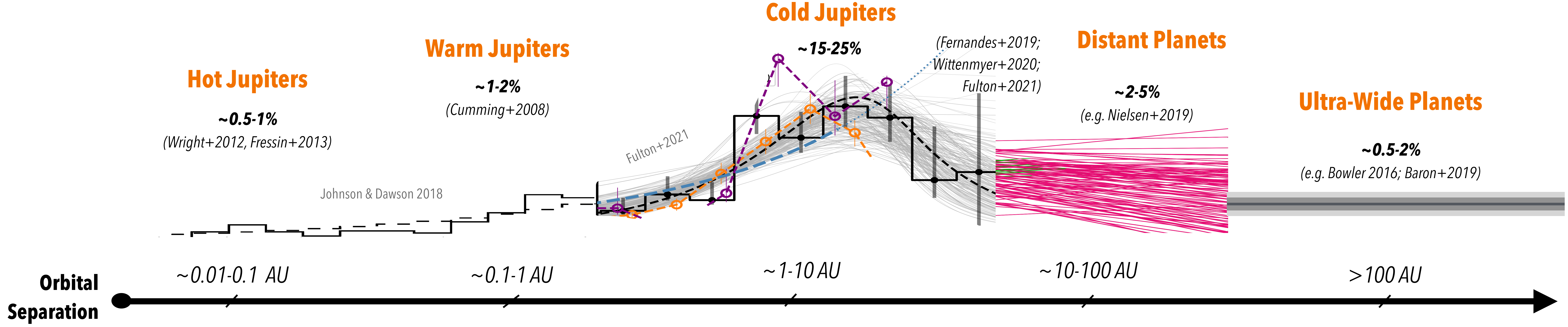


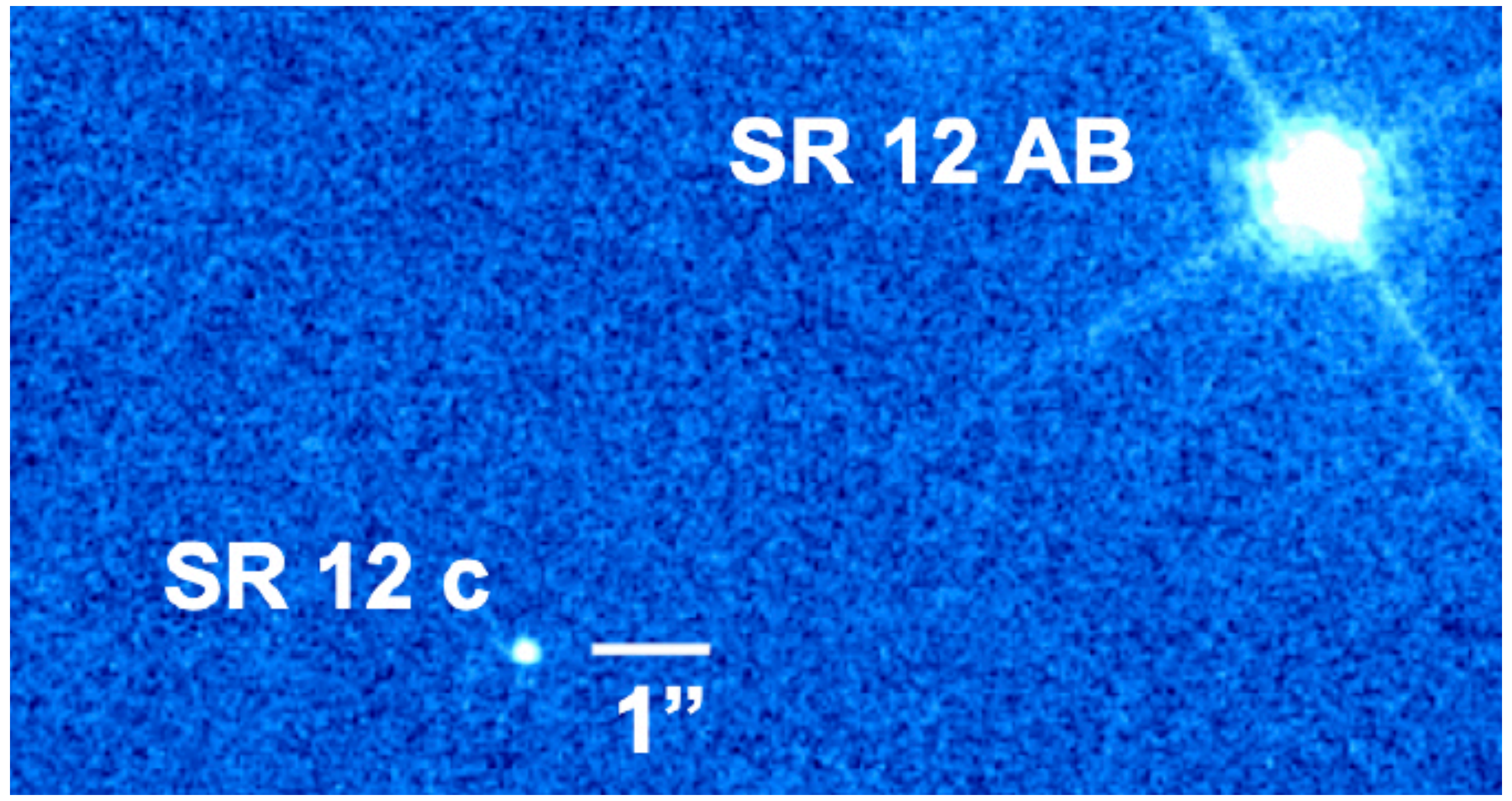
Ultra-Wide Planets (a > 100 AU)

- **Distant giant planets are rare but extend to a few thousand AU**

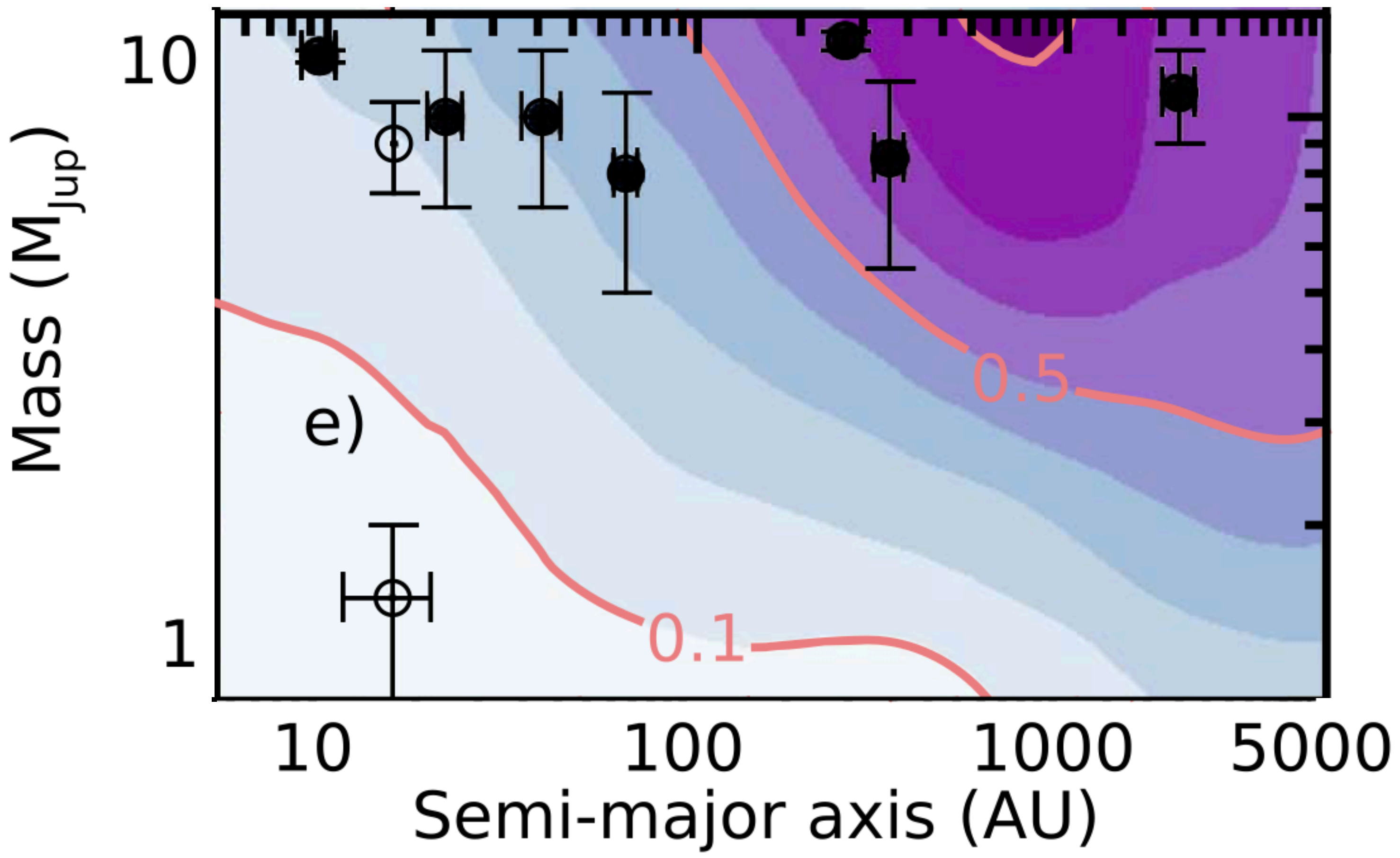
From 20-1000 AU, f ~ 2%

From 1000-5000 AU, f ~ 0.3%

e.g., Baron et al. 2019



Finley et al., in prep.



Baron et al. 2019

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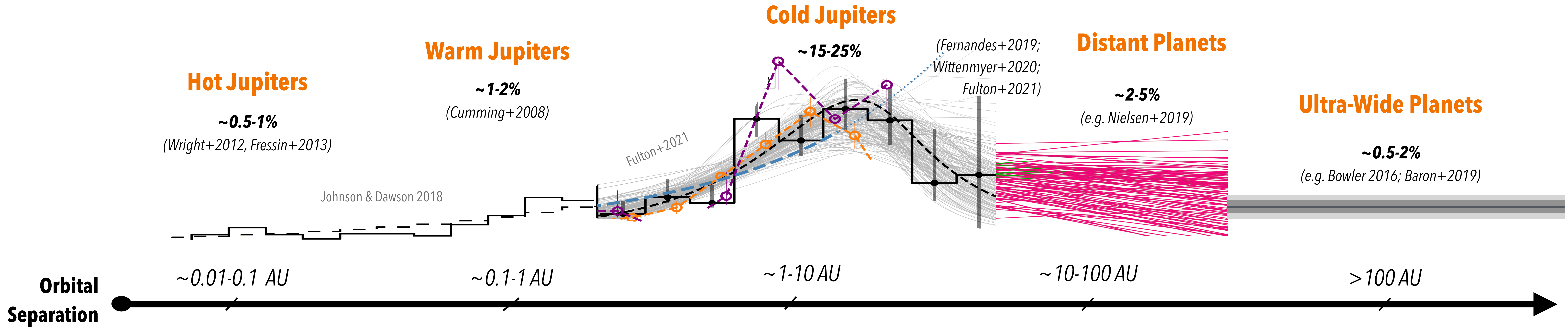


Summing these together....

$$f_{\rm GP} \sim 19 - 35\,\%$$

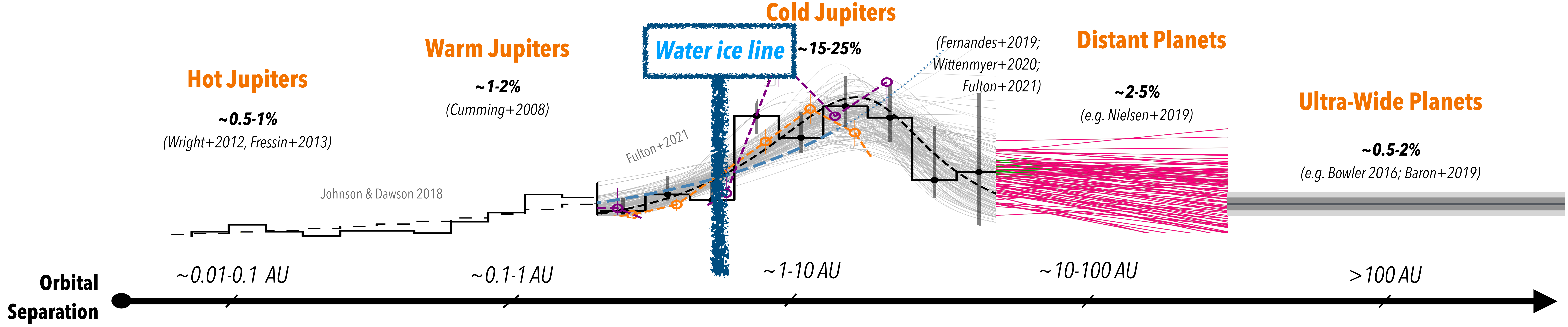
For ~0.3-15 M_{Jup} spanning ~0.1-1000 AU

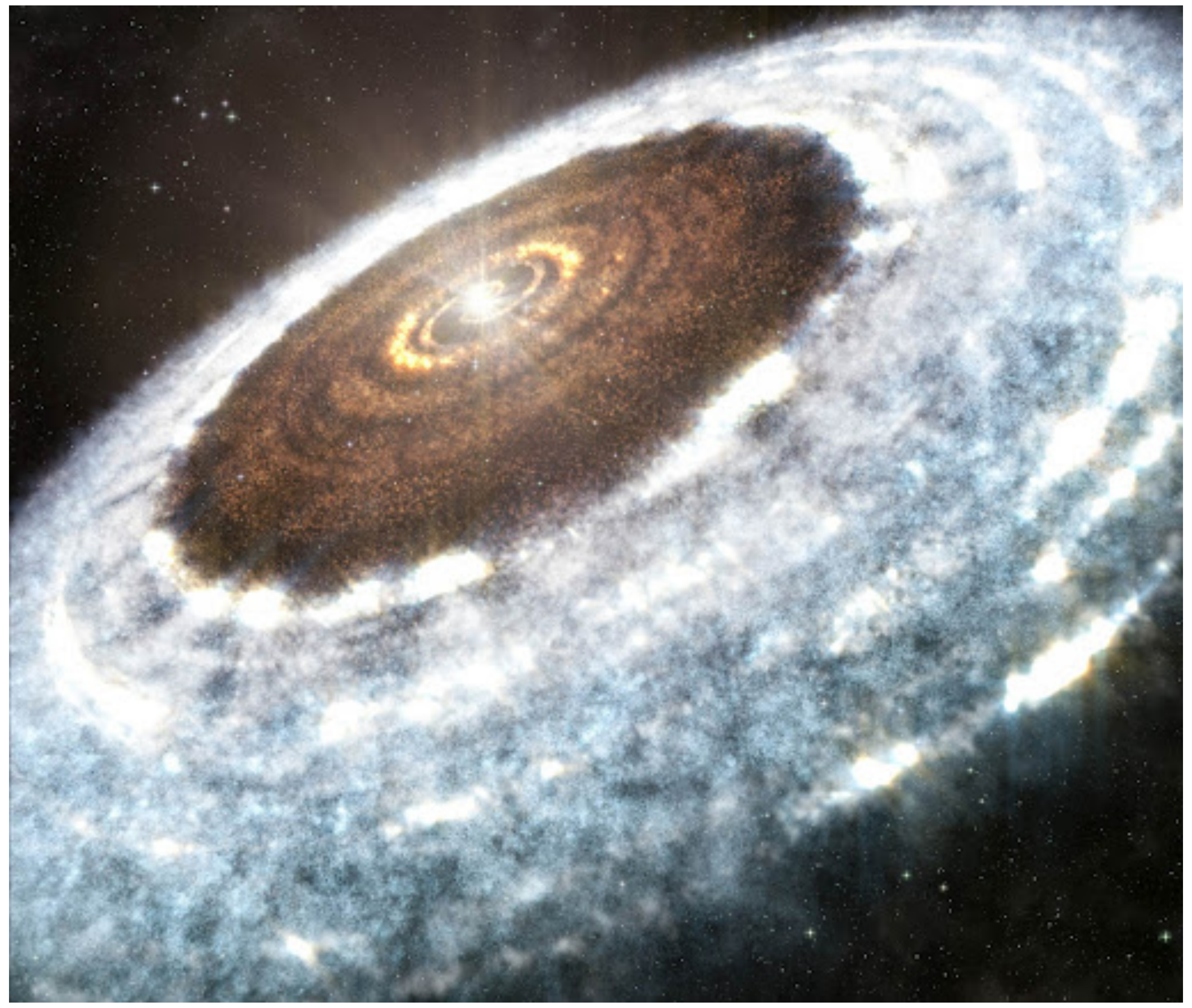
Compare with:

Fernandes et al. 2019:
$27^{+8}_{-5}\,\%$ for 0.1-20 M_{Jup} between 0.1-100 AU

Fulton et al. 2021:
$23^{+4}_{-3}\,\%$ for 0.1-20 M_{Jup} between 2-32 AU

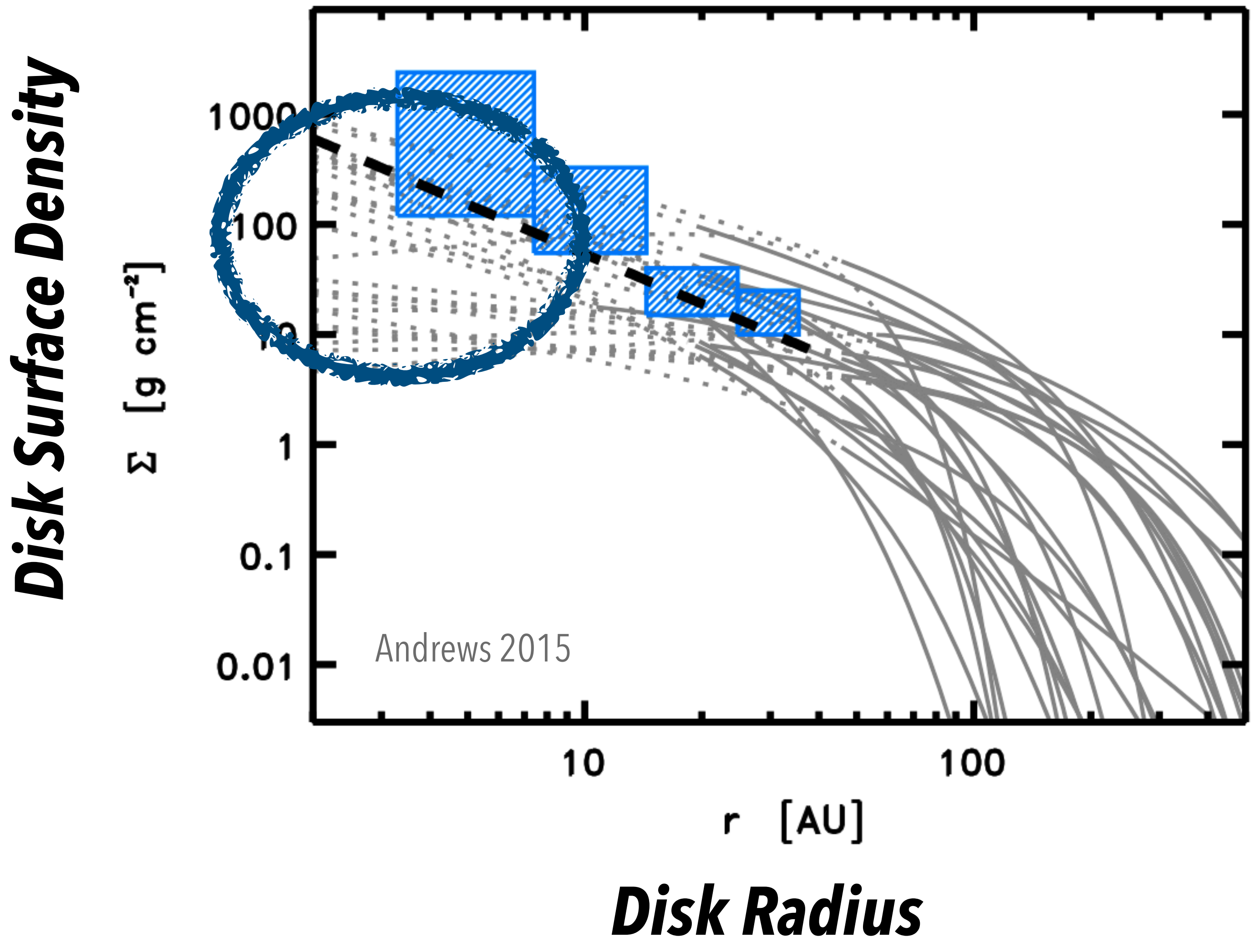
What story is this telling about giant planets?



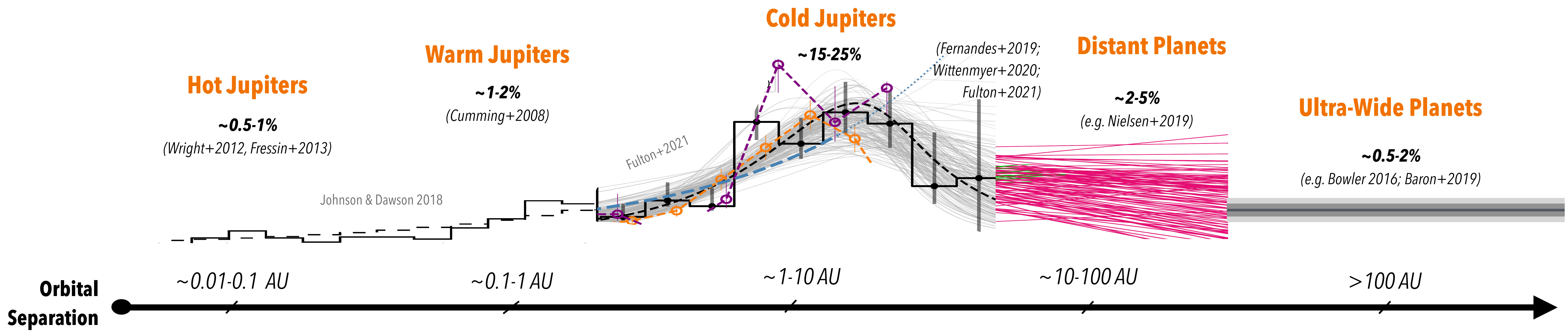


Credit: A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)

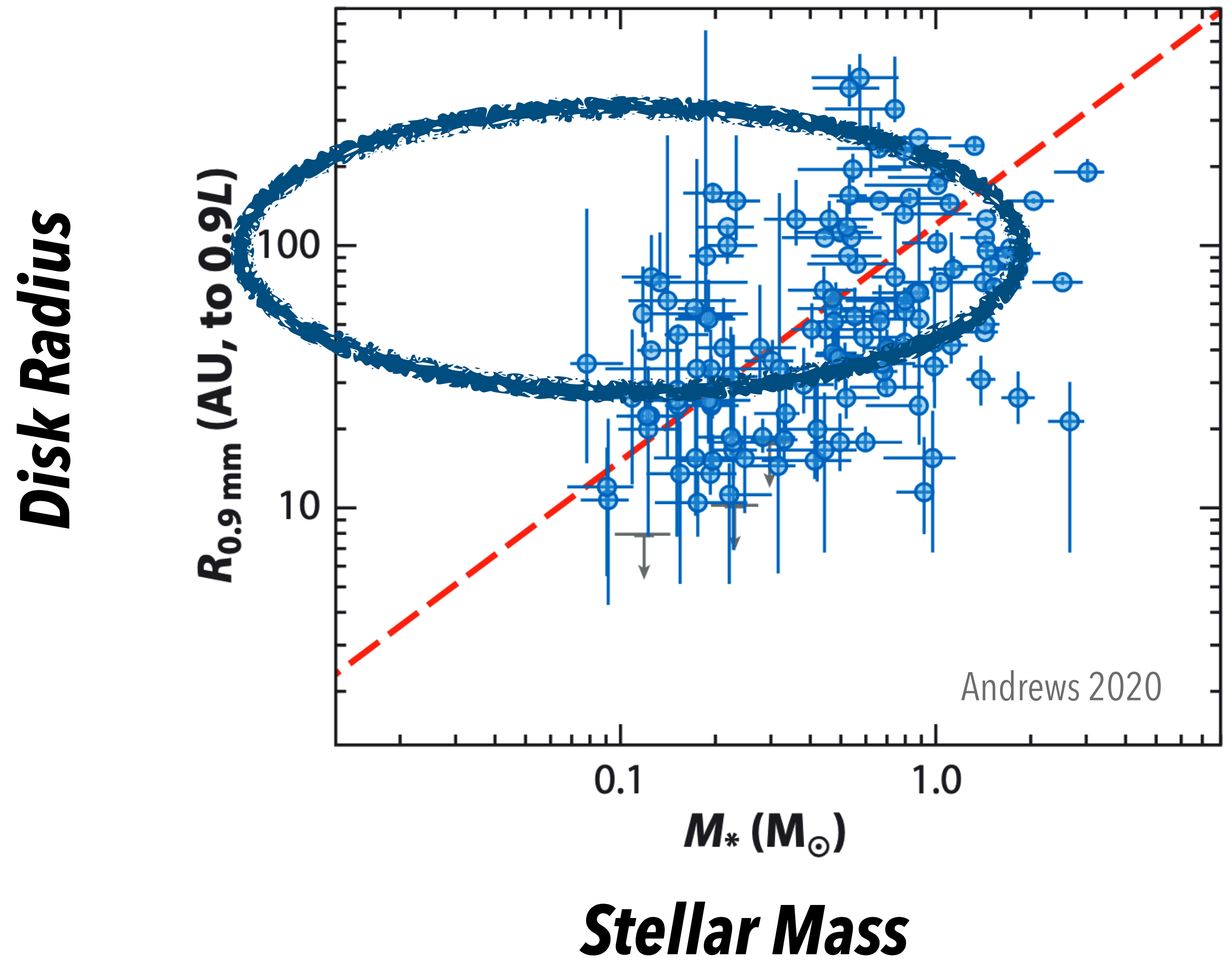
Disk Surface Density



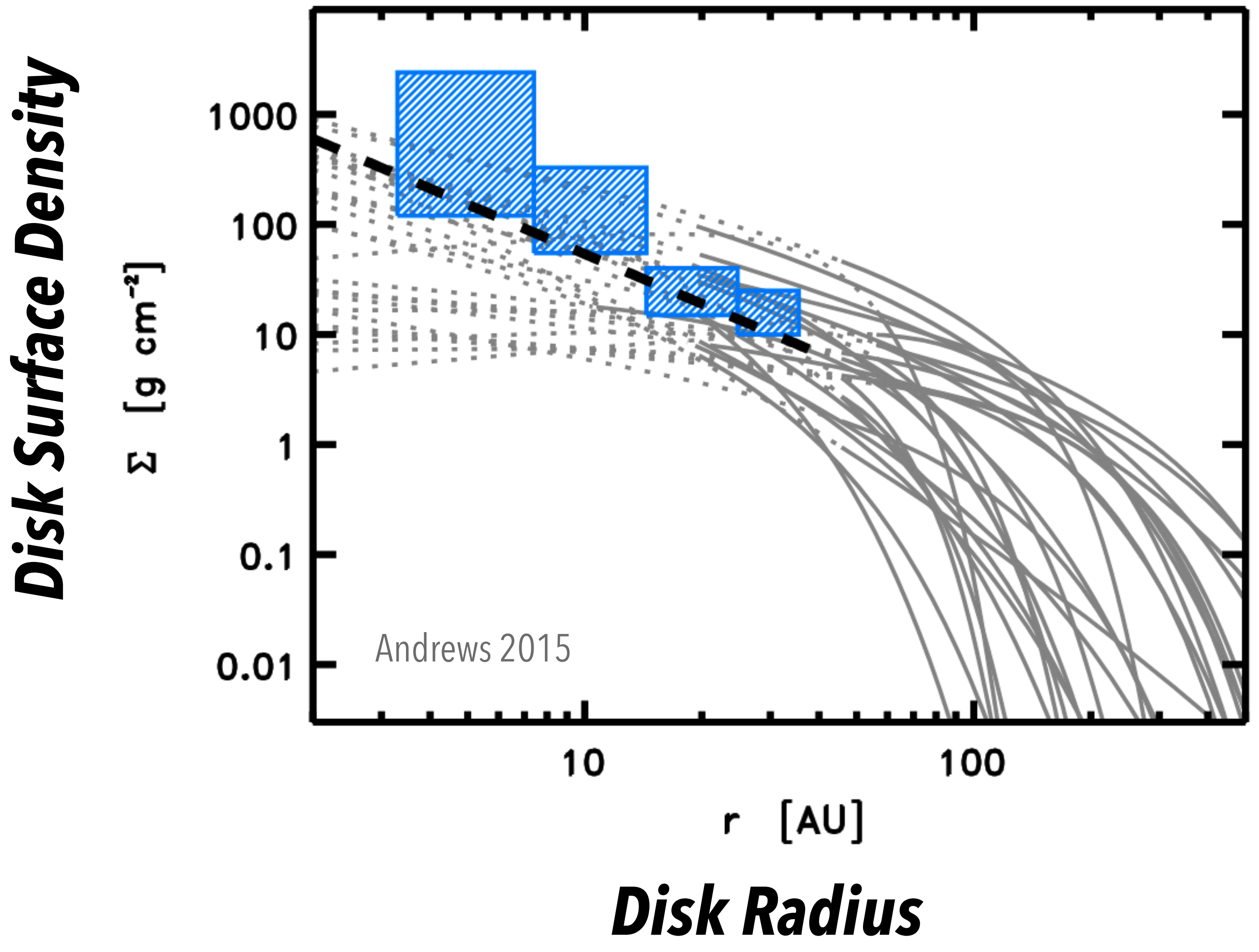
What story is this telling about giant planets?



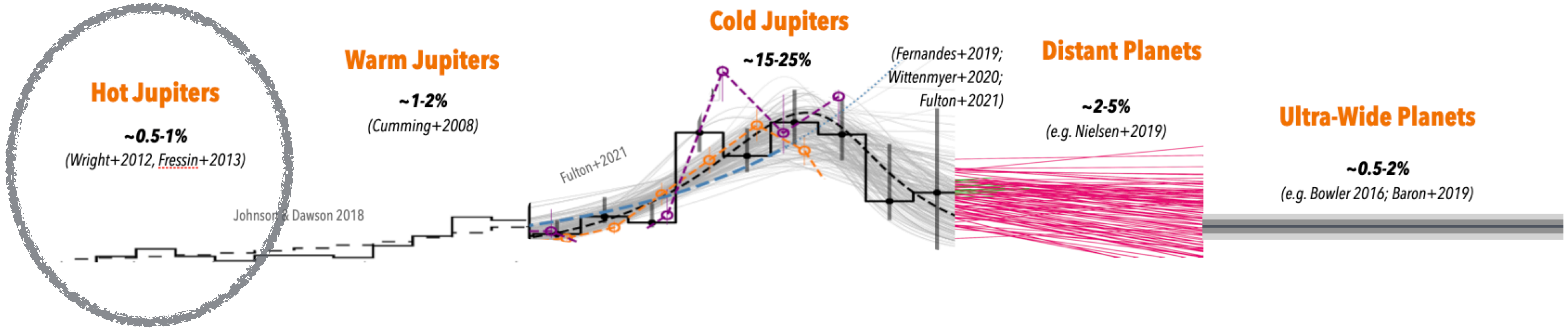
Protoplanetary Disk Size



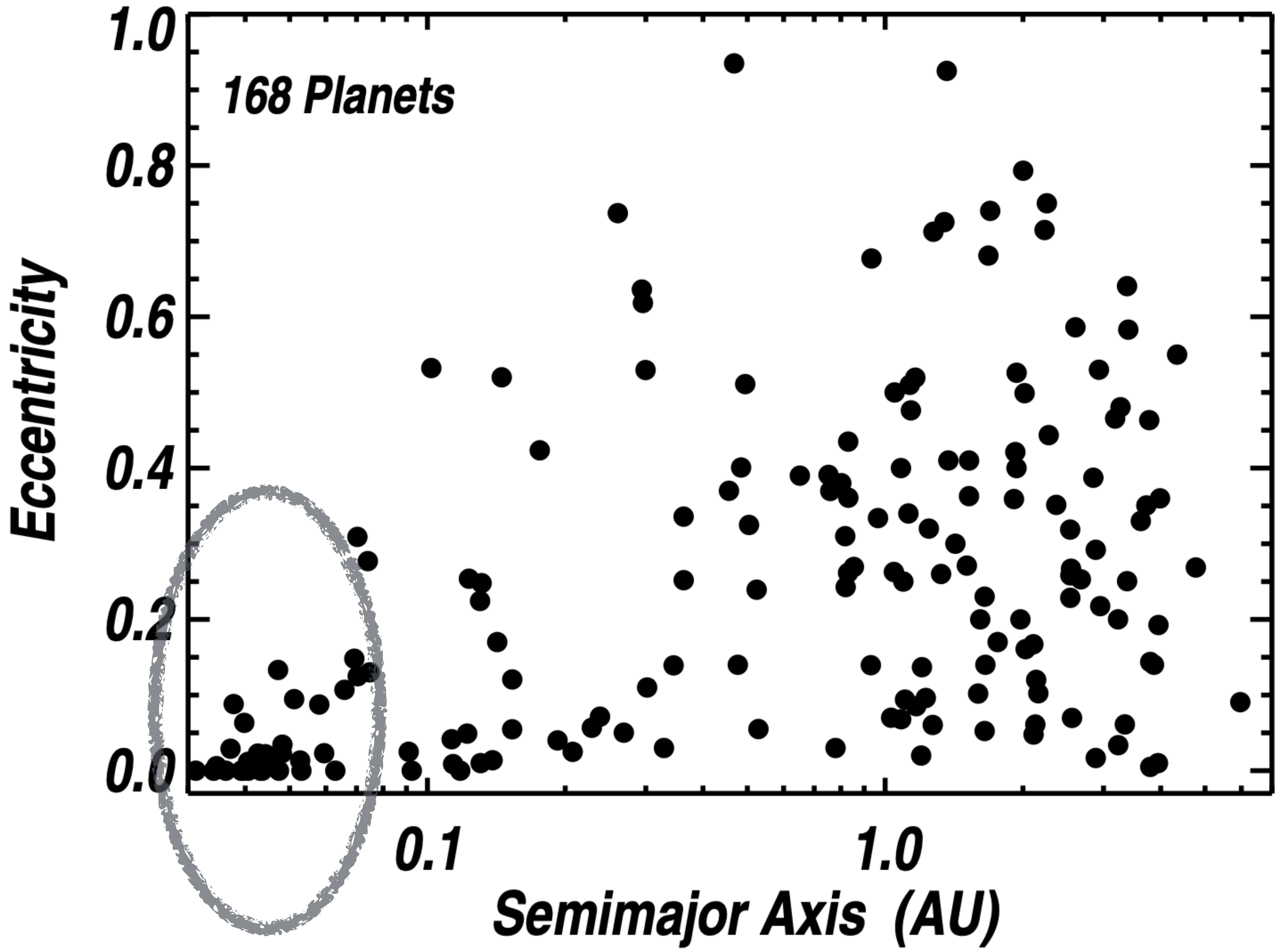
Disk Surface Density



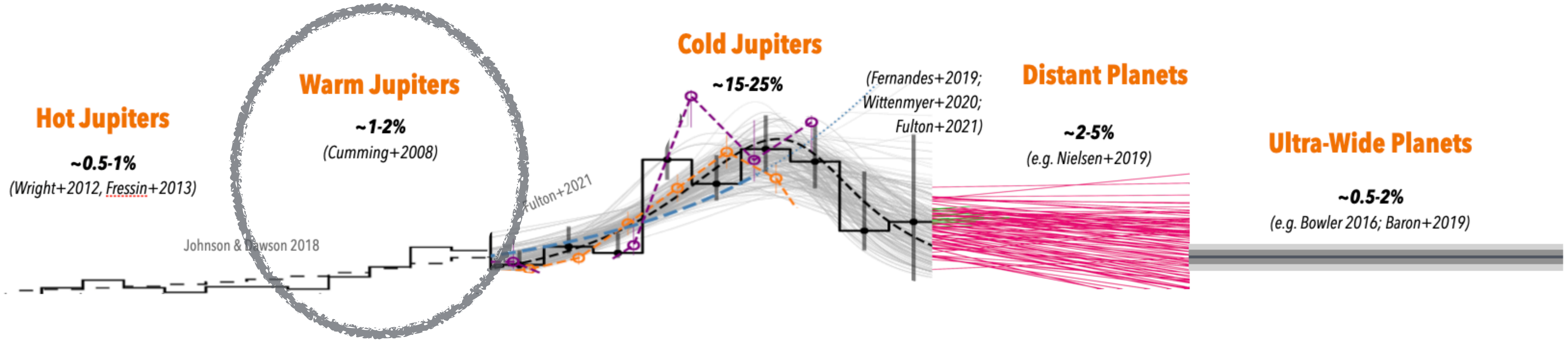
More clues from orbital eccentricities



- HJs reside on largely (but not exclusively) circular orbits

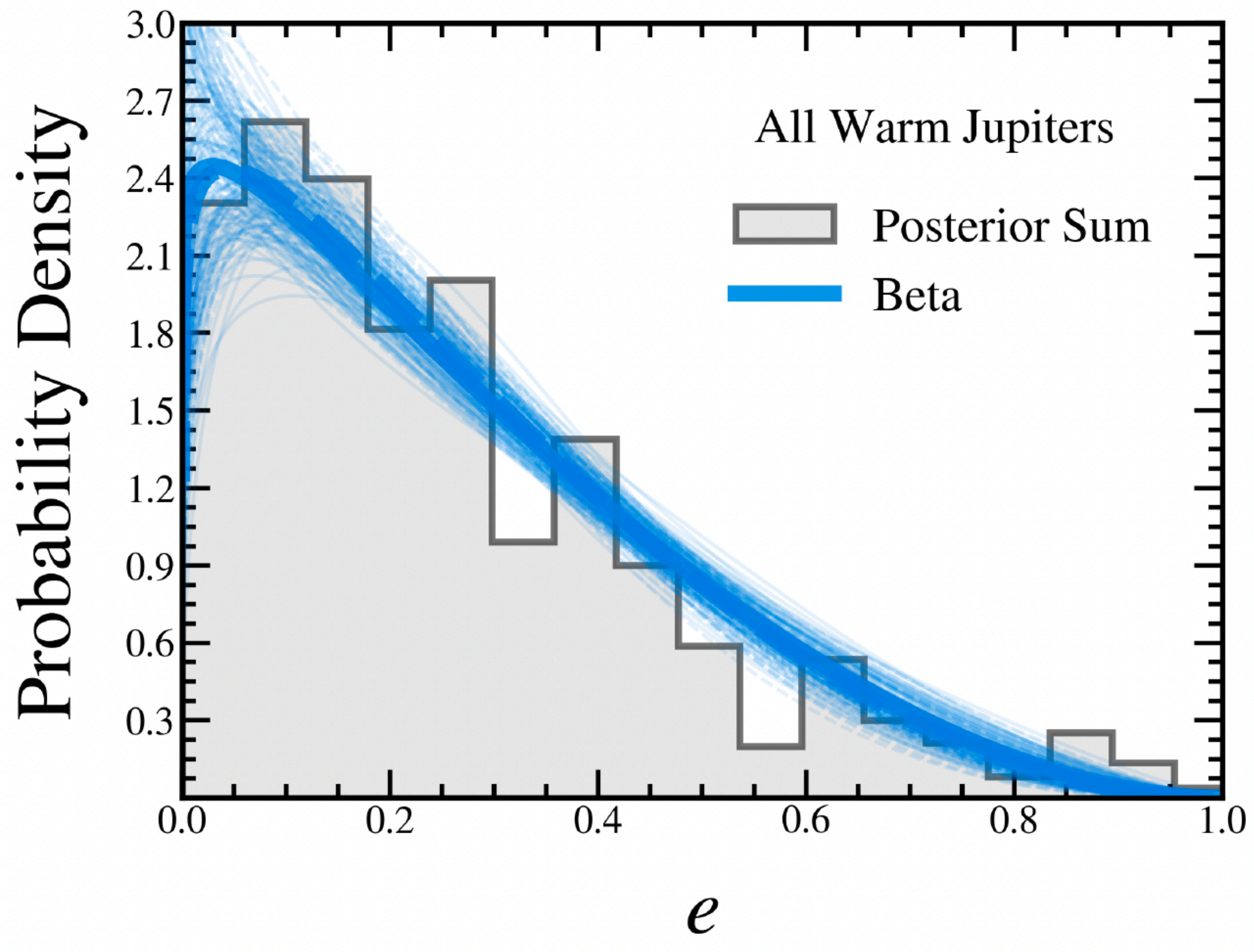


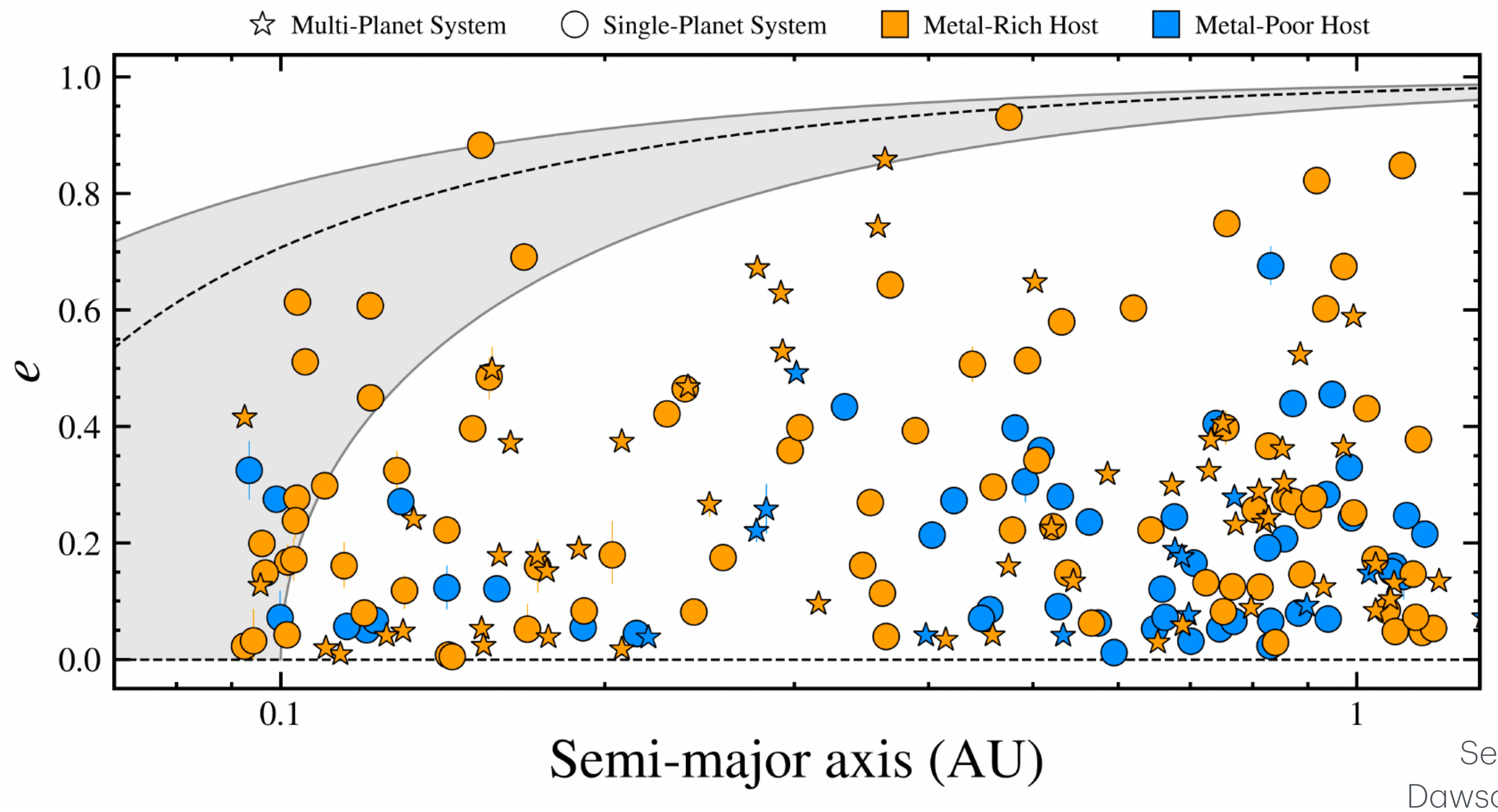
More clues from orbital eccentricities



- **73 ± 3% of WJs have non-zero eccentricities**
- **WJs are dynamically hotter around metal-rich host stars**

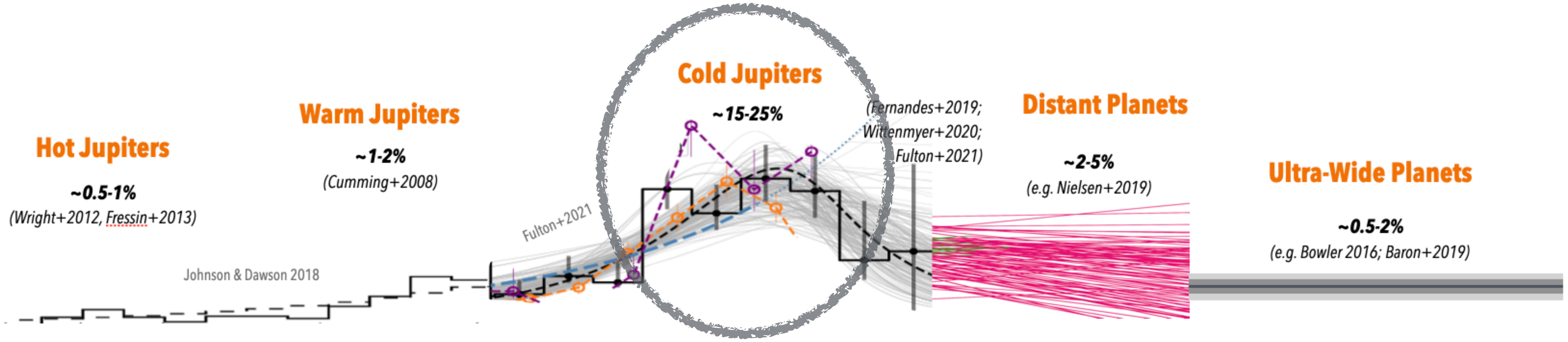
Morgan et al. 2025ab, submitted





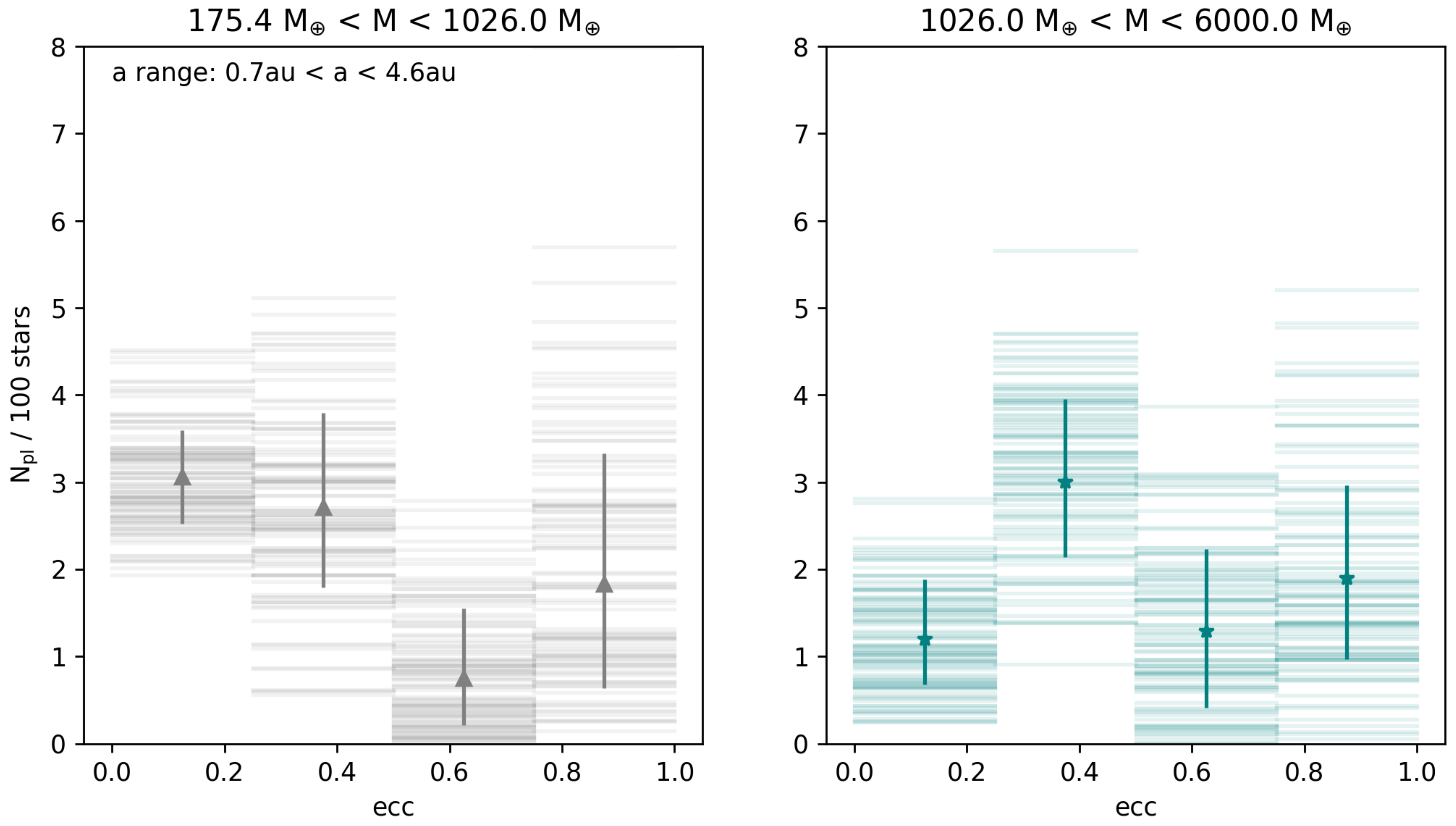
See also Gan et al. 2025,
Dawson & Murray-Clay 2013

More clues from orbital eccentricities

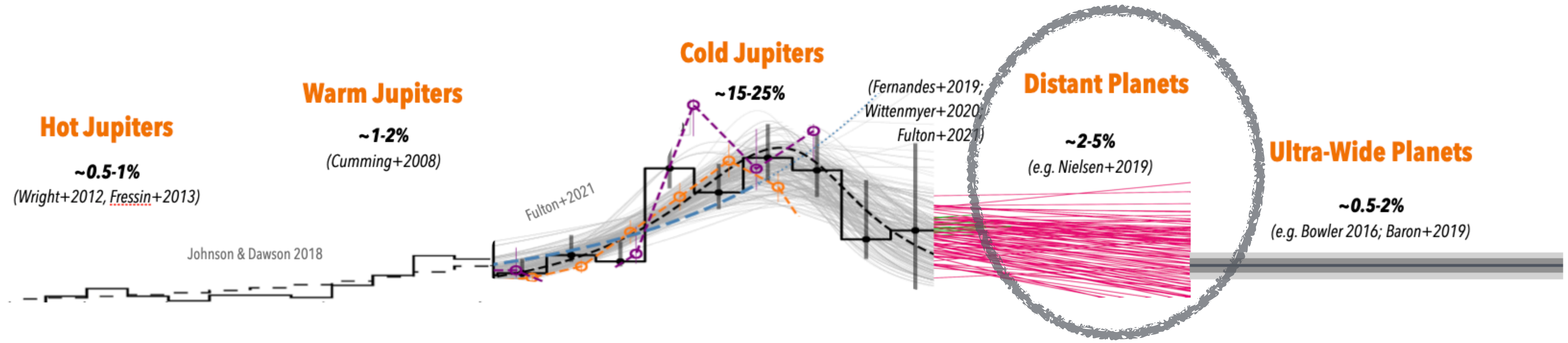


Blunt et al., in prep.

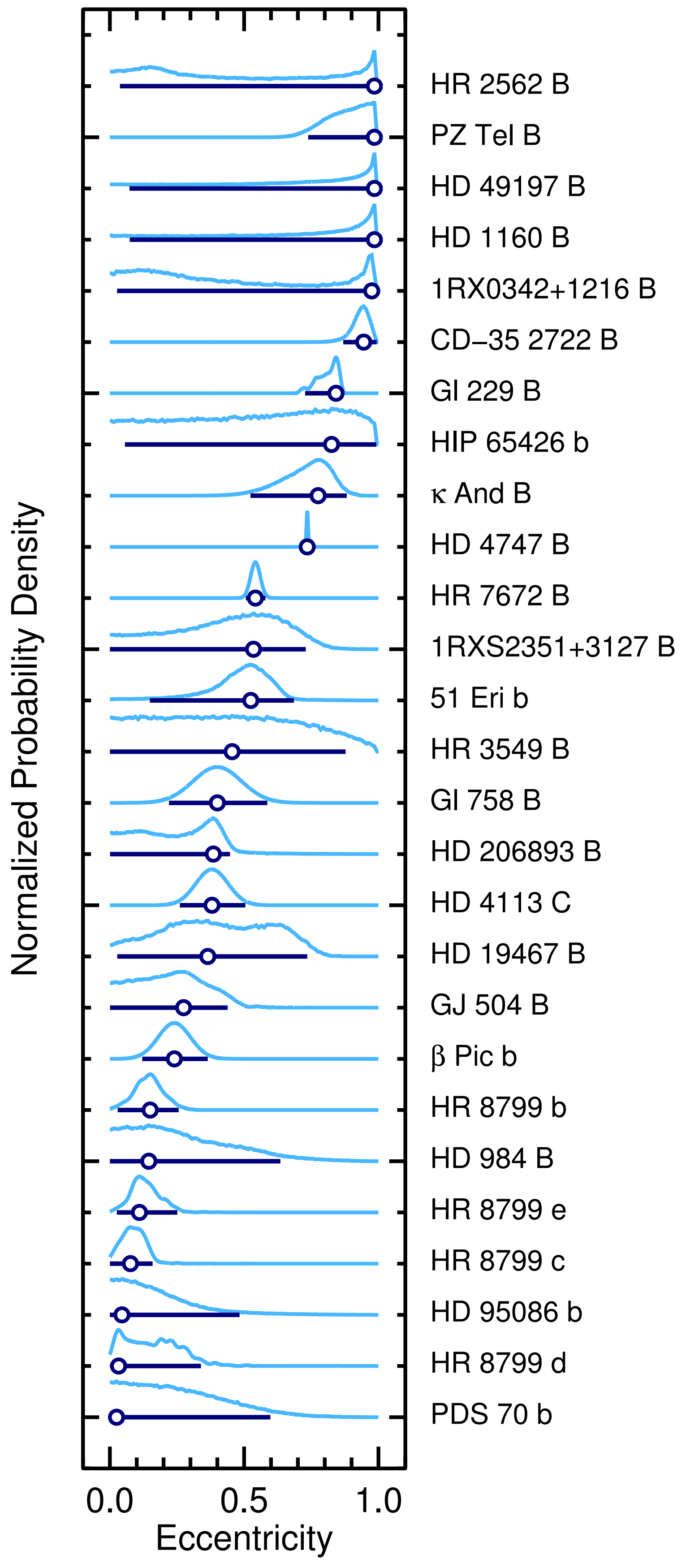
- **Cold Jupiters take on a range of eccentricities**

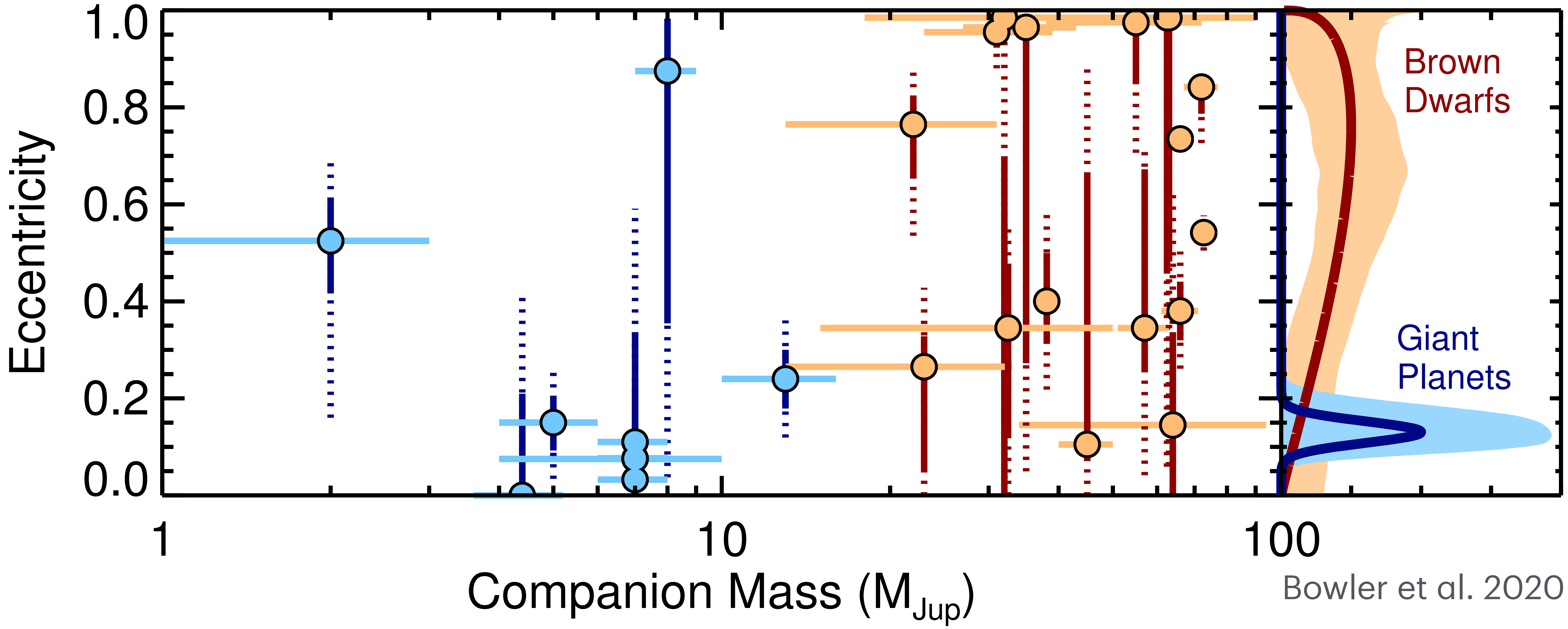


More clues from orbital eccentricities



- **Imaged planets have low eccentricities compared to distant brown dwarf companions**





Bowler et al. 2020

See also Nagpal et al. 2023, Do Ó et al. 2023

A few open questions:

What is the demographics of giant planet multiplicity?

How does giant planet demographics evolve over time?

When do giant planets develop eccentricities?

Is there hidden structure in the radial distribution function?

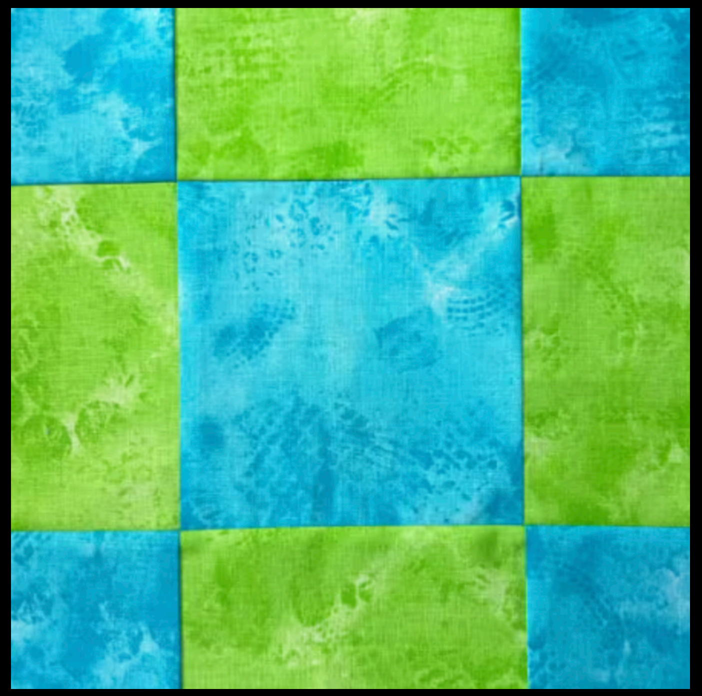
What is the demographics of Saturns out to 100 AU?

Does birth environment impact planet demographics?

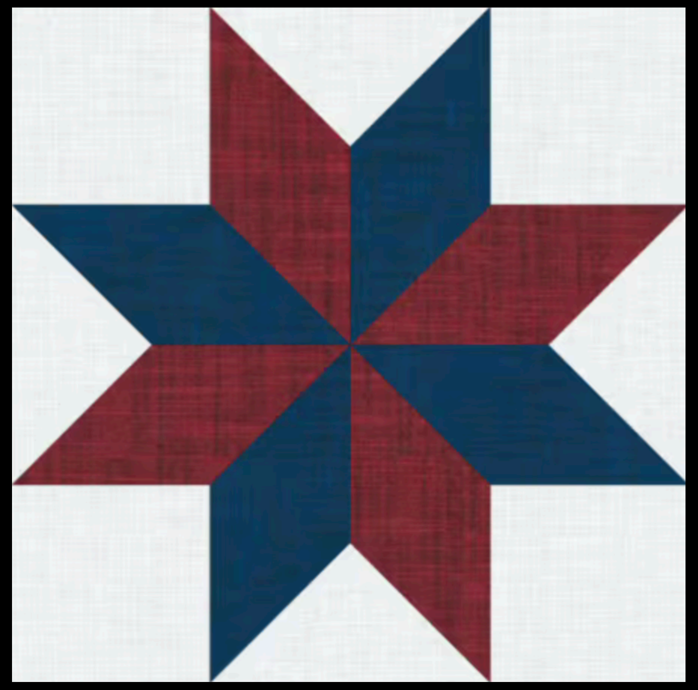
Astronomical Quilt #1, multiple makers, ca. 2014. Astronomical Quilts! Block Challenge Collection, 2016-316-01. Gift of Karoline Patterson Bresenhan and Nancy O’Bryant Puentes

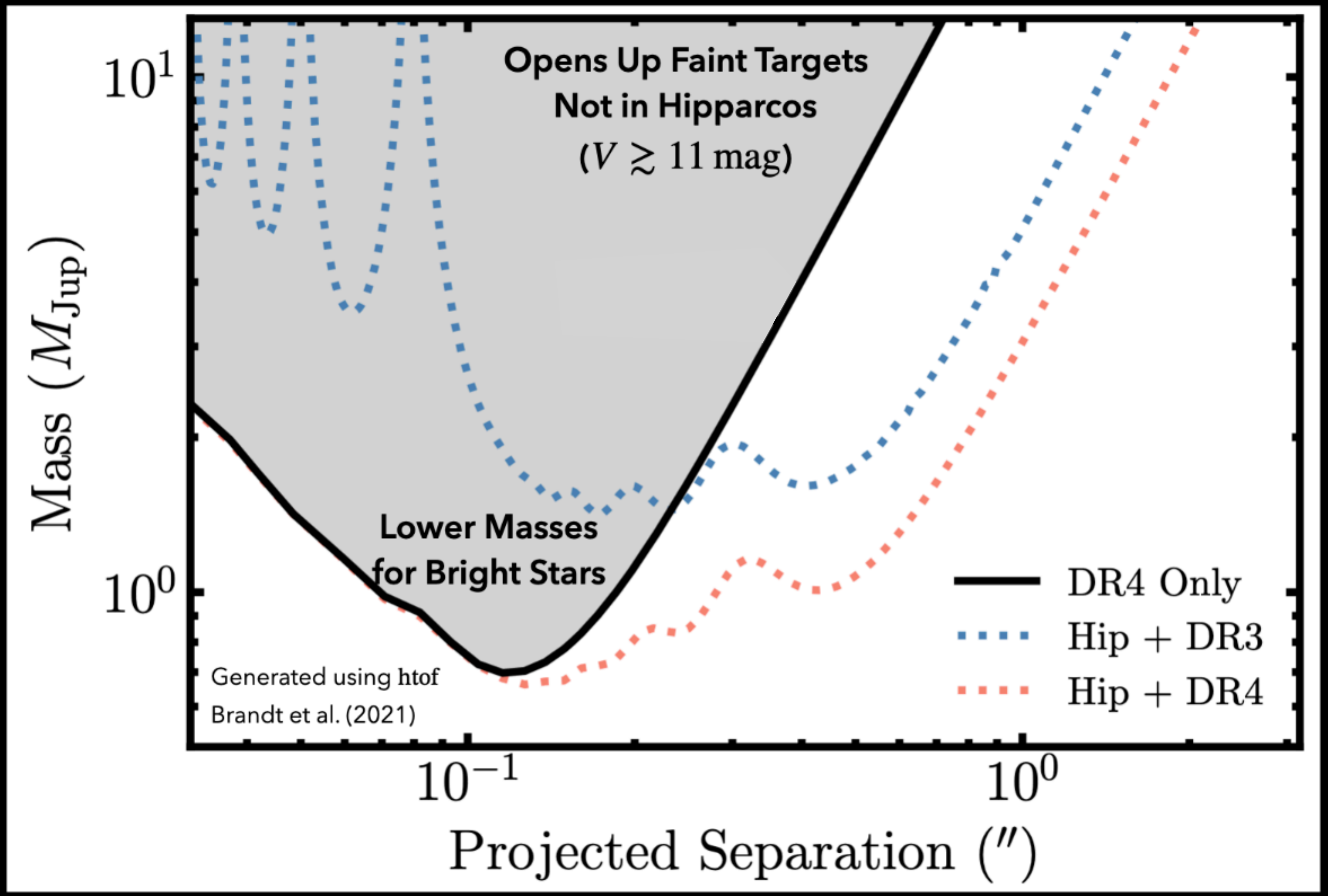

Gaia
DR5
2030?
DR4
2026
DR3
2022

Demographics with Gaia DR4 (astrometry)

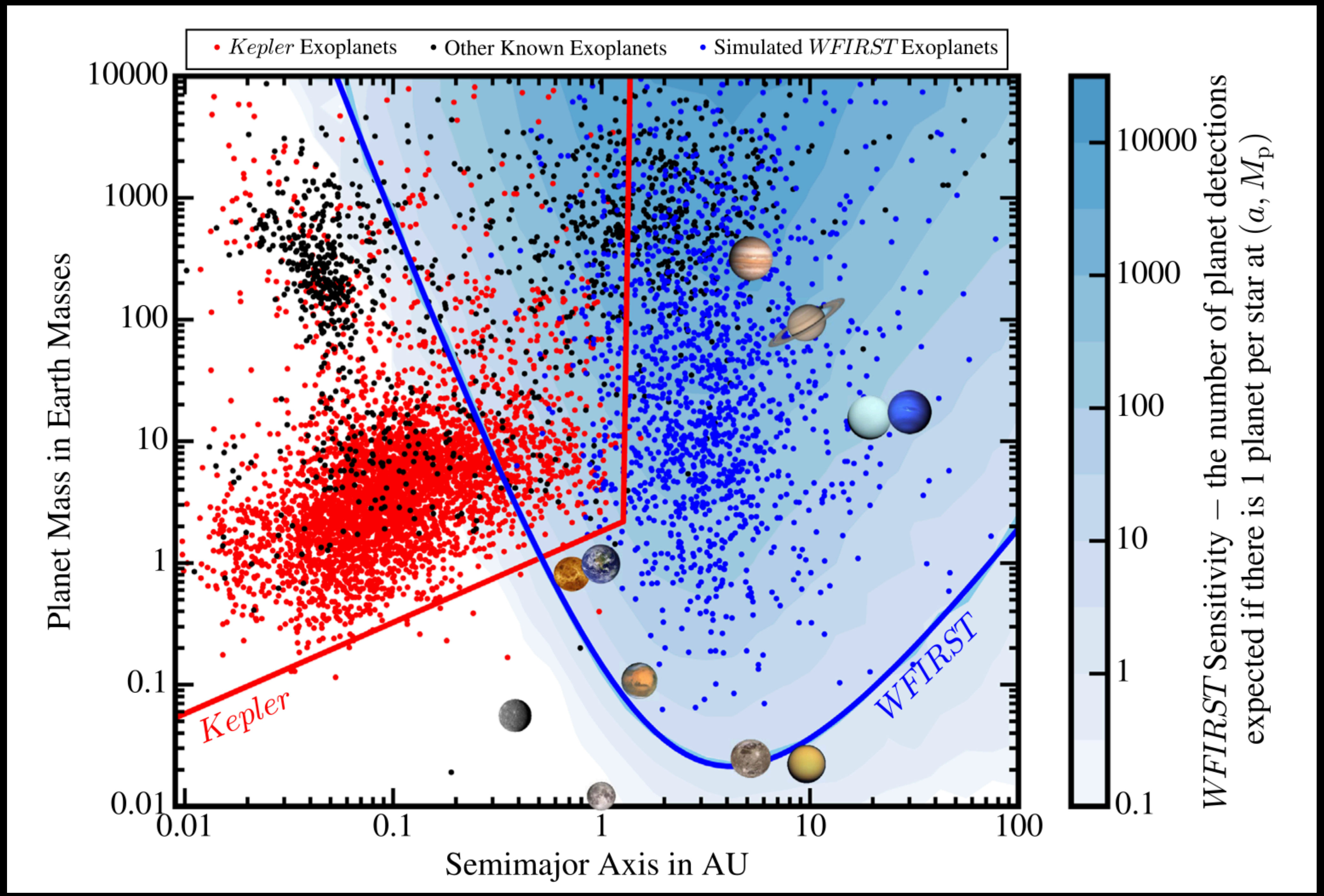


Demographics with Roman (microlensing)





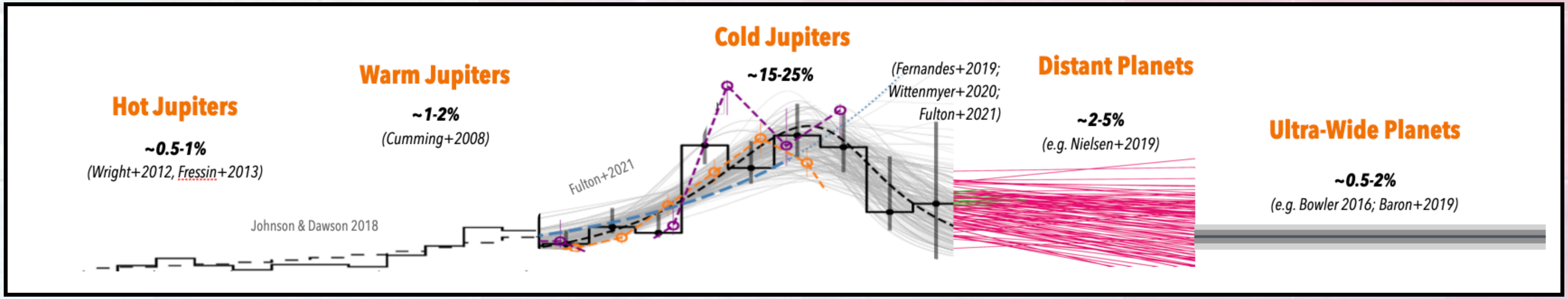
Courtesy Kyle Franson



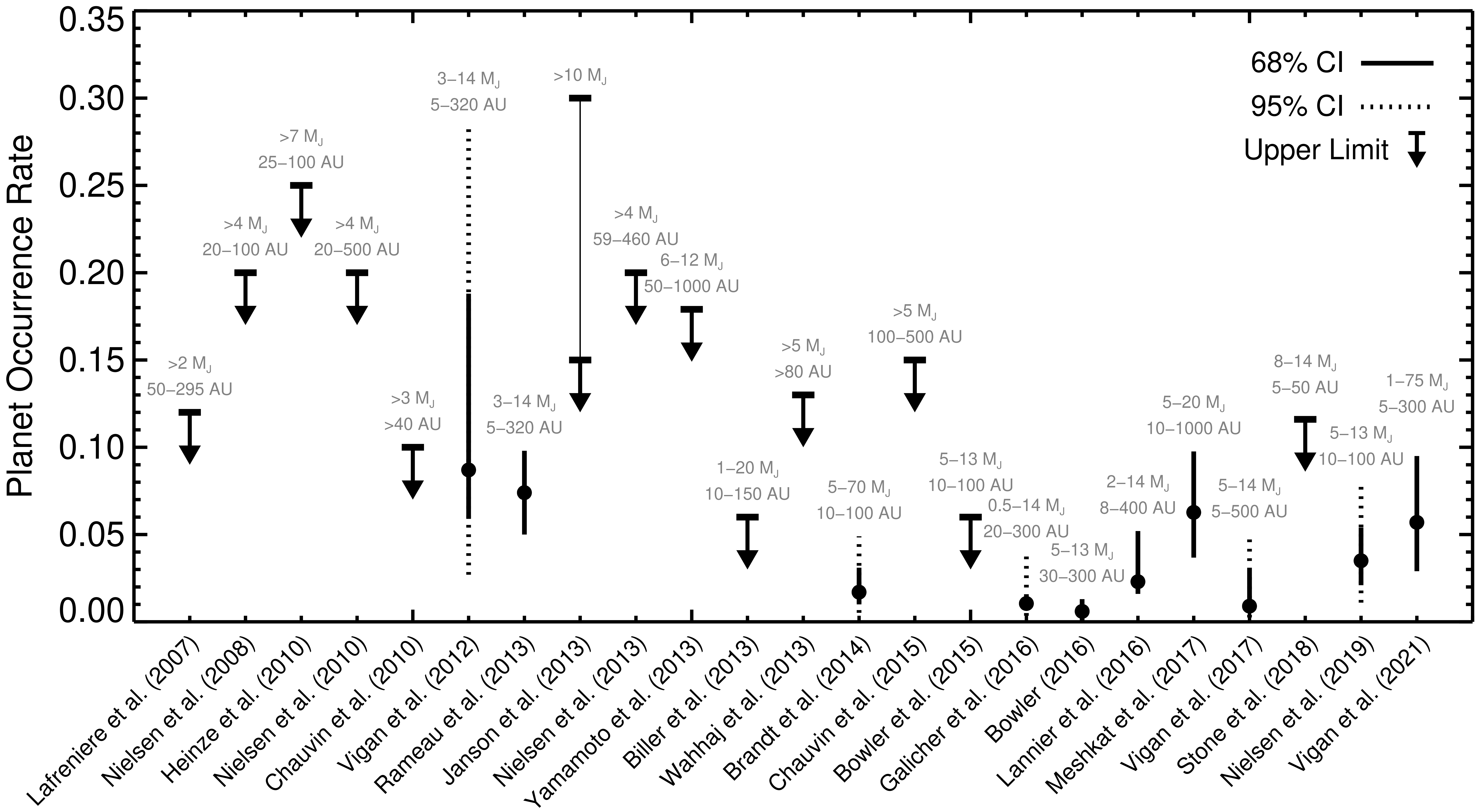
Penny et al. 2019

Takeaway points

- Demographics is currently a patchwork of largely distinct stellar and planetary parameters



- The prevalence of Hot and Warm Jupiters strongly correlates with stellar metallicity and mass
- Multiple surveys have found a general peak in the giant planet radial distribution at ~3-10 AU
- Signs that brown dwarfs are distinct populations
- Most giant planets are dynamically excited
- Support surveys! These are what enable statistics and inform how, when, and where planets form and migrate.



Planet Occurrence Rate
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
68% CI
95% CI
Upper Limit
>2 M_J 50–295 AU
>4 M_J 20–100 AU
>7 M_J 25–100 AU
>4 M_J 20–500 AU
>3 M_J >40 AU
3–14 M_J 5–320 AU
3–14 M_J 5–320 AU
>10 M_J
>4 M_J 59–460 AU
6–12 M_J 50–1000 AU
1–20 M_J 10–150 AU
>5 M_J >80 AU
5–70 M_J 10–100 AU
>5 M_J 100–500 AU
5–13 M_J 10–100 AU
0.5–14 M_J 20–300 AU
5–13 M_J 30–300 AU
2–14 M_J 8–400 AU
5–20 M_J 10–1000 AU
5–14 M_J 5–500 AU
8–14 M_J 5–50 AU
5–13 M_J 10–100 AU
1–75 M_J 5–300 AU
Lafreniere et al. (2007)
Nielsen et al. (2008)
Heinze et al. (2010)
Nielsen et al. (2010)
Chauvin et al. (2010)
Vigan et al. (2012)
Rameau et al. (2013)
Janson et al. (2013)
Nielsen et al. (2013)
Yamamoto et al. (2013)
Biller et al. (2013)
Wahhaj et al. (2013)
Brandt et al. (2014)
Chauvin et al. (2015)
Bowler et al. (2015)
Galicher et al. (2016)
Bowler (2016)
Lannier et al. (2016)
Meshkat et al. (2017)
Vigan et al. (2017)
Stone et al. (2018)
Nielsen et al. (2019)
Vigan et al. (2021)

Planets can migrate large distances on a range of timescales after they form

Disk migration
($\tau \lesssim 10^7$ yr)

Planet-planet scattering
($\tau \sim 10^{7\text{-}9}$ yr)

Kozai-Lidov high-e migration
($\tau \sim 10^{7\text{-}9}$ yr)