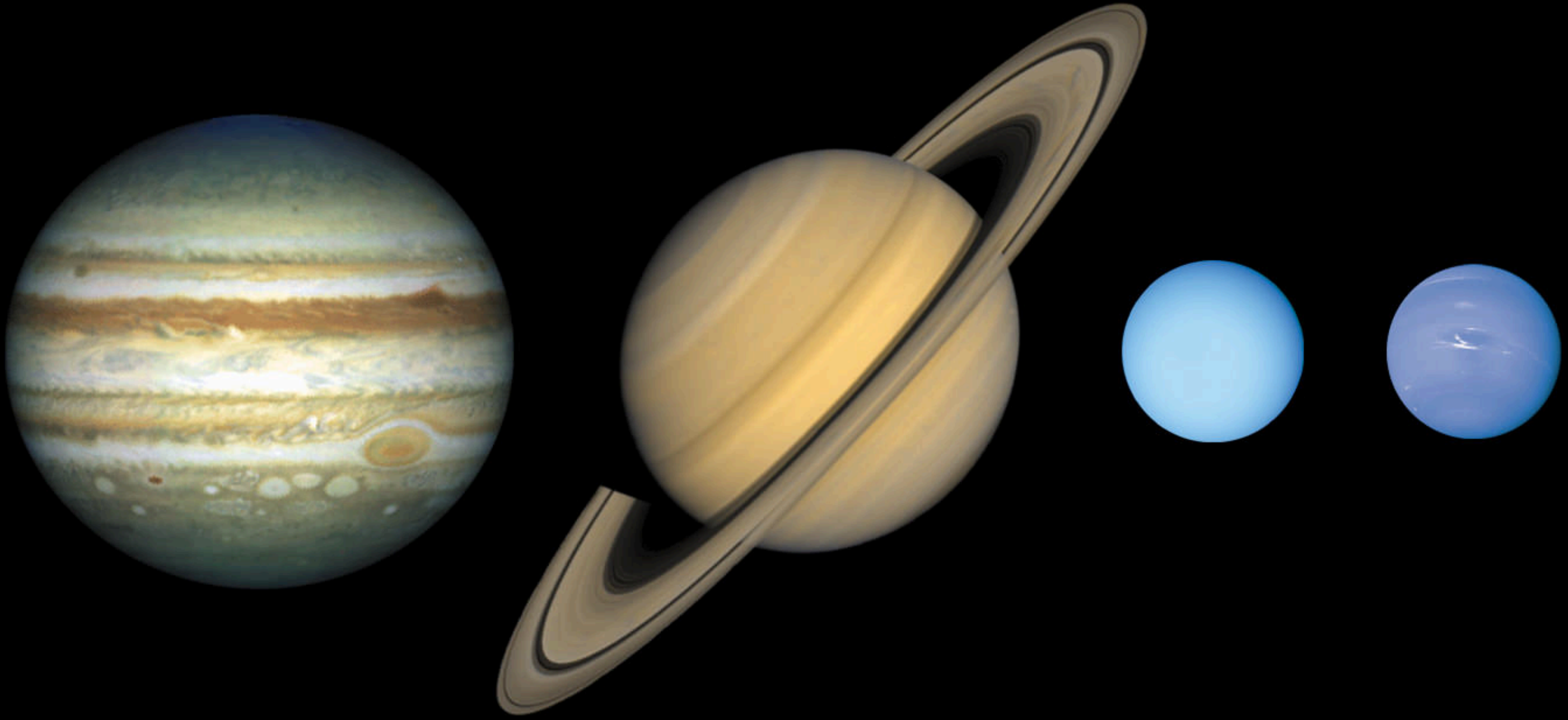
Great Barriers in planet Formation - Palm Cove, Australia - July 23, 2019

The Masses and Origins of Directly Imaged (Exo)-Planets

+ Bonus Material on MWC 758

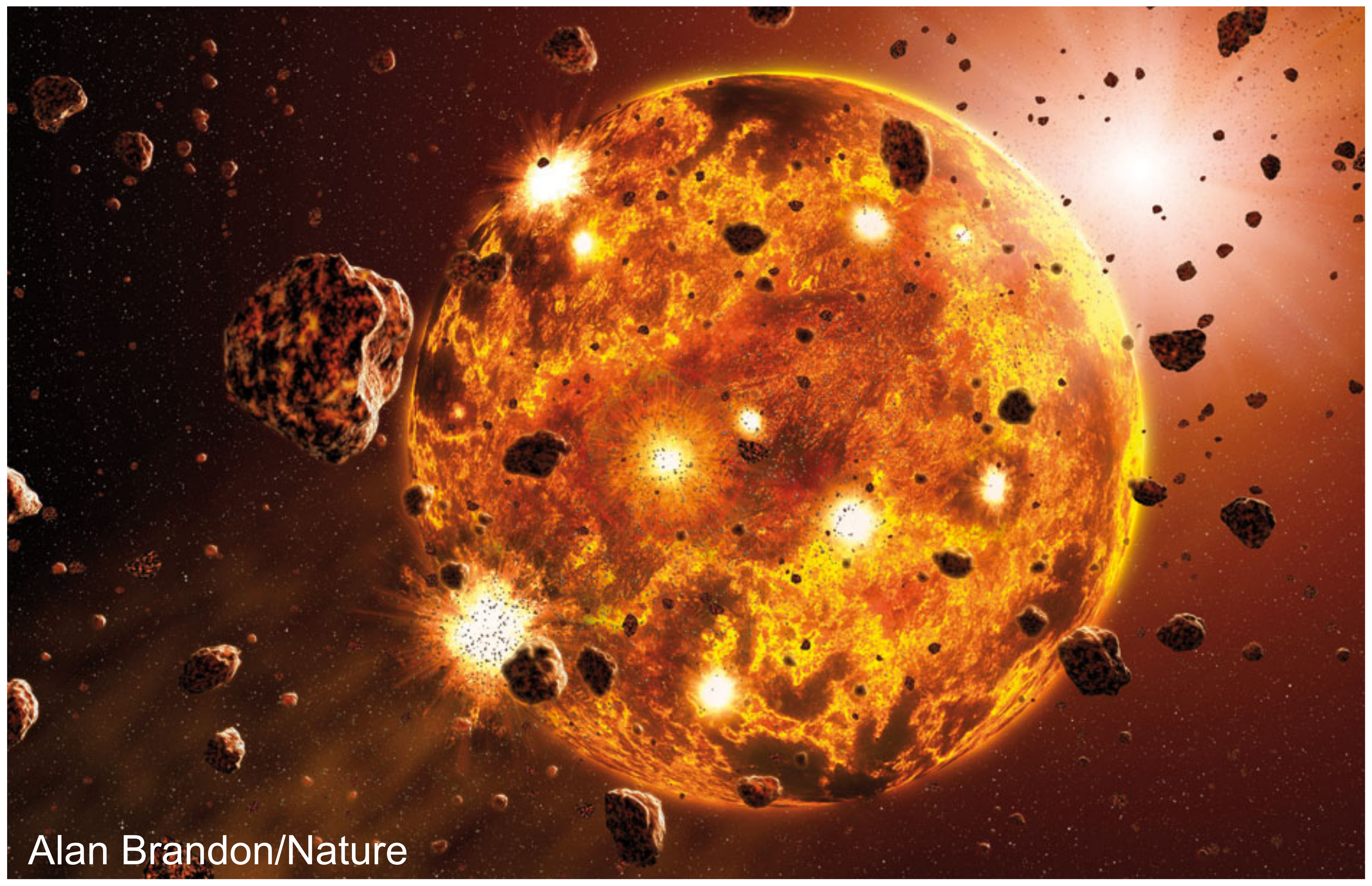


Kevin Wagner
University of Arizona / NSF+NExSS

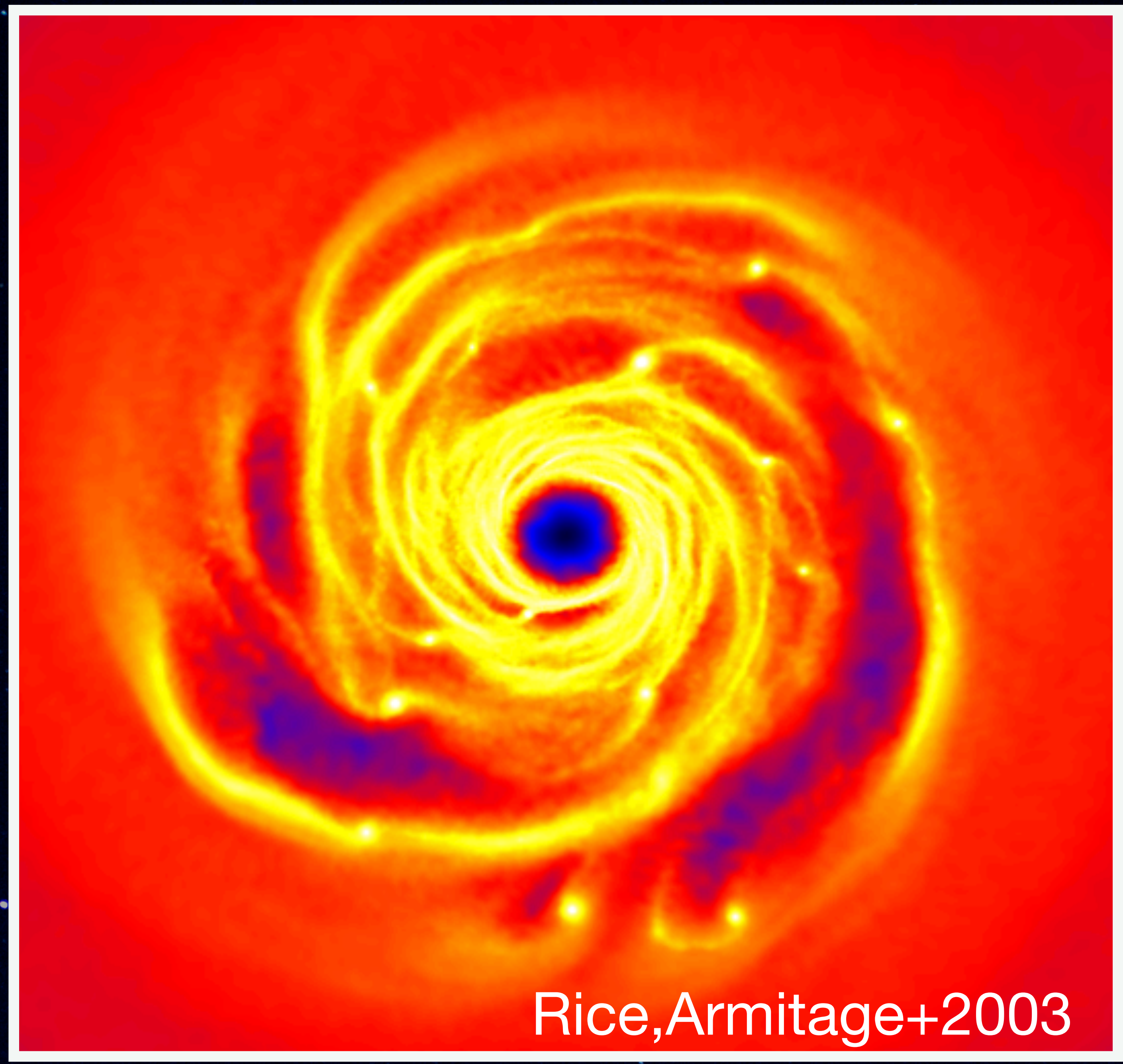
@AstroWagner

How do giant planets form?

Core Accretion and/or Gravitational Instability?



vs.



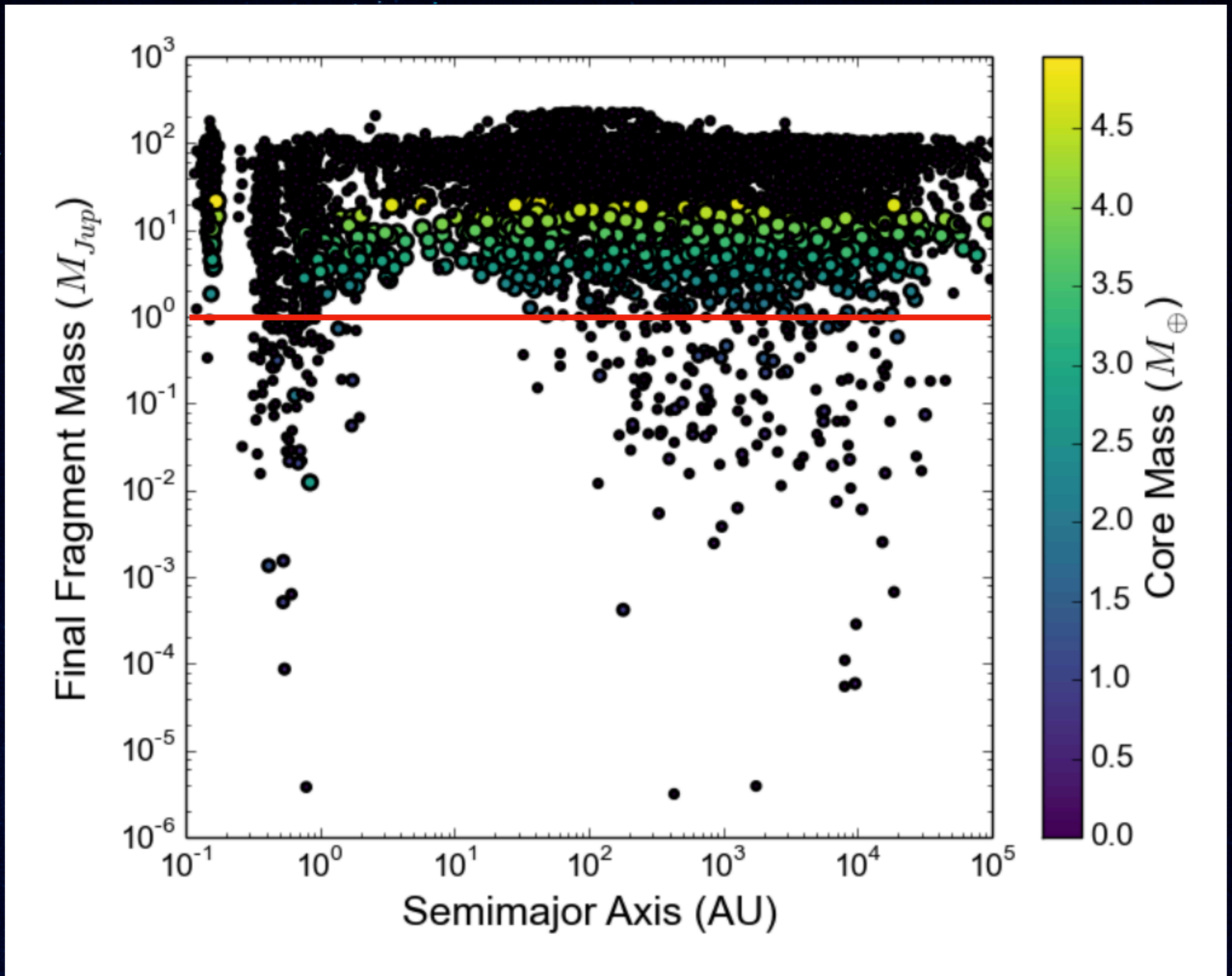
Different Timescales, Challenges, Resulting Populations

CA: Pollack+1996, Mordasini+2009,2012

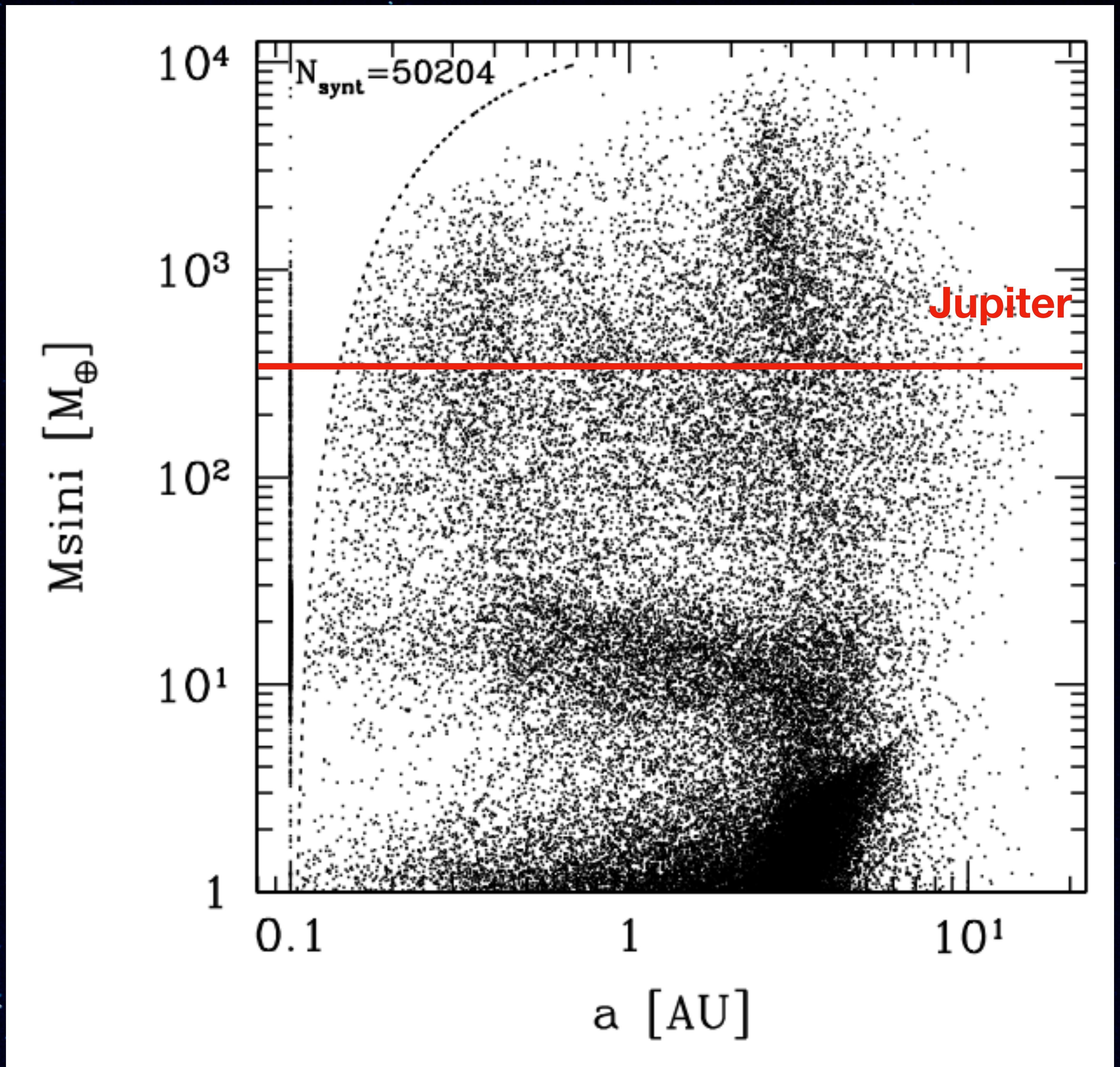
GI: Boss 1997, Kratter+2010, 2016 review, Forgan+2018

Population Synthesis of GI vs. CA:

Top vs. Bottom Heavy Mass Distributions



GI: Forgan+2018



Mordasini+2009

The Mass Function is a Clear Diagnostic of the Dominant Formation Mechanism

“THE MASS FUNCTION, MULTIPLICITY, AND ORIGINS OF WIDE-ORBIT GIANT PLANETS”

Wagner, Apai, Kratter 2019, ApJ **arXiv:1904.04638**

Conventional approach:

1. carry out a survey

2. assume a mass function and radial profile
↑ ↓
3. compare predictions with survey results

(Metchev & Hillenbrand 2009, Galicher et al. 2016, Vigan et al. 2017, Stone et al. 2018, Nielsen et al. 2019 etc.)

Our new approach:

1. measure the *relative companion* mass function (CMF) directly from the detections of past surveys

2. use survival analysis estimate the correction for biases at low masses from the detection limits*

3. estimate multiplicity from CMF+detection limits

***enabled by very deep follow-up observations**

4. link results to formation scenarios

Defining our Sample

Publications of the Astronomical Society of the Pacific, 128:102001 (38pp), 2016 October
doi:10.1088/1538-3873/128/968/102001

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Imaging Extrasolar Giant Planets

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Received 2016 March 18; accepted 2016 May 8; published 2016 August 29

Abstract

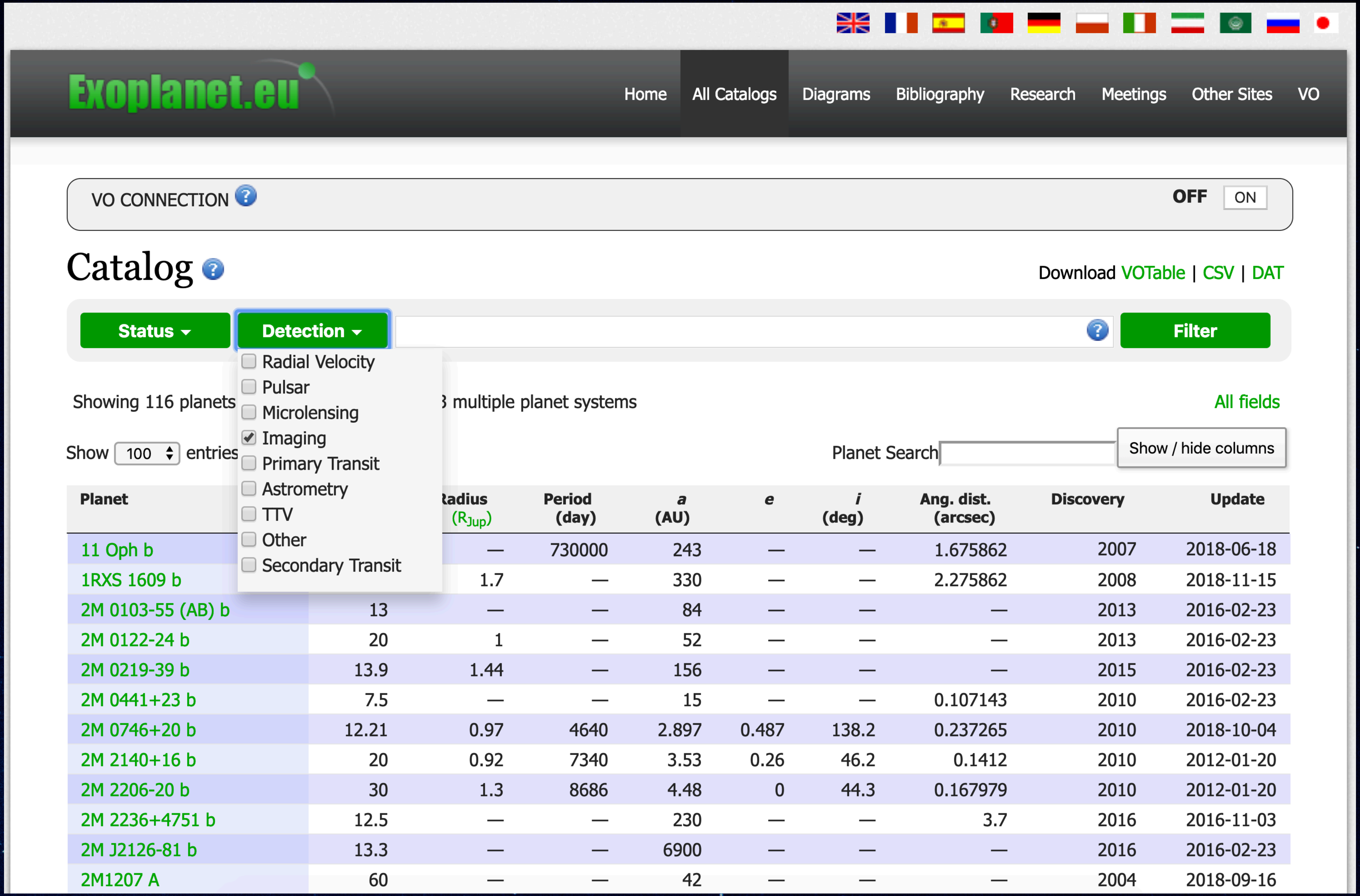
High-contrast adaptive optics (AO) imaging is a powerful technique to probe the architectures of planetary systems from the outside-in and survey the atmospheres of self-luminous giant planets. Direct imaging has rapidly matured over the past decade and especially the last few years with the advent of high-order AO systems, dedicated planet-finding instruments with specialized coronagraphs, and innovative observing and post-processing strategies to suppress speckle noise. This review summarizes recent progress in high-contrast imaging with particular emphasis on observational results, discoveries near and below the deuterium-burning limit, and a practical overview of large-scale surveys and dedicated instruments. I conclude with a statistical meta-analysis of deep imaging surveys in the literature. Based on observations of 384 unique and single young (≈5–300 Myr) stars spanning stellar masses between 0.1 and 3.0 $M_{\odot}$, the overall occurrence rate of 5–13 M_{Jup} companions at orbital distances of 30–300 au is $0.6^{+0.7}_{-0.5}$% assuming hot-start evolutionary models. The most massive giant planets regularly accessible to direct imaging are about as rare as hot Jupiters are around Sun-like stars. Dividing this sample into individual stellar mass bins does not reveal any statistically significant trend in planet frequency with host mass: giant planets are found around $2.8^{+3.7}_{-2.3}$% of BA stars, <4.1% of FGK stars, and <3.9% of M dwarfs. Looking forward, extreme AO systems and the next generation of ground- and space-based telescopes with smaller inner working angles and deeper detection limits will increase the pace of discovery to ultimately map the demographics, composition, evolution, and origin of planets spanning a broad range of masses and ages.

Key words: planets and satellites: detection – planets and satellites: gaseous planets

Online material: color figures

Bowler 2016, *PASP*

Defining our sample



Planet		Radius (R_{Jup})	Period (day)	*a* (AU)	*e*	*i* (deg)	Ang. dist. (arcsec)	Discovery	Update
11 Oph b		—	730000	243	—	—	1.675862	2007	2018-06-18
1RXS 1609 b		1.7	—	330	—	—	2.275862	2008	2018-11-15
2M 0103-55 (AB) b	13	—	—	84	—	—	—	2013	2016-02-23
2M 0122-24 b	20	1	—	52	—	—	—	2013	2016-02-23
2M 0219-39 b	13.9	1.44	—	156	—	—	—	2015	2016-02-23
2M 0441+23 b	7.5	—	—	15	—	—	0.107143	2010	2016-02-23
2M 0746+20 b	12.21	0.97	4640	2.897	0.487	138.2	0.237265	2010	2018-10-04
2M 2140+16 b	20	0.92	7340	3.53	0.26	46.2	0.1412	2010	2012-01-20
2M 2206-20 b	30	1.3	8686	4.48	0	44.3	0.167979	2010	2012-01-20
2M 2236+4751 b	12.5	—	—	230	—	—	3.7	2016	2016-11-03
2M J2126-81 b	13.3	—	—	6900	—	—	—	2016	2016-02-23
2M1207 A	60	—	—	42	—	—	—	2004	2018-09-16

Cross-checking our sample

NASA EXOPLANET ARCHIVE
NASA EXOPLANET SCIENCE INSTITUTE

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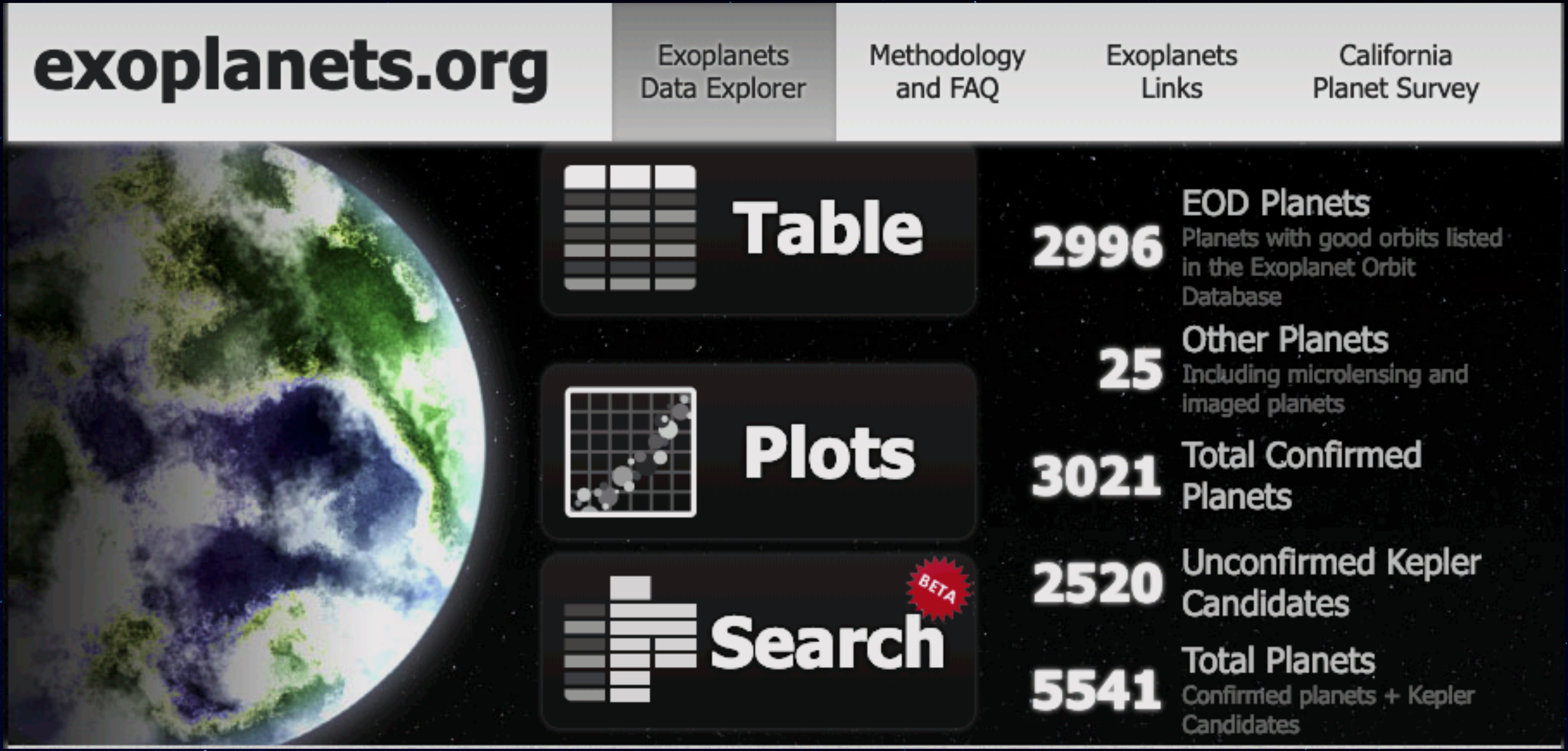
Confirmed Planets

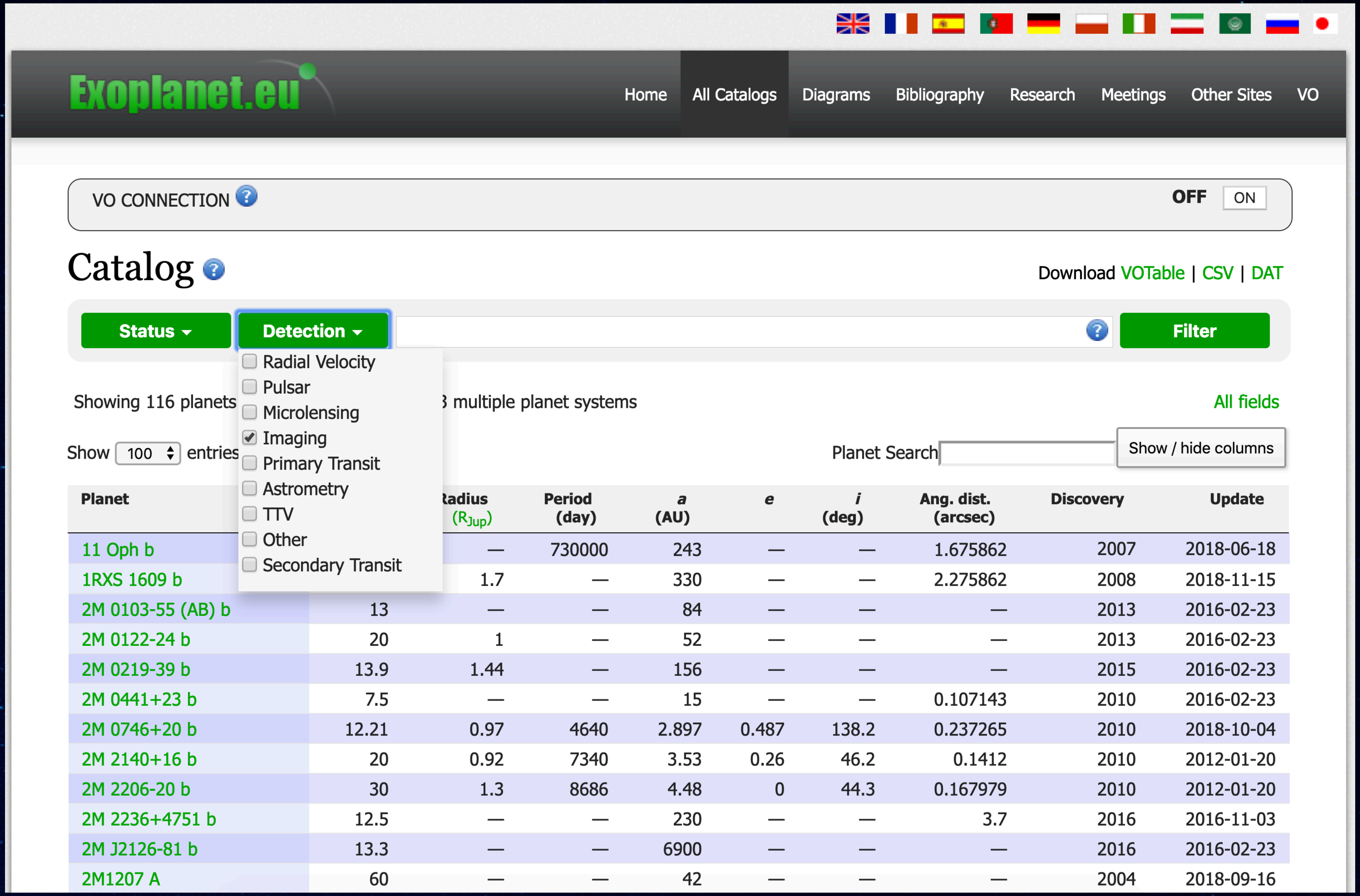
Host Name	Planet Letter	Planet Name	Discovery Method	Number of Planets in System	Orbital Period [days]	Orbit Semi-Major Axis [AU]	Eccentricity	Planet Mass or M*sin(i) [Jupiter mass]	Planet Mass or M*sin(i) Provenance	Planet Radius [Jupiter radii]	Planet D [g/cm*
			Imaging								
1RXS J160929.1-210524	b	1RXS J160929.1-	Imaging	1		330		8±1	Mass		
2MASS J01225093-2439505	b	2MASS J0122509	Imaging	1		52±6		24.5±2.5	Mass		
2MASS J02192210-3925225	b	2MASS J0219221	Imaging	1		156±10		13.9±1.1	Mass	1.44±0.03	
2MASS J04414489+2301513	b	2MASS J0441448	Imaging	1		15.0		7.5±2.5	Mass		
2MASS J12073346-3932539	b	2MASS J1207334	Imaging	1		46±5		4±1	Mass		
2MASS J21402931+1625183 A	b	2MASS J2140293	Imaging	1	7336.5 $^{+1934.5}_{-584.0}$		0.26±0.06	20.95 $^{+83.79}_{-20.95}$	Mass	0.92 $^{+0.39}_{-0.36}$	
2MASS J22362452+4751425	b	2MASS J2236245	Imaging	1		230±20		12.5±1.5	Mass		
51 Eri	b	51 Eri b	Imaging	1		13.2±0.2		2	Mass		
AB Pic	b	AB Pic b	Imaging	1		260		13.5±0.5	Mass		
CFBDSIR J145829+101343	b	CFBDSIR J14582	Imaging	1	10037.5±2737.5	2.6±0.3		10.5±4.5	Mass		
CHXR 73	b	CHXR 73 b	Imaging	1		210		12.569 $^{+8.379}_{-5.237}$	Mass		
CT Cha	b	CT Cha b	Imaging	1		440		17±6	Mass	2.20 $^{+0.81}_{-0.60}$	
DH Tau	b	DH Tau b	Imaging	1		330		11 $^{+10}_{-3}$	Mass		
FU Tau	b	FU Tau b	Imaging	1		800		16	Mass		
Fomalhaut	b	Fomalhaut b	Imaging	1	555530 $^{+184690}_{-353320}$	160 $^{+33}_{-79}$	0.87 $^{+0.11}_{-0.05}$				
GJ 504	b	GJ 504 b	Imaging	1		43.5		4.0 $^{+4.5}_{-1.0}$	Mass		
GQ Lup	b	GQ Lup b	Imaging	1		100		20	Mass	3.0±0.5	
GSC 06214-00210	b	GSC 06214-0021(	Imaging	1		320±30		16±1	Mass		
GU Psc	b	GU Psc b	Imaging	1		2000±200		11.3±1.7	Mass	1.265±0.115	
HD 100546	b	HD 100546 b	Imaging	1		53±2				6.9 $^{+2.7}_{-2.9}$	
HD 106906	b	HD 106906 b	Imaging	1		650		11±2	Mass		
HD 203030	b	HD 203030 b	Imaging	1		487.1±1.8		24.090 $^{+8.379}_{-11.521}$	Mass		
HD 95086	b	HD 95086 b	Imaging	1		55.7±2.5		5±2	Mass		
HIP 65426	b	HIP 65426 b	Imaging	1		92		9.0±3.0	Mass	1.5±0.1	
HIP 78530	b	HIP 78530 b	Imaging	1		740±60		23±1	Mass		
HN Peg	b	HN Peg b	Imaging	1		773±13		21.9987±9.42803	Mass	1.05066 $^{+0.136197}_{-0.0583702}$	
HR 2562	b	HR 2562 b	Imaging	1		20.3±0.3		30±15	Mass	1.11±0.11	

https://exoplanetarchive.ipac.caltech.edu/

Cross-checking our sample



Potentially useful aside: exoplanet.eu was the most complete, exoplanets.org was the least complete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- [ ] Microlensing
- [x] Imaging
- [ ] Primary Transit
- [ ] Astrometry
- [ ] TTV
- [ ] Other
- [ ] Secondary Transit

Showing 116 planets … 3 multiple planet systems — All fields

Show 100 entries — Planet Search — Show / hide columns

Planet		Radius (R_{Jup})	Period (day)	a (AU)	e	i (deg)	Ang. dist. (arcsec)	Discovery	Update
11 Oph b		—	730000	243	—	—	1.675862	2007	2018-06-18
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2M1207 A	60	—	—	42	—	—	—	2004	2018-09-16

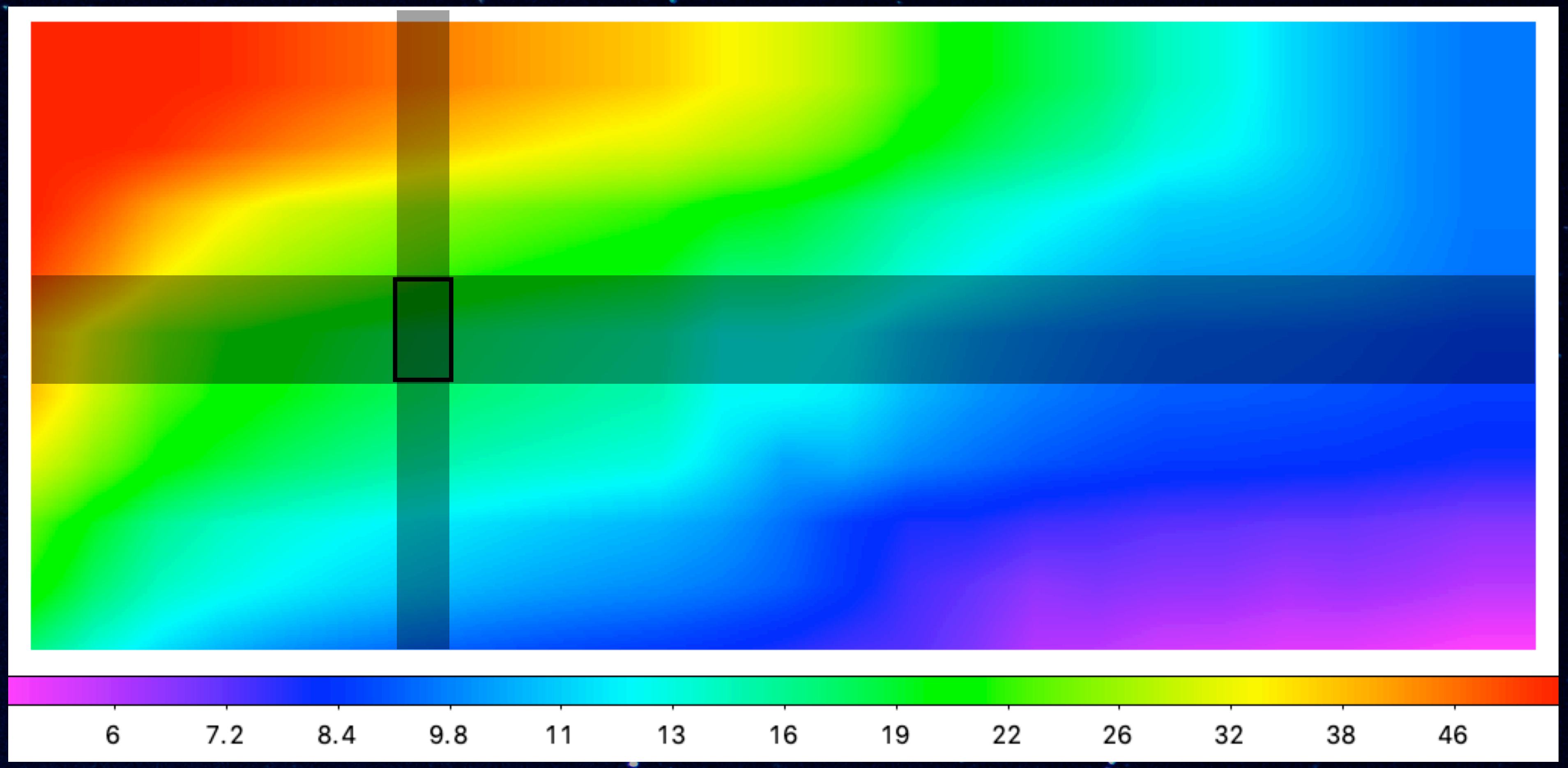
N=57 companions (as of February 2019)

Converting Photometry to Mass Probability Distributions

Inputs: age, distance, photometry ➔ *evolutionary model (initial conditions + cooling curve)*

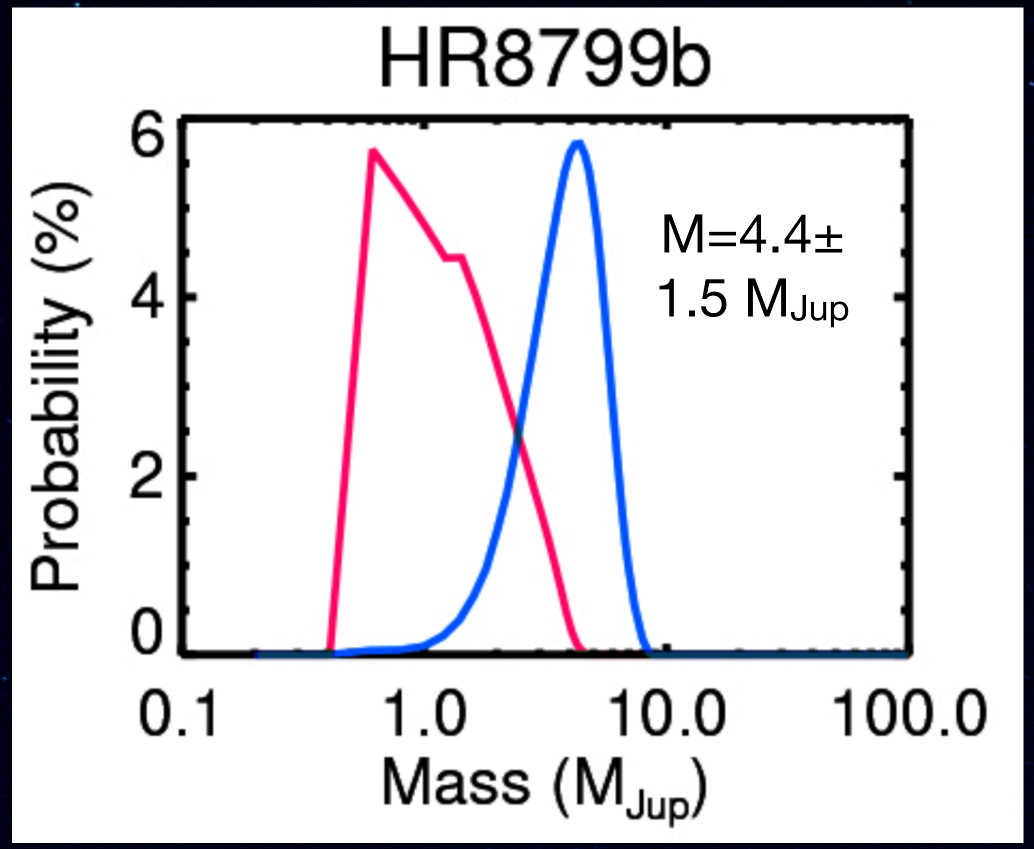
Mass

Age



Color (in chart) = K-band Photometric Magnitude

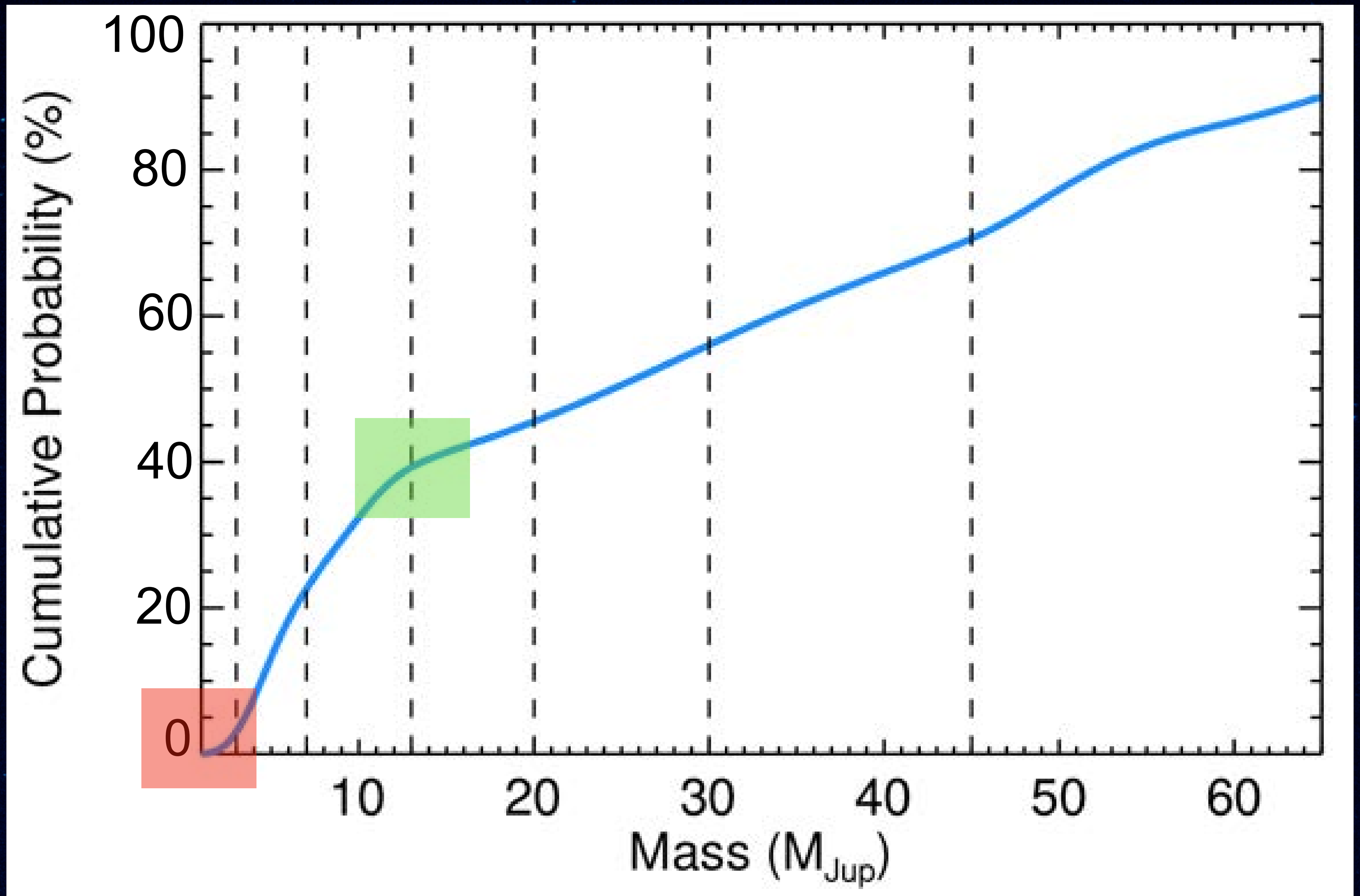
Final Mass Distributions



and Mass Detection Limit Distributions

MC Simulation over measurement uncertainties, thousands of trials

Estimating the mass function from detections alone



Wagner, Apai, & Kratter 2019

Derivative gives the relative mass function, or companion mass function (CMF)

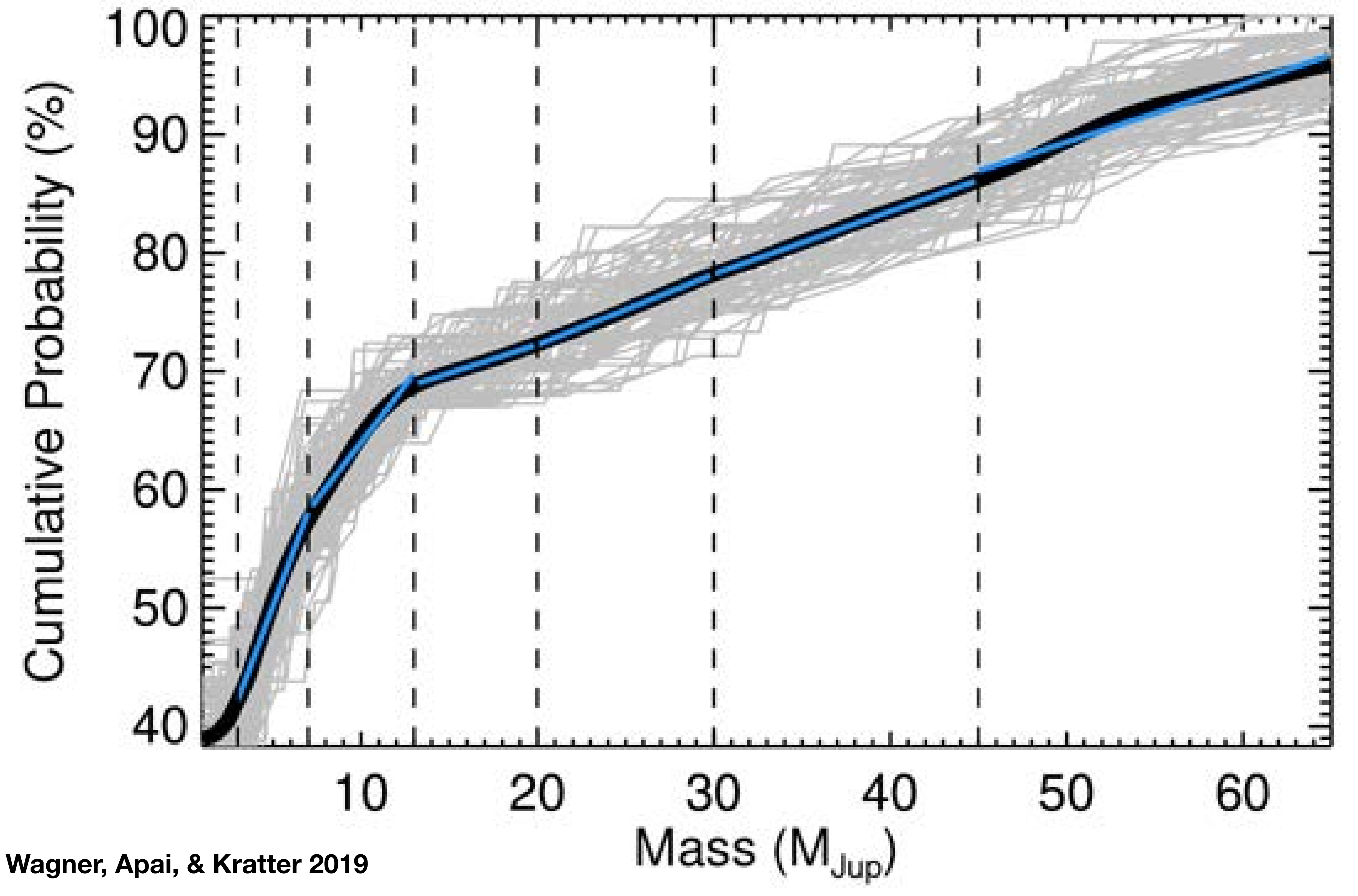
Inflection points: changes in the observed frequency

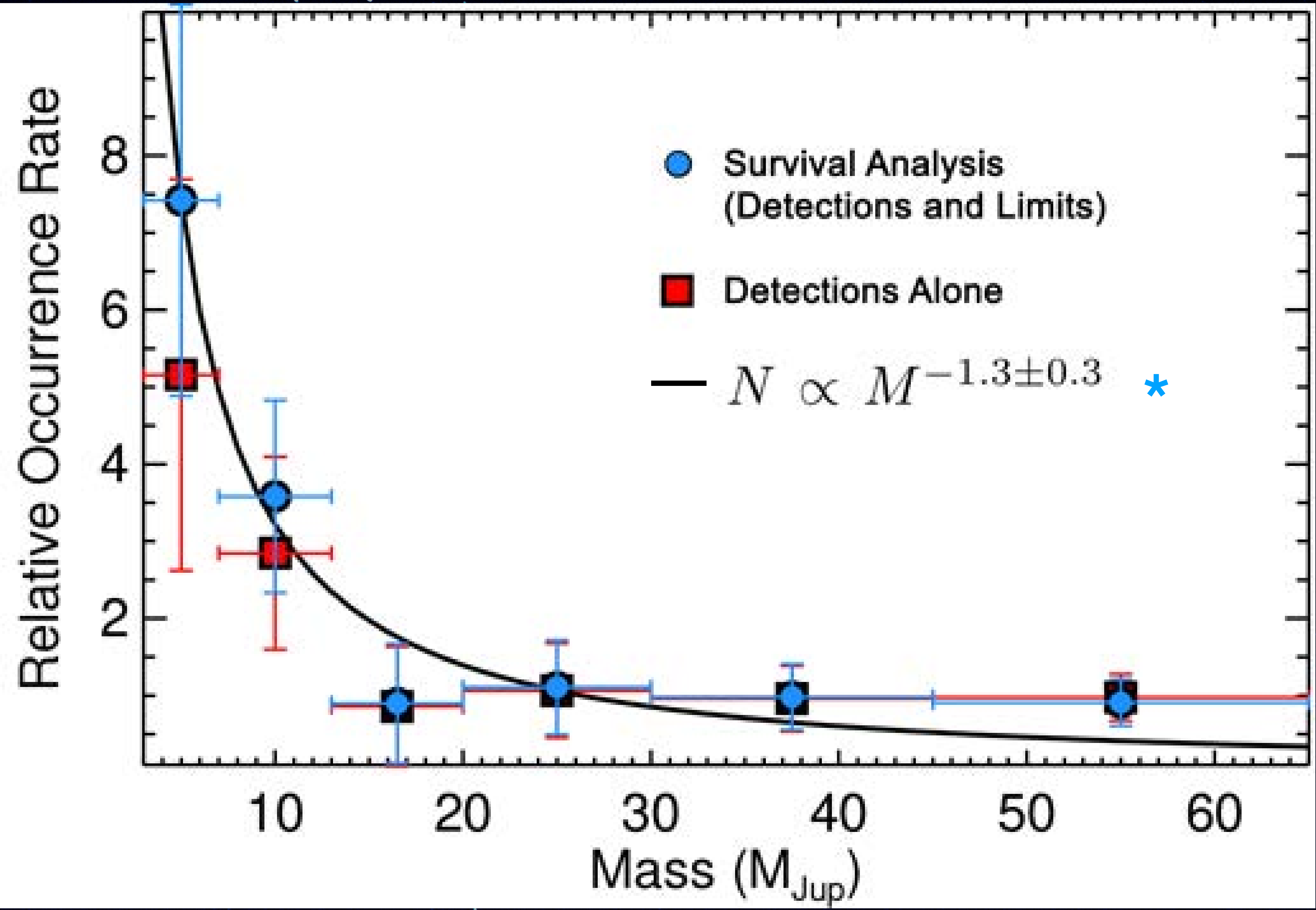
Problems: unphysical starting point at zero near 1-2 MJup (detection limit floor, observational bias)

Estimated correction for observational biases at low masses

KM estimator + MC simulation drawing from companion mass and detection limit probability distributions

Feigelson+Nelson 1985



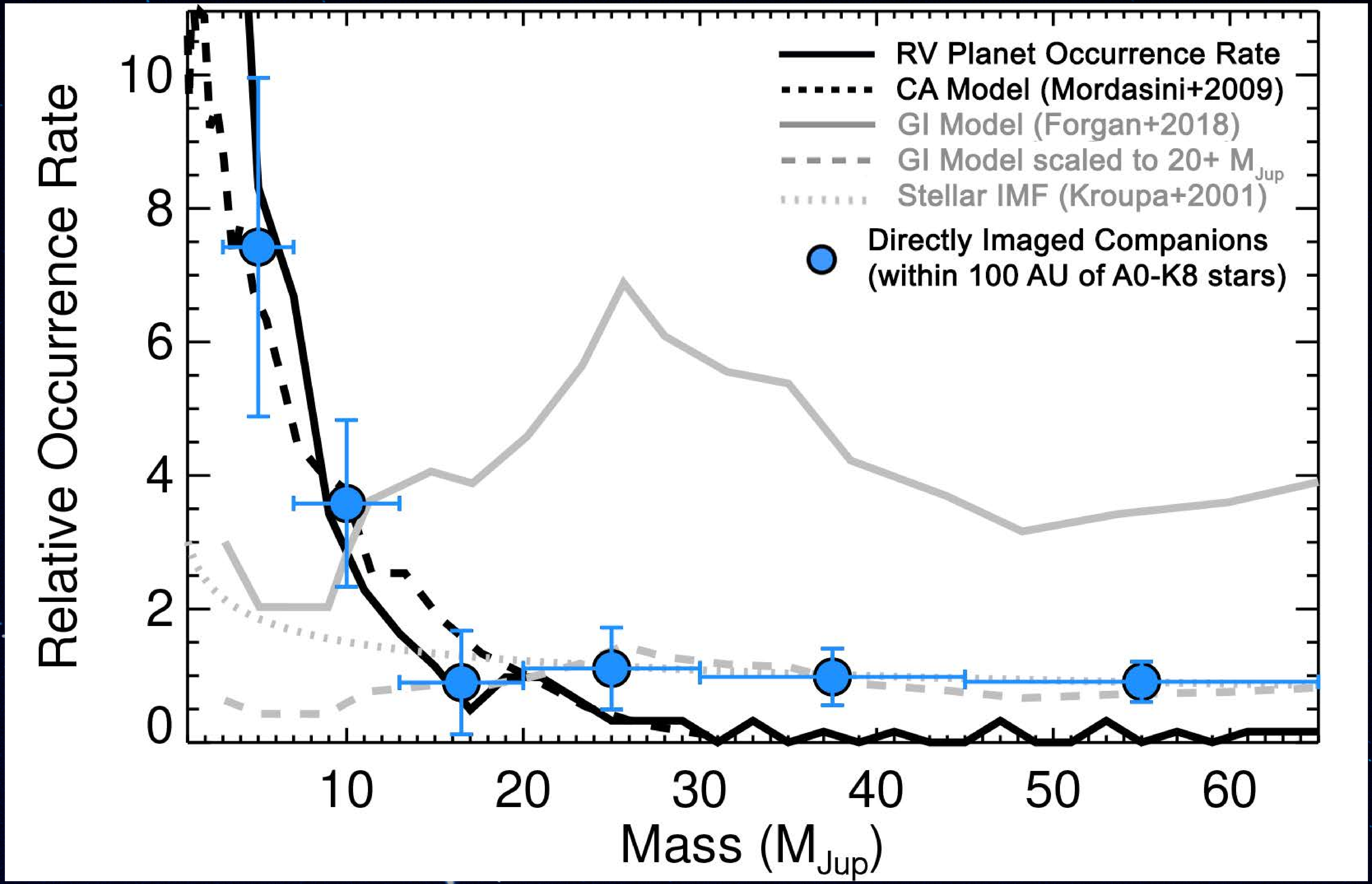


- Key assumption: one detection limit corresponds to *one* planet
- effective lower limit set by the detections alone (red points)

*Nielsen+2019, GPIES independently find a similar exponent (N ~ M^-1.4±0.8)

Comparison to Population Synthesis and Inner Planets

- Good match to CA pop. synth. (black dashed) models, and RV planets (black solid)
- Over-abundance of higher mass brown dwarfs: some instability-born companions
- Possibility to assign a probability of formation based on an object's mass



Wagner, Apai, & Kratter 2019

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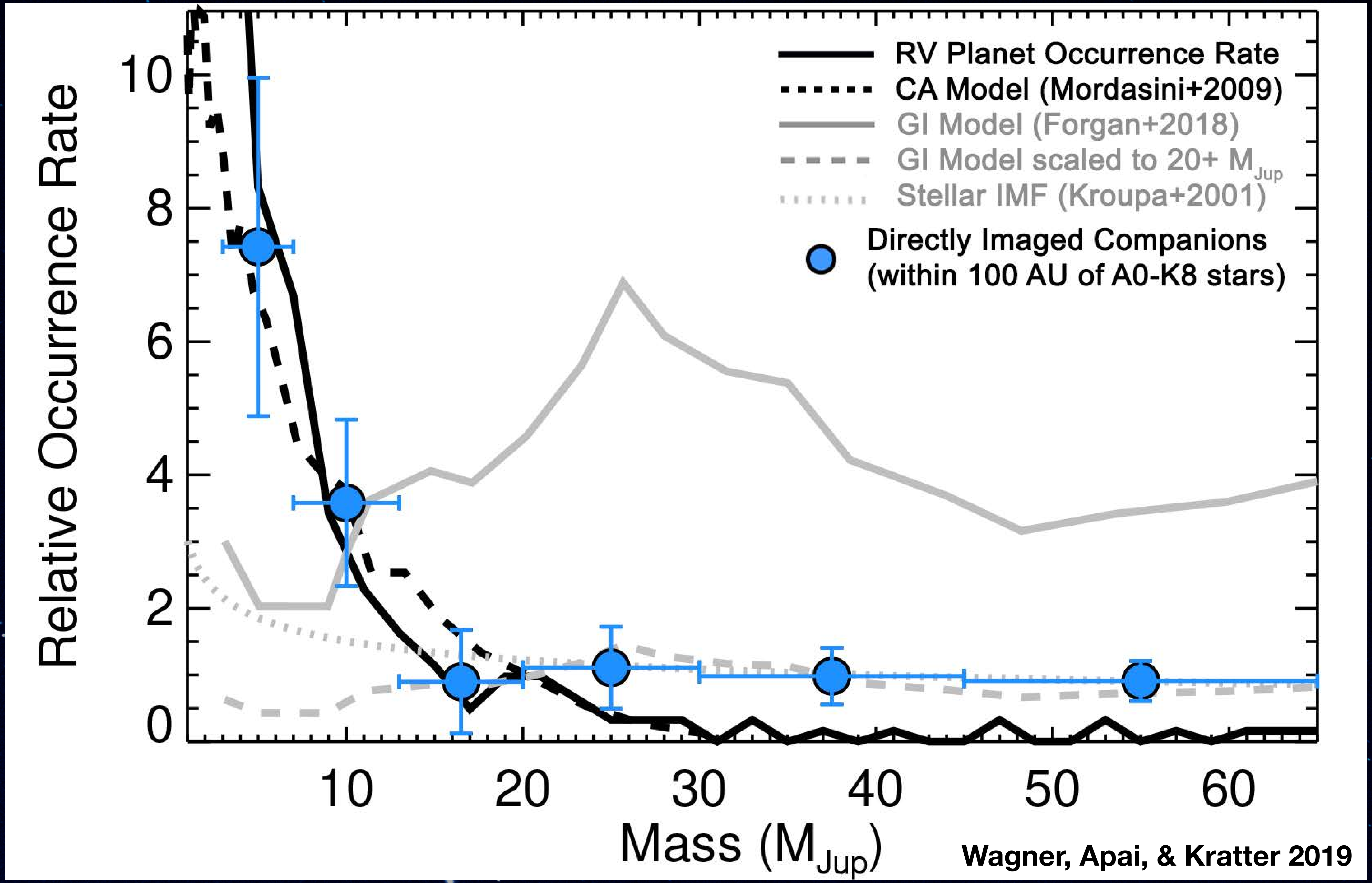

★ **Takeaway: the mass function is rising steeply toward smaller masses**

Multiplicity Among the Directly Imaged Planets

- Assume that each system has a second planet whose mass is drawn independently from the CMF

- P = the probability that a second planet would be
  a) a super-Jupiter (>2 MJup), and
  b) beneath the current detection limit

- *Many systems are consistent with hosting one or more additional super-Jupiters (mean = 68%).*

*** PDS 70 has since had a second planet discovery (Haffert+2019)**

TABLE 1
MULTIPLICITY PROBABILITIES

System	P(Double) %	P(Triple) %	P(Quad) %
51Erib	34.1	11.6	3.97
GJ504b	77.9	60.7	47.3
GJ758b	85.6	73.3	62.7
HD1160B	79.1	62.6	49.5
HD19467b	94.1	88.5	83.3
HD206893b	84.2	70.9	59.7
HD4113C	89.3	79.7	71.2
HD95086b	40.9	16.7	6.84
HD984b	76.2	58.1	44.2
HIP65426b	53.3	28.4	15.1
HIP73990b	100.	79.6	63.4
HIP74865b	74.3	55.2	41.0
HR2562b	68.3	46.6	31.9
HR3549b	60.8	37.0	22.5
HR8799b	100.	100.	100.
PDS70b	65.7	43.2	28.4
PZTelb	48.4	23.4	11.3
BetaPicb	22.5	5.06	1.14
KappaAndb	40.8	16.6	6.79
Mean	68.2%	50.4%	39.5%

NOTE. — Note: this table also serves to identify the companions that were considered as part of our primary analysis (those within 100 AU of A0-K8 stars), and is a subset of the objects whose properties are described Table 2.

Wagner+2019

Prospects for Future Discoveries

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Multiplicity Probabilities

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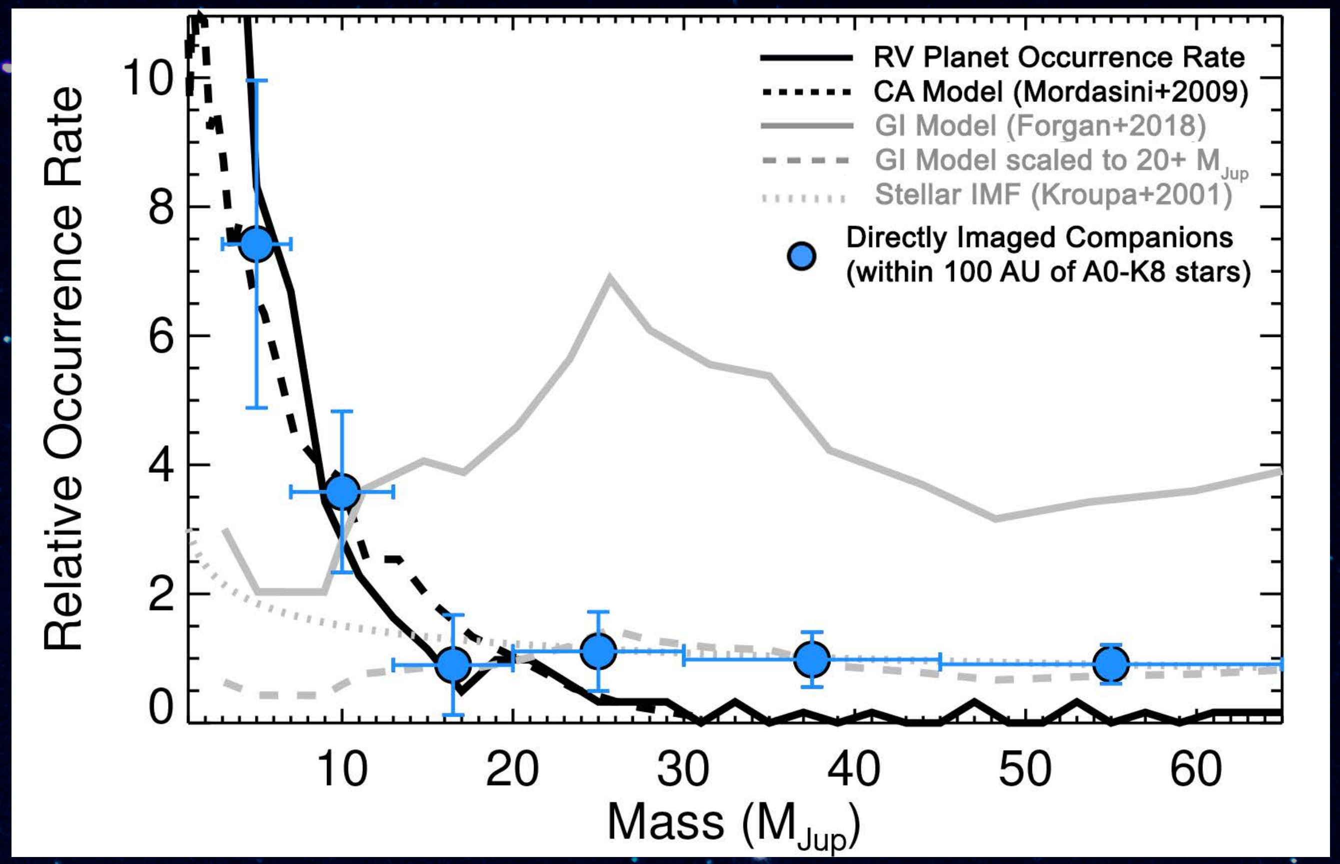
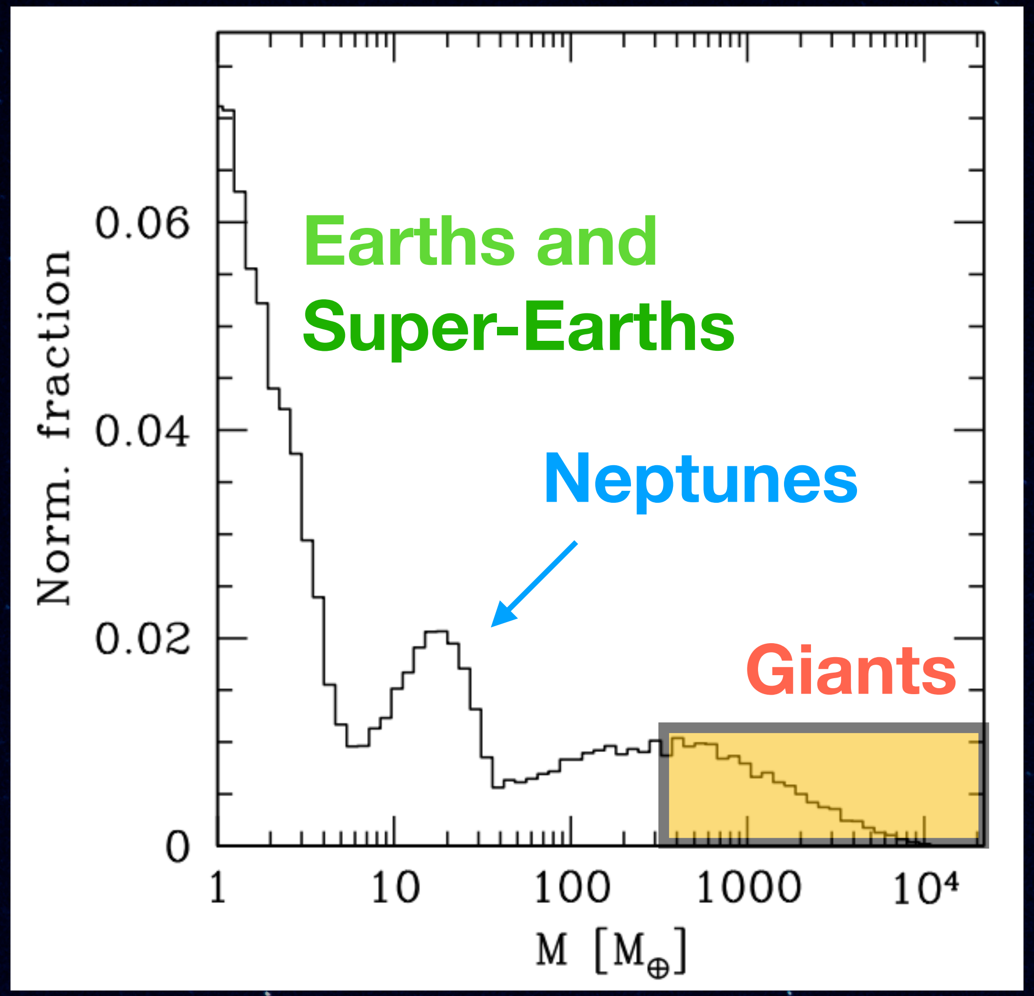
- **Multiplicity Probabilities -> new LBT program**
- **JWST will open up discovery space for young Saturn-mass planets in thermal light**
- **GMT and TMT will enable searches for Neptunes and Super-Earths (around select targets)**



Wagner+2019



Mordasini+2009

Prospects for Future Discoveries

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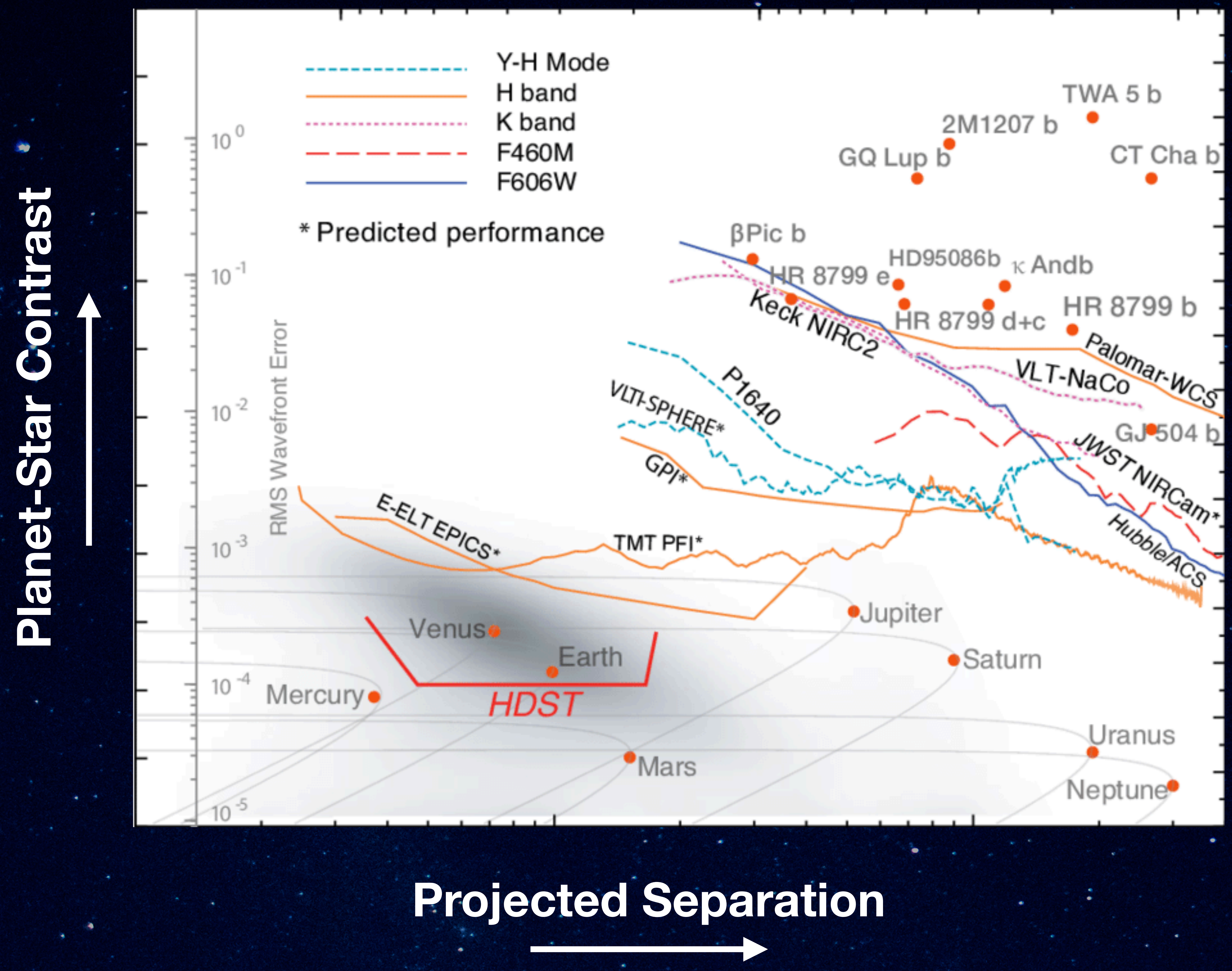
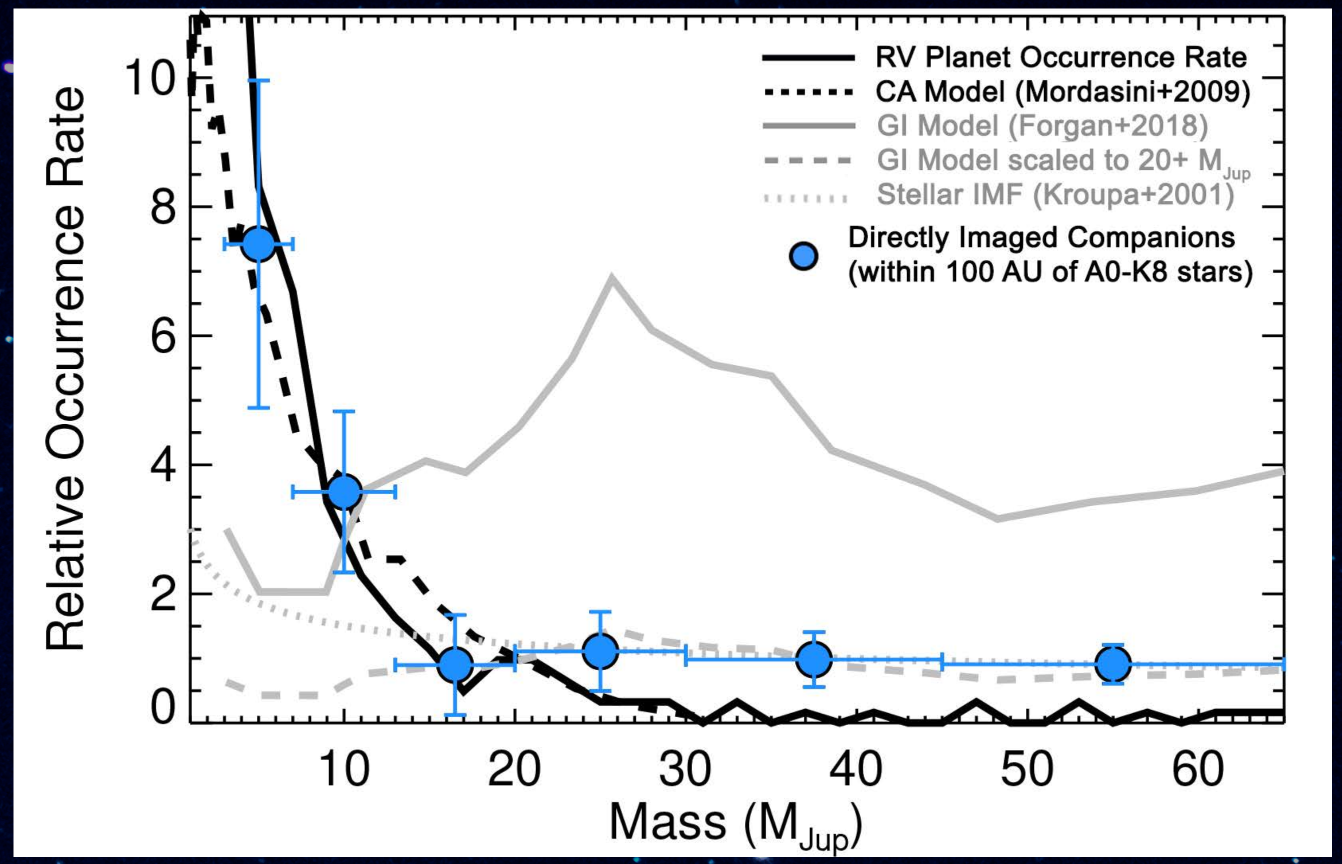
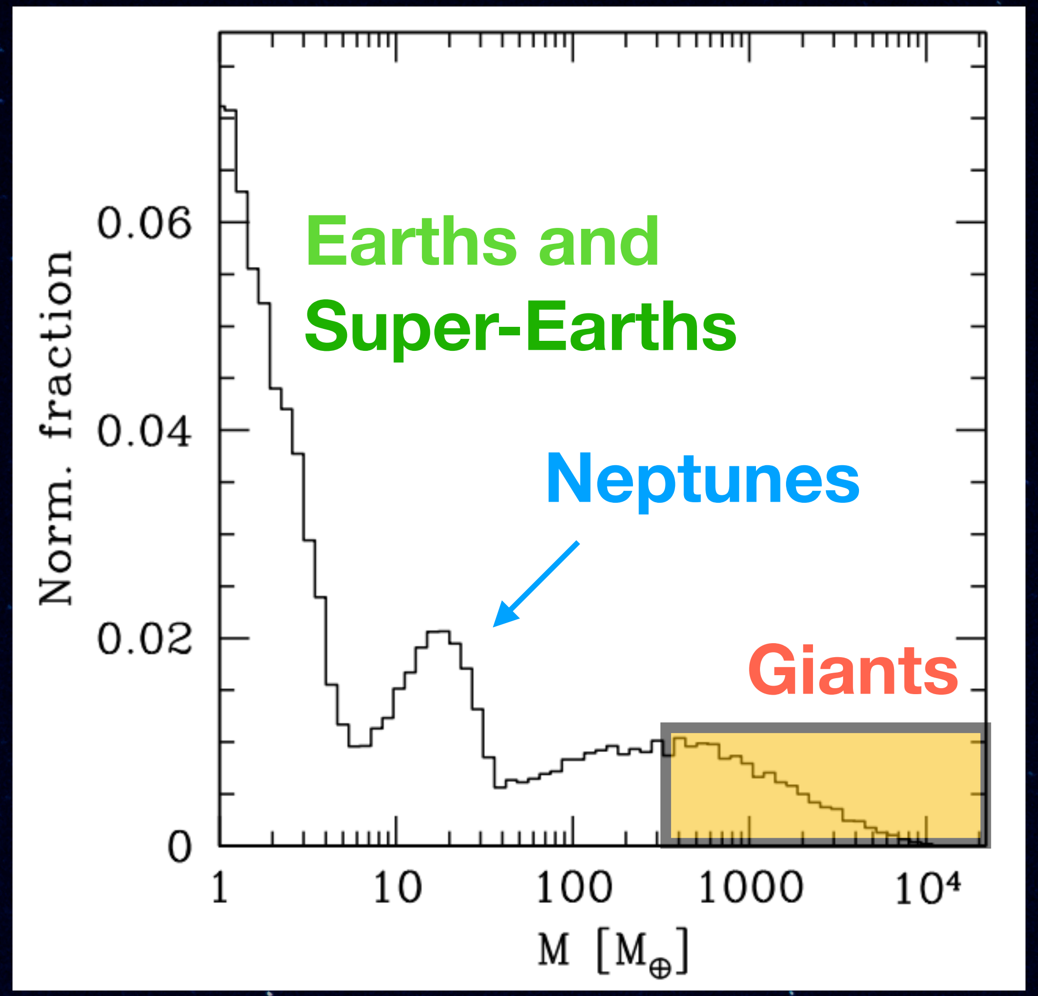


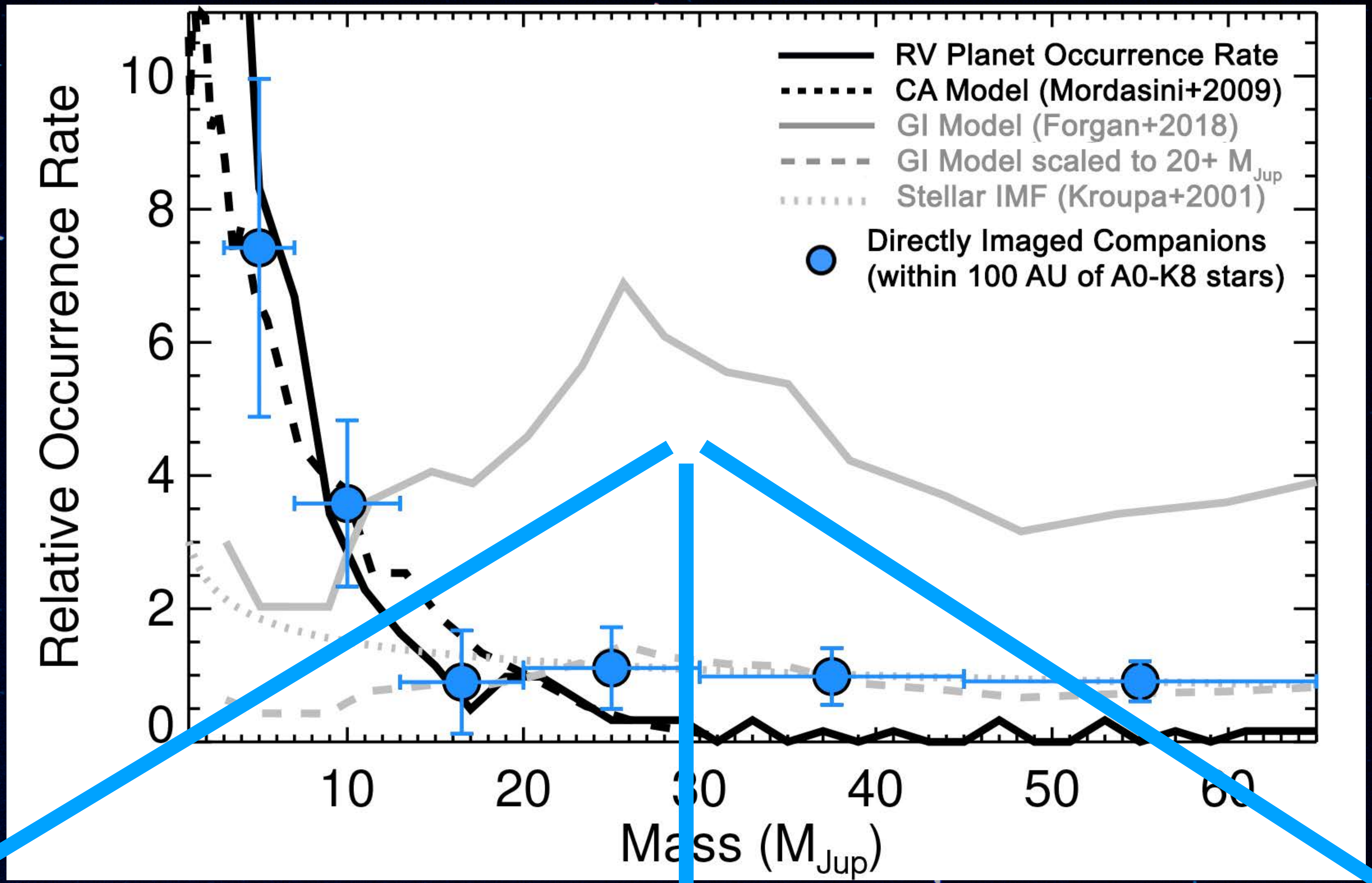


Wagner+2019



Mordasini+2009

Summary and Conclusions

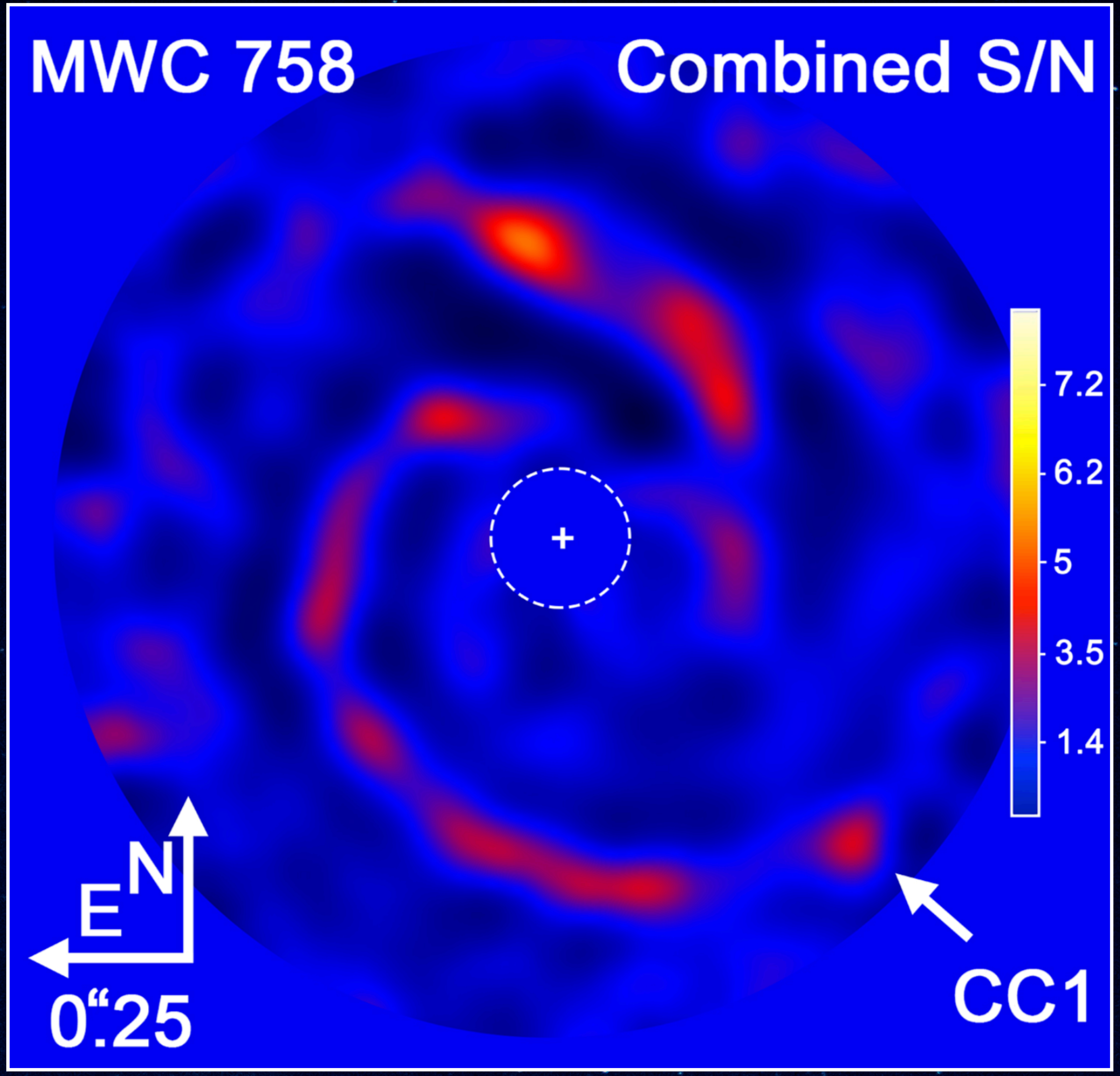


1) Directly Imaged Planets Have a Similar Mass Function to Inner Planets

2) Many of the known systems may have undetected planets.

3) Future, deeper surveys should reveal many more low-mass planets

Bonus Slide: A New Planet Candidate around MWC 758

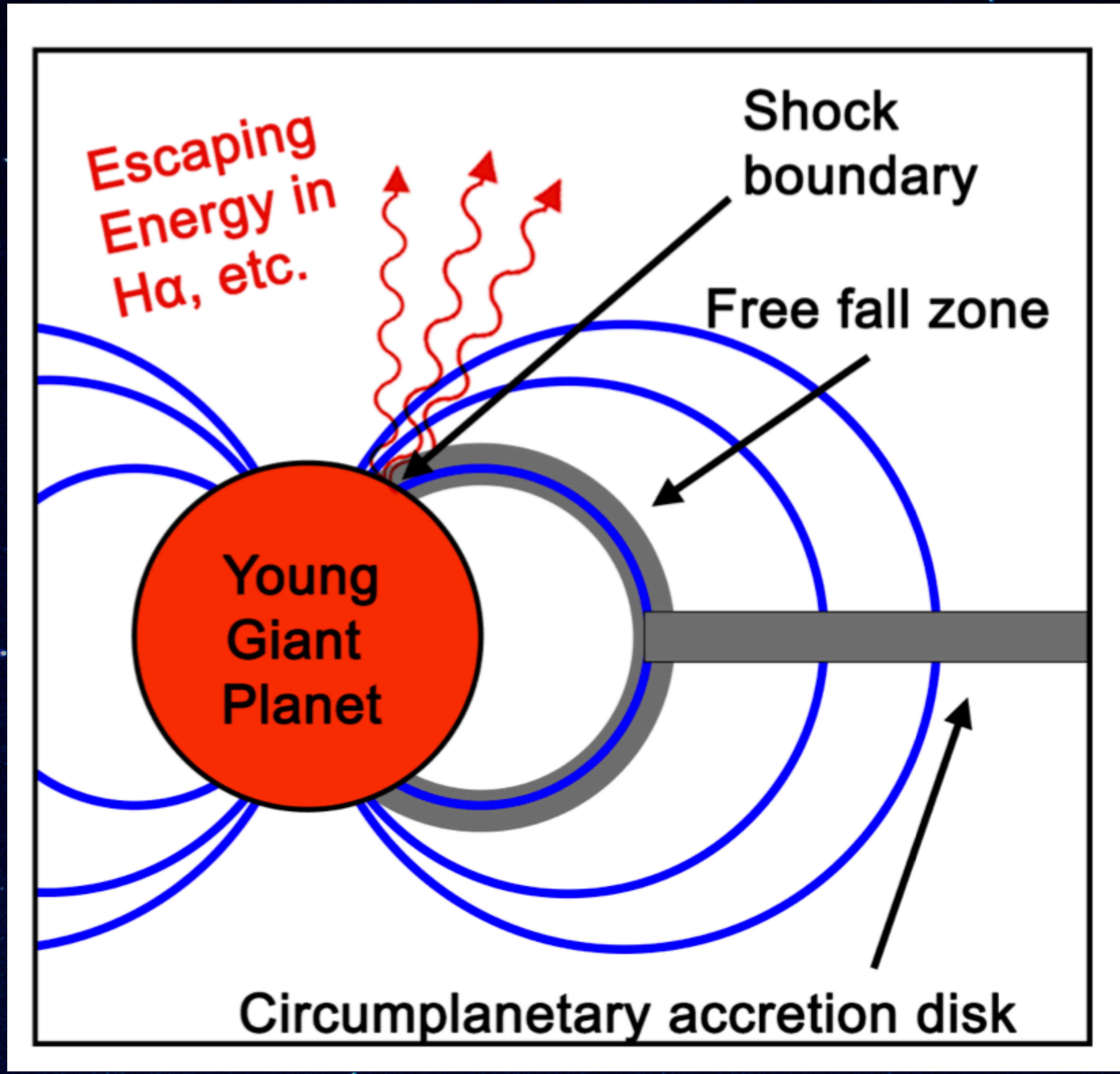


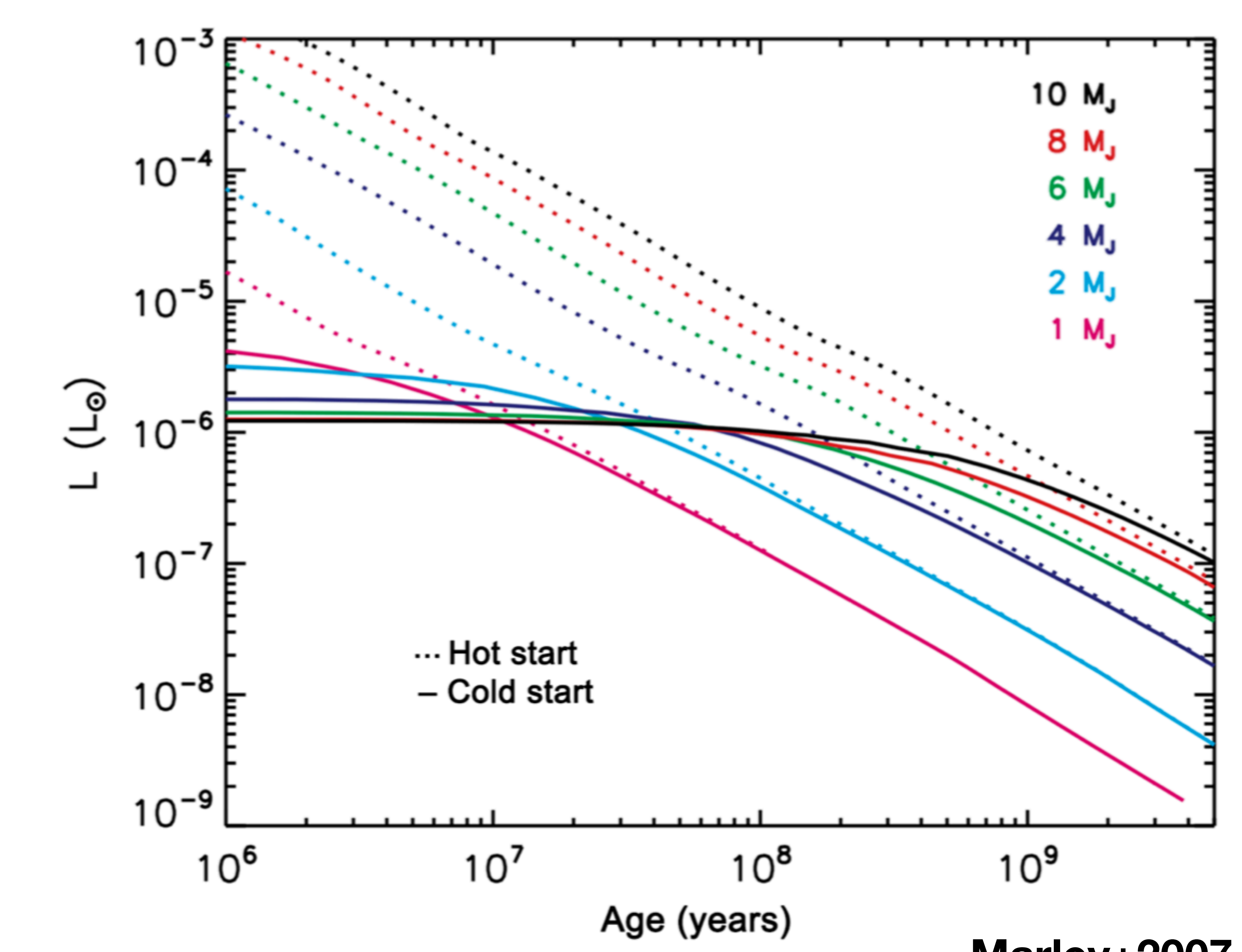
- Positioned at the end of the Southern (primary) arm (Dong+2018)
- No polarized light counterpart (Benisty+2015)
- L' - M' = 0.75 -> the source is red, while the rest of the disk is gray
- Most likely separation of 0.6" predicted from spiral rotation speed (Ren et al. 2018) – CC1 is observed at 0.62"
- Mass estimate: 2–5 Jupiter masses -> likely capable of driving spiral arms (Fung&Dong 2015)
- Forward modeling -> would likely have detected the Reggiani+2018 candidate interior to the spiral arms

Wagner+2019, ApJ in press, arxiv:1907.06655

Extra Slides

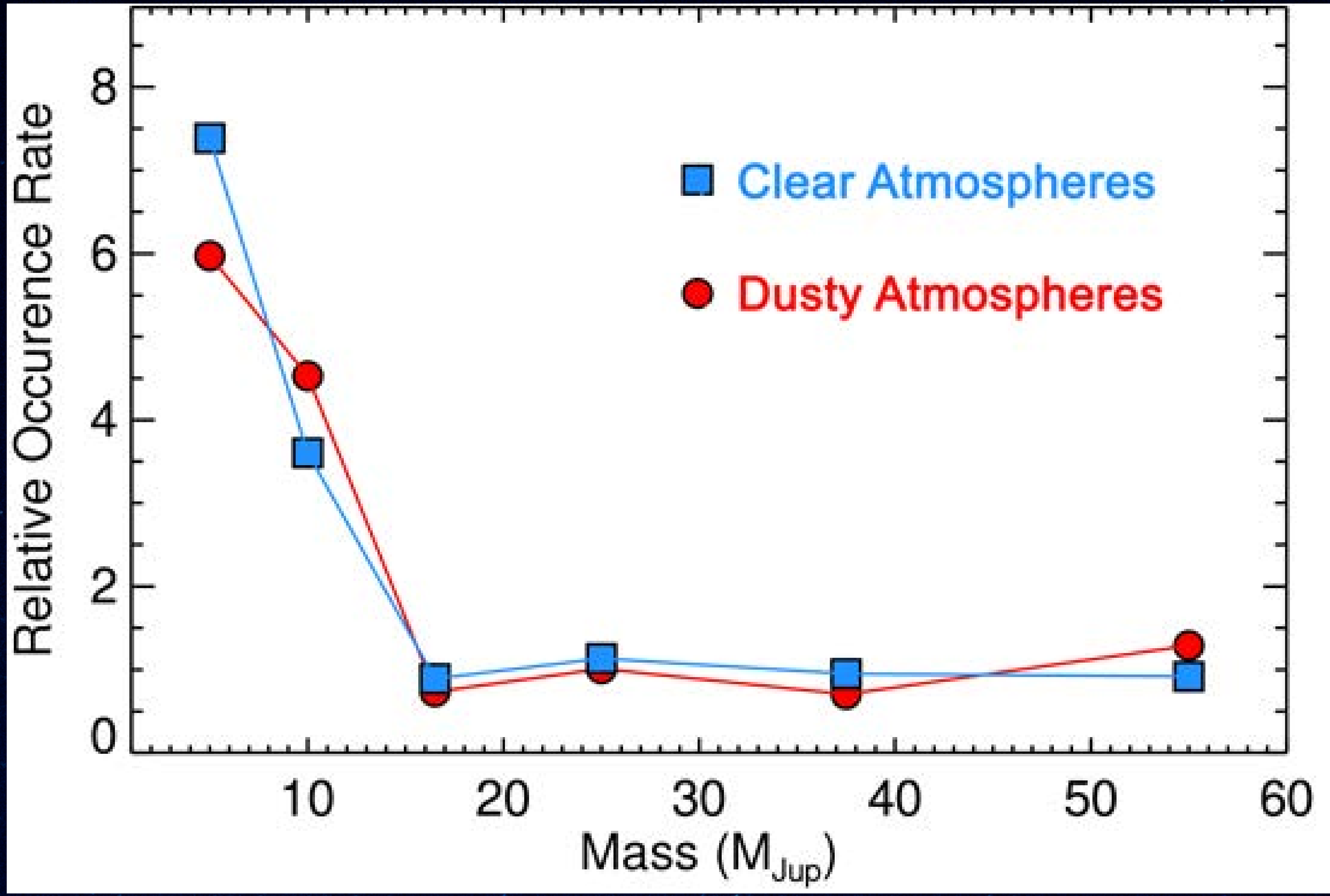
Evolutionary Models:
Initial Conditions and Cooling Curves

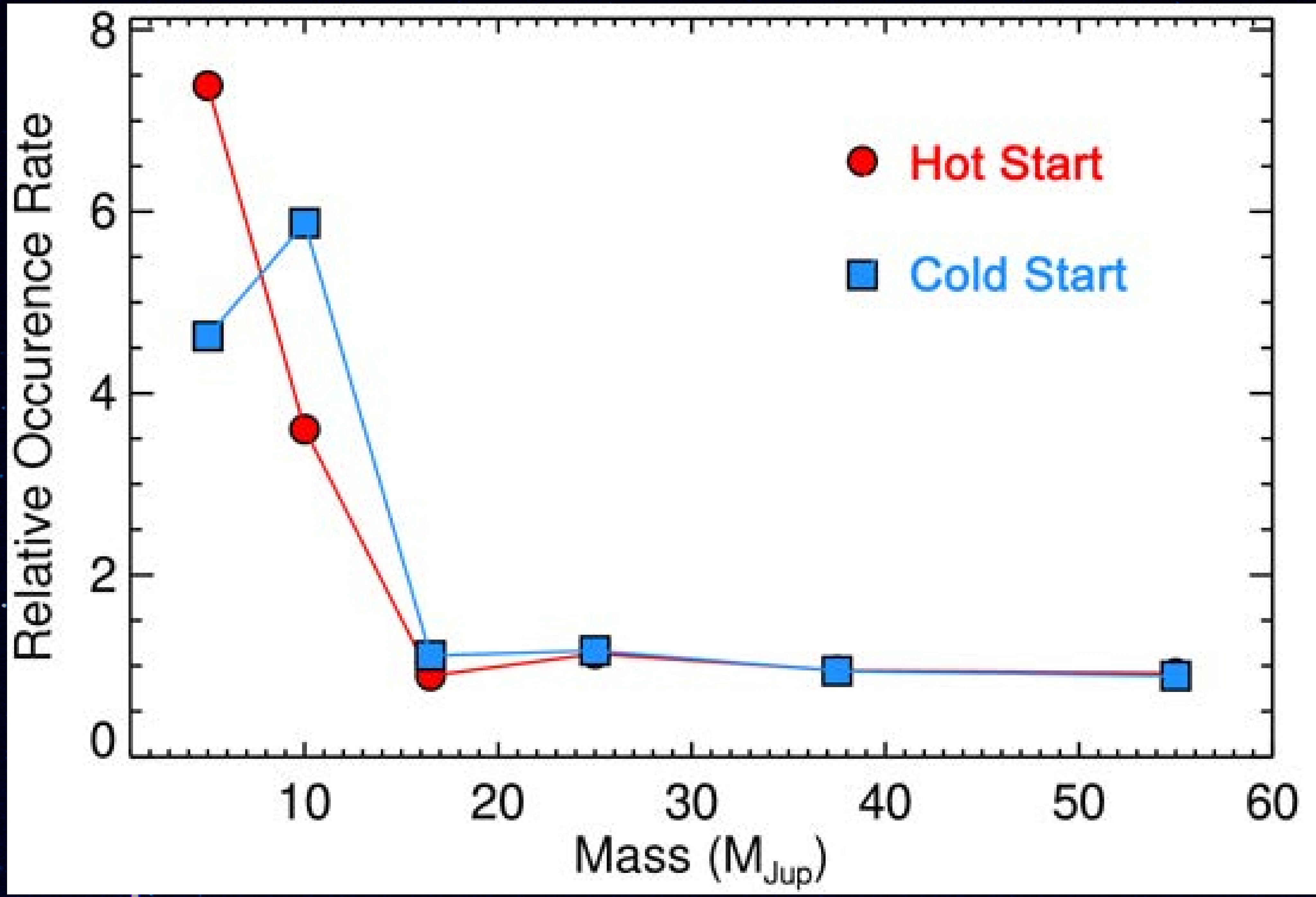




Marley+2007

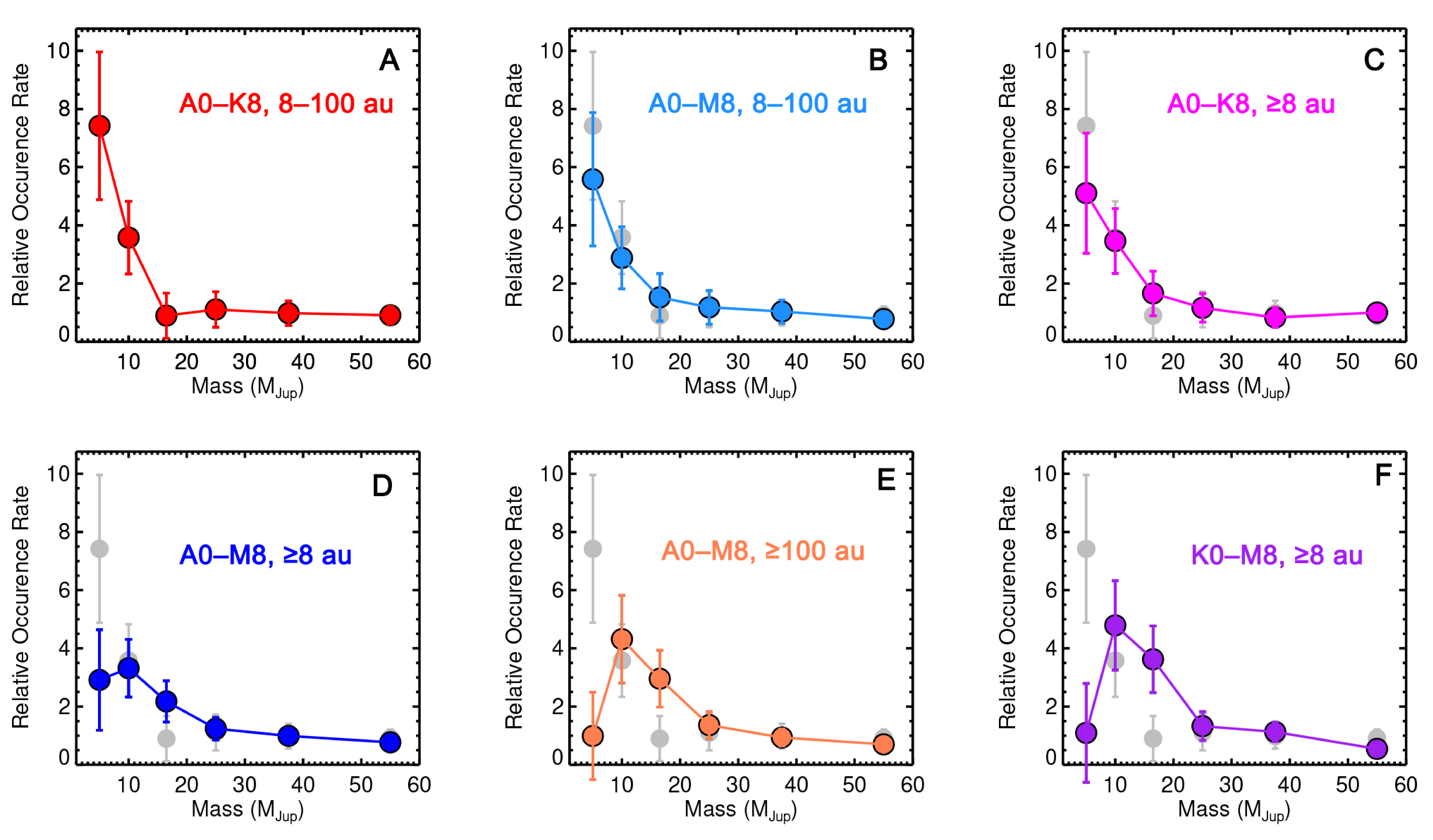
Checking Model Assumptions, Exploring Sub-Samples





Wagner, Apai, & Kratter 2019

What about >100 AU companions, and >K8 type hosts?



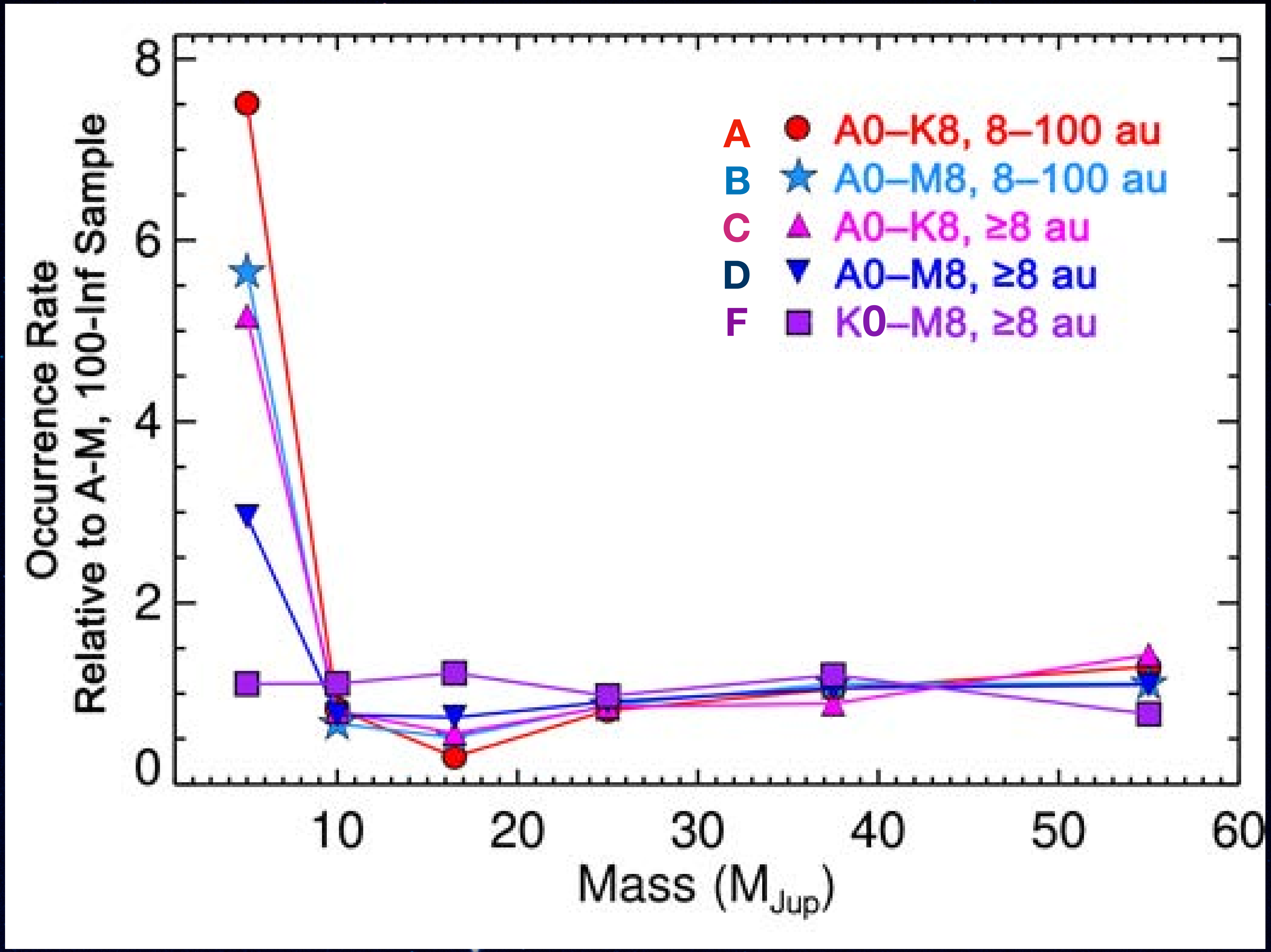
Wagner+2019, submitted

Mass Functions Re-Normalized to *Very* Wide-Orbit Companions

TABLE 2
SUB-SAMPLES OF COMPANIONS

ID	SpT	Proj. Sep.	#	§
A	A0-K8	8−100 AU	23	3.1-3.4
B	A0-M8	8−100 AU	28	3.5.1
C	A0-K8	≥8 AU	37	3.5.2
D	A0-M8	≥8 AU	57	3.5.3
E	A0-M8	≥100 AU	28	3.5.4
F	K0-M8	≥8 AU	27	3.5.5

Wagner+2019, submitted

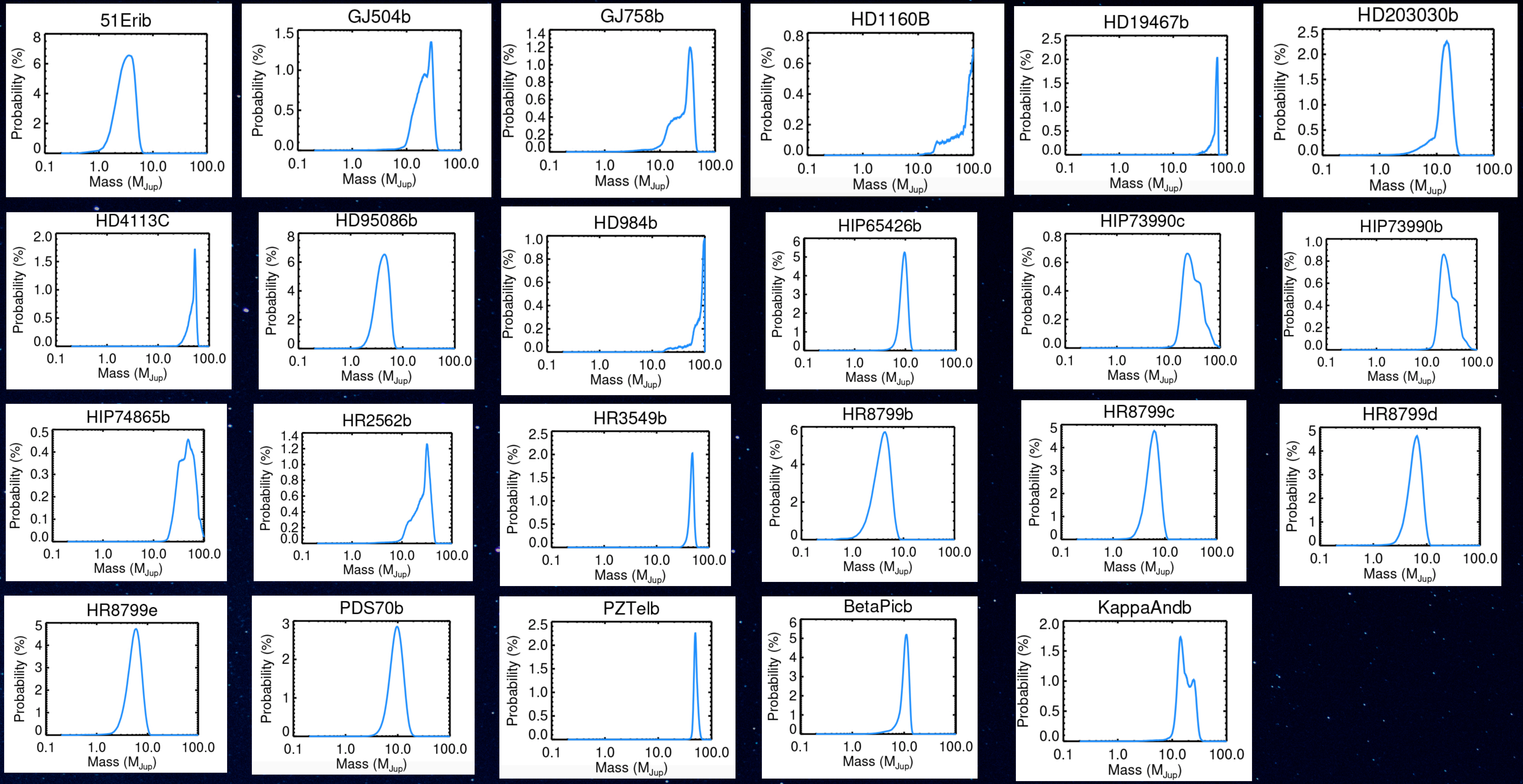


Same plot, normalized to >100 AU companions (E)

Over-abundance of planets around earlier-type stars, and with decreasing separation

Primary sample: 23 companions, ≤100 AU projected separation around A0-K8 stars.
(wider companions, and later spectral types considered separately)

System
51Erib
GJ504b
GJ758b
HD1160B
HD19467b
HD206893b
HD4113C
HD95086b
HD984b
HIP65426b
HIP73990b
HIP74865b
HR2562b
HR3549b
HR8799b
PDS70b
PZTelb
BetaPicb
KappaAndb



Wagner+2019

Survival Analysis

Feigelson and Nelson 1985

Counting statistics for data involving measurements and upper/lower limits

Example: calculating lifetimes

$$n_j = \#\{k,\ x_k \geq x'_{(j)}\}\ ,$$
$$d_j = \#\{k,\ x_k = x'_{(j)}\}\ ,$$

number greater than the jth element (= nj), and those equal to the jth element (=dj)

Xj = 100 years
Nj = number ≥ 100
dj = # who survived to exactly 100

fraction of survivors changes by dj/Nj

Survival function decreases only at measured values, with the size of the jumps being determined by the relative numbers of measurements *and limits* above a given t

$$\delta_i^L = \begin{cases} 1 & \text{if meas.;} \\ 0 & \text{if limit} \end{cases}$$

$$\hat{S}(t) = \prod_{j,x'_{(j)} < t} (1 - d_j/n_j)^{\delta'_{(j)}}\ , \quad \text{when } t > x'_{(1)}\ ,$$
$$\hat{S}(t) = 1\ , \quad \text{when } t \leq x'_{(1)}\ .$$

Invert values for the opposite problem, upper limits:

$$\hat{F}^L(t) = \hat{S}(M - t)$$

Is HR 8799 Rare?

- 1% occurrence for brown dwarf companions
  (Metchev & Hillenbrand 2009, Galicher et al. 2016, Vigan et al. 2017, Stone et al. 2018)

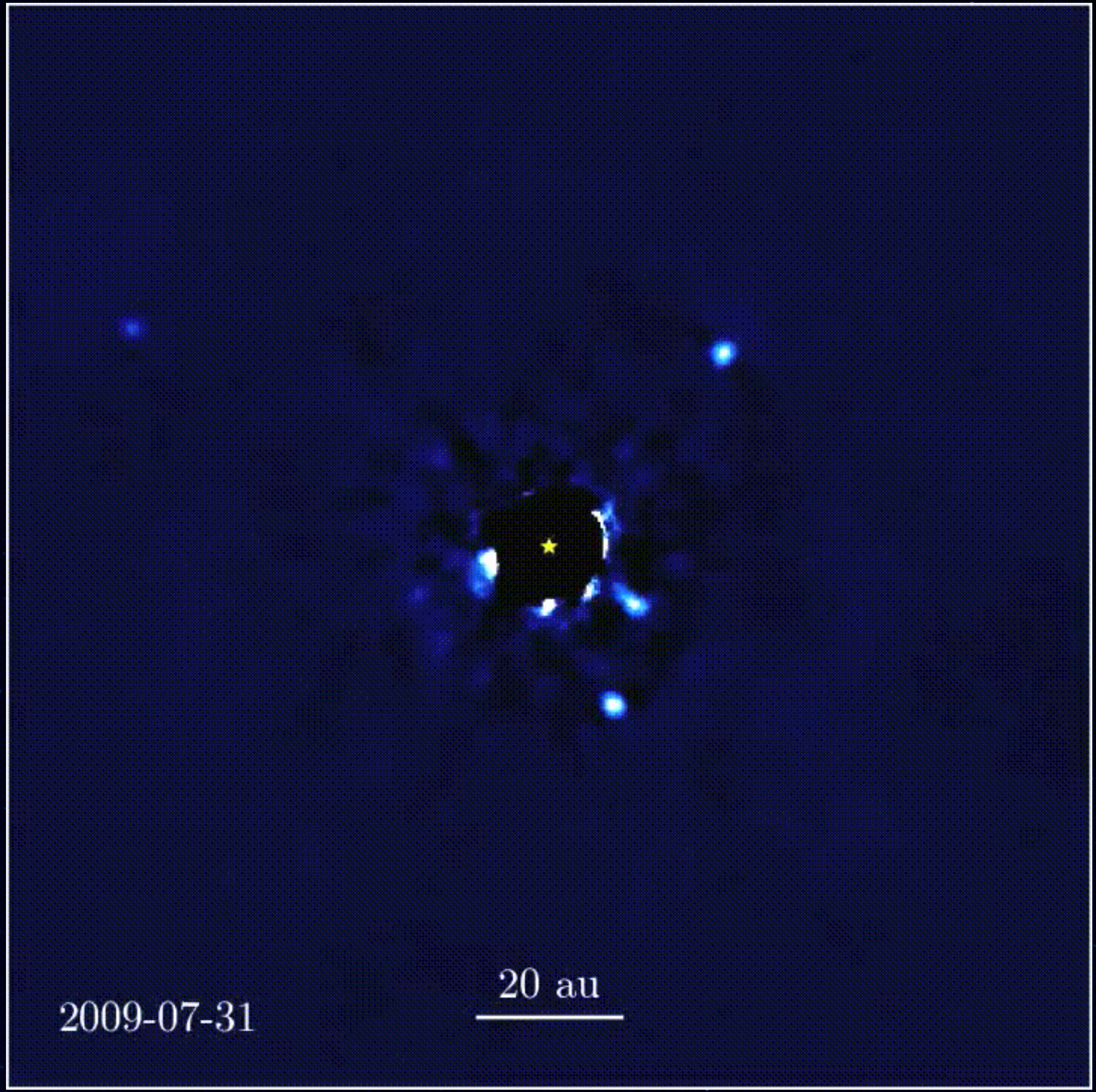
  => 10% of stars have *one* super-Jupiter

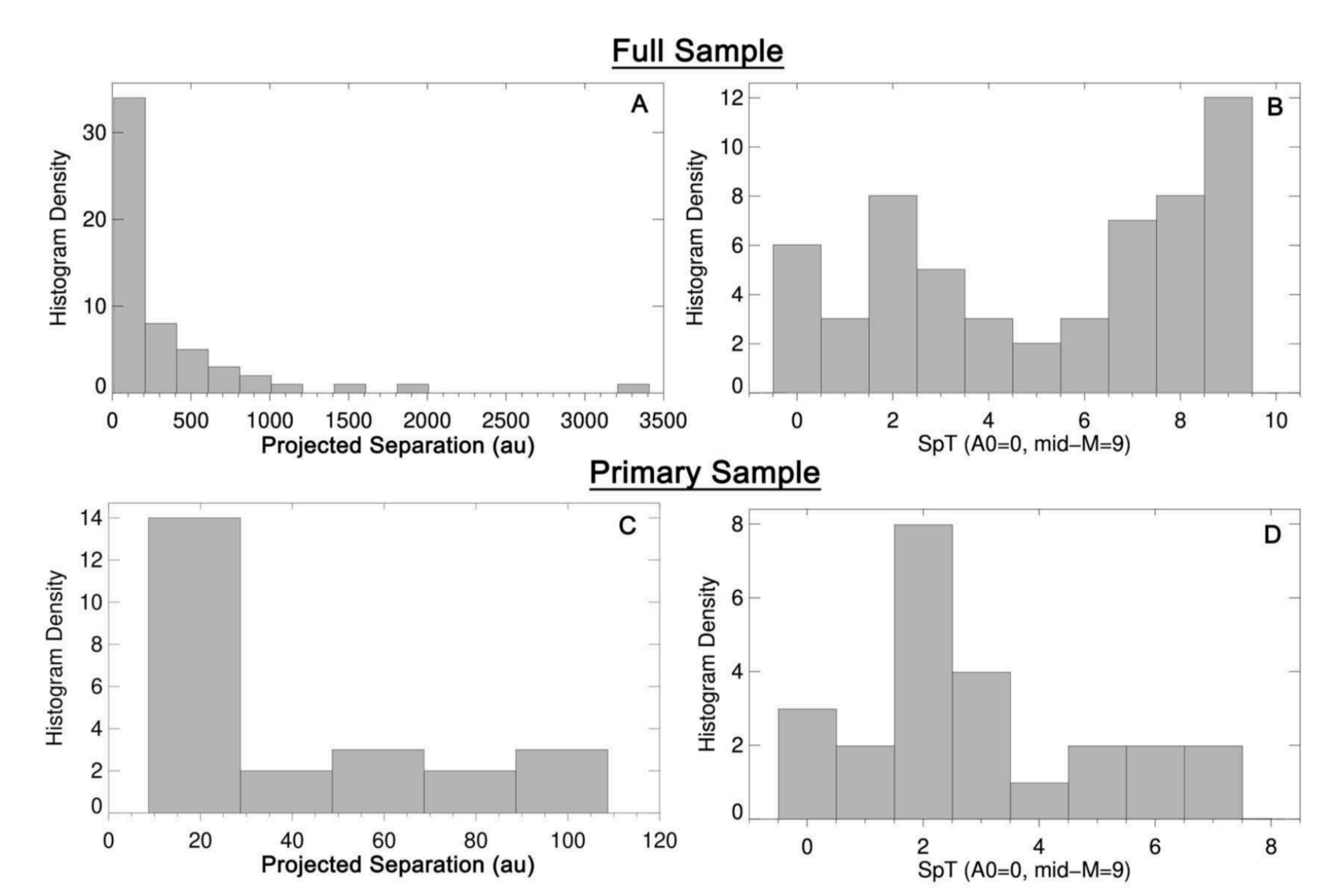
- each star has a ~10% potential to form one planet
  => ~1 in 10,000 will form *four*

- Within 100 pc there are roughly 400,000 stars
  => 40 such systems
  but how many will be young?

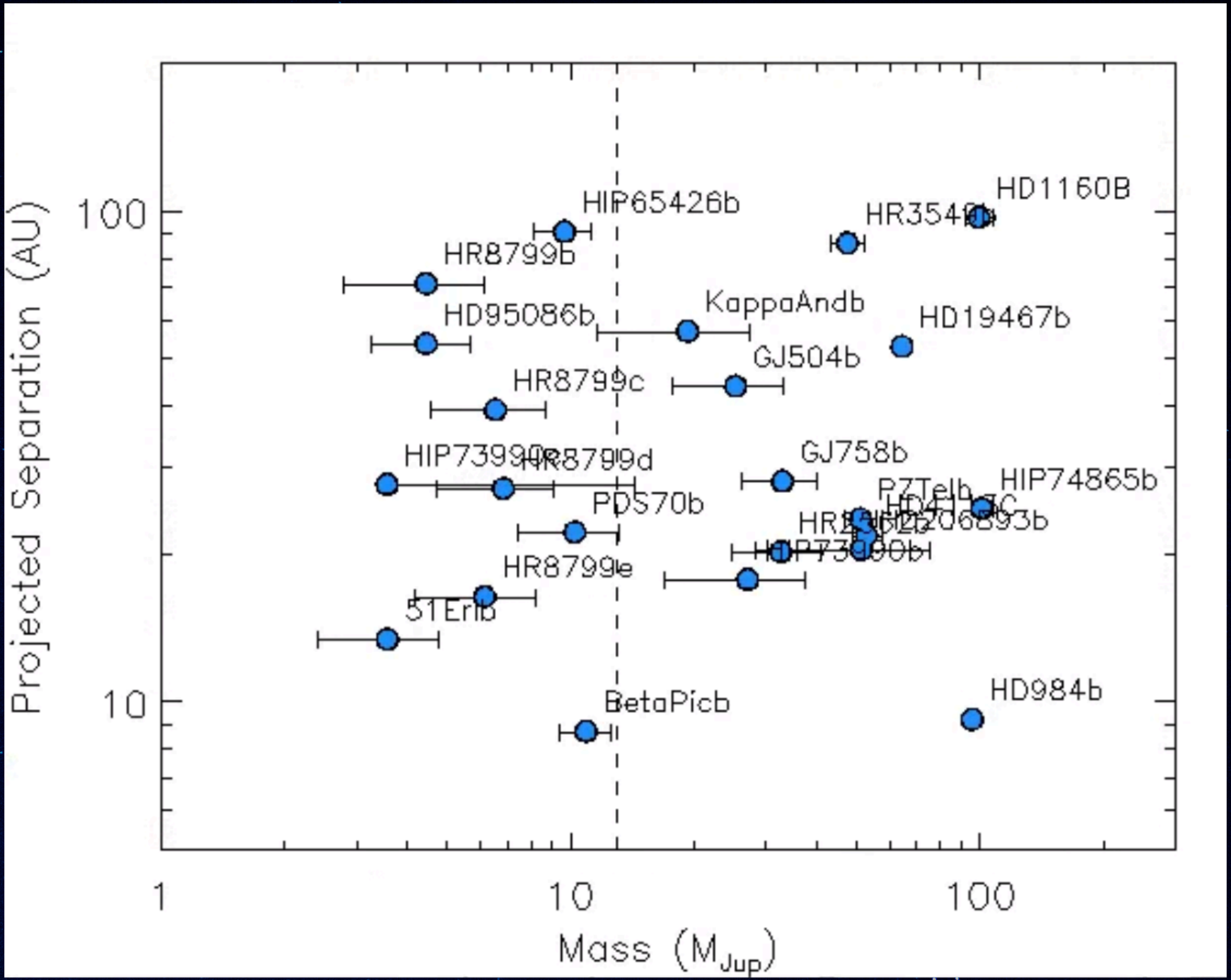
- Assuming a flat SFR, 1% of stars in a 10 Gyr old galaxy will be <100 Myr old

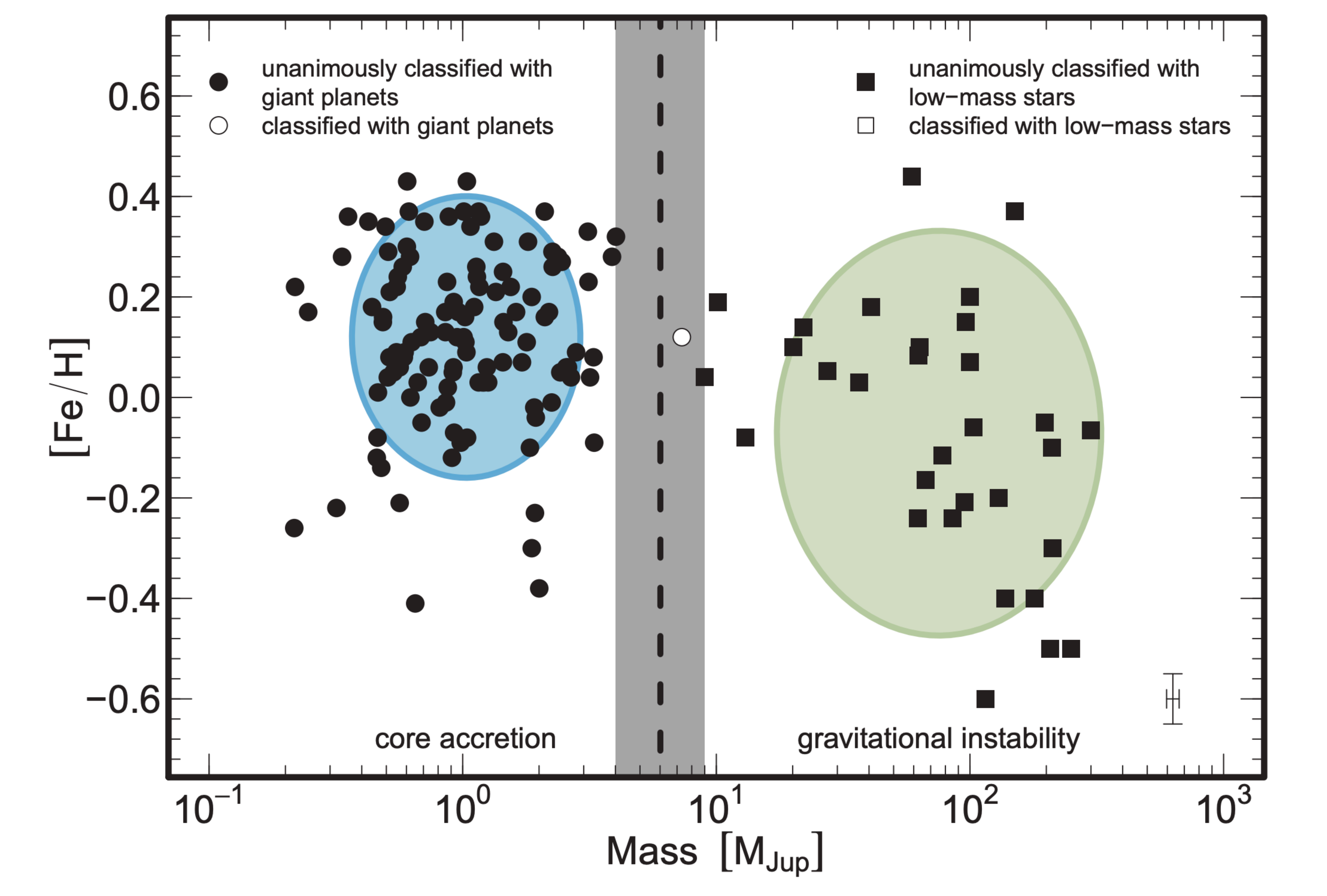
  => 40% chance of detecting one such system




Full Sample
A
Histogram Density
0
10
20
30
0 500 1000 1500 2000 2500 3000 3500
Projected Separation (au)
B
Histogram Density
0 2 4 6 8 10 12
0 2 4 6 8 10
SpT (A0=0, mid–M=9)
Primary Sample
C
Histogram Density
0 2 4 6 8 10 12 14
0 20 40 60 80 100 120
Projected Separation (au)
D
Histogram Density
0 2 4 6 8
0 2 4 6 8
SpT (A0=0, mid–M=9)

Projected Separation vs. Mass





Schlaufman 2018: transiting planets with RV-measured masses and well-characterized stellar hosts