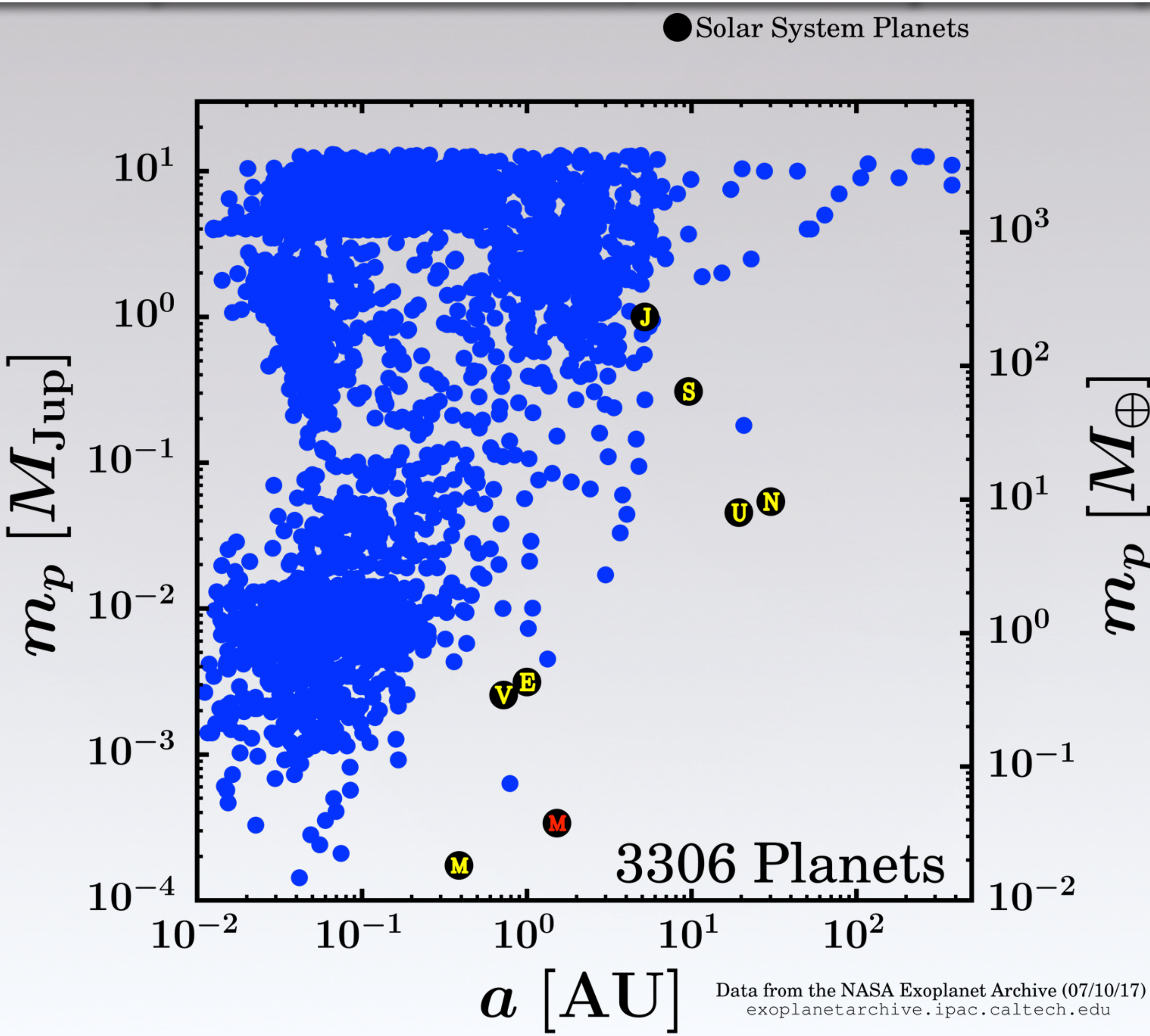
The Observed Distribution of Planets

{Inferences from Microlensing, Radial Velocity, and Direct Imaging Surveys

Sagan Summer Workshop, Aug 2017

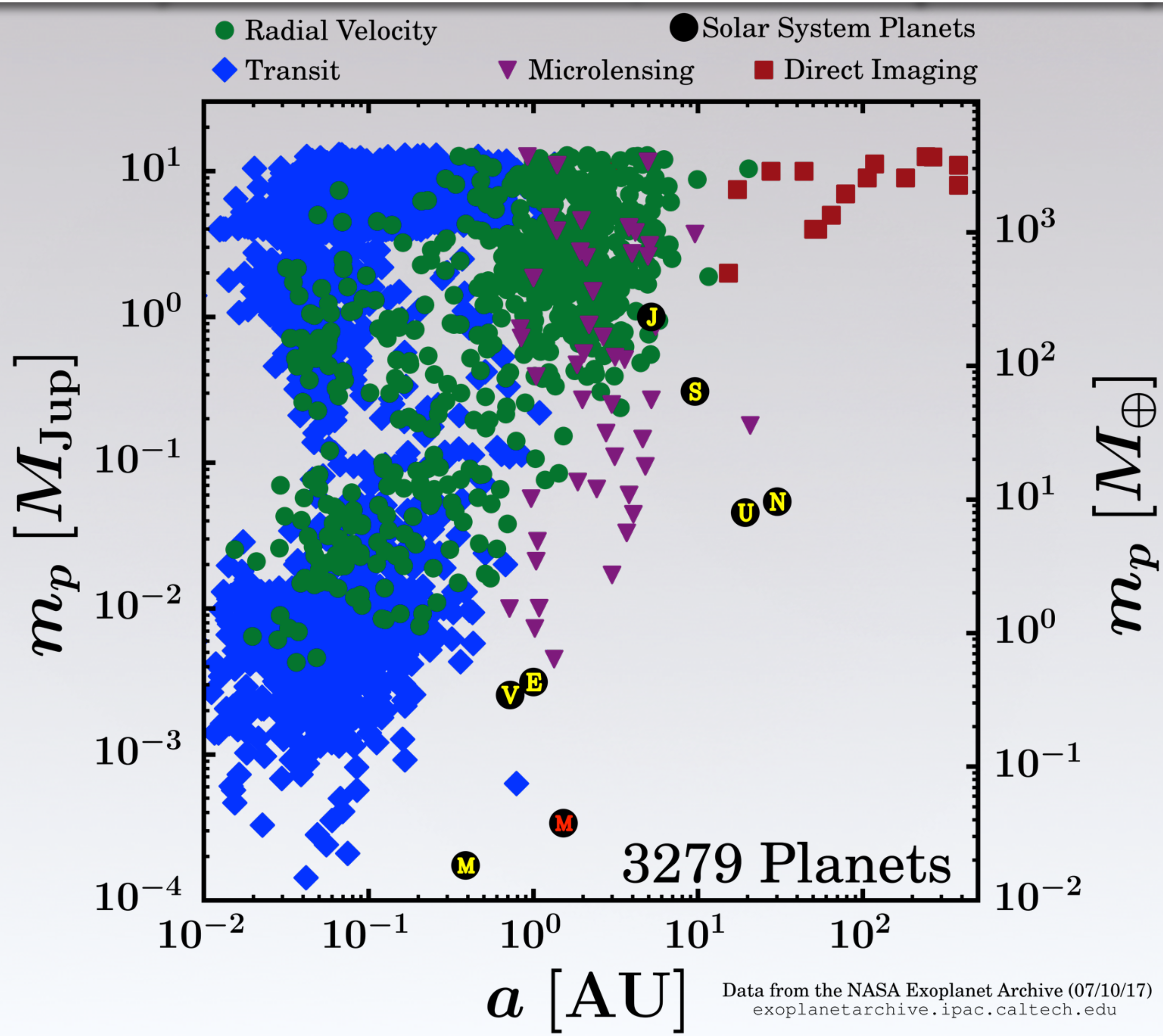
Christian Clanton

Currently Known Planets (All Host Spectral Types)



Data from the NASA Exoplanet Archive (07/10/17)
exoplanetarchive.ipac.caltech.edu

Currently Known Planets (All Host Spectral Types)



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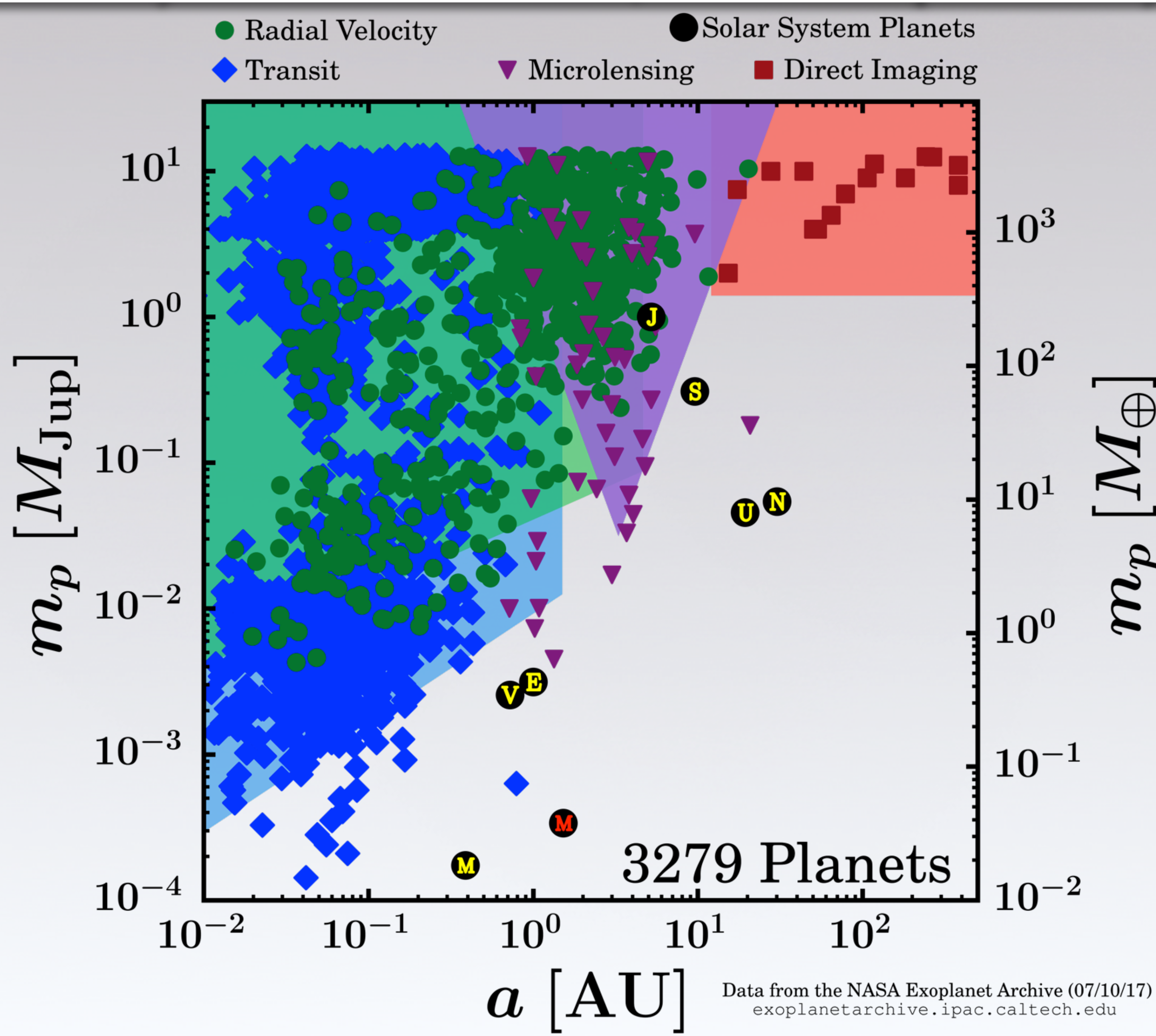

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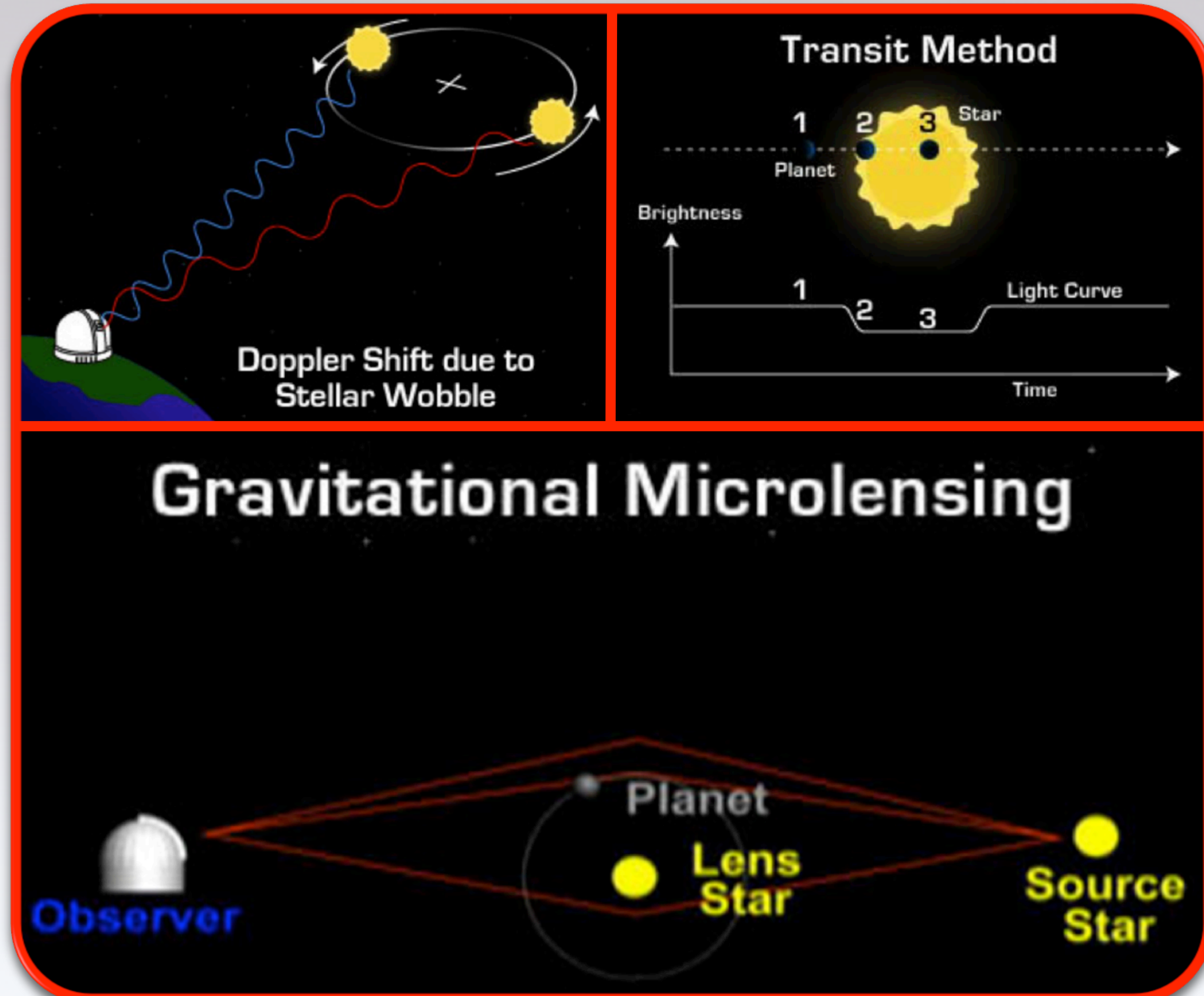
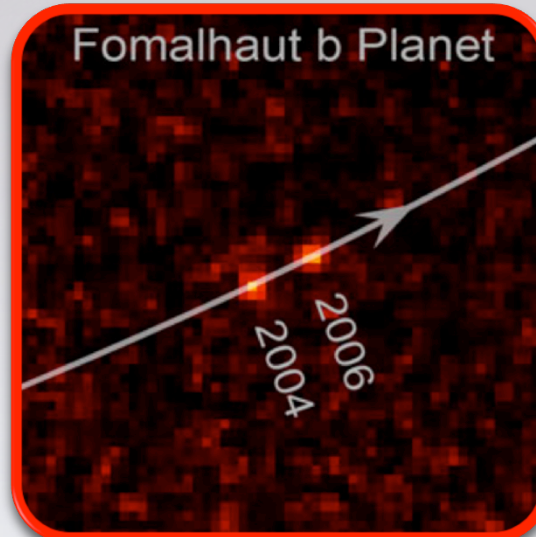
Exoplanet Detection Methods

–Indirect–

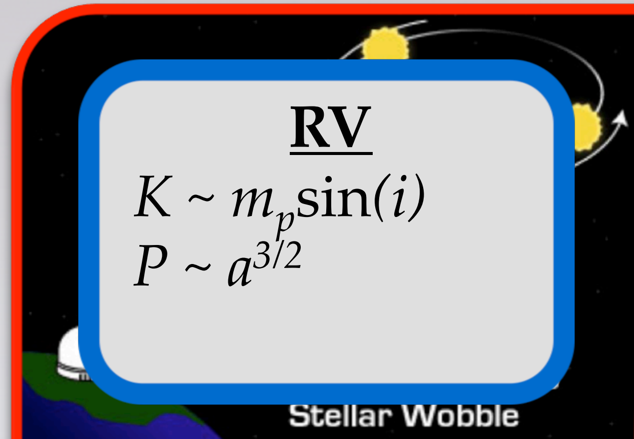


–Direct–



Exoplanet Detection Methods

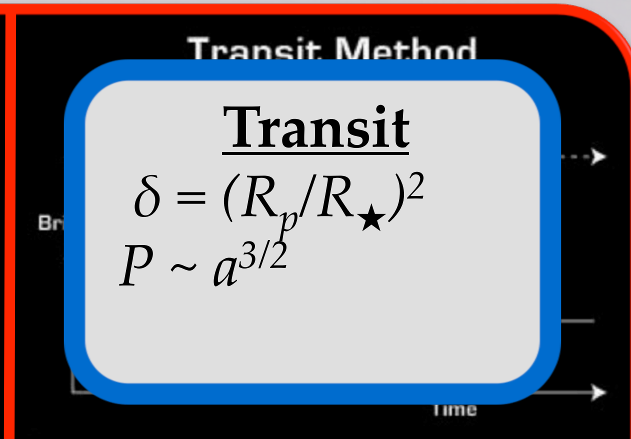
–Indirect–



RV

$K \sim m_p \sin(i)$

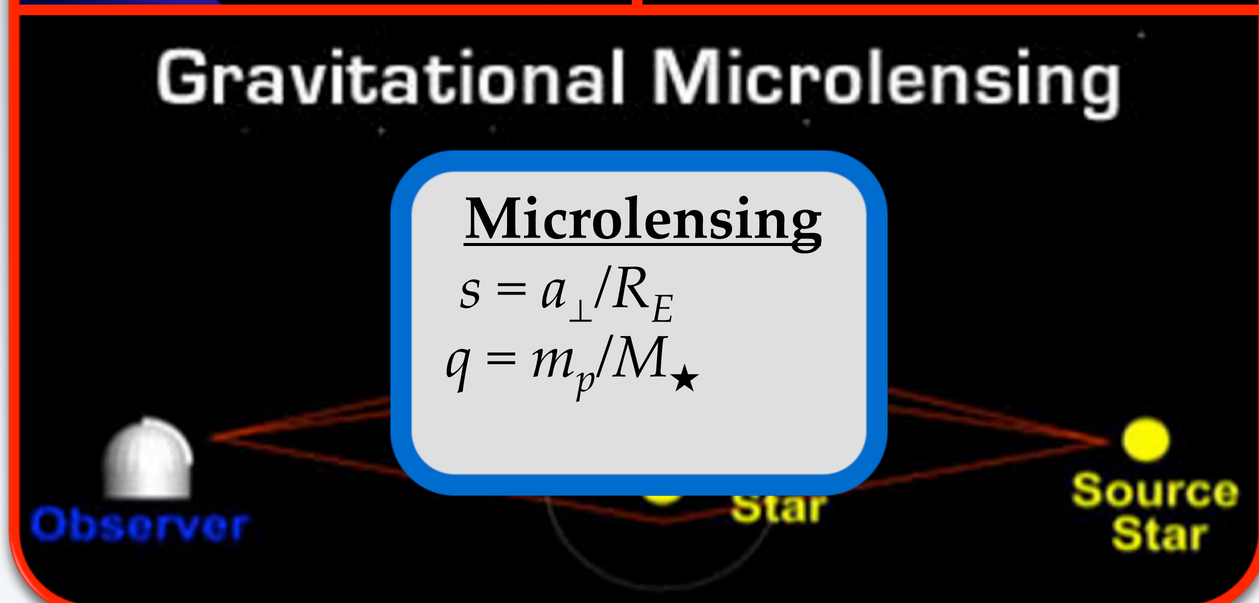
$P \sim a^{3/2}$



Transit

$\delta = (R_p/R_\star)^2$

$P \sim a^{3/2}$

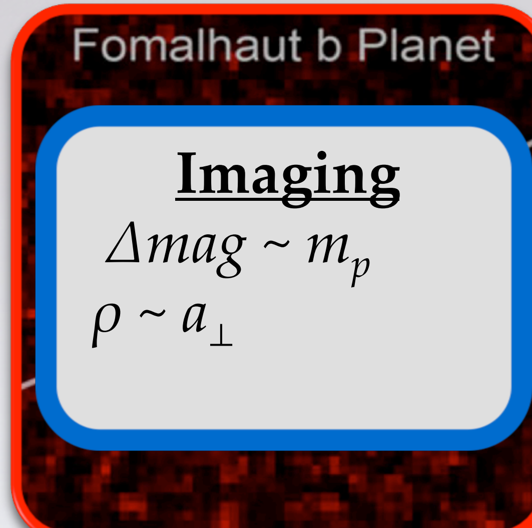


Microlensing

$s = a_\perp/R_E$

$q = m_p/M_\star$

–Direct–

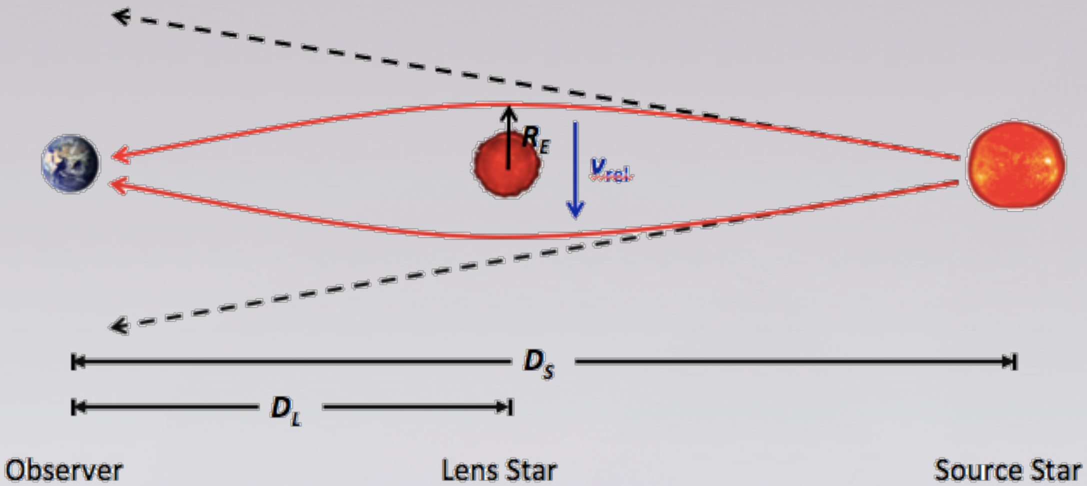


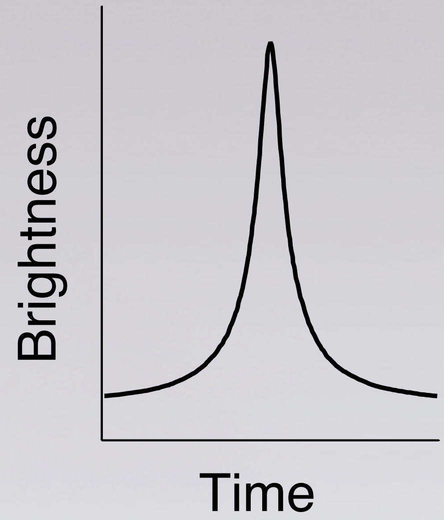
Imaging

$\Delta mag \sim m_p$

$\rho \sim a_\perp$

Microlensing Method





$$R_E(M_L, D_L, D_S) = \left[\frac{4GM_L}{c^2}\frac{D_L(D_S - D_L)}{D_S}\right]^{1/2}$$

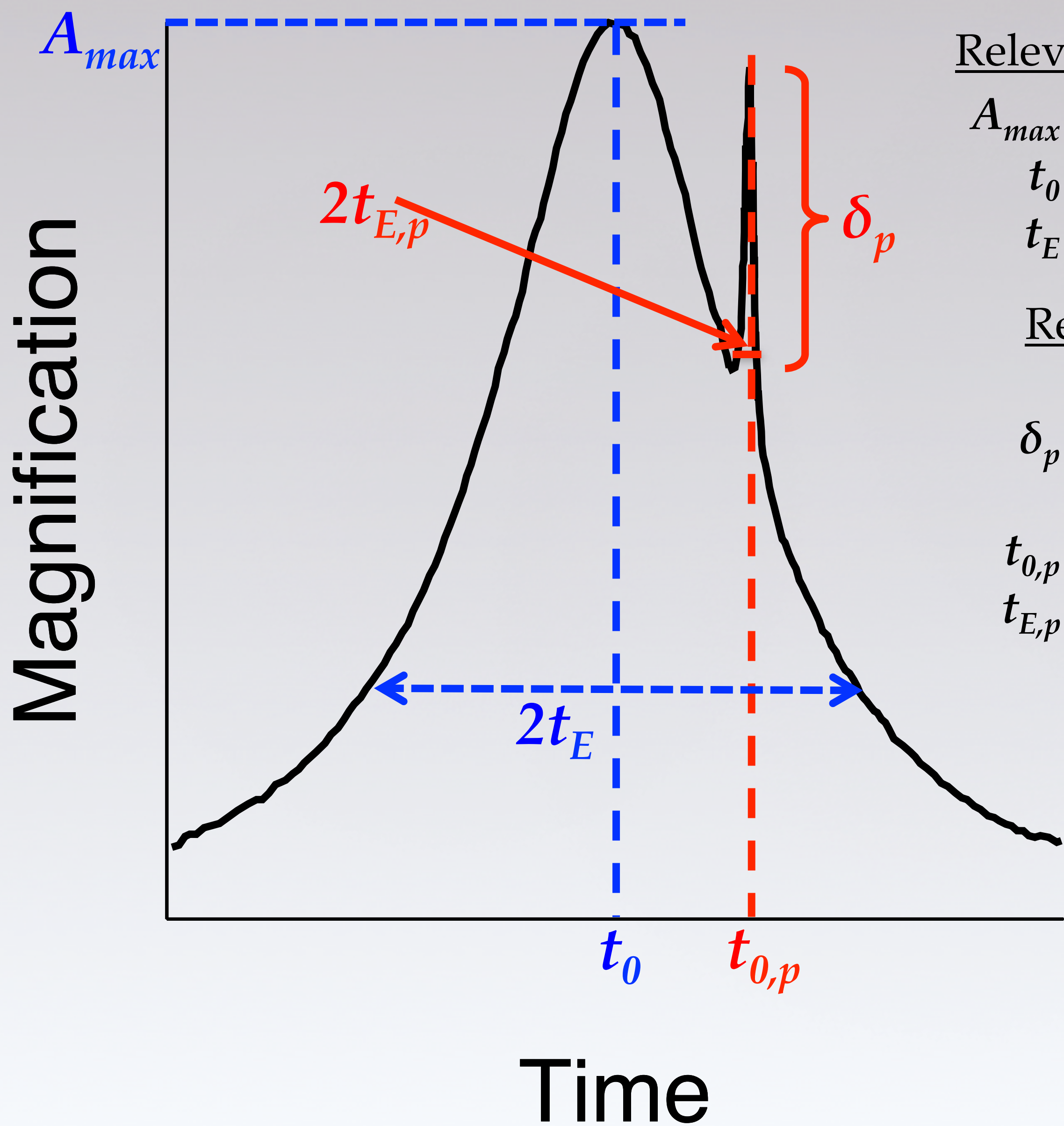
$$\simeq 2.85\ \text{AU}\left(\frac{M_L}{0.5\ M_\odot}\right)^{1/2}\left(\frac{D_S}{8\ \text{kpc}}\right)^{1/2}\left[\frac{x(1-x)}{0.25}\right]^{1/2}$$

$$\text{where } x \equiv \frac{D_L}{D_S}$$

$$t_E(R_E, v_{\rm rel}) = \frac{R_E}{v_{\rm rel}}$$

$$\simeq 24.8\ \text{days}\left(\frac{R_E}{2.85\ \text{AU}}\right)\left(\frac{v_{\rm rel}}{200\ \text{km s}^{-1}}\right)^{-1}$$

Microlensing Observables



<u>Relevant Single Lens Event Properties</u>

A_{max} = peak observed magnification
t_0 = time of peak magnification
t_E = primary Einstein crossing time

<u>Relevant Planetary Perturbation Properties</u>

δ_p = peak fractional deviation from the single lens magnification
$t_{0,p}$ = time of planetary perturbation
$t_{E,p}$ = planetary Einstein crossing time

<u>Inferred Planet Properties</u>

$$q \equiv \frac{m_p}{M_L} = \left(\frac{t_{E,p}}{t_E}\right)^2$$

$$A_{max}, t_0, t_{0,p}, t_E \rightarrow s$$

Microlensing Observables

★ Fundamental degeneracies leave inferred planet properties relative to host star properties ★

Projected Separation in Units of the Einstein Radius

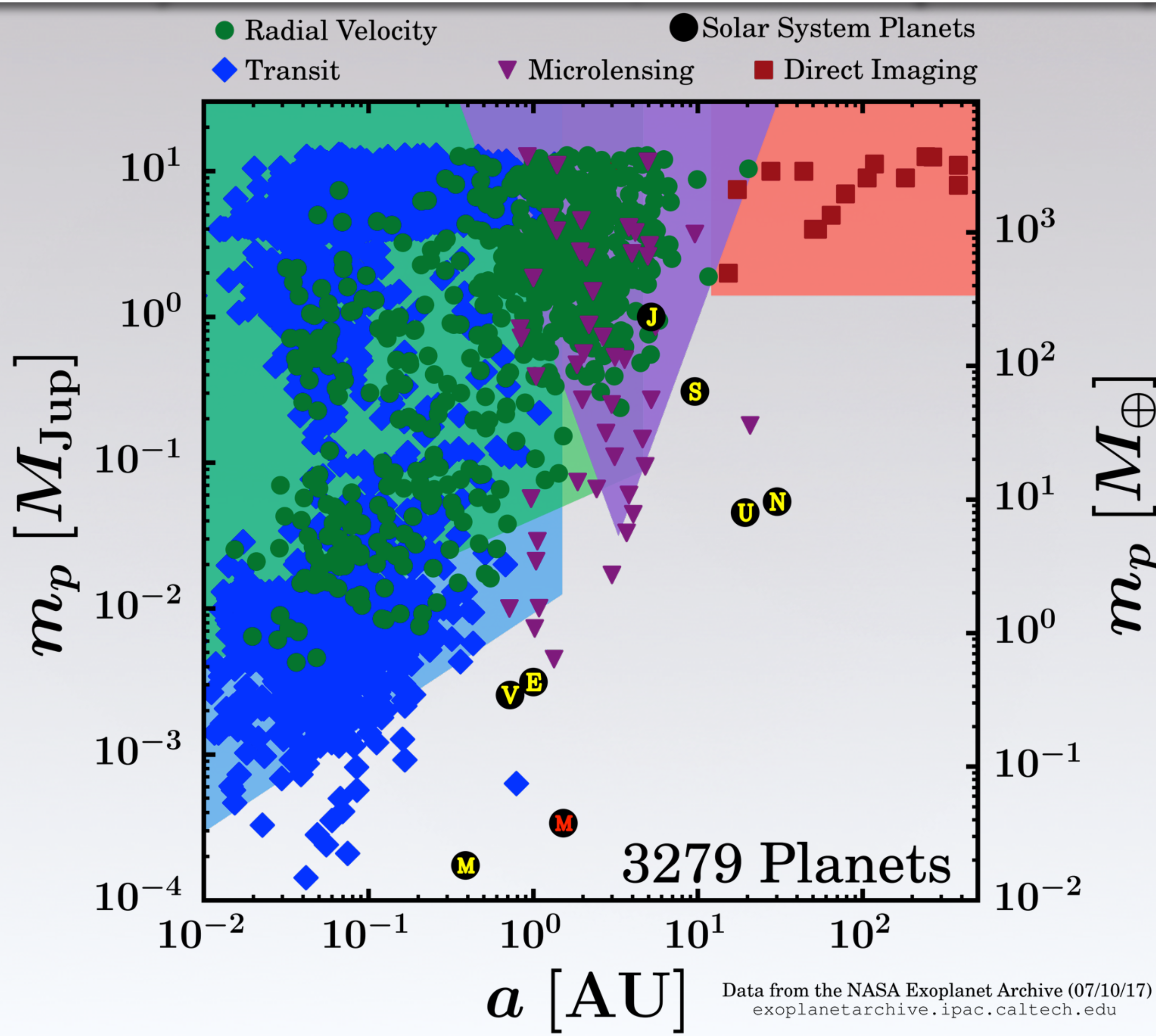
$$s \equiv \frac{r_\perp}{R_E(M_L, D_L, D_S)}$$

Planet-to-Star Mass Ratio

$$q \equiv \frac{m_p}{M_L}$$

$$t_E(R_E, v_{\rm rel}) = \frac{R_E(M_L, D_L, D_S)}{v_{\rm rel}}$$

Currently Known Planets (All Host Spectral Types)



Demographics of Planets Around M Dwarfs

Microlensing Event Rate

>>The contribution to the microlensing event rate for a given lens with mass M_L and distance D_L, and with a lens-source relative velocity, v_{rel}, along a given line of sight is

$$\frac{d^4\Gamma}{dM_L dD_L d\vec{\boldsymbol{v}}_{\mathrm{rel}}} = 2R_E|\vec{\boldsymbol{v}}_{\mathrm{rel}}|\nu \frac{d^2\Gamma}{d\vec{\boldsymbol{v}}_{\mathrm{rel}}} \frac{d\Gamma}{dM_L}$$

Microlensing Event Rate

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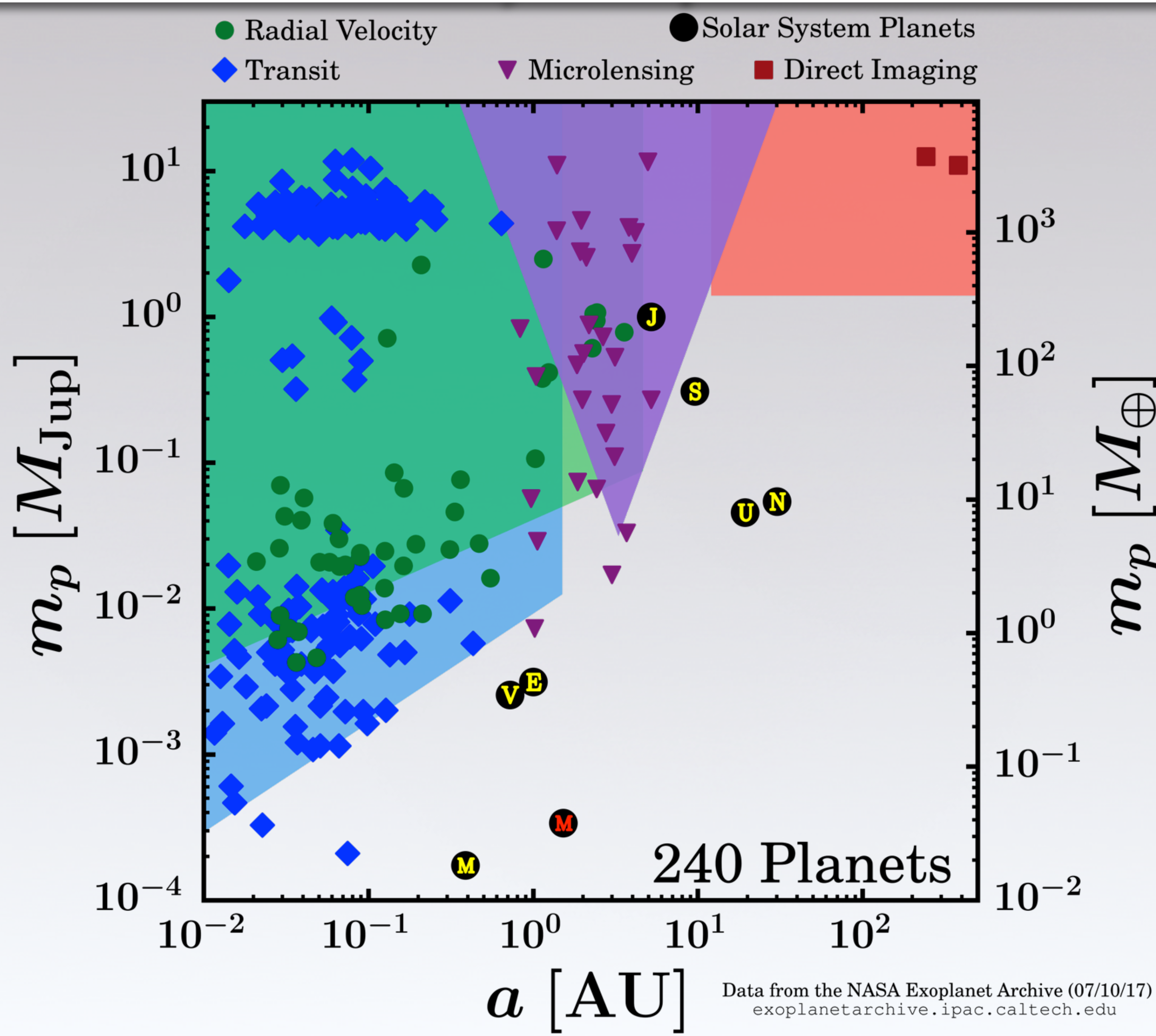
Confirmed Planetary Companions to M Dwarfs



Data from the NASA Exoplanet Archive (07/10/17)
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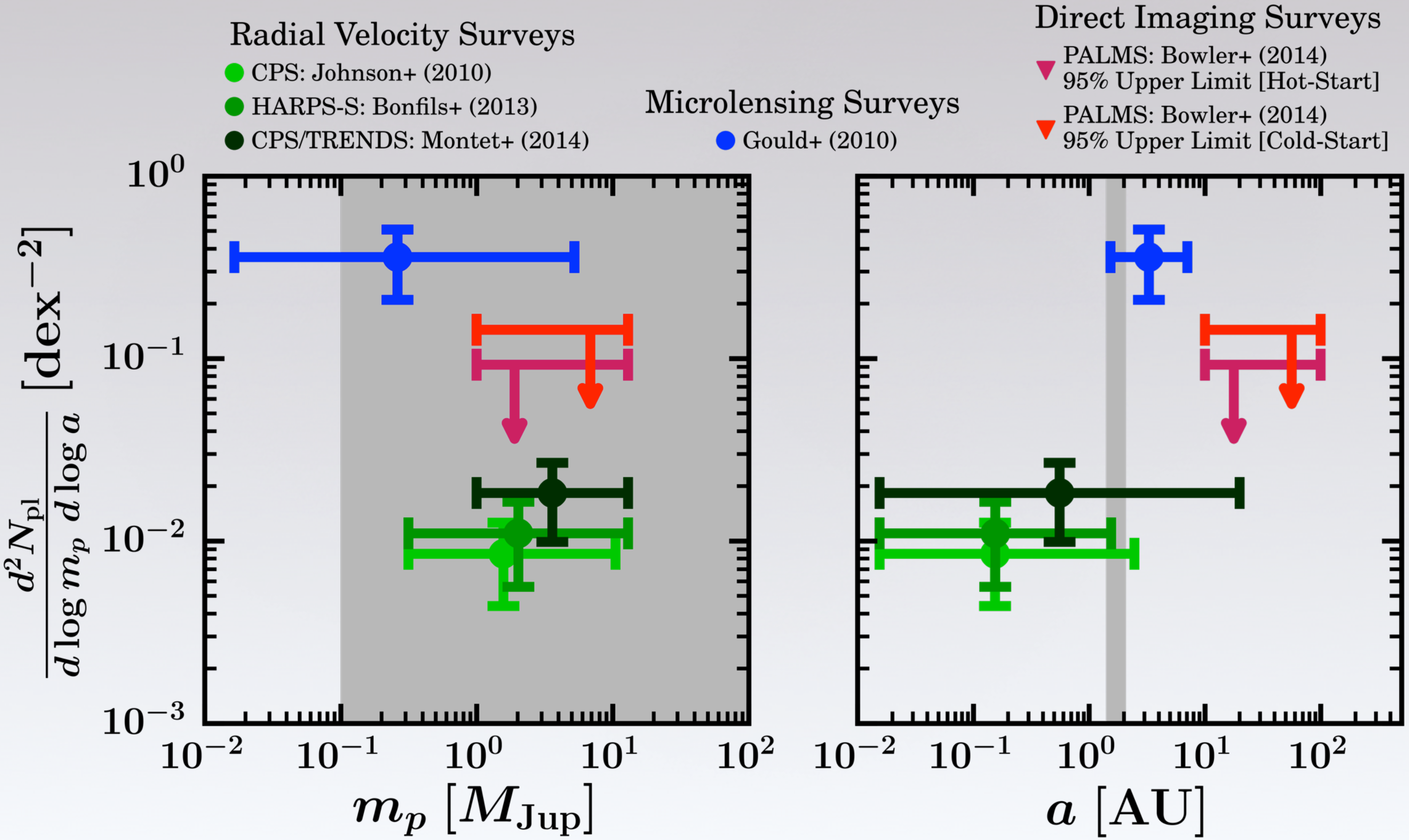
Exoplanet Censuses of M Dwarfs from Individual Methods



Comparing Microlensing + RV

1. Start with the population of planets inferred by microlensing surveys

2. Map their properties into the observables of RV

   >> Marginalizing over all unknown galactic, kinematic, and stellar properties

3. Apply actual (or estimated) detection limits from RV surveys to determine number of expected detections of microlensing analogs

4. Compare with reported detections

"Microlensing Planets"

Sumi+ (2010) & Gould+ (2010)

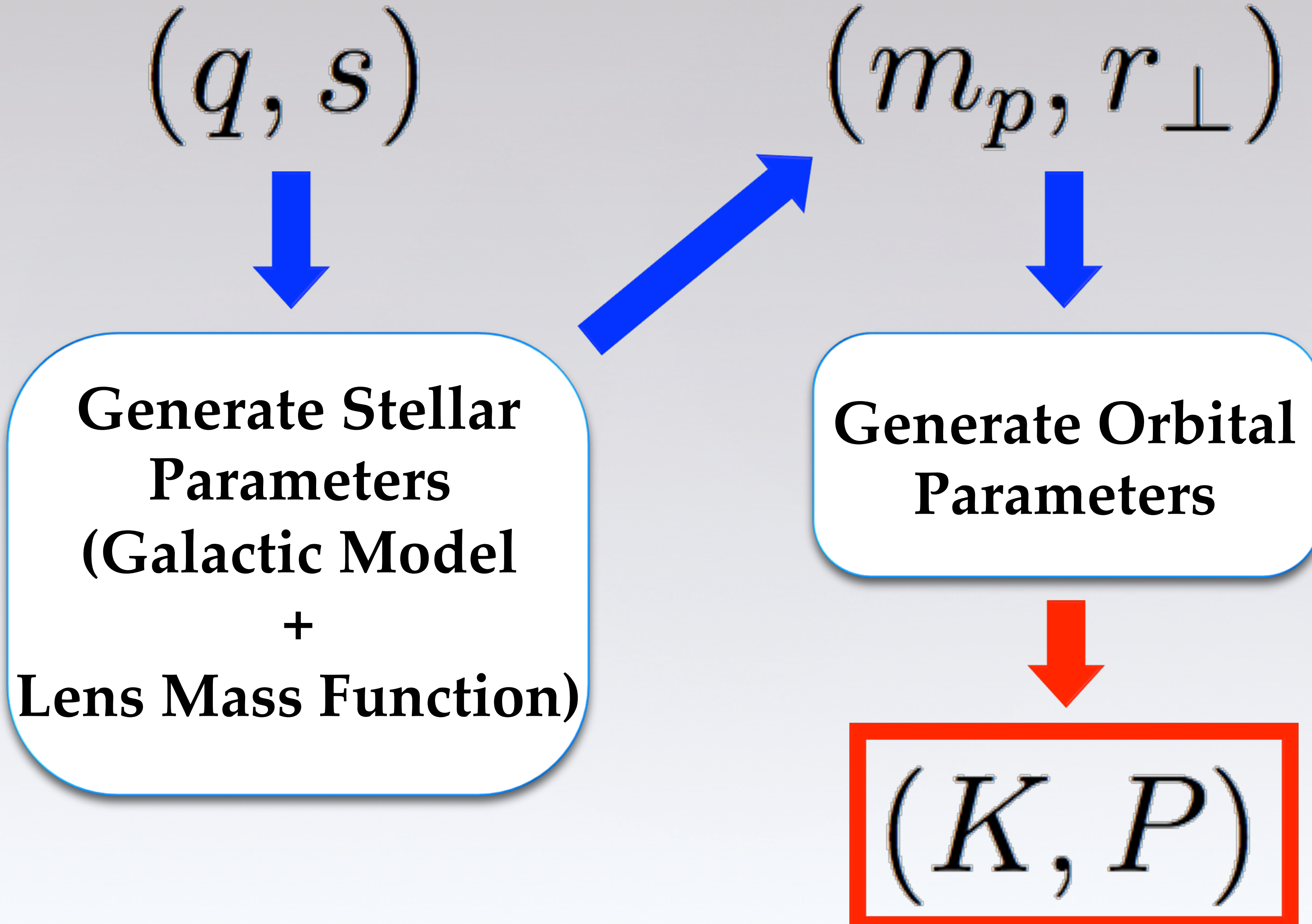
Sumi+ (2010)

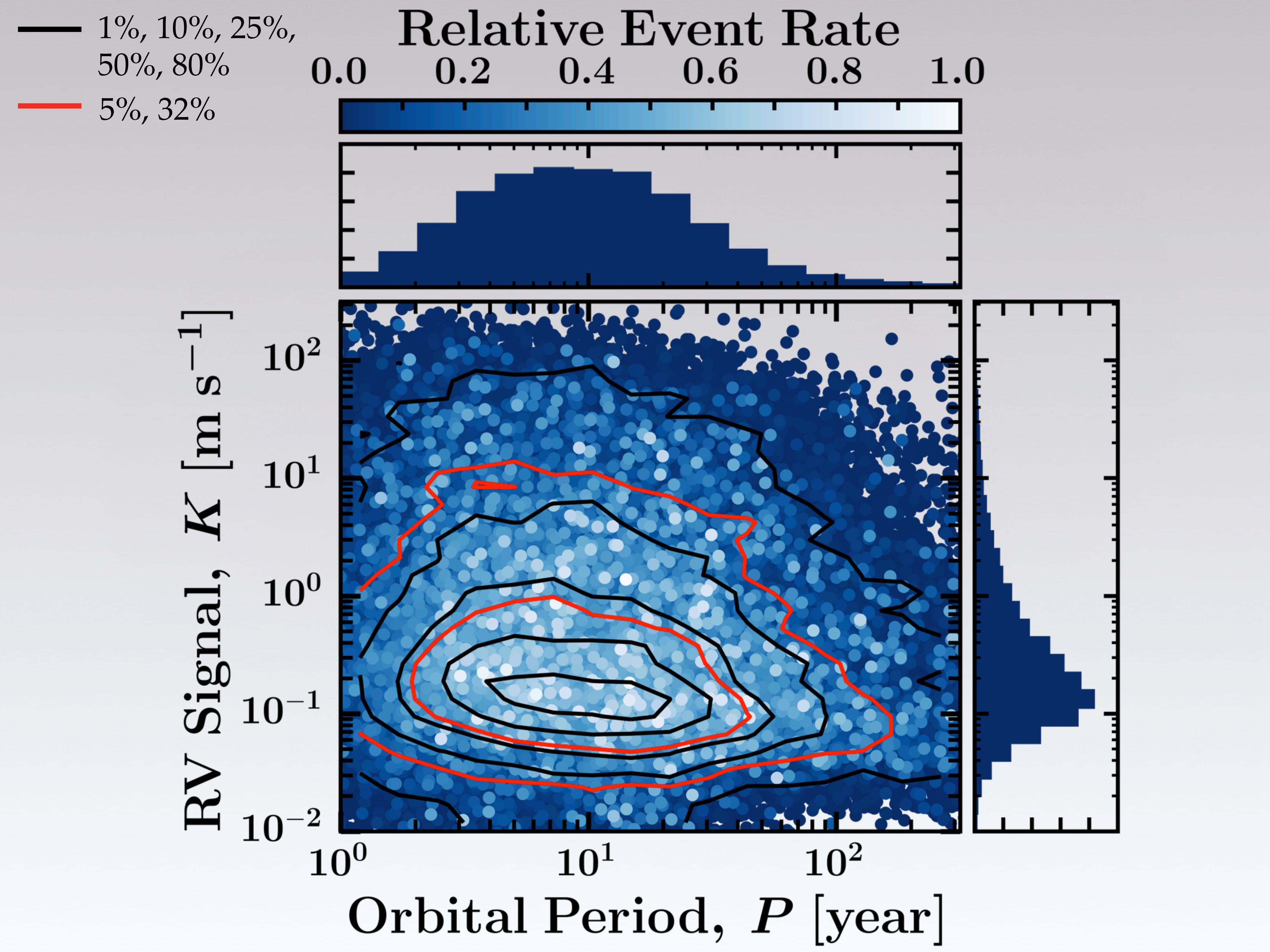
$$\frac{d^2 N_{\rm pl}}{d\log q \; d\log s} = (0.23 \pm 0.10) \left(\frac{q}{5 \times 10^{-4}} \right)^{-0.68 \pm 0.20}$$

Map the properties of such planets into the space of RV observables:

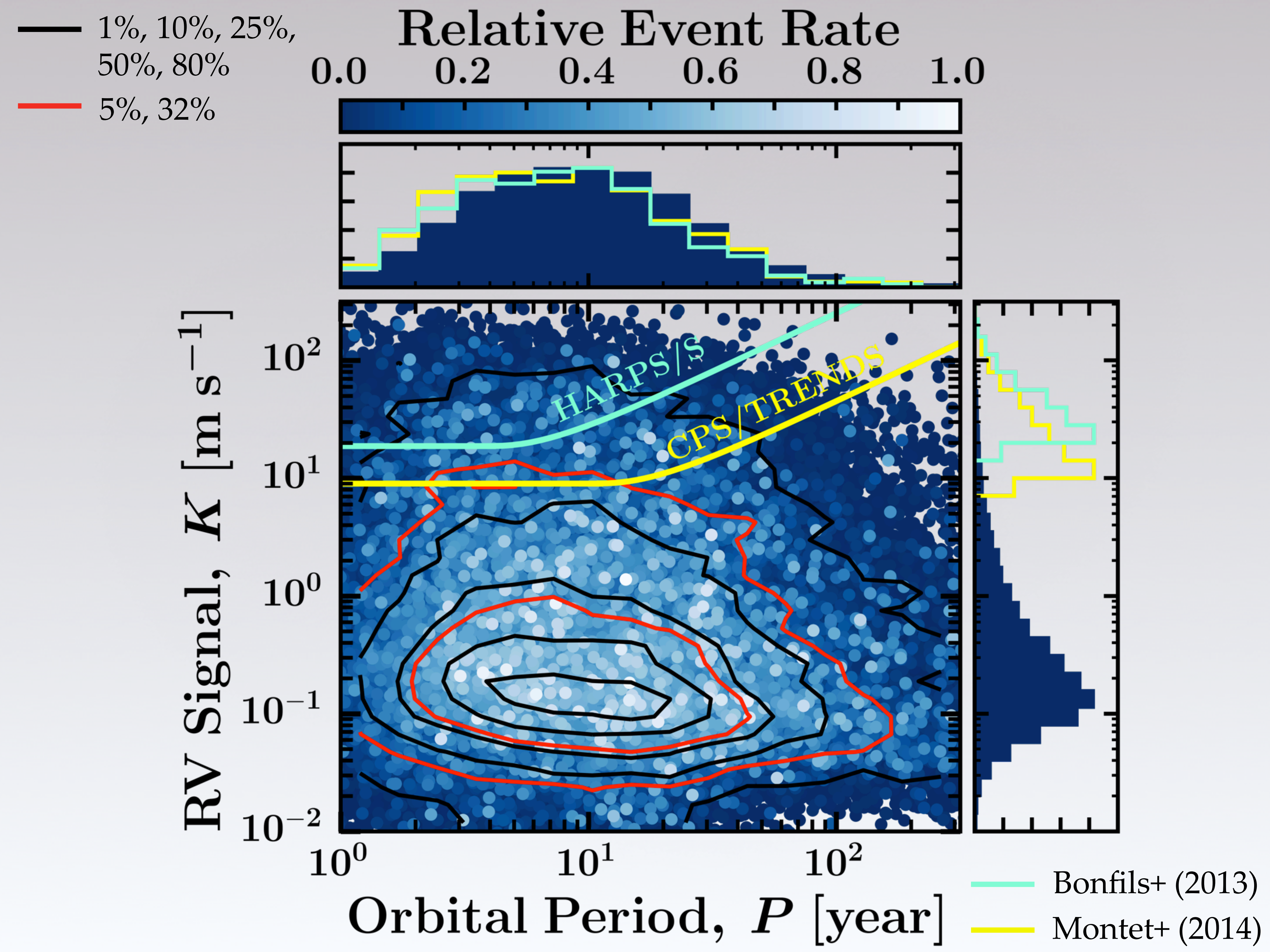
(q,s) → (K,P)

Mapping to RV Observables





1%, 10%, 25%, 50%, 80%
5%, 32%
Relative Event Rate
0.0
0.2
0.4
0.6
0.8
1.0
RV Signal, K [m s^{-1}]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
Orbital Period, P [year]



1%, 10%, 25%, 50%, 80%
5%, 32%
Relative Event Rate
0.0
0.2
0.4
0.6
0.8
1.0
HARPS/S
CPS/TRENDS
RV Signal, K [m s−1]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
Orbital Period, P [year]
Bonfils+ (2013)
Montet+ (2014)

Comparison with HARPS-S (Bonfils+ 2013)

Expected:	Actual:
1.1 ± 0.8	**1**

$$1 \lesssim m_p/M_{\rm Jup} \lesssim 13 \quad ; \quad 3 \lesssim P/{\rm years} \lesssim 10$$

Comparison with CPS/TRENDS (Montet+ 2014)

Expected Number:

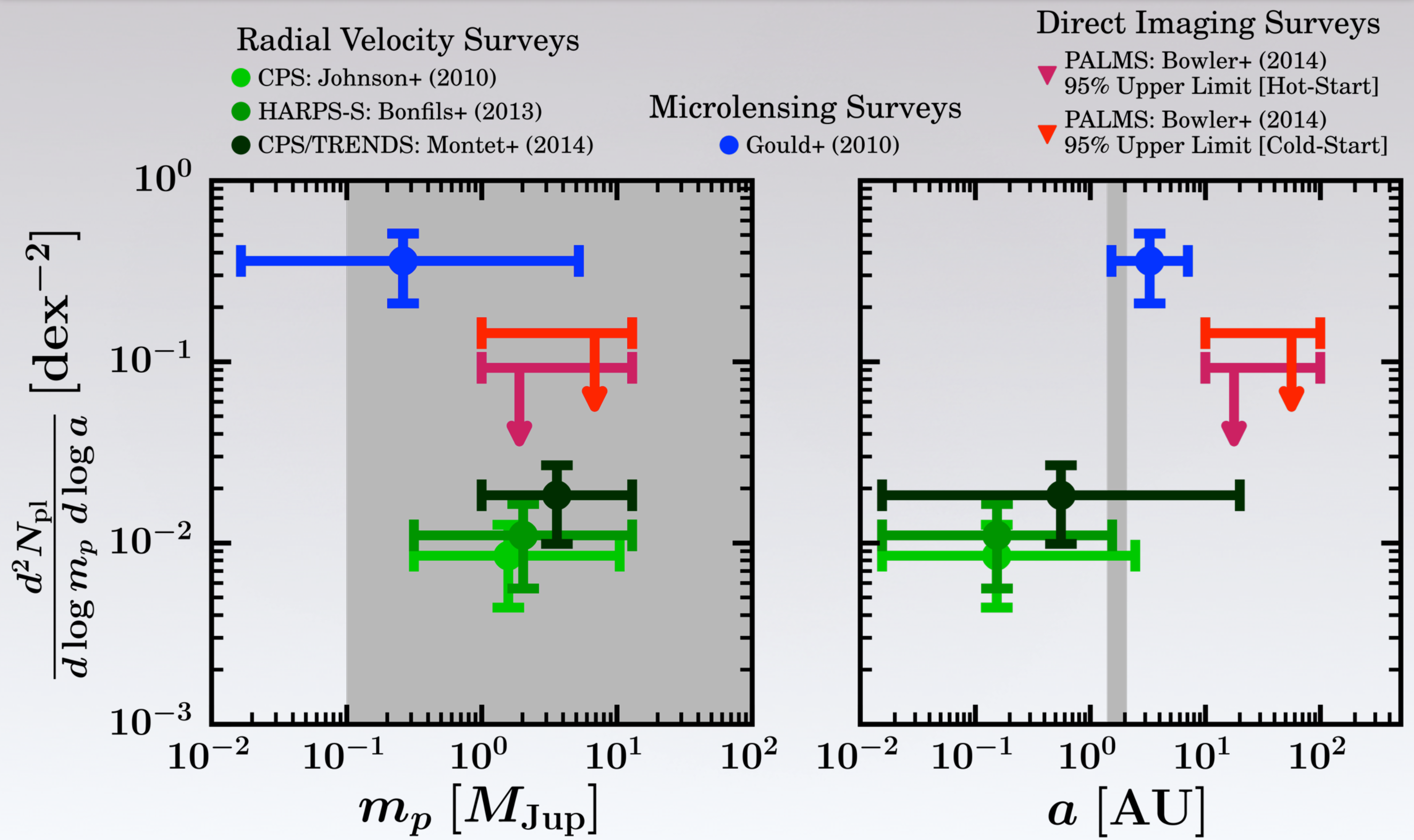
4.7 ± 2.7

Actual Number:

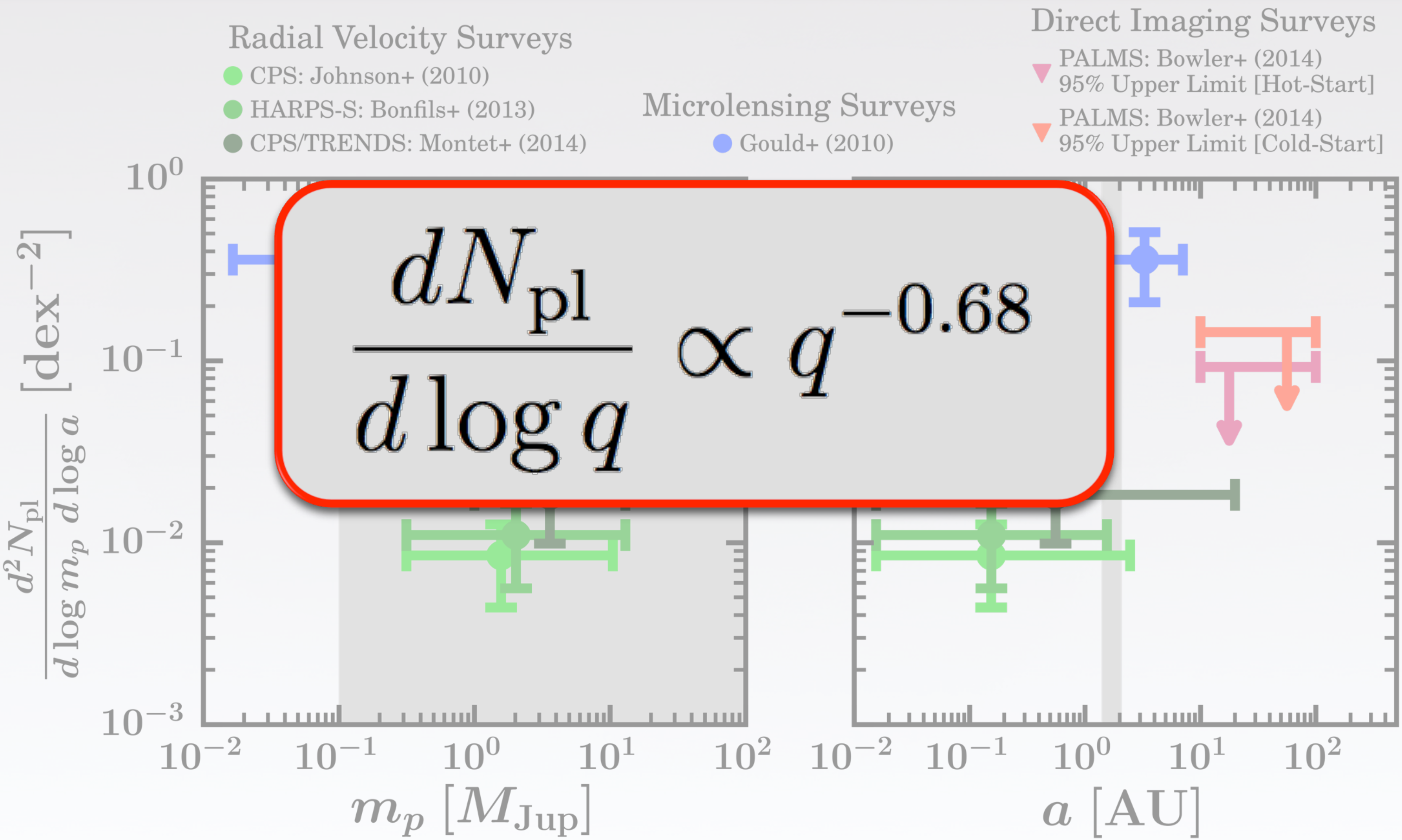
4

Similar Masses and Orbital Periods

Consistency Between Microlensing and RV Surveys of M Dwarfs

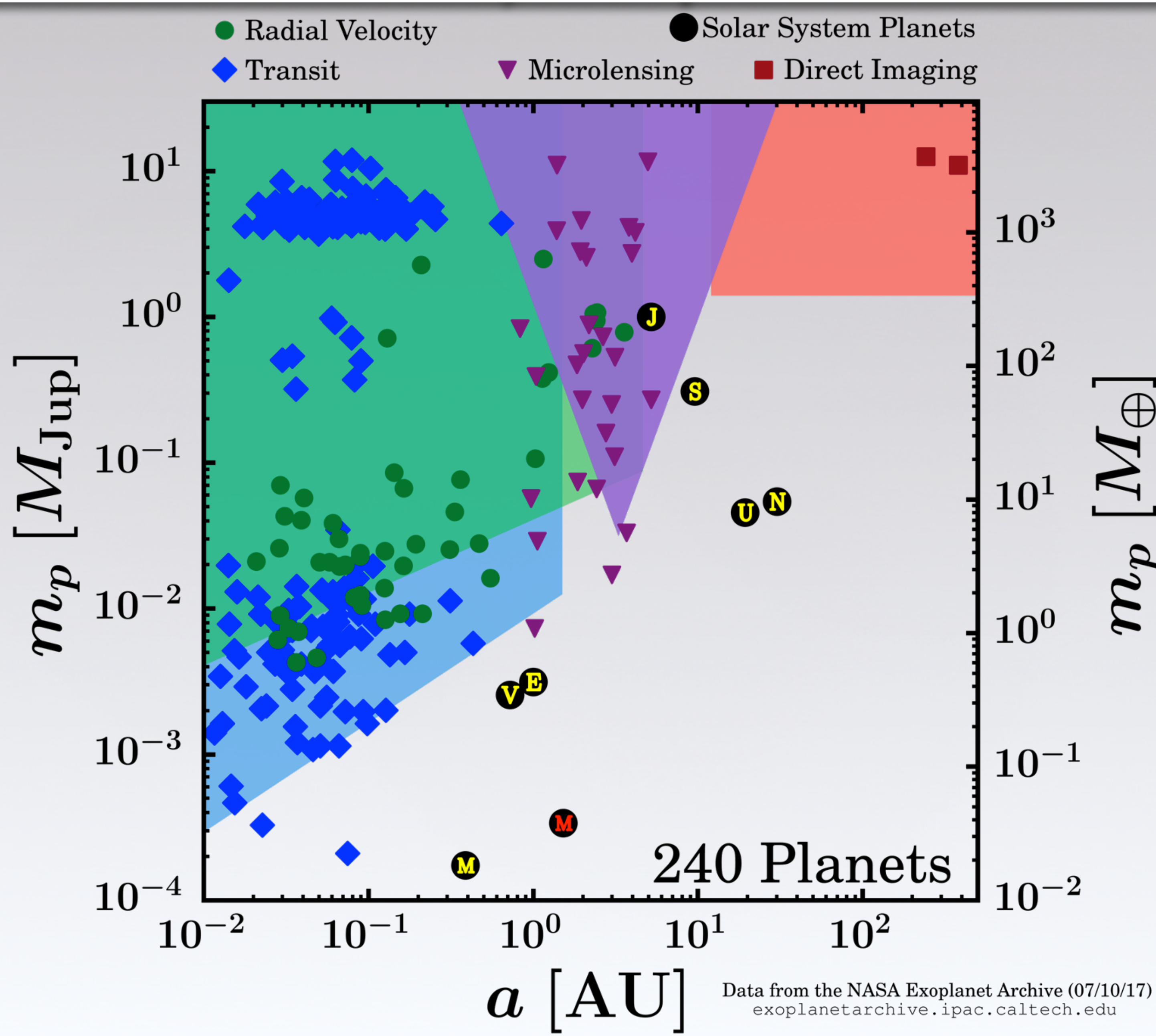


Consistency Between Microlensing and RV Surveys of M Dwarfs



$$\frac{dN_{\rm pl}}{d\log q} \propto q^{-0.68}$$

Confirmed Planetary Companions to M Dwarfs



Constraints on Long-Period Planetary Companions to M Dwarfs

Microlensing Surveys	Radial Velocity Surveys	Direct Imaging Surveys
Gould+ (2010)	Montet+ (2014)	Bowler+ (2014)
Sumi+ (2010)		Lafrenière+ (2007)

Model

$$\frac{d^2 N_{\rm pl}}{d\log m_p\ d\log a} = \mathcal{A}\left(\frac{m_p}{M_{\rm Sat}}\right)^{\alpha}\left(\frac{a}{2.5\ {\rm AU}}\right)^{\beta}$$

$$\{\alpha, \beta, \mathcal{A}, a_{\rm out}\}$$

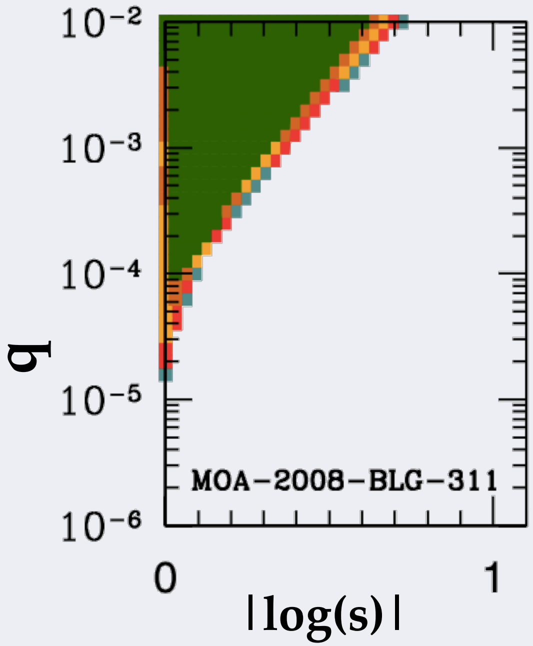
Methodology

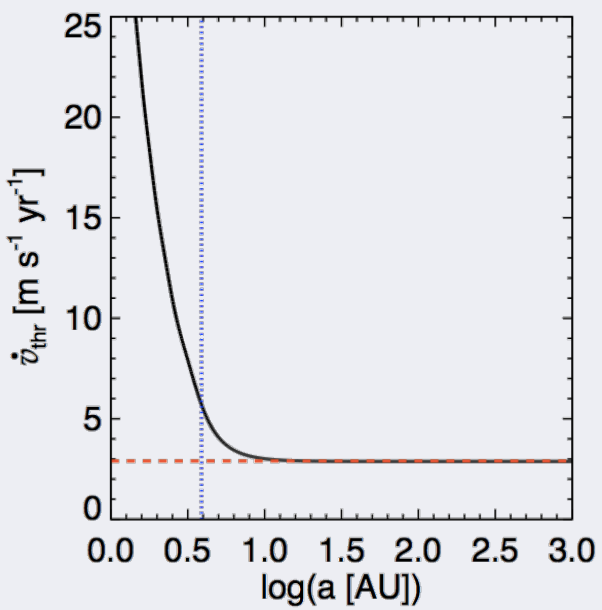
$$(m_p, a)$$

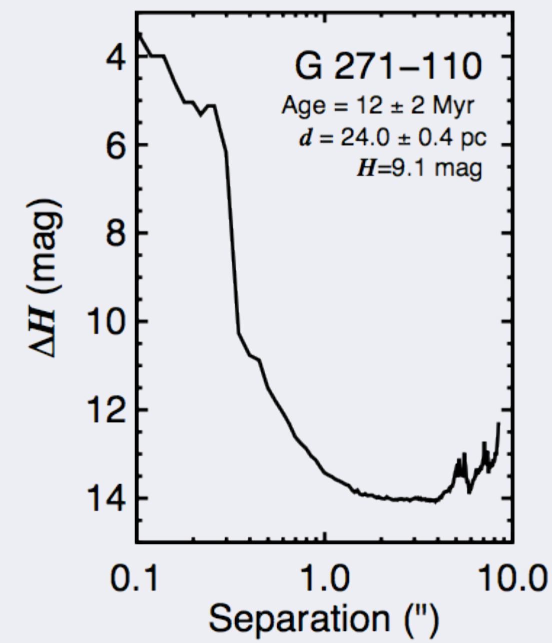
Microlensing	RV	Direct Imaging
(q, s)	$(\dot{v}, P)$	$(\Delta\mathrm{mag}, \rho)$
- Orbital Parameters - Lens Distances - Lens Mass Function - Galactic Model	- Orbital Parameters - Host masses	- Orbital Parameters - Ages and Distances - Planet Evolution Models (Hot-/Cold-Start)

Methodology

Microlensing	RV	Direct Imaging



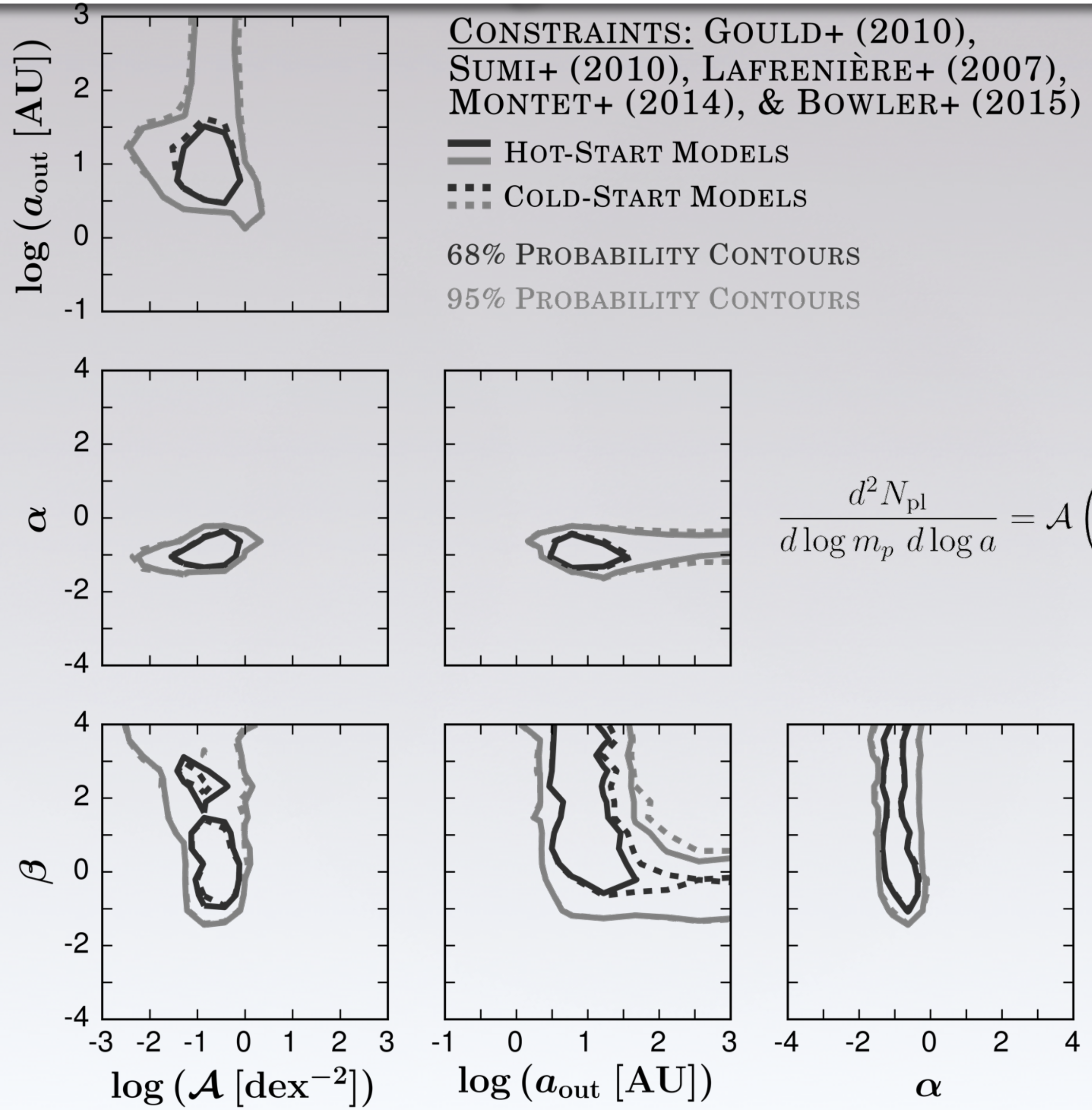




Above figure from Gould+ (2010)

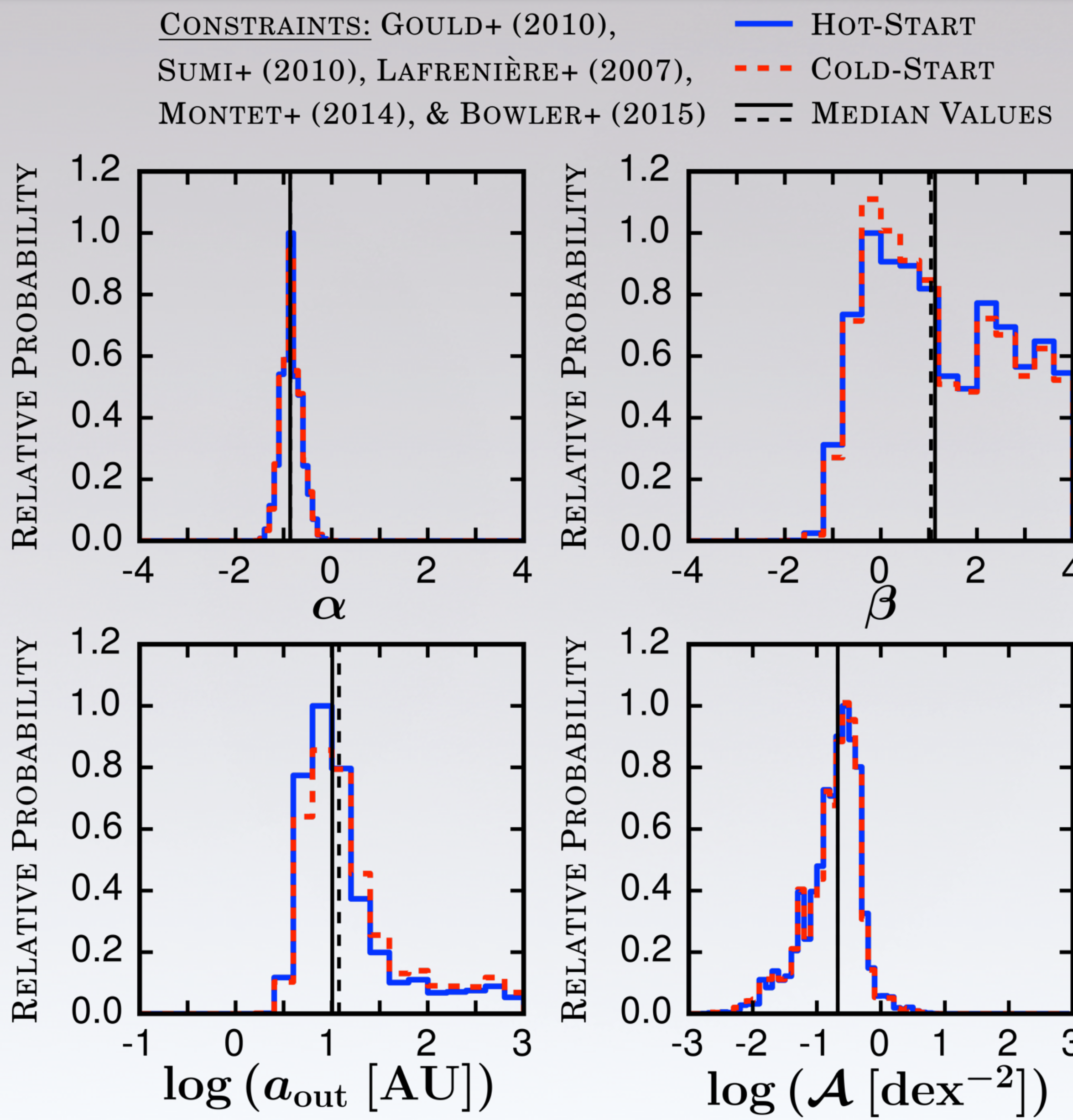
Above figure from Bowler+ (2015)

Results: Microlensing + RV Trends + Imaging



$$\frac{d^2 N_{\rm pl}}{d\log m_p \, d\log a} = \mathcal{A}\left(\frac{m_p}{M_{\rm Sat}}\right)^{\alpha}\left(\frac{a}{2.5\ \rm AU}\right)^{\beta}$$

Results: Marginal Distributions

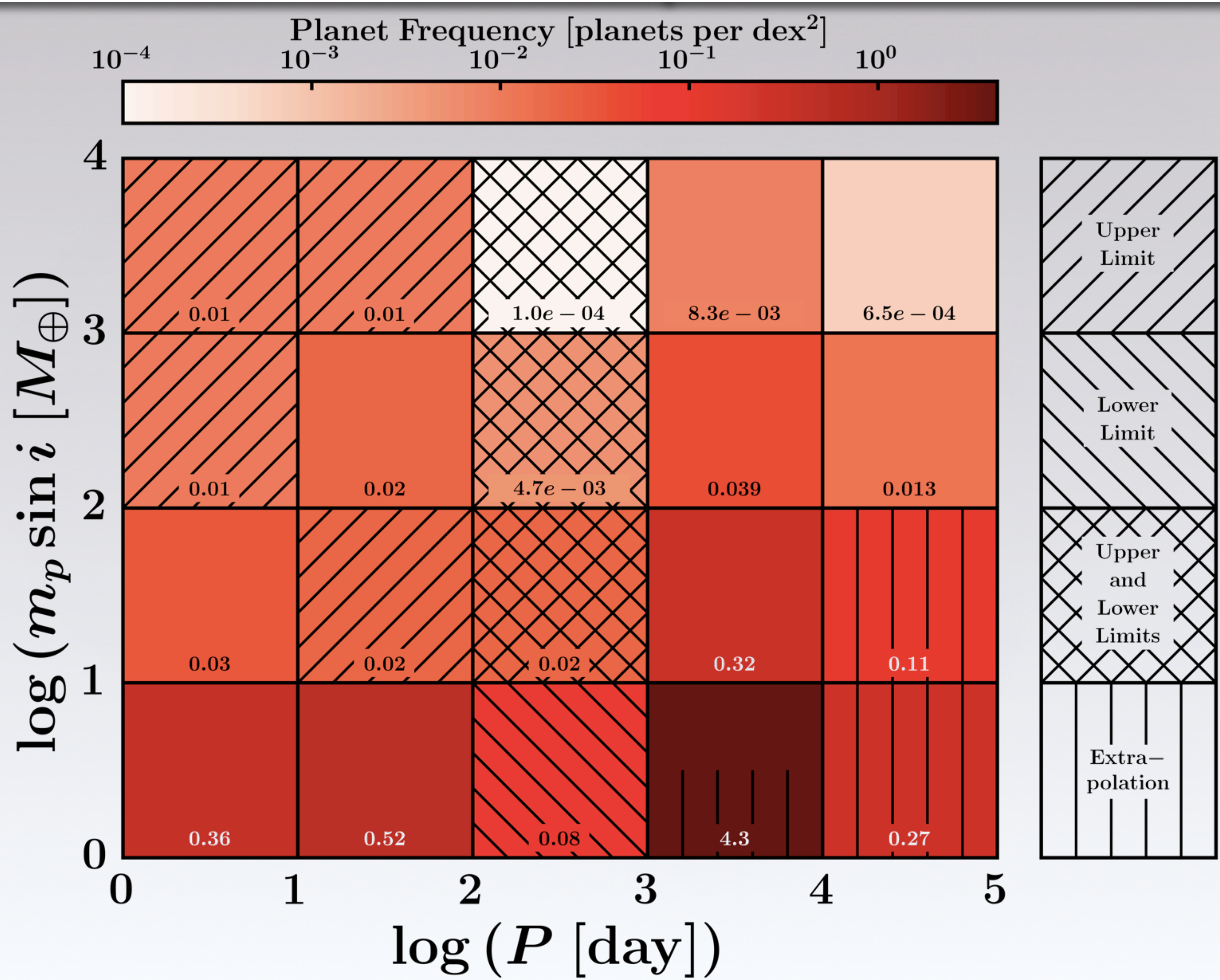


Results: Final Parameter Constraints

Planet Evolutionary Models	Median Values and 68% Uncertainties			
	α	β	$\mathcal{A}$ [dex^{-2}]	$a_{\rm out}$ [AU]
"Hot-Start" (Baraffe et al. 2003)	$-0.86^{+0.21}_{-0.19}$	$1.1^{+1.9}_{-1.4}$	$0.21^{+0.20}_{-0.15}$	$10^{+26}_{-4.7}$
"Cold-Start" (Fortney et al. 2008)	$-0.85^{+0.21}_{-0.19}$	$1.1^{+1.9}_{-1.3}$	$0.21^{+0.20}_{-0.15}$	$12^{+50}_{-6.2}$

$$\frac{d^2 N_{\rm pl}}{d \log m_p \, d \log a} = \mathcal{A} \left(\frac{m_p}{M_{\rm Sat}} \right)^{\alpha} \left(\frac{a}{2.5 \text{ AU}} \right)^{\beta}$$

The M Dwarf Exoplanet Census



Future Work

Include New Microlensing Results

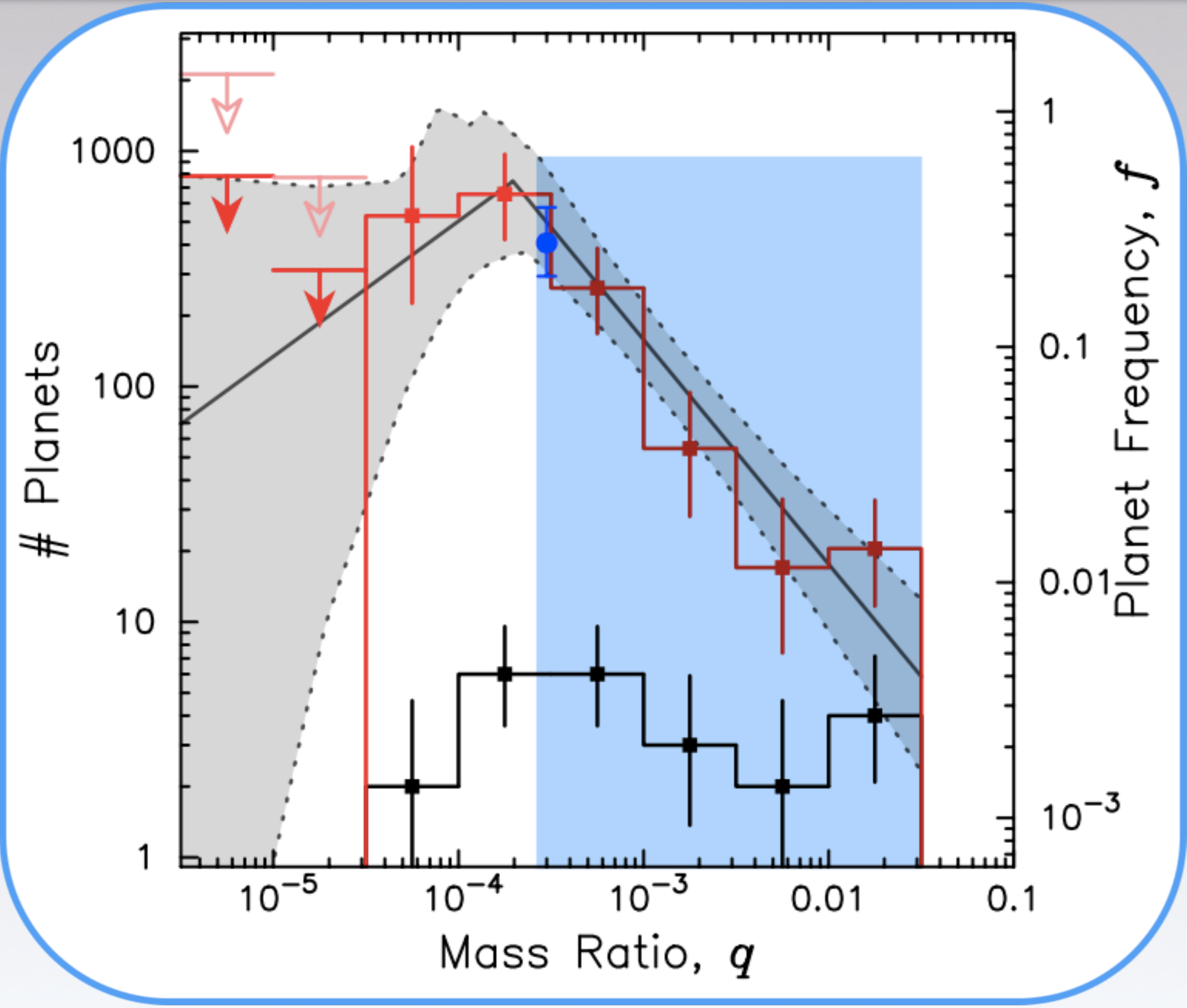
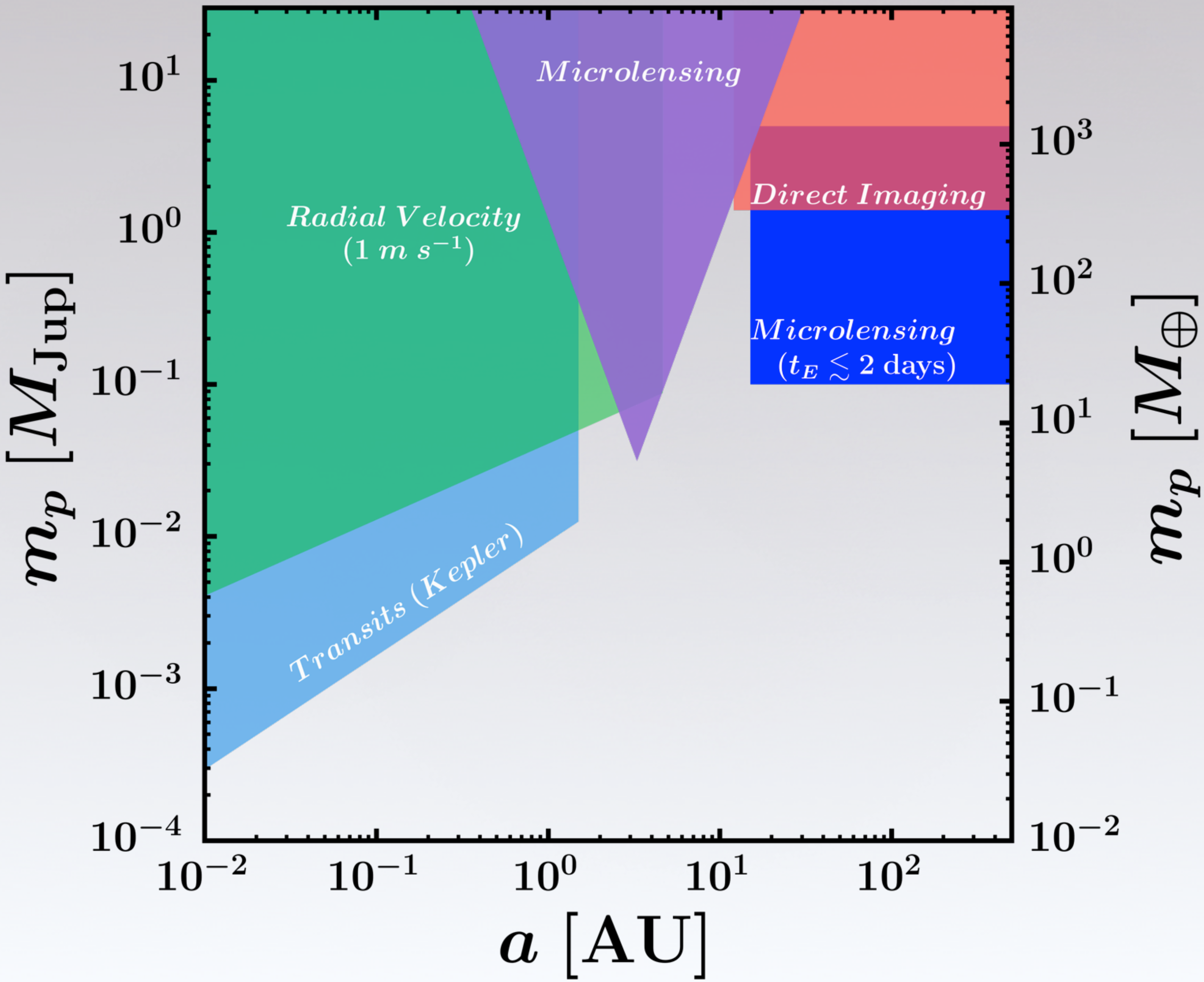


Figure from Suzuki et al. 2016

Synthesis of "The Big Four"



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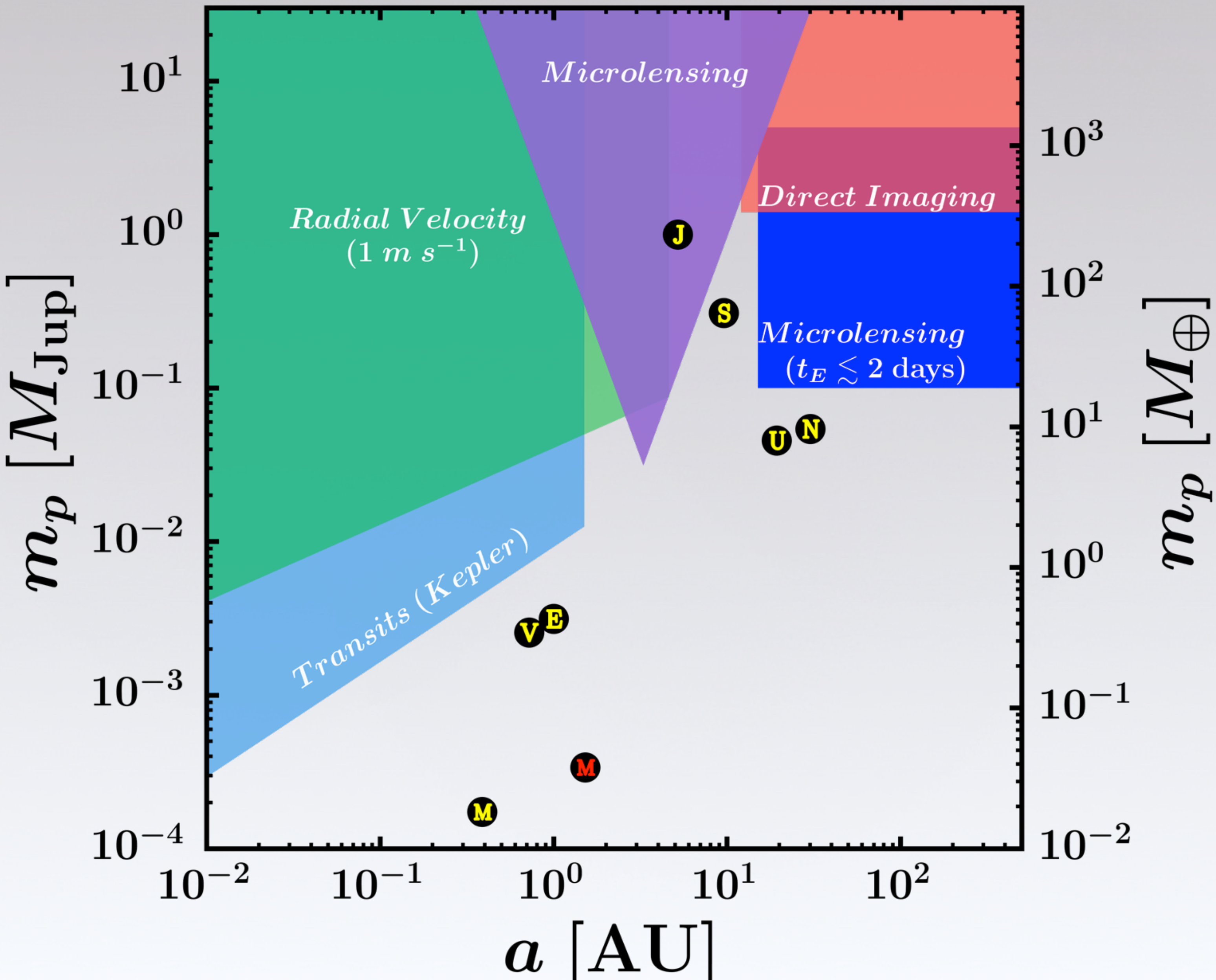
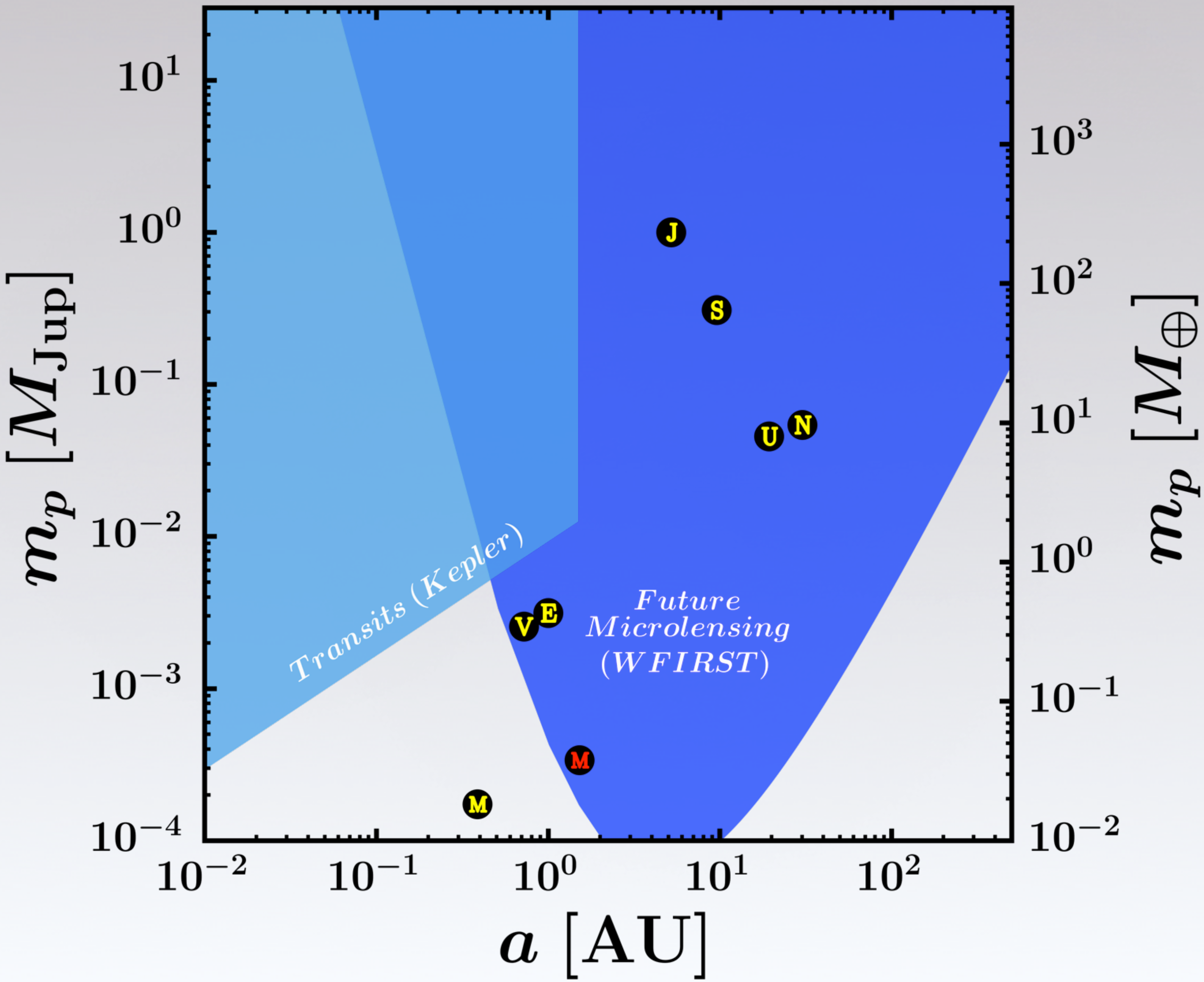
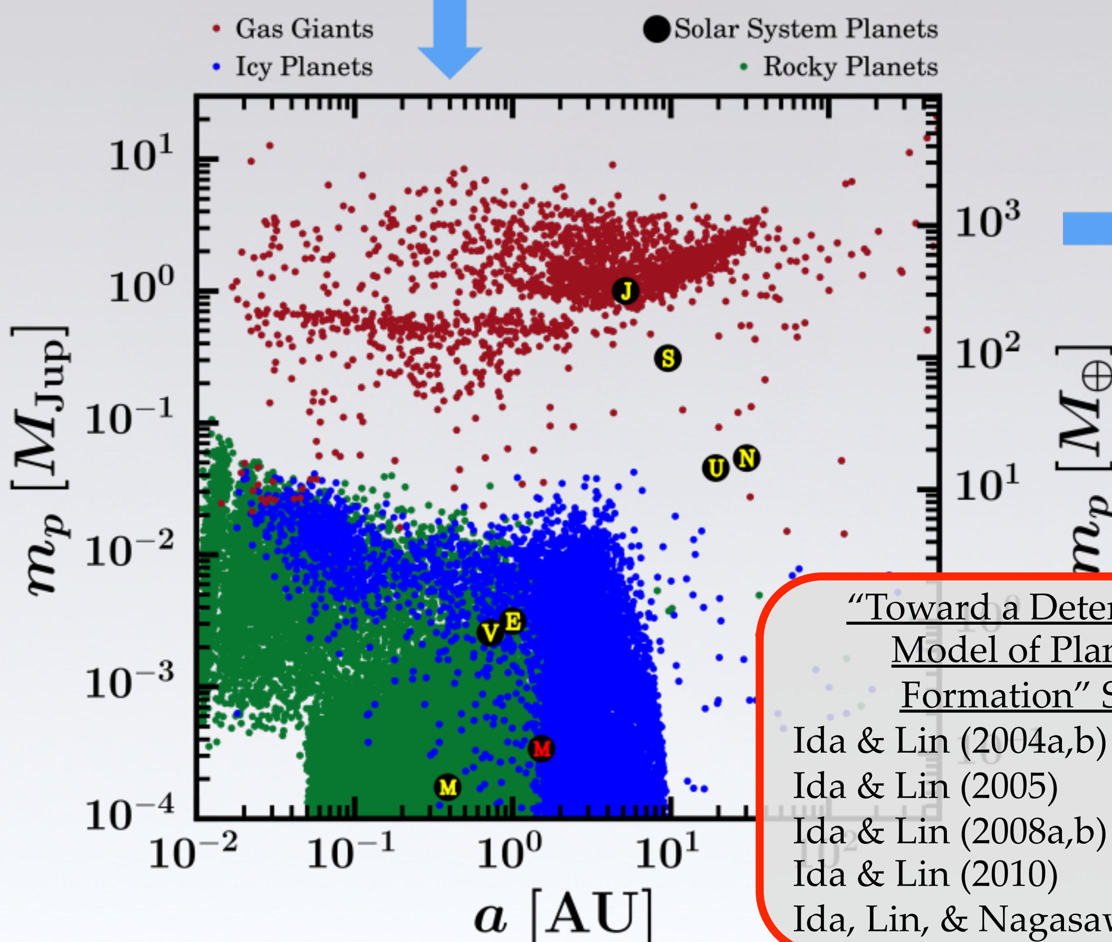


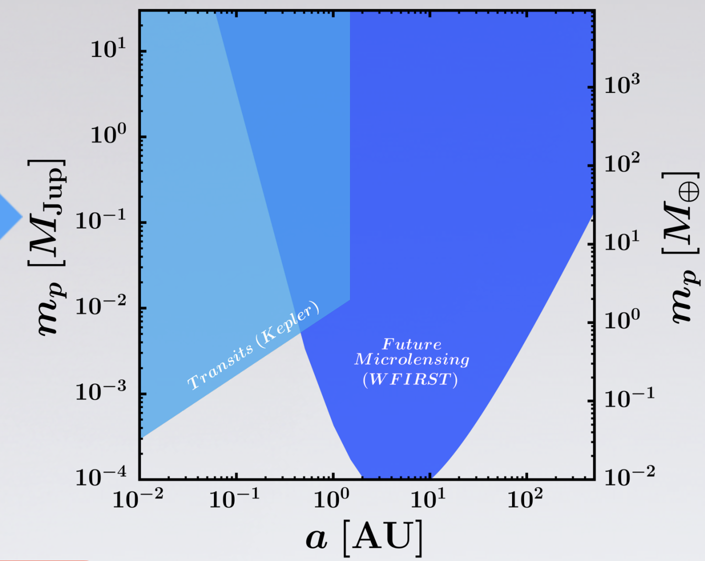
Kepler + WFIRST



Kepler + WFIRST

Initial Conditions & Input Physics
(Disk Masses, Disk Lifetimes, Surface Density Profiles, Migration Mechanisms/Rates, Turbulence, Core Accretion, etc.)





"Toward a Deterministic Model of Planetary Formation" Series

Ida & Lin (2004a,b)
Ida & Lin (2005)
Ida & Lin (2008a,b)
Ida & Lin (2010)
Ida, Lin, & Nagasawa (2013)

References

RV + μlensing → Clanton, C. & Gaudi, B. S. 2014, ApJ, 791, 90

RV + μlensing → Clanton, C. & Gaudi, B. S. 2014, ApJ, 791, 91

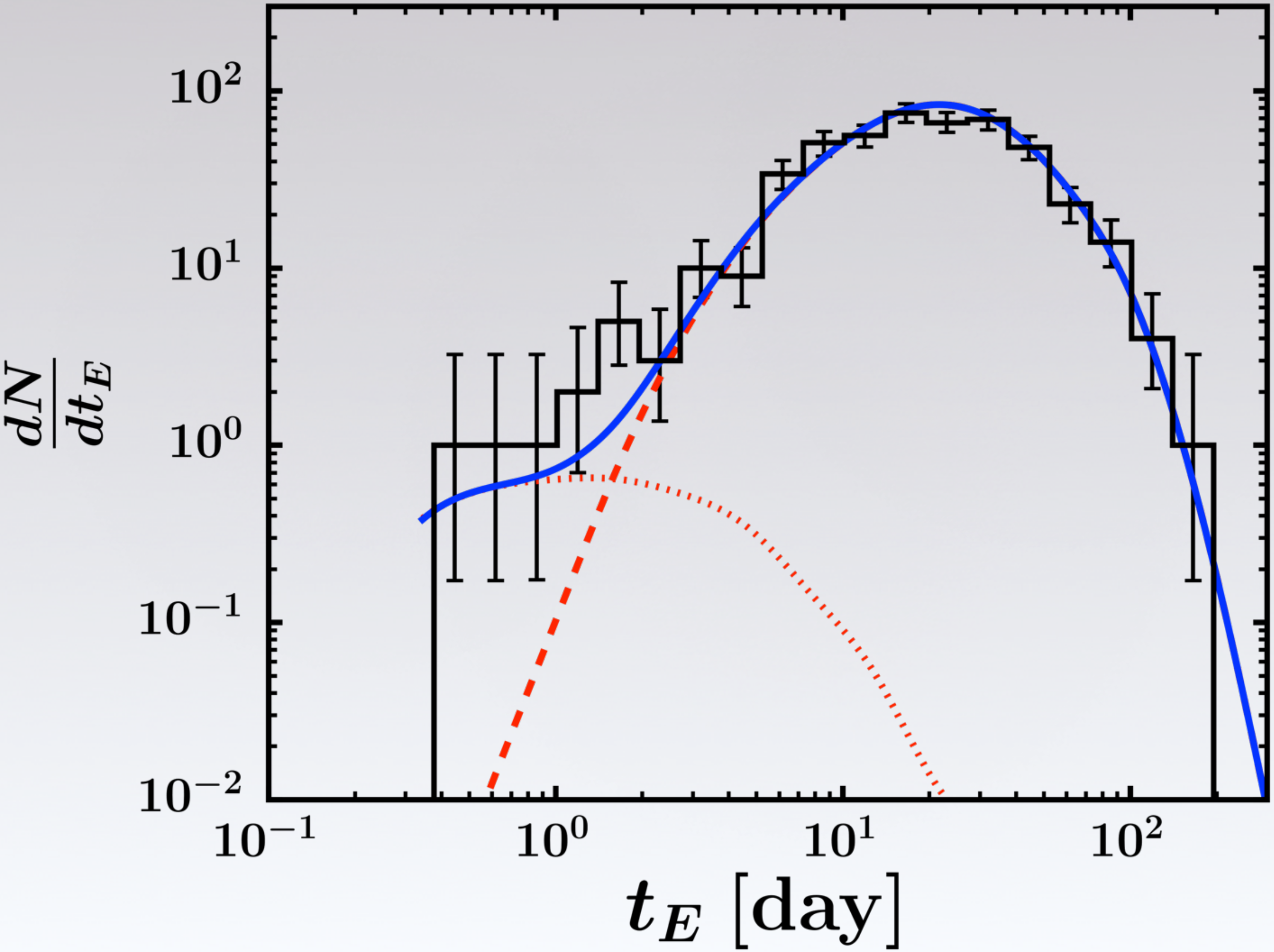
RV + μlensing + Imaging → Clanton, C. & Gaudi, B. S. 2016, ApJ, 819, 125

Free-Floating Planets → Clanton, C. & Gaudi, B. S. 2017, ApJ, 834, 46

End

Constraining the Galactic Population of Free-Floating Planets

Maximum Likelihood Estimation: Bound Planets + LMF Fit to Observed Timescale Distribution



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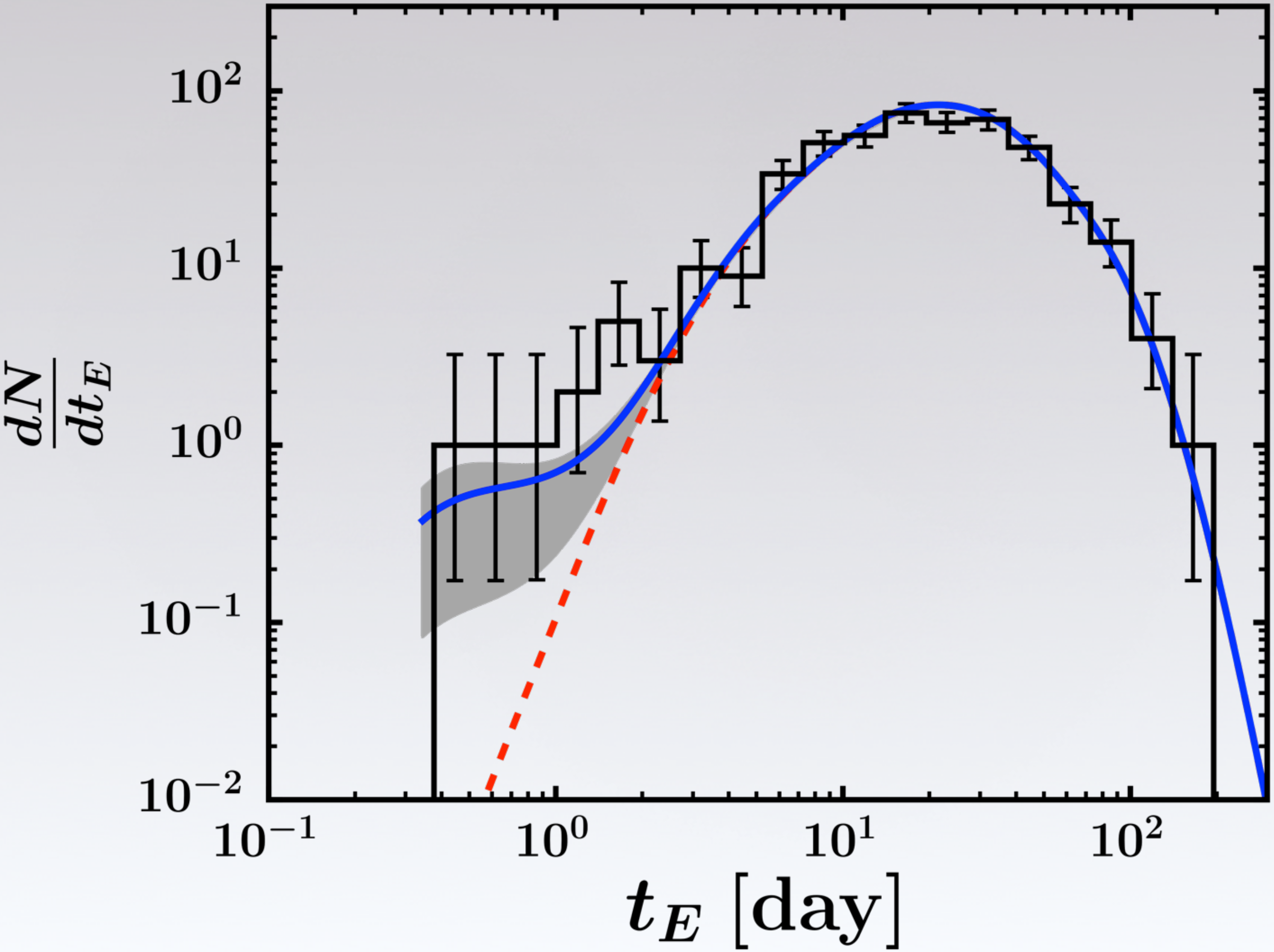
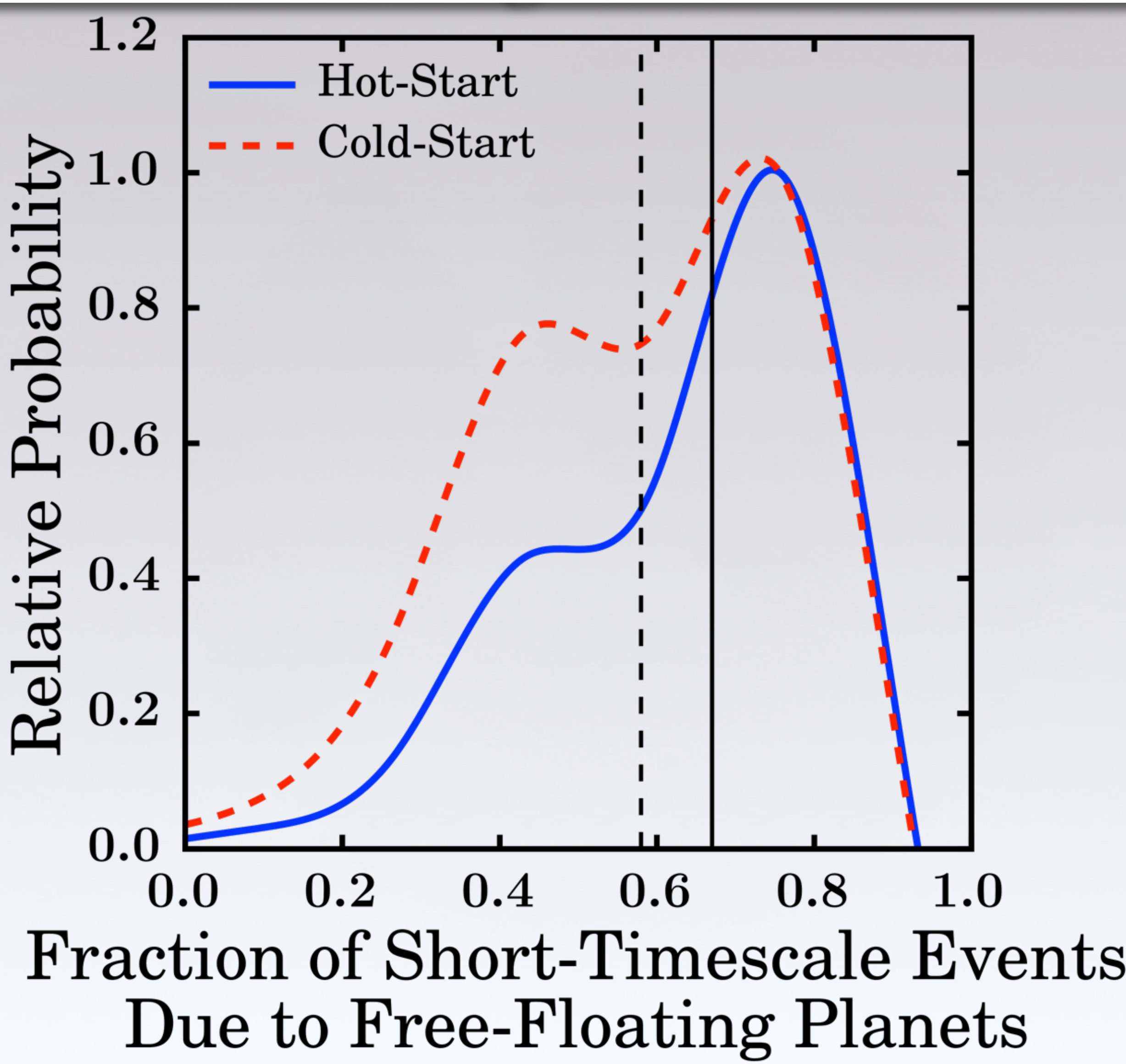


Constraints on the Galactic Population of Free-Floating Planets



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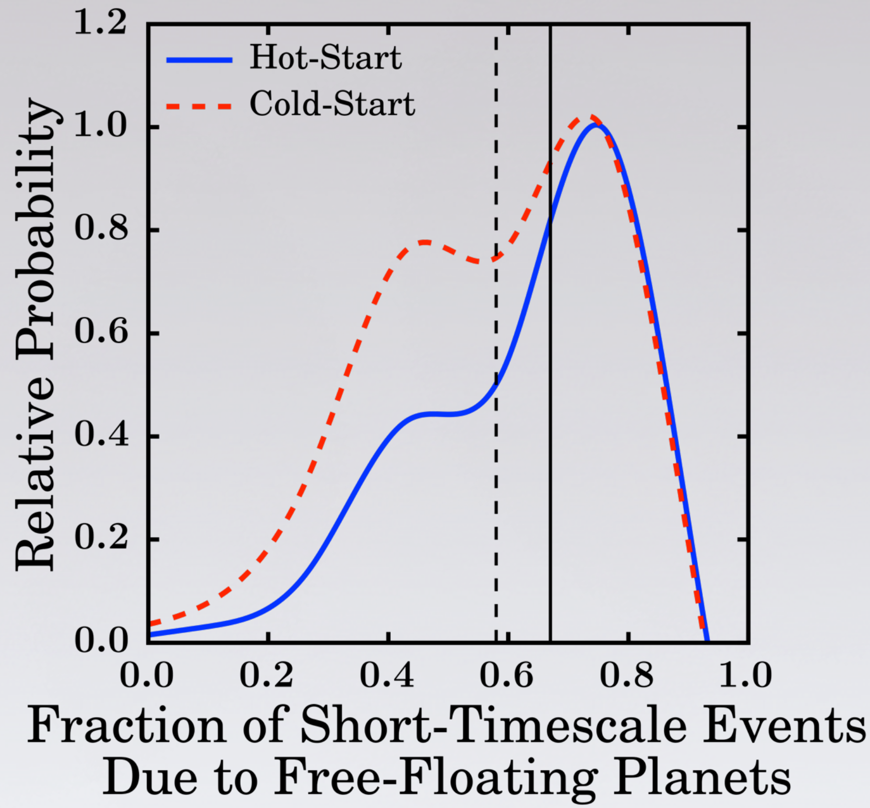
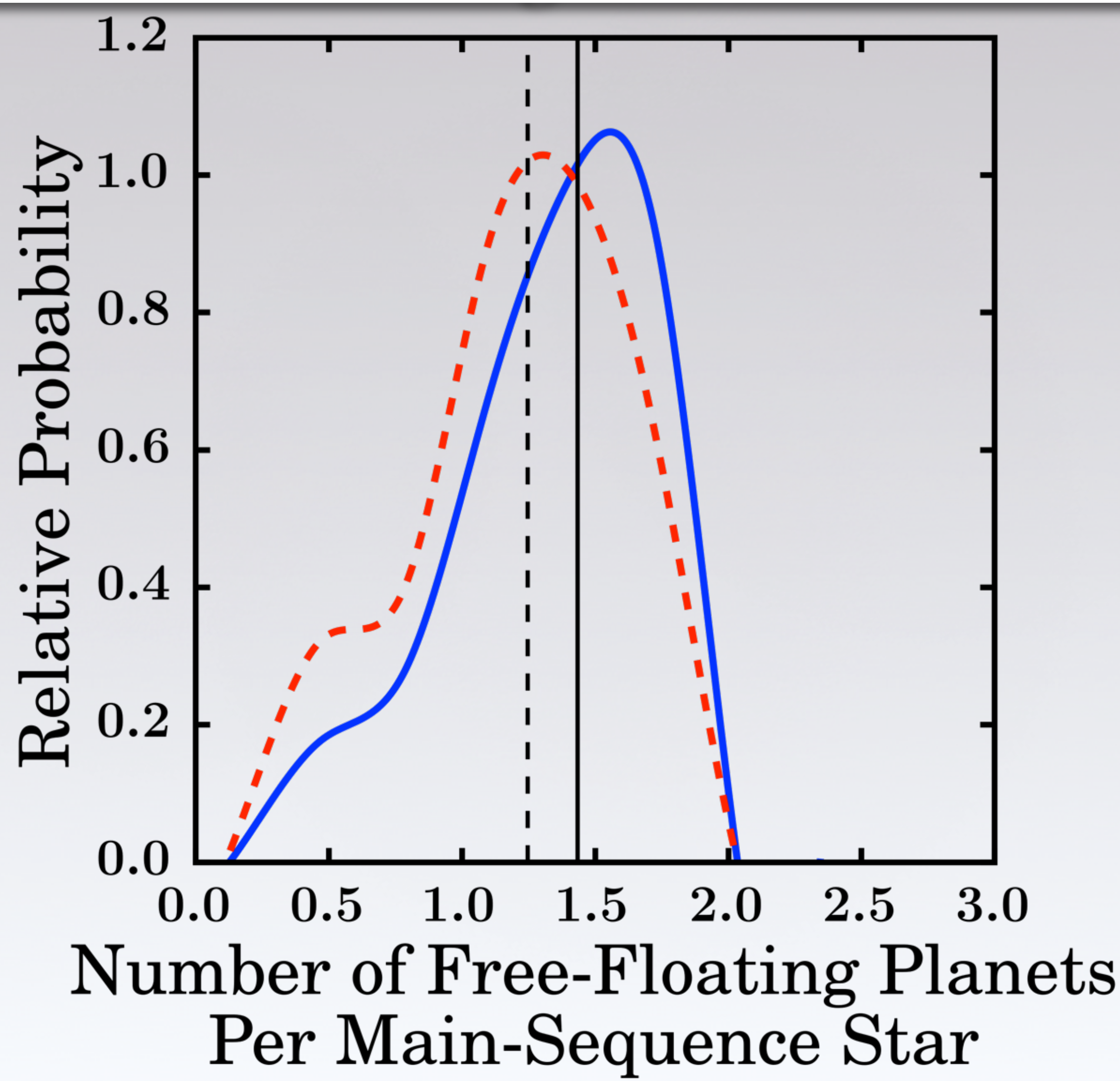


	Median	68% CI	95% CI
Hot—Start	0.67	0.44—0.78	0.23—0.85
Cold—Start	0.58	0.40—0.74	0.14—0.83

Constraints on the Galactic Population of Free-Floating Planets



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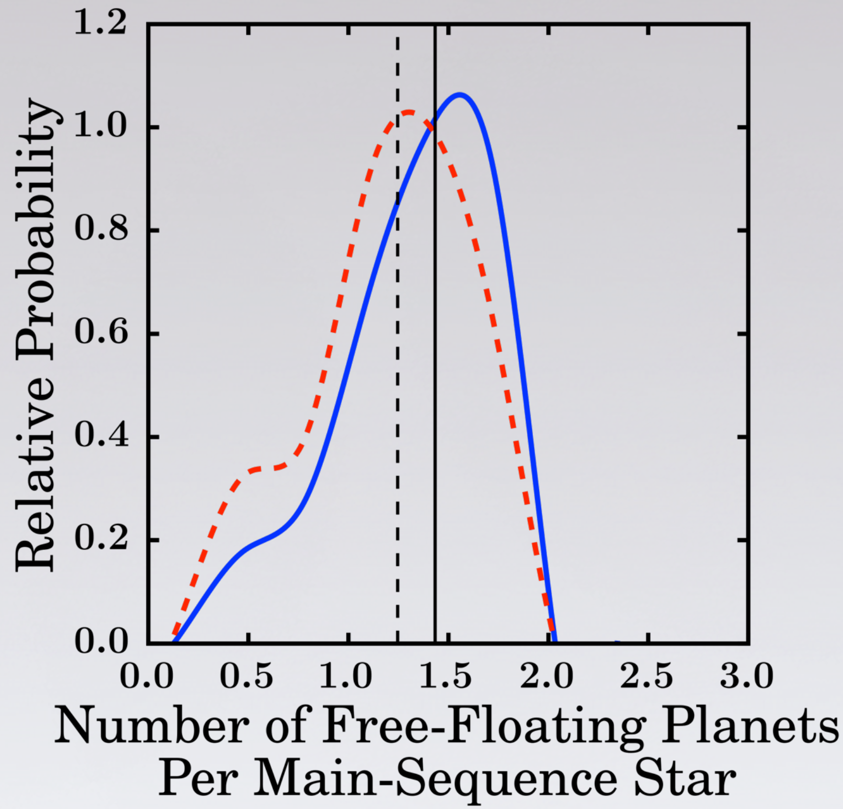

	Median	68% CI	95% CI
Hot—Start	1.4	0.95—1.7	0.48—1.8
Cold—Start	1.2	0.87—1.6	0.29—1.8