The Demographics of Exoplanetary Companions to M Dwarfs and Free-Floating Planets

Synthesizing Results from Microlensing, Radial Velocity, and Direct Imaging Surveys

Sagan Exoplanet Summer Workshop 2016

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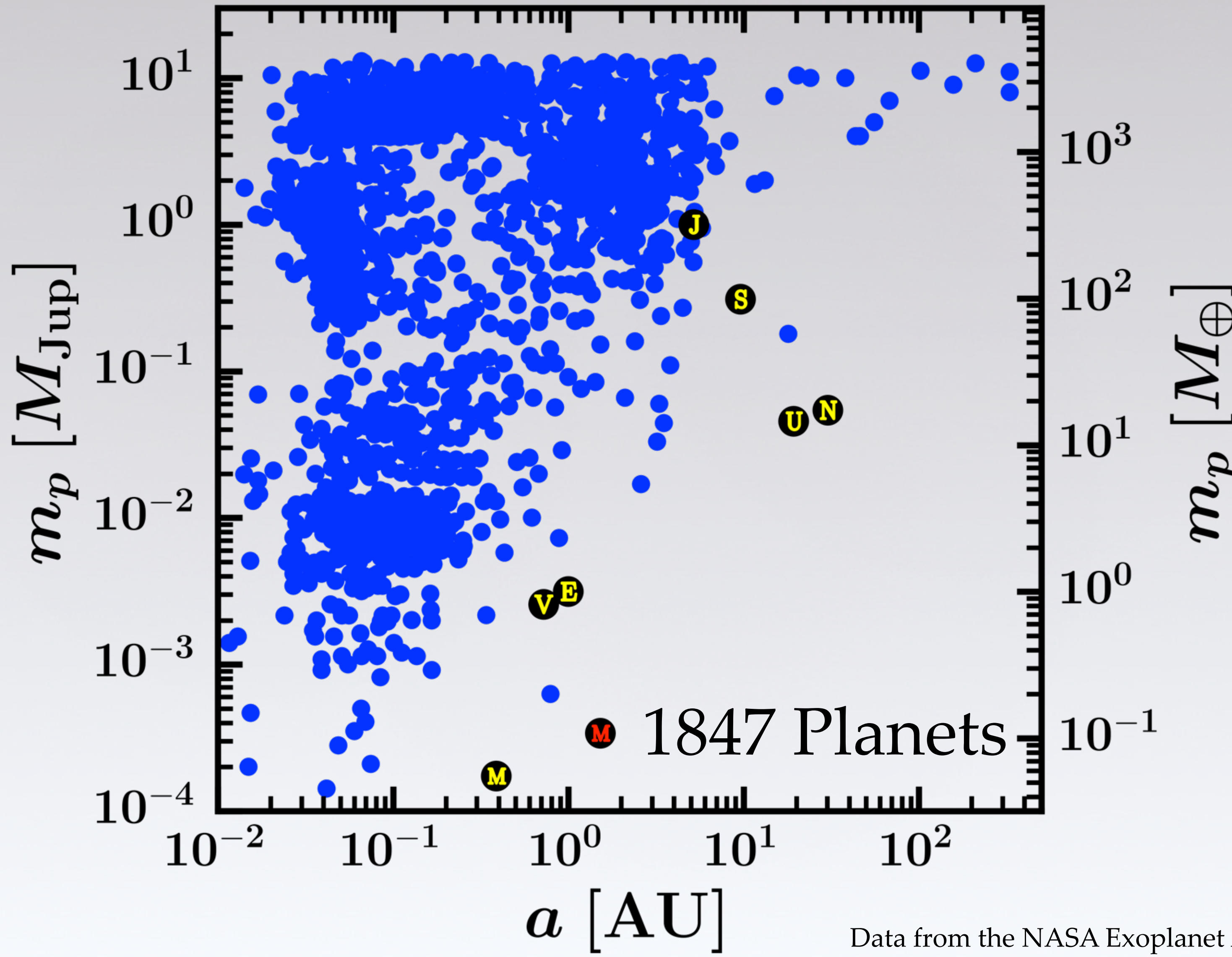
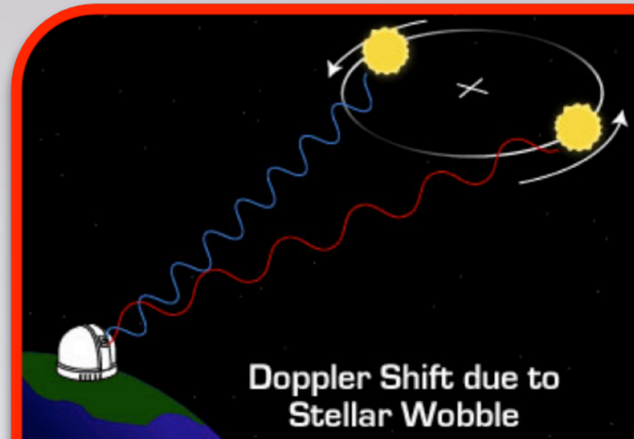
Currently Known Planets (All Host Spectral Types)

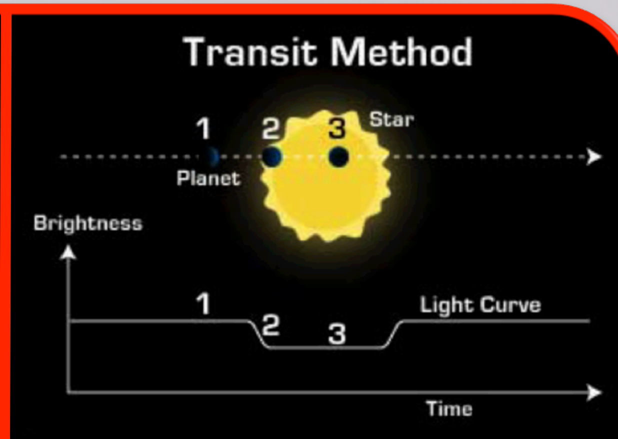


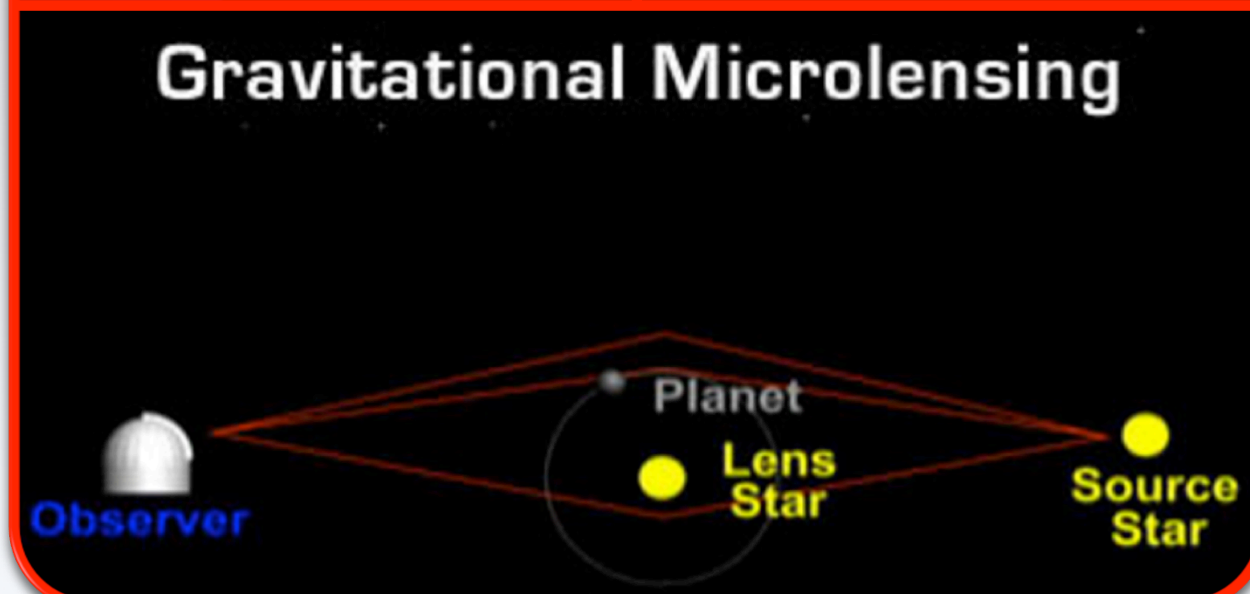
Data from the NASA Exoplanet Archive
exoplanetarchive.ipac.caltech.edu

Exoplanet Detection Methods

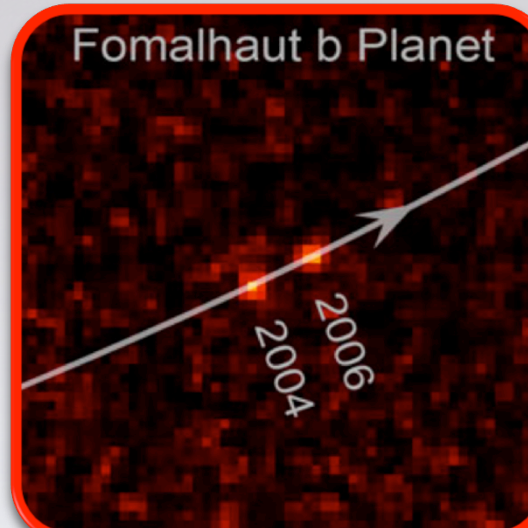
–Indirect–



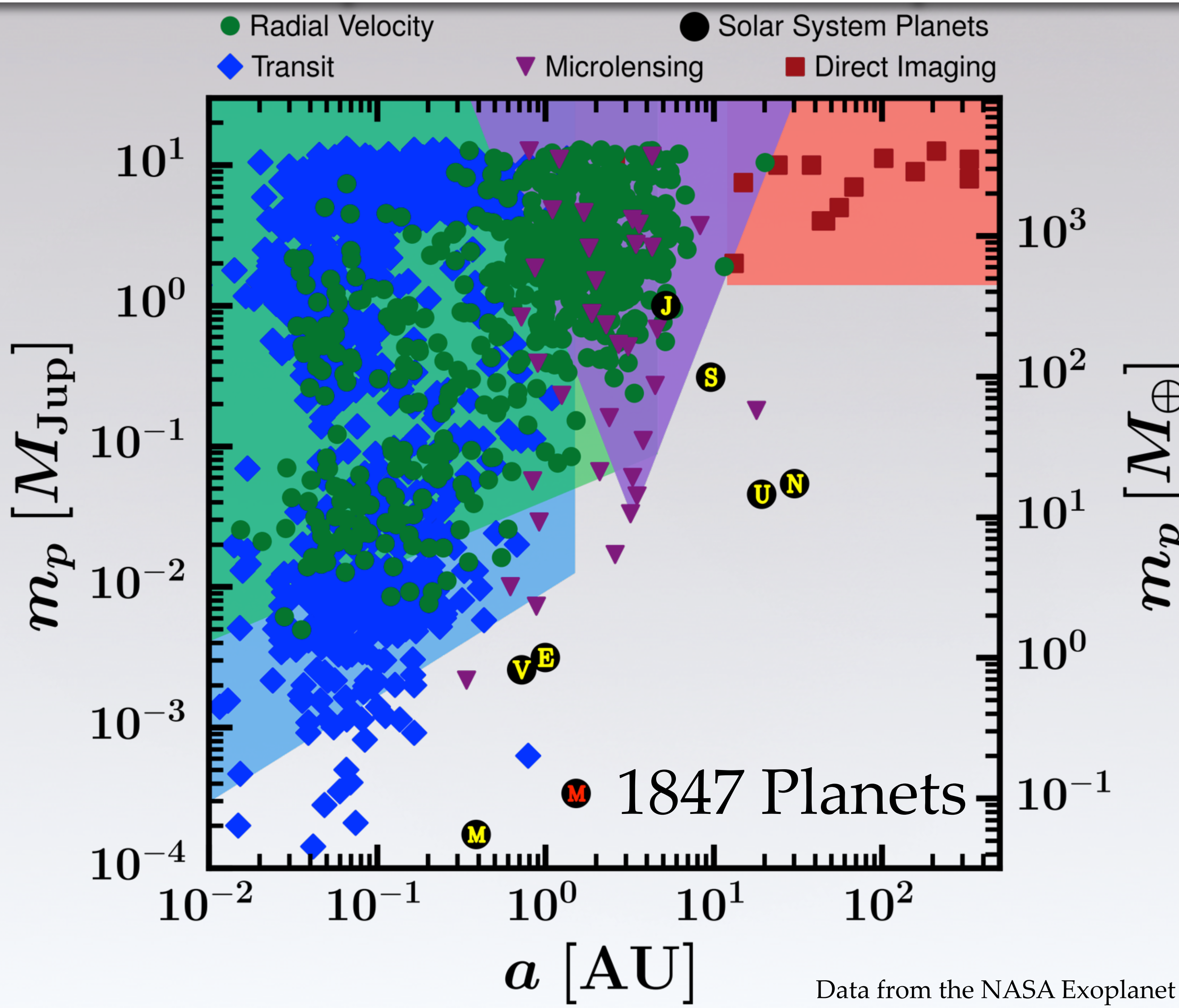




–Direct–



Full Sample of Confirmed Exoplanets



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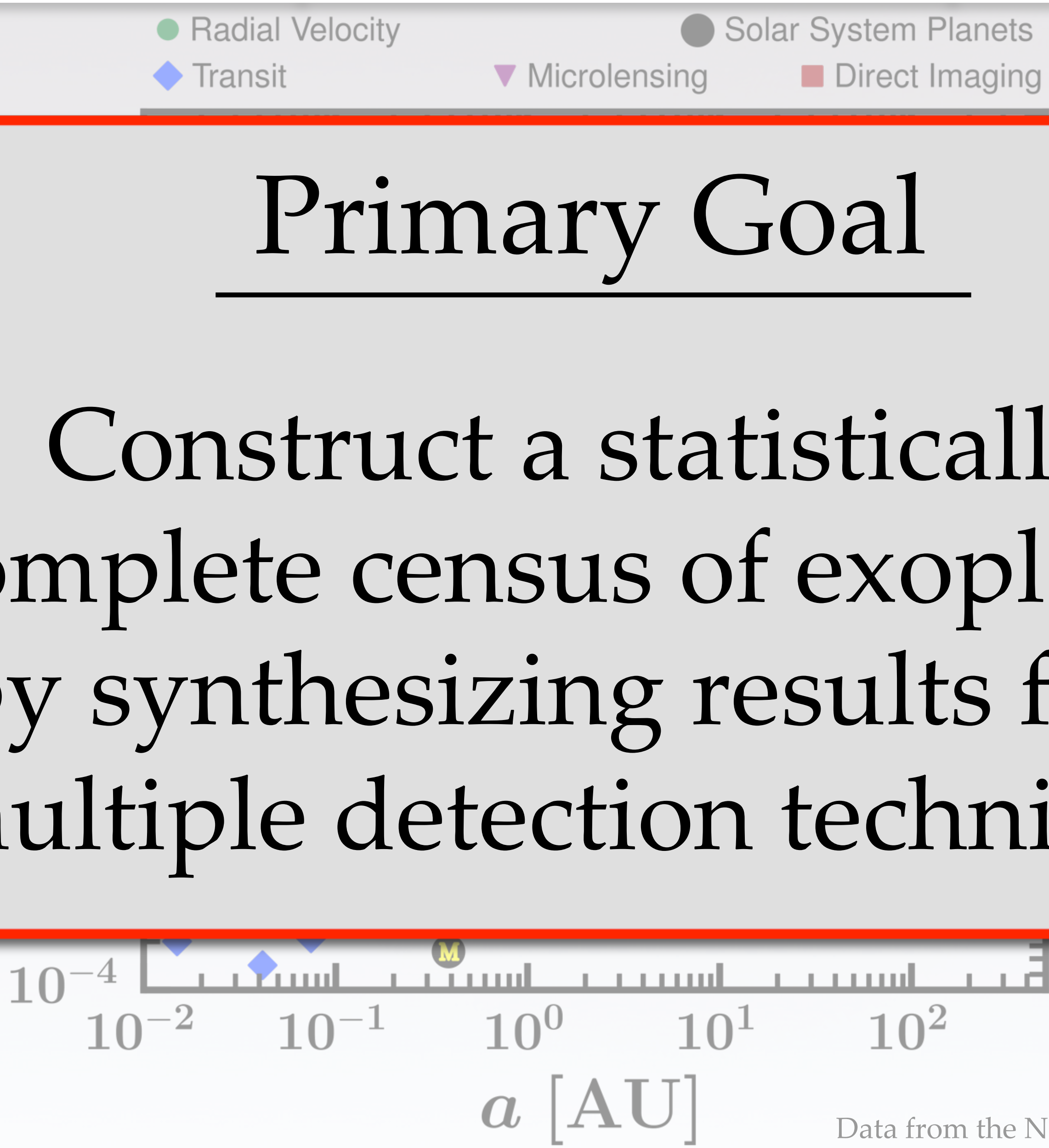
Full Sample of Confirmed Exoplanets



Primary Goal

Construct a statistically-complete census of exoplanets by synthesizing results from multiple detection techniques

Data from the NASA Exoplanet Archive
exoplanetarchive.ipac.caltech.edu

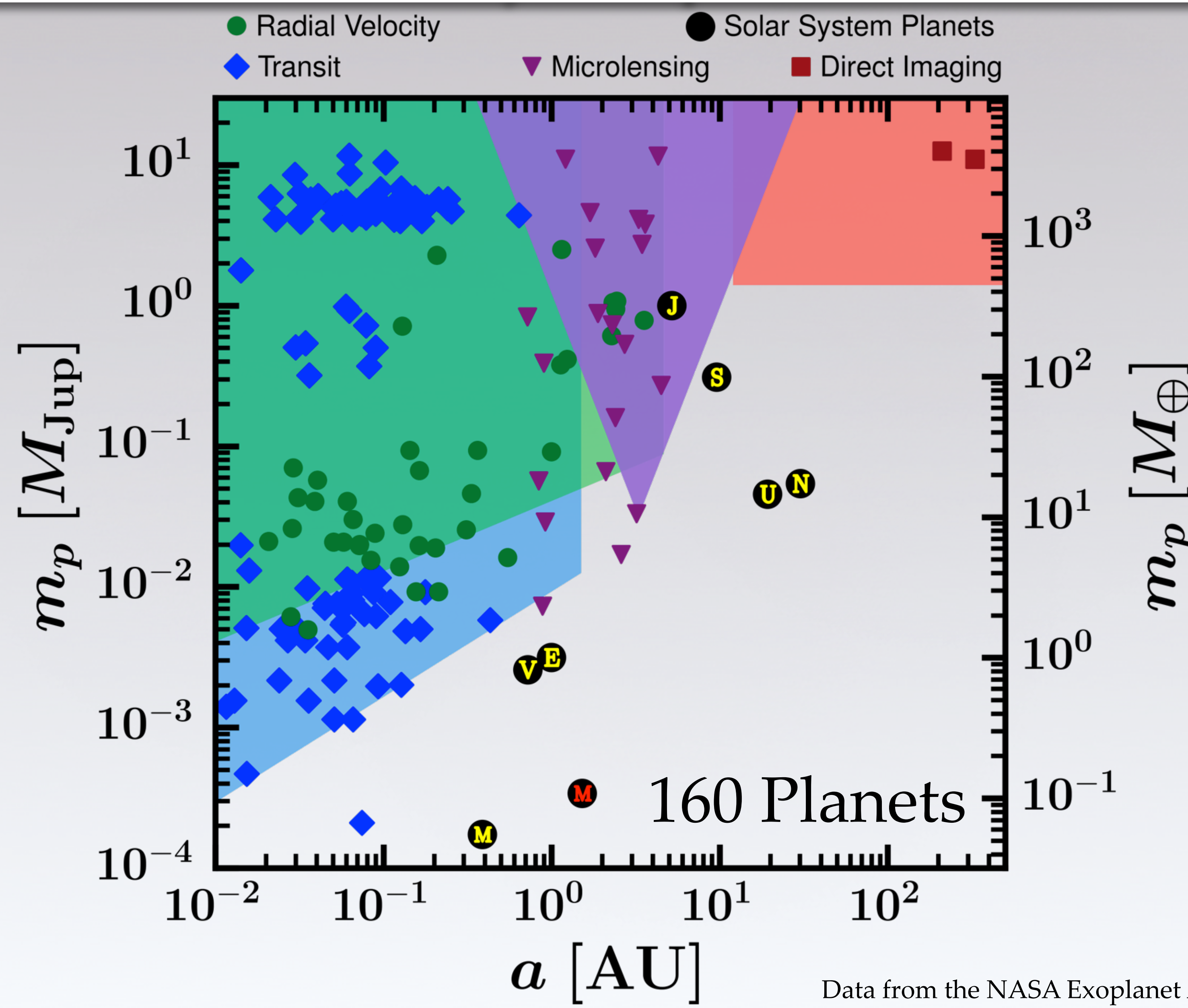
Part I.
Demographics of Planets Around M Dwarfs

M Dwarfs

Common

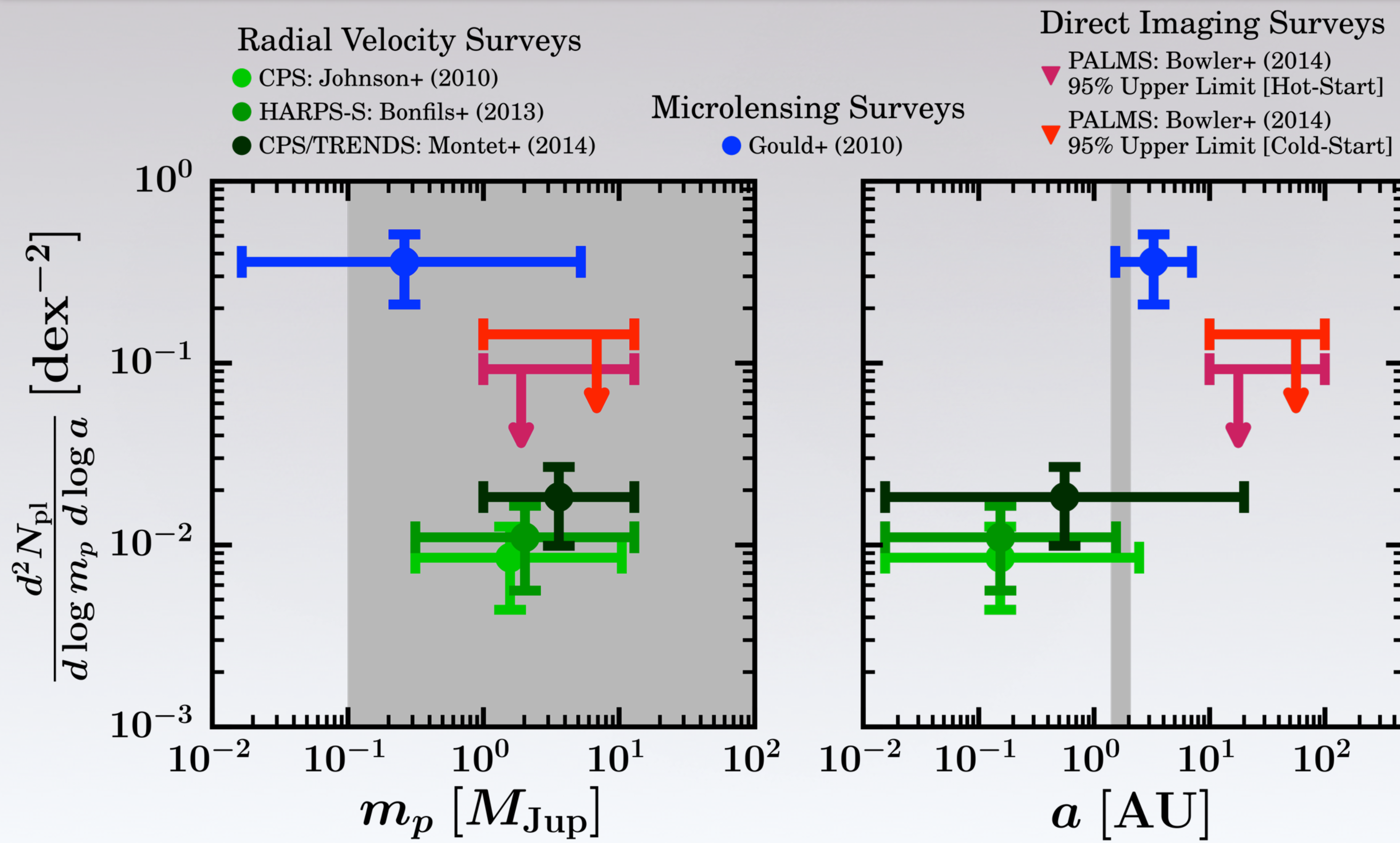
Well-Characterized Demographics

Confirmed Planetary Companions to M Dwarfs

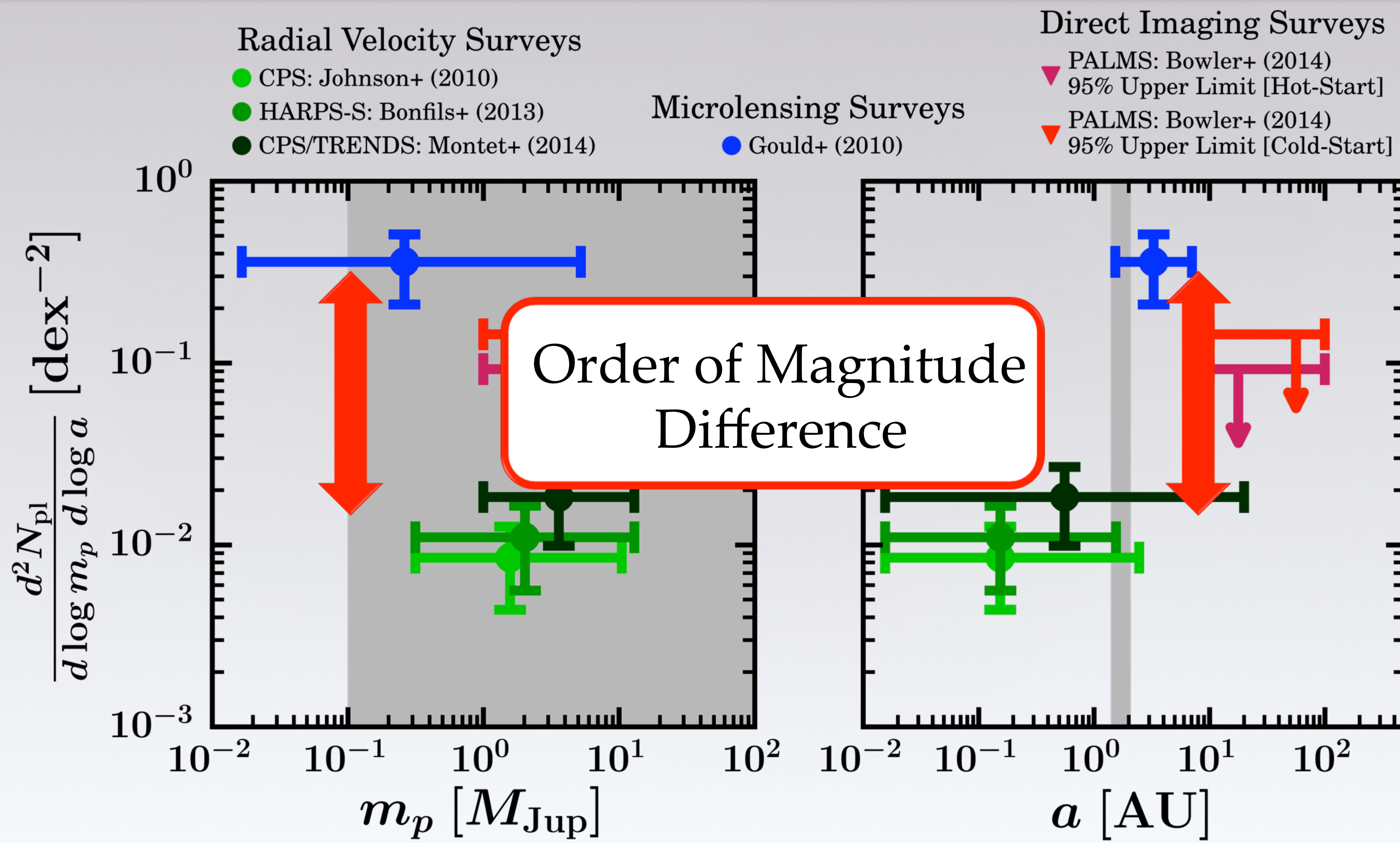


Data from the NASA Exoplanet Archive
exoplanetarchive.ipac.caltech.edu

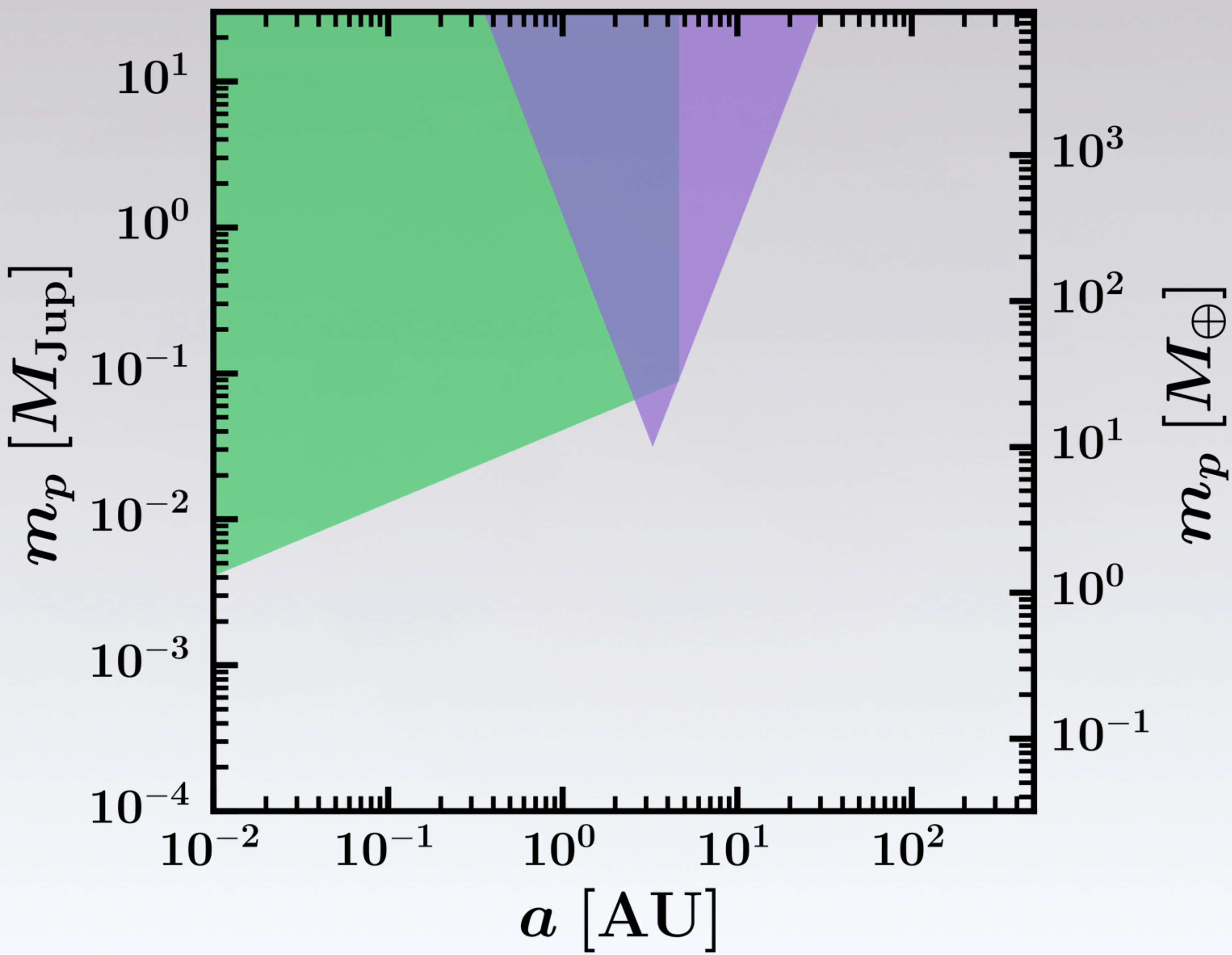
Exoplanet Censuses of M Dwarfs from Individual Methods



Exoplanet Censuses of M Dwarfs from Individual Methods



Sensitivities of Microlensing and RV Surveys



"Microlensing Planets"

$$\frac{d^2 N_{\rm pl}}{d\log q\ d\log s} = (0.23 \pm 0.10)\left(\frac{q}{5\times 10^{-4}}\right)^{-0.68\pm0.20}$$

"Microlensing Planets"

Sumi+ (2010) & Gould+ (2010)

Sumi+ (2010)

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

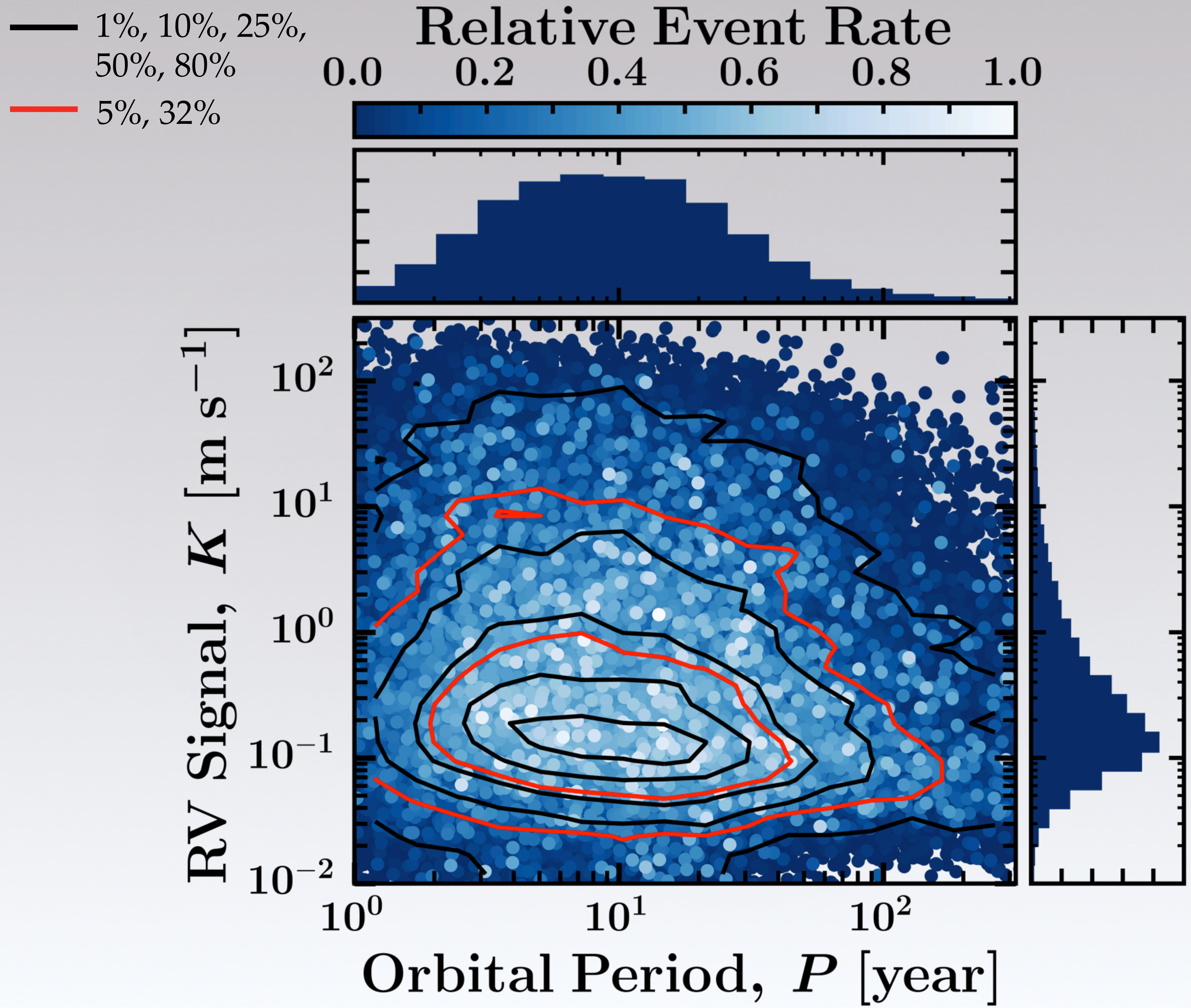
"Microlensing Planets"

Sumi+ (2010) & Gould+ (2010) Sumi+ (2010)

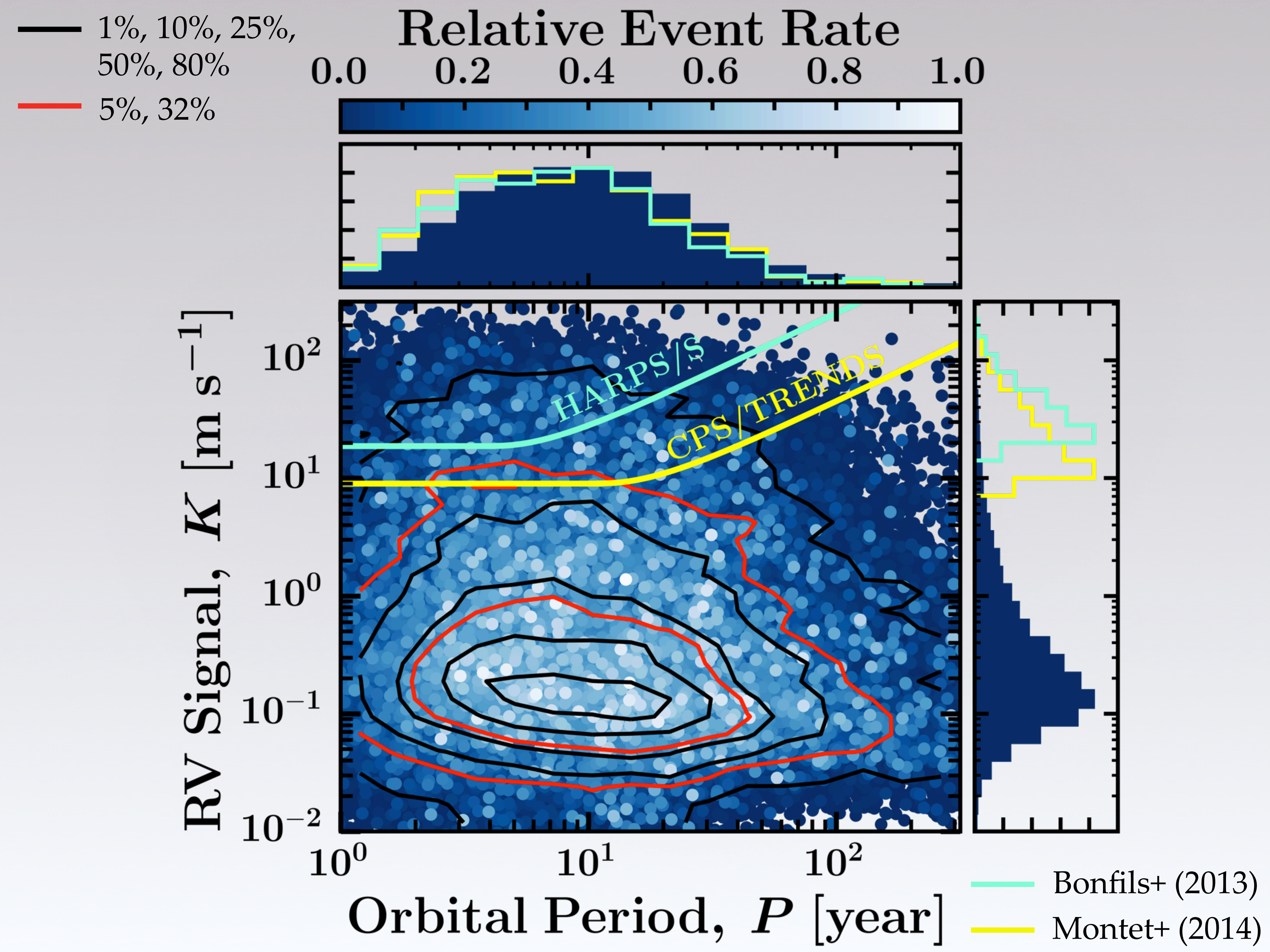
$$\frac{d^2 N_{\rm pl}}{d\log q \; d\log s} = (0.23 \pm 0.10)\left(\frac{q}{5\times 10^{-4}}\right)^{-0.68\pm0.20}$$

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

$(q,s) \rightarrow (K,P)$



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]
10²
10¹
10⁰
10⁻¹
10⁻²
10⁰
10¹
10²
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]
10²
10¹
10⁰
10⁻¹
10⁻²
10⁰
10¹
10²
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:

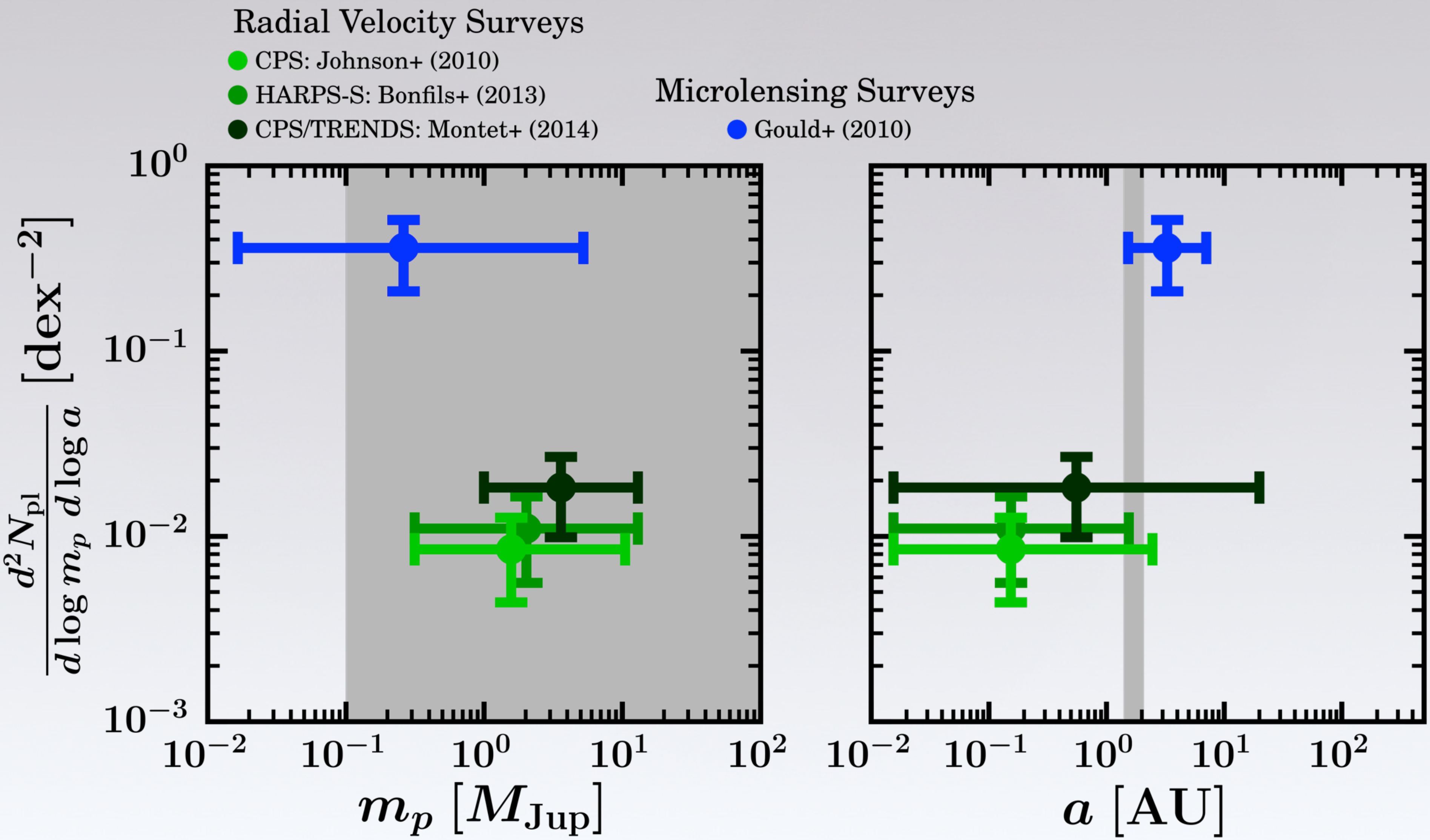
4.7 ± 2.7

Actual Number:

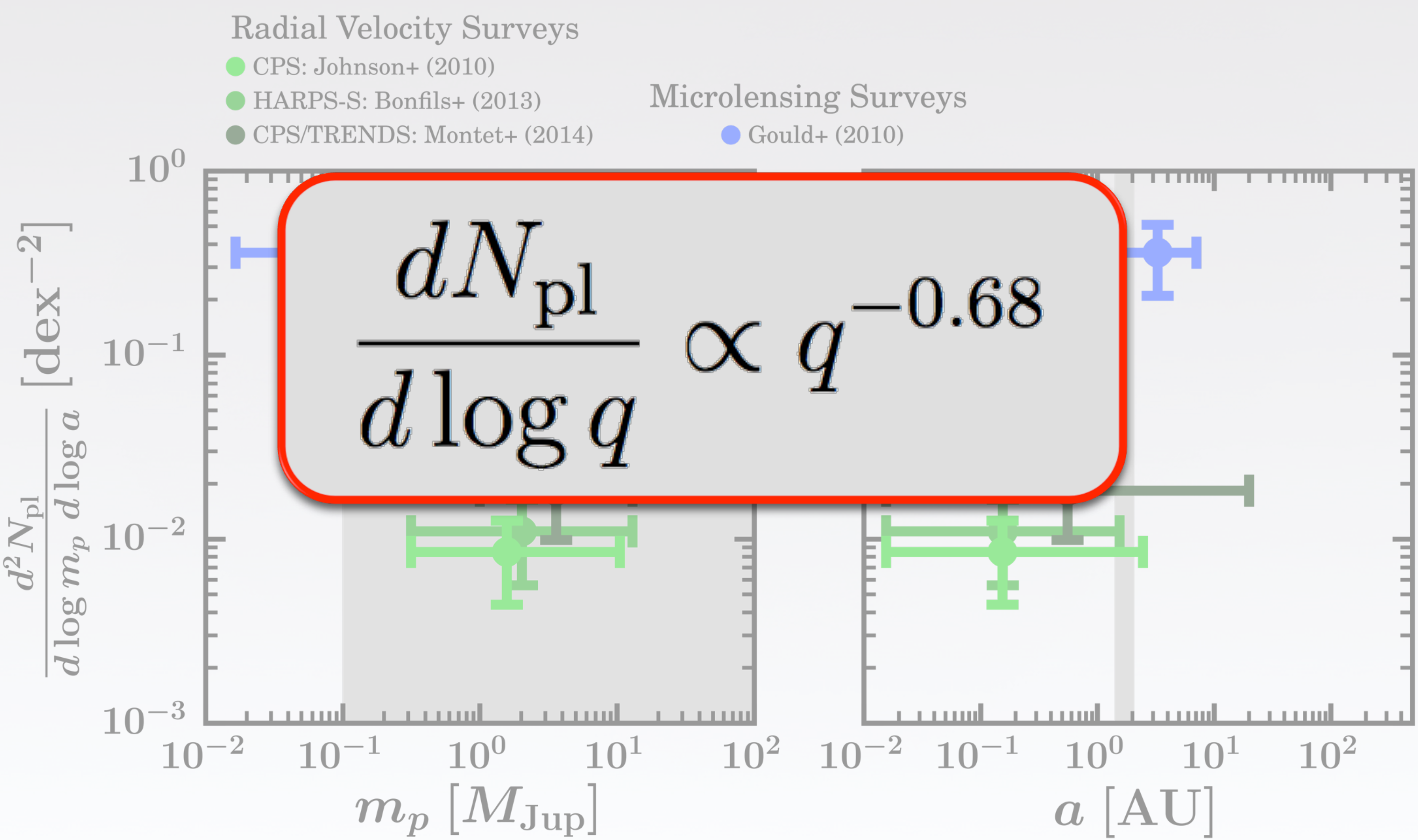
4

Similar Masses and Orbital Periods

Consistency Between Microlensing and RV Results

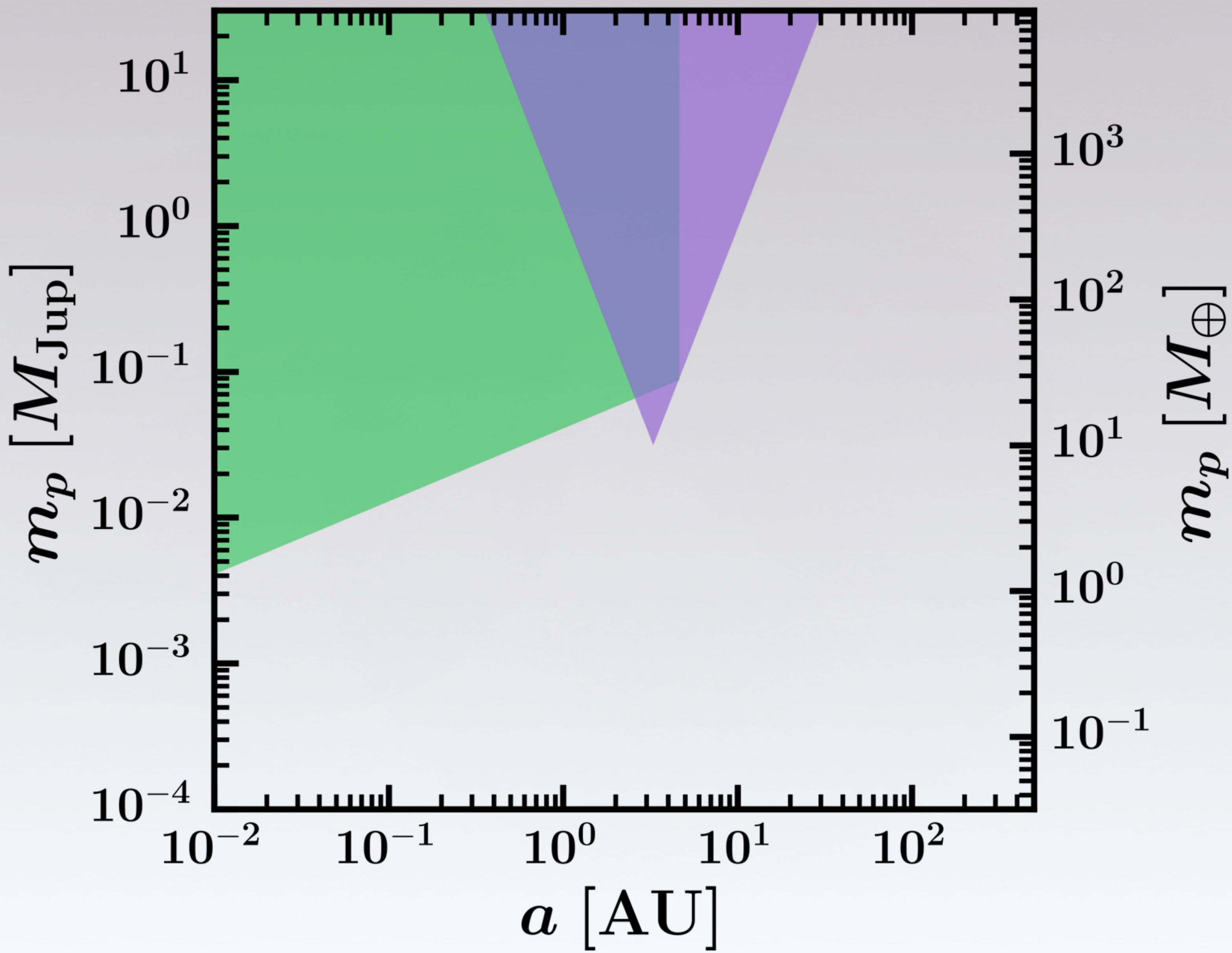


Consistency Between Microlensing and RV Results

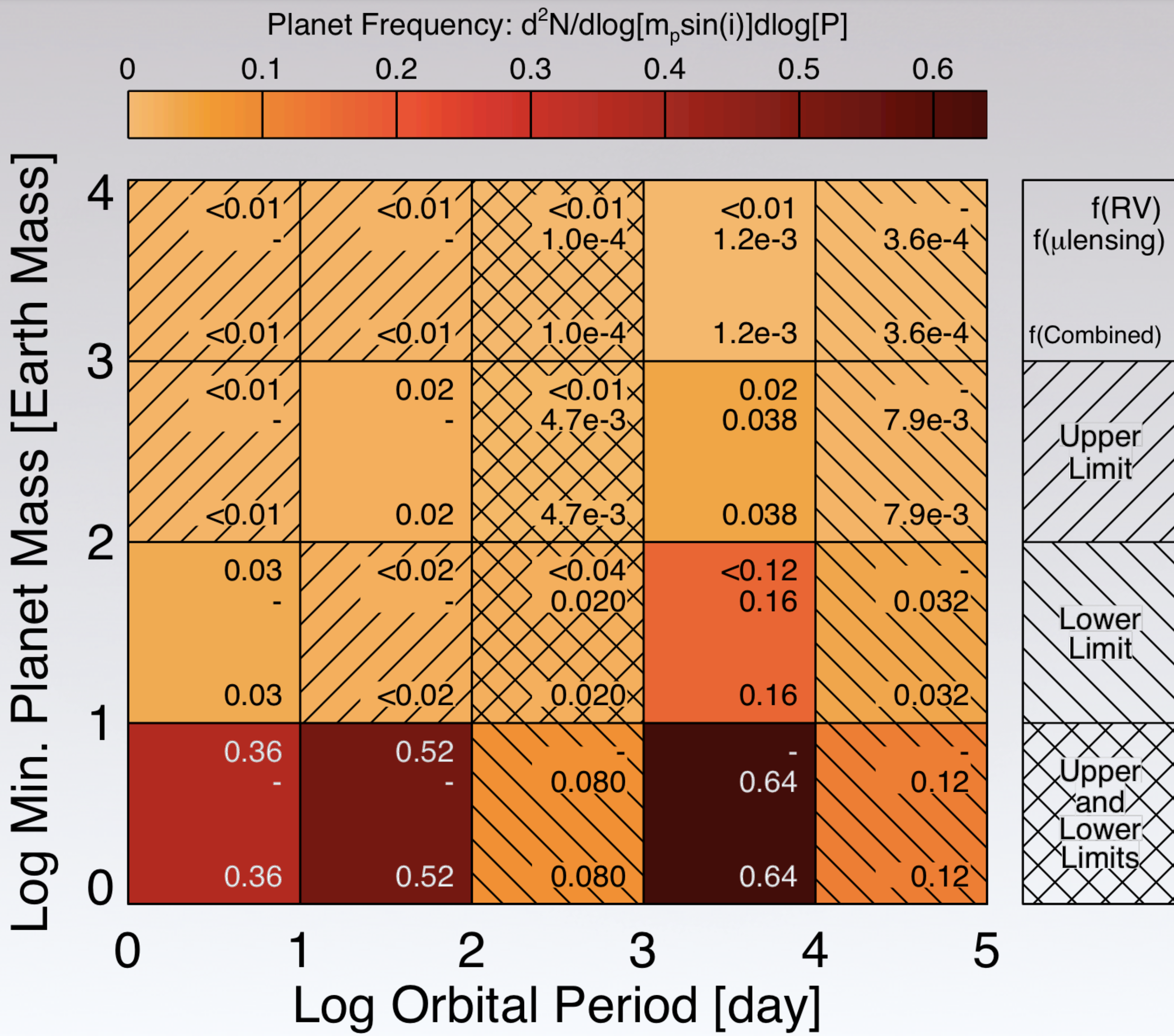


$$\frac{dN_{\rm pl}}{d\log q} \propto q^{-0.68}$$

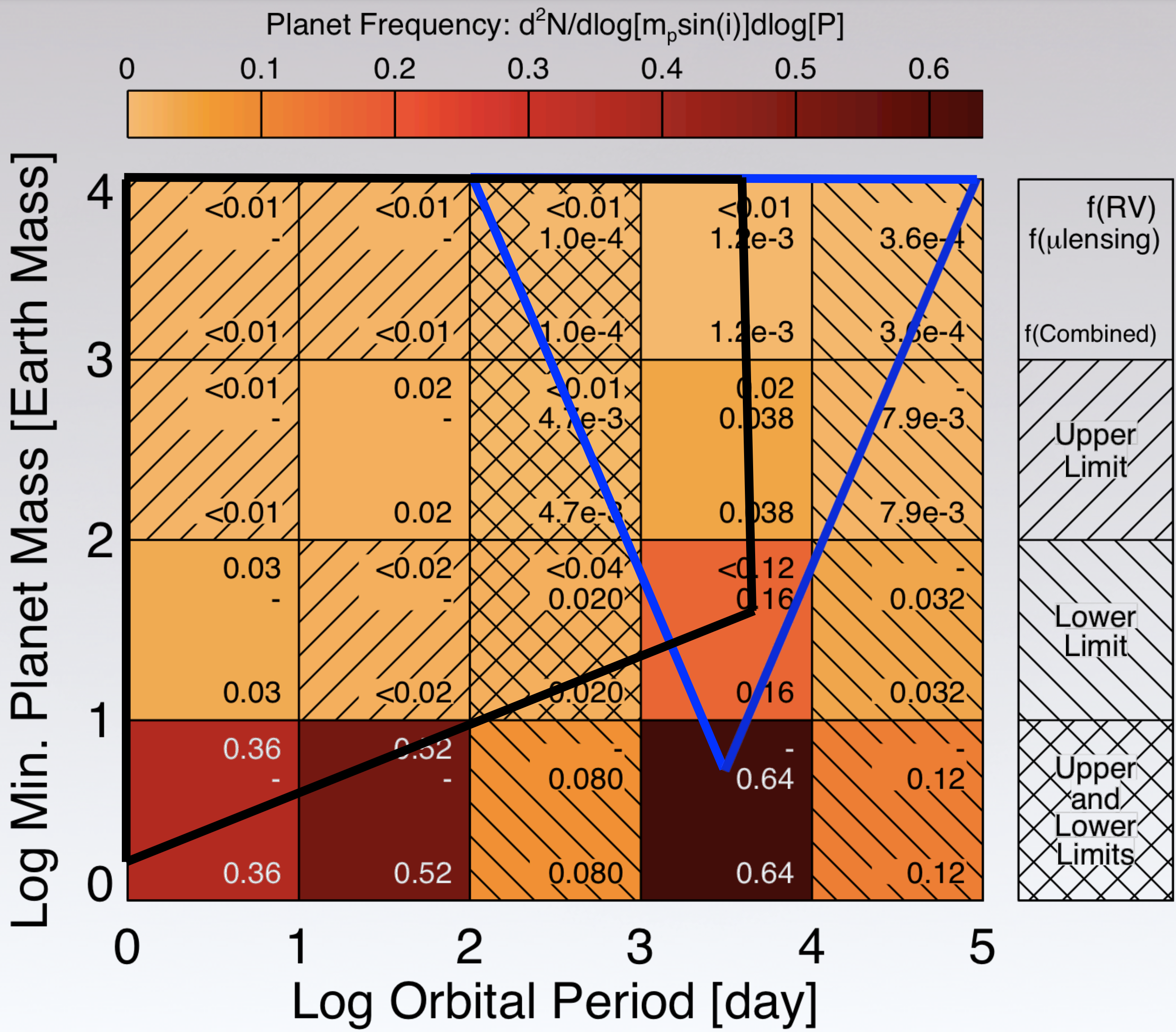
Synthesizing Microlensing and RV Results



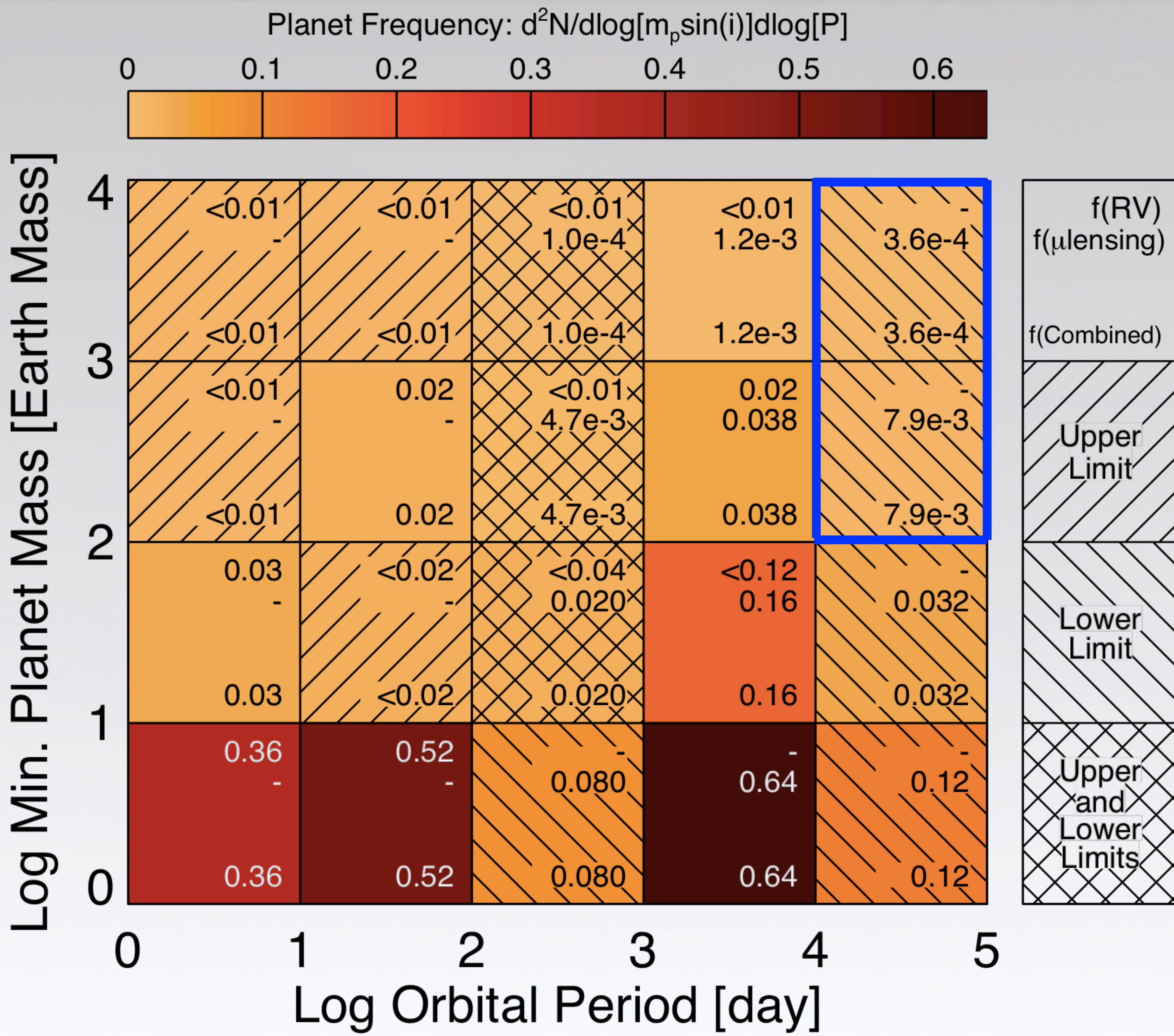
Synthesized Constraints



Synthesized Constraints

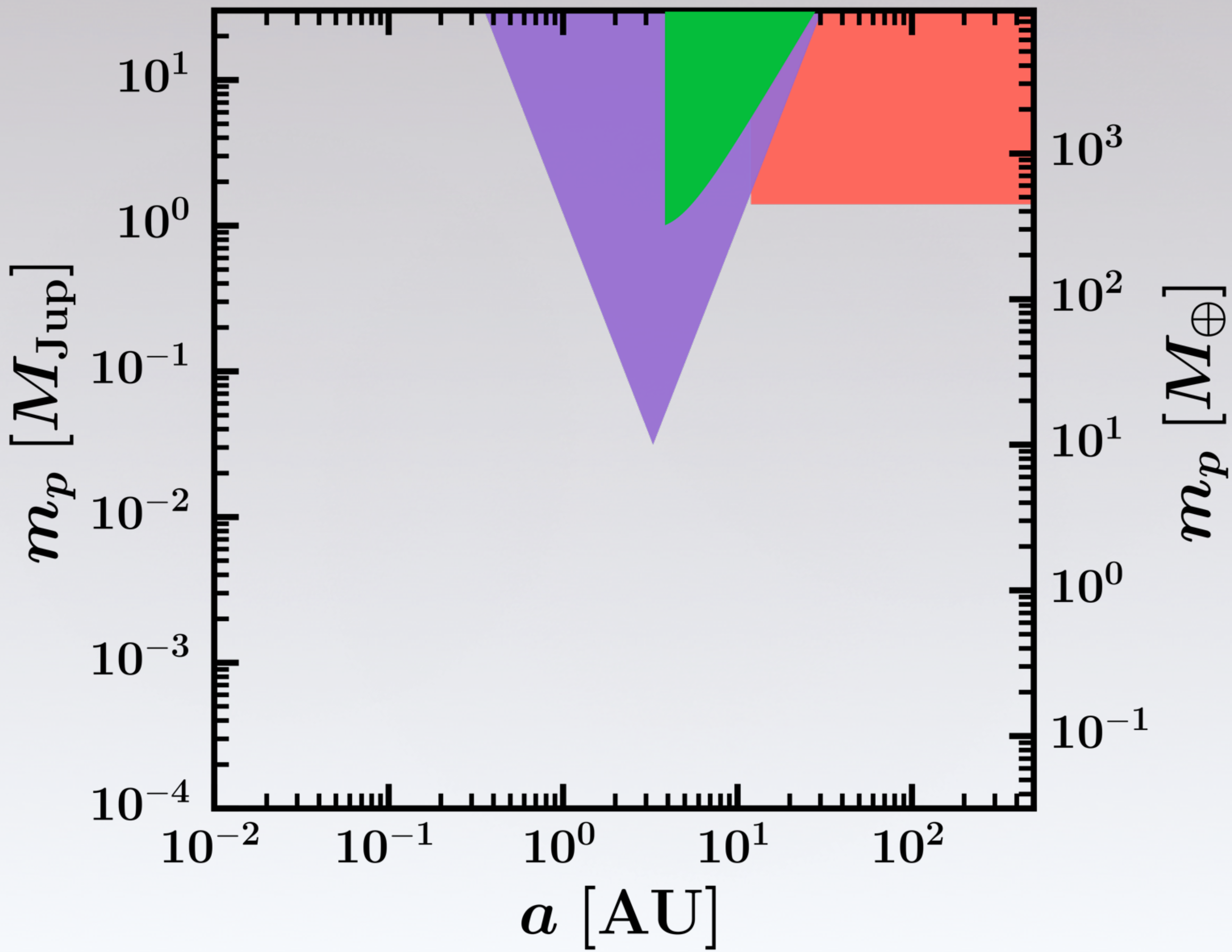


Improving Constraints on Long-Period Planets



Part II.
Long-Period Planets: Synthesizing Results from Microlensing, Radial Velocity, and Direct Imaging Surveys

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)

Constraints on Long-Period Planetary Companions to M Dwarfs

Primary Question

Is there a single planet population that is consistent with the results of these surveys?

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)	$(\dot{v}, P)$	$(\Delta\mathrm{mag}, \rho)$

Microlensing

$$(\boldsymbol{m_p}, \boldsymbol{a}) \;\rightarrow\; (\boldsymbol{q}, \boldsymbol{s})$$

$$q(m_p, M_L)$$

$$s(a, i, e, \omega, E, M_L, D_L, D_S)$$

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		

RV Trends

$$(\boldsymbol{m_p}, \boldsymbol{a}) \rightarrow (\dot{\boldsymbol{v}}, \boldsymbol{P})$$

$$\dot{v}(m_p, a, M_L, i, e, M_0)$$

$$P(a, M_L)$$

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	

Direct Imaging

$$(\boldsymbol{m_p}, \boldsymbol{a}) \rightarrow (\boldsymbol{\Delta}\mathbf{mag}, \boldsymbol{\rho})$$

$$\Delta\mathrm{mag}(M_{H,\mathrm{pl}}, D_L, H_L)$$

$$\rho(a, i, e, \omega, M_0, D_L)$$

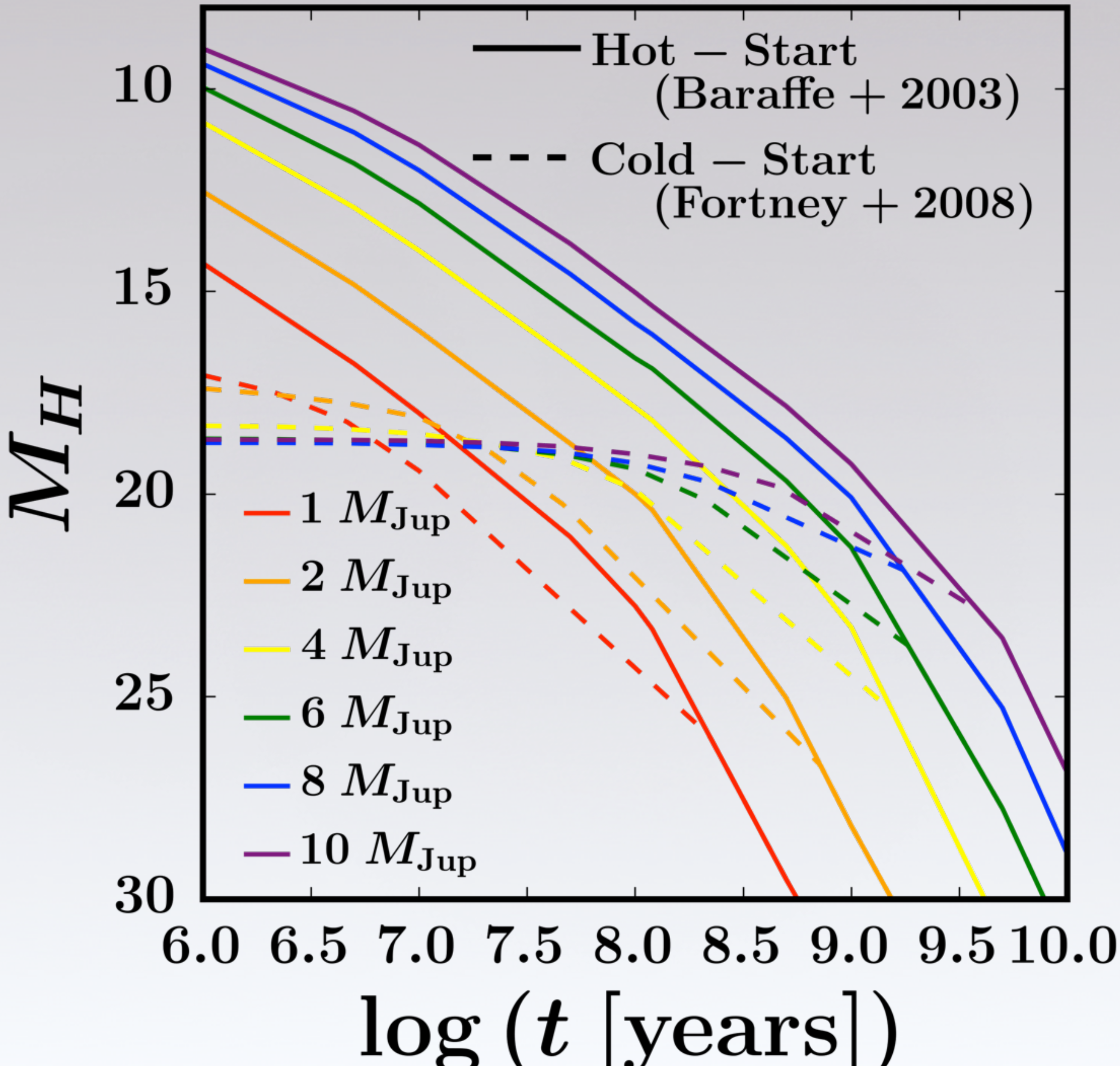
Direct Imaging

$$(m_p, a) \rightarrow (\Delta\text{mag}, \rho)$$

$$\Delta\text{mag}(M_{H,\text{pl}}, D_L, H_L)$$

$$\rho(a, i, e, \omega, M_0, D_L)$$

Planet Evolutionary Models

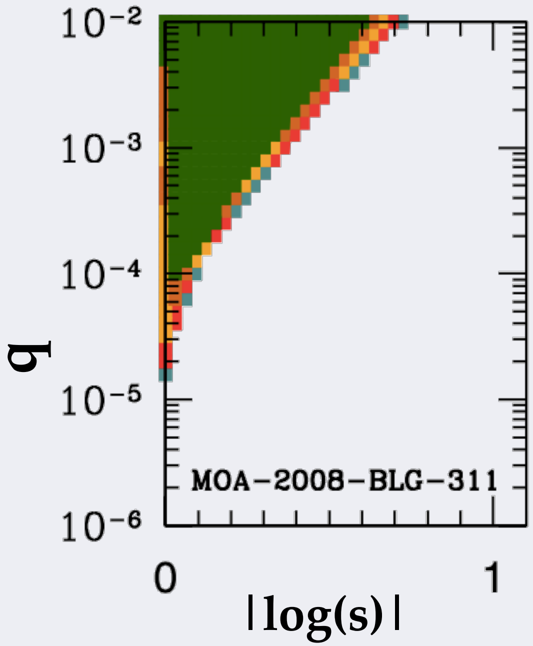
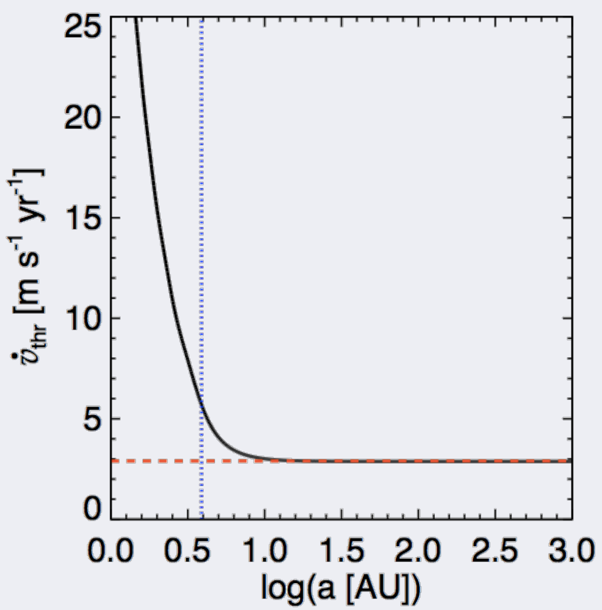
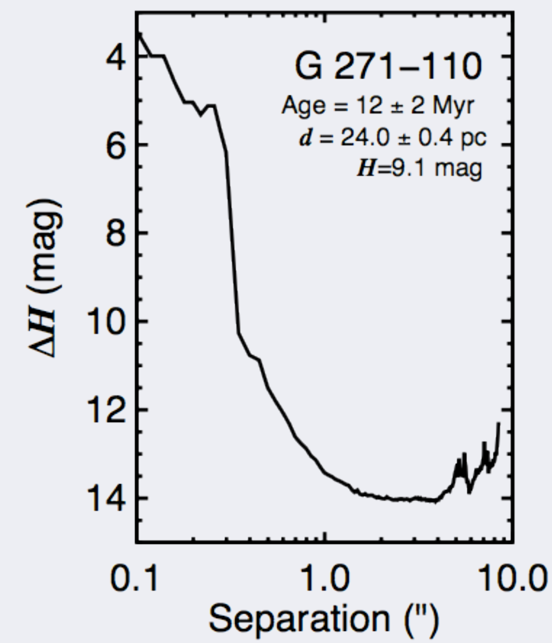


Methodology

$$(m_p, a)$$

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)

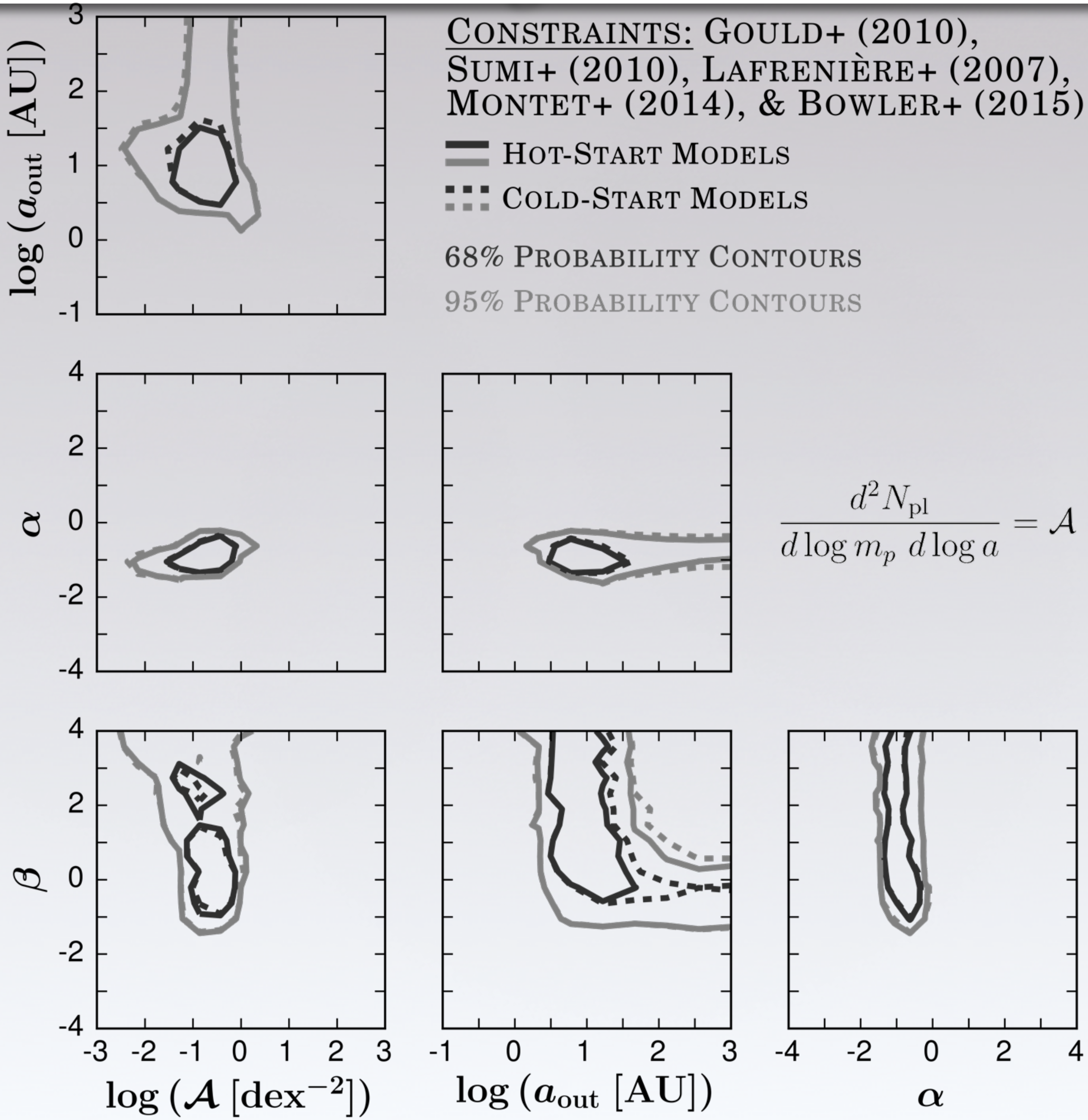
Above figure from Bowler+ (2015)

Model

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

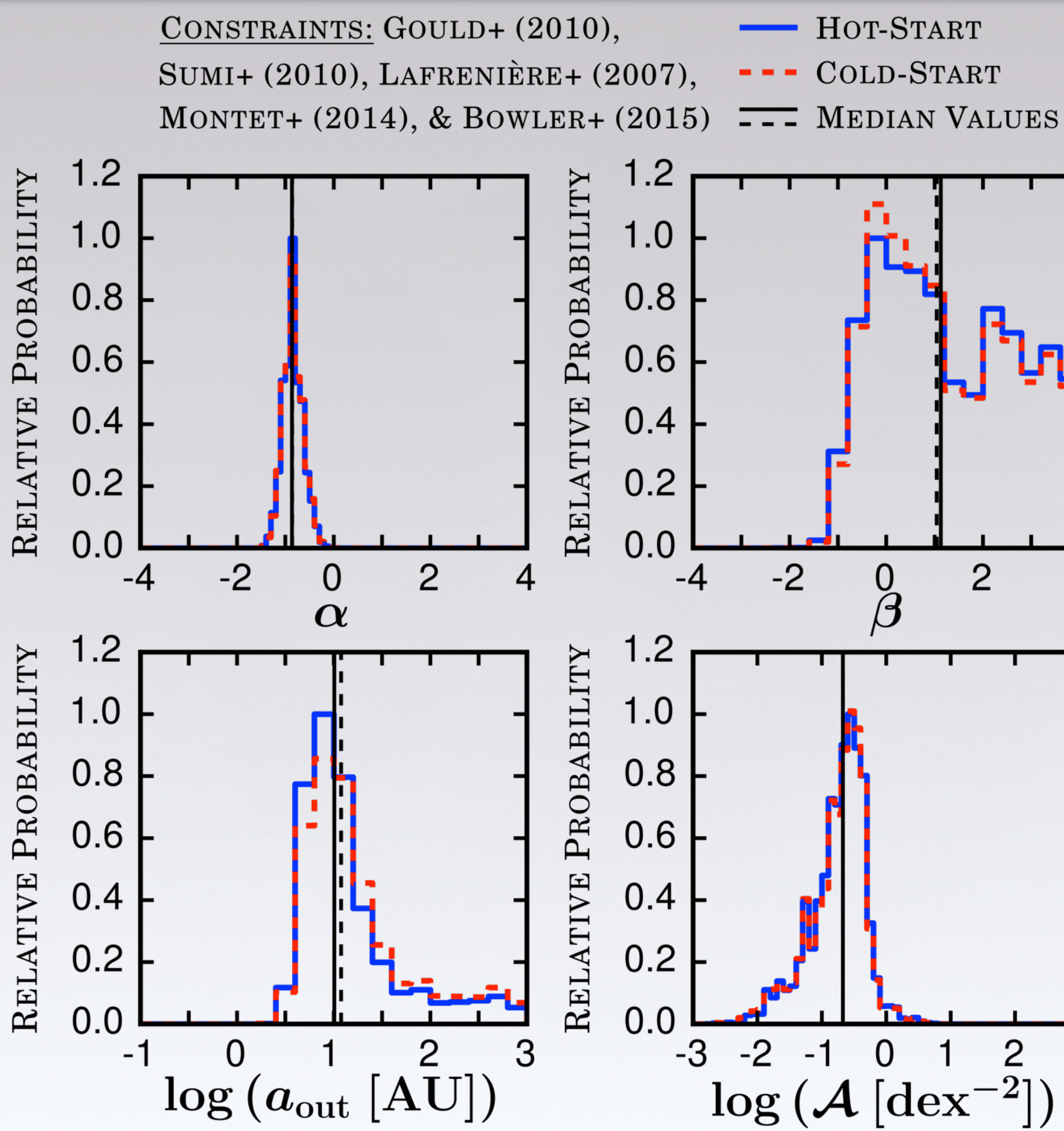
$$\{\alpha, \beta, \mathcal{A}, a_{\rm out}\}$$

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

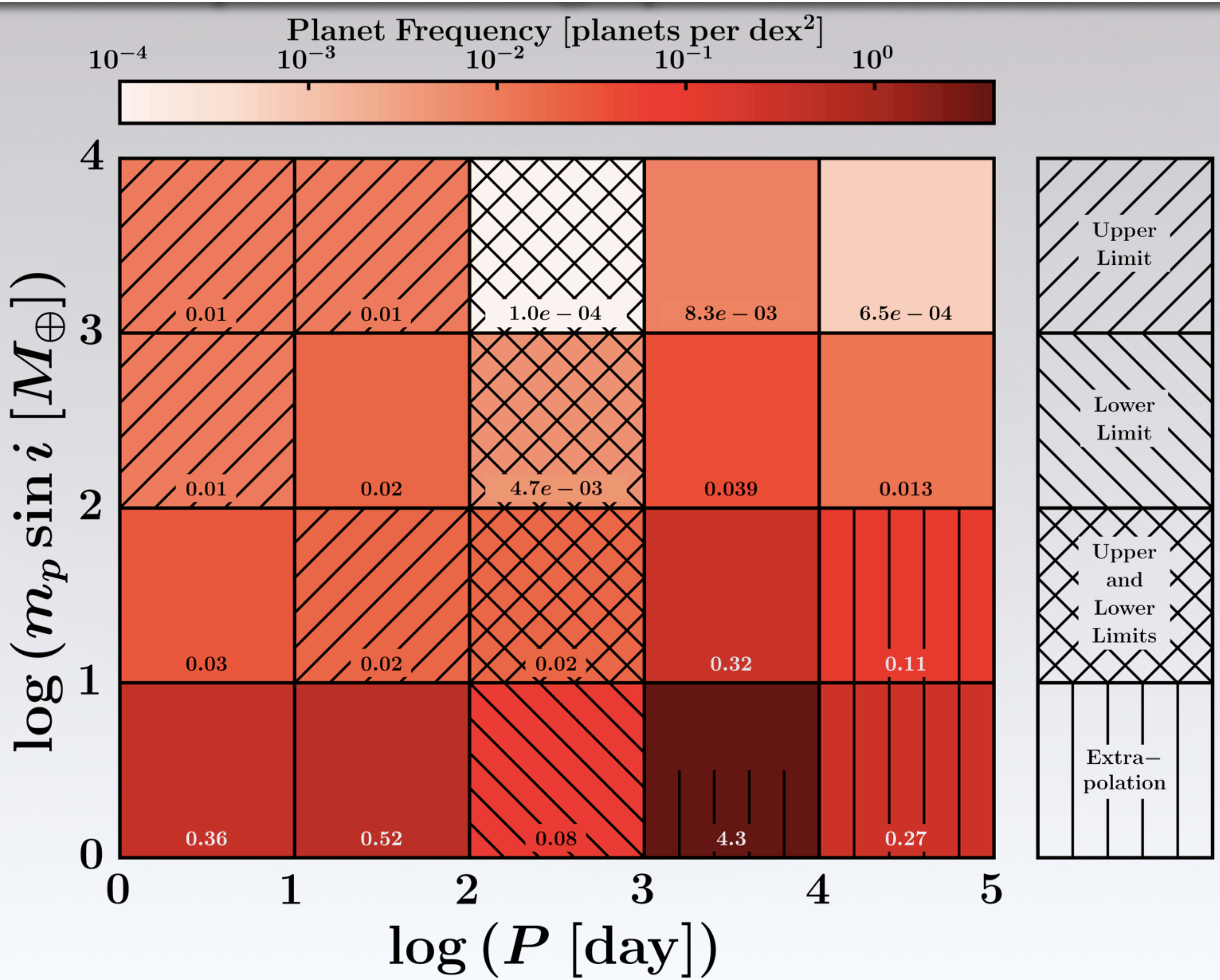


Results: Final Parameter Constraints

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)	$-0.85^{+0.21}_{-0.19}$	$1.1^{+1.9}_{-1.3}$	$0.21^{+0.20}_{-0.15}$	$12^{+50}_{-6.2}$

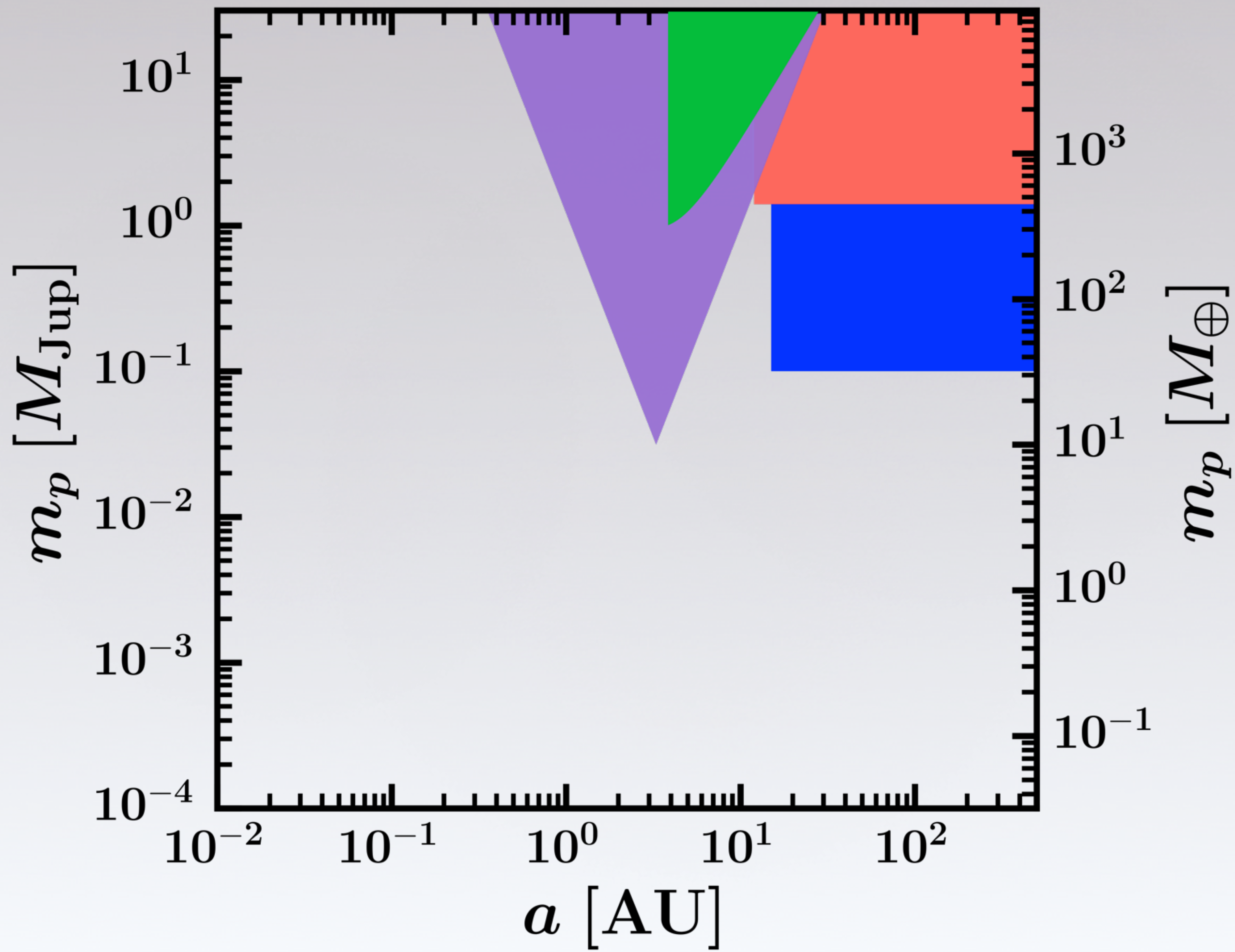
$$\frac{d^2 N_{\rm pl}}{d\log m_p \, d\log a} = \mathcal{A}\left(\frac{m_p}{M_{\rm Sat}}\right)^{\alpha}\left(\frac{a}{2.5\ {\rm AU}}\right)^{\beta}$$

Updated Demographic Constraints

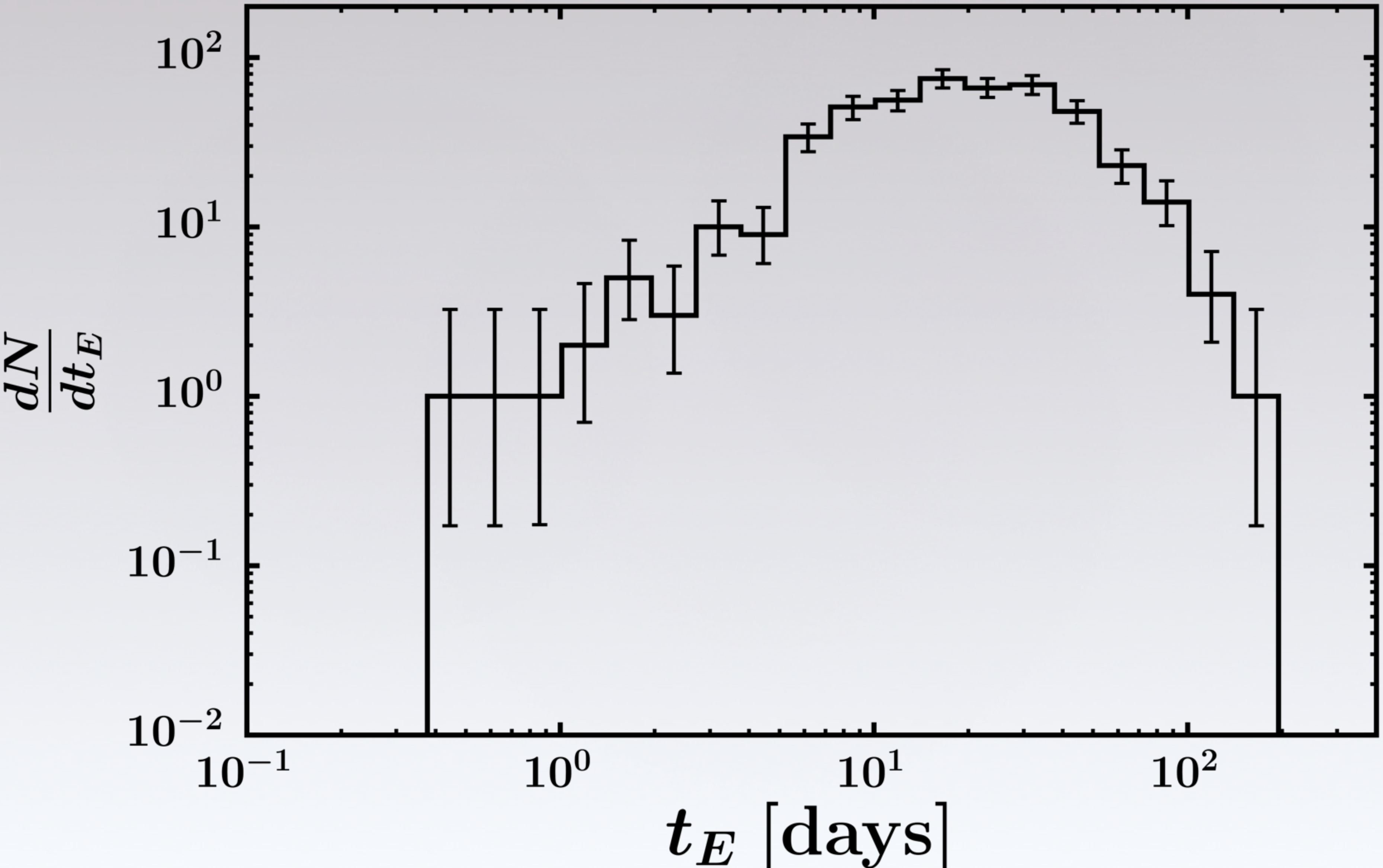


Part III.
Constraining the Galactic Population of Free-Floating Planets

Short-Timescale Microlensing Events

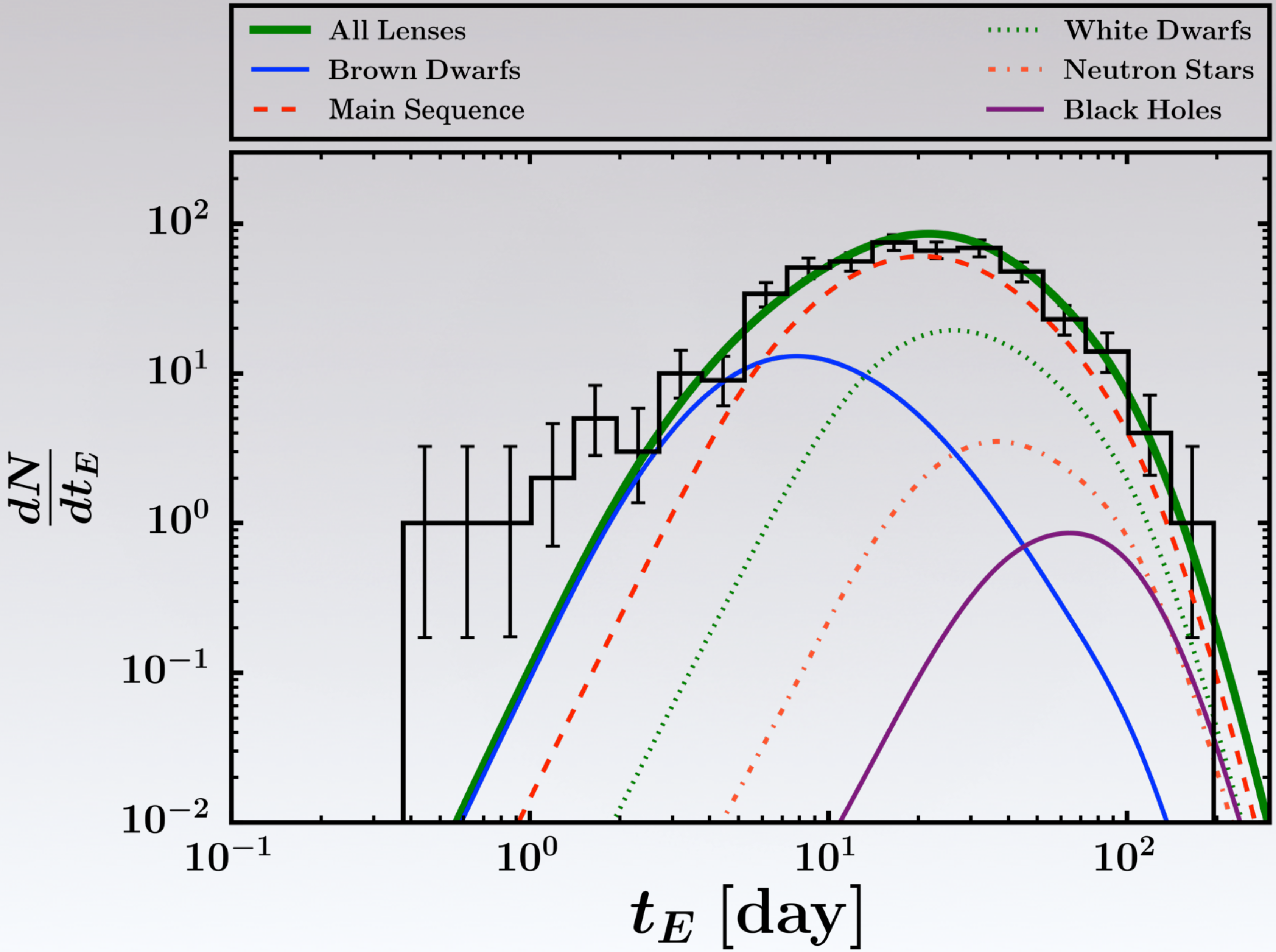


MOA-II Data (2006-2007)

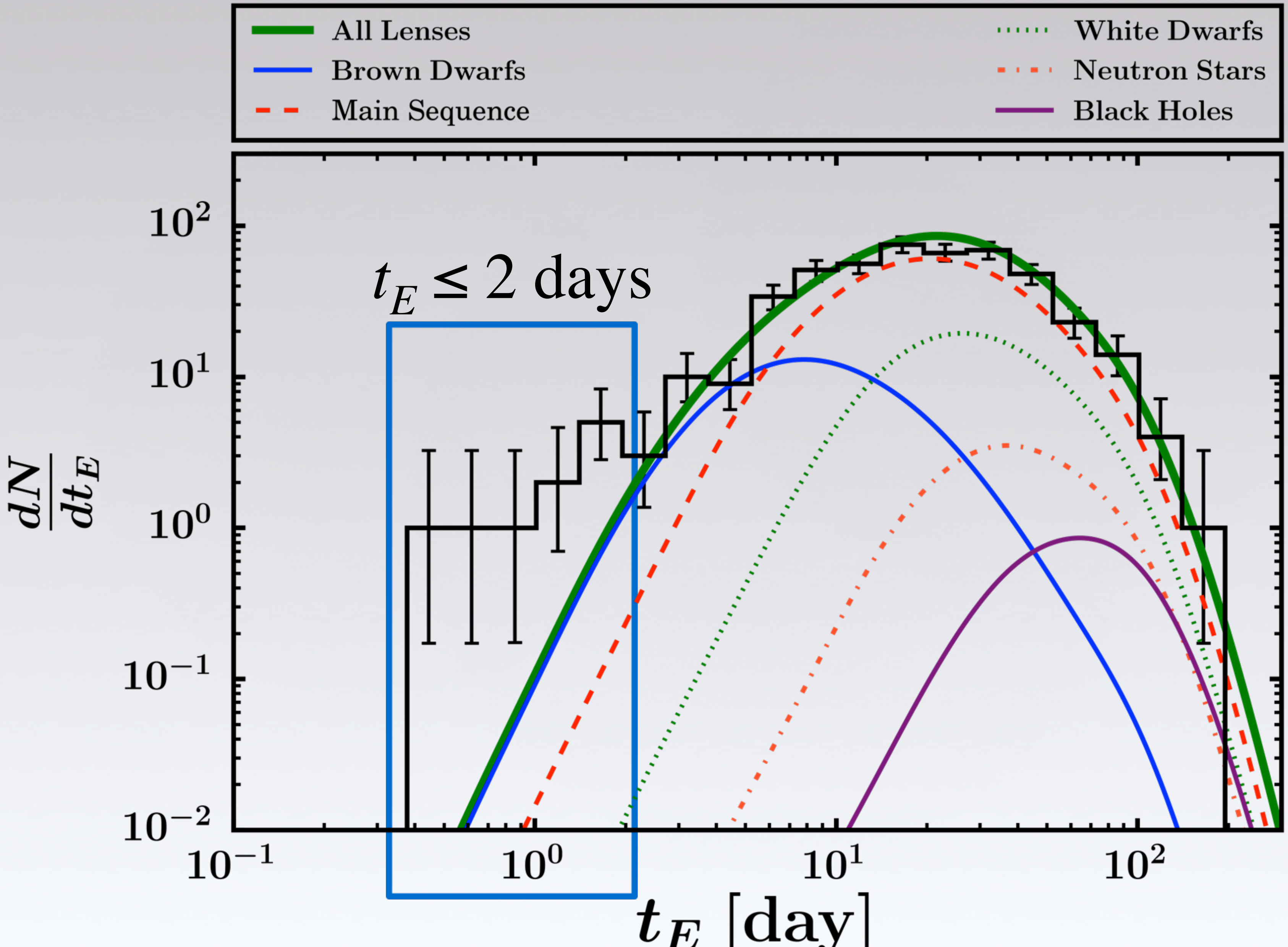


Data from Sumi+ (2011); Sumi+ (2013)

Explaining the Observed Timescale Distribution



Explaining the Observed Timescale Distribution



Free-Floating Planets?

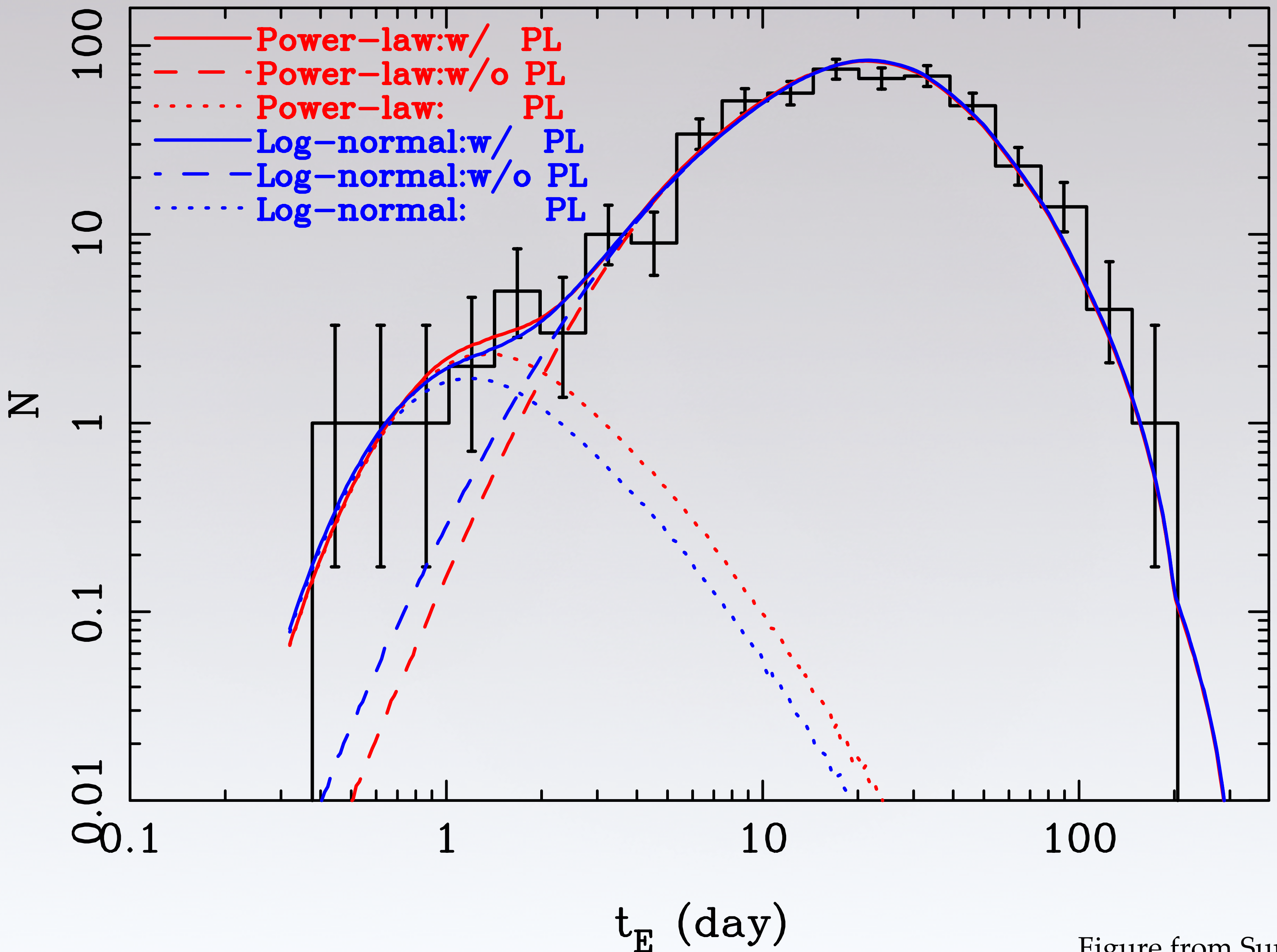
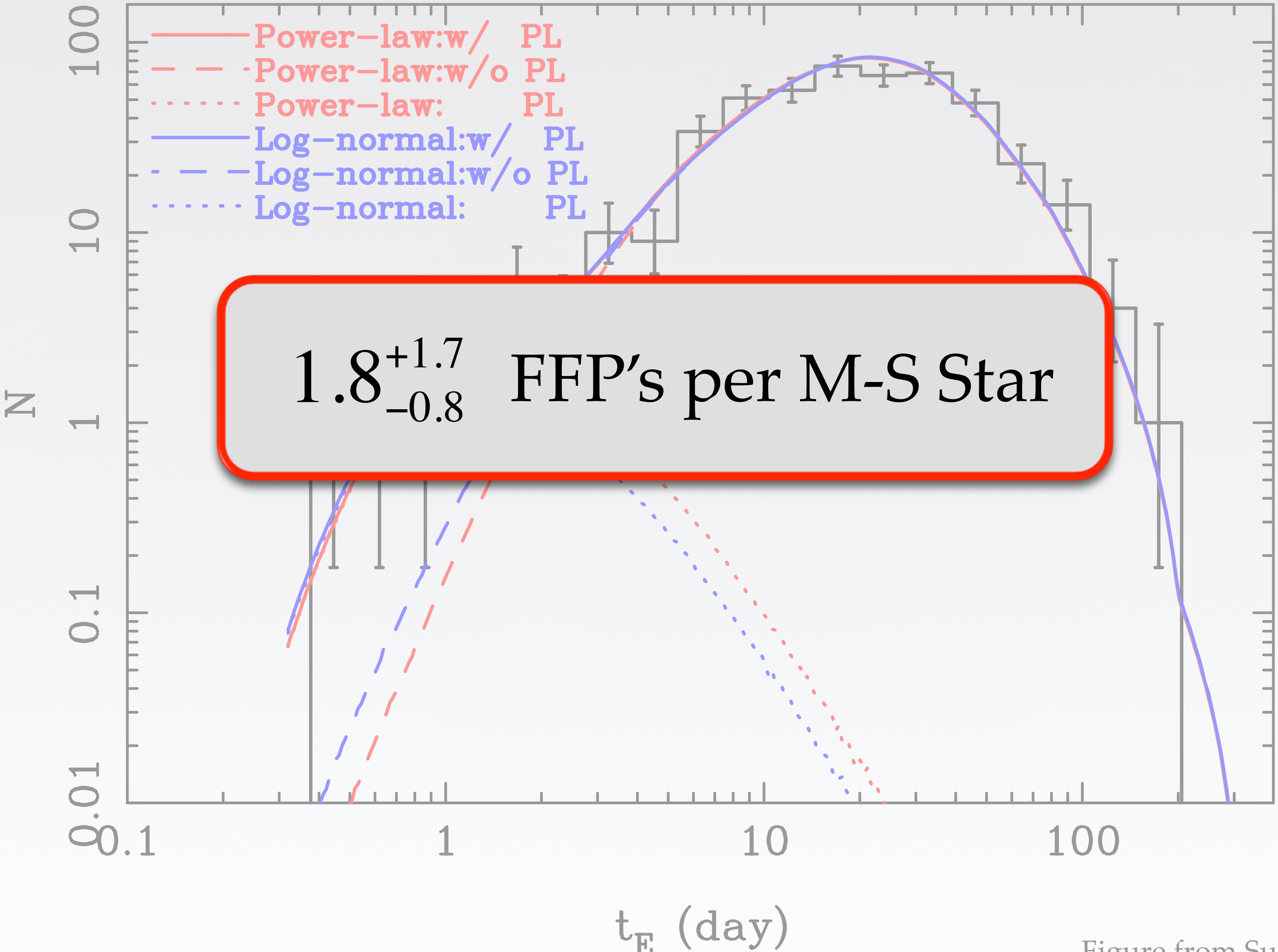


Figure from Sumi+ (2011)

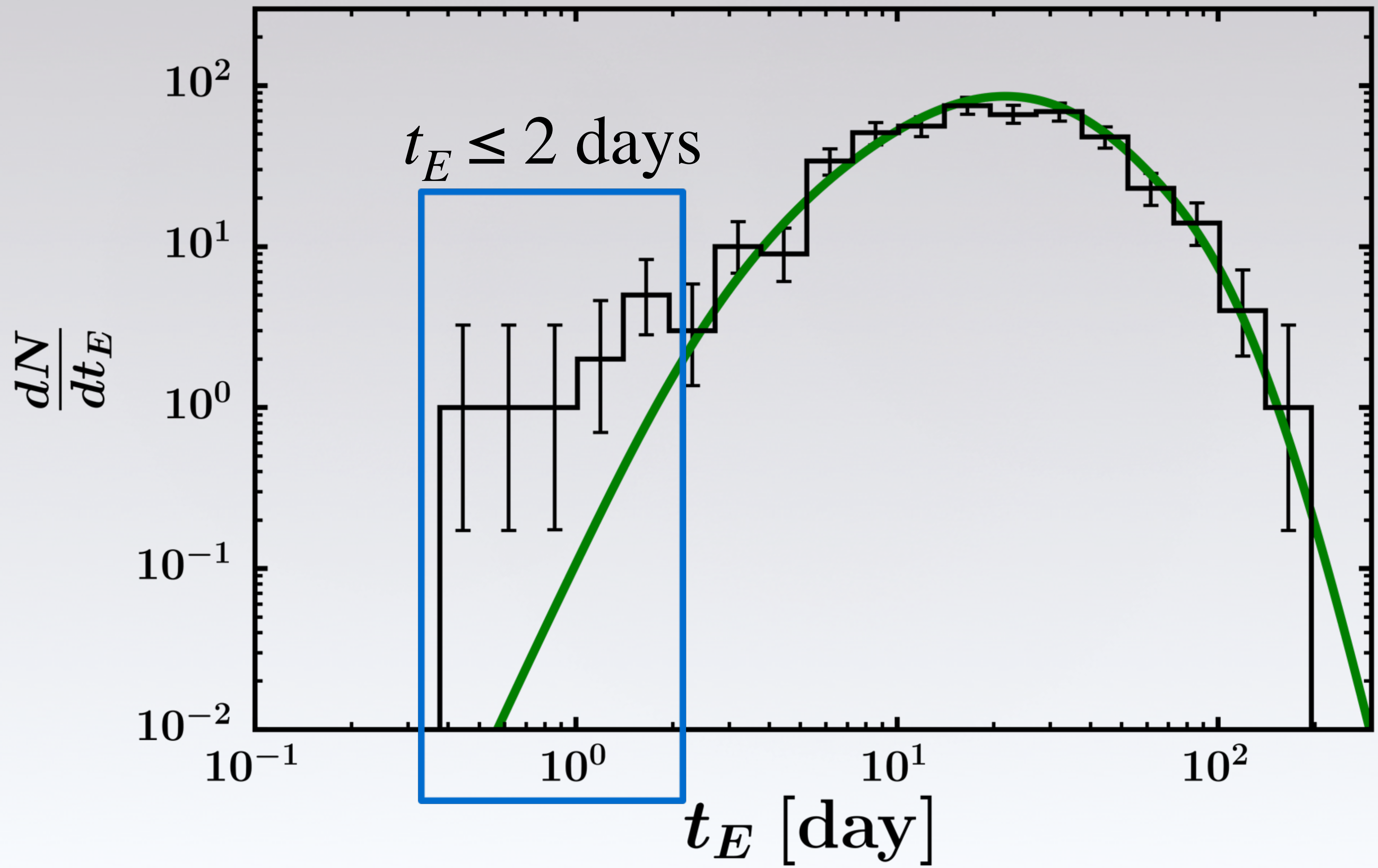
Free-Floating Planets?



$1.8^{+1.7}_{-0.8}$ FFP's per M-S Star

Figure from Sumi+ (2011)

Shortimescale Events Show No Evidence of a Primary



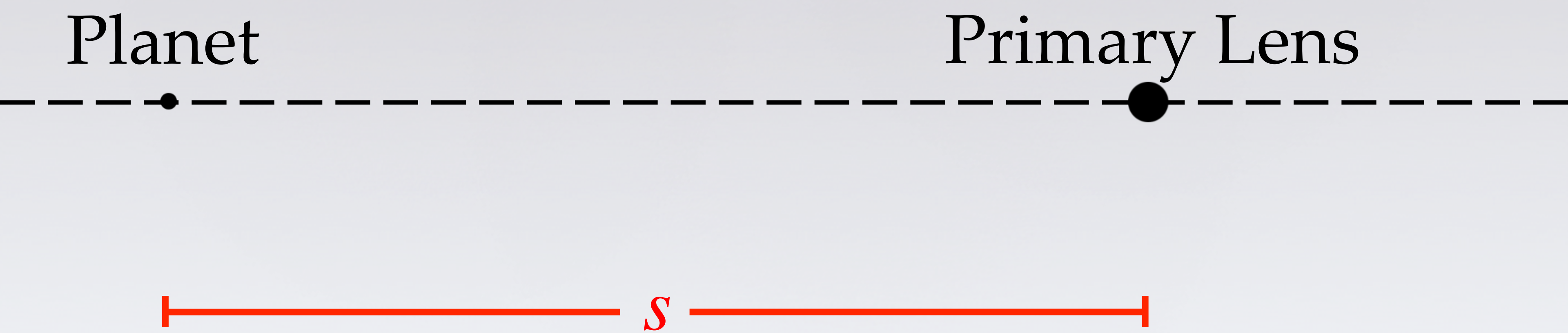
Distinguishing Wide-Separation from Free-Floating Planets

1. Low-Magnification Primary "Bump"
2. Planetary Caustic Events

Distinguishing Wide-Separation from Free-Floating Planets

Distinguishing Wide-Separation from Free-Floating Planets

$$s = r_{\perp}/R_E$$
$$q = m_p/M_L$$



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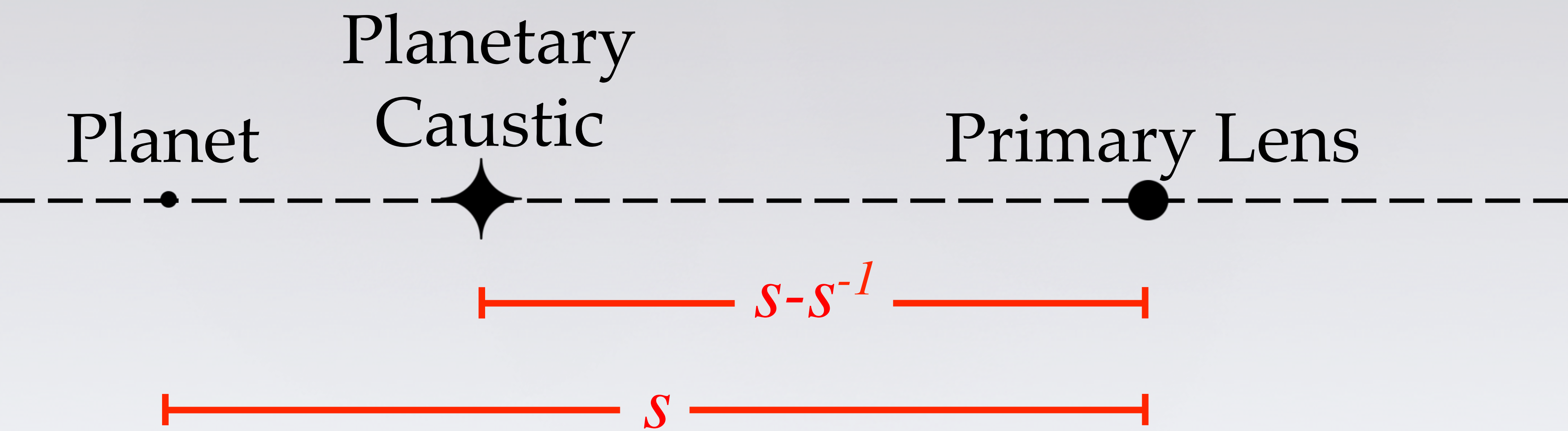
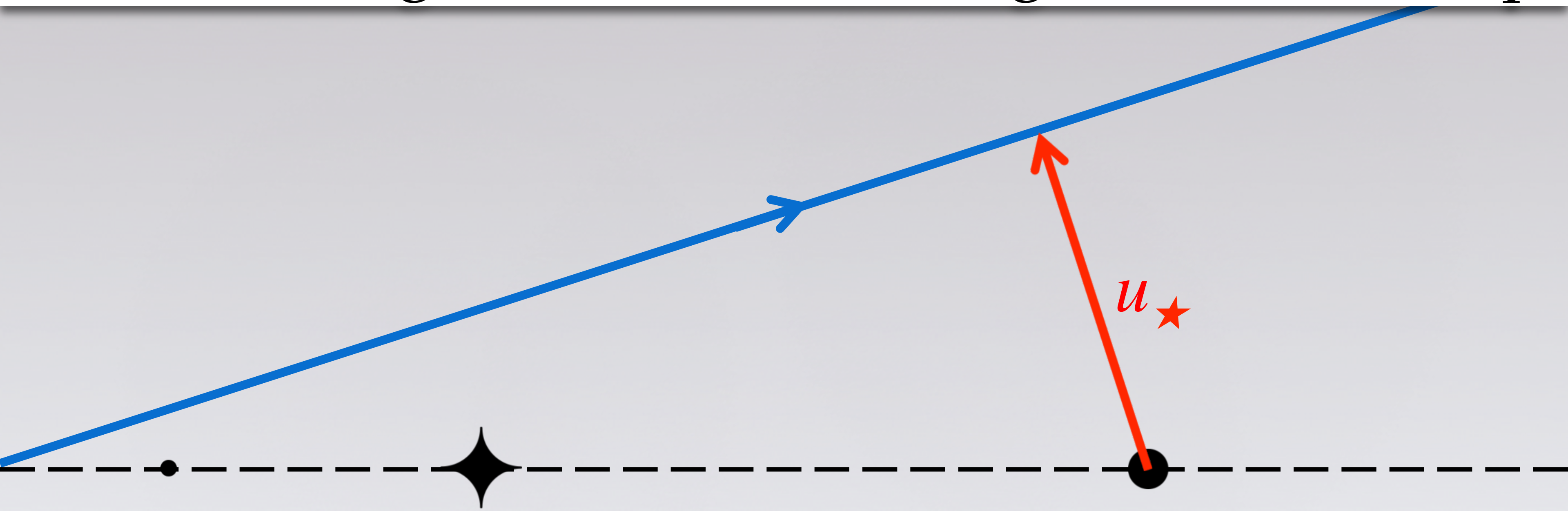
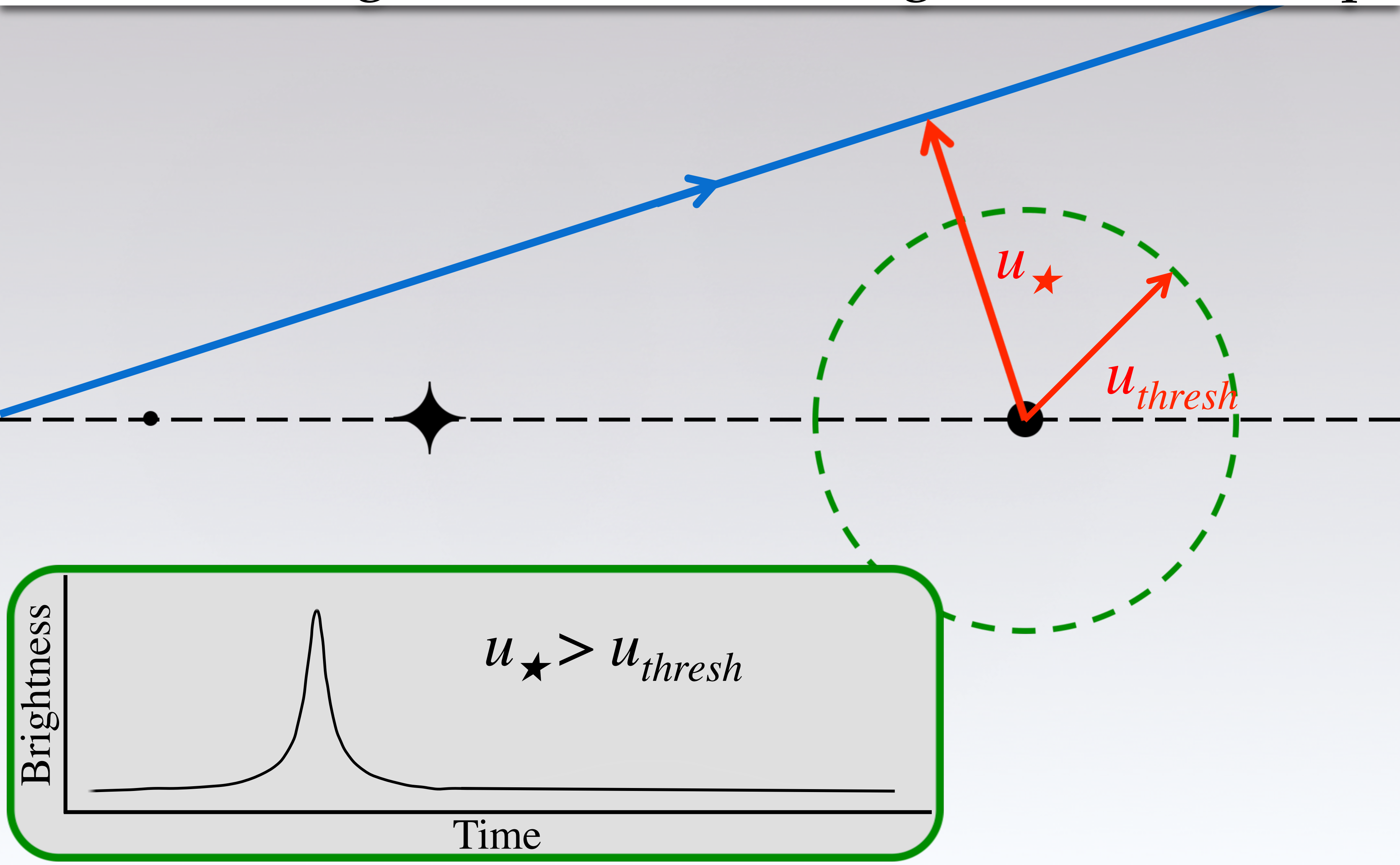


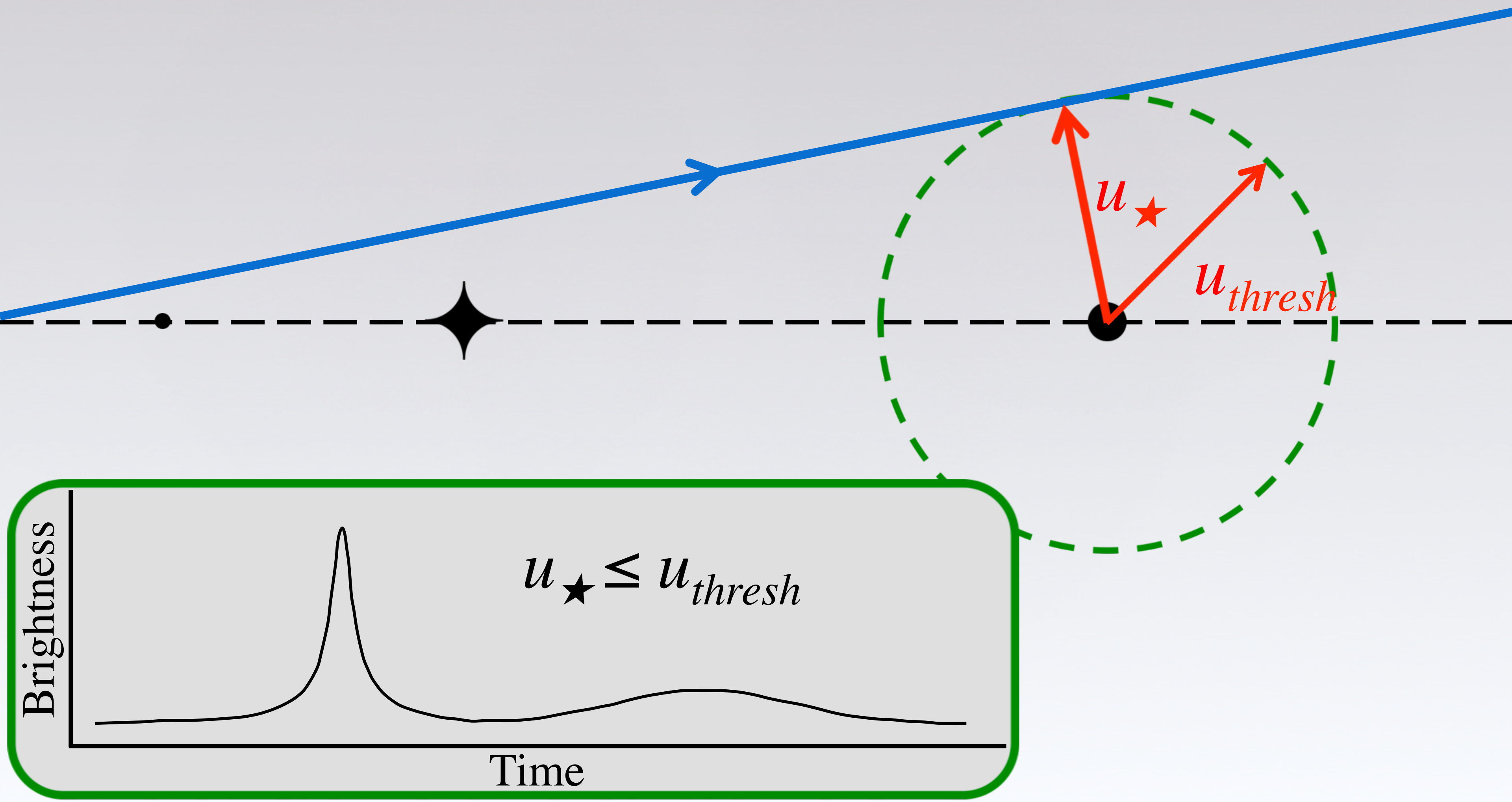
Distinguishing Wide-Separation from Free-Floating Planets – Low-Magnification Bump



Distinguishing Wide-Separation from Free-Floating Planets – Low-Magnification Bump



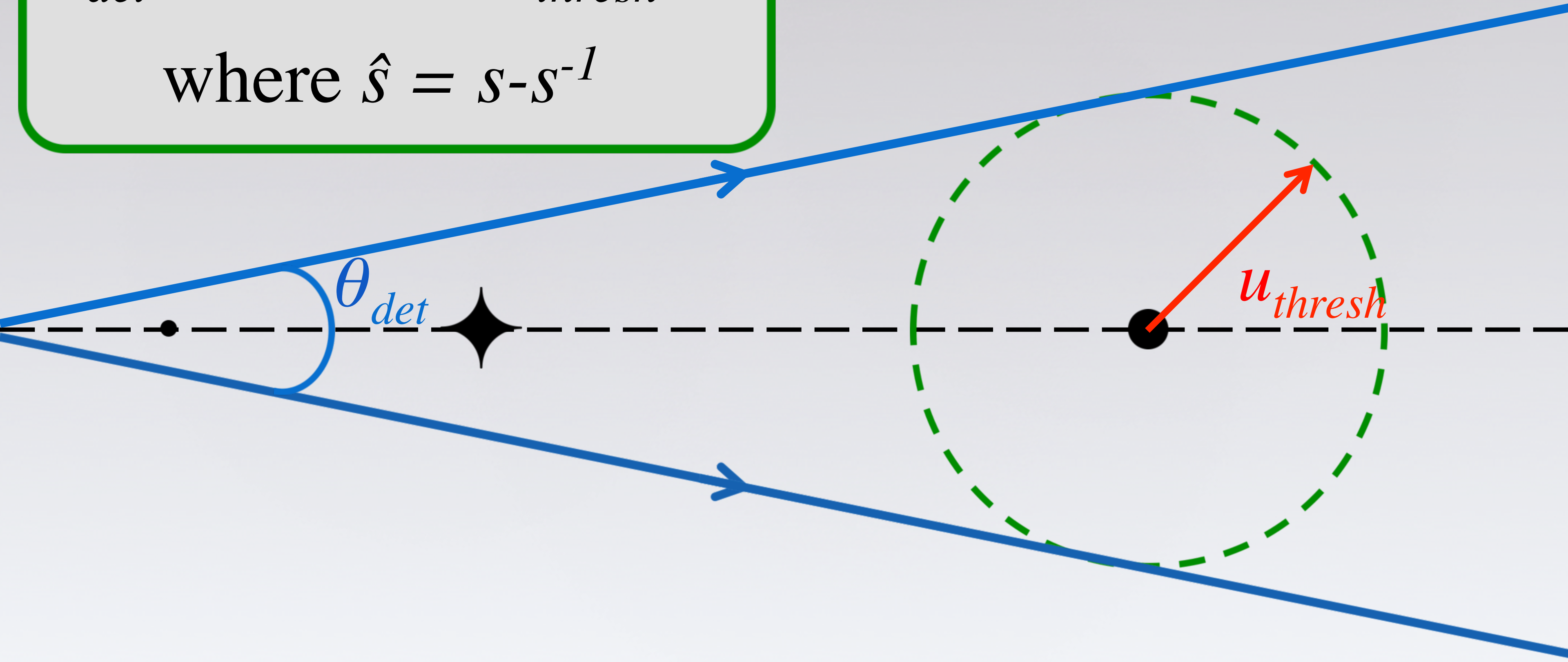
Distinguishing Wide-Separation from Free-Floating Planets – Low-Magnification Bump



Distinguishing Wide-Separation from Free-Floating Planets – Low-Magnification Bump

$$\theta_{det}(s) = 2\sin^{-1}(u_{thresh}/\hat{s}),$$

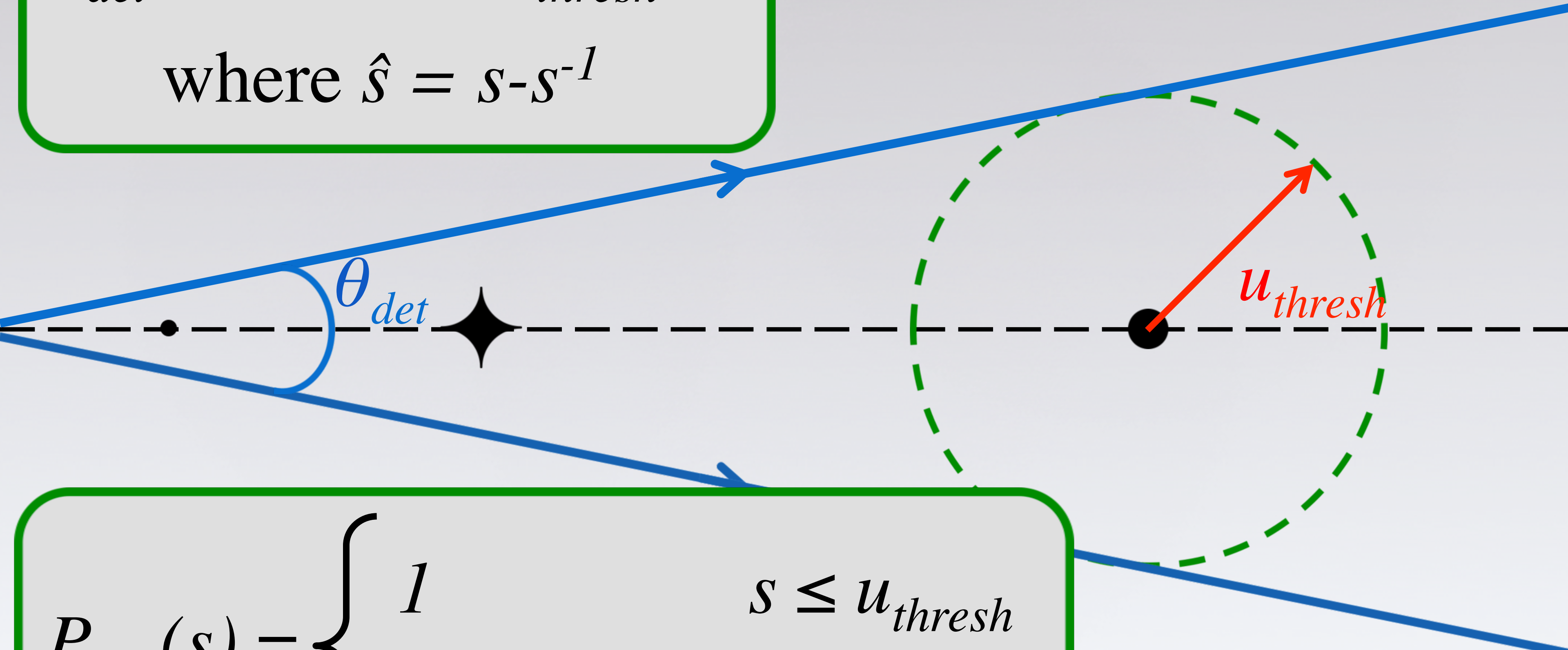
$$\text{where } \hat{s} = s - s^{-1}$$



Distinguishing Wide-Separation from Free-Floating Planets – Low-Magnification Bump

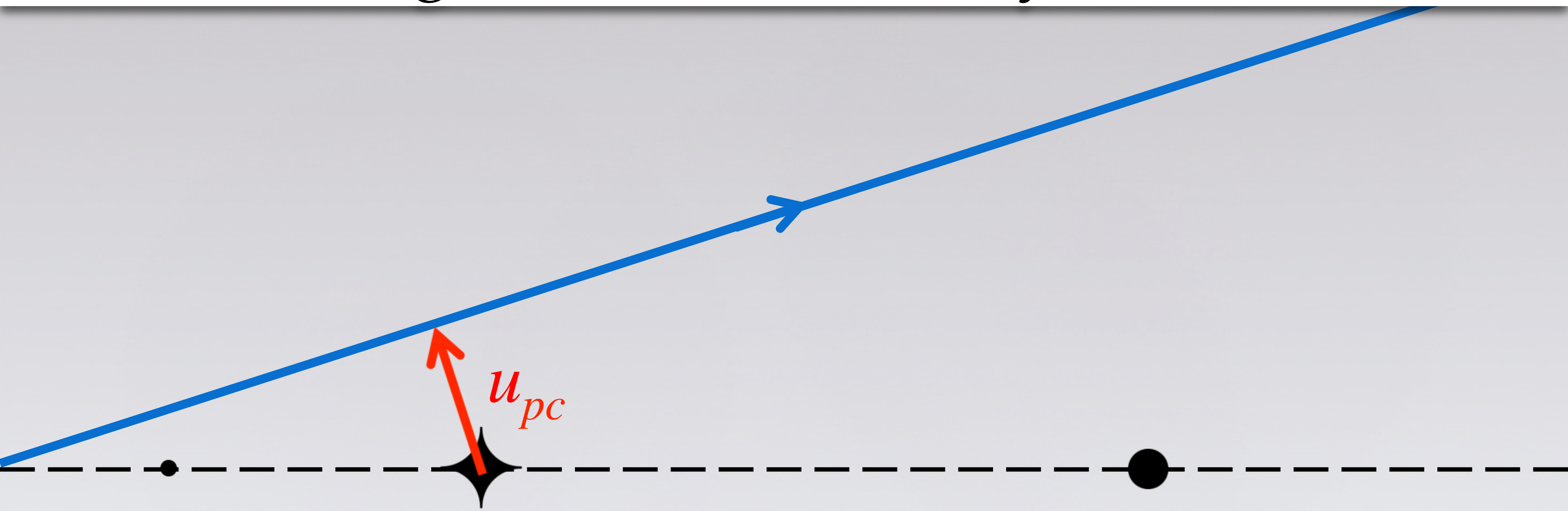
$$\theta_{det}(s) = 2\sin^{-1}(u_{thresh}/\hat{s}),$$

where $\hat{s} = s\text{-}s^{-1}$

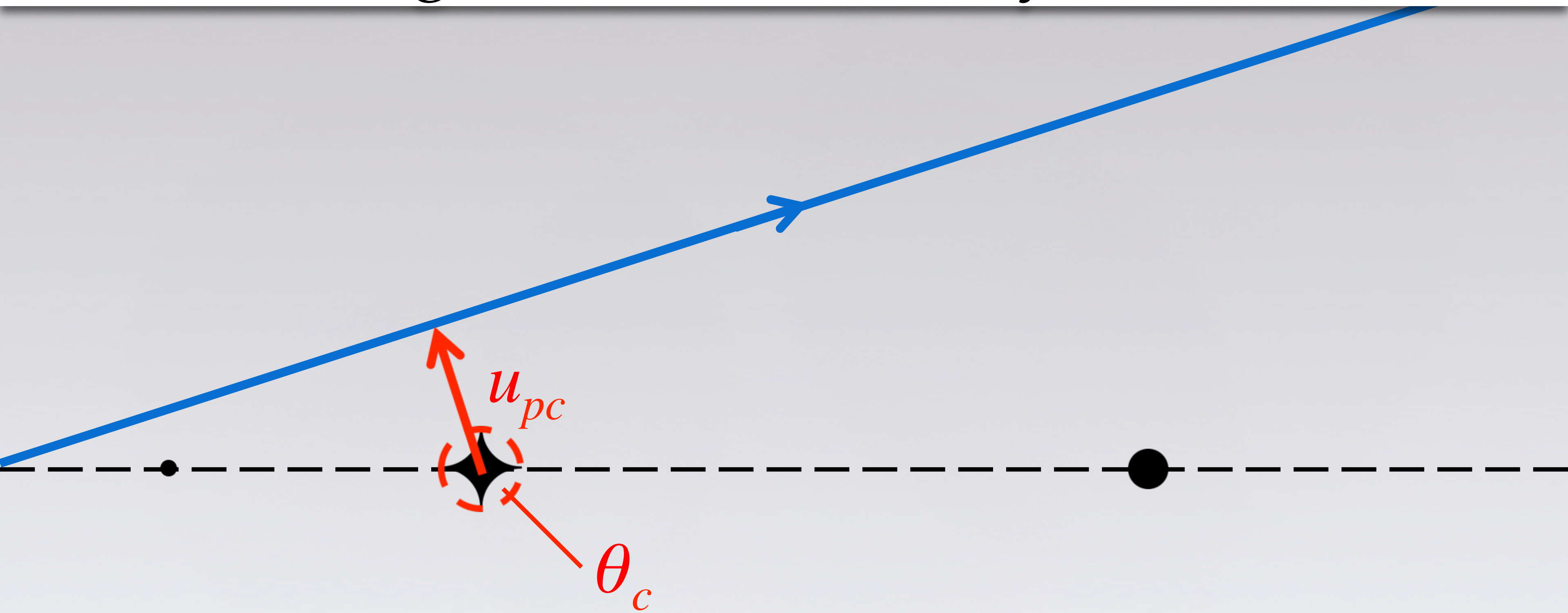


$$P_{LM}(s) = \begin{cases} 1 & s \leq u_{thresh} \\ \theta_{det}(s)/\pi & s > u_{thresh} \end{cases}$$

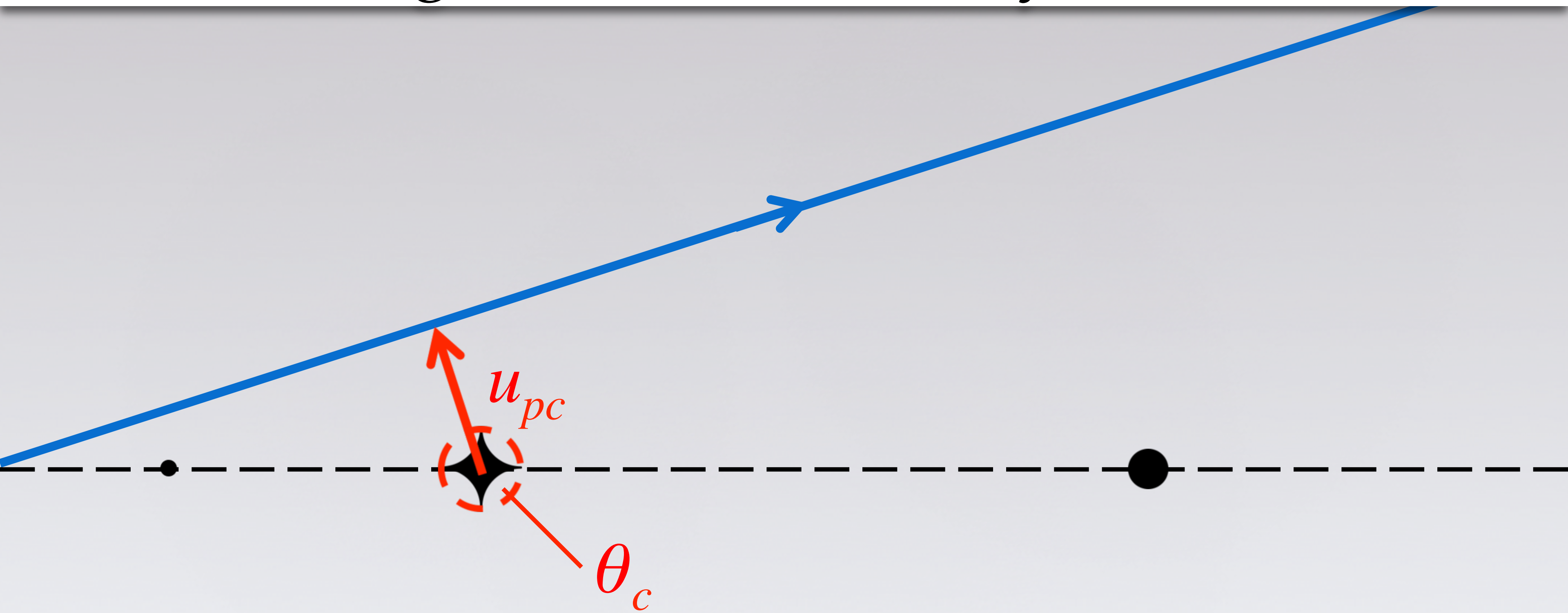
Distinguishing Wide-Separation from Free-Floating Planets – Planetary Caustic Events



Distinguishing Wide-Separation from Free-Floating Planets – Planetary Caustic Events



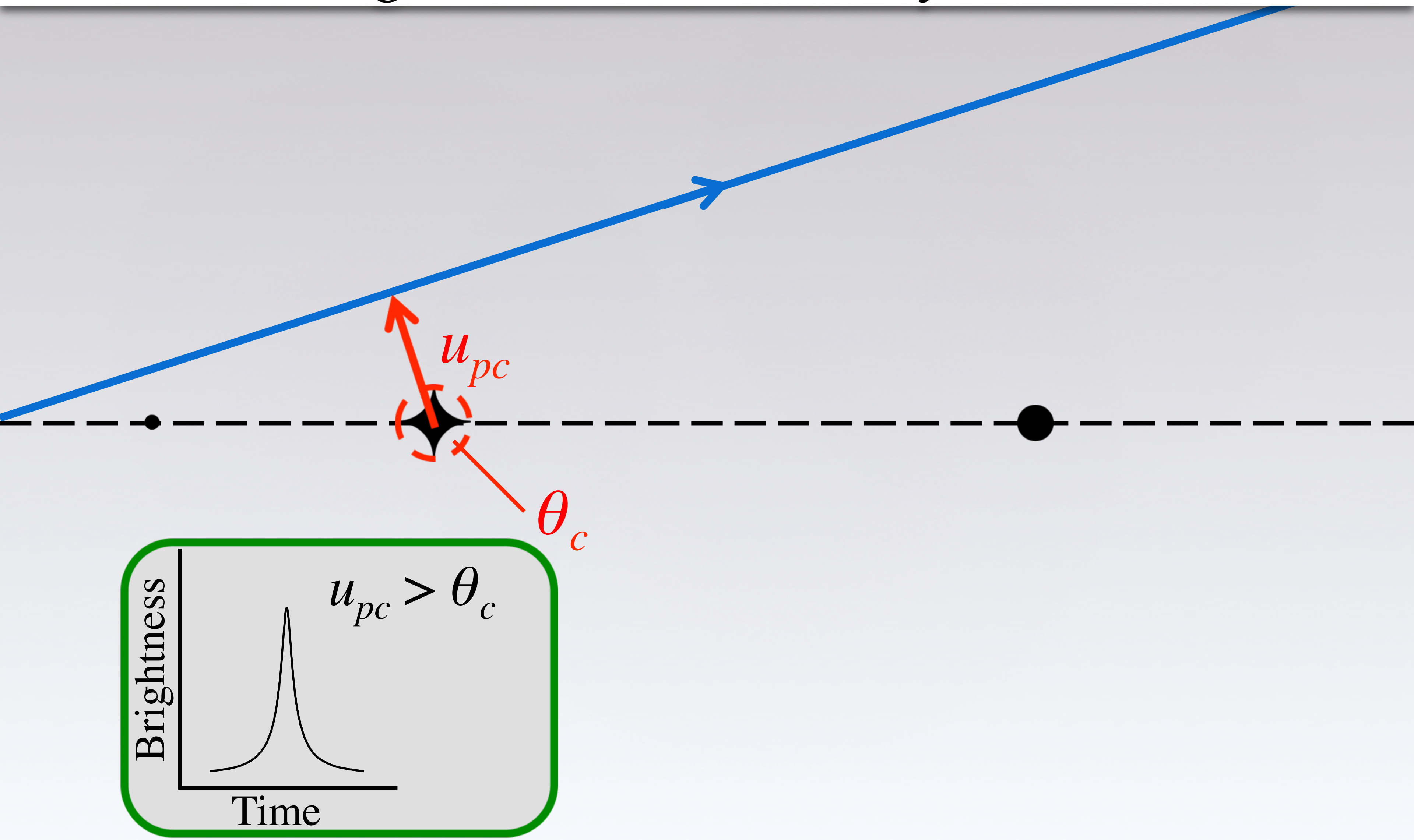
Distinguishing Wide-Separation from Free-Floating Planets – Planetary Caustic Events



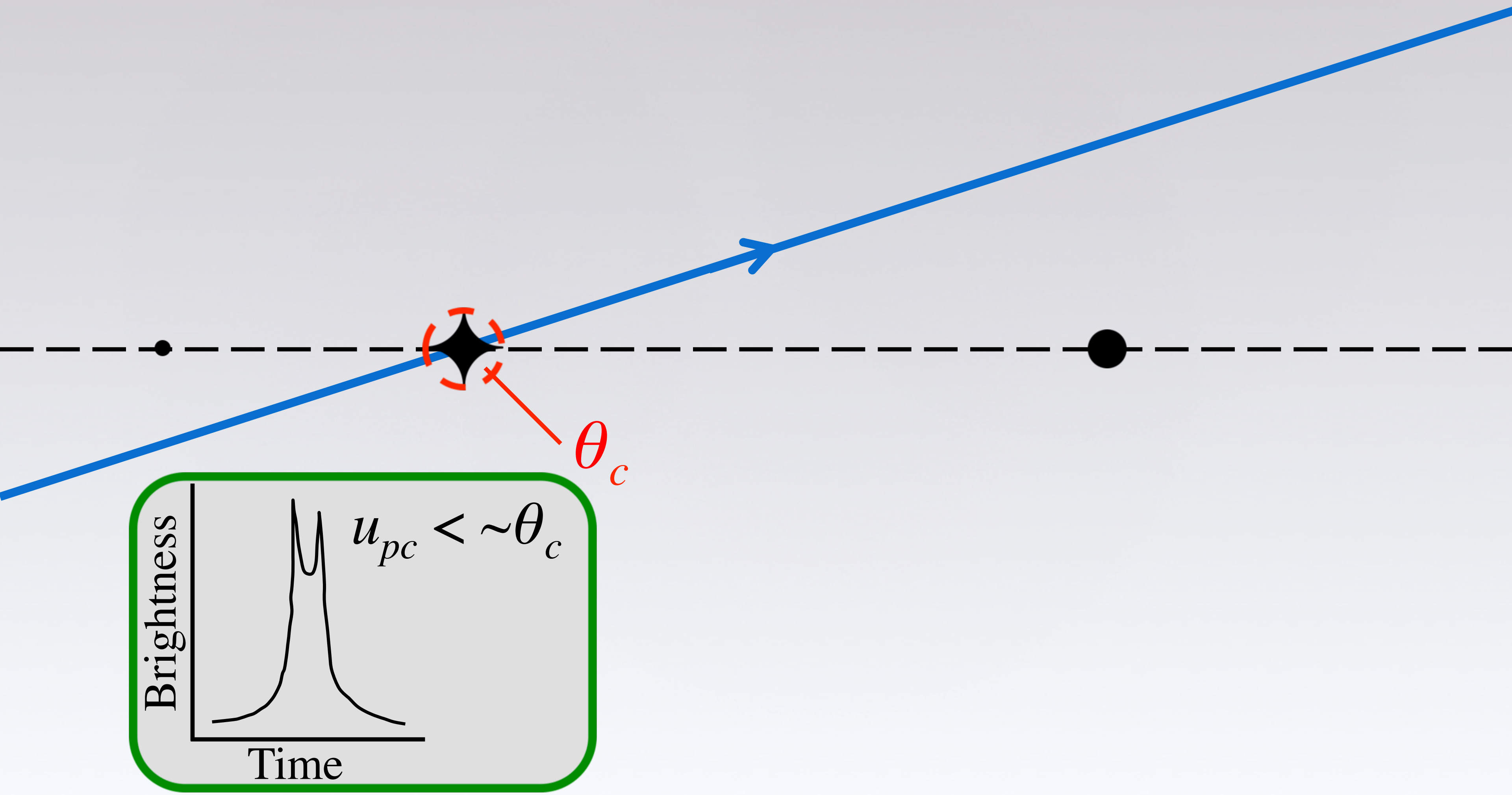
$$\theta_c(q,s) = 2q^{1/2} / s\sqrt{s^2+1}$$

Han (2006)

Distinguishing Wide-Separation from Free-Floating Planets – Planetary Caustic Events

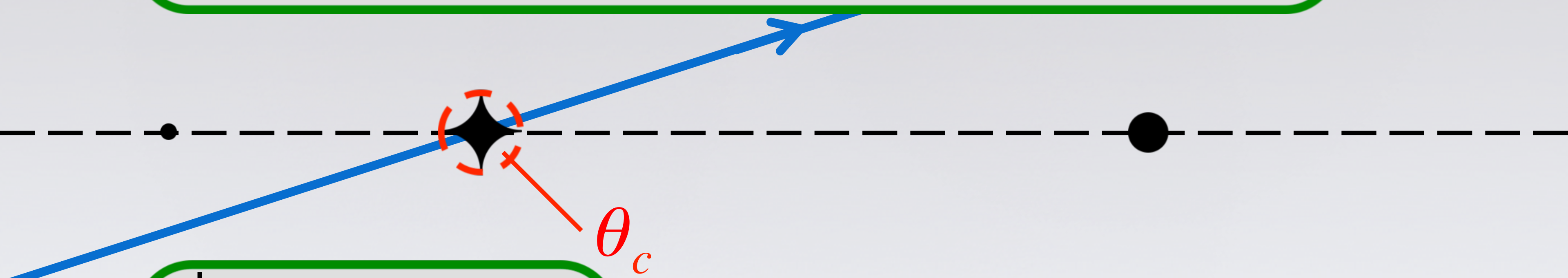


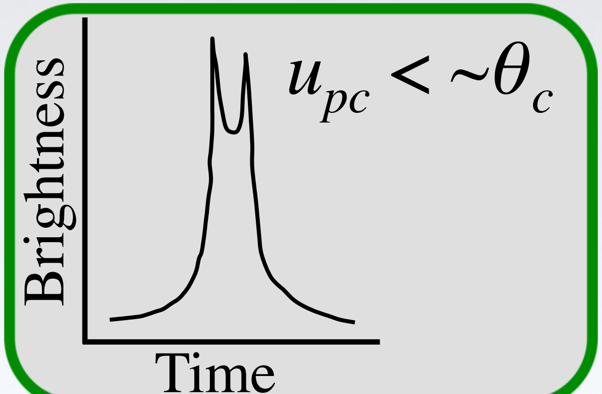
Distinguishing Wide-Separation from Free-Floating Planets – Planetary Caustic Events



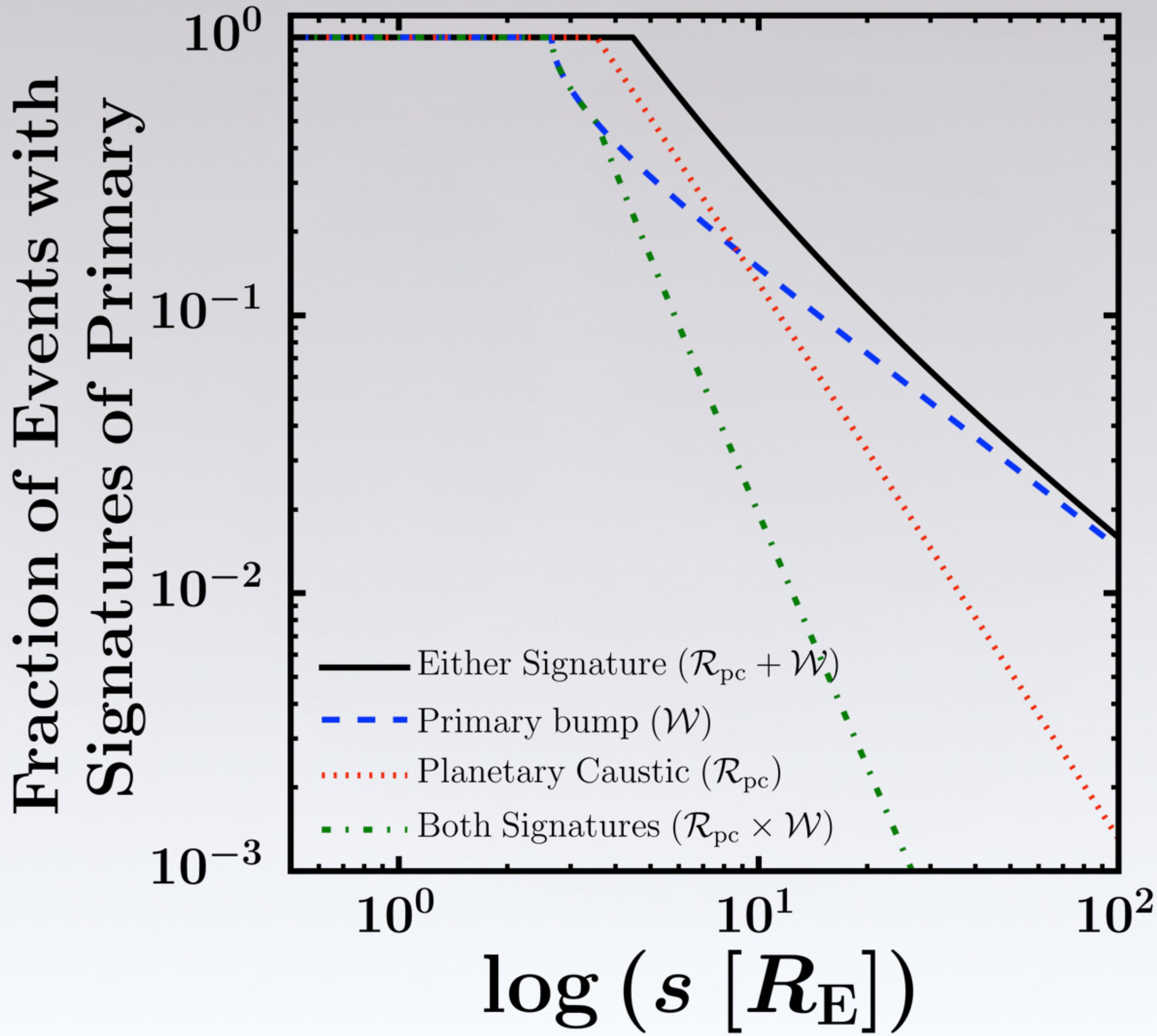
Distinguishing Wide-Separation from Free-Floating Planets – Planetary Caustic Events

$$R_{pc}(q,s) = \begin{cases} 1 & s \le s_c \\ \theta_c(q,s)/const. & s > s_c \end{cases}$$

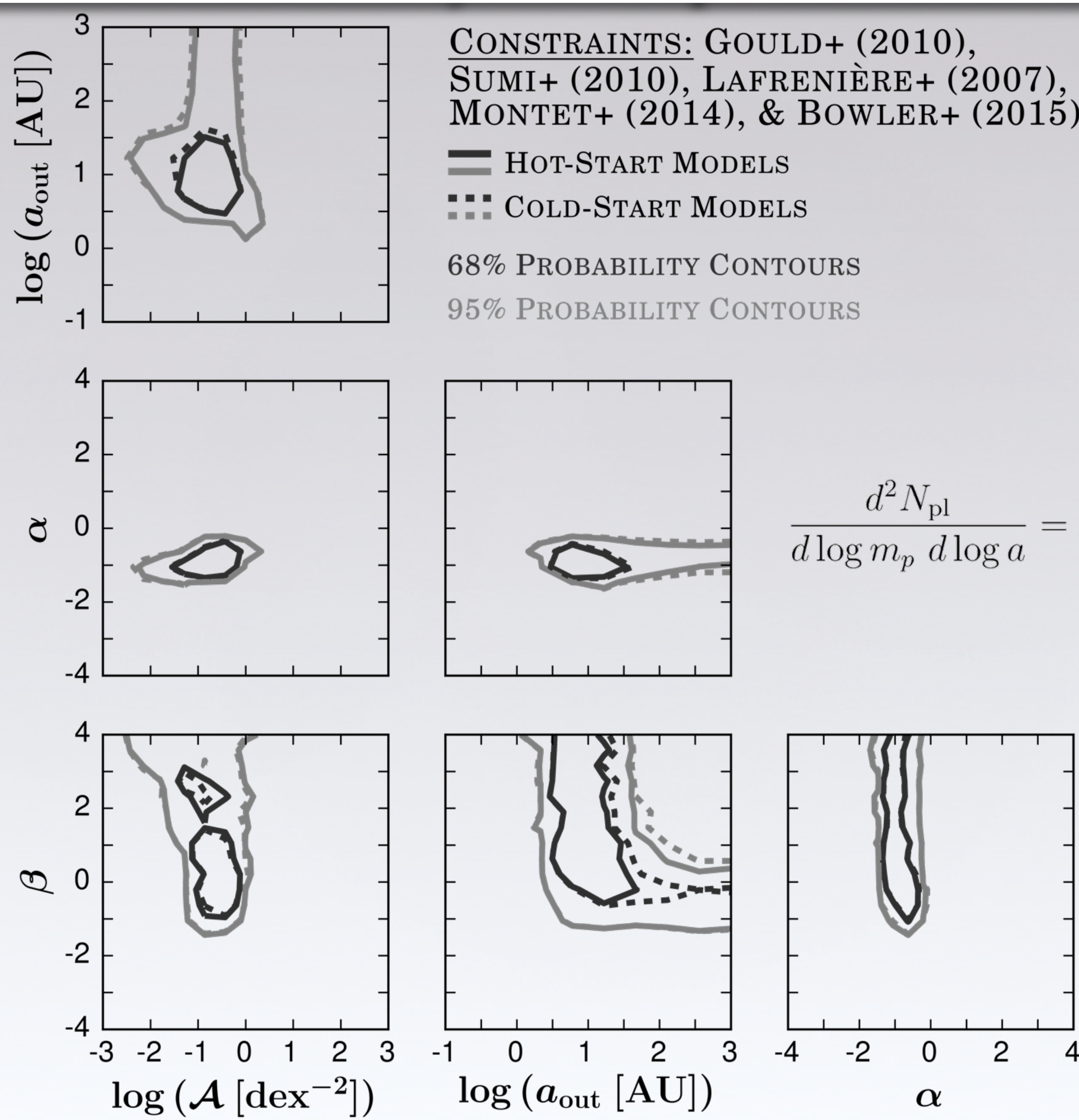




Distinguishing Wide-Separation from Free-Floating Planets

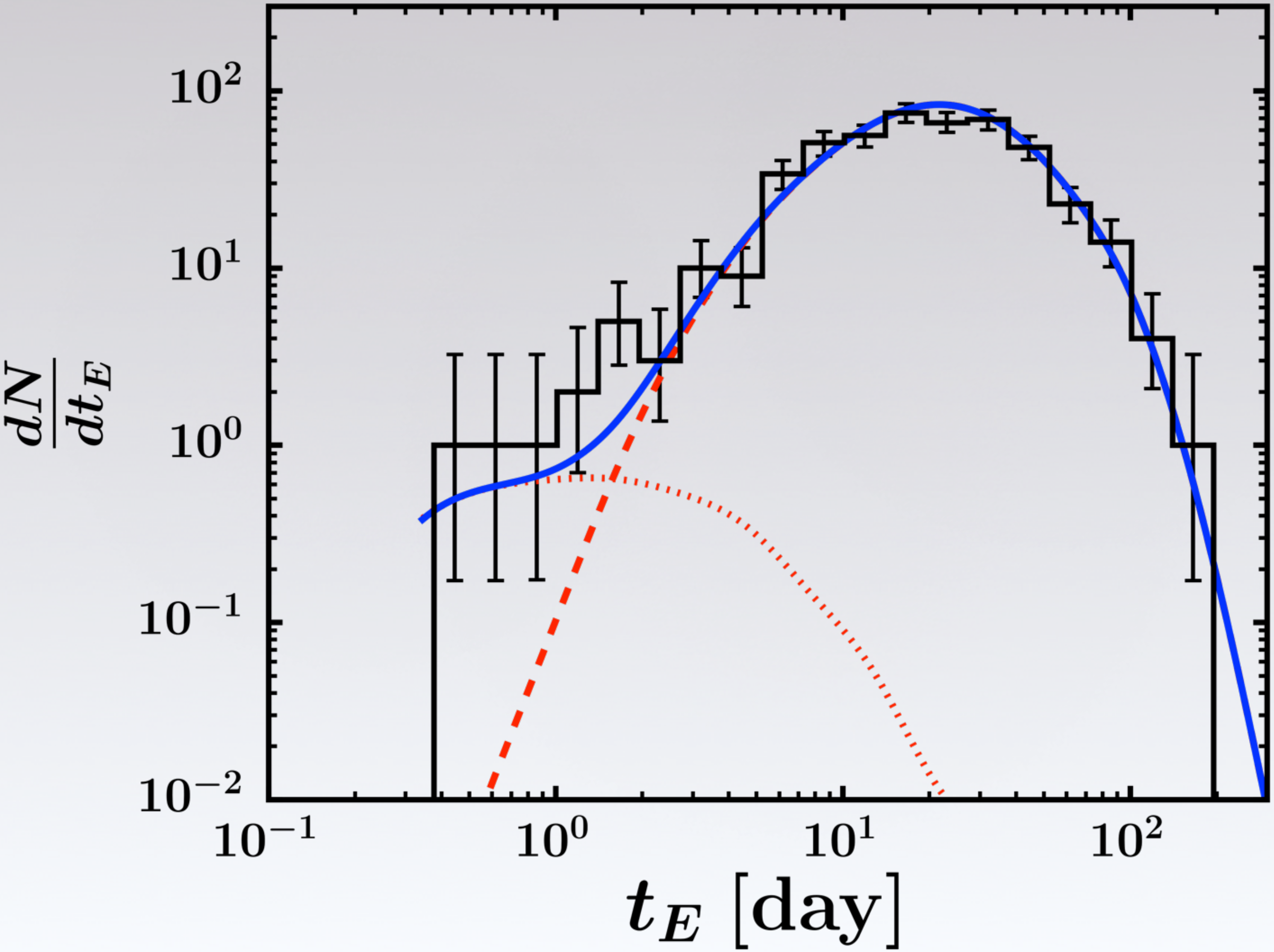


Constructing the Timescale Distribution of Bound Planetary Companions

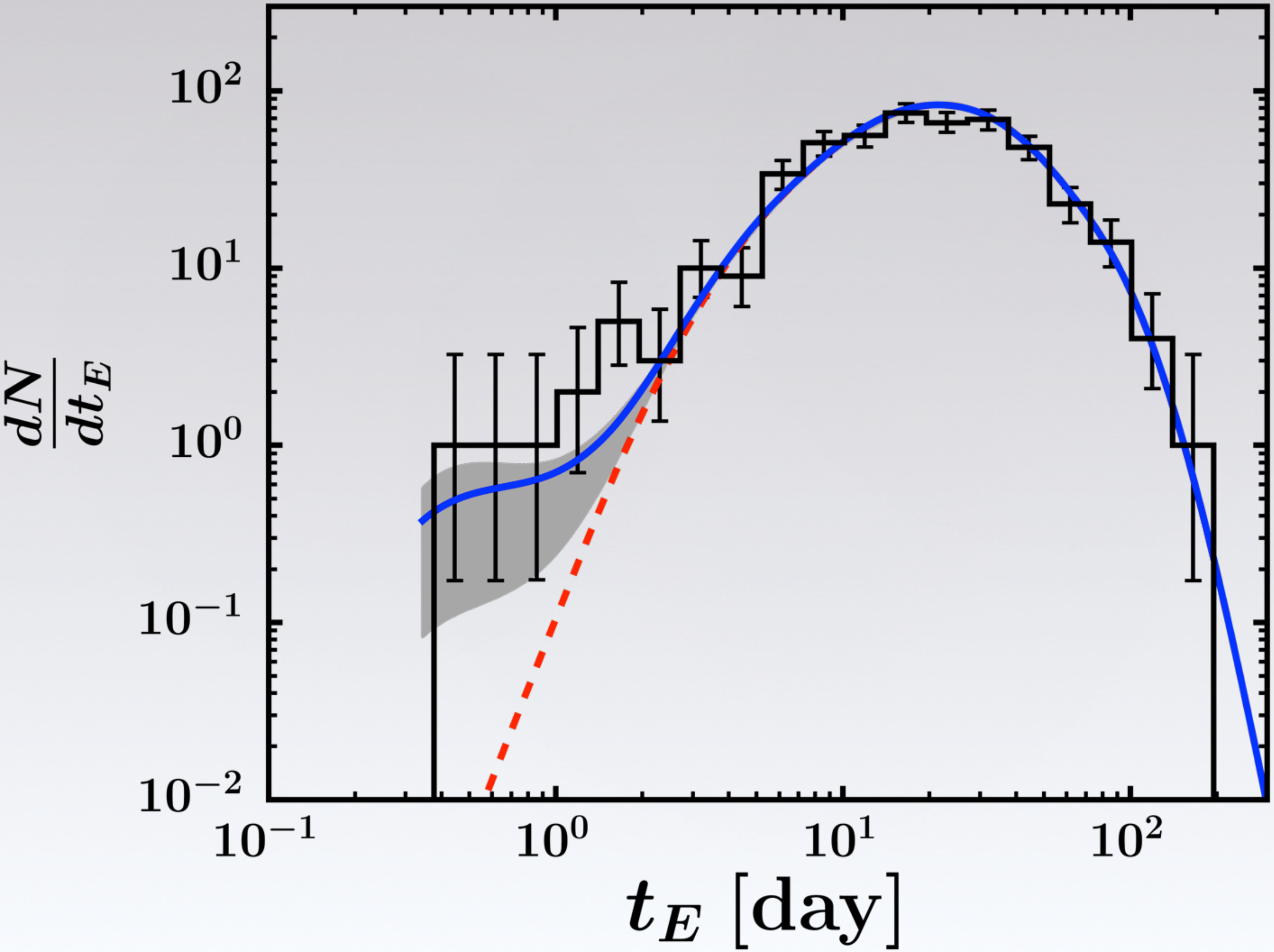


$$\frac{d^2 N_{\rm pl}}{d\log m_p \, d\log a} = \mathcal{A}\left(\frac{m_p}{M_{\rm Sat}}\right)^{\alpha}\left(\frac{a}{2.5\ \rm AU}\right)^{\beta}$$

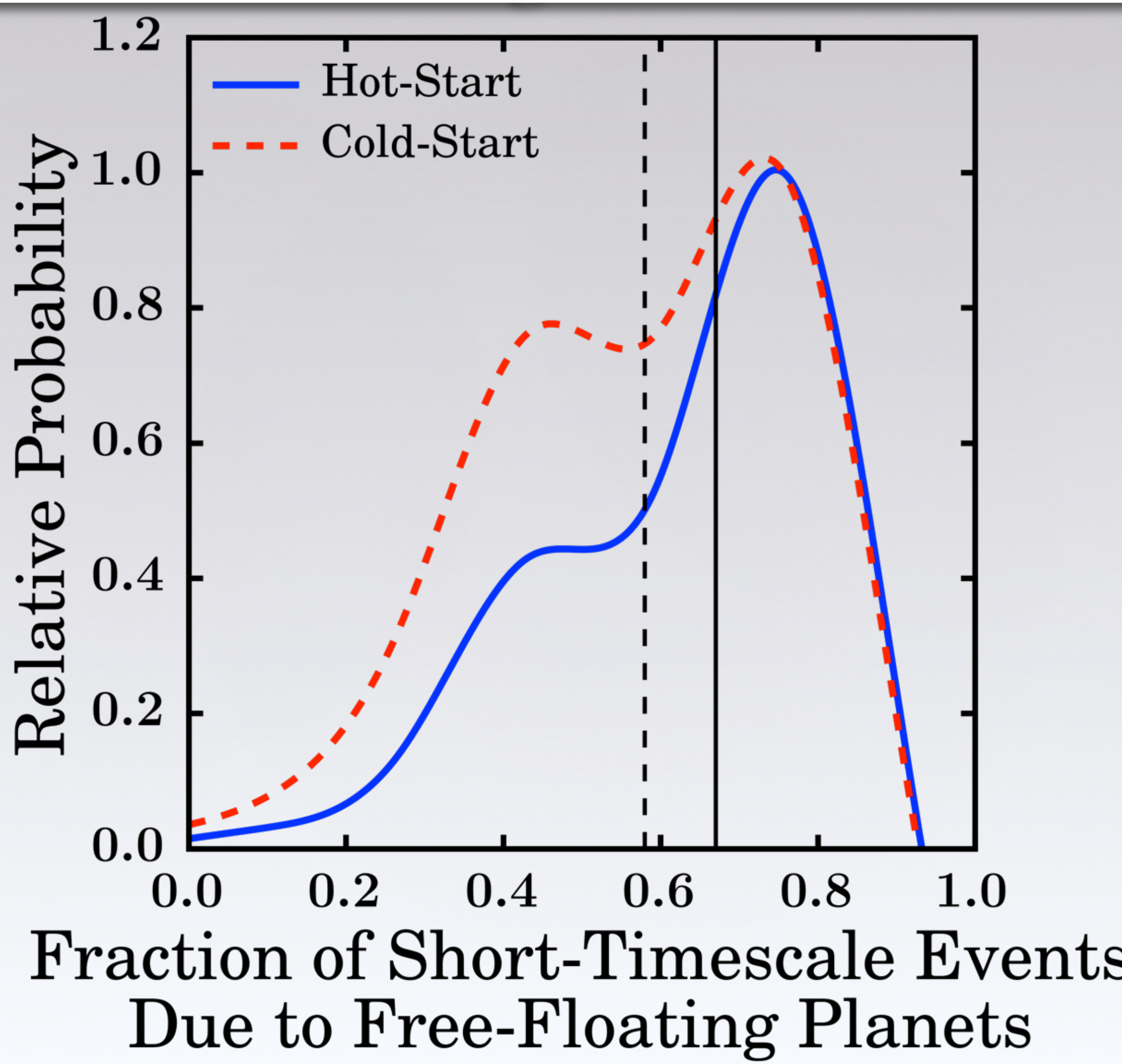
Maximum Likelihood Estimation: Bound Planets + LMF Fit to Observed Timescale Distribution



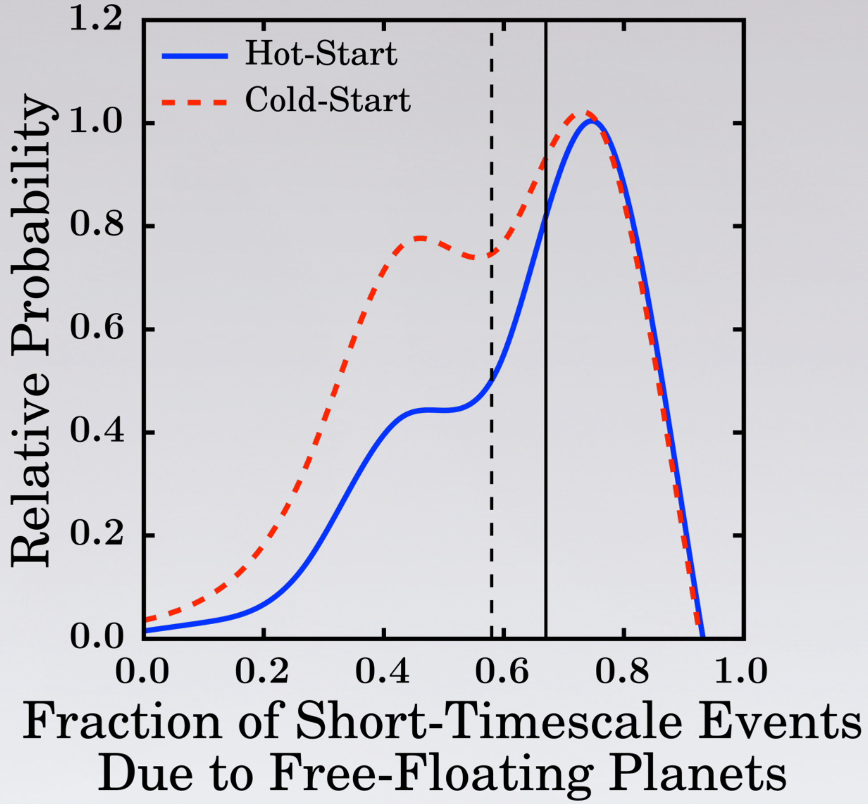
Maximum Likelihood Estimation: Bound Planets + LMF Fit to Observed Timescale Distribution



Constraints on the Galactic Population of Free-Floating Planets

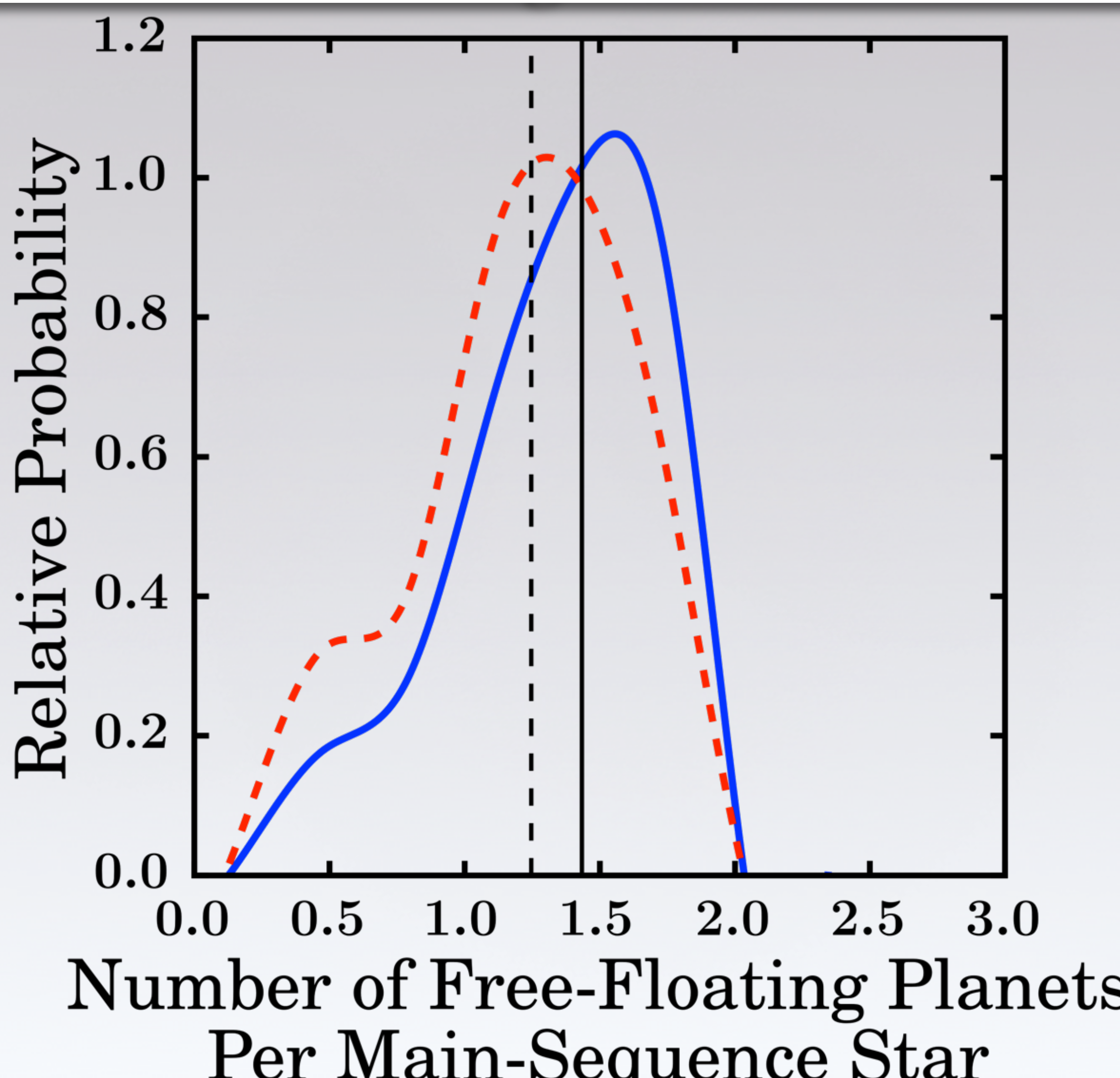


Constraints on the Galactic Population of Free-Floating Planets

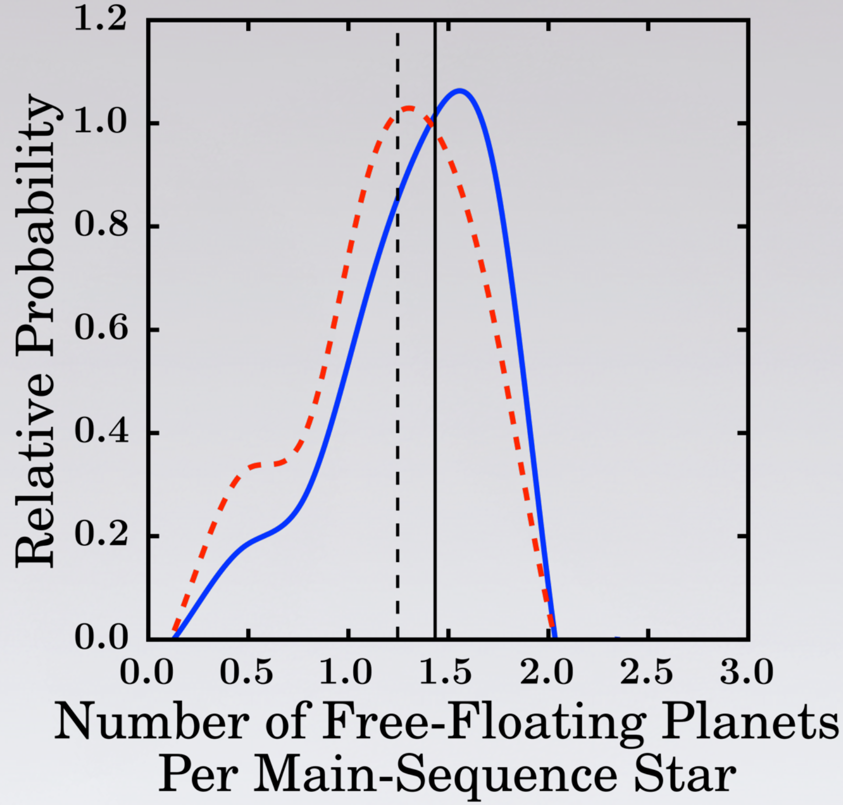


	Median	68% Credibility	95% Credibility
Hot—Start	0.67	0.44—0.78	0.23—0.85
Cold—Start	0.58	0.40—0.74	0.14—0.83

Constraints on the Galactic Population of Free-Floating Planets



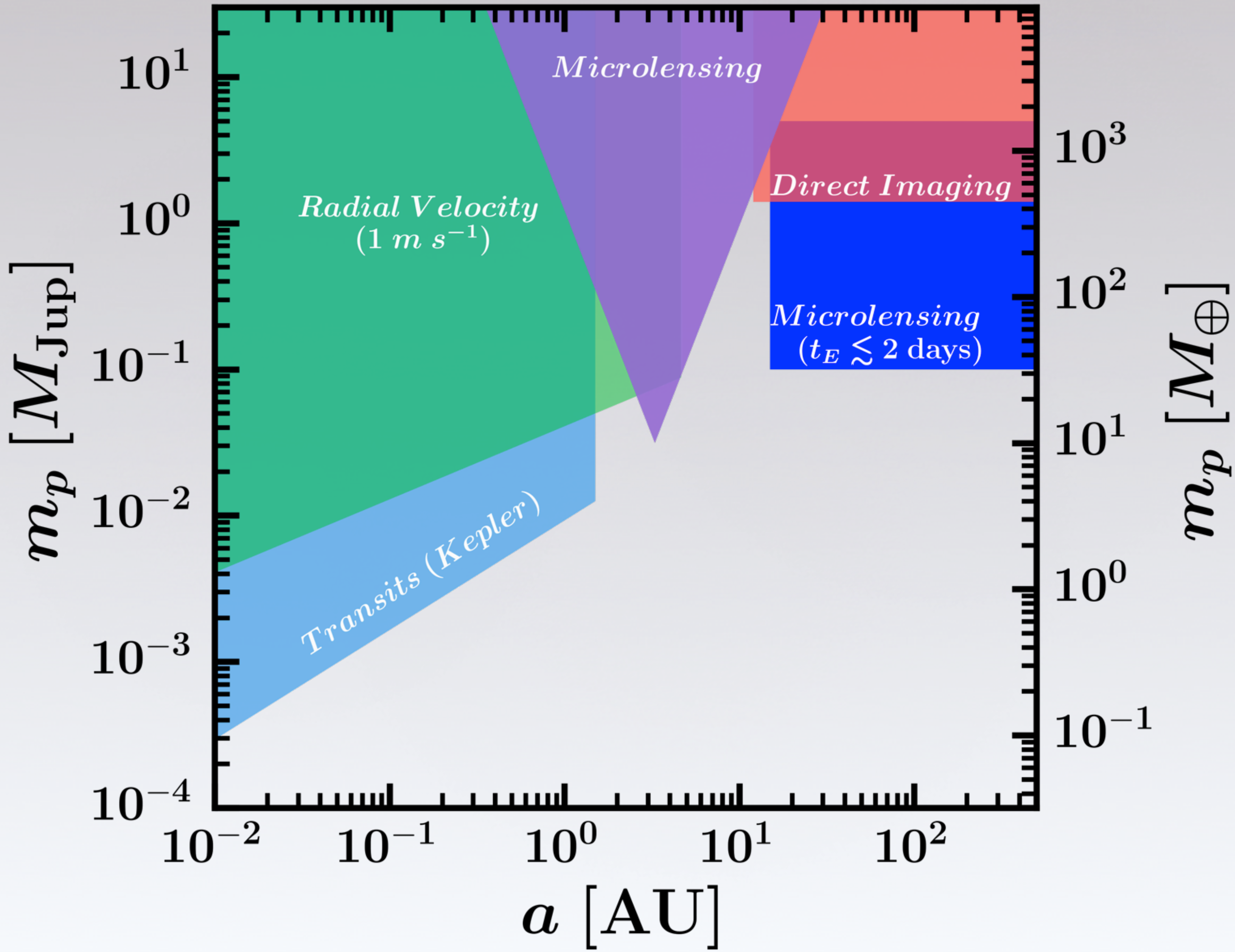
Constraints on the Galactic Population of Free-Floating Planets



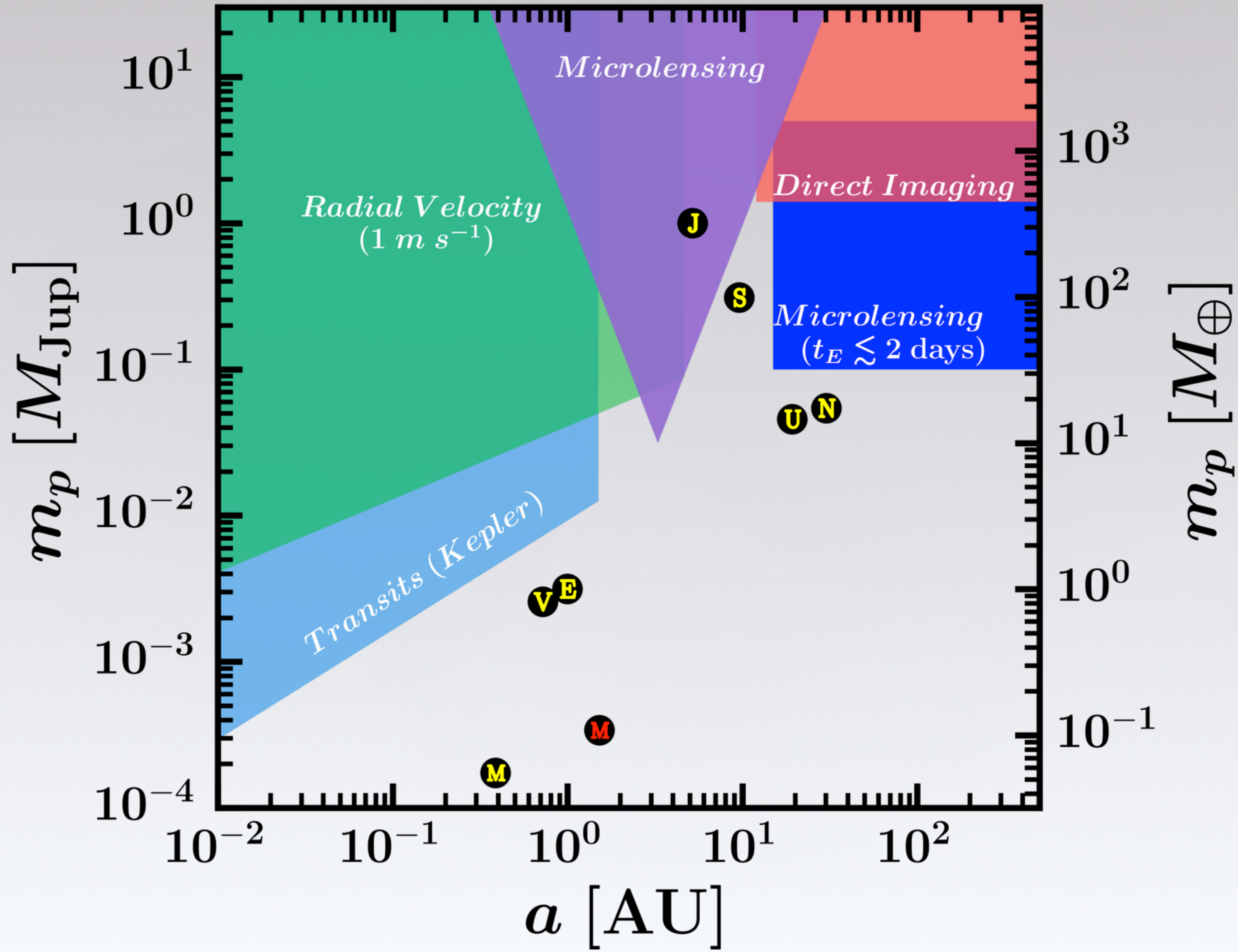
	Median	68% Credibility	95% Credibility
Hot—Start	1.4	0.95—1.7	0.48—1.8
Cold—Start	1.2	0.87—1.6	0.29—1.8

Part IV.
Future Prospects

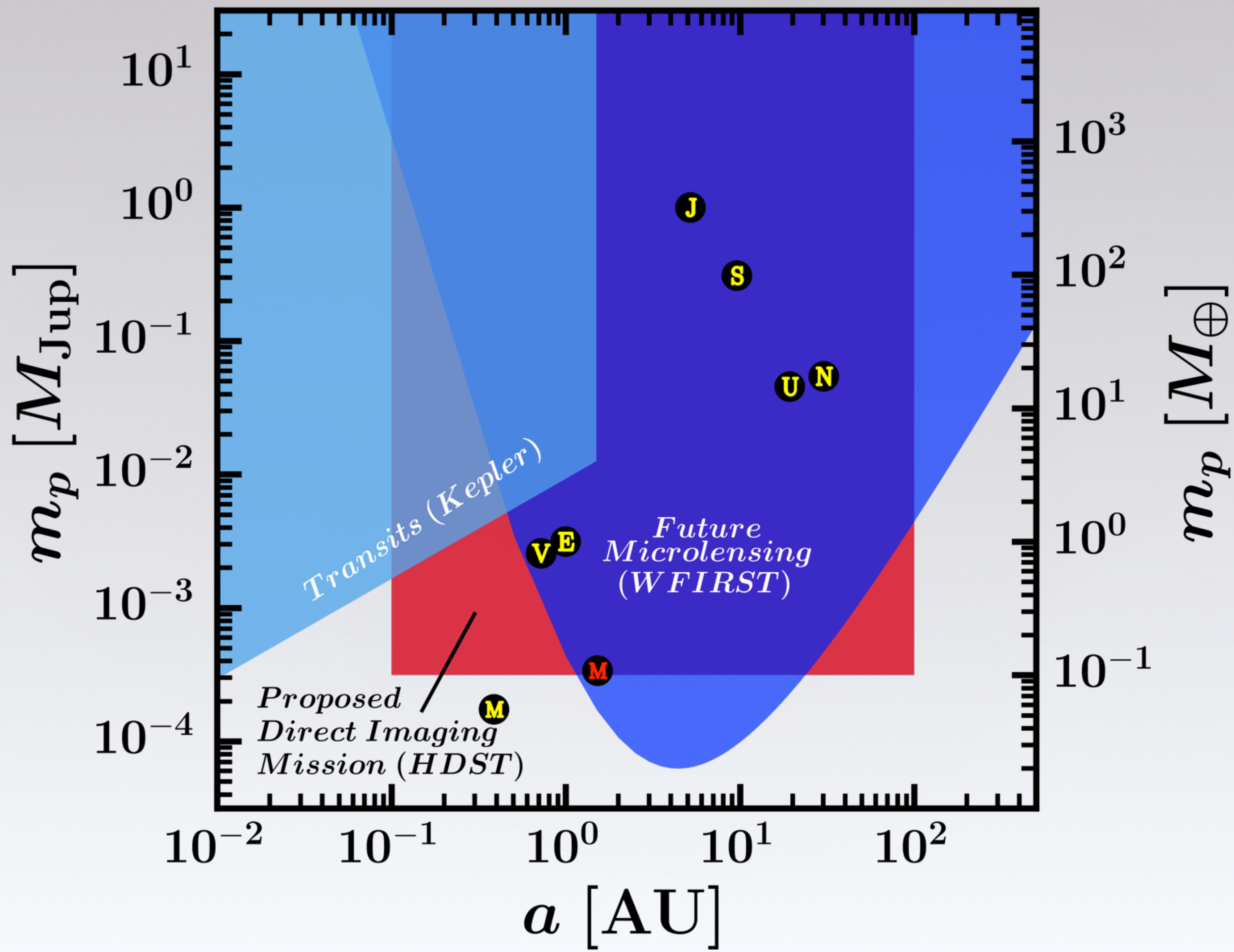
Synthesis of “The Big Four”



Synthesis of "The Big Four"



Kepler + WFIRST (+ HDST)



References

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

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. in prep.

End

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