

Orbital Architectures and Dynamics of Giant Planets

Occurrence rates, trends, and orbits in single star systems

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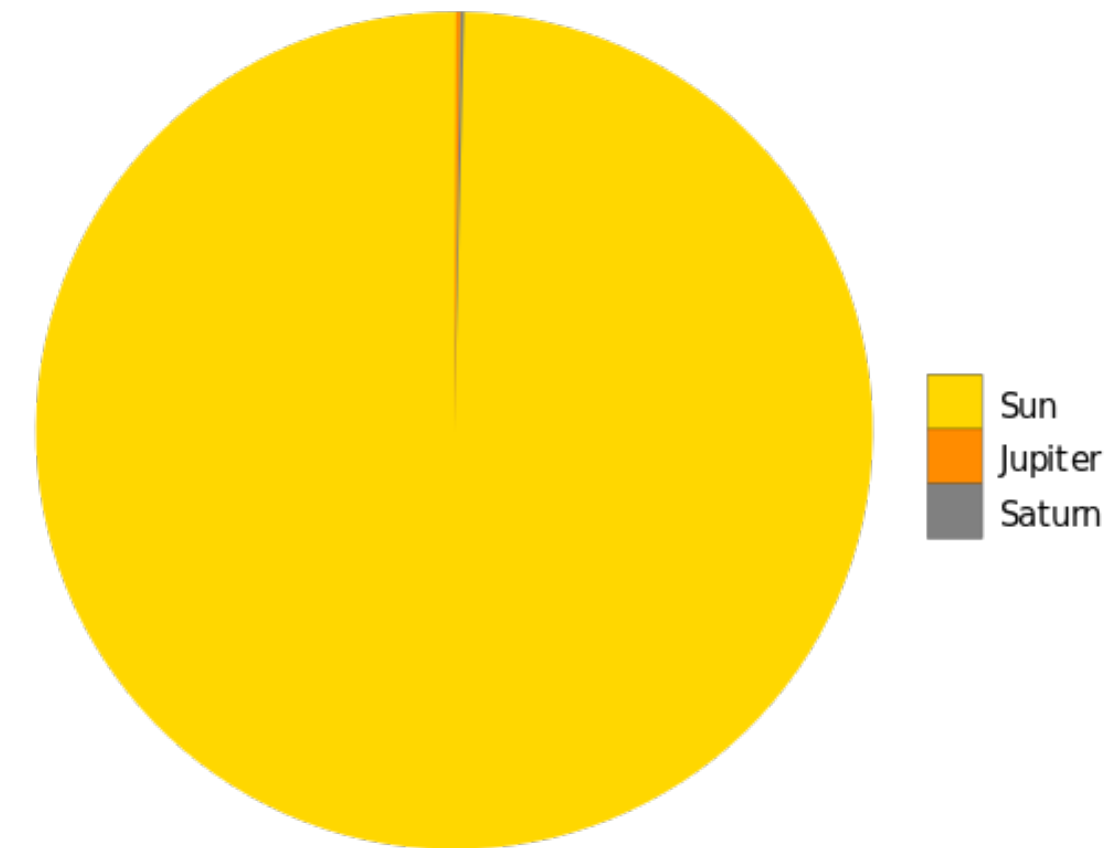
51 Pegasi b: Cool Giant Planets and their Systems — Oct 7, 2025

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

Giant planets dominate (nearly) everything in planetary systems

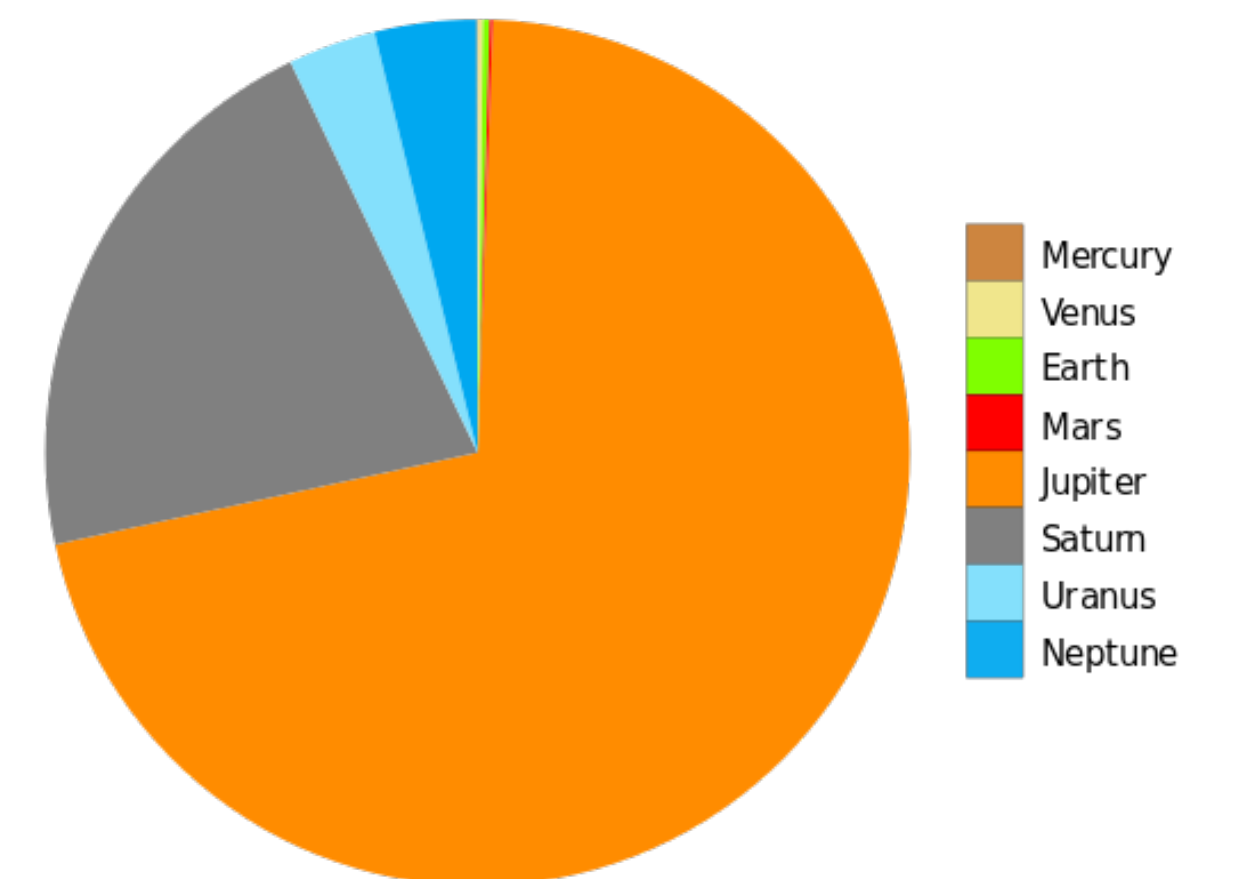
- **Mass budget**

Mass in the solar system



Jupiter + Saturn: **~0.1%**

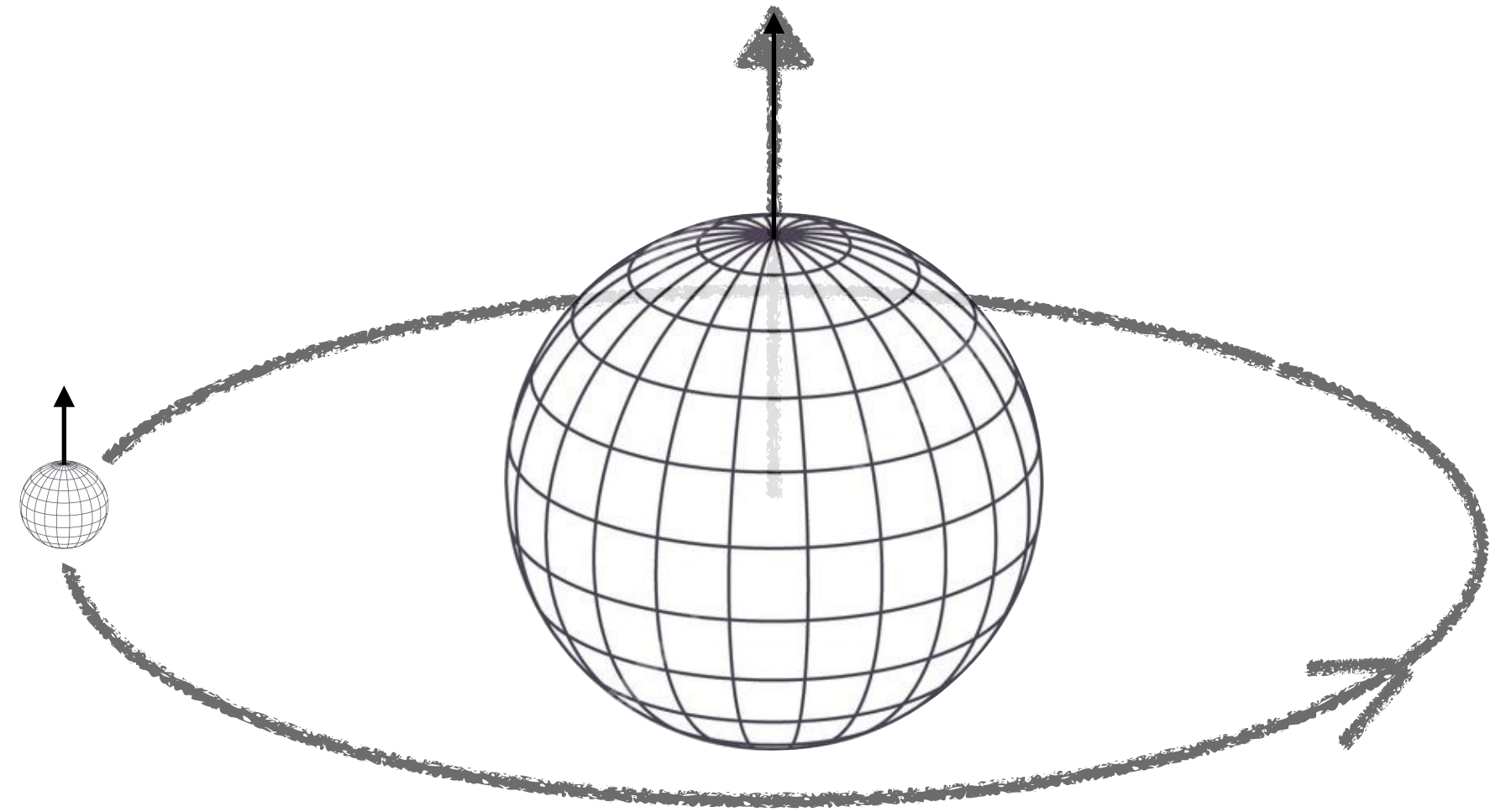
Mass of planets



~92%

Giant planets dominate (nearly) everything in planetary systems

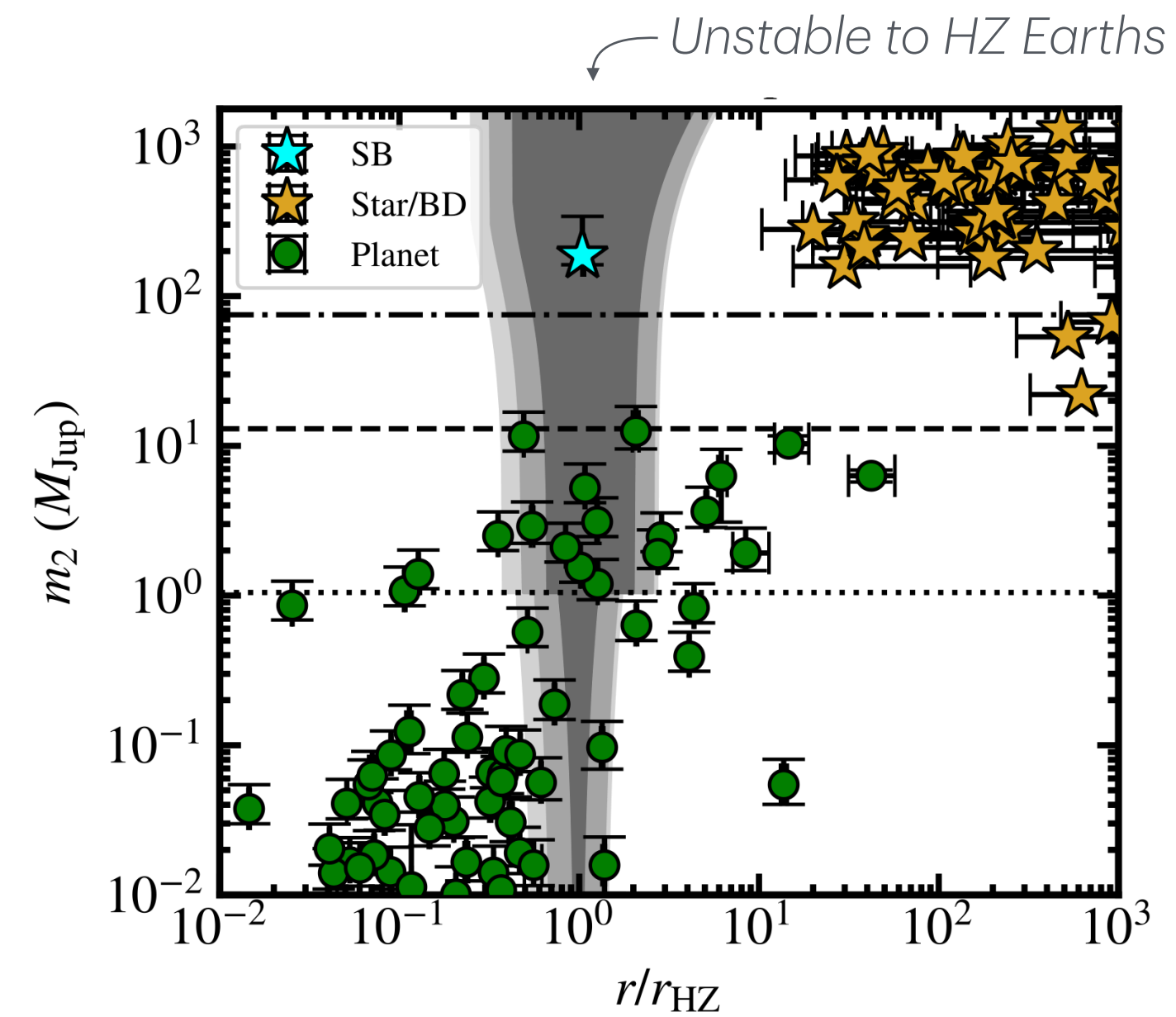
- Mass budget
- **Angular Momentum Budget**



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

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

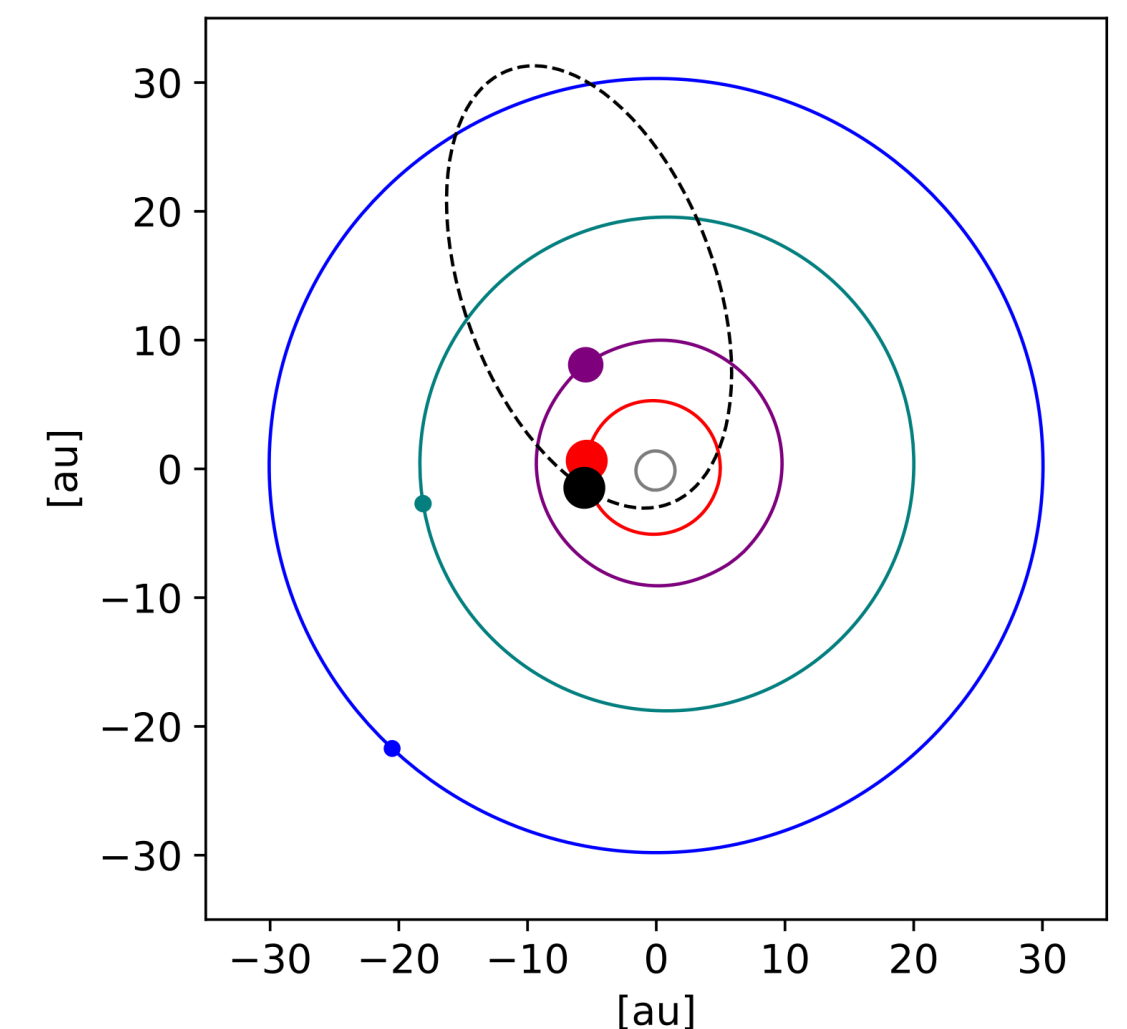
Painter et al. 2025

Eccentricities

HR 5183 b, a highly eccentric ($e=0.84$)

“wrecking ball”

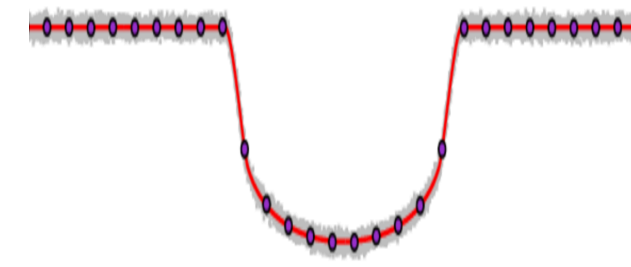
Blunt et al. 2019



Giant planets dominate (nearly) everything in planetary systems

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

transit depth



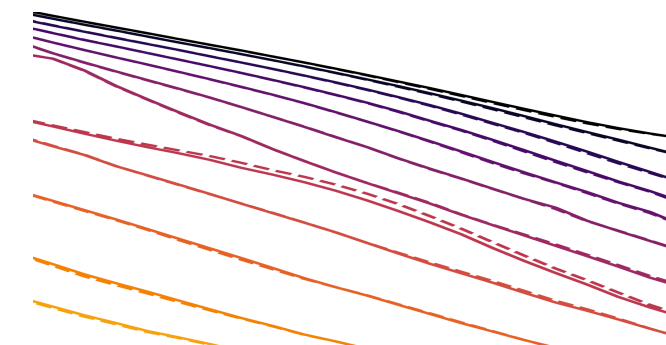
$$\delta \propto R_p^2$$

RV semi-amplitude



$$K \propto m_p$$

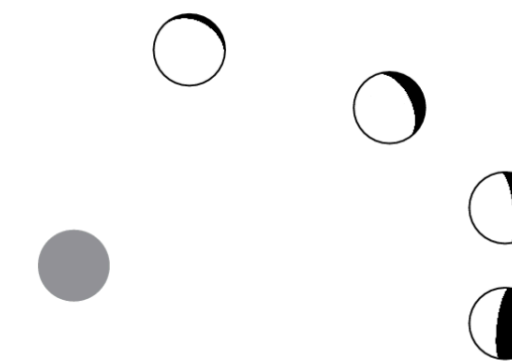
bolometric luminosity



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

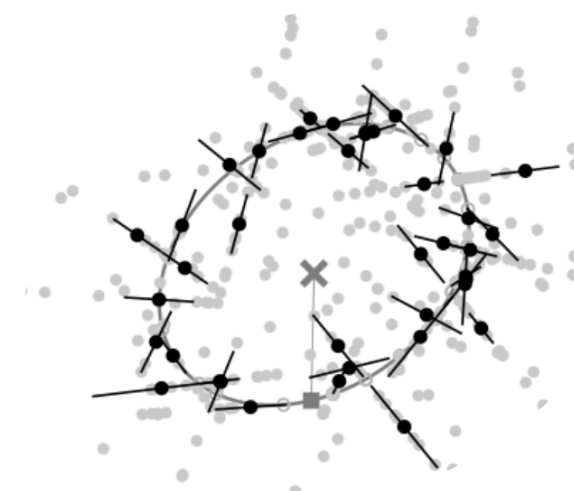
star-planet contrast

(reflected and thermal)



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

astrometric reflex amplitude

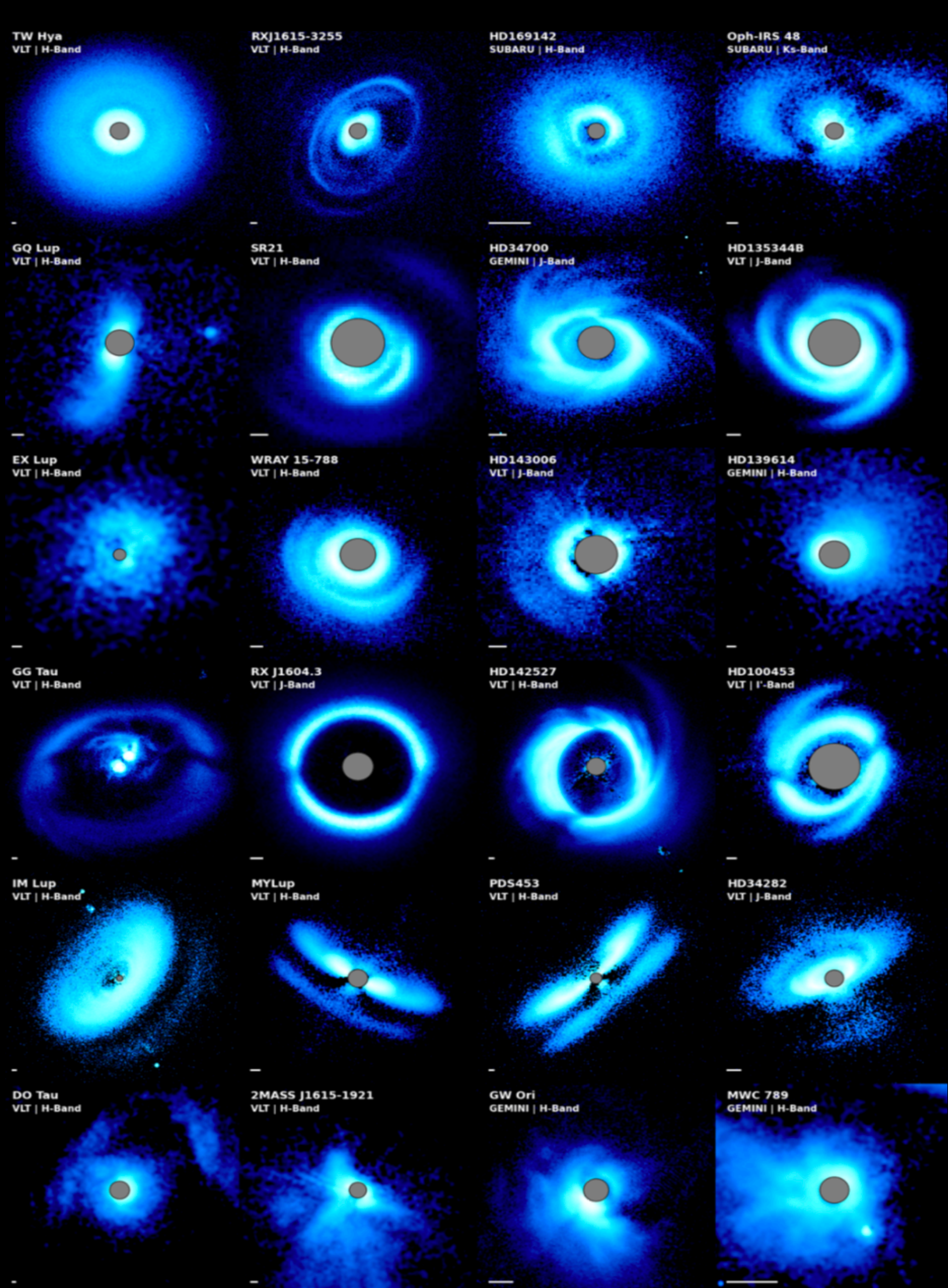


$$\theta \propto m_p$$

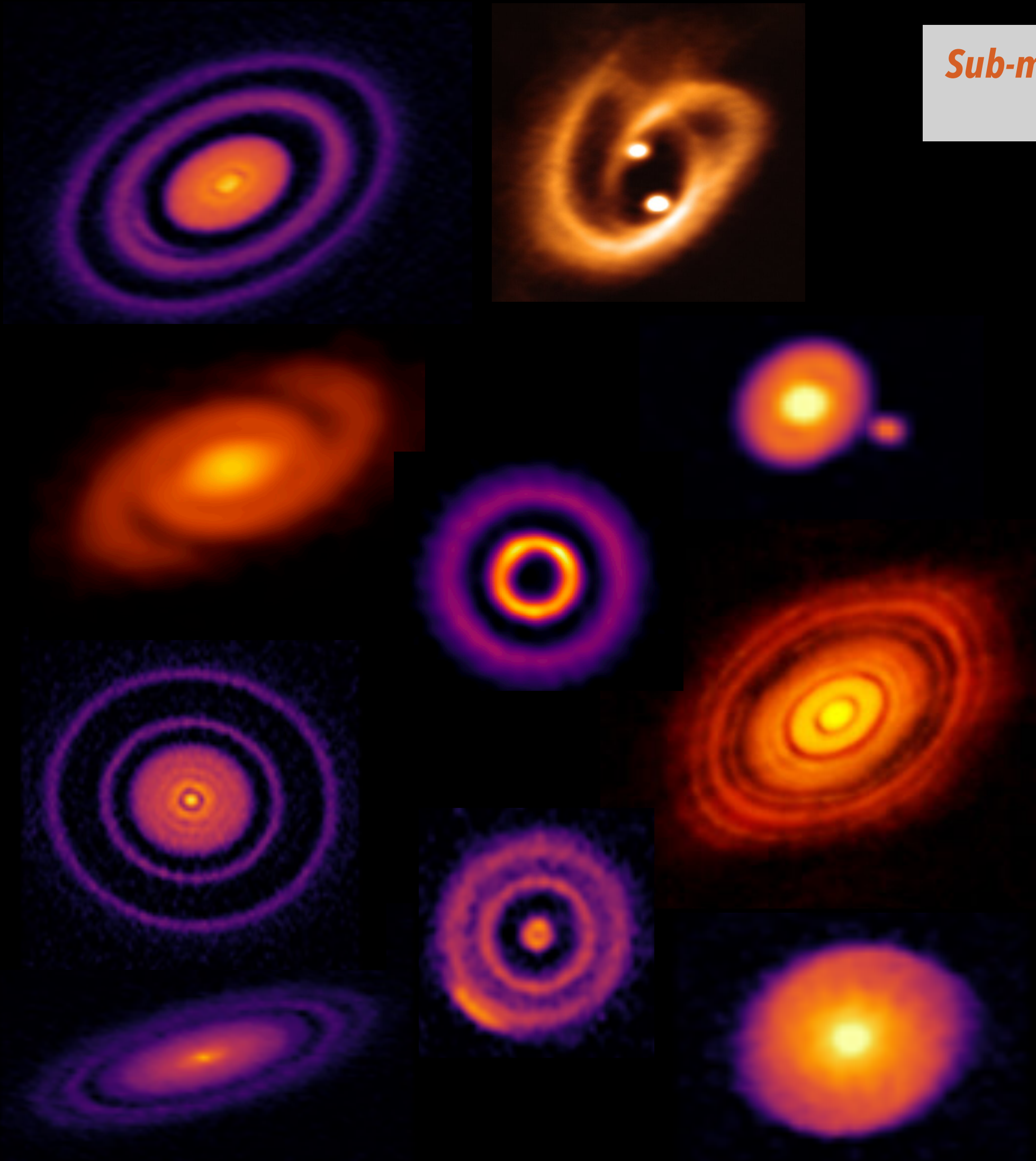
Protoplanetary disks are remarkably diverse

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

NIR scattered light
(e.g., GPI, SPHERE)



Sub-mm continuum
(ALMA)



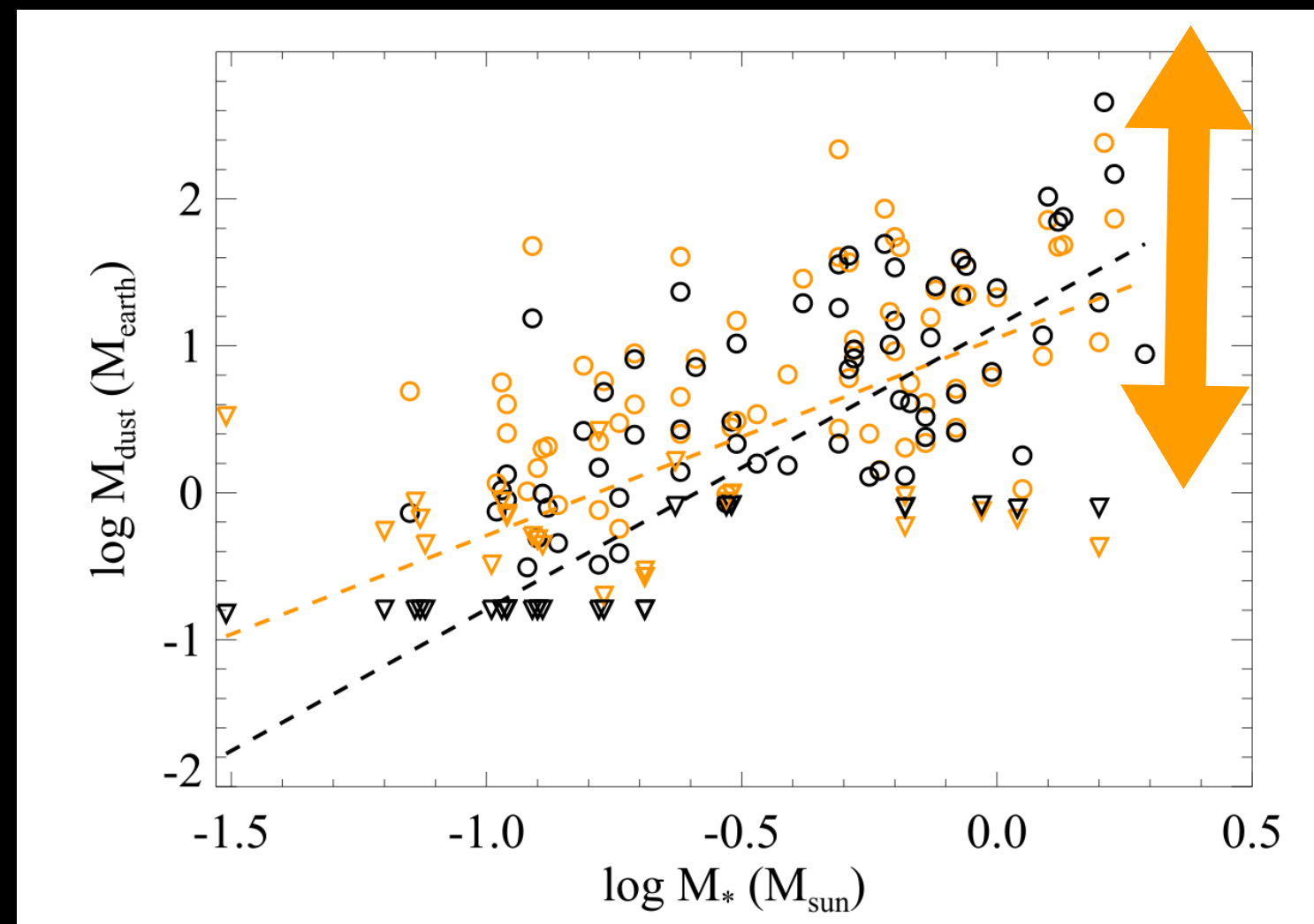
Benisty et al. 2023

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 correlates with host mass

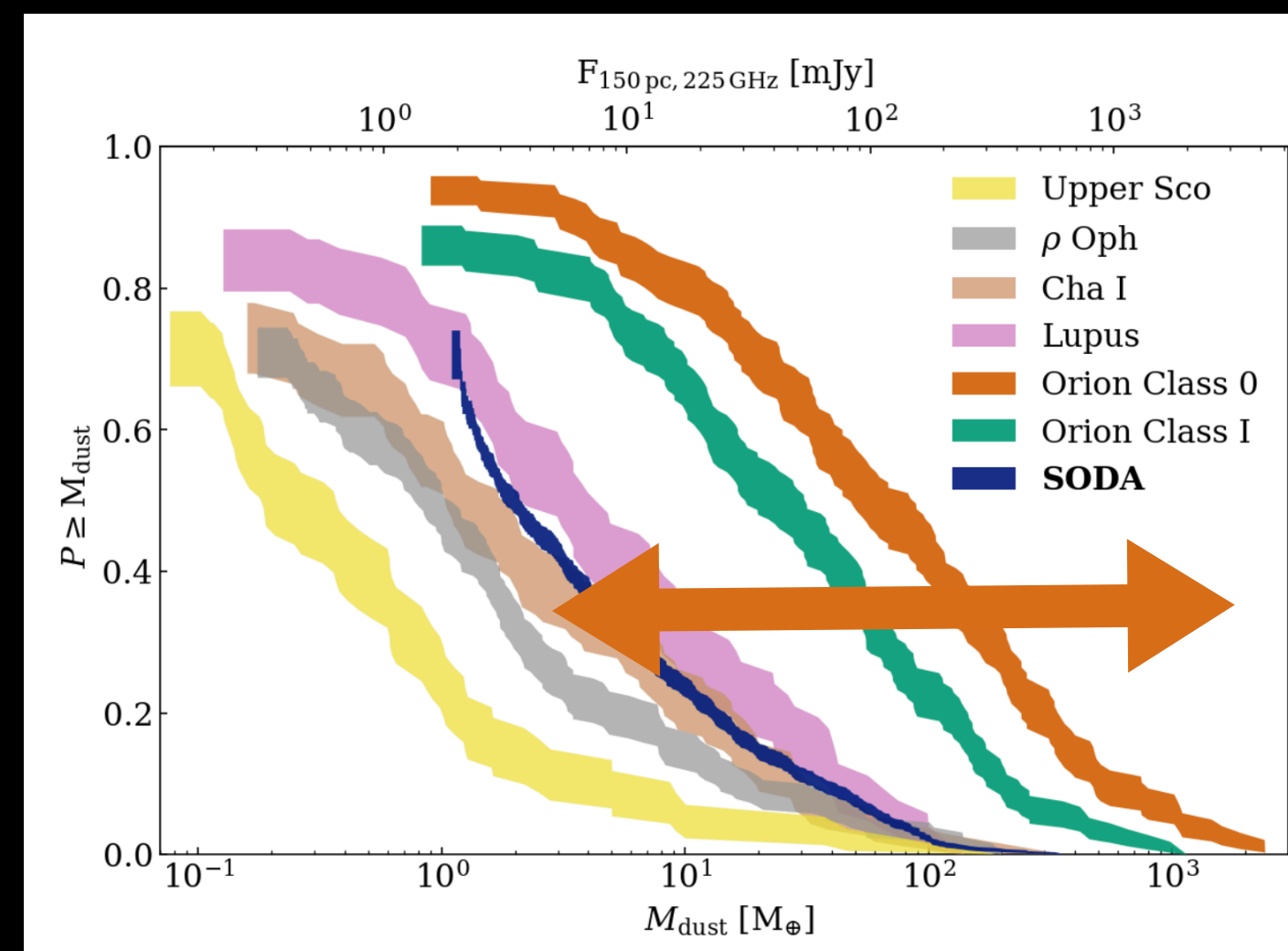


Pascucci et al. 2016

See also Andrews et al. 2013

>2 orders of magnitude for a given mass

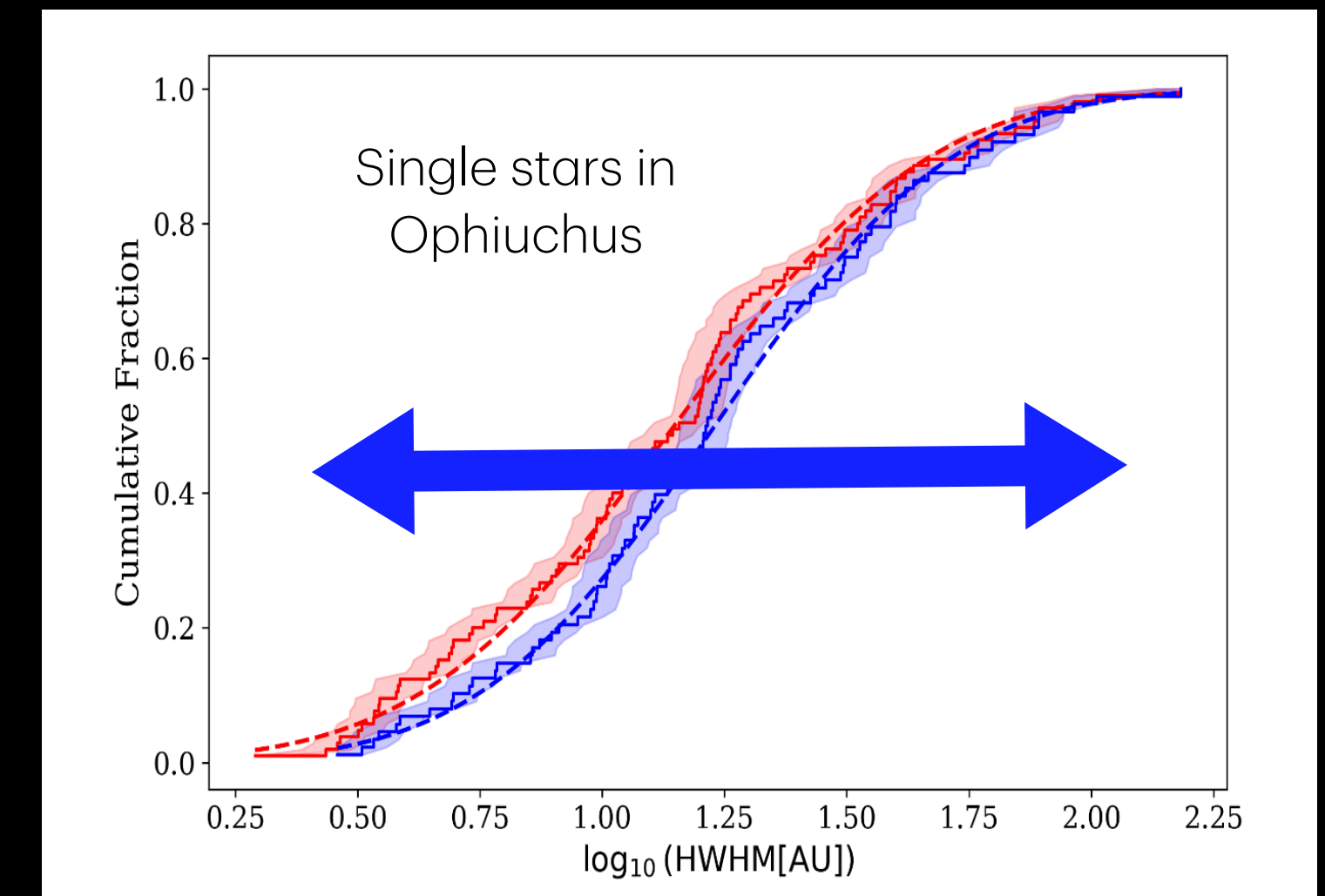
Large dynamic range for a given age



van Terwisga et al. 2022

>2 orders of magnitude for a given age
Spread is preserved over time

Wide range of disk sizes

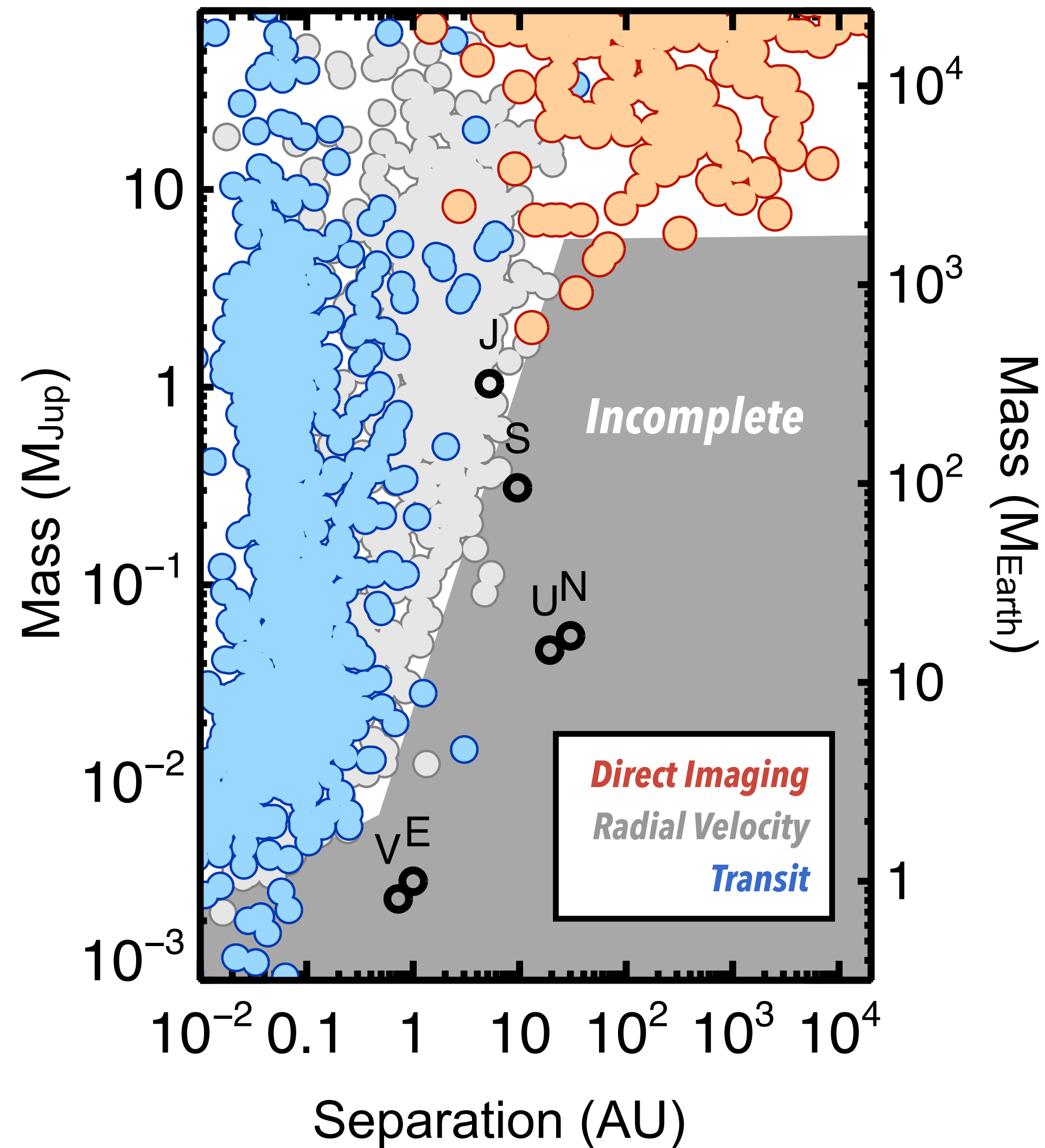


Dasgupta et al. 2025

2 orders of magnitude in sizes of dust disks

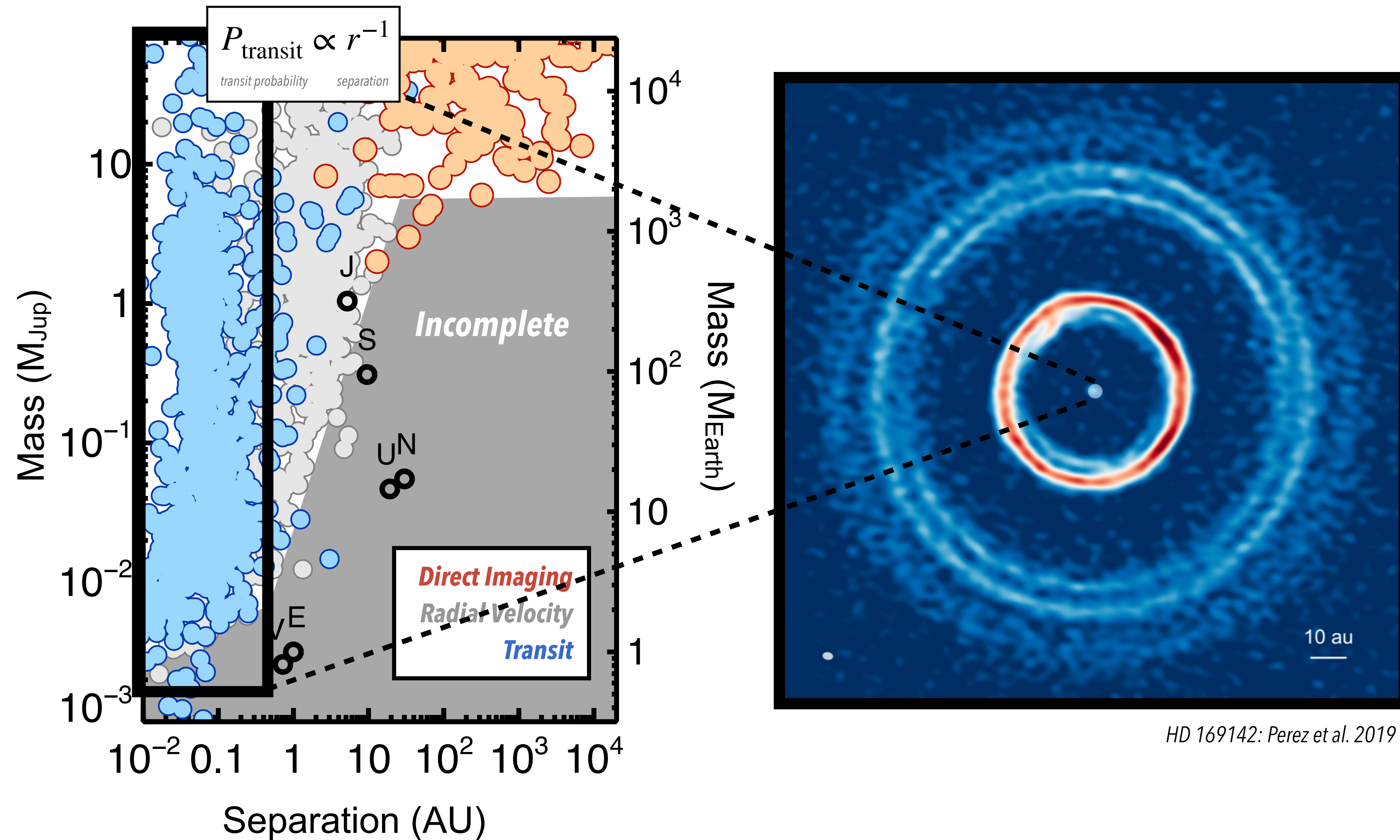
Planetary systems inherit this diversity

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



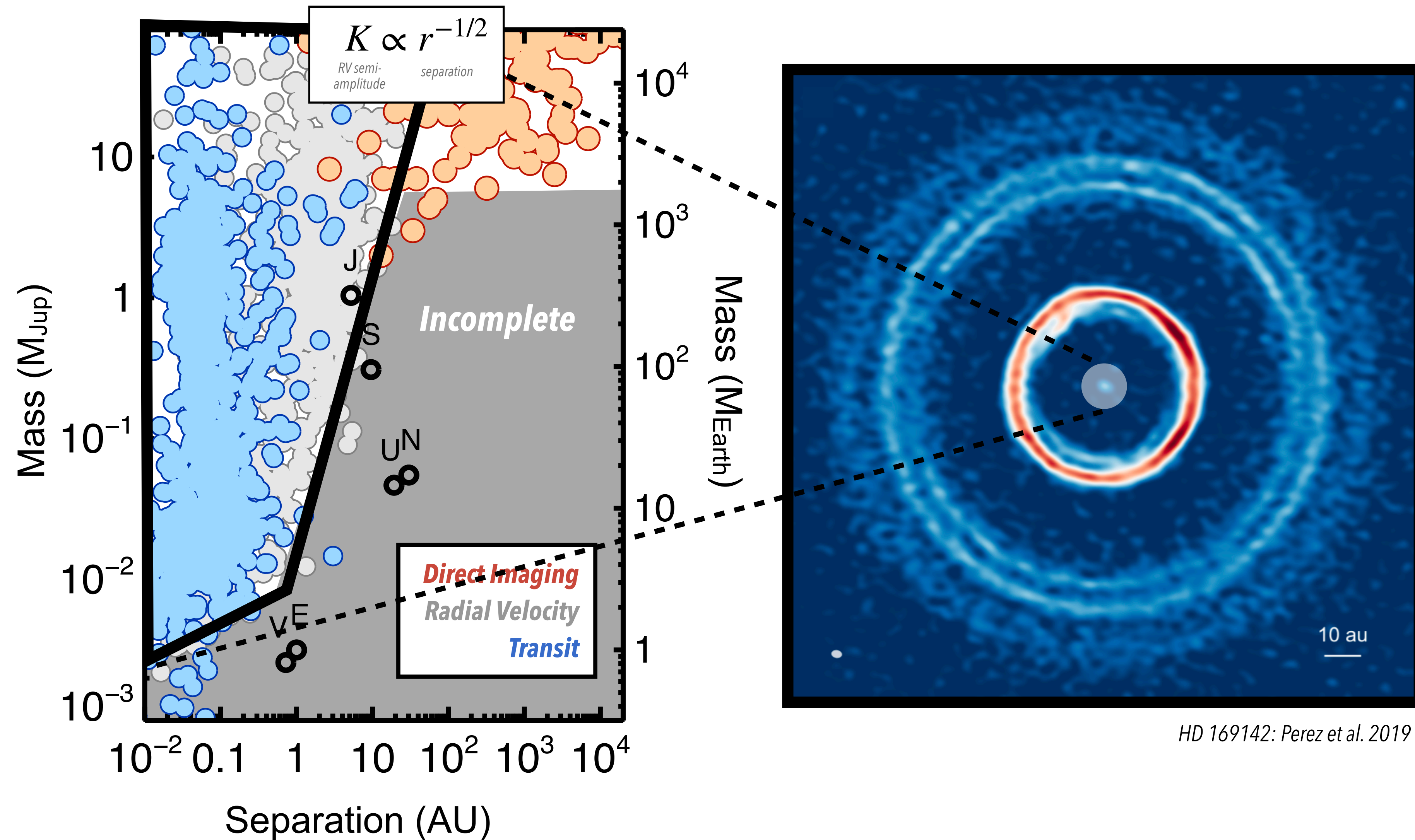
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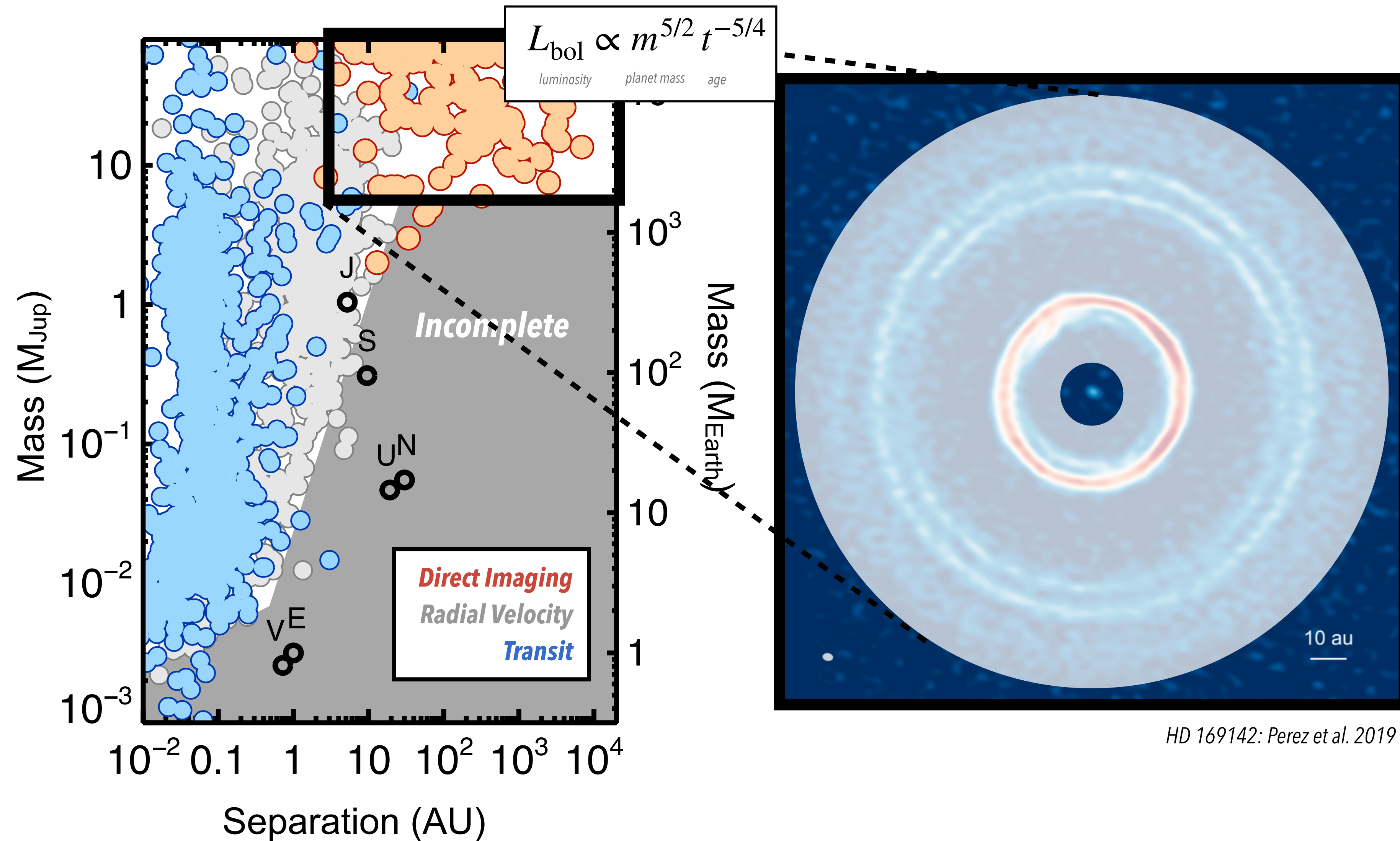
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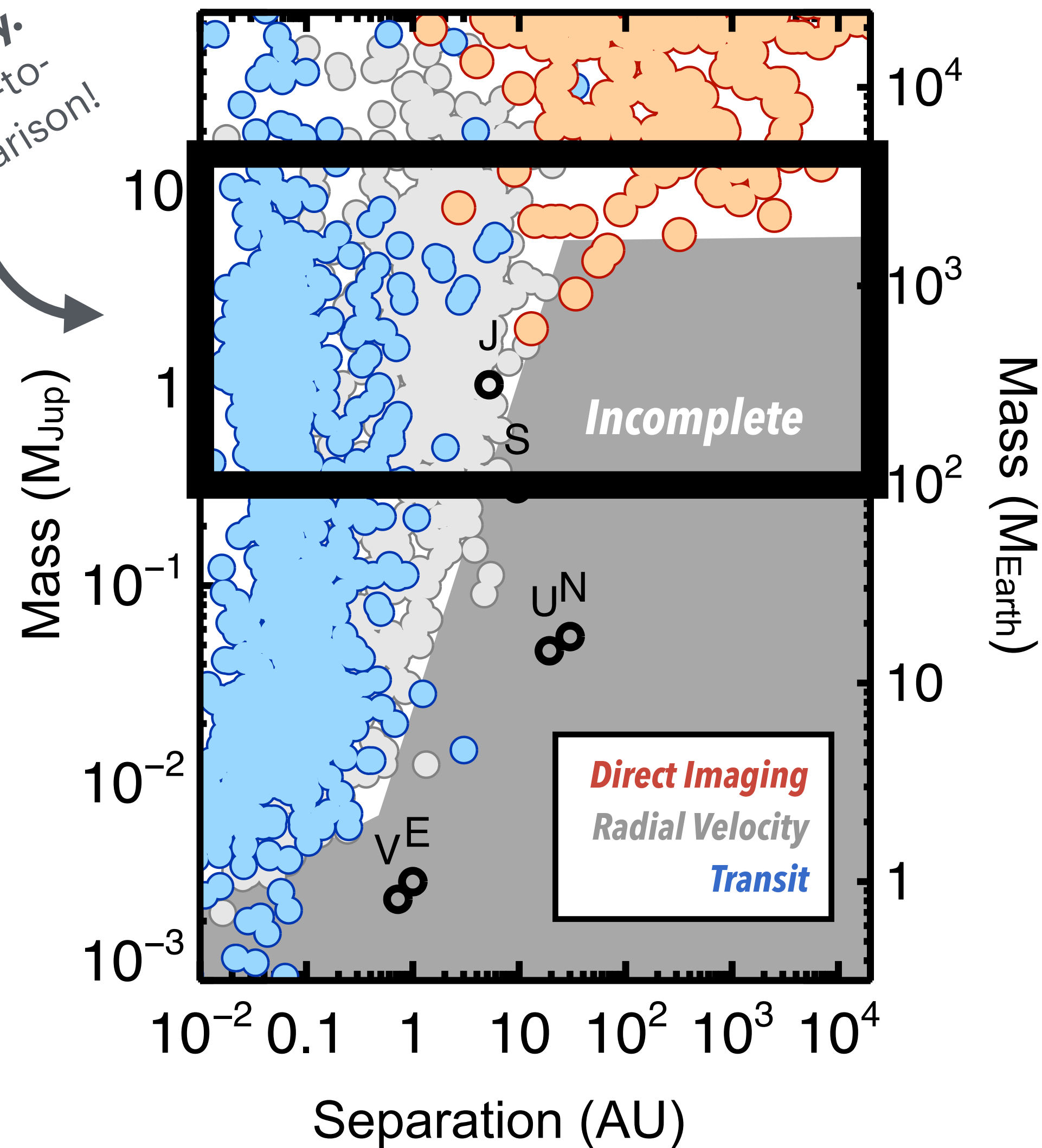
Only giant planets can currently be studied across the entire scale of protoplanetary disk sizes



Planetary systems inherit this diversity

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

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



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

Inferring planetary system architectures is like a patchwork quilt

Transits



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

Planet size

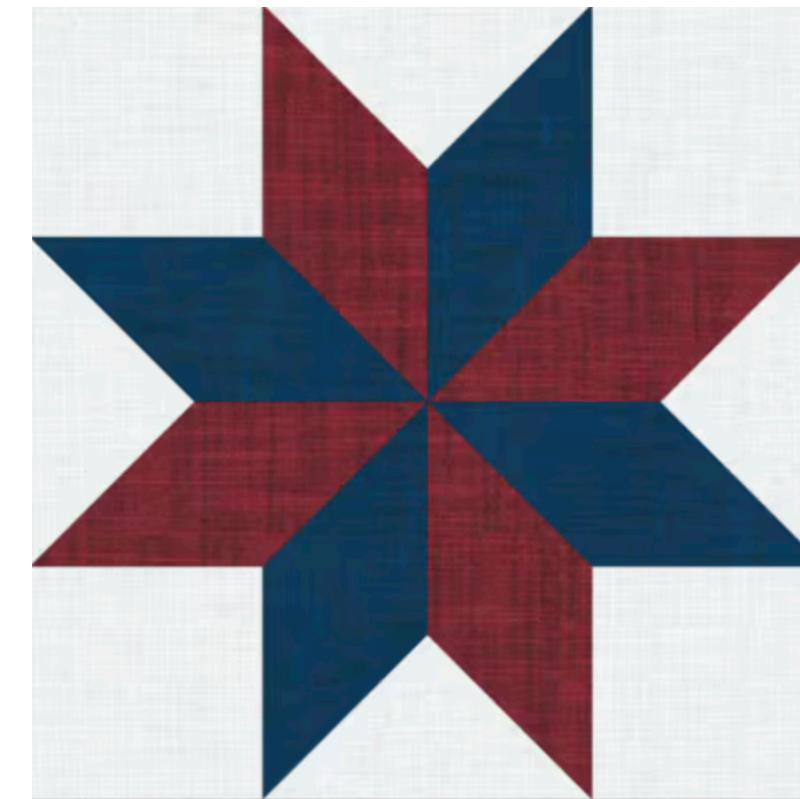
RVs



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

Planet minimum mass

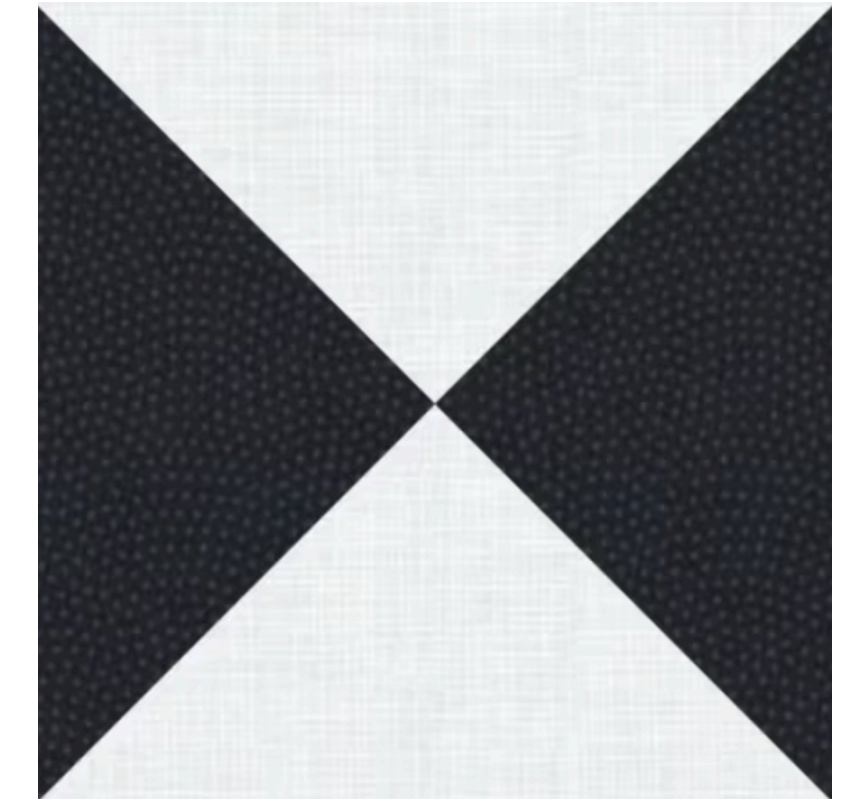
Microlensing



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

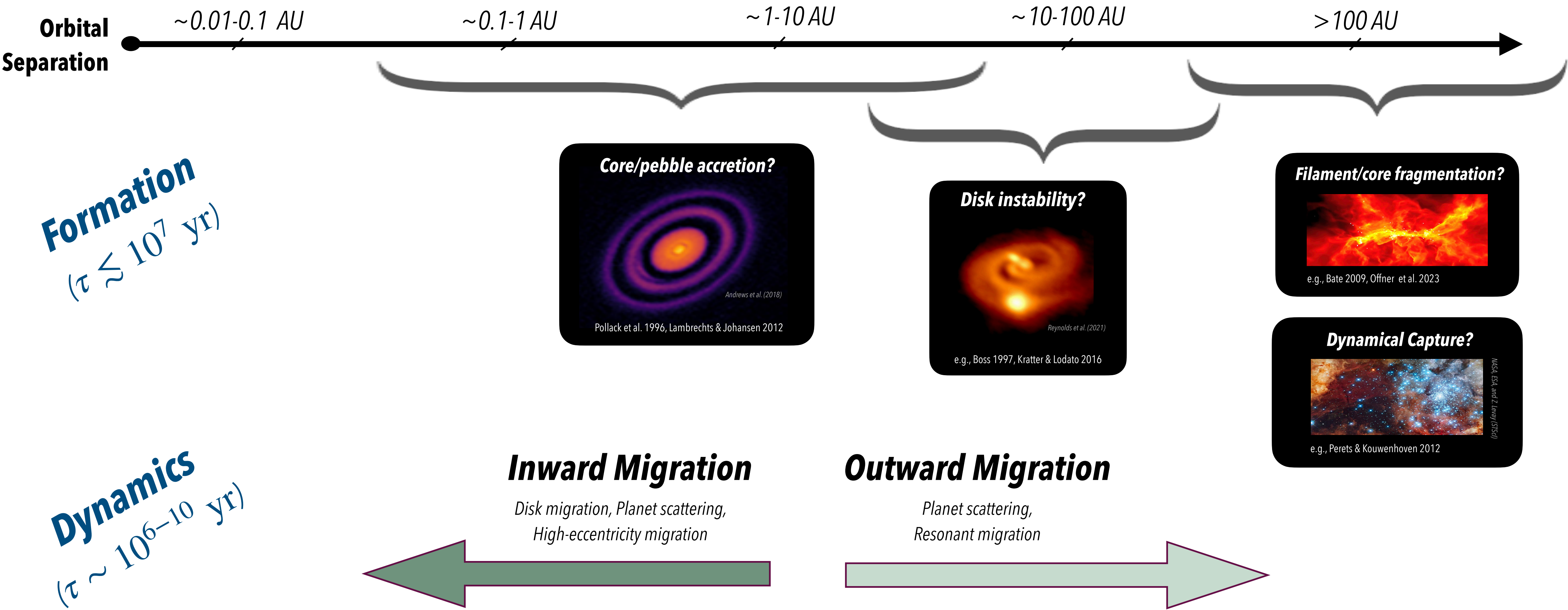
Why does this matter?

Each approach ignores potentially important effects like age, host mass, stellar multiplicity, metallicity, and birth environment

*in thermal emission

Imprints of planet formation and migration across space and time

Demographics gives clues about how planetary systems form and evolve

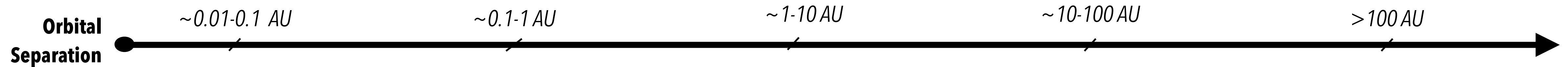


How common are giant planets?

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

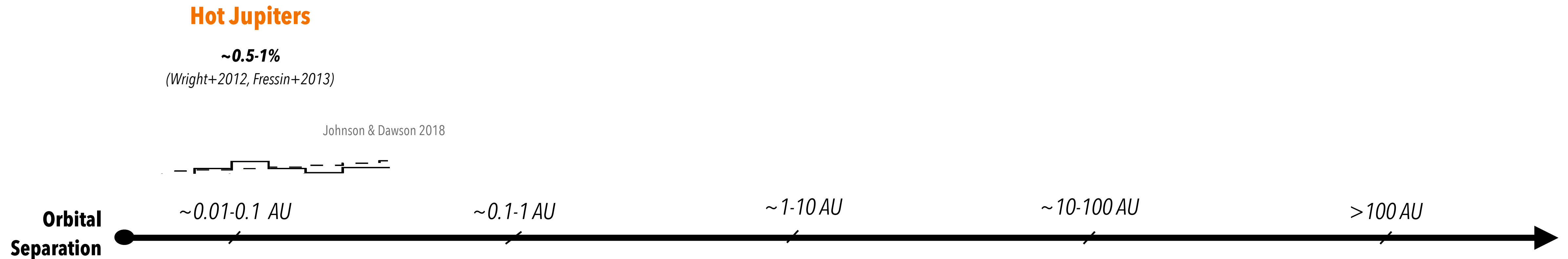
What are we marginalizing over?

M_* , $[\text{Fe}/\text{H}]$, m_p , t , binarity, evolutionary phase, etc . . .



How common are giant planets?

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Hot Jupiters (P = 1-10 d)

- **Occurrence rates differ slightly between **RV** and **transit** surveys**

- $1.2 \pm 0.4\%$ -> Wright et al. (2012) from RVs
- $0.9 \pm 0.4\%$ -> Mayor et al. (2011) from RVs
- $0.4 \pm 0.1\%$ -> Howard et al. (2012) from Kepler
- $0.6 \pm 0.1\%$ -> Petigura et al. (2018) from Kepler
- $1.0 \pm 0.4\%$ -> Beleznay & Kunitomo (2022), single stars from TESS

Reviews:

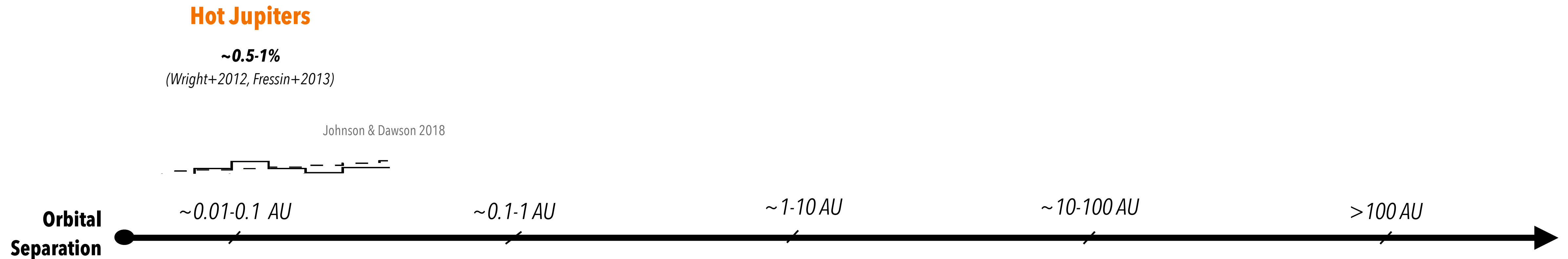
- **Dawson & Johnson 2018**
Origins of Hot Jupiters
- **Fortney, Dawson, & Komacek 2021**
Hot Jupiters: Origins, Structure, Atmospheres
- **Winn & Petigura 2024**
Planet Occurrence: Doppler and Transit Surveys

Metallicity differences? Multiplicity?

See Guo et al. 2017, Moe & Kratter 2021

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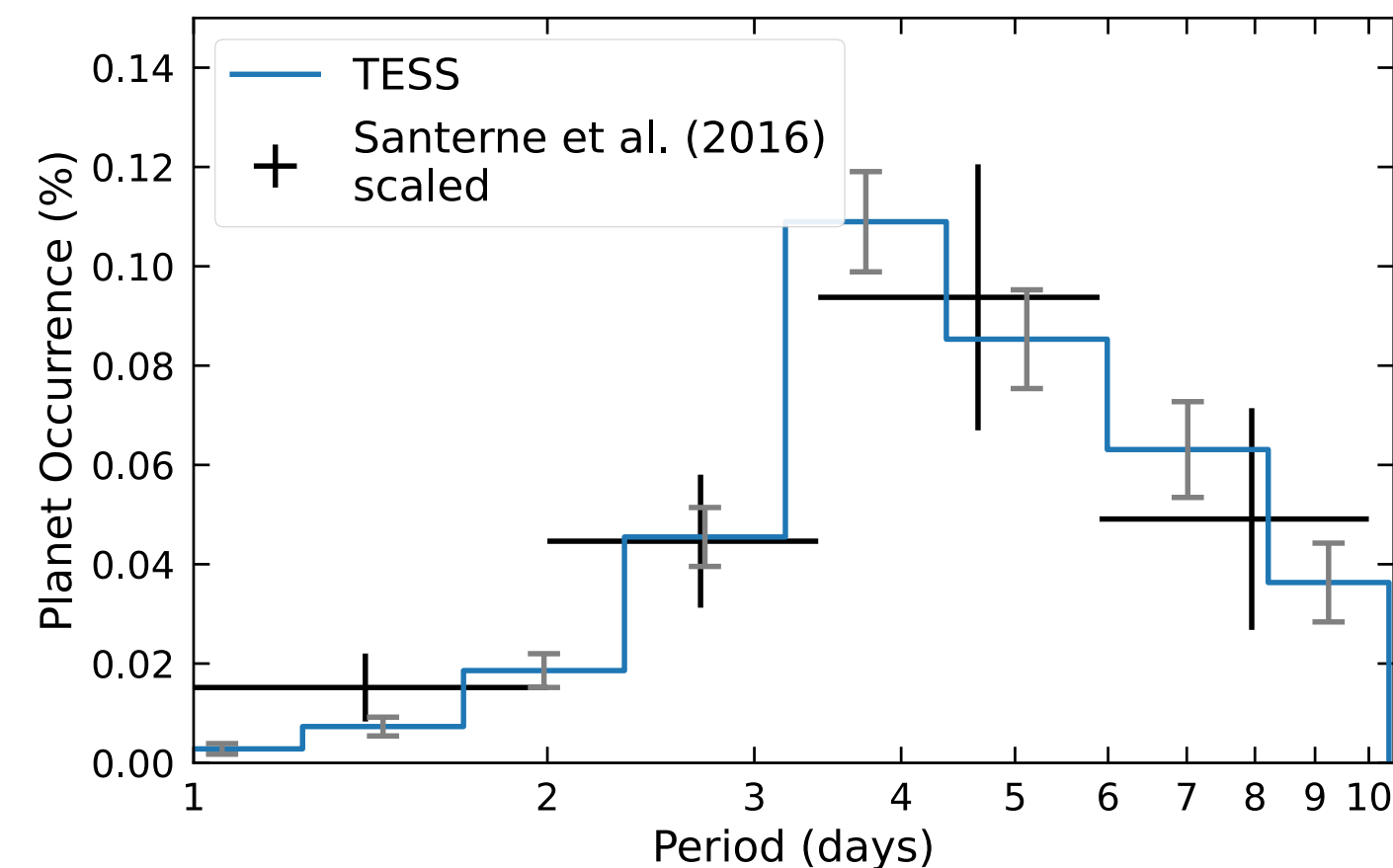
Hot Jupiters (P = 1-10 d)

• 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

Reviews:

- **Dawson & Johnson 2018**

Origins of Hot Jupiters

- **Fortney, Dawson, & Komacek 2021**

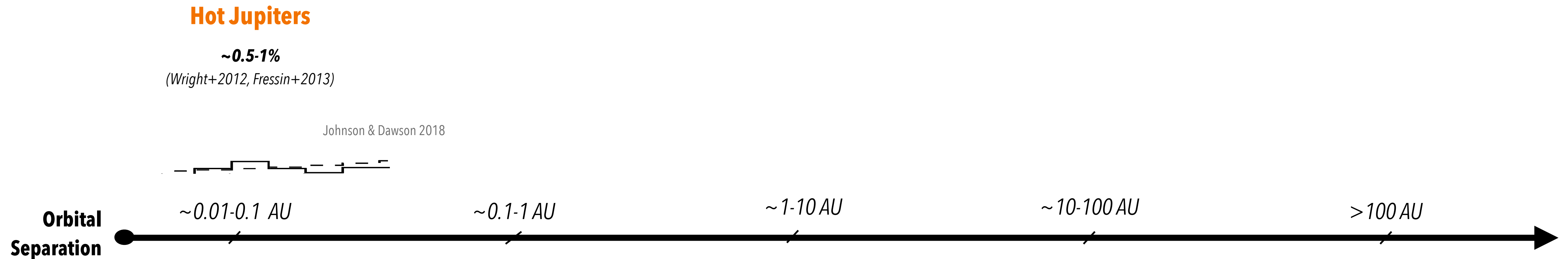
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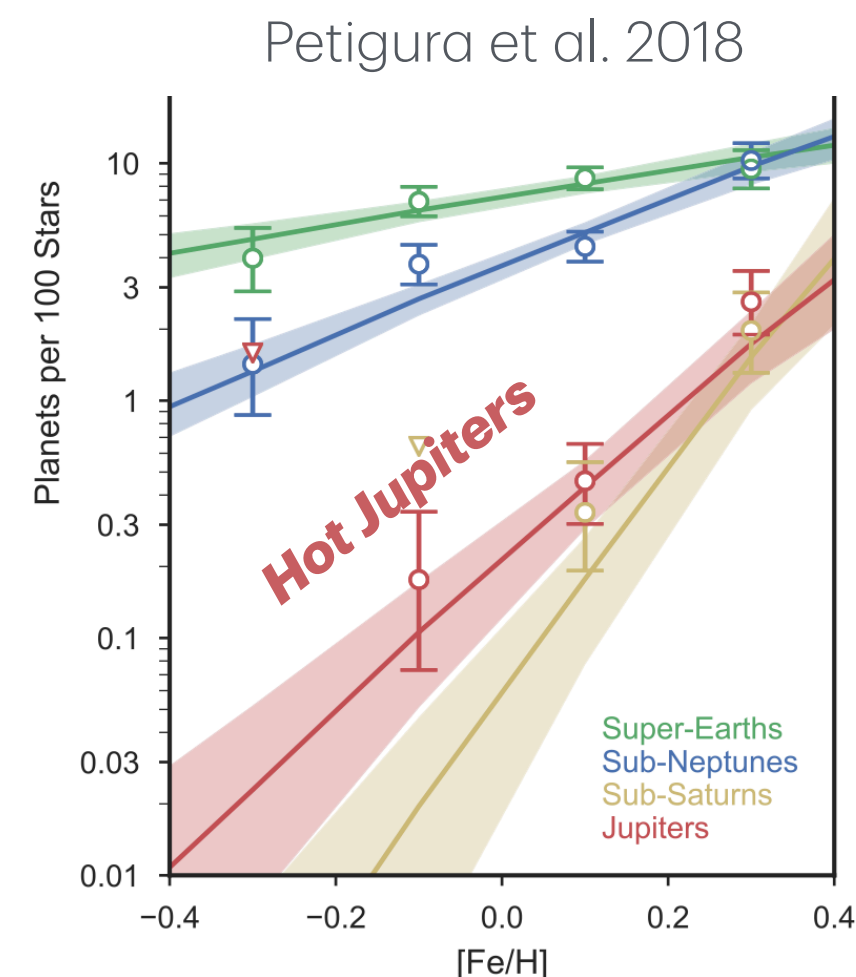
Hot Jupiters (P = 1-10 d)

• 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

⇒ A signature of planet-planet scattering?
More efficient inward migration?



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

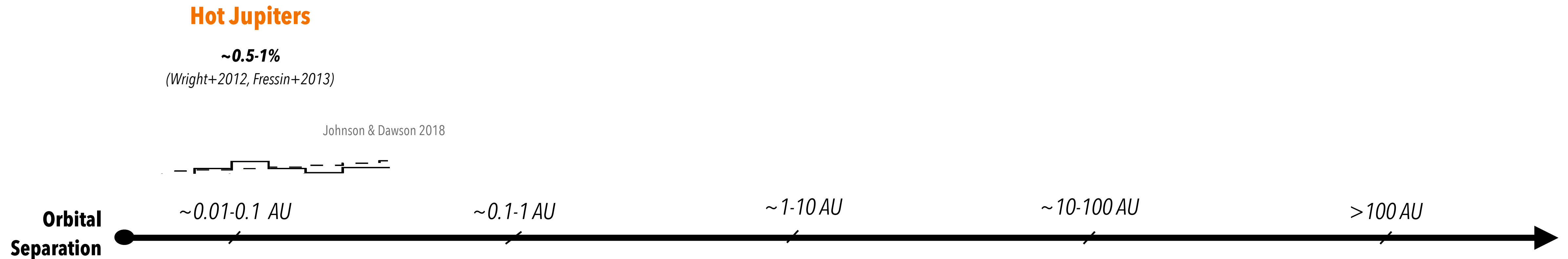
$$\beta = 3.4^{+0.9}_{-0.8}$$

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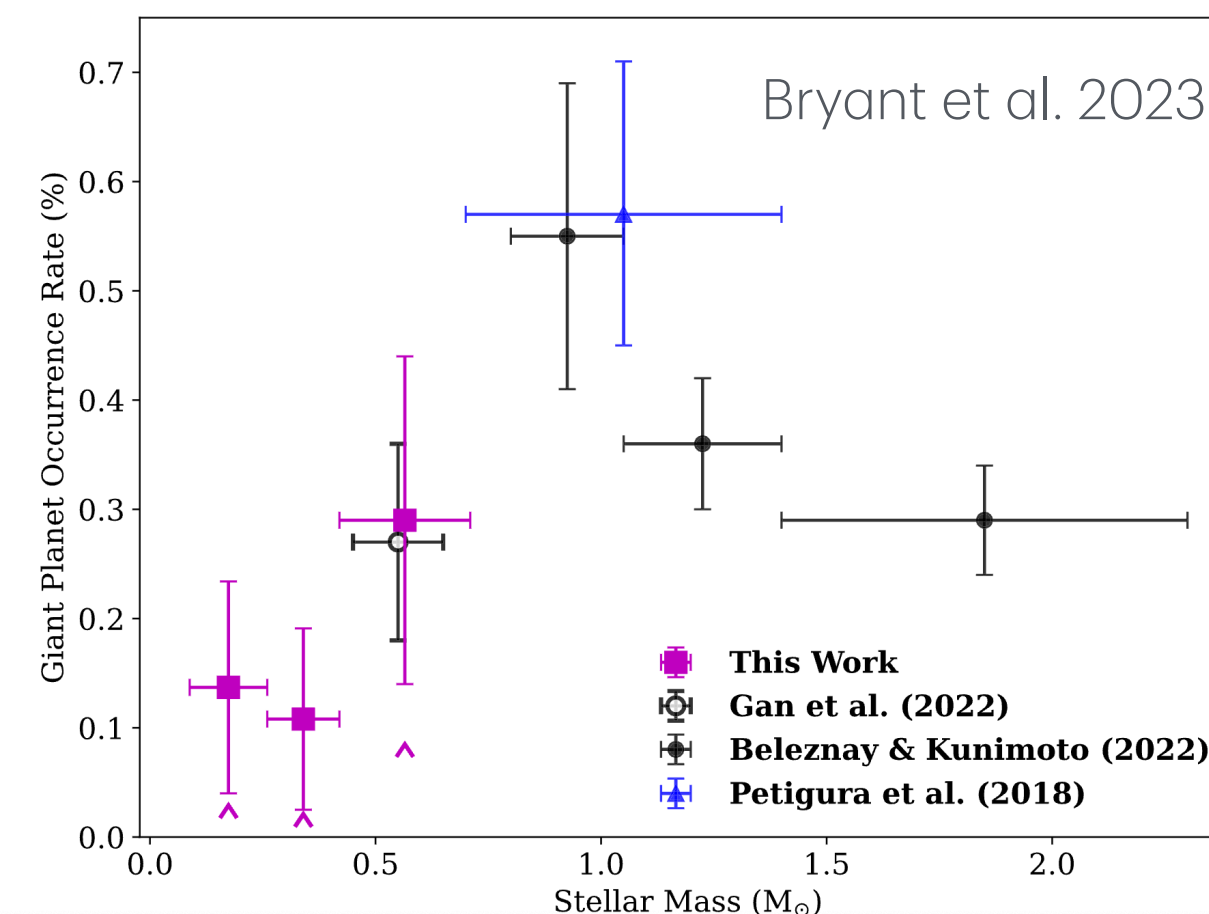


Hot Jupiters (P = 1-10 d)

• An optimal mass for creating hot Jupiters?

Occurrence rate rises with M_* , peaks near $1 M_\odot$.
Gan et al. 2022, Bryant et al. 2023

⇒ In line with predictions from core accretion at low stellar masses and rapid disk dispersal at high masses

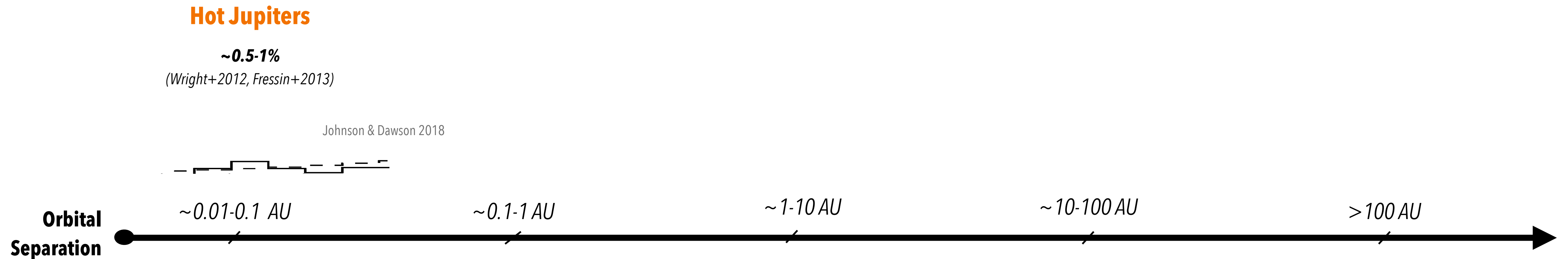


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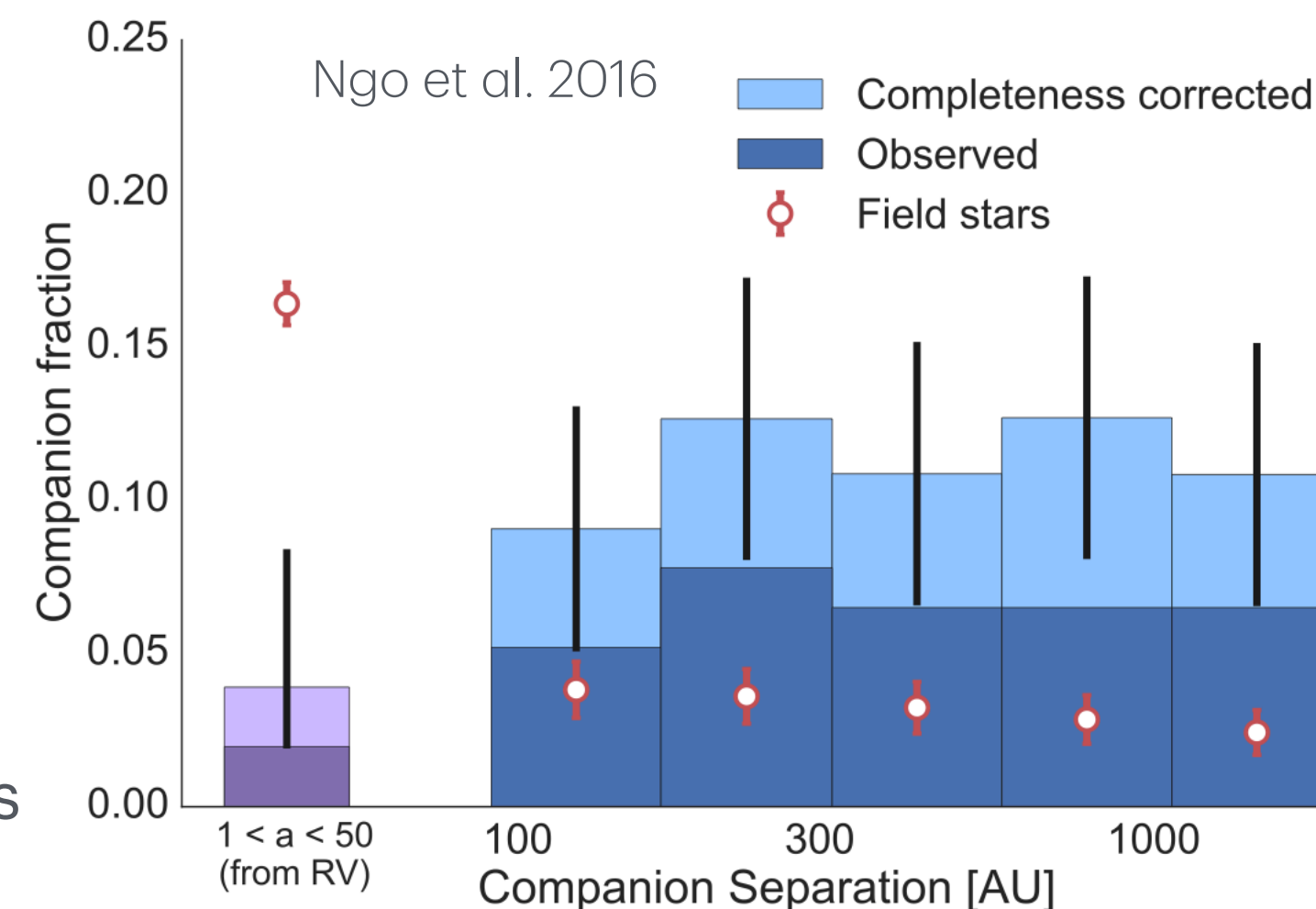
Hot Jupiters (P = 1-10 d)

• Friends of hot Jupiters are common

~50% of hot Jupiters have distant stellar companions beyond 100 AU

Knutson et al. 2014, Ngo et al. 2016, Zink & Howard 2023

⇒ Some may be related to the formation of hot Jupiters through dynamical interactions

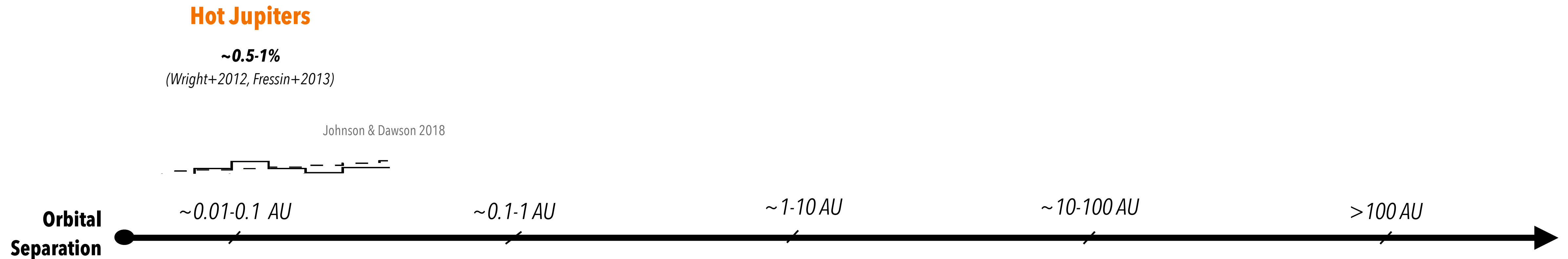


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- **Dawson & Johnson 2018**
Origins of Hot Jupiters
- **Fortney, Dawson, & Komacek 2021**
Hot Jupiters: Origins, Structure, Atmospheres
- **Winn & Petigura 2024**
Planet Occurrence: Doppler and Transit Surveys

How common are giant planets?

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



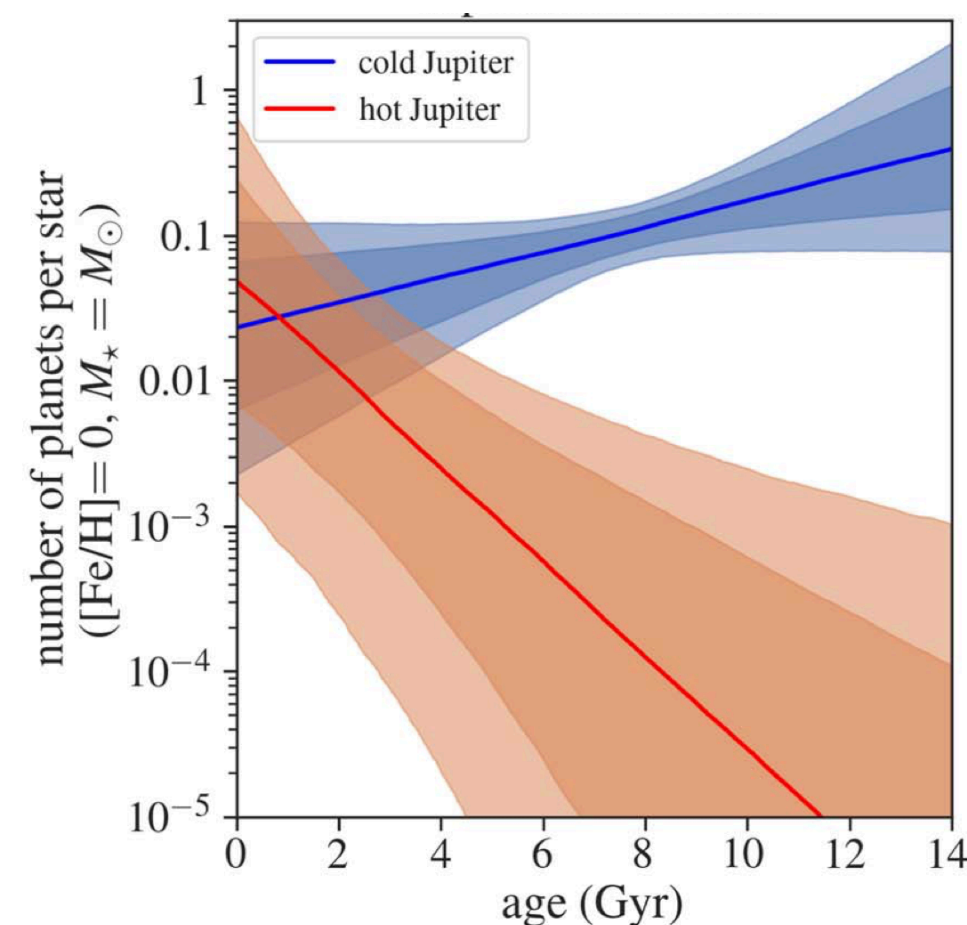
Hot Jupiters (P = 1-10 d)

• 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

⇒ A signature of tidal decay?



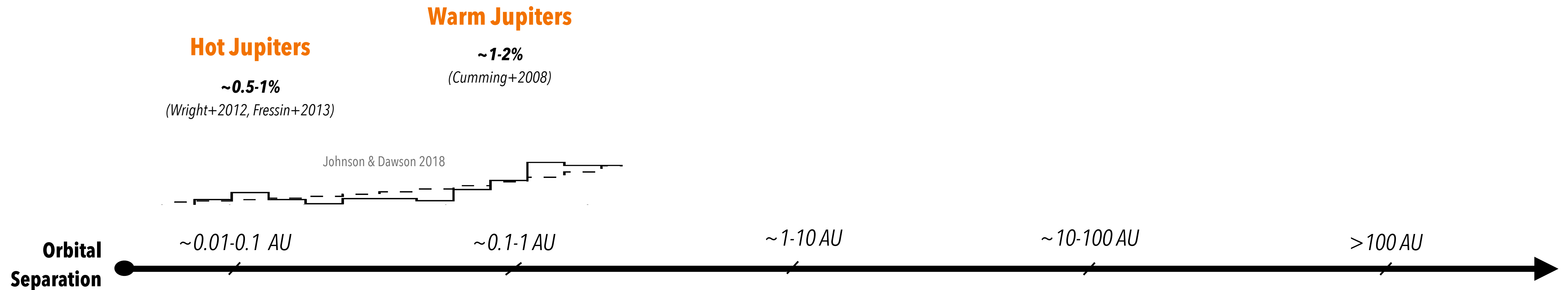
Miyazaki & Masuda 2023

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Hot Jupiters: Origins, Structure, Atmospheres
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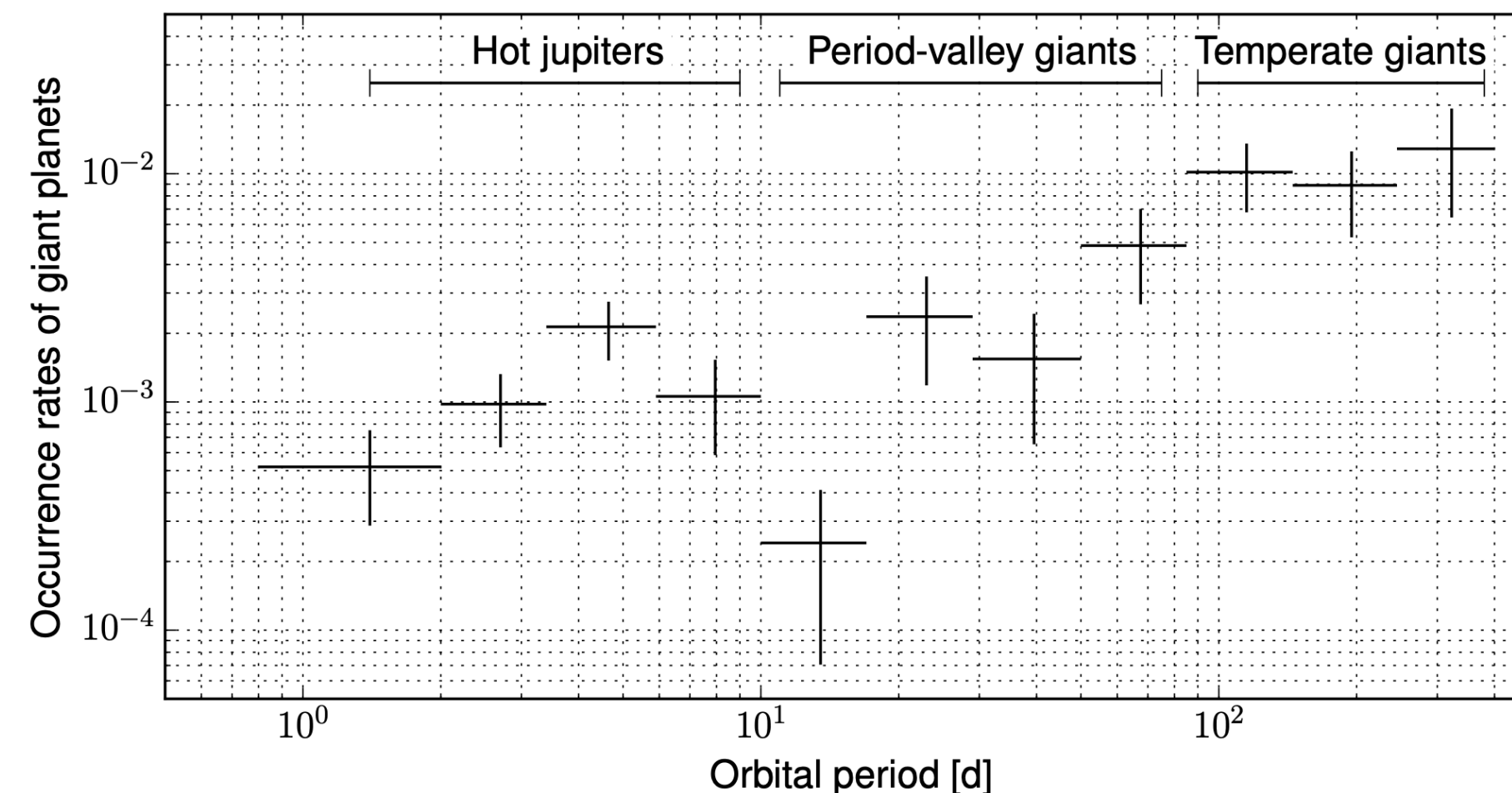
Warm Jupiters (P ~ 10-365 d)

• 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?



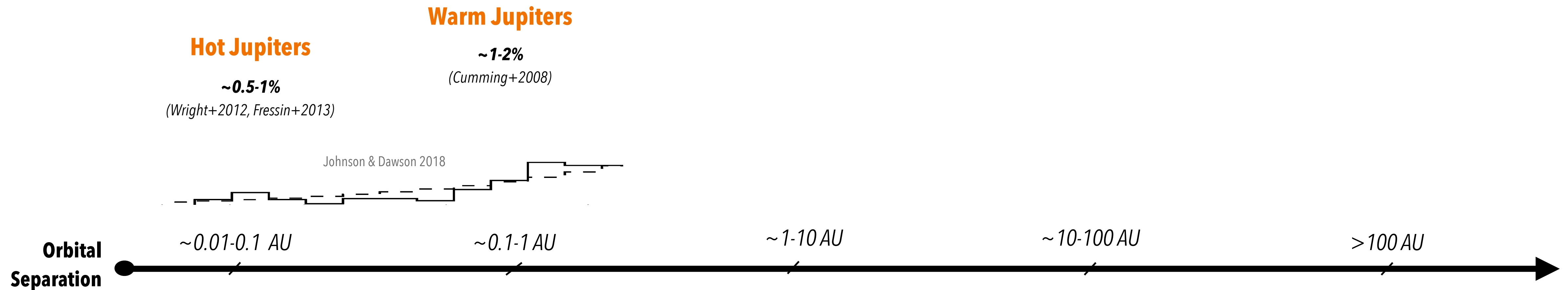
Santerne et al. 2016

Reviews:

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

How common are giant planets?

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Warm Jupiters (P ~ 10-365 d)

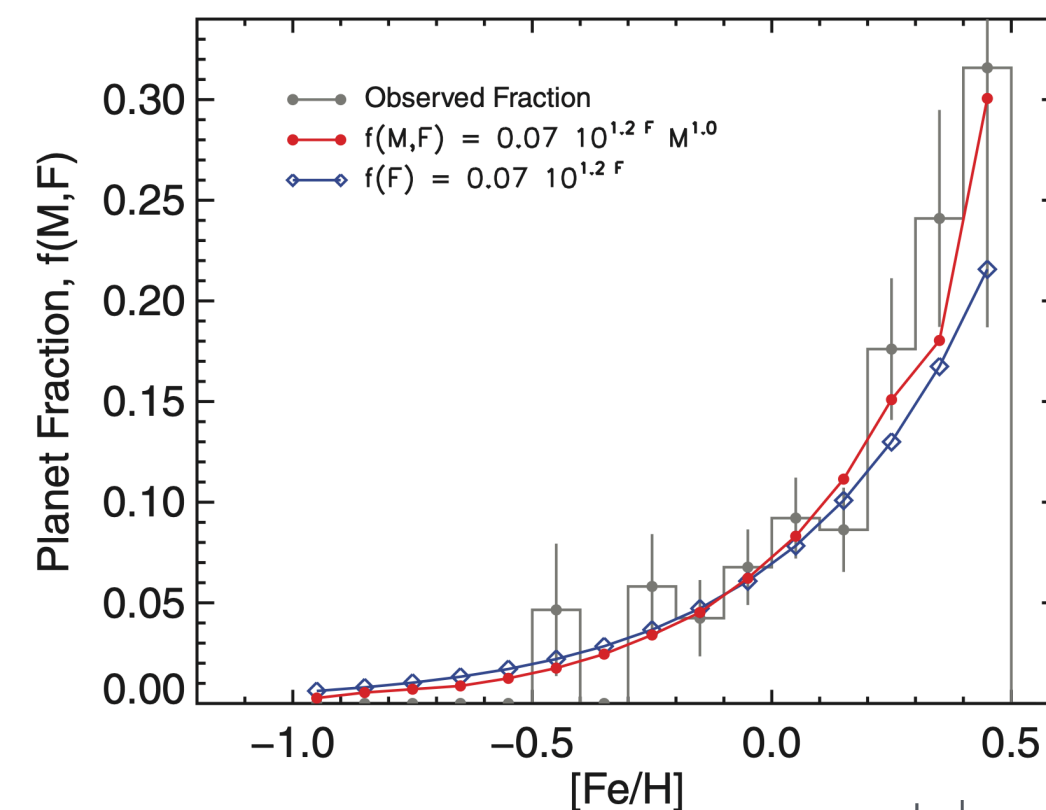
• Steep dependence with...

Giant planets are more prevalent around high-metallicity and high-mass stars.

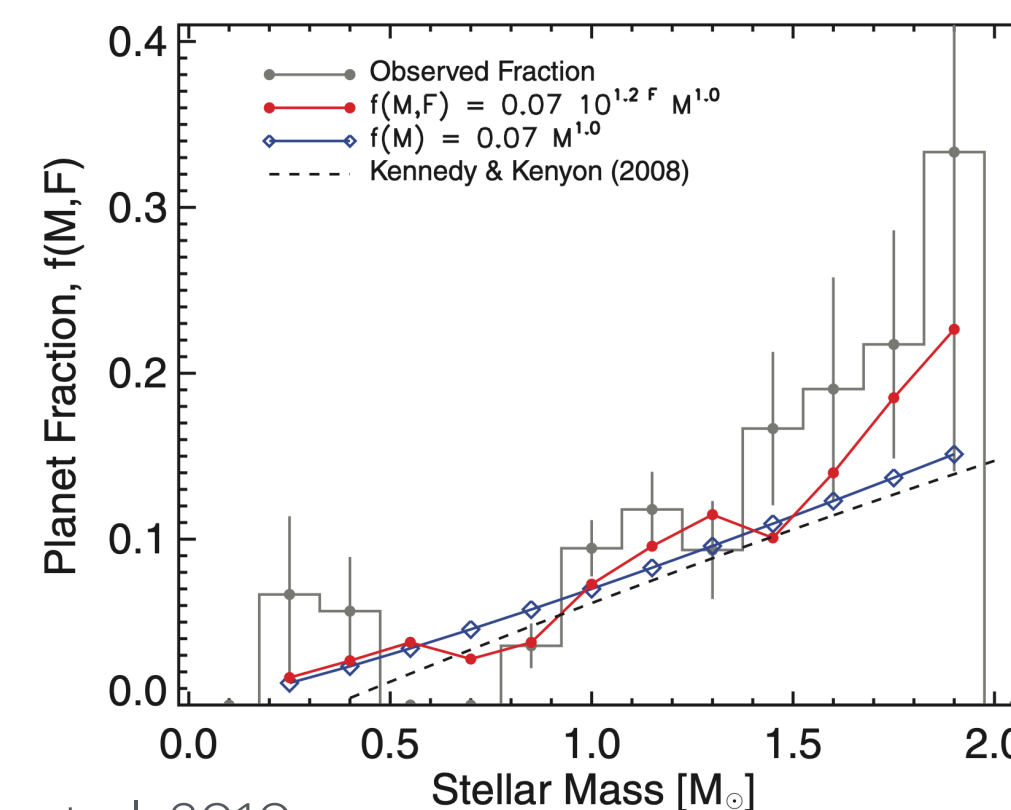
e.g., Santos et al. 2004,
Fischer & Valenti 2005
Endl et al. 2006
Bowler et al. 2010
Johnson et al. 2010

⇒ A signature of more efficient
core formation?

stellar metallicity and stellar mass



Johnson et al. 2010

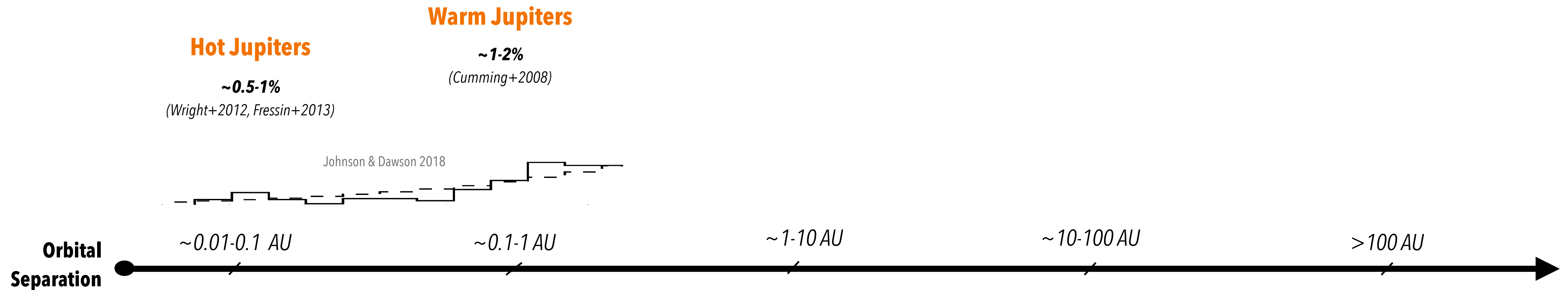


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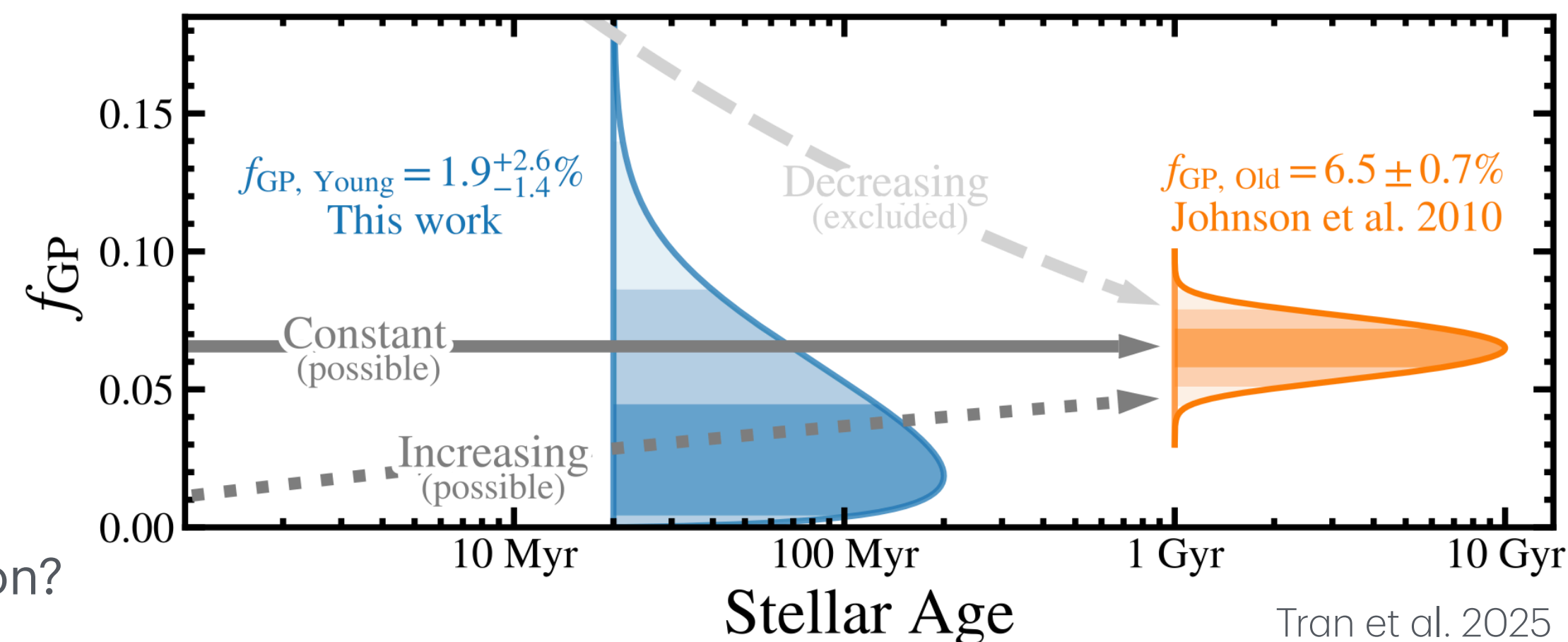
Warm Jupiters ($P \sim 10\text{-}365\text{ d}$)

• Hints of *increasing* occurrence rate over time

RV surveys of young stars are finding lower frequencies compared to field stars.

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

⇒ A signature of late inward migration?

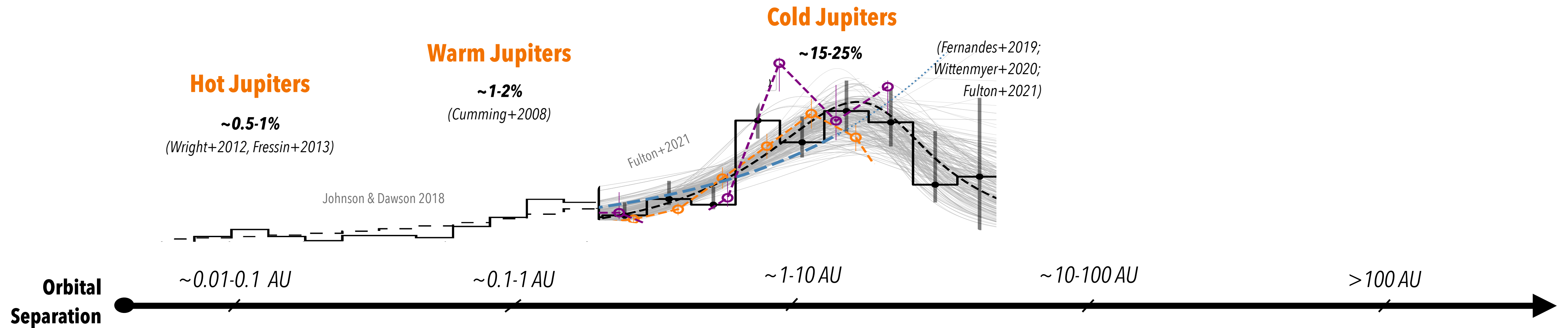


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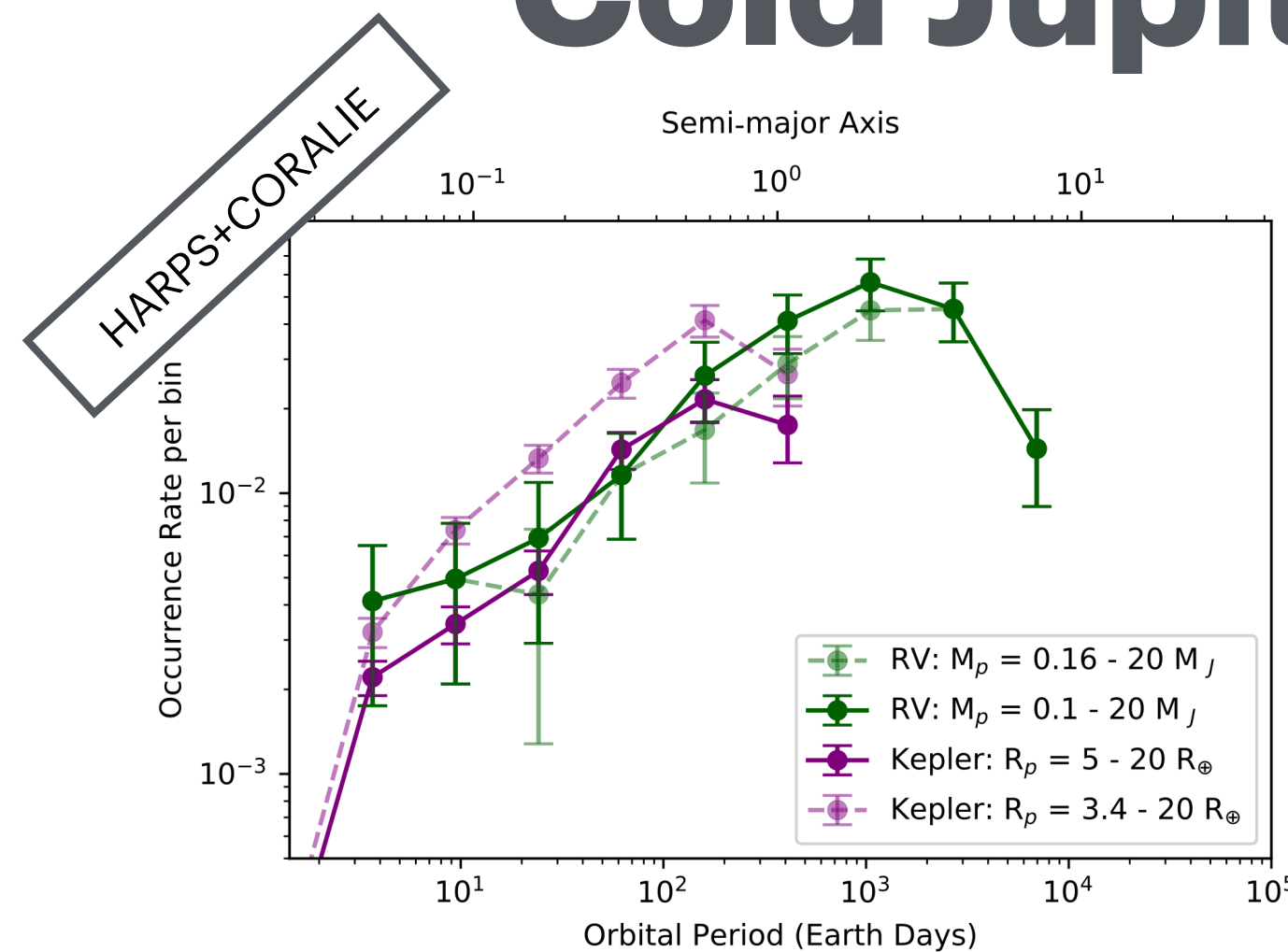
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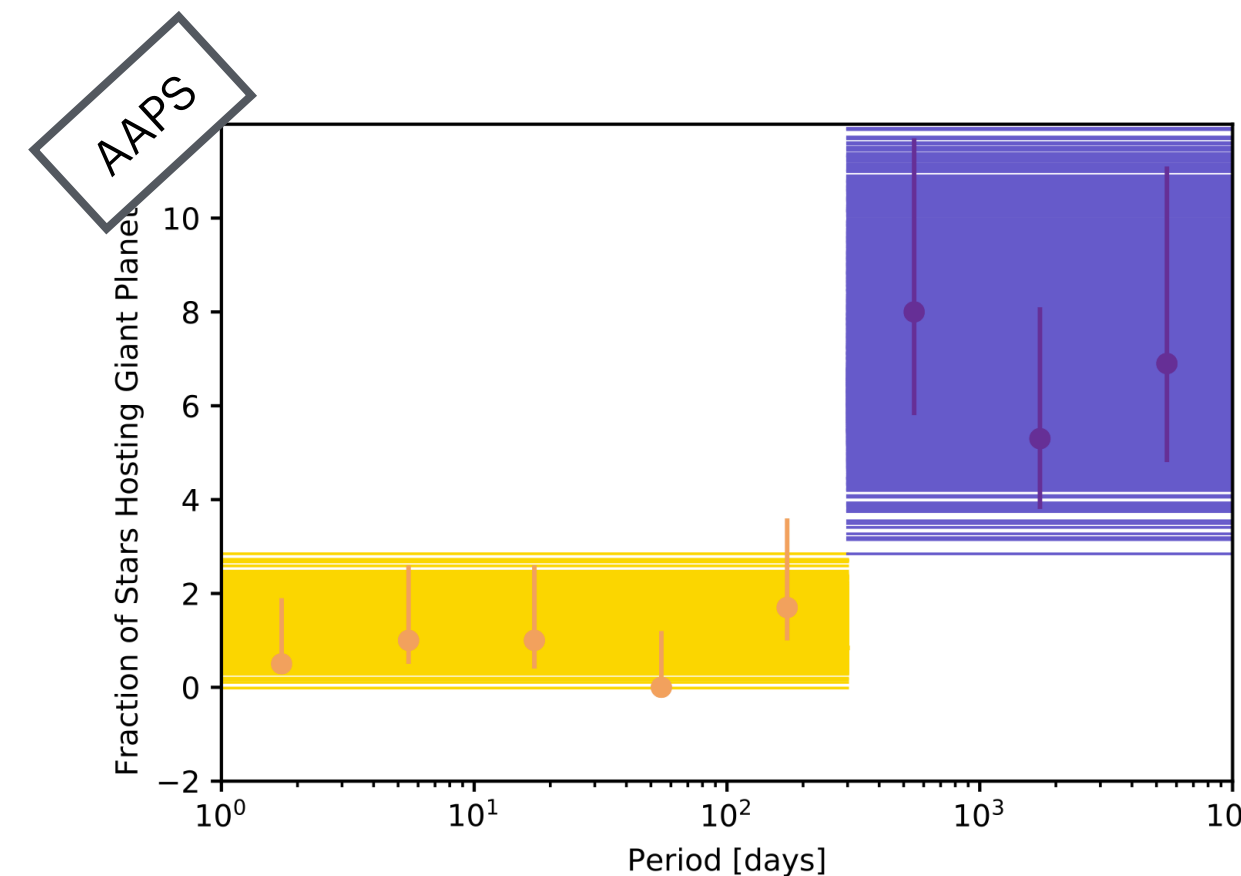
Cold Jupiters (a ~ 1-10 AU)

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

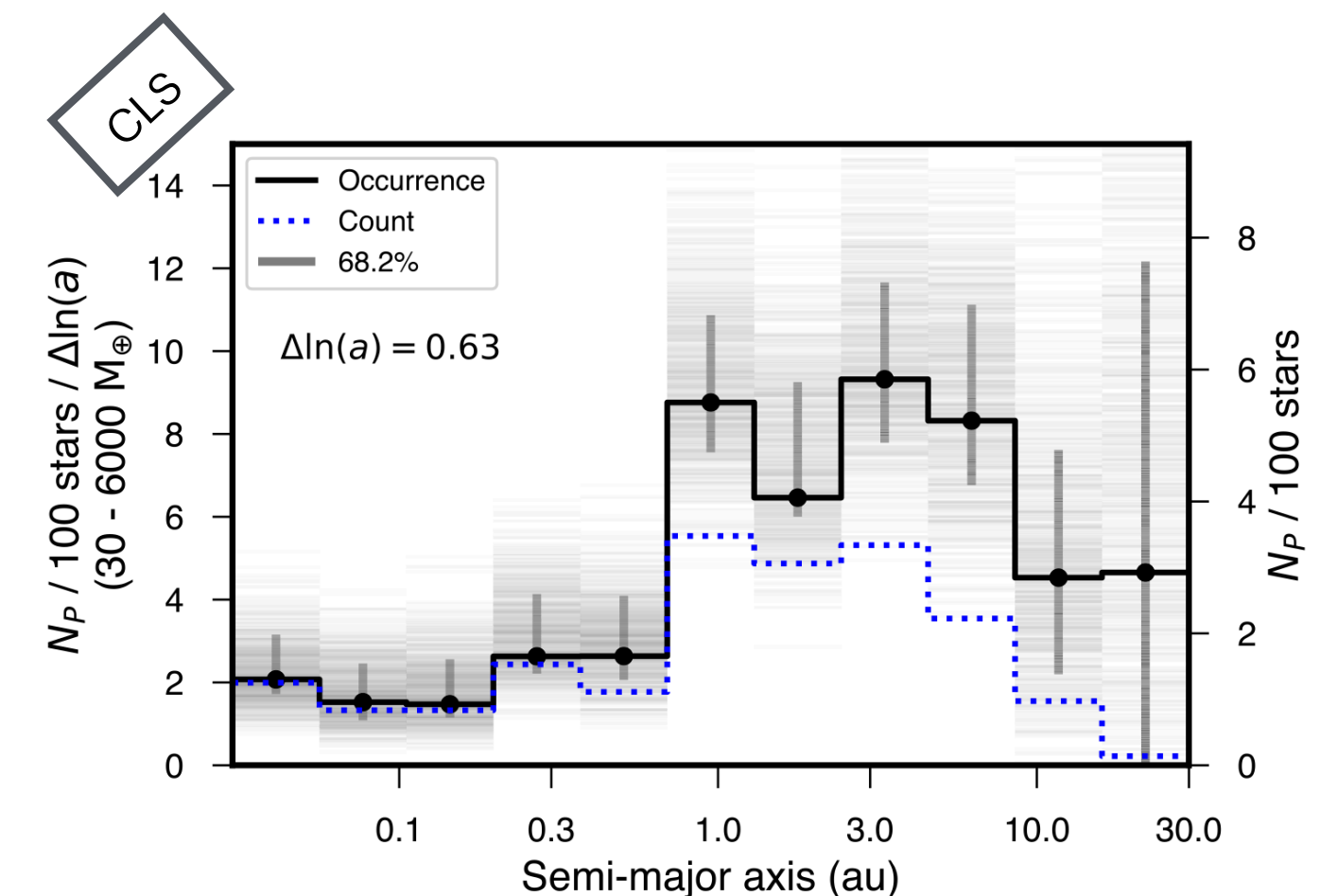
Giant planets are produced most readily at 1-10 AU



Fernandes et al. 2019



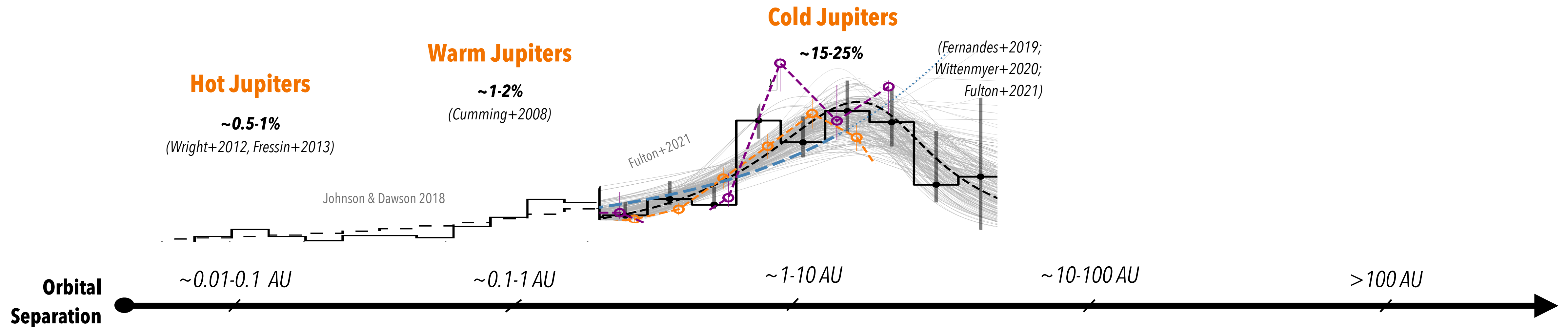
Wittenmyer et al. 2020



Fulton et al. 2021

How common are giant planets?

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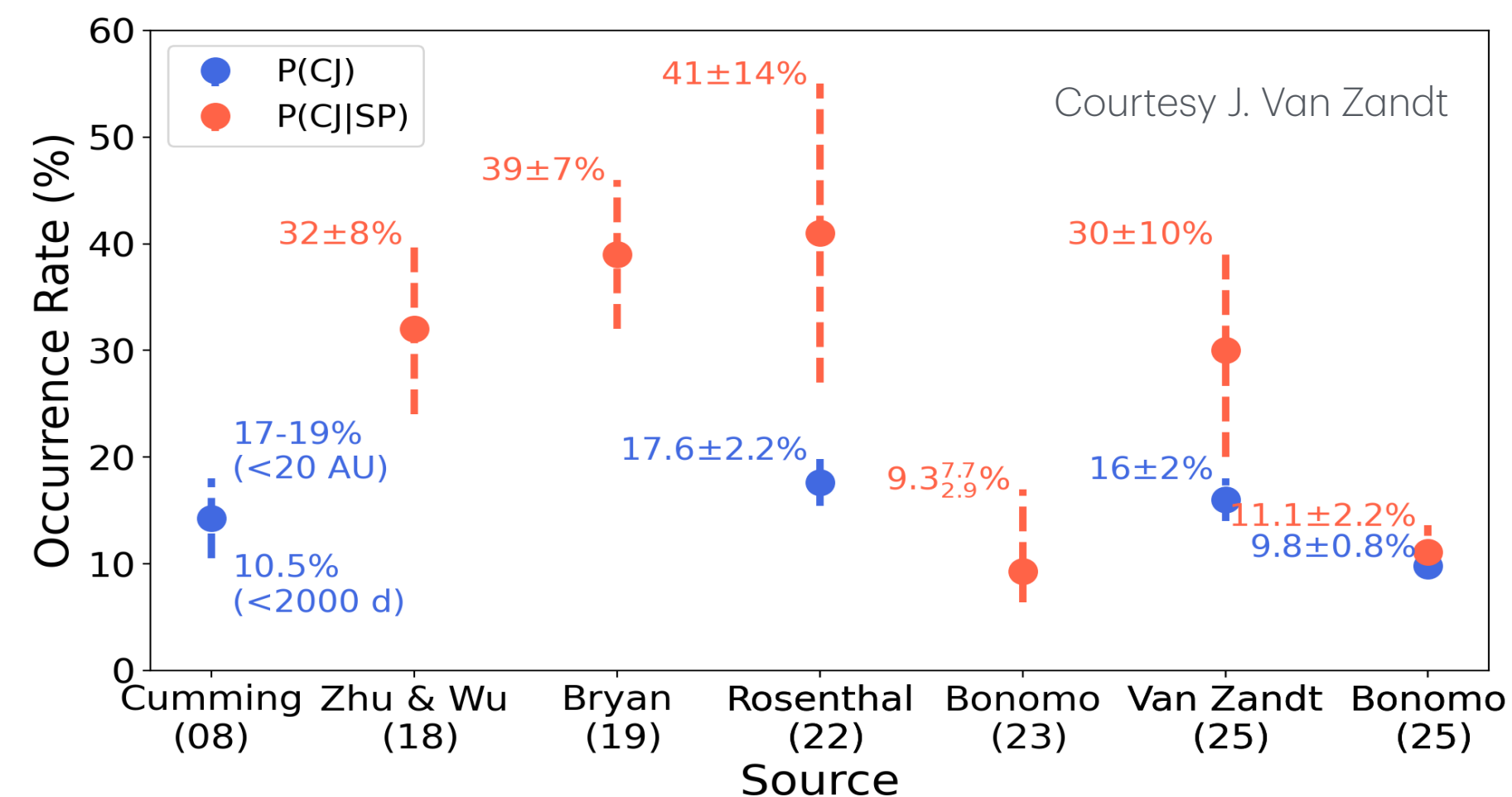


Cold Jupiters (a ~ 1-10 AU)

- **Occurrence rates dependence on inner planet population?**

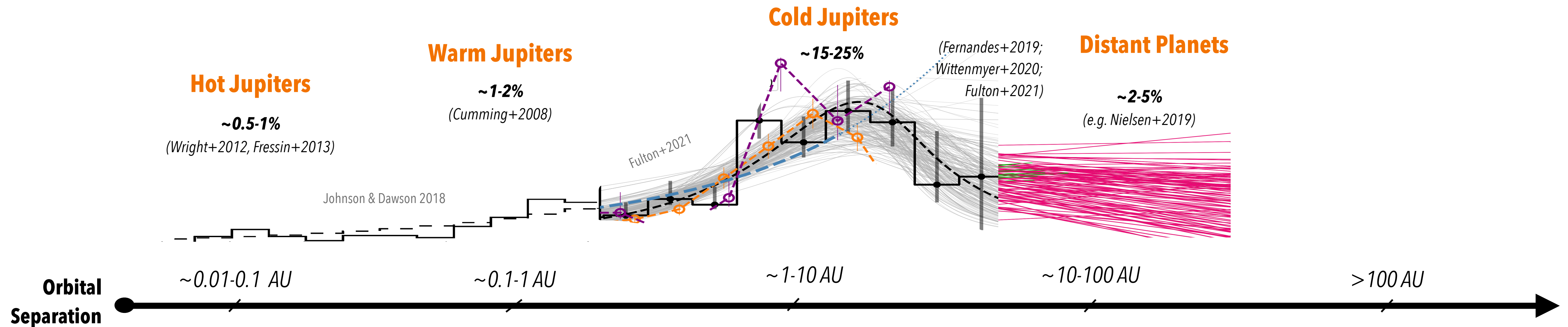
Cold Jupiters may be more prevalent around stars with inner small planets; mixed evidence.

e.g., Zhu & Wu 2018,
Bryan et al. 2019,
Rosenthal et al. 2022,
Bryan & Lee 2024, 2025,
Van Zandt et al. 2024, 2025
Bonomo et al. 2025



How common are giant planets?

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

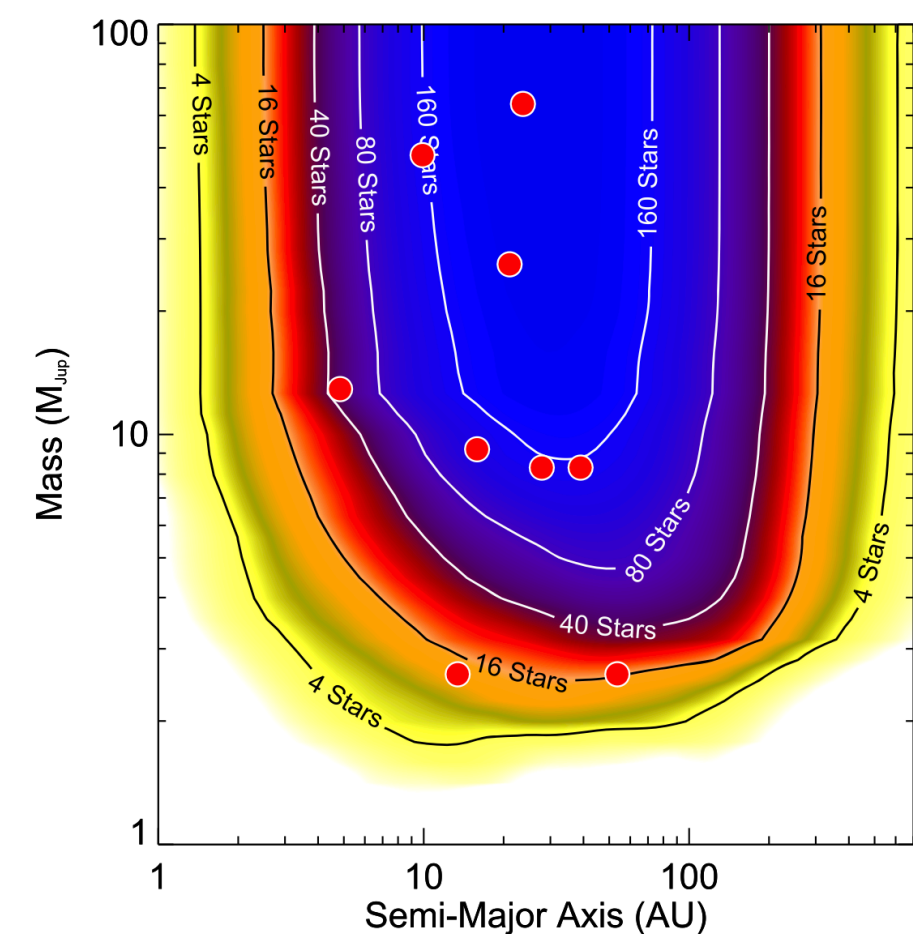


Distant Planets (a ~ 10–100 AU)

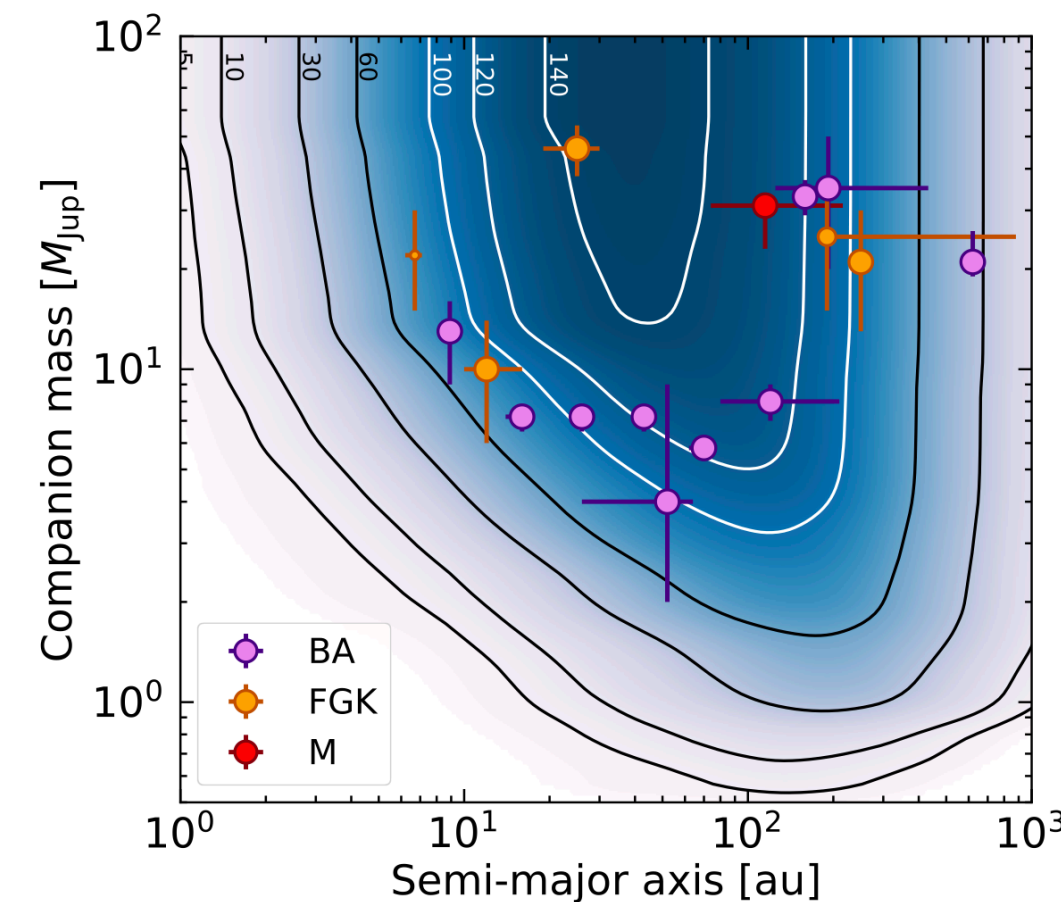
• Occurrence rates fall with distance for massive planets

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



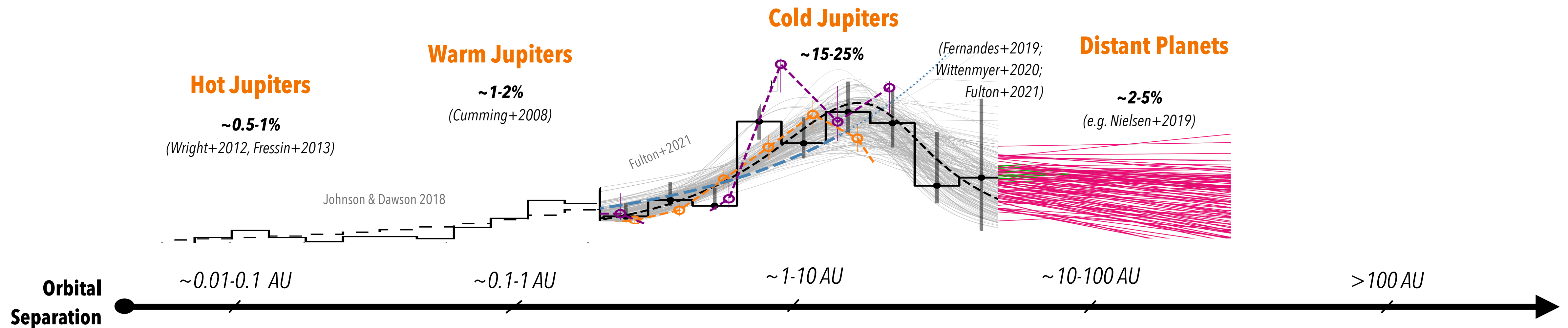
Vigan et al. 2021

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

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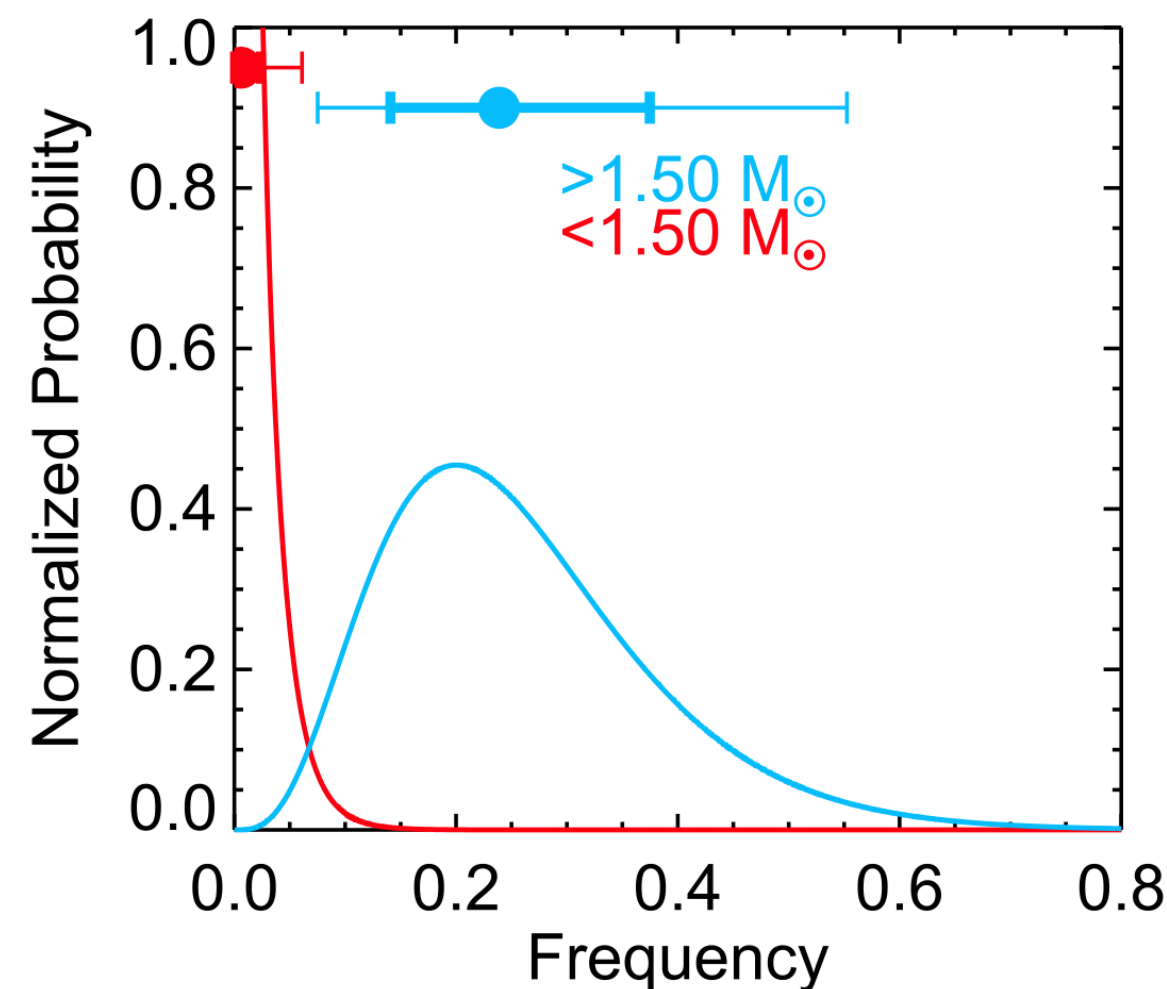
Distant Planets (a ~ 10–100 AU)

• 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, Squicciarini et al. 2024

⇒ Larger mass reservoir?
Signatures of disk instability?

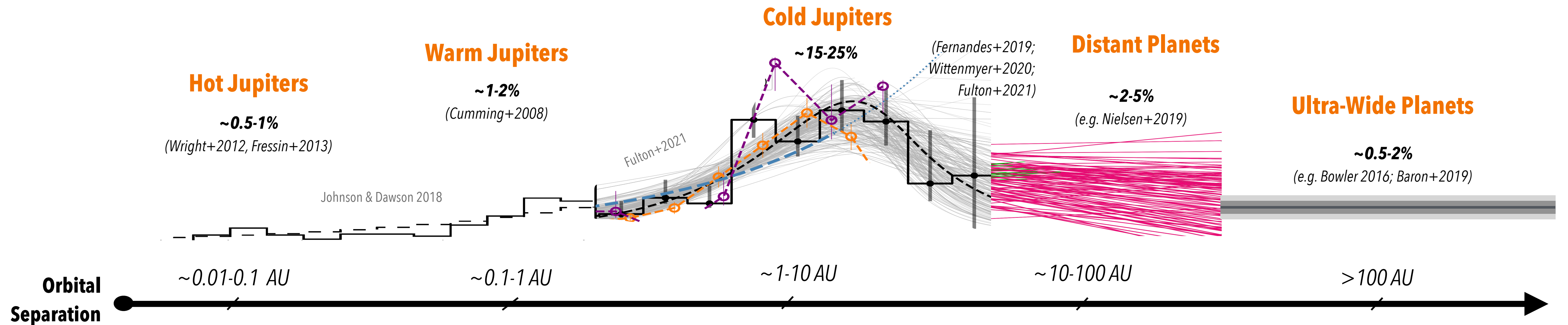


Reviews:

- **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



Ultra-Wide Planets ($a > 100$ AU)

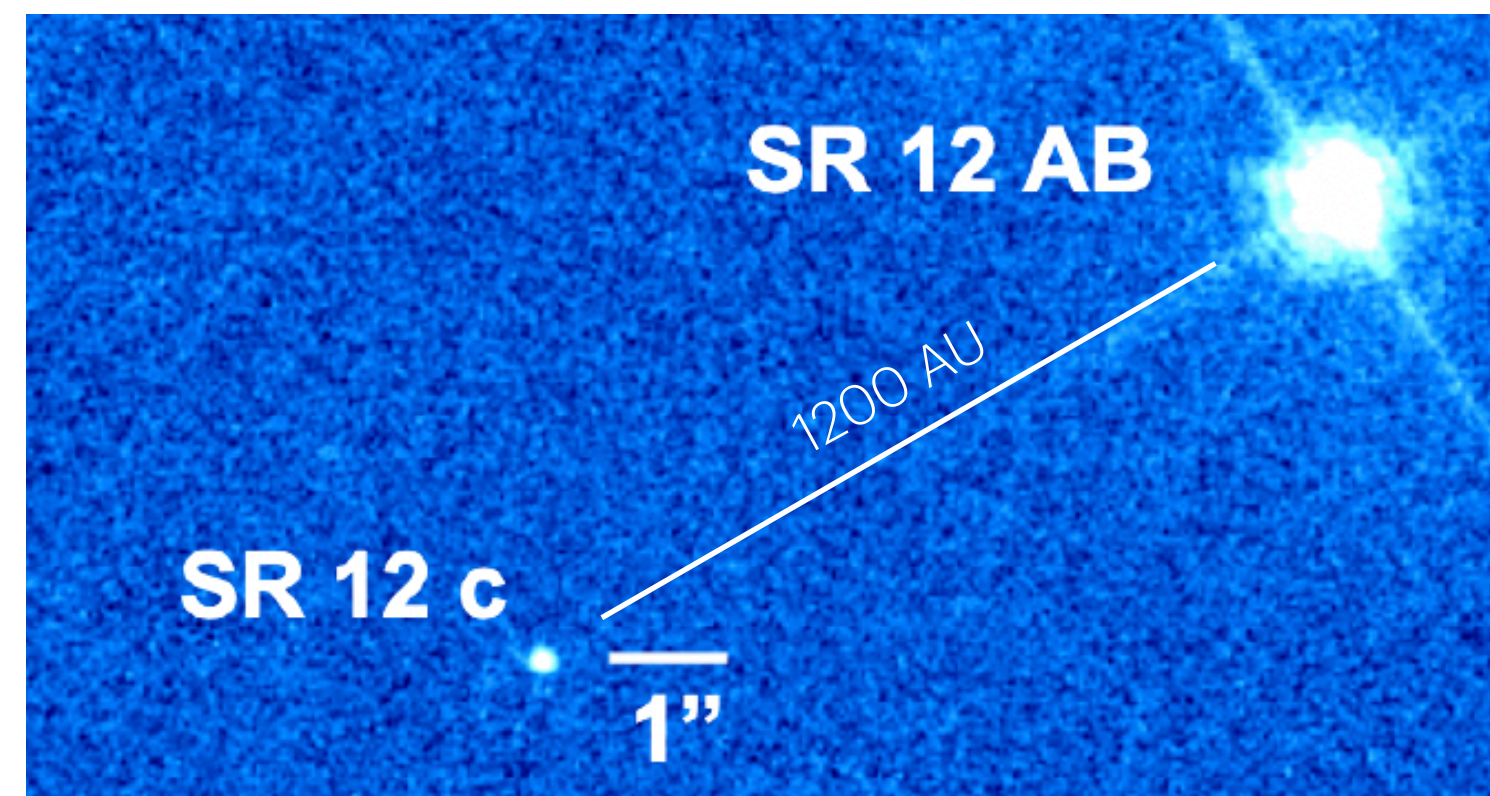
- **Distant giant planets are rare but extend to a few thousand AU**

From 20-1000 AU, $f \sim 2\%$

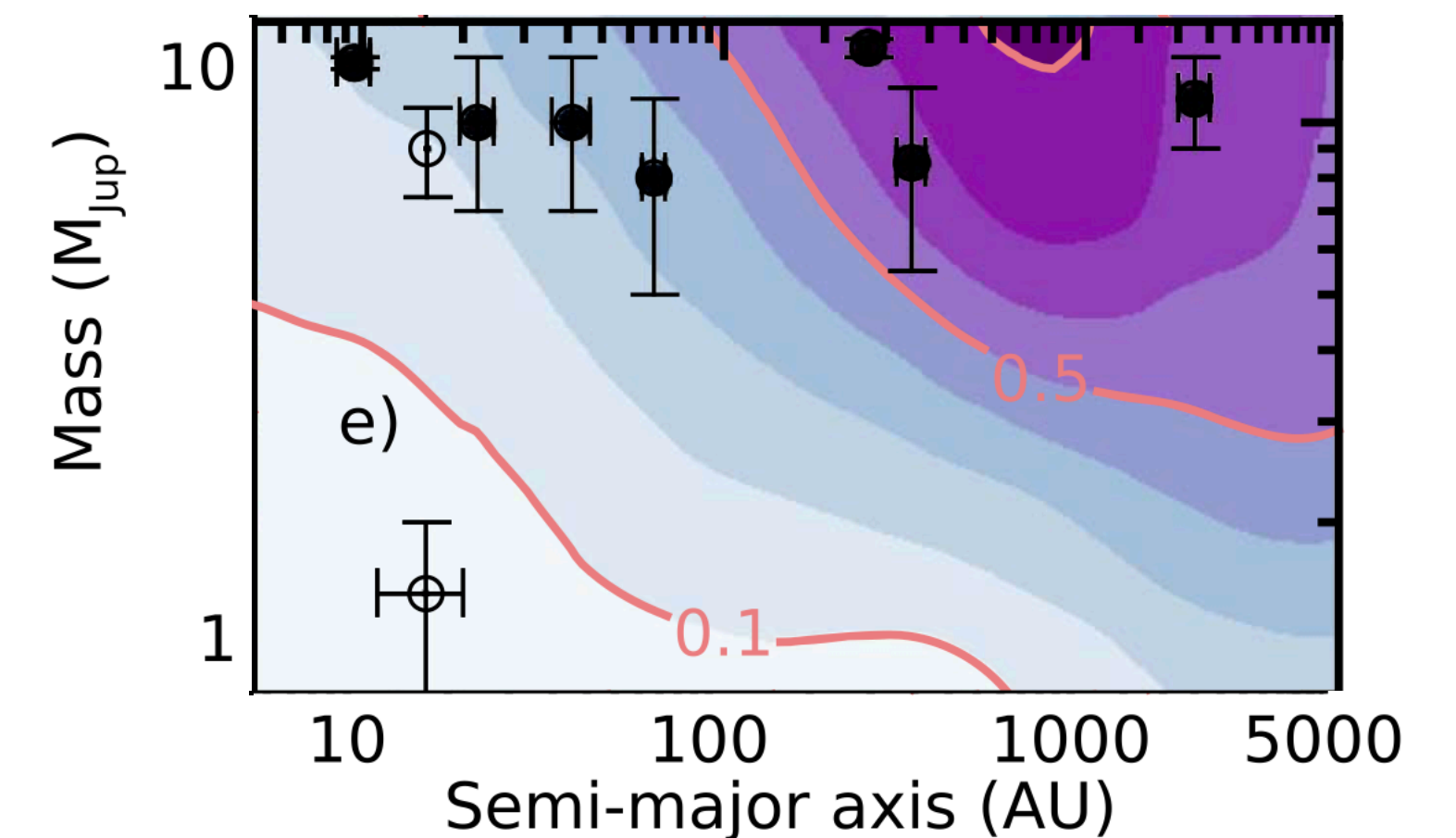
From 1000-5000 AU, $f \sim 0.3\%$

e.g., Baron et al. 2019

⇒ Ejected planets?
The tail end of fragmentation?



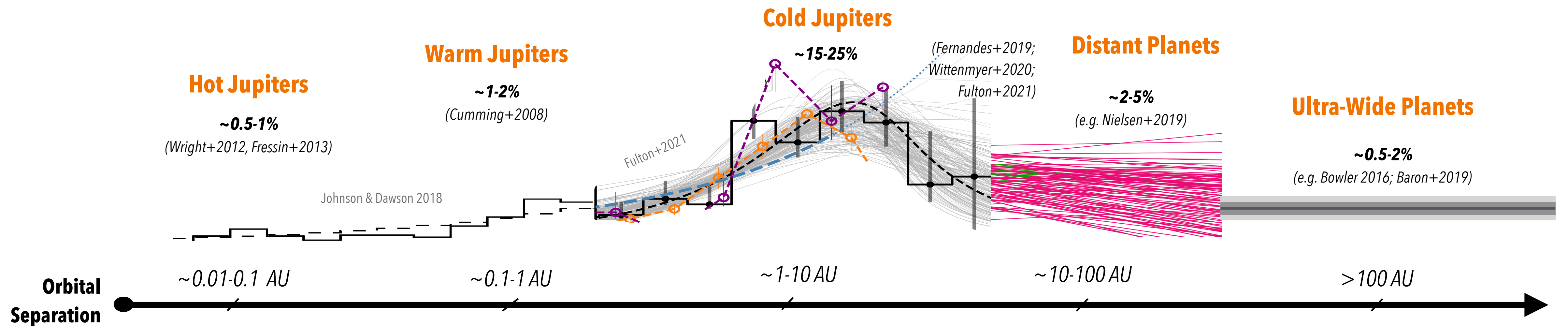
Finley et al., in prep.



Baron et al. 2019

How common are giant planets?

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



Summing these together....

$$f_{\text{GP}} \sim 19 - 35 \%$$

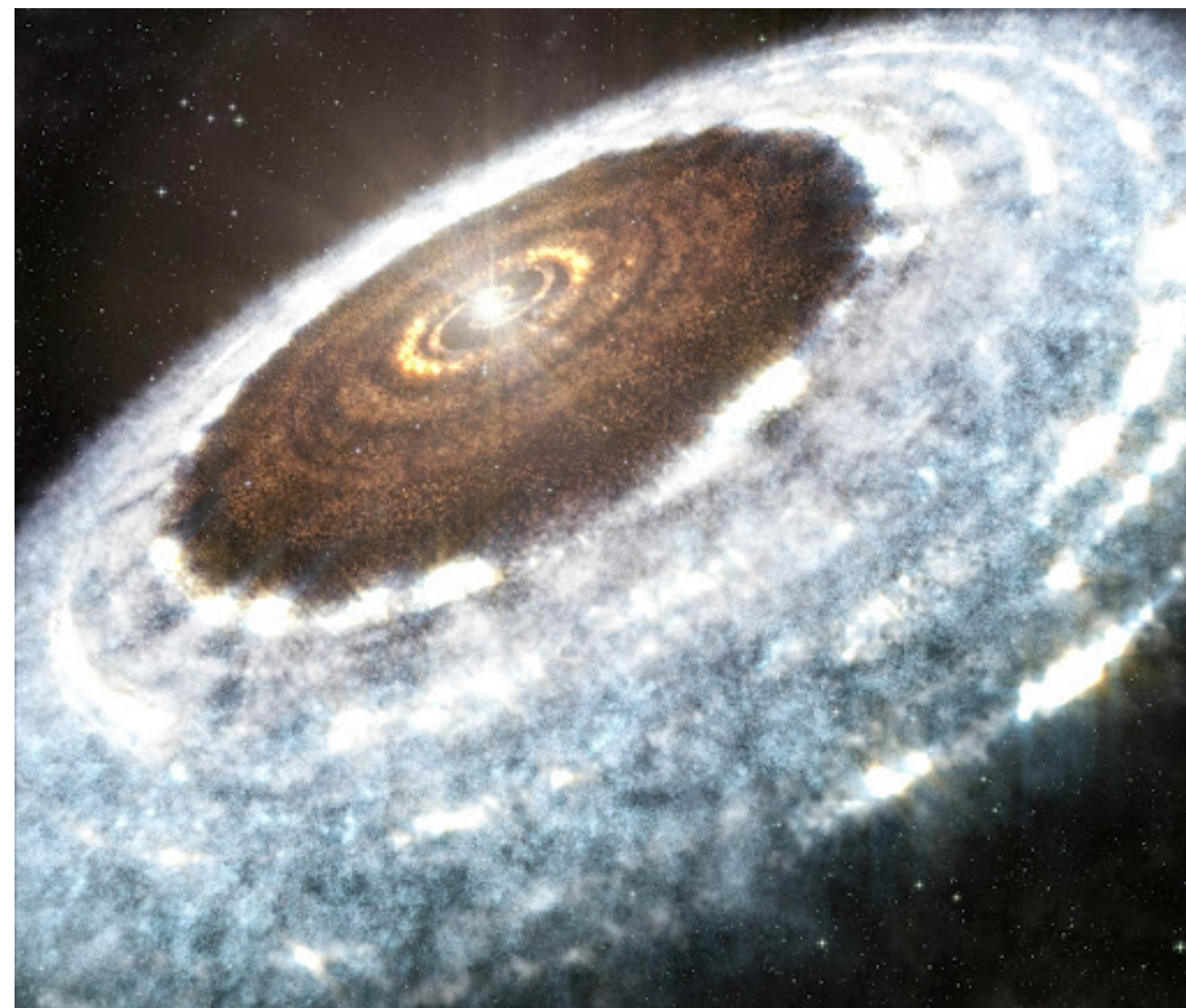
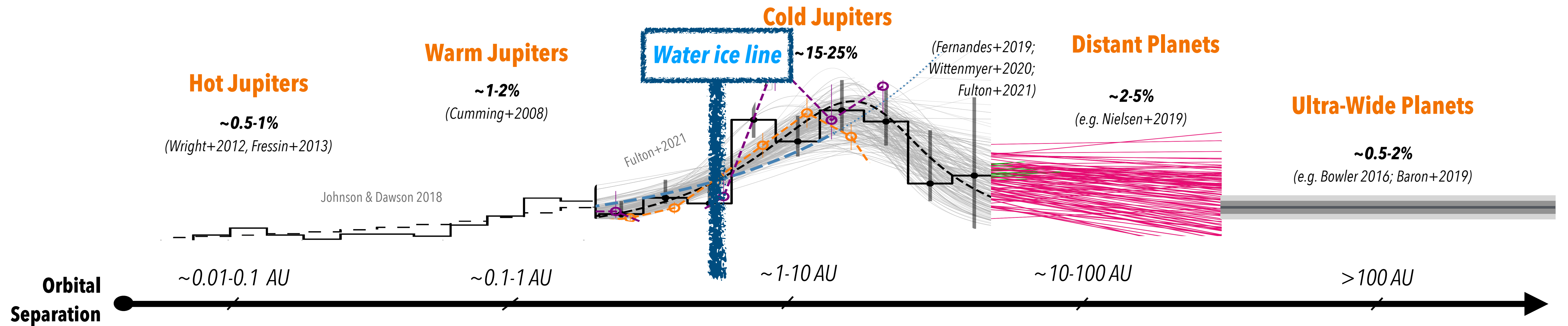
For ~0.3-15 M_{Jup} spanning ~0.1-10000 AU

Compare with:

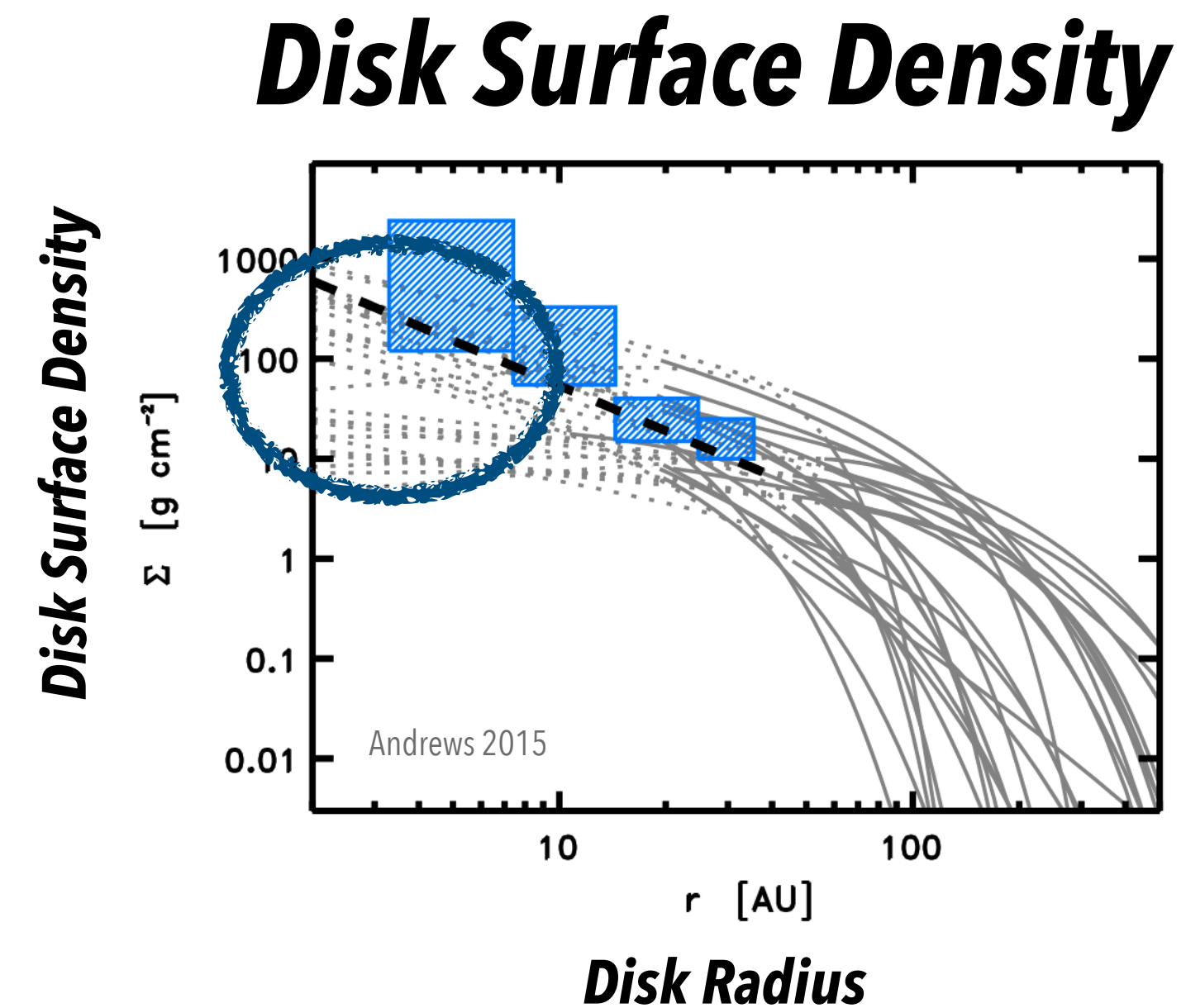
Fernandes et al. 2019:
 $27^{+8}_{-5} \%$ for 0.1-20 M_{Jup}
between 0.1-100 AU

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

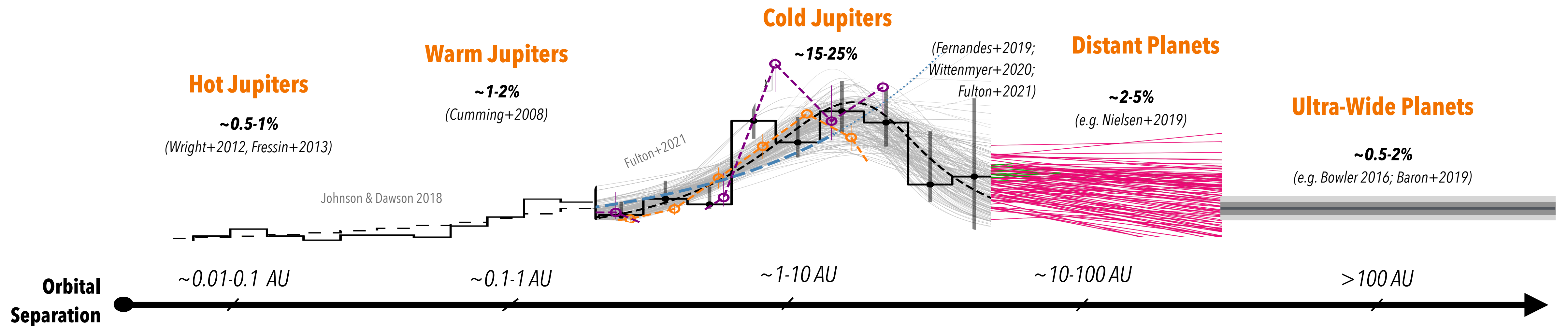
What story is this telling about giant planets?



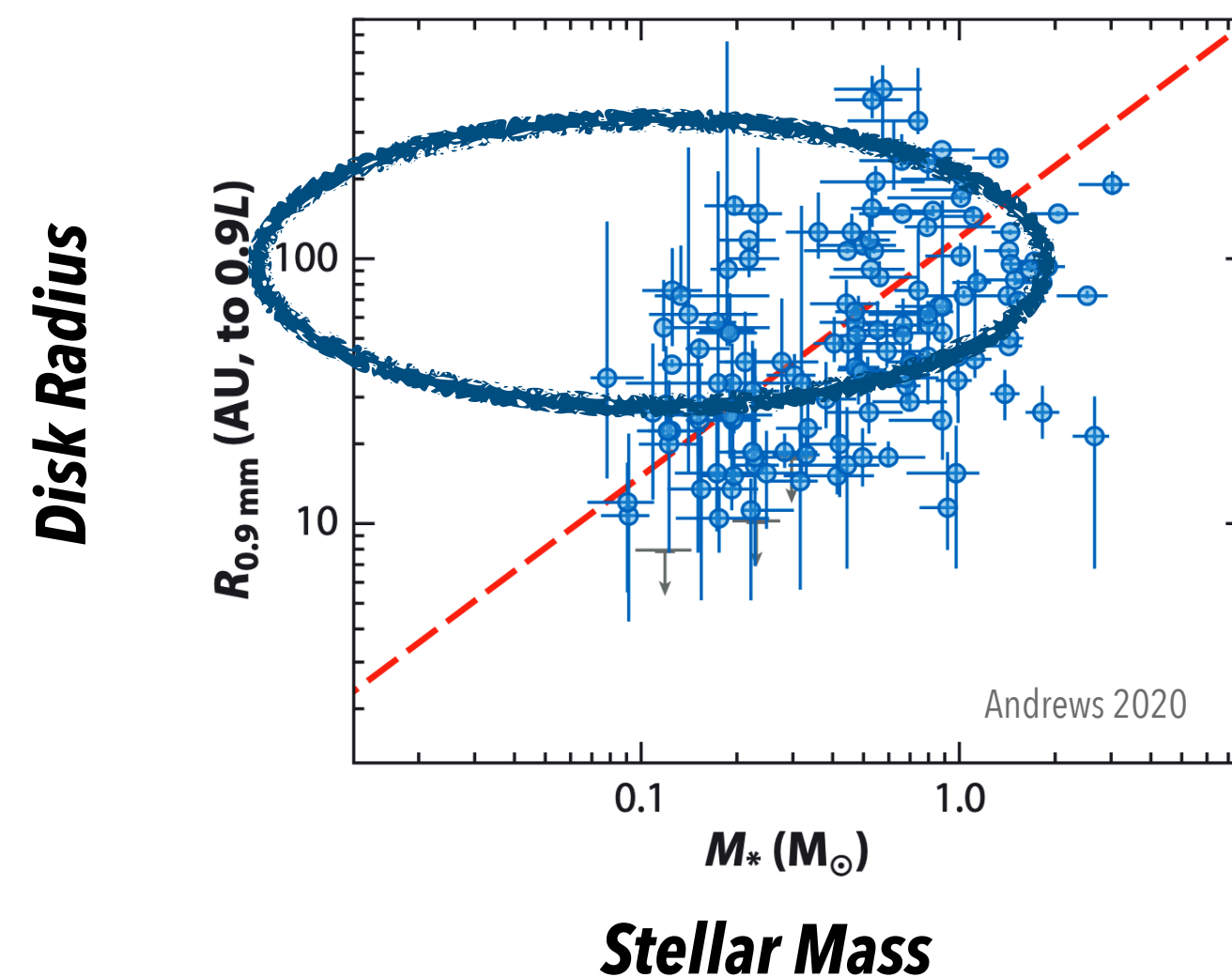
Credit: A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)



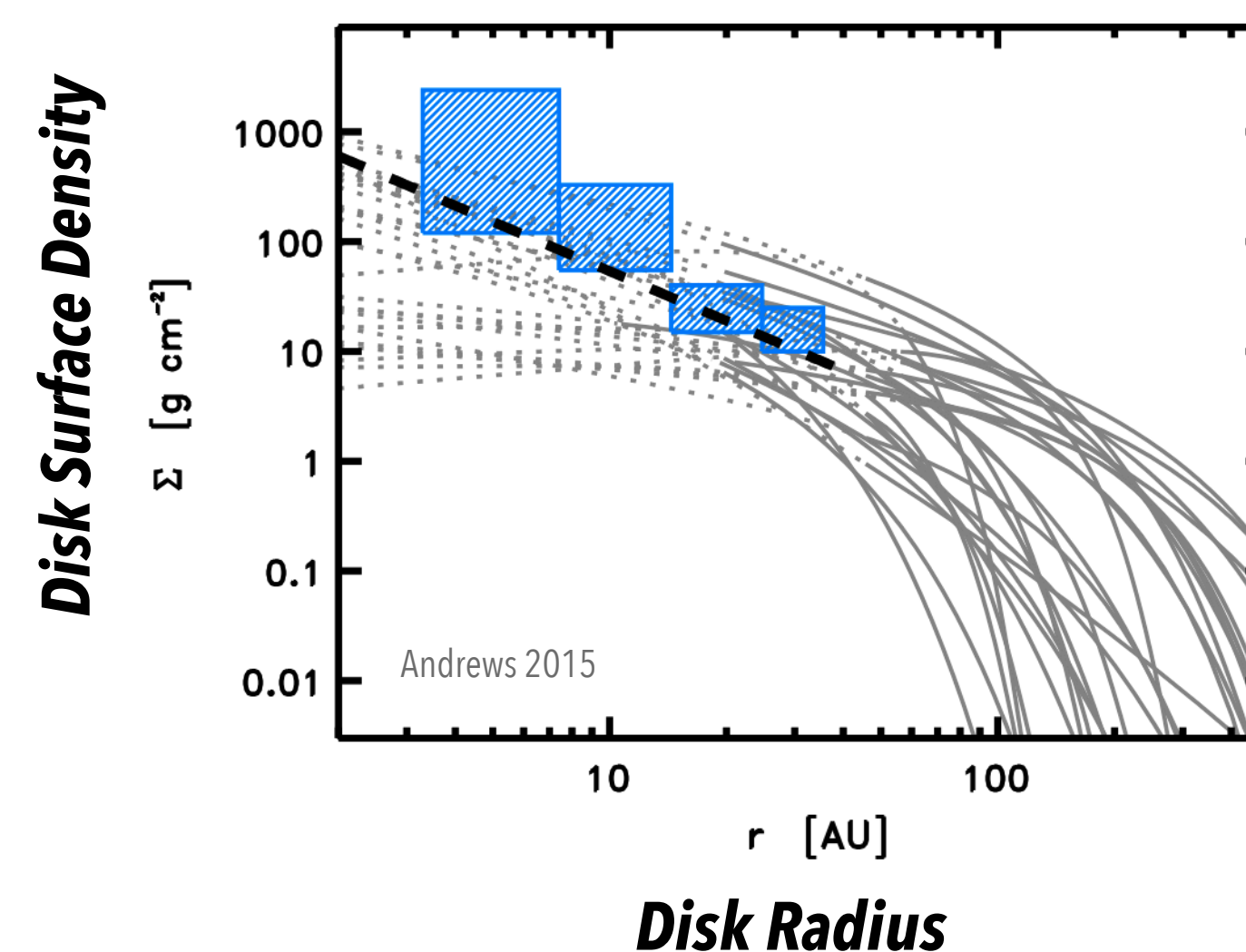
What story is this telling about giant planets?



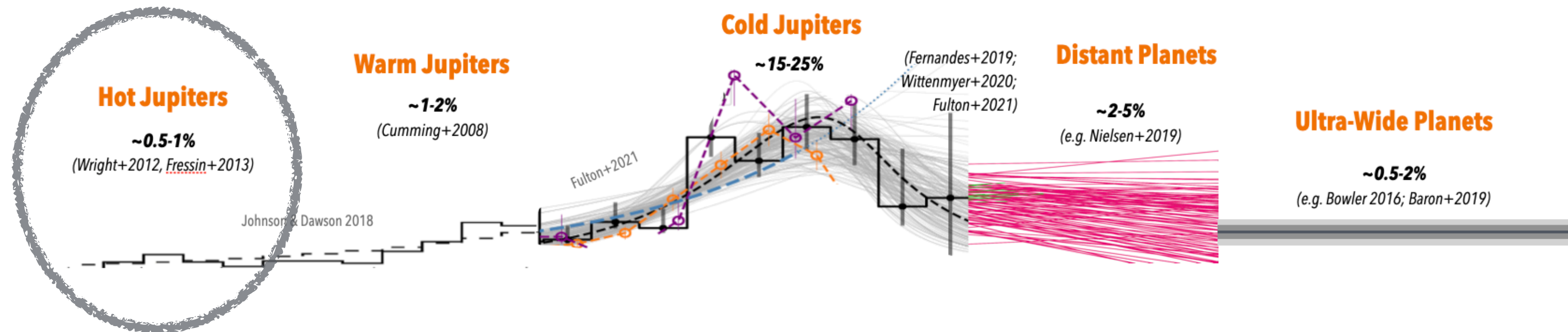
Protoplanetary Disk Size



Disk Surface Density

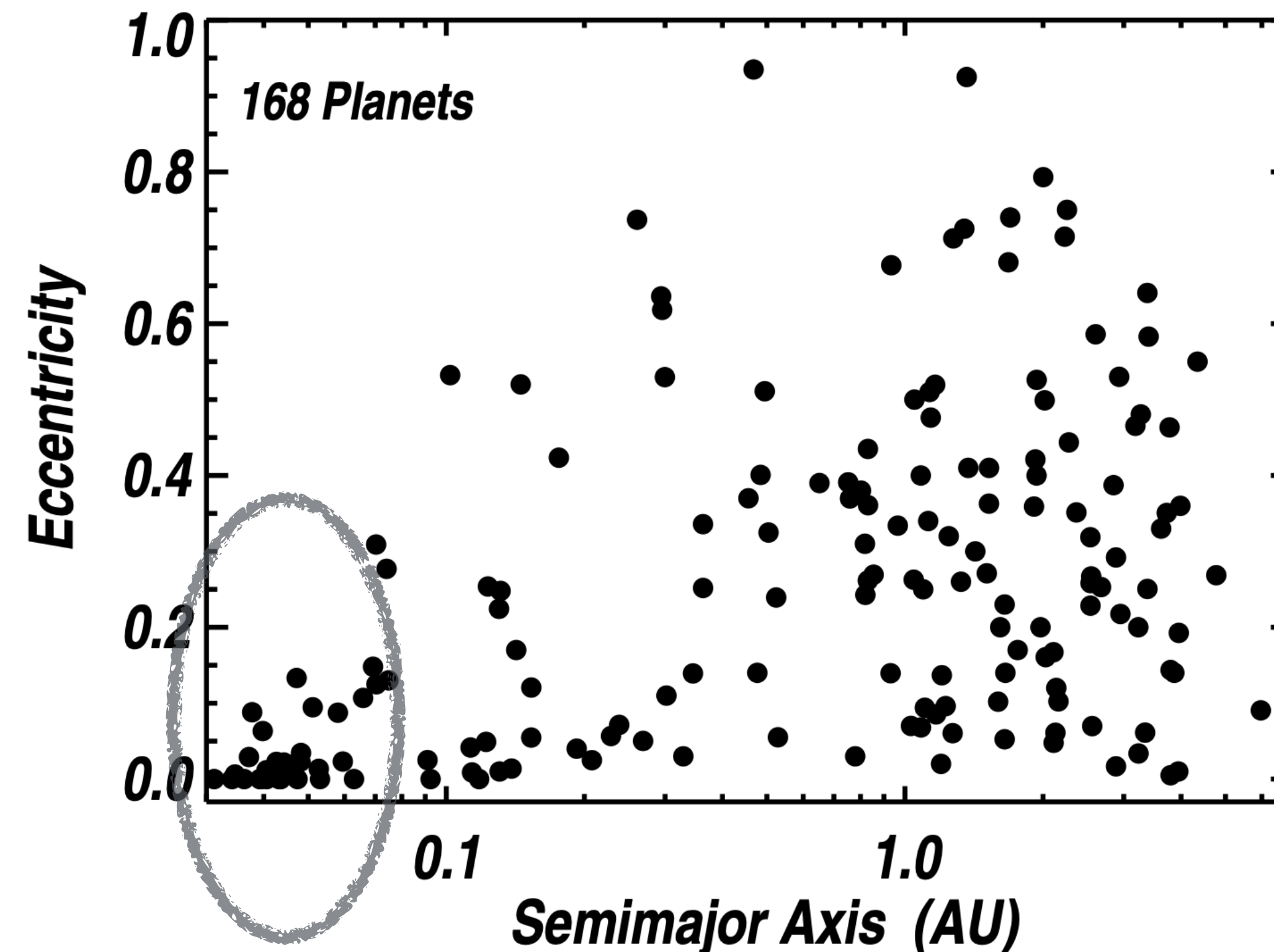


More clues from orbital eccentricities

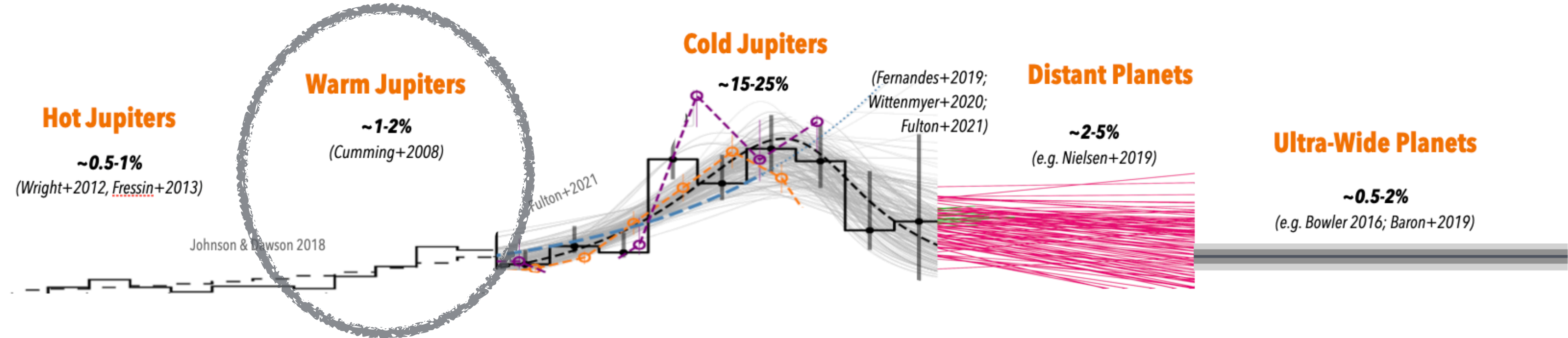


- **HJs reside on largely (but not exclusively) circular orbits**

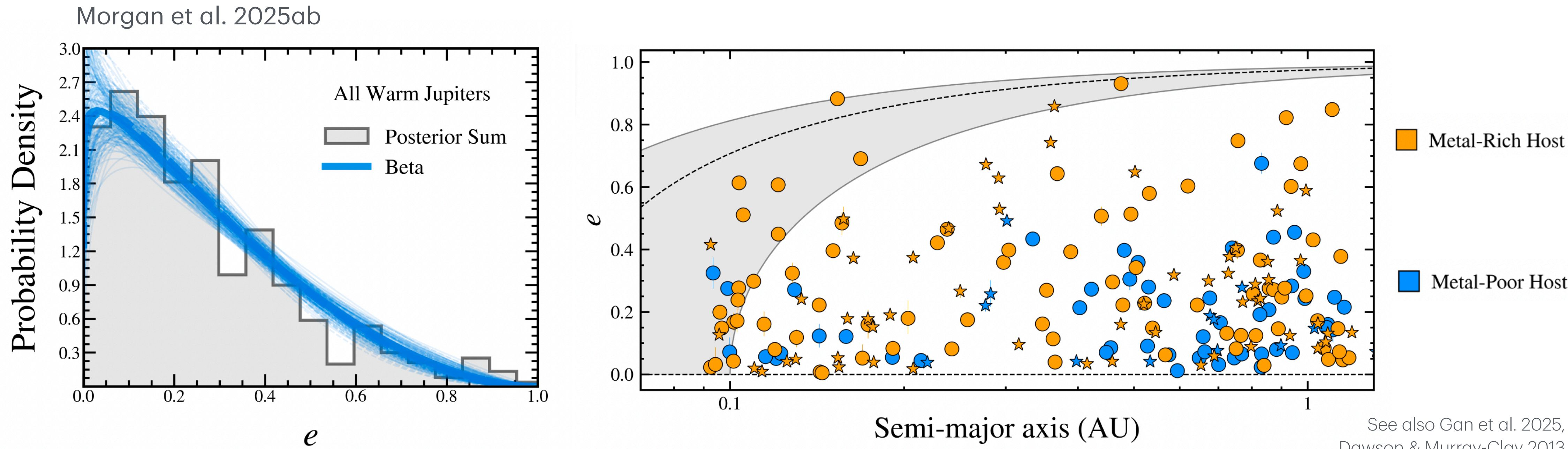
Tidal circularization,
inward disk migration,
in situ formation



More clues from orbital eccentricities

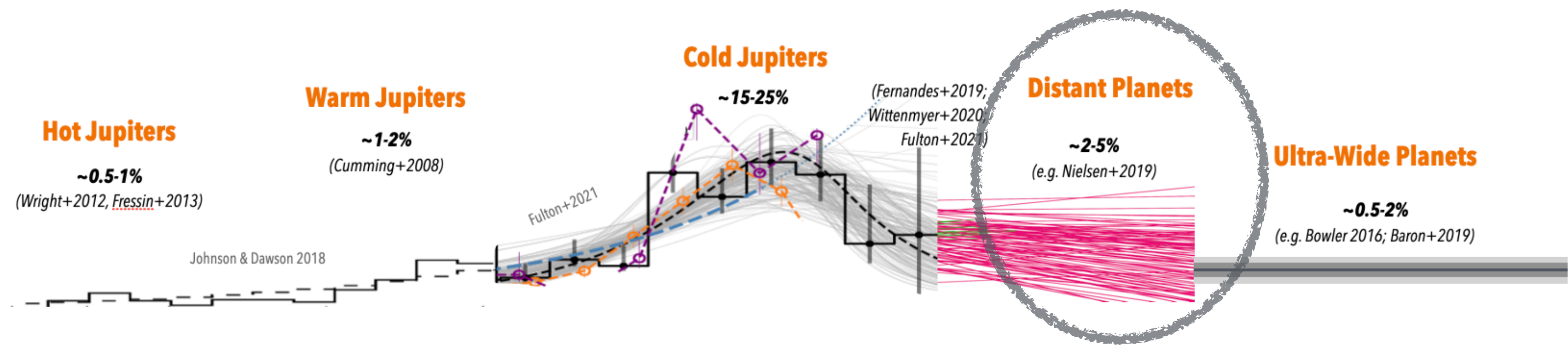


- **$73 \pm 3\%$ of WJs have non-zero eccentricities**
- **WJs are dynamically hotter around metal-rich host stars**

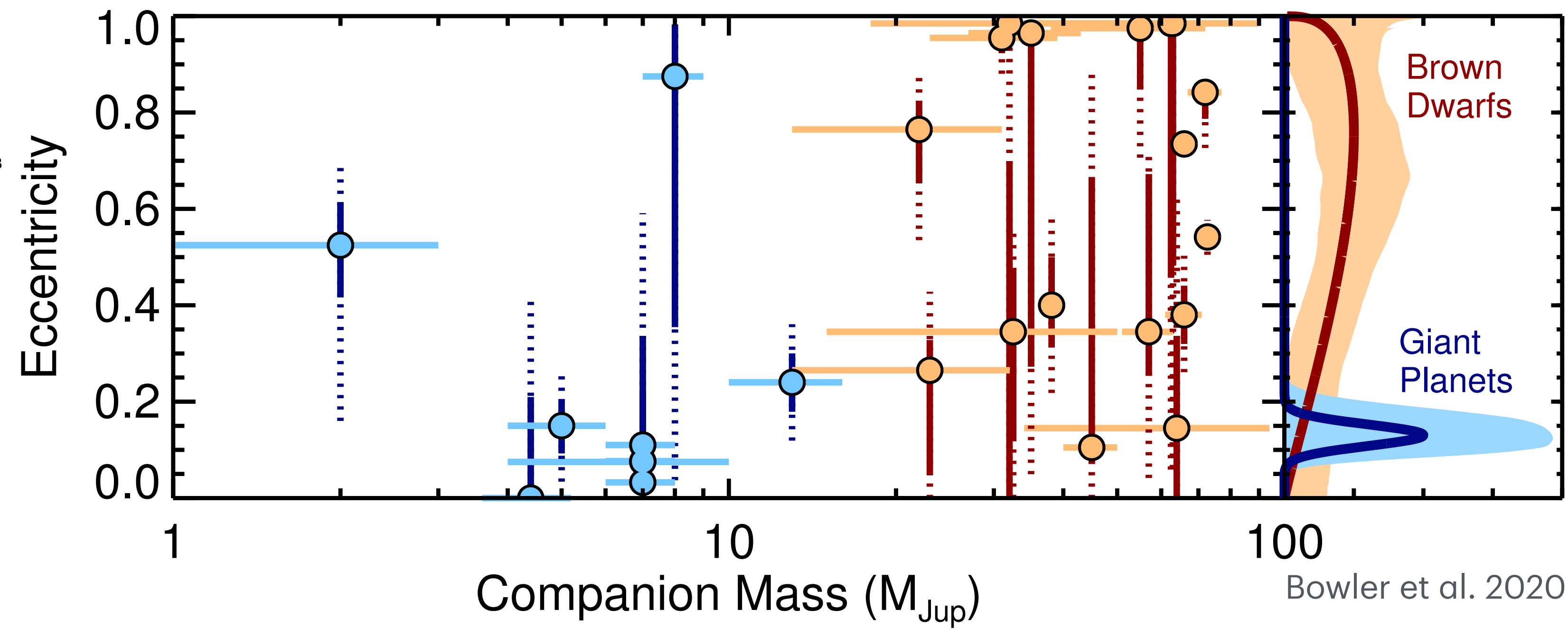
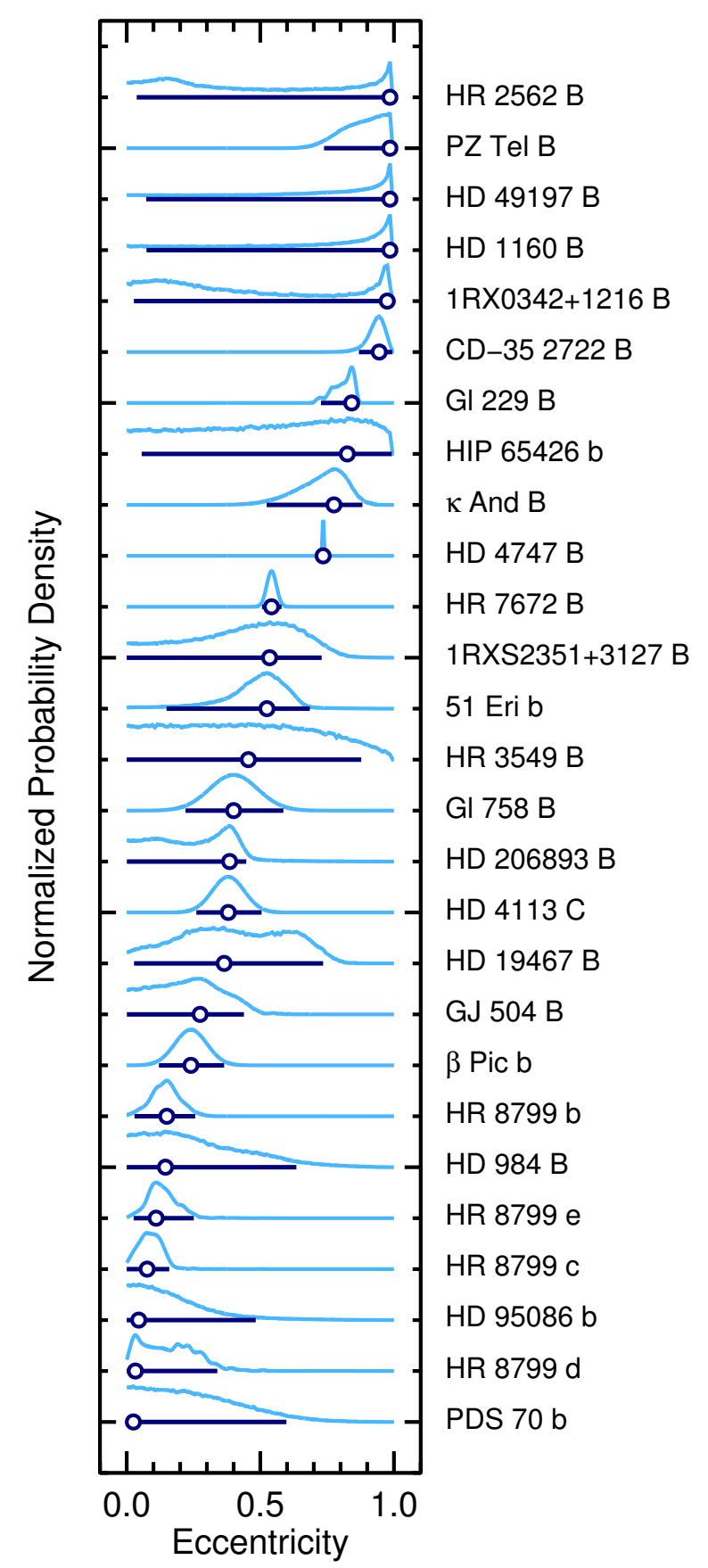


See also Gan et al. 2025,
Dawson & Murray-Clay 2013

More clues from orbital eccentricities



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



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

Just a few open questions:

What is the occurrence rate of multiple giant planets?

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 relationship between giant planets and habitability?

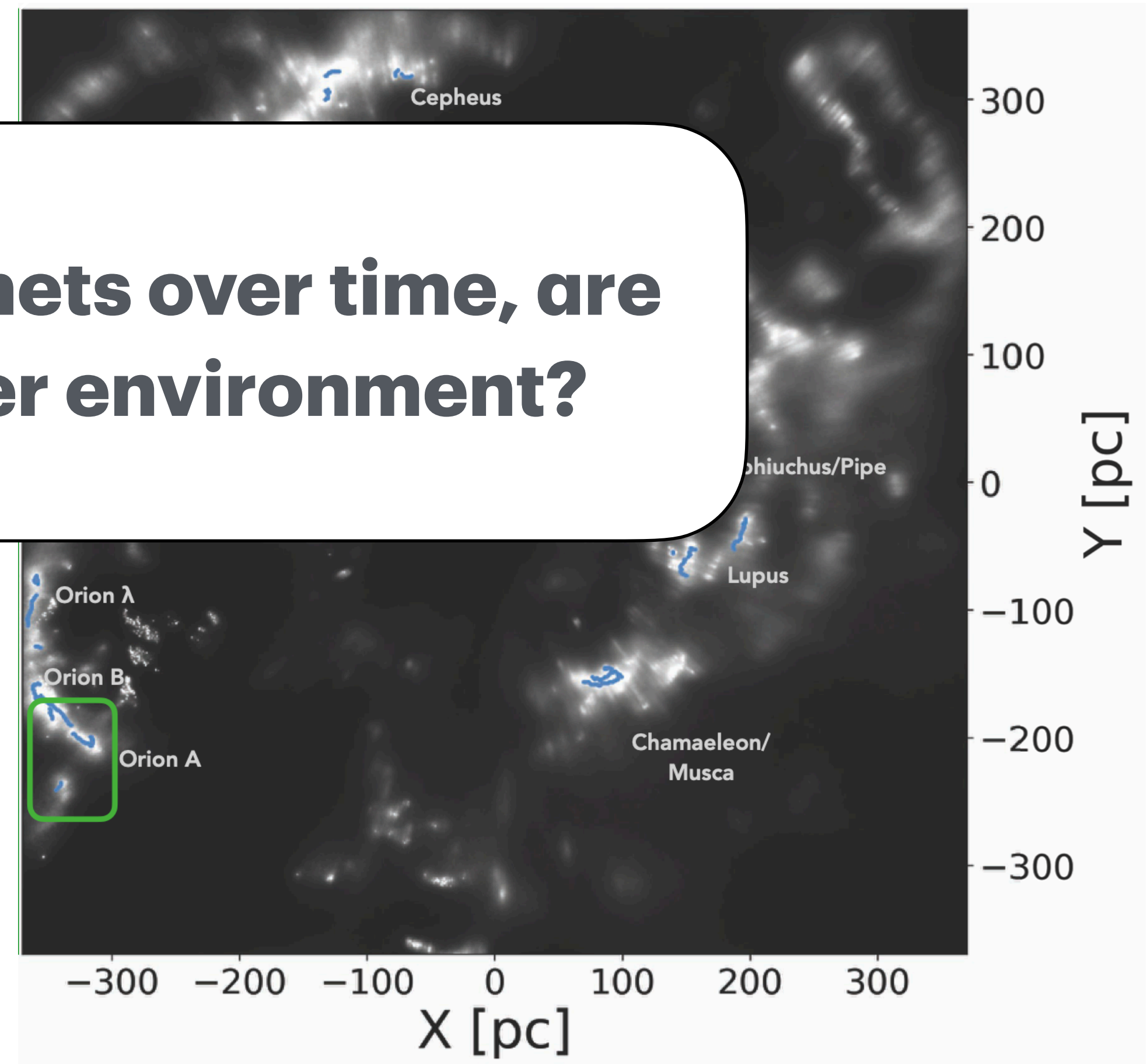
Are we correctly interpreting correlations?

Most stars in the solar neighborhood formed in rich clusters with hundreds to thousands of stars (Lada & Lada 2003).

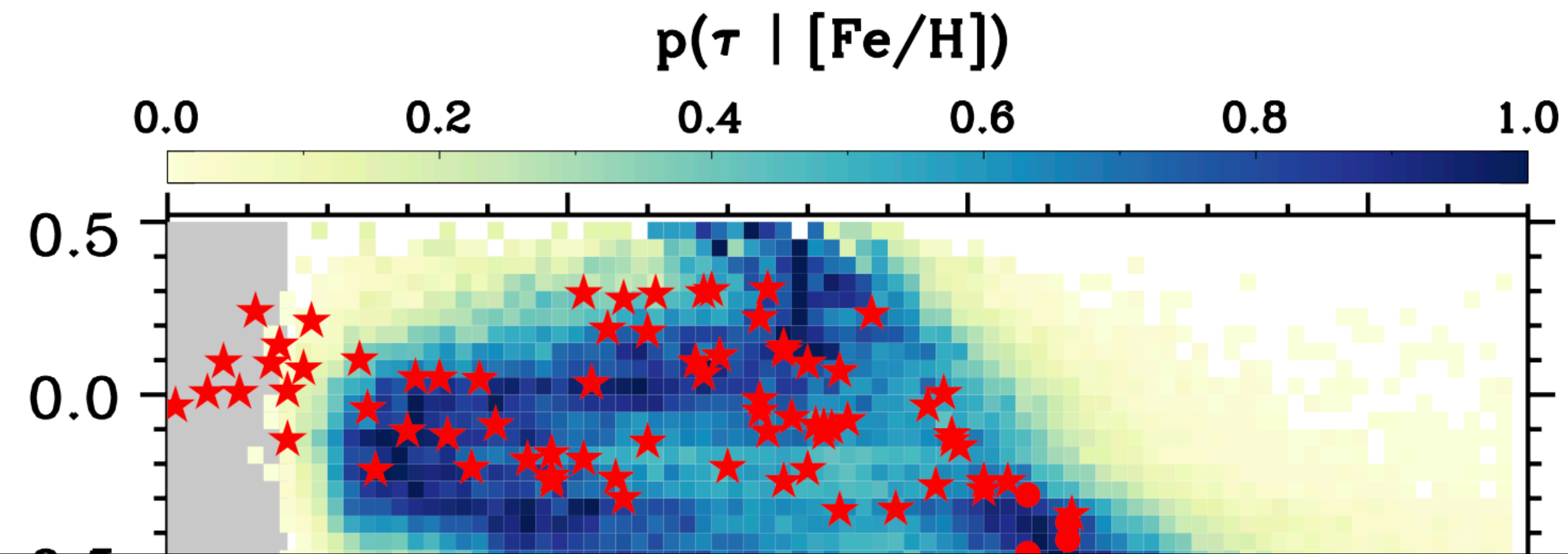
Most protoplanetary disks and young imaged planets orbit small clusters and moving groups.

When we think we're probing planets over time, are we actually probing birth cluster environment?

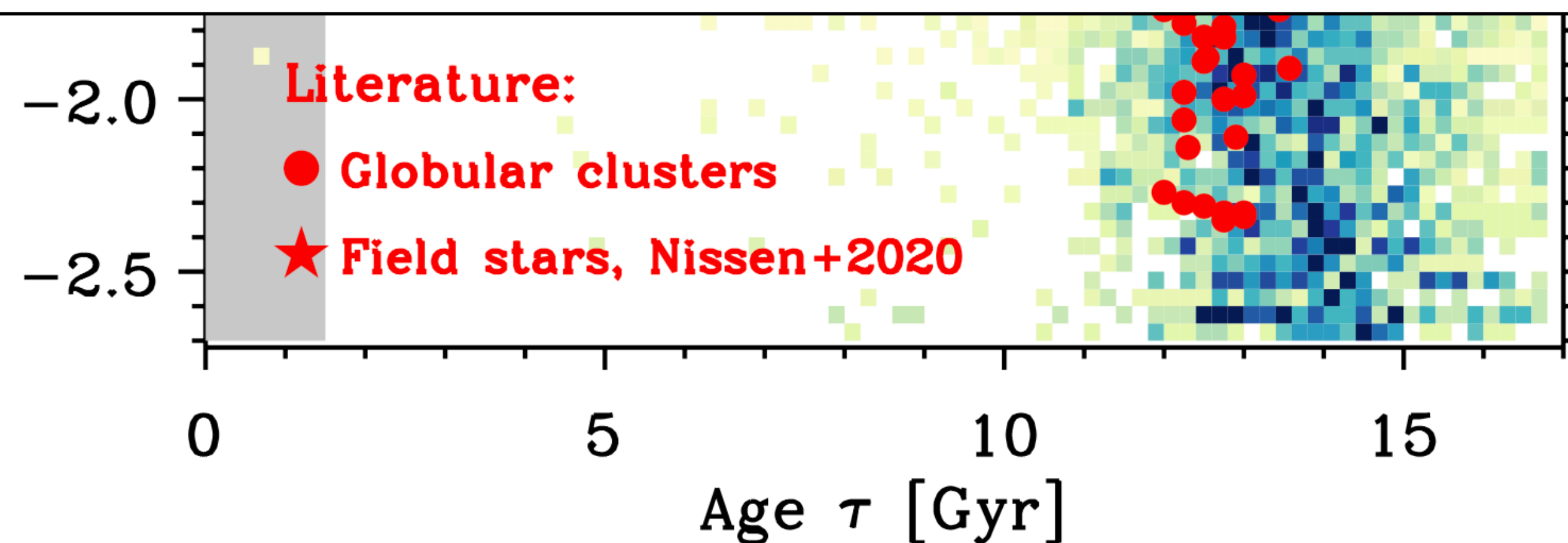
Zucker et al. 2023



There is a strong (and complex) relationship between stellar abundance and age.



When we think we're probing metallicity, are we actually probing age—and therefore dynamical evolution?



Gaia

DR4
2026

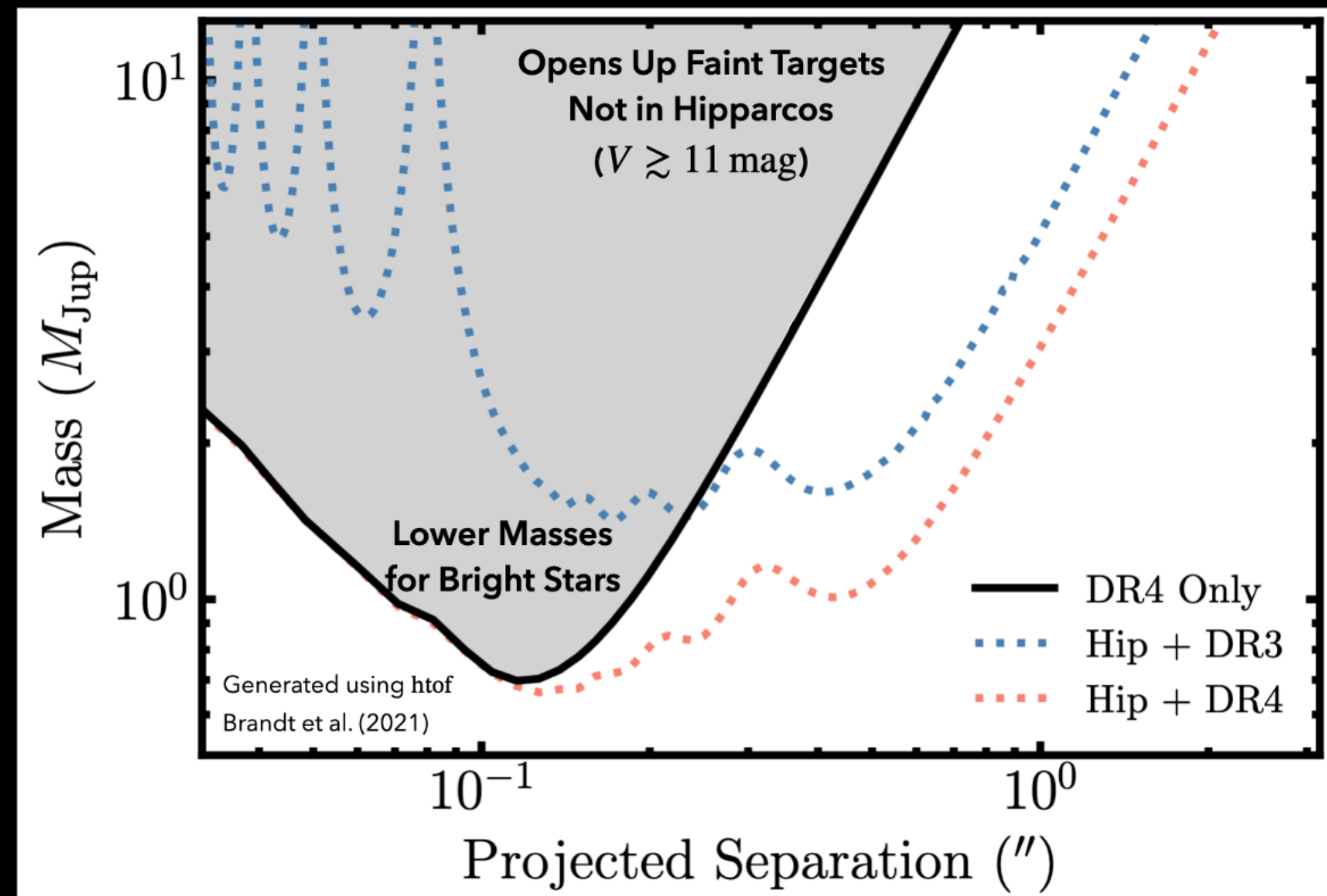
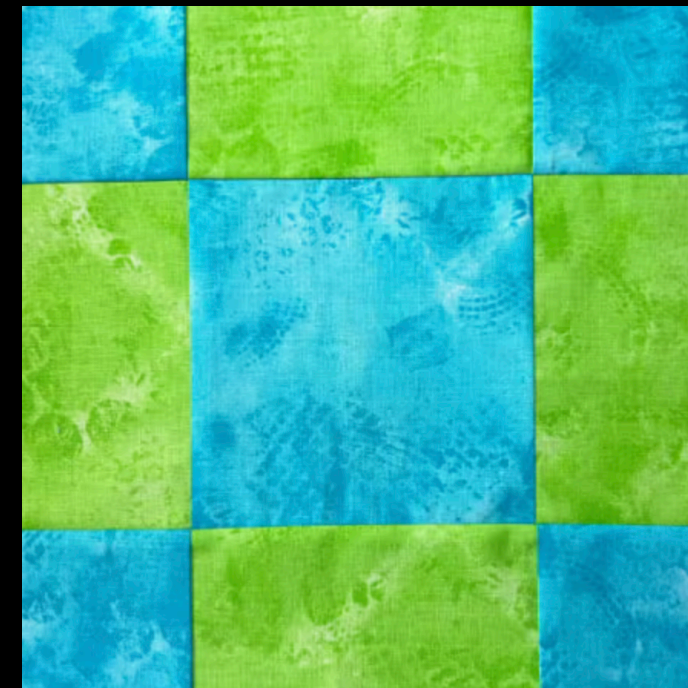
DR5
2030?

DR3
2022

Astrometry is (mostly) insensitive to stellar age.

Planets can't hide from astrometry

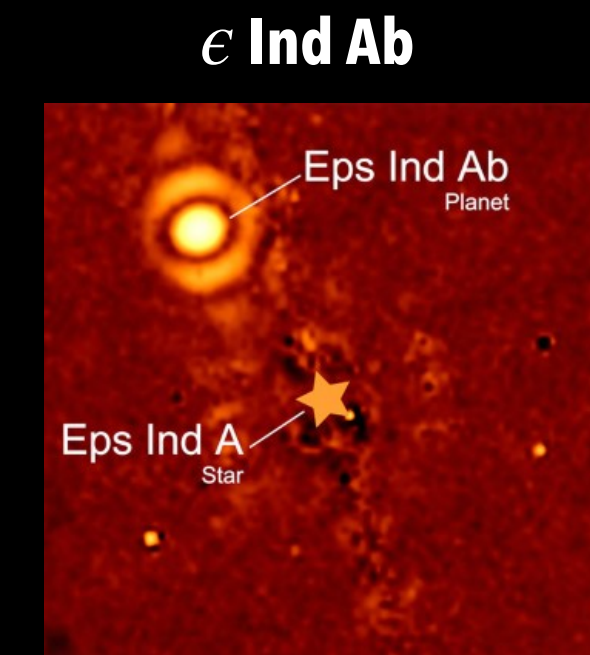
Demographics with Gaia DR4 (astrometry)



Courtesy Kyle Franson

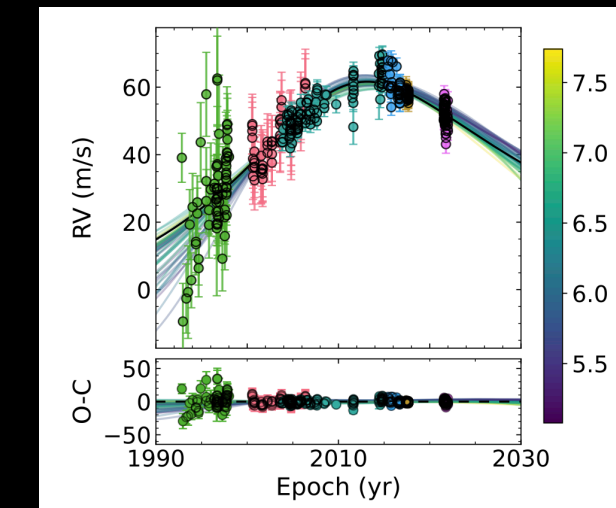
Closing the gap with multiple techniques...

RV + Astrometry + Imaging



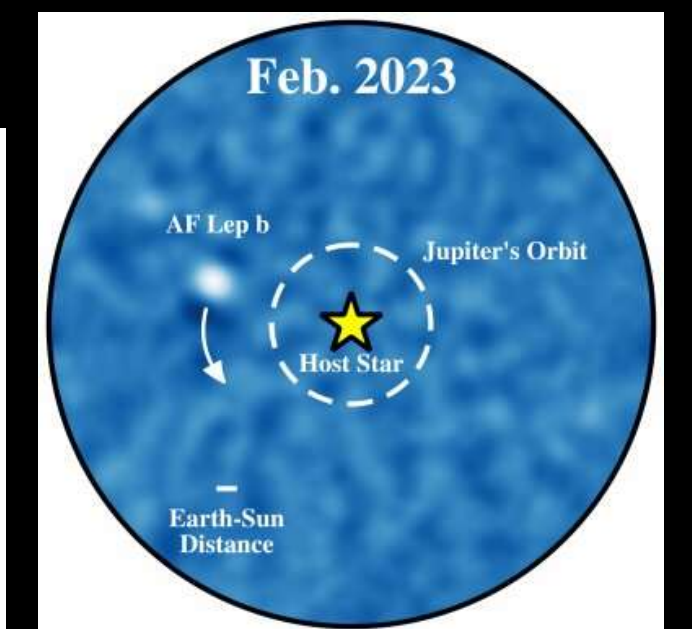
Matthews et al. 2024

→ 8 AU

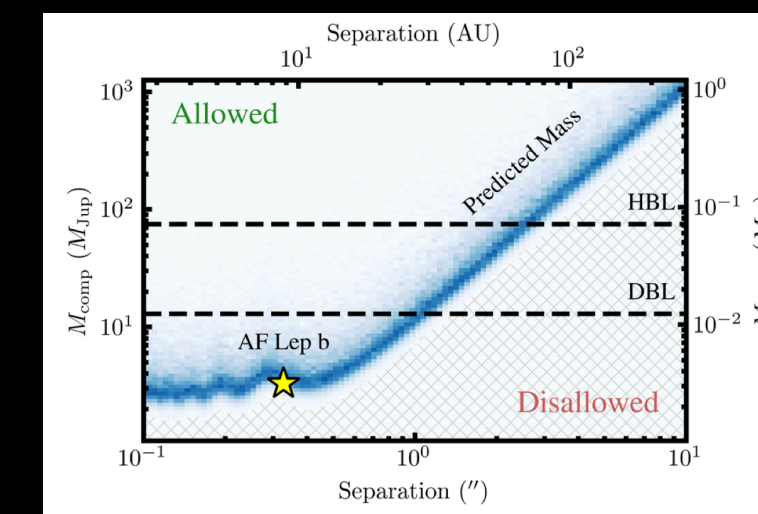


→ 15 AU

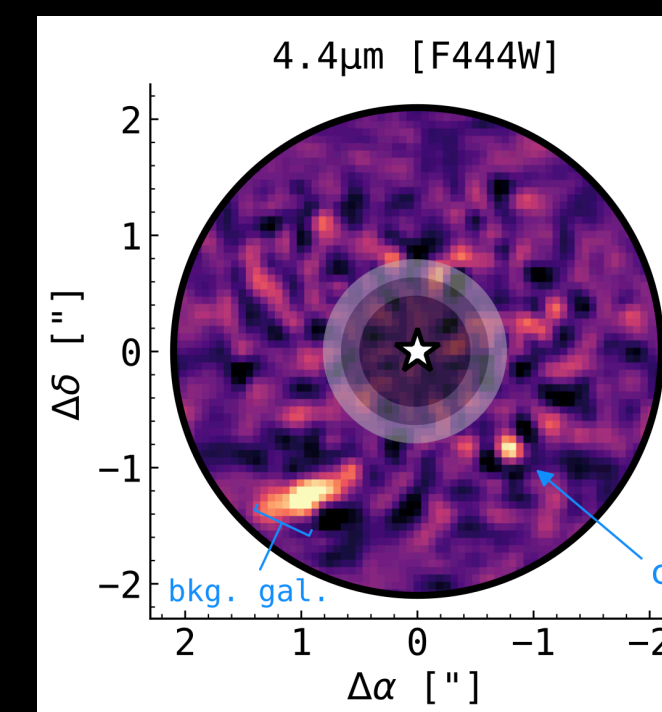
AF Lep b



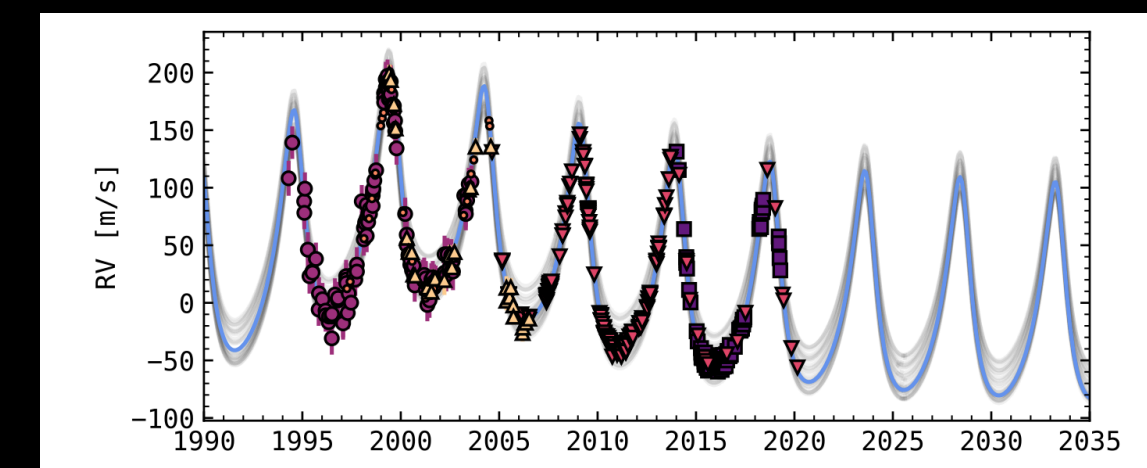
Franson et al. 2023;
Mesa et al. 2023;
de Rosa et al. 2023



14 Her c



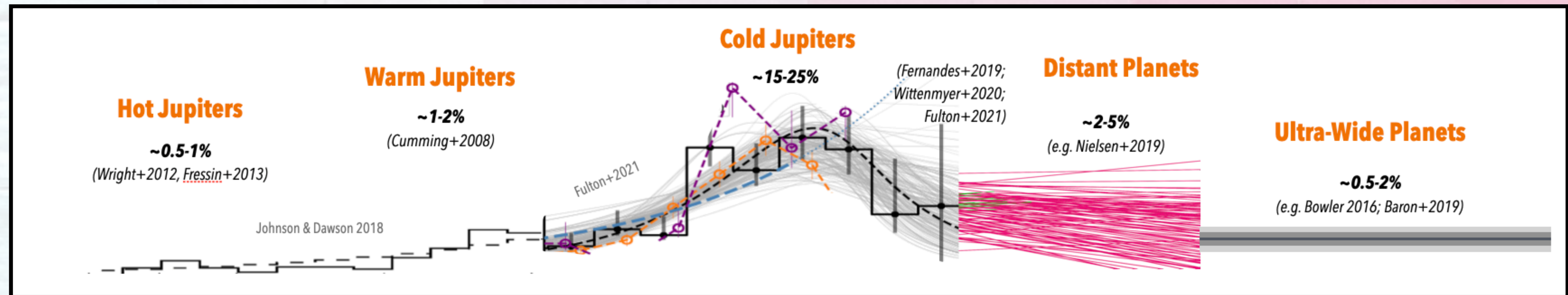
Bardalez-Gagliuffi et al. 2025



→ 20 AU

Takeaway points

- **Giant planet architectures and demographics is a patchwork of largely distinct stellar and planetary parameters**



- The prevalence of Hot and Warm Jupiters strongly correlates with stellar metallicity and mass
- A general peak in the giant planet radial distribution at ~3-10 AU is robust
- Strong signs that giant planets and brown dwarfs are distinct populations
- Most giant planets are dynamically excited
- Gaia DR4 and DR5 will probe giant planet architectures and evolution from 1-10 AU
- Looking ahead, multiple techniques offer the best way to close this gap to inform how, when, and where planets form and migrate