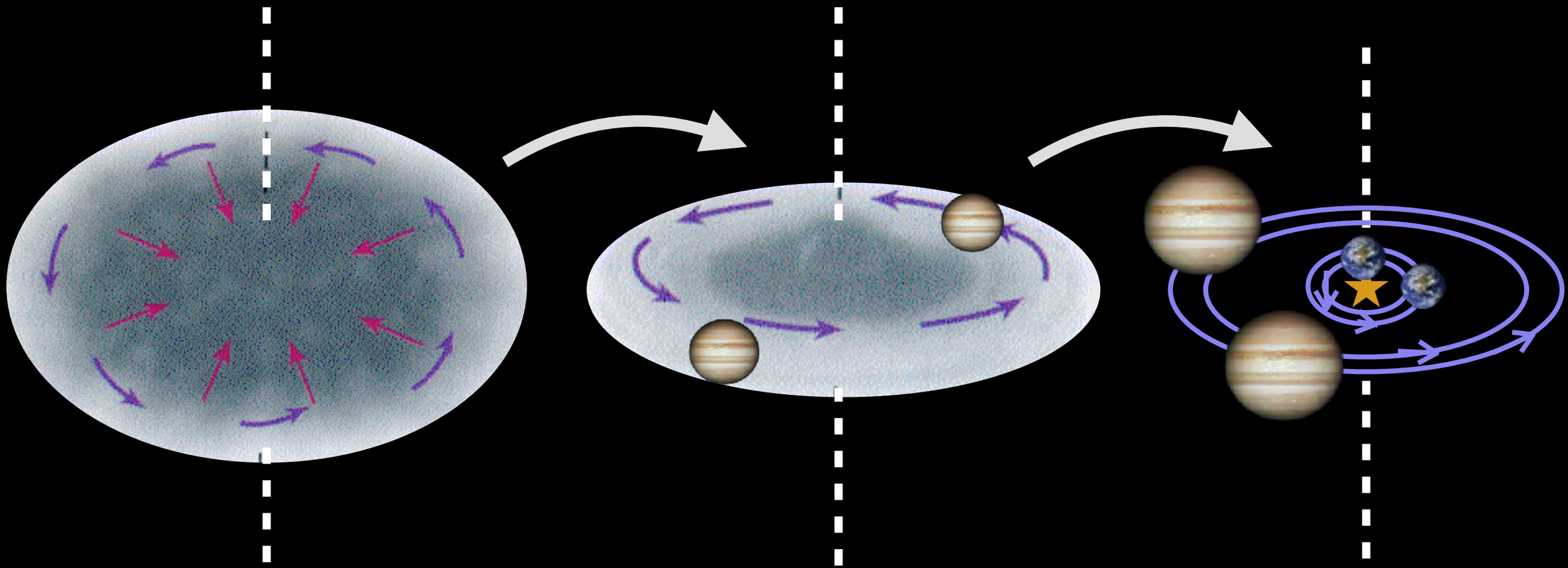
Origins of Hot Jupiters

Rebekah Dawson, Penn State, Center for Exoplanets and Habitable Worlds
ESO Exoplanet Atmospheres Workshop, August 27 2021

Pre-Exoplanets/Kuiper belt

ORIGINS OF PLANETARY SYSTEMS
TEXTBOOK VERSION



collapsing cloud

gas disk

planetary system

Pre-Exoplanets/Kuiper belt

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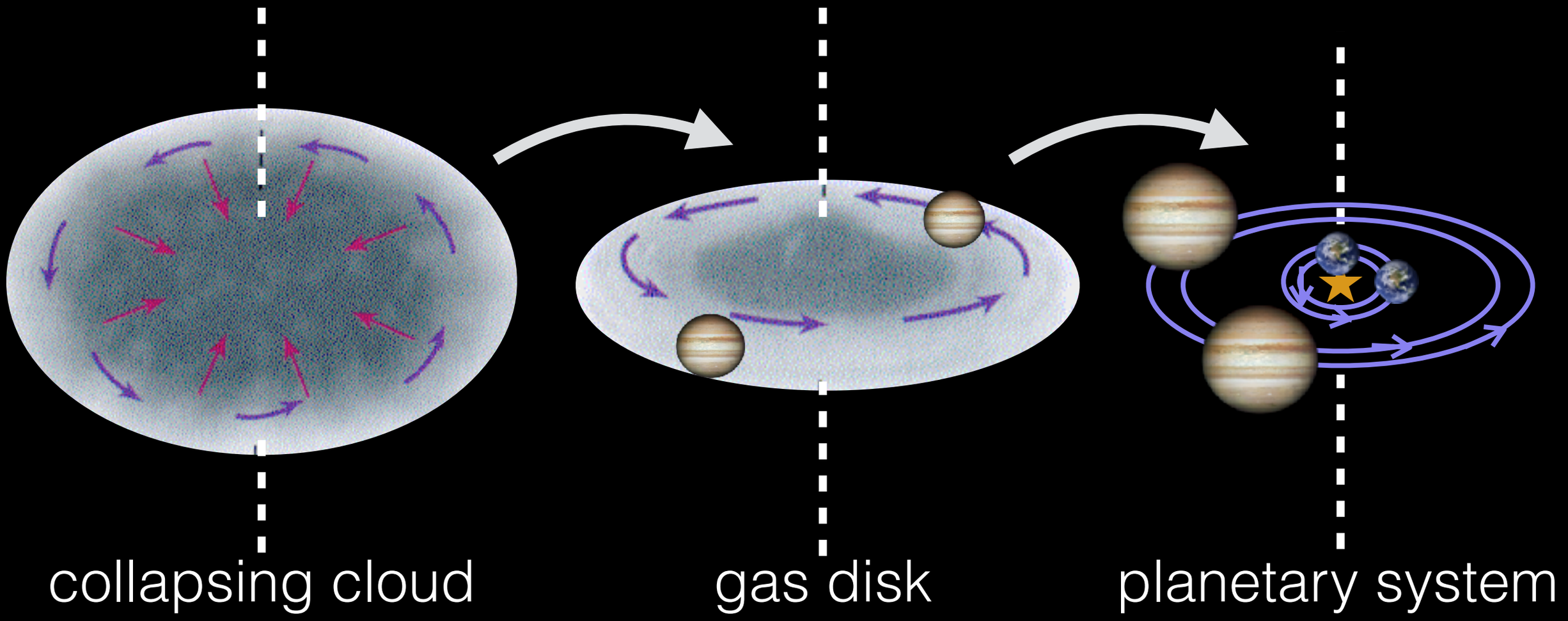
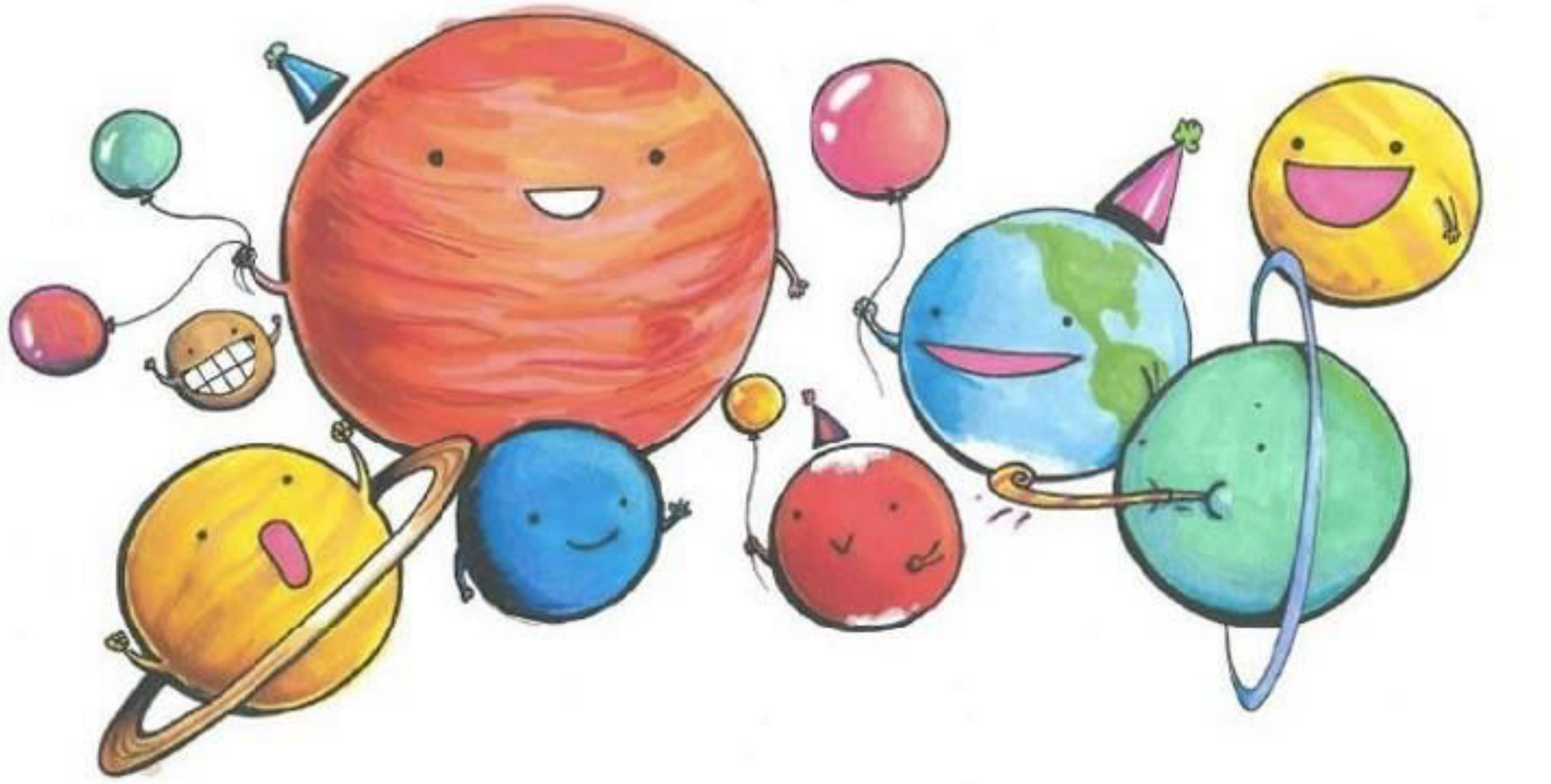


<u>Key Characteristics:</u>

- Rocky planets in inner region, gas giants in outer region
- Circular orbits (damped by gas)
- Planets orbit in same plane

R. Da

HOW DO YOU ORGANIZE A SPACE PARTY?



YOU PLANET.

R. Da

HOW DO YOU ORGANIZE A SPACE PARTY ?

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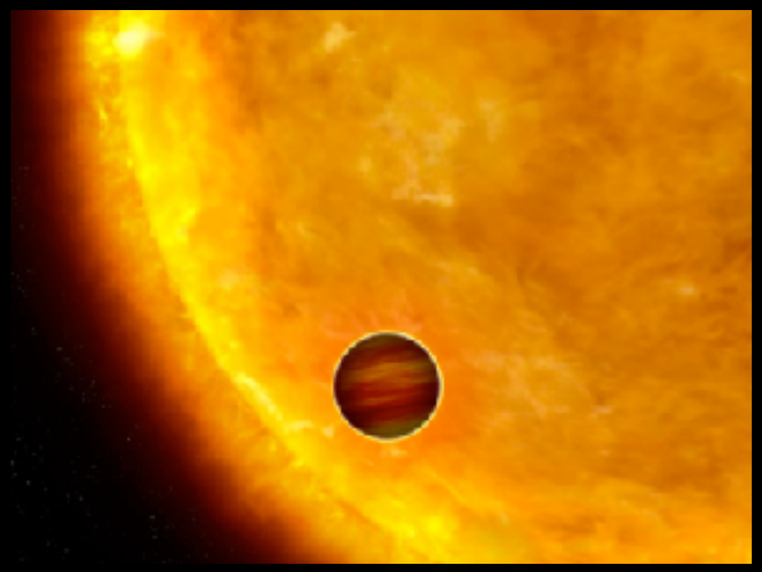
Unexpected guests: hot and warm Jupiters defy our expectations of how planets form and evolve

hot Jupiters

10x closer to their star than Mercury to the Sun



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highly elliptical orbits

e.g., HD 80606b
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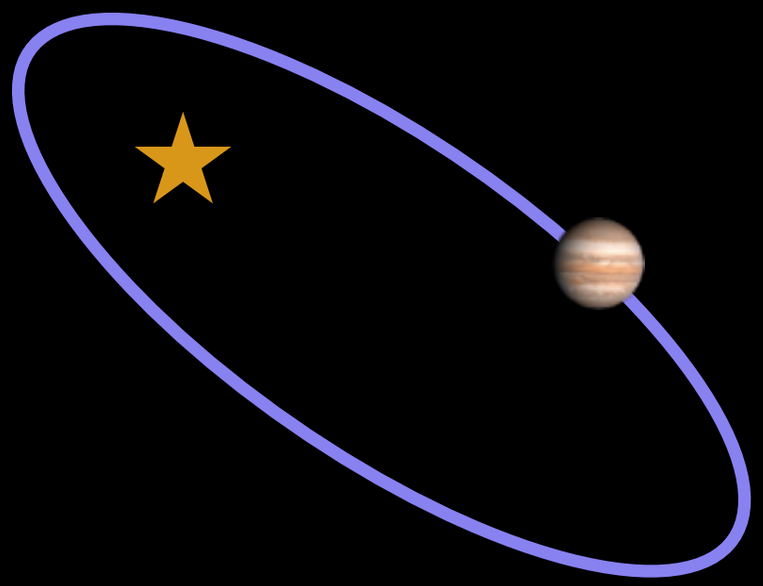

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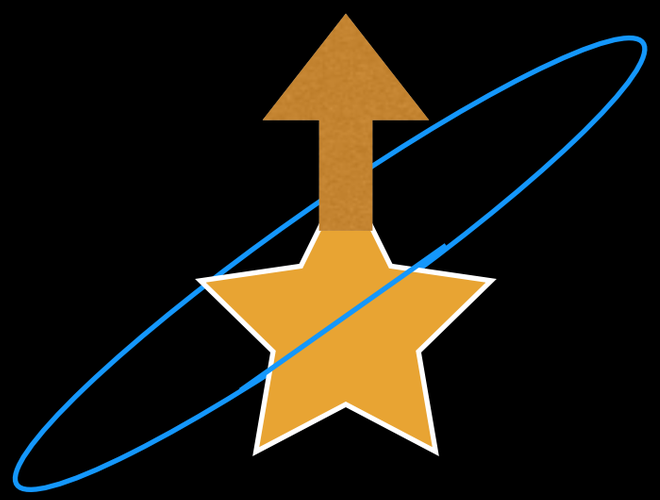

Hebrard+ 2008

Pre-Exoplanets/Kuiper belt

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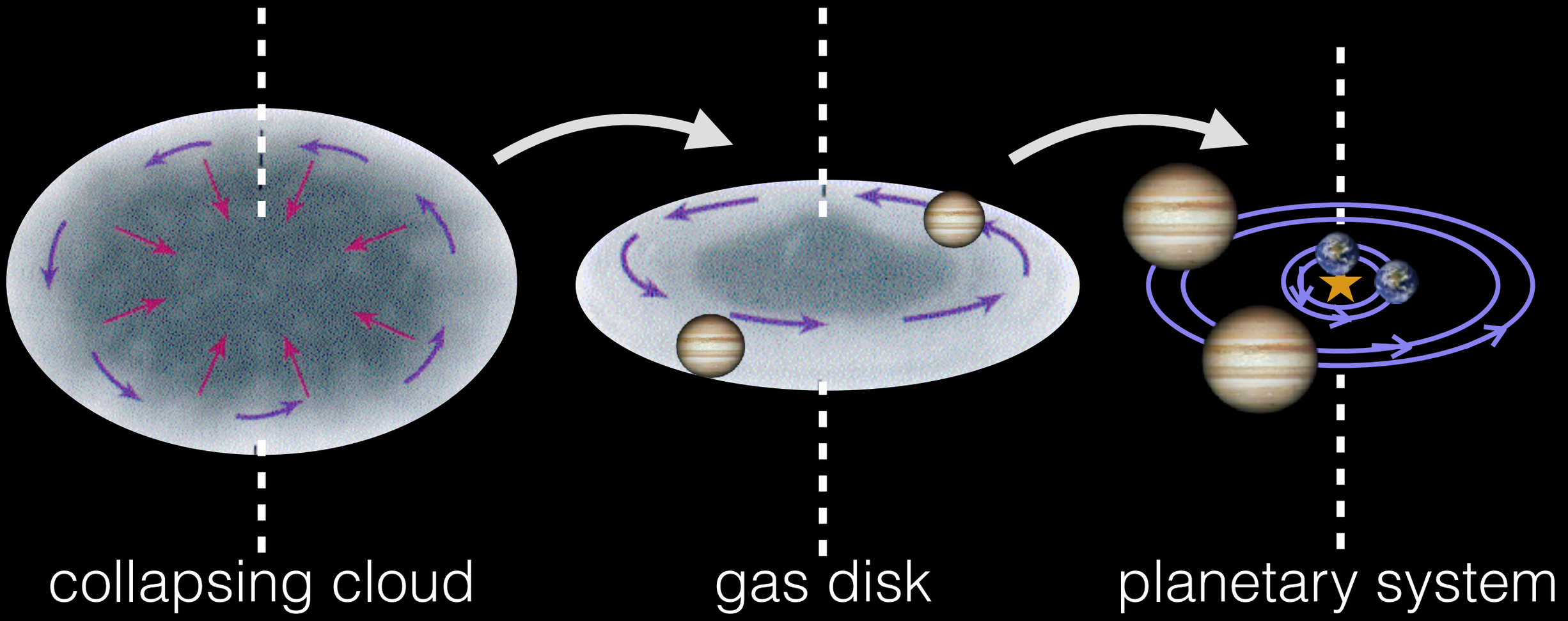

collapsing cloud gas disk planetary system

Key Characteristics:

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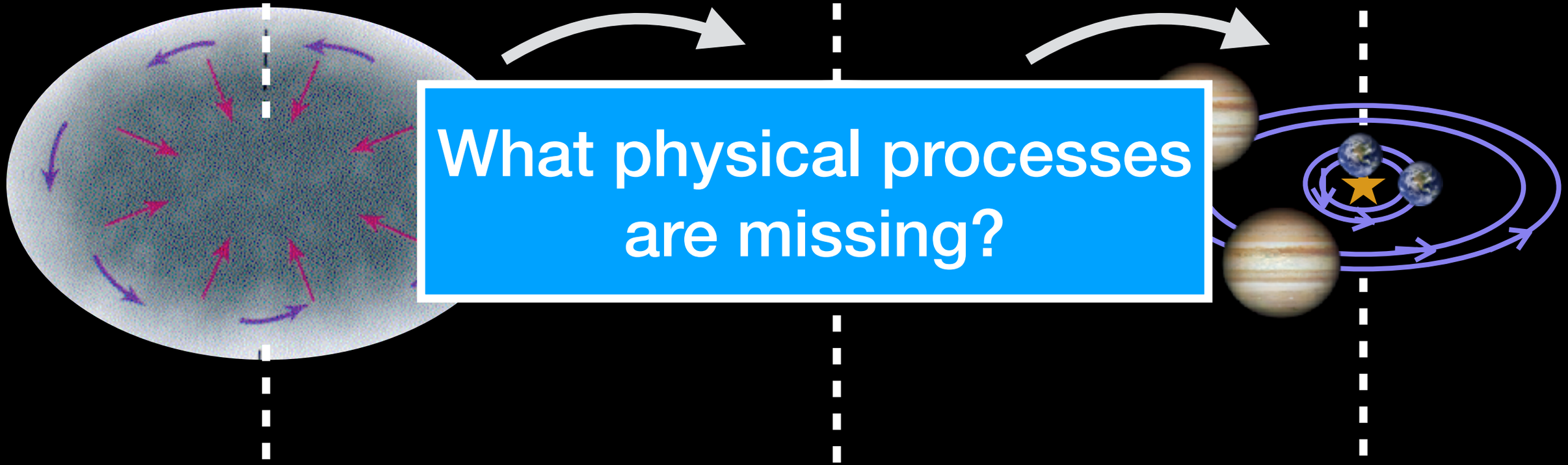
Pre-Exoplanets/Kuiper belt

ORIGINS OF PLANETARY SYSTEMS TEXTBOOK VERSION



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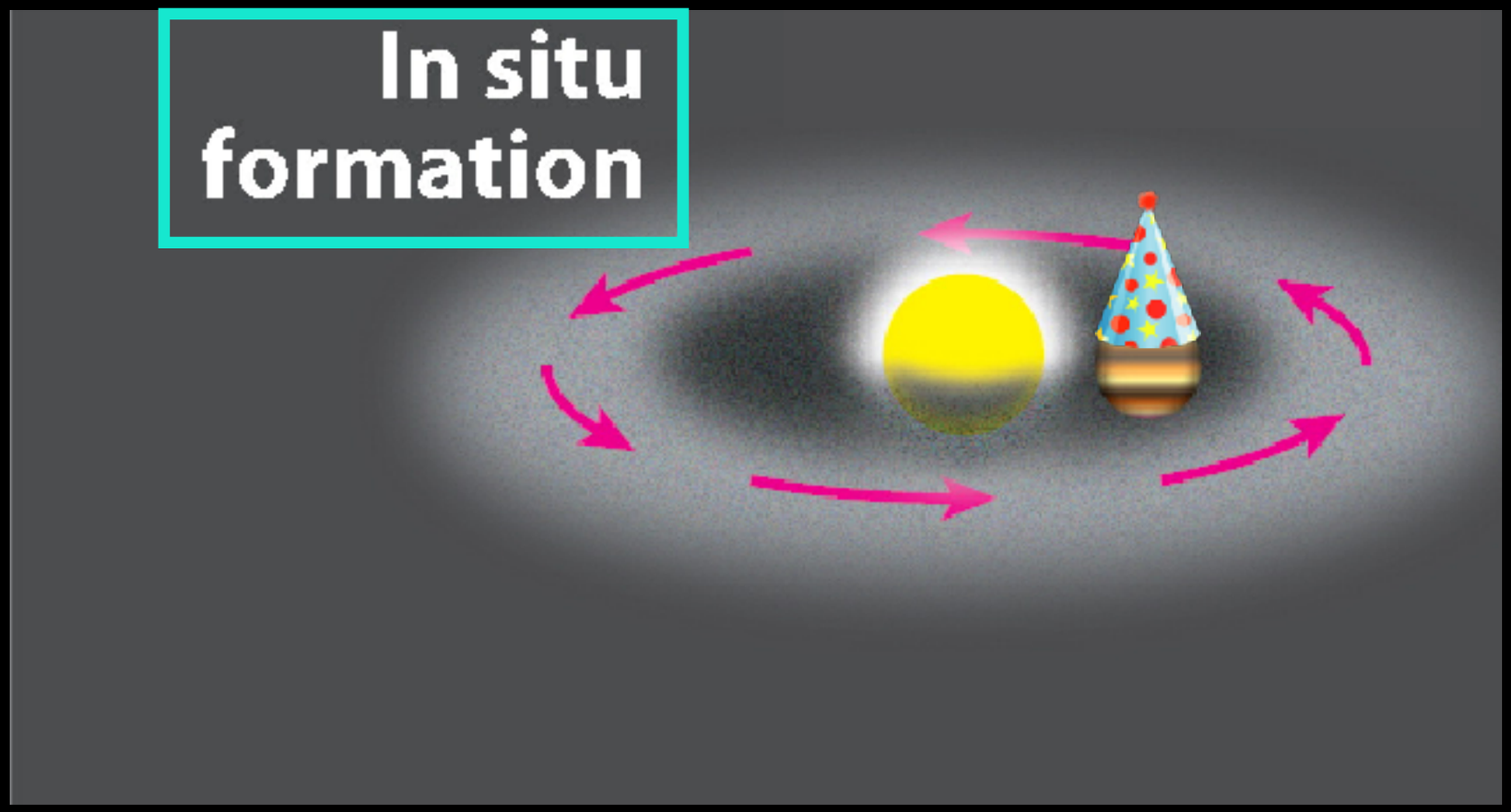
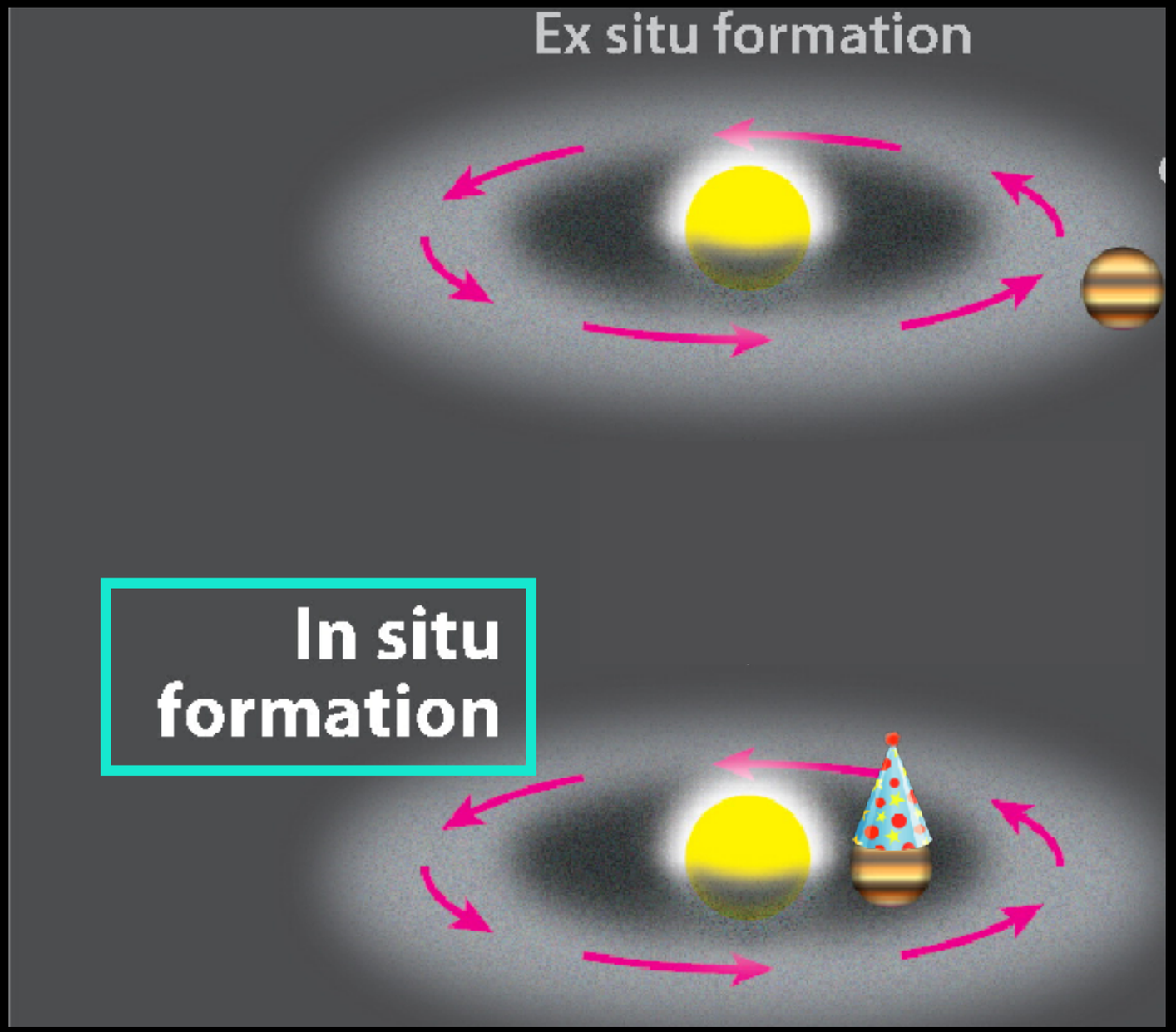
Three origins scenarios for giant planets close to their stars



RID & Johnson ARAA 18

Three origins scenarios for giant planets close to their stars



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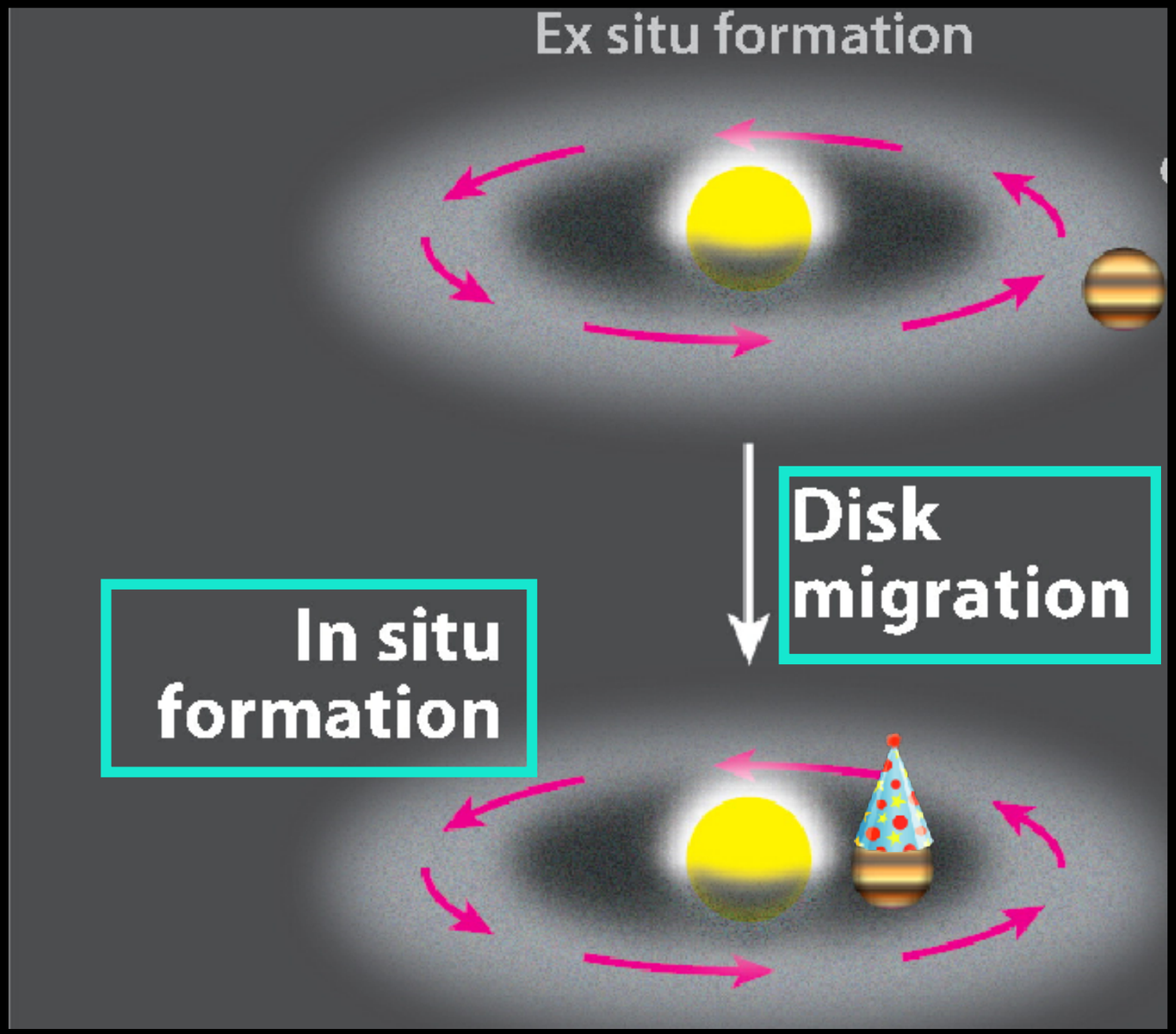

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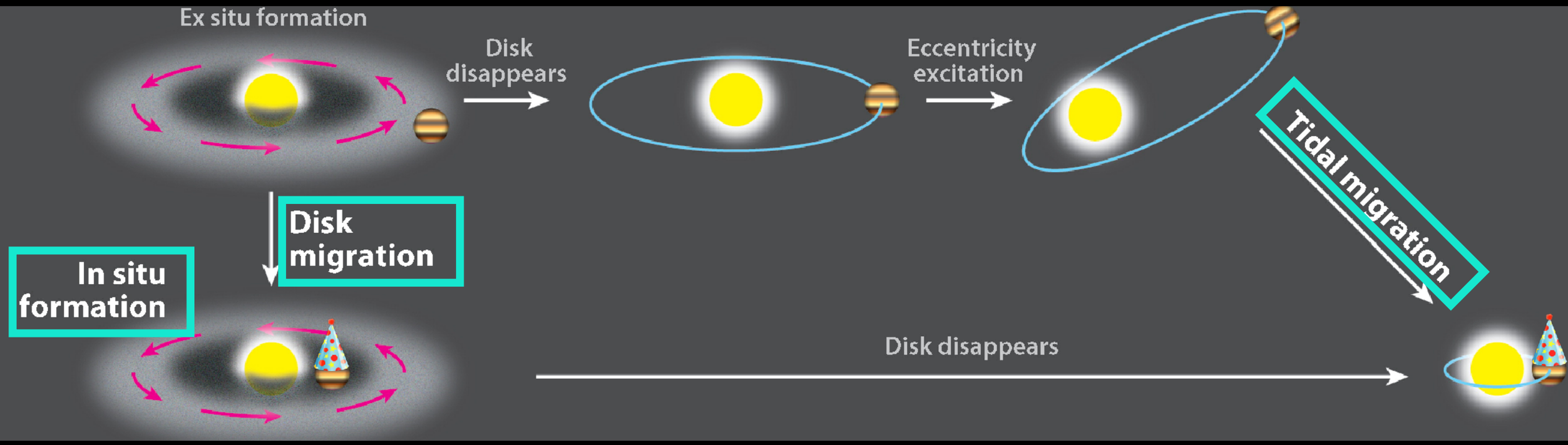

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~400 confirmed hot Jupiters: Testing theories using other properties

Hot Jupiters' other properties test origins theories

Comparisons to warm Jupiters, smaller planets

Age
Obliquity
Metallicity

Eccentricity
Semi-major axis
Occurence rates

Radius
Atmosphere

Companions (nearby, distant)

Evidence for (at least) two channels

Table 1 Evidence for origin hypotheses of hot Jupiters (HJs), including links to warm Jupiters (WJs)

Evidence	In situ formation (Section 2.1)	Disk migration (Section 2.2)	Tidal migration (Section 2.3)
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HJ obliquities (Section 3.2)	O	O	O
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HJ semimajor axes (Section 3.4)	✓	✓	✓
T Tauri HJs (Section 3.5)	✓	✓	X
Host star ages (Section 3.5)	O	O	O
Atmospheres (Section 3.6)	T	T	T
Occurrence rates (Section 4.1)	T	✓	X
Companions (Section 4.2)	X	X	✓
HJ versus WJ occurrence (Section 4.3)	X	✓	X
Circular WJs (Section 4.3)	✓	✓	X
Elliptical WJs (Section 4.3)	X	X	✓
Nearby WJ companions (Section 4.3)	✓	T	X
Small planets (Section 4.4)	X	X	T
Hot Neptunes (Section 4.4)	X	T	✓

Abbreviations: ✓, consistent; X, inconsistent; T, no clear prediction from theory yet; O, additional or complementary observations needed.

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R. Dawson, Atmospheres, 27 Aug 21

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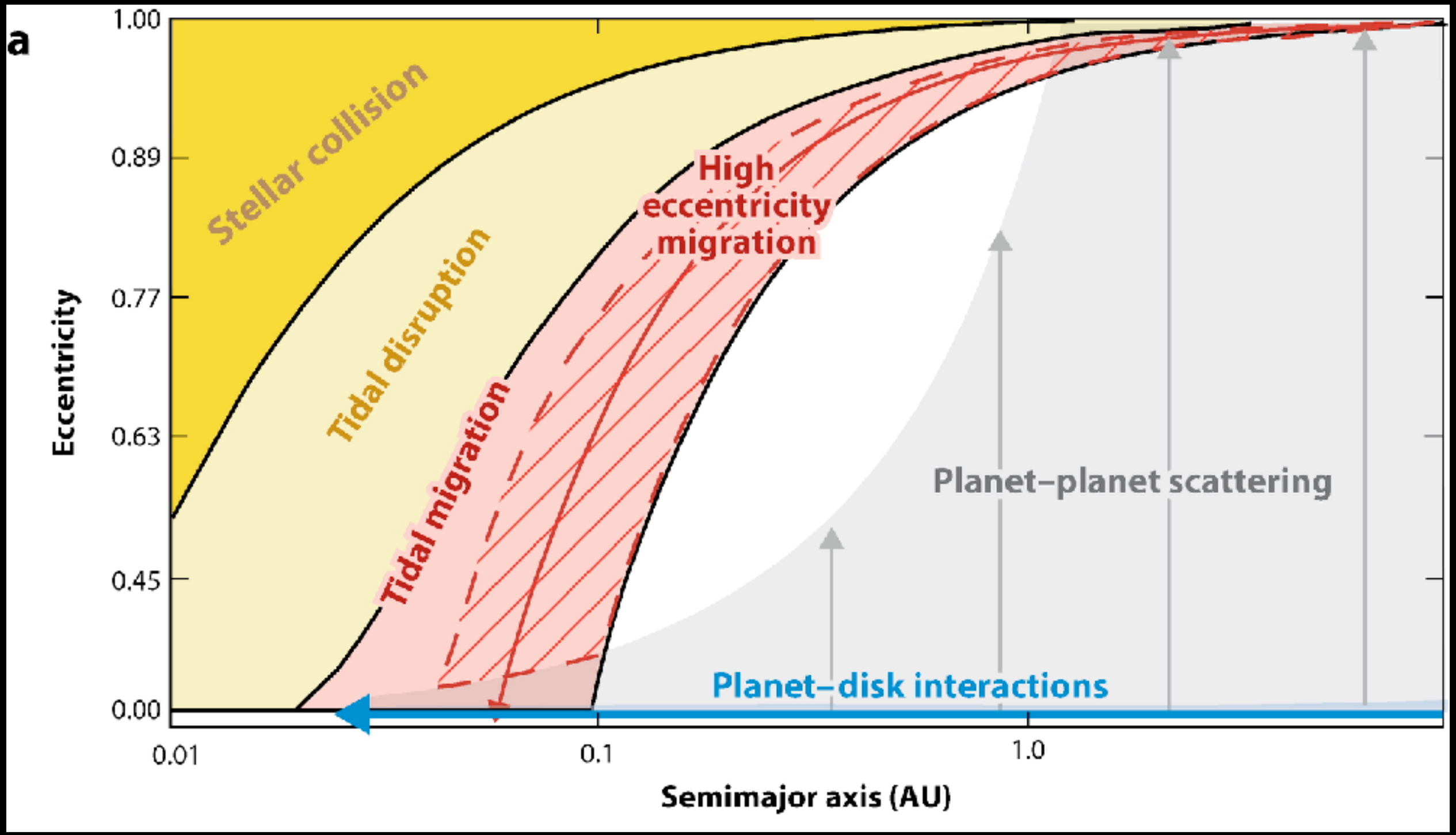

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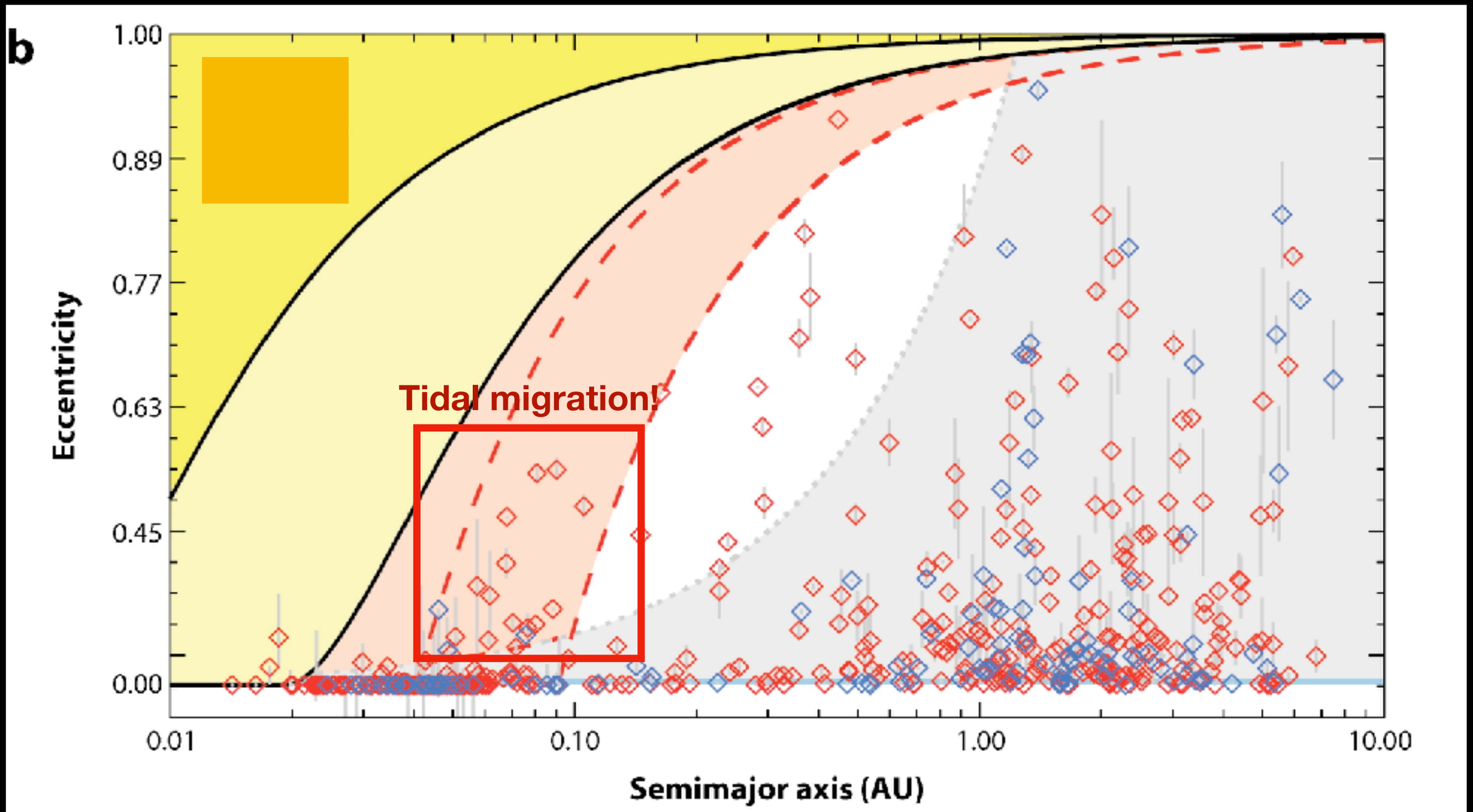

RID & Murray-Clay 13, RID & Johnson ARAA 18

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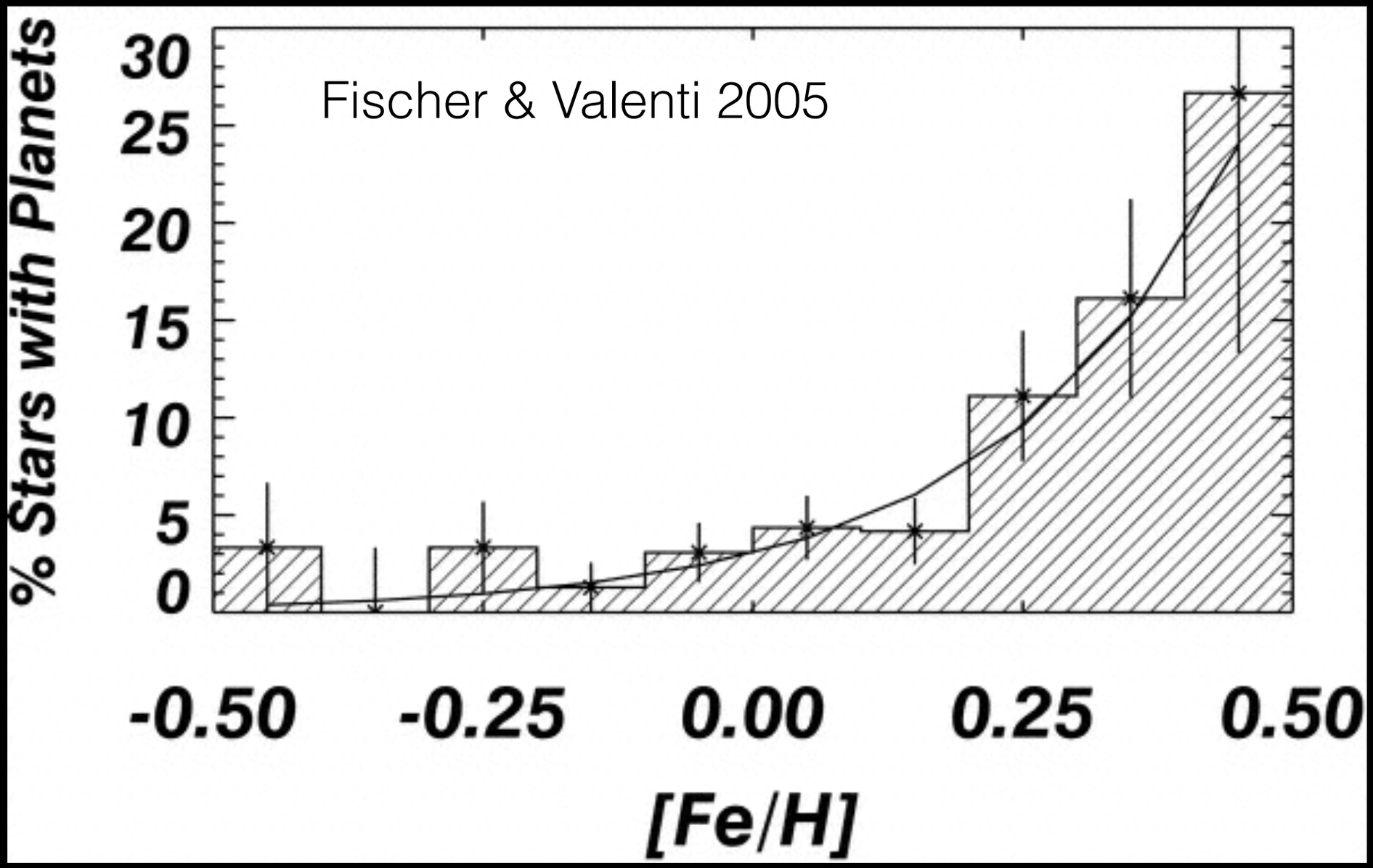
Giant planet metallicity correlation

gas giants



See also Santos+01,04

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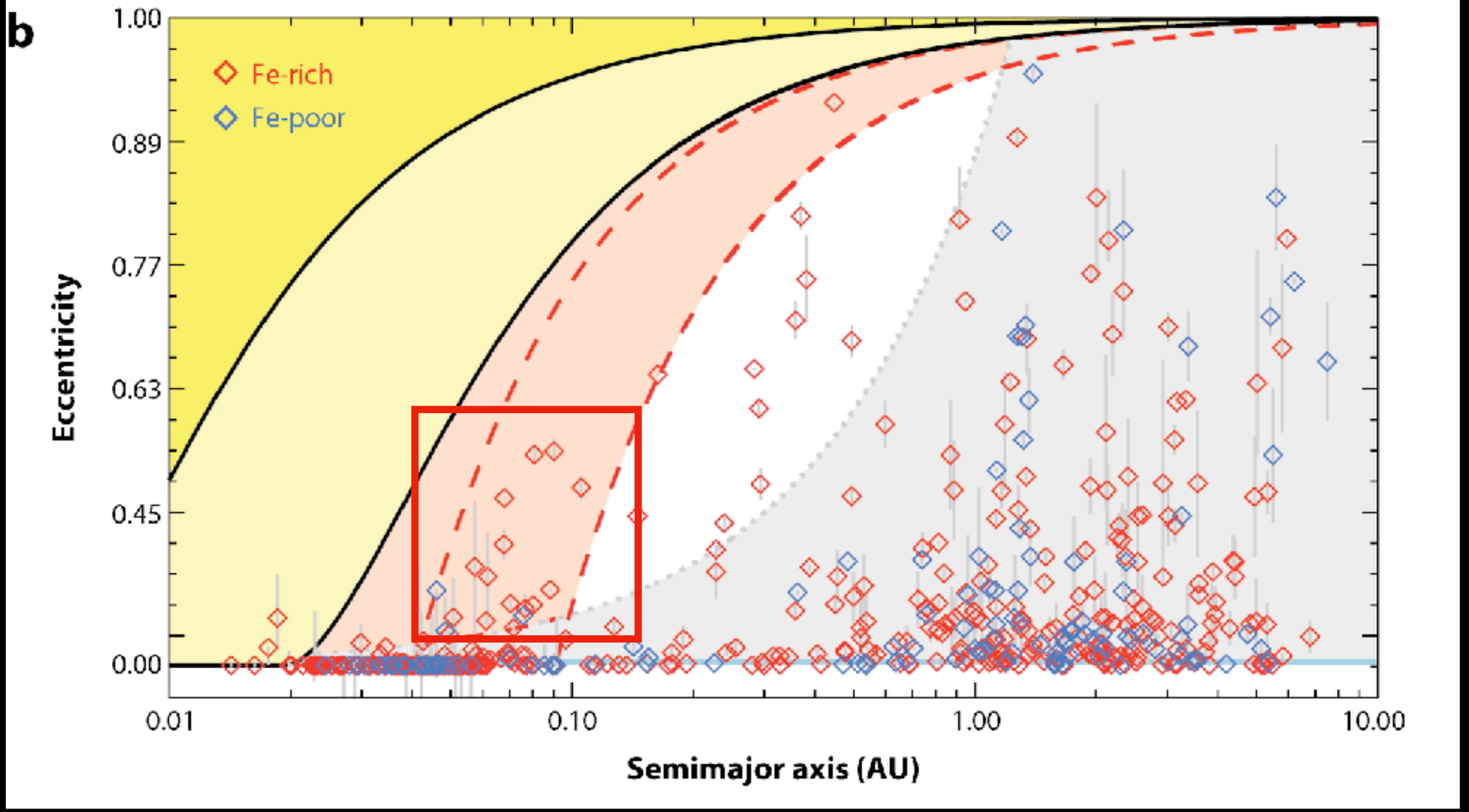

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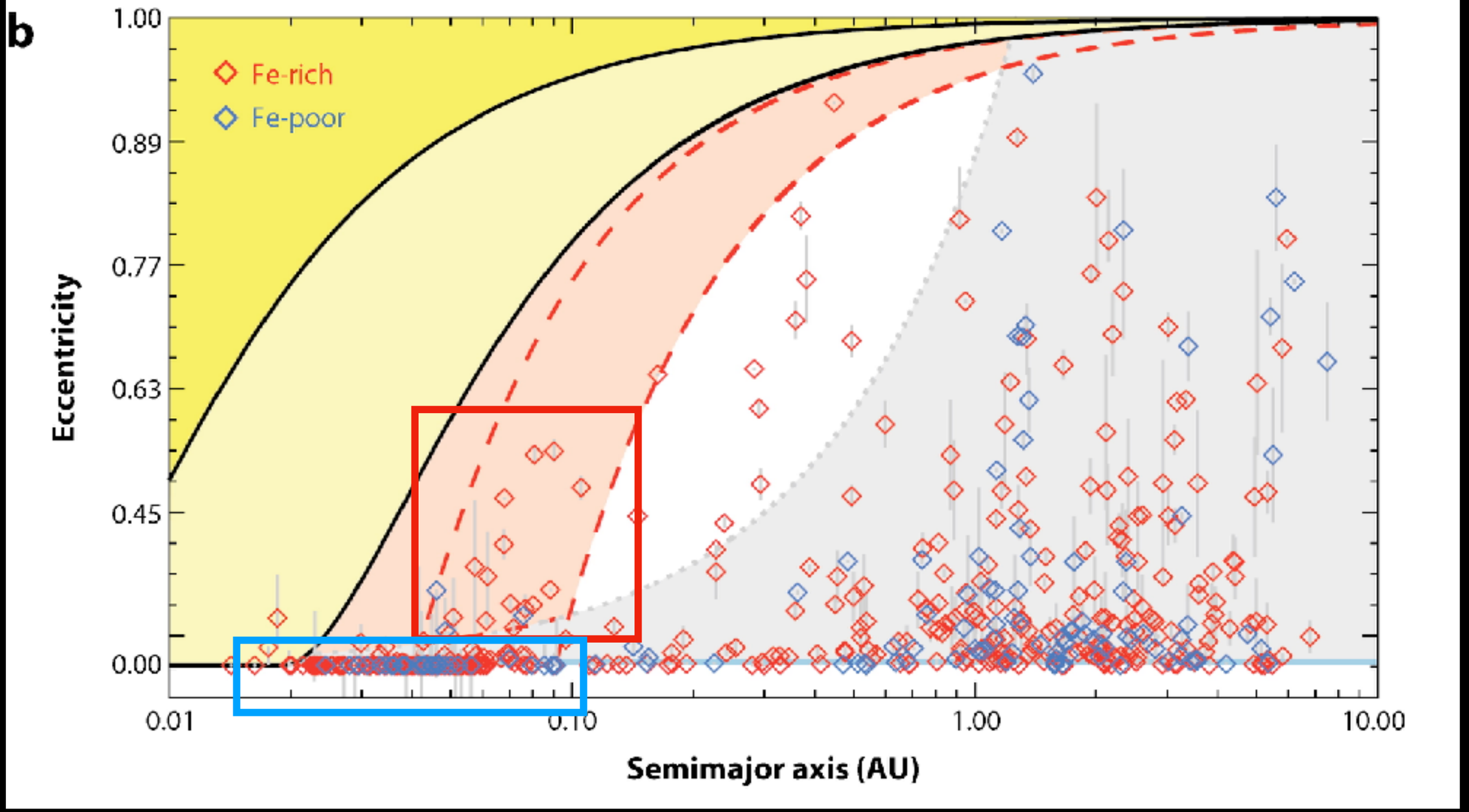
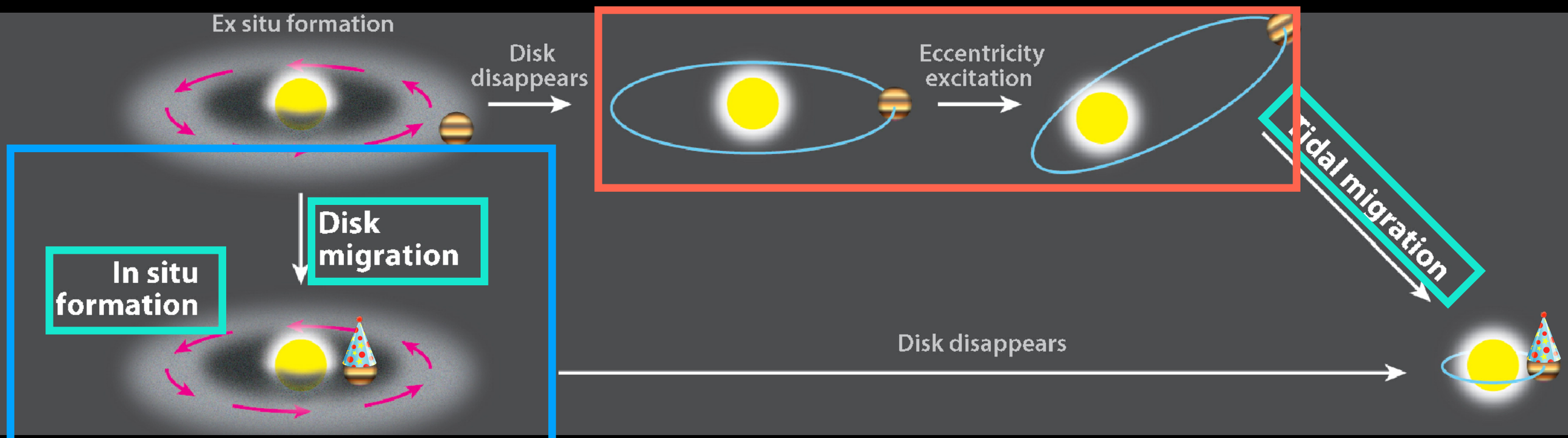


RID & Murray-Clay 13, RID & Johnson ARAA 18

Need two origins channels

Only happens around high metallicity stars: needs other giant planets?



Happens around Metal rich or metal poor stars

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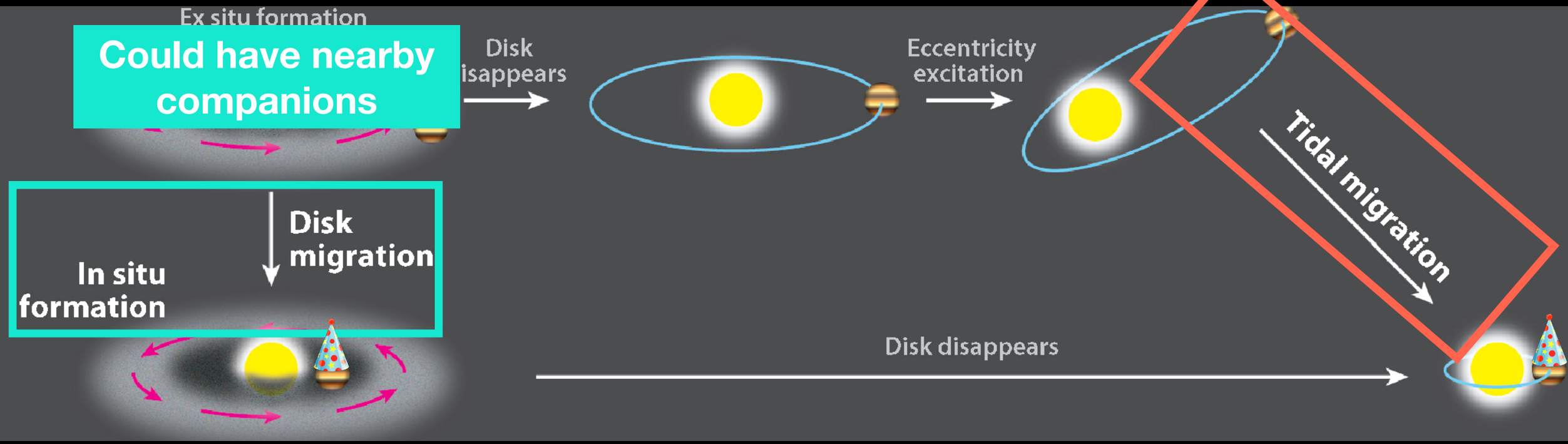
Companions (nearby, distant)

Small nearby planets ≠ tidal migration



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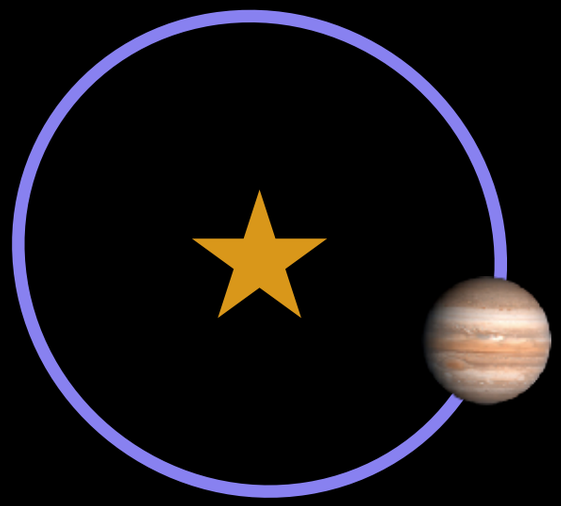
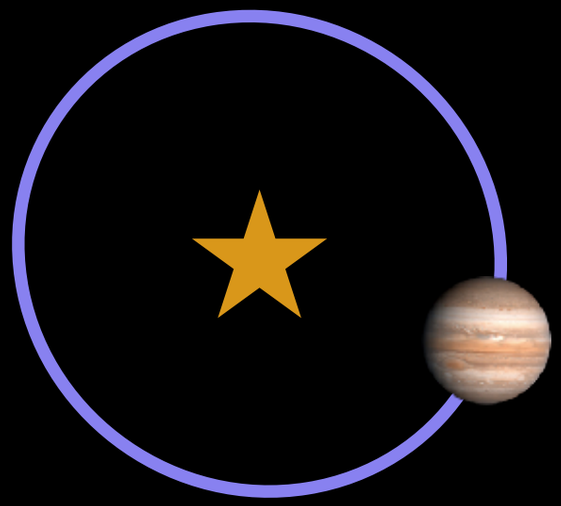


<u>Most</u> hot Jupiters lack nearby companions in contrast to other planets (Latham+ 11, Steffen+12, Huang+16) —> tidal migration



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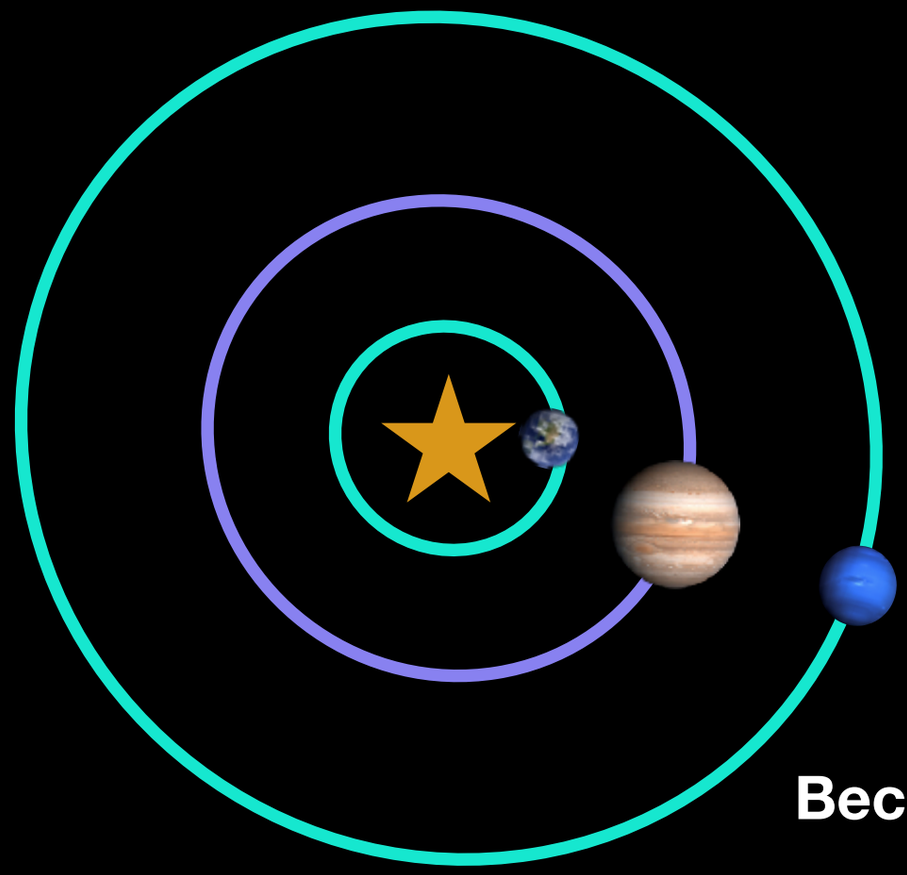

Becker 15

BUT **WASP-47b**
1.15 Jupiter radii
Orbital period 4.2 days

Two nearby companions discovered by K2

—> disk migration or In situ

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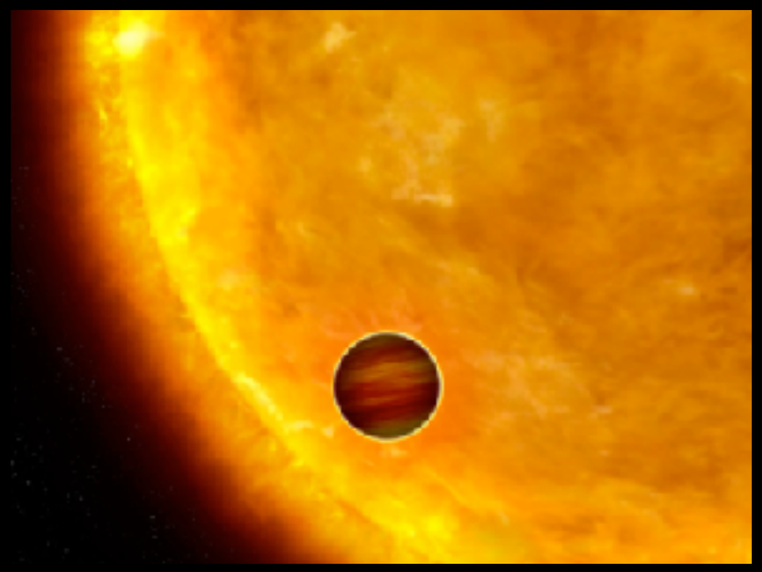
Unexpected guests: hot and warm Jupiters defy our expectations of how planets form and evolve

hot Jupiters

10x closer to their star than Mercury to the Sun



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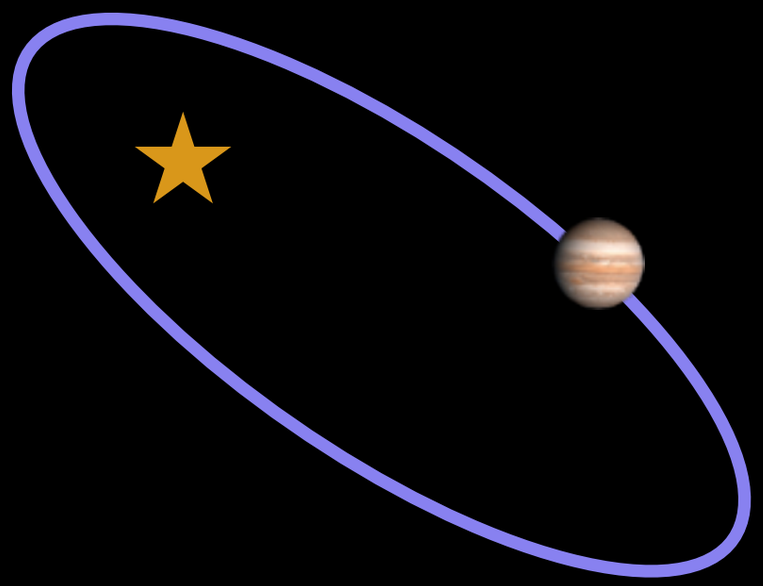
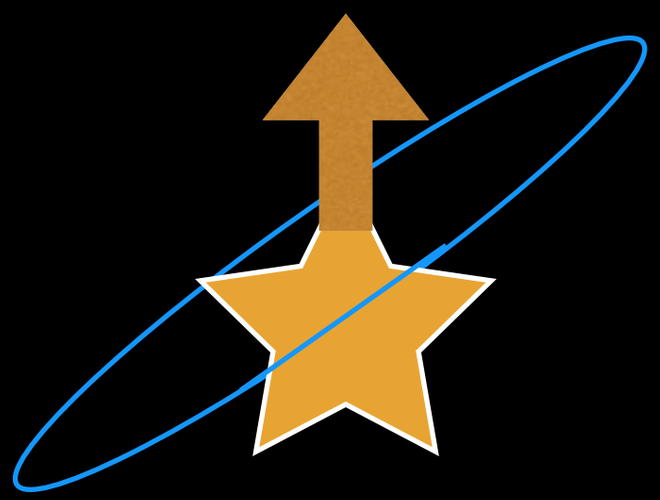


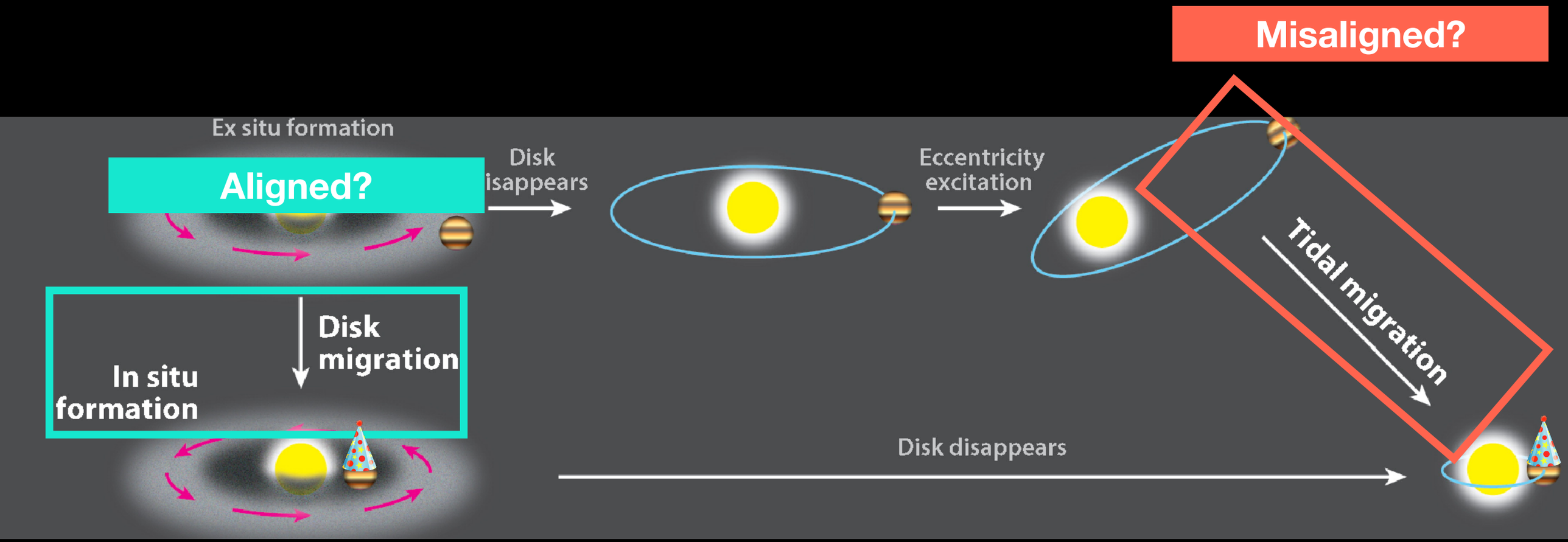
Naef+ 2001

misaligned from host star's spin axis



Hebrard+ 2008

Does misalignment with host star's spin reflect origins channel?



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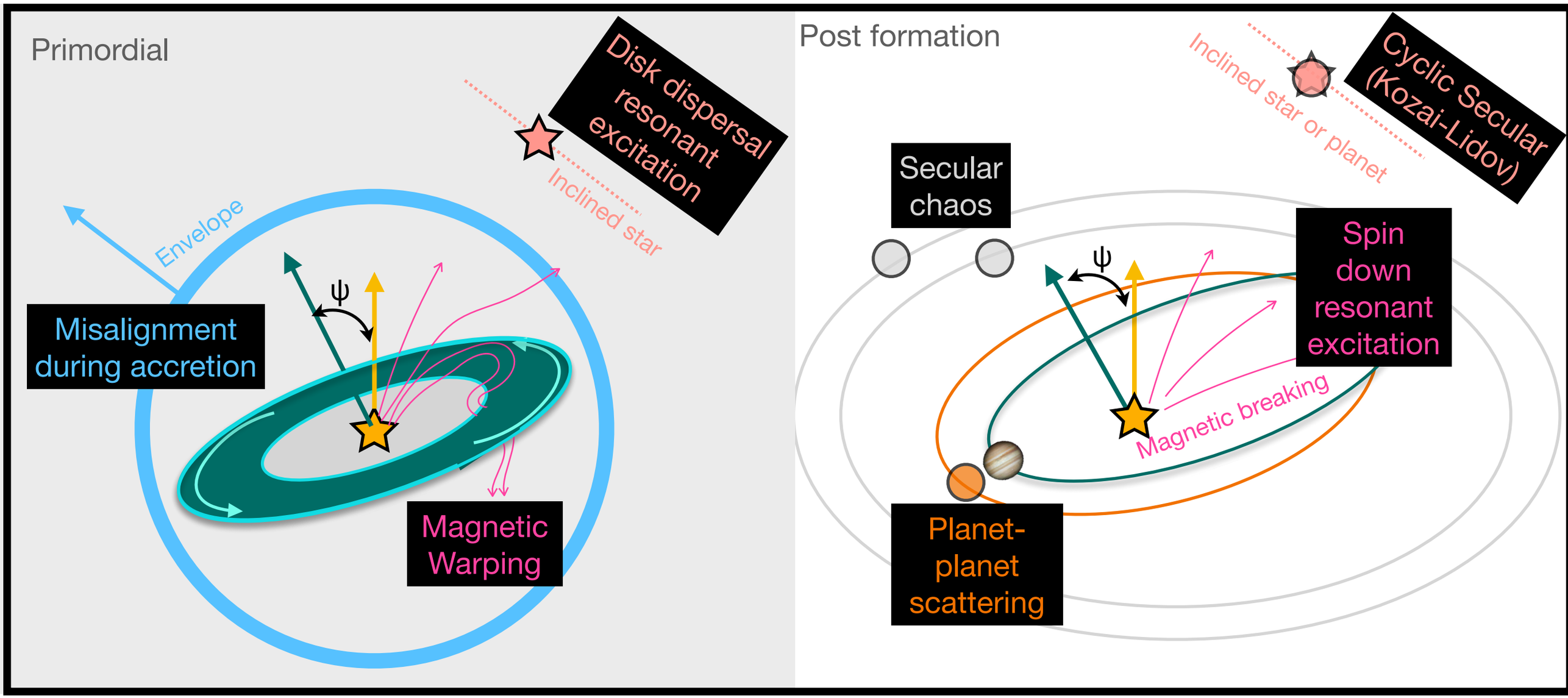
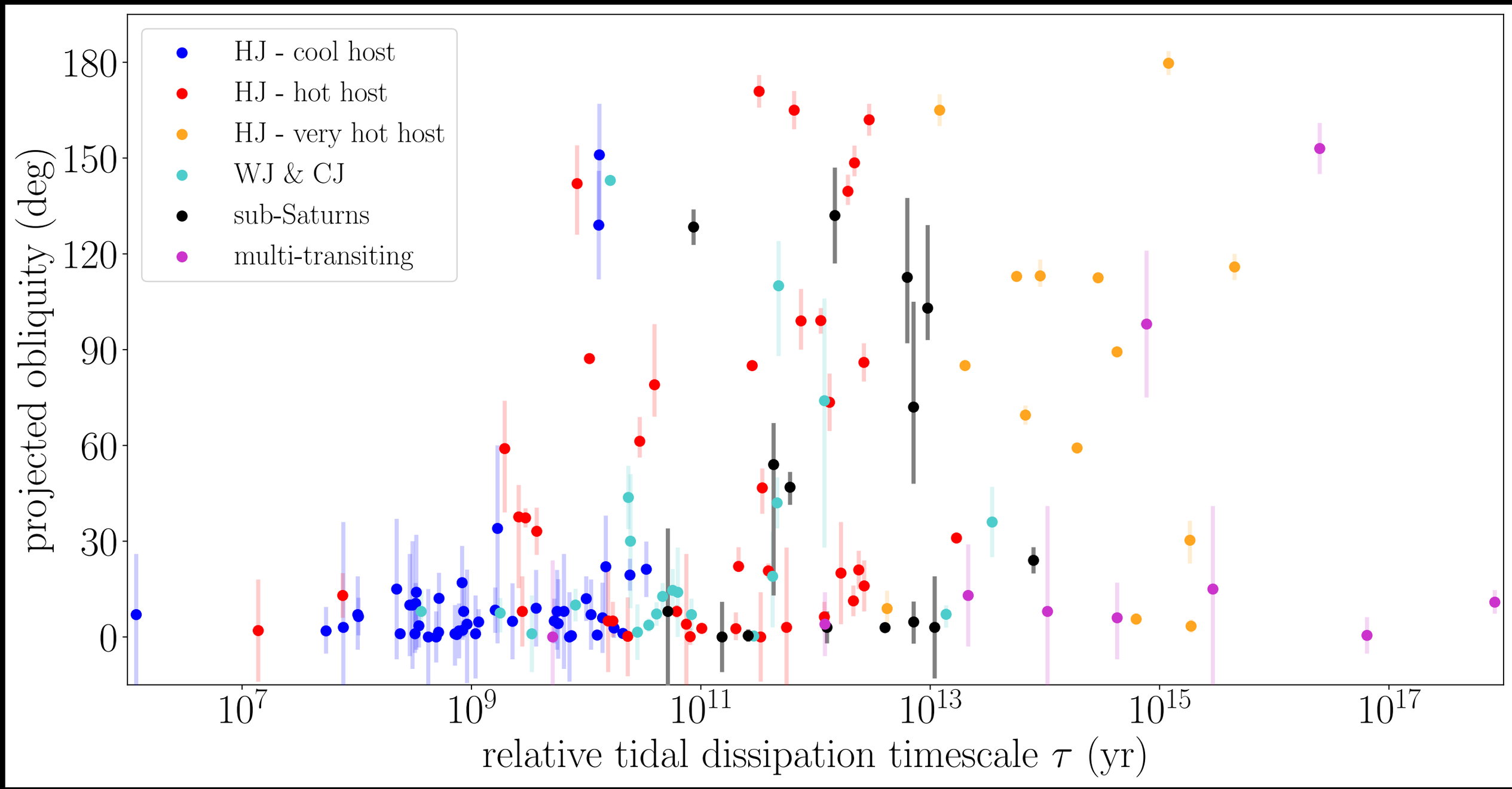
Many physical processes can excite obliquity before or after formation



Albrecht, Dawson, & Winn review, in prep

Strong evidence that tidal realignment has erased many obliquities



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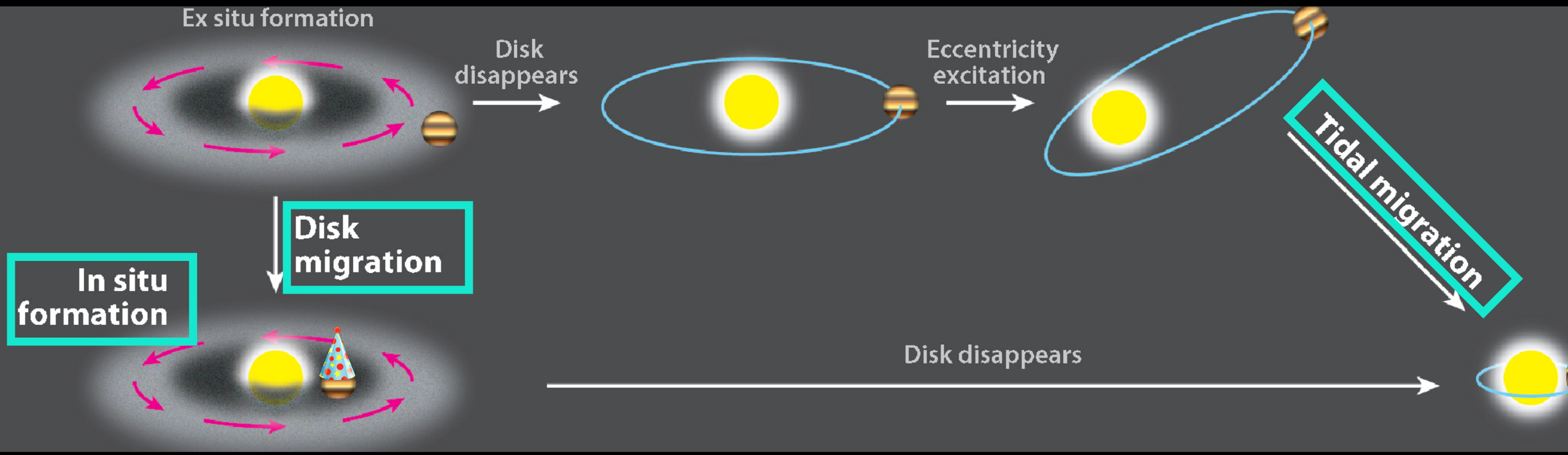
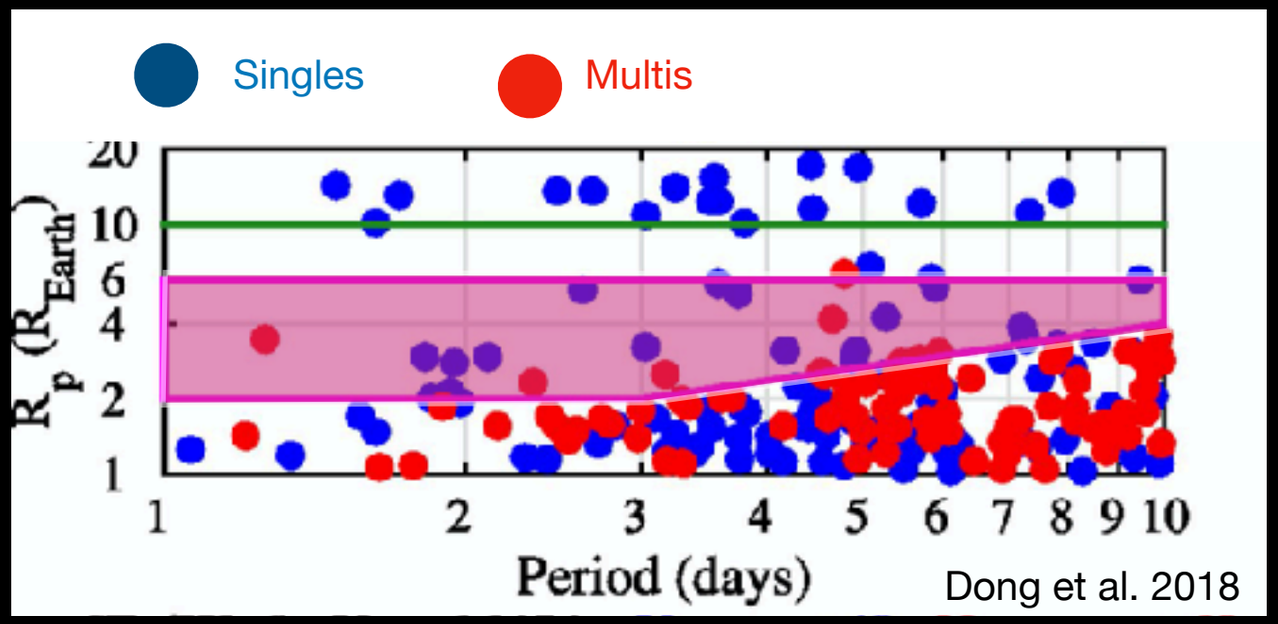
RID & Johnson ARAA 18

Assuming multiple origins channels…



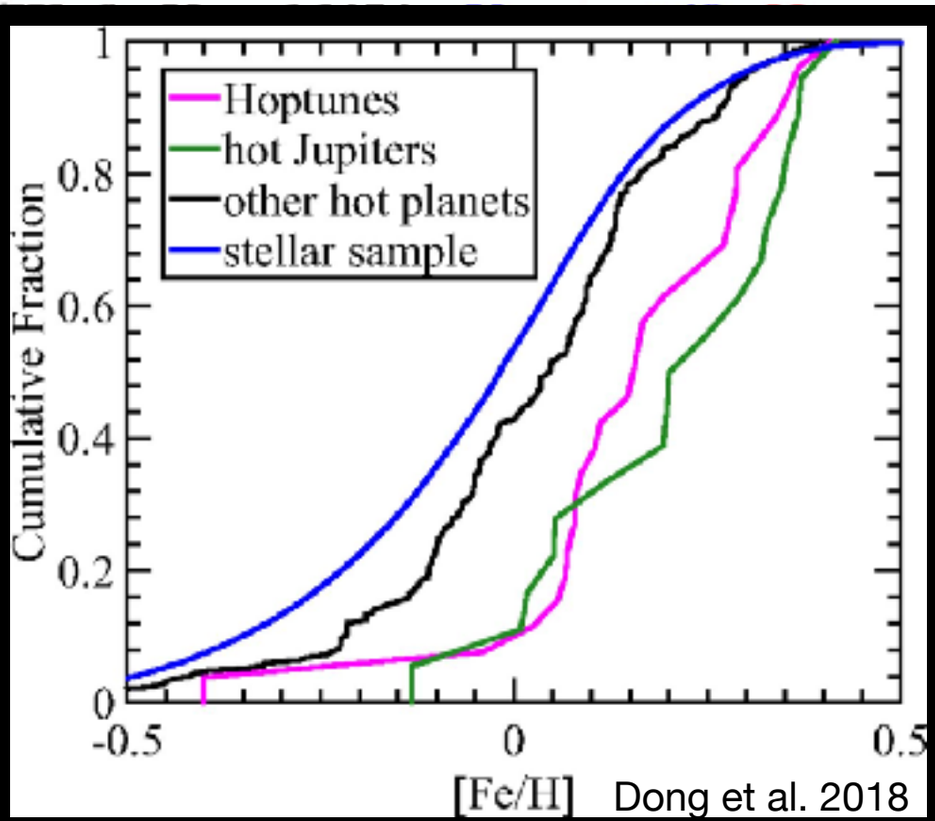
* What other planets share these origins channels, and what additional constraints do they provide?
* What are the consequences for the planet's atmosphere?

Hot Neptunes share hot Jupiter properties



Dong et al. 2018

Typically lack nearby planets

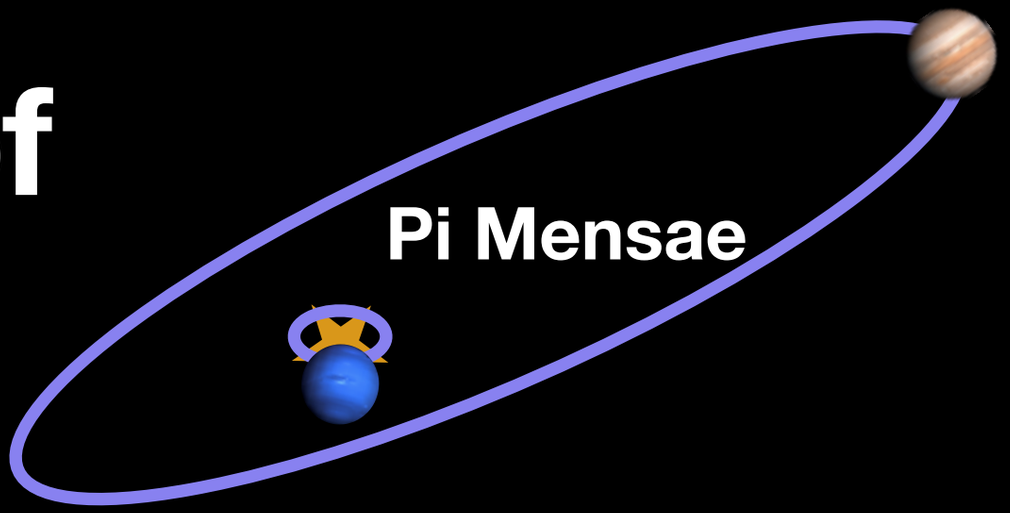


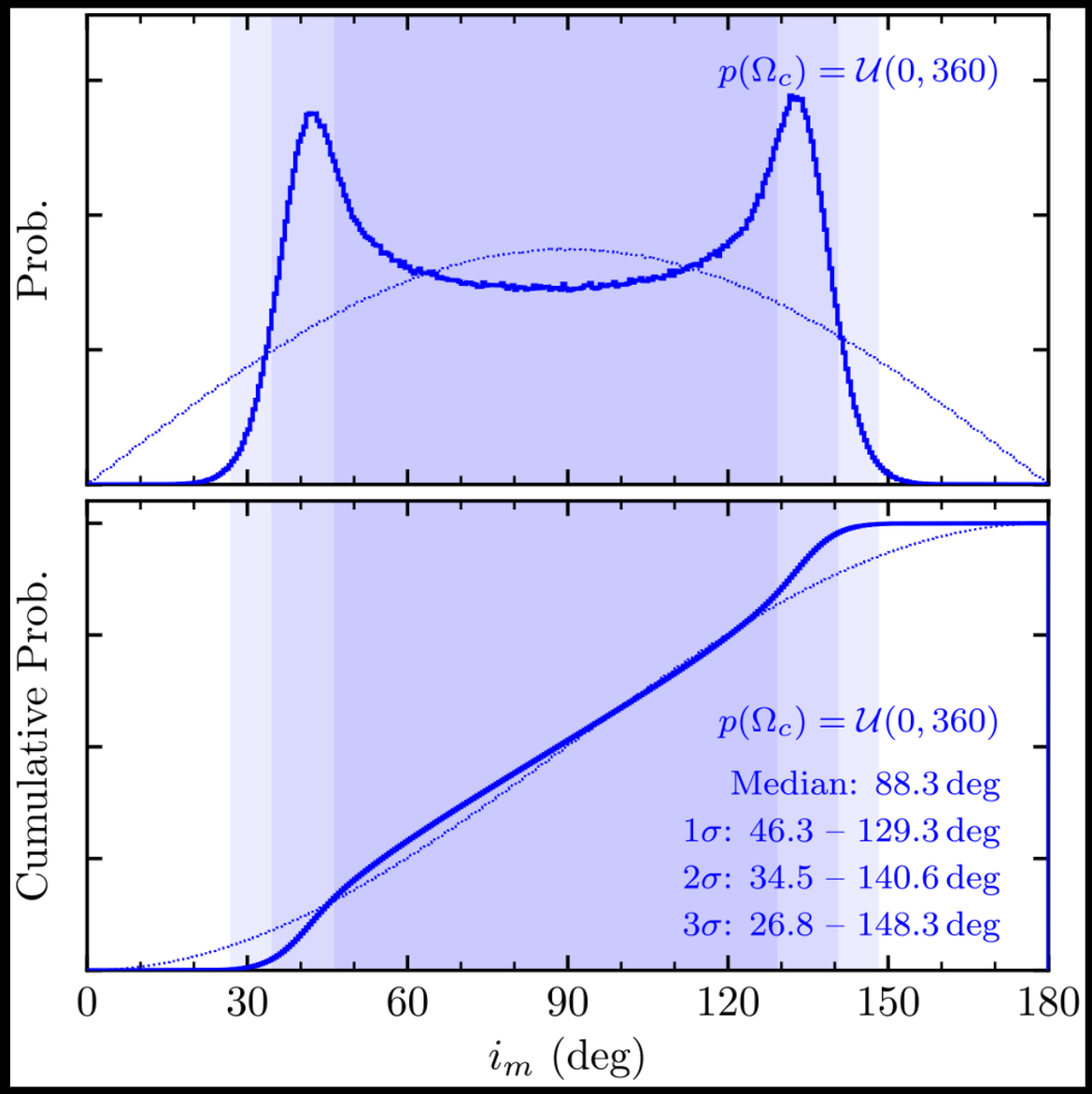
Dong et al. 2018

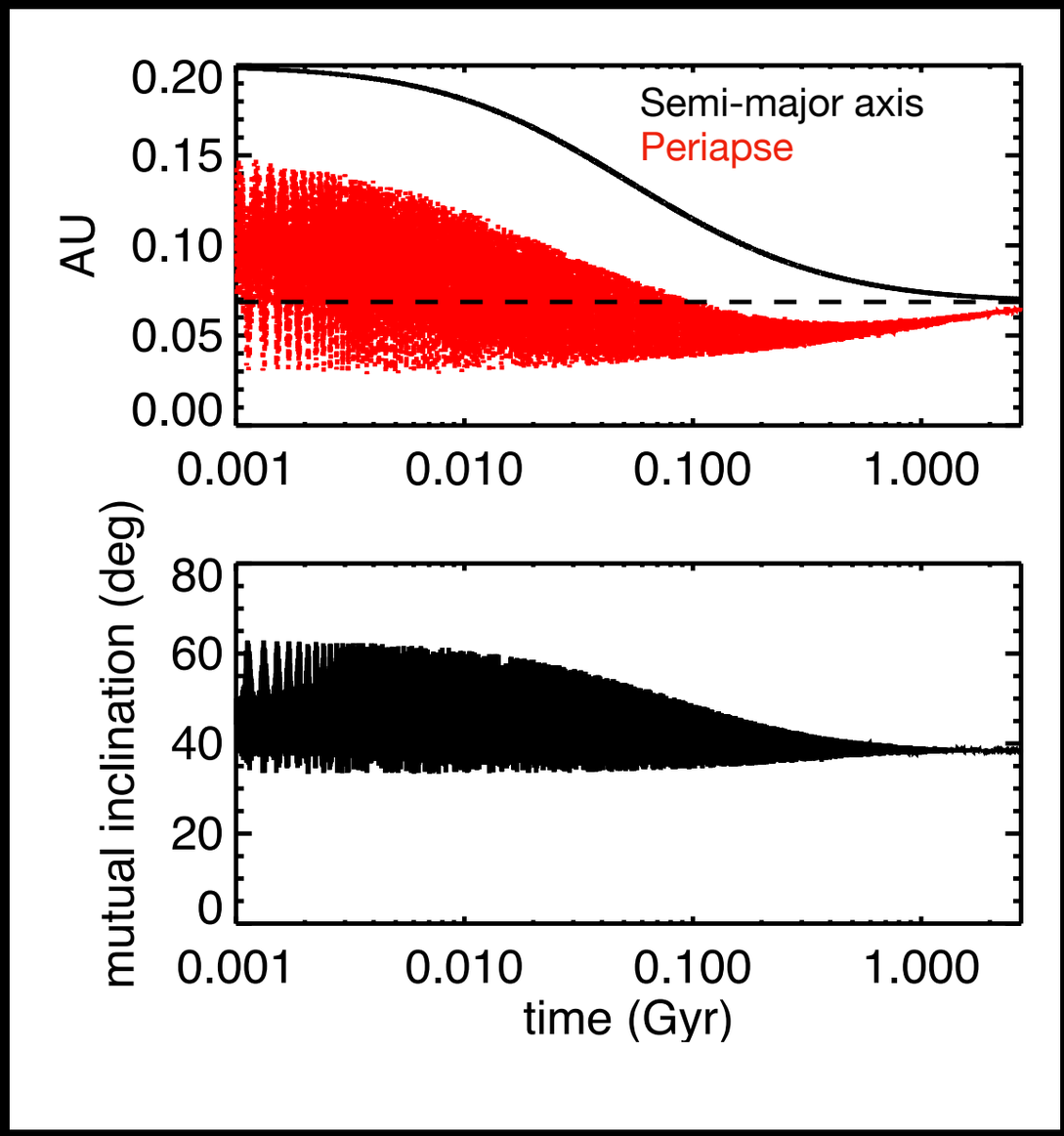
Elevated host star metallicities

Dong et al. 2018

3-D astrometry: mutual inclination of hot Neptune

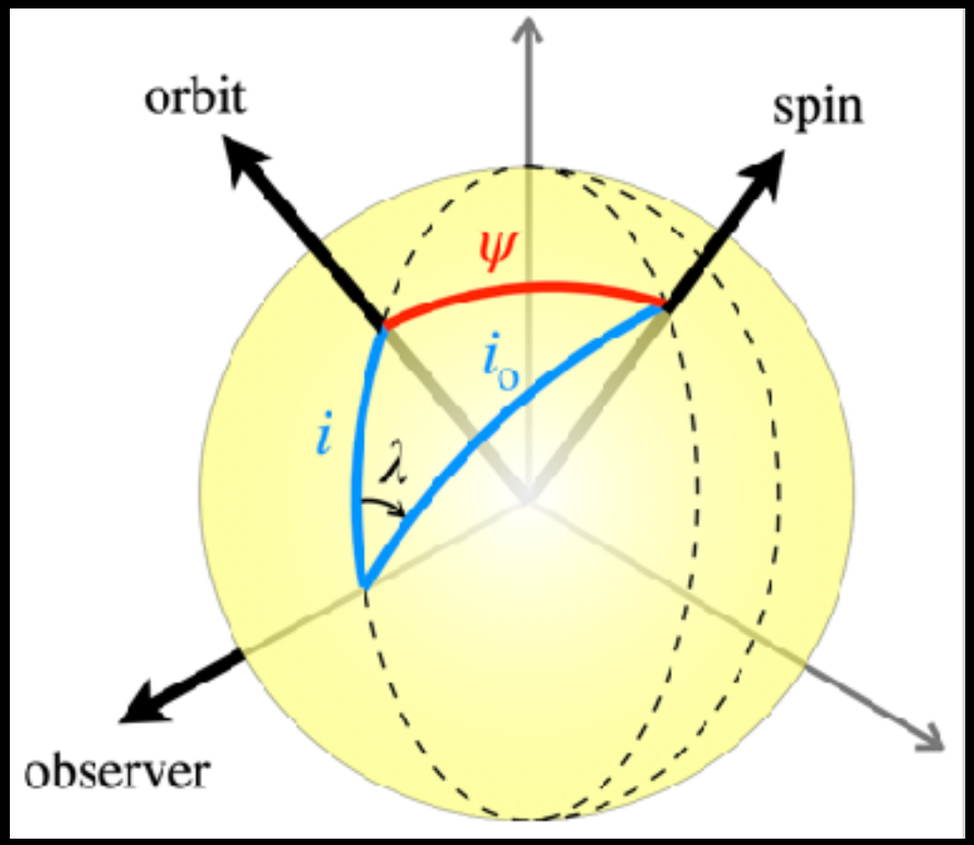


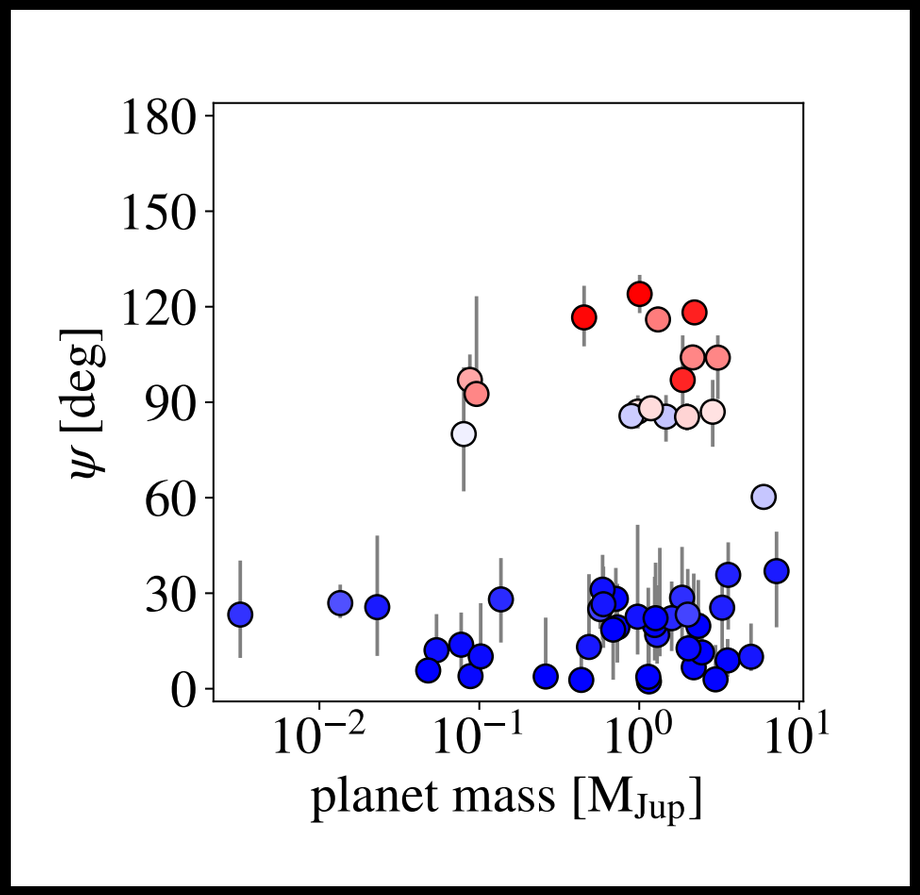




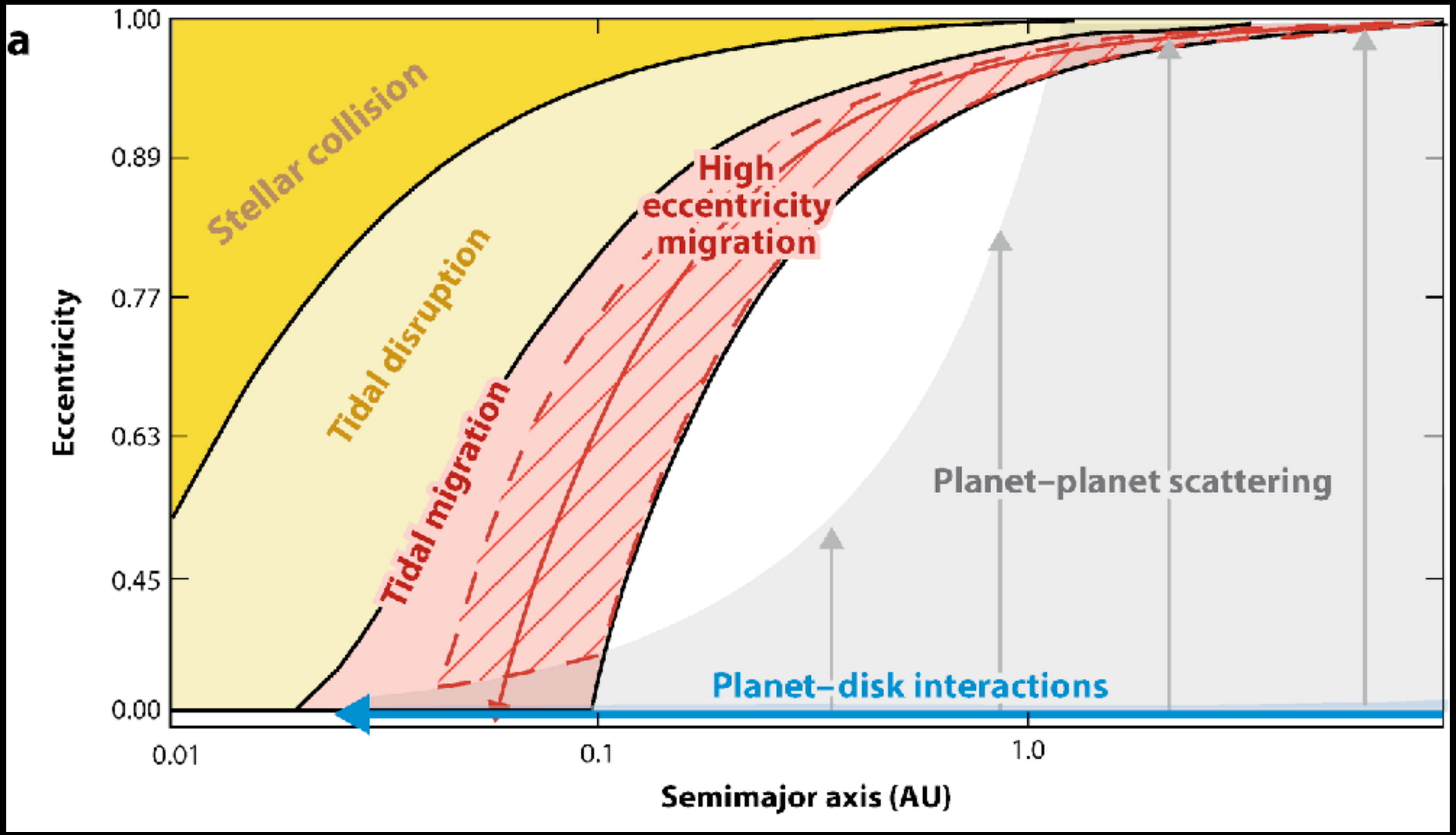
de Rosa, RID, & Nielsen 20; see also Damasso et al. 20, Xuan & Wyatt 20

Hot Neptunes share hot Jupiter properties: full obliquity is 90°



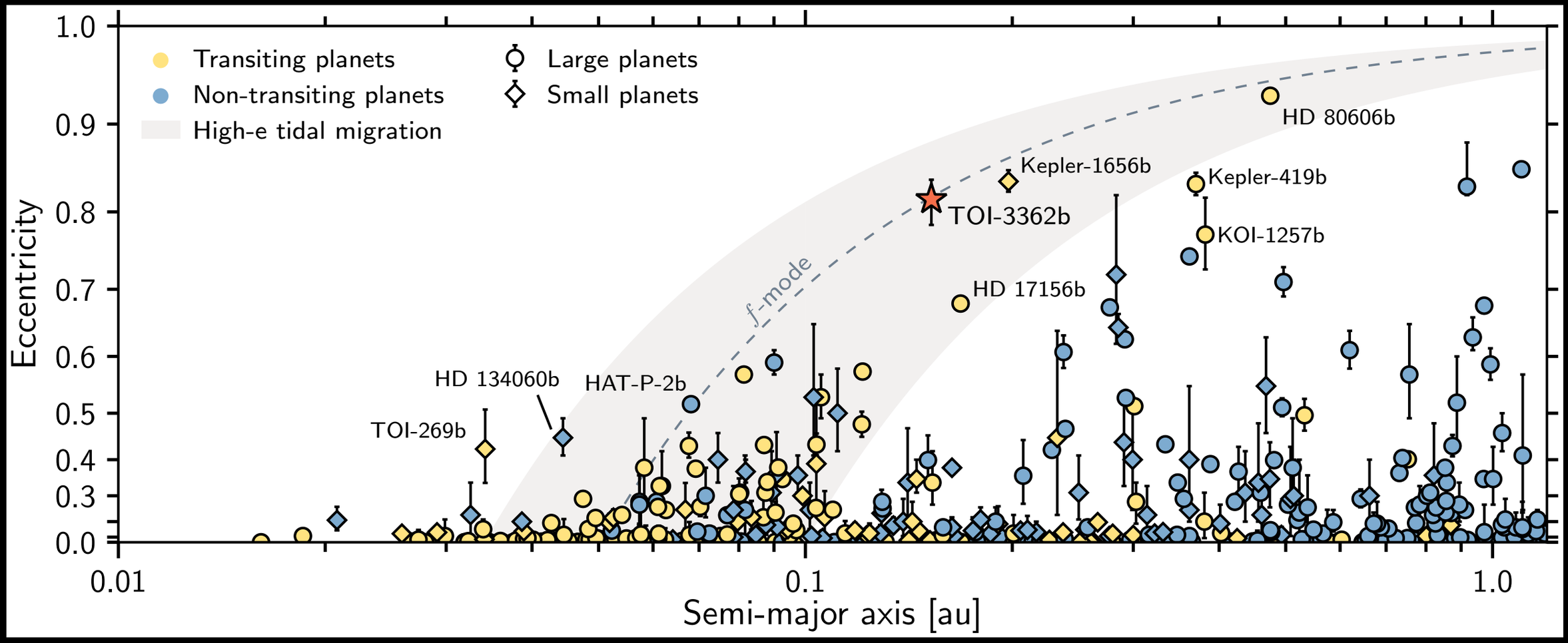


Albrecht et al. 2021



RID & Johnson ARAA 18

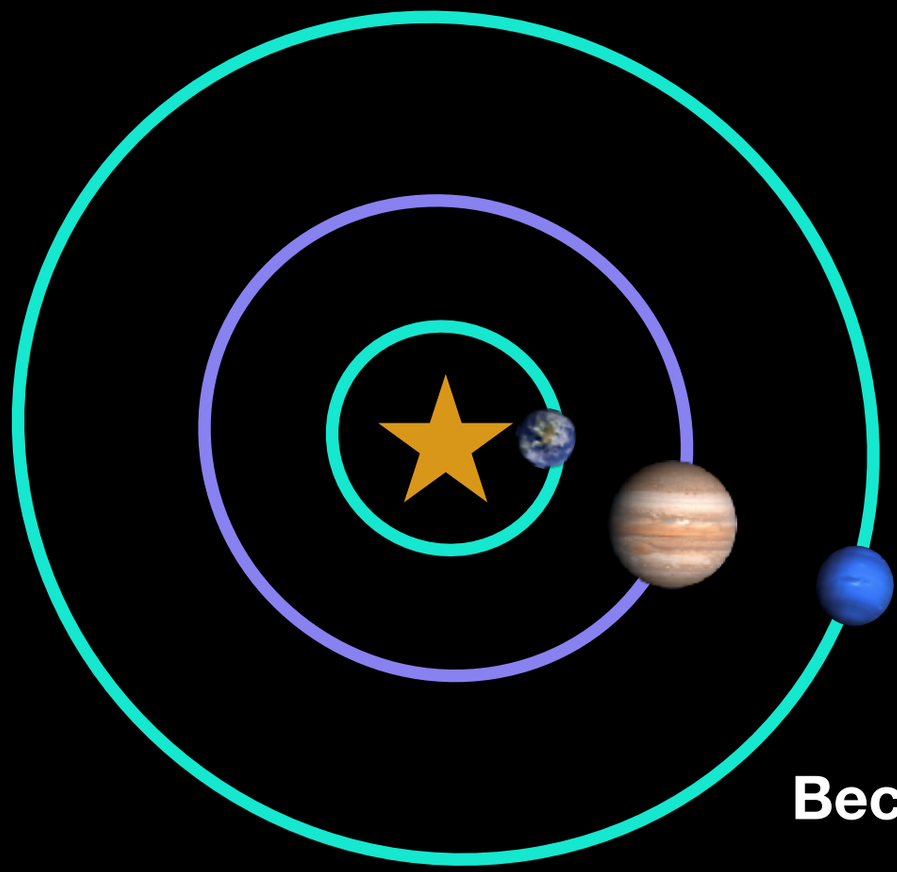
Possible warm origin for hot Jupiters: tidally migrating Jupiters and Neptunes are warm



Absence of longer period super-eccentric Jupiters (Dawson et al. 2015)

Dong, Huang, RID, et al., submitted

What is the second origins channel? Disk migration or in situ?



Becker 15

BUT **WASP-47b**
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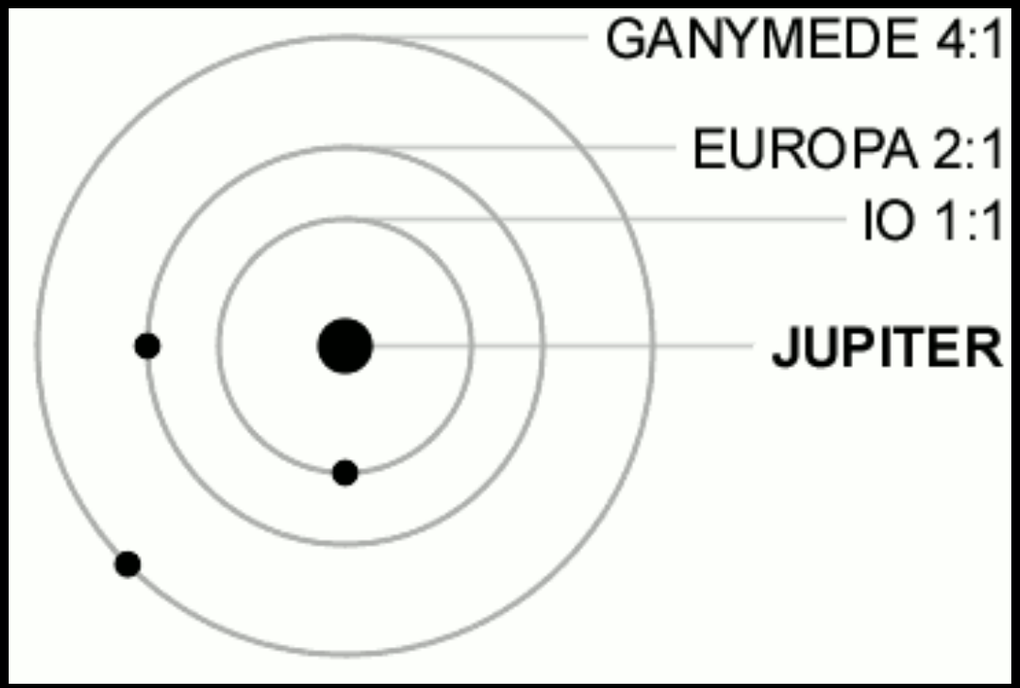
Two nearby companions discovered by K2

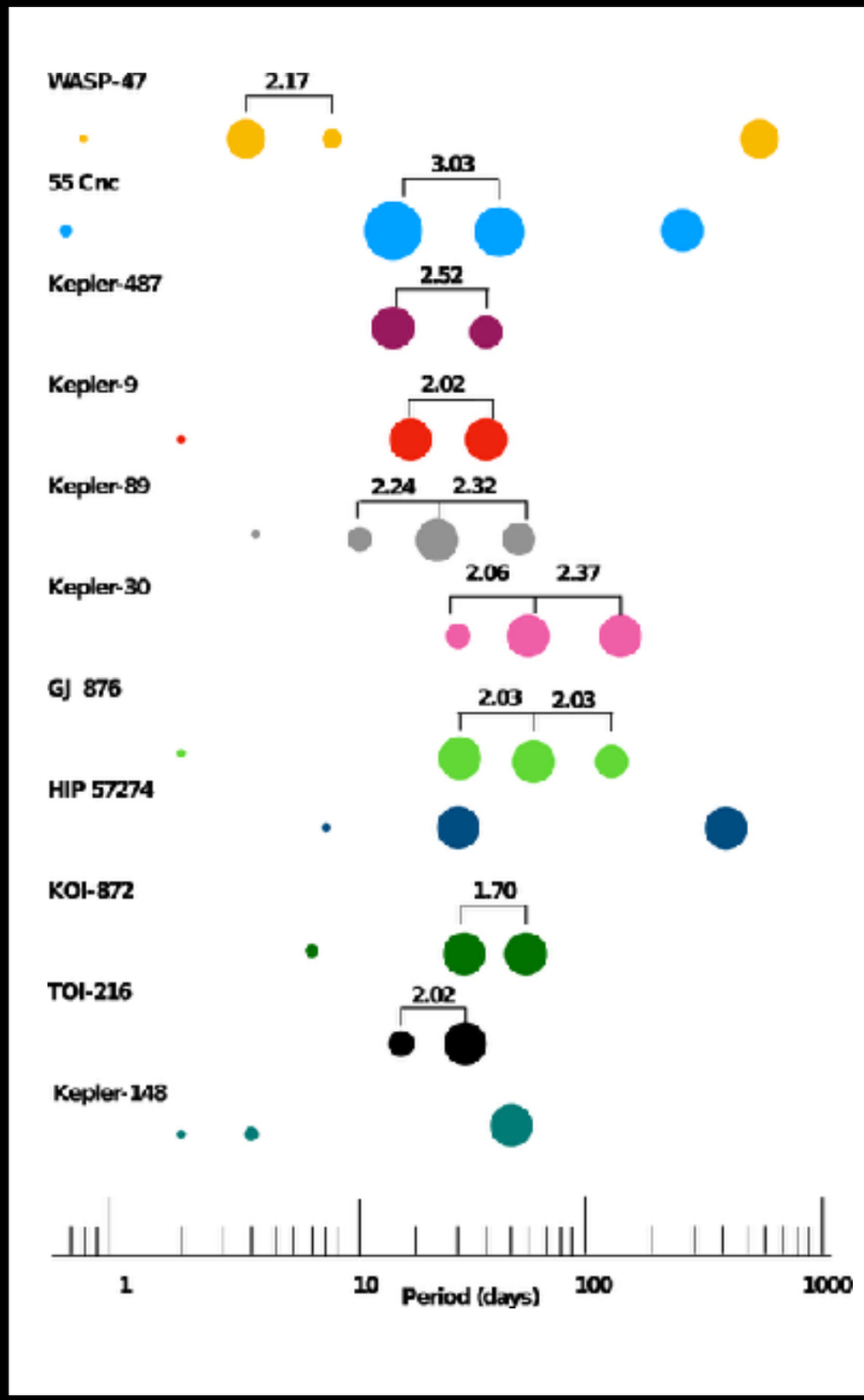
—> disk migration or In situ

Orbital resonances: captured by dissipative process (e.g., migration, planet-disk or tidal interactions)



$$\phi_{Eu-Io} = 2\lambda_{Eu} - \lambda_{Io} - \varpi_{Eu}$$
$$\phi_{Ga-Eu} = 2\lambda_{Ga} - \lambda_{Eu} - \varpi_{Eu}$$
$$\phi_{Ga-Eu-Io} = 2\lambda_{Ga} - \lambda_{3Eu} + \lambda_{Io}$$

WASP-47 and similar warm Jupiter systems commonly have companions in or near resonance but resonant behavior is usually uncertain



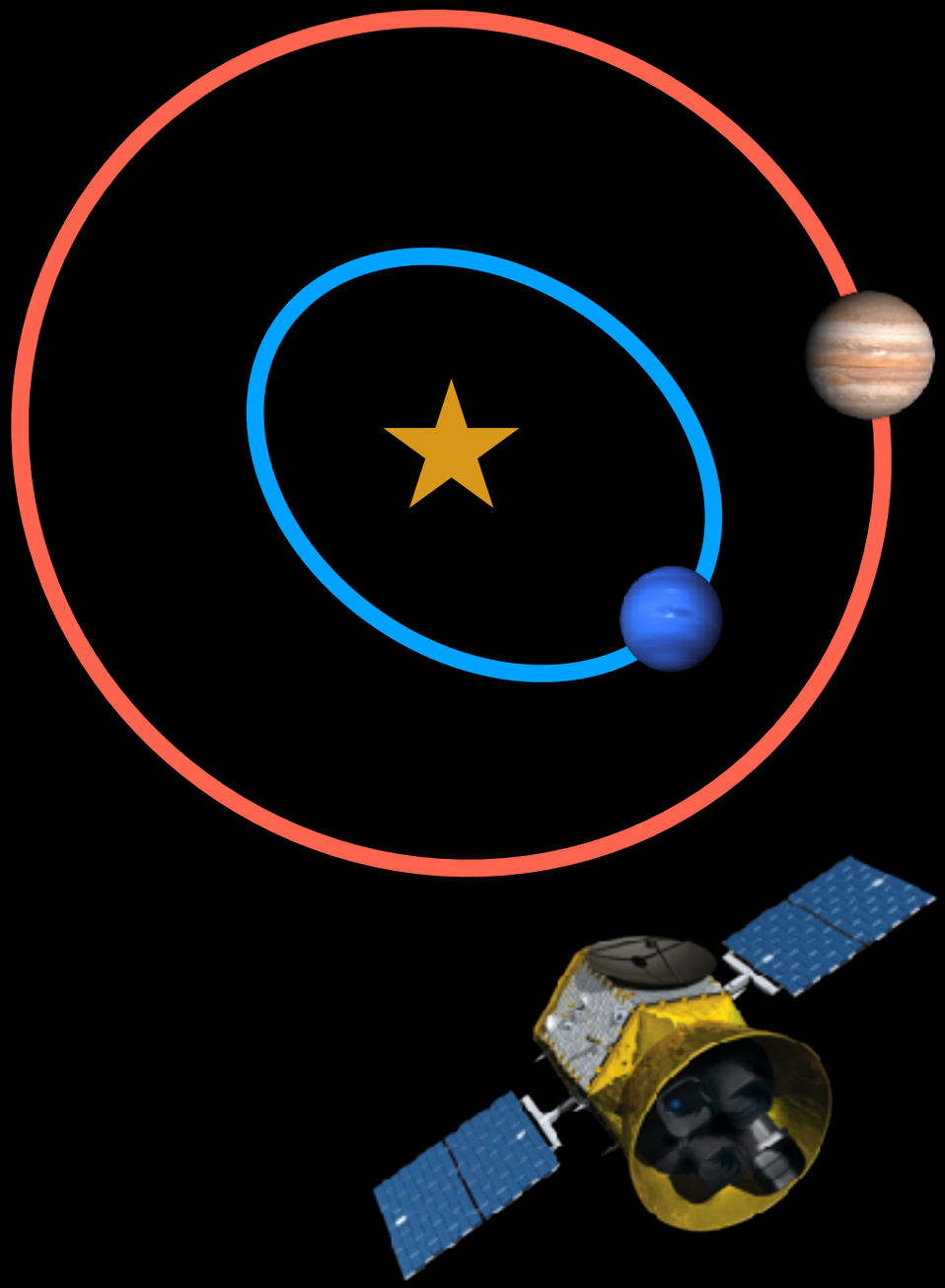
TOI-216: small but significant libration amplitude, free eccentricity, and mutual inclination

Libration amplitude
60°± 2°

Free eccentricity (b)
0.0222 +0.0005/-0.0003

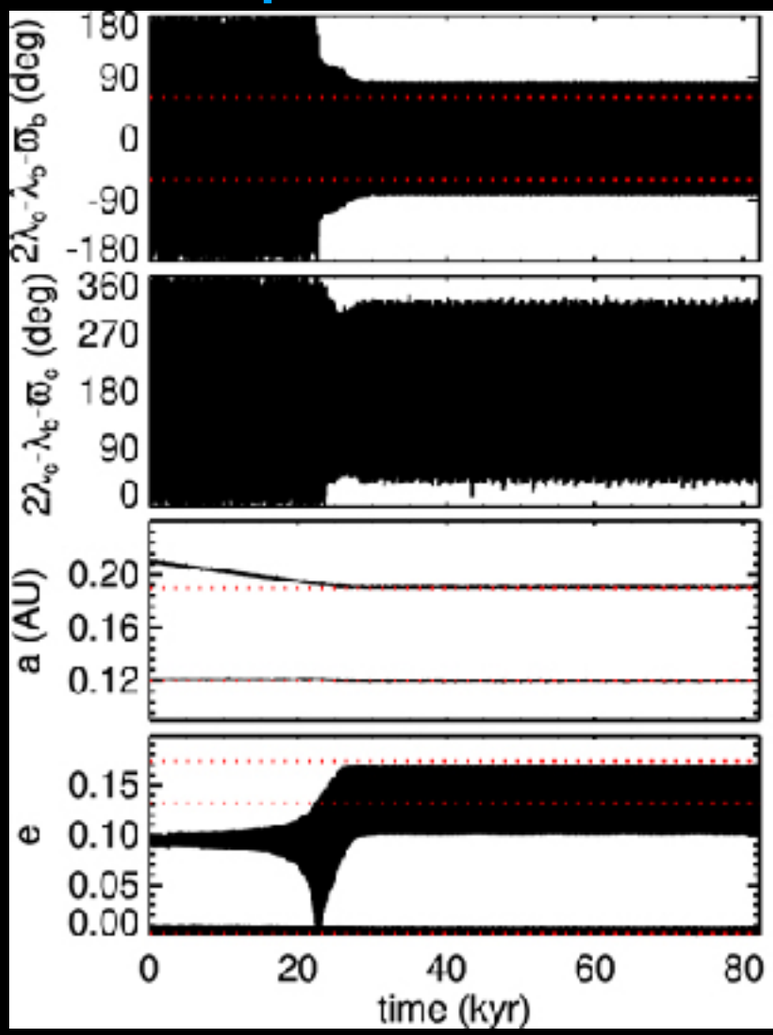
Mutual inclination
1.2—3.9°
(95% confidence interval)

Dawson et al. 2021

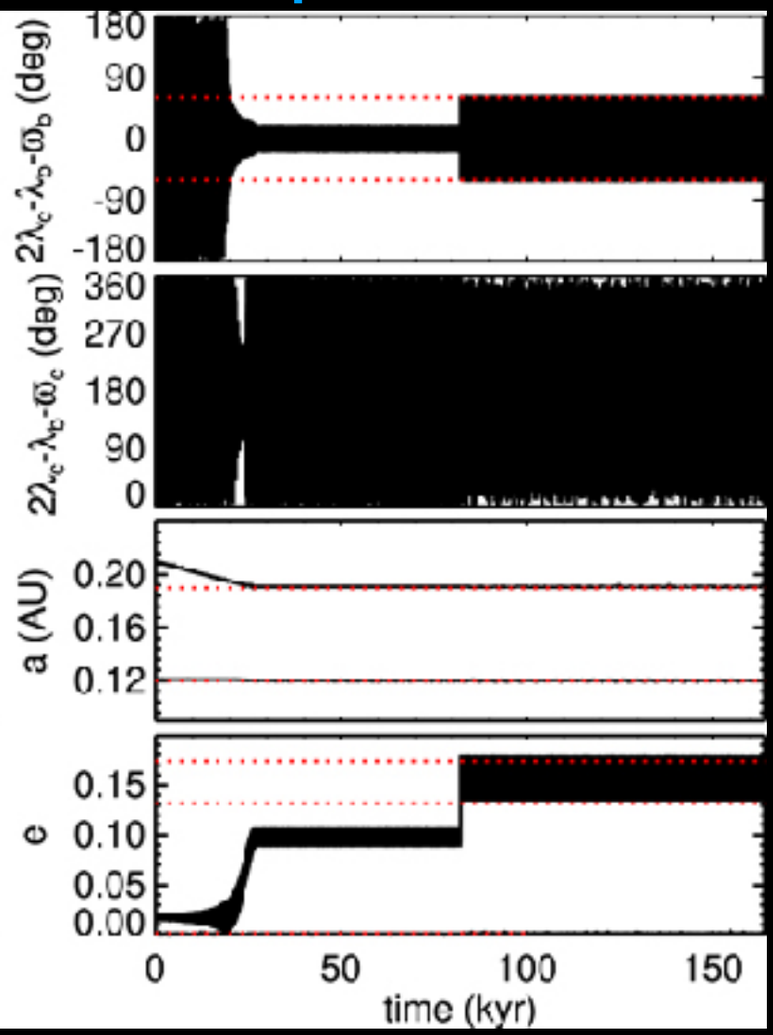


Example origins scenarios: disturbance from additional planet(s) and/or disk probably not just “vanilla” disk migration

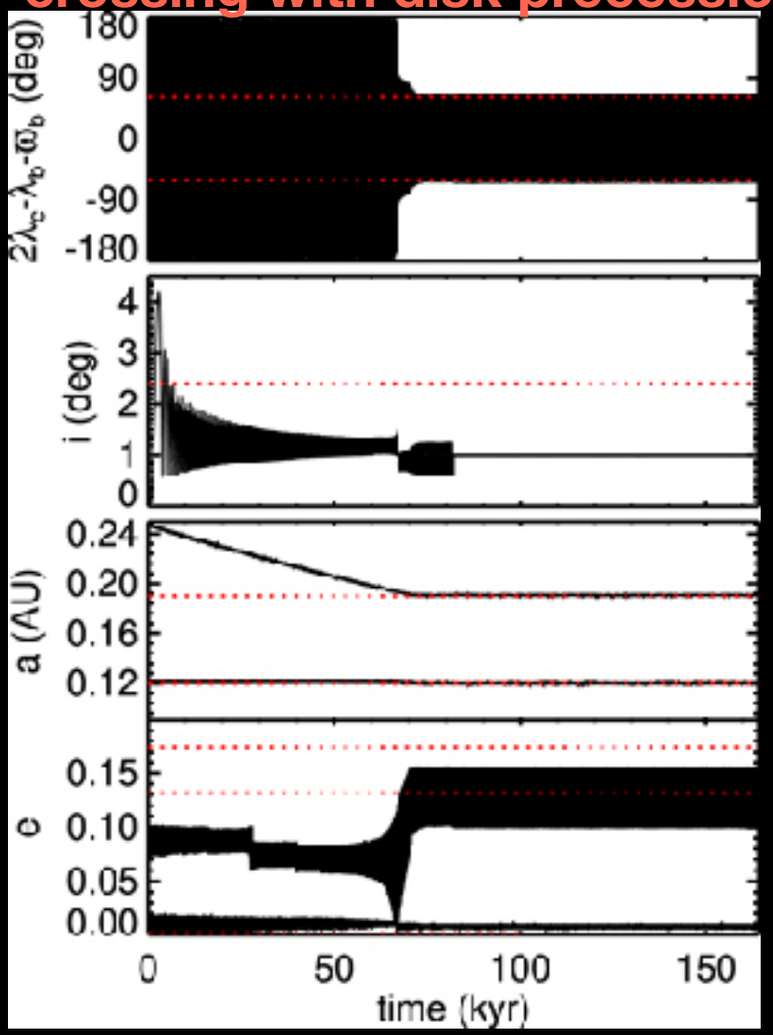
Pre-capture disturbance



Post-capture disturbance



Mutual inclination from 4:2 crossing with disk precession



Hot Jupiters' other properties test origins theories

Comparisons to warm Jupiters, smaller planets

Age
Obliquity
Metallicity

Eccentricity
Semi-major axis
Occurence rates

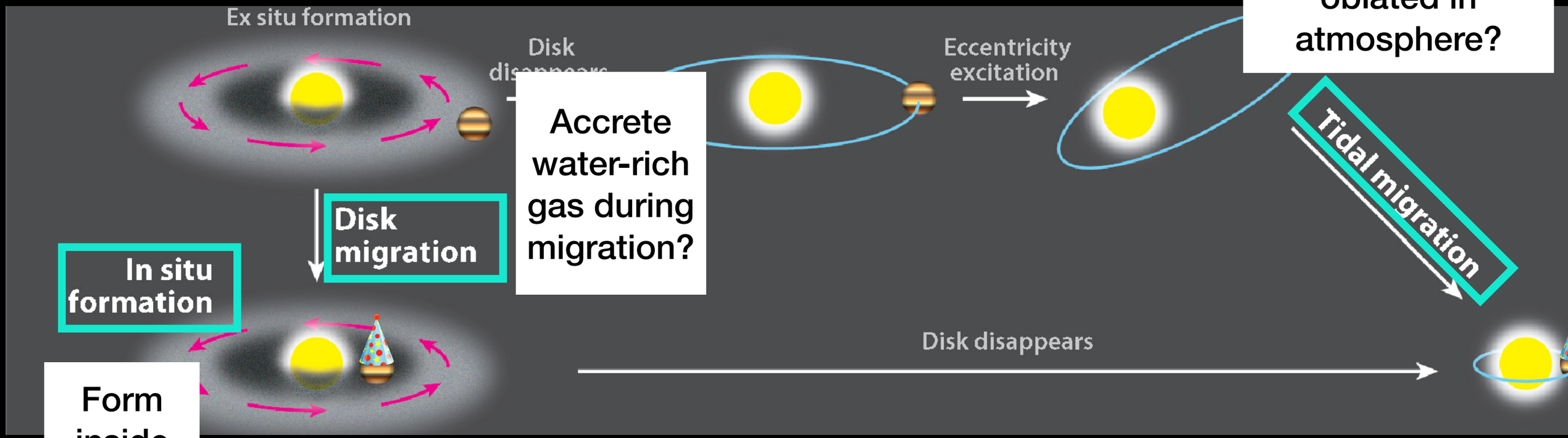
Radius
Atmosphere

Companions (nearby, distant)

Like obliquities, many processes can affect atmospheres before or after formation

- Formation location relative to snow line (e.g., Öberg et al. 2011; but snow lines can vary by orders of magnitude depending on disk conditions, e.g., Piso et al. 2015)
- Accretion of gas during gas disk migration or of icy planetesimals at formation location (e.g., Madhusudhan, Amin & Kennedy 2014)
- Nonetheless, links between atmospheric composition and orbital/architectural properties will be interesting to probe

Example: Water rich hot Jupiter atmospheres (e.g., Sing et al. 2016)



Key Follow Up to Disentangle Multiple Origins Channels

- Increase the sample and characterization of eccentric hot Jupiters
- Gaia astrometry to constrain mutual inclinations of planets
- Study solid transport within gas disks to test conditions for in situ formation
- Increase the sample of obliquities, particularly for warm Jupiters and hot Neptunes