

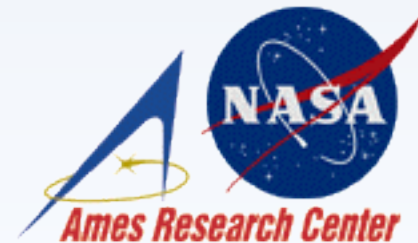
The Synthesis of Microlensing, Radial Velocity, and Direct Imaging Survey Results

{ Constraining the Abundance and Demographics
of Bound and Unbound Planets

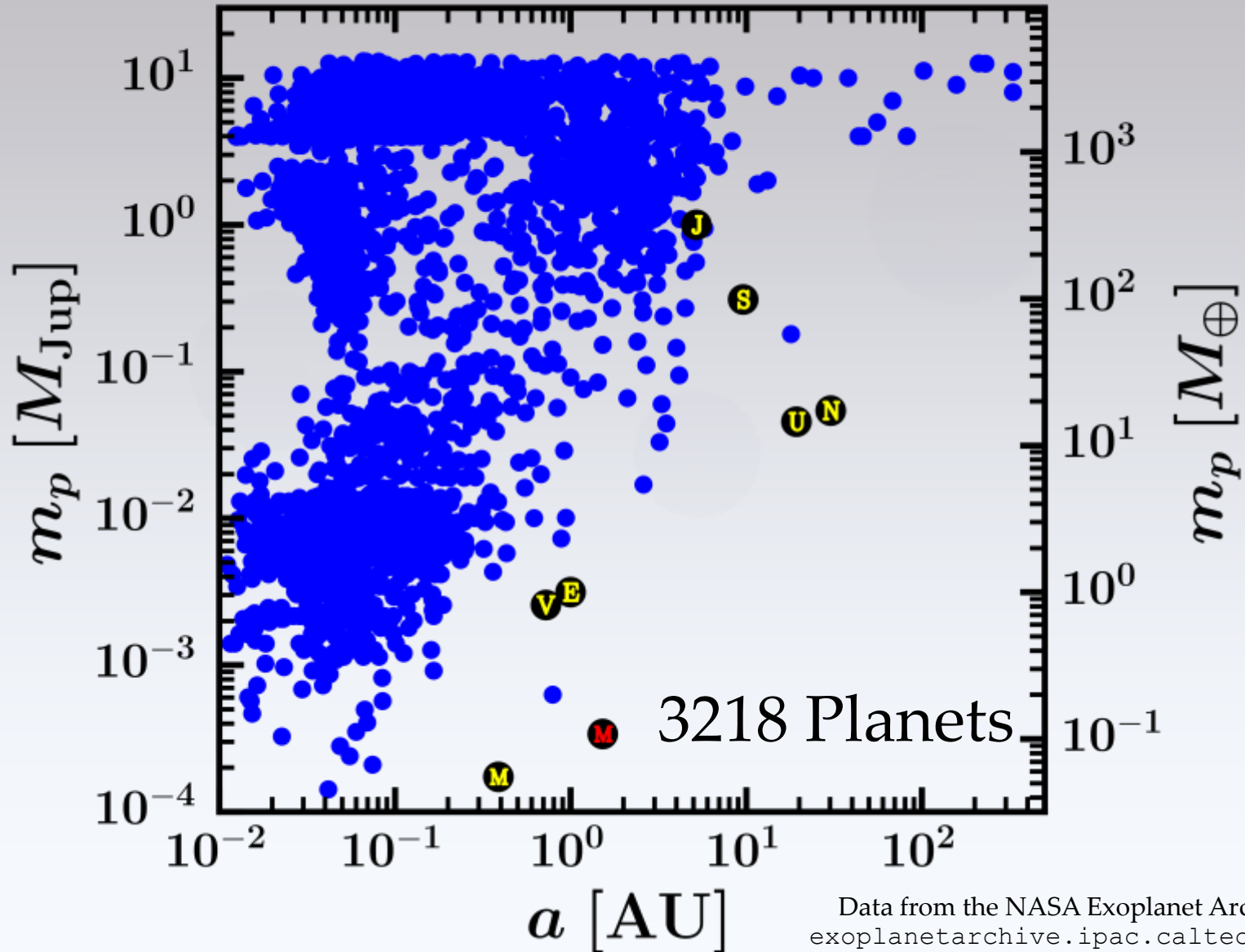
21st Microlensing Meeting, Pasadena, CA, Feb 2017

Christian Clanton

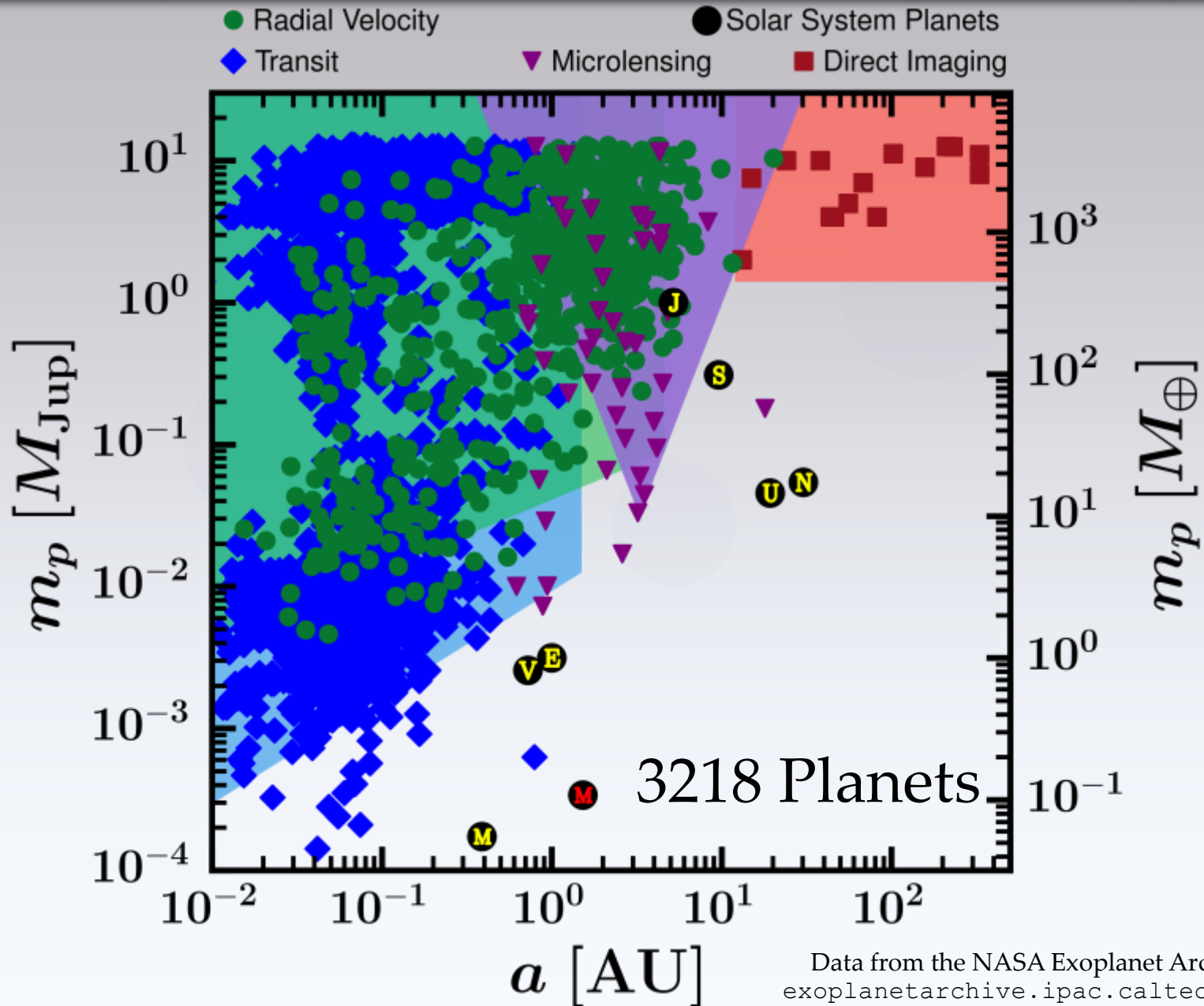
NPP Fellow



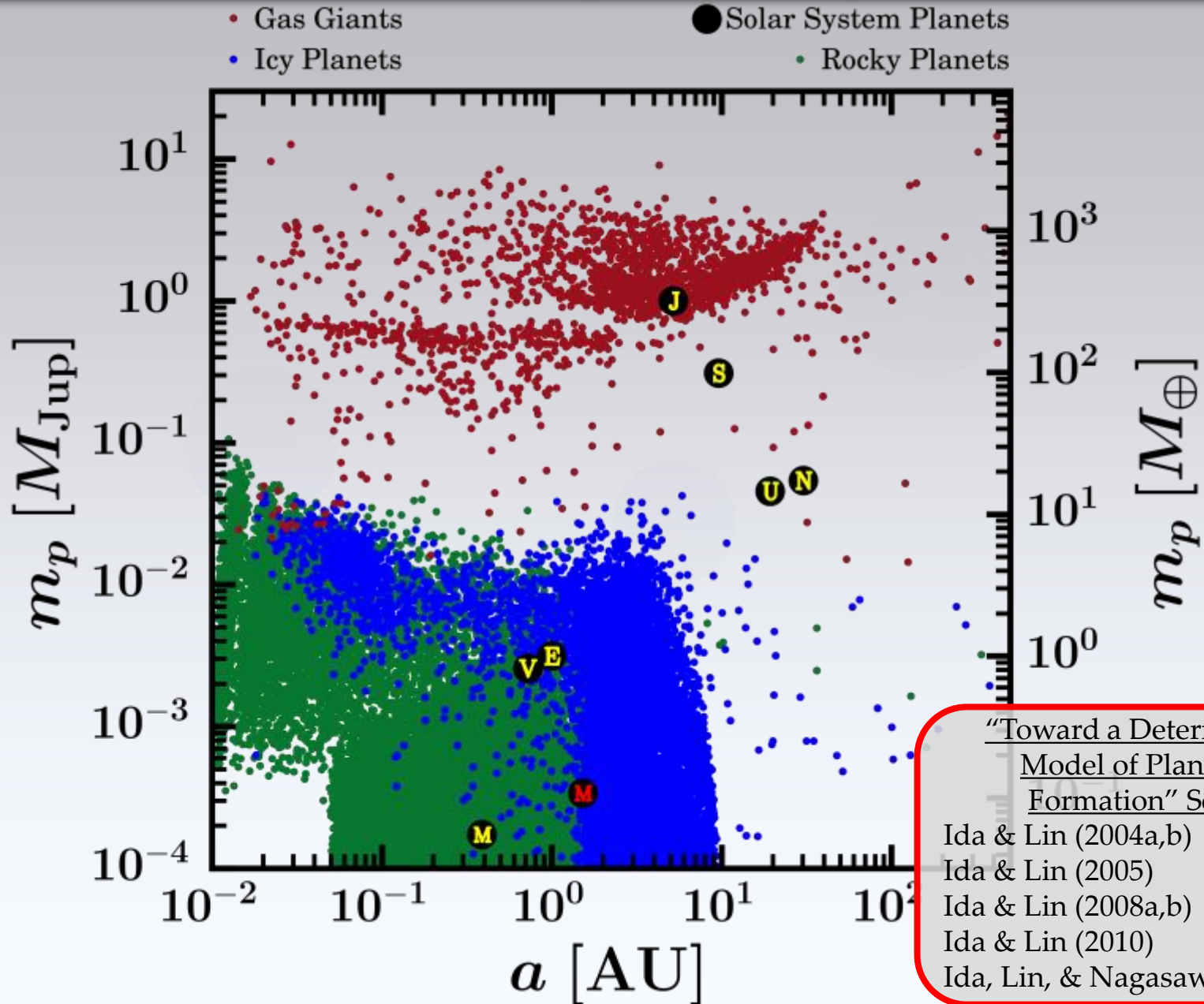
Currently Known Planets (All Host Spectral Types)



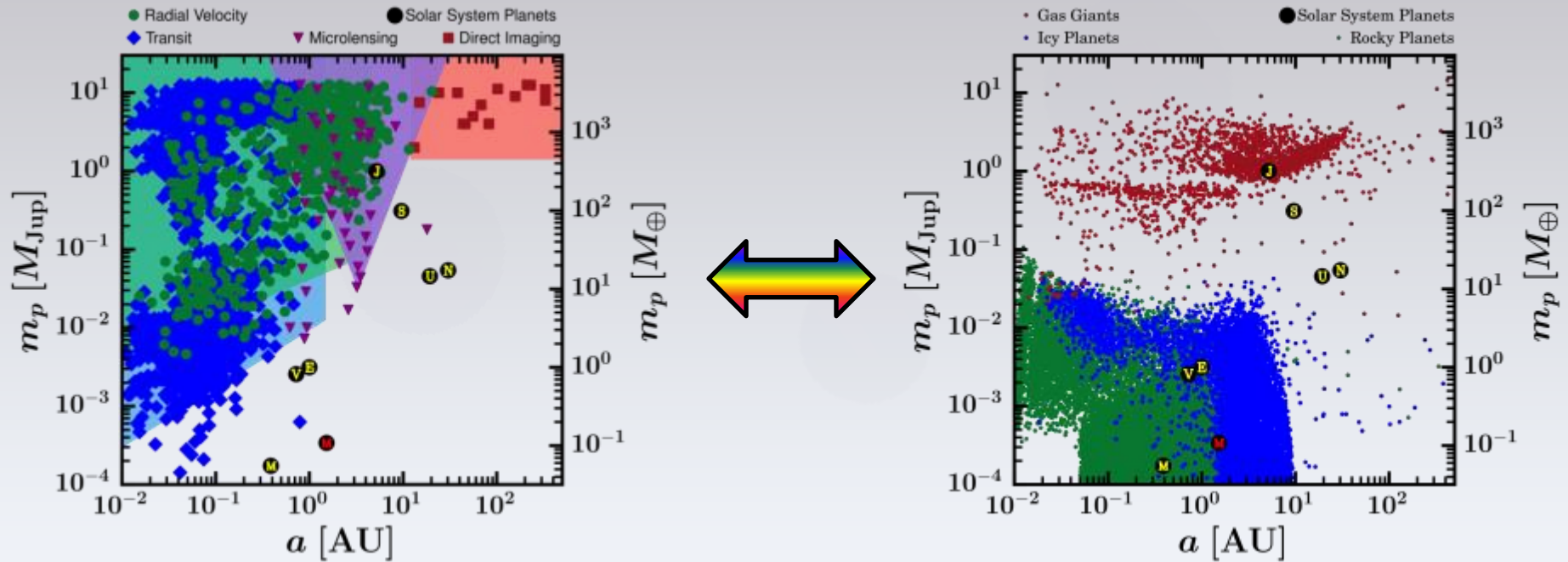
Currently Known Planets (All Host Spectral Types)



Planet Formation and Population Synthesis Models



Constraining Formation Models

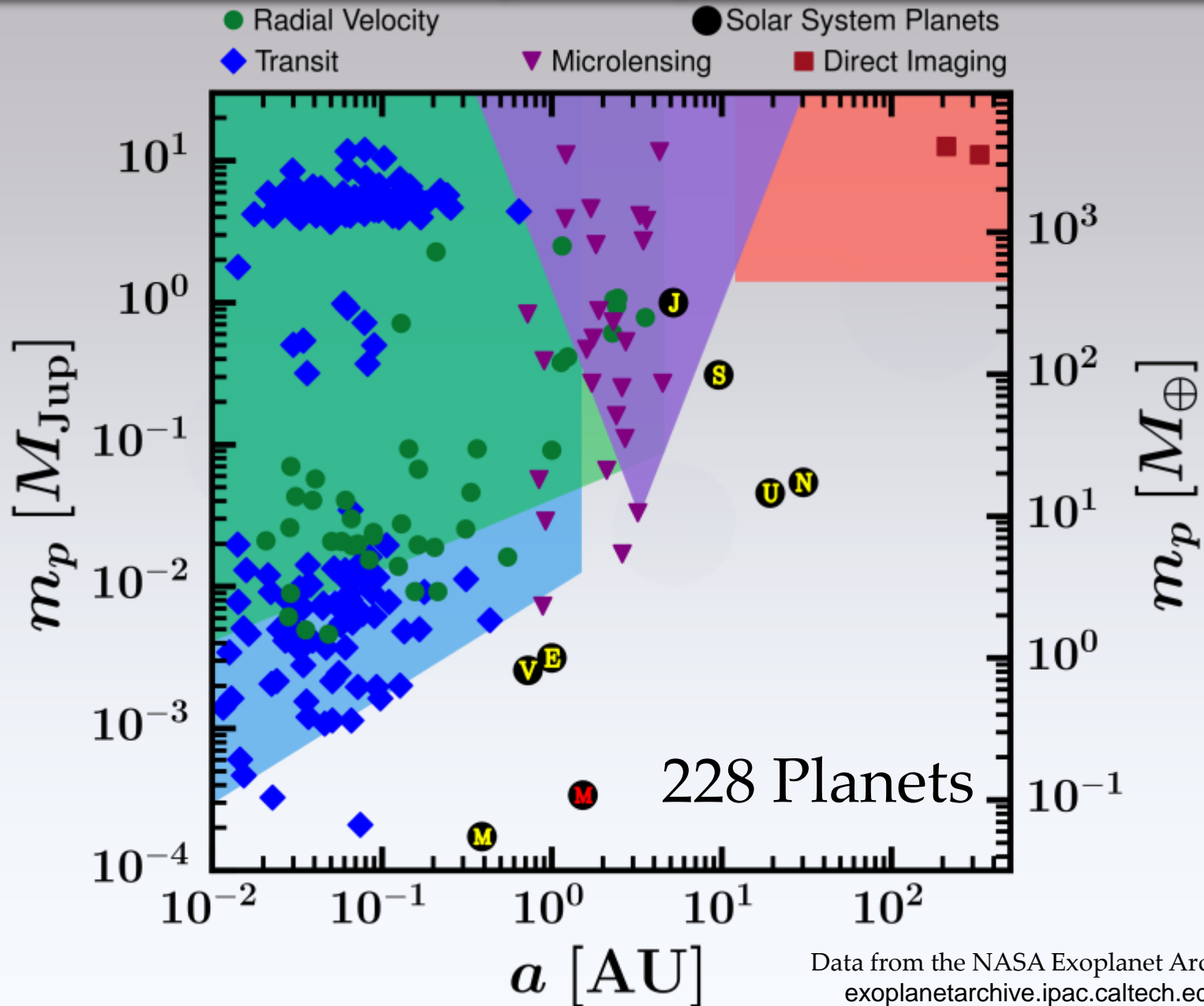


Part I.
Demographics of Planets
Around M Dwarfs

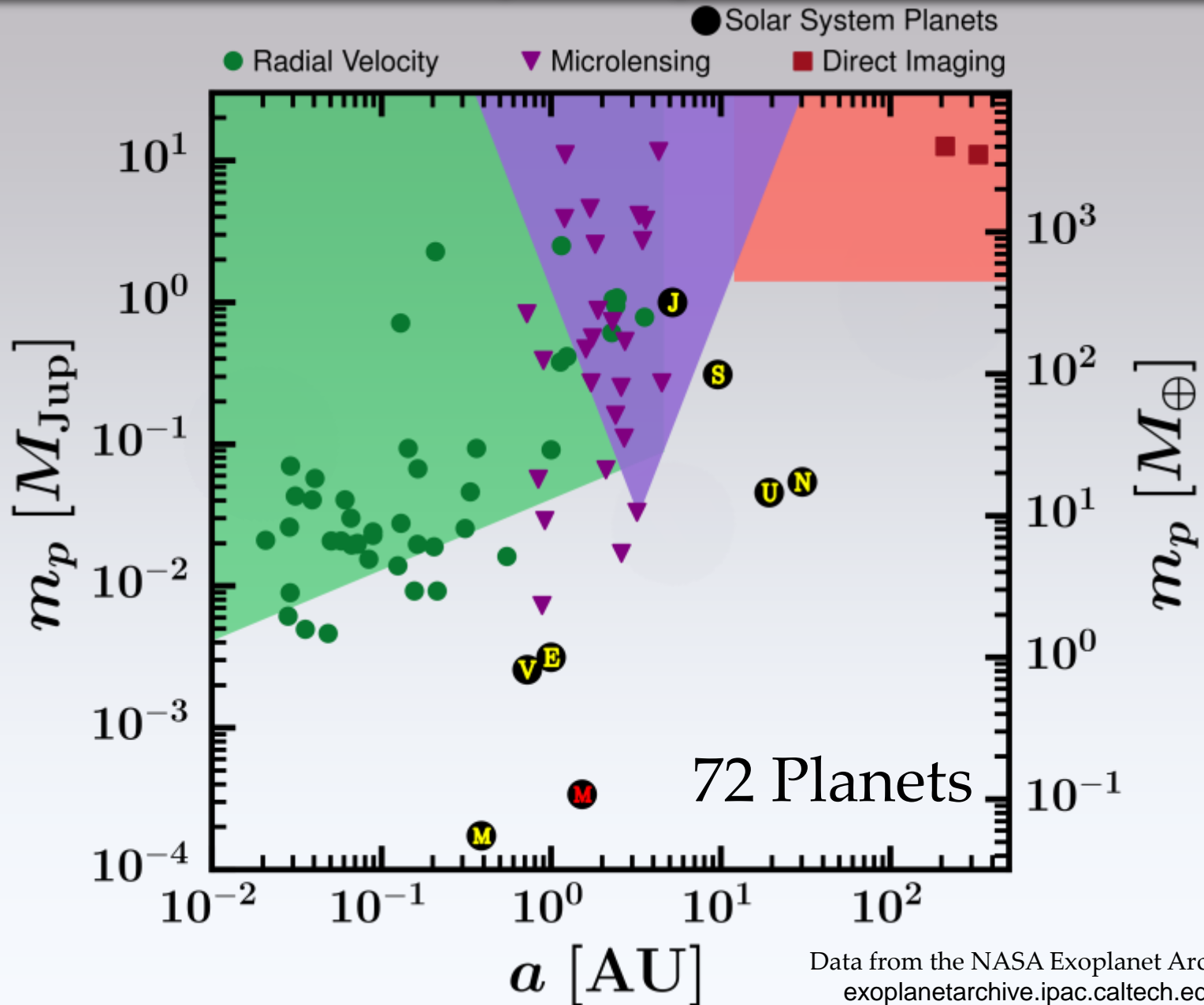
M Dwarfs

Common
Well-Characterized Demographics

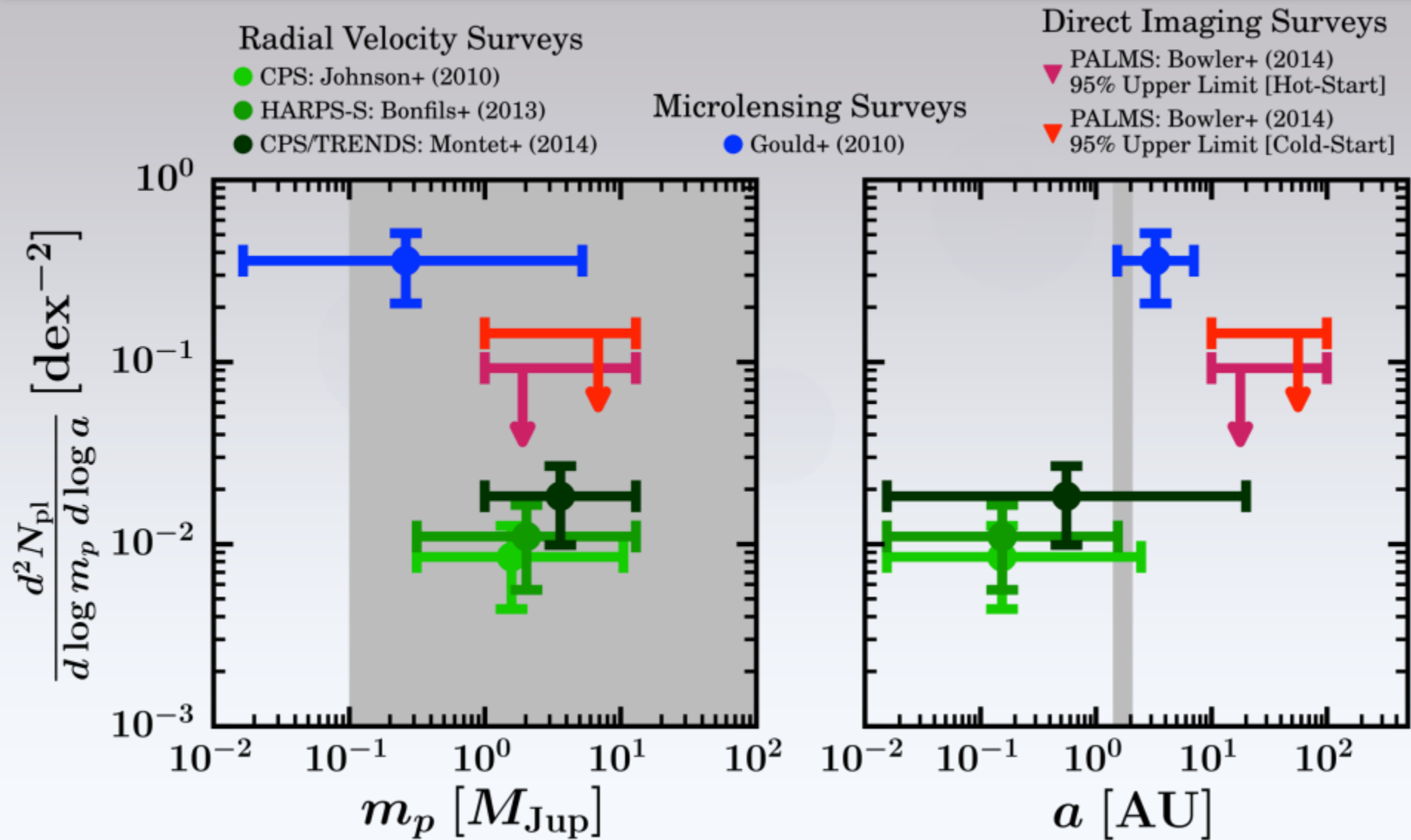
Confirmed Planetary Companions to M Dwarfs



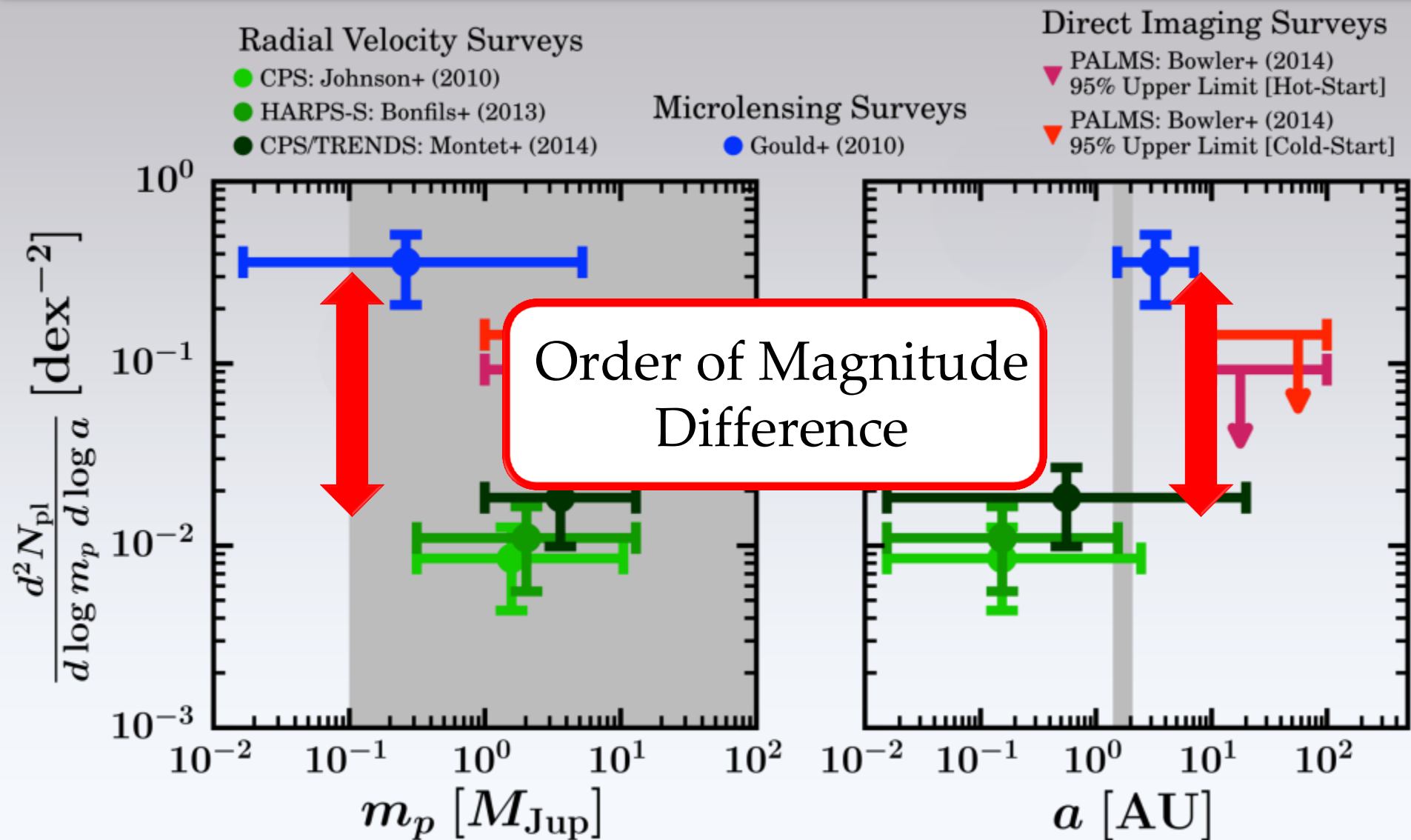
Confirmed Planetary Companions to M Dwarfs



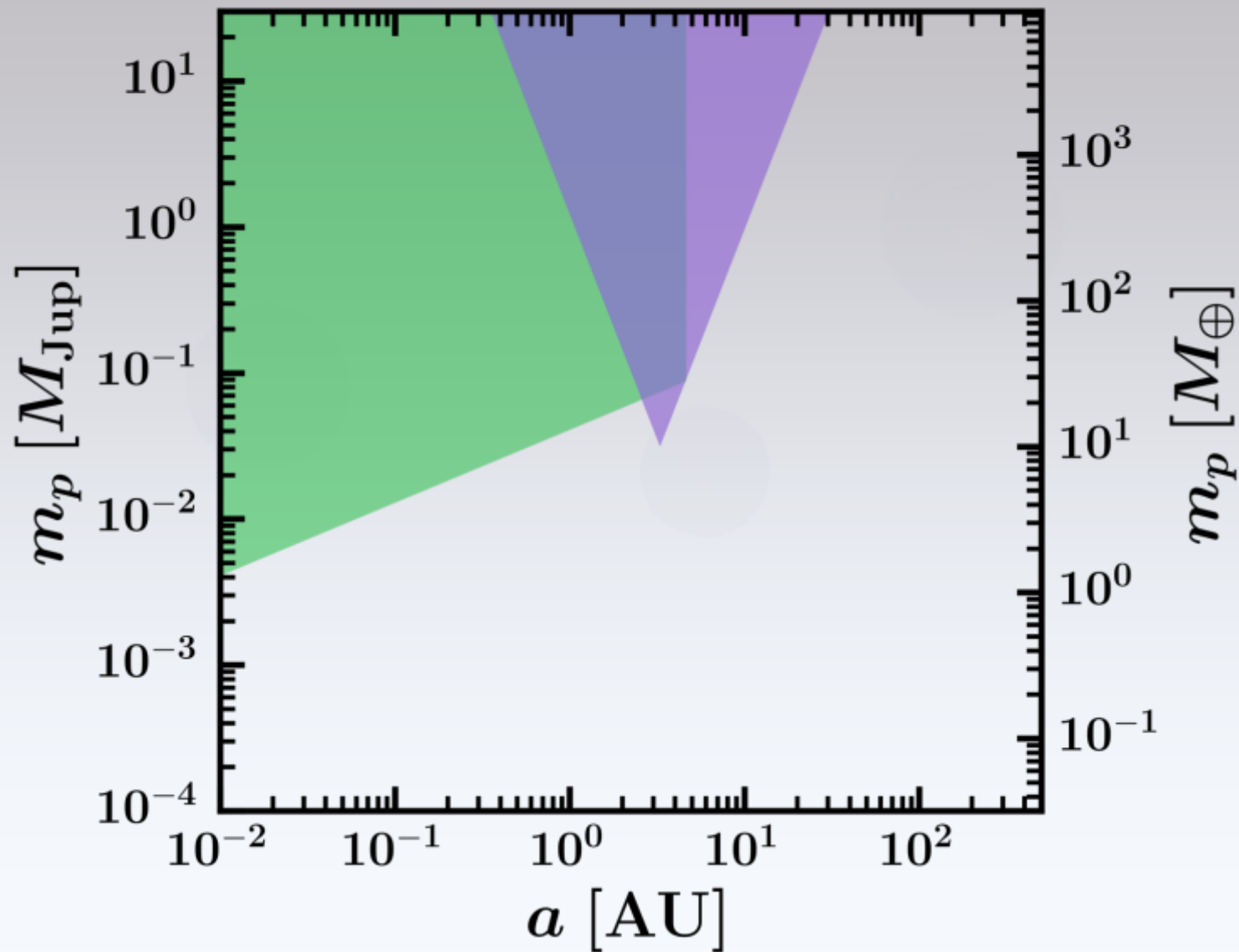
Exoplanet Censuses of M Dwarfs from Individual Methods



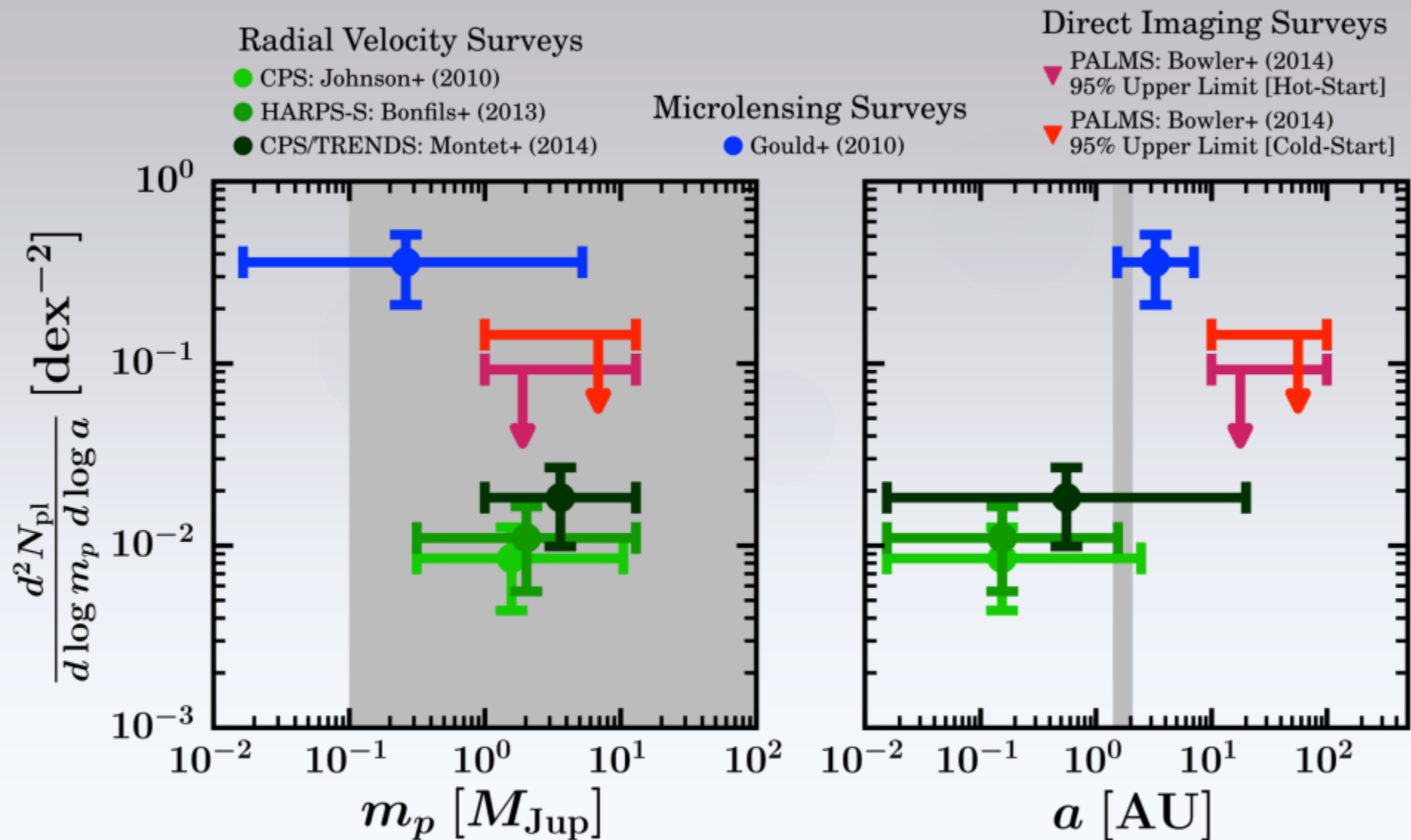
Exoplanet Censuses of M Dwarfs from Individual Methods



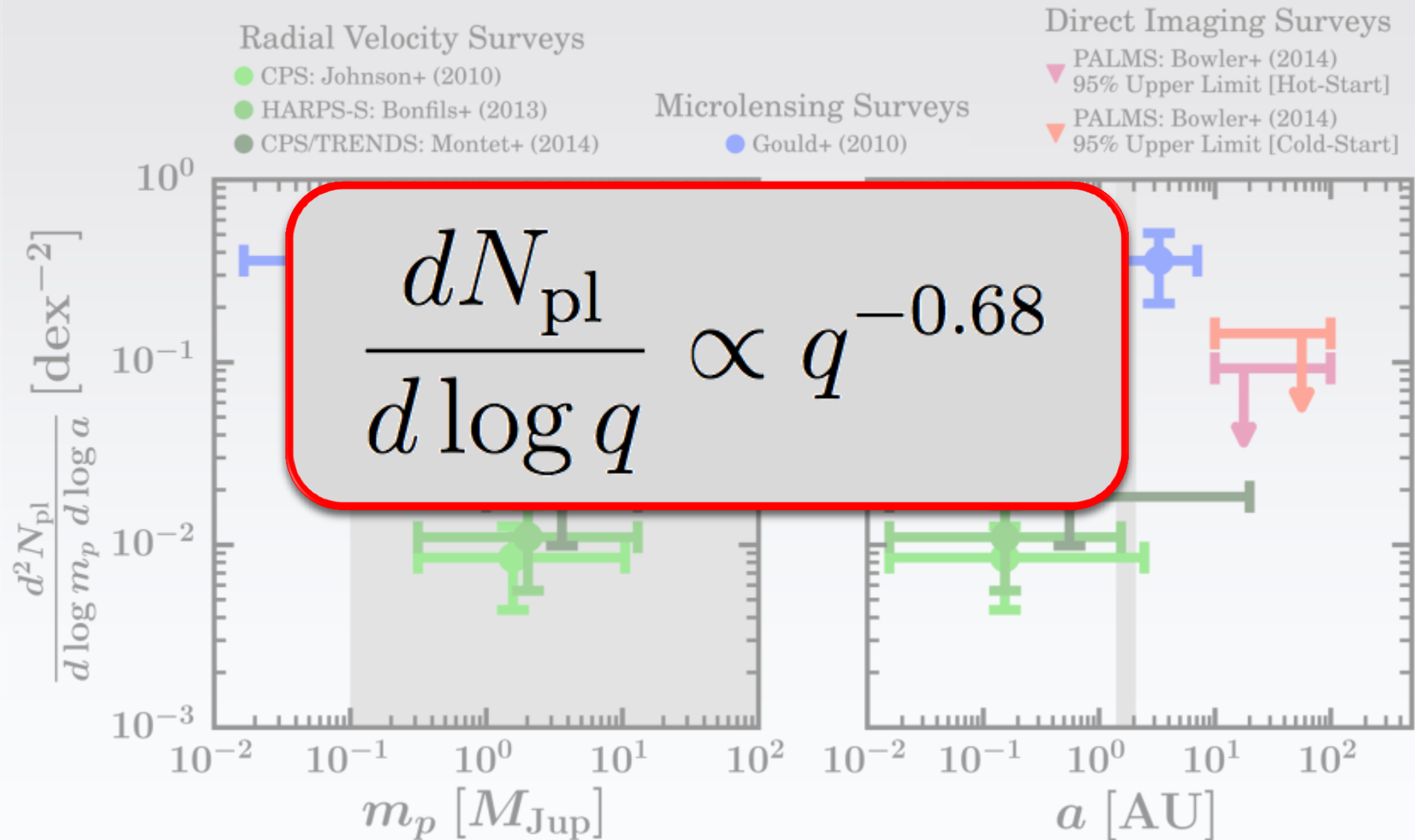
Sensitivities of Microlensing and RV Surveys



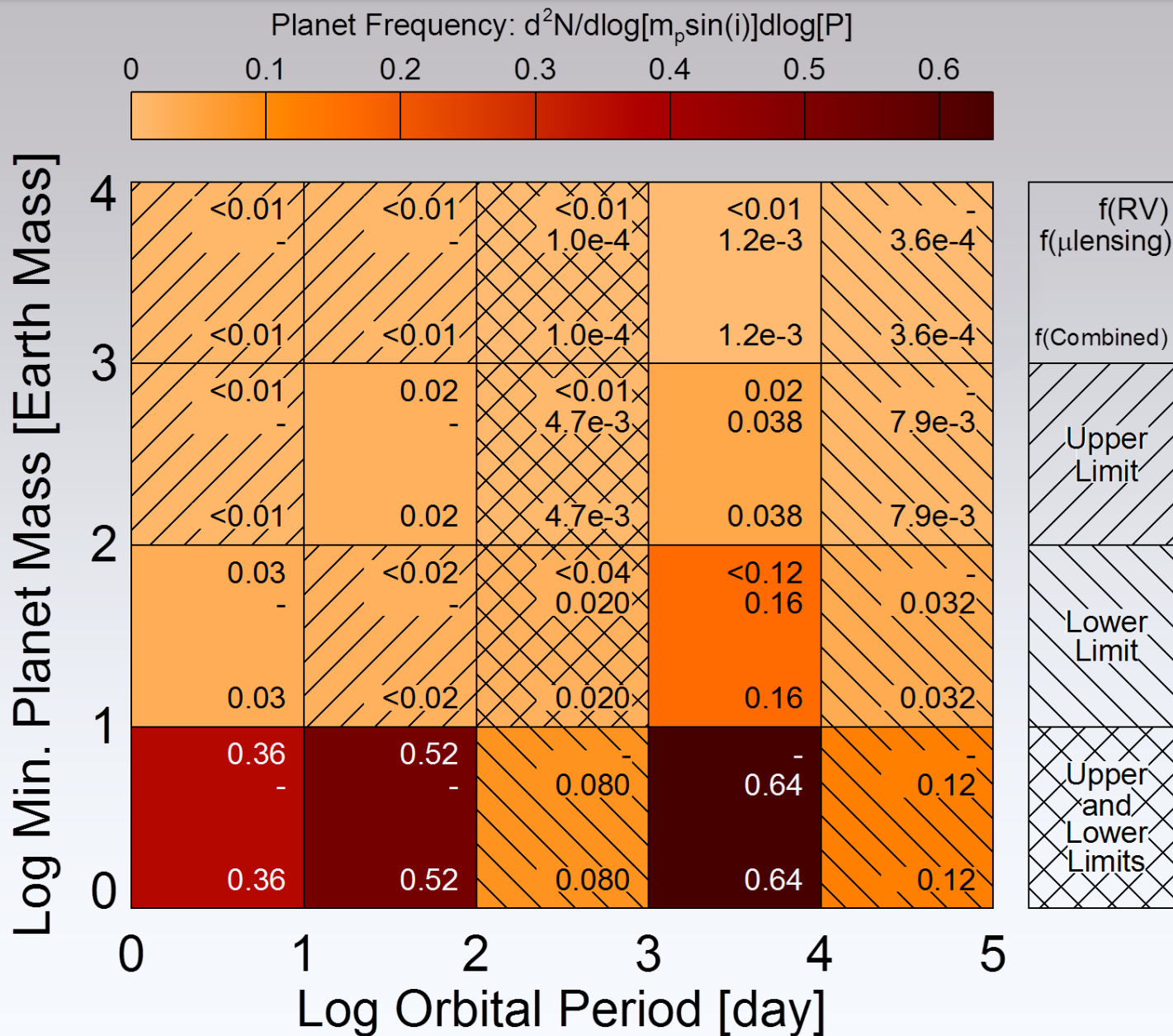
Consistency Between Microlensing and RV Results



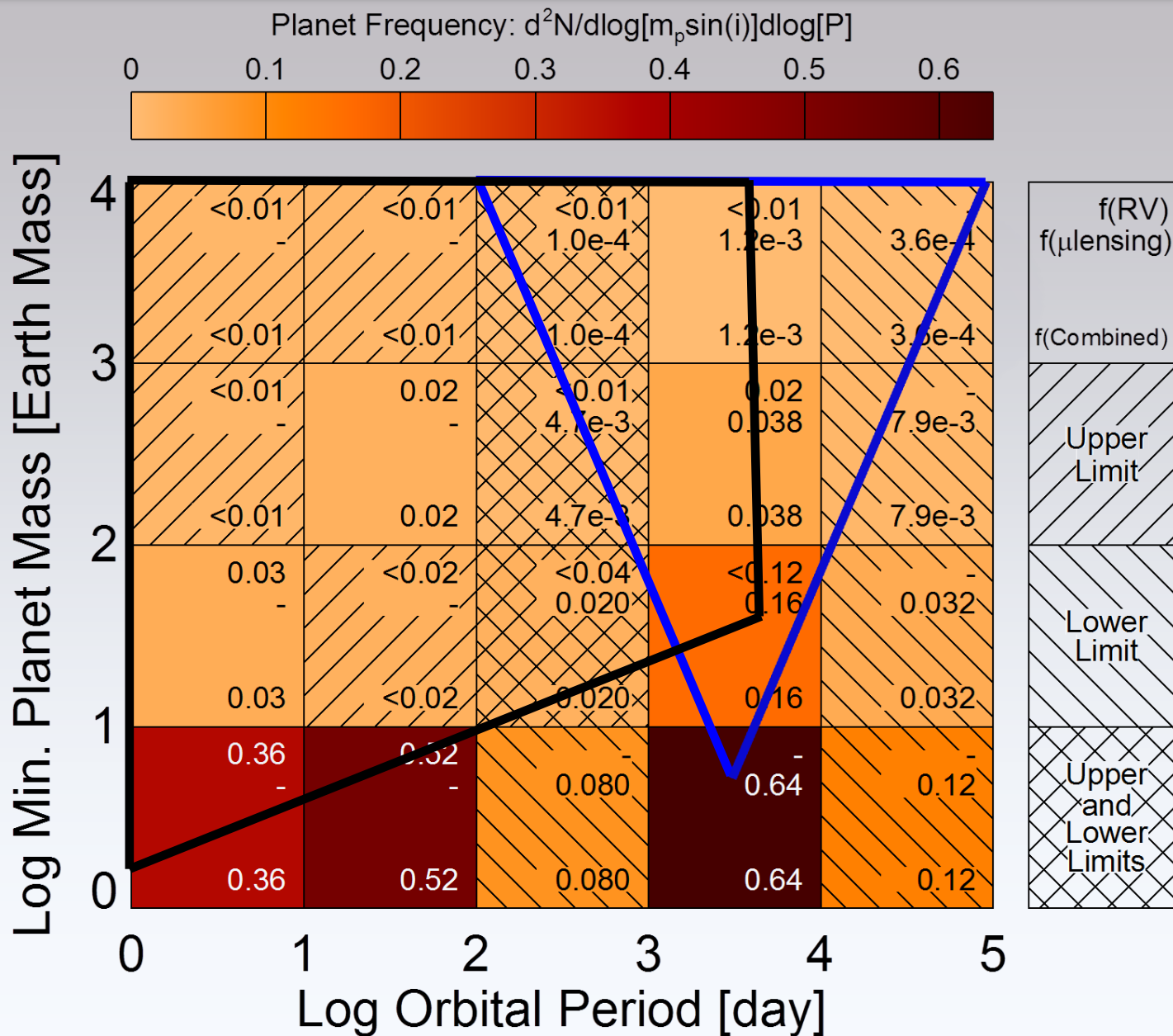
Consistency Between Microlensing and RV Results



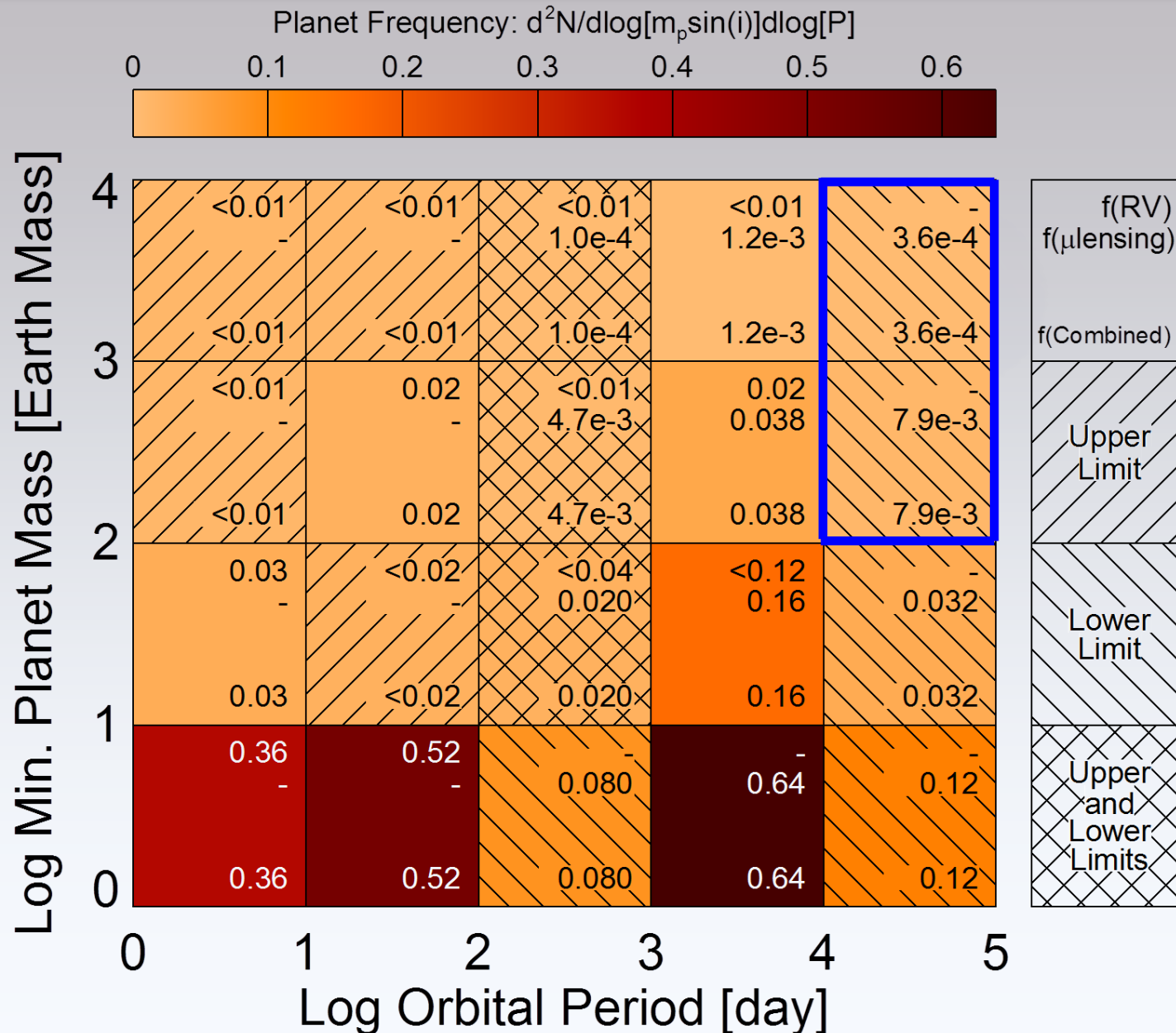
Synthesized Constraints



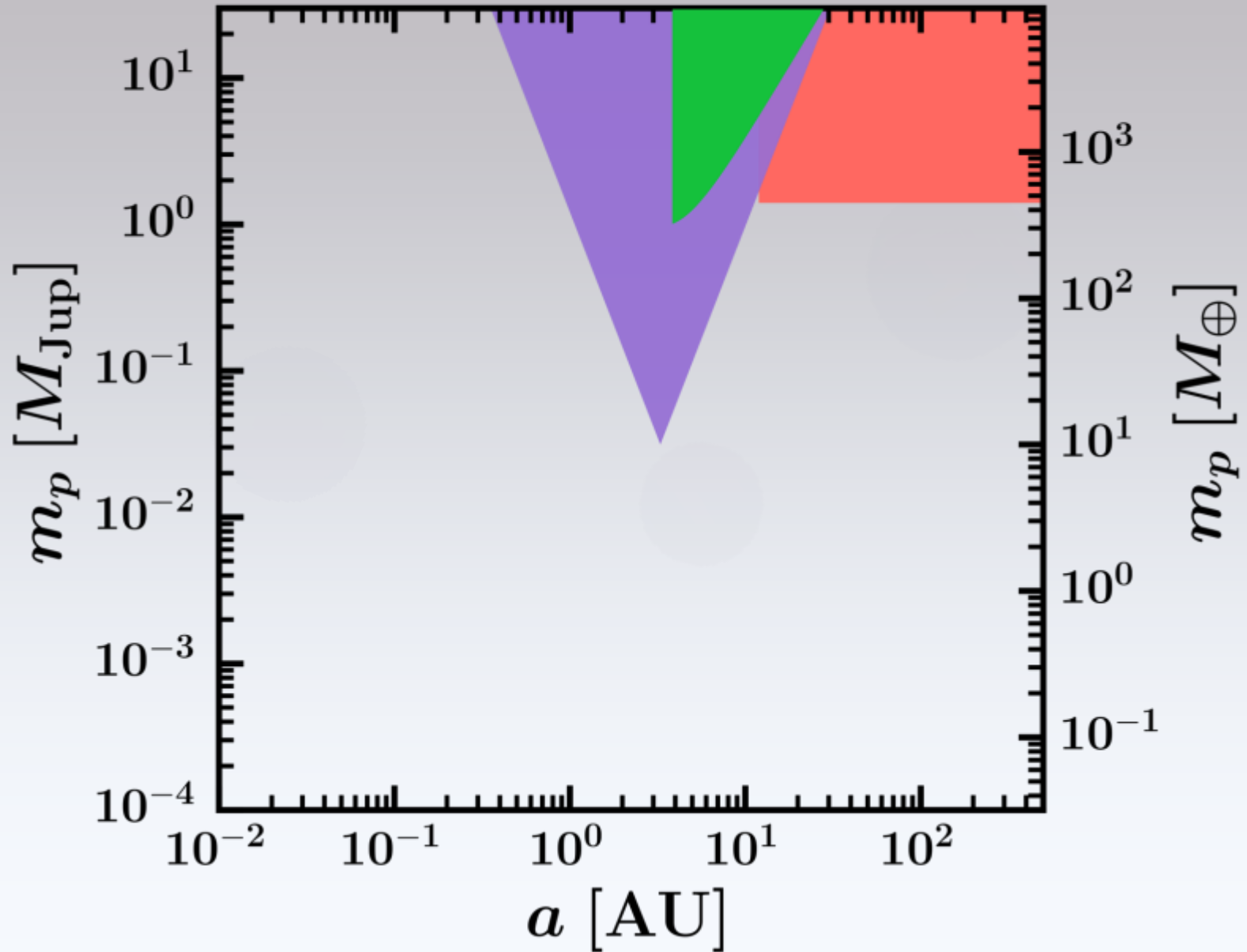
Synthesized Constraints



Improving Constraints on Long-Period Planets



Direct Imaging + Microlensing + RV Trends



Constraints on Long-Period Planetary Companions to M Dwarfs

Microlensing
Surveys

Gould+ (2010)

Sumi+ (2010)

Radial Velocity
Surveys

Montet+ (2014)

Direct Imaging
Surveys

Bowler+ (2014)

Lafrenière+ (2007)

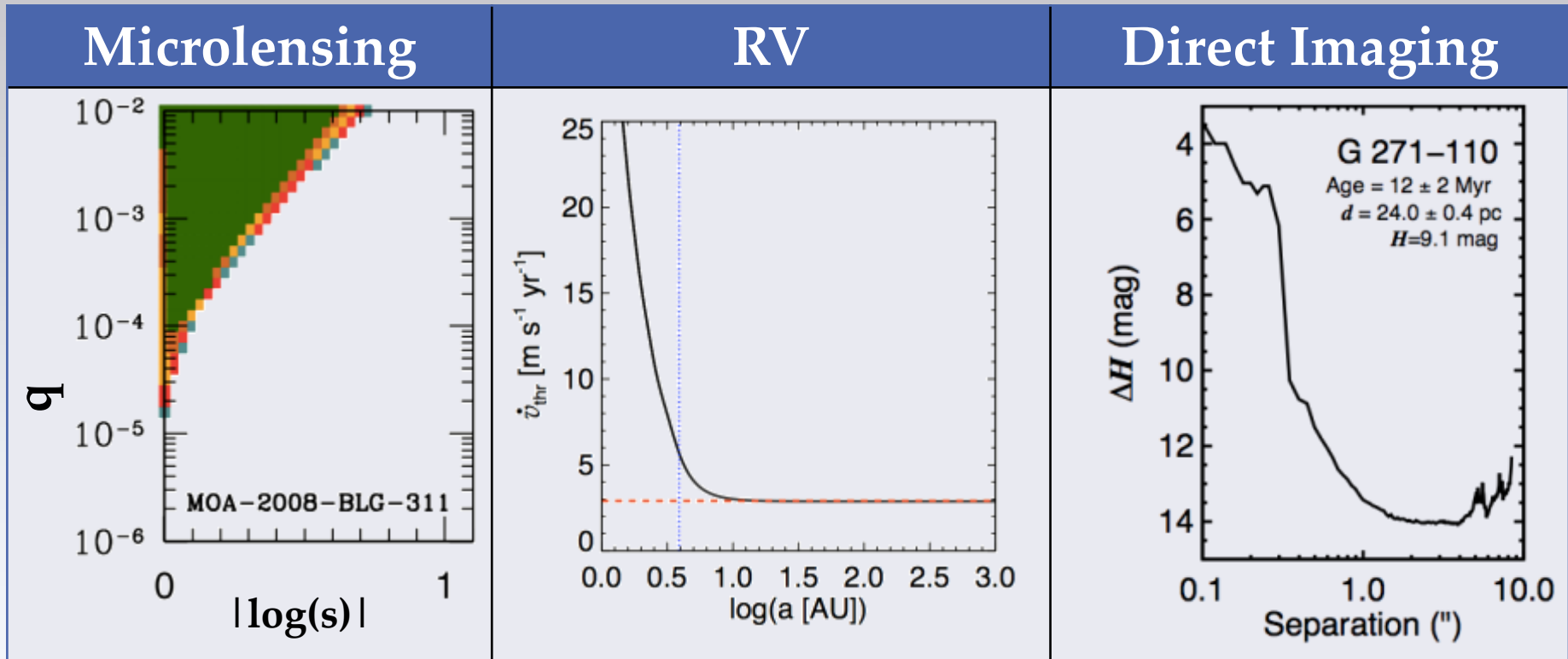
$$\frac{d^2 N_{\text{pl}}}{d \log m_p d \log a} = \mathcal{A} \left(\frac{m_p}{M_{\text{Sat}}} \right)^\alpha \left(\frac{a}{2.5 \text{ AU}} \right)^\beta$$

Methodology

$$(m_p, a)$$

Microensing	RV	Direct Imaging
(q, s)	(\dot{v}, P)	$(\Delta\text{mag}, \rho)$
<ul style="list-style-type: none">- Orbital Parameters- Lens Distances- Lens Mass Function- Galactic Model	<ul style="list-style-type: none">- Orbital Parameters- Host masses	<ul style="list-style-type: none">- Orbital Parameters- Ages and Distances- Planet Evolution Models (Hot-/Cold-Start)

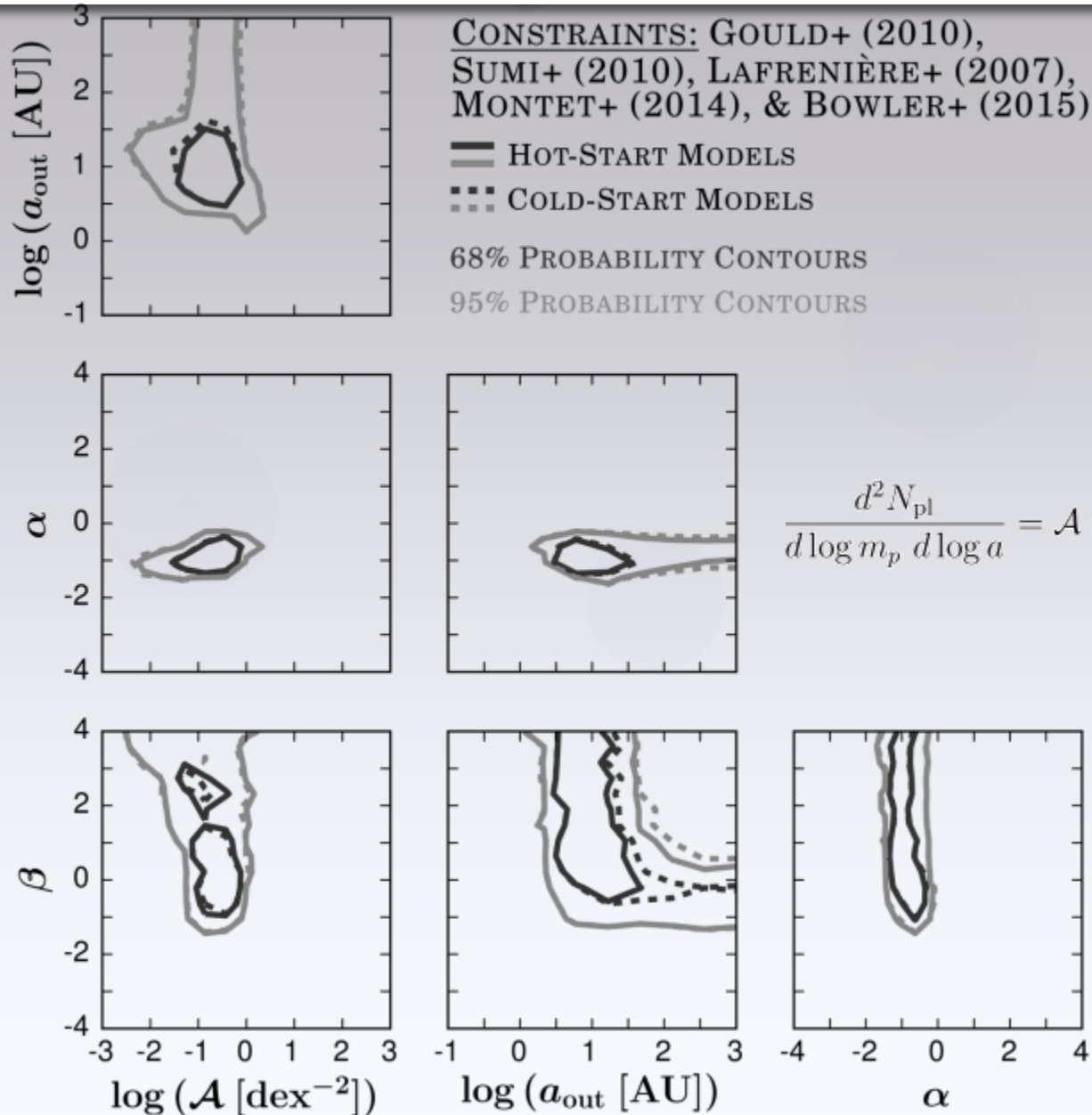
Methodology



Above figure from Gould+ (2010)

Above figure from Bowler+ (2015)

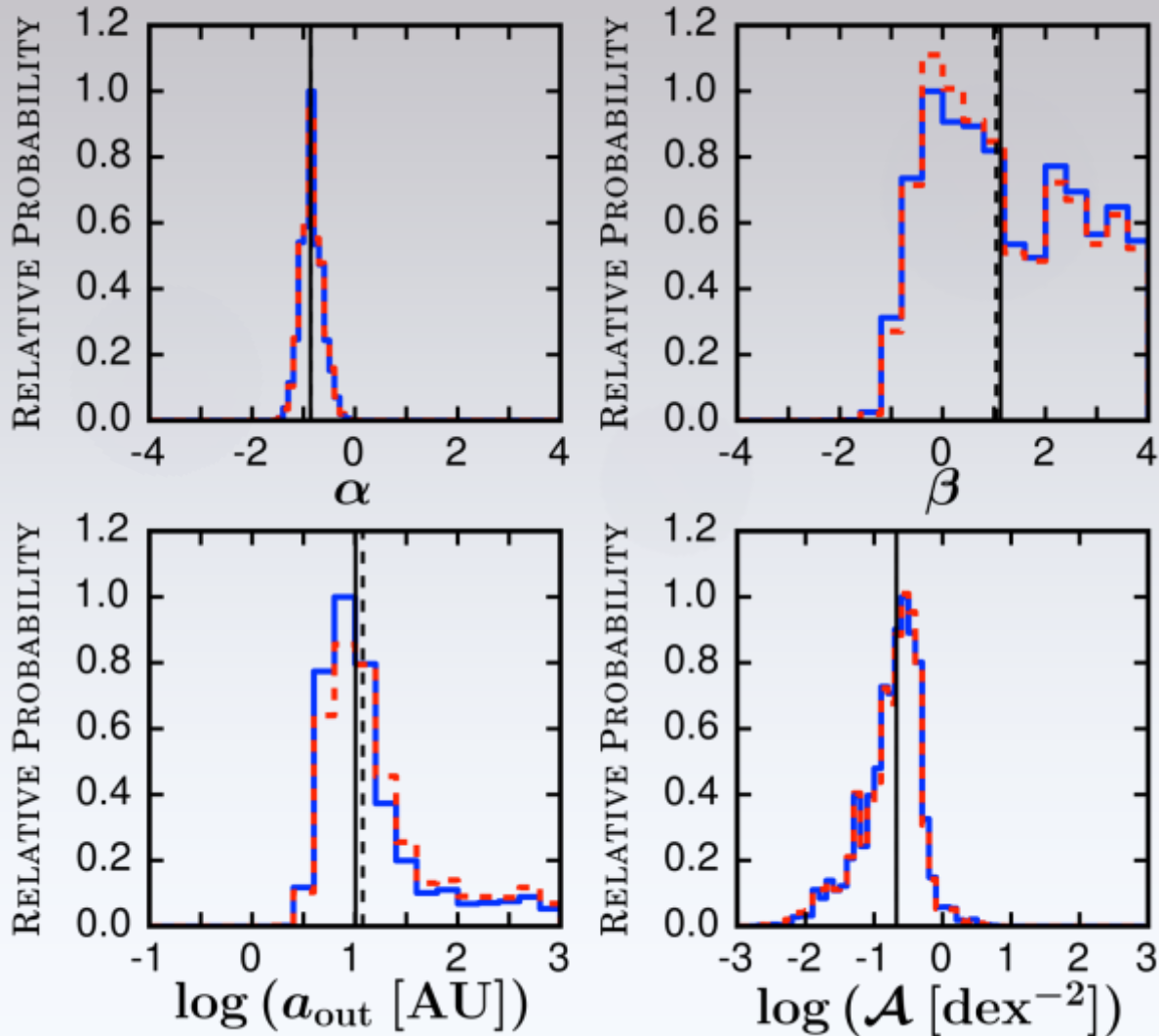
Results: Microlensing + RV Trends + Imaging



Results: Marginal Distributions

CONSTRAINTS: GOULD+ (2010),
SUMI+ (2010), LAFRENIÈRE+ (2007),
MONTET+ (2014), & BOWLER+ (2015)

— HOT-START
- - - COLD-START
- - - MEDIAN VALUES

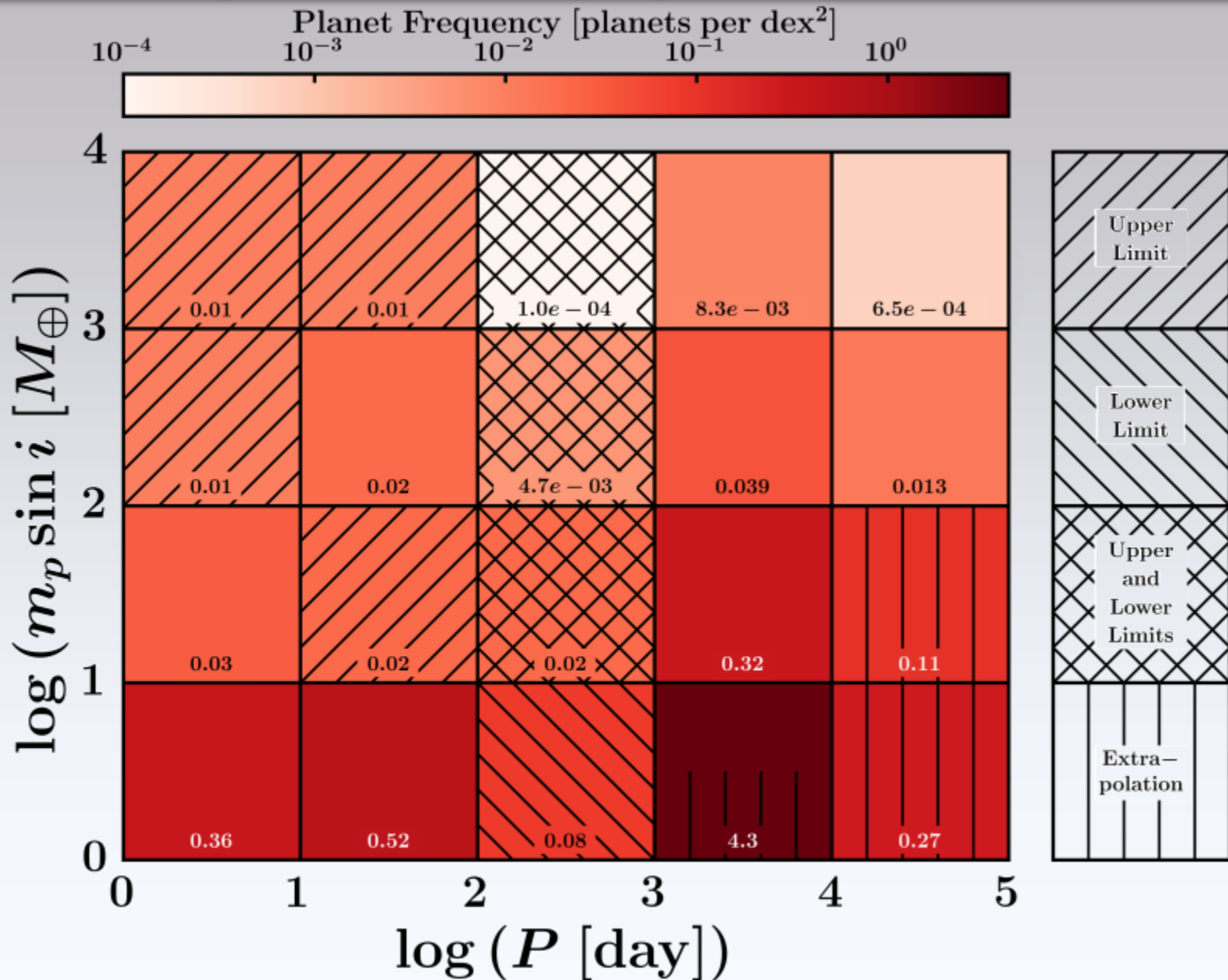


Results: Final Parameter Constraints

Planet Evolutionary Models	Median Values and 68% Uncertainties			
	α	β	\mathcal{A} [dex ⁻²]	a_{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)	$-0.85^{+0.21}_{-0.19}$	$1.1^{+1.9}_{-1.3}$	$0.21^{+0.20}_{-0.15}$	$12^{+50}_{-6.2}$

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

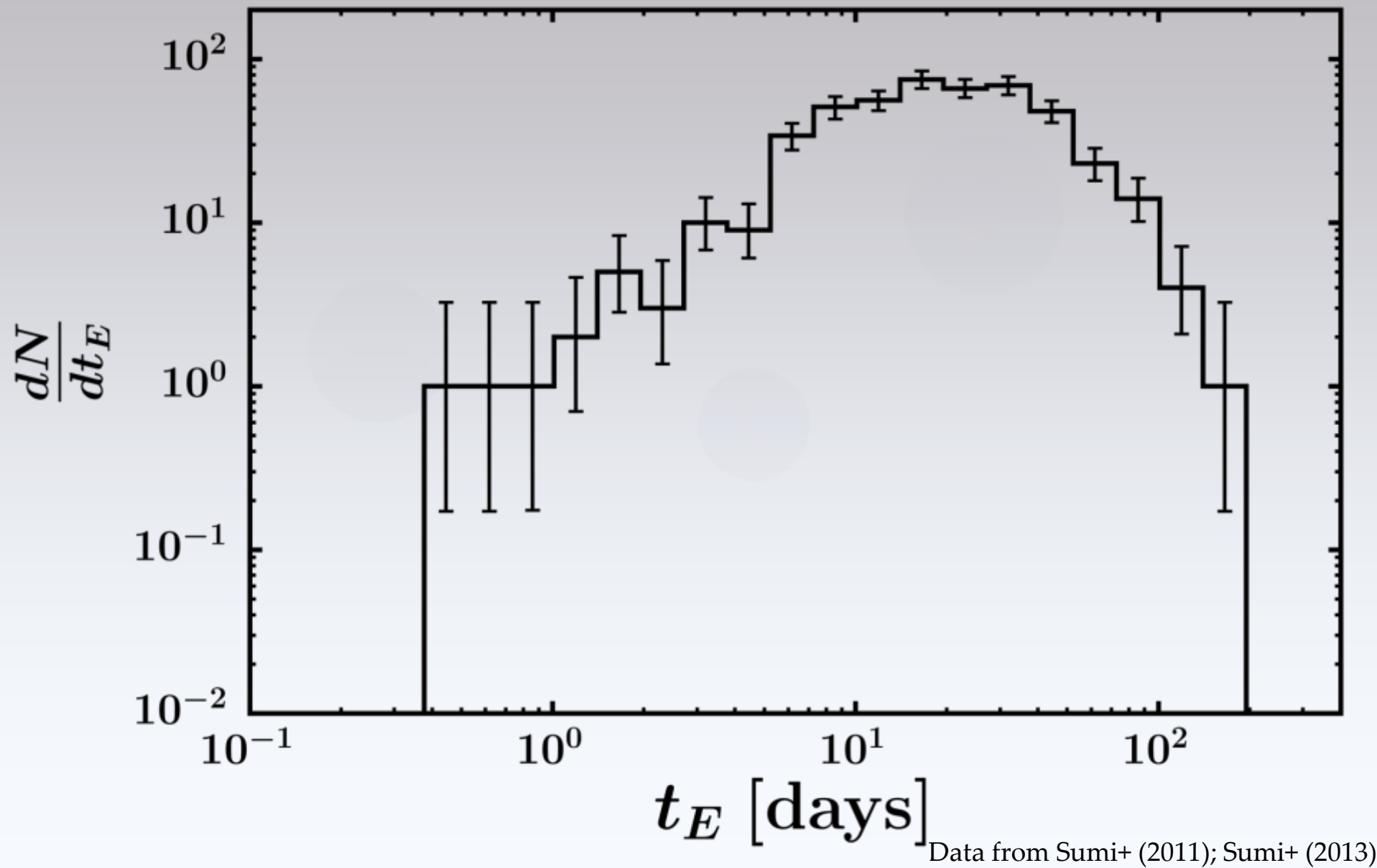
Updated Demographic Constraints



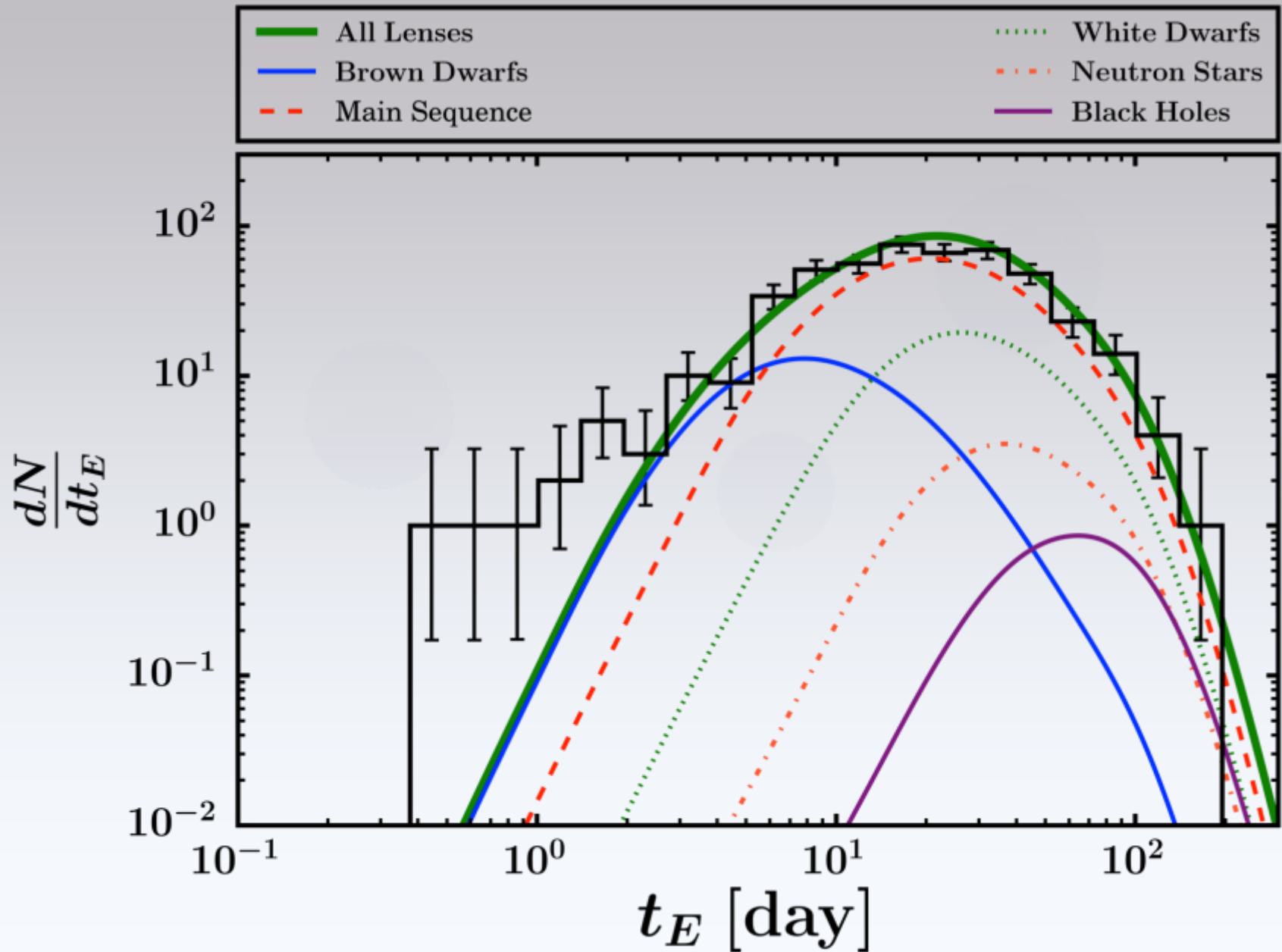
Part II.

Constraining the Galactic
Population of Free-Floating
Planets

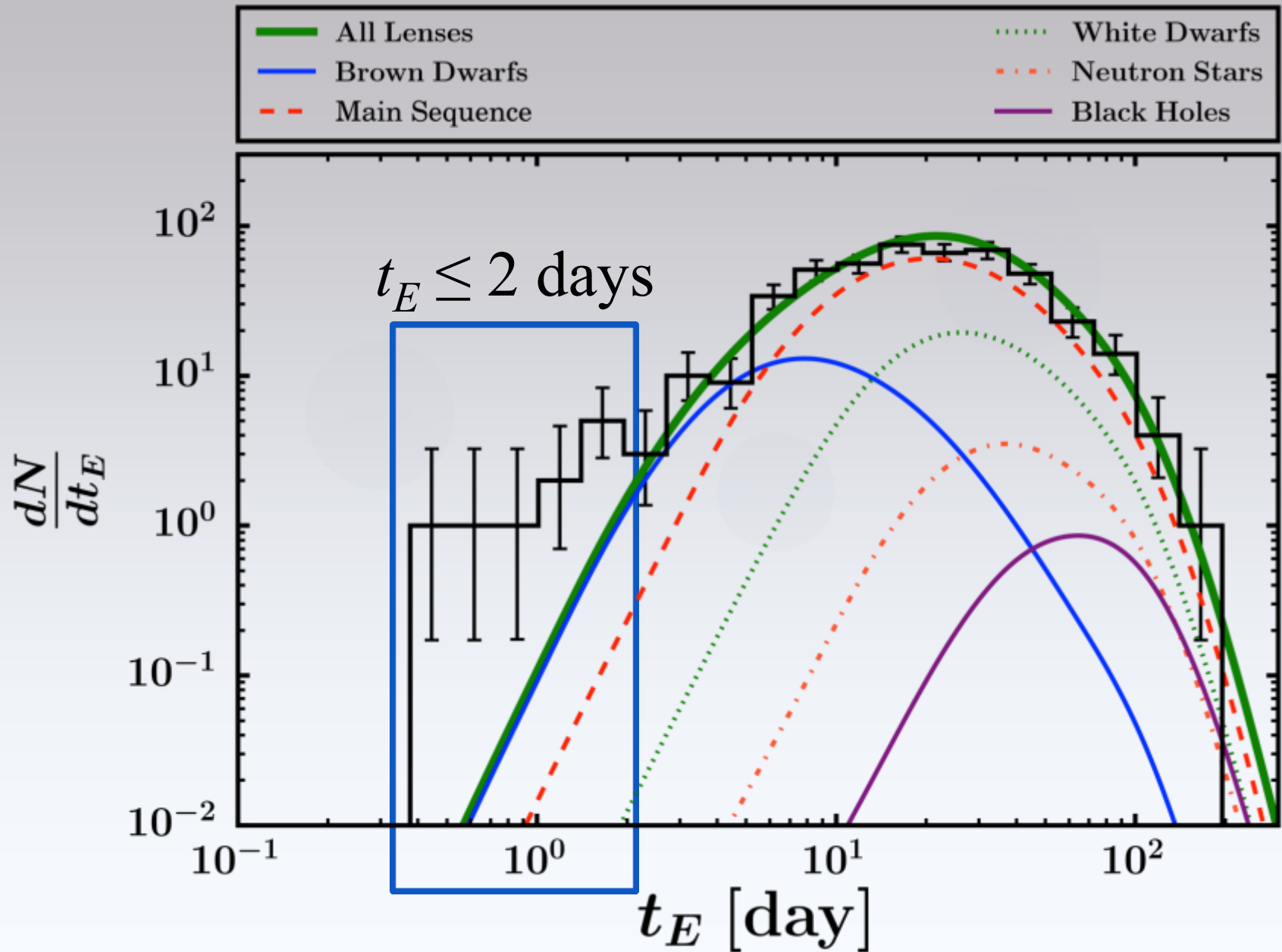
MOA-II Data (2006-2007)



Explaining the Observed Timescale Distribution



Explaining the Observed Timescale Distribution



Free-Floating Planets?

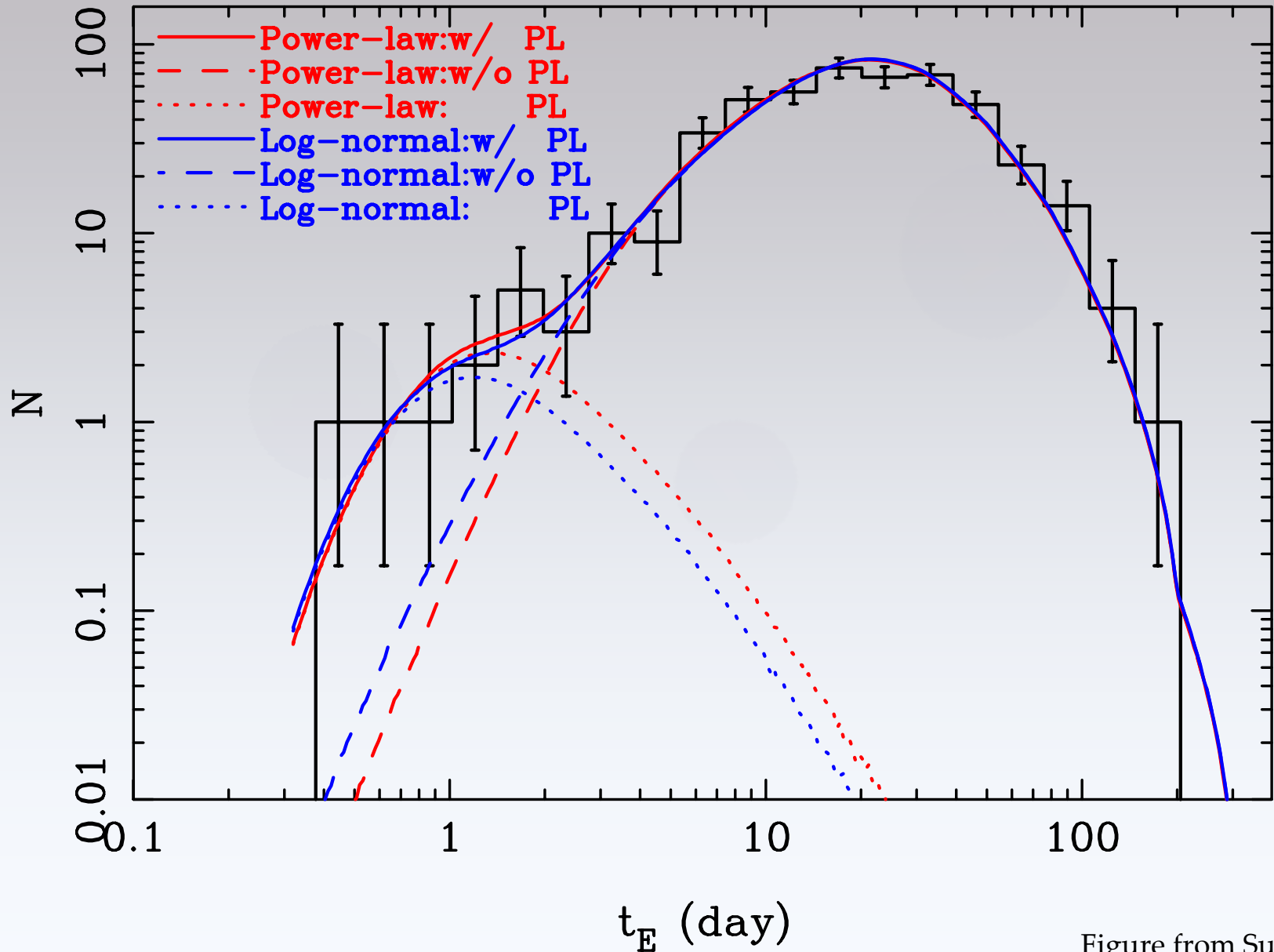
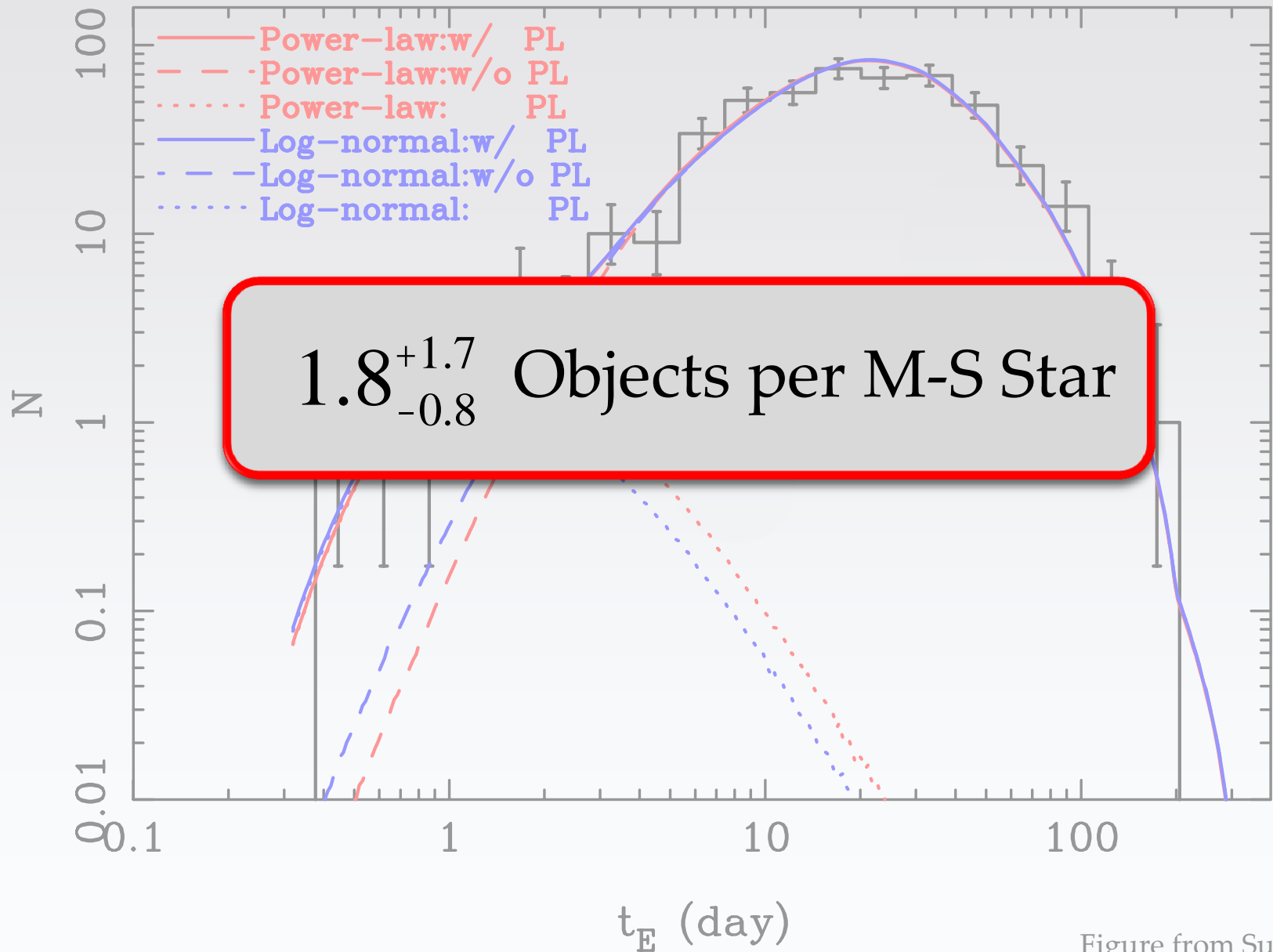
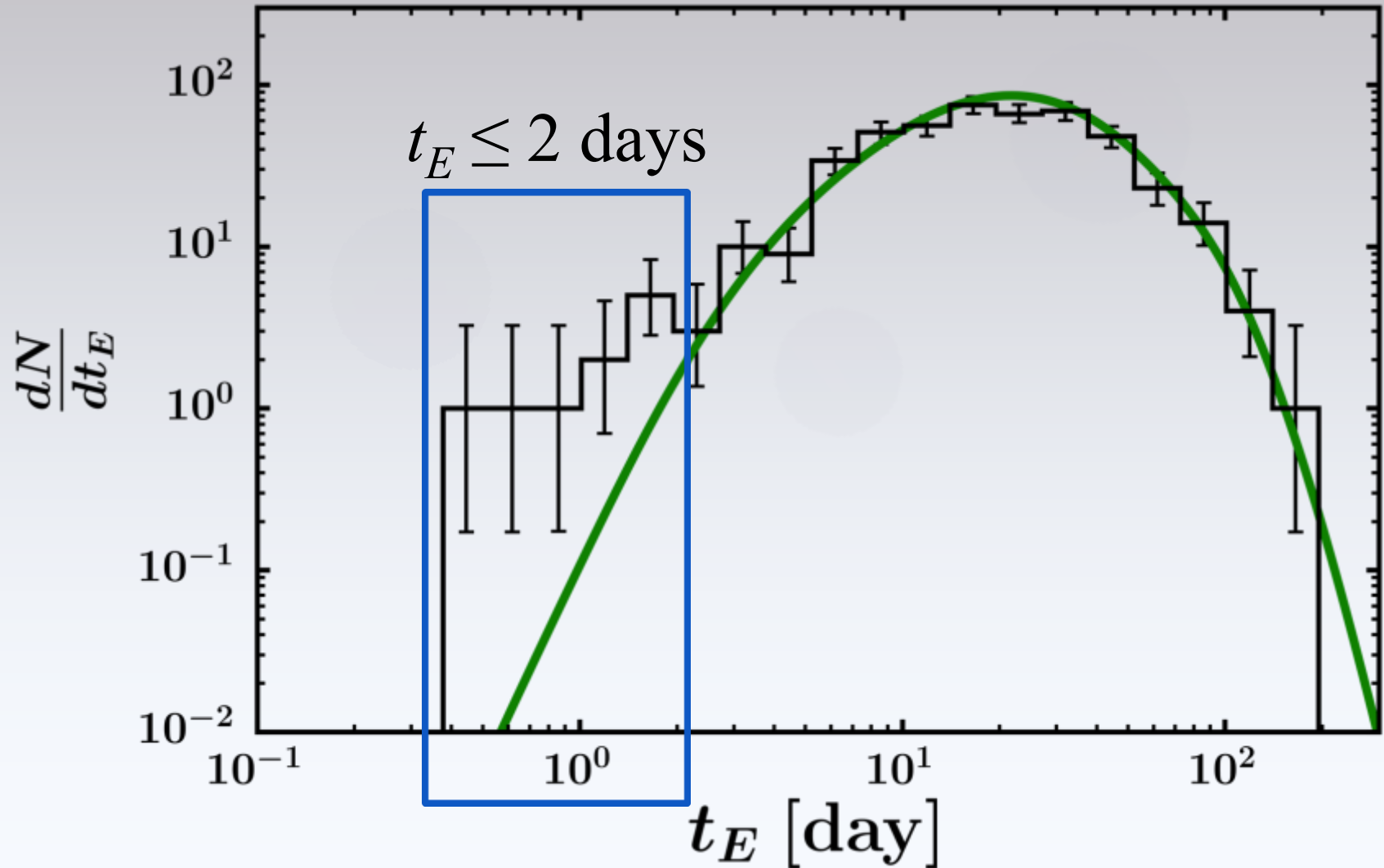


Figure from Sumi+ (2011)

Free-Floating Planets?



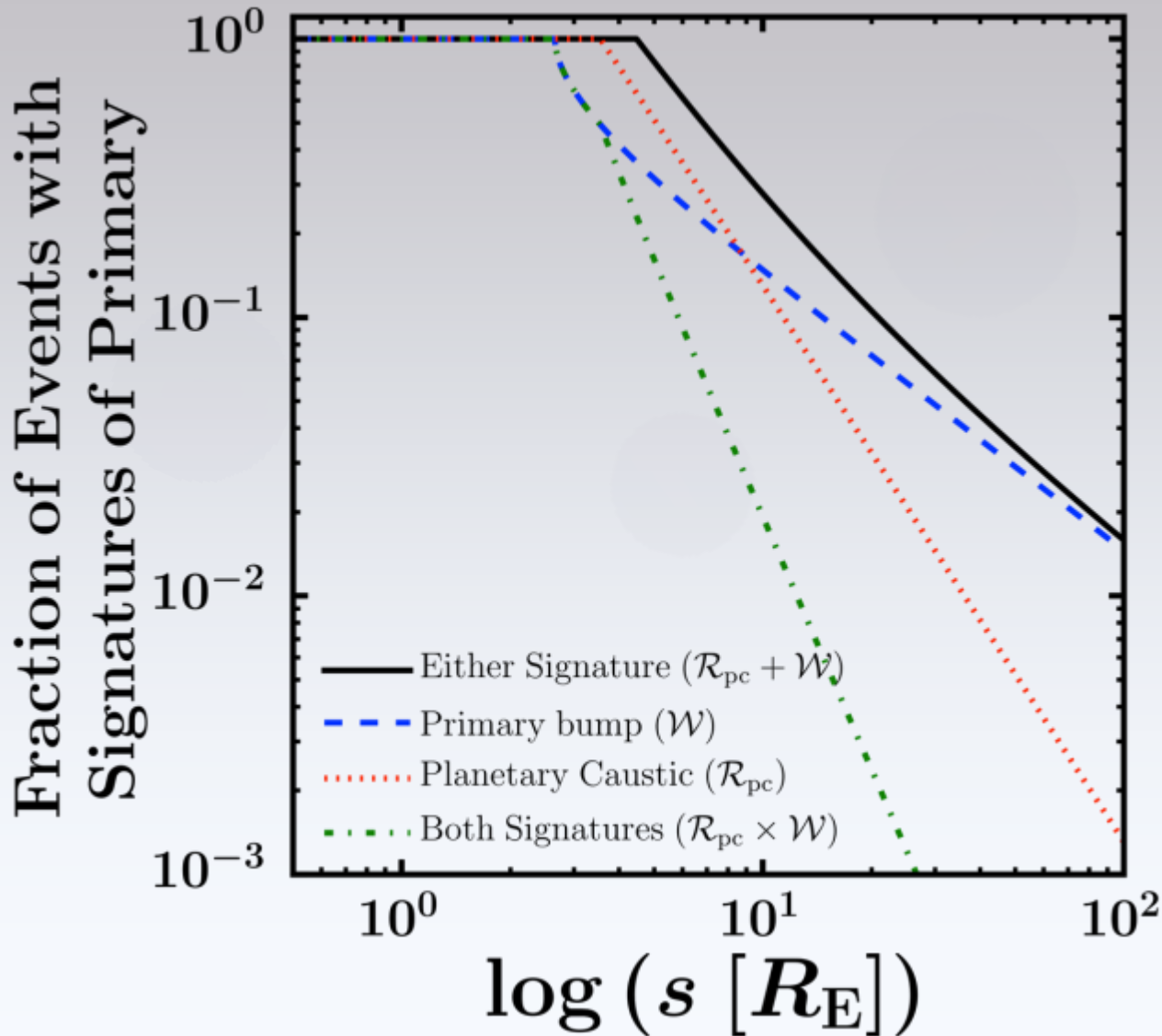
Short Timescale Events Show No Evidence of a Primary



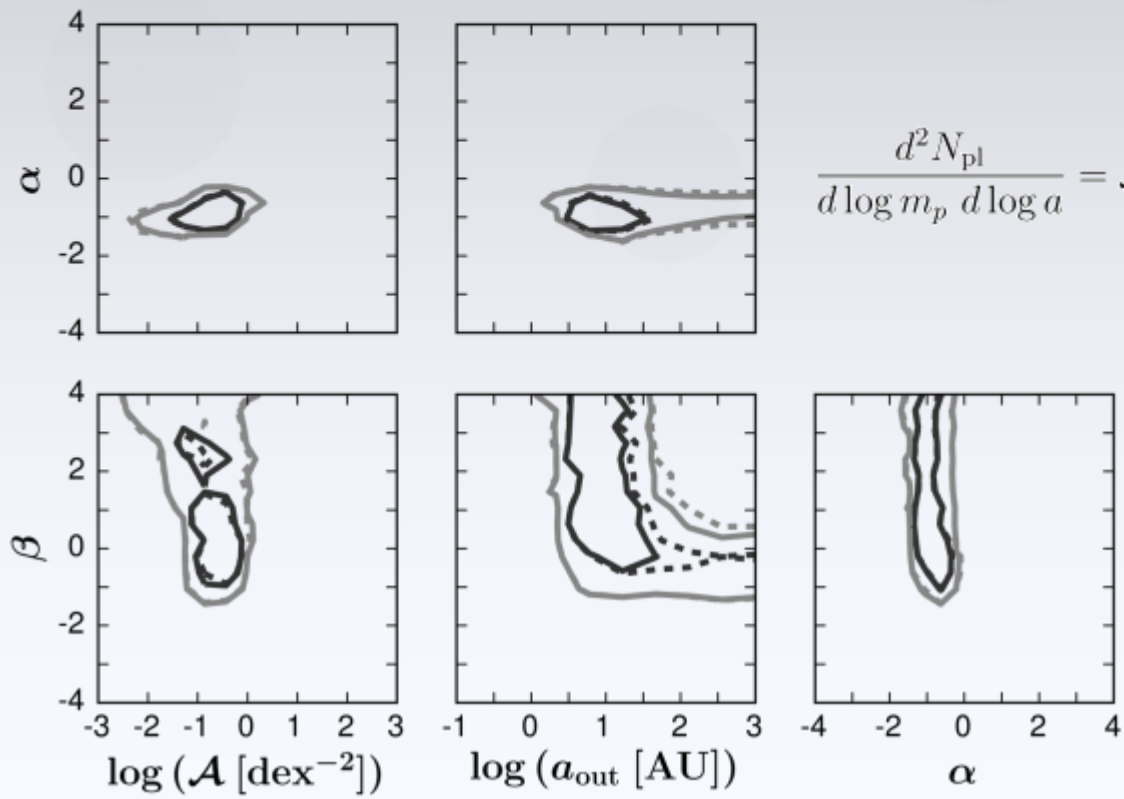
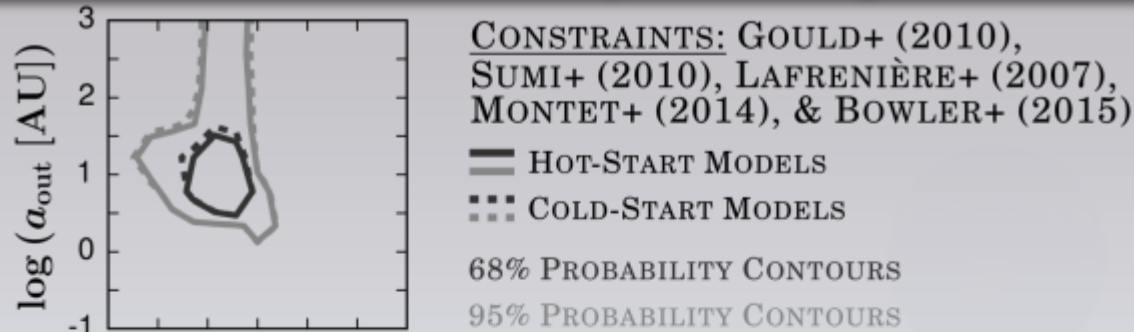
Distinguishing Wide-Separation from Free-Floating Planets

1. Low-Magnification Primary “Bump”
2. Planetary Caustic Events

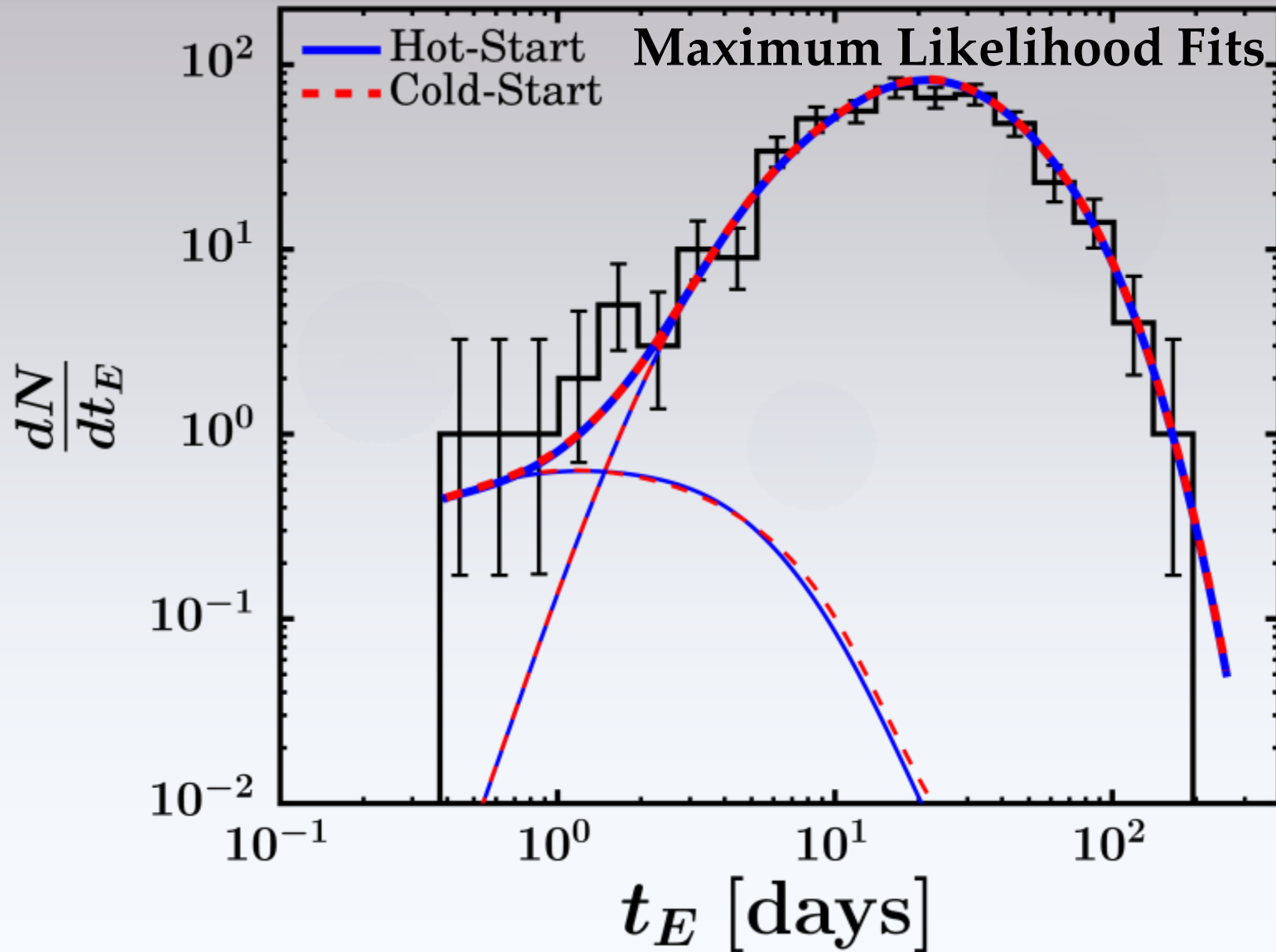
Distinguishing Wide-Separation from Free-Floating Planets



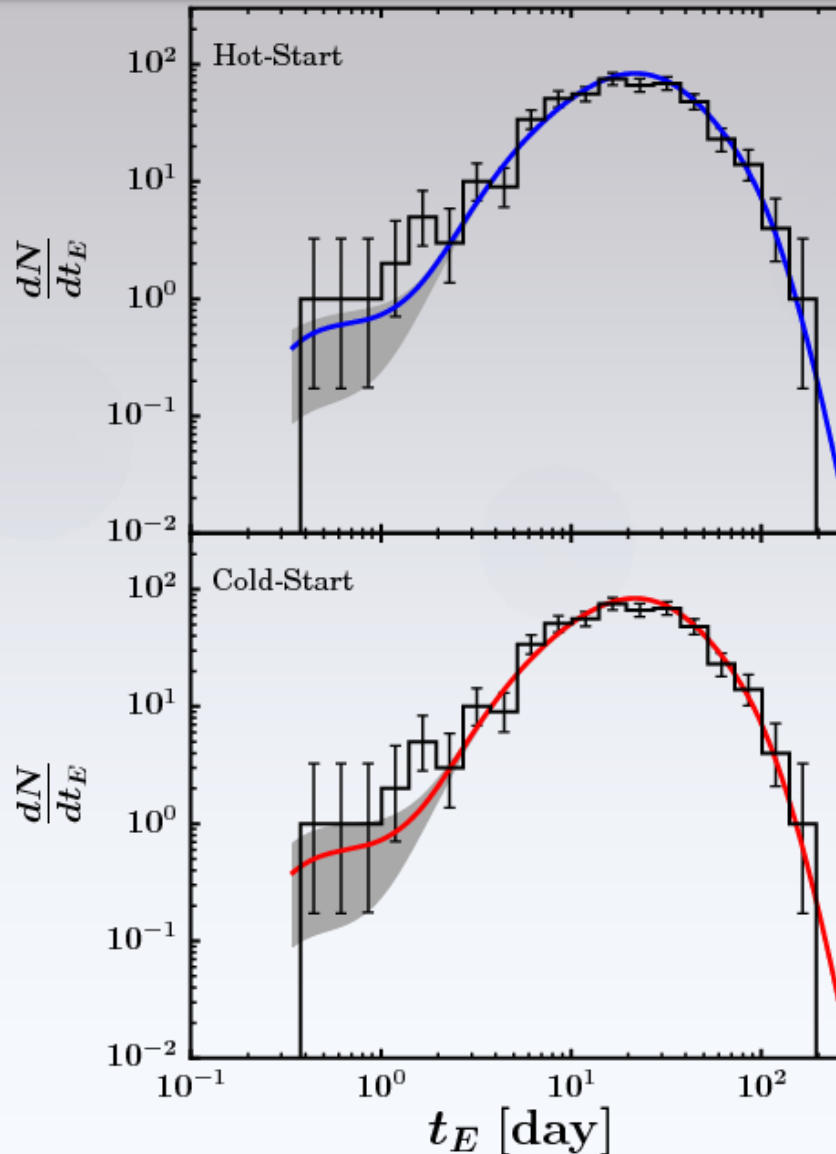
Constructing the Timescale Distribution of Bound Planetary Companions



Bound Planets + LMF: Fit to Observed Timescale Distribution

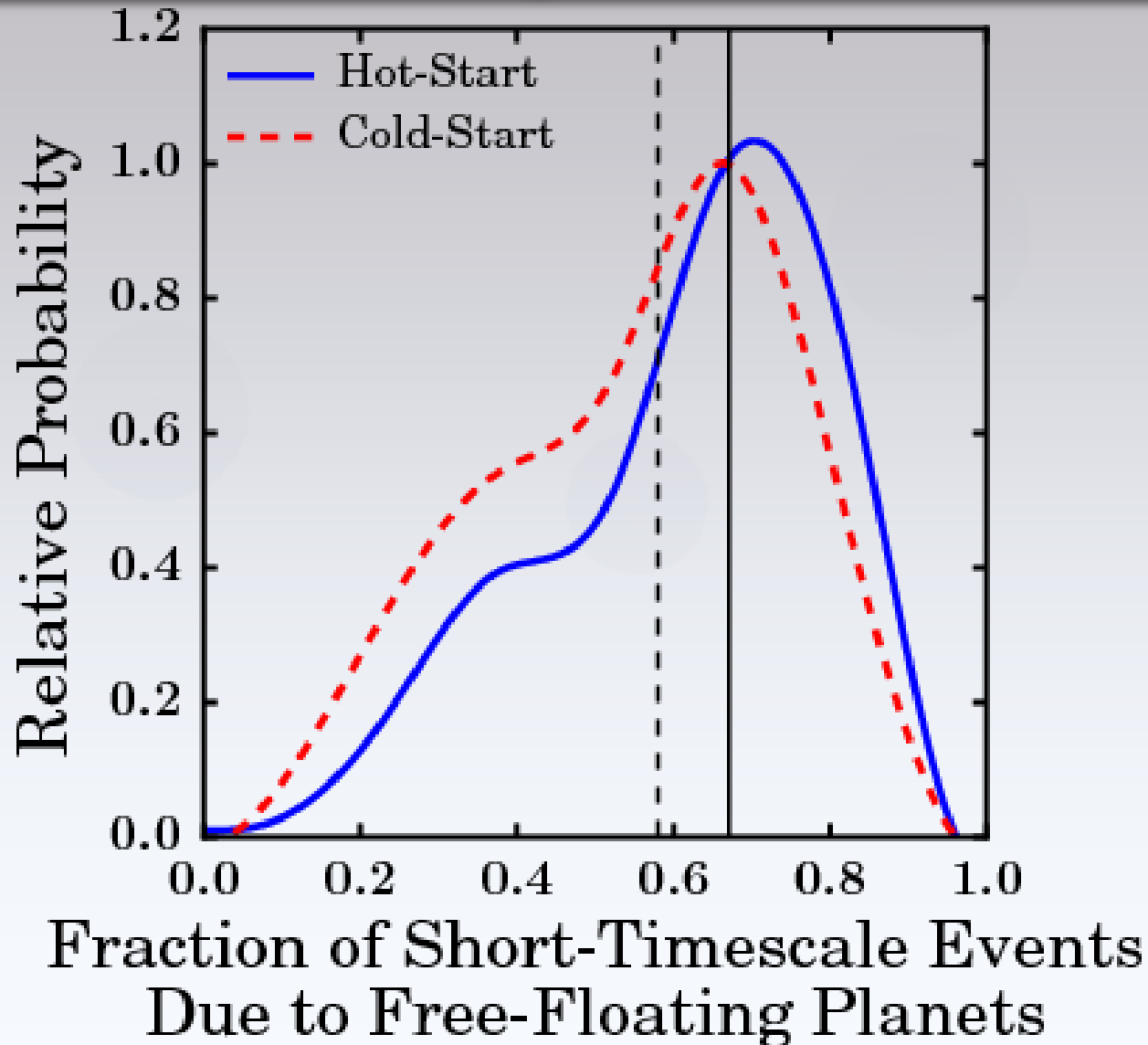


Bound Planets + LMF: Fit to Observed Timescale Distribution

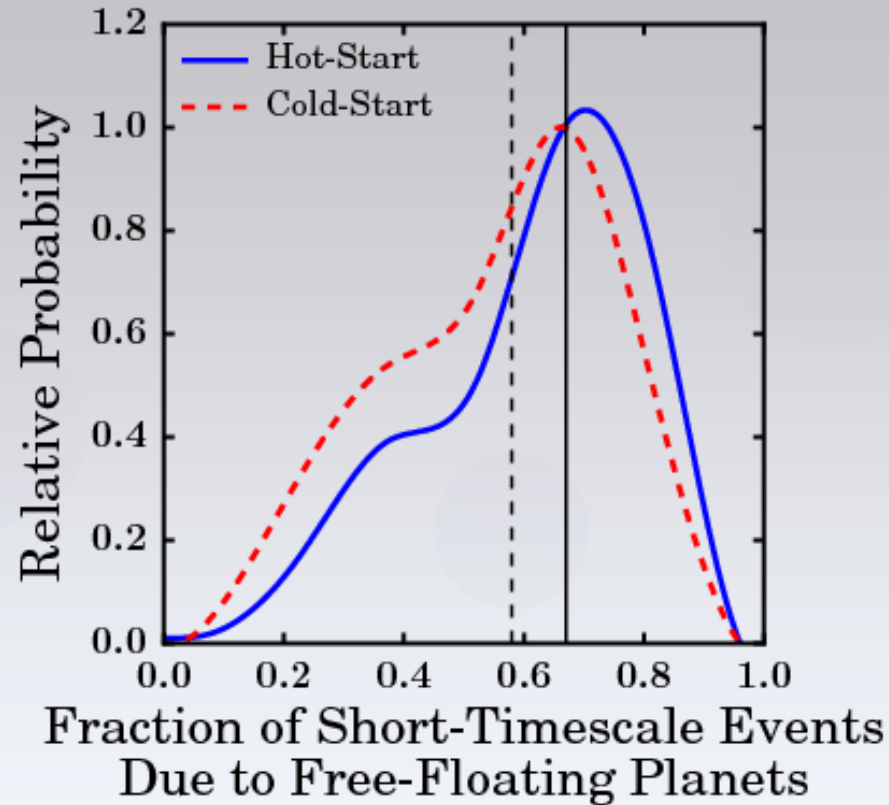


**Maximum
Likelihood and
68% Confidence
Interval Fits**

Constraints on the Galactic Population of Free-Floating Planets

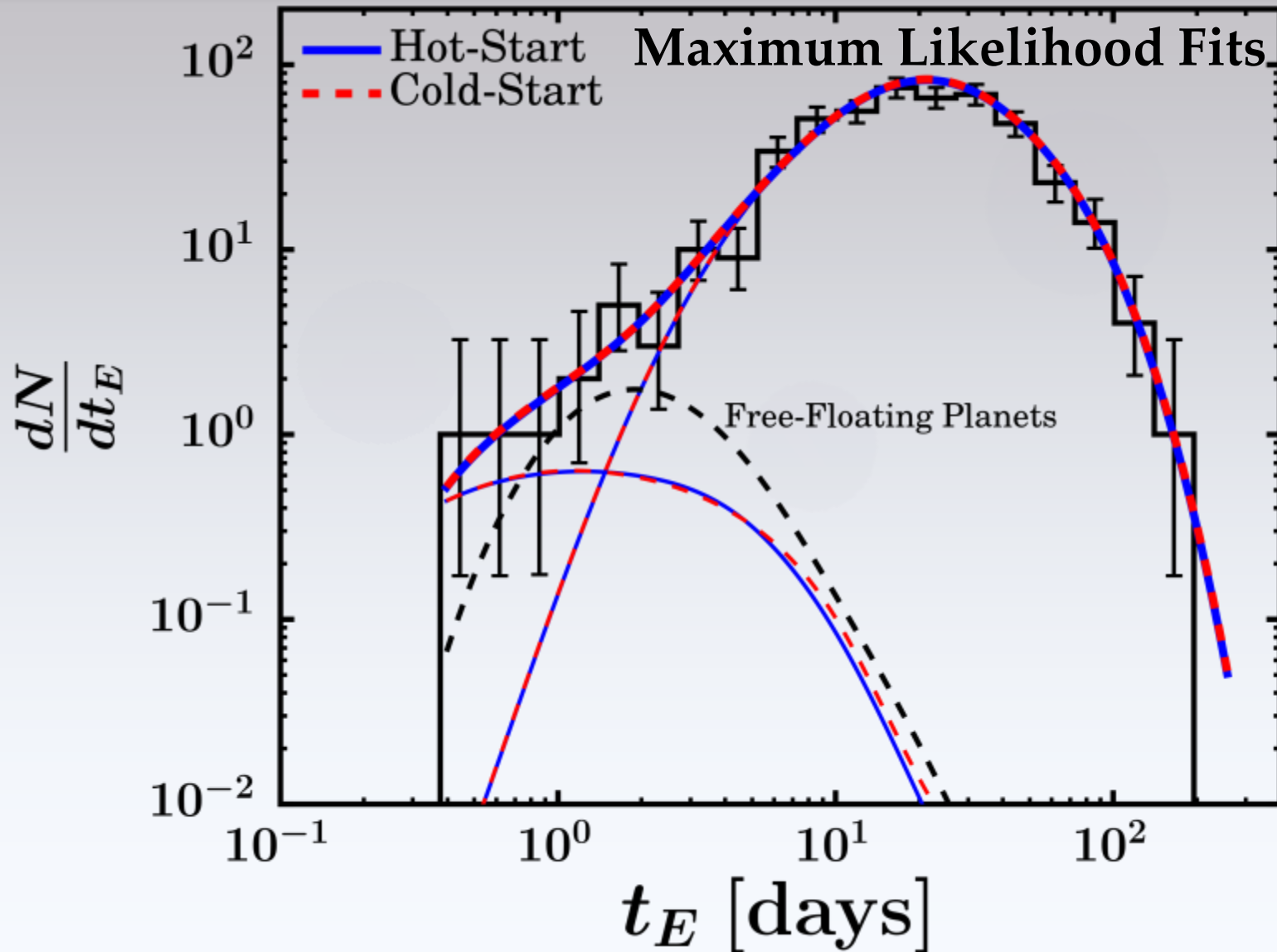


Constraints on the Galactic Population of Free-Floating Planets

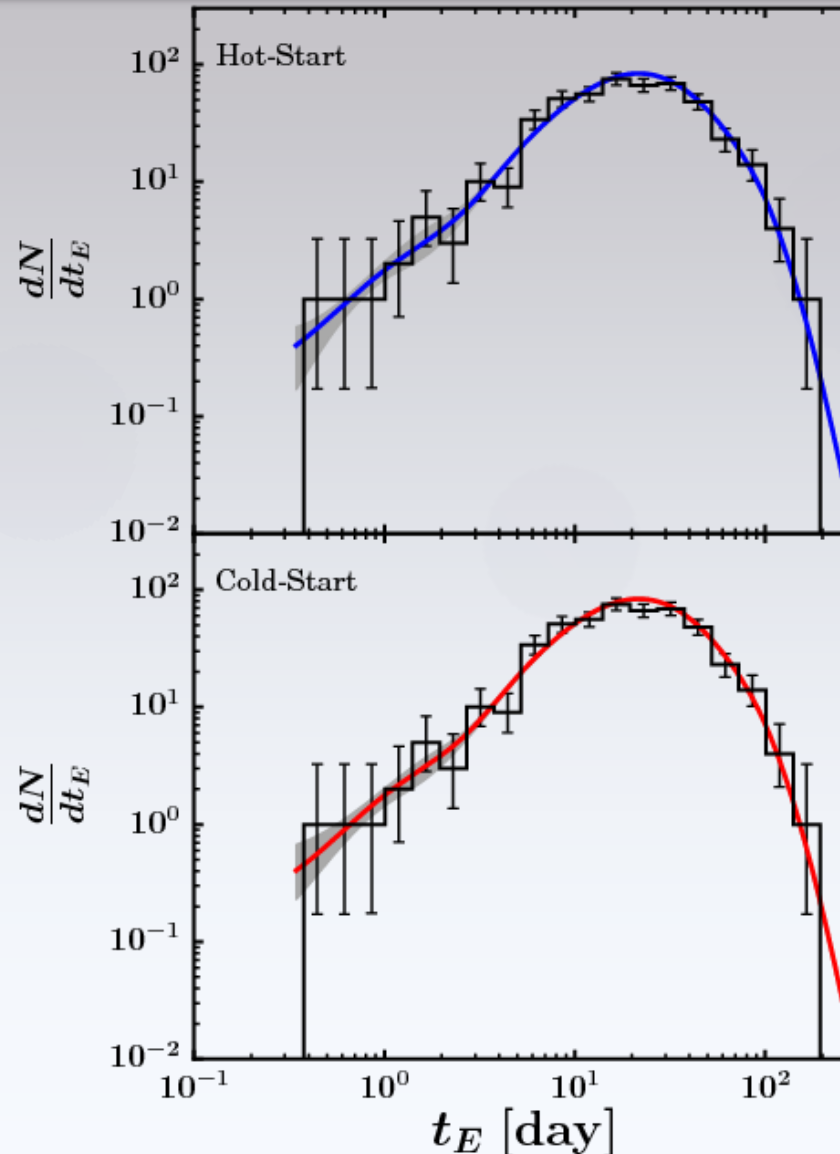


	Median	68% CI	95% CI
Hot-Start	0.67	0.44-0.78	0.23-0.85
Cold-Start	0.58	0.40-0.74	0.14-0.83

Bound Planets + FFP + LMF: Fit to Observed Timescale Distribution

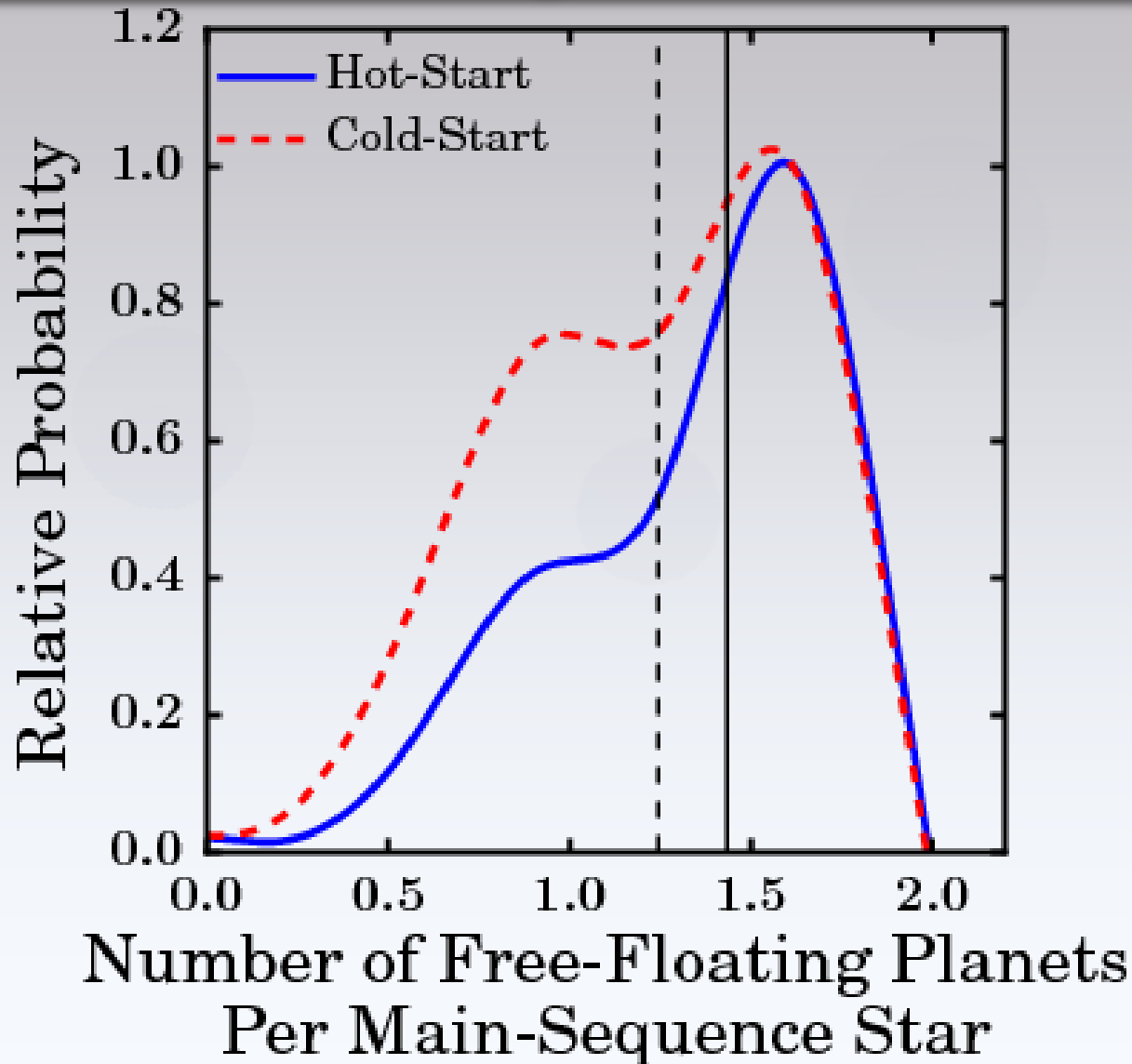


Bound Planets + FFP + LMF: Fit to Observed Timescale Distribution

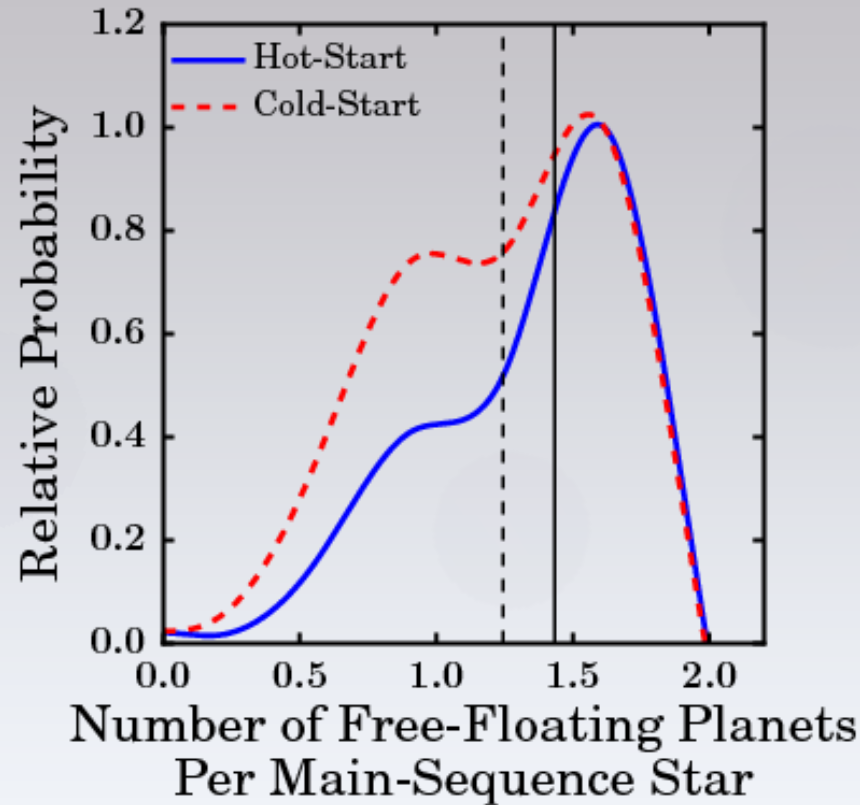


**Maximum
Likelihood and
68% Confidence
Interval Fits**

Constraints on the Galactic Population of Free-Floating Planets



Constraints on the Galactic Population of Free-Floating Planets

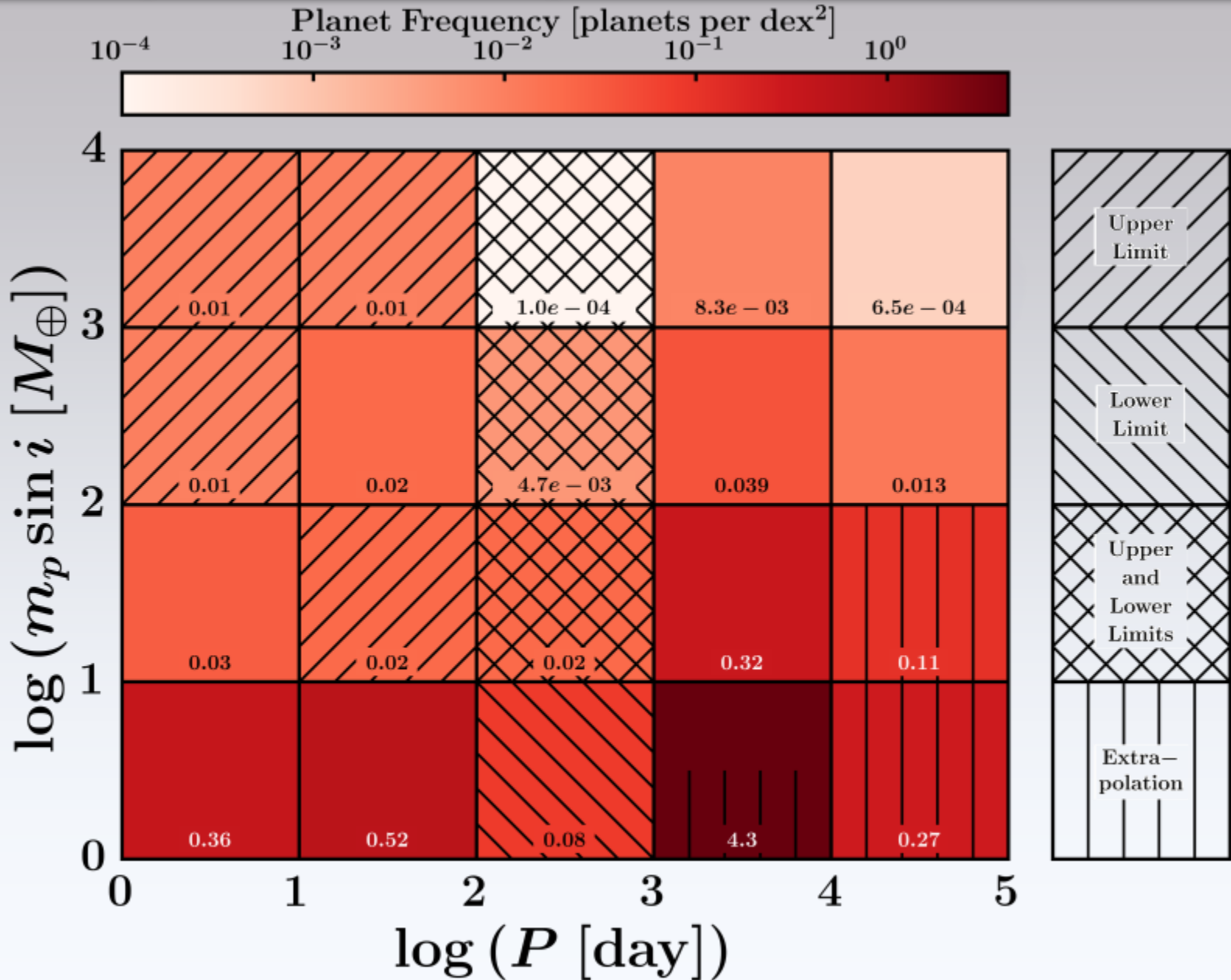


	Median	68% CI	95% CI
Hot-Start	1.4	0.95-1.7	0.48-1.8
Cold-Start	1.2	0.87-1.6	0.29-1.8

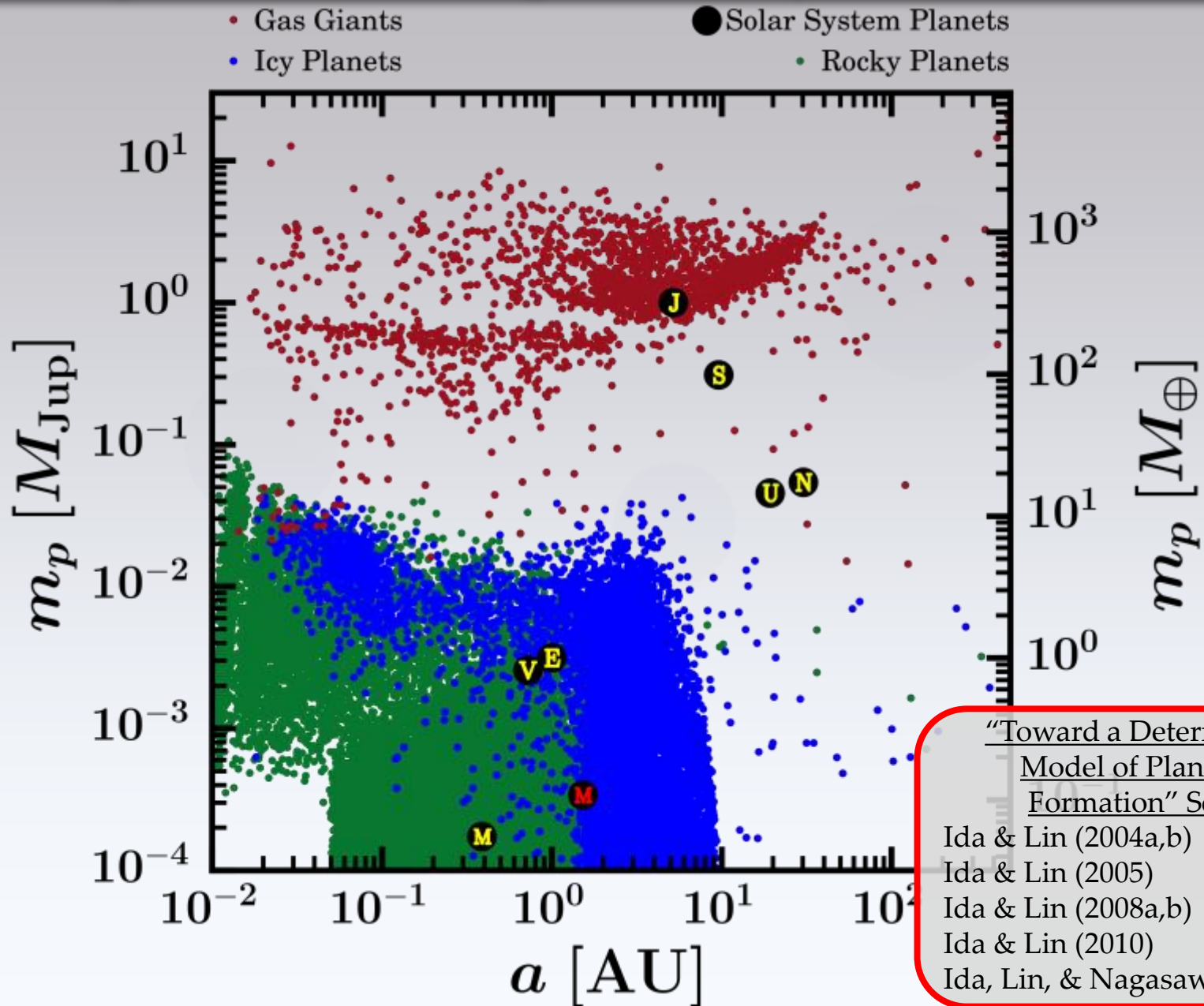
Part III.

Comparison with Population
Synthesis Models

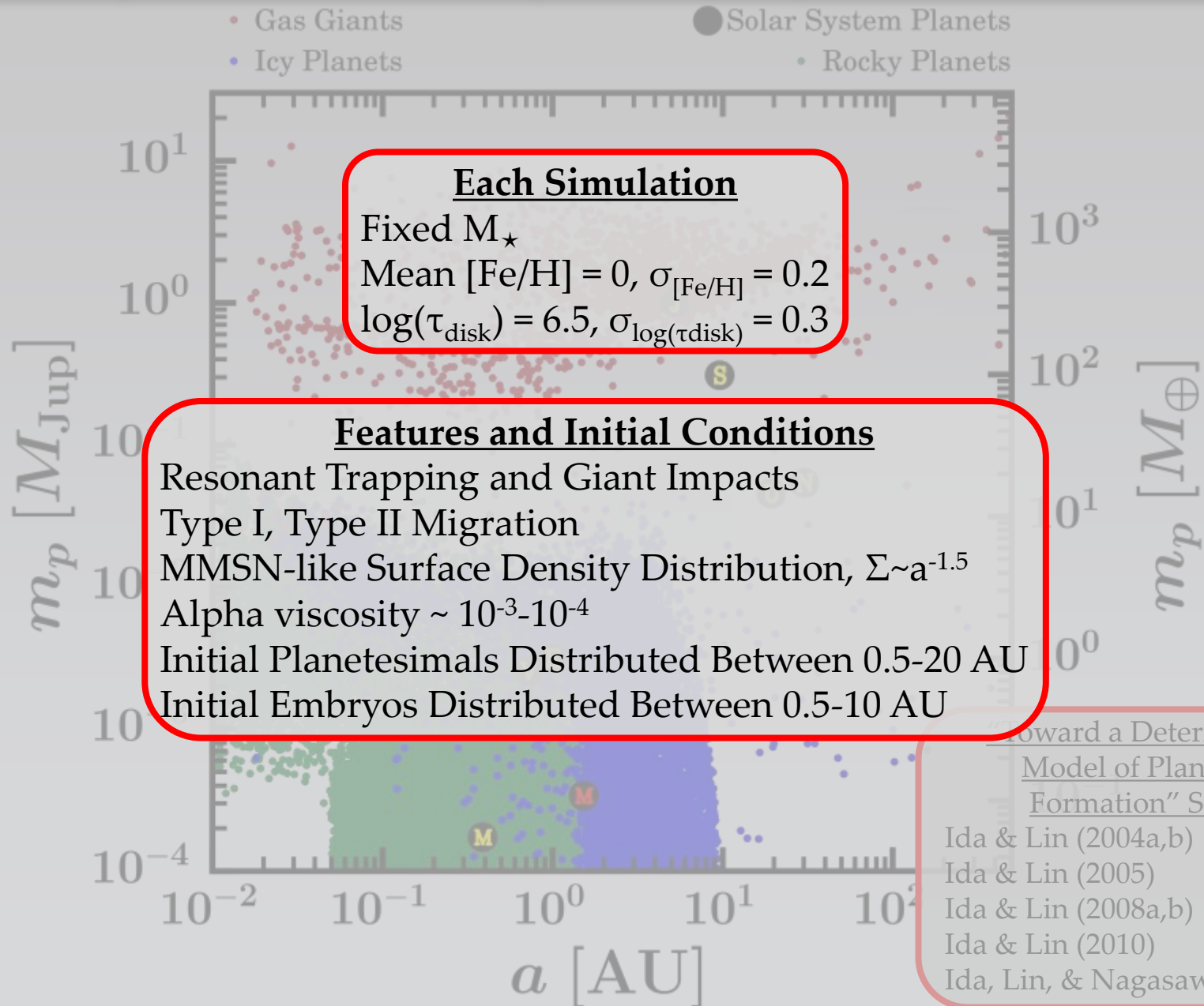
Comparison with Population Synthesis Models



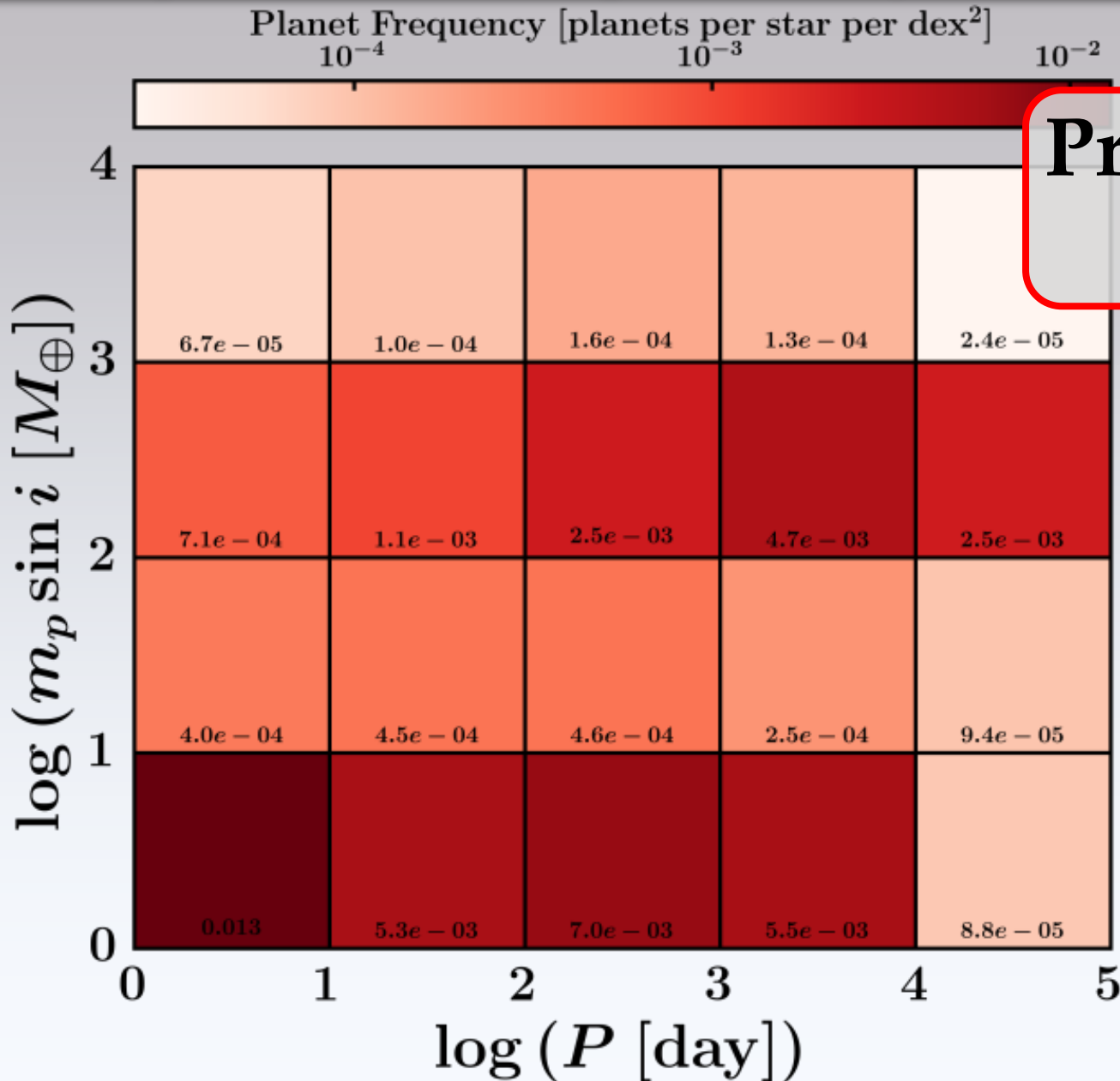
Comparison with Population Synthesis Models



Comparison with Population Synthesis Models



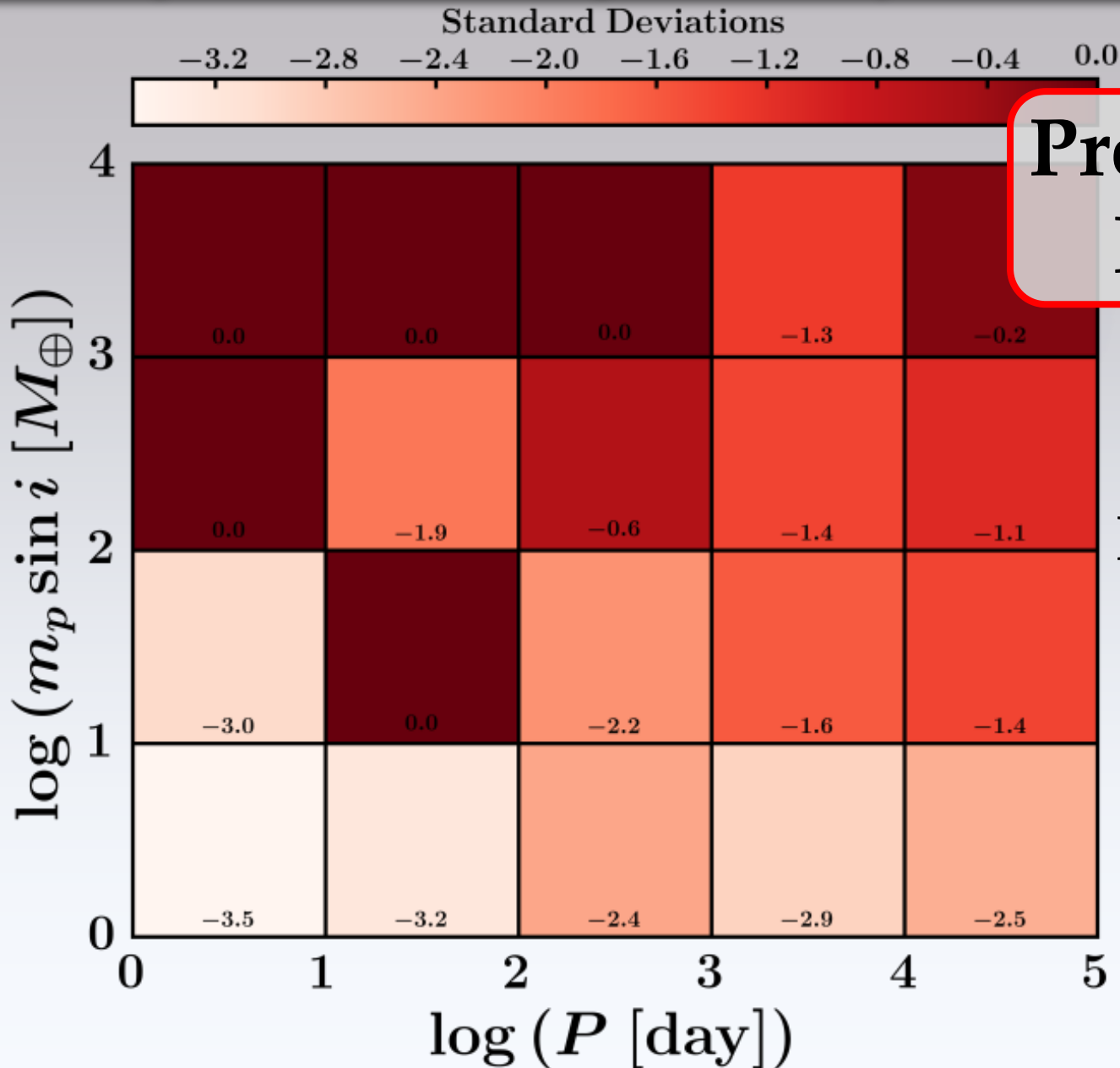
Comparison with Population Synthesis Models



Preliminary Results

$M_{\star} = 0.6 M_{\odot}$

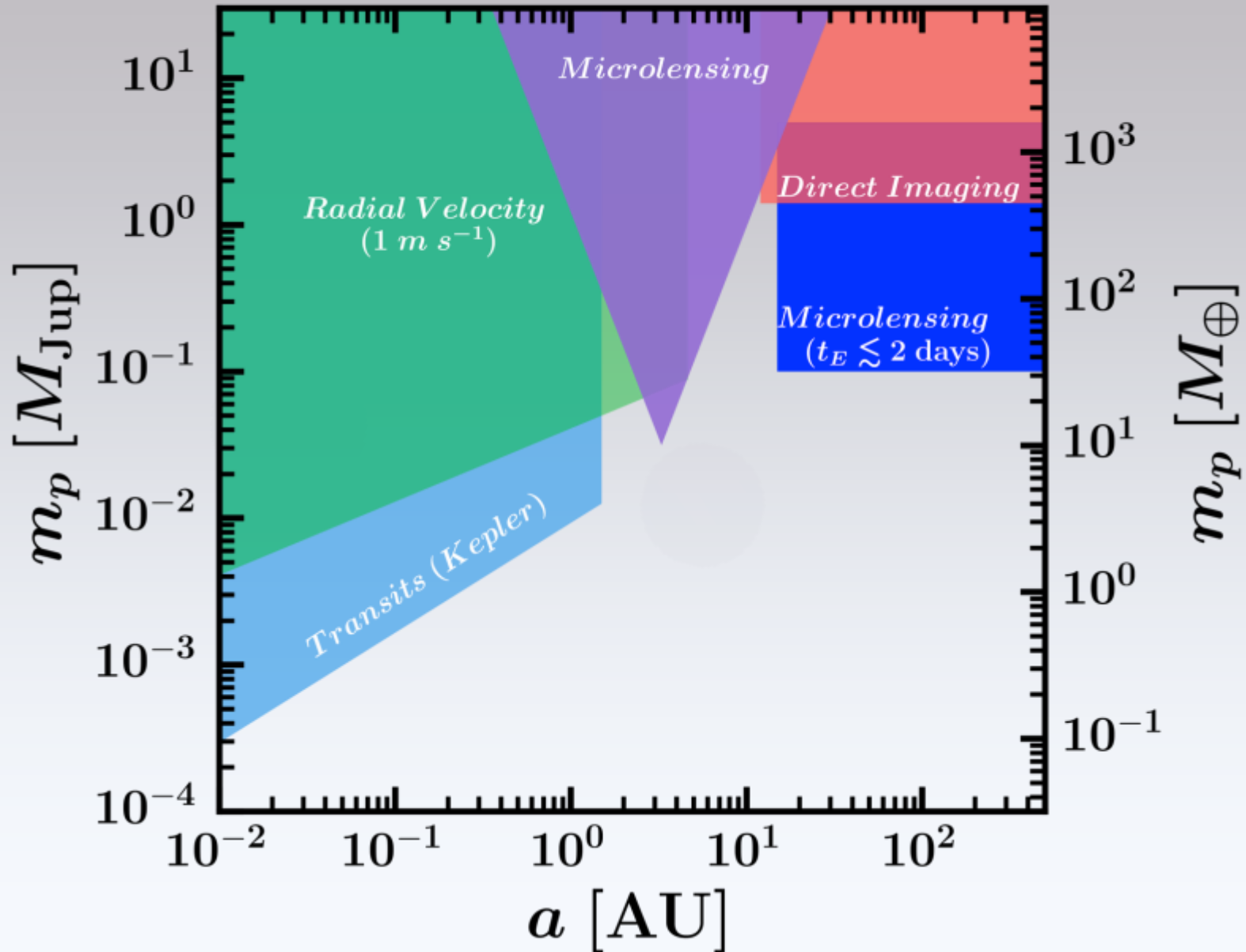
Comparison with Population Synthesis Models



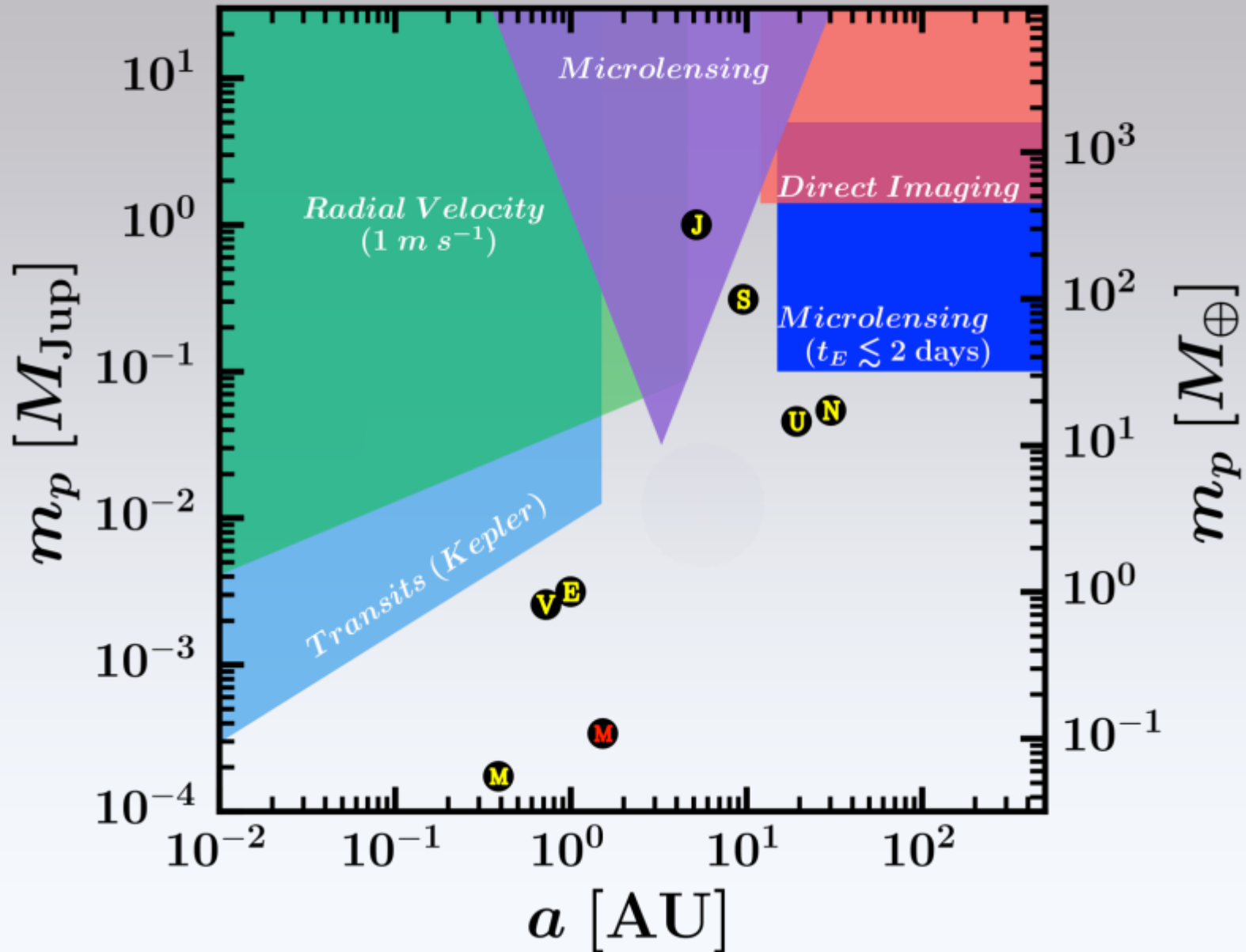
Preliminary Results

Part IV.
Future Research

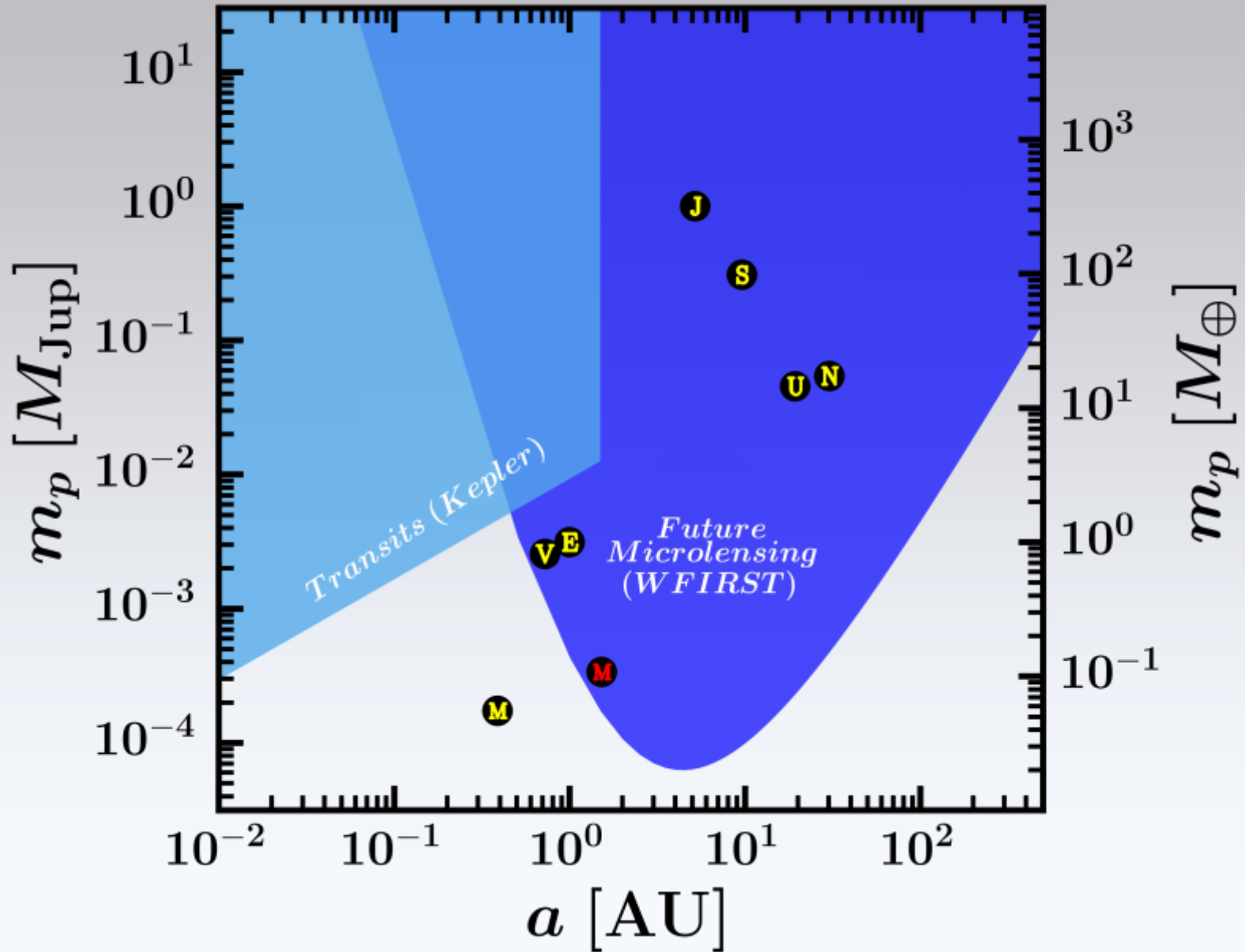
Synthesis of “The Big Four”



Synthesis of "The Big Four"



Kepler + WFIRST



Primary References

- RV + μ lensing → Clanton, C. & Gaudi, B. S. 2014, ApJ, 791, 90
→ Clanton, C. & Gaudi, B. S. 2014, ApJ, 791, 91
- RV + μ lensing +
Imaging → Clanton, C. & Gaudi, B. S. 2016, ApJ, 819, 125
- Free-Floating
Planets → Clanton, C. & Gaudi, B. S. 2017, ApJ Accepted
- Pop. Synth.
Comparison → Clanton, C. & Gaudi, B. S. in prep.

End

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