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

{ A Single Planet Population
Consistent with All Observations

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Sagan Exoplanet Summer Workshop
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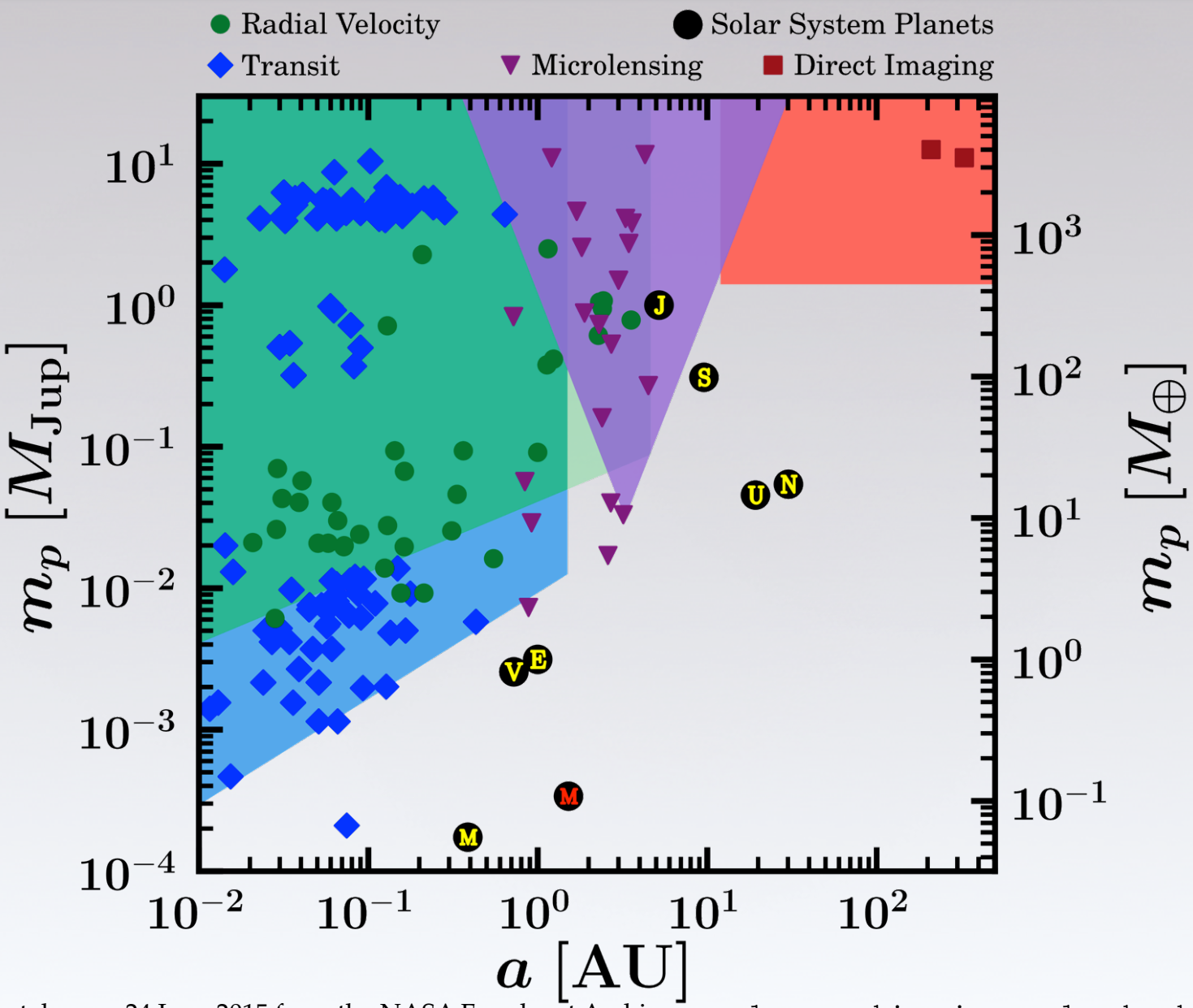
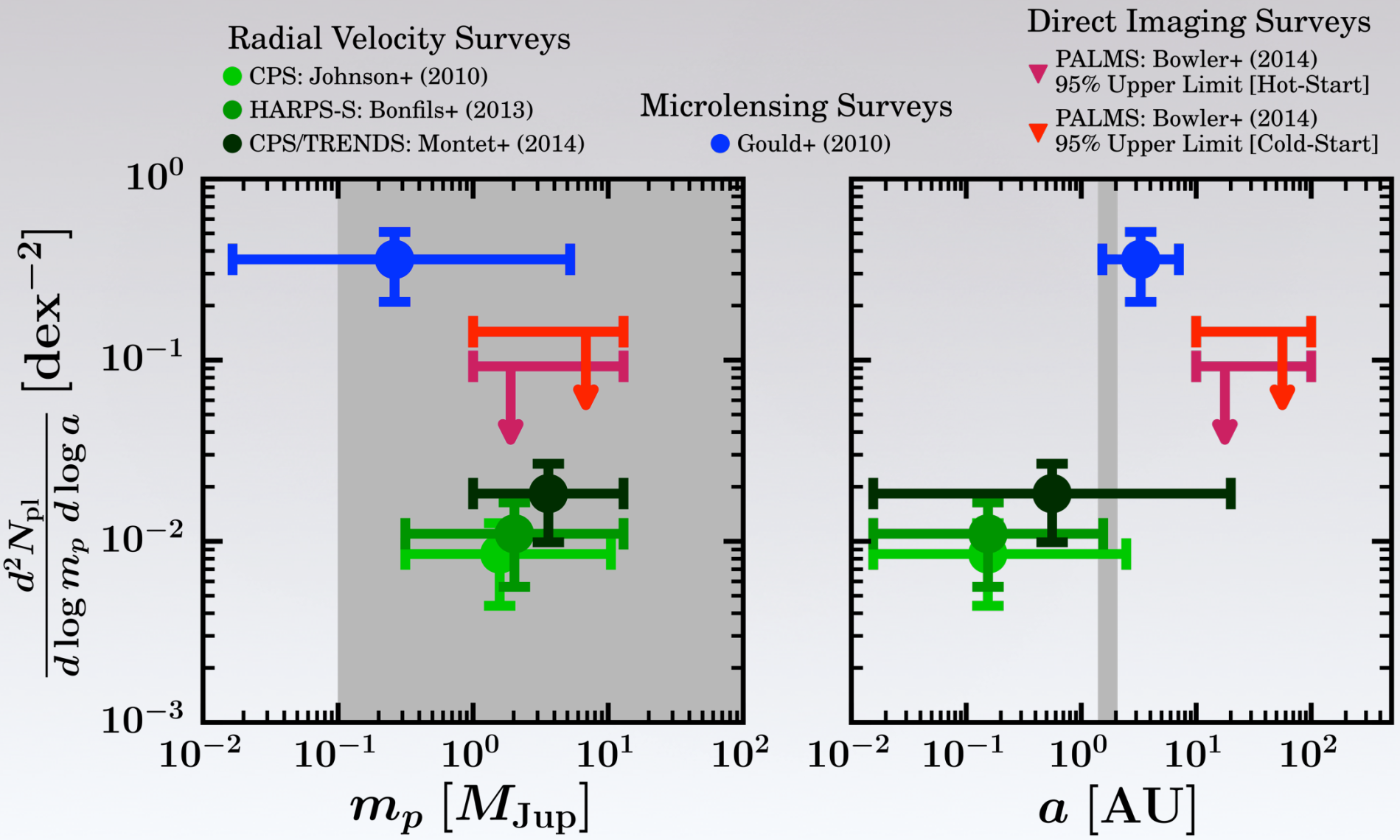
Confirmed Exoplanets Around M Dwarfs



Data taken on 24 June 2015 from the NASA Exoplanet Archive, `exoplanetarchive.ipac.caltech.edu`

Exoplanet Censuses of M Dwarfs from Individual Methods



Comprehensive Picture of Exoplanet Demographics

- Combine results from these various techniques
  - μLens+RV
    - Clanton & Gaudi (2014ab)
  - μLens+RV+Direct Imaging
    - Clanton & Gaudi (2015, in prep.)

Constraints on Long-Period Planetary Companions to M Dwarfs

Microlensing Surveys

Gould+ (2010)
- Integrated Planet Frequency

Sumi+ (2010)
- Slope of Mass Ratio Distribution Function

Radial Velocity Surveys

Montet+ (2014)
- Four Long-Term Trends, No AO Companion Detections

Direct Imaging Surveys

Bowler+ (2014)
- Upper Limit on Planet Frequency

Lafrenière+ (2007)
- Upper Limit on Planet Frequency

μLens + RV Trends + Imaging: Primary Objective

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

Methodology

1. Assume a simple planet population model described by four parameters,

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

defined implicitly by:

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

and where $a_{\rm out}$ is the outer cutoff radius.

→ Distribution of (m_p, a)

Methodology

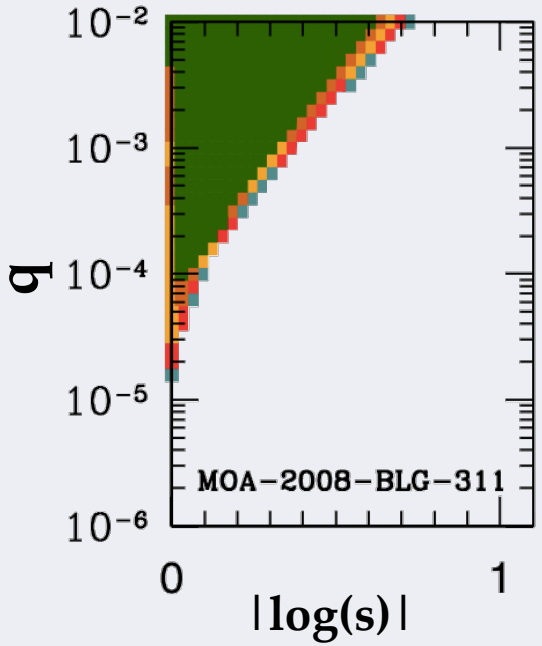
2. Map the distribution of (m_p, a) into distributions of the observables relevant to each technique.

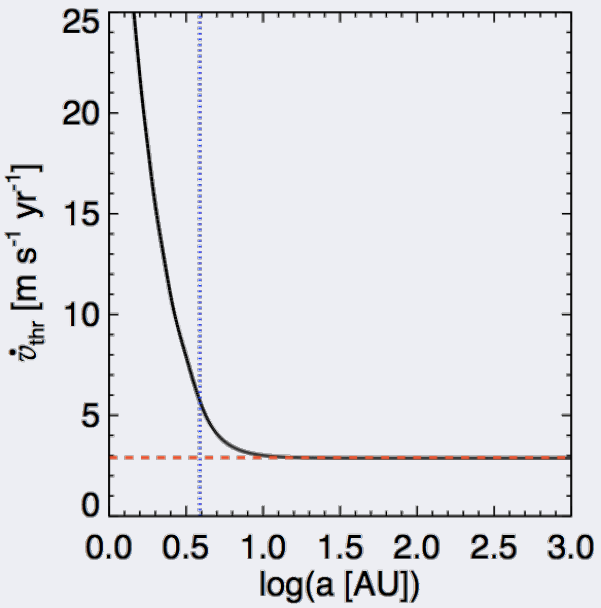
Microlensing	RV	Direct Imaging
(q, s)	$(\dot{v}, P)$	$(\Delta\mathrm{mag}, r_\perp)$
- Orbital Parameters - Lens Distances - Lens Mass Function - Galactic Model	- Orbital Parameters - Host masses	- Orbital Parameters - Ages and Distances - Planet Evolution Models (Hot-/Cold-Start)

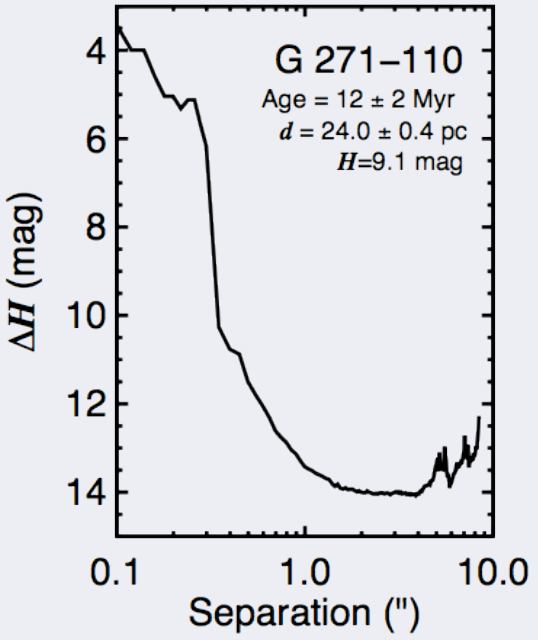
Methodology

3. Determine number of expected detections for each survey, and compare with actual reported results.

Microlensing	RV	Direct Imaging







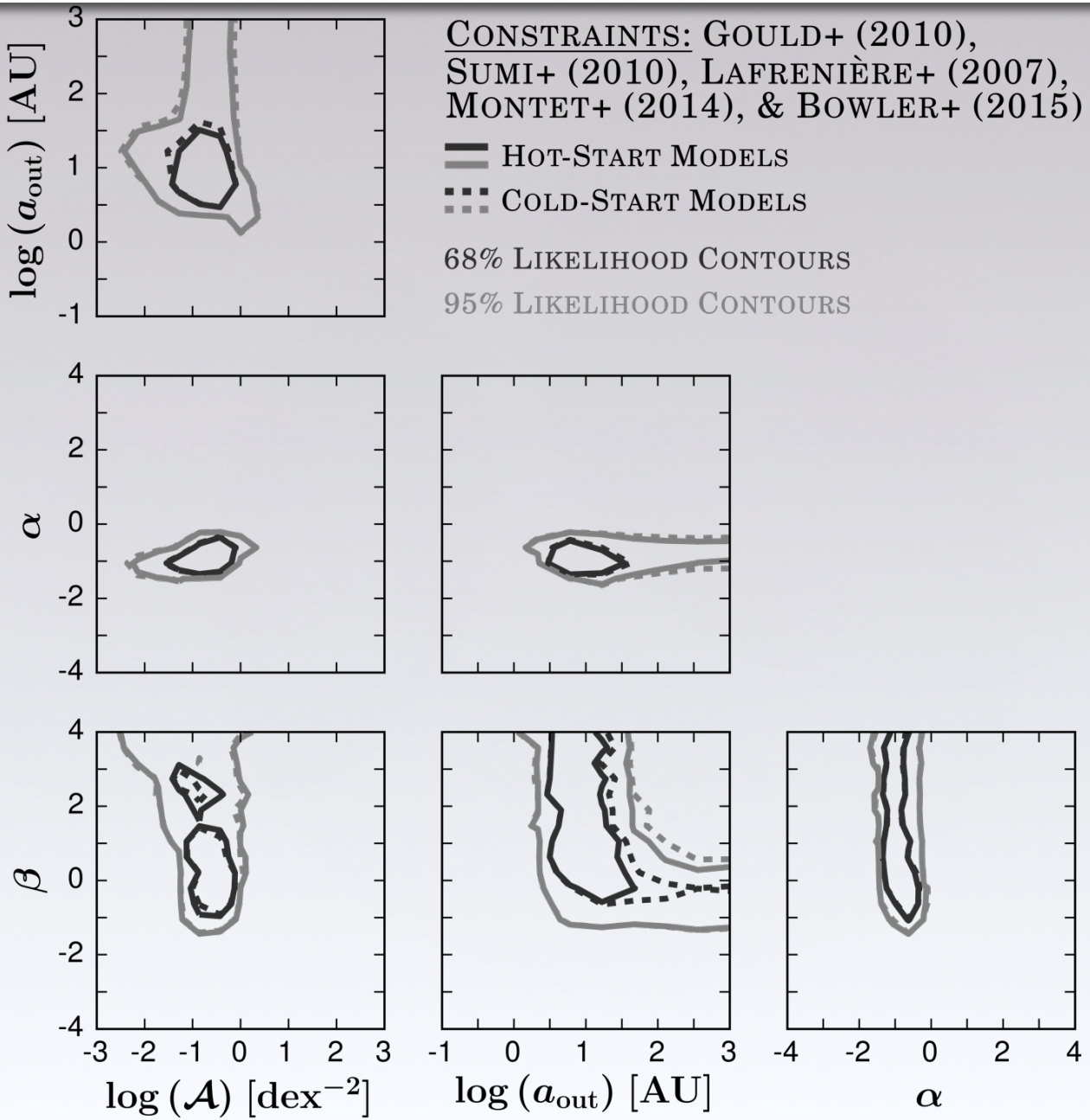
Above figure from Gould+ (2010)

Above figure from Bowler+ (2015)

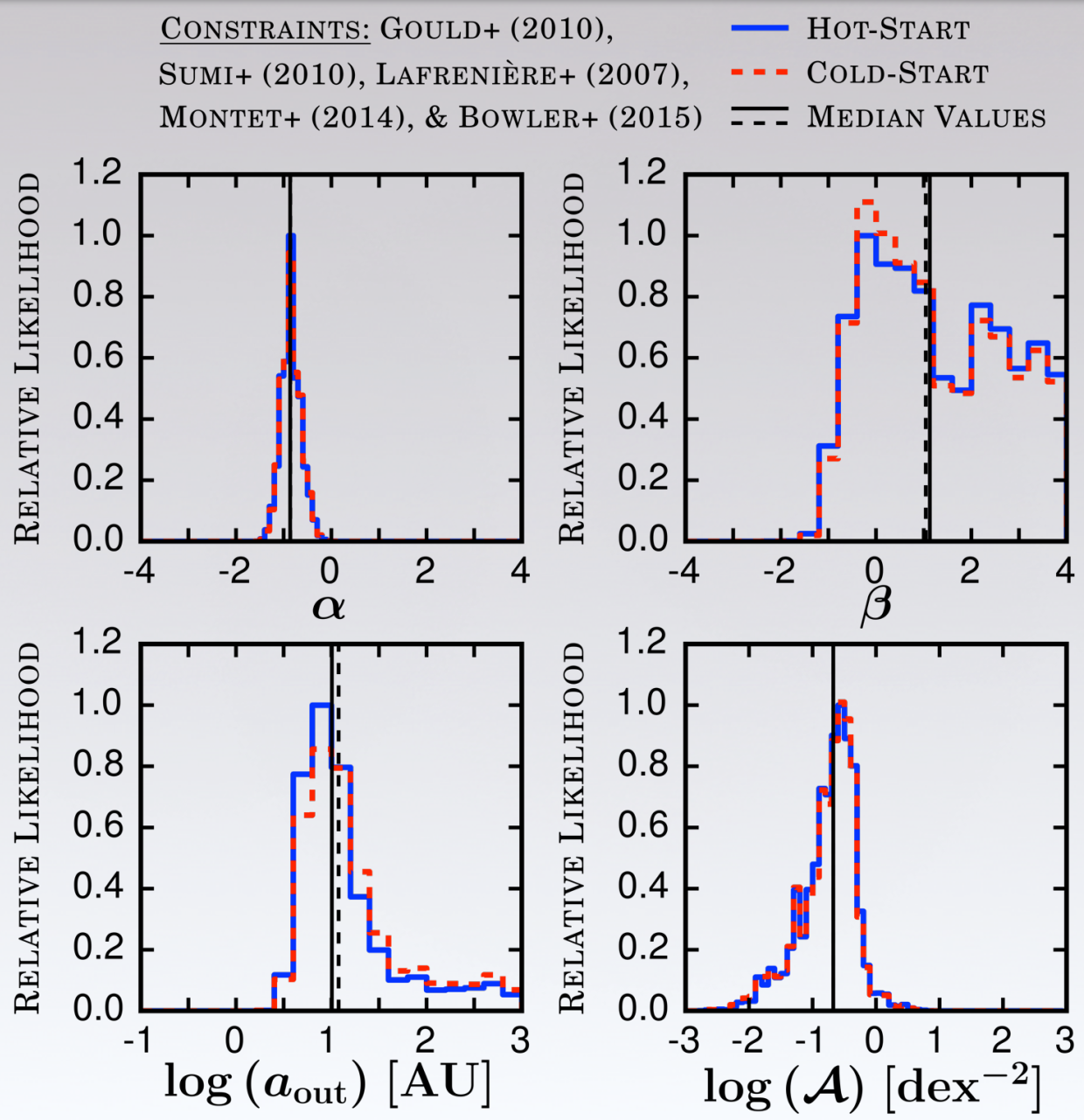
Methodology

4. Repeat analysis for many different populations to obtain constraints on $\{\alpha, \beta, \mathcal{A}, a_{\mathbf{out}}\}$ according to their relative likelihoods given by the actual results of each survey.

Results: Likelihood Contours



Results: 1D Likelihoods



Results: Final Parameter Constraints

The results of microlensing, RV, and direct imaging surveys are consistent with a single exoplanet population.

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

μLens + RV Trends + Imaging: Ongoing Research

- Can such a population, that is consistent with all other surveys, also explain the overabundance of short-timescale microlensing events (Sumi+ 2011)?

Future Work

- Include Results from the *Kepler* mission
- Compare our demographic constraints with the output of planet population synthesis models (e.g. Mordasini+, Ida & Lin)

For More Information

Please refer to:

Clanton, C. & Gaudi, B. S. 2015, in prep.
Clanton, C. & Gaudi, B. S. 2014, ApJ, 791, 90
Clanton, C. & Gaudi, B. S. 2014, ApJ, 791, 91

Visit my website at clantonastro.org!

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