# Frequency of Exoplanets Beyond the Snow Line from 6 Years of MOA Data

## Studying Exoplanets in Their Birthplace

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Analysis to appear in Suzuki et al. (2015)

PLANET
Probing Lensing Anomalies NETwork

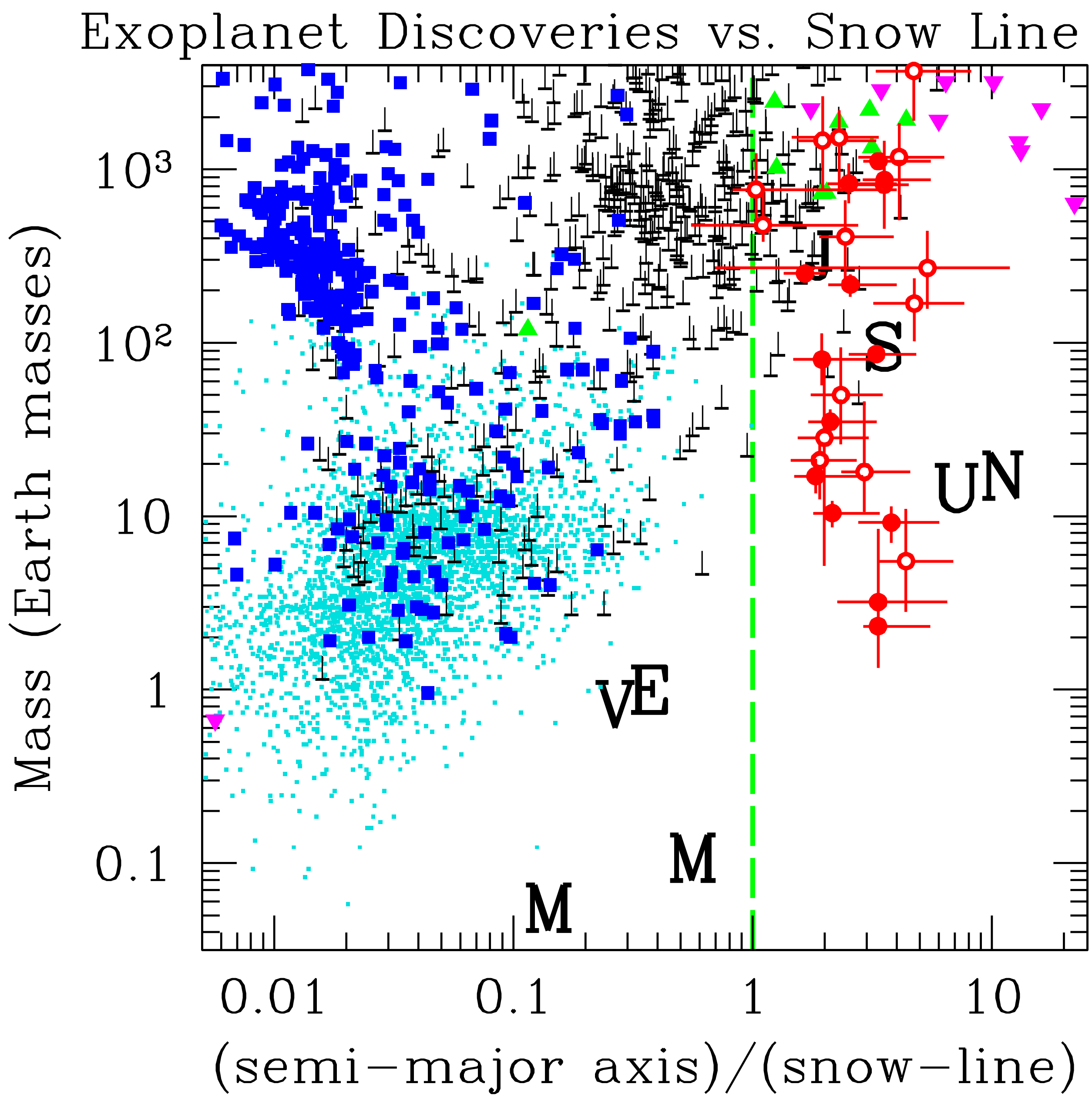
OGLE

*MicroFUN*
*Microlensing Follow-Up Network*

# Planet mass vs. semi-major axis/snow-line

- "snow-line" defined to be 2.7 AU ($M/M_\odot$)
  - since L∝ $M^2$ during planet formation
- Microlensing discoveries in **red.**
- Doppler discoveries in black
- Transit discoveries shown as blue circles
- Kepler candidates are cyan spots

- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered



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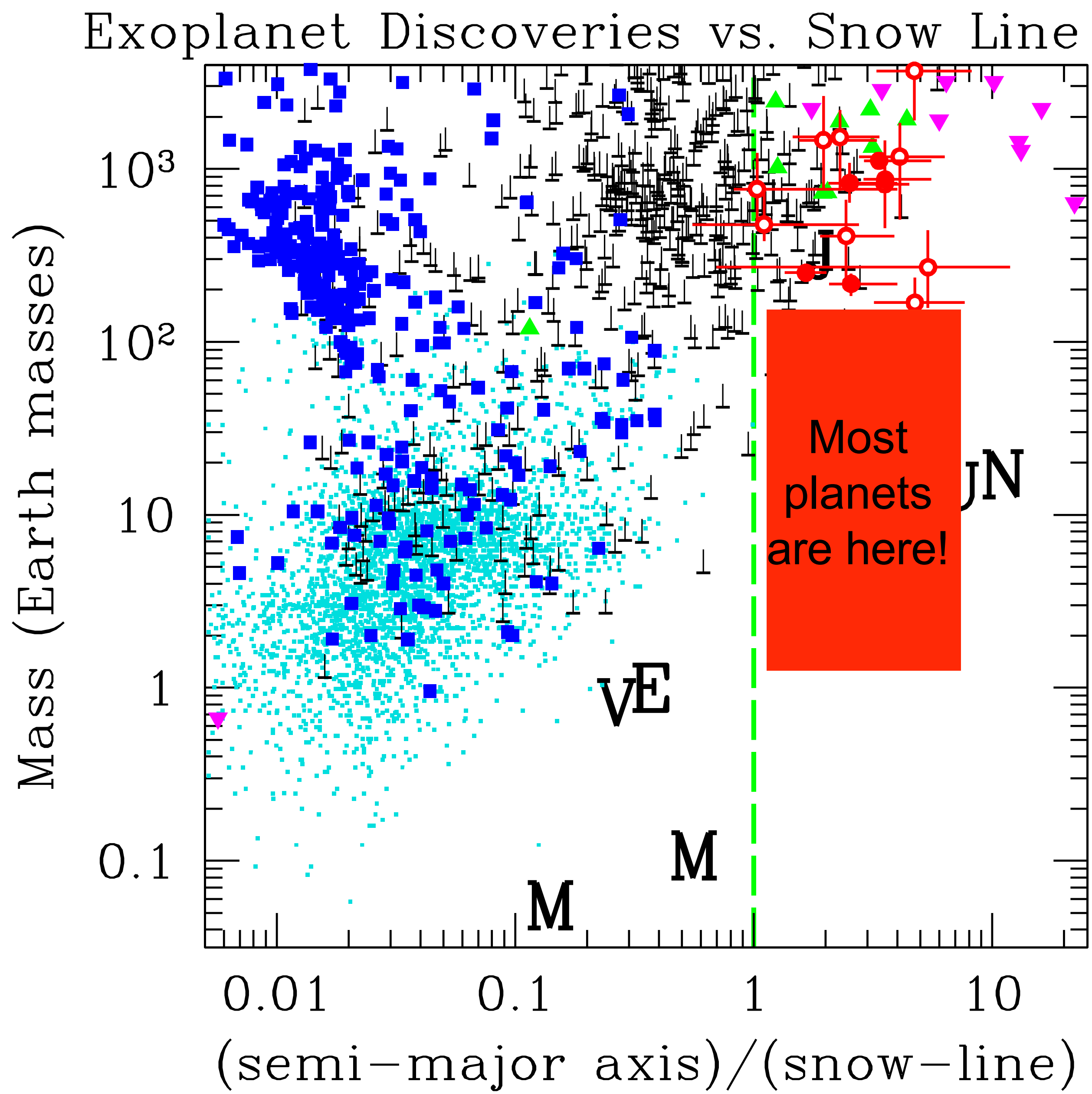
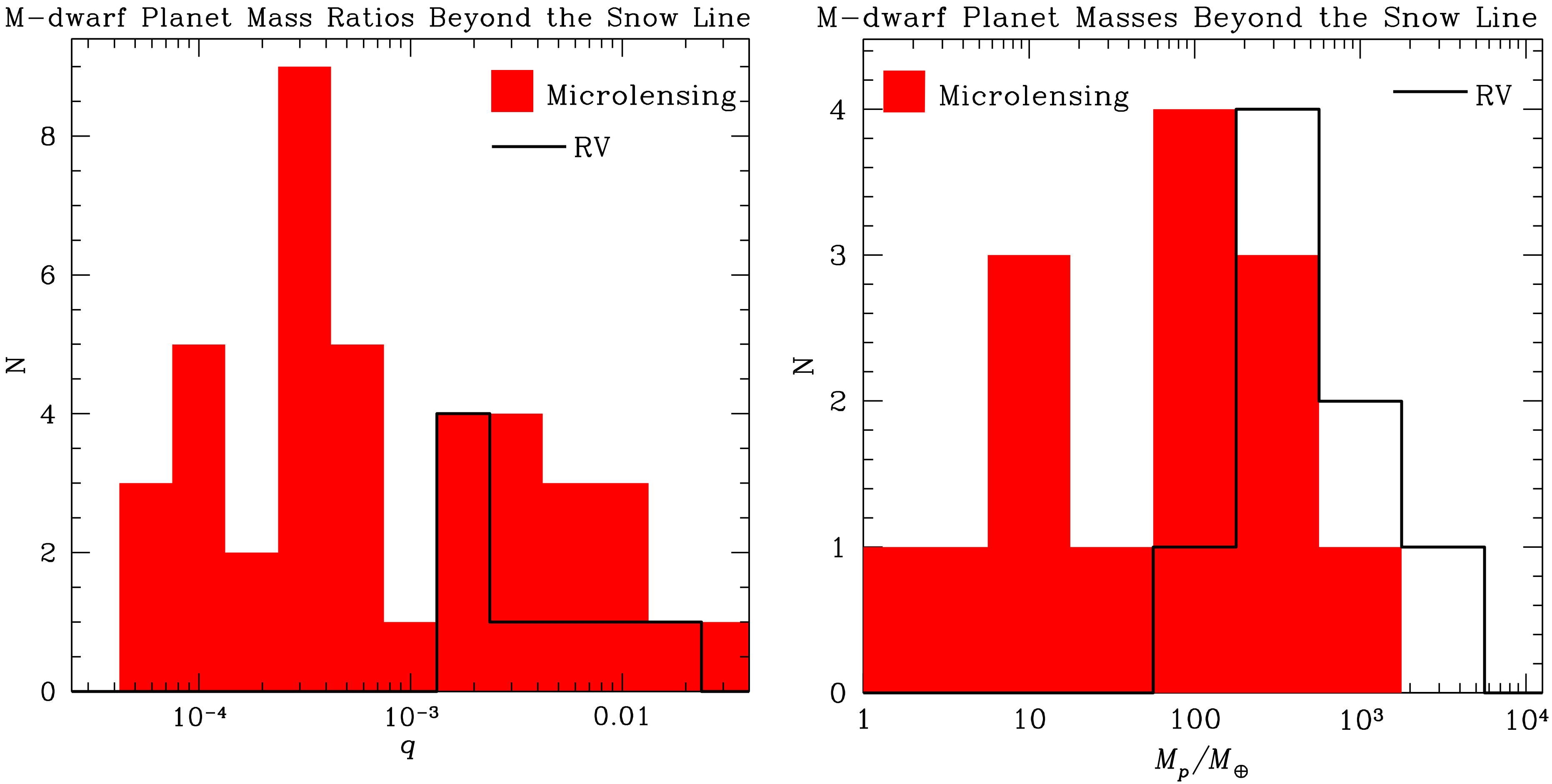


# Comparison of Microlensing and RV M-dwarf Planets Beyond the Snow-line

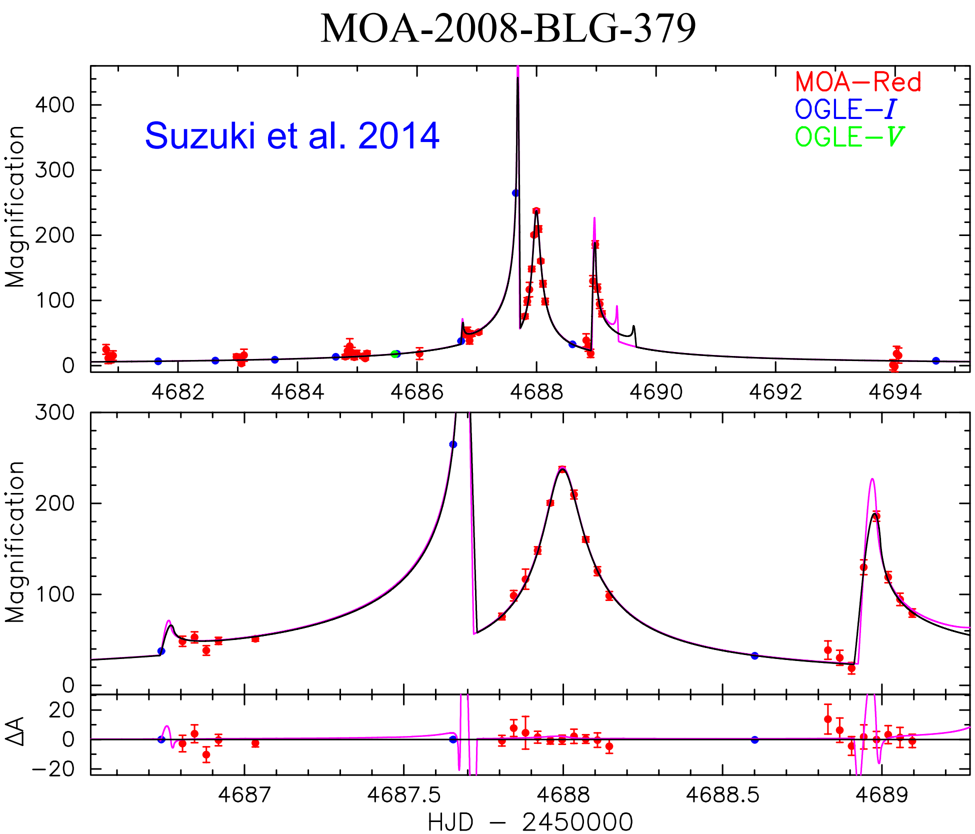


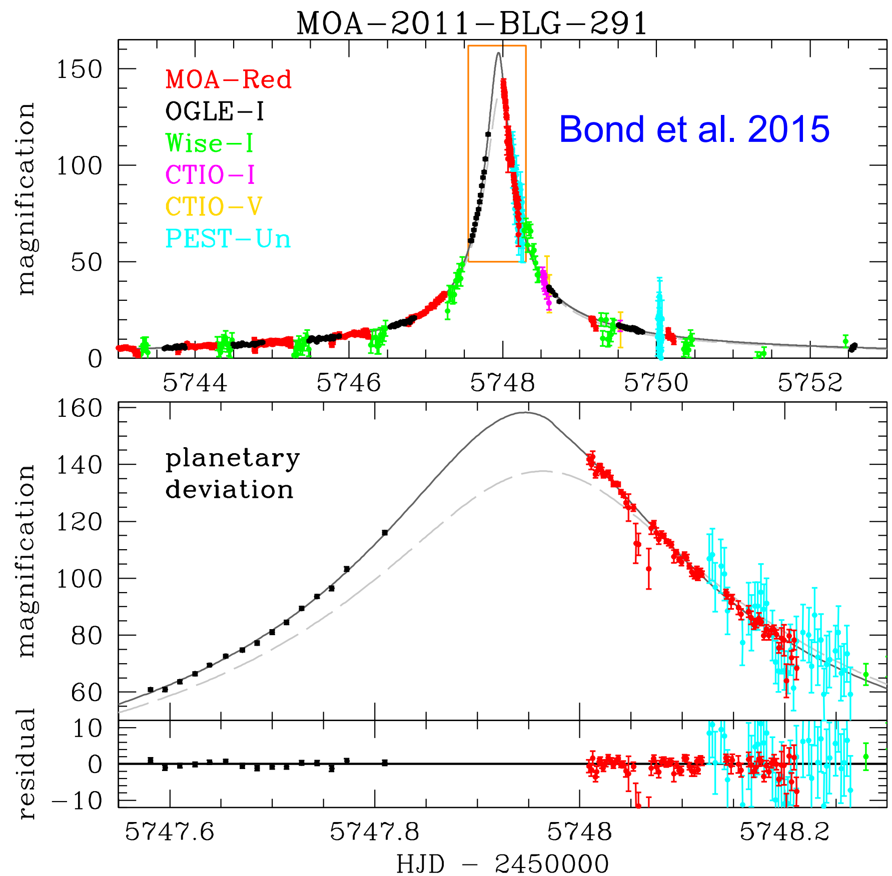

Comparison of planets hosted by (likely) M-dwarfs beyond the snow line from as a function of mass ratio, *q*, on the left and mass on the right. Microlensing is more sensitive to Saturn-mass planets and below. Clanton & Gaudi (2014) and Montet et al. (2014) show that RV and microlensing results are consistent.

# MOA-II Survey 6-Year Analysis 2007-2012

- Based on 3300 microlensing events found by the MOA Alert system in 2007-2012
- 1448 of these events are high quality enough to be included in the analysis
  - Other events are poorly sampled with poorly defined single-lens parameters
- All events were searched for anomalies, and those with anomalies were fit with binary lens models
- If binary lens model improves $\chi^2$ by $\Delta\chi^2 \geq 100$, it is considered a significant anomaly detection
- only MOA data is used to define a detection, but all available data is used to determine if the mass ratio $q < 0.03$, the threshold for a planet
- 23 planetary events found
  - Compares to 8 in previous statistical samples
  - 3 (MOA-2008-BLG-288, 379 and MOA-2011-BLG-291) were not initially recognized as planetary events
  - 1 (OGLE-2011-BLG-0950/MOA-2011-BLG-336) is ambiguous with planetary model favored over $q \approx 0.3$ model by $\Delta\chi^2 = 17.2$

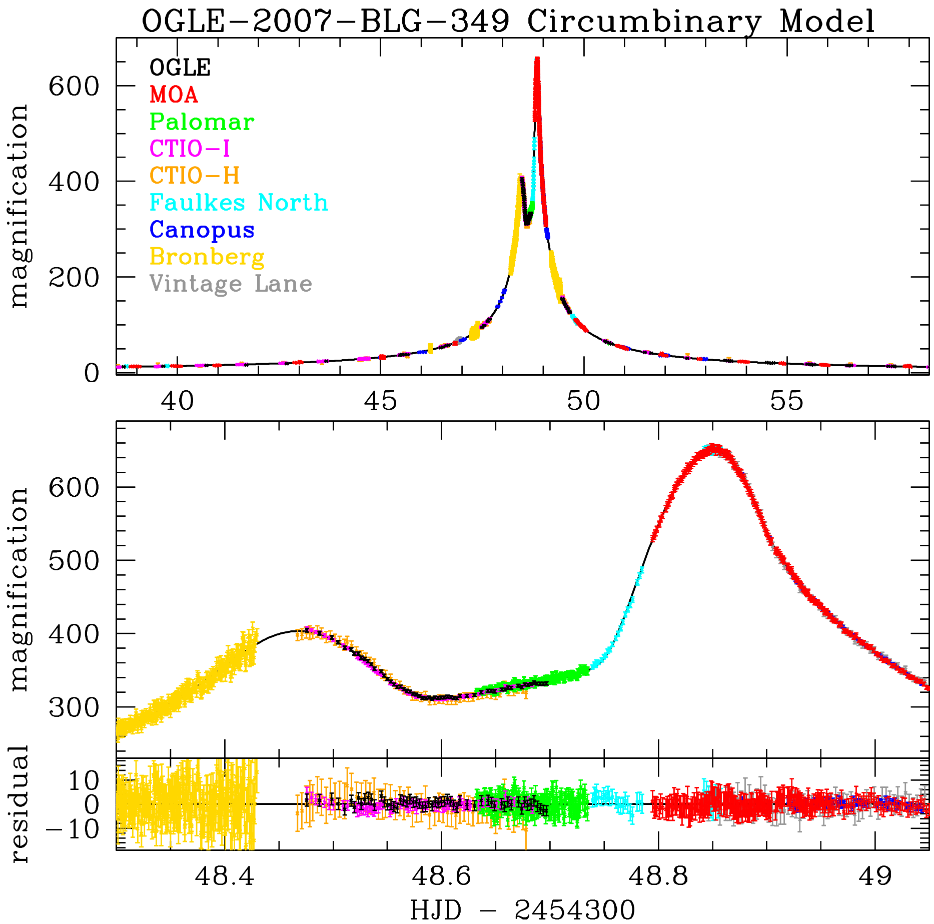
# New Planetary Events from Systematic Analysis

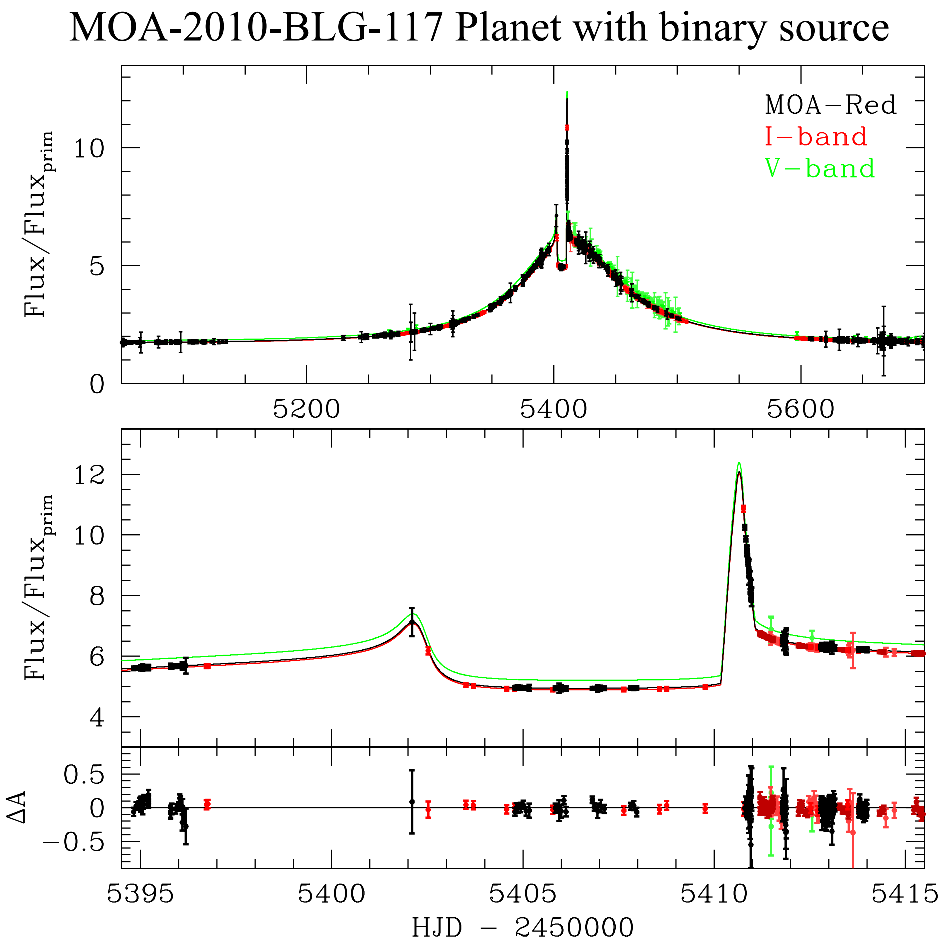



Re-analysis of all events identified by the MOA alert system reveals 3/22 planets not identified when they occurred: MOA-2008-BLG-288, MOA-2008-BLG-379, and MOA-2011-BLG-291, plus one ambiguous event, OGLE-2011-BLG-0950/MOA-336.

# Includes analysis of "Exotic Events"

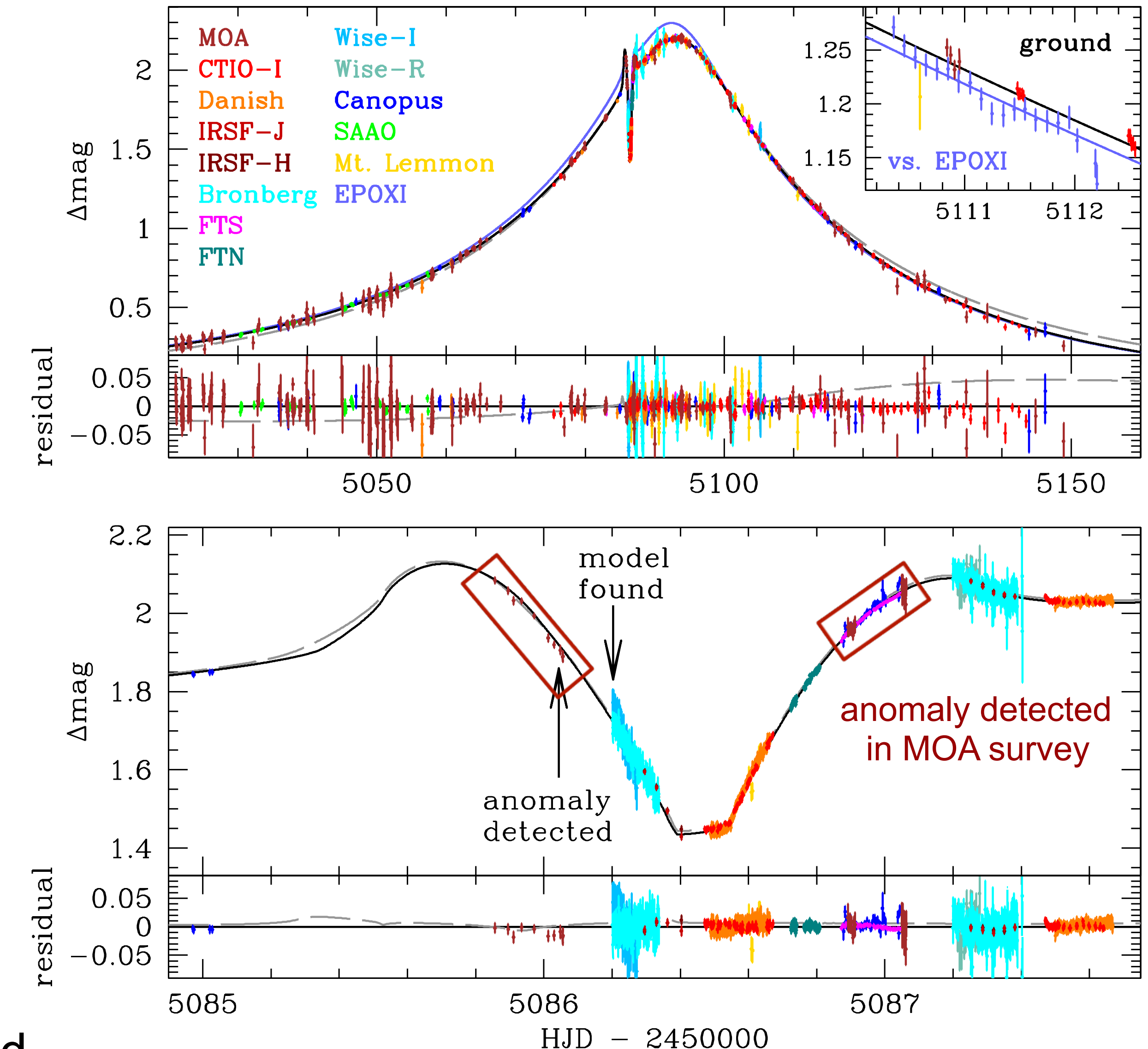



Includes first circumbinary planet and first planet in a binary source microlensing event (discovery papers in preparation).

# MOA-2009-BLG-266 Real-Time Discovery

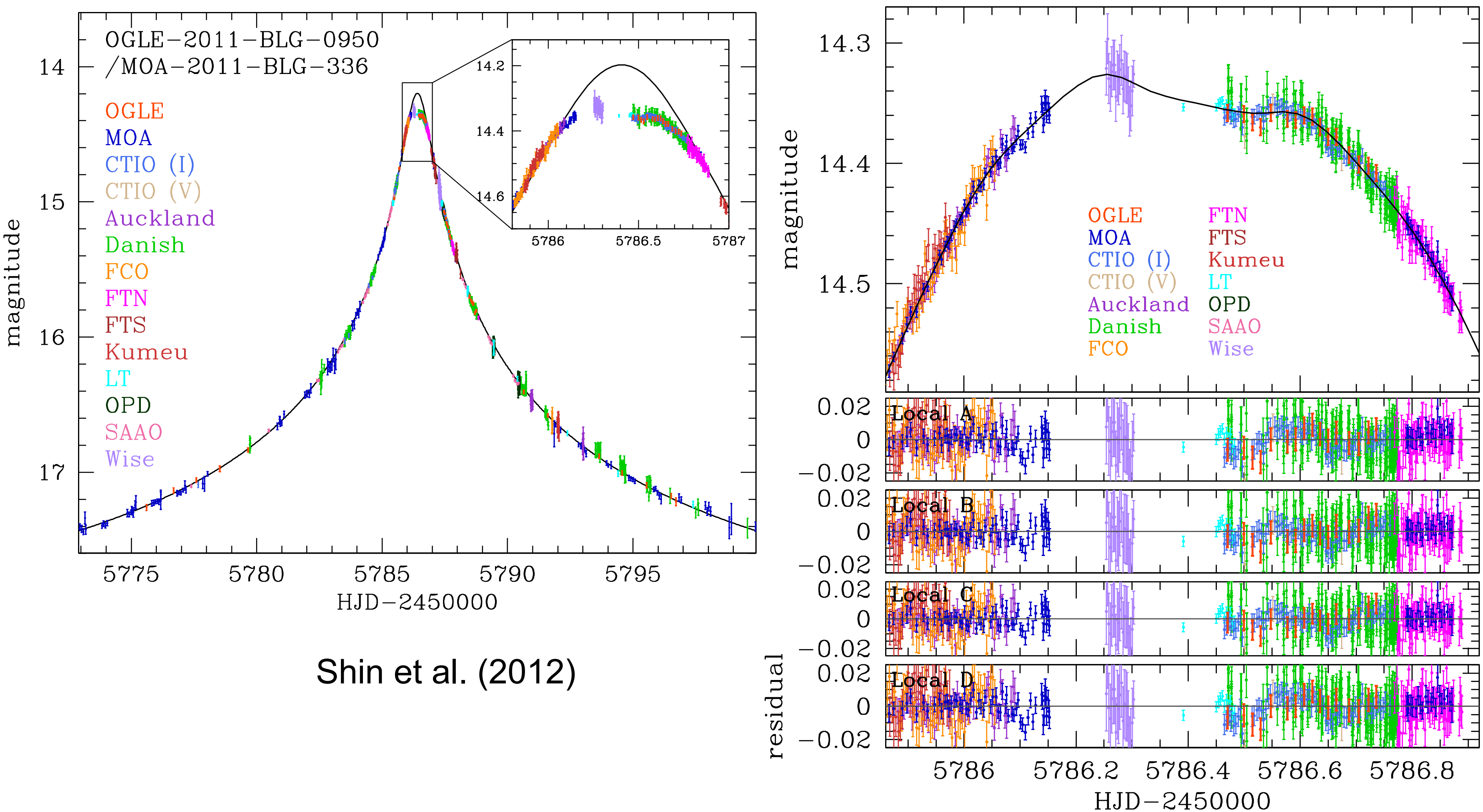
- Real-time discovery in MOA data.
- 2/3 of the planetary deviation covered by follow-up groups
- Detection efficiency calculation requires a significant signal in the MOA data
- Planet characterization uses full data set.
- Mass and distance measurements not used




$m_p = 10.4 \pm 1.7 M_\oplus$ $M_* = 0.56 \pm 0.09 M_\odot$

$a = 3.2^{+1.9}_{-1.5}$ AU $D_L = 3.0 \pm 0.3$ kpc

# Ambiguous Event: OGLE-2011-BLG-0950/ MOA-2011-BLG-336




Shin et al. (2012)

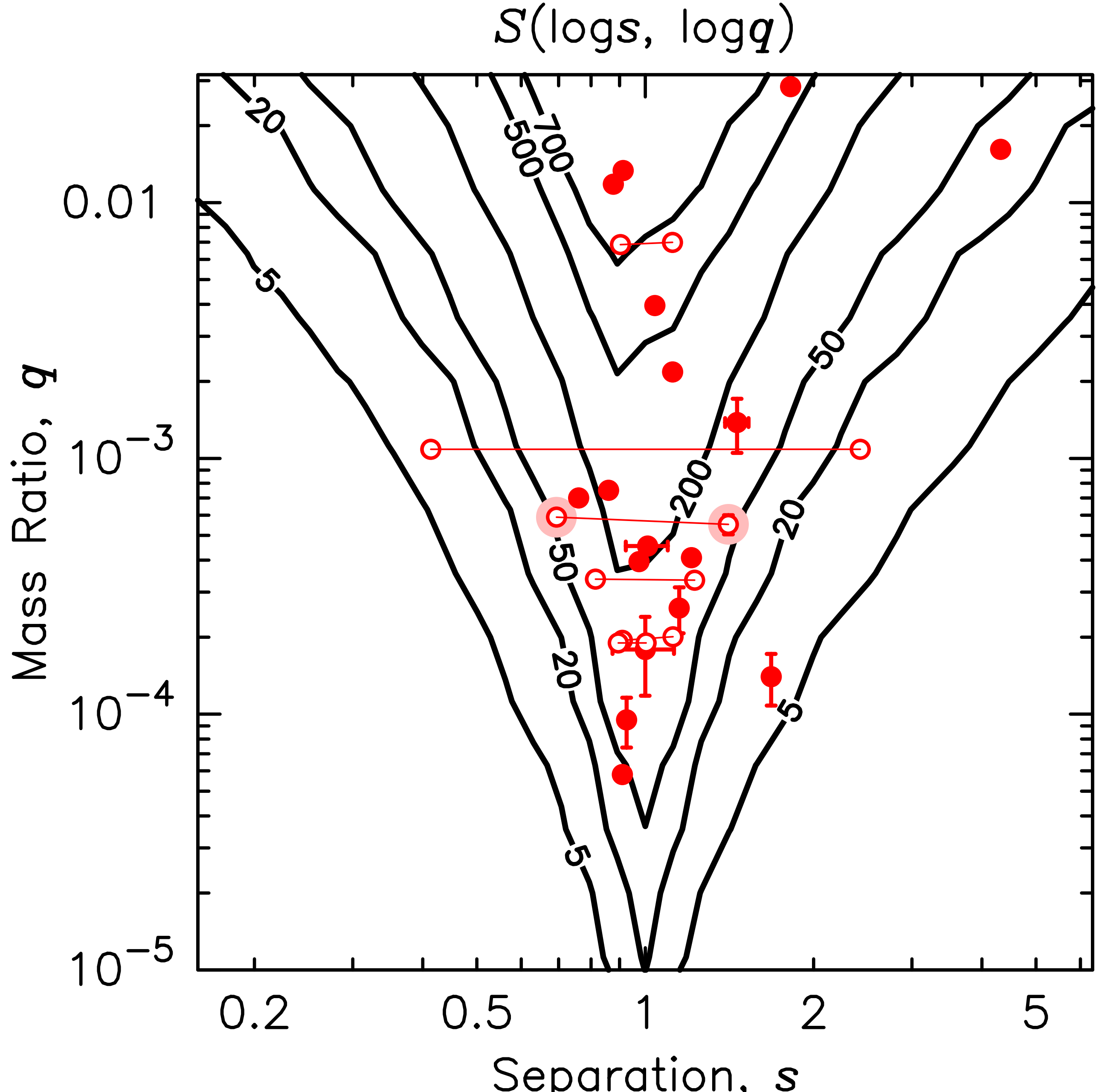
Handled with Bayesian Analysis – assuming a model of stellar binary frequency

# Combined Detection Efficiencies

23 planets from MOA-II sample plotted with total detection efficiency contours.

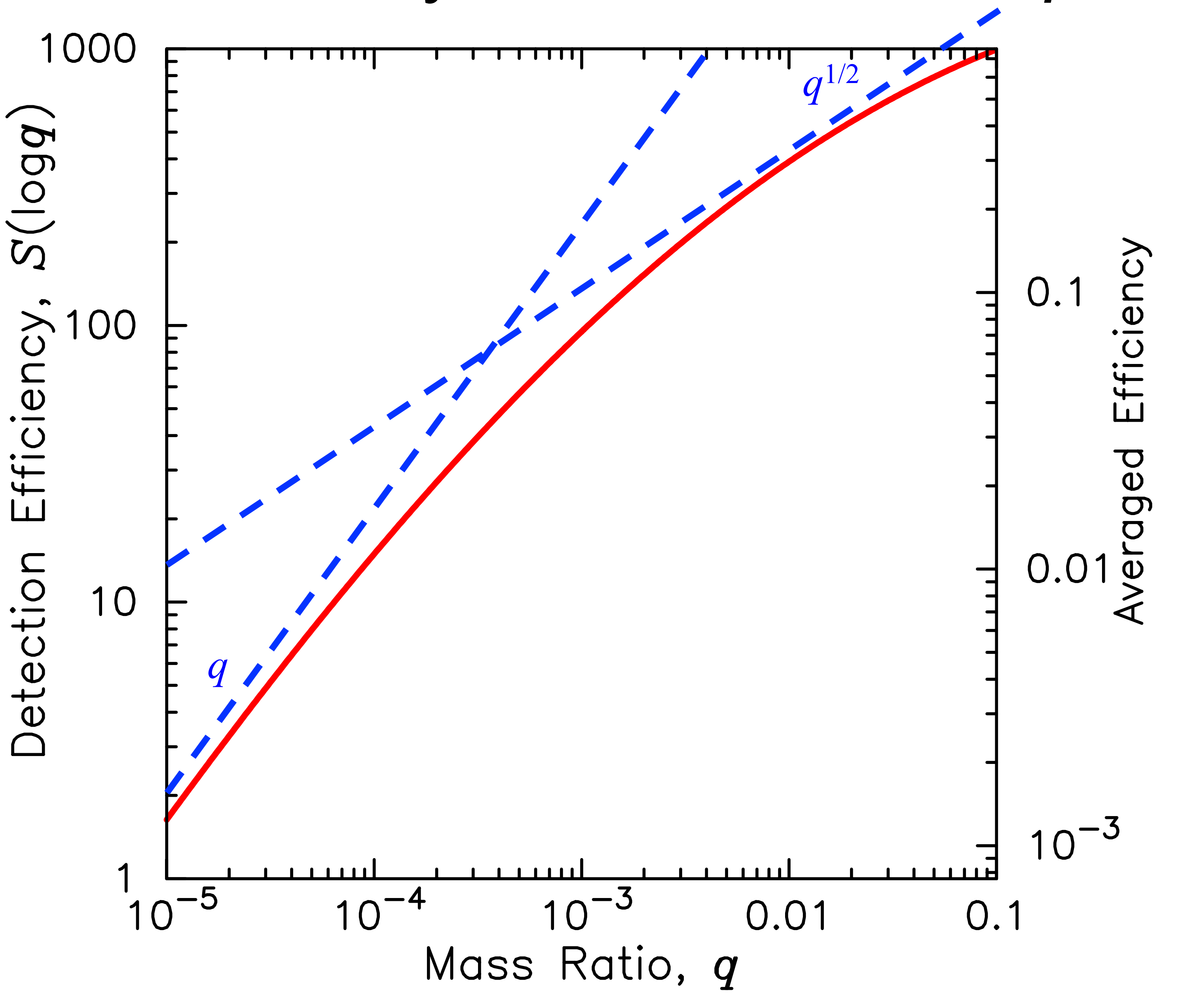
Contour numbers indicate the number of expected detections if every star has such a planet.

Open circles are high mag events with $s \longleftrightarrow 1/s$ degeneracy



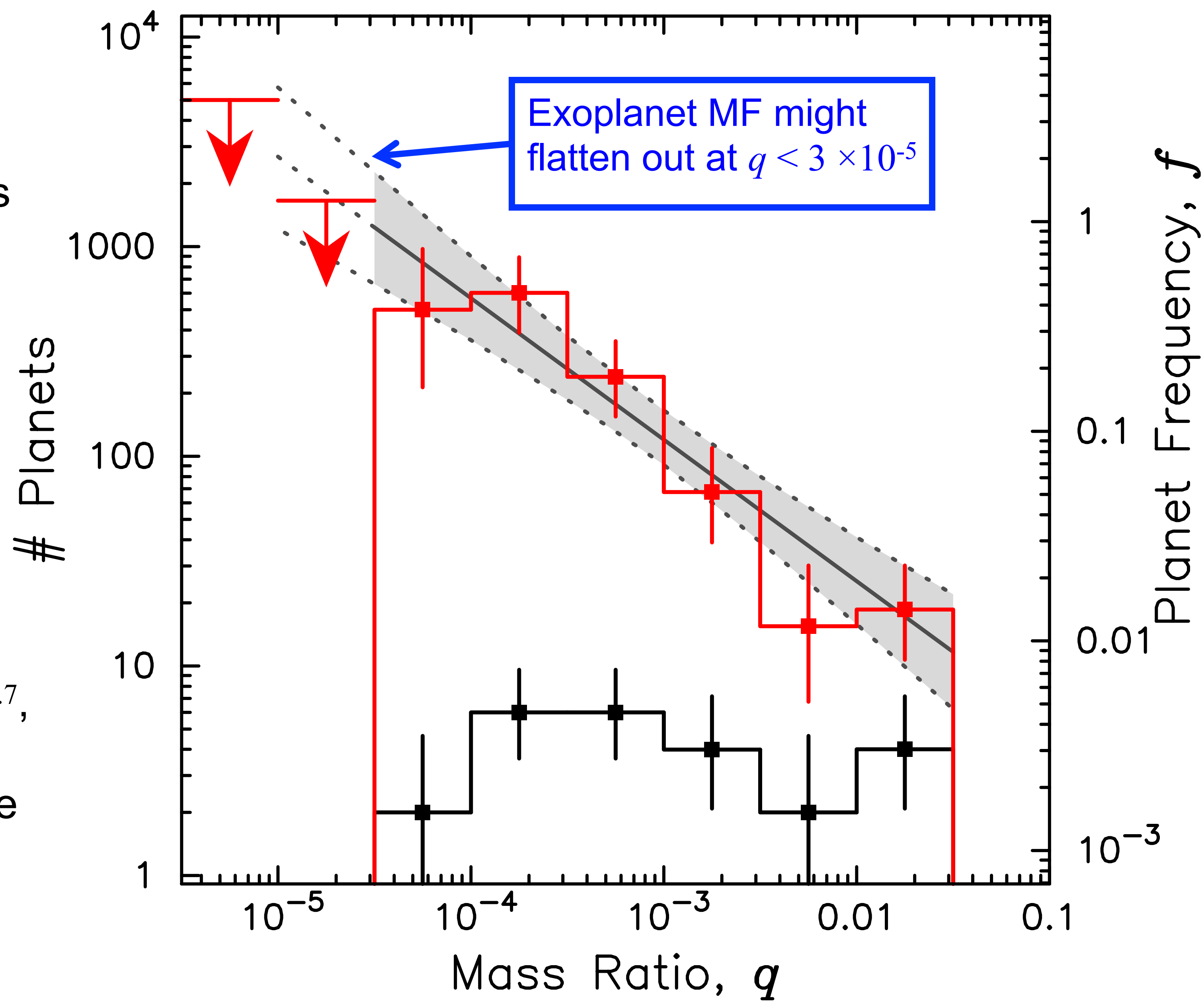
# Detection Efficiency vs. Mass Ratio, $q$

Detection efficiency scales as $q$ for low masses and $q^{1/2}$ for high masses



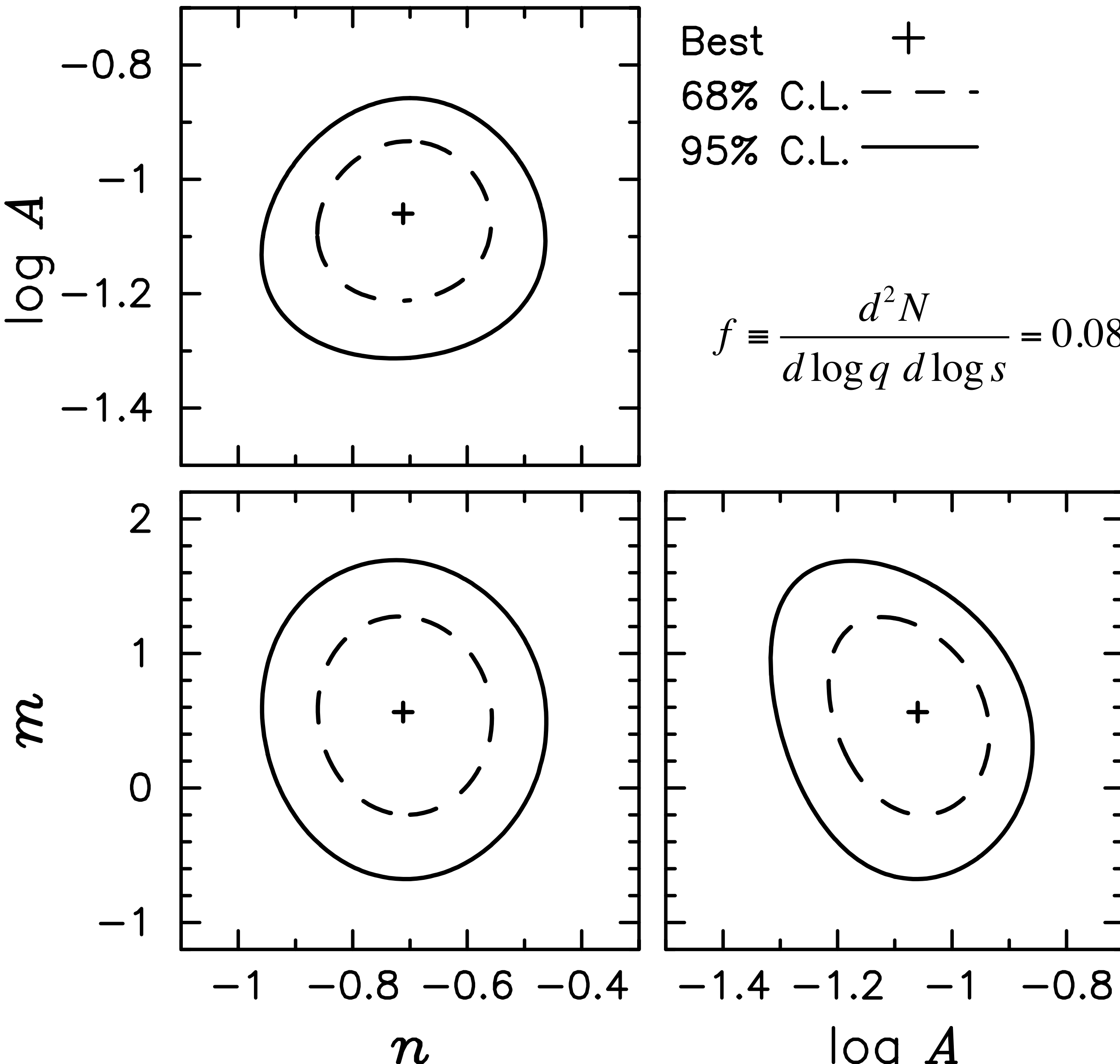
# Efficiency Corrected # of Planets vs. *q*

Observed distribution is flat in $\log q$




Efficiency corrected distribution scales as $q^{-0.7}$, which is the inverse of the detection efficiency

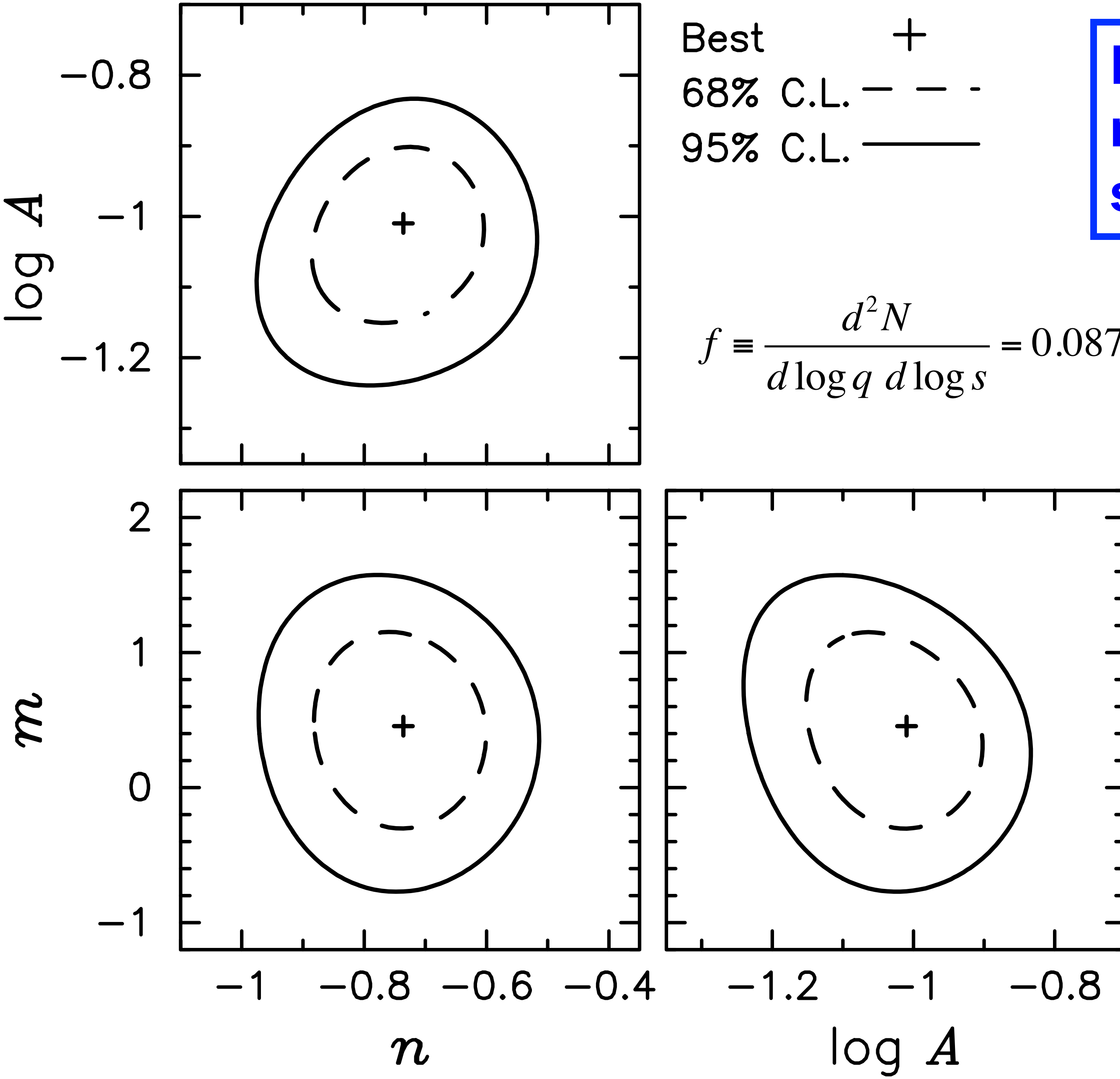
# Exoplanet Mass Function Model Parameters




**MOA-only**

$$f \equiv \frac{d^2N}{d\log q \; d\log s} = 0.082^{+0/020}_{-0.016}\left(\frac{q}{10^{-3}}\right)^{-0.71^{+0.11}_{-0.10}} s^{0.52\pm0.50}$$

# Exoplanet Mass Function Model Parameters




**Full 30-event microlensing sample**

$$f \equiv \frac{d^2N}{d\log q \; d\log s} = 0.087^{+0/020}_{-0.016}\left(\frac{q}{10^{-3}}\right)^{-0.72\pm0.10} s^{0.61^{+0.45}_{-0.50}}$$

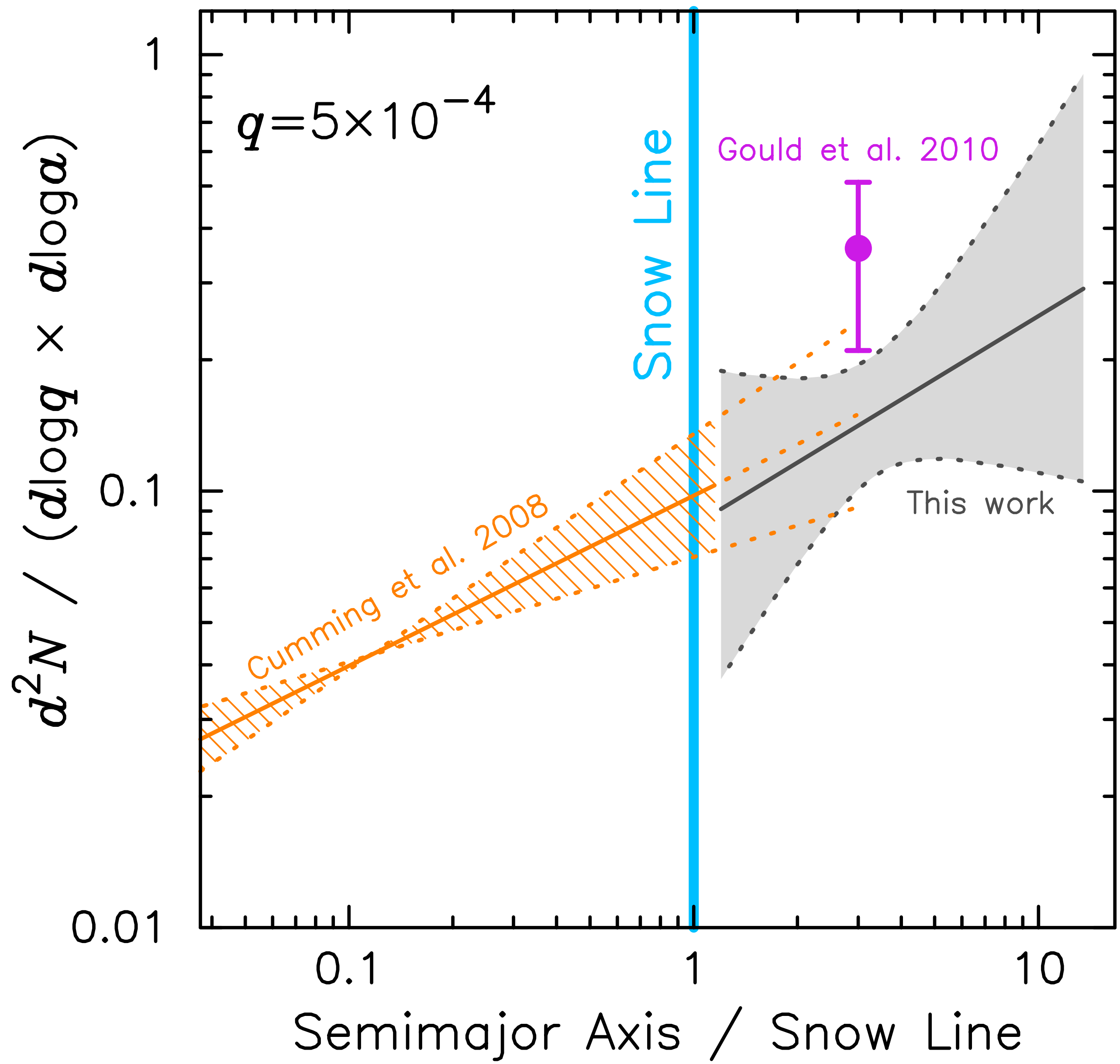
Includes 8 more events from Gould et al. (2010) and Cassan et al. (2012), but there is 1 event in common

# Exoplanet Frequency vs. Semi-Major Axis

**MOA-only**

MOA result is ~1.4σ lower than previous Gould et al. (2010) result.

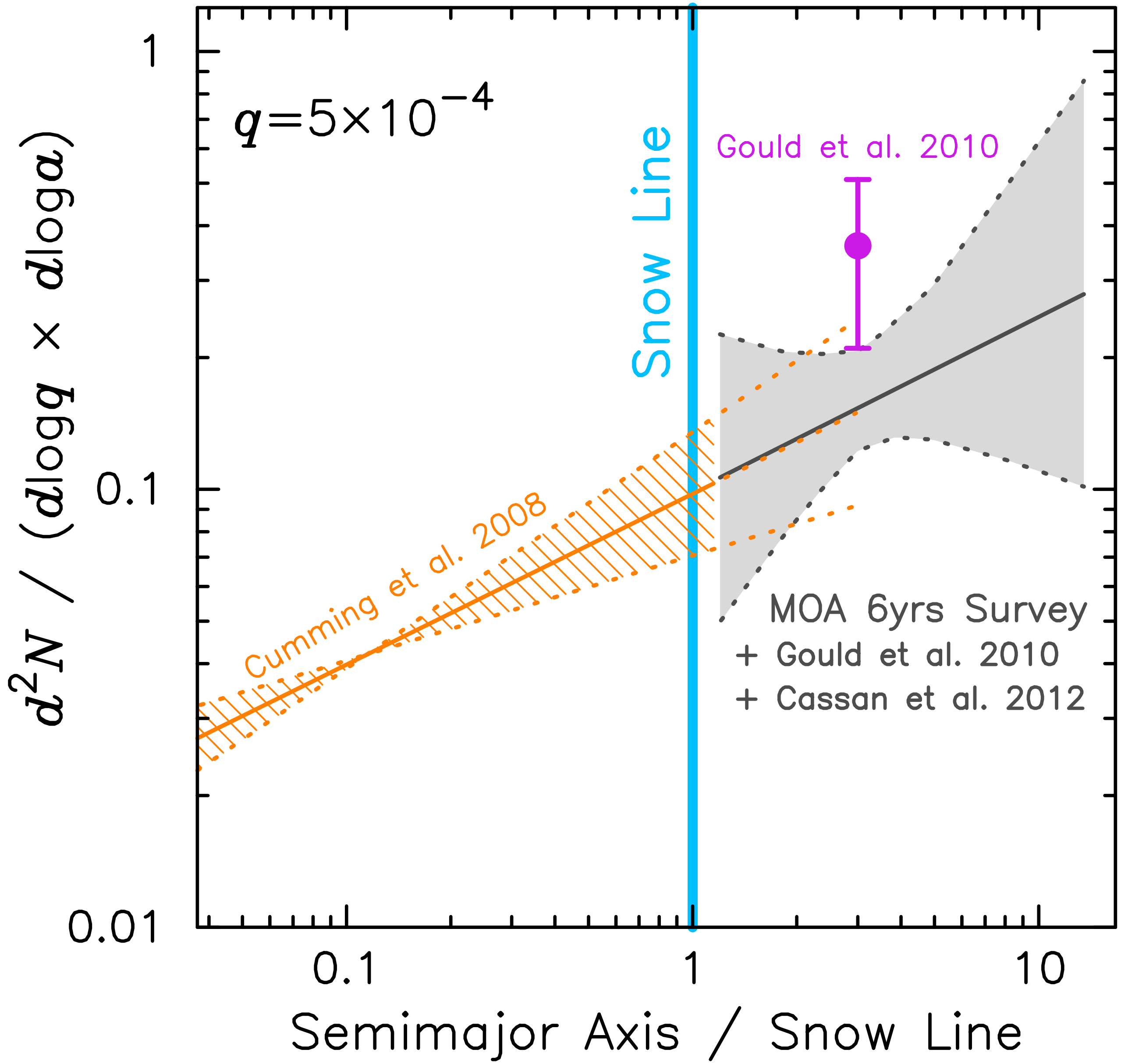
Gould (2010) result is low due to statistics and subtle biases, like "publication date bias". μFUN has fewer planets in 2009-2014 (6 yrs) than in 2005-2008 (4 yrs)



# Exoplanet Frequency vs. Semi-Major Axis

**Full 30-event microlensing sample**

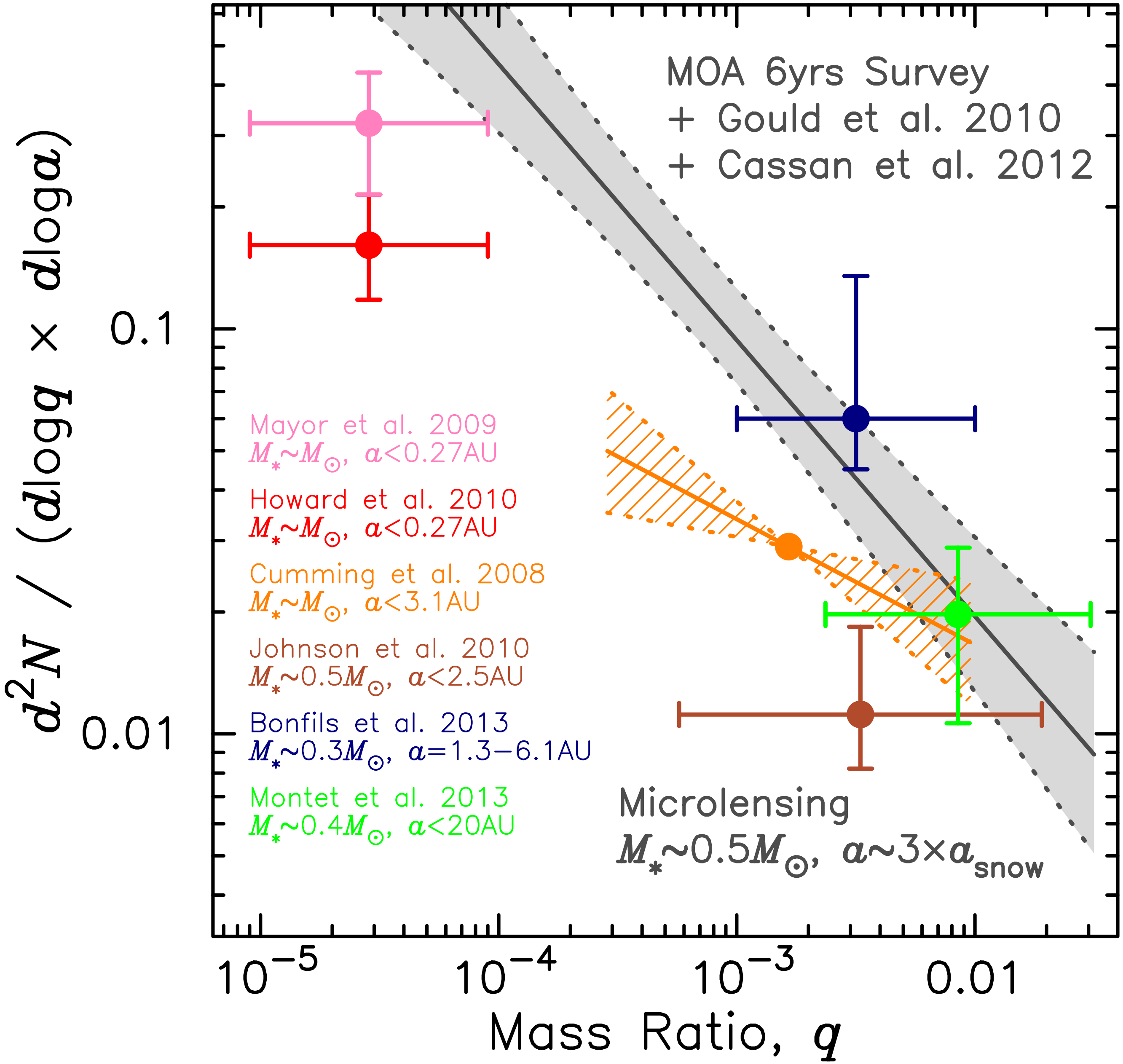
Combined RV (Cumming et al. 2008) and microlensing results may be well described by a power for fixed mass ratios from inside to outside the snow line



# Comparison to RV Samples

**Full 30-event microlensing sample**

Planets beyond the snow line are more common (per $\log a$) as planets inside the snow line and Ice Giants are ~8 times more common than Jupiters



# Future Work

- About half of the 30 planets in the full statistical sample have mass and distance measurements
  - Through microlensing parallax
  - Or direct detection of the host star
- These mass/distance measurements will be included in a Bayesian analysis
  - Exoplanet mass function dependence on host mass and Galactic position
- Comparison to Exoplanet population synthesis models
  - Protoplanetary disk mass $\sim M$ not $\sim M^2$