Ground-Based AO Surveys

Population-level results:

what we learned!

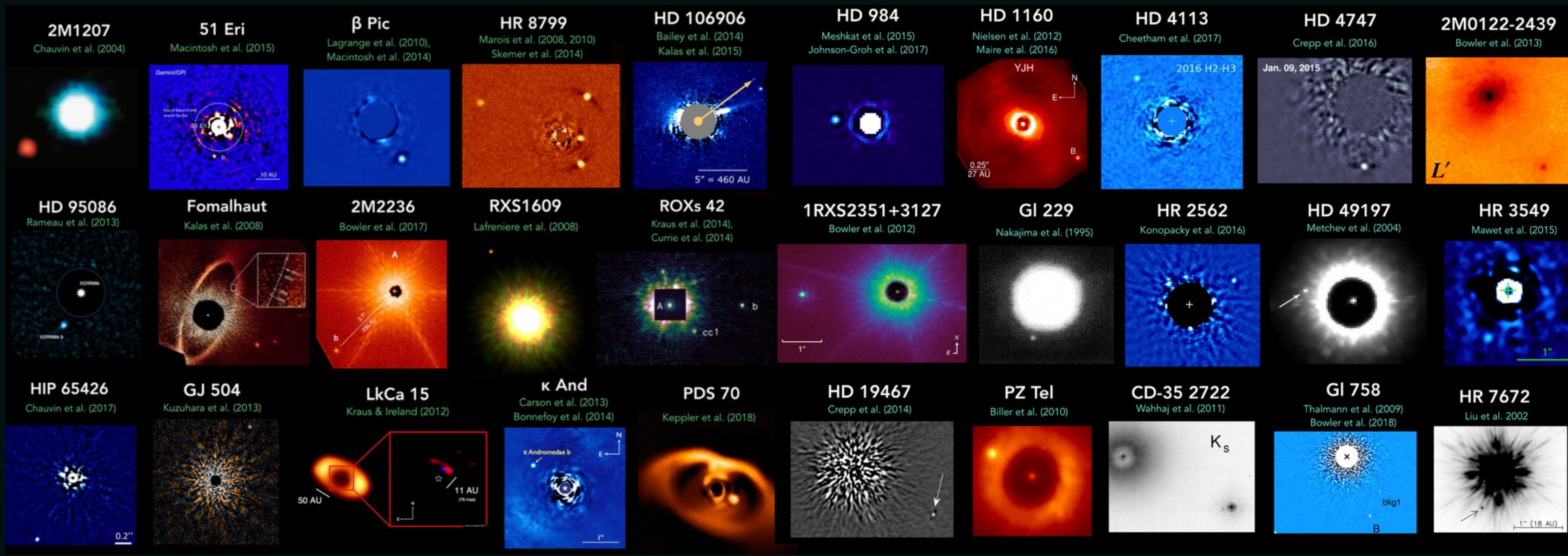
(and still don't know...)

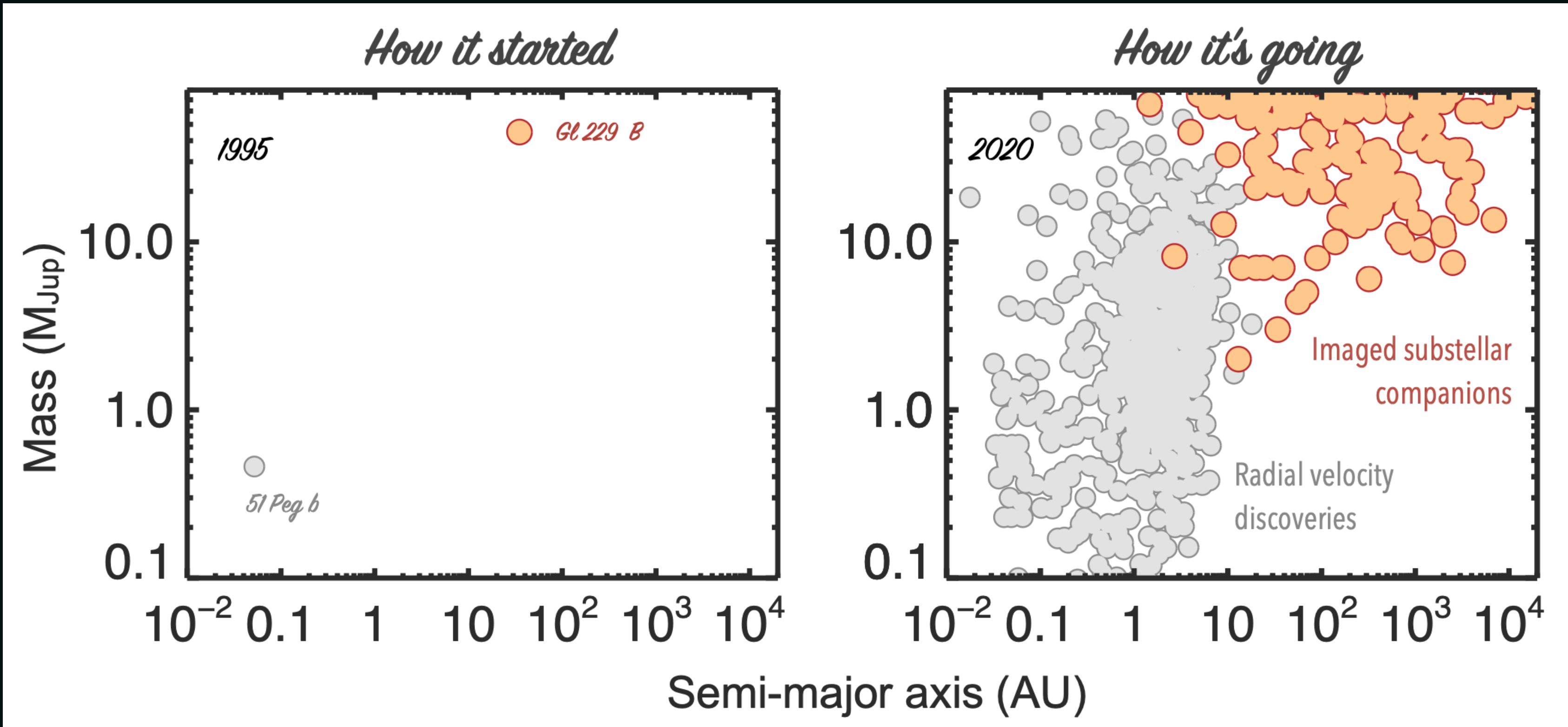
Clémence Fontanive
Trottier Fellow
iREx, Université de Montréal

Sagan Summer Workshop

July 24, 2024

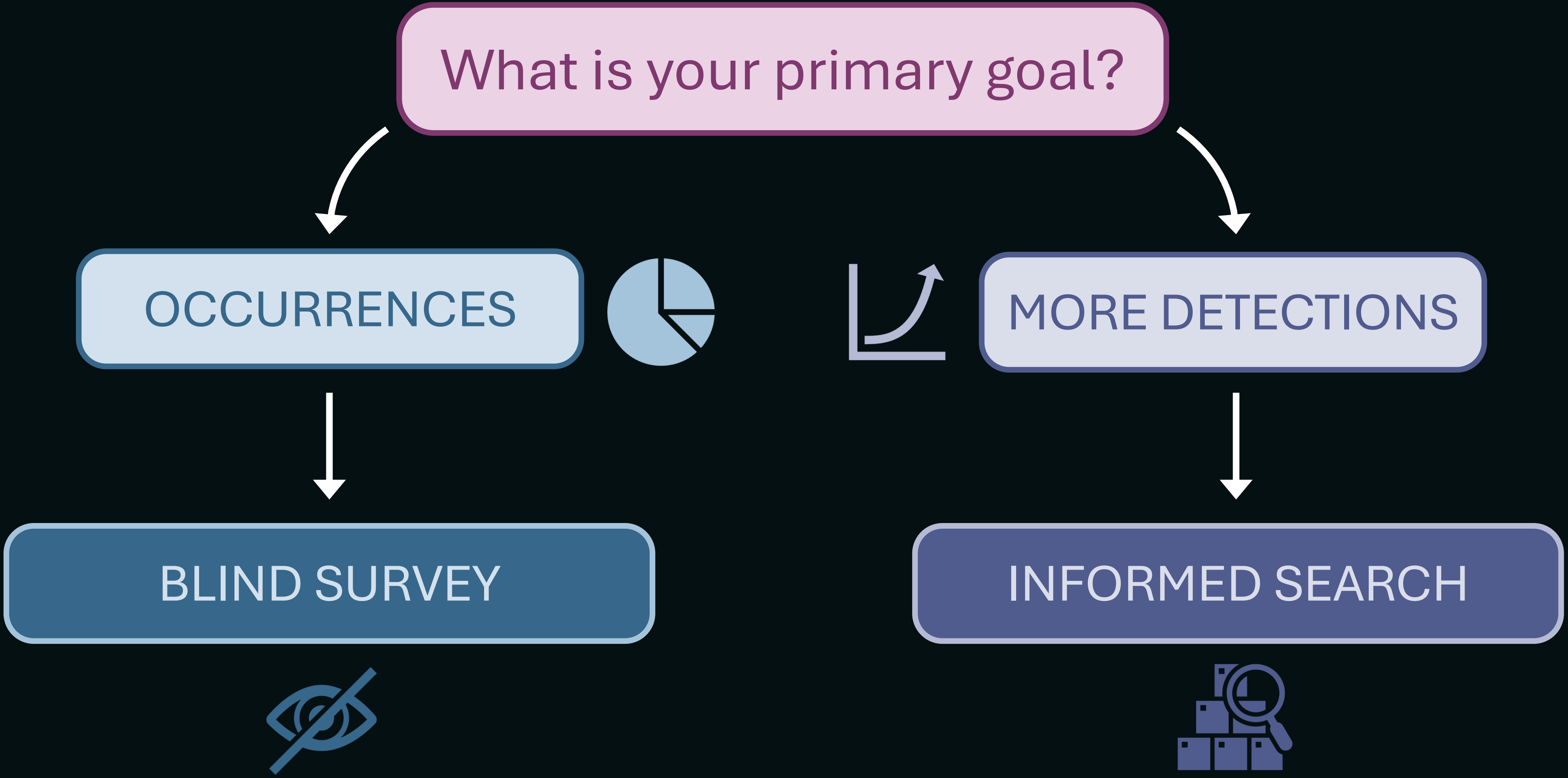
A ZOO OF YOUNG SUPER-JUPITERS & BROWN DWARFS





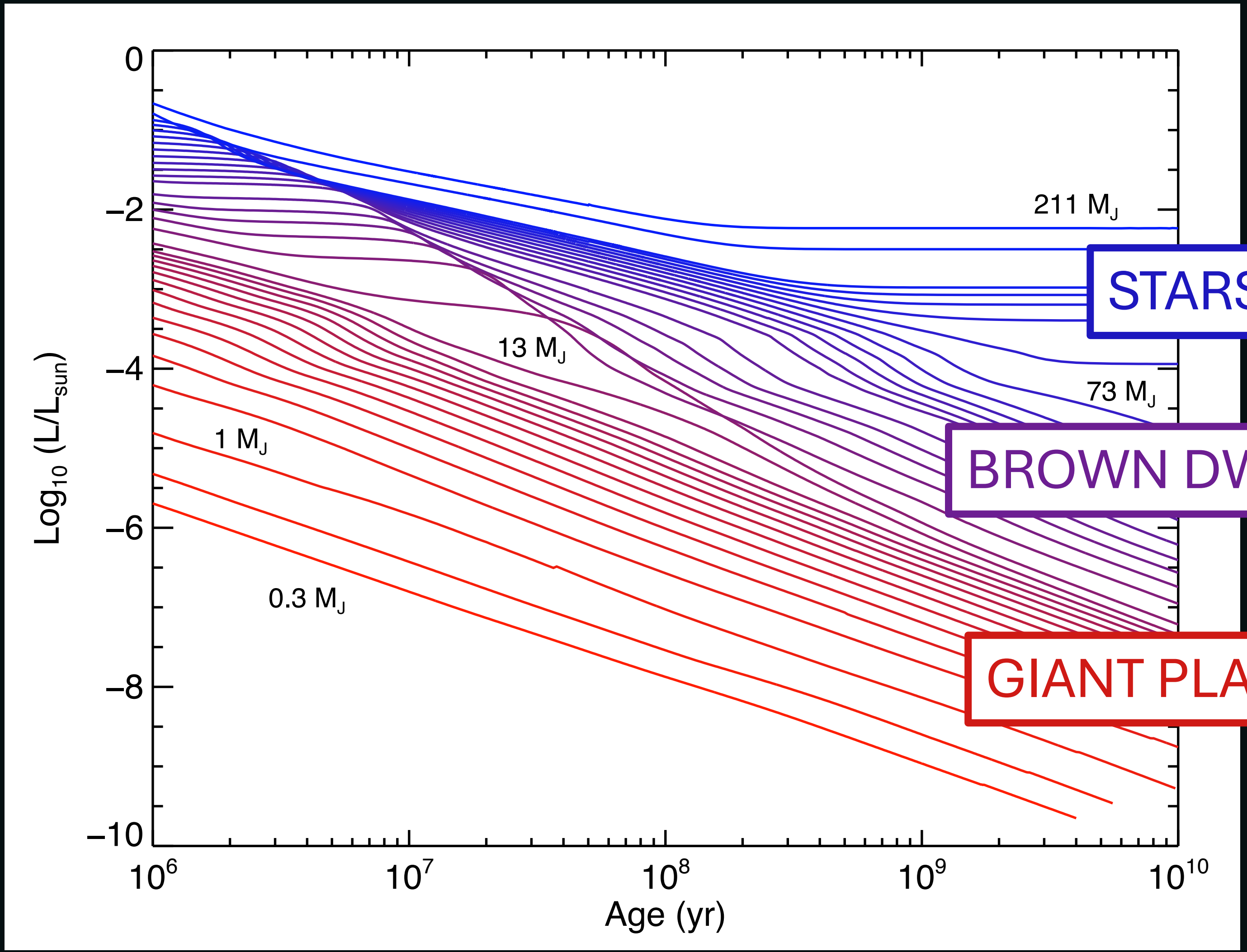
Credit: B. Bowler

DESIGNING A DIRECT IMAGING PROGRAM



DESIGNING A DIRECT IMAGING PROGRAM

DILEMMA#1: the luminosity-mass-age degeneracy

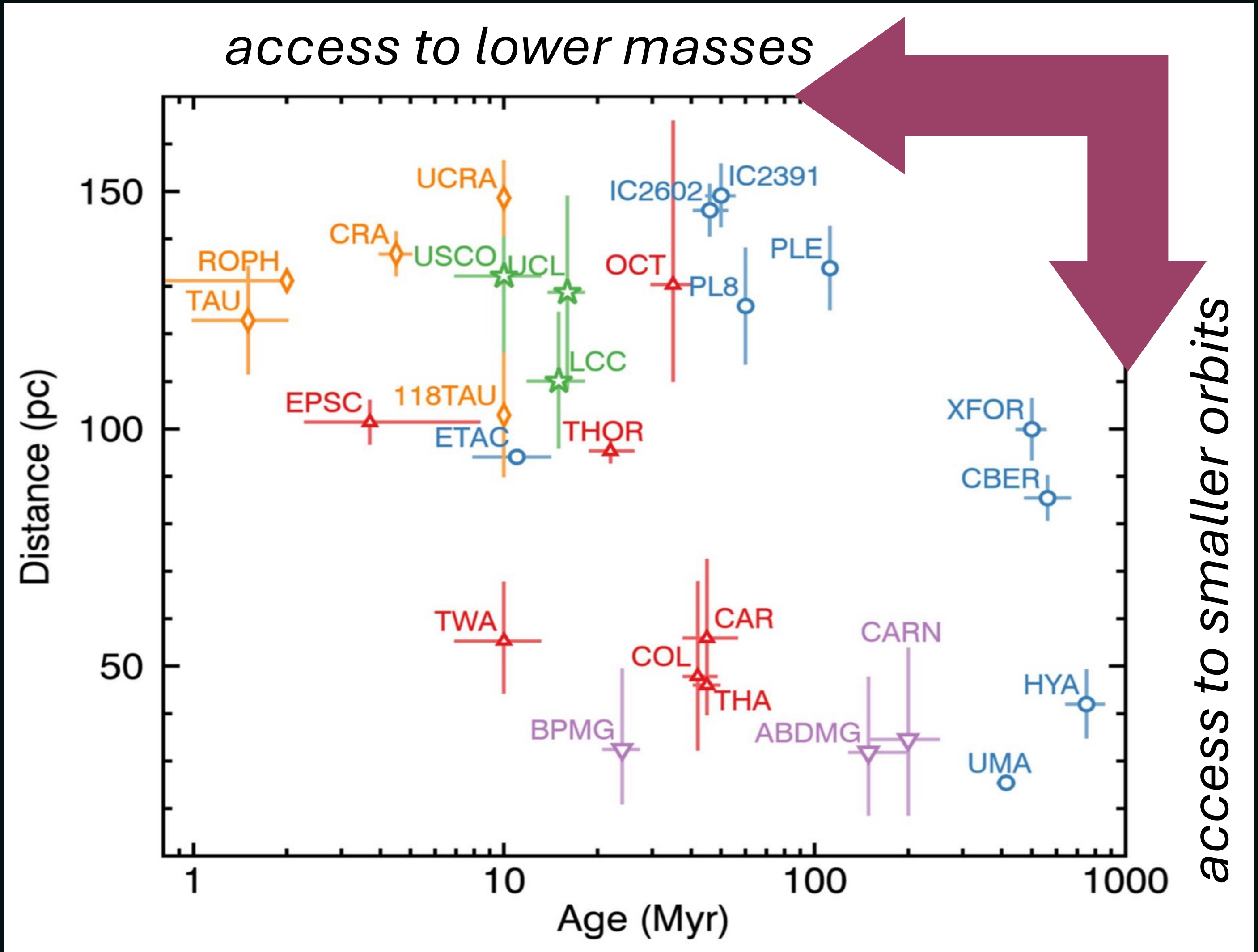


A brightness vs. age compromise

Models from Burrow+1997
Credit: M. Cushing

DESIGNING A DIRECT IMAGING PROGRAM

DILEMMA#2: the choice of stellar association



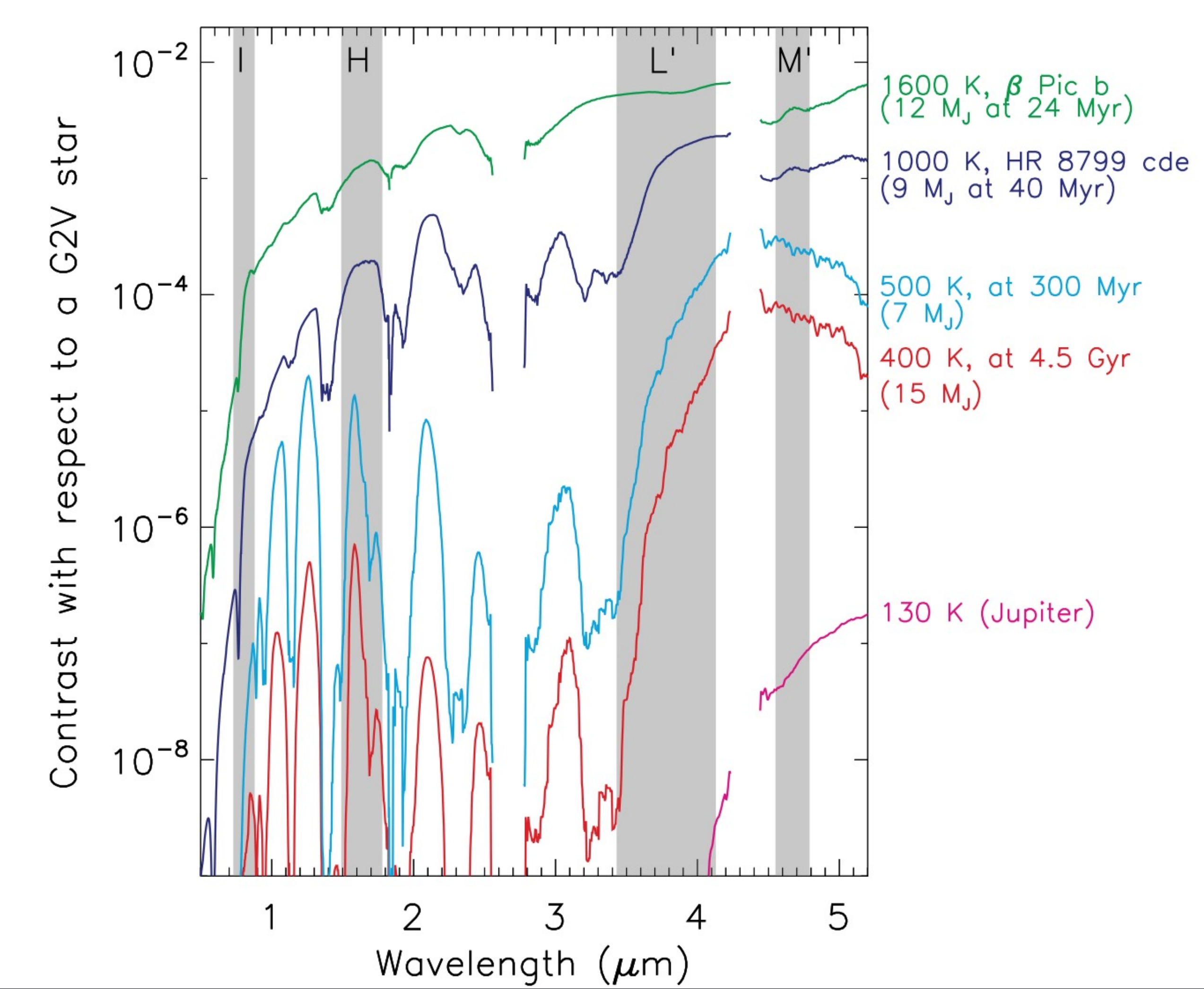
A brightness vs. age compromise

A distance vs. youth compromise

Gagné et al. 2018

DESIGNING A DIRECT IMAGING PROGRAM

DILEMMA#3: the choice of wavelength



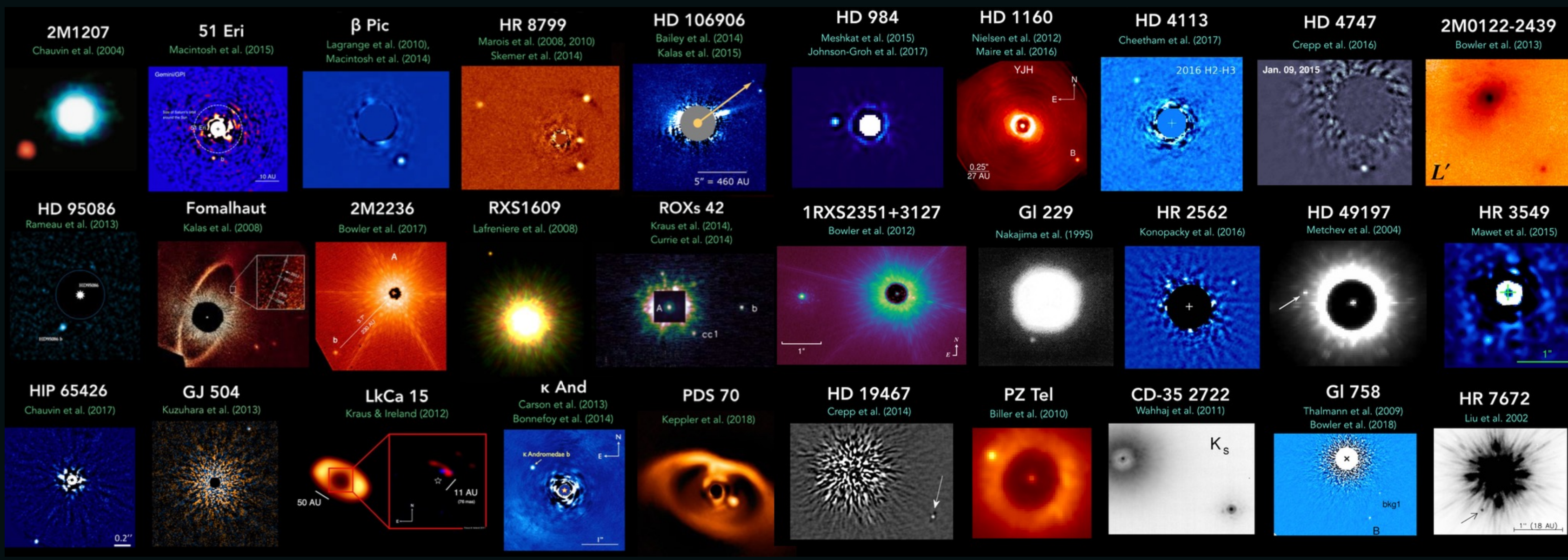
A brightness vs. age compromise

A distance vs. youth compromise

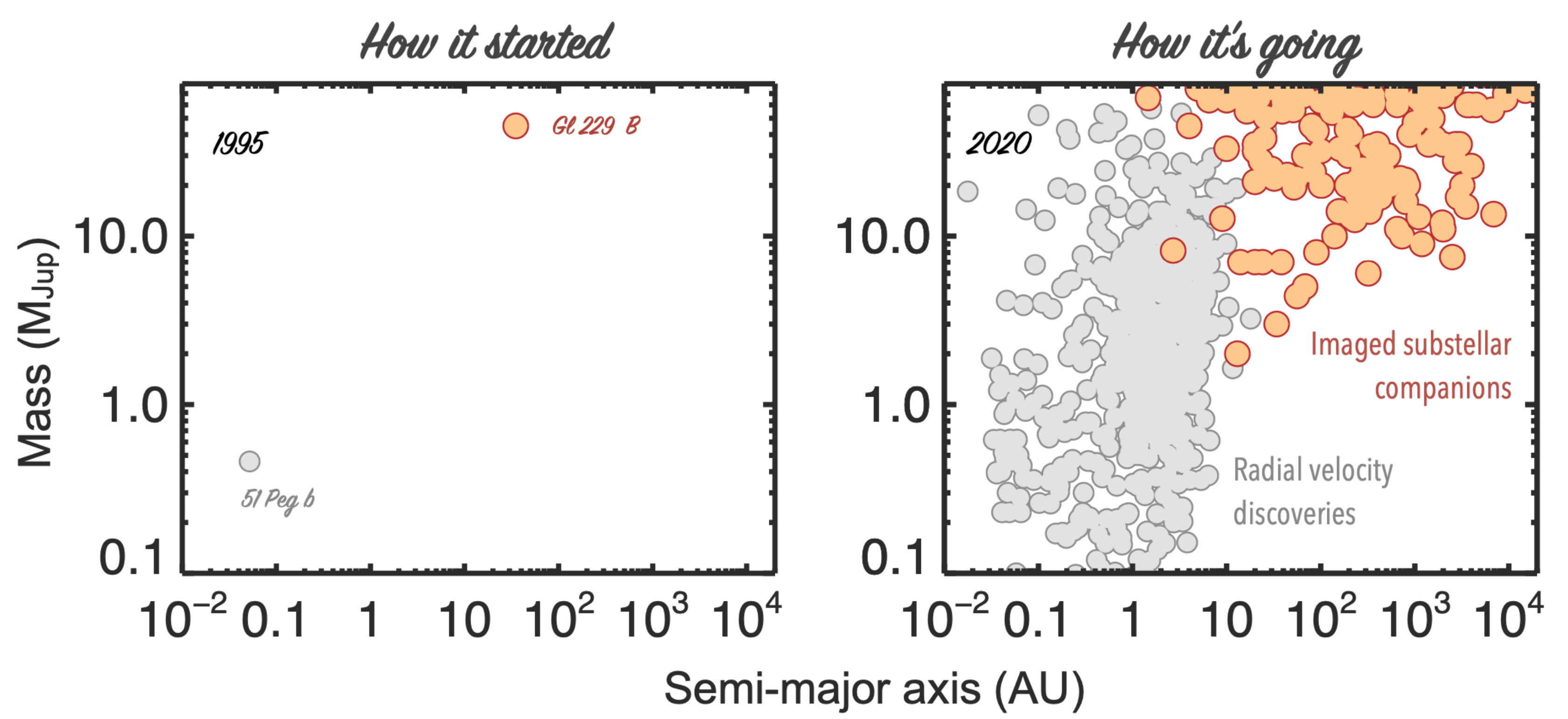
A resolution vs. contrast compromise

Currie, Biller et al. 2023, PVII

A ZOO OF YOUNG SUPER-JUPITERS & BROWN DWARFS

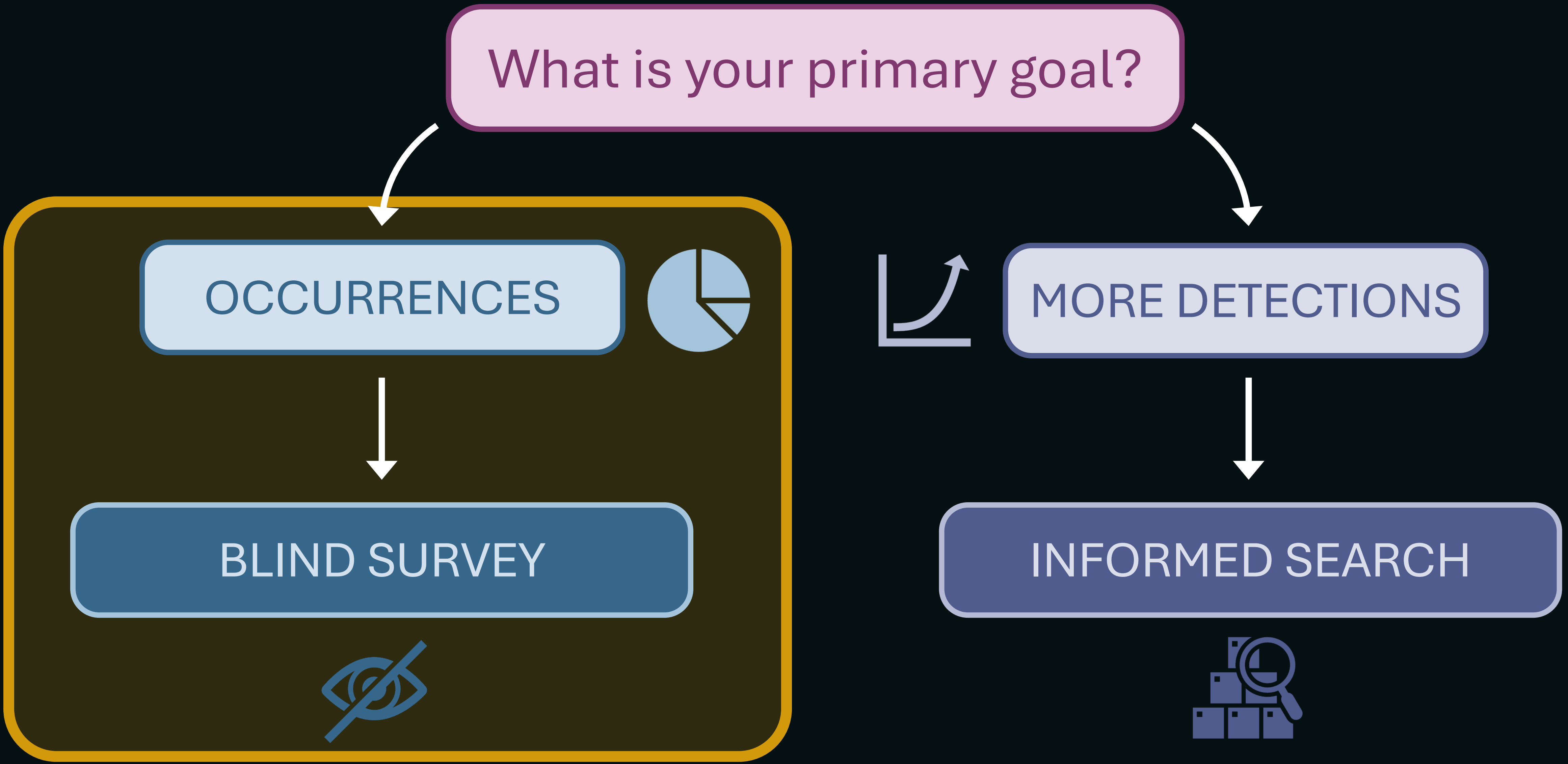


- ✦ mostly *blind* surveys
- ✦ 8m-telescopes @NIR
- ✦ ages < 100 Myr
- ✦ masses > 3 M_{Jup}
- ✦ temperatures > 800 K
- ✦ orbits ~10–100s au

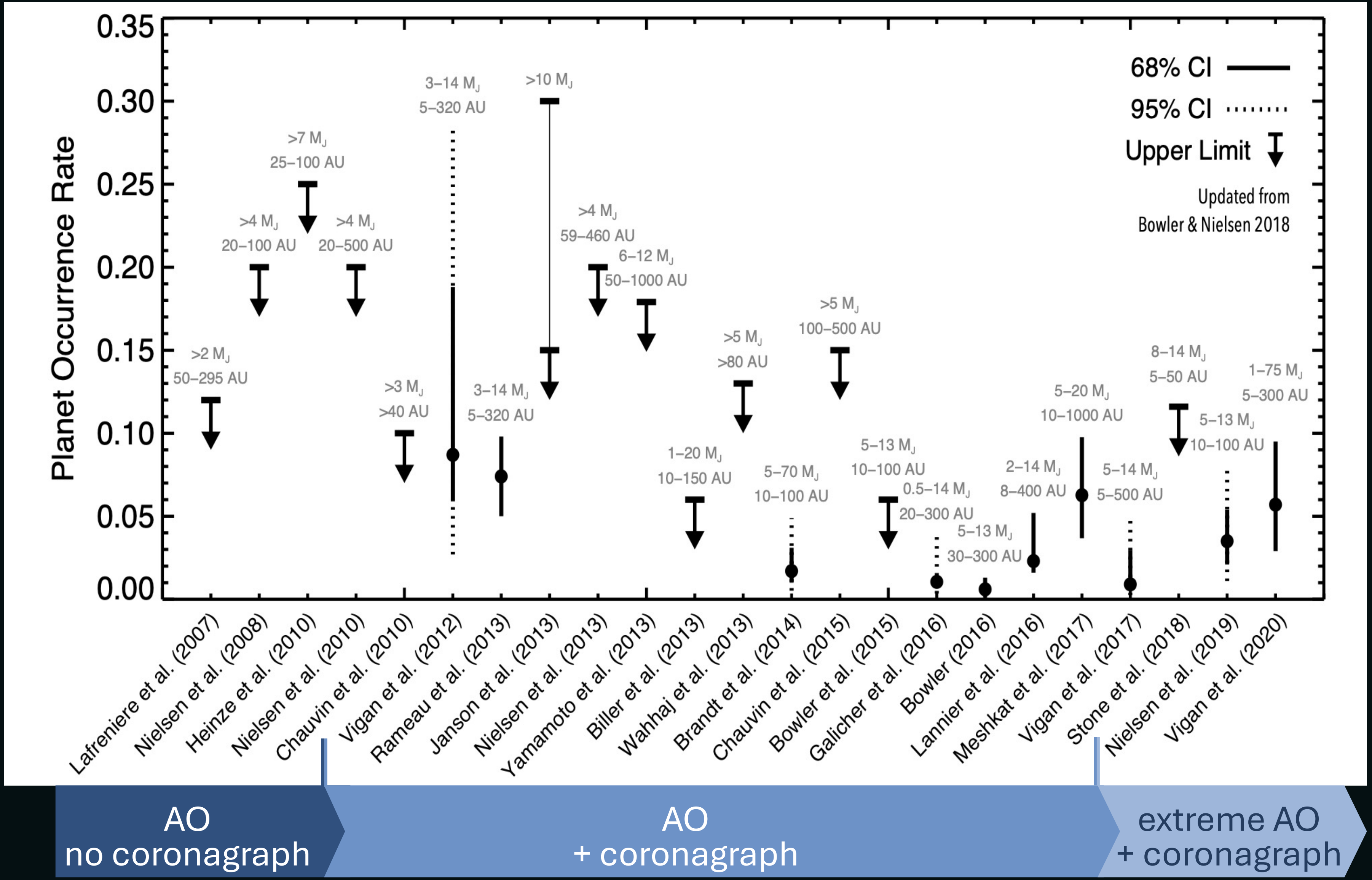


Credit: B. Bowler

1. DECADES OF DEMOGRAPHIC IMAGING PROGRAMS



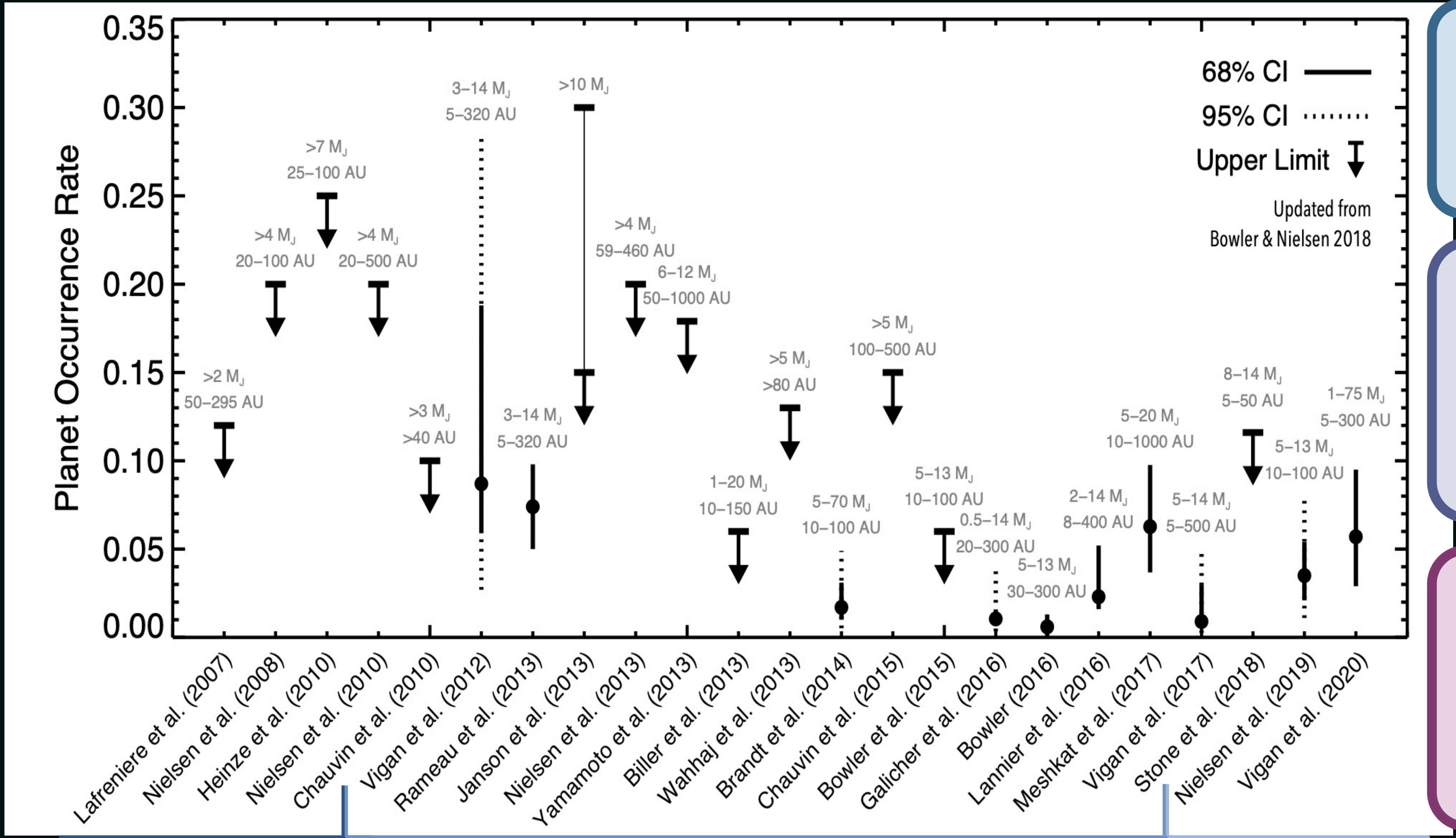
OCCURRENCE RATES FROM BLIND SURVEYS



Credit: B. Bowler

See also
ISPY – *Launhardt et al. 2020*
YSES – *Bohn et al. 2020, 2021*

OCCURRENCE RATES FROM BLIND SURVEYS



NOTE#1:
different mass and separation ranges

NOTE#2:
number of *planet*/star vs. number of *planetary system*/star

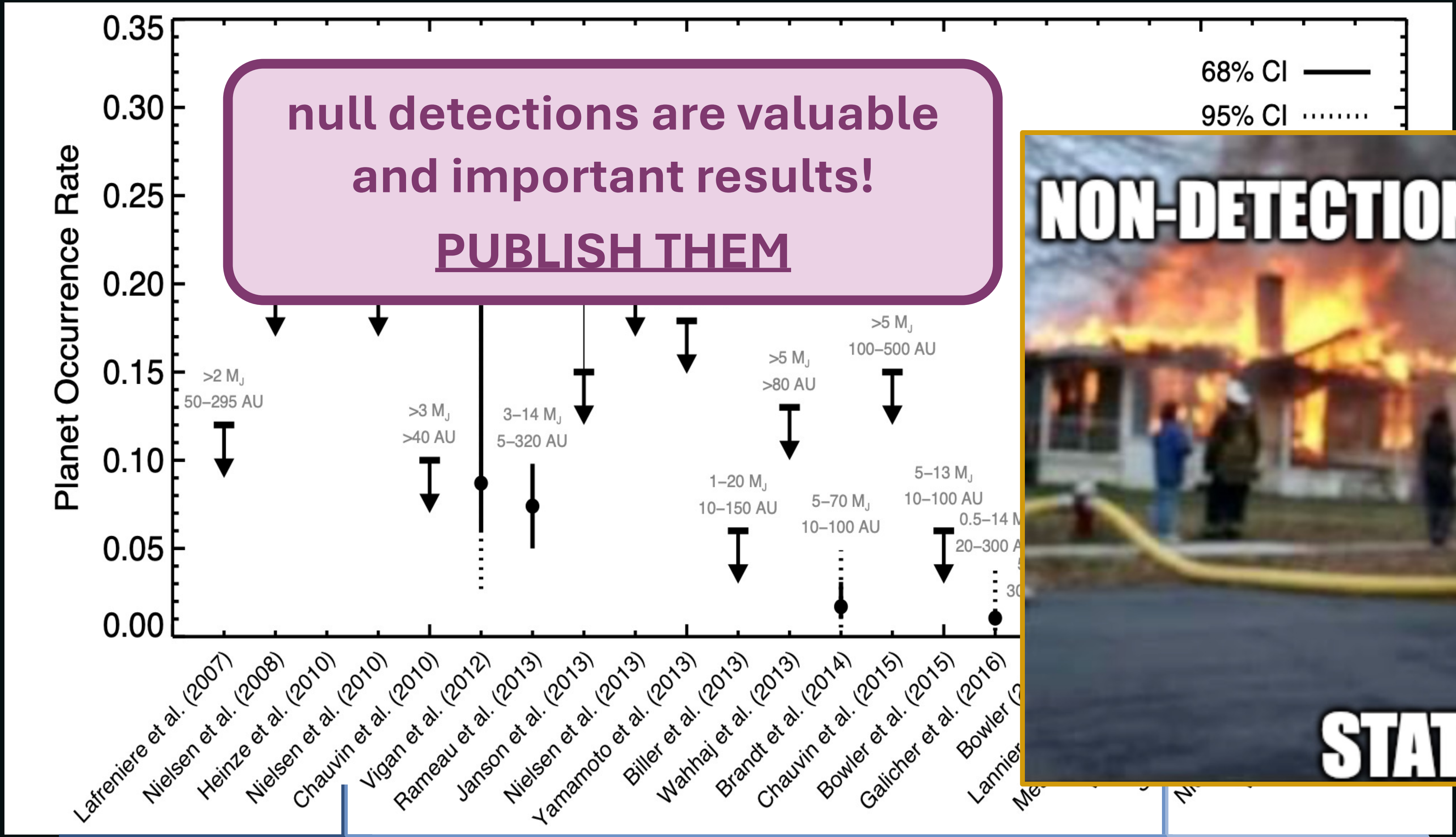
NOTE#3:
as many ways to do statistics as there are surveys

AO
no coronagraph

→ **WIDE-ORBIT GIANT PLANETS ARE RARE…**

Credit: B. Bowler

OCCURRENCE RATES FROM BLIND SURVEYS



null detections are valuable and important results!
PUBLISH THEM

AO
no coronagraph

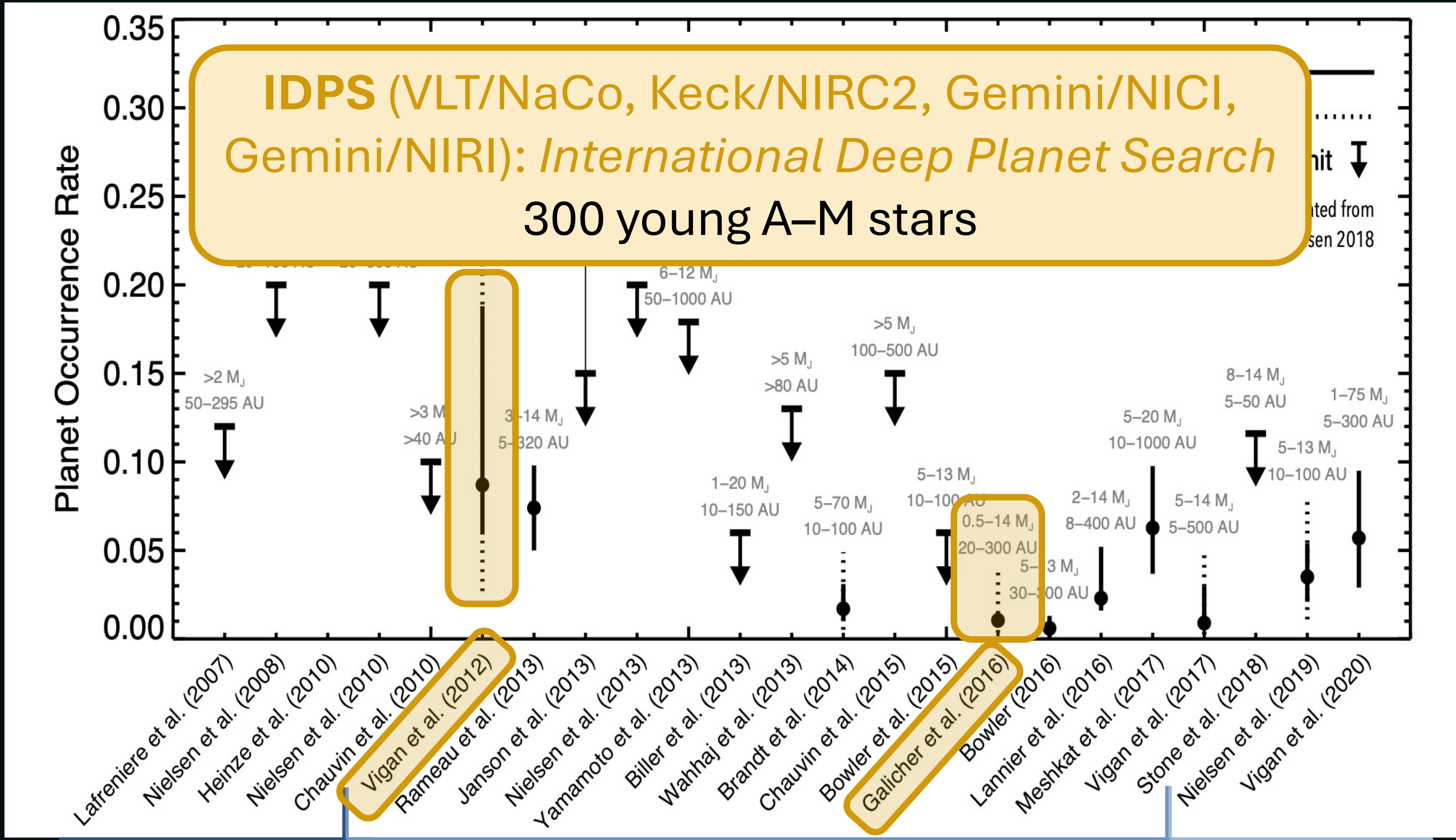
AO
+ coronagraph

extreme AO
+ coronagraph

Credit: B. Bowler

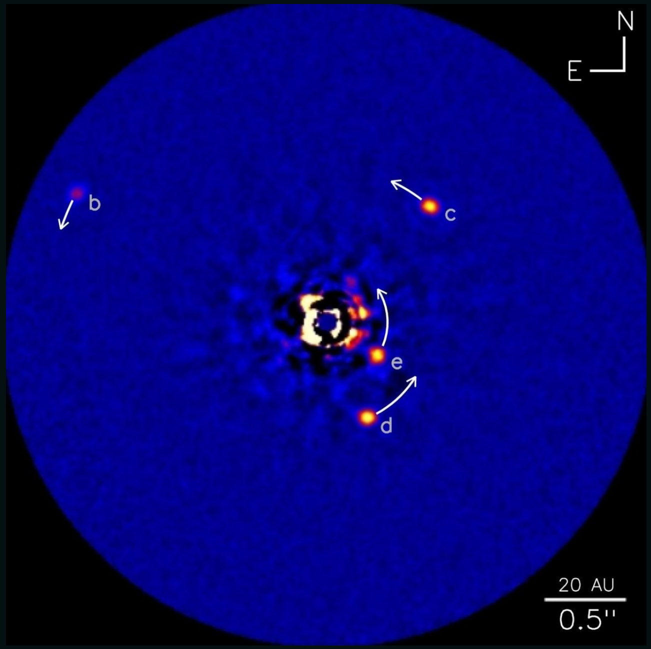
OCCURRENCE RATES FROM BLIND SURVEYS

IDPS (VLT/NaCo, Keck/NIRC2, Gemini/NICI, Gemini/NIRI): *International Deep Planet Search*
300 young A–M stars



AO no coronagraph | AO + coronagraph | extreme AO + coronagraph

HR 8799 bcde

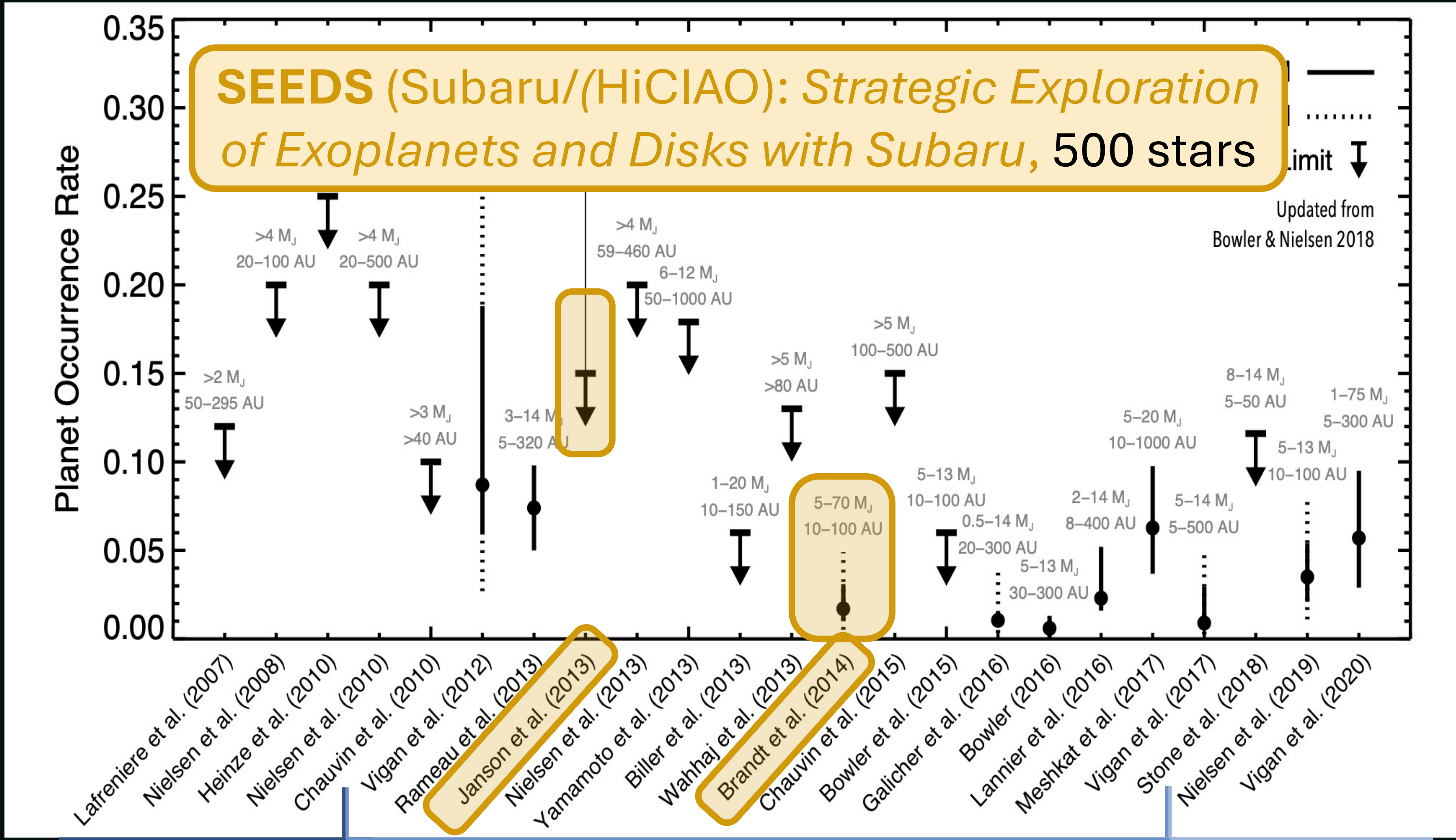


Marois et al. 2008, 2010

Credit: B. Bowler

OCCURRENCE RATES FROM BLIND SURVEYS

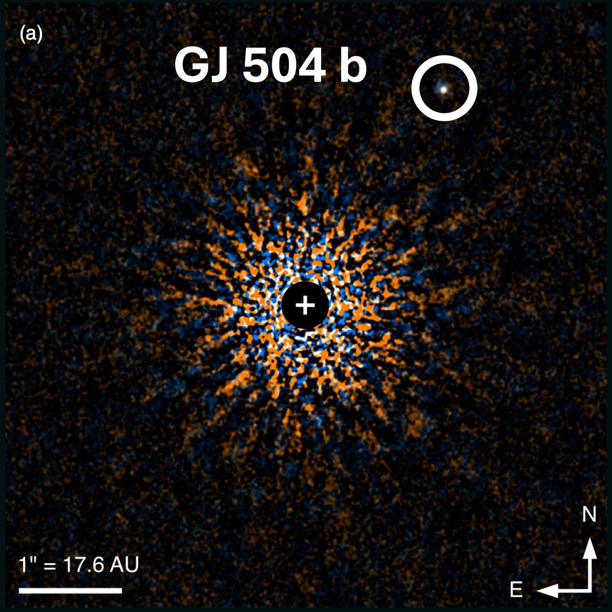
SEEDS (Subaru/(HiCIAO): *Strategic Exploration of Exoplanets and Disks with Subaru*, 500 stars



AO
no coronagraph

AO
+ coronagraph

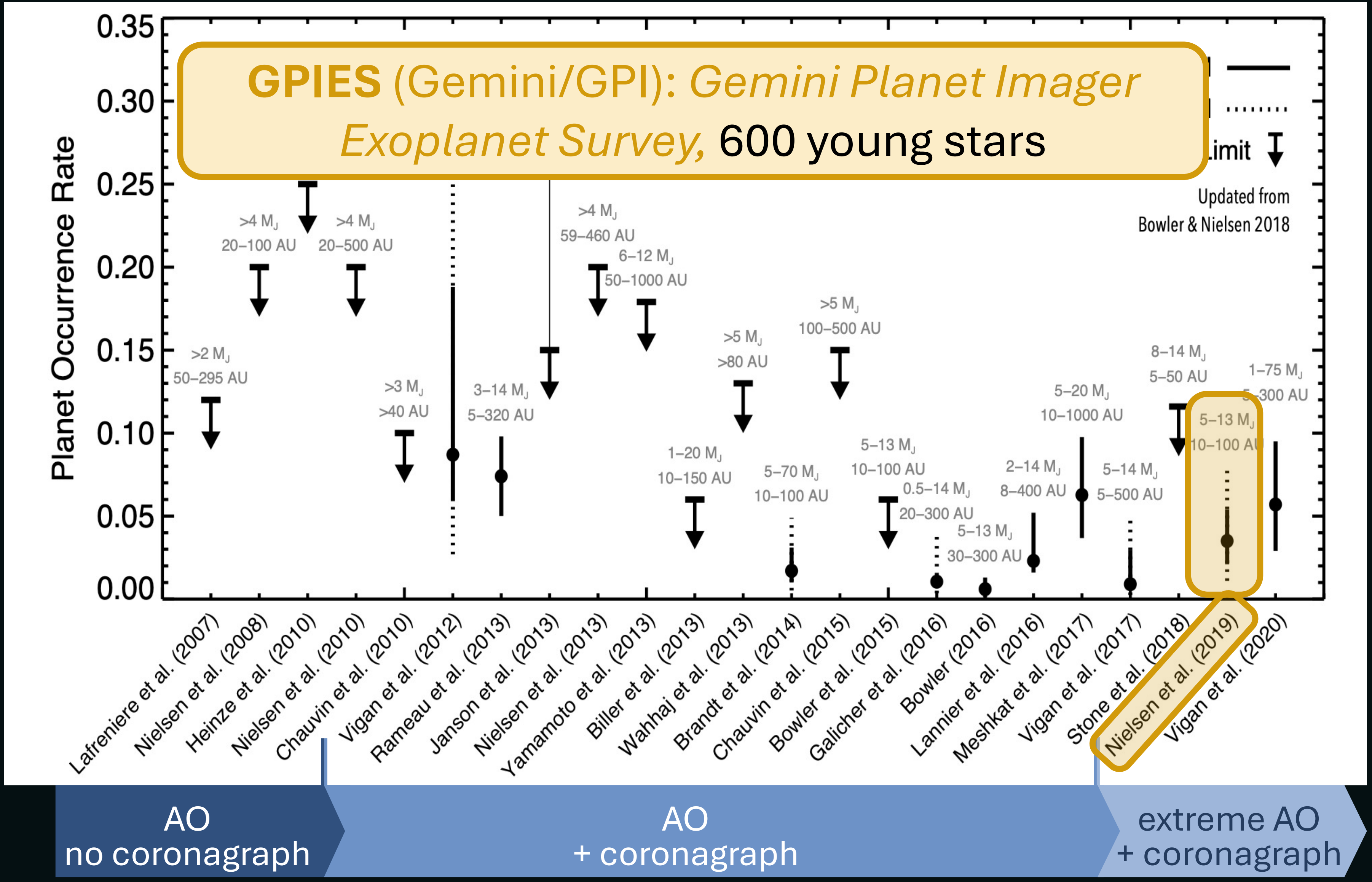
extreme AO
+ coronagraph

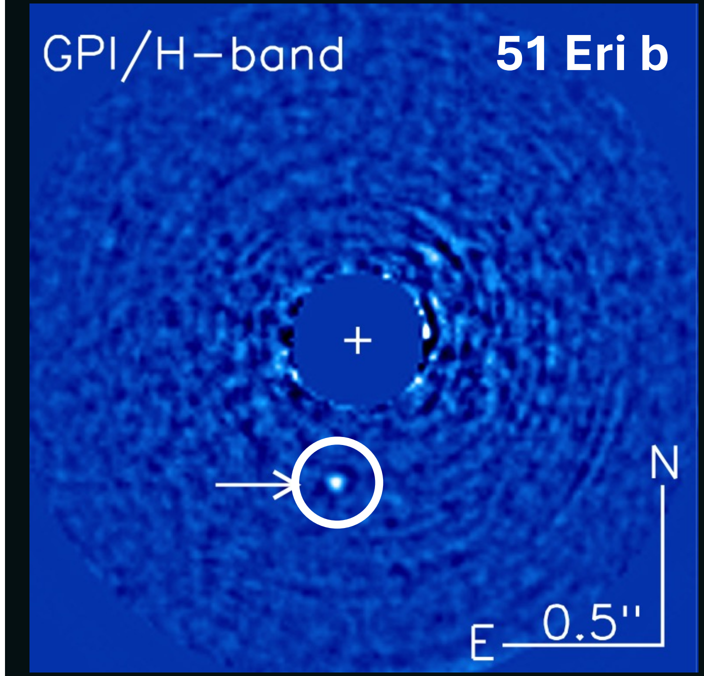


Kuzuhara et al. 2013

Credit: B. Bowler

OCCURRENCE RATES FROM BLIND SURVEYS

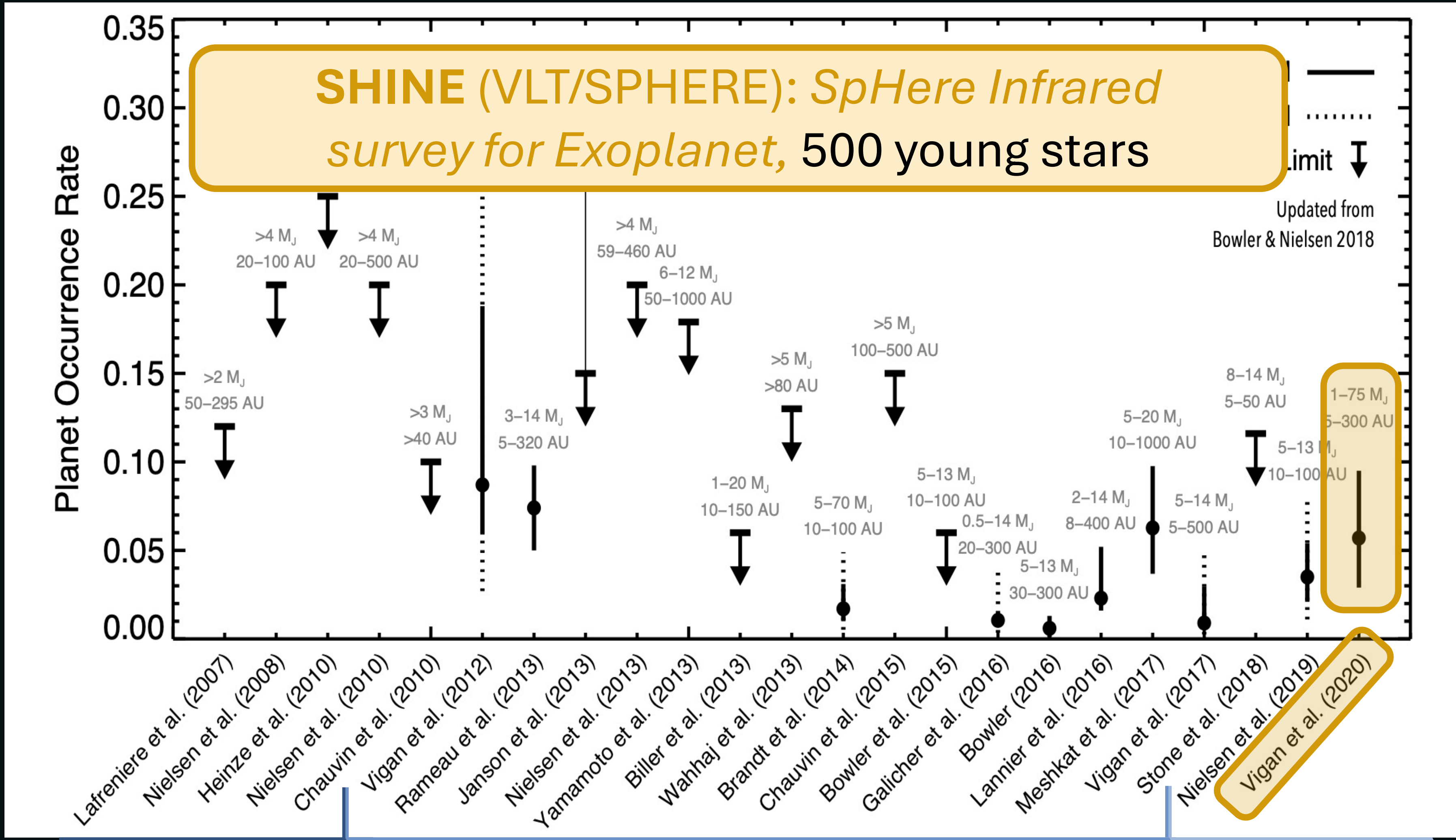




Macintosh et al. 2015

Credit: B. Bowler

OCCURRENCE RATES FROM BLIND SURVEYS

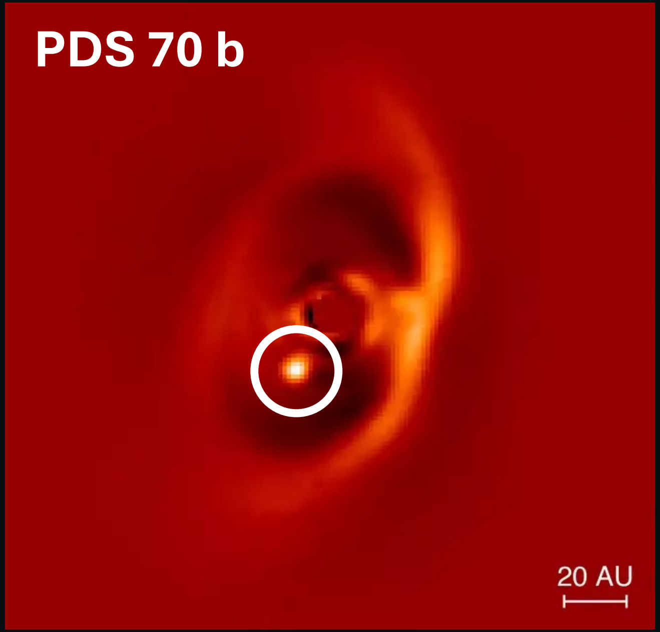


SHINE (VLT/SPHERE): *SpHere Infrared survey for Exoplanet,* 500 young stars

AO
no coronagraph

AO
+ coronagraph

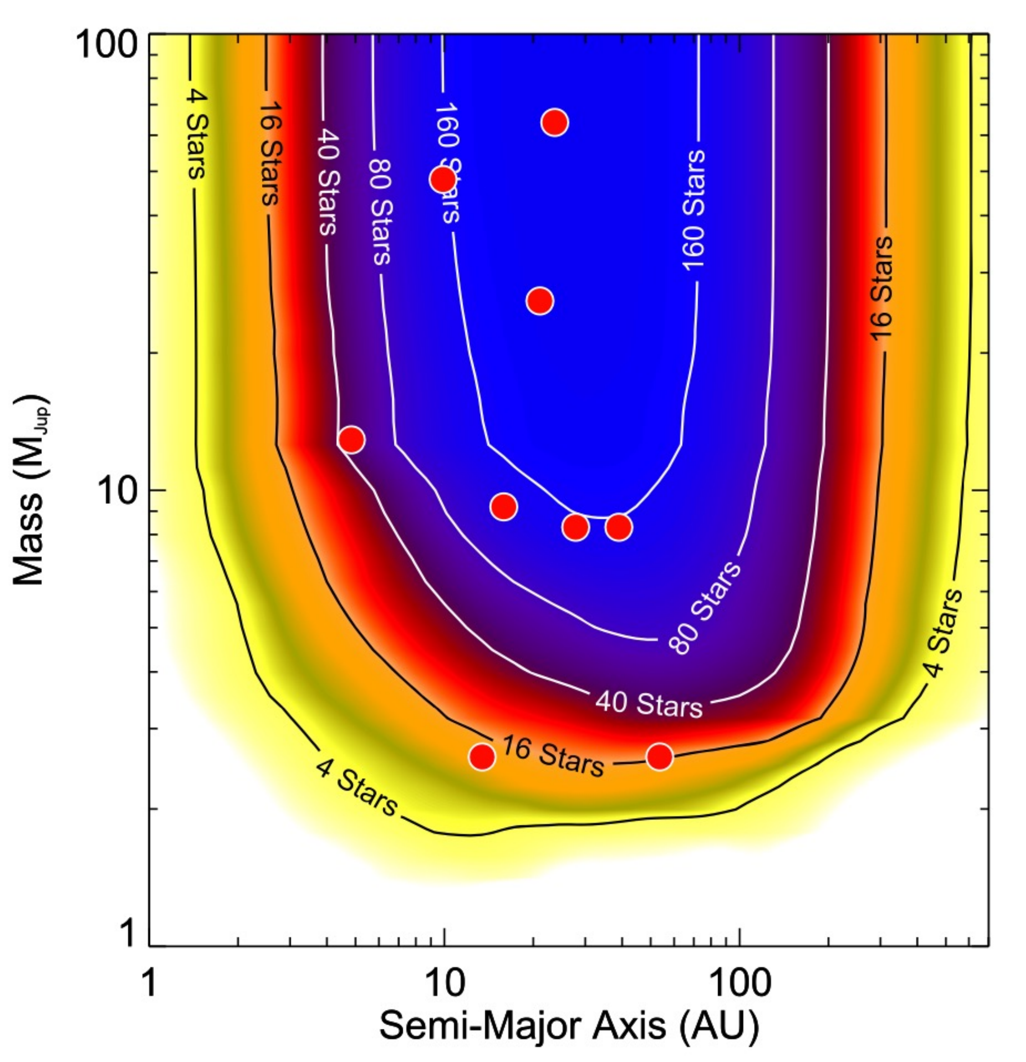
extreme AO
+ coronagraph



Keppler et al. 2018
Müller et al. 2018

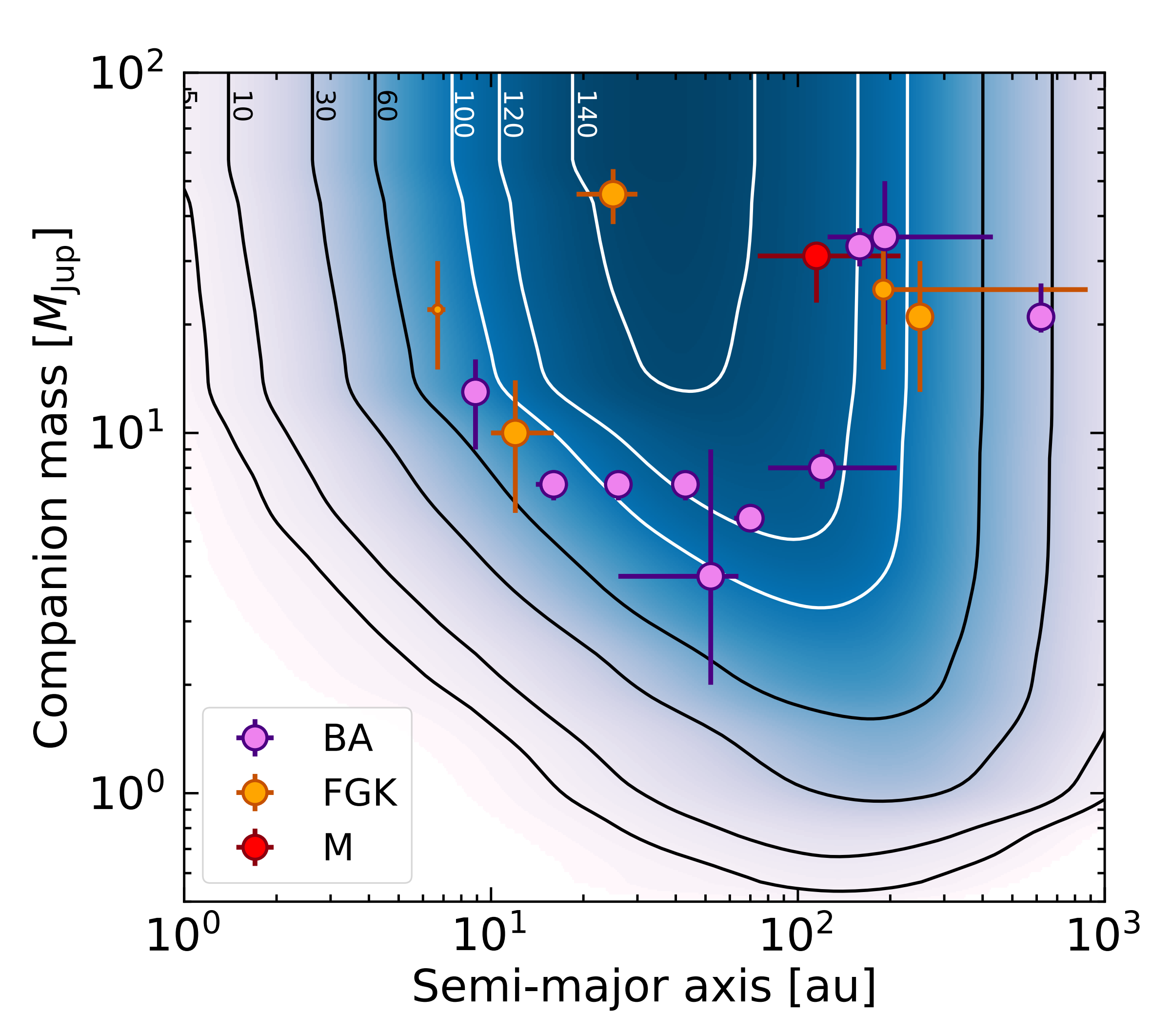
Credit: B. Bowler

SURVEY SENSITIVITIES



Gemini GPIES – 300 stars

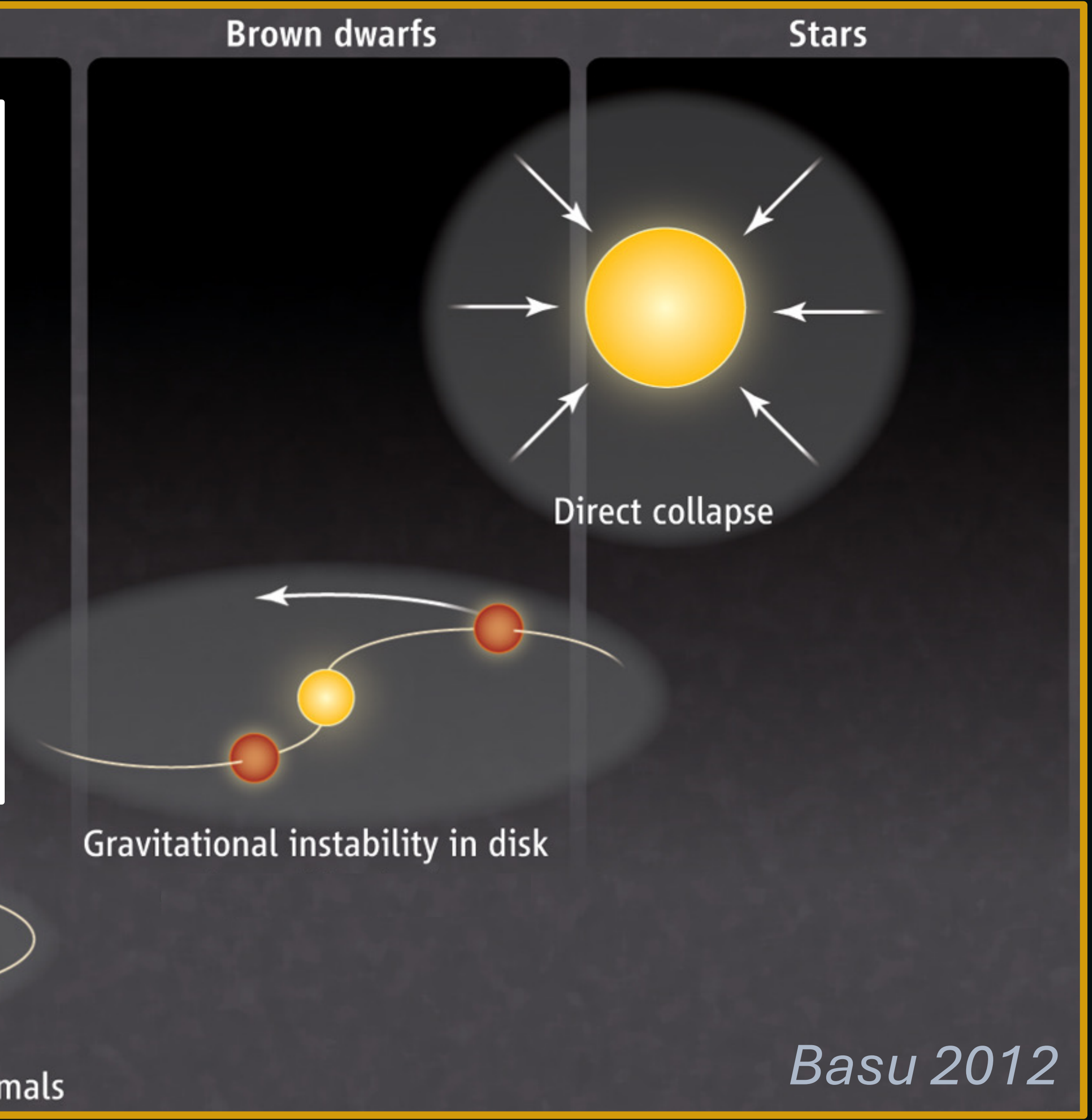
Nielsen et al. 2019

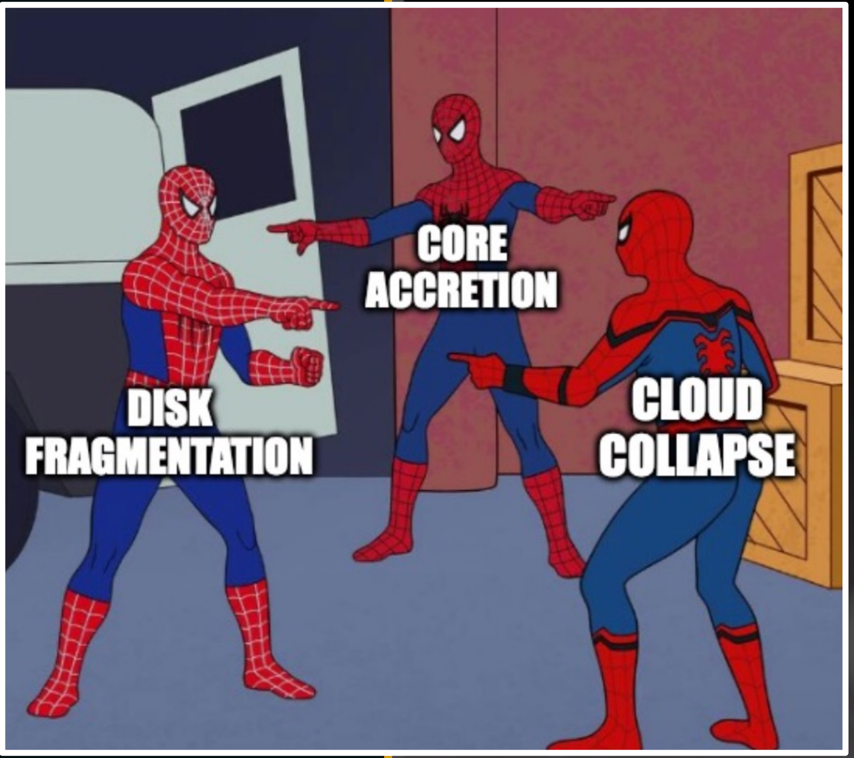


VLT SHINE – 150 stars

Vigan, Fontanive et al. 2021

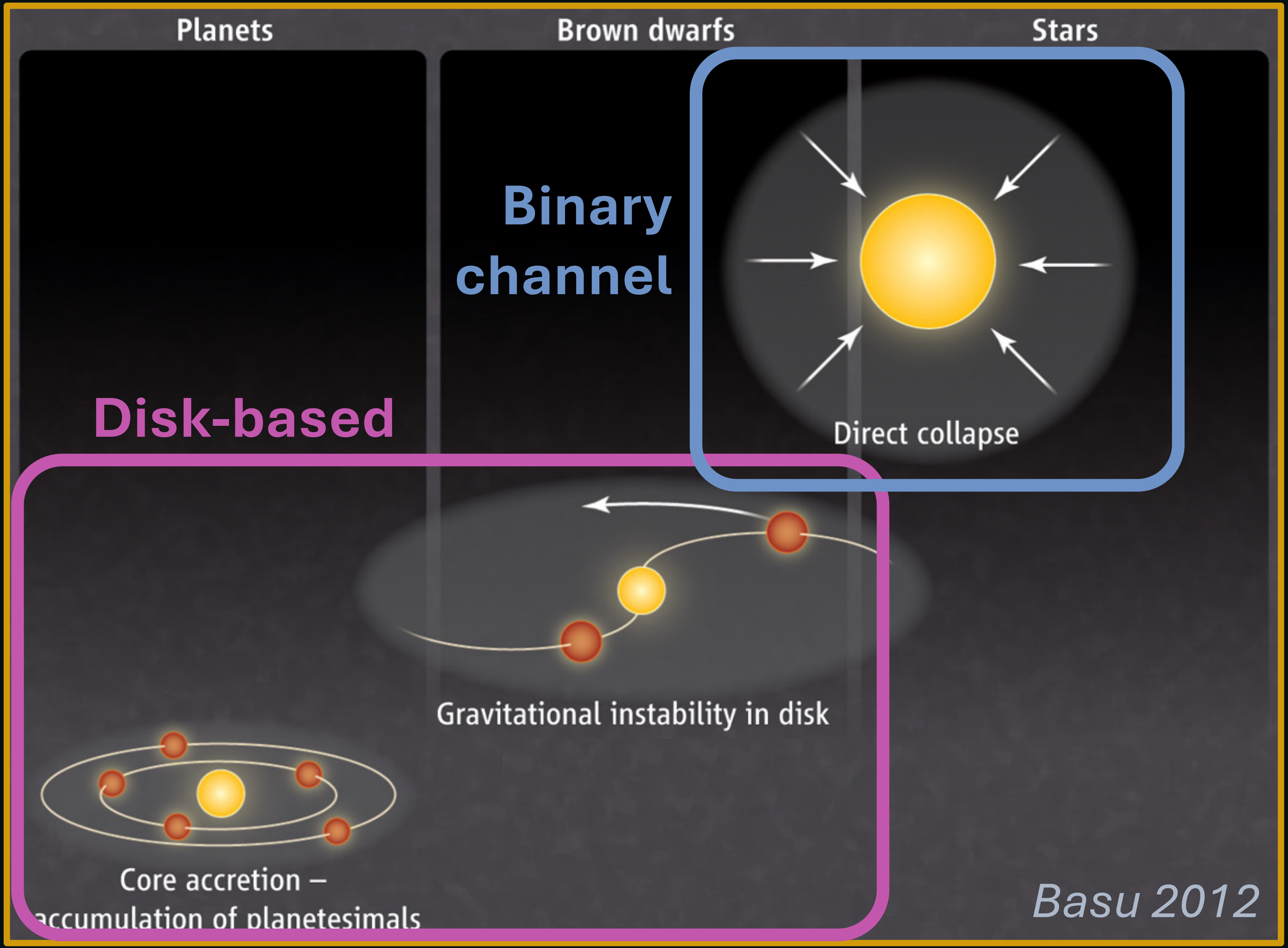
FORMATION MECHANISMS



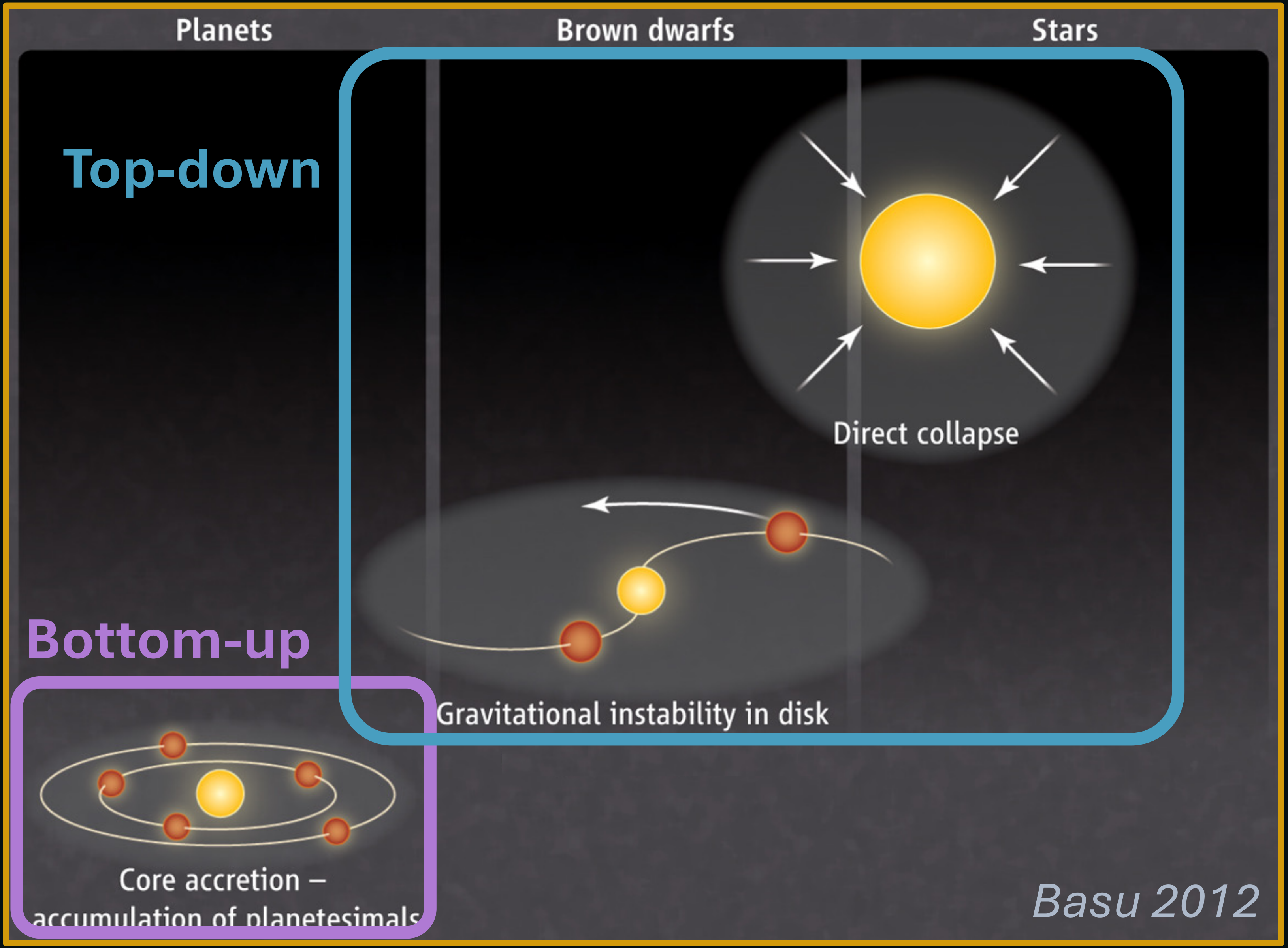


Basu 2012

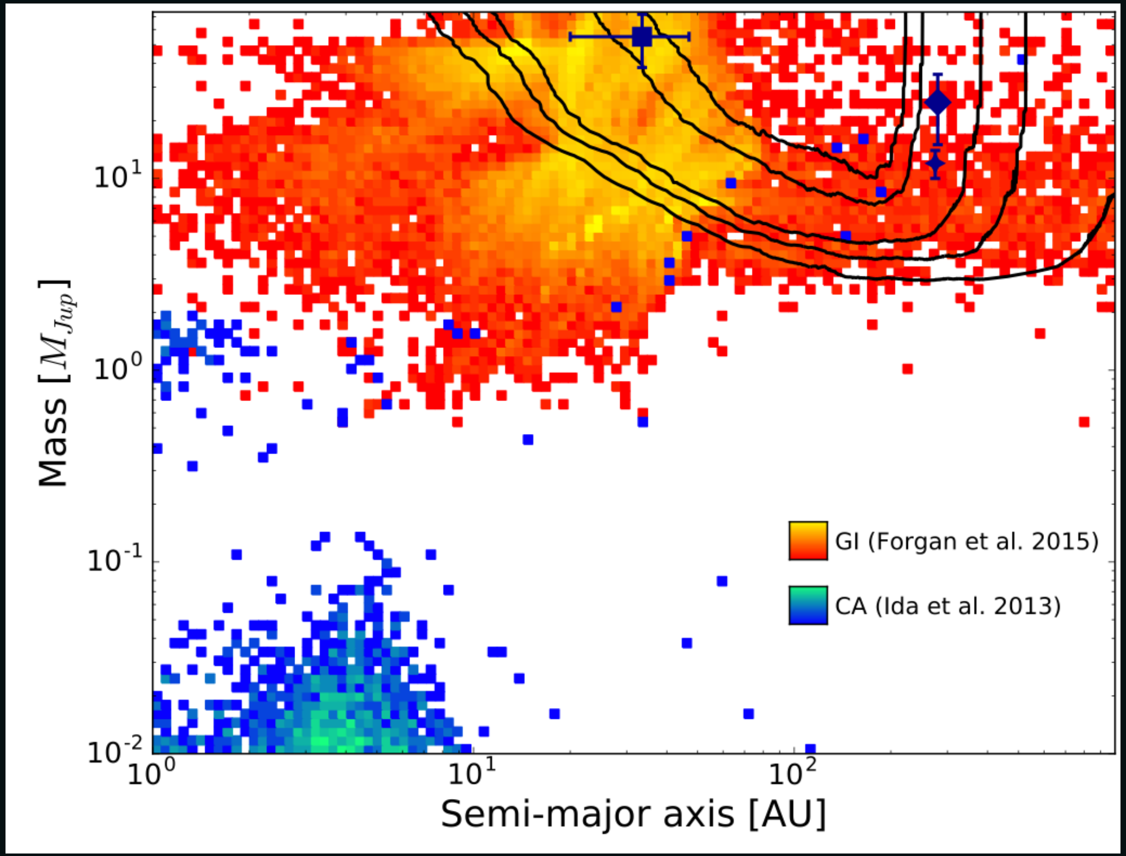
FORMATION MECHANISMS



FORMATION MECHANISMS



CORE ACCRETION VS GRAVITATIONAL INSTABILITY?

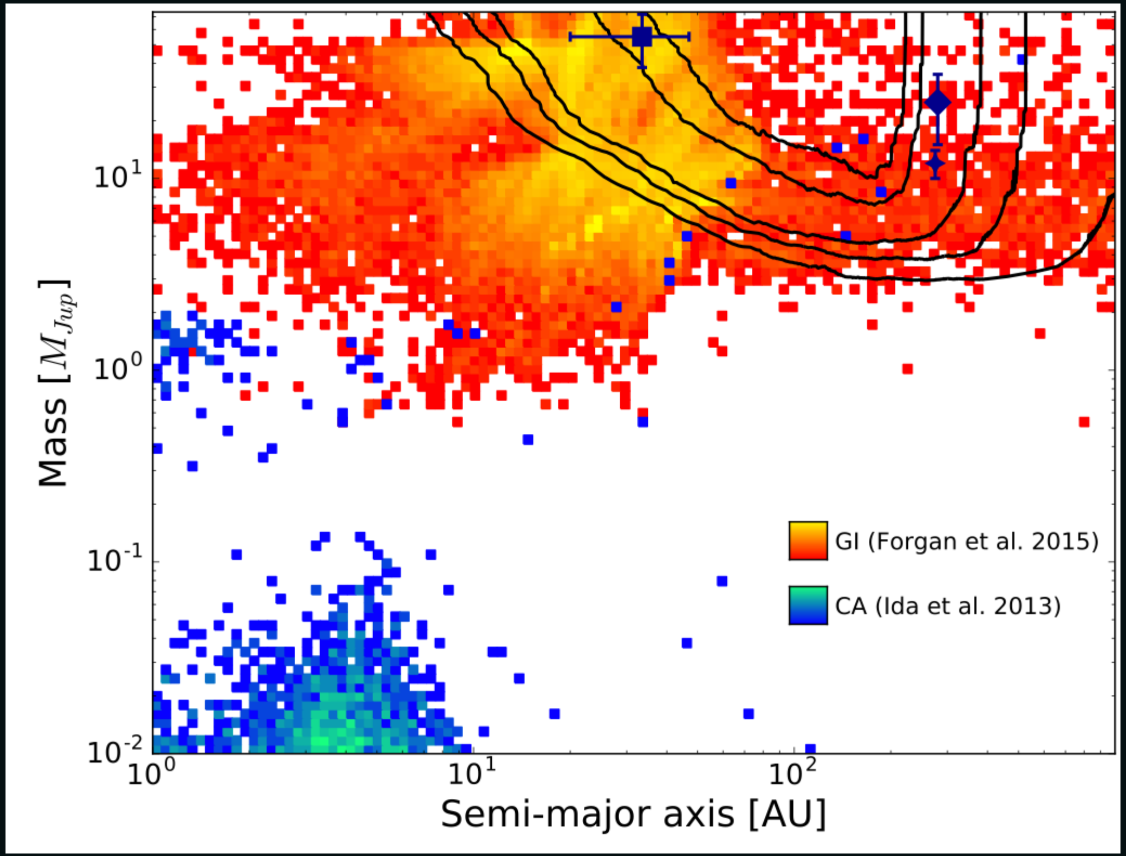


VLT/NACO Large Program

Vigan et al. 2017

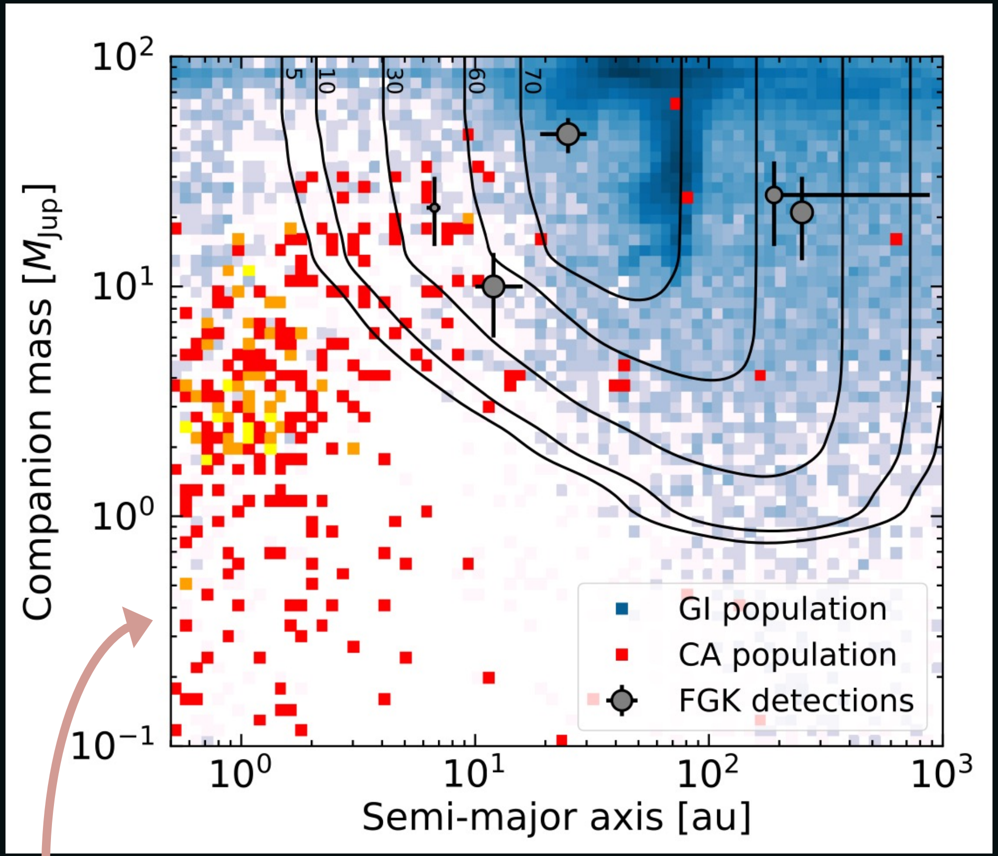
DISK FRAGMENTATION IS INEFFICIENT

CORE ACCRETION VS GRAVITATIONAL INSTABILITY?



VLT/NACO Large Program

Vigan et al. 2017



VLT SHINE

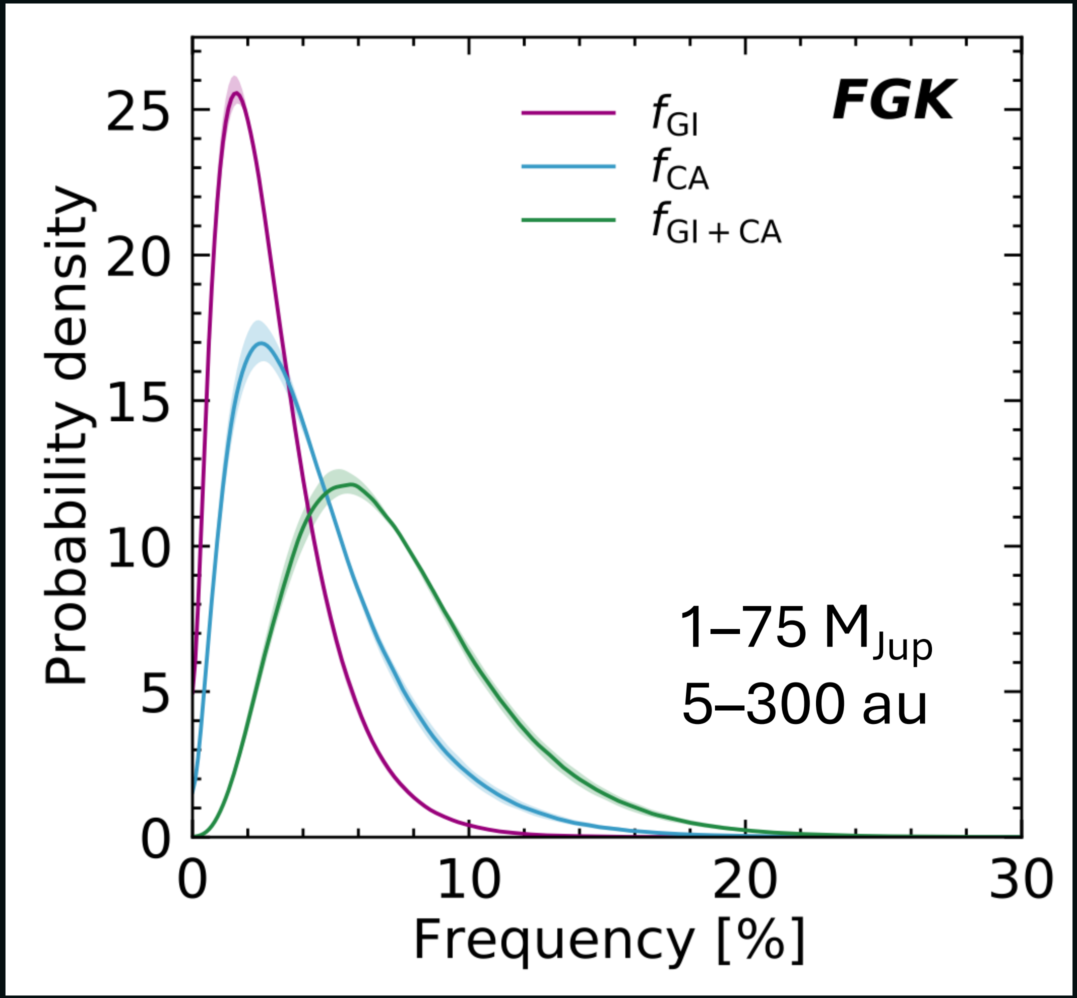
Vigan, Fontanive et al. 2021

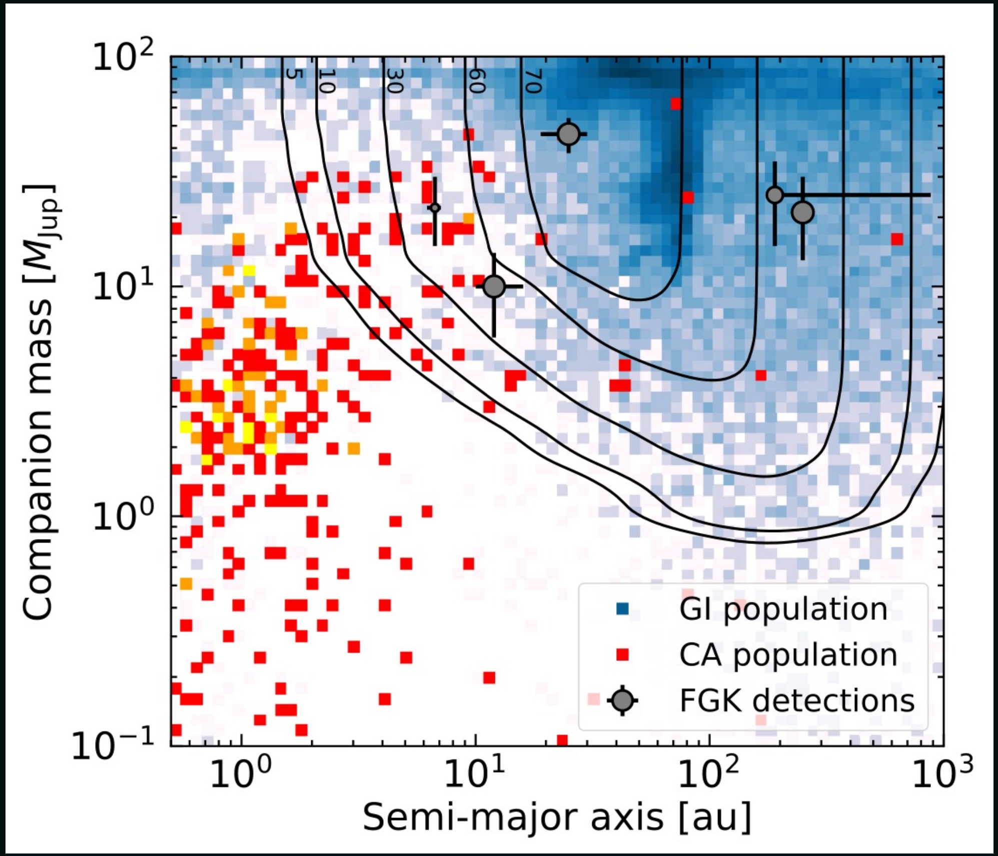
DISK FRAGMENTATION IS INEFFICIENT

New CA population synthesis:

Emsenhuber et al. 2020, Mordasini 2018

CORE ACCRETION VS GRAVITATIONAL INSTABILITY?





VLT SHINE

Vigan, Fontanive et al. 2021

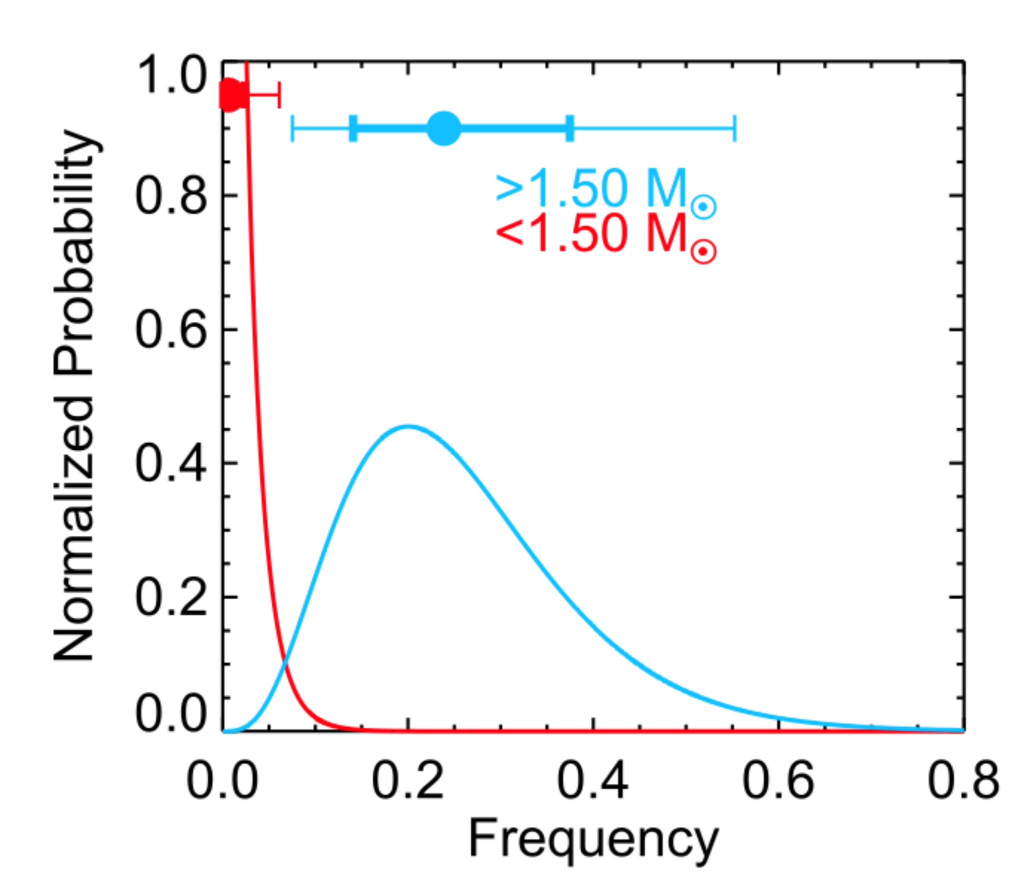
MORE CLOSE-IN PLANETS FROM CORE ACCRETION

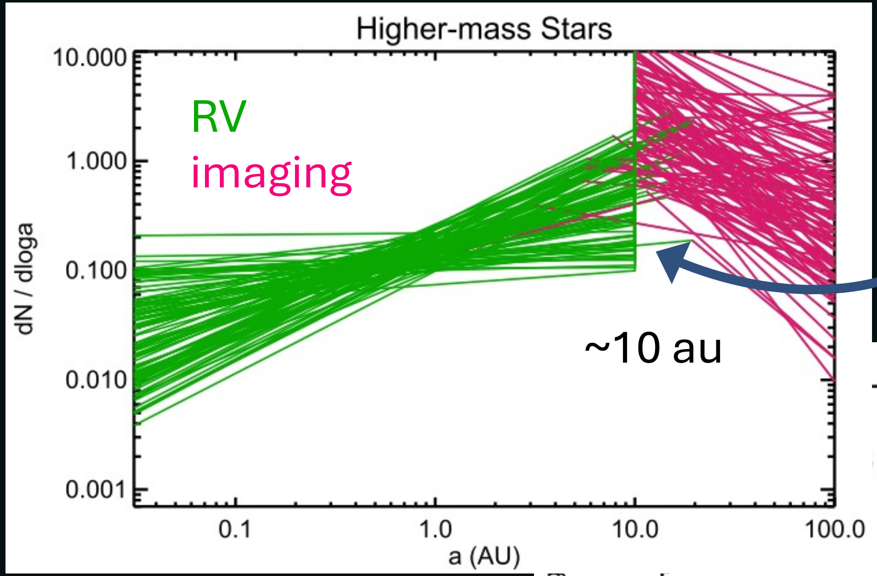
DEPENDENCE ON STELLAR MASS?

Name	Pri. Mass ($M_\odot$)	Mass ($M_{\rm Jup}$)	Sep. (au)
51 Eri b	1.75	2 ± 1	13
HD 95086 b	1.6	5 ± 2	56
HR 8799 b	1.5	5 ± 1	68
HR 8799 c	1.5	7 ± 2	38
HR 8799 d	1.5	7 ± 2	24
HR 8799 e	1.5	7 ± 2	14
β Pic b	1.6	12.7 ± 0.3	9

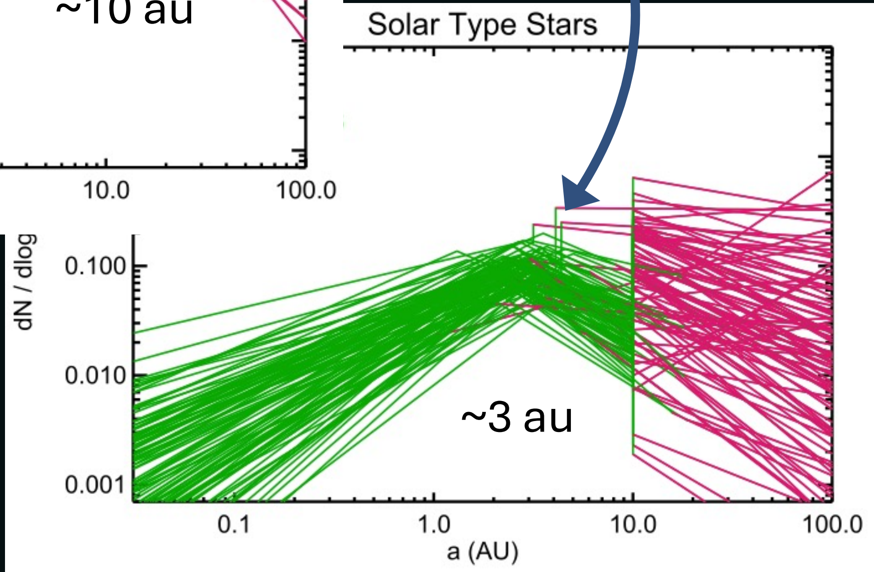
DEPENDENCE ON STELLAR MASS?

more wide-orbit giant exoplanets around massive stars





peak at wider separations

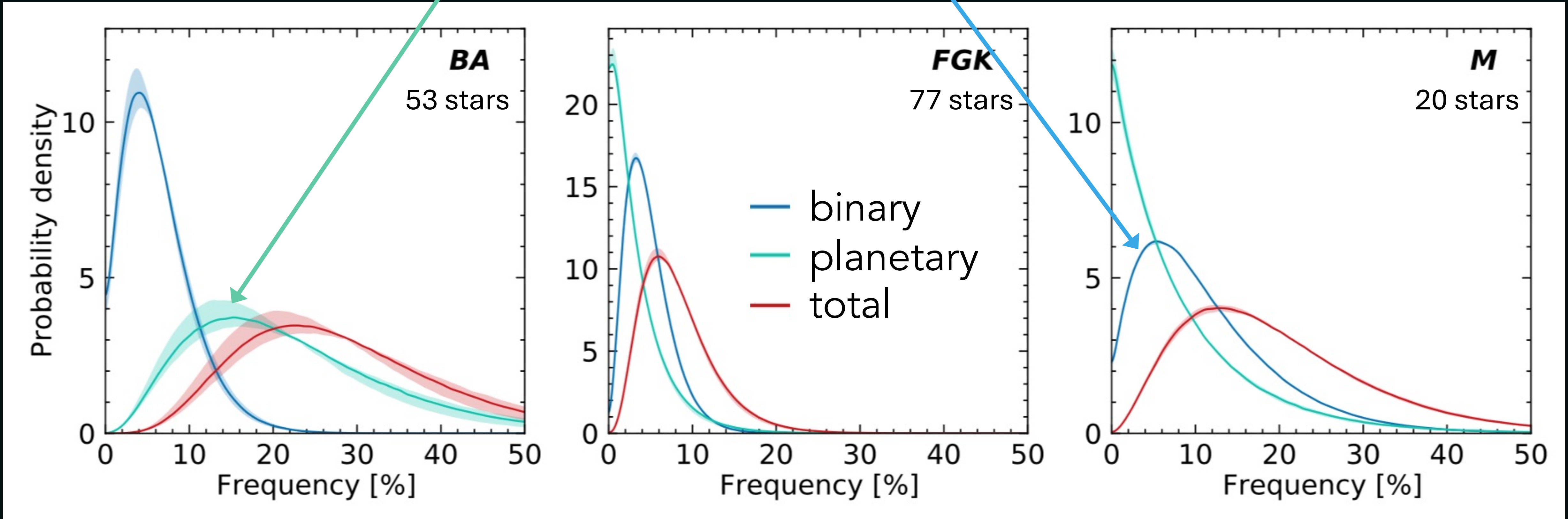


extends RV trends ☑

Gemini GPIES [2–13 M_{Jup} & 3–100 au] *Nielsen et al. 2019*

DEPENDENCE ON STELLAR MASS?

inversion between **planetary** and **binary** prevalences with host mass



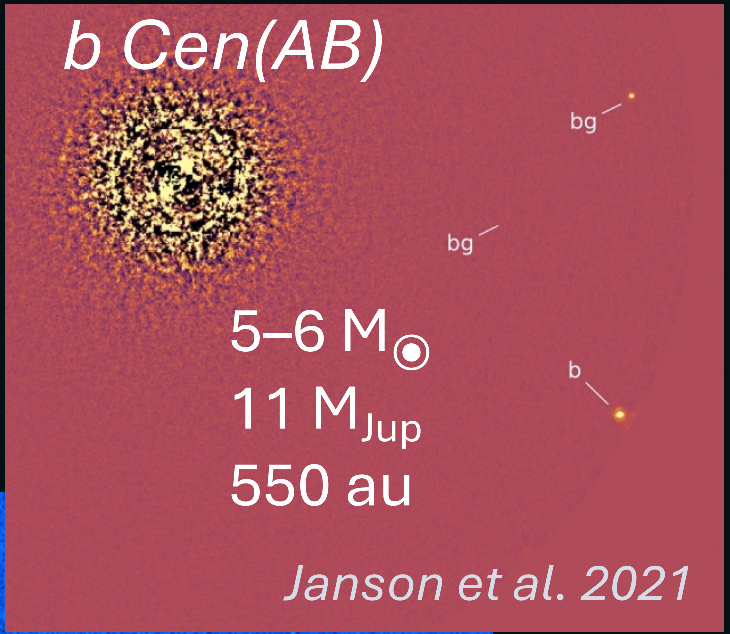
VLT SHINE

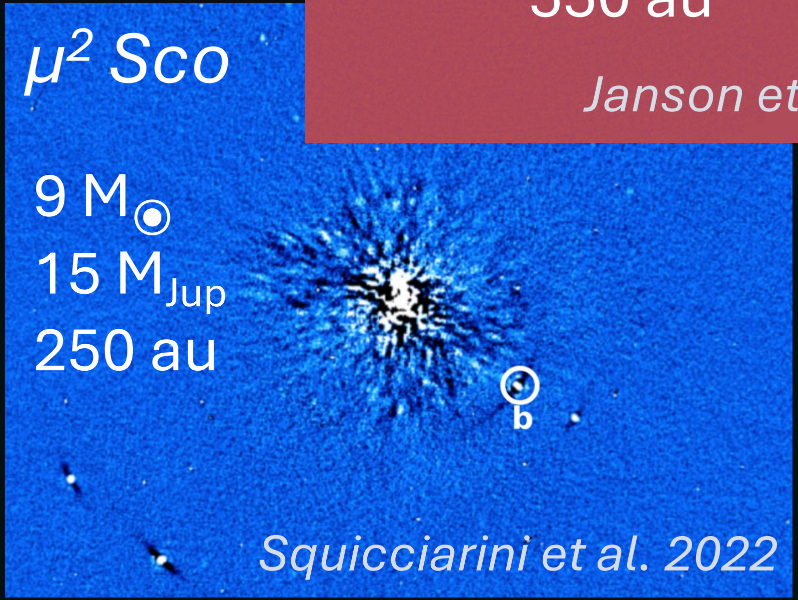
[1–75 M_{Jup} & 5–300 au]

Vigan, Fontanive et al. 2021

DEPENDENCE ON STELLAR MASS?

BEAST (VLT/SPHERE): *B-star Exoplanet Abundance Study*





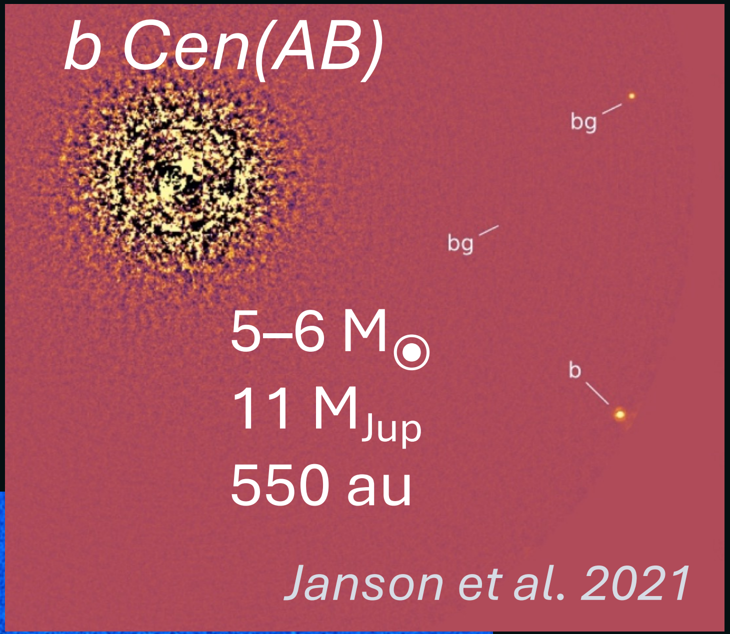
lower mass ratios and wider separations for giant planets around massive stars ☑

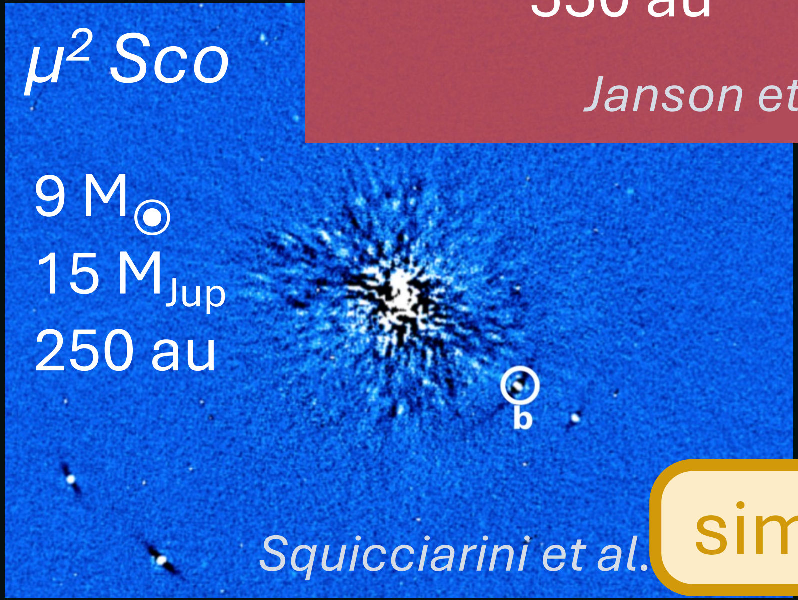
1st & 7th stars observed

DEPENDENCE ON STELLAR MASS?

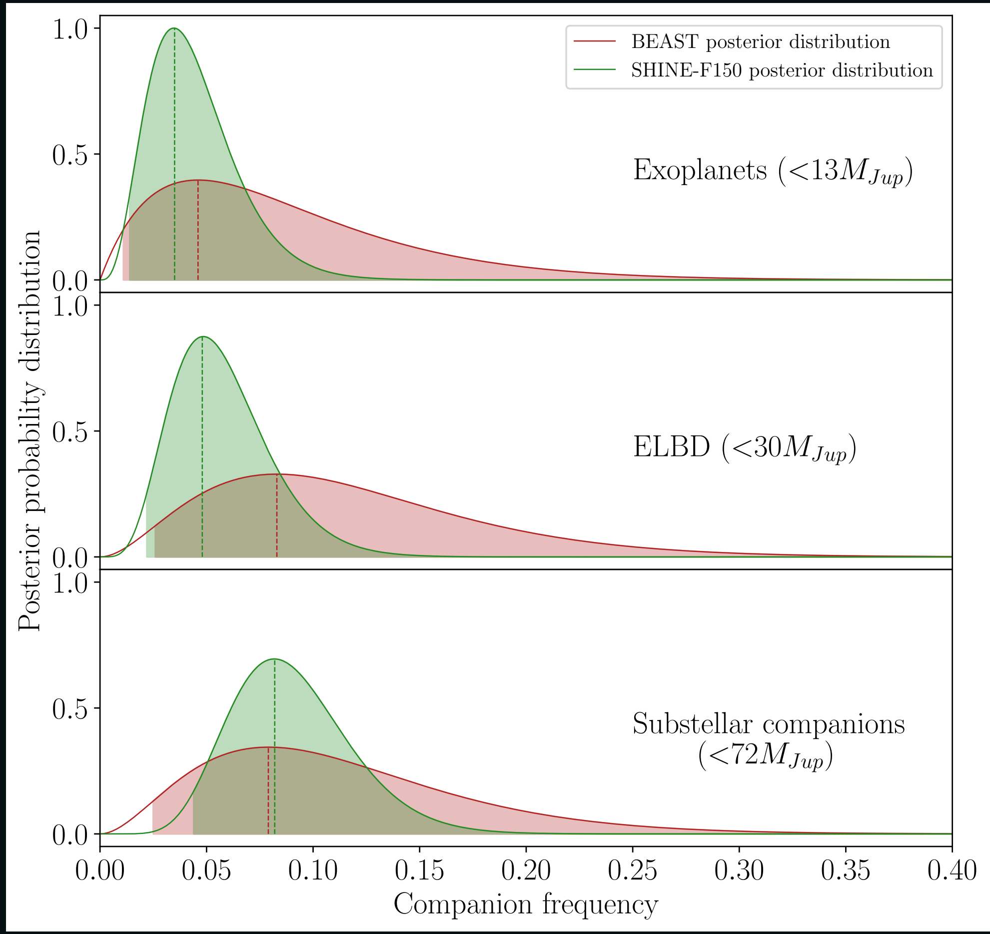
Delorme et al. submitted

BEAST (VLT/SPHERE): *B-star Exoplanet Abundance Study*





1[st] & 7[th] stars observed / 85

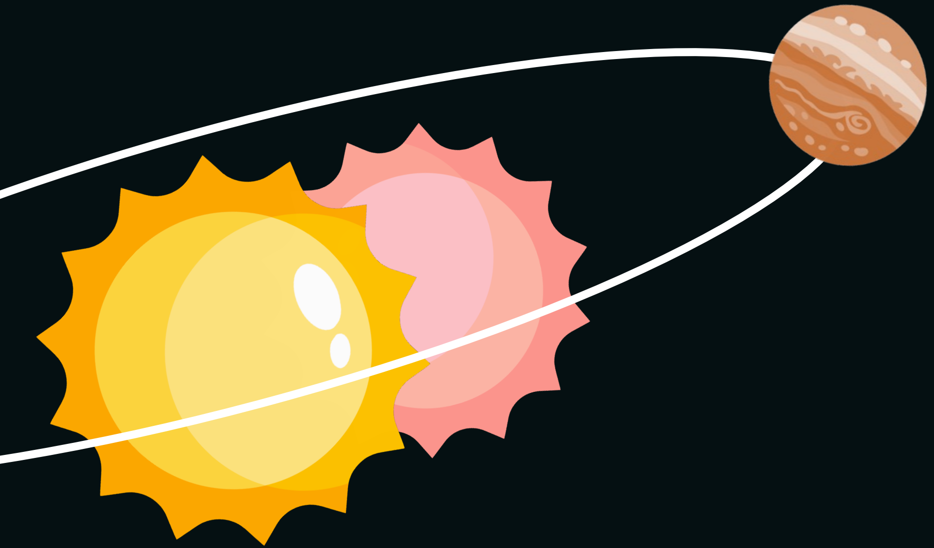


similar occurrence rates to Sun-like stars (for now)

INFLUENCE OF STELLAR MULTIPLICITY?

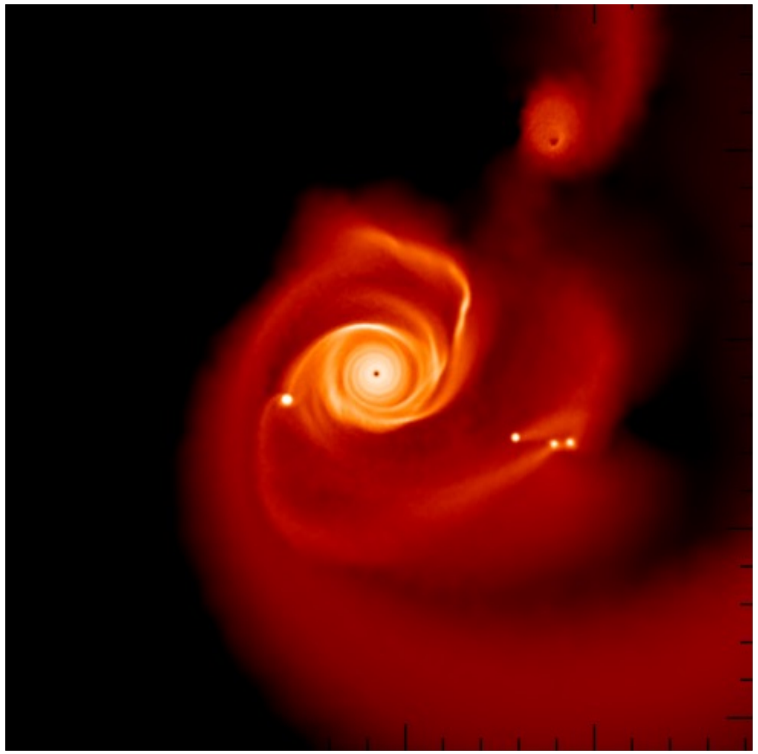
Circumbinary (P-type)

e.g., ROXs42 B b; b Cen AB b



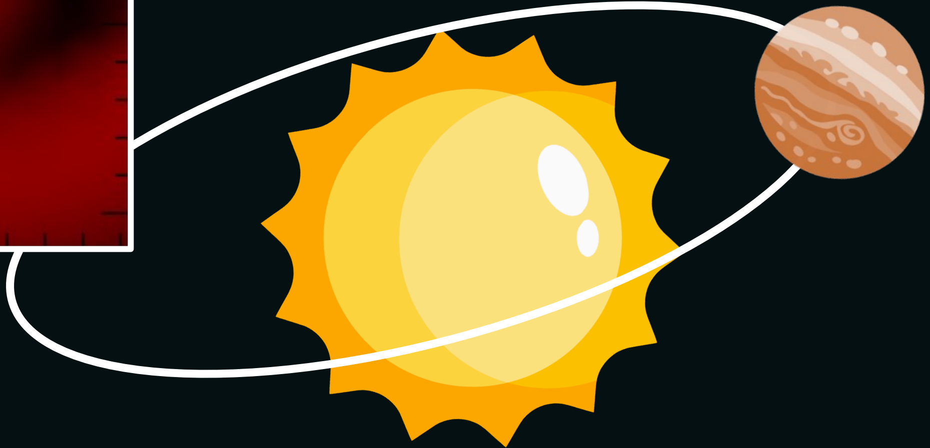
Circumstellar (S-type)

e.g., 51 Eri b + GJ3305 AB



Disk fragmentation triggered by outer stellar companions

Cadman, Hall, Fontanive et al. 2021



INFLUENCE OF STELLAR MULTIPLICITY?

Circumbinary (P-type)

e.g., ROXs42 B b; b Cen AB b

SPOTS: *Search for Planets Orbiting Two Stars* (VLT/NaCo+SPHERE)

f = 1.9 % (< 10.5 %)
[2–15 M_{Jup}; 1–300 au]

Asensio-Torres et al. 2018

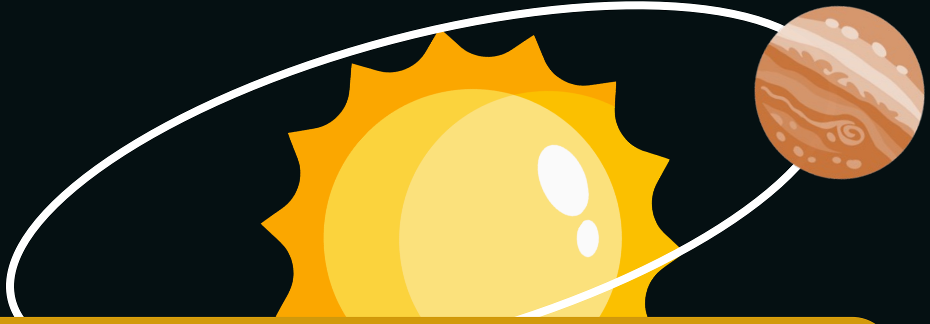
Circumstellar (S-type)

e.g., 51 Eri b + GJ3305 AB

VIBES: *Visual Binary Exoplanet survey with SPHERE*

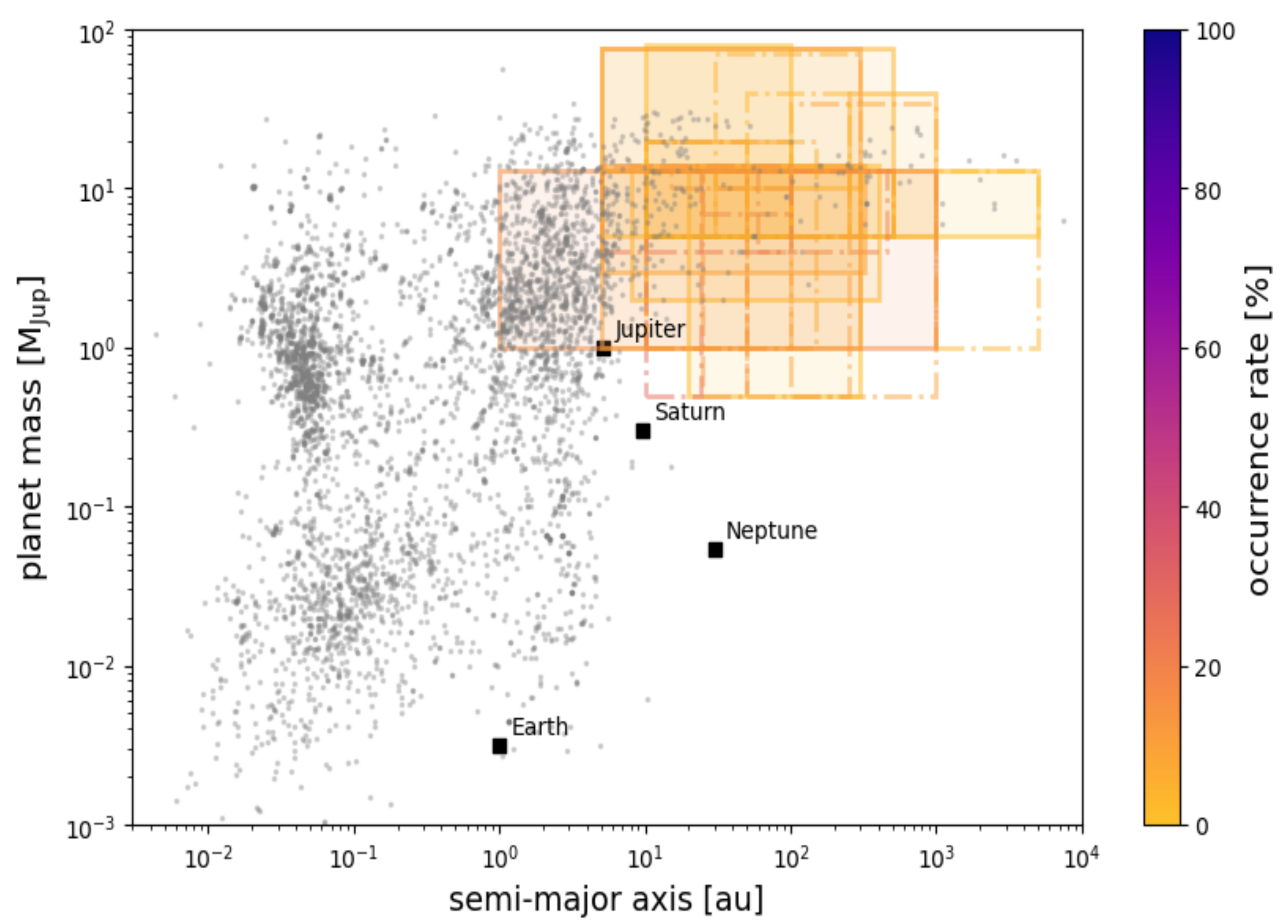
f < 9 %
[10–75 M_{Jup}; 10–200 au]

Hagelberg et al. 2020



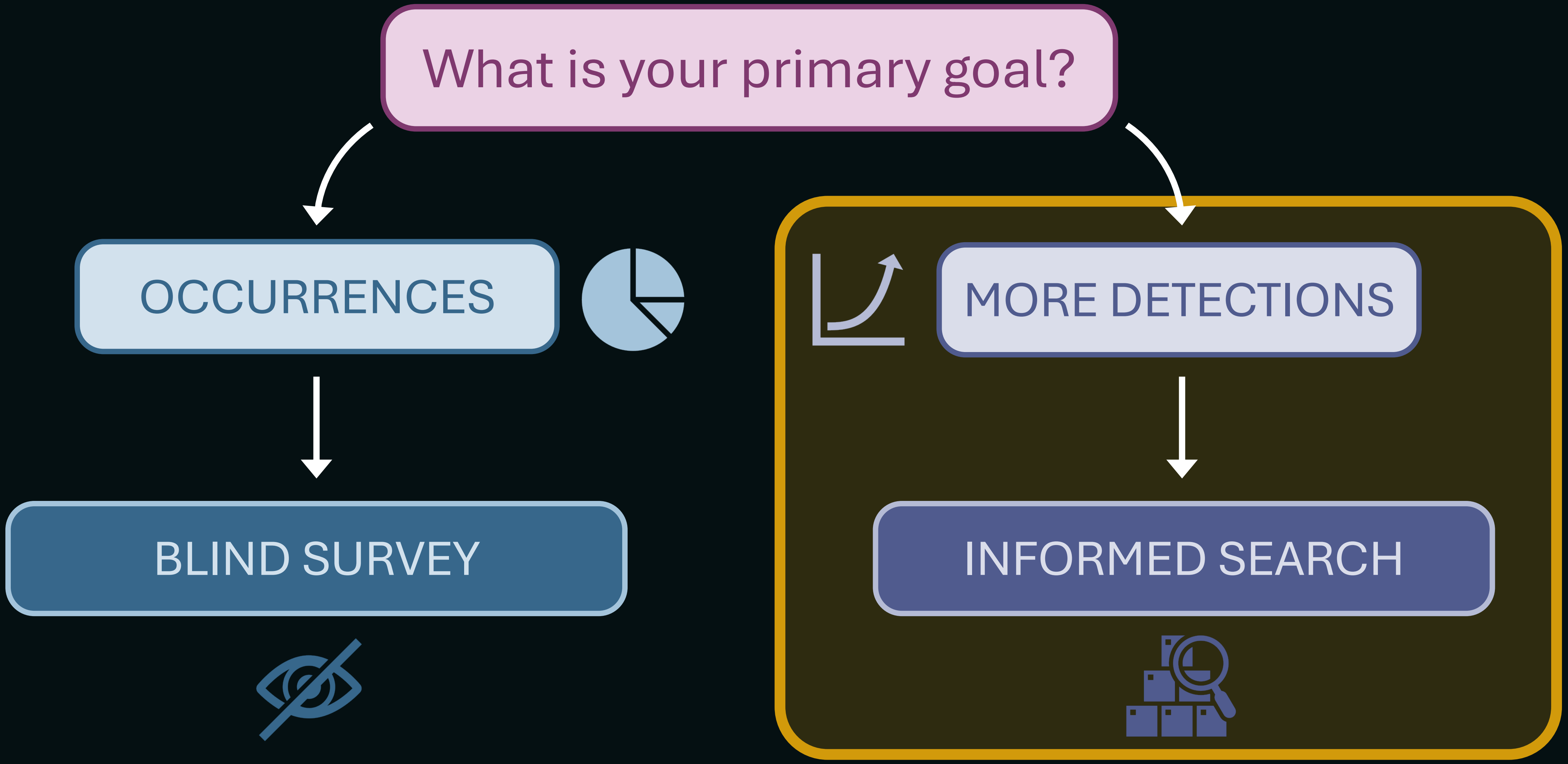
→ No evidence that binarity impacts occurrence rates (for now)

OCCURRENCE RATES ARE LOW – NOW WHAT?



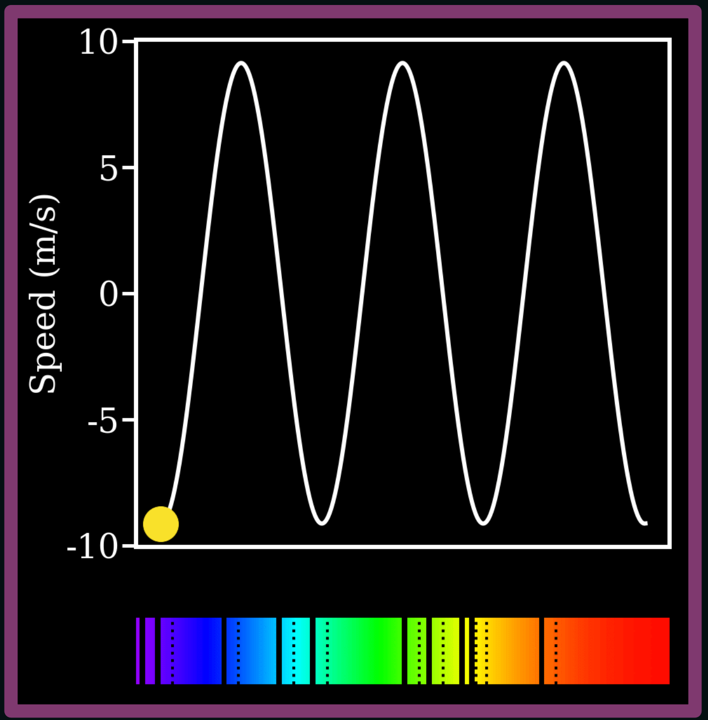
Credit: L. Pearce & R. Bowens-Rubin

2. INCREASING SAMPLE SIZES WITH TARGETED SEARCHES

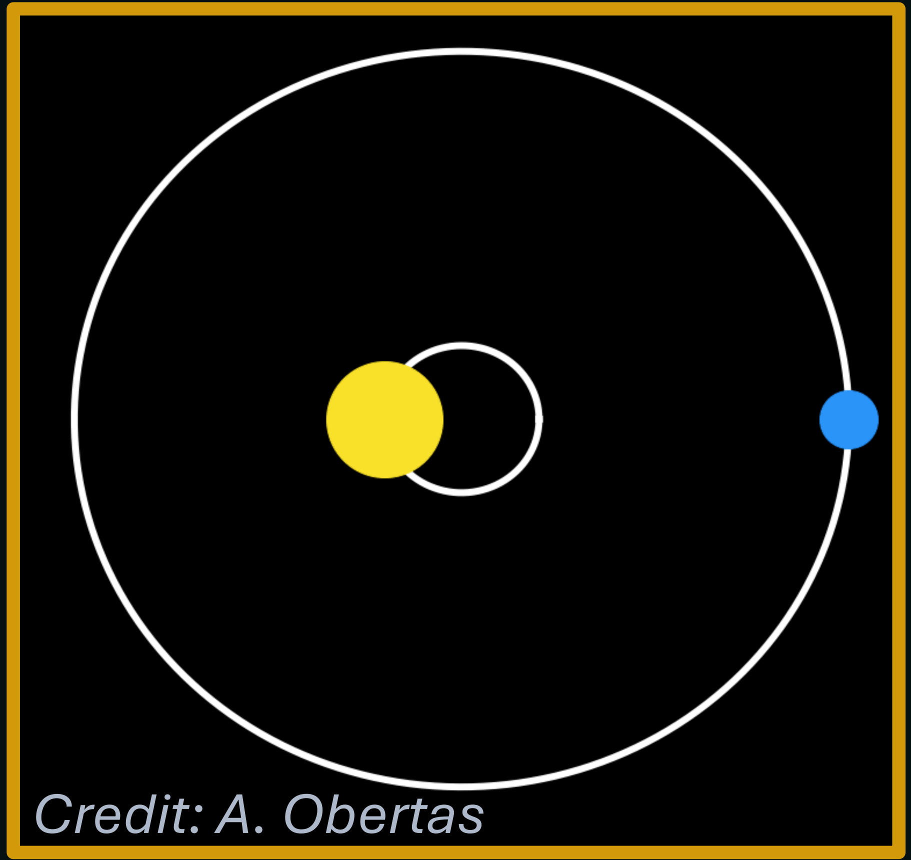


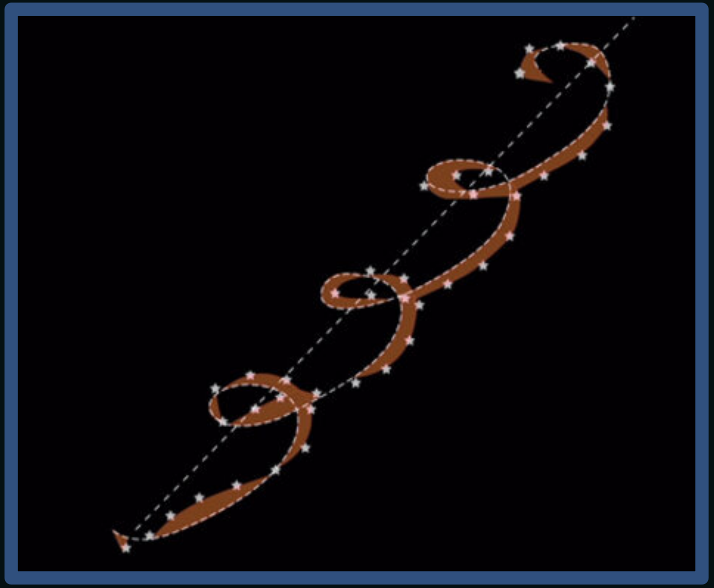
INFORMED TARGET SELECTIONS

New search strategies through signatures of hidden companions
e.g., wobbles from *RV trends* & *astrometric accelerations*



in the line of the sight

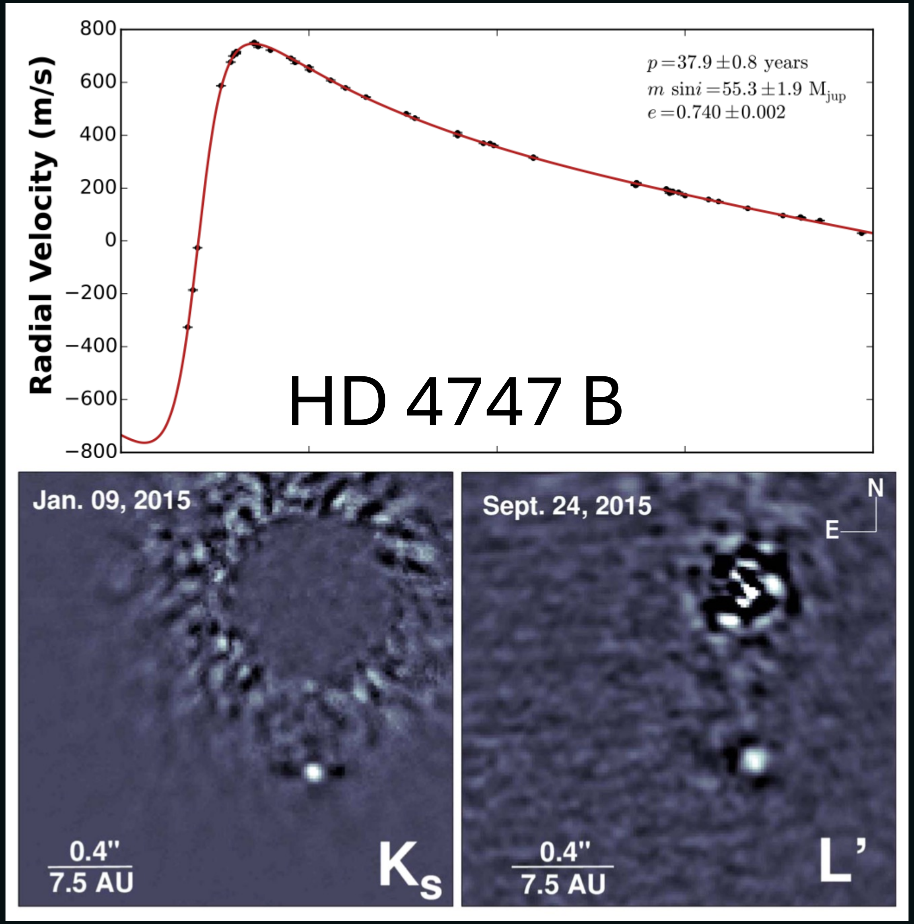




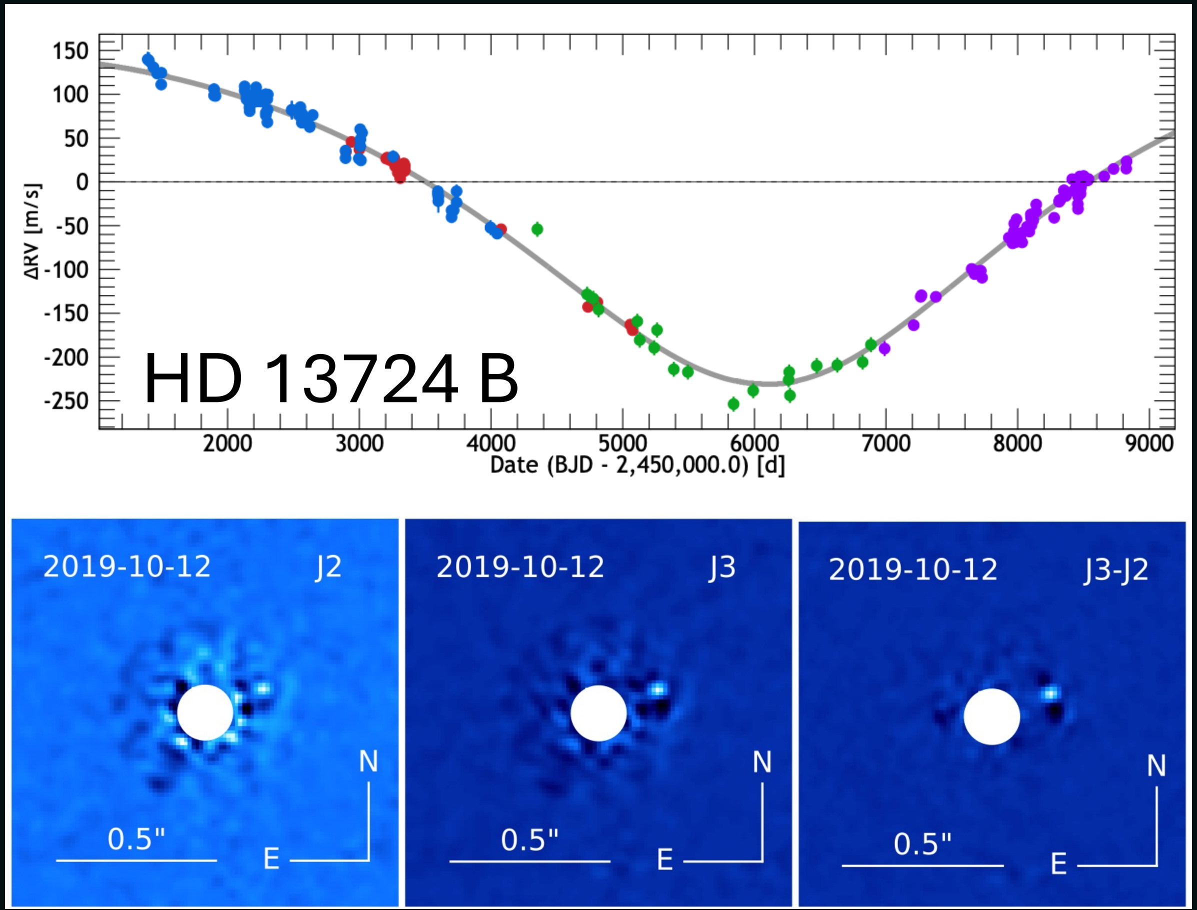
in the plane of the sky

INFORMED TARGET SELECTIONS

Long-term radial velocity trends



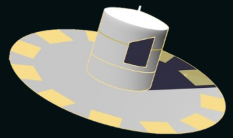
The TRENDS survey *Crepp et al. 2016*

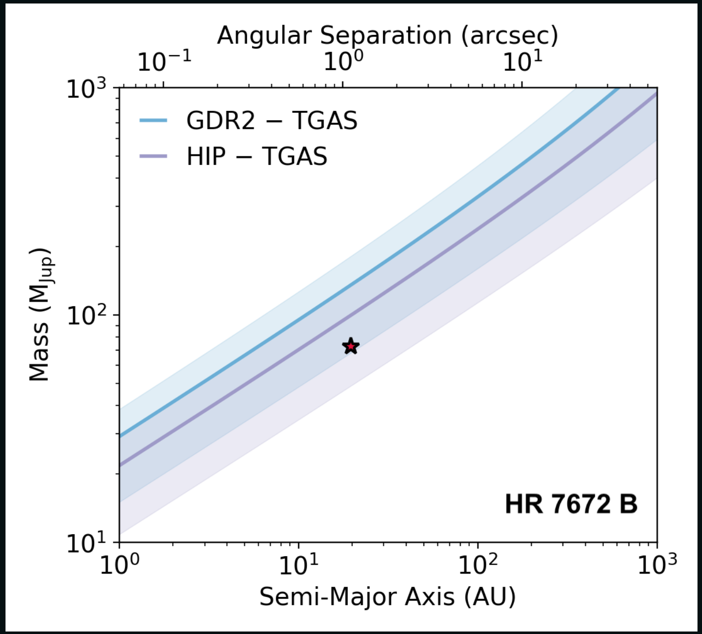


Rickman et al. 2020

INFORMED TARGET SELECTIONS

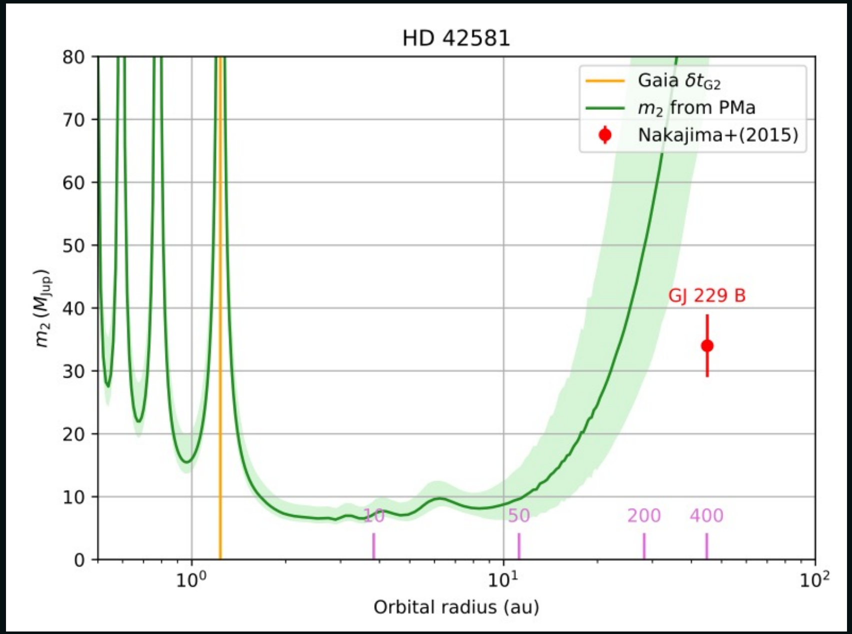
Gaia proper motion anomalies



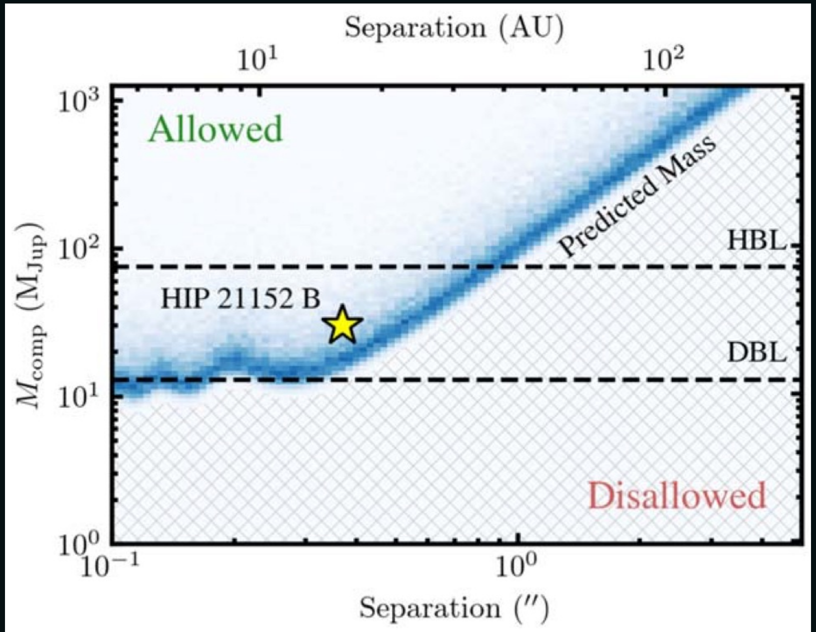


COPAINS

Fontanive et al. 2019



Kervella et al. 2019



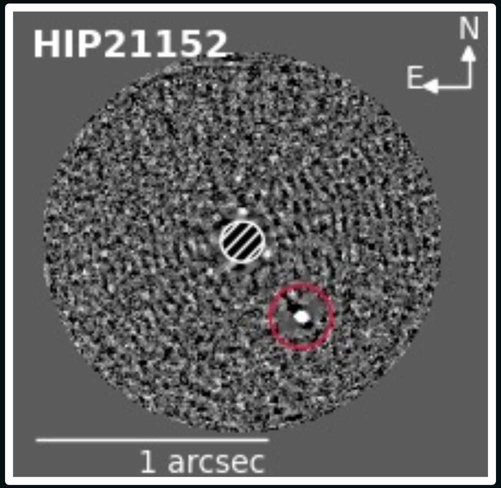
Franson et al. 2022

Brandt 2018, 2021

The Hipparcos–Gaia Catalog of Accelerations: Gaia EDR3 Edition

Timothy D. Brandt

A STRONG BOOST IN DISCOVERY RATES!

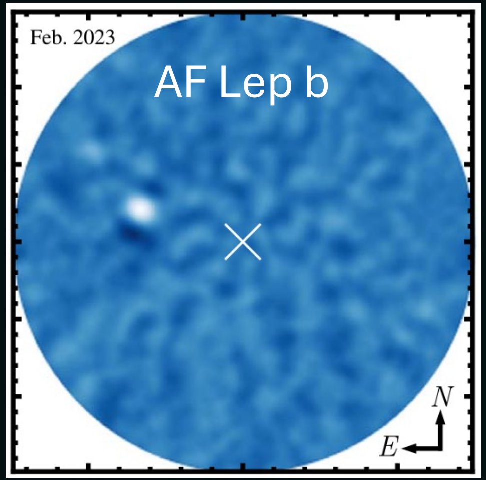


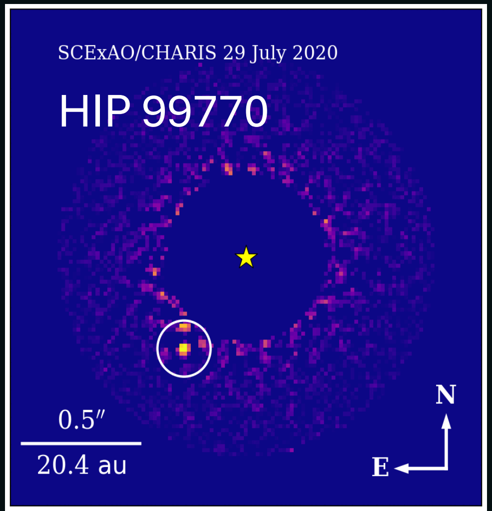
COPAINS Survey: 4 new brown dwarfs / 25 stars

Bonavita, Fontanive et al. 2022

Dynamical Beacons Program

Franson et al. 2023

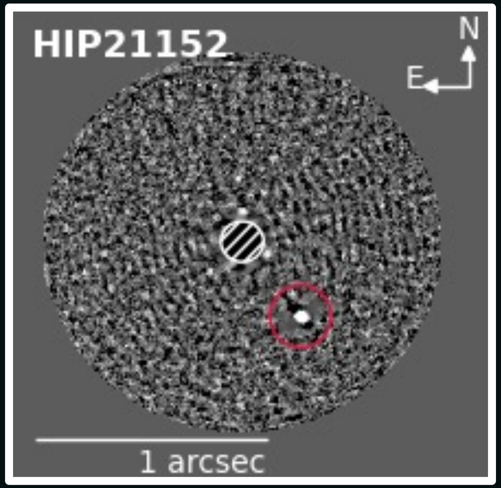




Subaru SCExAO Campaign

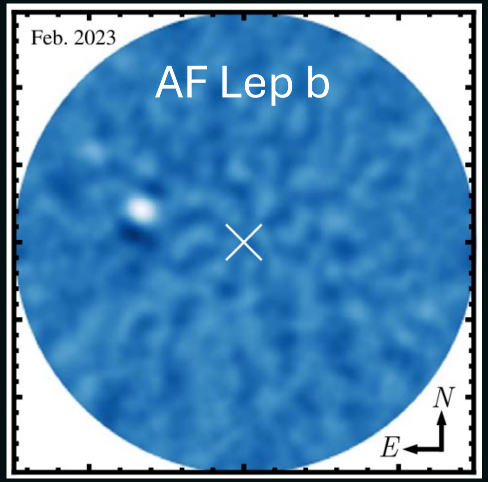
Currie et al. 2023

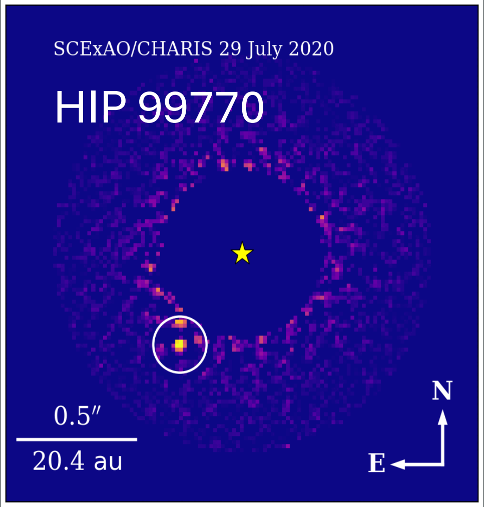
A STRONG BOOST IN DISCOVERY RATES!



COPAINS Survey: 4 new brown dwarfs / 25 stars
Bonavita, Fontanive et al. 2022

Franson et al. 2022
Dynamical Beacons Program
Franson et al. 2023



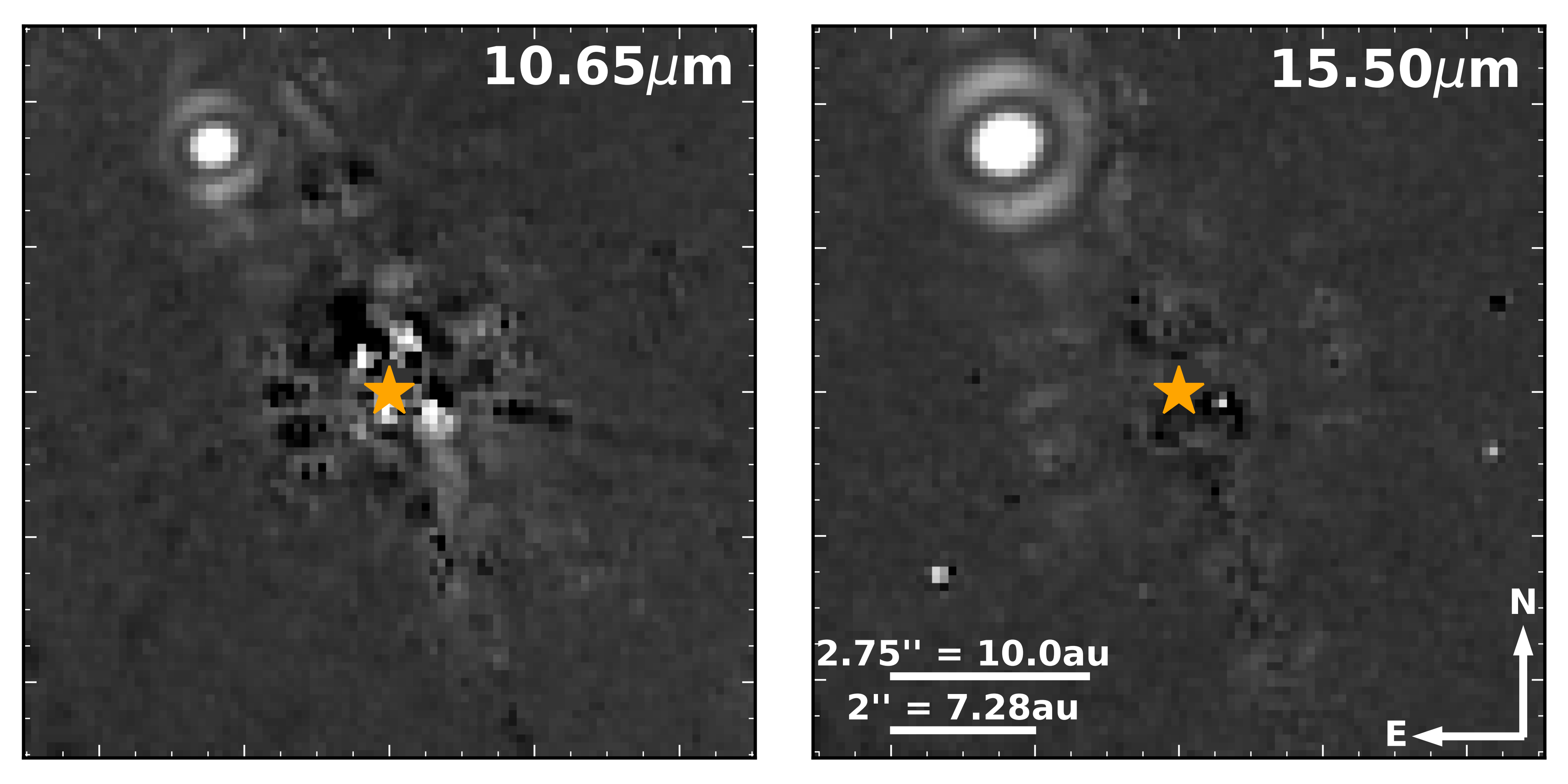


Kuzuhara et al. 2022
Subaru SCExAO Campaign
Currie et al. 2023

more to come with the next Gaia Data Releases

Mesa et al. 2023
De Rosa et al. 2023

A STRONG BOOST IN DISCOVERY RATES!

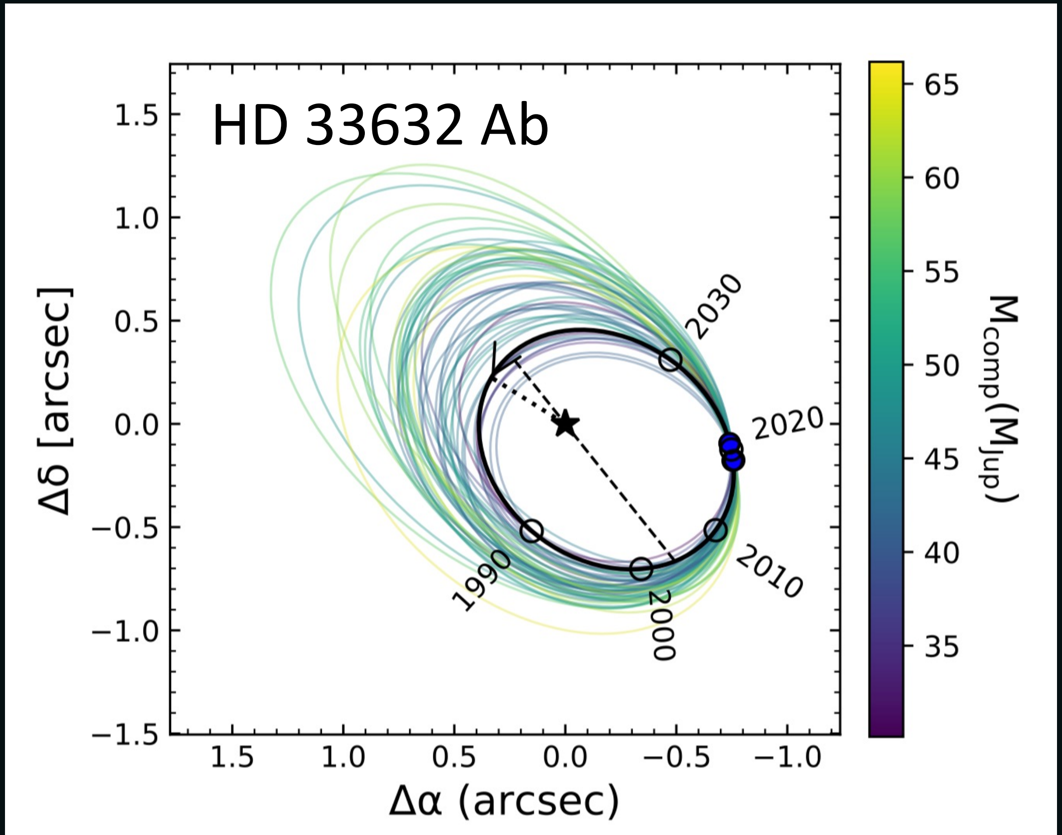


Matthews et al. 2024

JWST detection of Eps Ind Ab (275K !!!)

ORBITS AND DYNAMICAL MASSES

25-year baseline with Hipparcos–Gaia data + decades of RVs

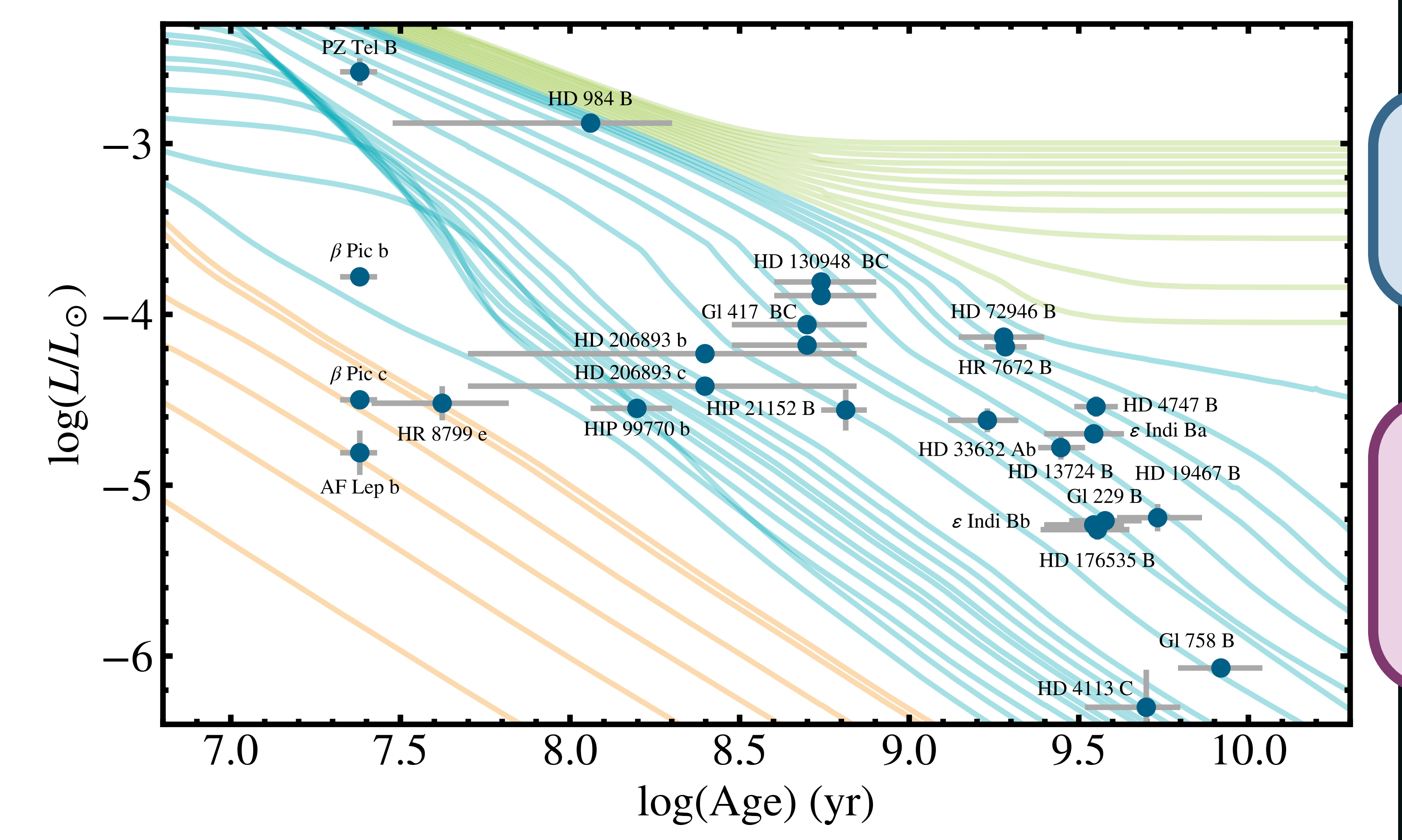


Calissendorff & Janson 2018
Dupuy et al. 2019
Grandjean et al. 2019
Brandt et al. 2020, 2021
Currie et al. 2020
Nielsen et al. 2020
Franson et al. 2022, 2023
Rickman et al. 2024
...

absolute + relative astrometry + RVs ⟶ masses straight away!

ORBITS AND DYNAMICAL MASSES

Directly-imaged companions with dynamical masses

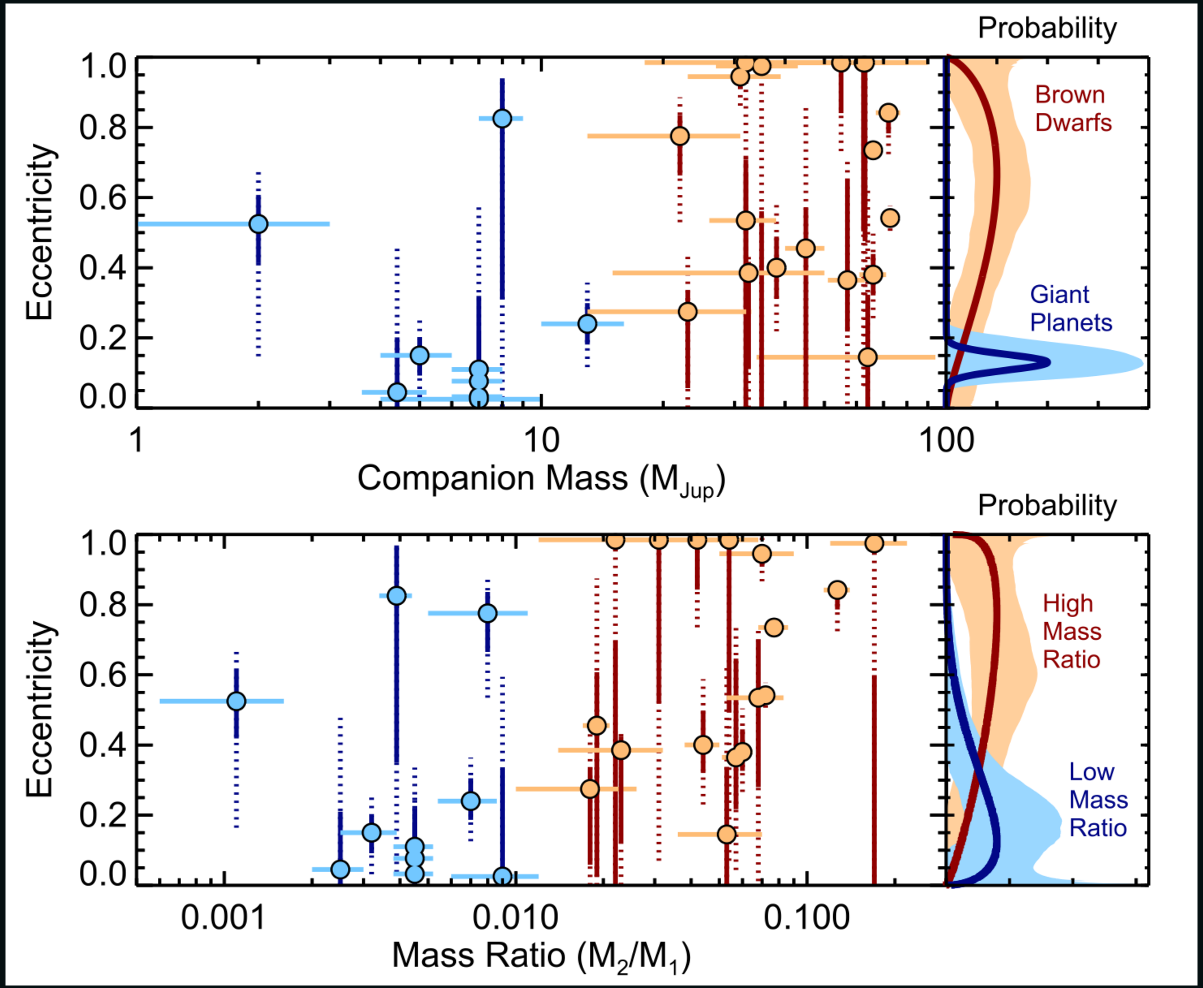


crucial to refine evolutionary models

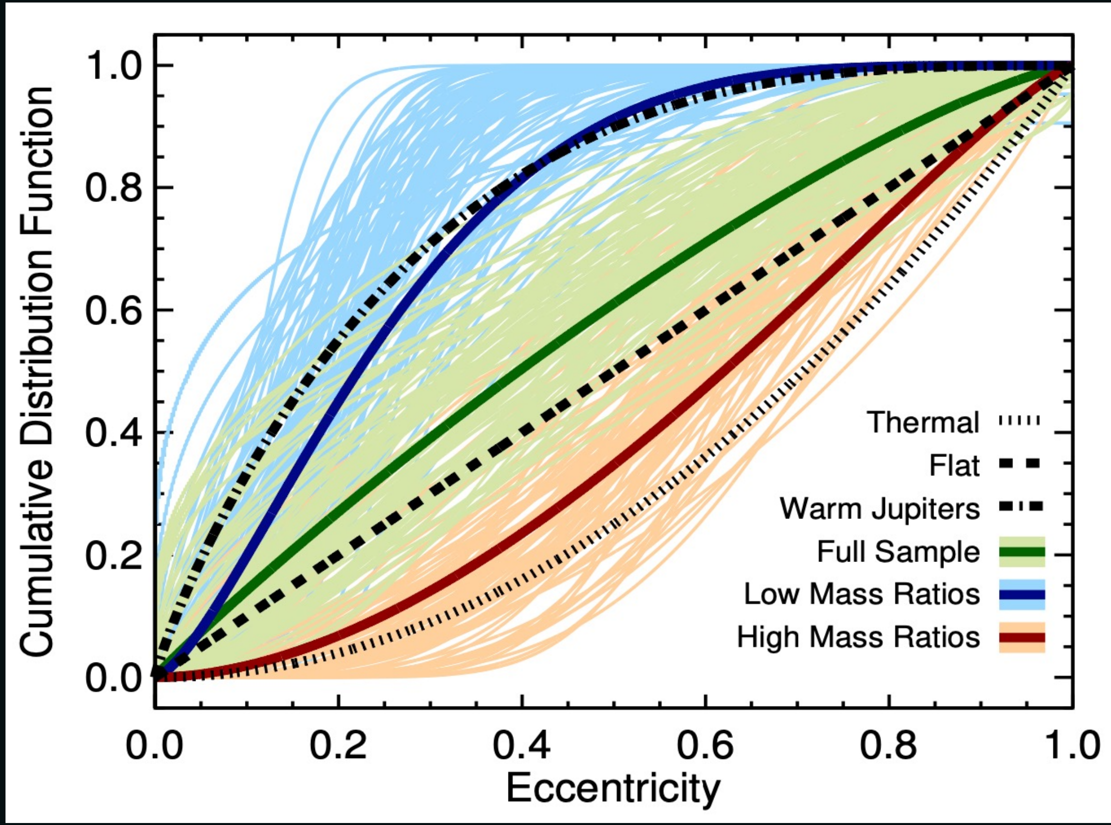
demographics from physical & orbital properties

Credit: K. Franson

TWO DISTINCT SUBSTELLAR POPULATIONS?

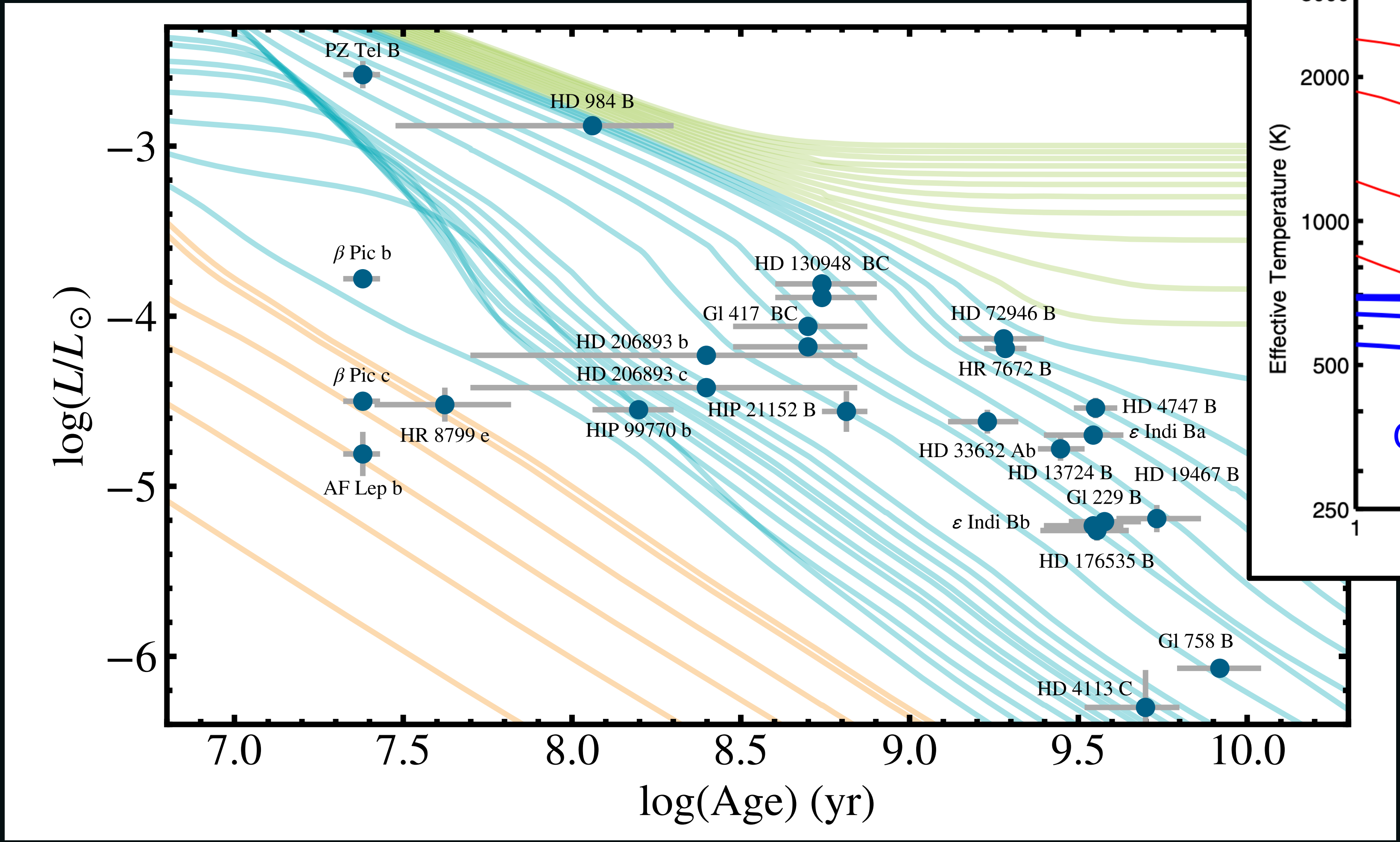


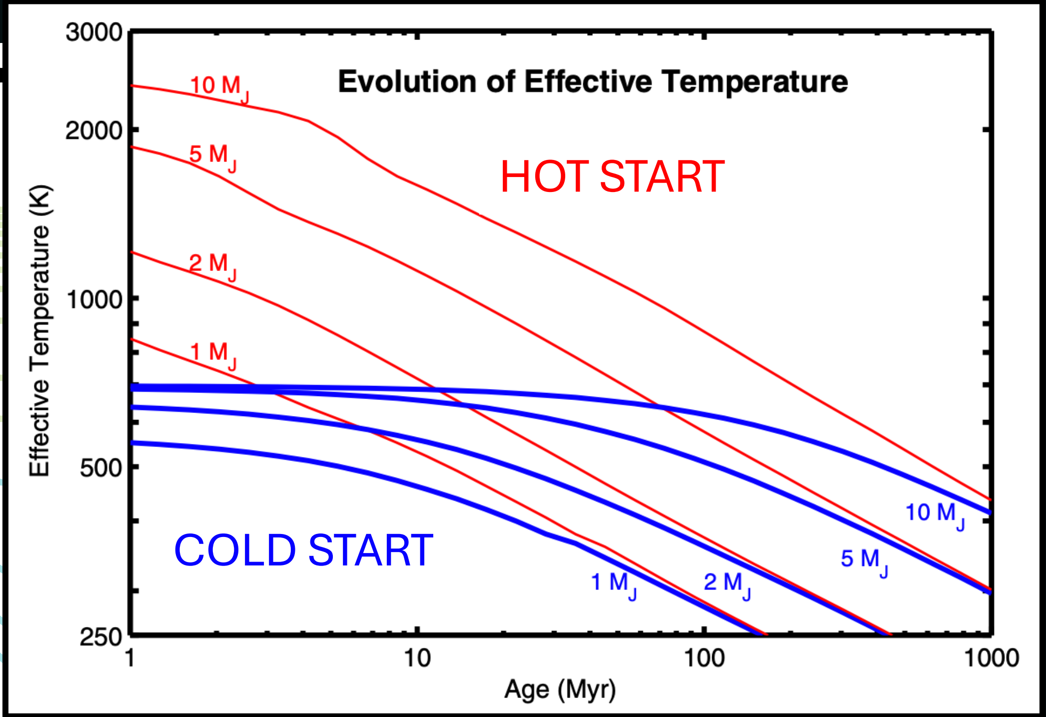
Bowler et al. 2020



→ **wide-orbit giant planets have lower eccentricities than brown dwarf companions**

EFFECTS OF INITIAL ENTROPY?

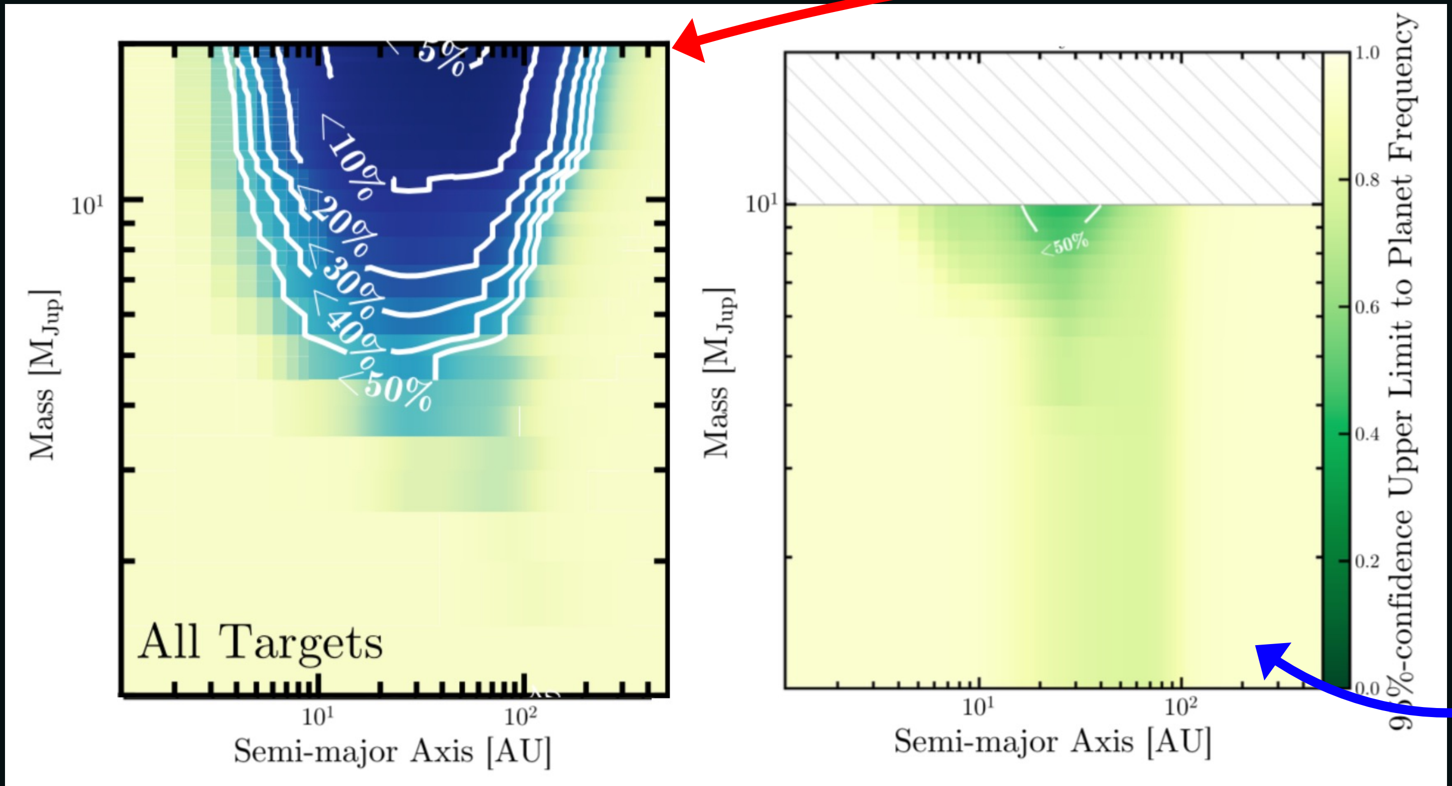


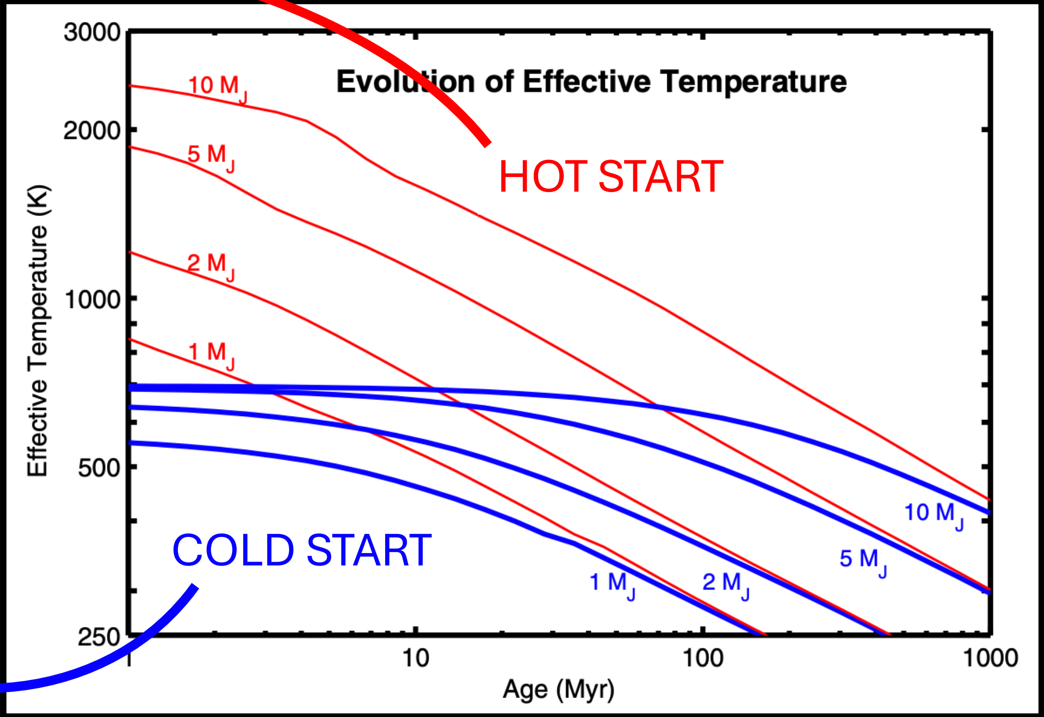


Spiegel & Burrows 2012

Credit: K. Franson

EFFECTS OF INITIAL ENTROPY?





Spiegel & Burrows 2012

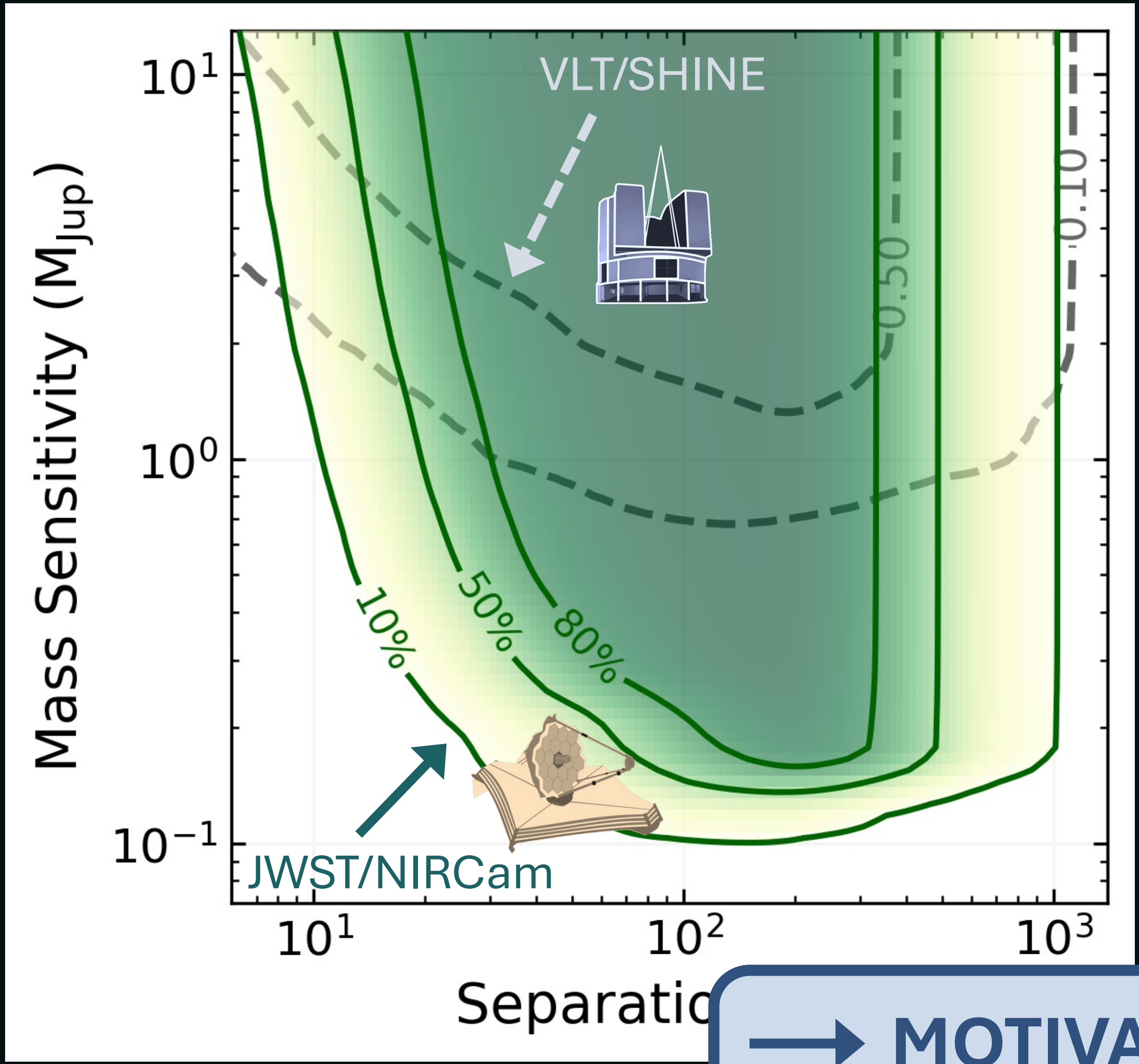
$f_{pl} < 24$ %
[4–14 M_{Jup}; 5–50 au]

$f_{pl} < 90$ %
[7–10 M_{Jup}; 5–50 au]

giant exoplanets could be common if they are born cold

LBT LEECH Survey *Stone et al. 2018*

EXPLORING NEW REGIONS OF THE PARAMETER SPACE

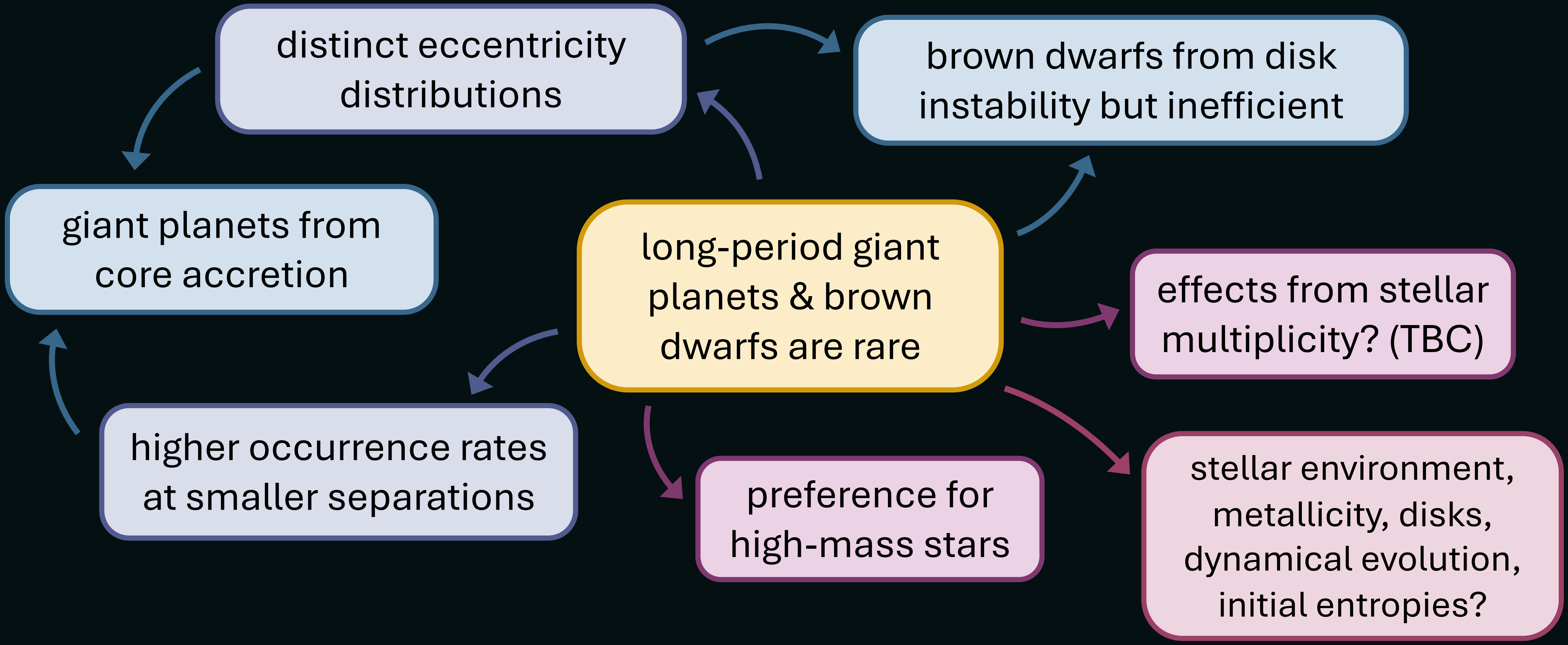


JWST mid-IR sensitivity can probe sub-Jupiter masses for the first time!

4050	Uncharted Worlds: Towards a Legacy of Direct Imaging of Sub-Jupiter Mass Exoplanets	PI: Aarynn Carter
5835	Into The Spotlight: Unveiling Wide-Separation Sub-Jupiters for Future JWST Characterization	PI: Aarynn Carter
6005	Imaging Young Sub-Jupiter Planets down to Solar-System Scales	PI: Beth Biller

→ **MOTIVATION FOR NEW BLIND SURVEYS**

Credit: A. Carter



targeted searches for larger samples in current sensitivity regions

=

new blind surveys in uncharted regions of the parameter space

Clémence Fontanive – Université de Montréal *clemence.fontanive@umontreal.ca*