

Astrometric Accelerations as Dynamical Beacons

*Imaging Planets and Brown Dwarfs
Around Accelerating Stars*



Kyle Franson

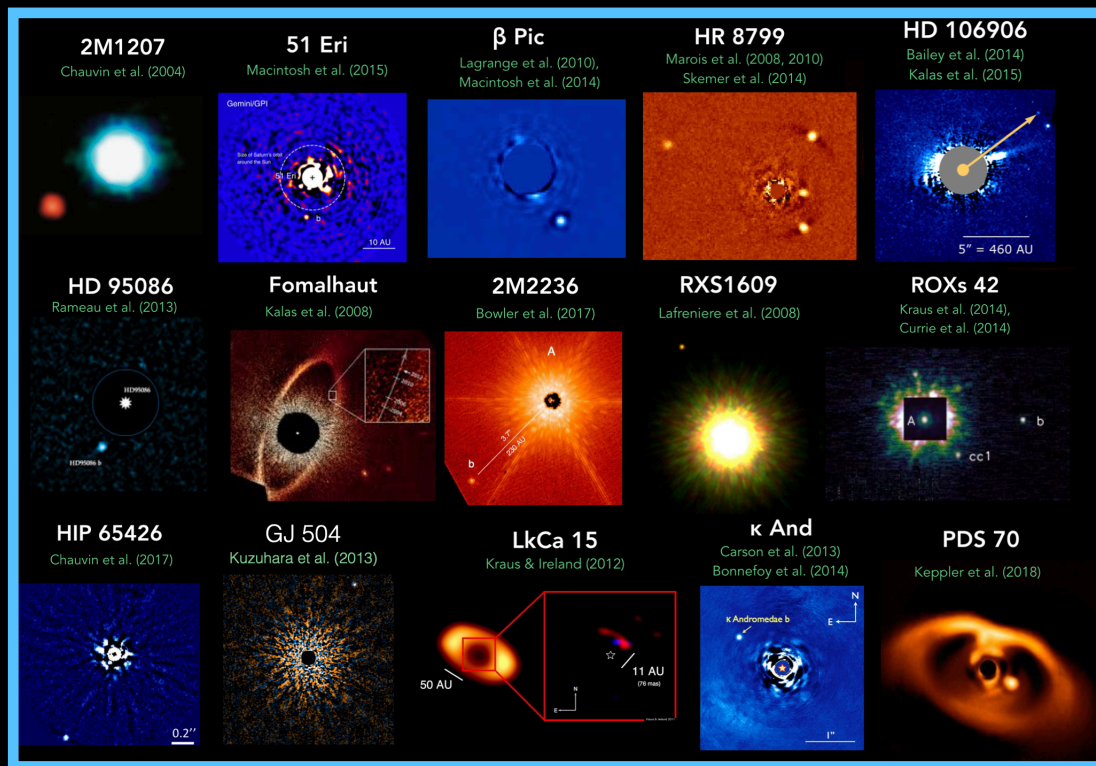
NASA Sagan Fellow
UC Santa Cruz

Collaborators: Brendan Bowler, Tim Brandt, Trent Dupuy, Jackie Faherty, Daniella Bardalez-Gagliuffi, Justin Crepp, Rebecca Jensen-Clem, among many others!

Formation of Wide-Separation Substellar Companions

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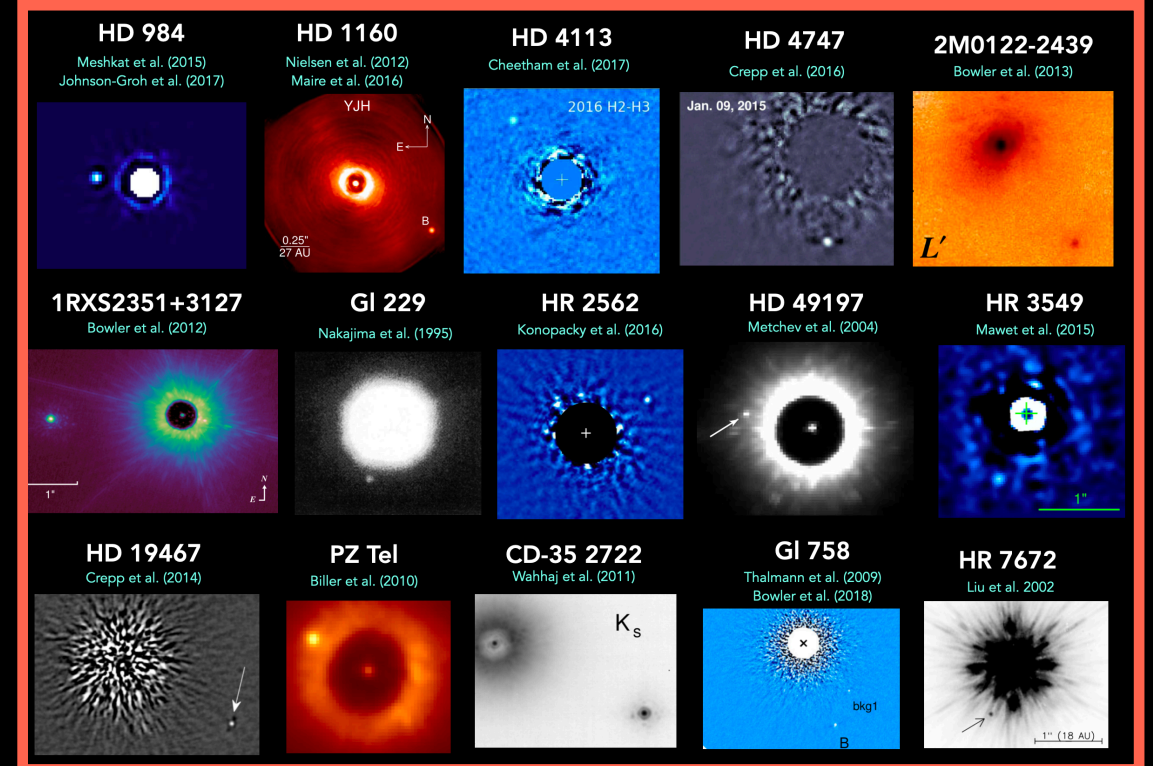
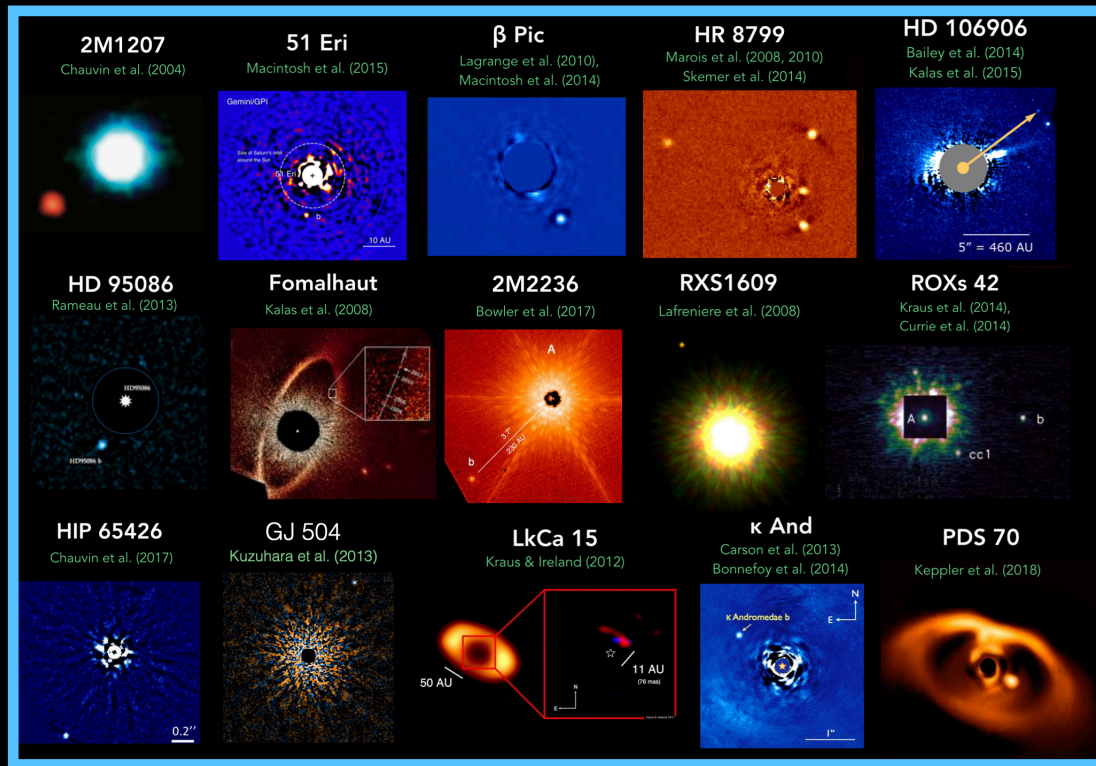
Giant Planets



Formation of Wide-Separation Substellar Companions

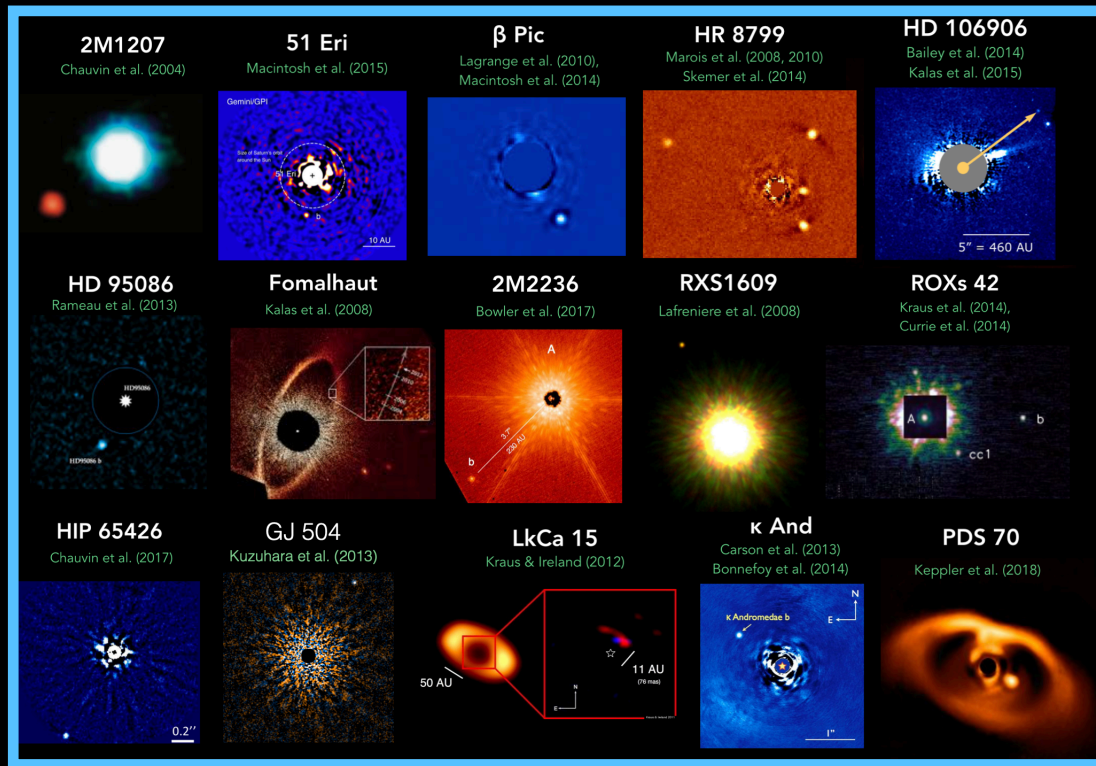
Giant Planets

Brown Dwarfs

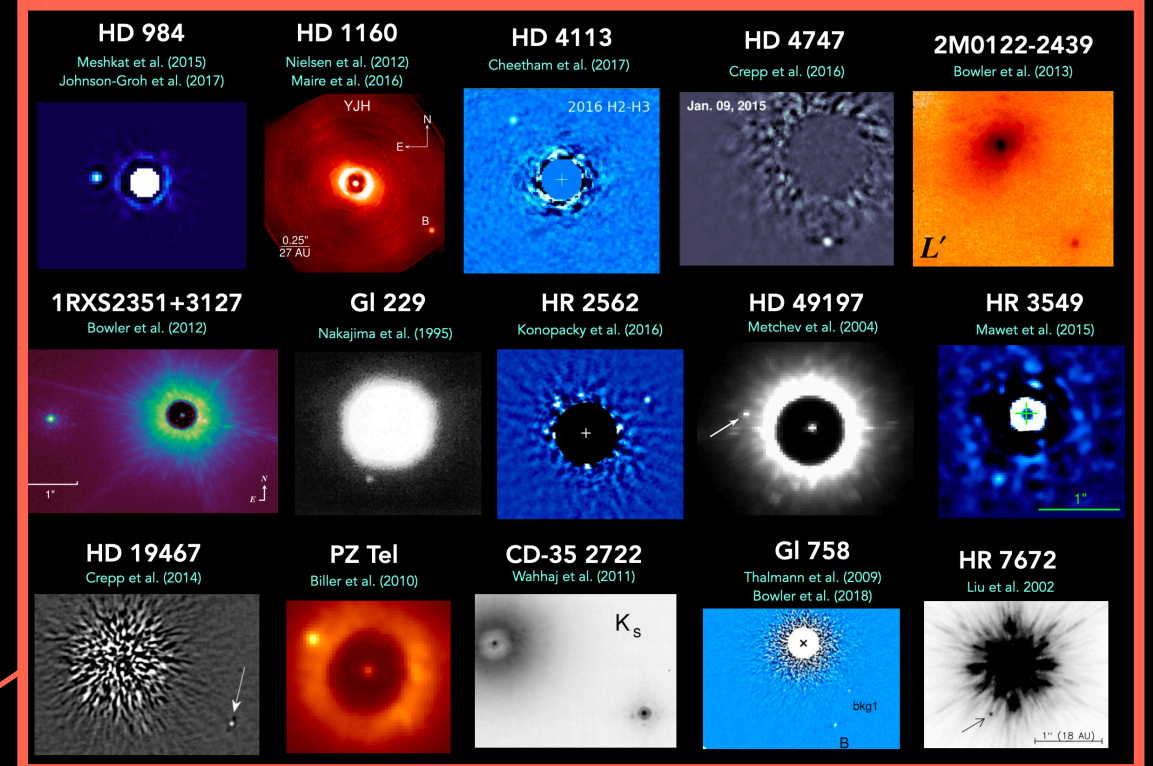


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Giant Planets



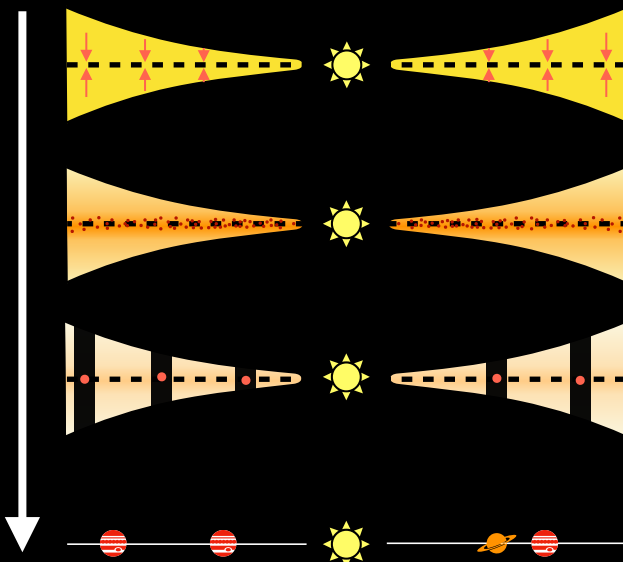
Brown Dwarfs



Core/Pebble Accretion

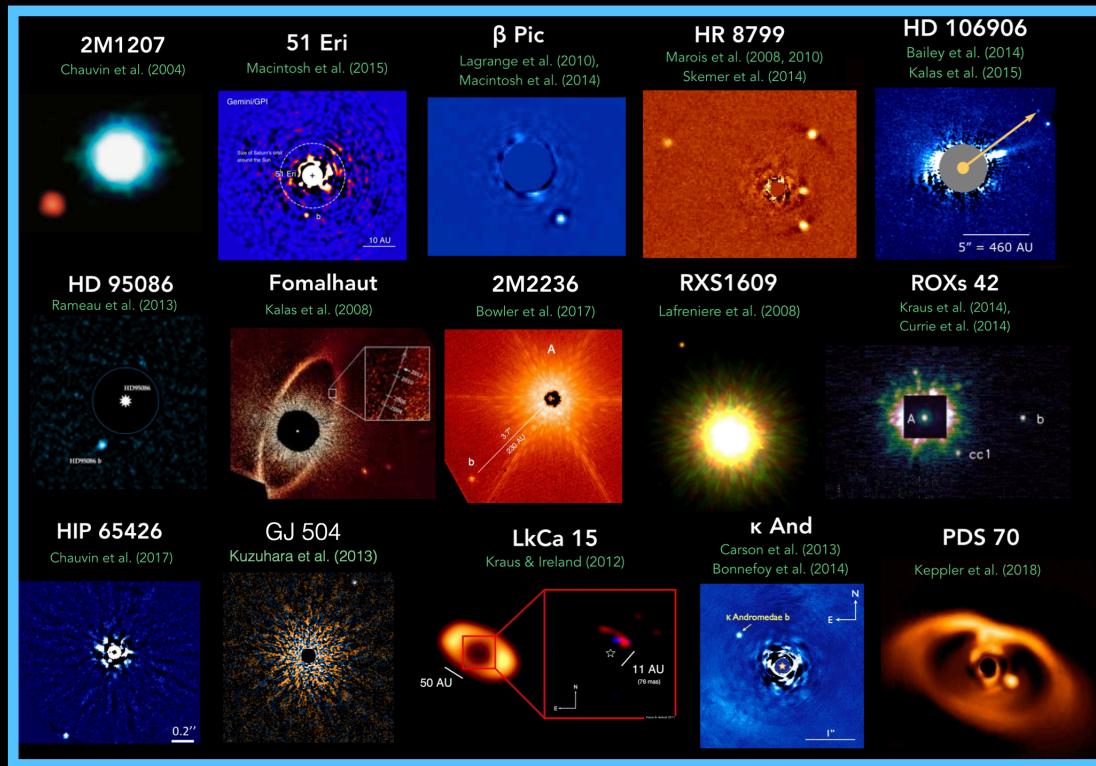
Pollack et al. (1996)

Lambrechts & Johansen (2012)

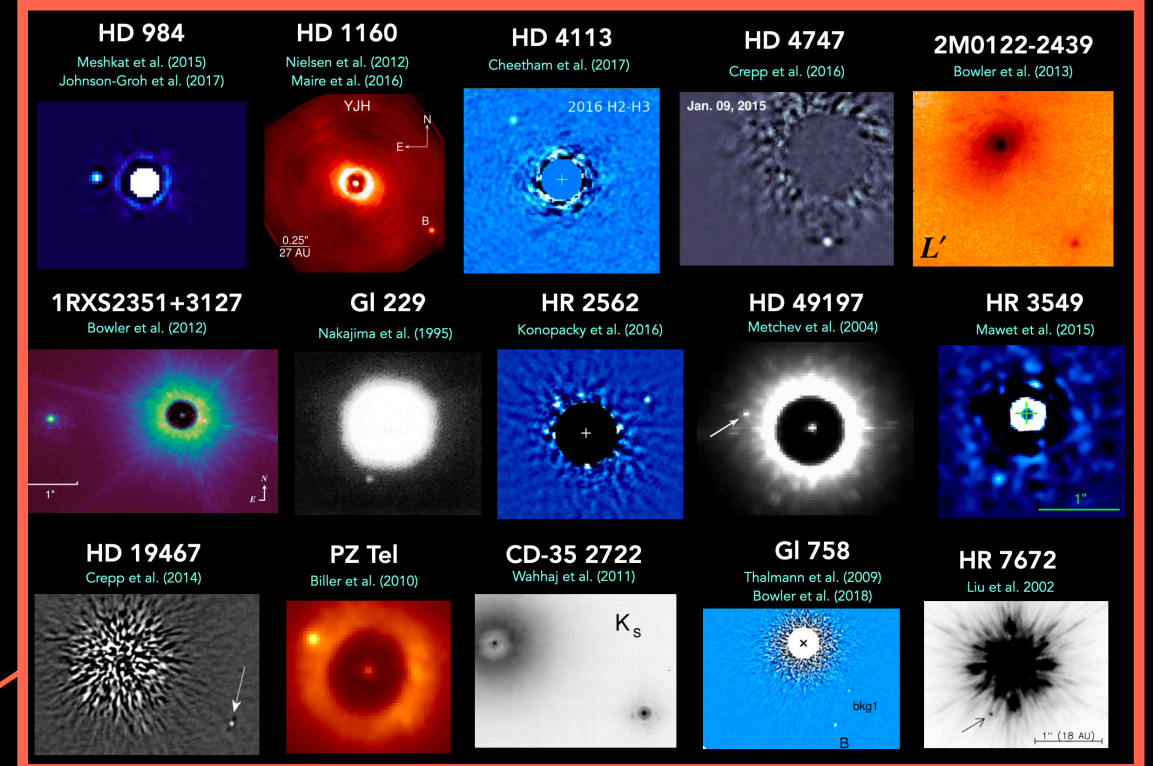


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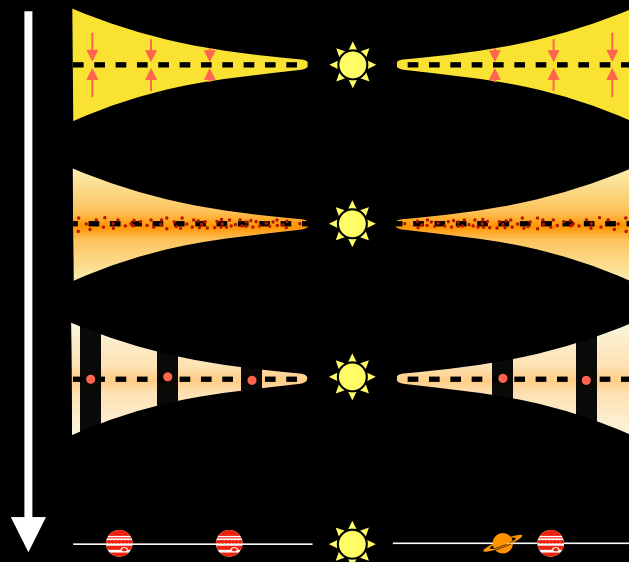


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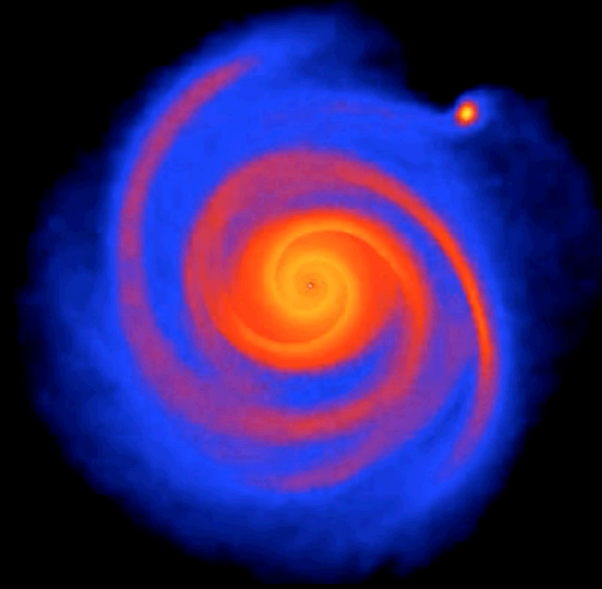
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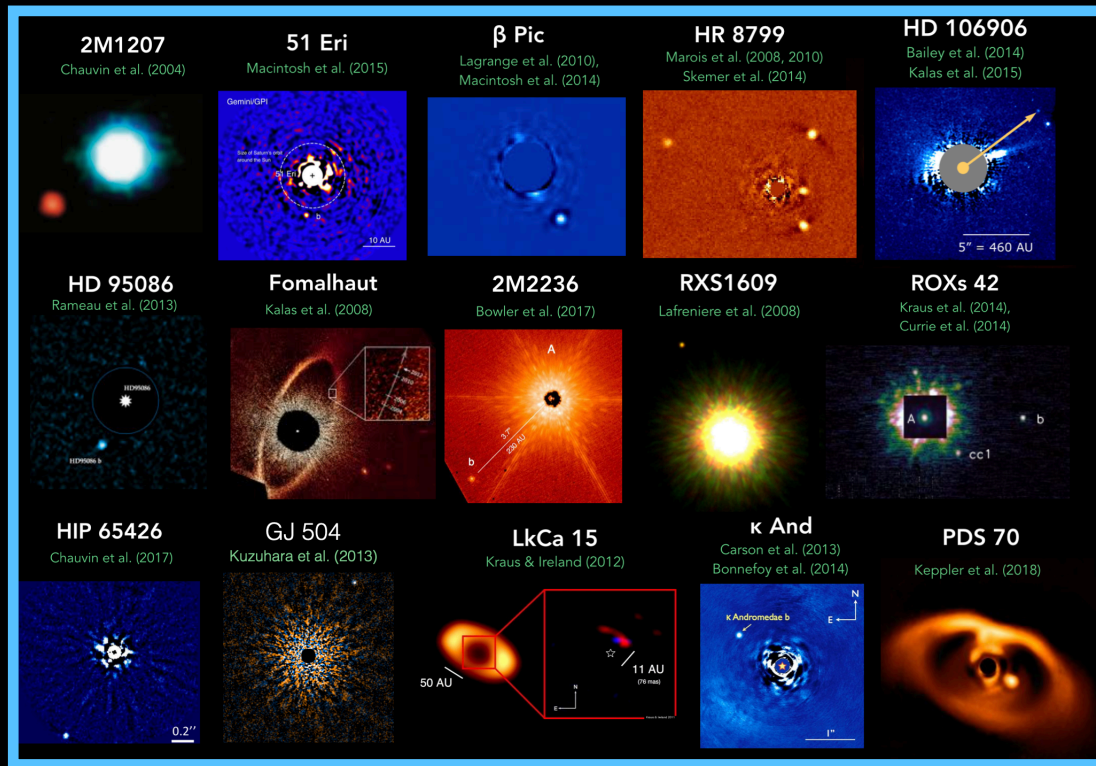
Gravitational Instability

Boss (1997)

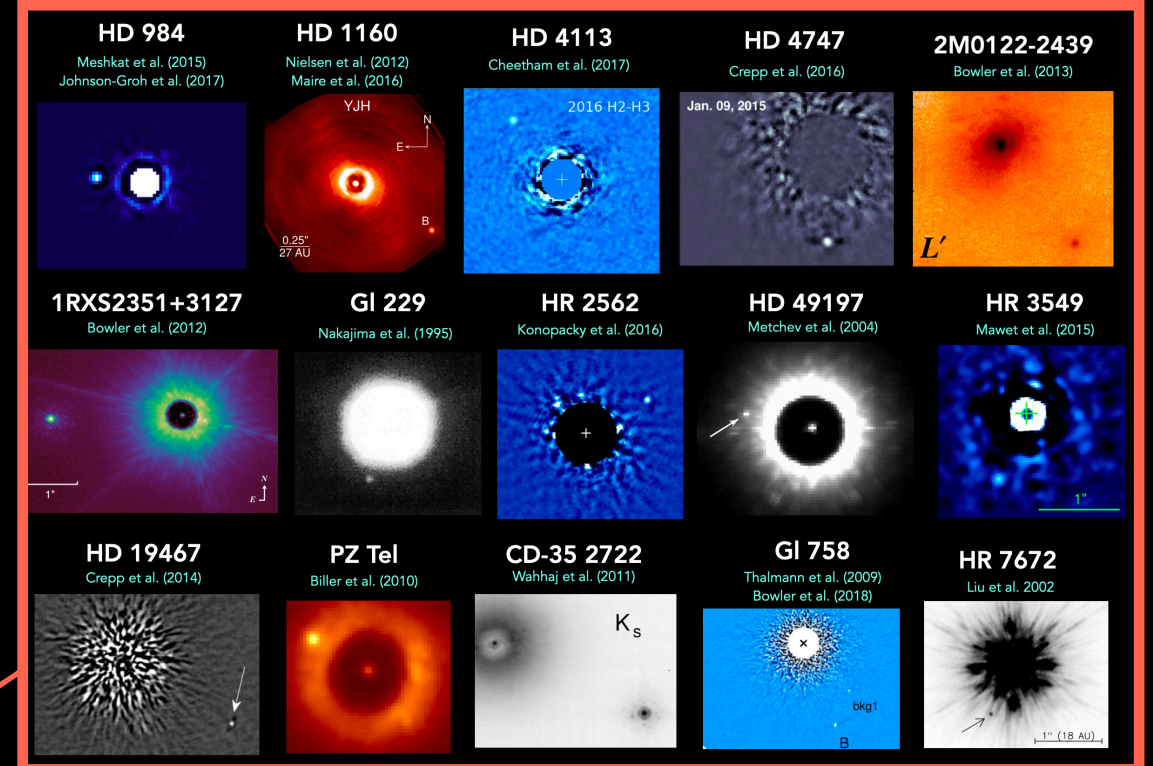


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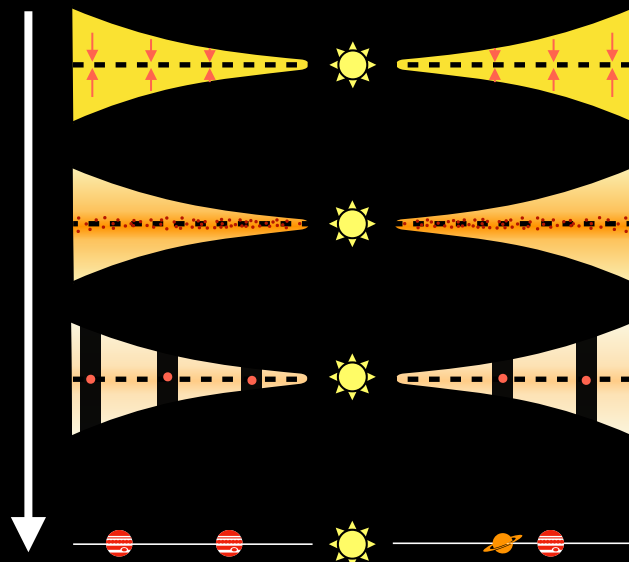


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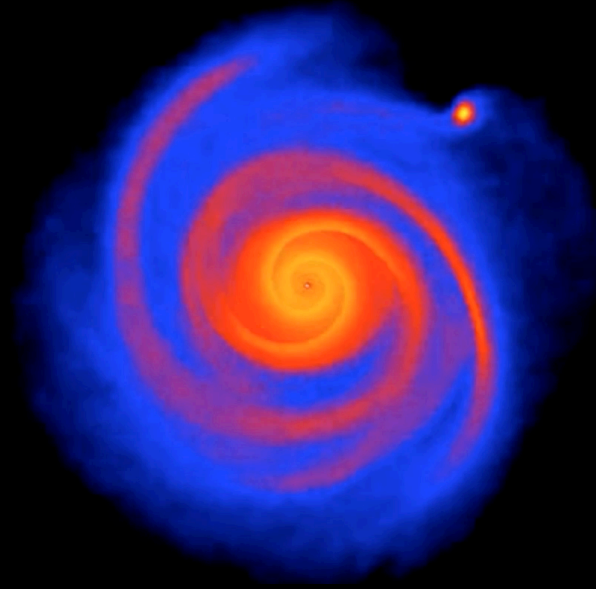
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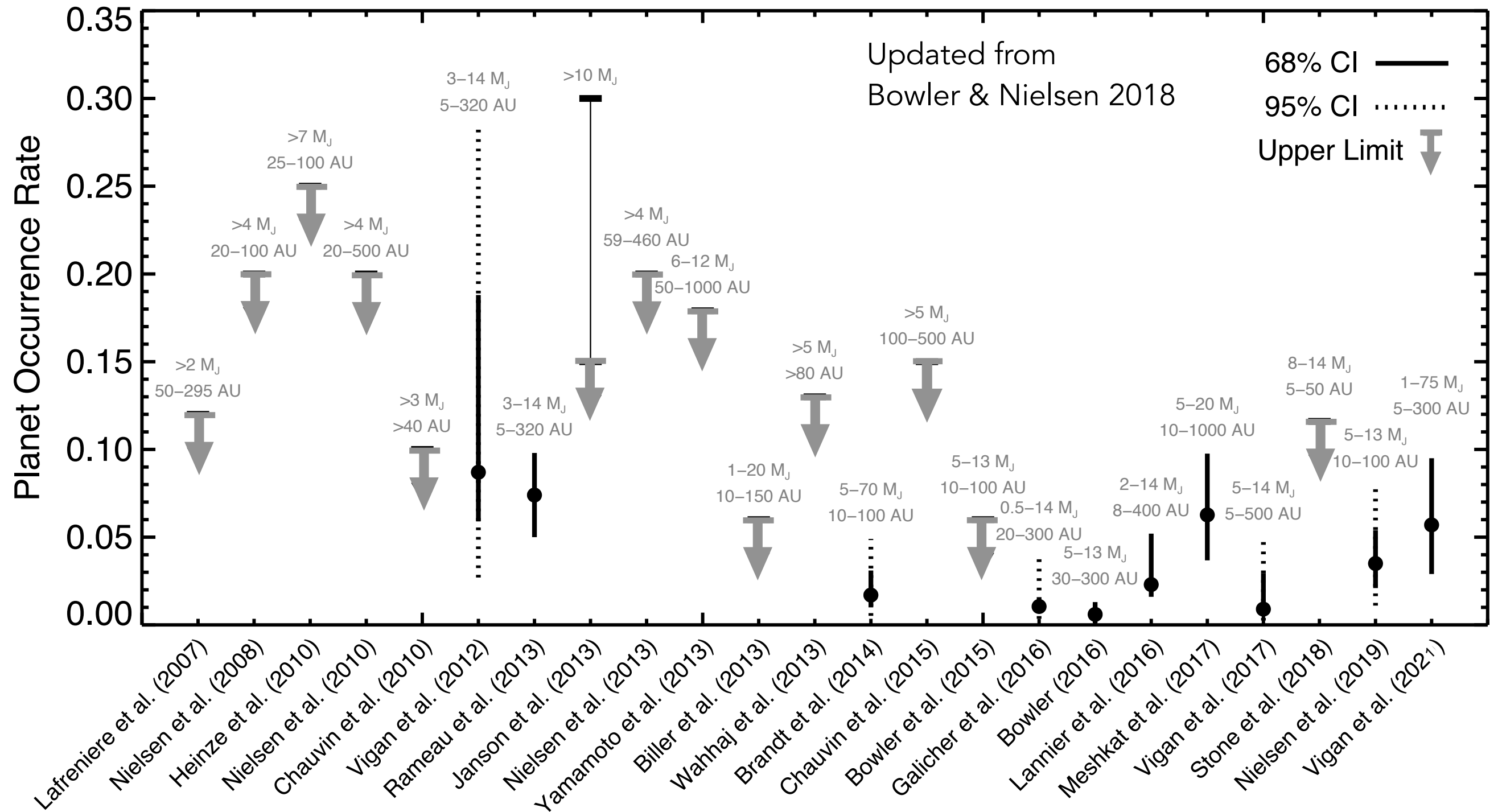


Cloud-Fragmentation

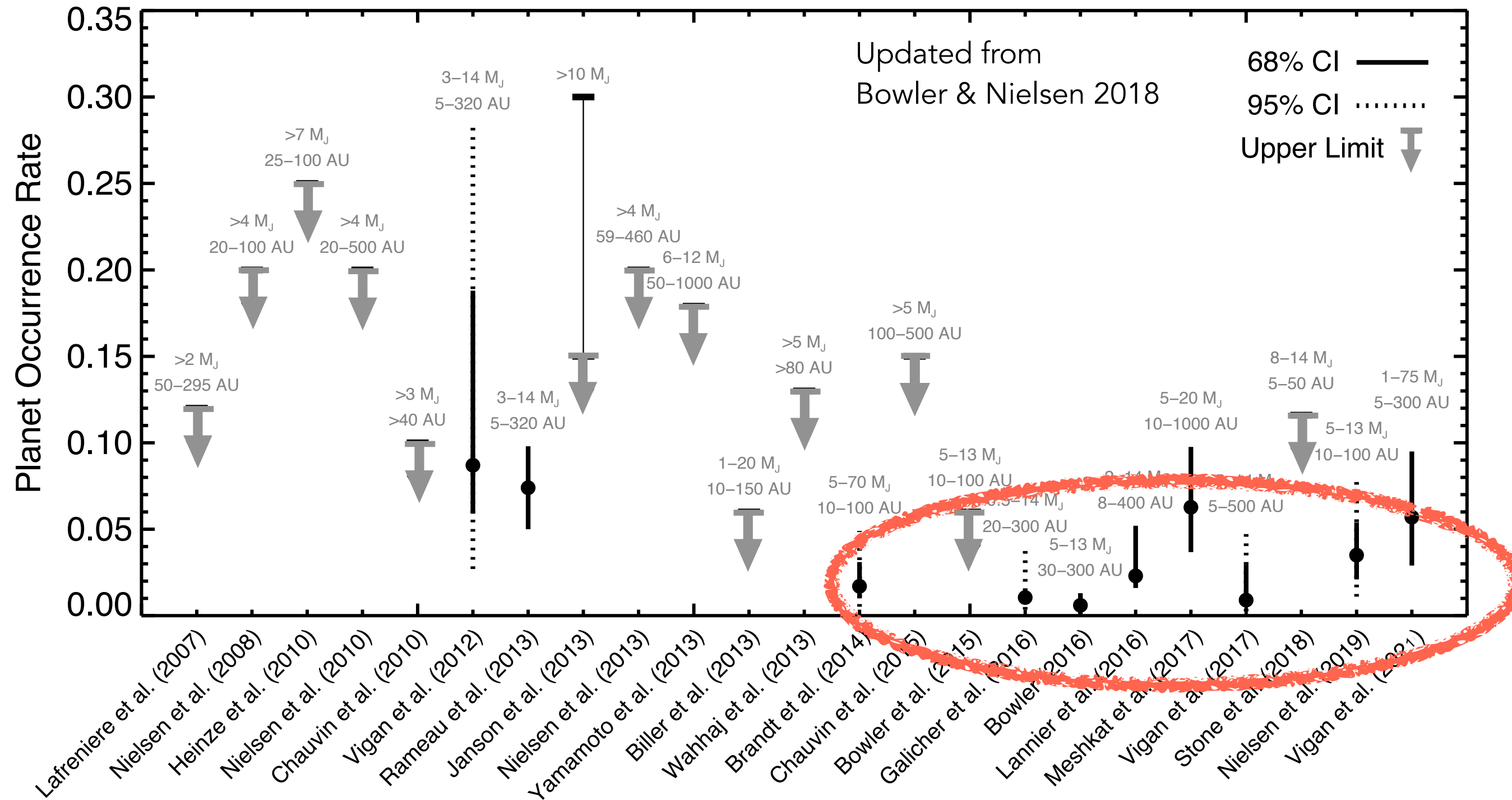
Bate et al. (2002)



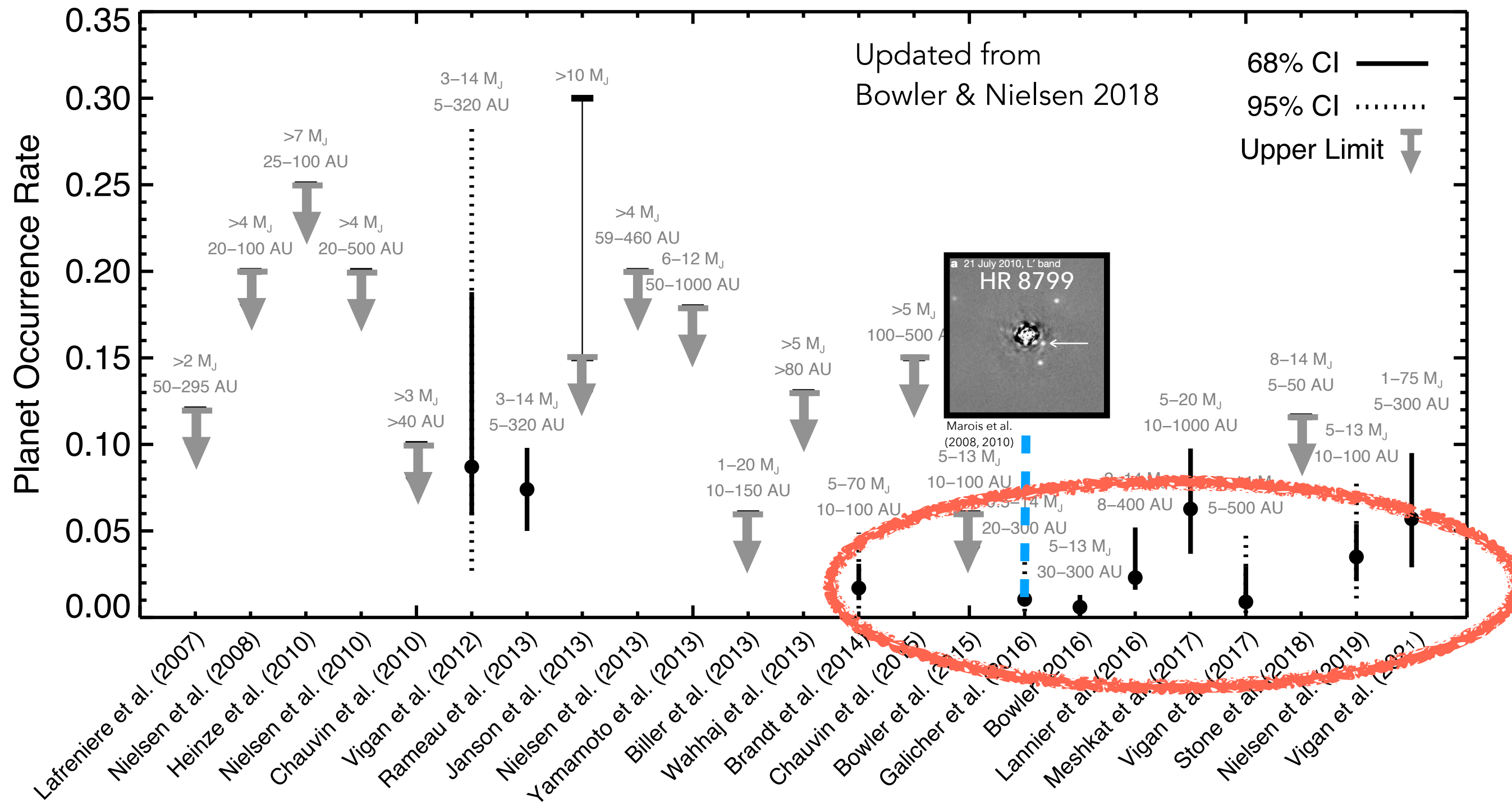
Giant Planets on Wide Orbits Have a Low Occurrence Rate



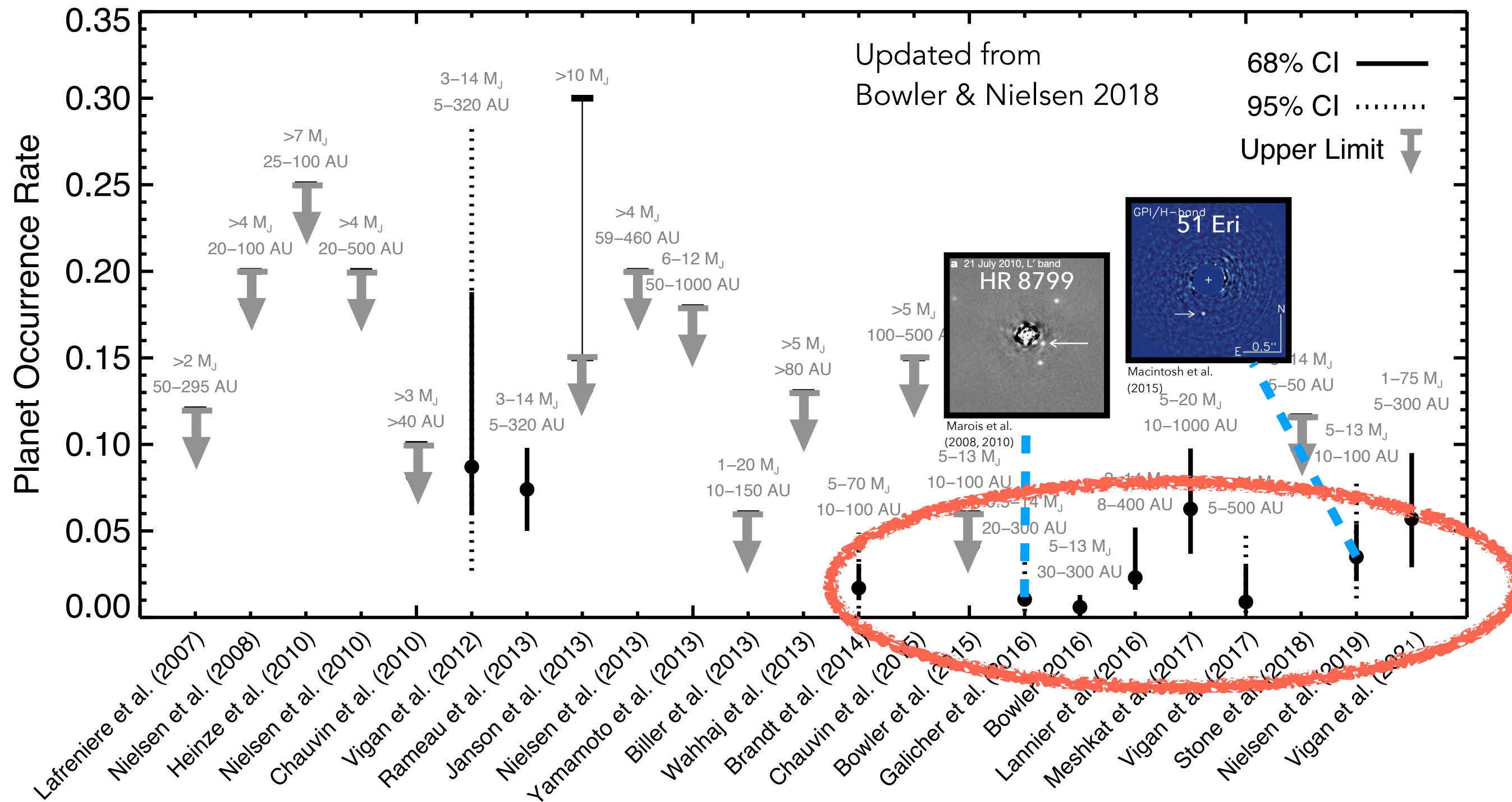
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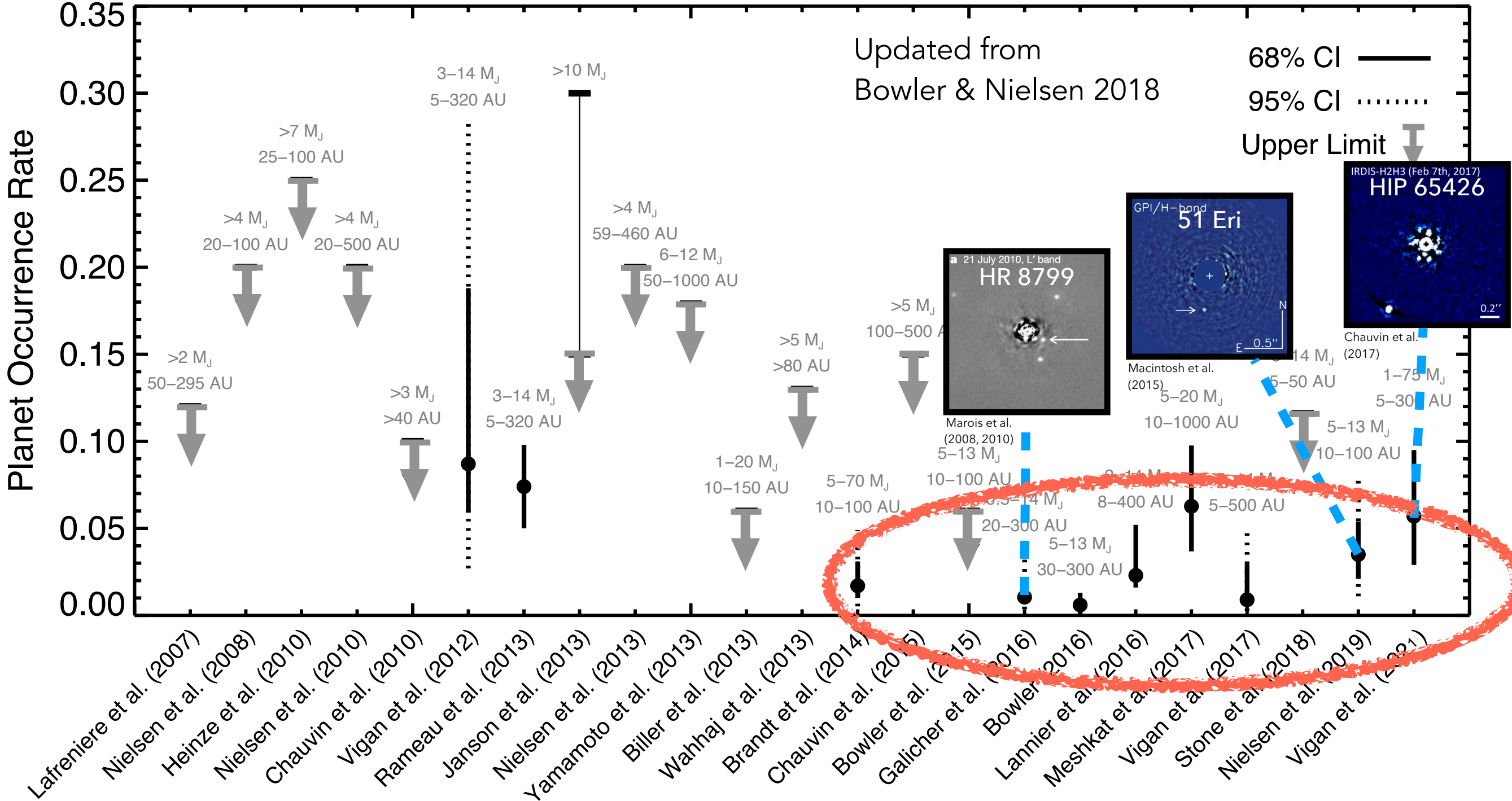
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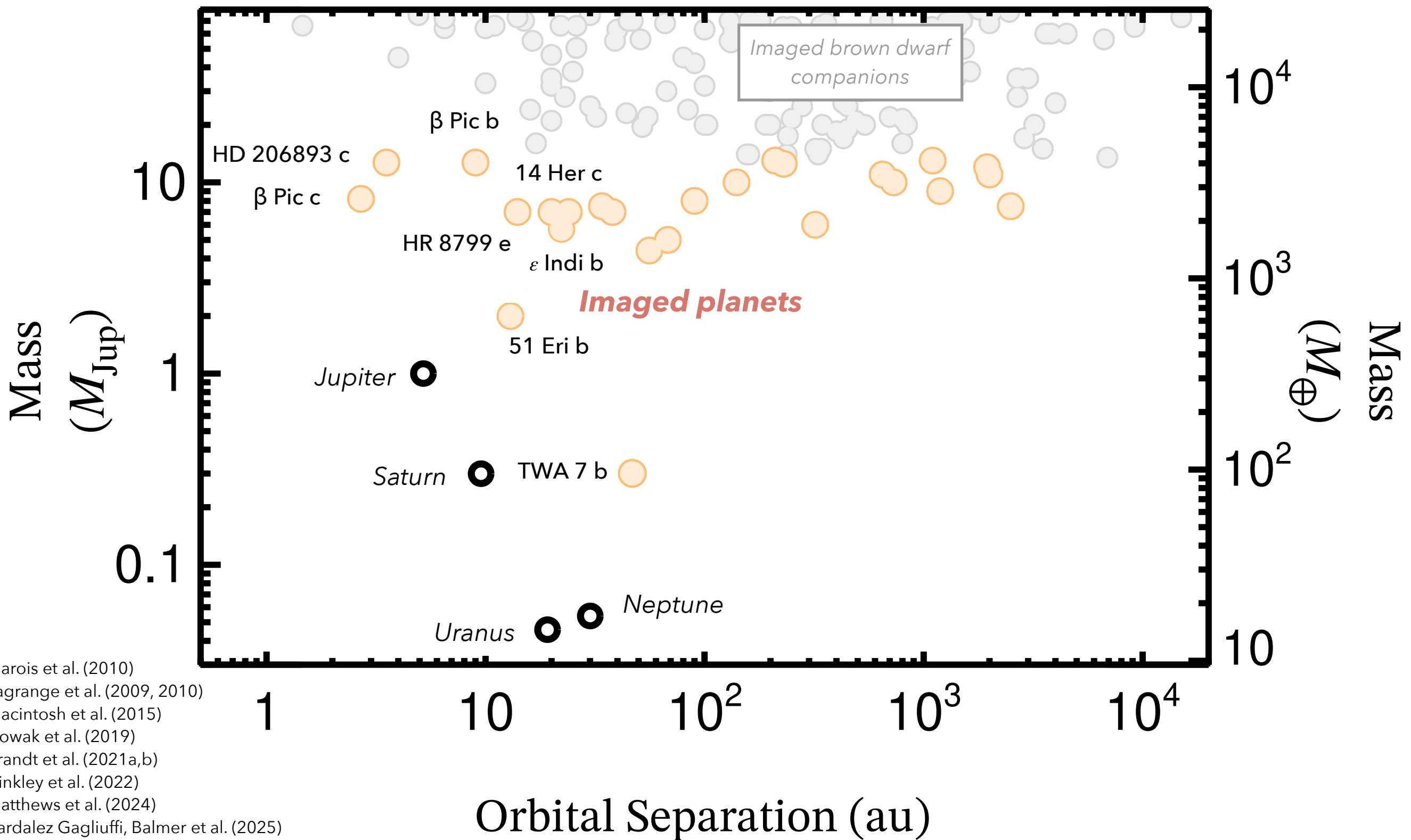
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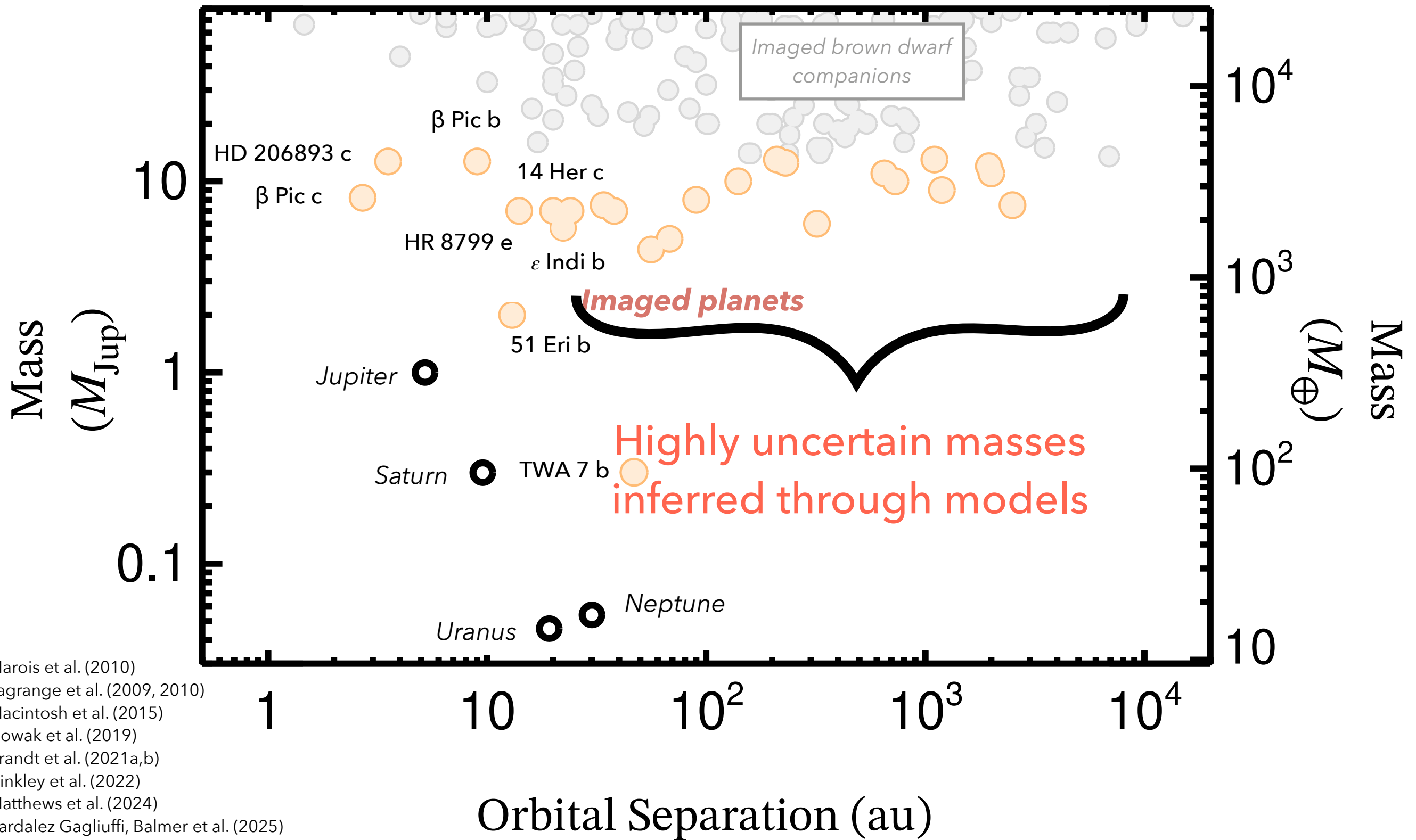


Few Imaged Exoplanets Have Direct Mass Measurements



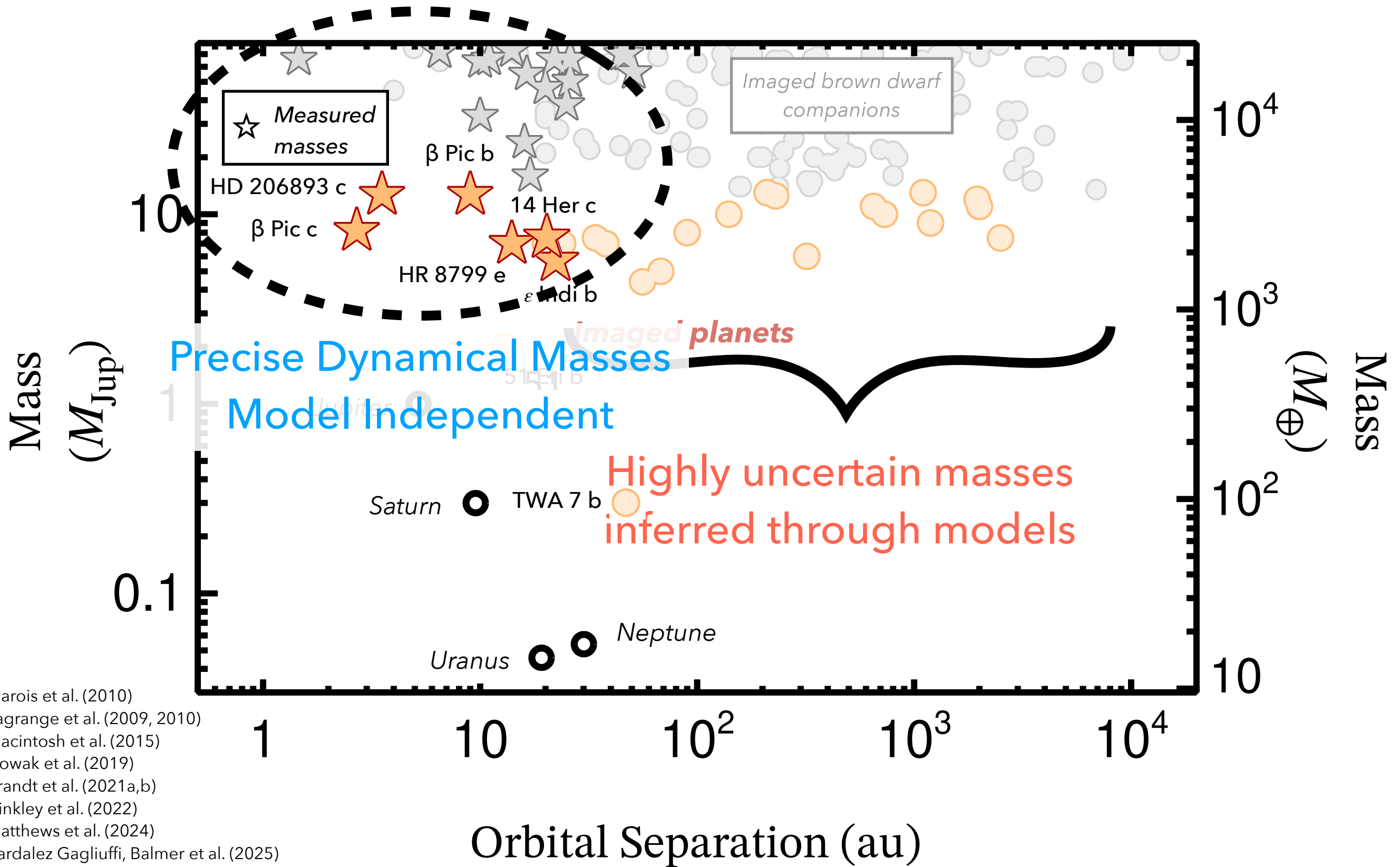
Marois et al. (2010)
Lagrange et al. (2009, 2010)
Macintosh et al. (2015)
Nowak et al. (2019)
Brandt et al. (2021a,b)
Hinkley et al. (2022)
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Bardalez Gagliuffi, Balmer et al. (2025)
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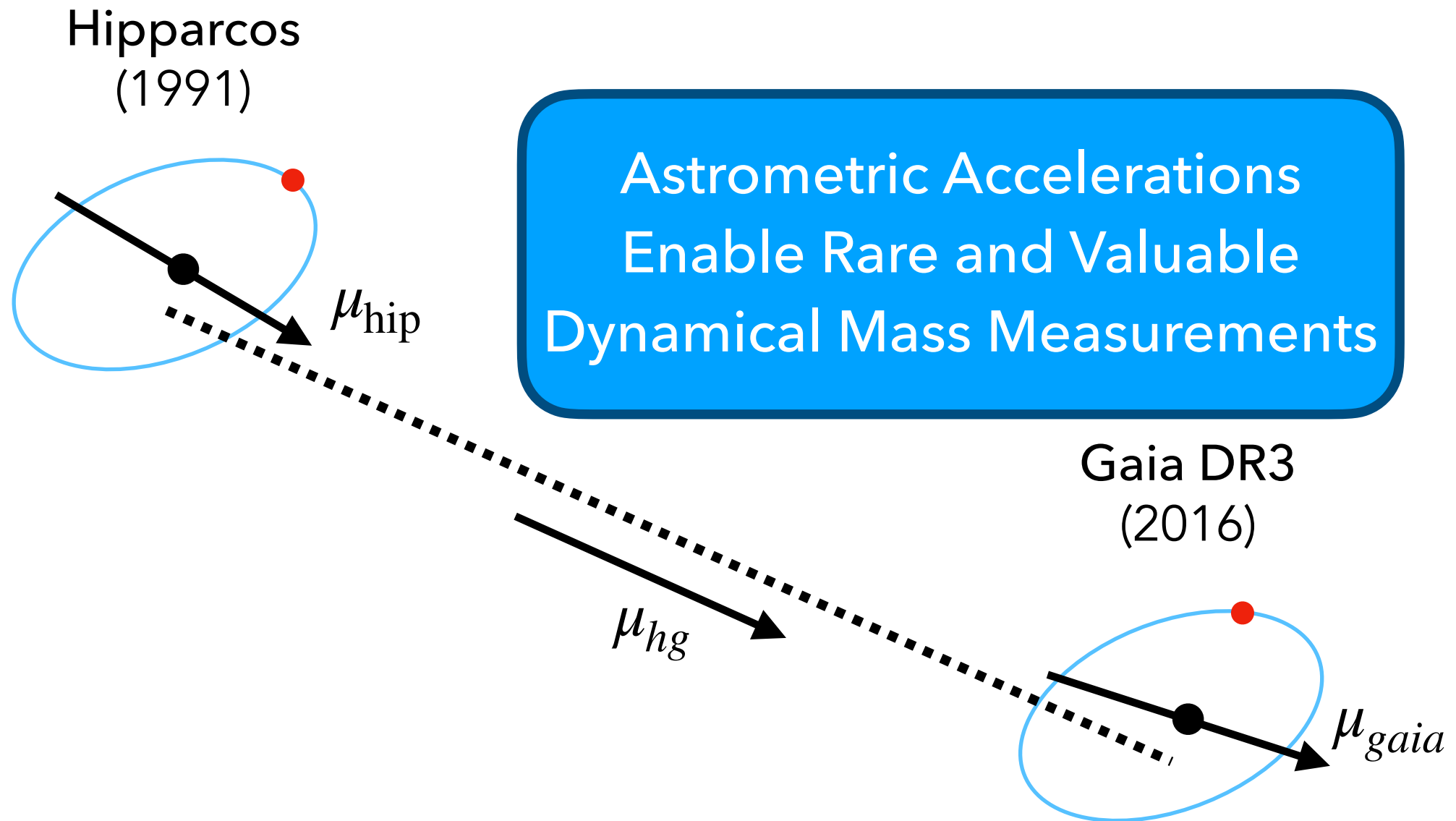
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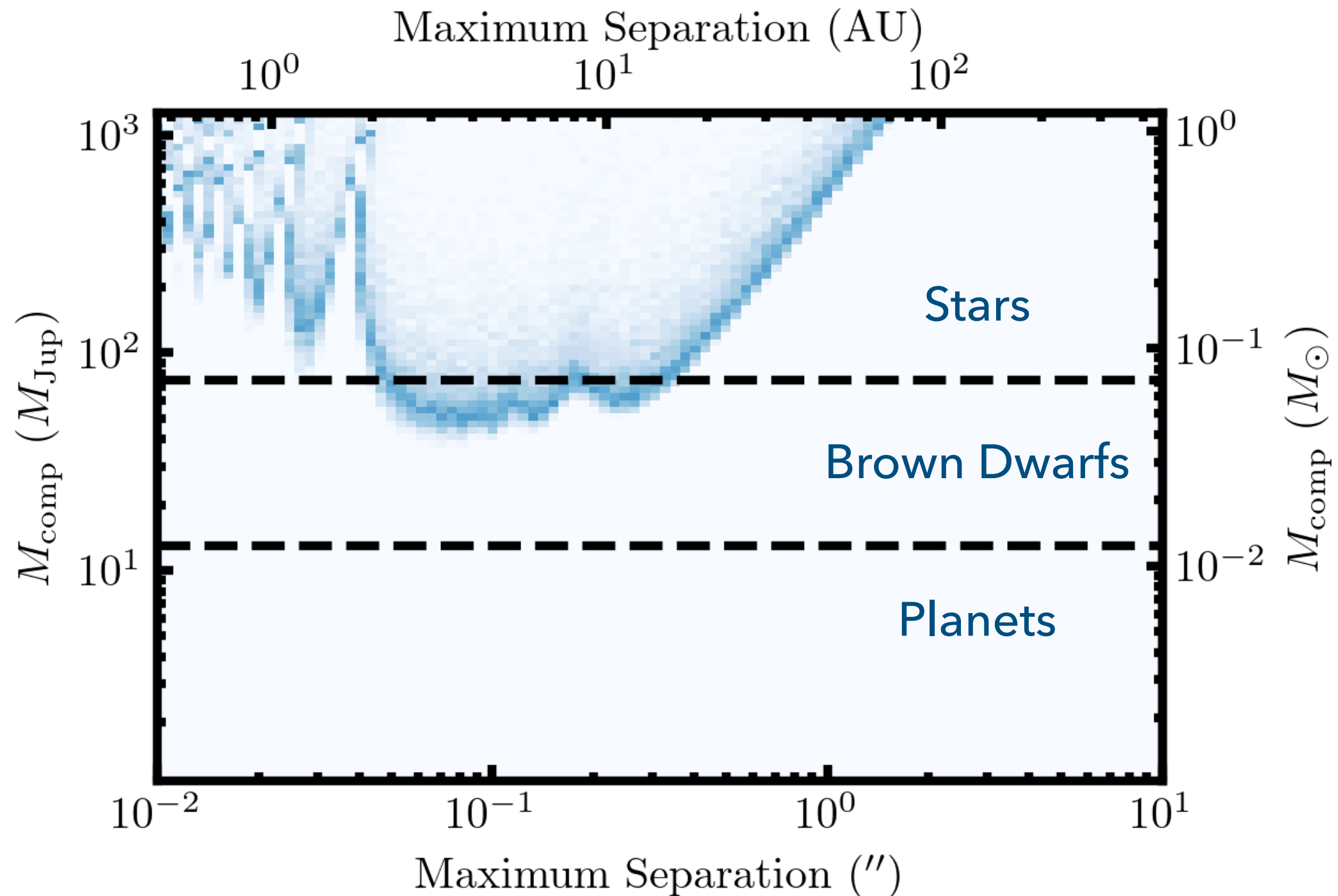
Astrometric Accelerations Reveal Unseen Wide-Orbiting Planets



Planets and Brown Dwarfs Induce Small Proper Motion Differences over 25 years between Hipparcos and Gaia DR3

(See Brandt 2018, 2021; Kervella et al. 2019, 2021)

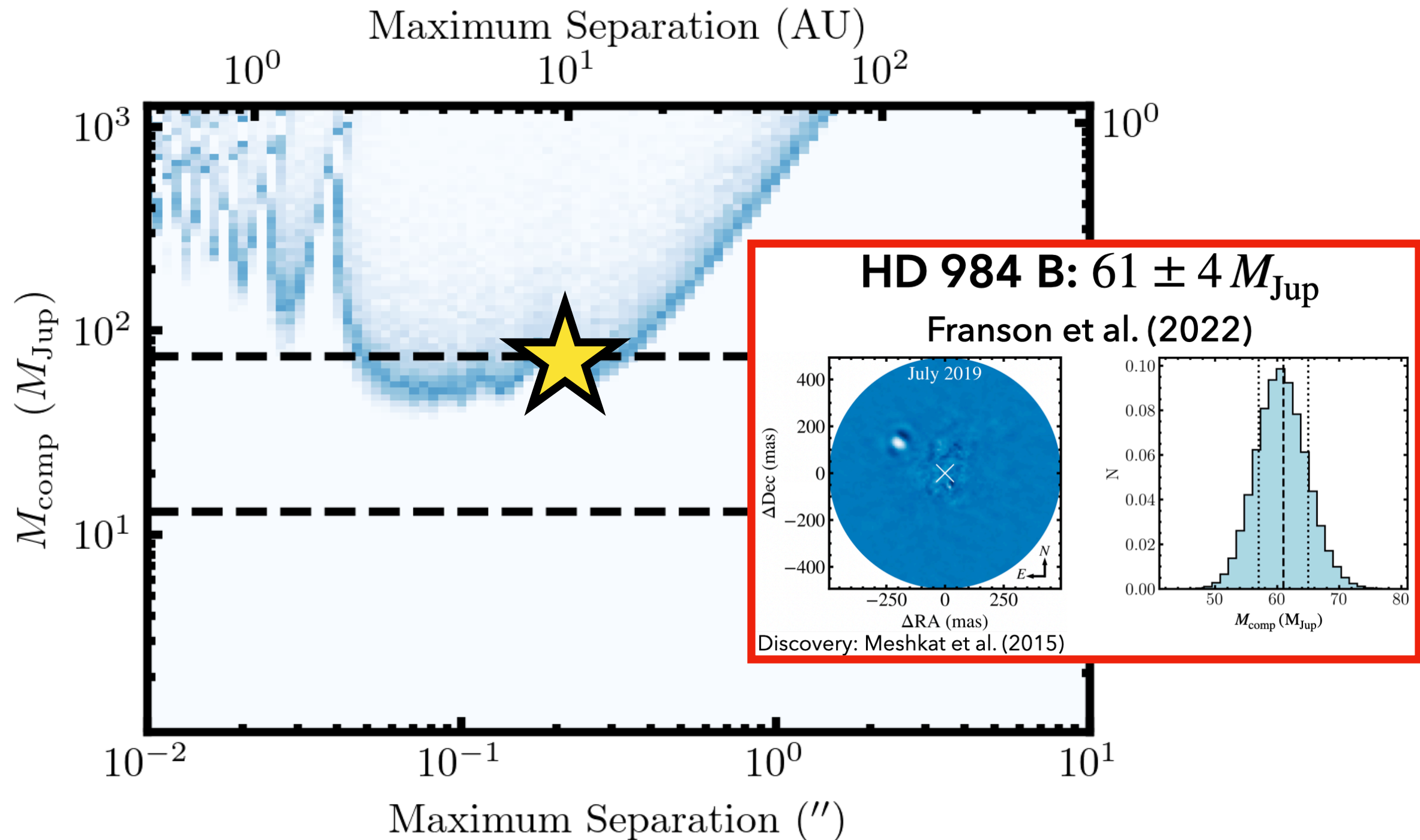
Predicted Mass From Astrometric Acceleration



See Franson et al. (2023a,b); Franson & Bowler (2023)

See also e.g., Brandt et al. (2019, 2021); De Rosa et al. (2019a,b); Fontanive et al. (2019); Mesa et al. (2022), Li et al. (2023, 2024)

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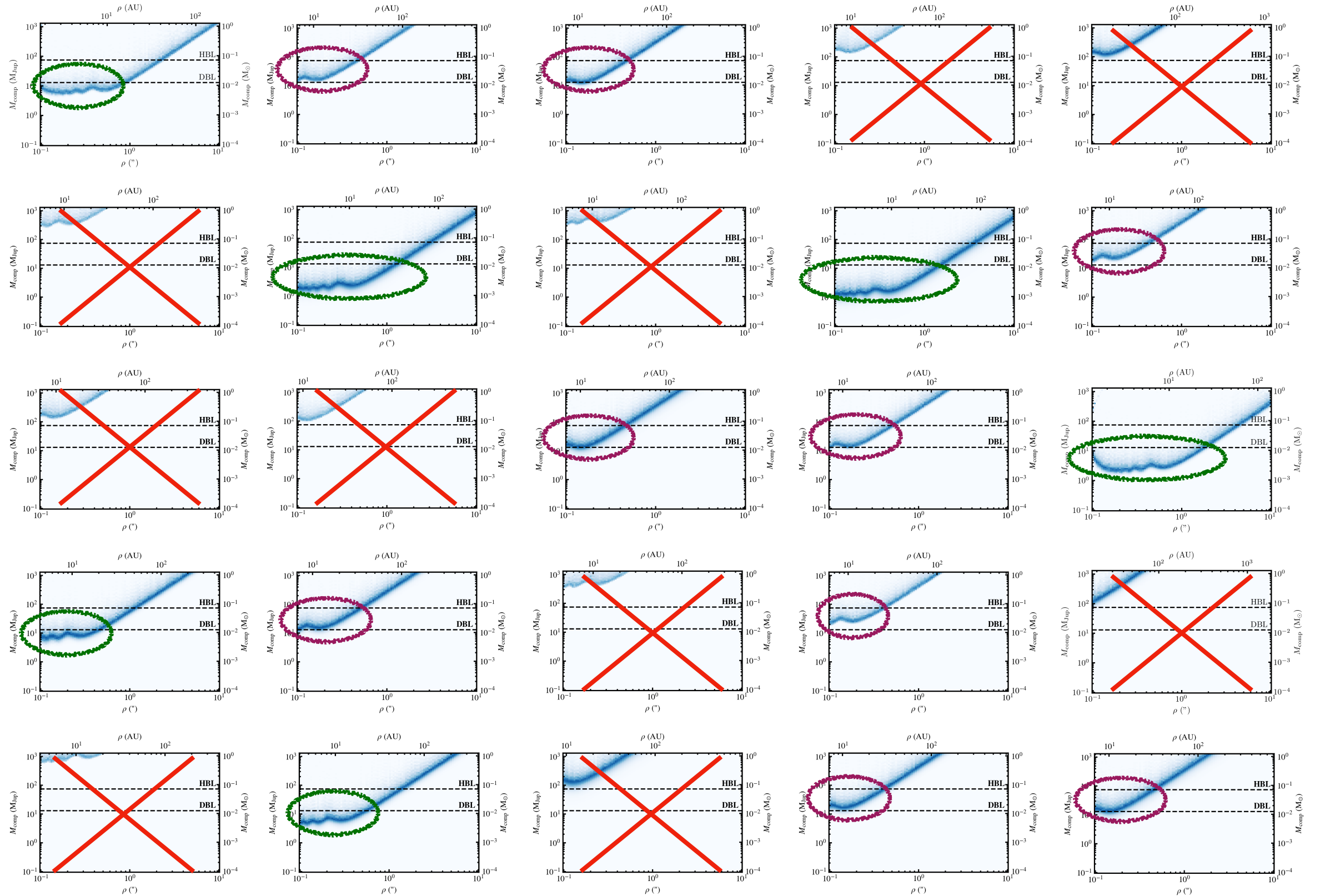


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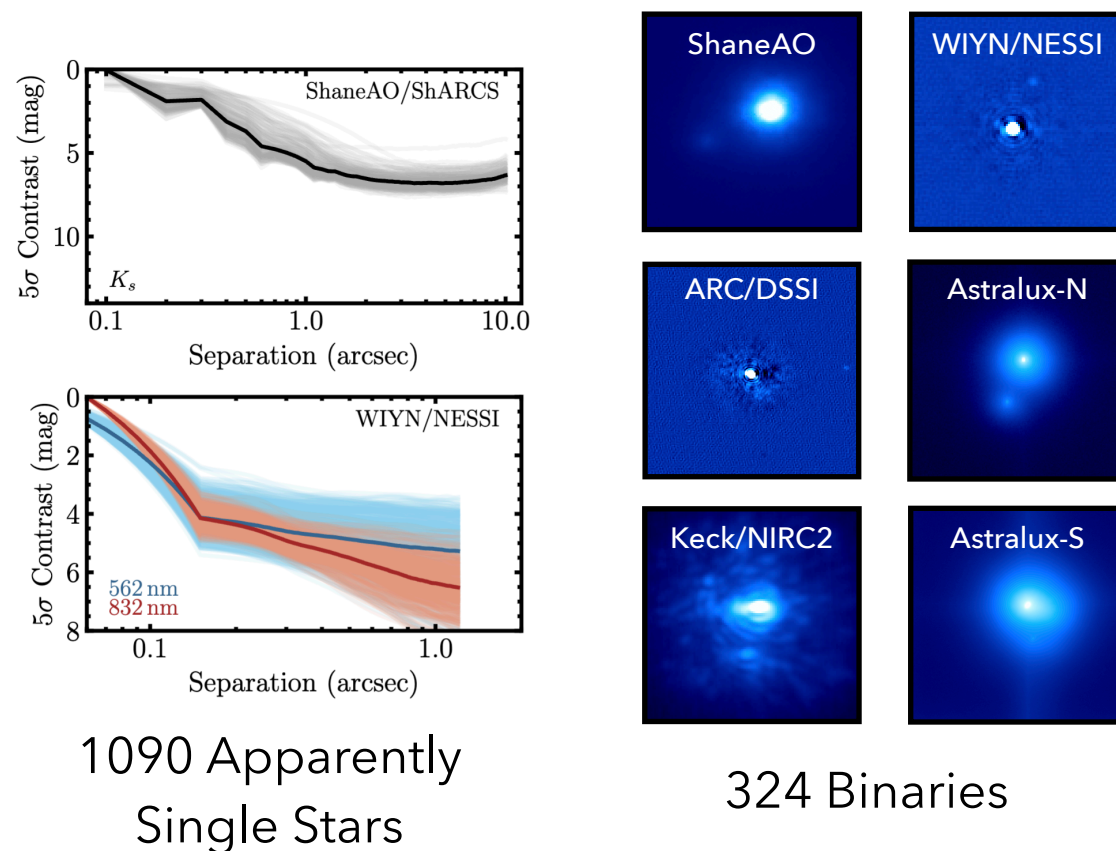
Franson et al. (2023a,b)



Astrometric Accelerations as Dynamical Beacons

Franson et al. (2023a,b)

Shallow Imaging of 1400 Accelerating Stars



*Keck/NIRC2, WIYN/HRCam, ARC/DSSI,
ShaneAO, SOAR/HRCam, Astralux-N/S*

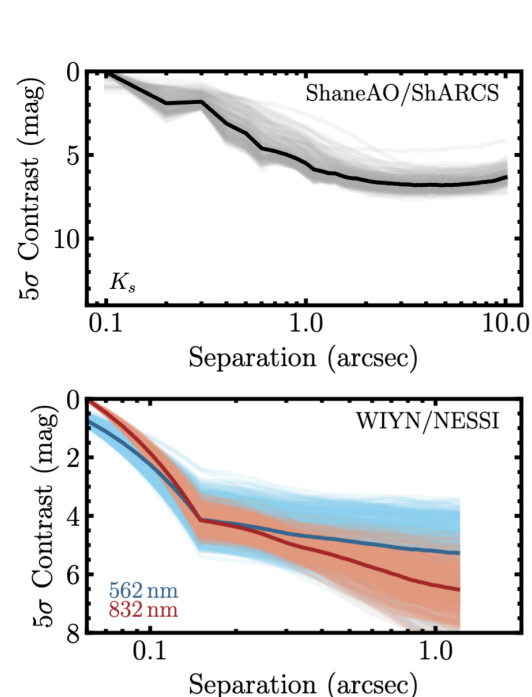
Franson et al. (in prep.)

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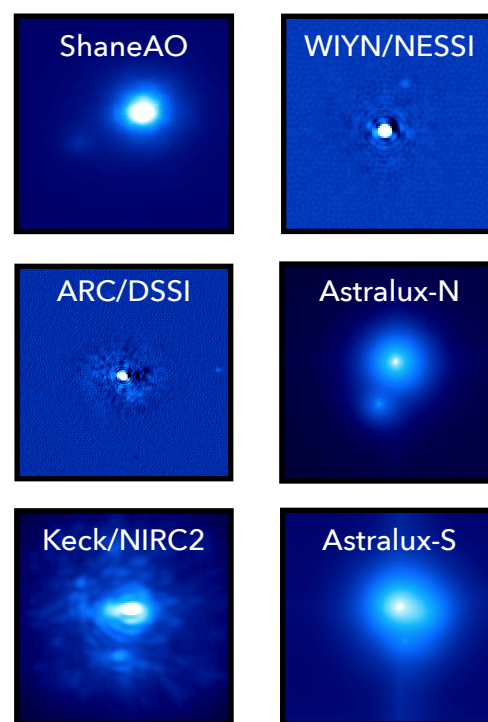
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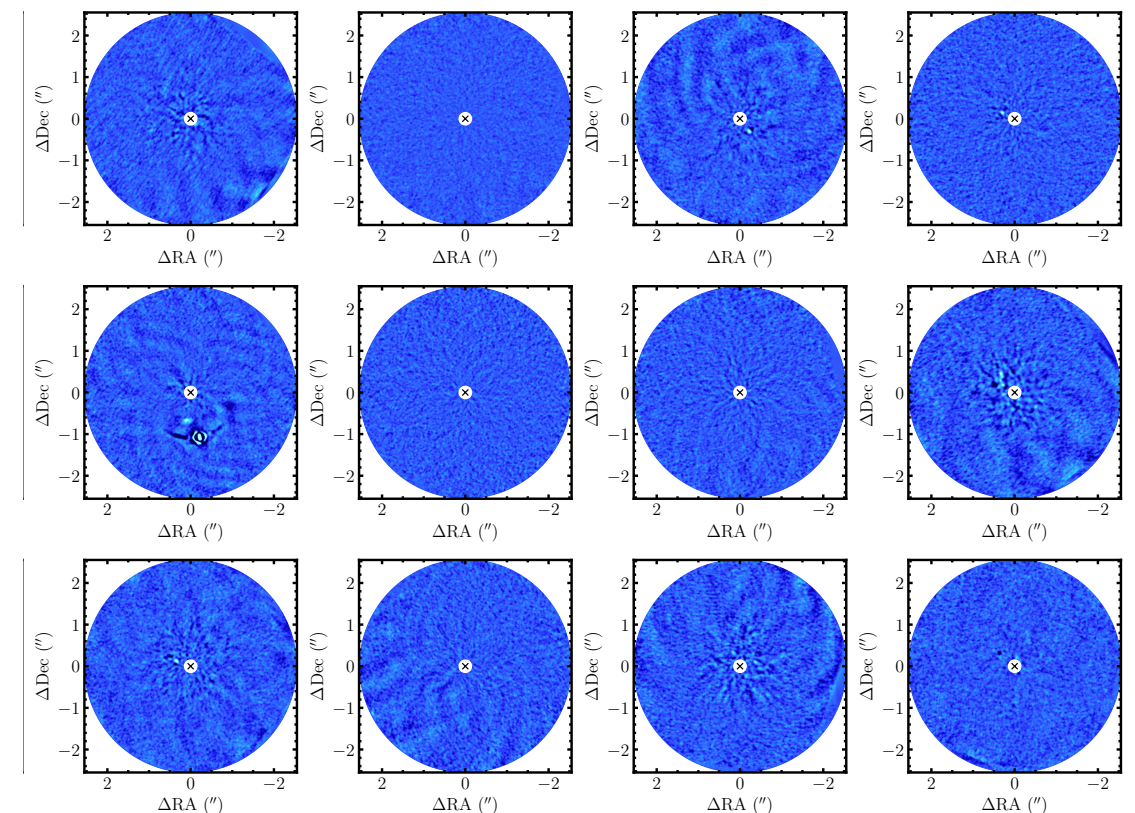
High-Contrast Imaging of 34
Young Accelerating Stars



1090 Apparently
Single Stars



324 Binaries



*Keck/NIRC2, WIYN/HRCam, ARC/DSSI,
ShaneAO, SOAR/HRCam, Astralux-N/S*

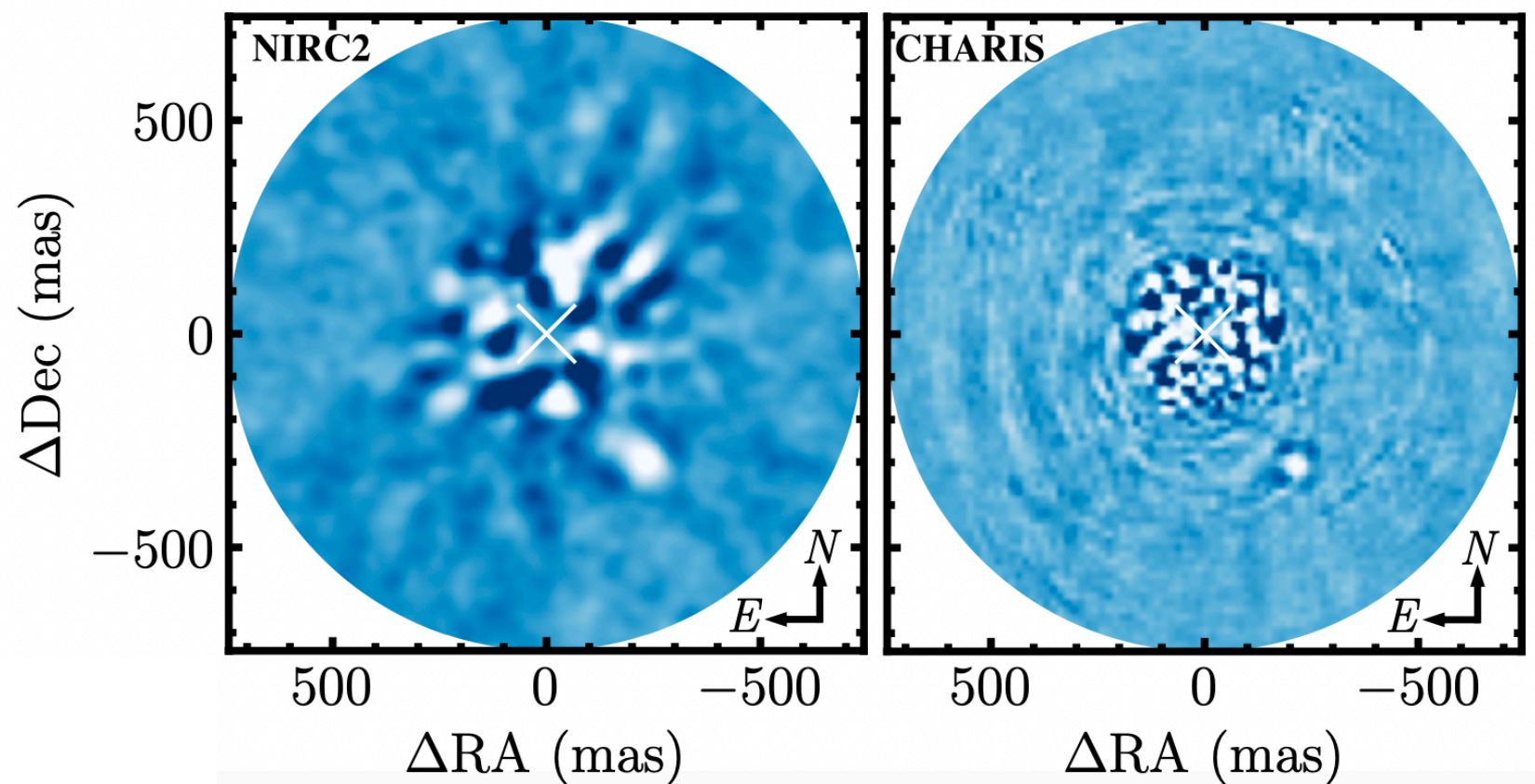
*Keck/NIRC2, VLT/SPHERE,
SCEXAO/CHARIS*

Franson et al. (in prep.)

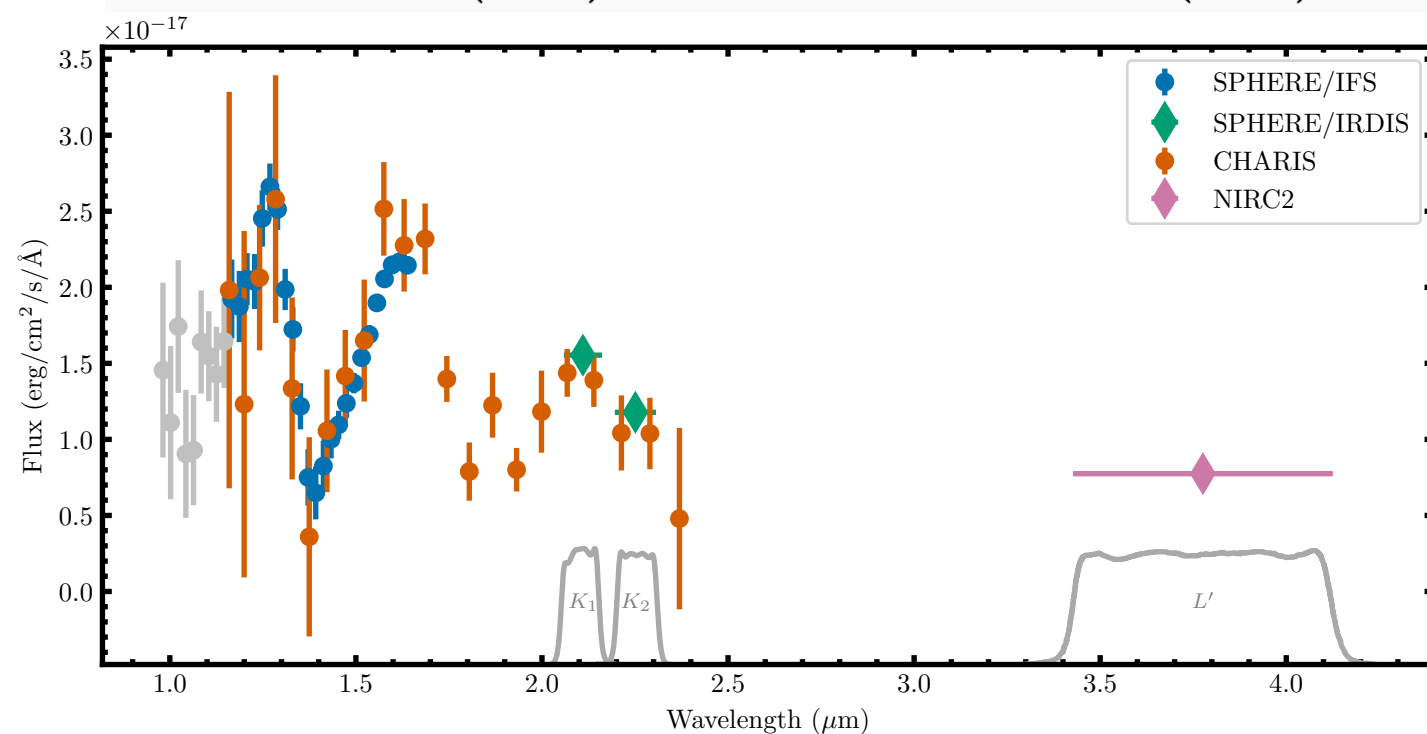
HIP 21152 B: First Imaged Brown Dwarf Companion in the Hyades

Franson et al. (2023a)

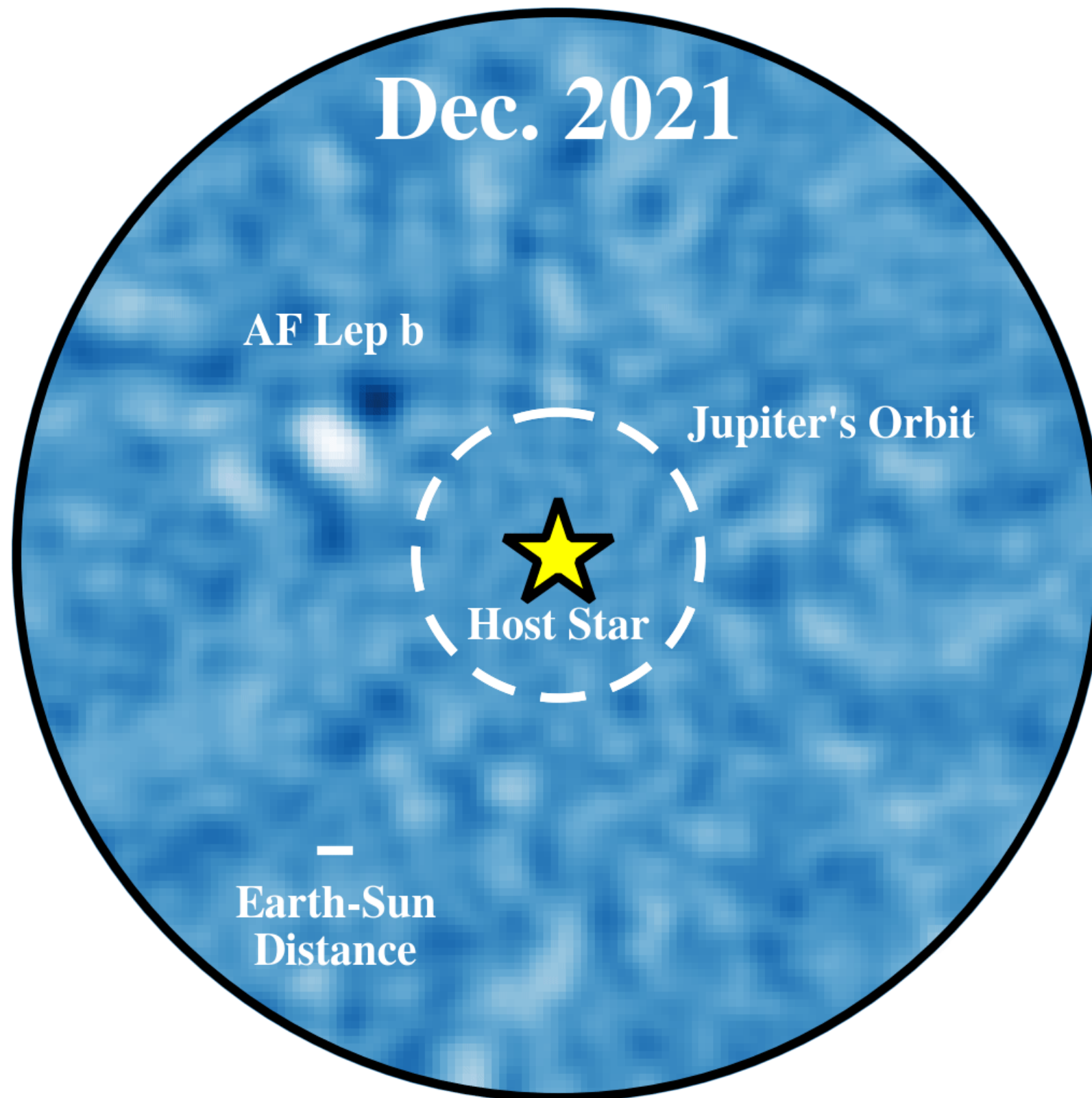
See also Bonavita et al. (2022) and Kuzuhara et al. (2022)



- ♦ 370 mas separation
- ♦ L' contrast of 9.3 mag
- ♦ F5 Host-Star in Hyades Cluster
- ♦ Age of 650 ± 100 Myr
- ♦ Dynamical mass of $24^{+6}_{-4} M_{\text{Jup}}$
 - 1-2 σ lower than hot-start model predictions



AF Lep b: Lowest Mass Imaged Planet with a Dynamical Mass

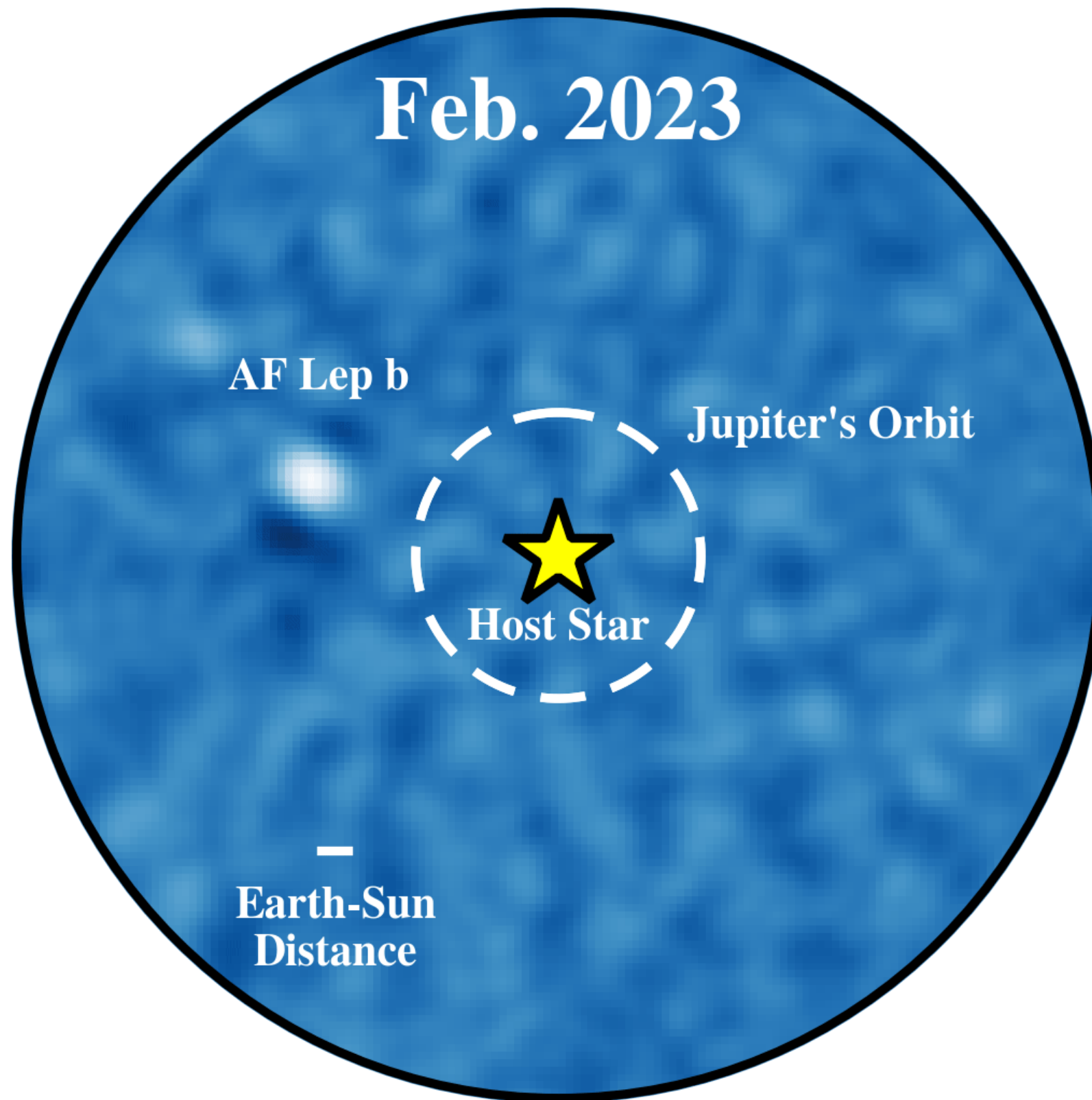


Franson et al. (2023b)

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51 Peg 30th Anniversary

AF Lep b: Lowest Mass Imaged Planet with a Dynamical Mass



Franson et al. (2023b)

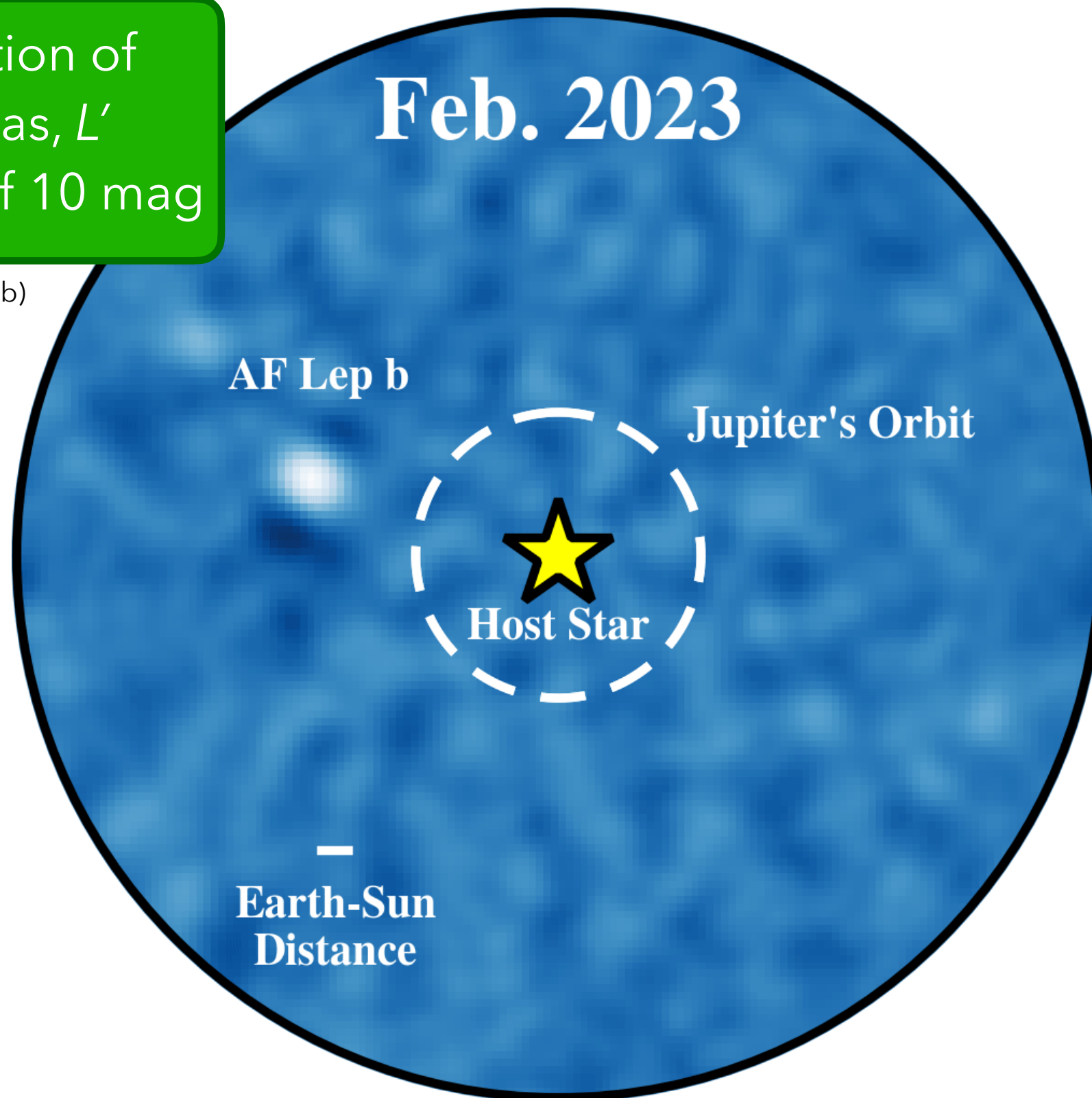
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Separation of
350 mas, L'
Contrast of 10 mag

Franson et al. (2023b)



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51 Peg 30th Anniversary

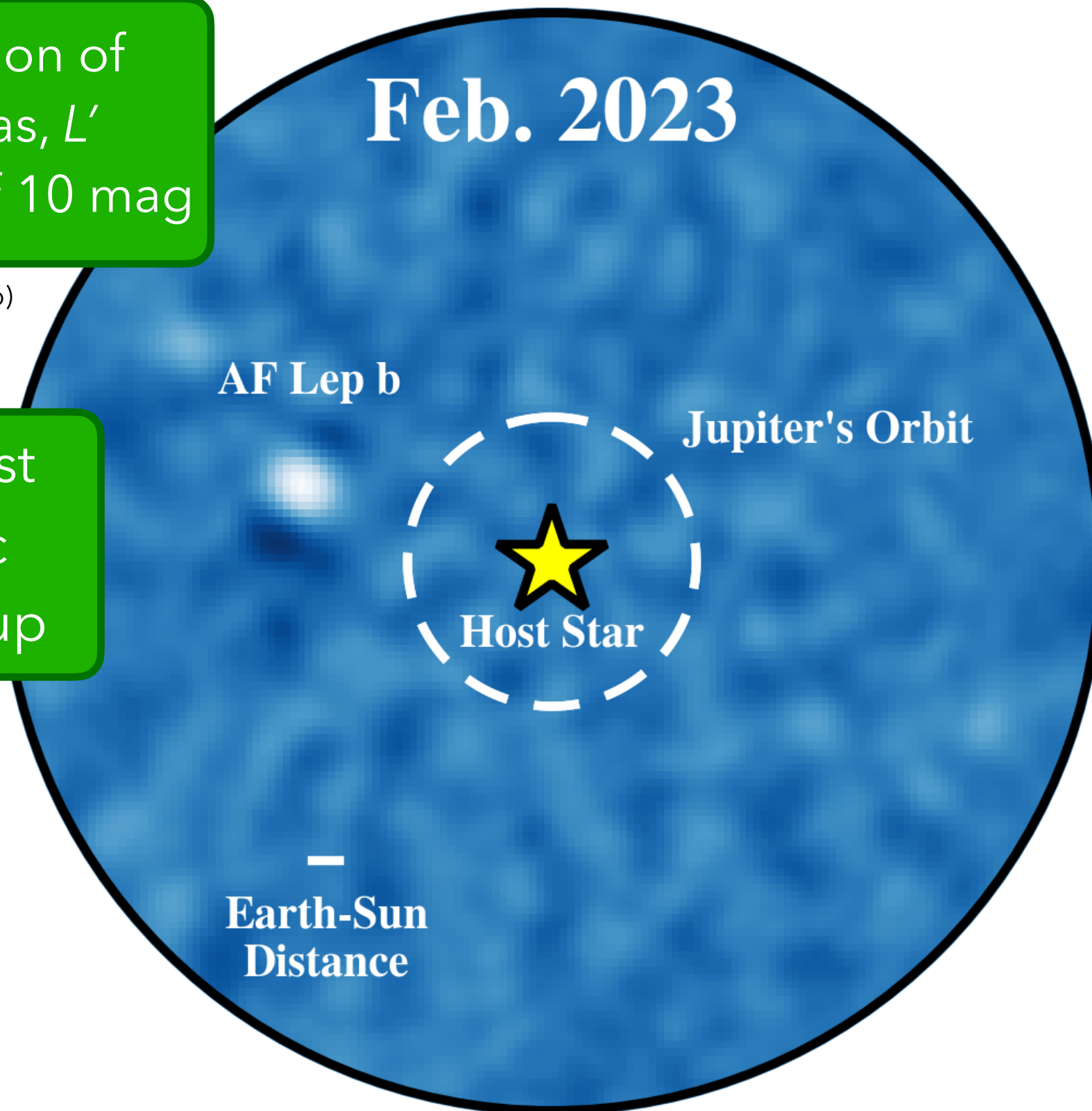
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Franson et al. (2023b)

Sun-Like Host
Star in β Pic
Moving Group

Zuckerman & Song (2004)



Franson et al. (2023b)

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Sun-Like Host
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Age of
 24 ± 3 Myr

Bell et al. (2015)

Feb. 2023

AF Lep b

Jupiter's Orbit

Host Star

—
Earth-Sun
Distance

Franson et al. (2023b)

See also De Rosa et al. (2023) and Mesa et al. (2023)

51 Peg 30th Anniversary

AF Lep b: Lowest Mass Imaged Planet with a Dynamical Mass

Separation of
350 mas, L'
Contrast of 10 mag

Franson et al. (2023b)

Feb. 2023

Debris Disk
with Radius of
30–70 au

Pawellek et al. (2021)

AF Lep b

Jupiter's Orbit

Sun-Like Host
Star in β Pic
Moving Group

Zuckerman & Song (2004)

Host Star

Age of
 24 ± 3 Myr

Bell et al. (2015)

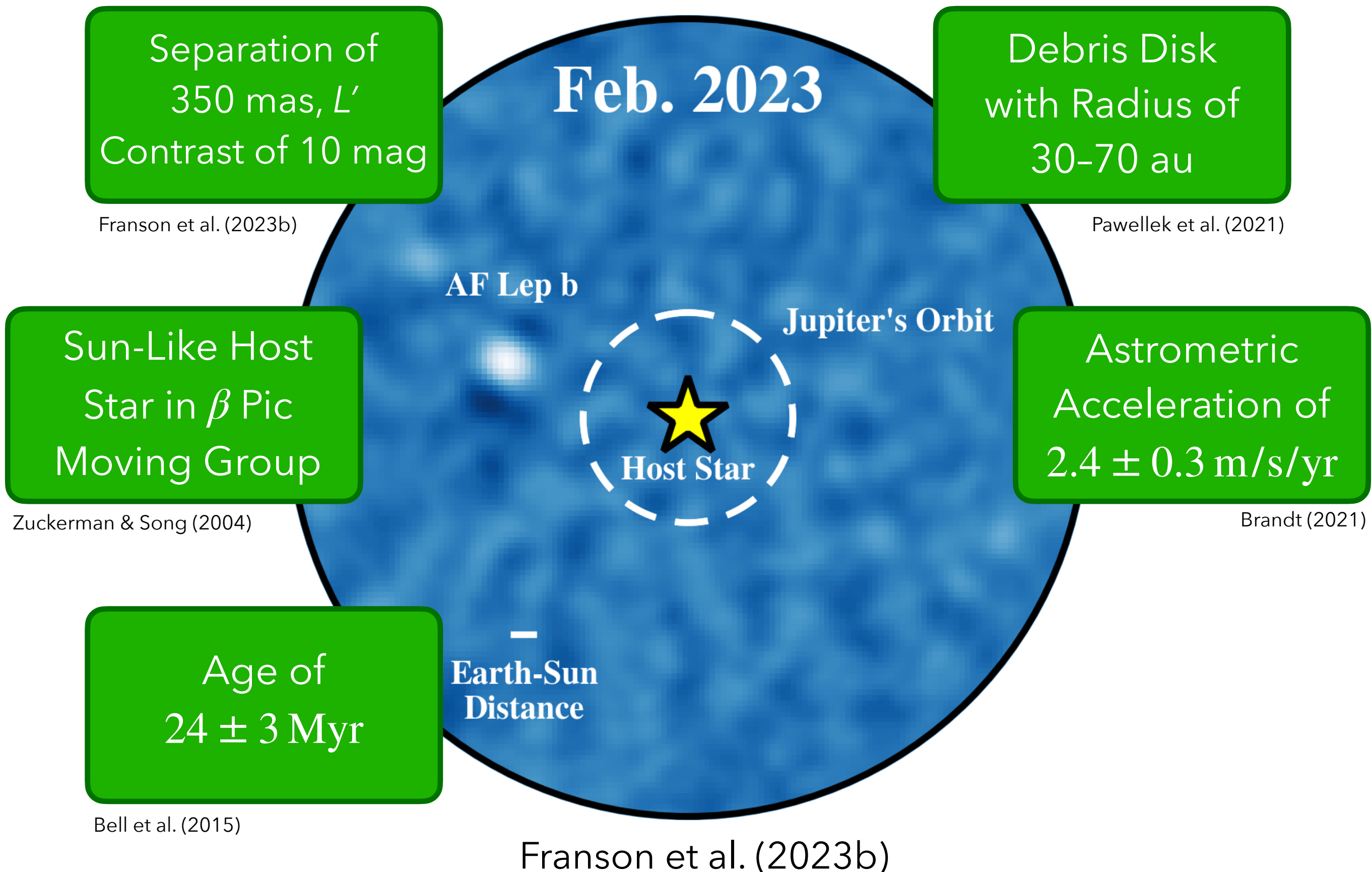
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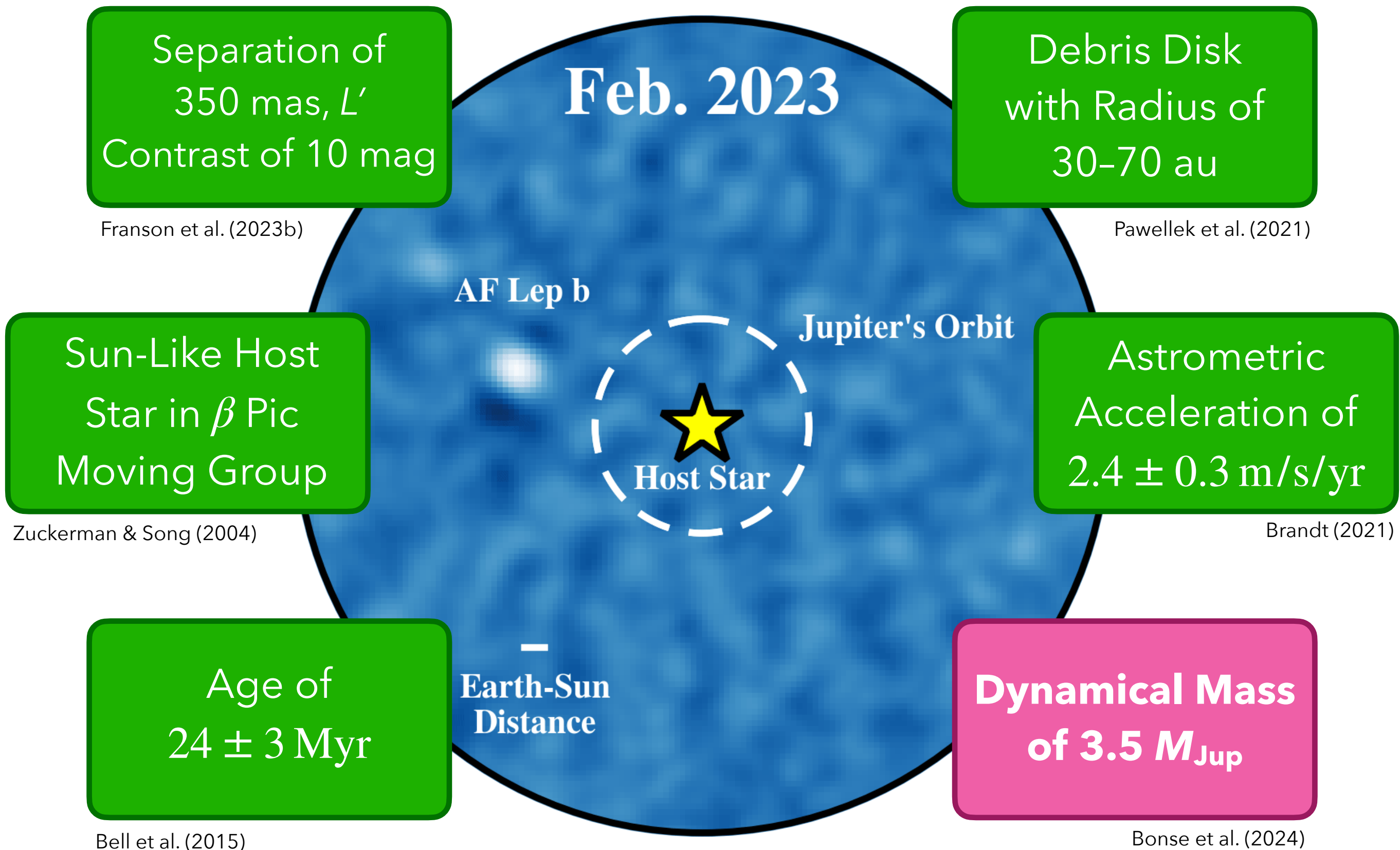
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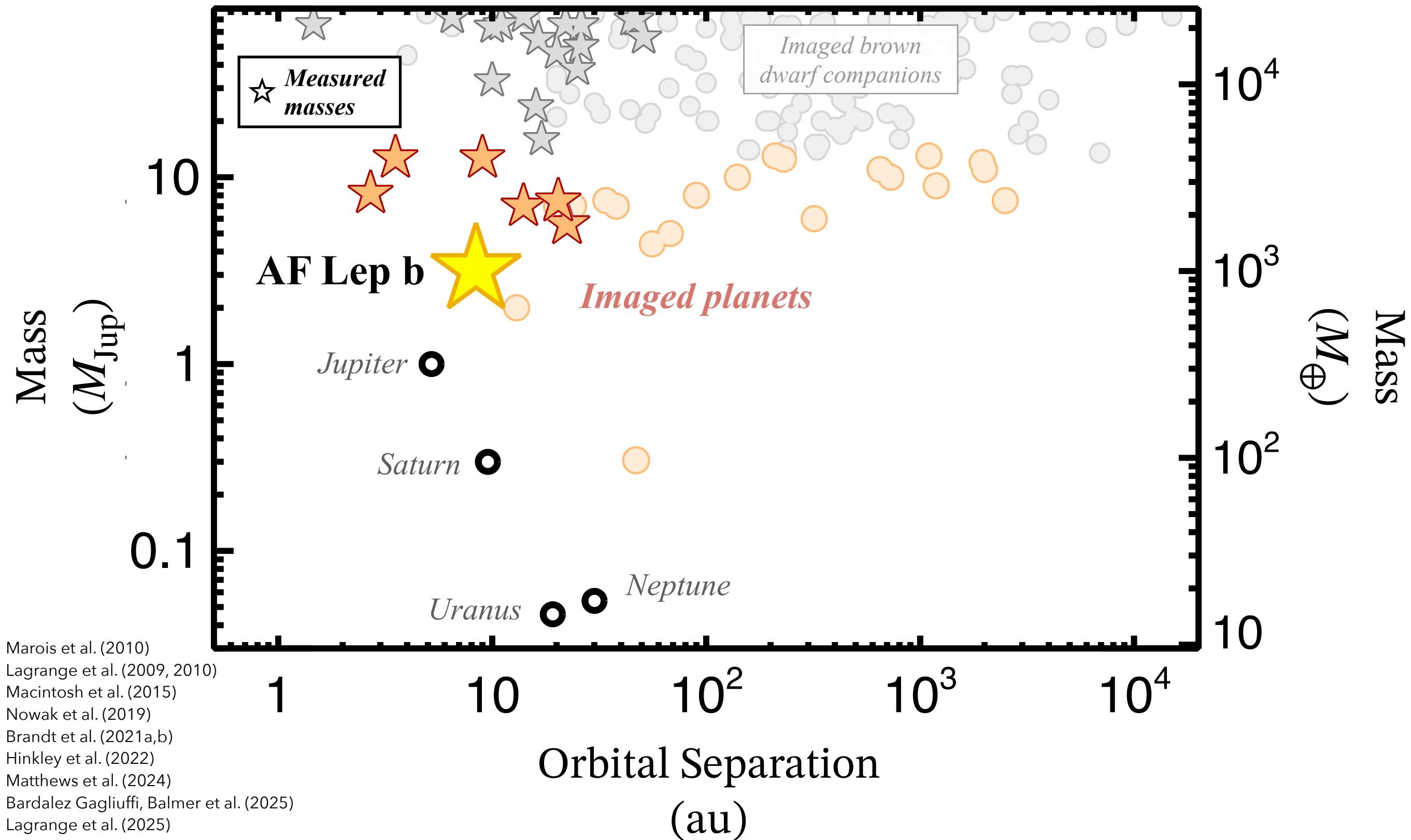
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Franson et al. (2023b)
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51 Peg 30th Anniversary

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AF Lep b has been Characterized at Record Pace

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ELemental abundances of Planets and brown dwarfs Imaged around Stars (ELPIS): I. Potential Metal Enrichment of the Exoplanet AF Lep b and a Novel Retrieval Approach for Cloudy Self-luminous Atmospheres

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Atmospheric properties of AF Lep b with forward modeling

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Giant Exoplanet AF Lep b in High-Contrast Imaging Data from 2011

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VLT/GRAVITY Observations of AF Lep b: Preference for Circular Orbits, Cloudy Atmospheres, and a Moderately Enhanced Metallicity

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High-contrast spectroscopy with the new VLT/ERIS instrument

Molecular maps and radial velocity of the gas giant AF Lep b[★]

Hayoz et al. (2025)

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**Characterization of AF Lep b
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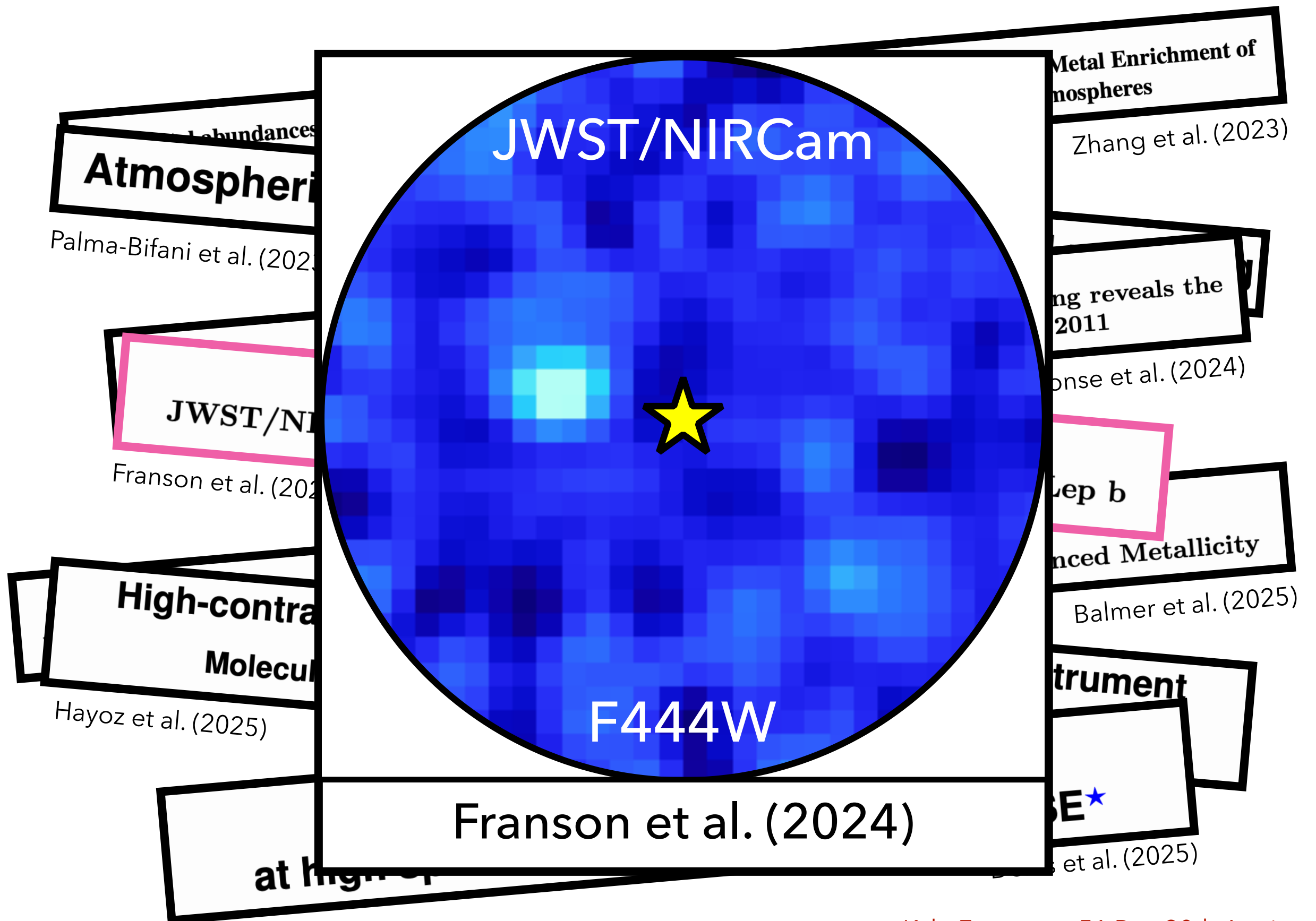
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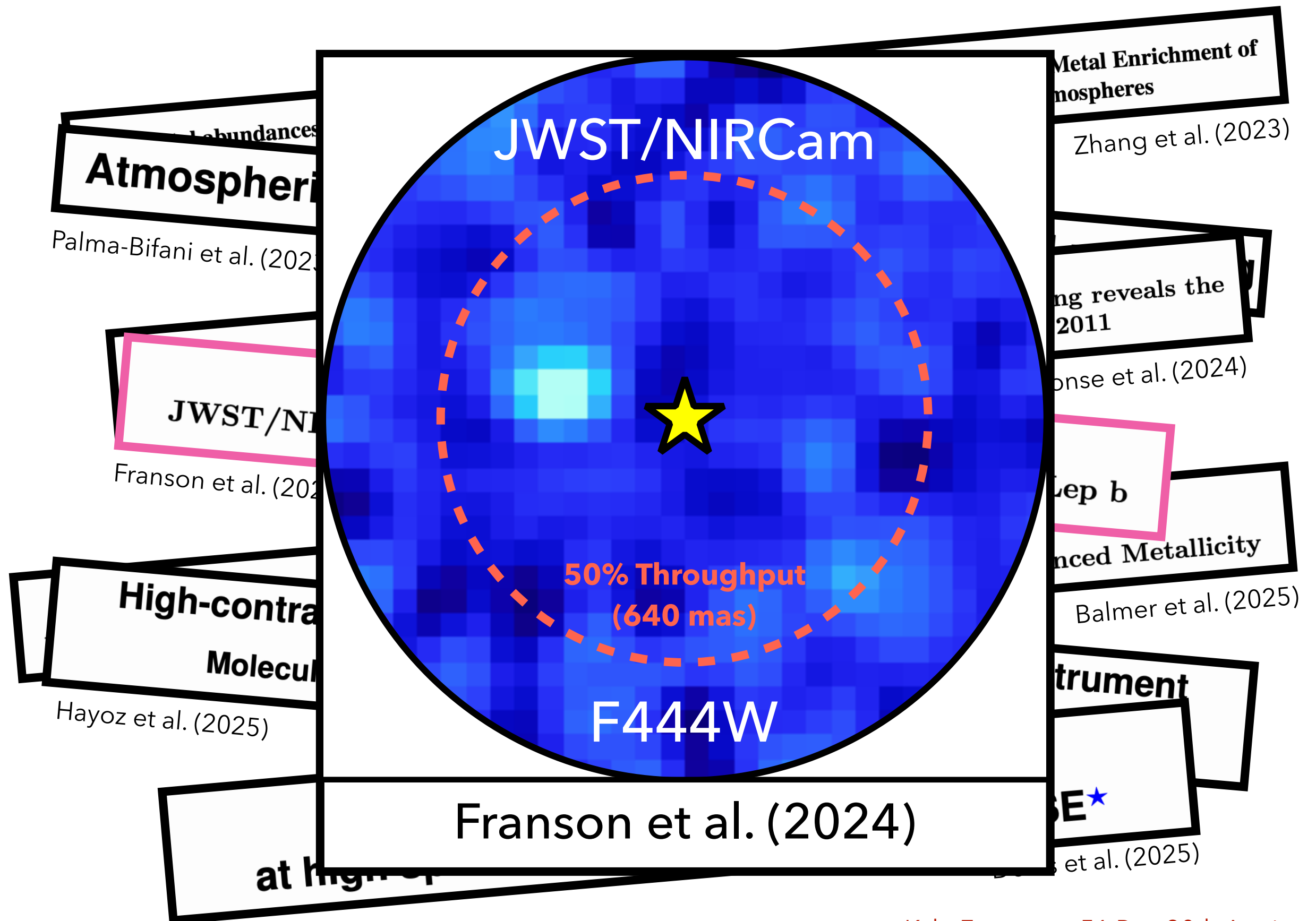
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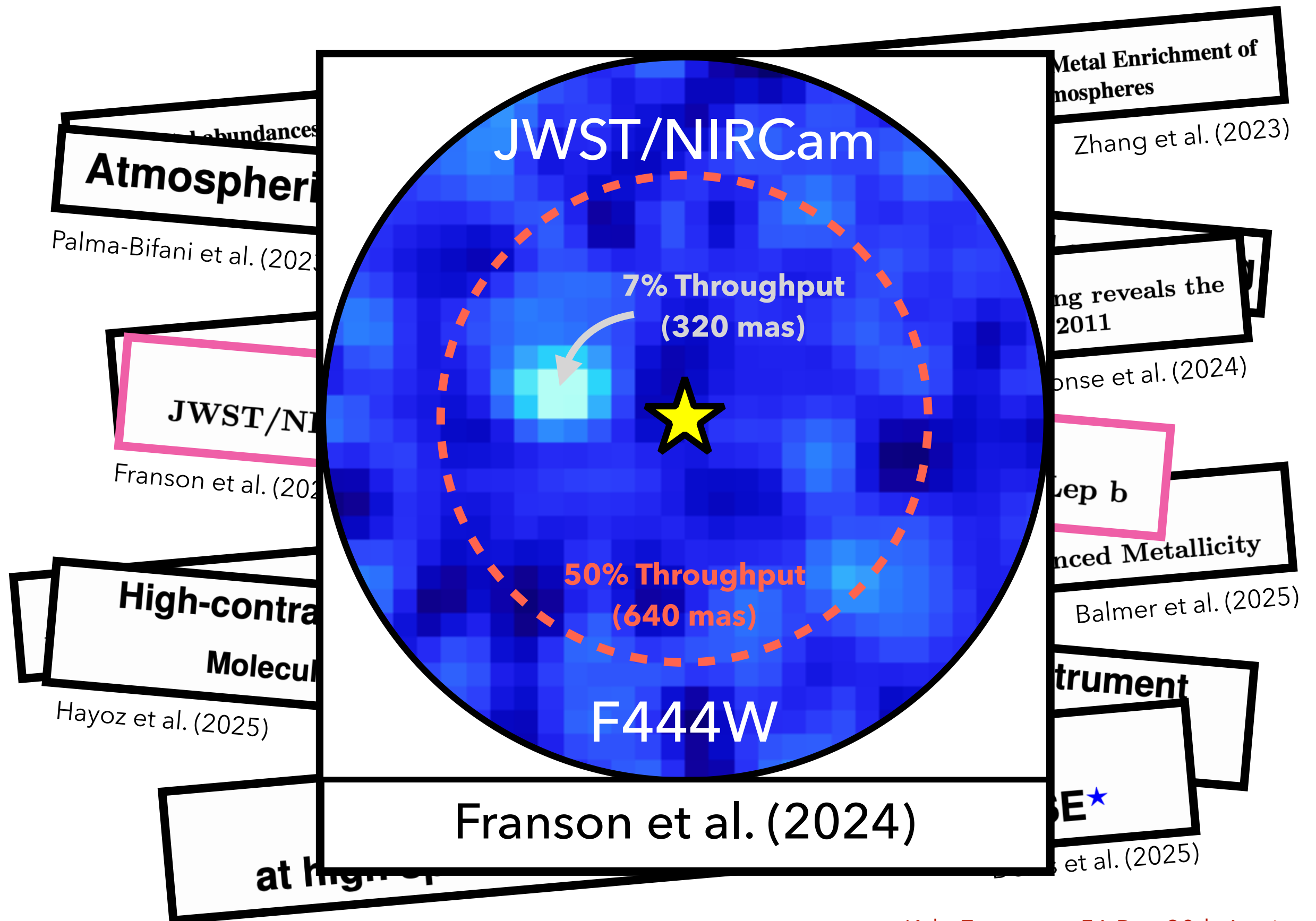
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Clues About the Formation of AF Lep b

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Circular Orbit

$$e = 0.01 \pm 0.02$$

Clues About the Formation of AF Lep b

Spin-Orbit Alignment

$$i_{\text{pl}} = 57.5 \pm 0.7^\circ$$

$$i_* = 54^{+11}_{-9}^\circ$$

Circular Orbit

$$e = 0.01 \pm 0.02$$

Clues About the Formation of AF Lep b

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Semi-Major Axis at Gas Giant Production Peak

$$a = 9.0 \pm 0.1 \text{ au}$$

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Dynamical Mass

$$M_{\text{comp}} = 3.7 \pm 0.5 M_{\text{Jup}}$$

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Semi-Major Axis at Gas Giant Production Peak

$$a = 9.0 \pm 0.1 \text{ au}$$

Enhanced Metallicity

$$[\text{M}/\text{H}] = 0.75 \pm 0.25 \text{ dex}$$

Dynamical Mass

$$M_{\text{comp}} = 3.7 \pm 0.5 M_{\text{Jup}}$$

Clues About the Formation of AF Lep b

Spin-Orbit Alignment

$$i_{\text{pl}} = 57.5 \pm 0.7^\circ$$
$$i_* = 54_{-9}^{+11^\circ}$$

Circular Orbit

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Semi-Major Axis at Gas Giant Production Peak

$$a = 9.0 \pm 0.1 \text{ au}$$

Core Accretion

Enhanced Metallicity

$$[\text{M}/\text{H}] = 0.75 \pm 0.25 \text{ dex}$$

Dynamical Mass

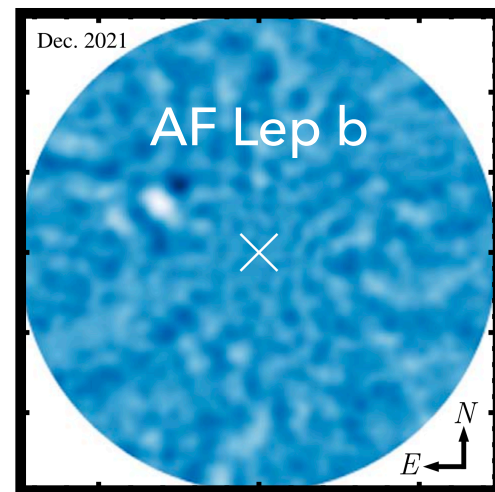
$$M_{\text{comp}} = 3.7 \pm 0.5 M_{\text{Jup}}$$

Increasing the Efficiency of Imaging Exoplanets

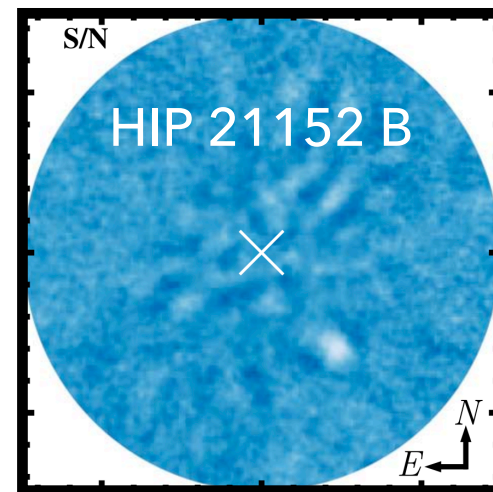
Increasing the Efficiency of Imaging Exoplanets

Astrometric Accelerations as Dynamical Beacons

34 star sample



Franson et al. (2023b)

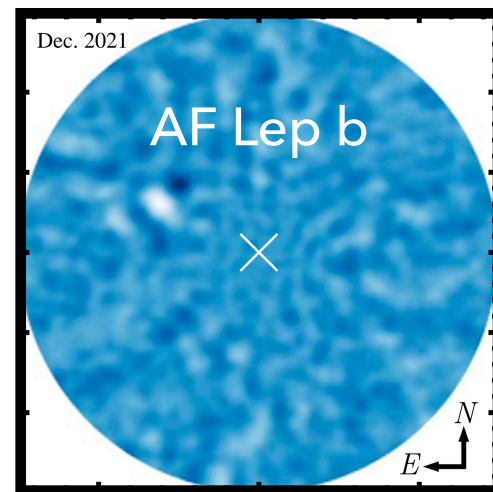


Franson et al. (2023a)

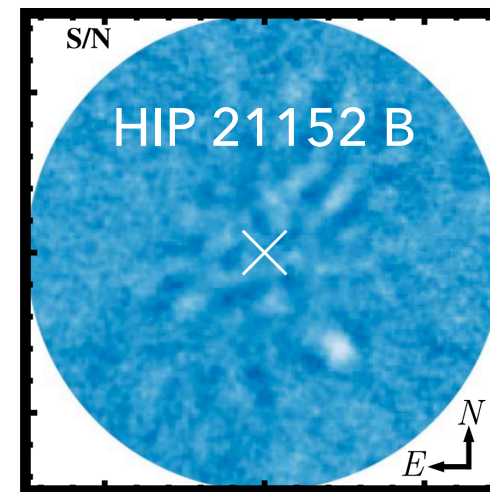
Increasing the Efficiency of Imaging Exoplanets

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34 star sample



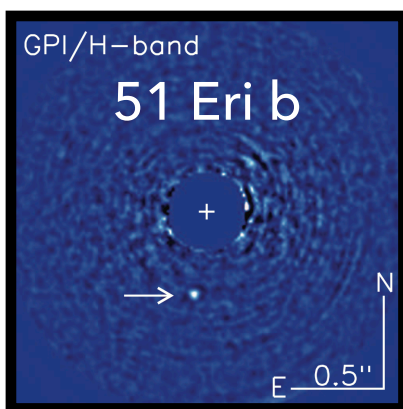
Franson et al. (2023b)



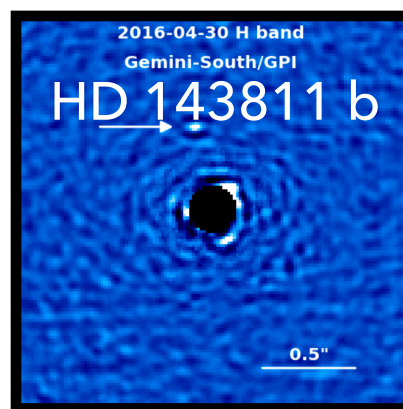
Franson et al. (2023a)

GPIES

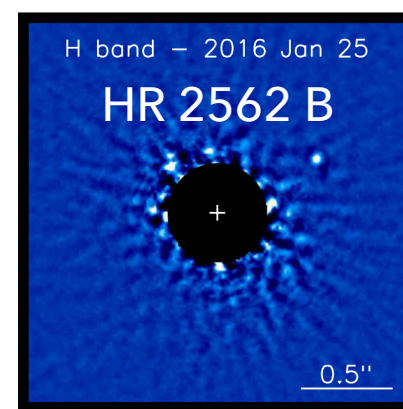
600 star sample



Macintosh et al. (2015)



Jones et al. (2025)
Squicciarini et al. (2025)

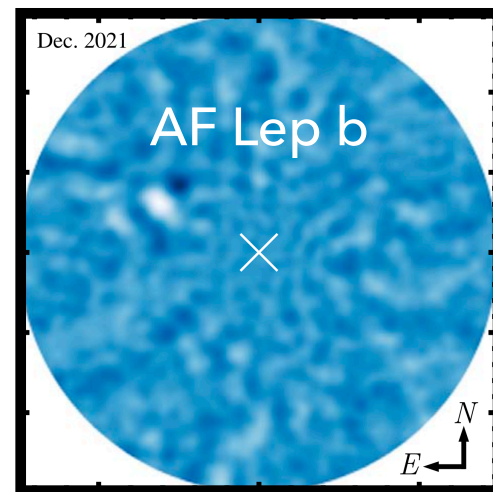


Konopacky et al. (2016)

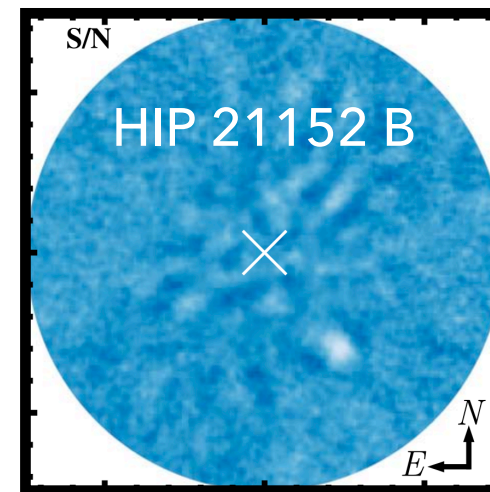
Increasing the Efficiency of Imaging Exoplanets

Astrometric Accelerations as Dynamical Beacons

34 star sample



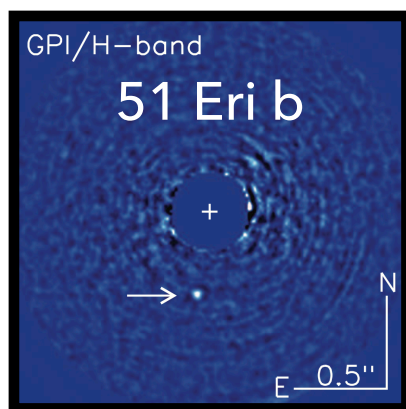
Franson et al. (2023b)



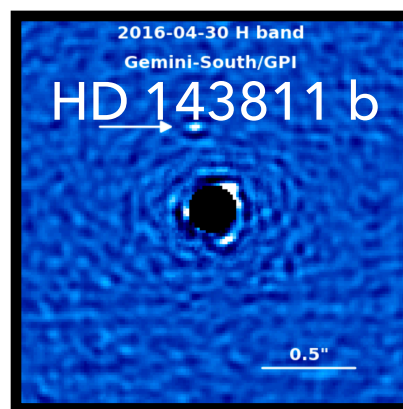
Franson et al. (2023a)

GPIES

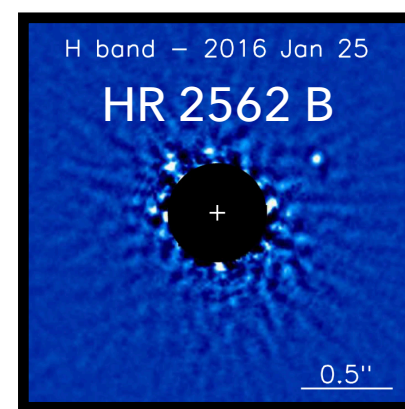
600 star sample



Macintosh et al. (2015)



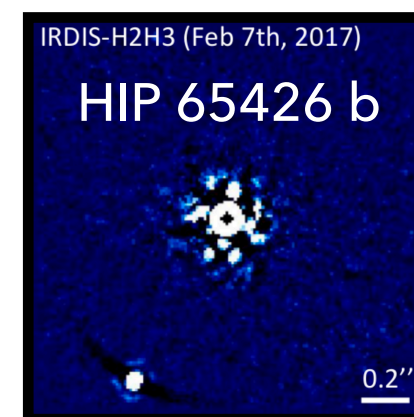
Jones et al. (2025)
Squicciarini et al. (2025)



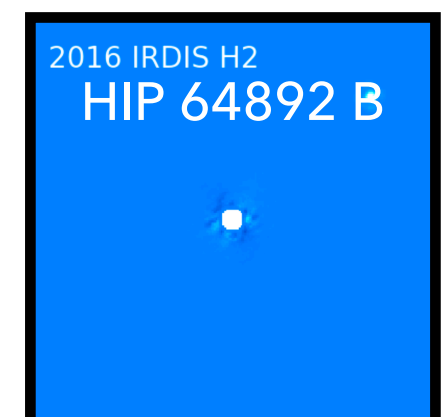
Konopacky et al. (2016)

SHINE

400 star sample



Chauvin et al. (2017)

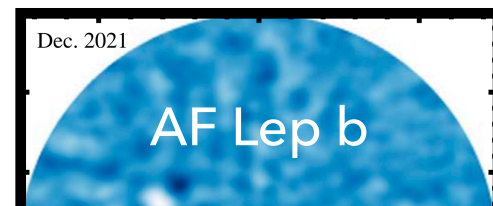


Cheetham et al. (2018)

Increasing the Efficiency of Imaging Exoplanets

Astrometric Accelerations as Dynamical Beacons

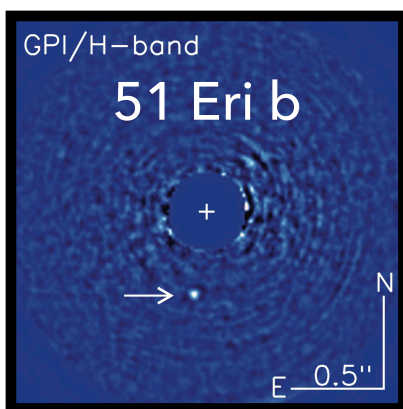
34 star sample



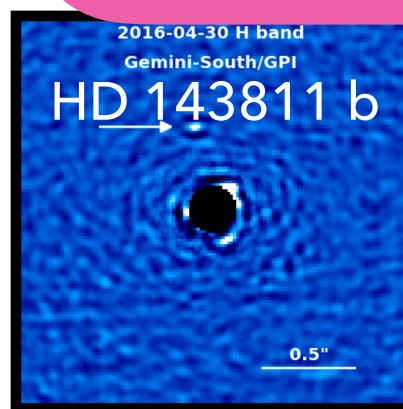
Astrometric Accelerations Yield
Tenfold Improvement in Planet-
Discovery Efficiency

6

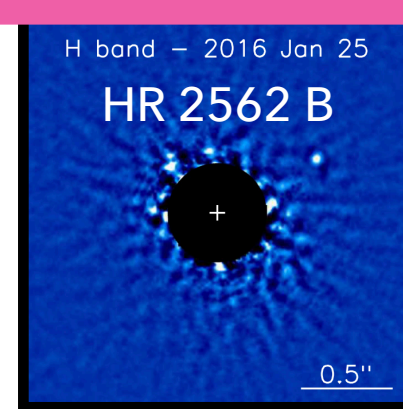
e



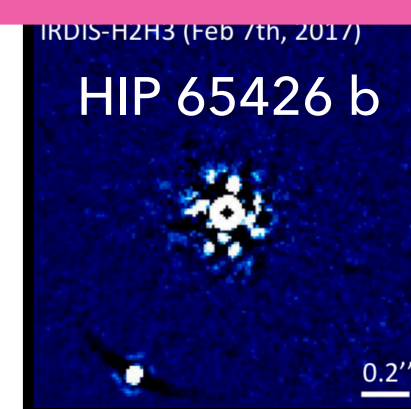
Macintosh et al. (2015)



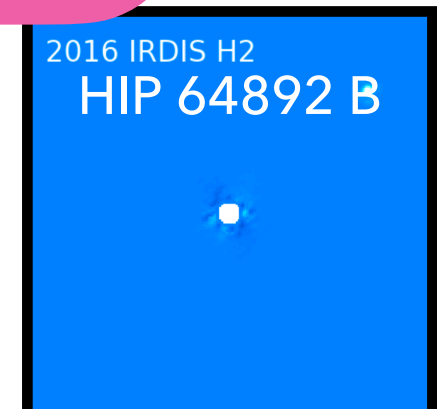
Jones et al. (2025)
Squicciarini et al. (2025)



Konopacky et al. (2016)

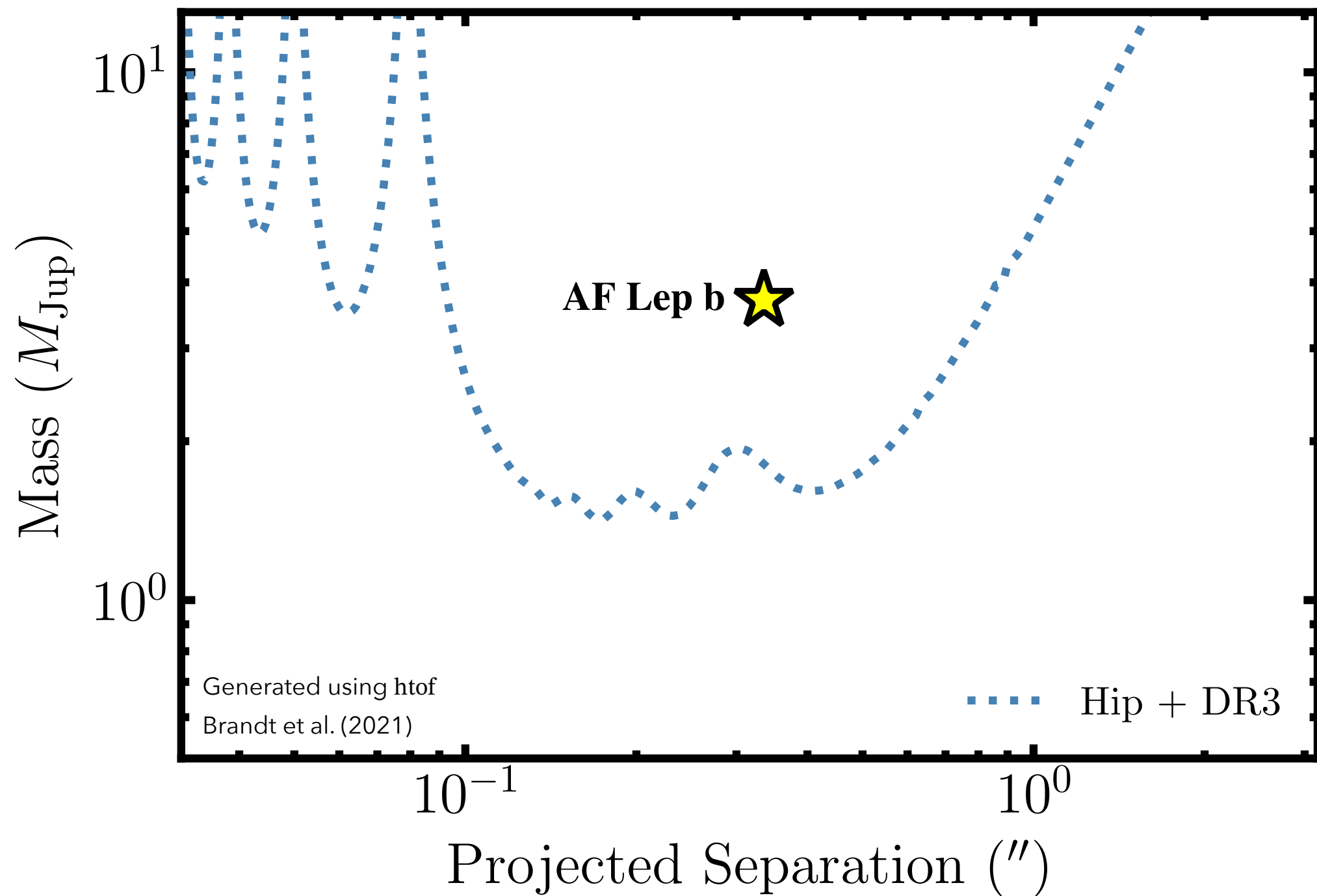


Chauvin et al. (2017)



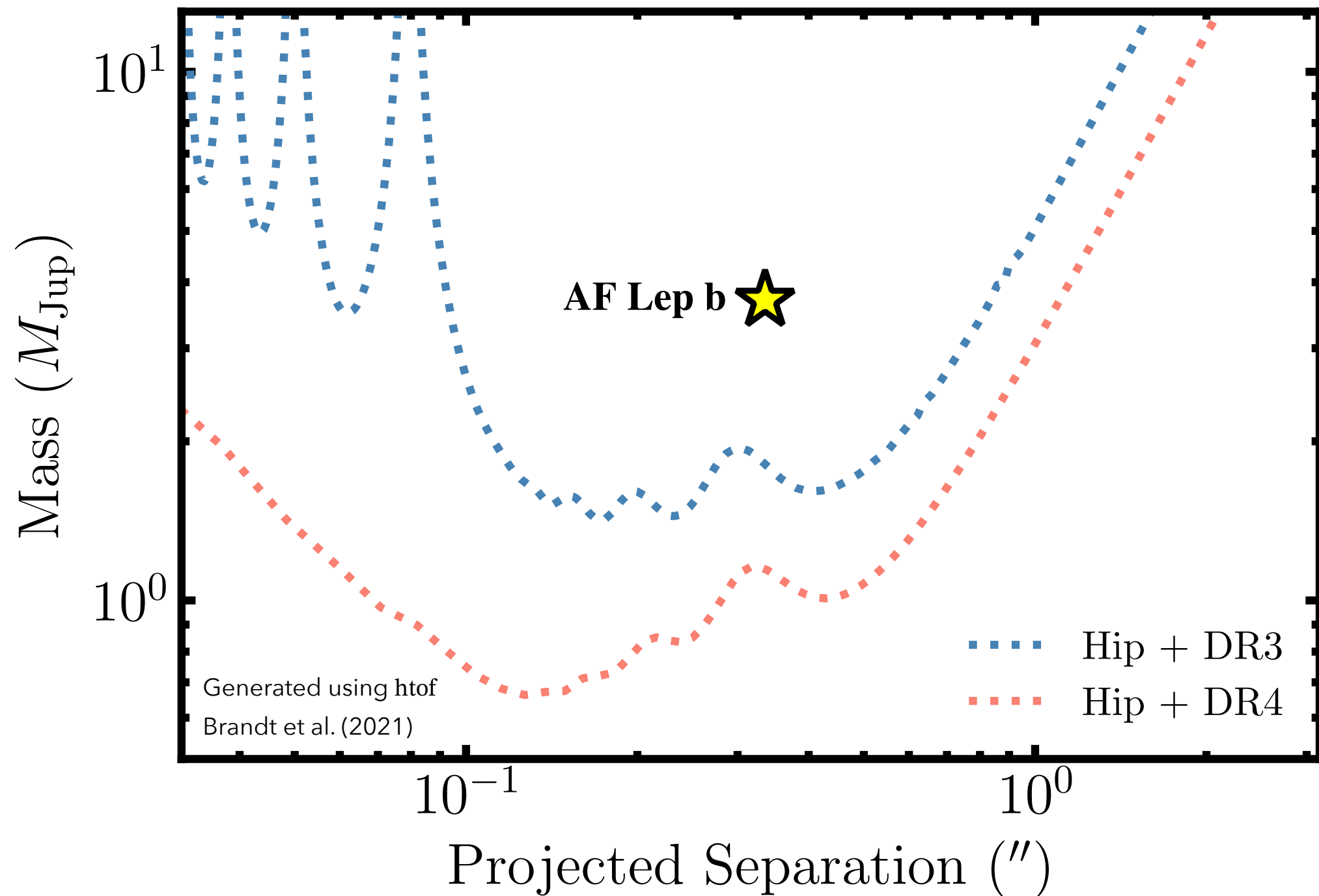
Cheetham et al. (2018)

Gaia DR4: Expected December 2026



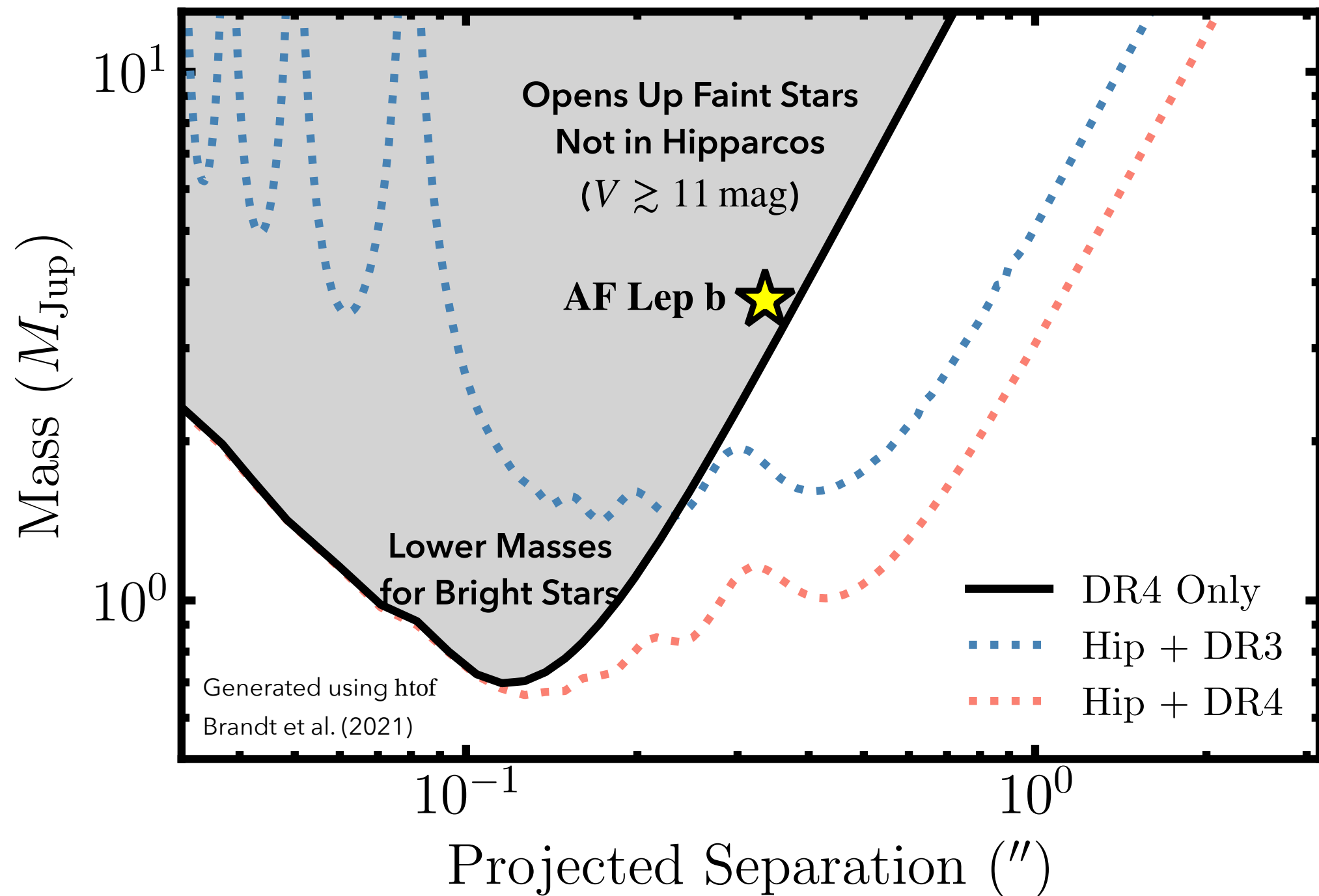
*A Treasure Trove of Informed Targets for Next-Generation
High-Contrast Imaging Instruments*

Gaia DR4: Expected December 2026



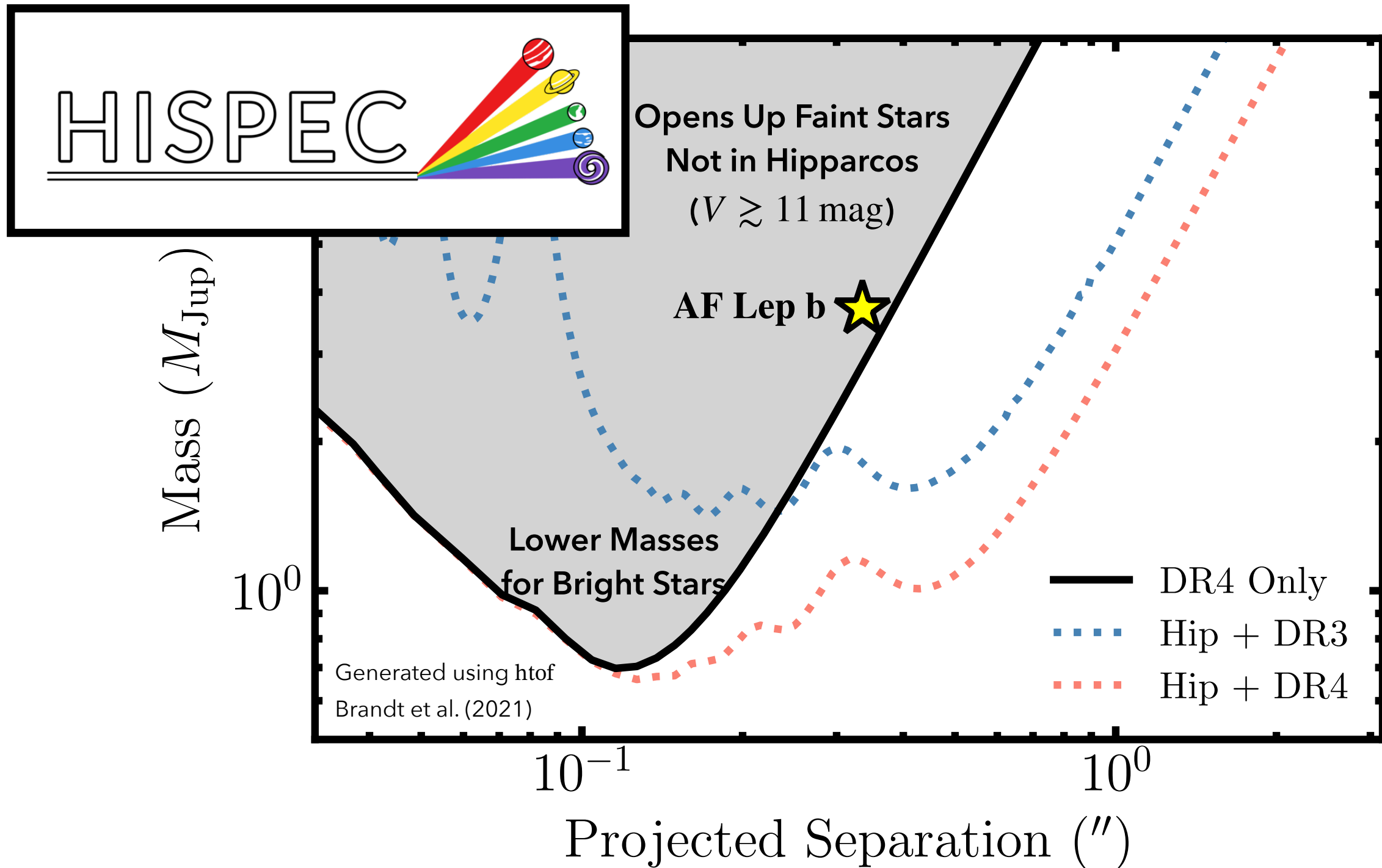
*A Treasure Trove of Informed Targets for Next-Generation
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Gaia DR4: Expected December 2026



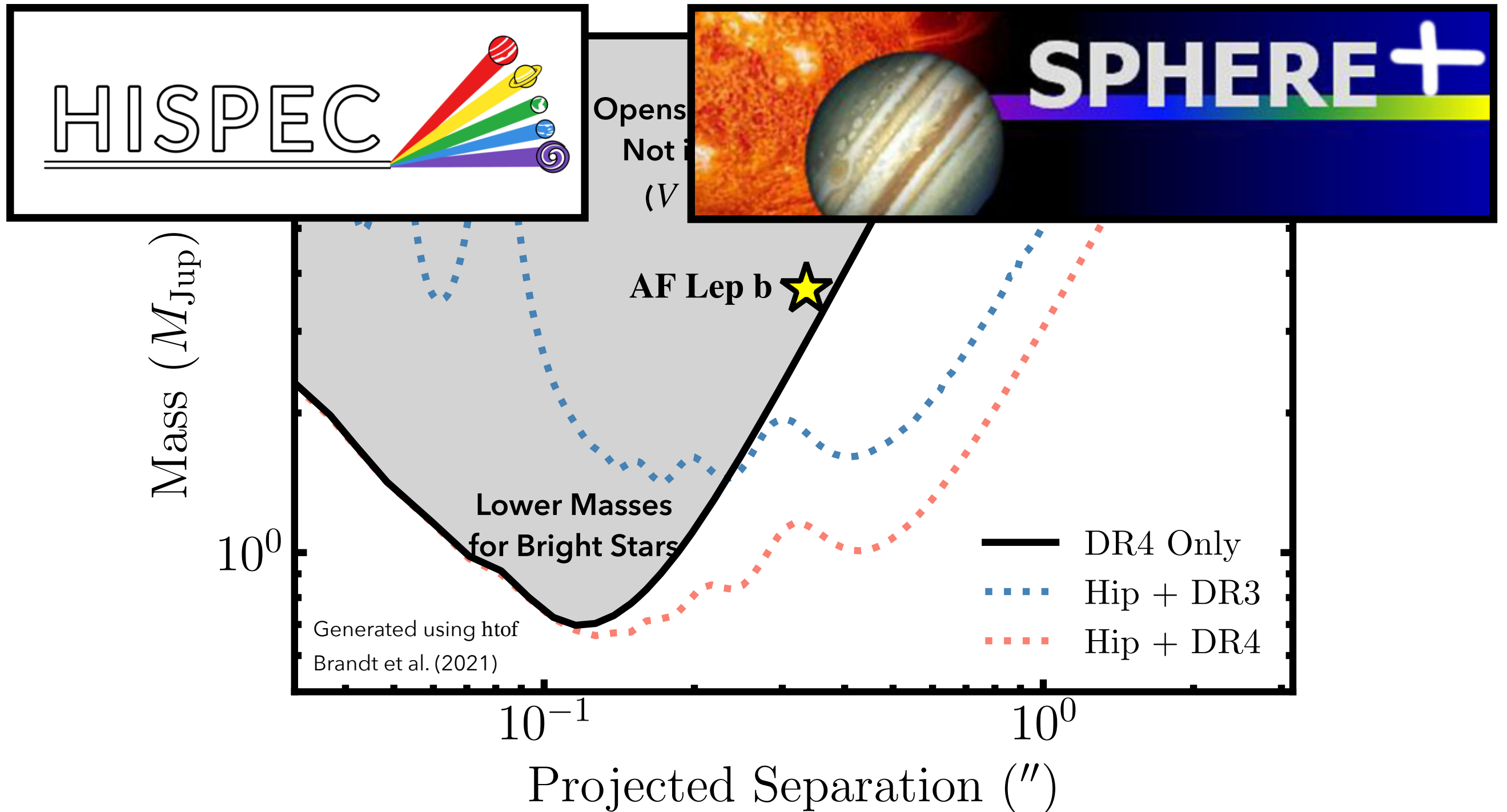
*A Treasure Trove of Informed Targets for Next-Generation
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Gaia DR4: Expected December 2026



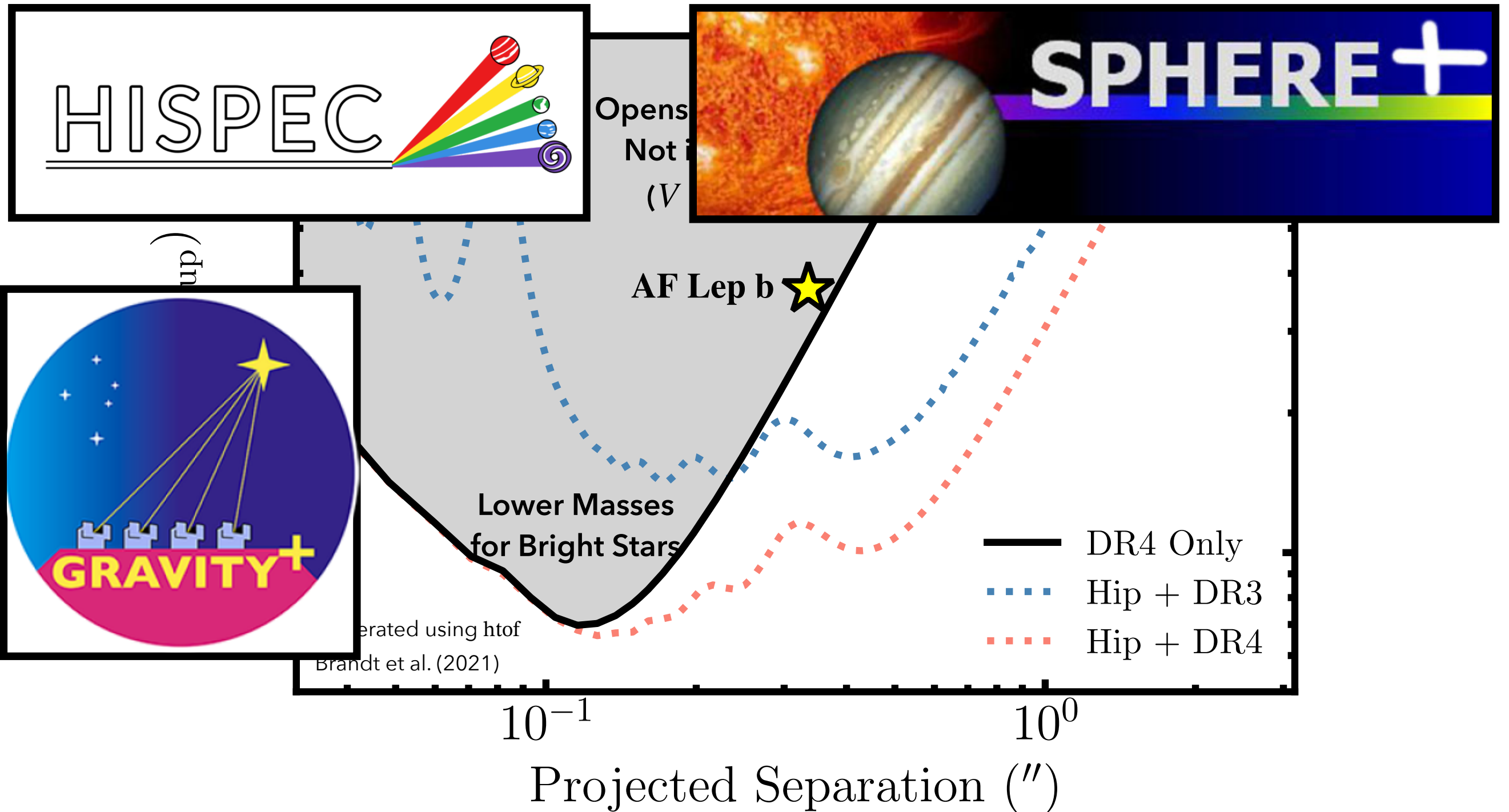
*A Treasure Trove of Informed Targets for Next-Generation
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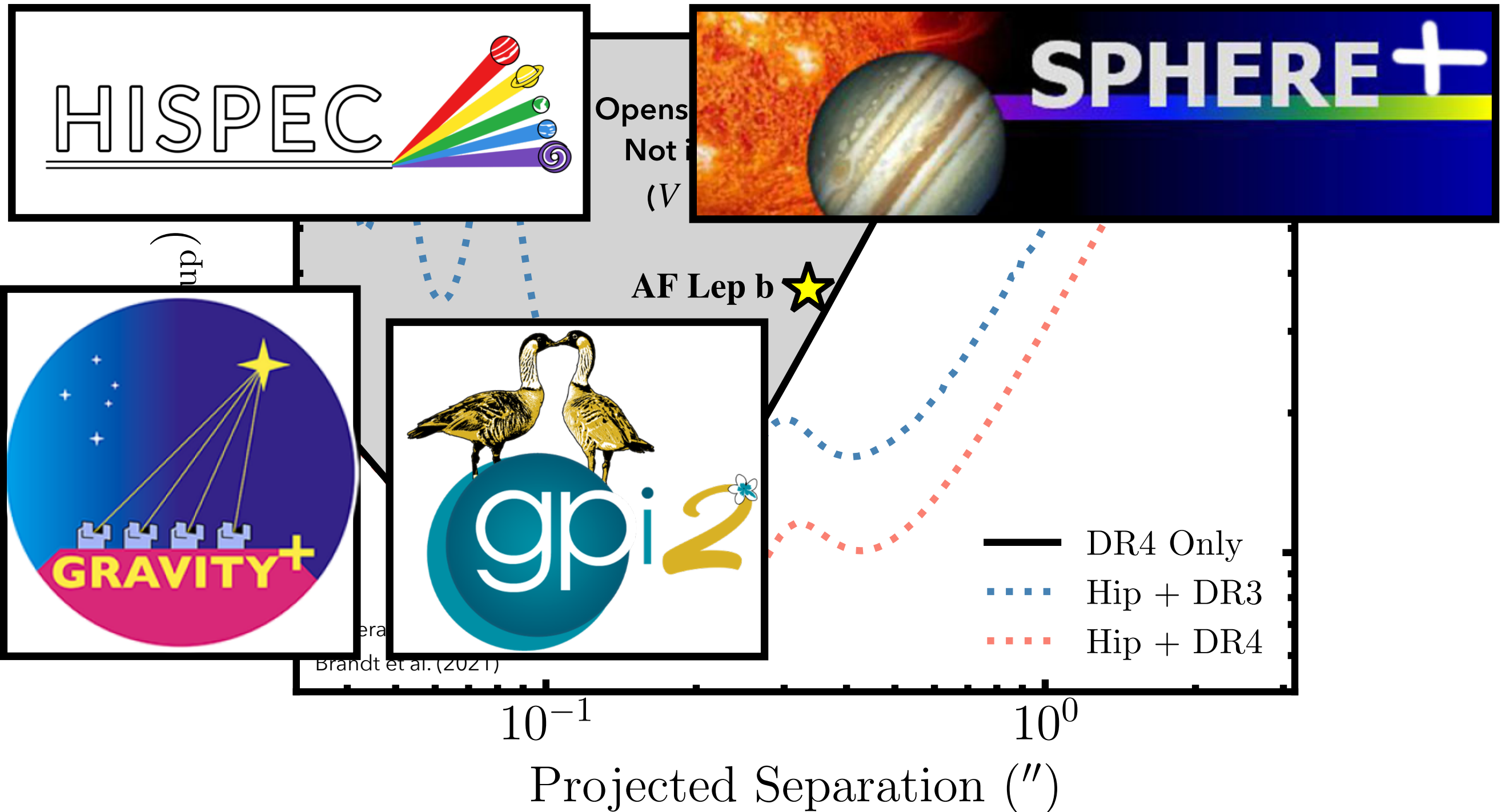
*A Treasure Trove of Informed Targets for Next-Generation
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Gaia DR4: Expected December 2026



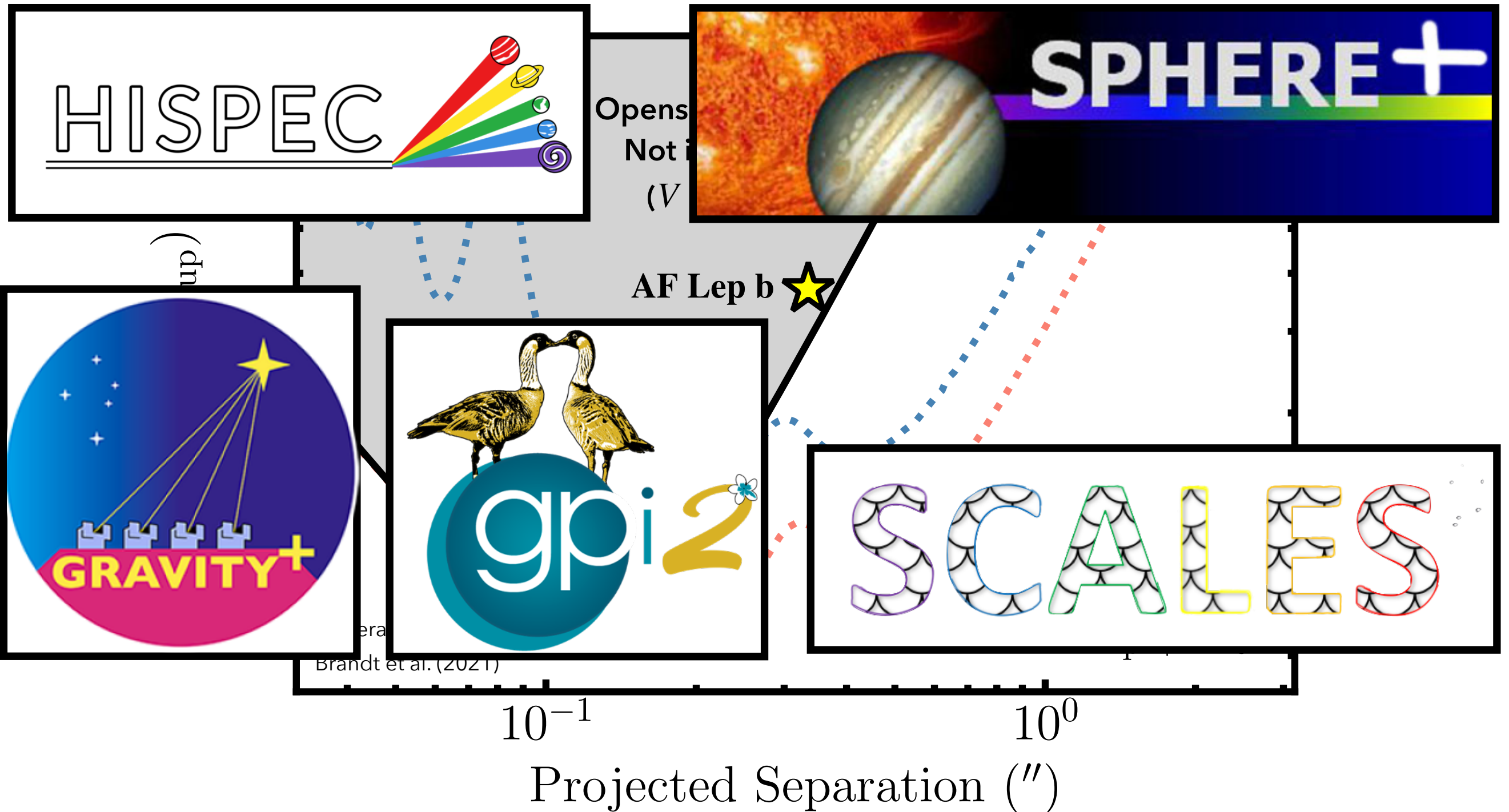
A Treasure Trove of Informed Targets for Next-Generation High-Contrast Imaging Instruments

Gaia DR4: Expected December 2026



A Treasure Trove of Informed Targets for Next-Generation High-Contrast Imaging Instruments

Gaia DR4: Expected December 2026

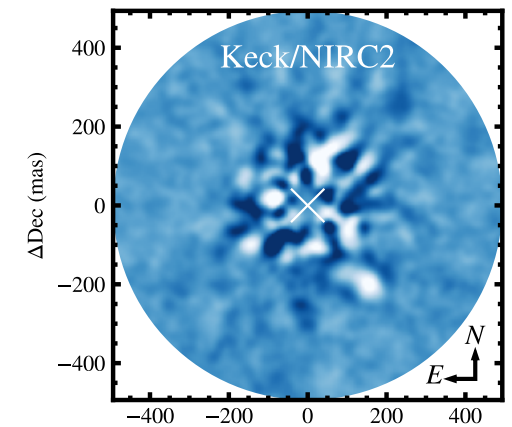


*A Treasure Trove of Informed Targets for Next-Generation
High-Contrast Imaging Instruments*

Summary

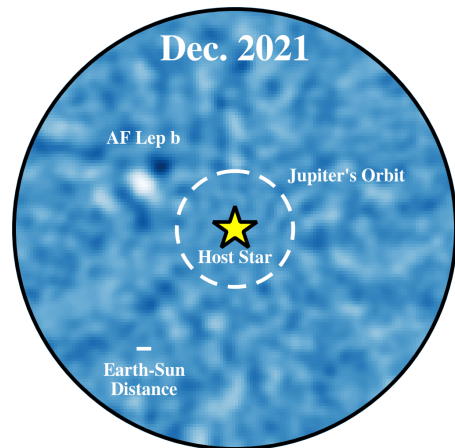
Summary

HIP 21152 B: The First Imaged Brown Dwarf Companion in the Hyades

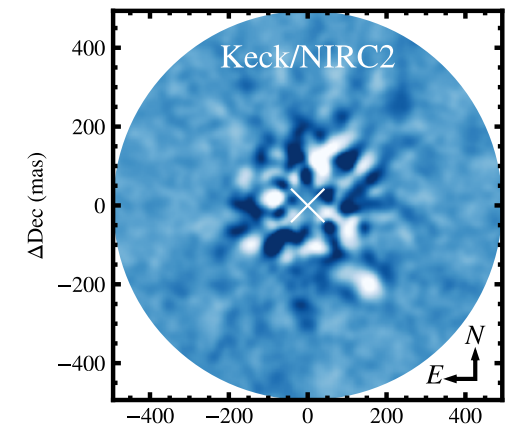


Summary

HIP 21152 B: The First Imaged Brown Dwarf Companion in the Hyades

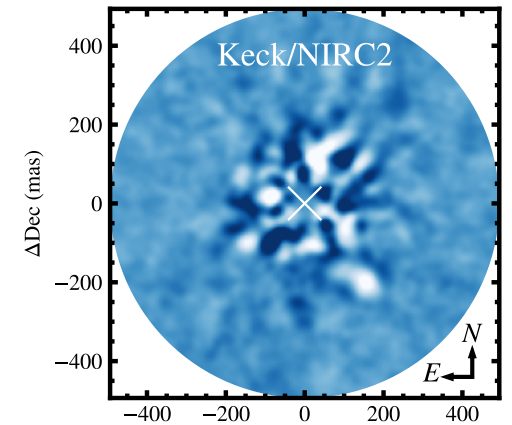


AF Lep b: The Lowest-Mass Imaged Planet with a Dynamical Mass



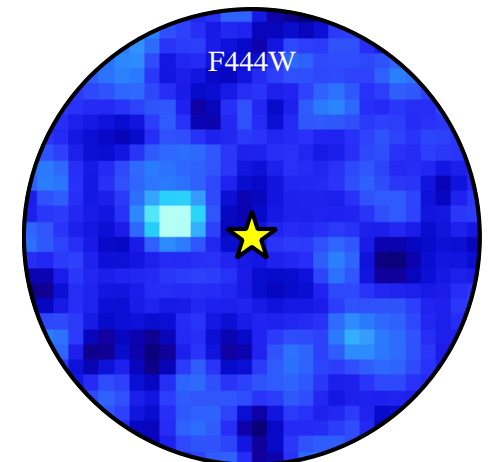
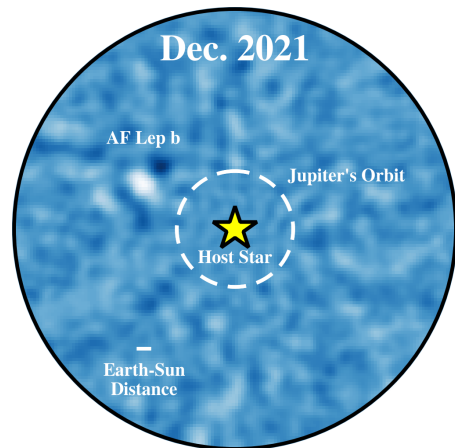
Summary

HIP 21152 B: The First Imaged Brown Dwarf Companion in the Hyades



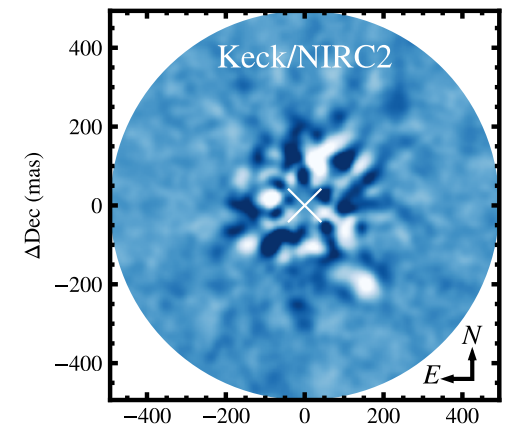
AF Lep b: The Lowest-Mass Imaged Planet with a Dynamical Mass

Successful recovery of AF Lep b with **JWST** at a separation of **320 mas**



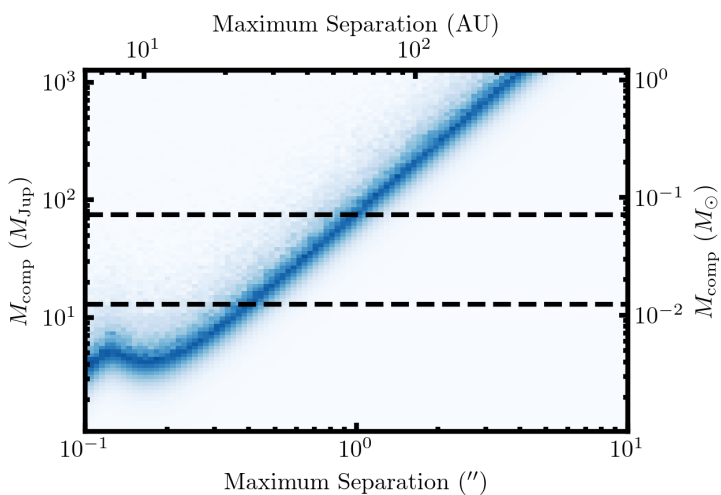
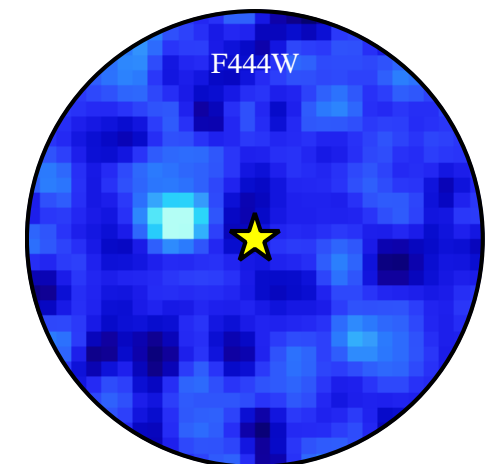
Summary

HIP 21152 B: The First Imaged Brown Dwarf Companion in the Hyades



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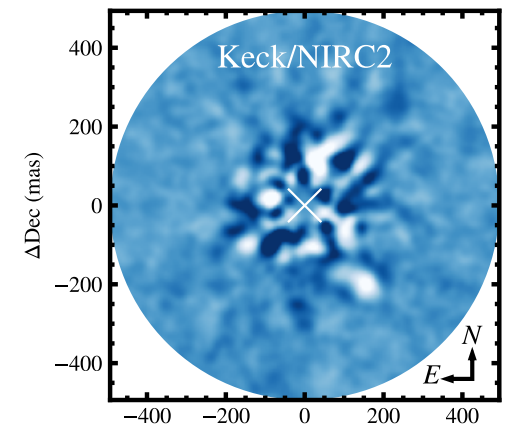
Successful recovery of AF Lep b with **JWST** at a separation of **320 mas**



Astrometric Accelerations Improve Planet **Discovery Efficiency** by a Factor of **Ten**

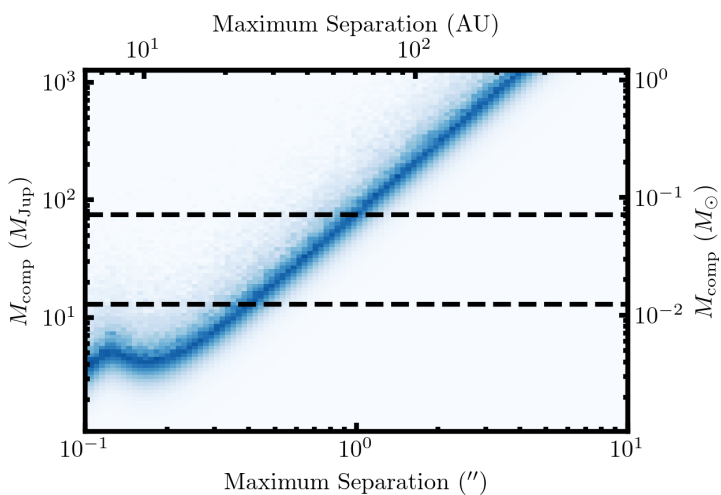
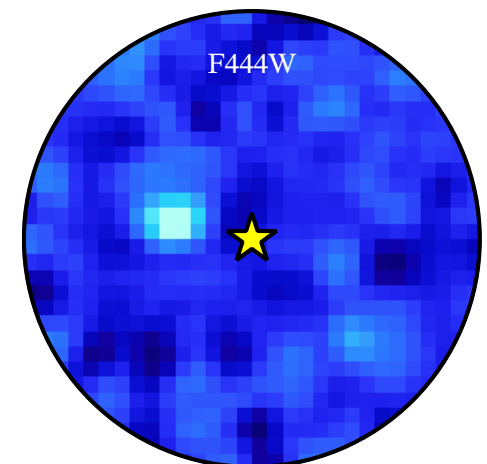
Summary

HIP 21152 B: The First Imaged Brown Dwarf Companion in the Hyades



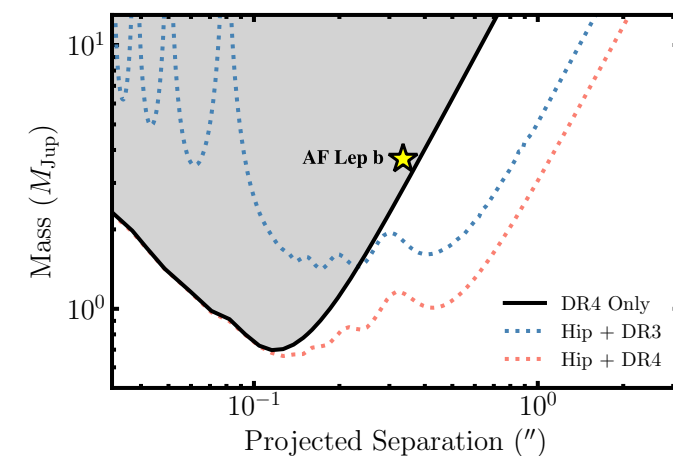
AF Lep b: The Lowest-Mass Imaged Planet with a Dynamical Mass

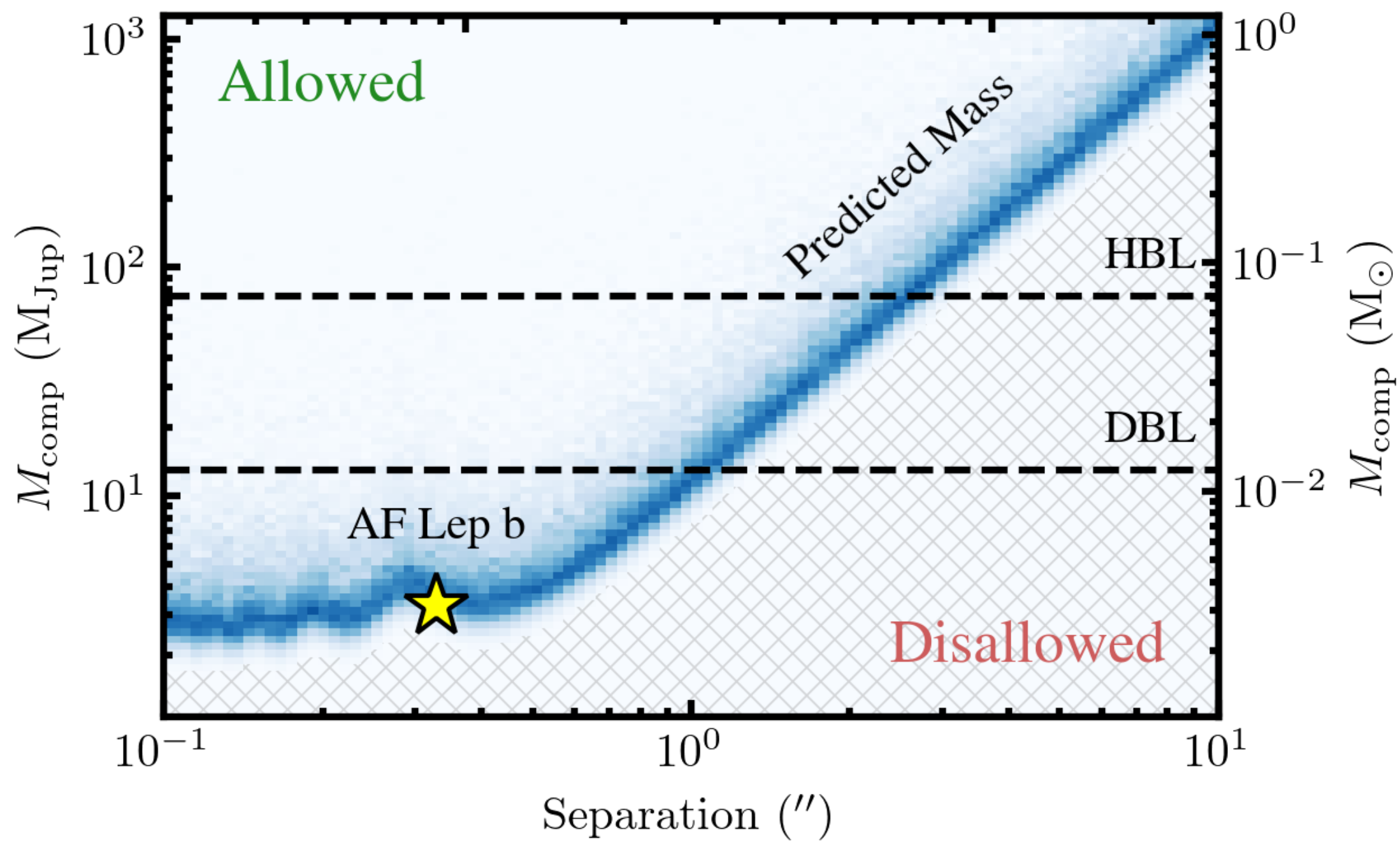
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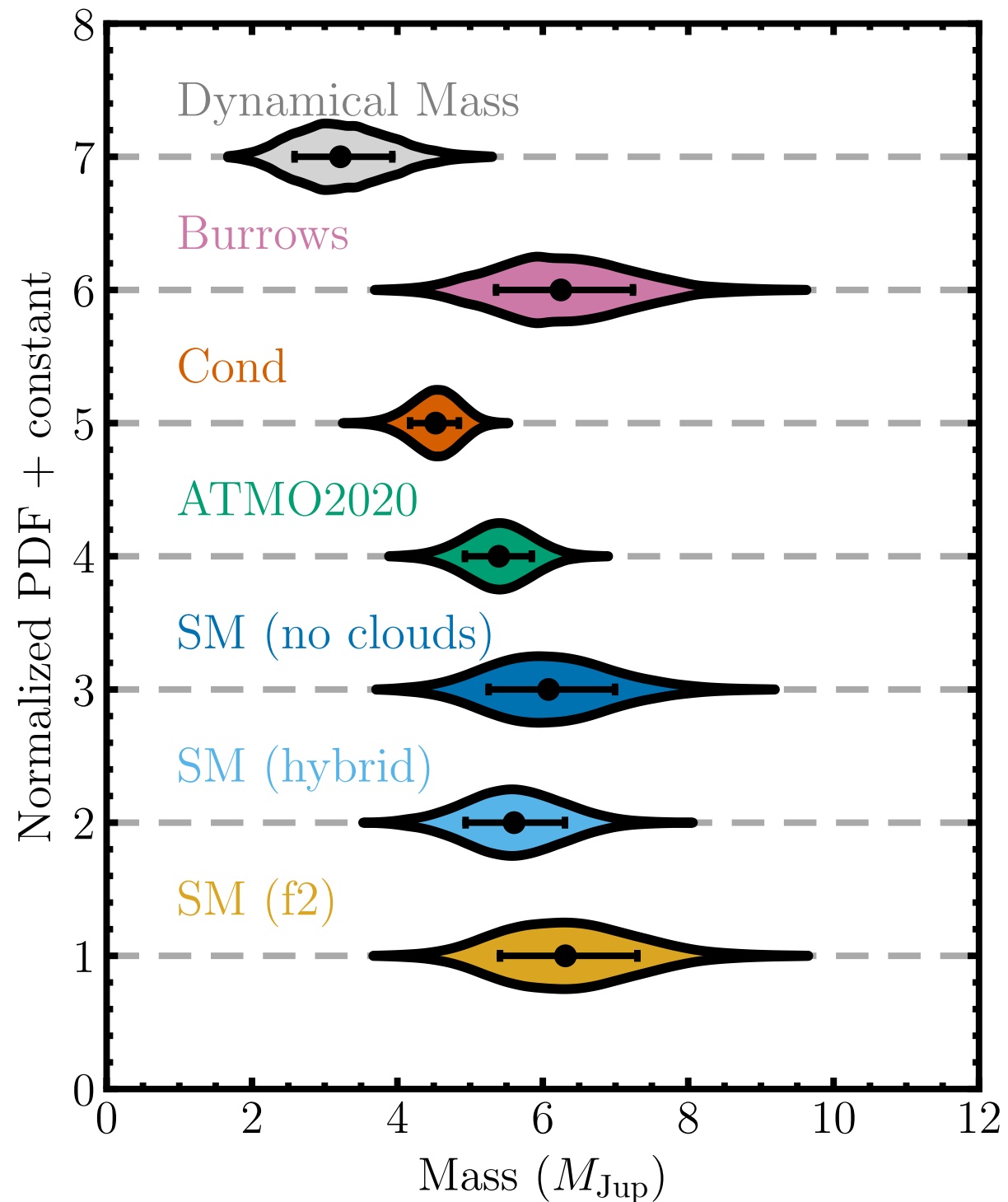
Astrometric Accelerations Improve Planet **Discovery Efficiency** by a Factor of **Ten**

The Future of Astrometric Accelerations: **Gaia DR4** + **New High-Contrast Instrumentation**

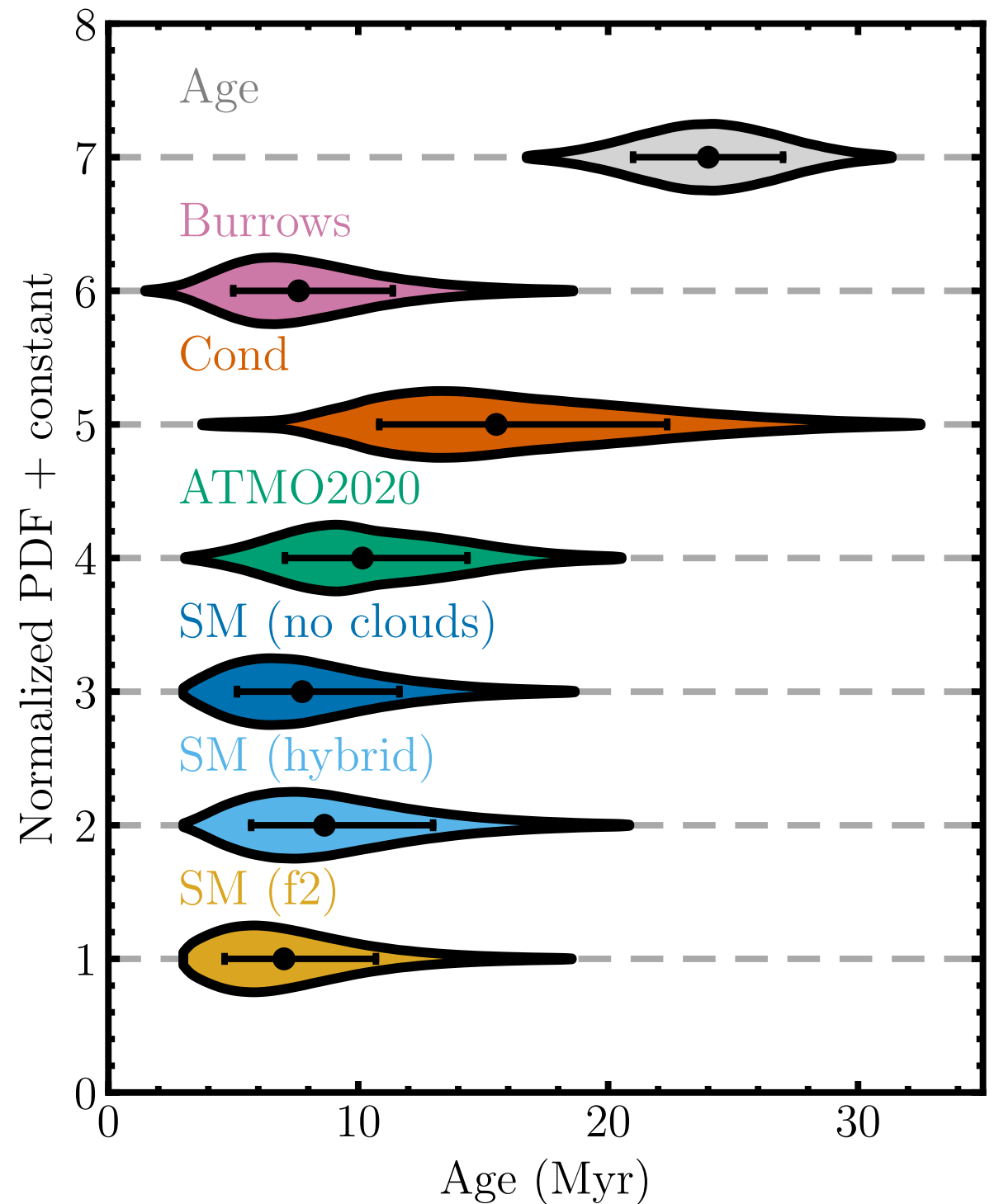
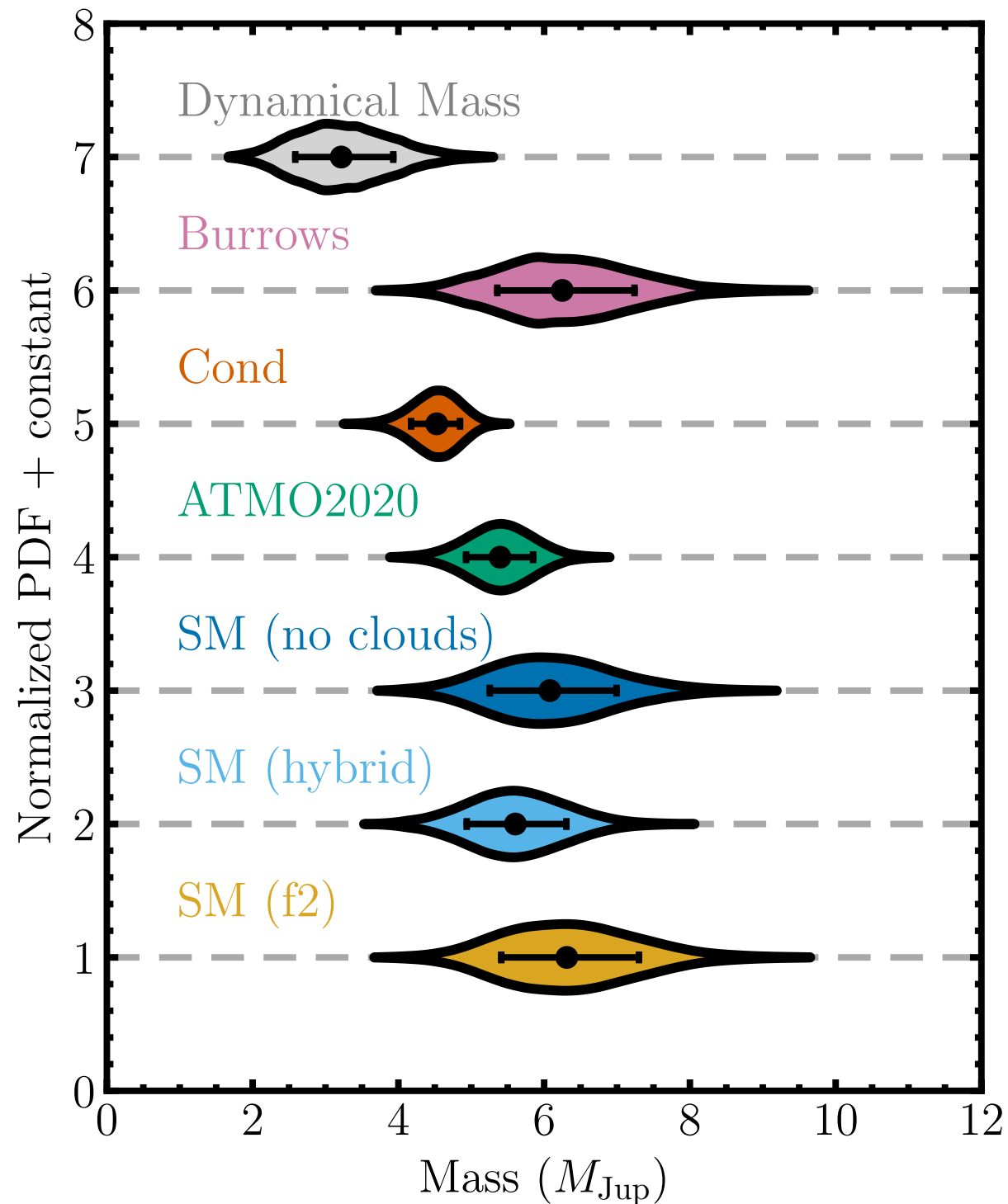




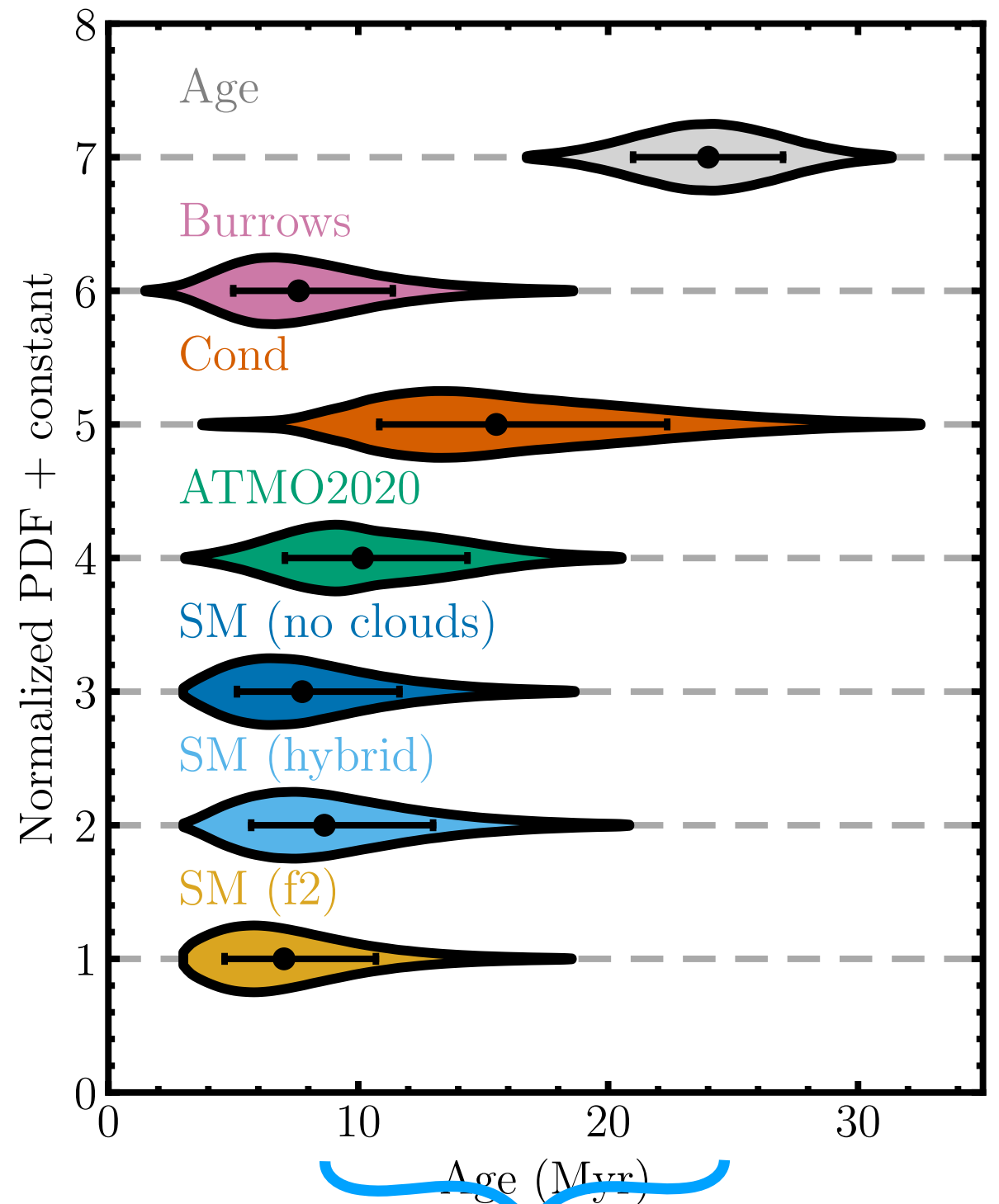
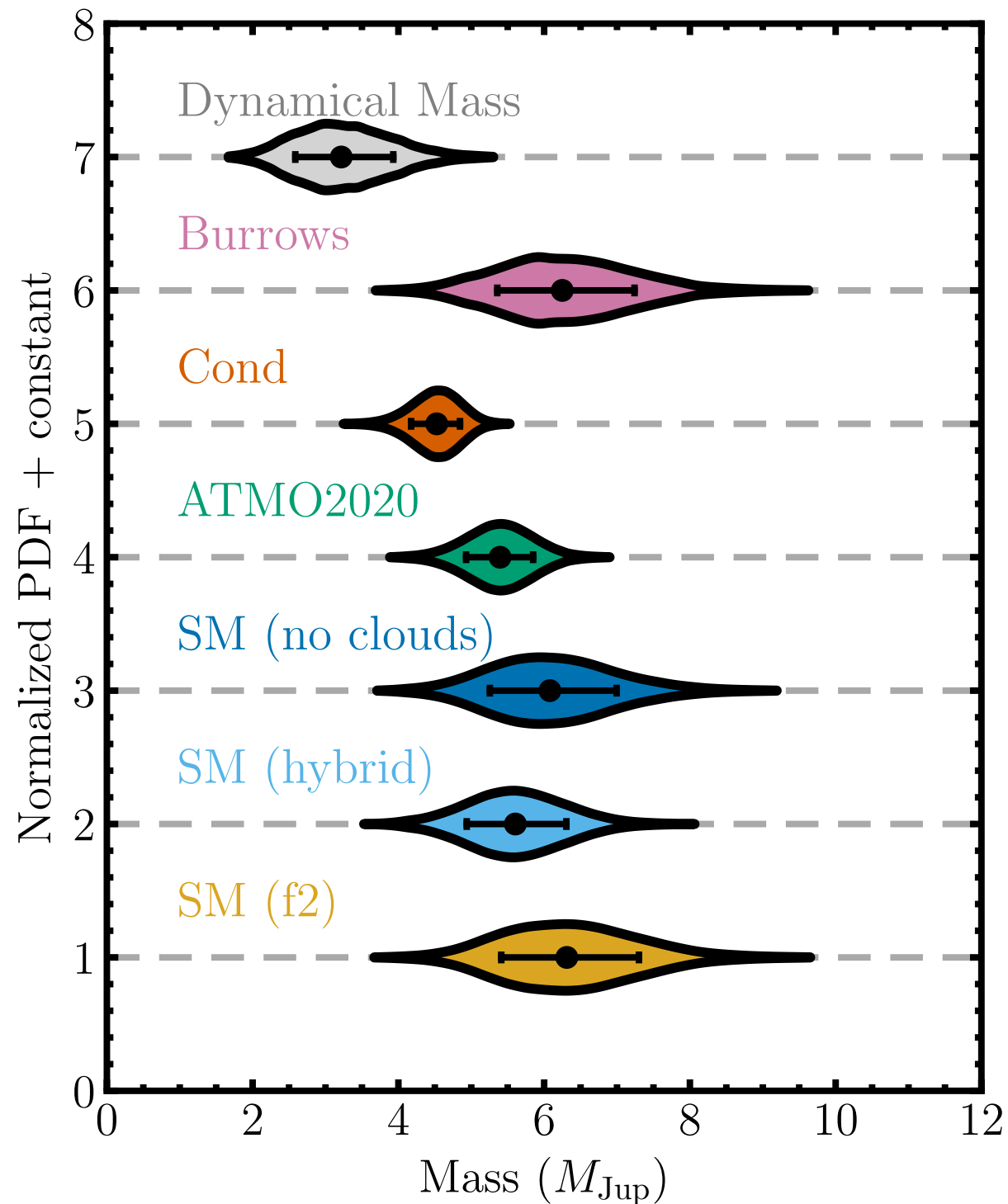
Comparison Against Evolutionary Models: Delayed Formation?



Comparison Against Evolutionary Models: Delayed Formation?



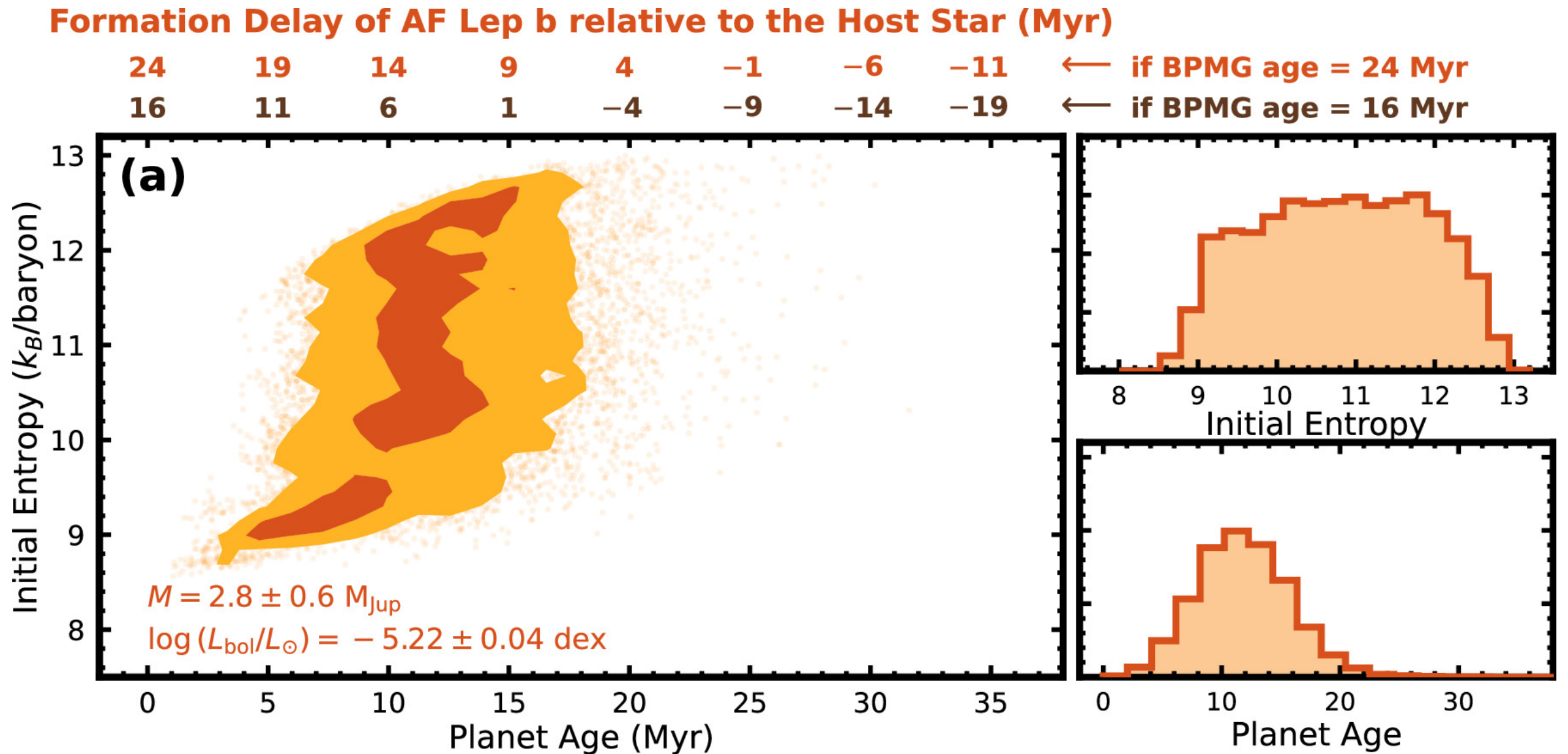
Comparison Against Evolutionary Models: Delayed Formation?



~10 Myr to form planet?

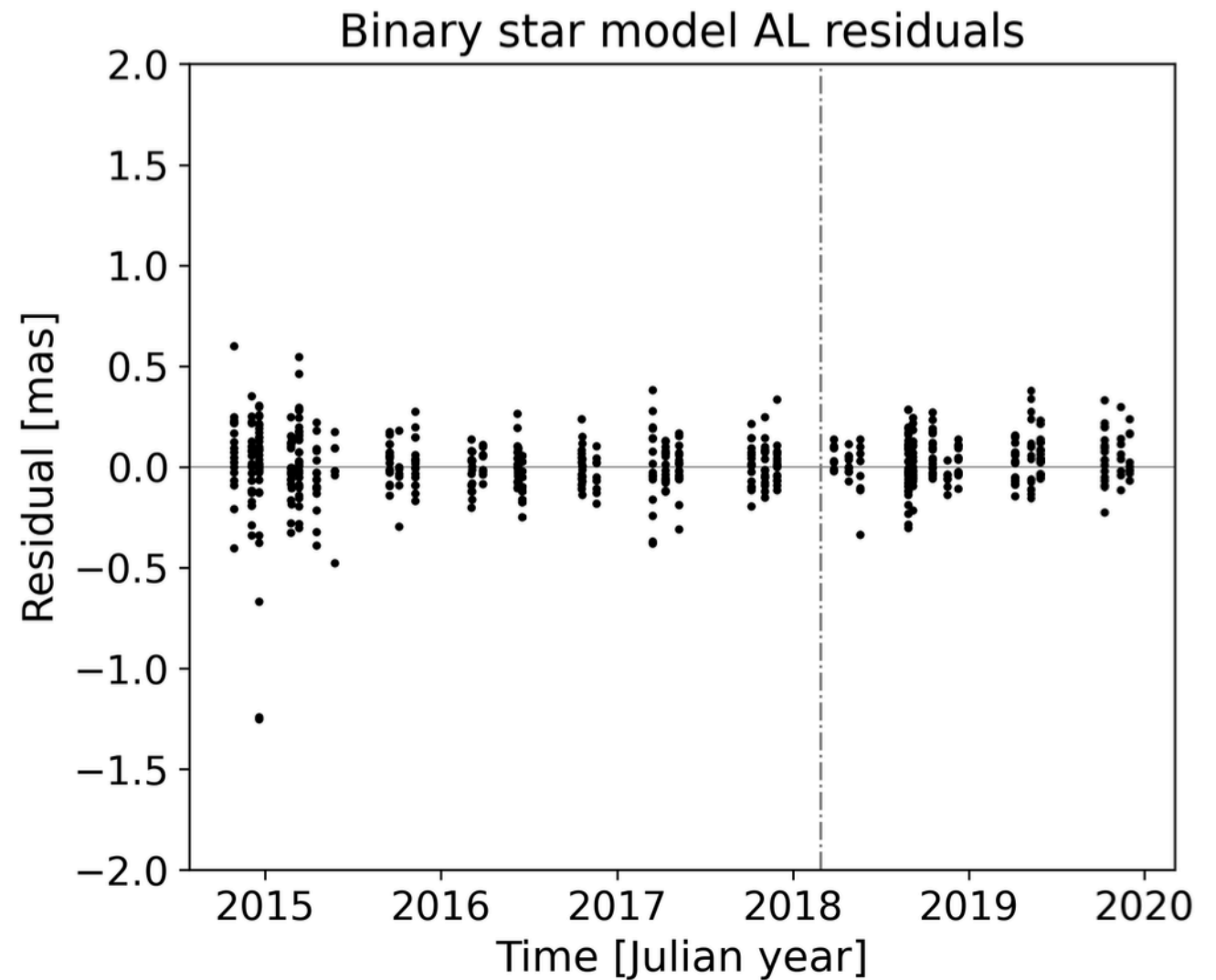
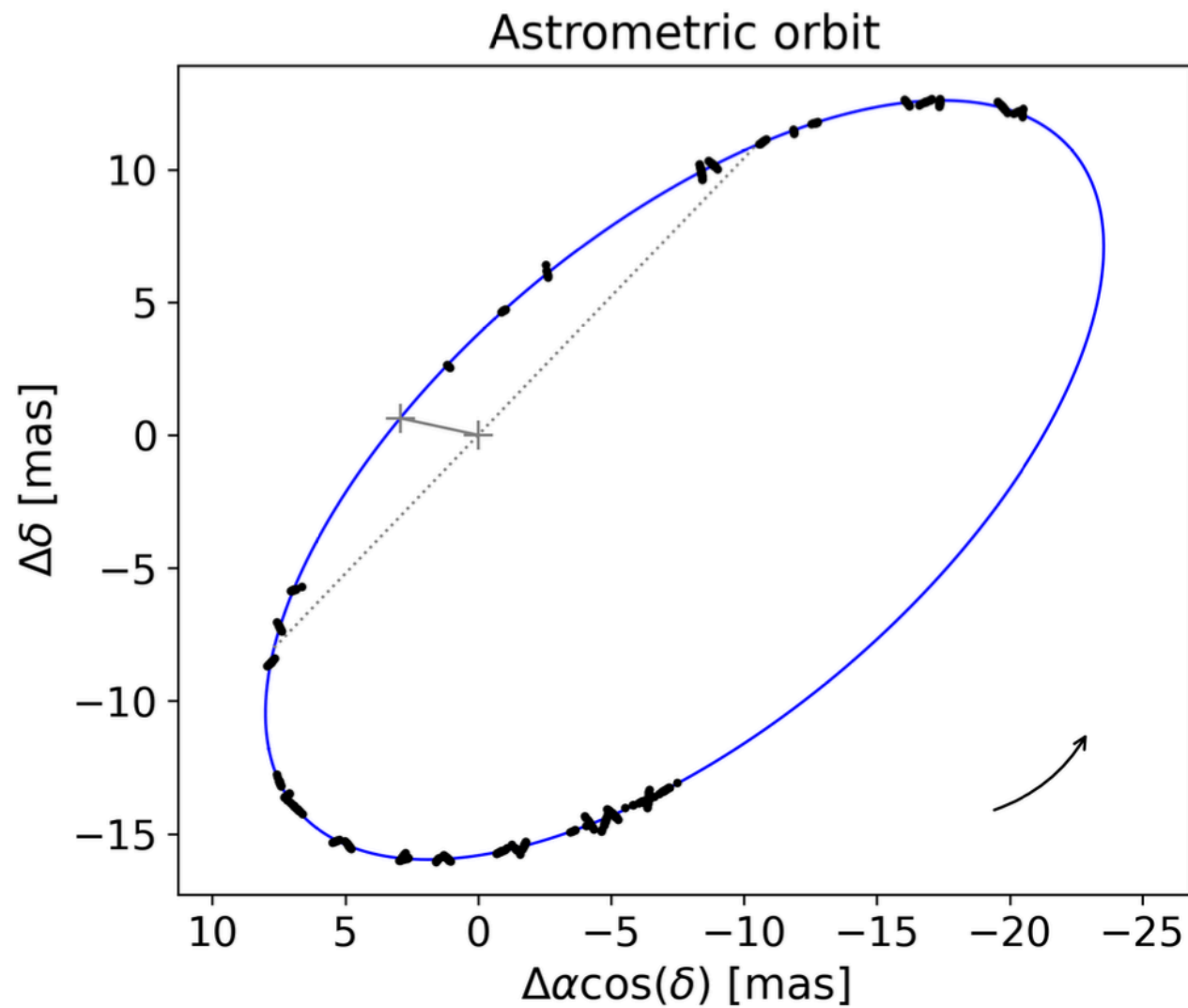
Kyle Franson – Keck Science Meeting 2025

Constraining the Initial Entropy and Formation Timescale of AF Lep b



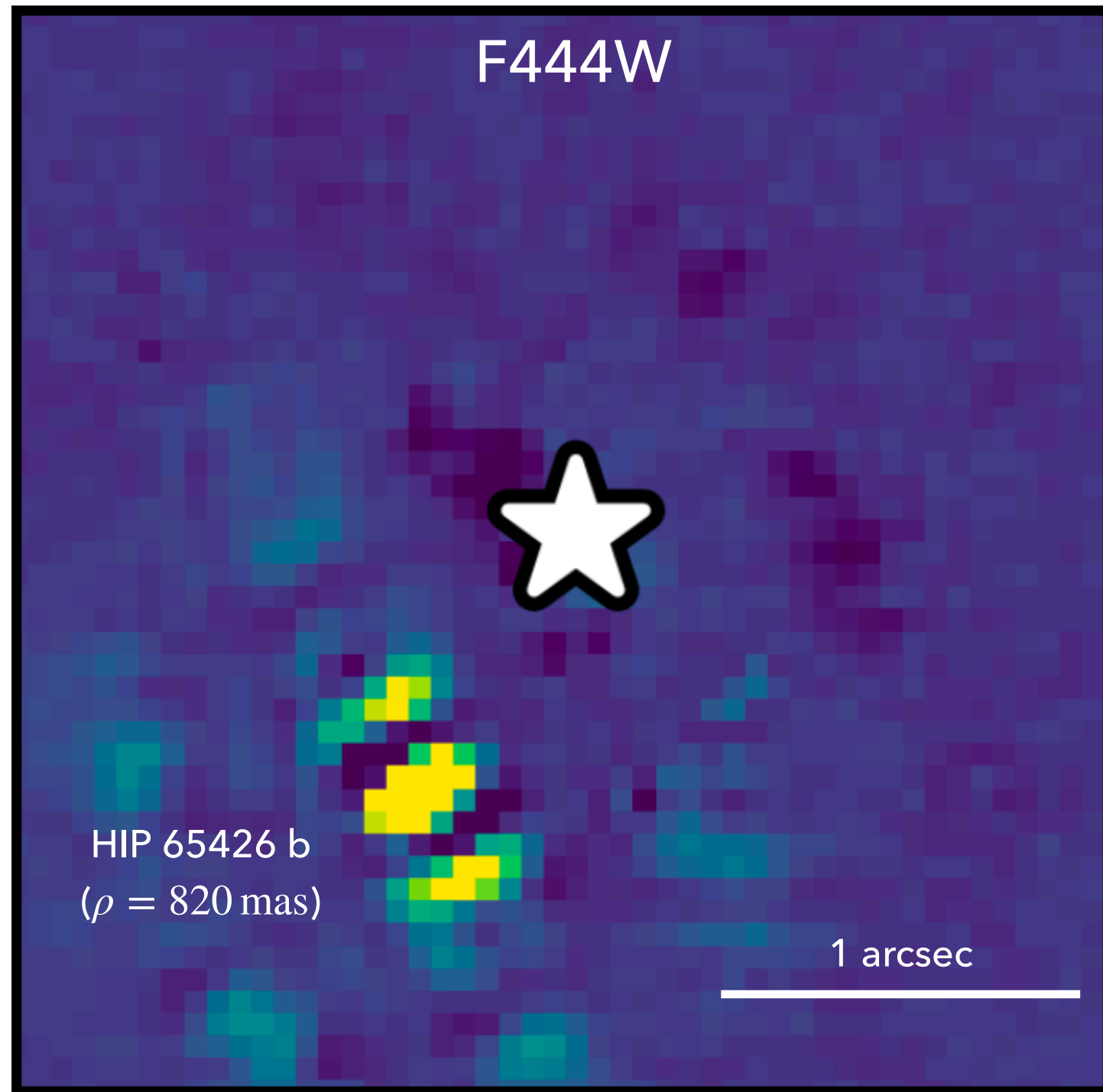
Zhang (2024)

Gaia BH3: First Taste of Gaia DR4 Science



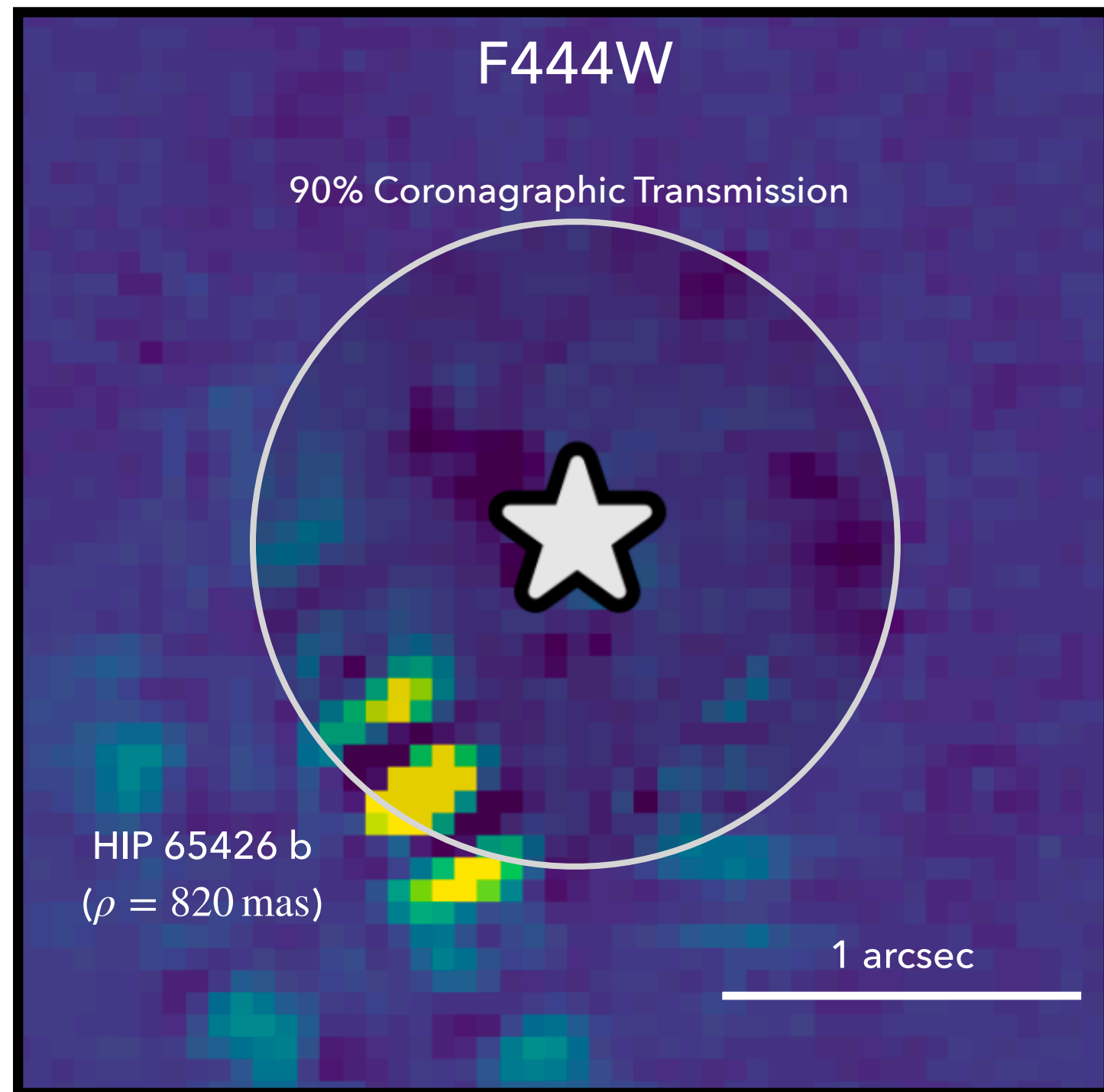
Gaia Collaboration et al. (2024)

Accessing Small Separations is Challenging with JWST



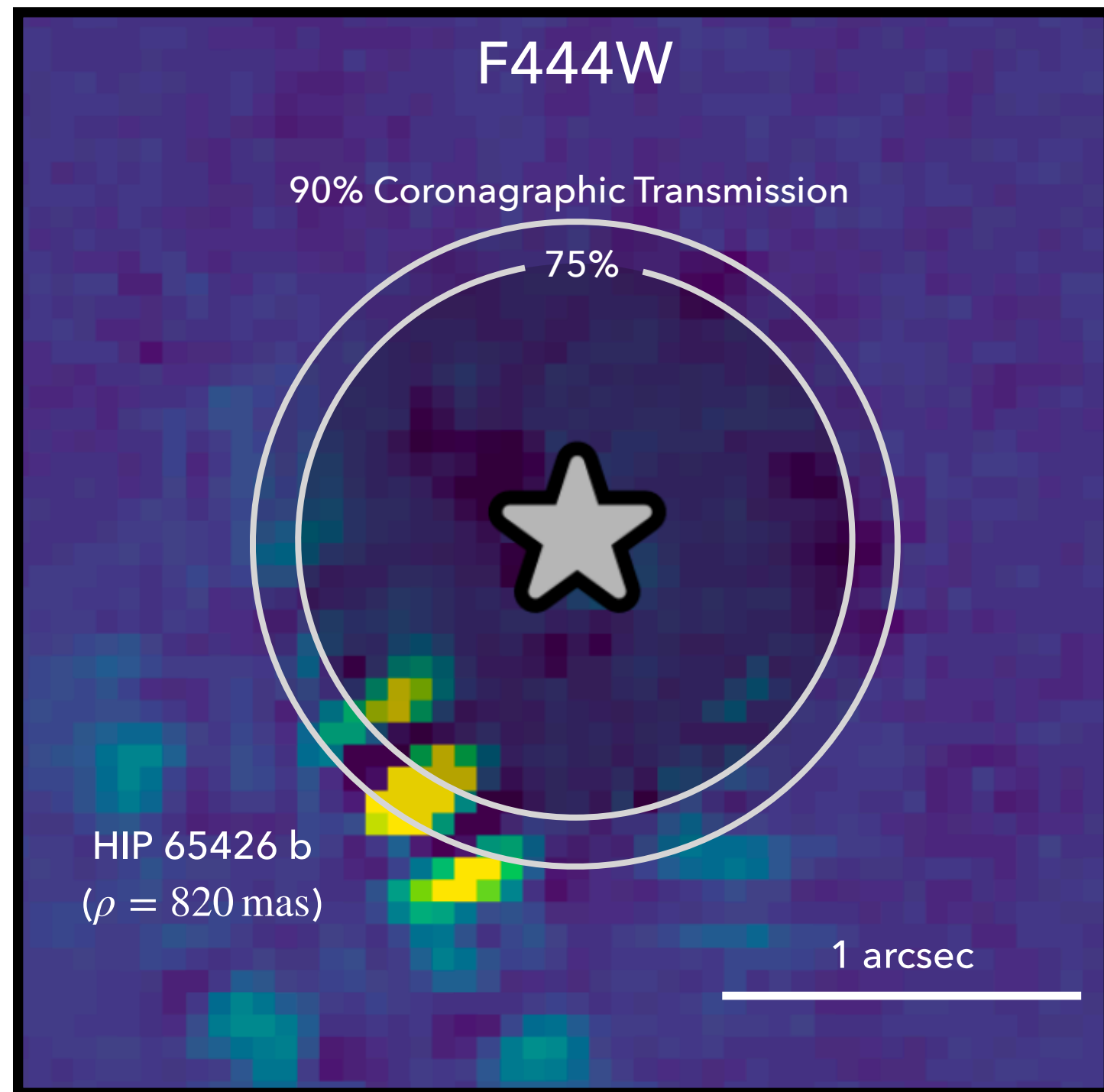
Carter et al. (2023)

Accessing Small Separations is Challenging with JWST



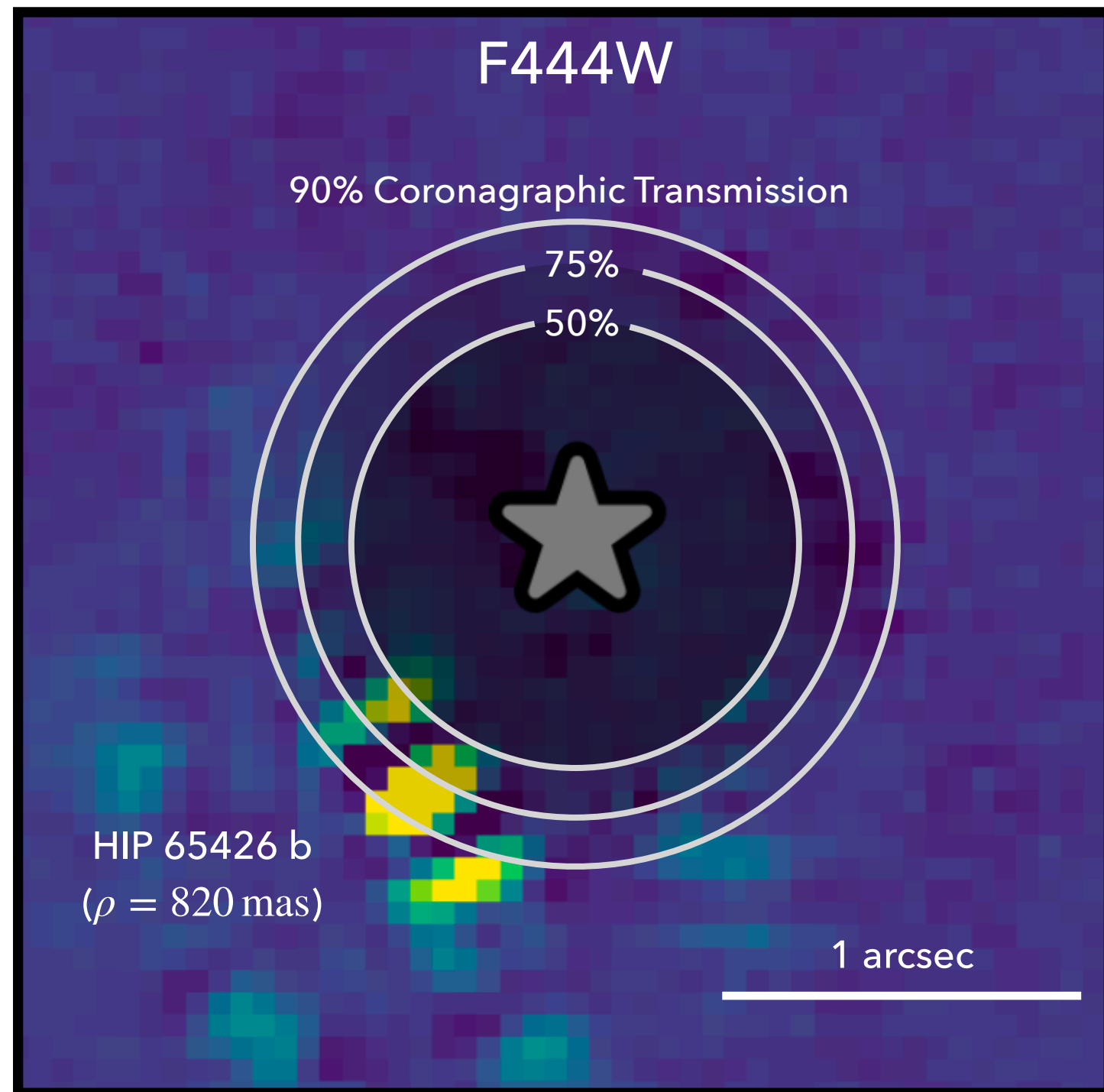
Carter et al. (2023)

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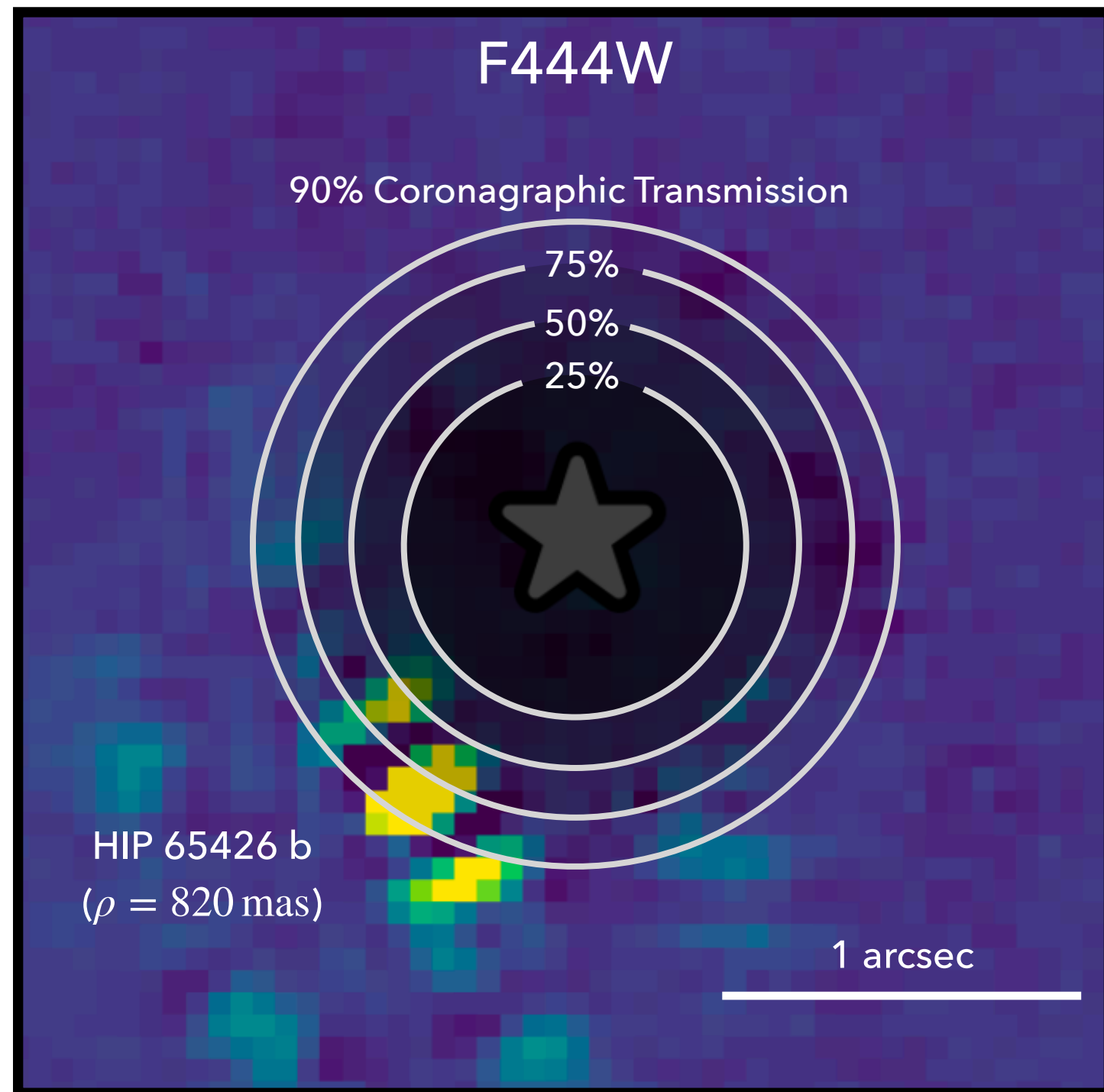
Carter et al. (2023)

Accessing Small Separations is Challenging with JWST



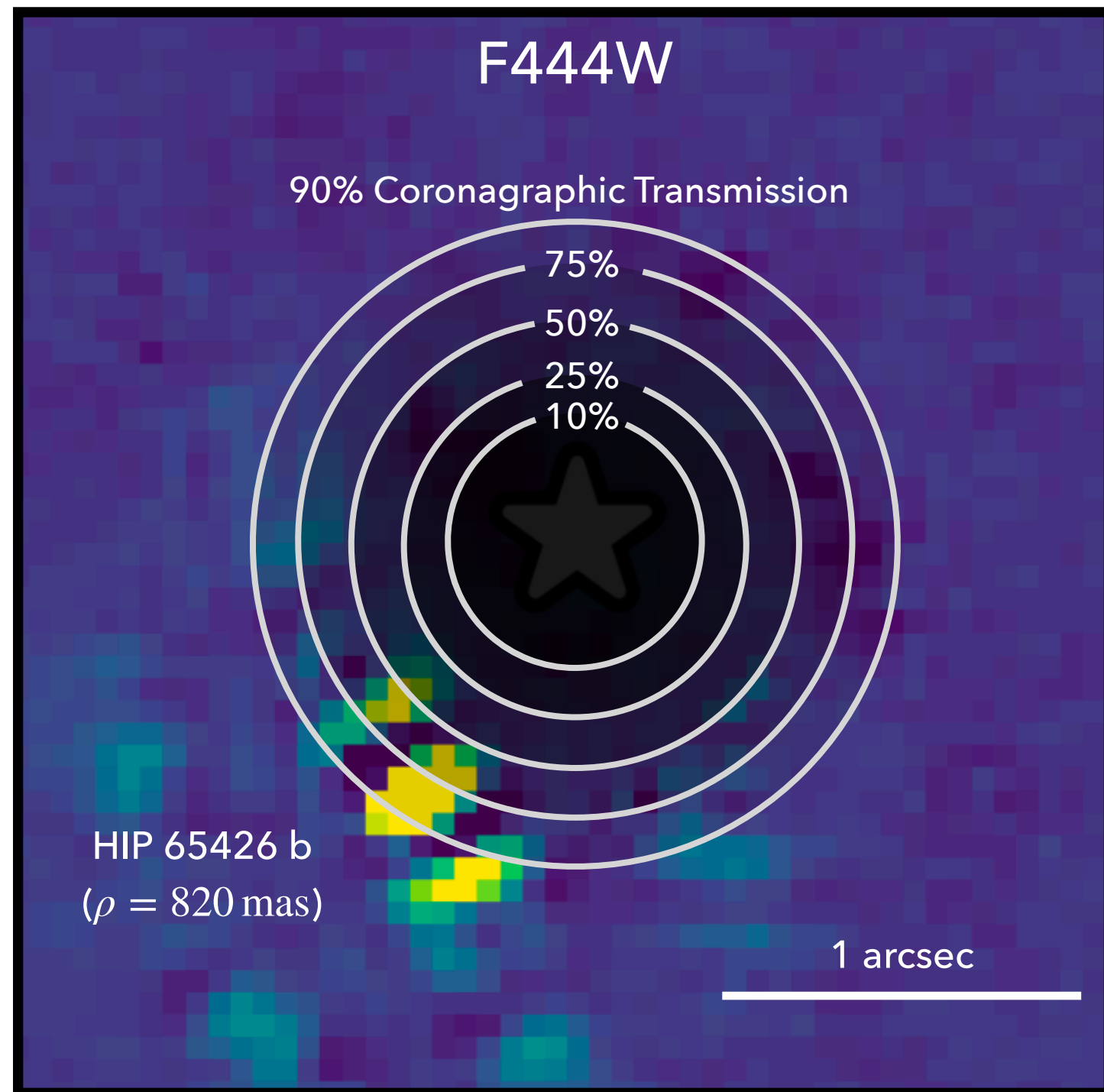
Carter et al. (2023)

Accessing Small Separations is Challenging with JWST



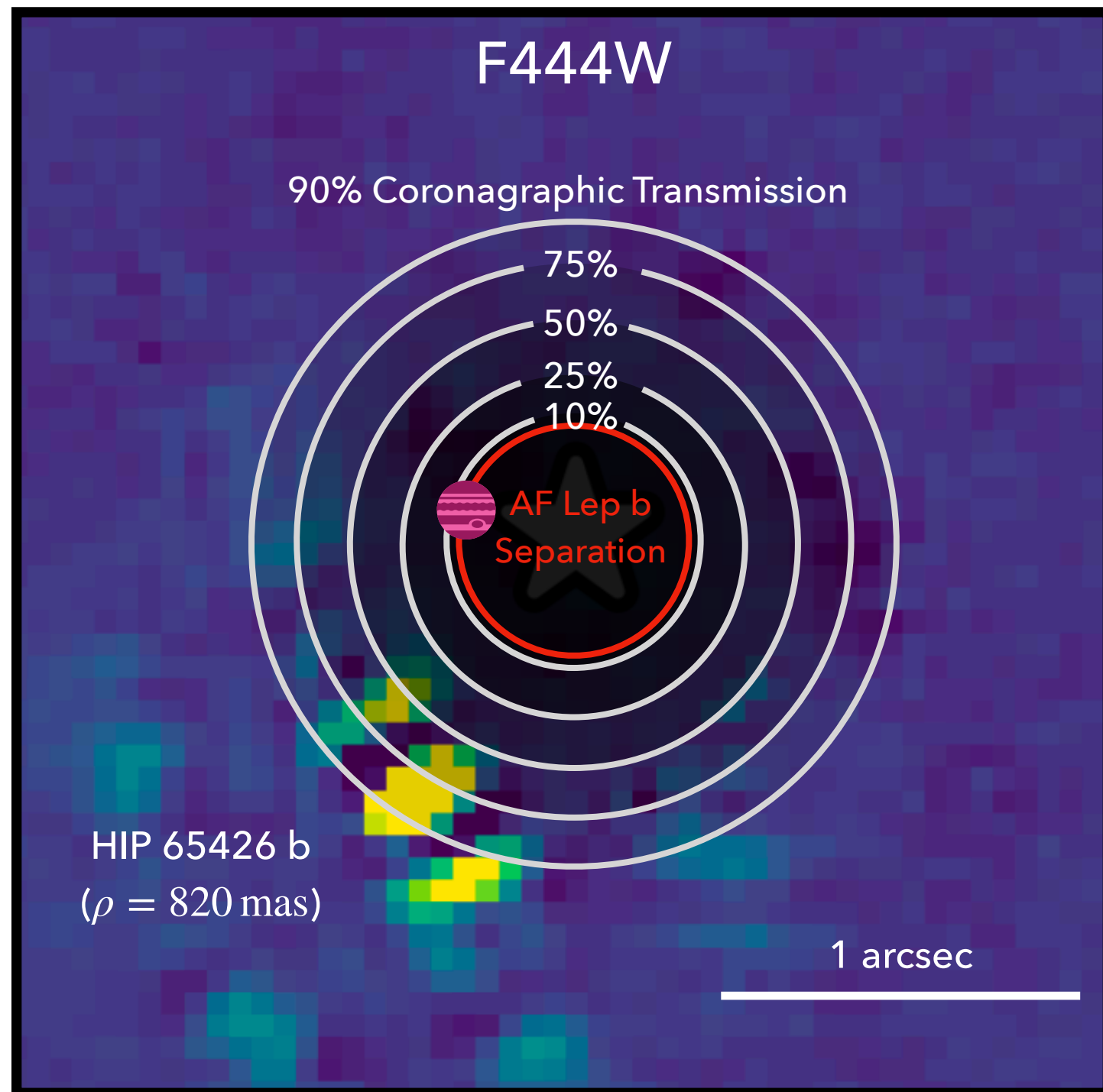
Carter et al. (2023)

Accessing Small Separations is Challenging with JWST



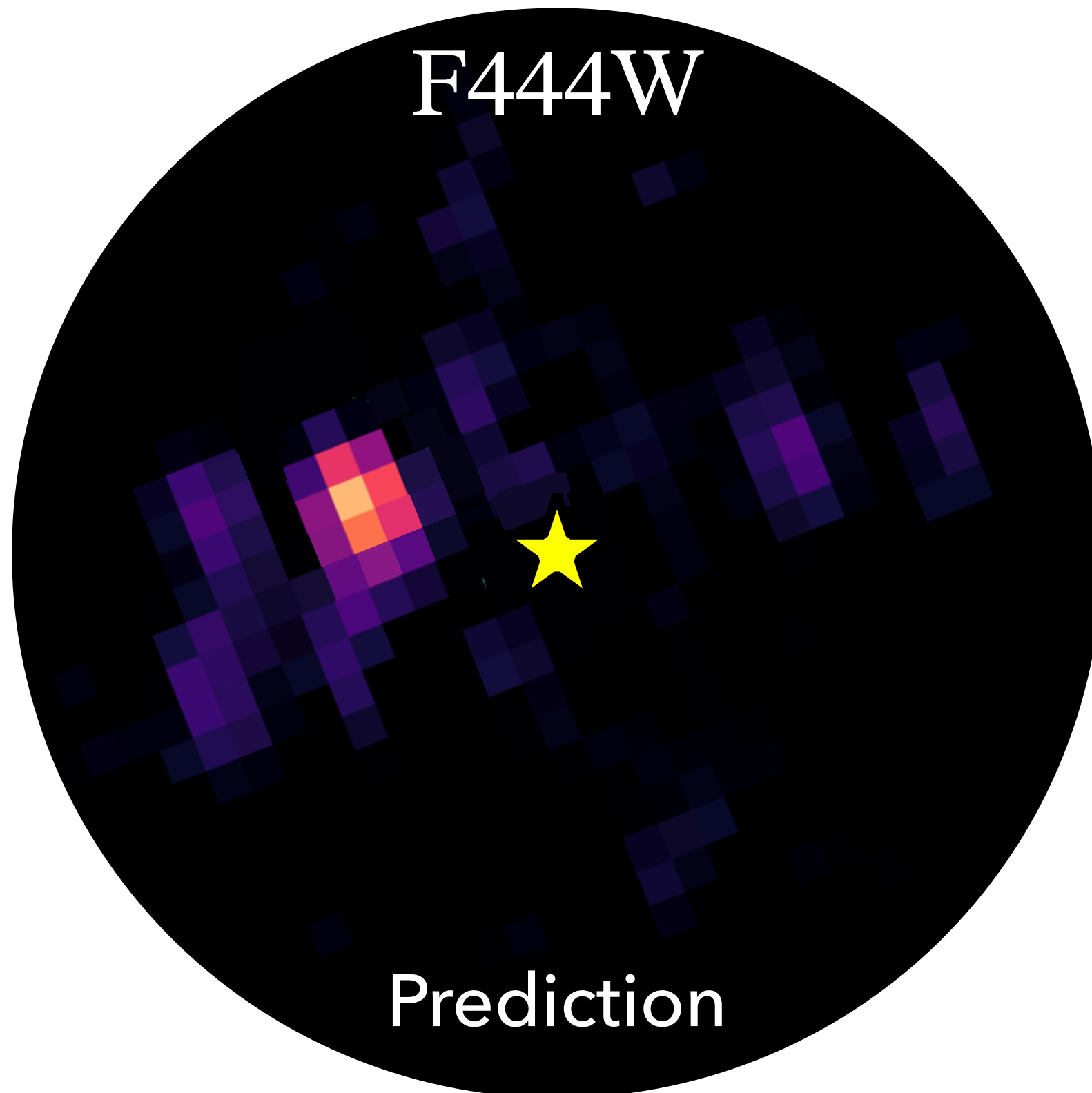
Carter et al. (2023)

Accessing Small Separations is Challenging with JWST



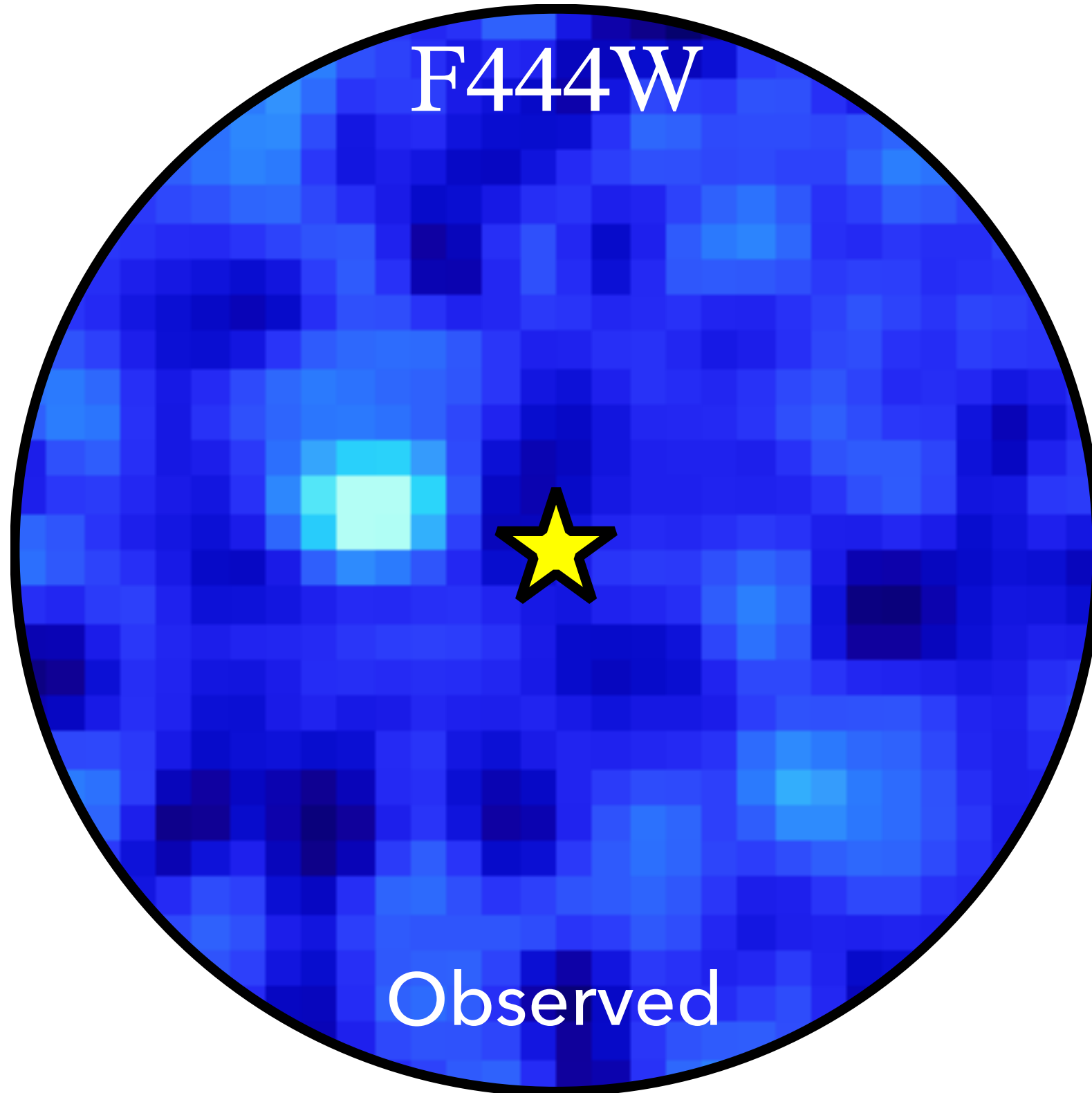
Carter et al. (2023)

JWST Imaging of AF Lep b at 4.4 μm



Franson et al. (2024)

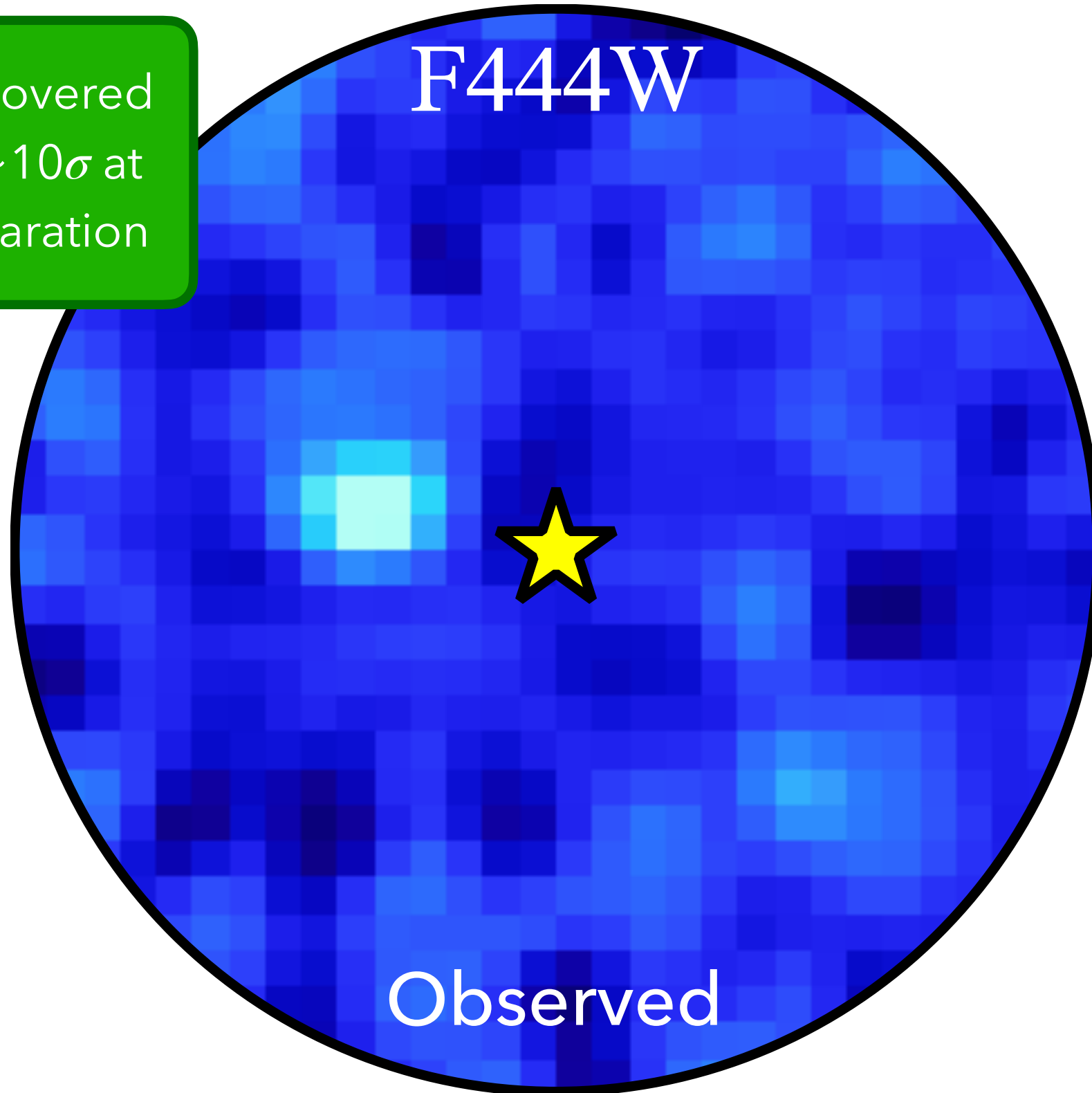
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Franson et al. (2024)

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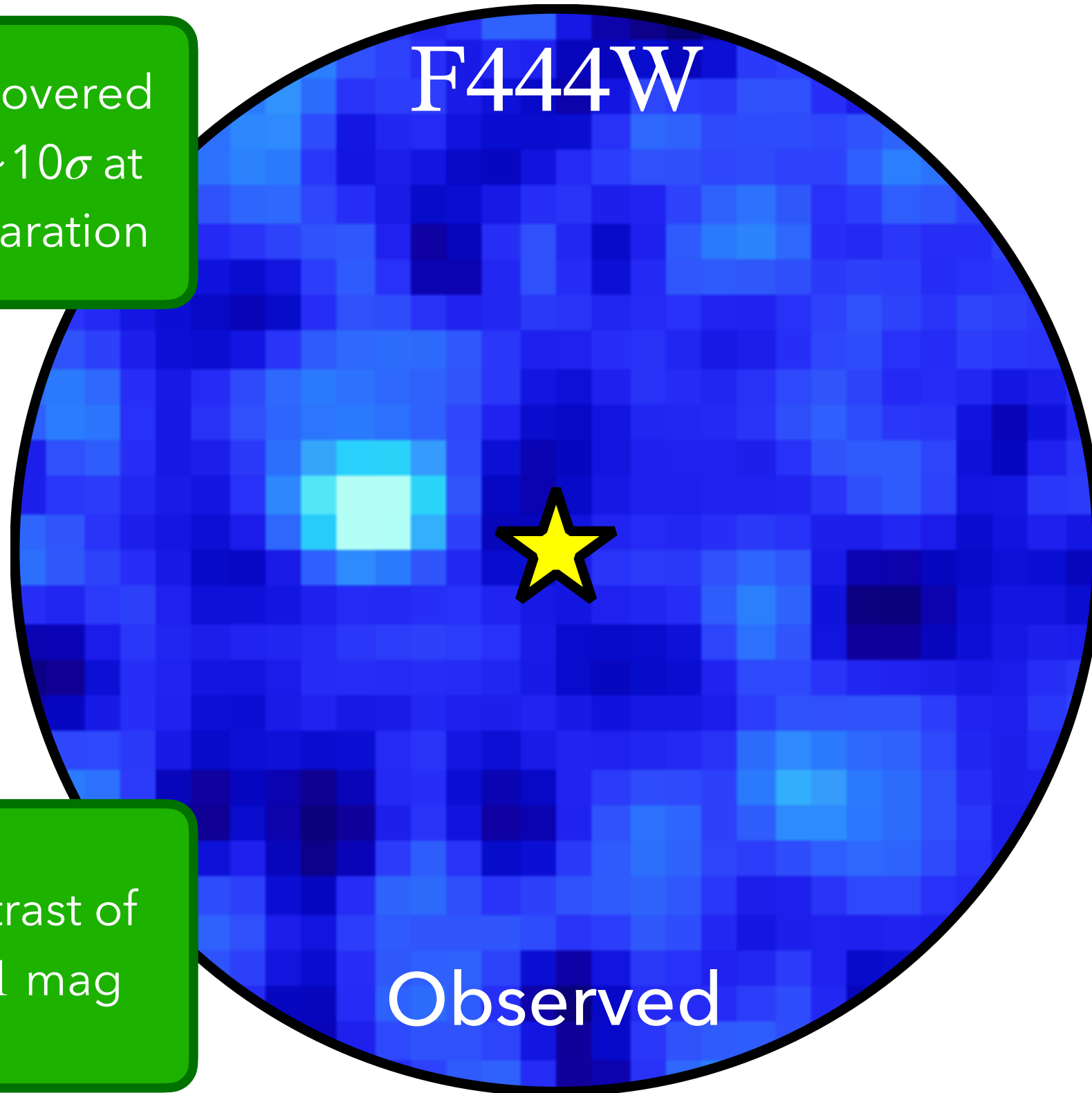
AF Lep b Recovered
with S/N of $\sim 10\sigma$ at
320 mas Separation



Franson et al. (2024)

JWST Imaging of AF Lep b at 4.4 μm

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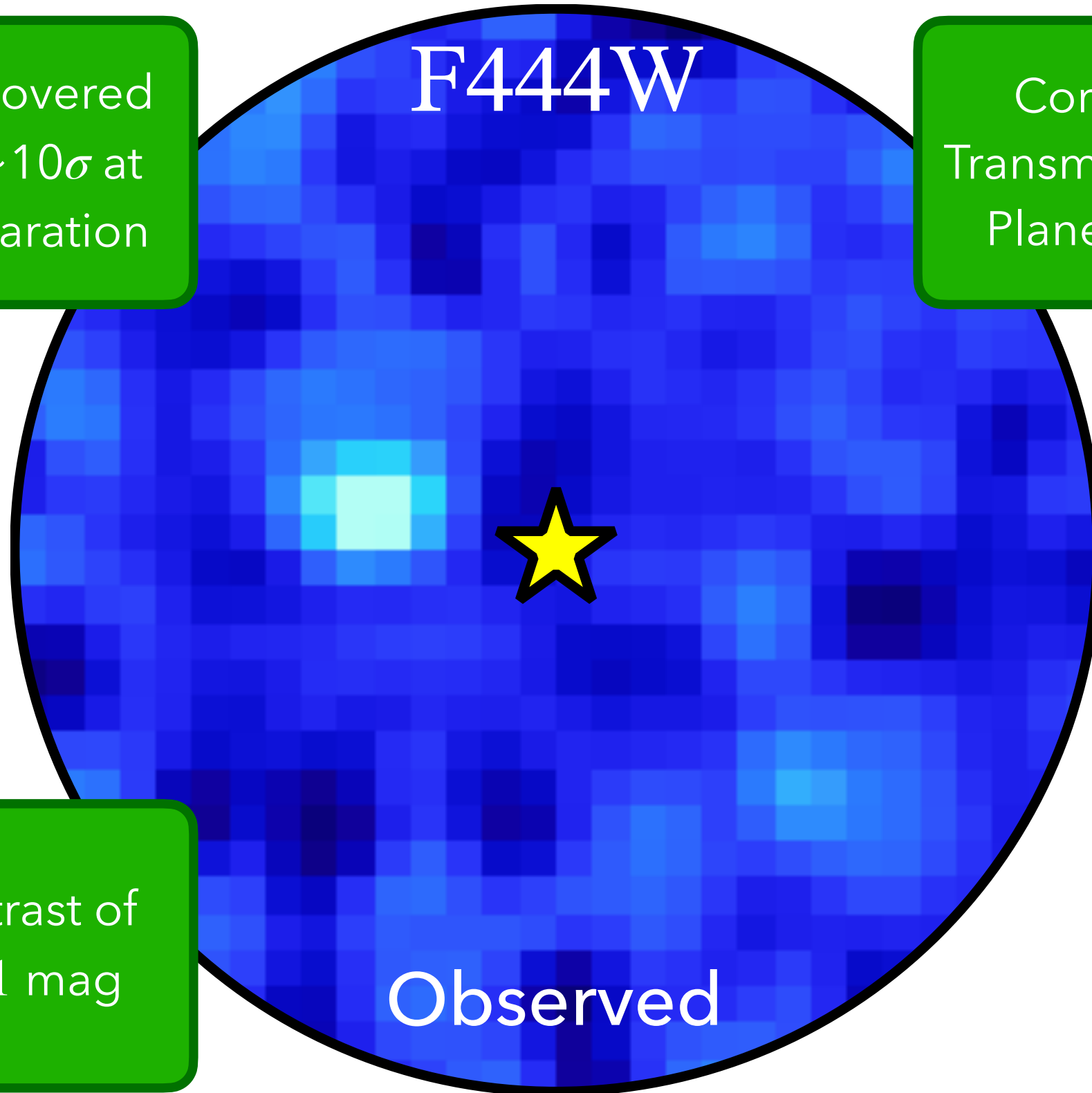
F444W Contrast of
 10.01 ± 0.11 mag

Franson et al. (2024)

JWST Imaging of AF Lep b at 4.4 μm

AF Lep b Recovered
with S/N of $\sim 10\sigma$ at
320 mas Separation

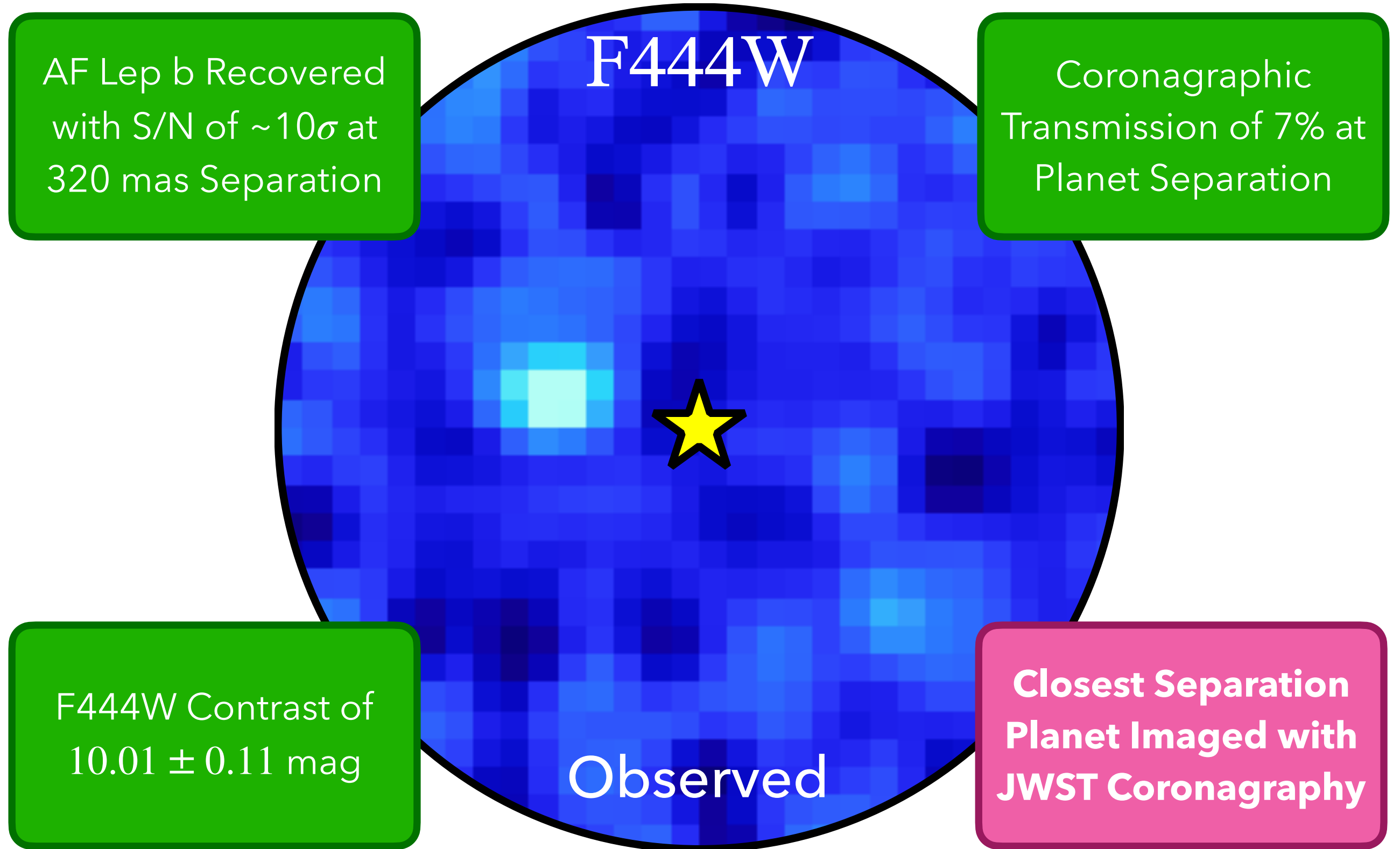
Coronagraphic
Transmission of 7% at
Planet Separation



F444W Contrast of
 10.01 ± 0.11 mag

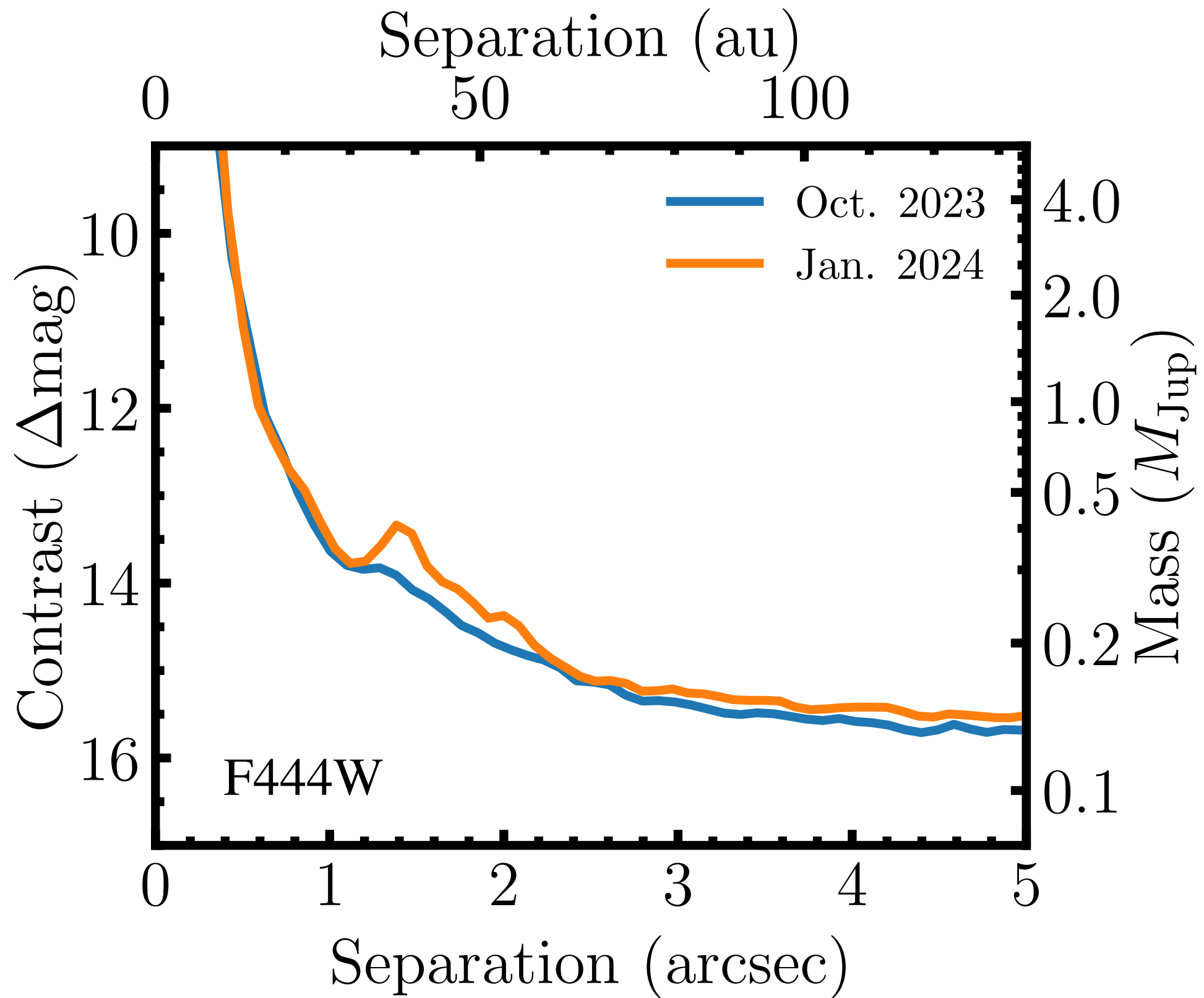
Franson et al. (2024)

JWST Imaging of AF Lep b at 4.4 μm



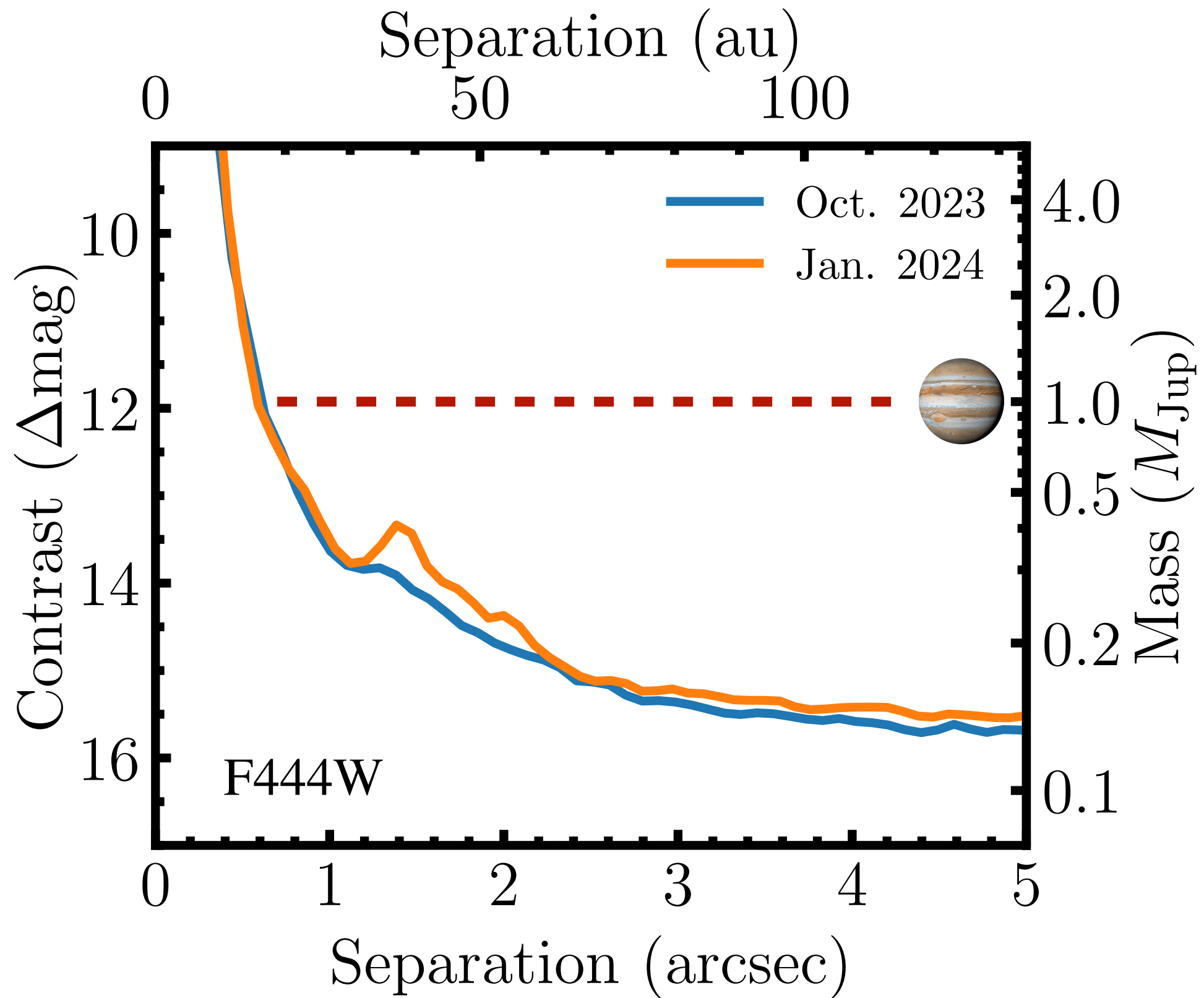
Franson et al. (2024)

No Additional Planets at Wider Separations



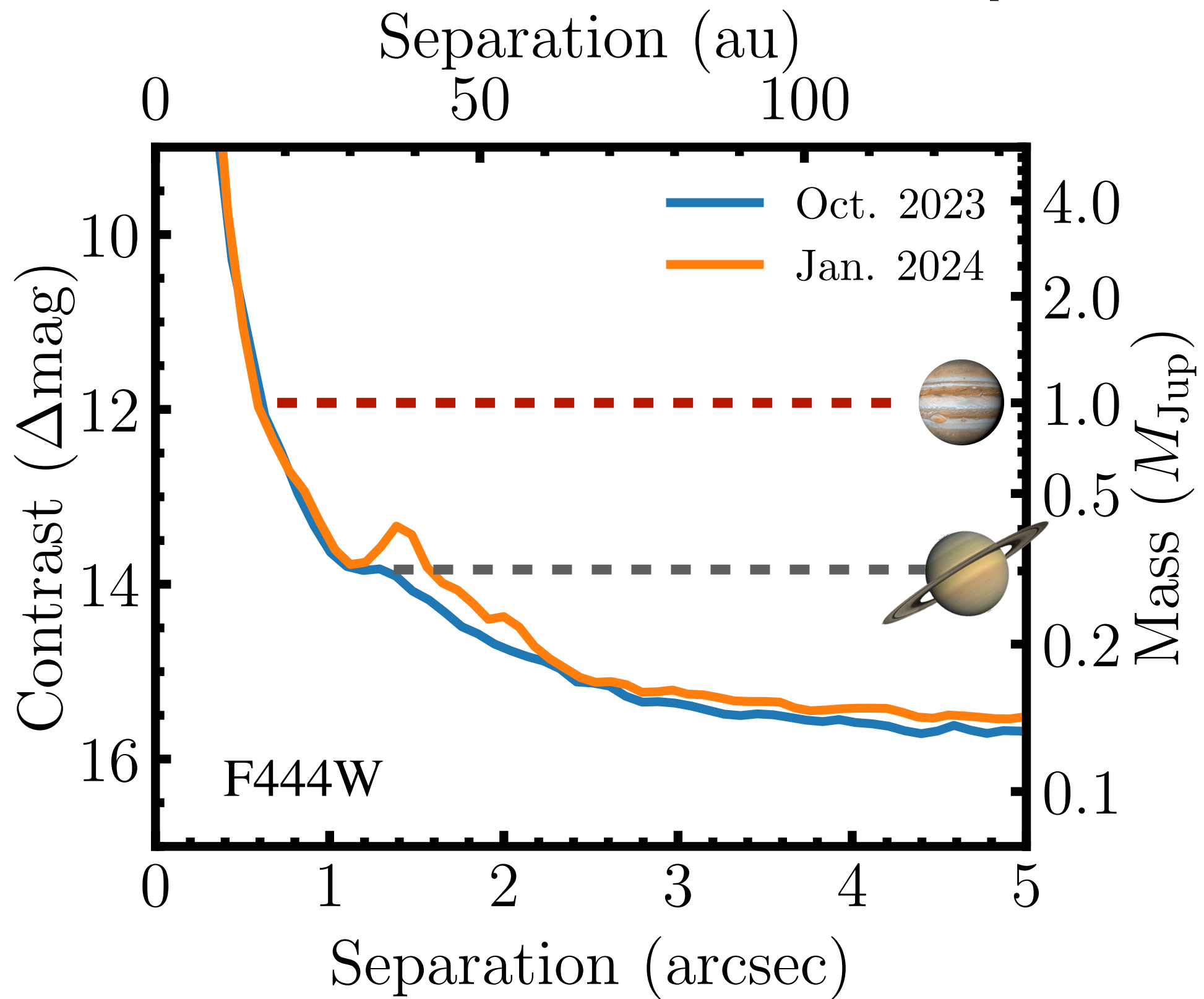
Franson et al. (2024)

No Additional Planets at Wider Separations



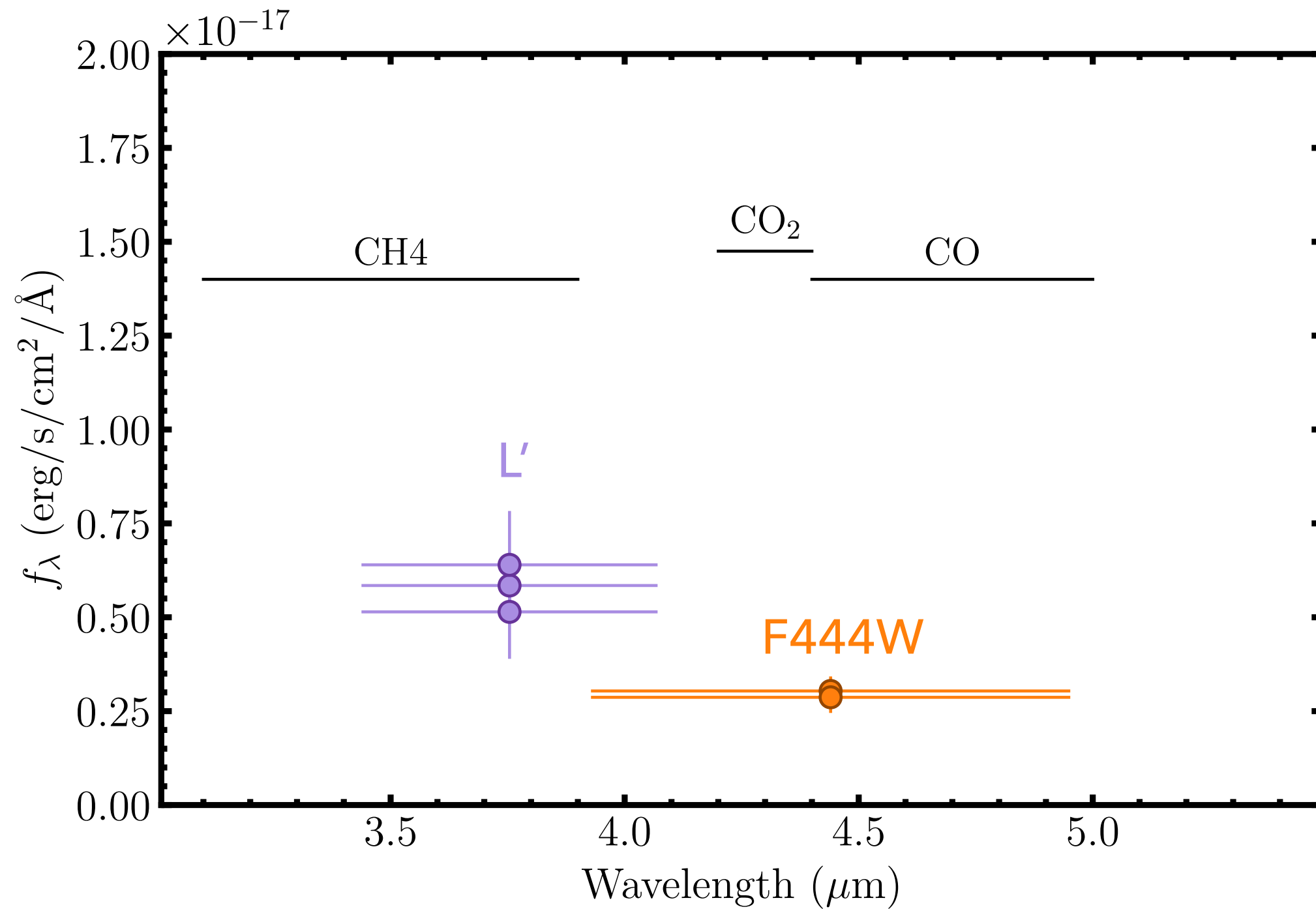
Franson et al. (2024)

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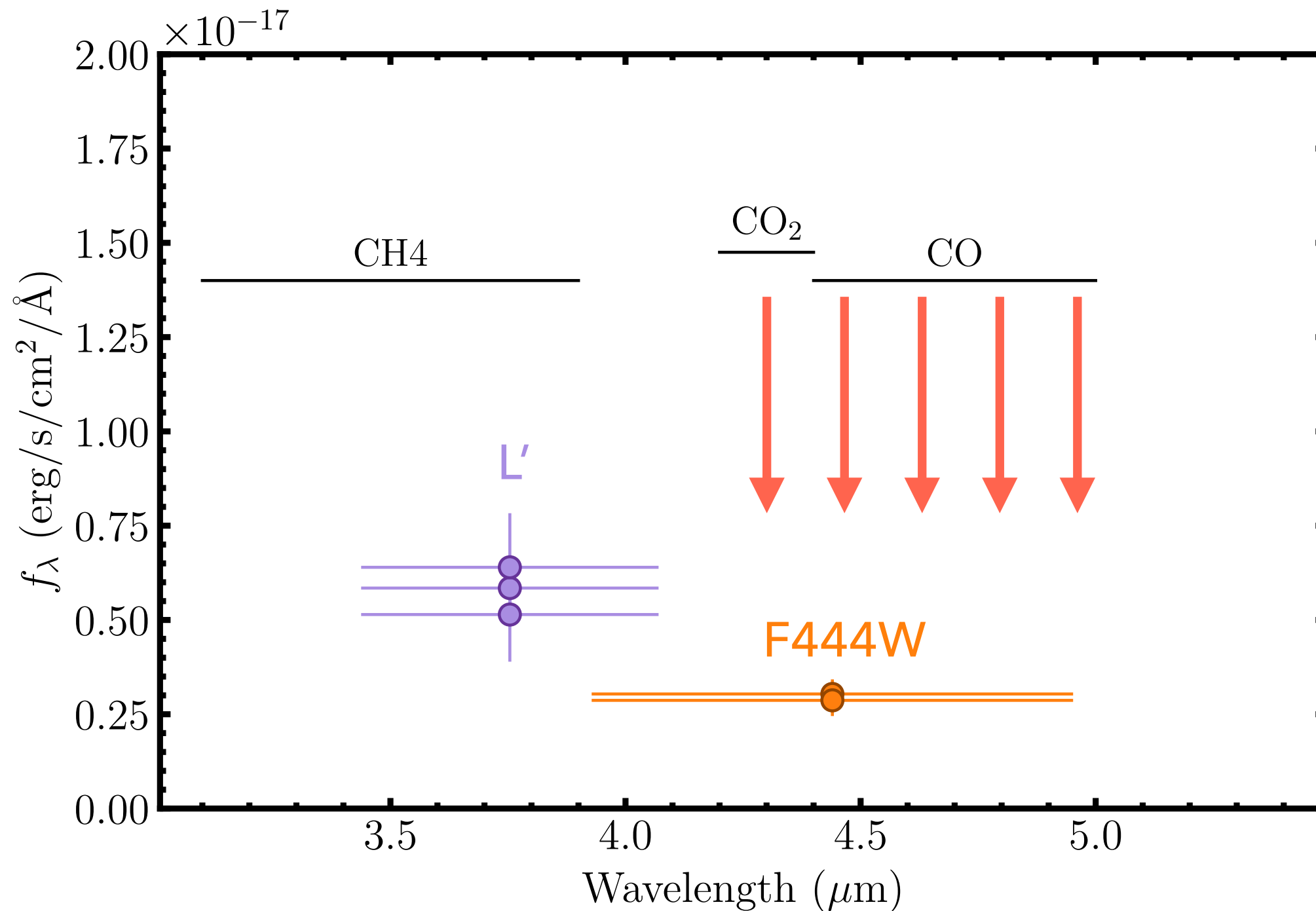
Franson et al. (2024)

3-5 μm Spectrum of AF Lep b



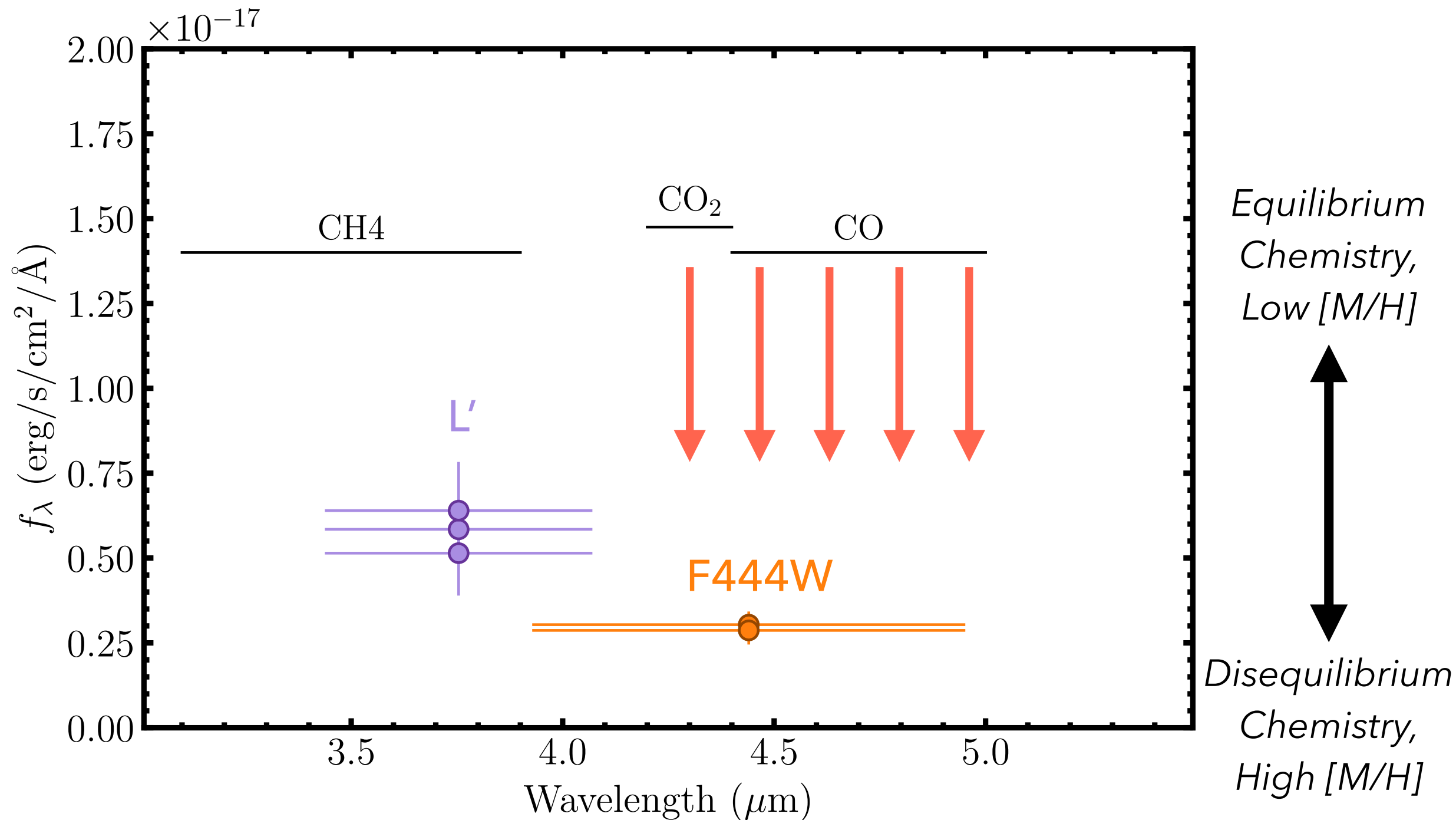
Franson et al. (2024)

3-5 μm Spectrum of AF Lep b



Franson et al. (2024)

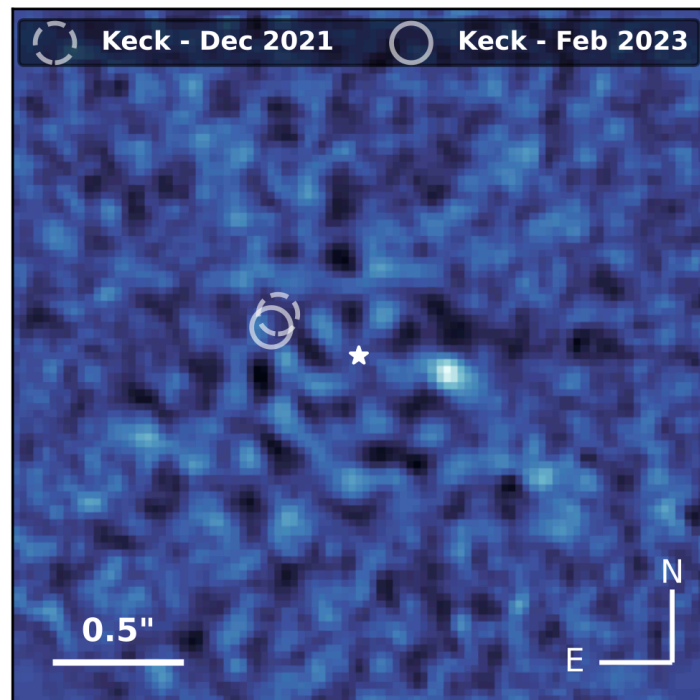
3-5 μm Spectrum of AF Lep b



Franson et al. (2024)

Updated Orbit of AF Lep b

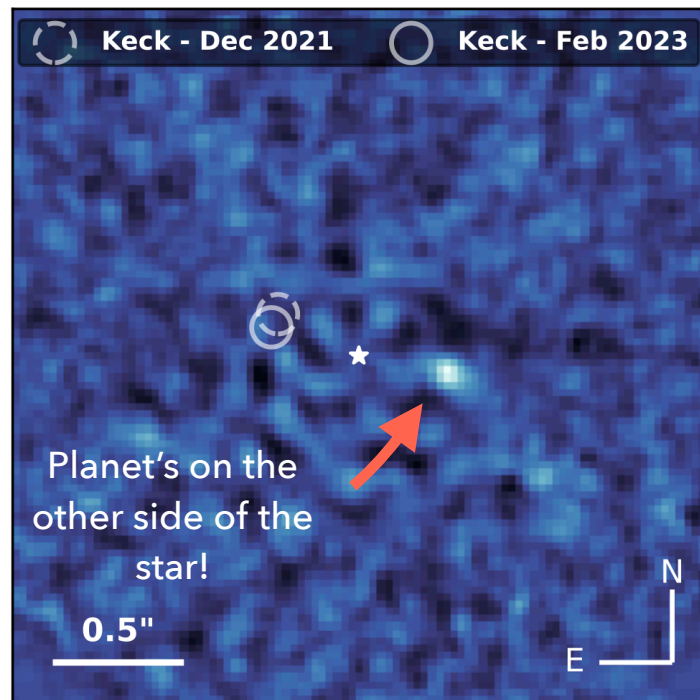
VLT/NACO



Bonse et al. (2024)

Updated Orbit of AF Lep b

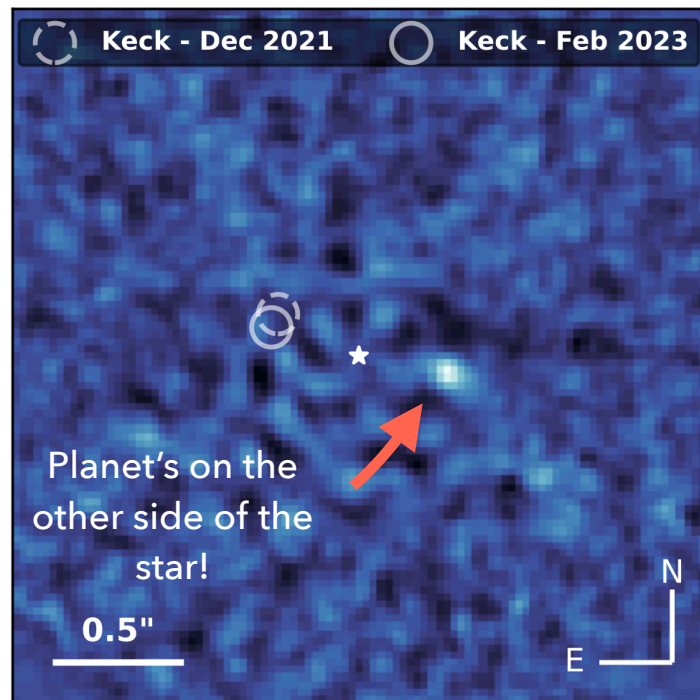
VLT/NACO



Bonse et al. (2024)

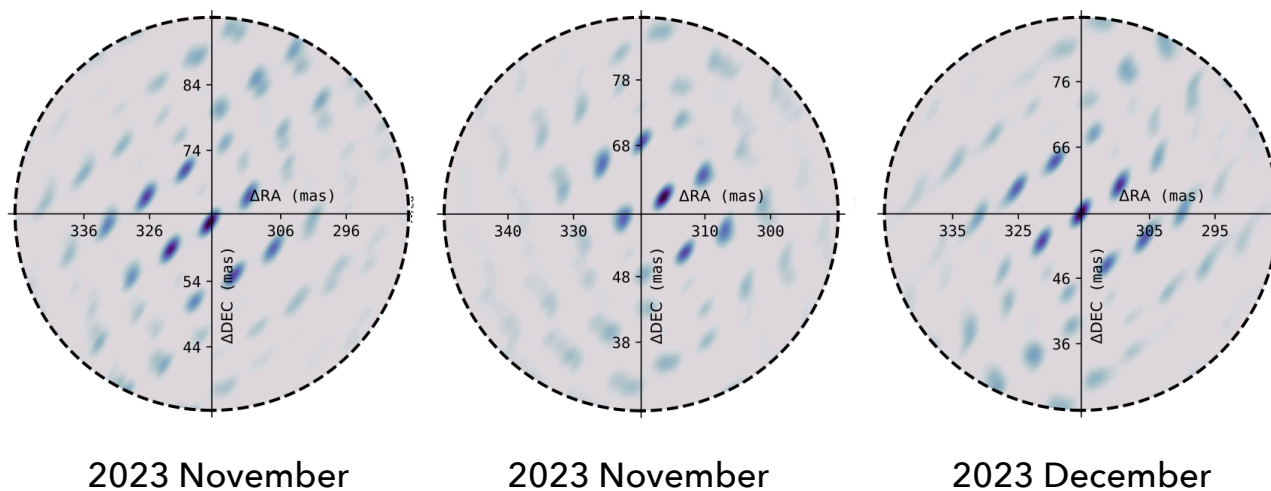
Updated Orbit of AF Lep b

VLT/NACO



Bonse et al. (2024)

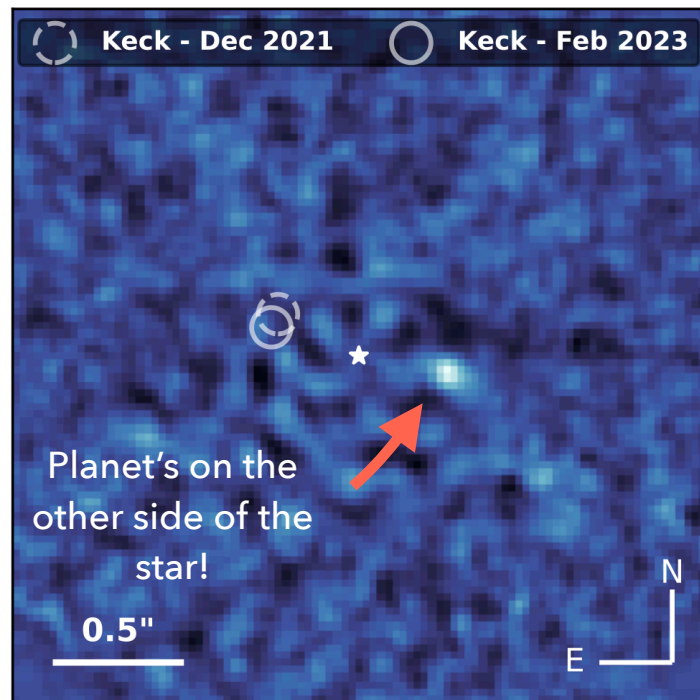
VLT/GRAVITY



Balmer et al. (2024)

Updated Orbit of AF Lep b

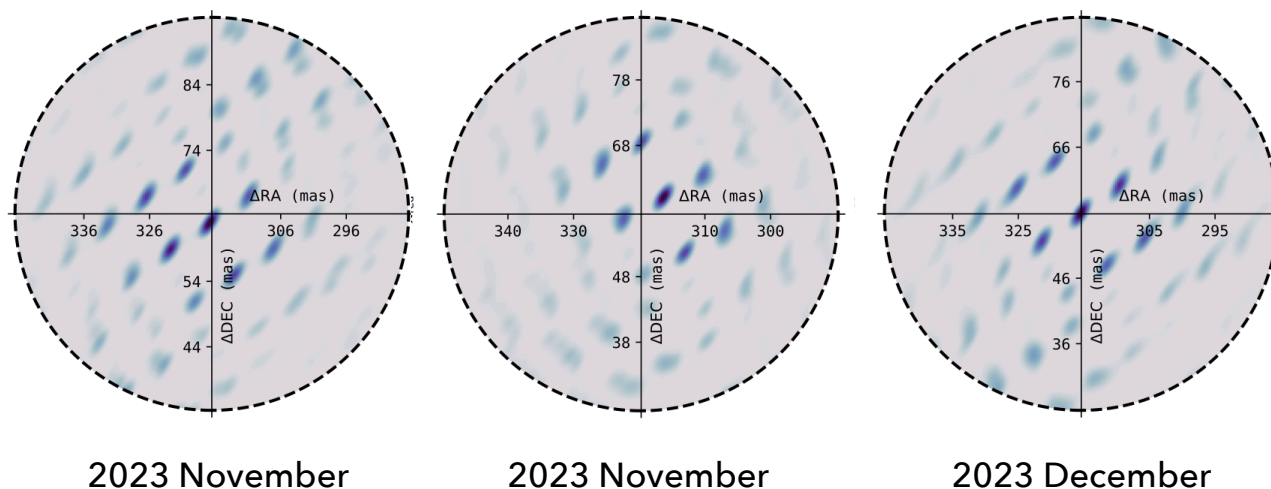
VLT/NACO



◆ Semi-Major Axis: 9.0 ± 0.2 au

Bonse et al. (2024)

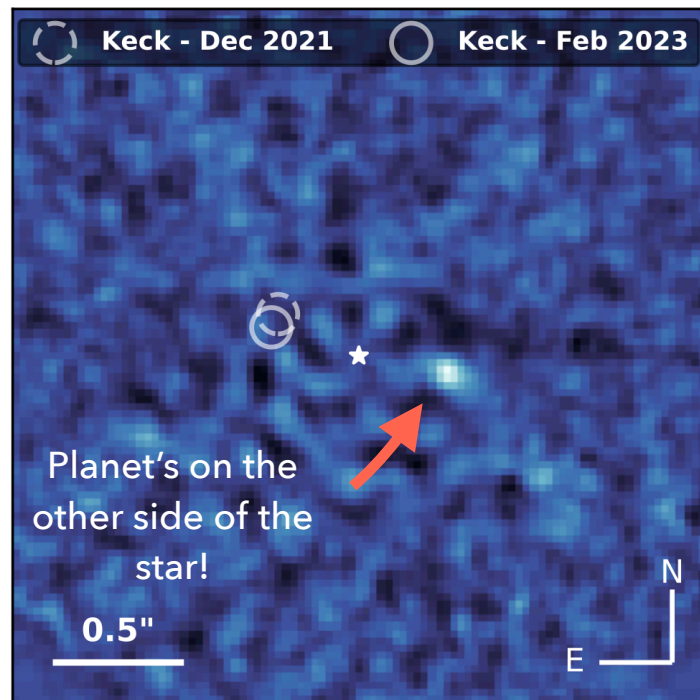
VLT/GRAVITY



Balmer et al. (2024)

Updated Orbit of AF Lep b

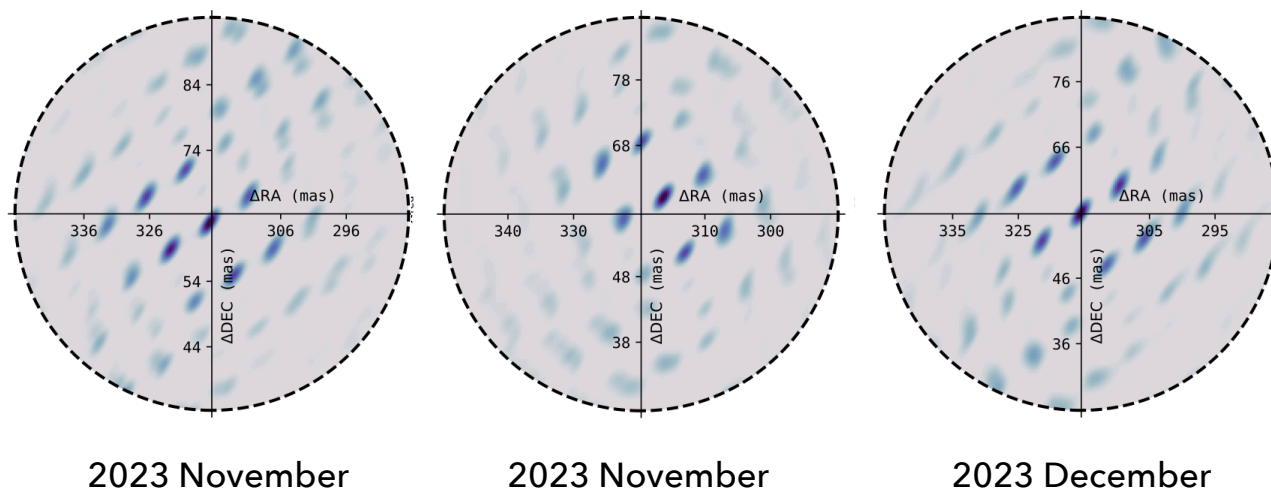
VLT/NACO



Bonse et al. (2024)

- ◆ Semi-Major Axis: 9.0 ± 0.2 au
- ◆ Eccentricity: 0.01 ± 0.02 (Circular)

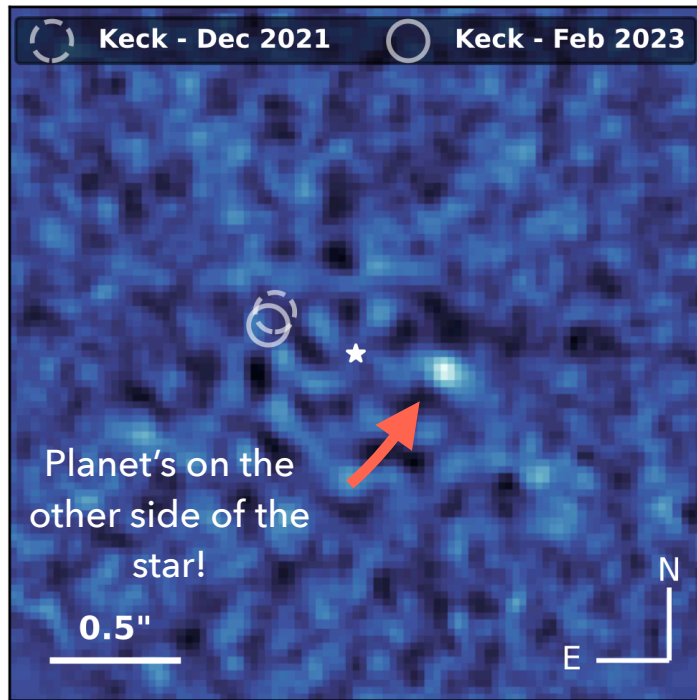
VLTI/GRAVITY



Balmer et al. (2024)

Updated Orbit of AF Lep b

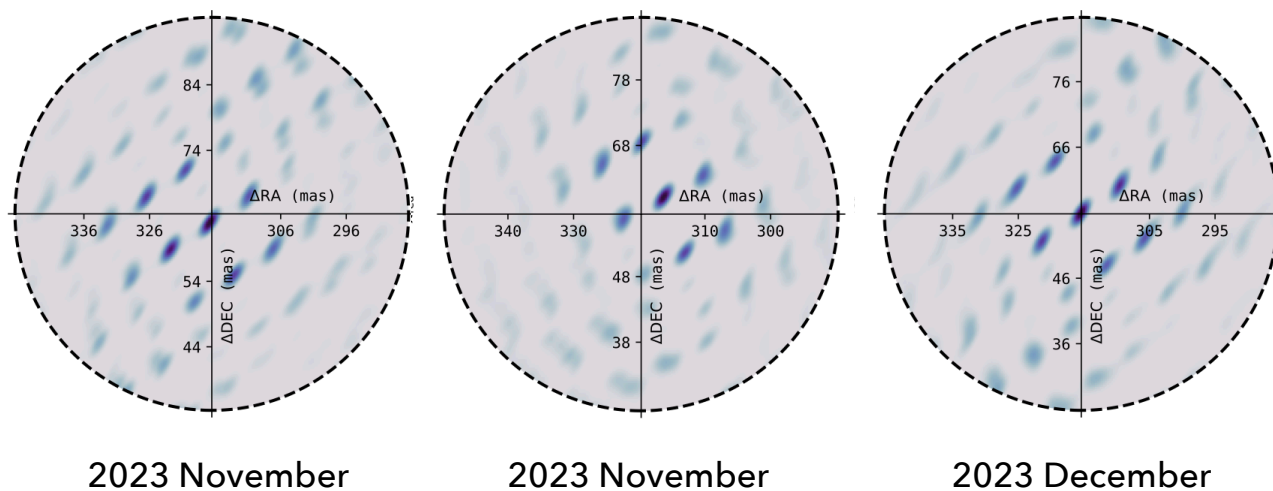
VLT/NACO



Bonse et al. (2024)

- ◆ Semi-Major Axis: 9.0 ± 0.2 au
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- ◆ Orbital inclination: $57.5 \pm 0.7^\circ$

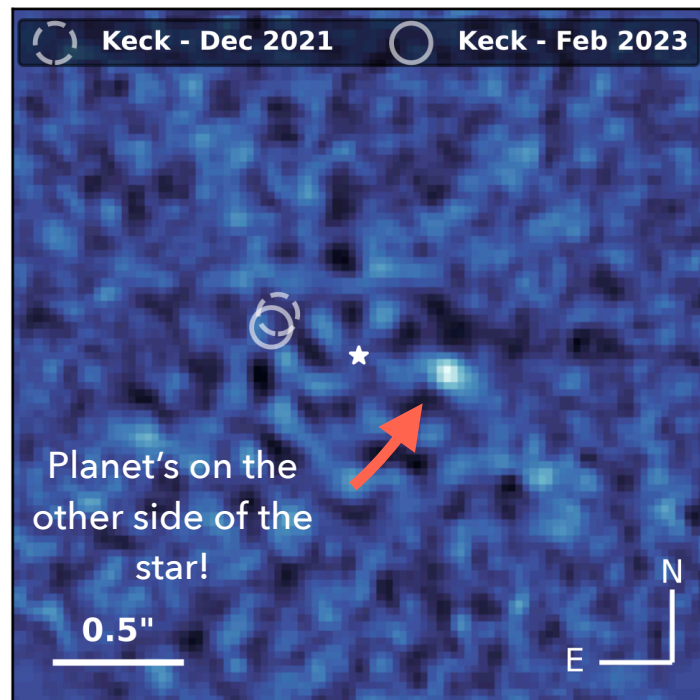
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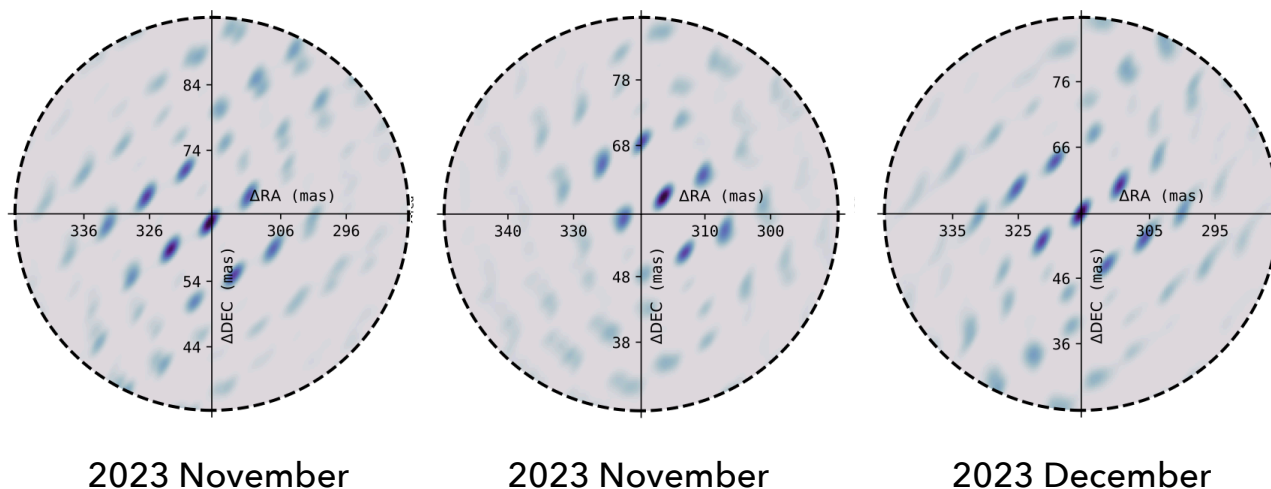
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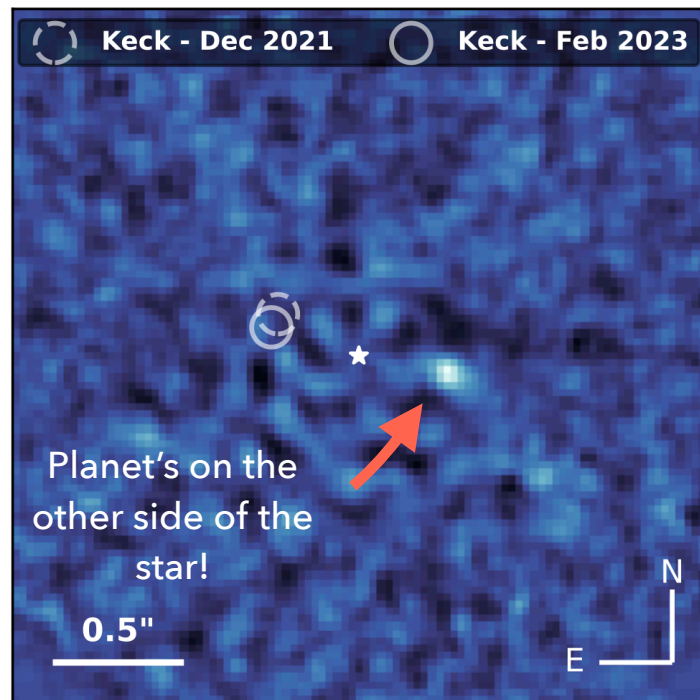
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Updated Orbit of AF Lep b

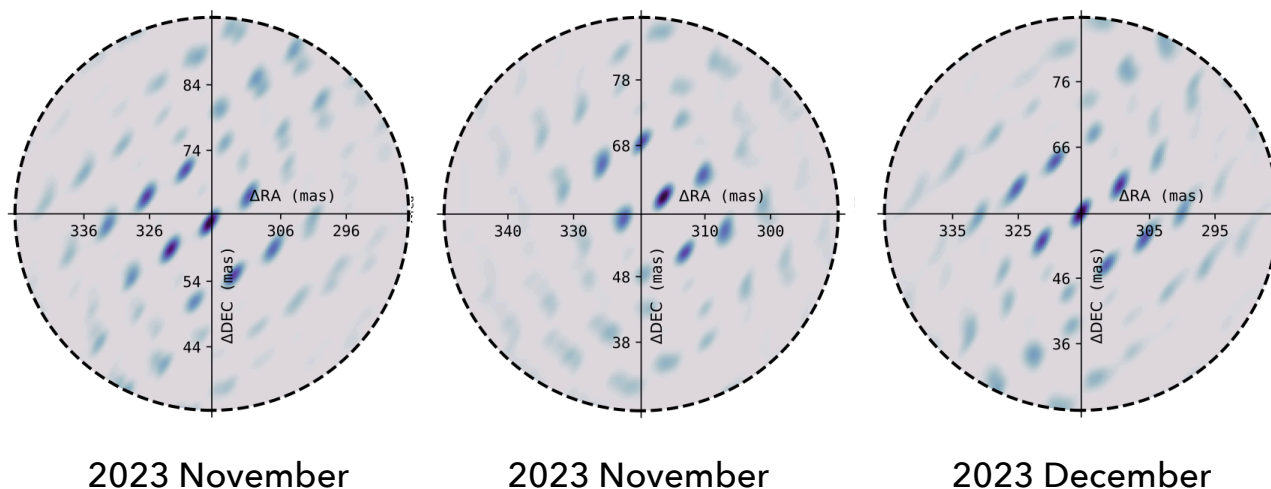
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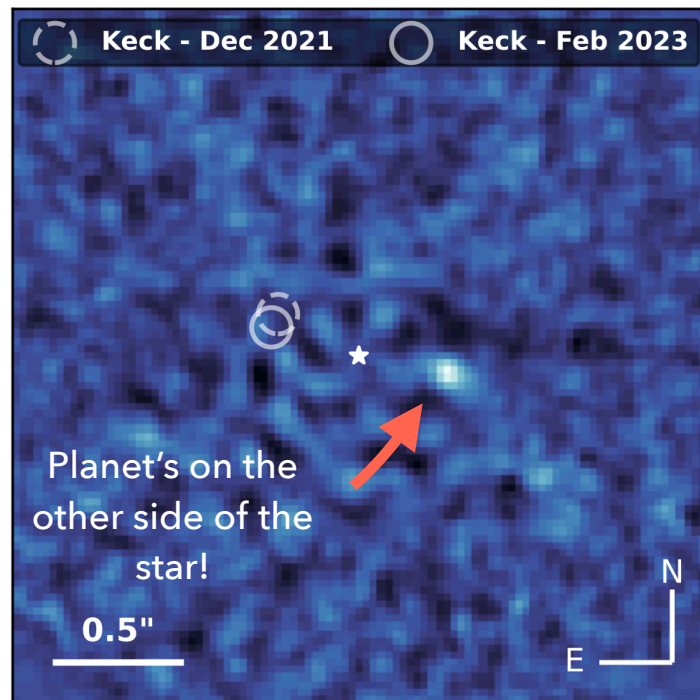
VLTI/GRAVITY



Balmer et al. (2024)

Updated Orbit of AF Lep b

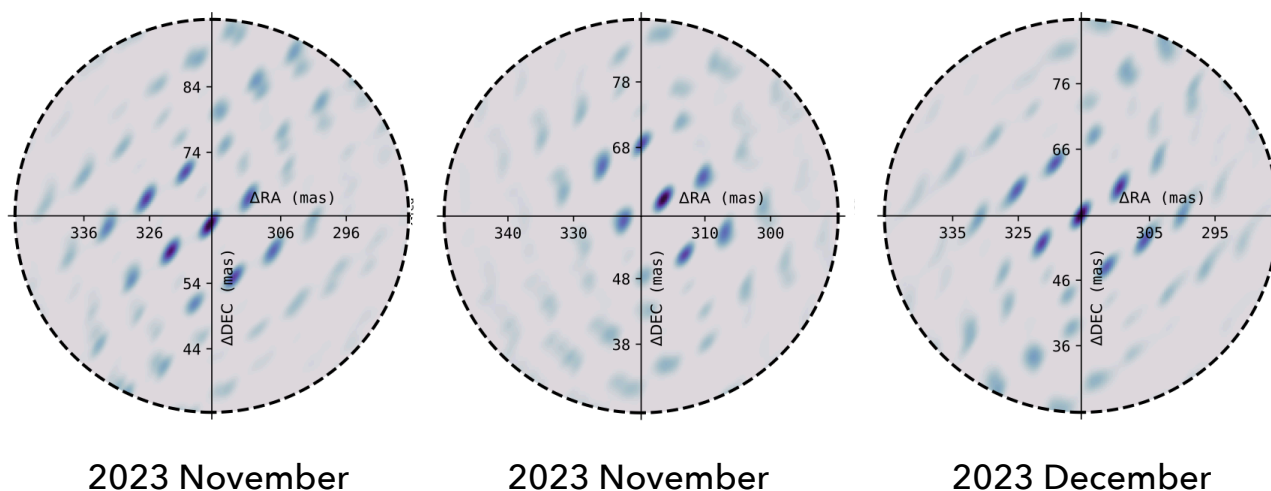
VLT/NACO



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 - Consistent with hot-start, warm-start if delayed formation

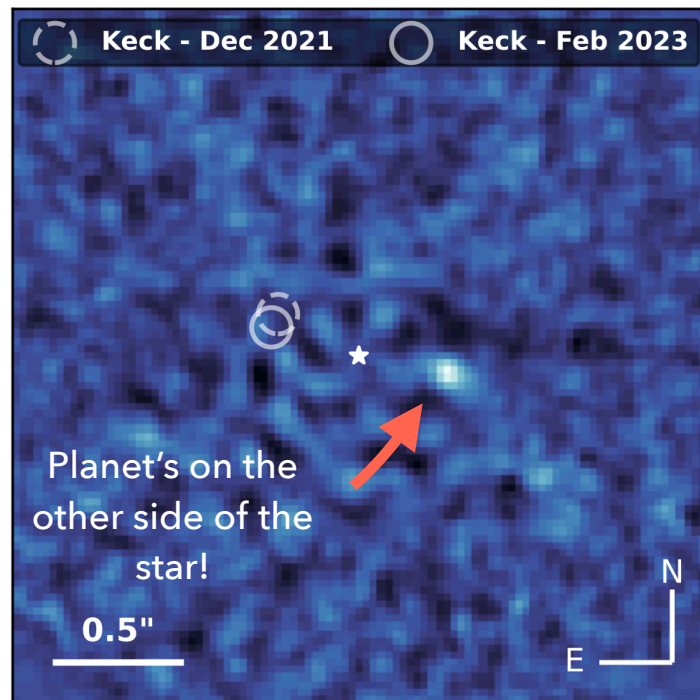
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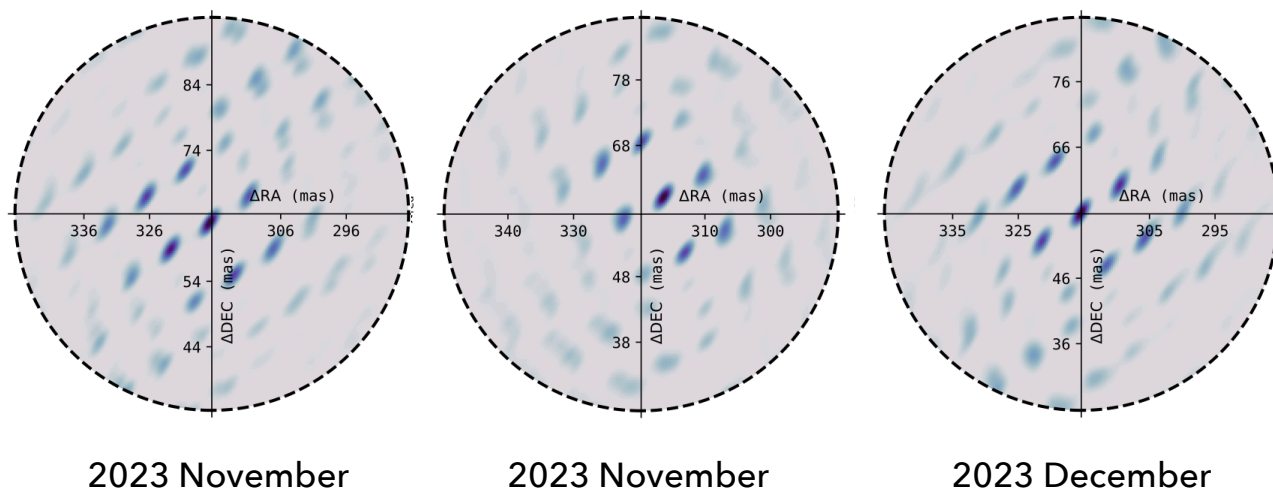
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Bonse et al. (2024)

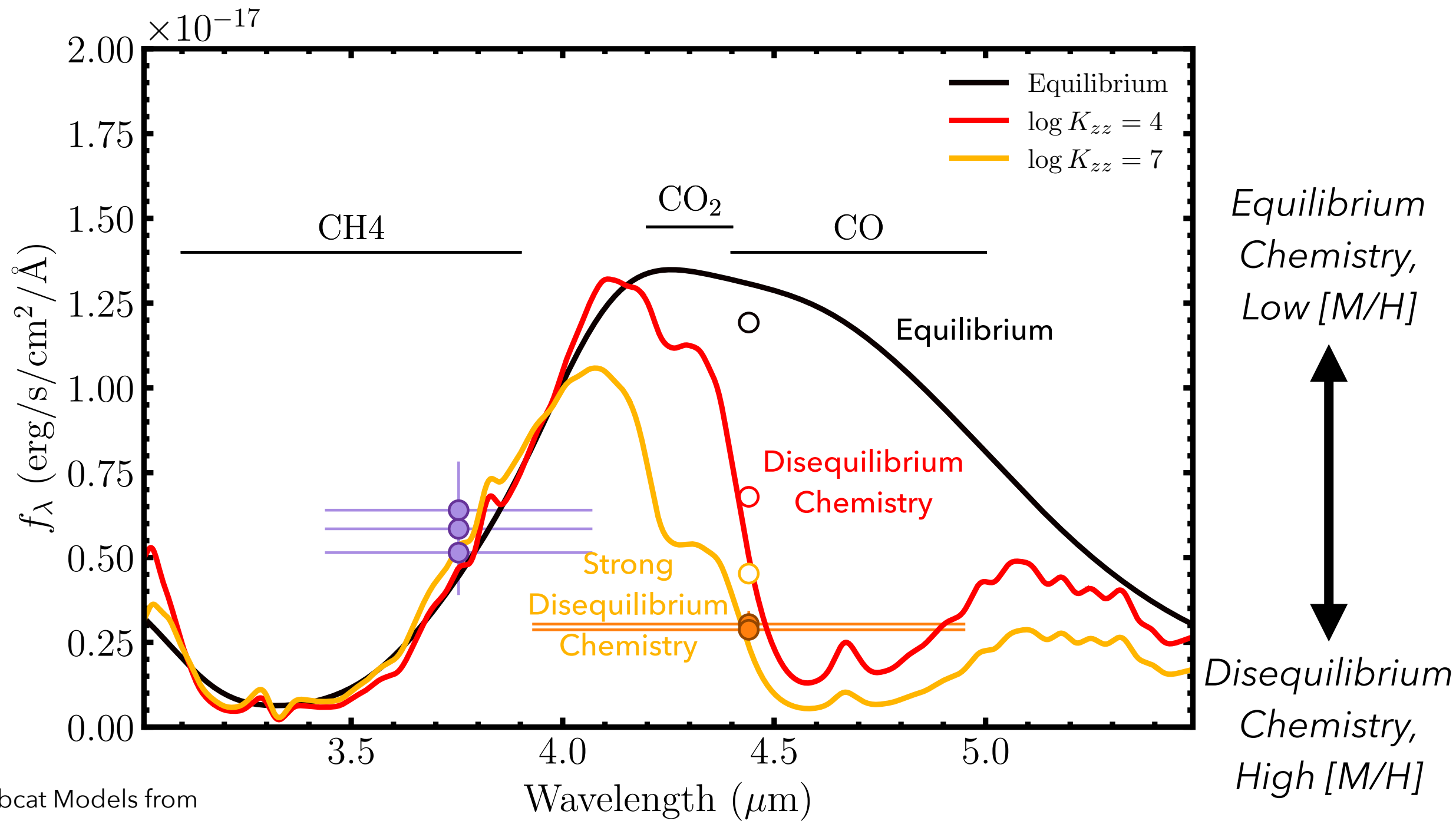
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- ◆ Dynamical mass: $3.7 \pm 0.5 M_{\text{Jup}}$
 - Consistent with hot-start, warm-start if delayed formation
- ◆ Reinforces emerging trends in eccentricity and spin-orbit alignment (Bowler et al. 2020, 2023; Do Ó et al. 2023; Nagpal et al. 2023; Sepulveda et al. 2024)

3-5 μm Spectrum of AF Lep b



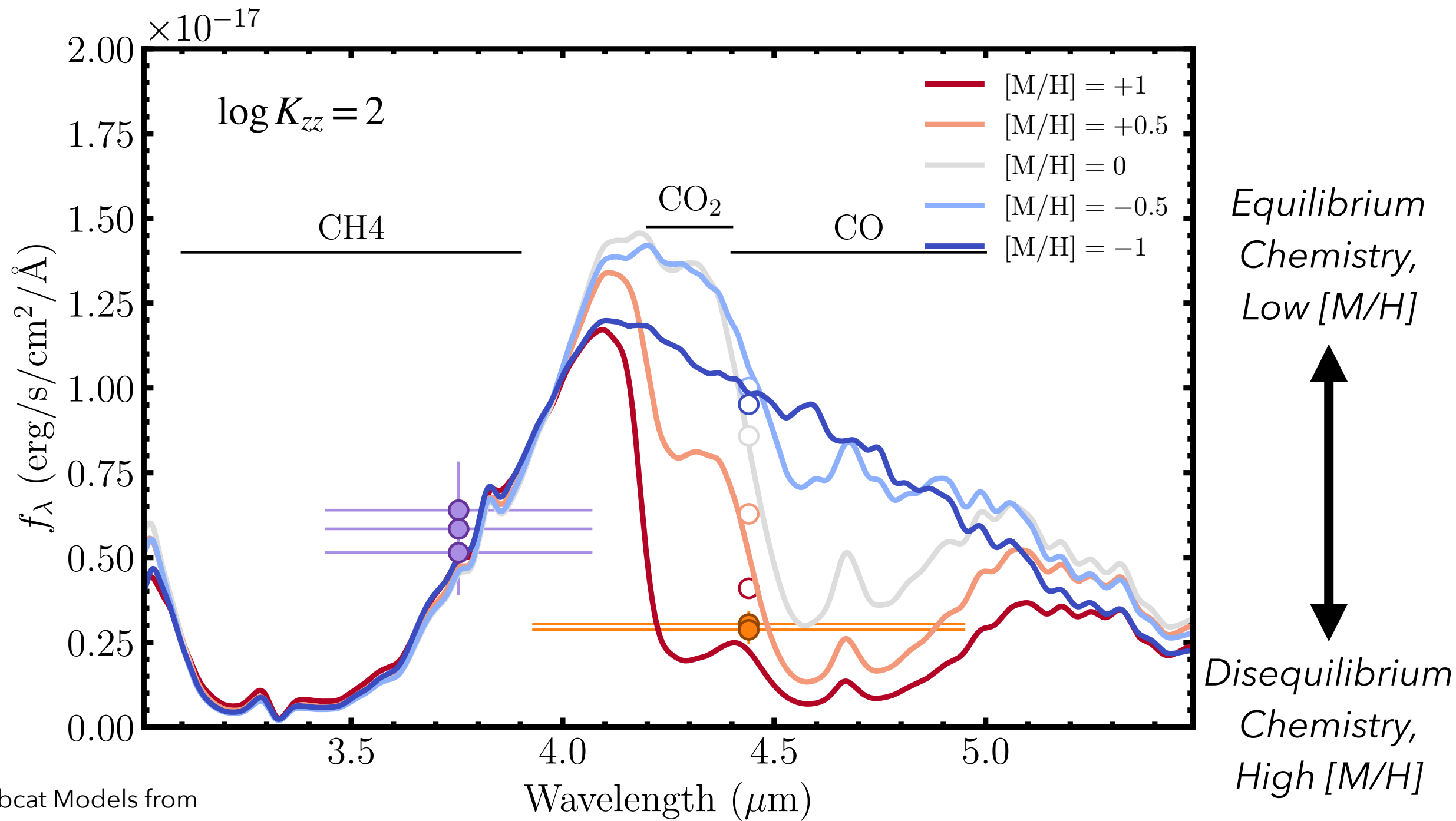
Sonora Bobcat Models from
Marley et al. (2021)

Sonora Elf Owl Models from
Mukherjee et al. (2023)

Franson et al. (2024)

Kyle Franson – Keck Science Meeting 2025

3-5 μm Spectrum of AF Lep b



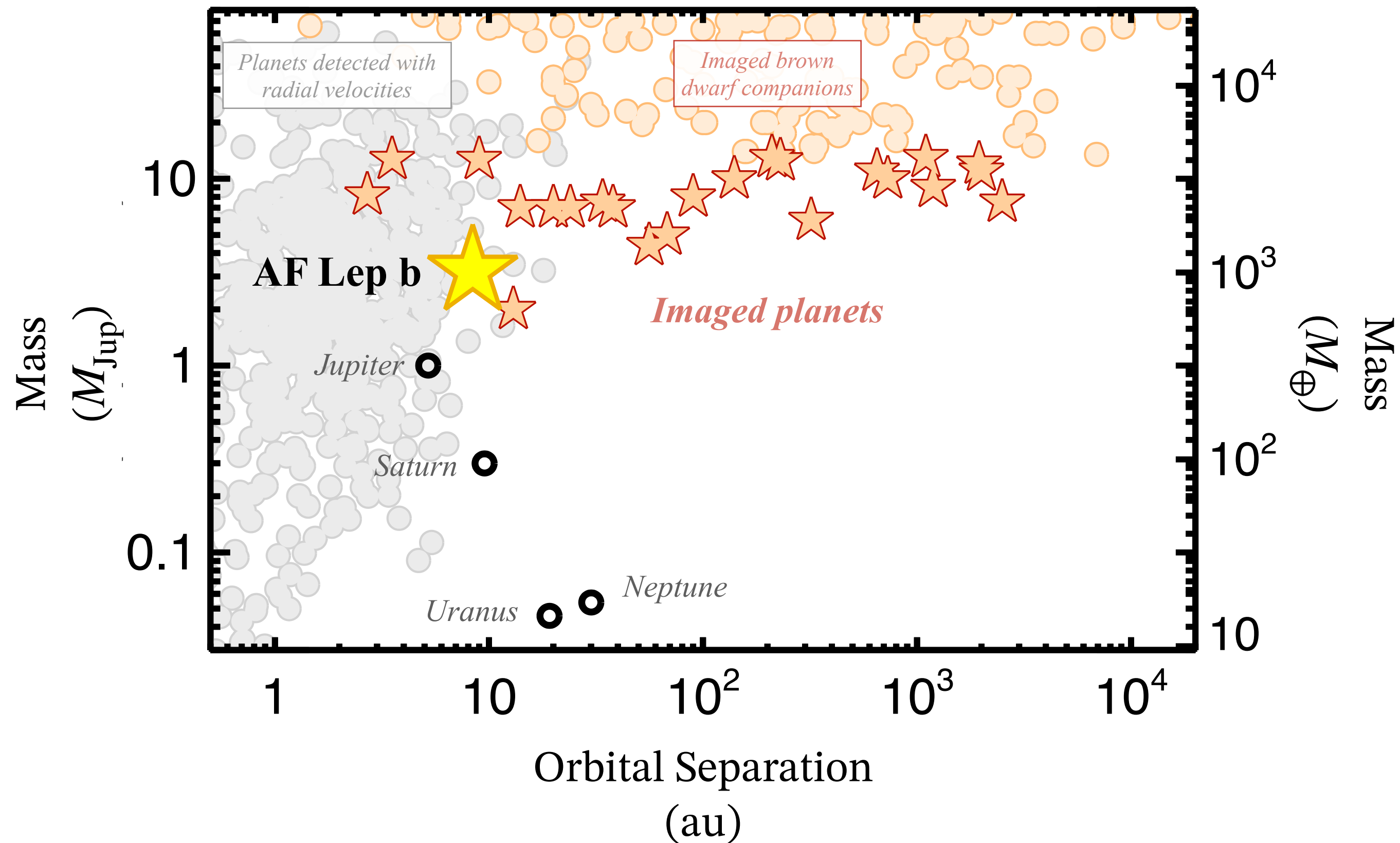
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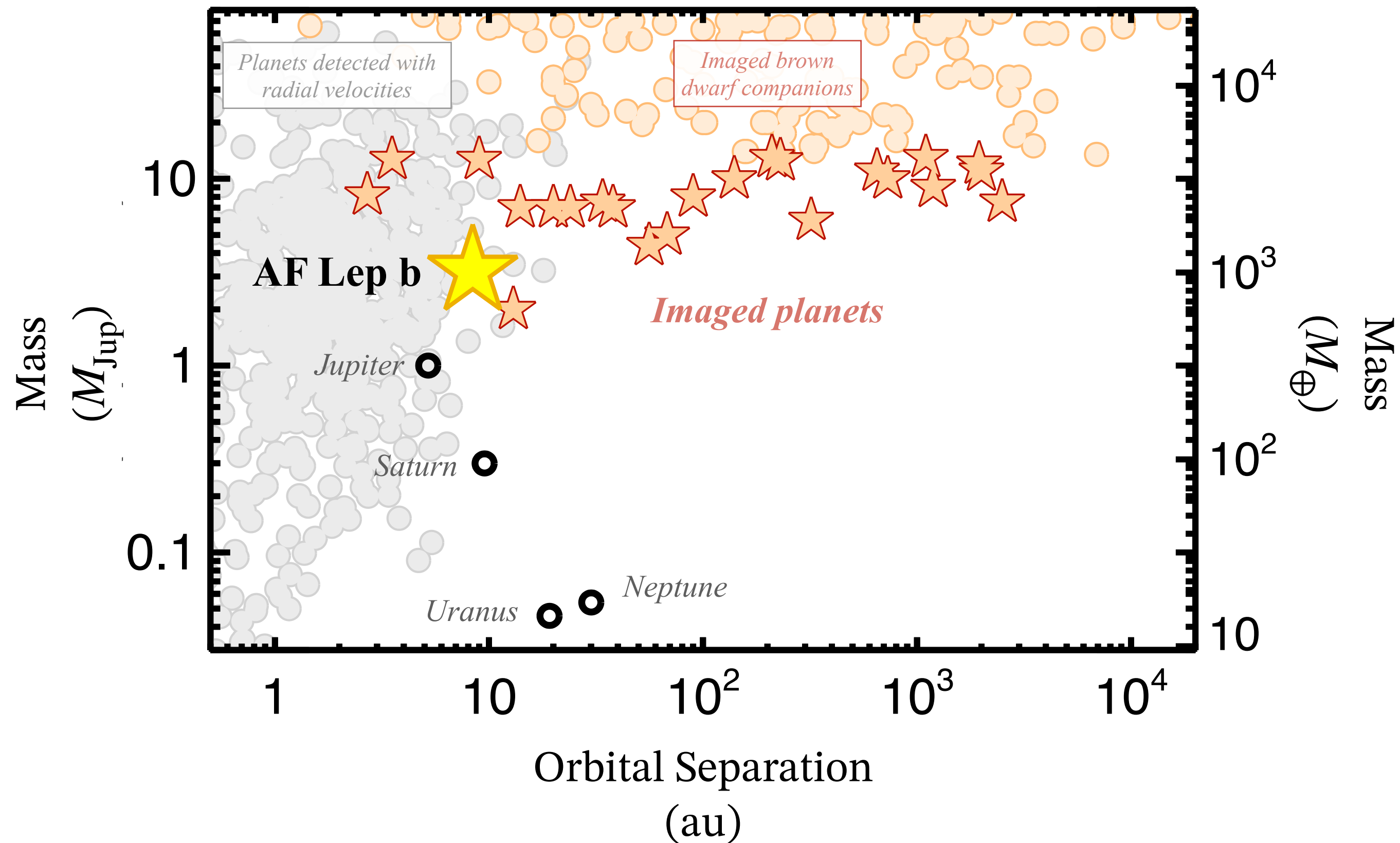
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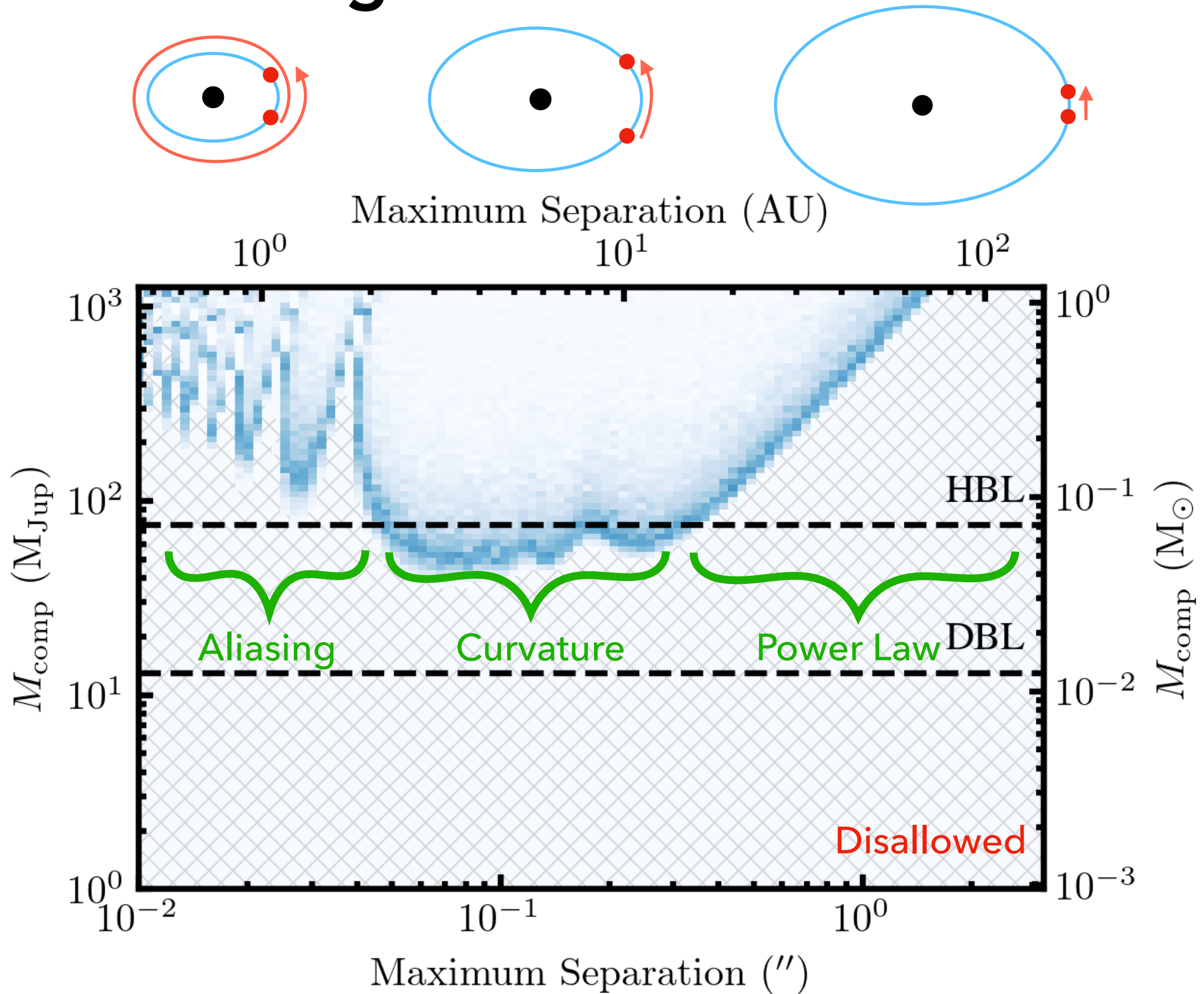
AF Lep b Bridges Imaged and RV Planets

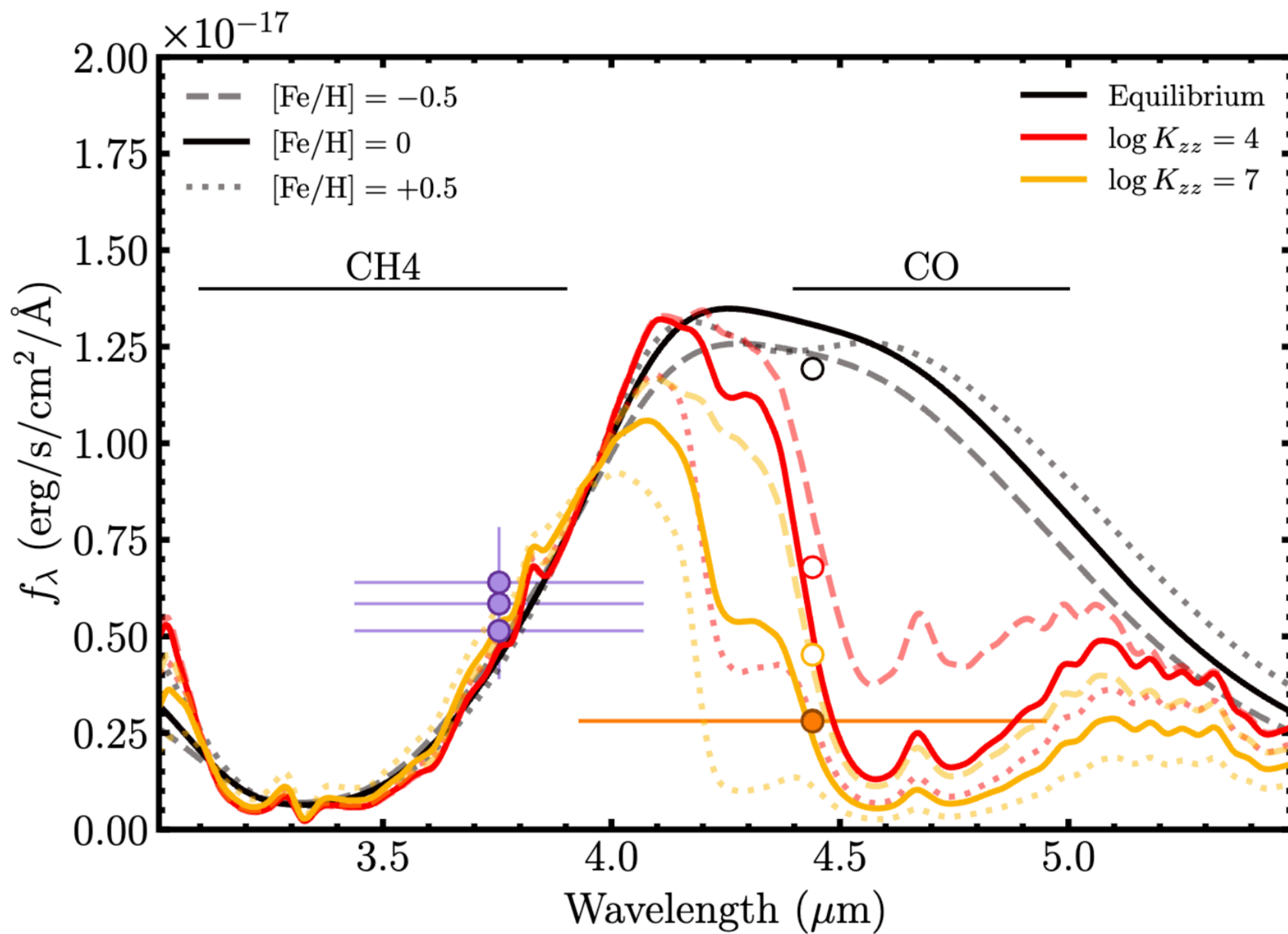


AF Lep b Bridges Imaged and RV Planets

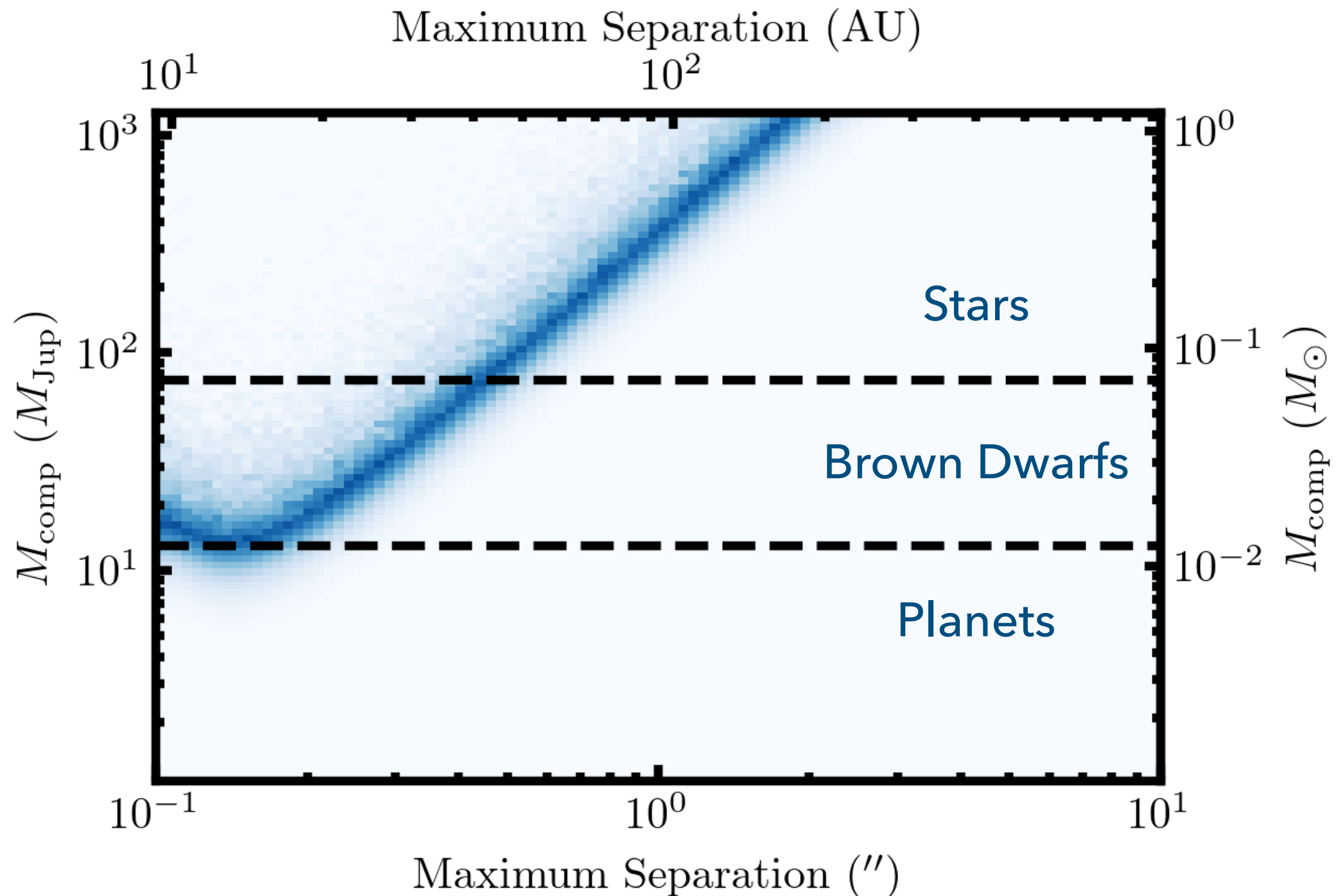


Three Regimes of Predicted Mass





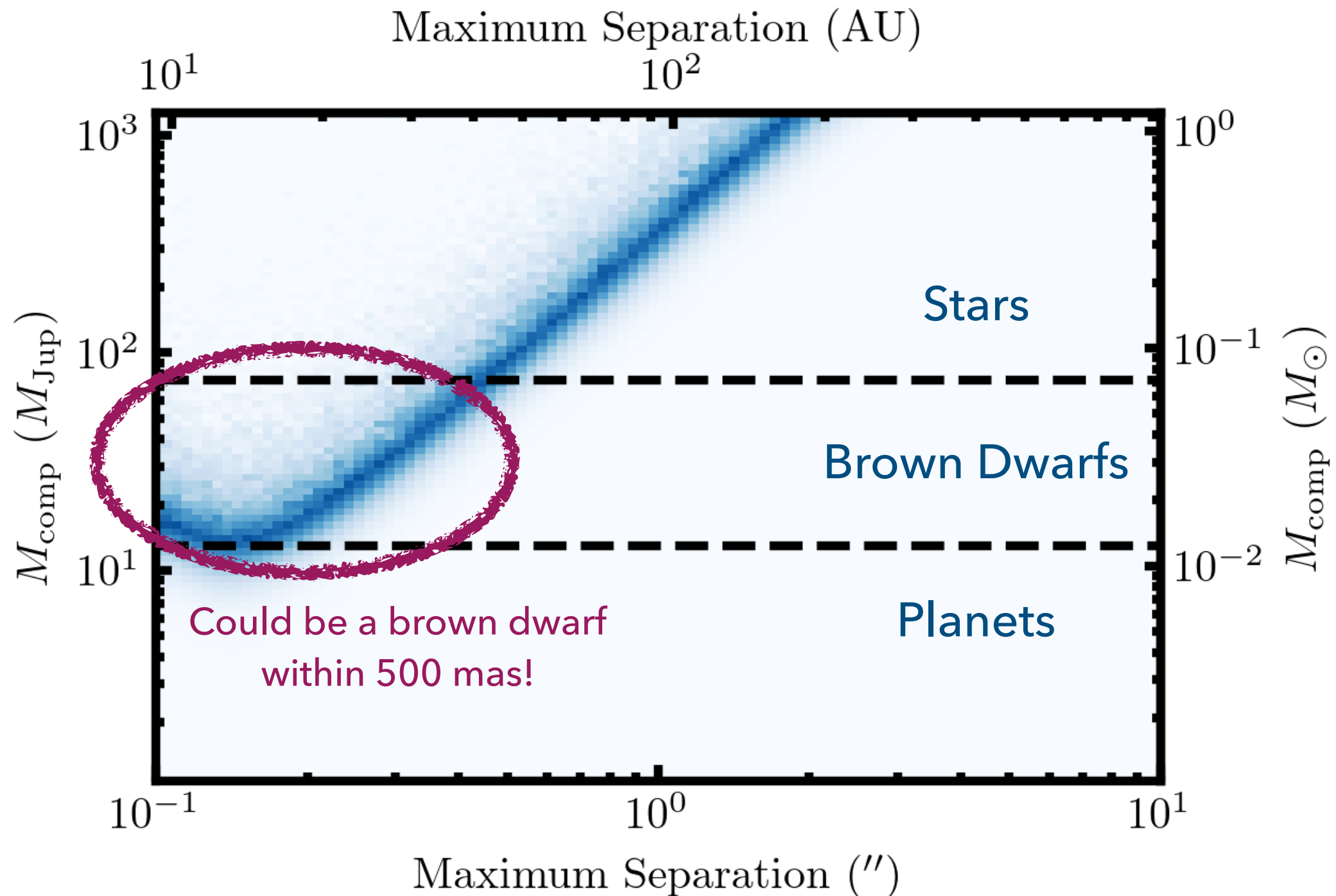
Predicted Mass From Astrometric Acceleration



See Franson et al. (2023a,b); Franson & Bowler (2023)

See also e.g., Brandt et al. (2019, 2021); De Rosa et al. (2019a,b); Fontanive et al. (2019); Mesa et al. (2022), Li et al. (2023, 2024)

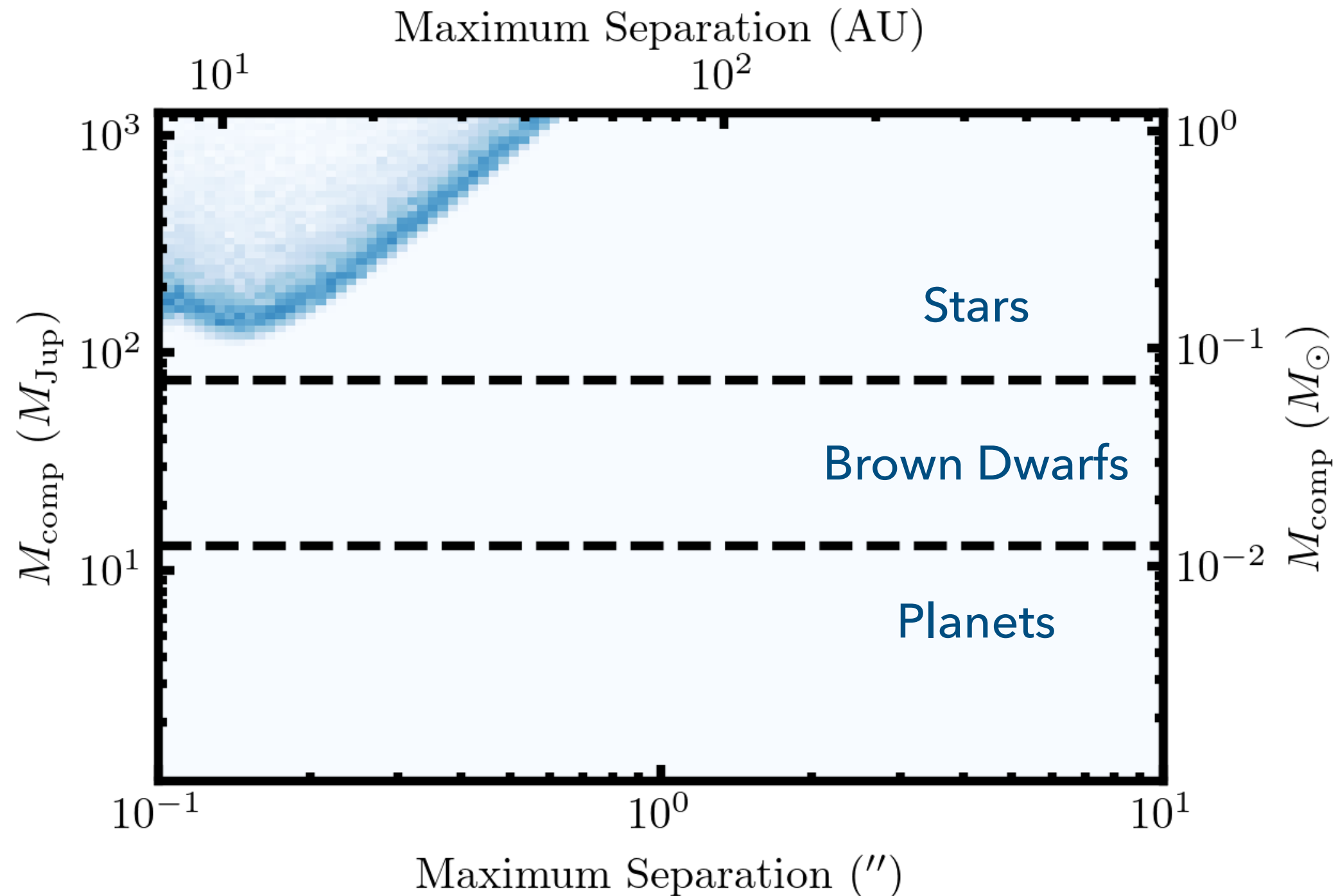
Predicted Mass From Astrometric Acceleration



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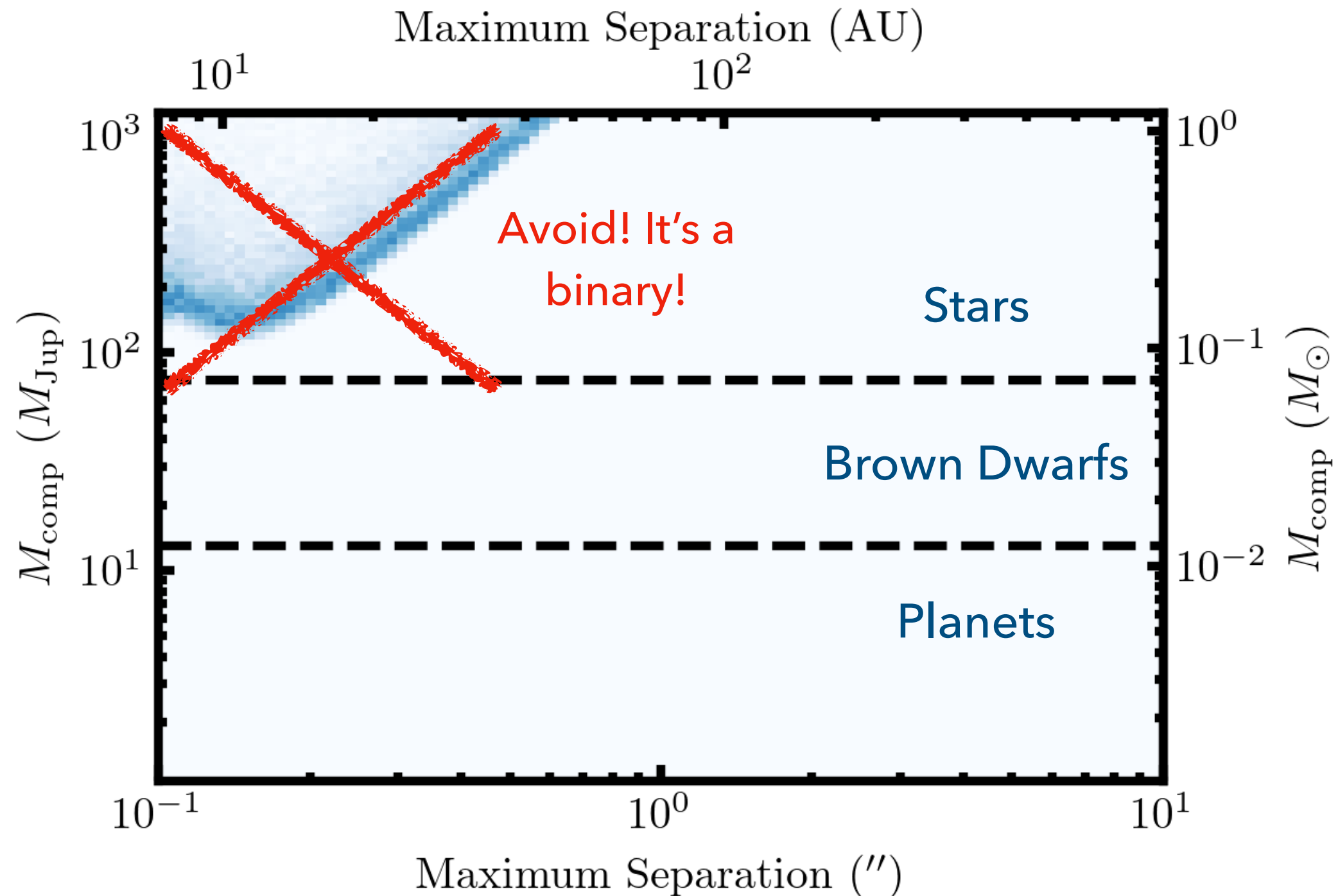
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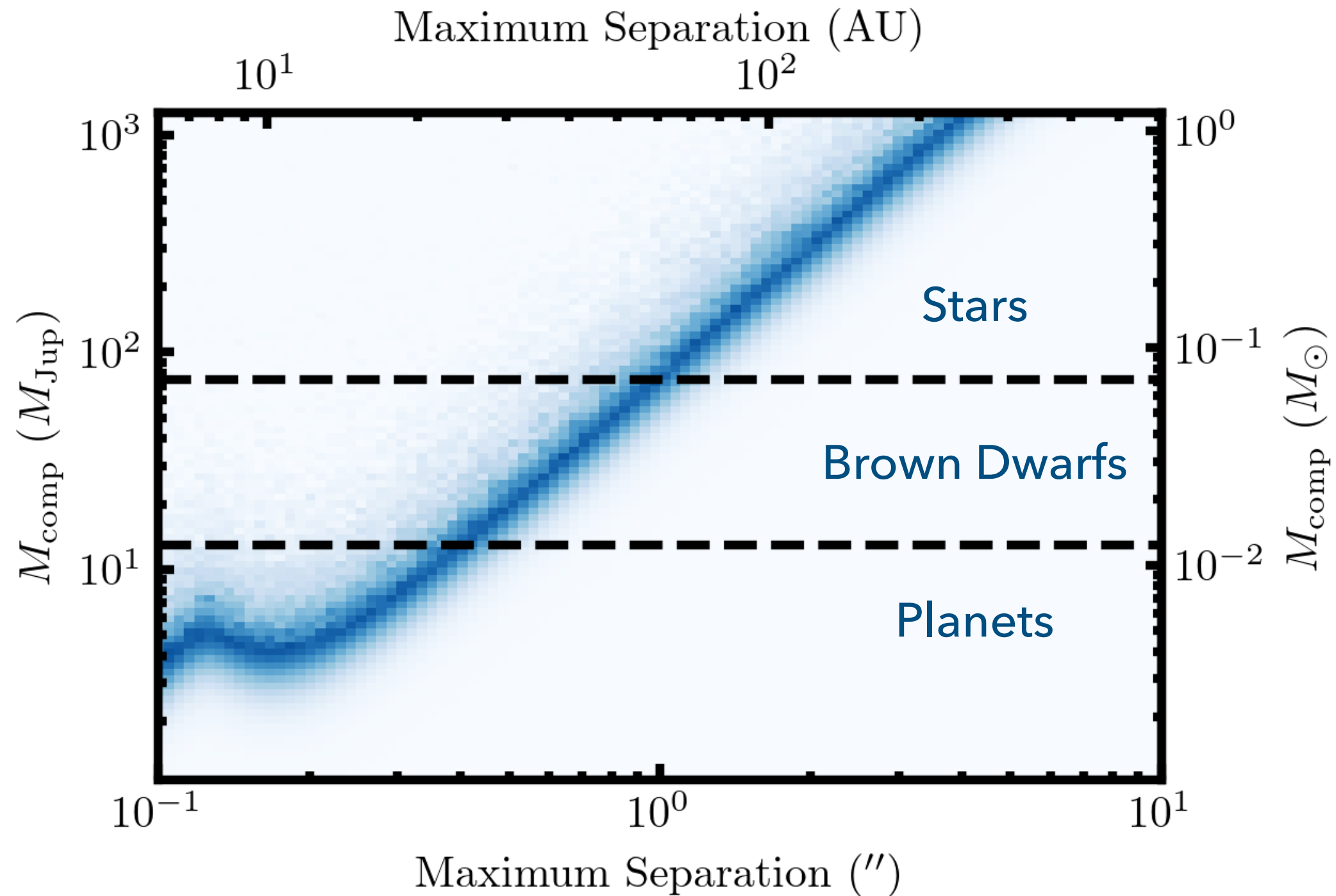
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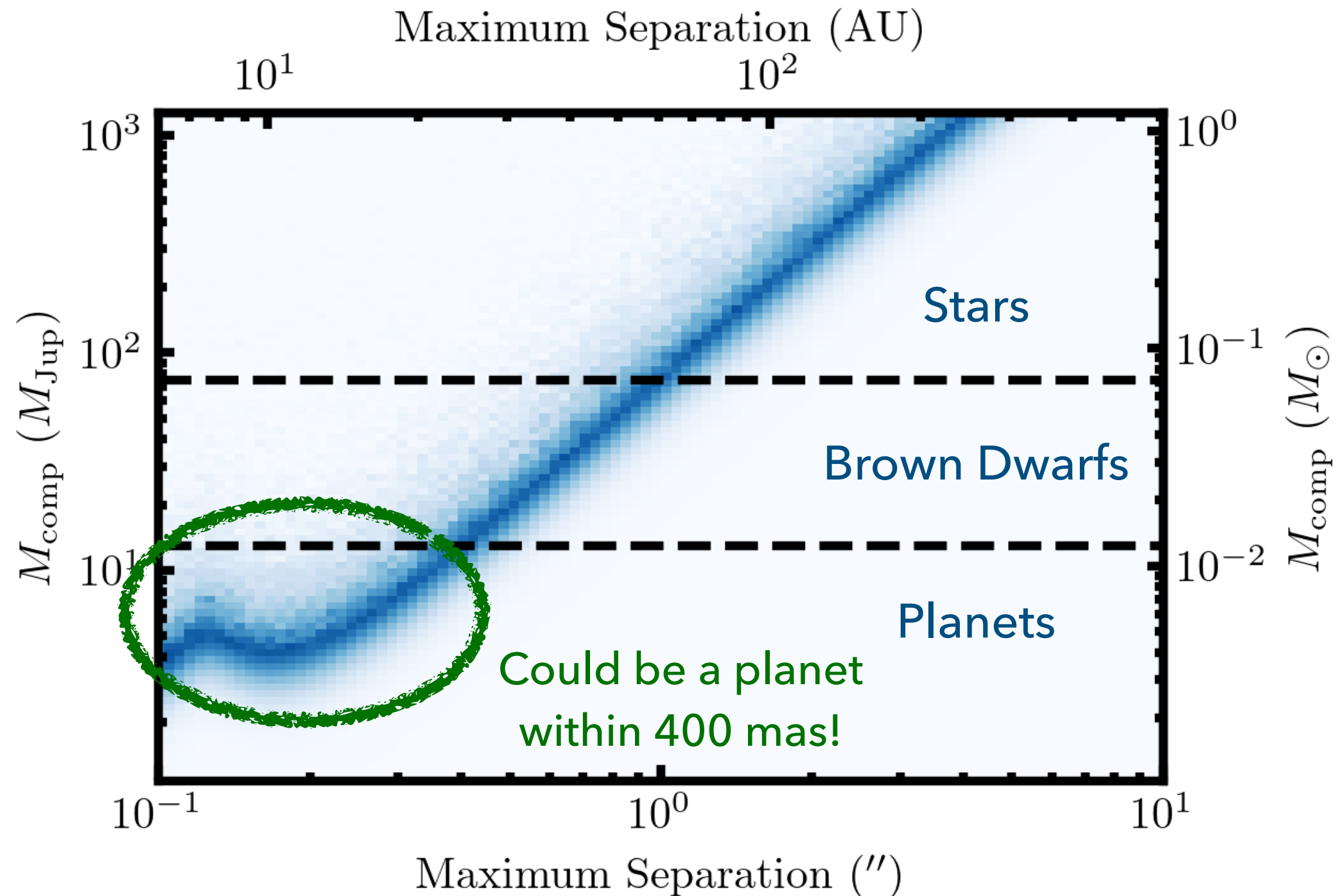
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