Introduction to Microlensing Occurrence Rate Methods

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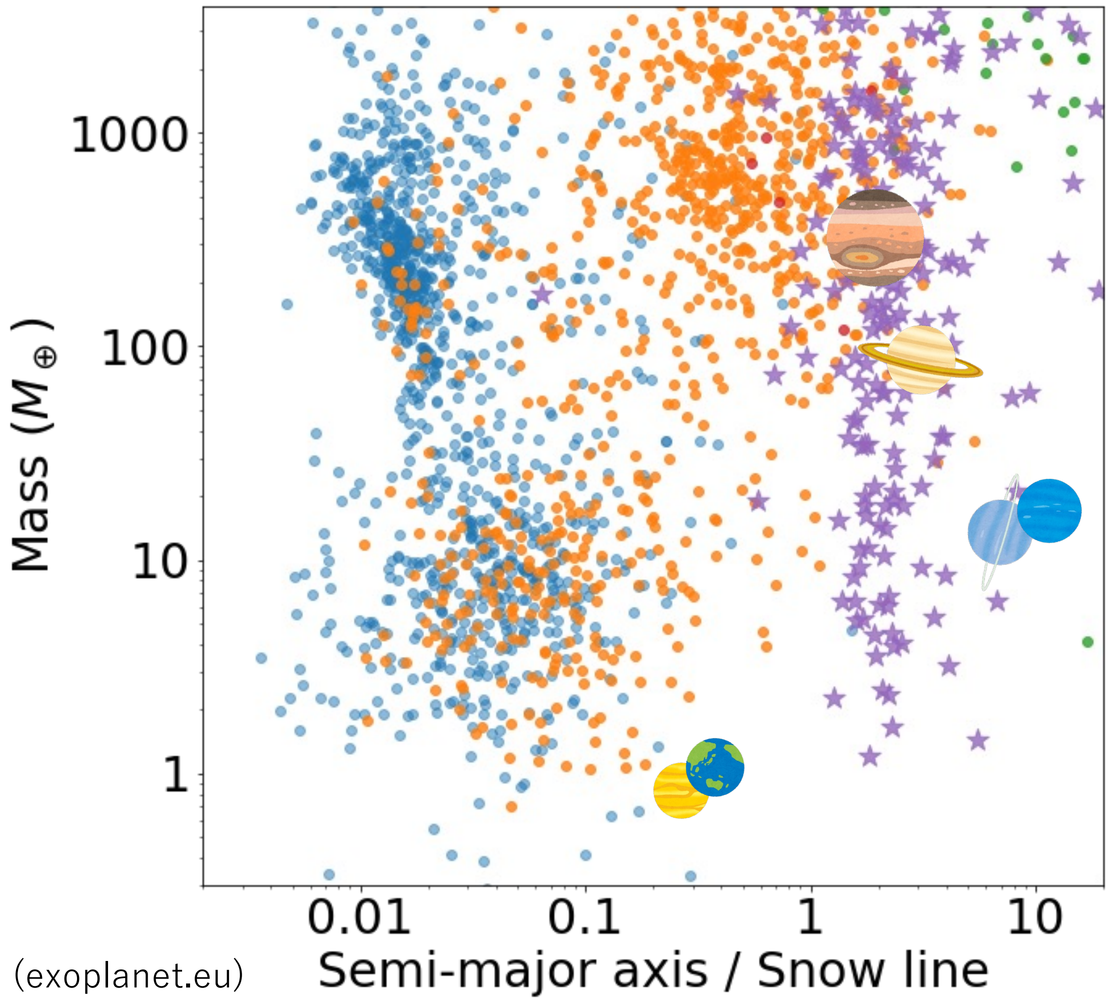
2026 Sagan Summer Workshop

Introduction: Exoplanet demographics



(exoplanet.eu)

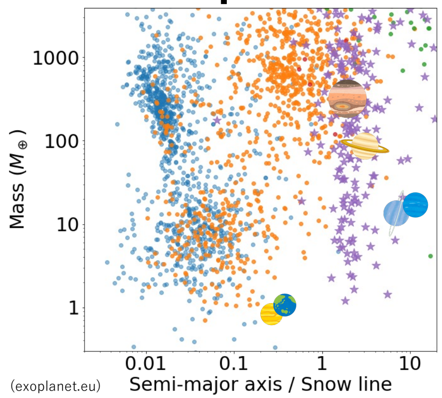
- Obseved distribution is biased.
- How abundant are they?
- Only the intrinsic distribution can be compared with theoretical predictions and results from other methods.

Bias correction by detection efficiency

N_{planet} = f x ε x N_{star}

Occurrence rate

Detection efficiency



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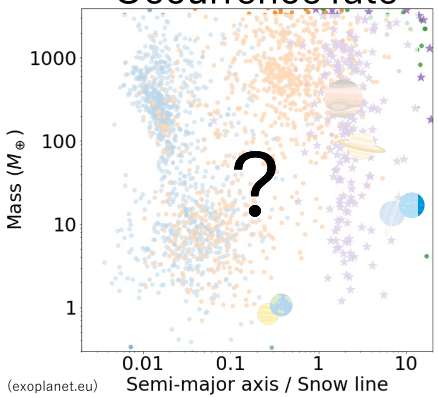
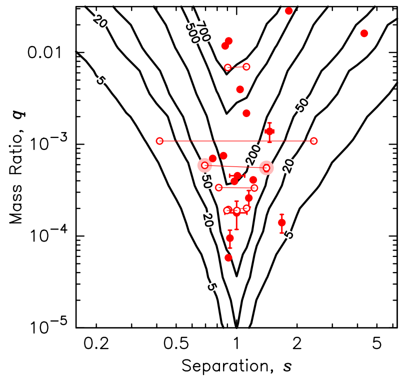


x



x N_{star}

$$N_{\text{planet}} = f \epsilon N_{\text{event}}$$

$$f = \frac{N_{\text{planets}}}{\epsilon N_{\text{event}}}$$

- ✓ In microlensing, the occurrence rate is the average number of planets per lens system.
- ✓ it could exceed 1, if the planets are really abundant.

Build a statistical sample

- ➢ The statistical sample for the μlens occurrence rate study : single lens events + planetery events
- ➢ These events should be selected with the criteria that are not relevant to the planetary signal
  - 🙅 Selected this event as it has a planetary signal.
  - 🙅 Rejected this event as it does not show a planetary signal.
  - 🙆 Selected this event as the light curve coverage is good.

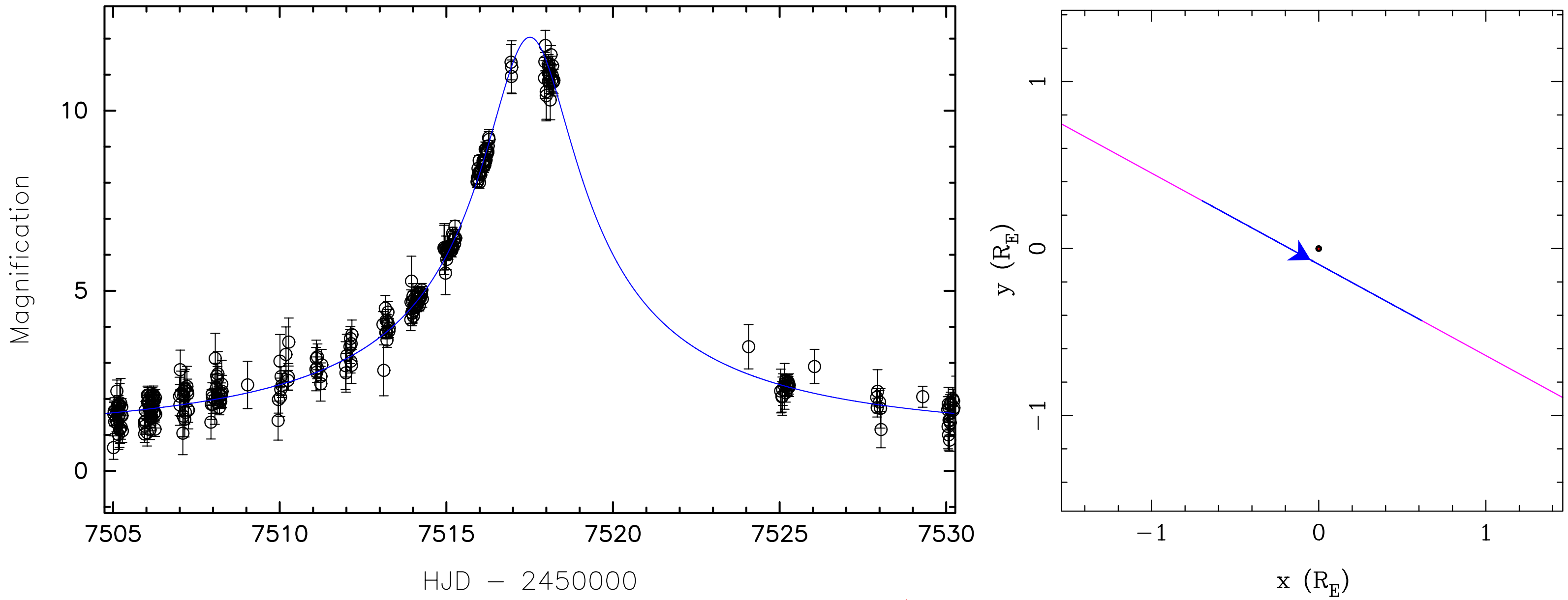
- Treatment of **ambiguous and degenerate events** is difficult and important

Gould+10: Used only high magnification events, where 6 planets are included in 13 events.

Suzuki+16 (the MOA-II sample): Used good coverage events, where 23 planets are included in 1474 events.
-> 1 ambiguous event tuned out to be a binary system(Terry+22).
-> Further analysis found a new planetery model for the ambiguous event(Zhang+26)

Zang+25 (the KMT sample): Used good coverage events, where 63 planets are included from 2016-2019 data.
-> they extrapolate the detection efficiency from 2018-2019 data to 2016-2017
-> some ambiguous events were excluded from the sample

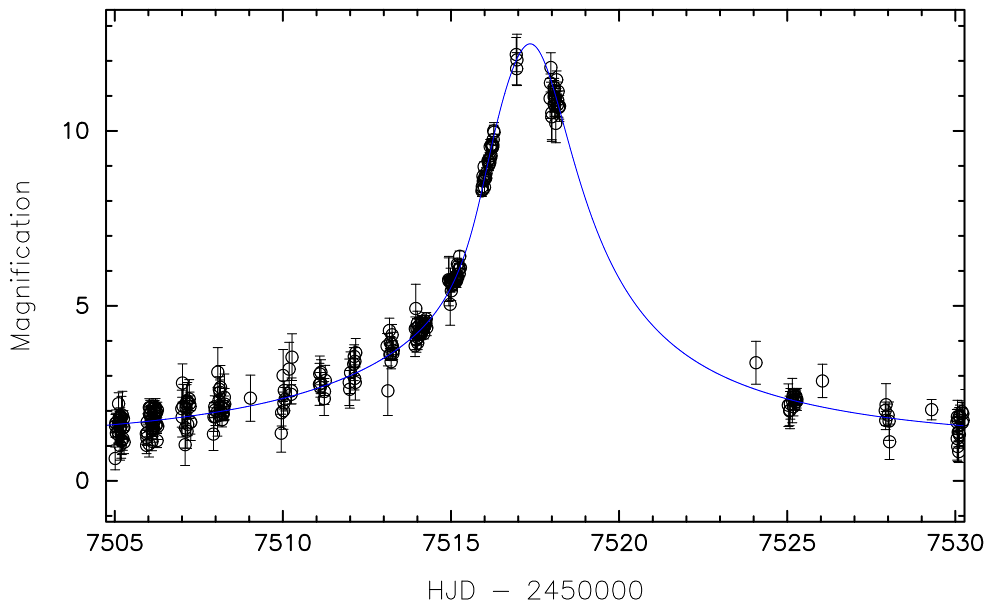
Injection and recovery for detection efficiency

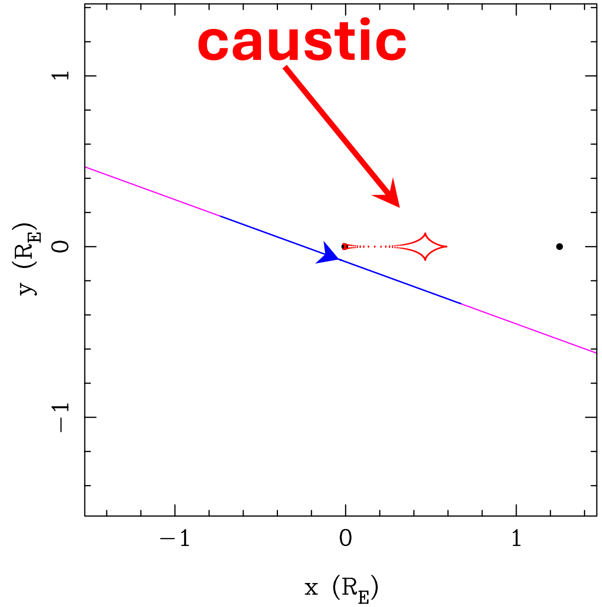


Injection and recovery for detection efficiency

$q = 0.006$, $s = 1.26$, $\alpha = 0.35$ (20deg)

Not detectable

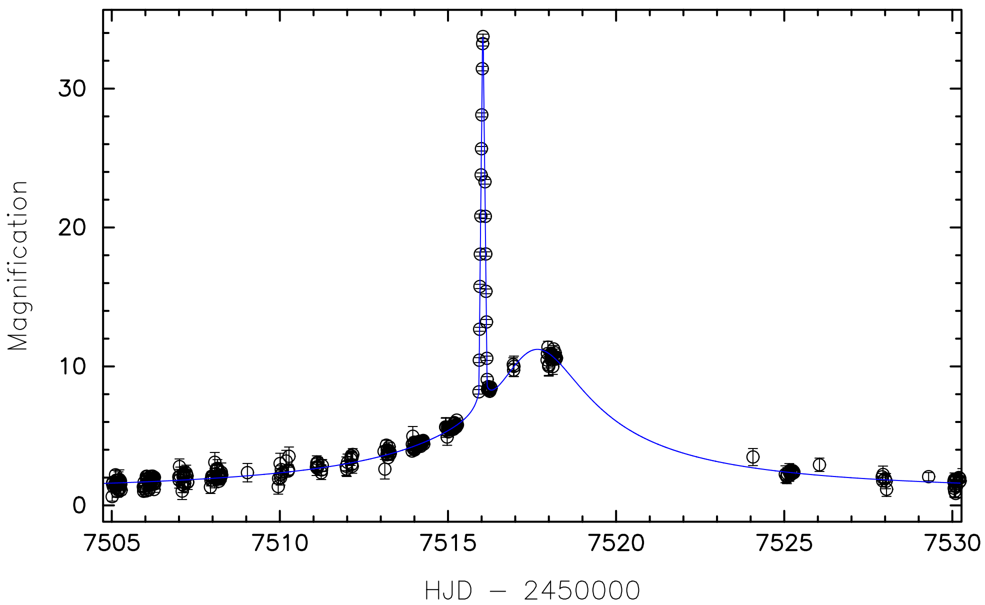


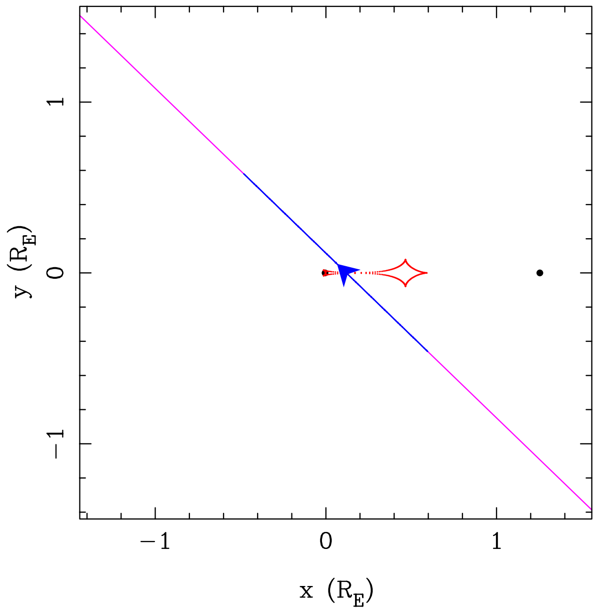


Injection and recovery for detection efficiency

$q = 0.006,\ s = 1.26,\ \alpha = 3.91$ (224deg)

Detectable

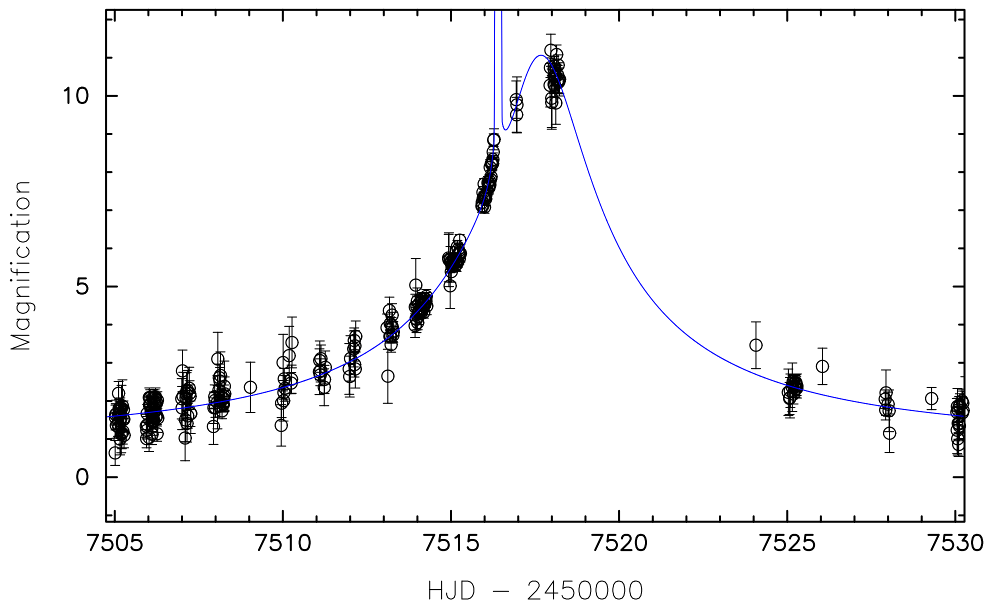


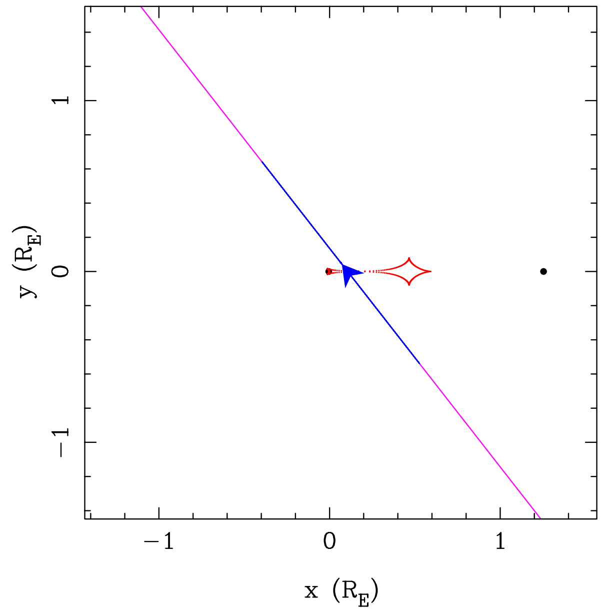


Injection and recovery for detection efficiency

$q = 0.006, s = 1.26, \alpha = 4.05$ (232deg)

Not detectable





Injection and recovery for detection efficiency

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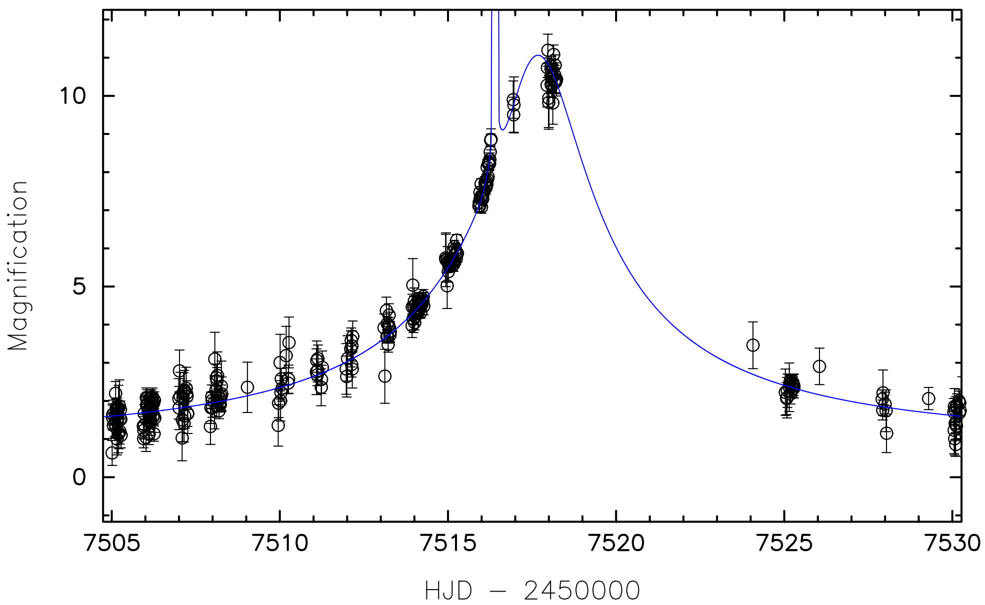
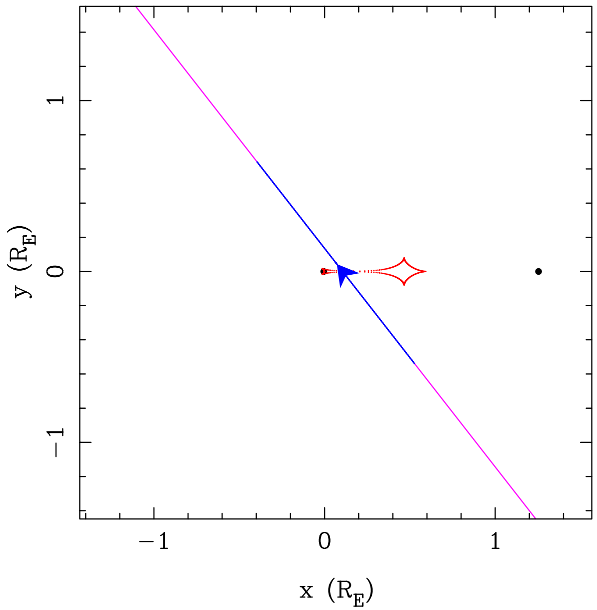
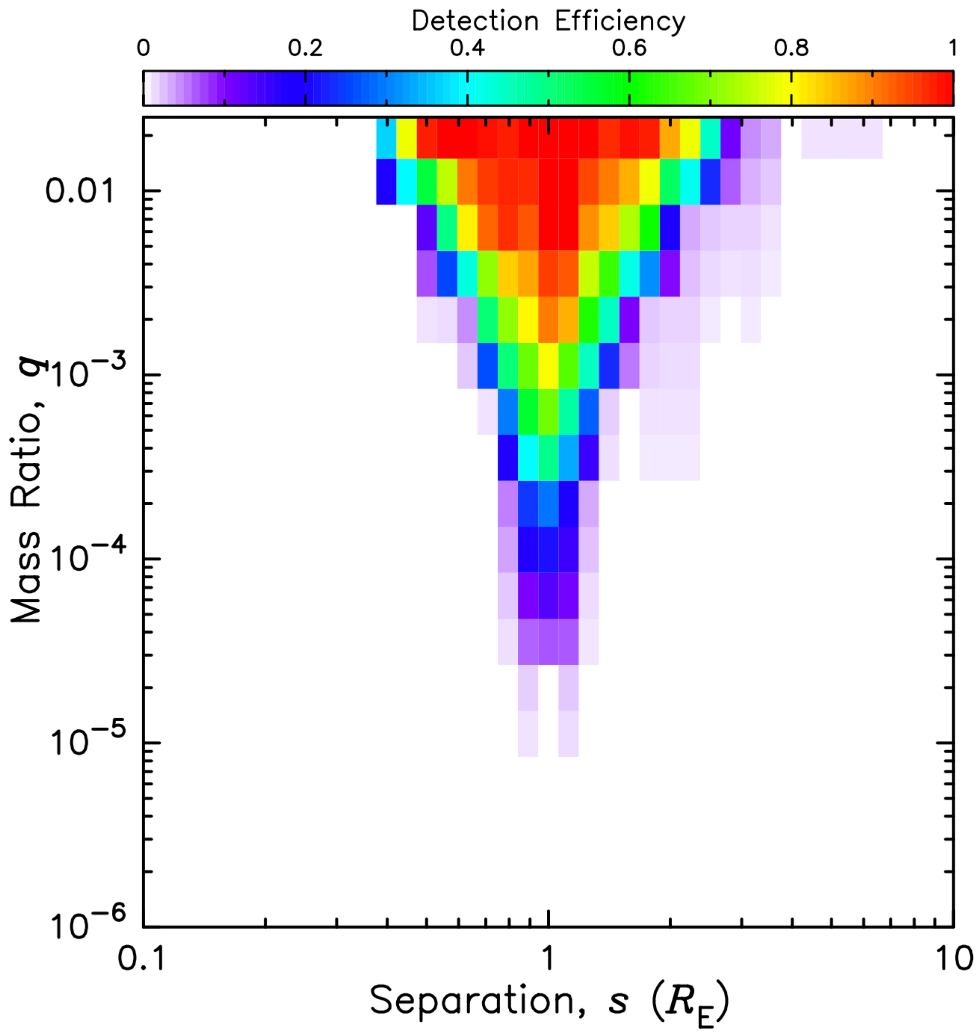
Not detectable





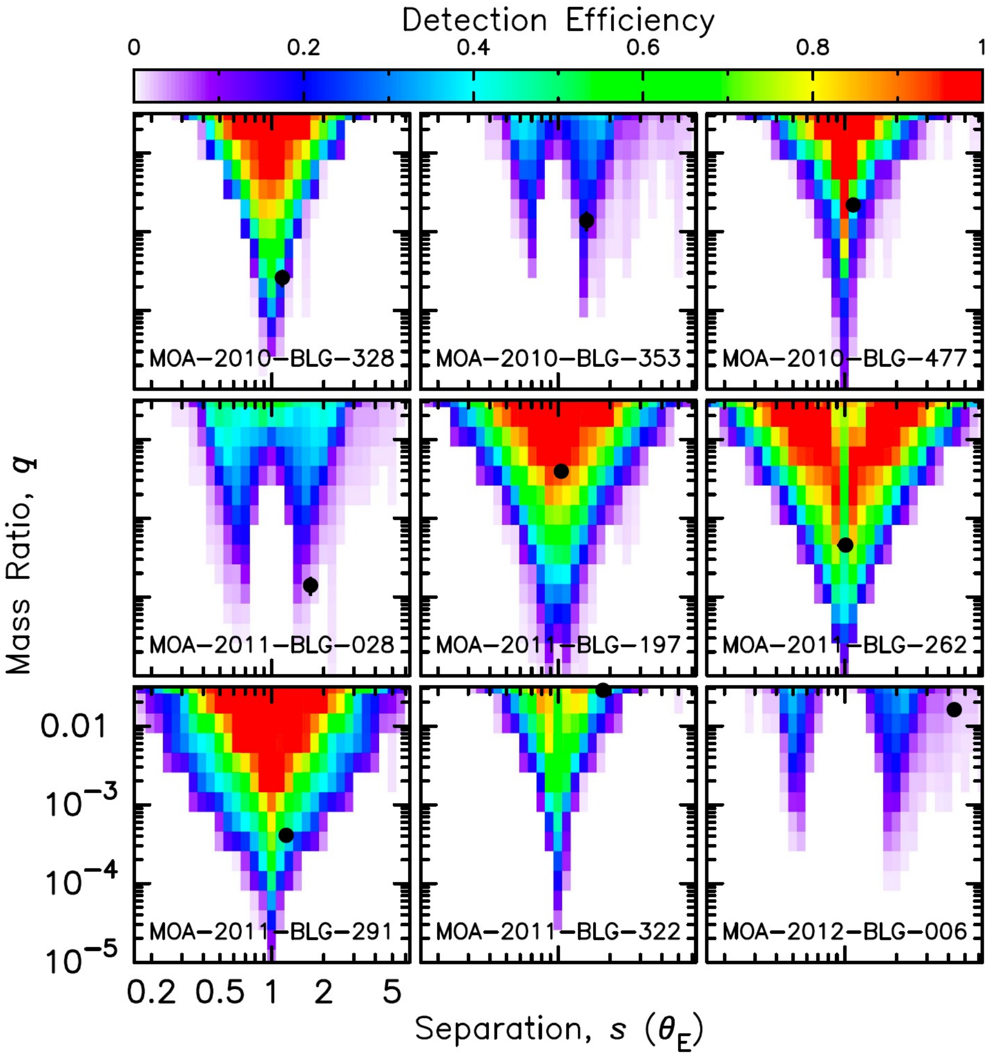
- Detection: if $\chi^2_{\rm single} - \chi^2_{\rm planetary} > \Delta\chi^2_{\rm threshold}$
- $\varepsilon(\log s, \log q)$: Fraction of detections within $0 < \alpha < 2\pi$

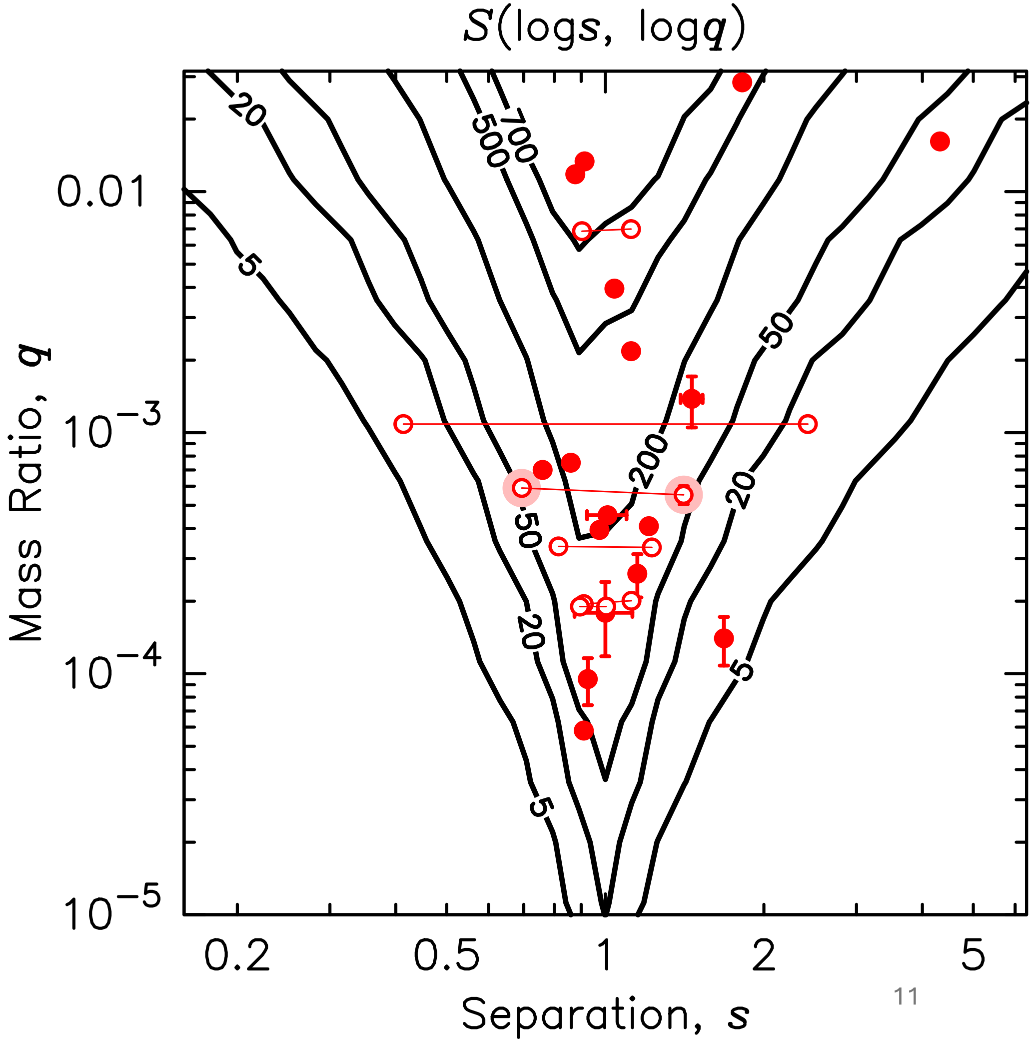
Detection efficiency, ε (log s, log q)



Detection efficiency, ε (log s, log q)

Suzuki+16

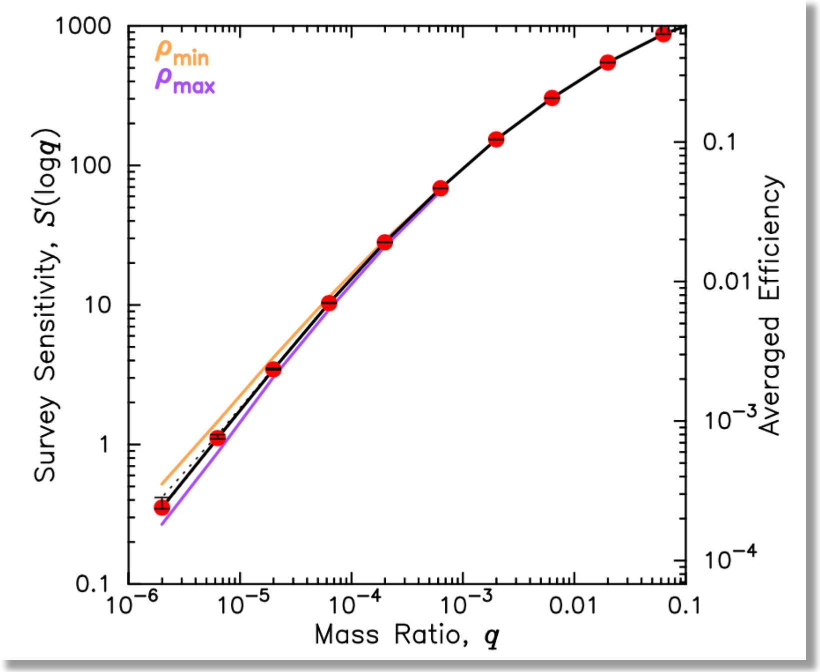




Mass-ratio corrected distribution

Suzuki+16

Detection efficiency on the mass-ratio



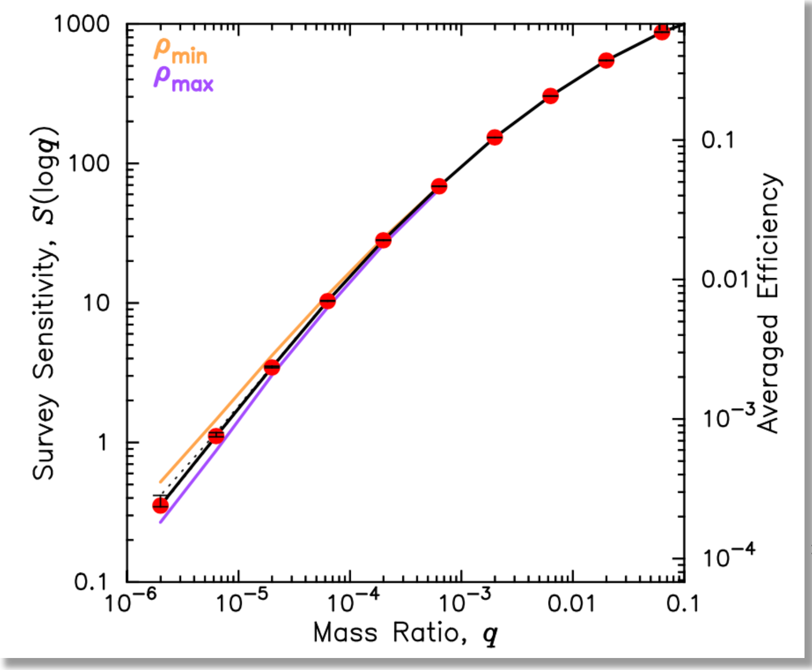
MOA-II

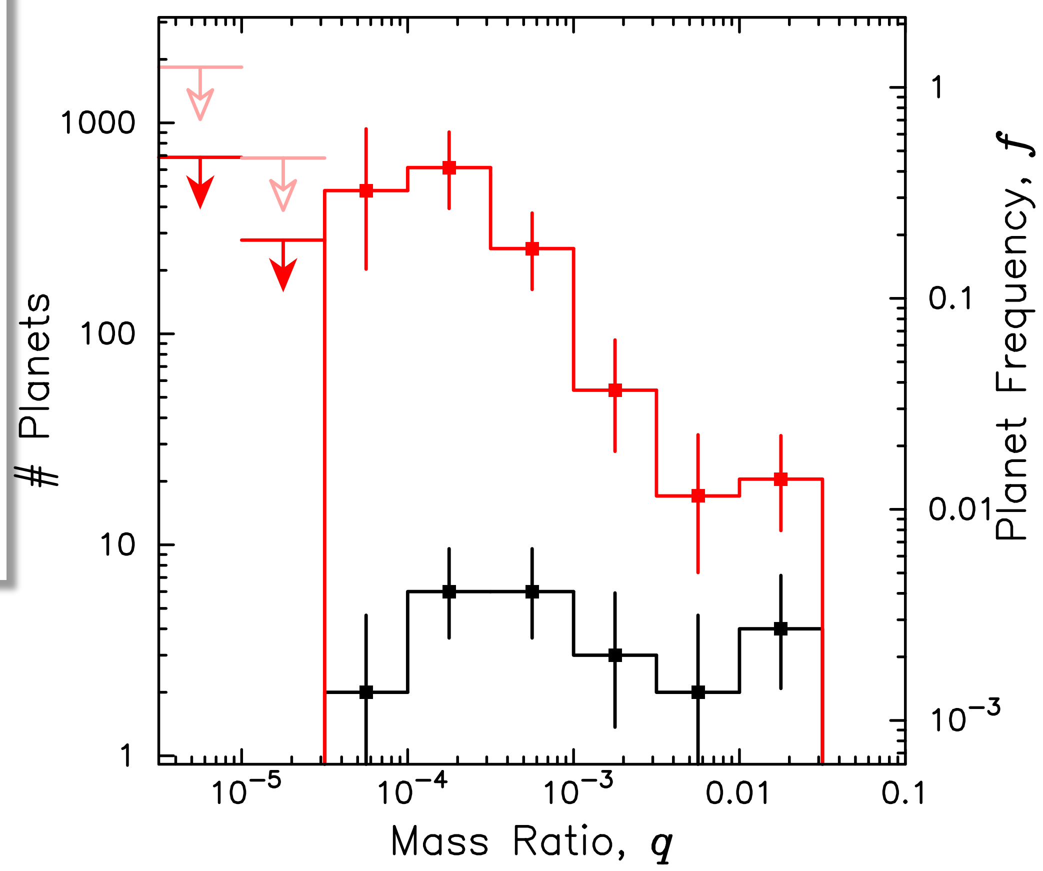
23-planet sample

Mass-ratio corrected distribution

Suzuki+16

Detection efficiency on the mass-ratio





MOA-II

23-planet sample

Occurrence, planet frequency

Suzuki+16

$$f \equiv \frac{d^2N}{d\log q\, d\log s} = A\left(\frac{q}{q_{br}}\right)^n s^m \quad [q \geq q_{br}]$$

$$= A\left(\frac{q}{q_{br}}\right)^p s^m \quad [q < q_{br}]$$

- By integrating the mass-ratio function, we got roughly 1 cold planet(s) in the microlensing sensitivity region.

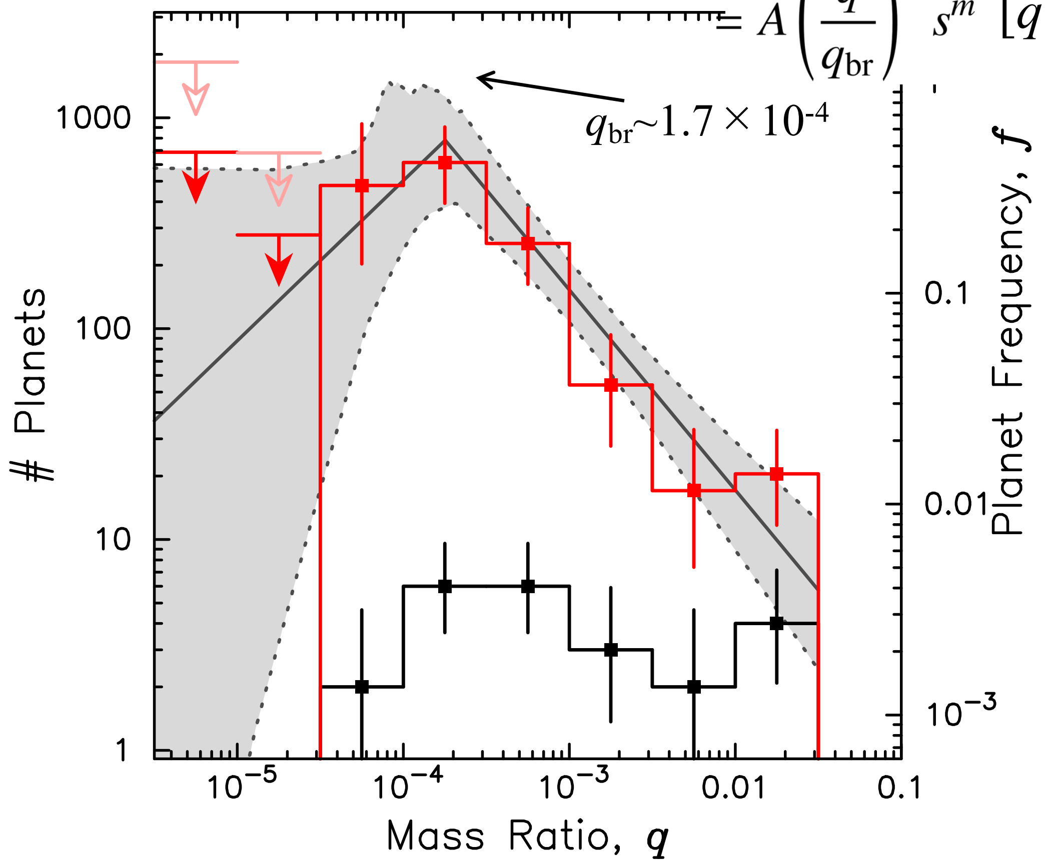
- When combined the MOA-II sample with the previous surveys (30 planets) w/ fixed q_{br}

  $A = 0.61^{+0.21}_{-0.16}$

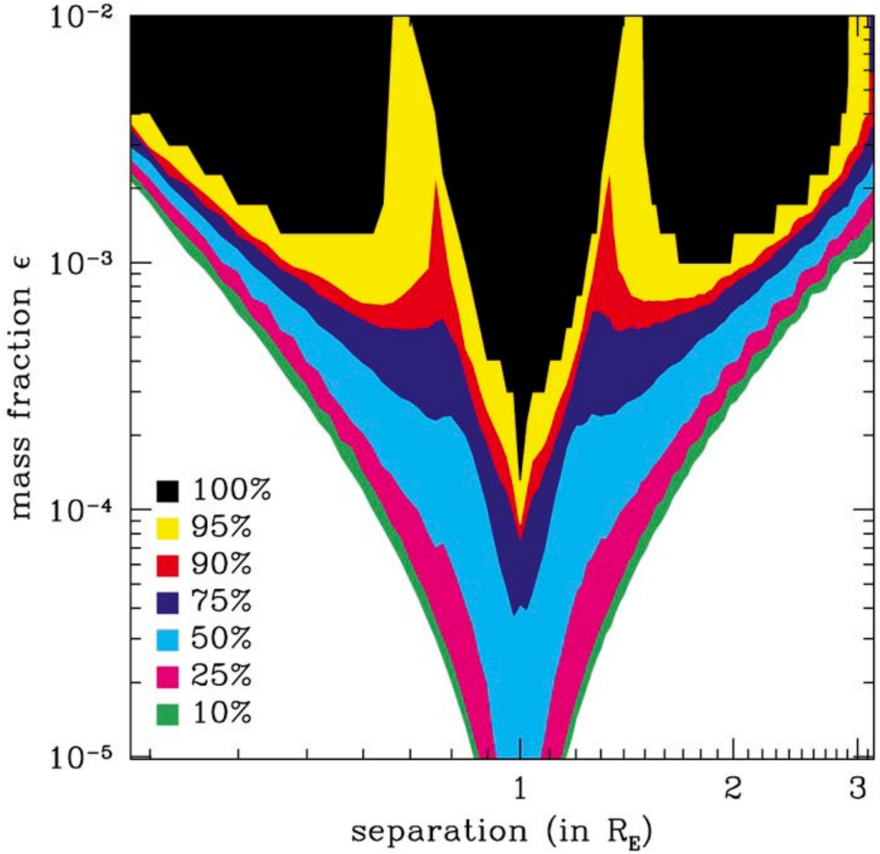
  $n = -0.94 \pm 0.13$

  $m = 0.49^{+0.47}_{-0.49}$

  $p = 0.6^{+0.5}_{-0.4}$

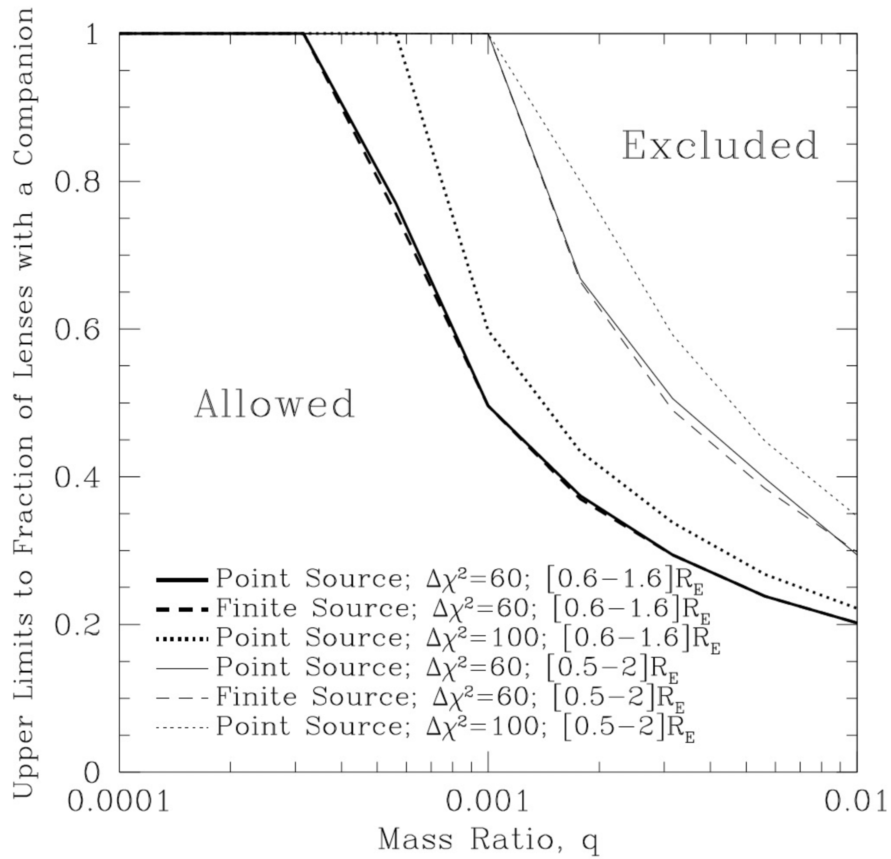


History (before the first μlens planet discovery)



Rhie+00

Detection efficiency for MACHO 98-BLG-35

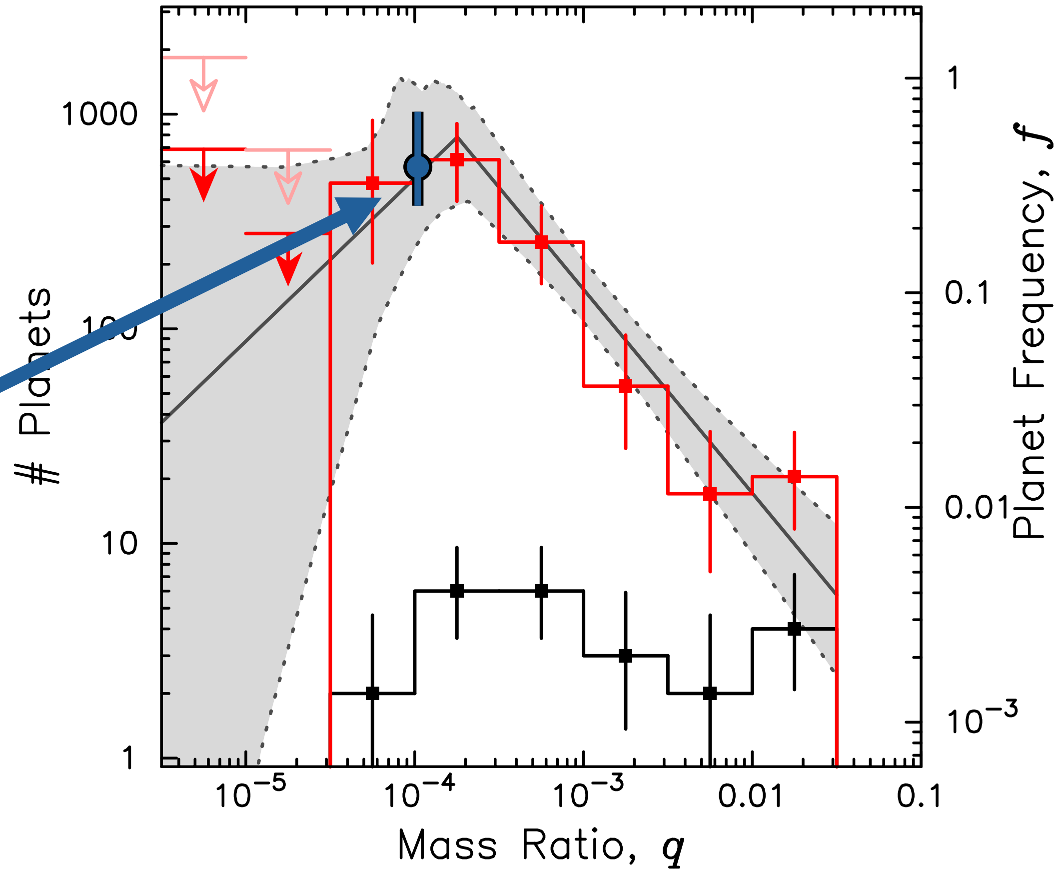


Upper limit on the plane occurrence by 5-year PLANET collaboration data (Gaudi+02)

History (a few detection)

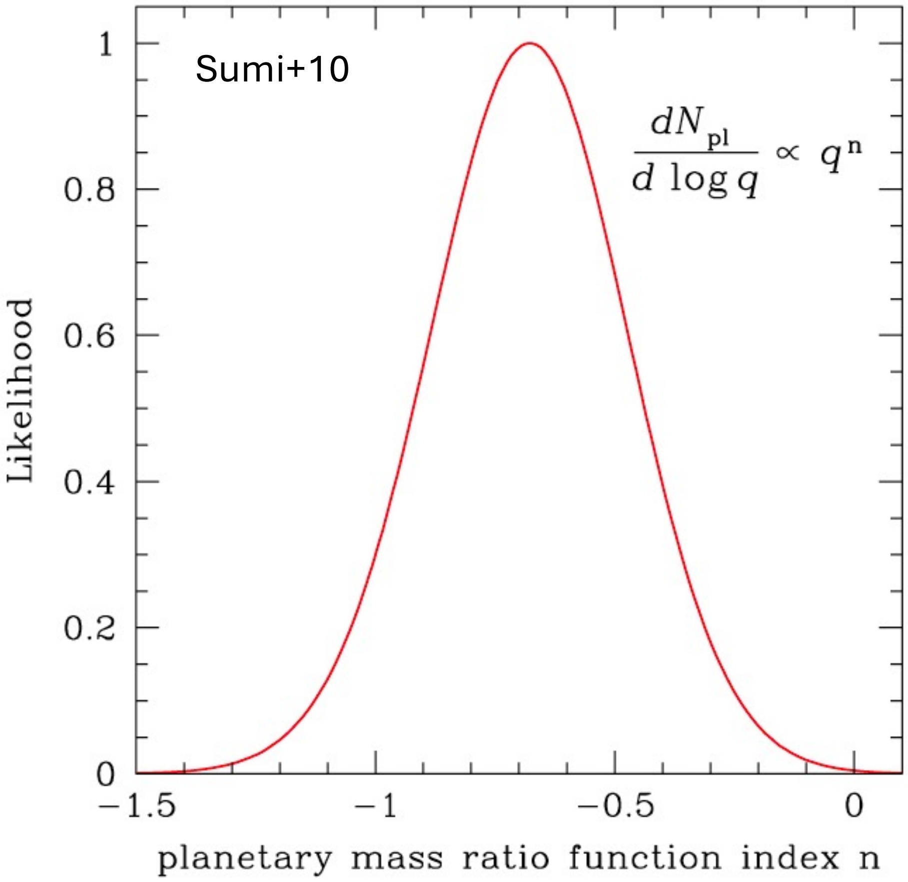
- Gould et al. 2006 used just two discoveries of q ~10^{-4} planets (OGLE-2005-BLG-169Lb, OGLE-2005-BLG-390Lb) to estimate the occurrence

Combining the two detections yields 90% upper and lower frequency limits f = $0.38^{+0.31}_{-0.22}$ just 0.4 decades of planet-star separation. In particular, f > 16% at 90% confidence. (Gould+06)

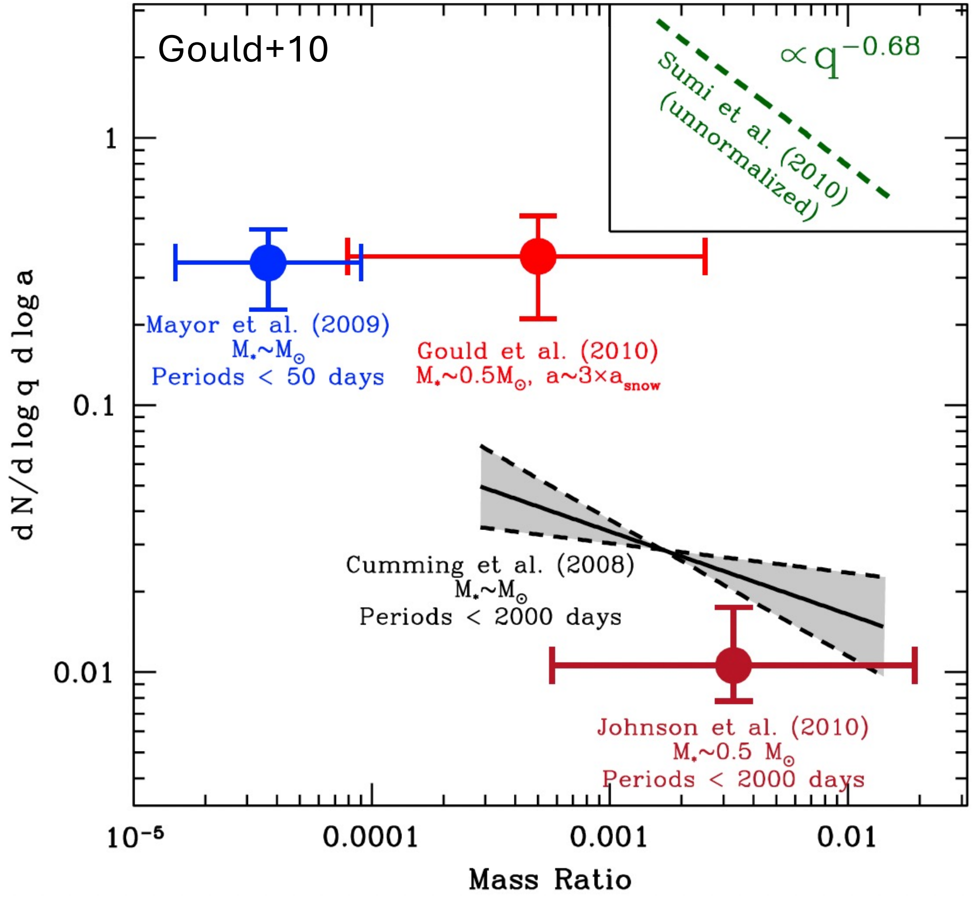


Note: The blue point w/ error was plotted by hand, and the x-axis values are approximate.

History (10 detections, 6 detections)

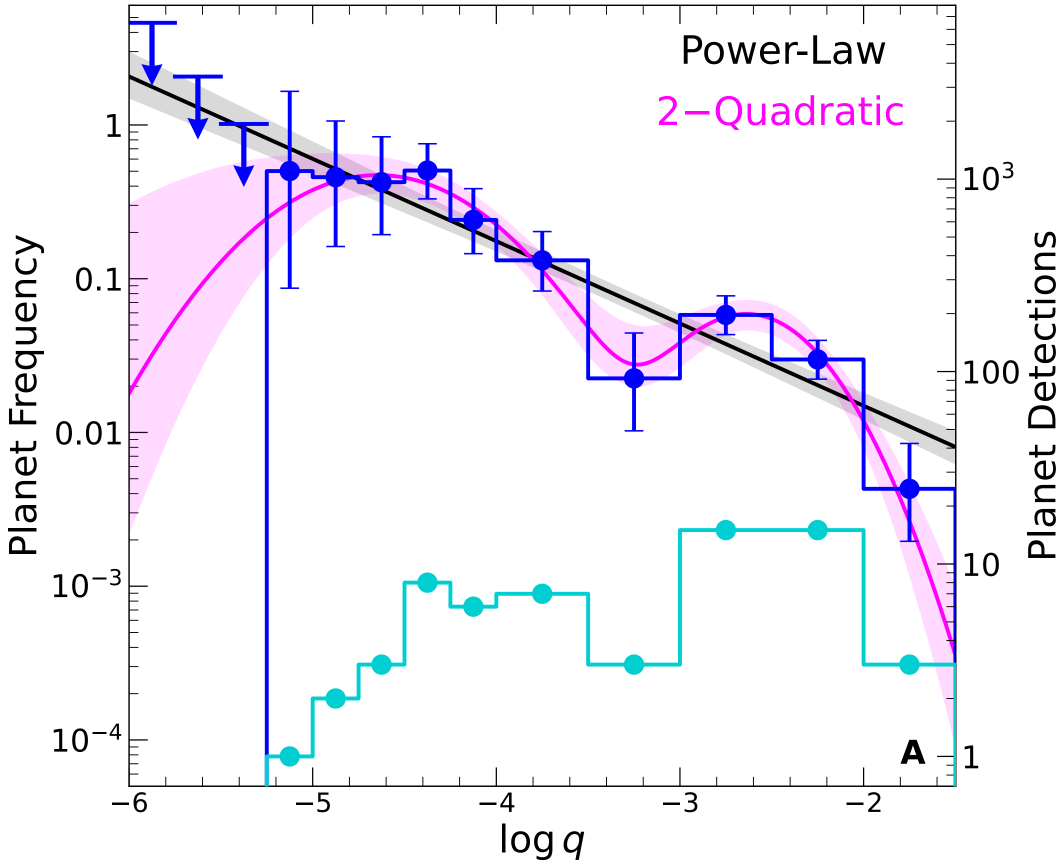


Using 10 planets and asummed detection efficiency slope, only slop was constrained as n = -0.68±0.20



6 planets from the high-magnification sample

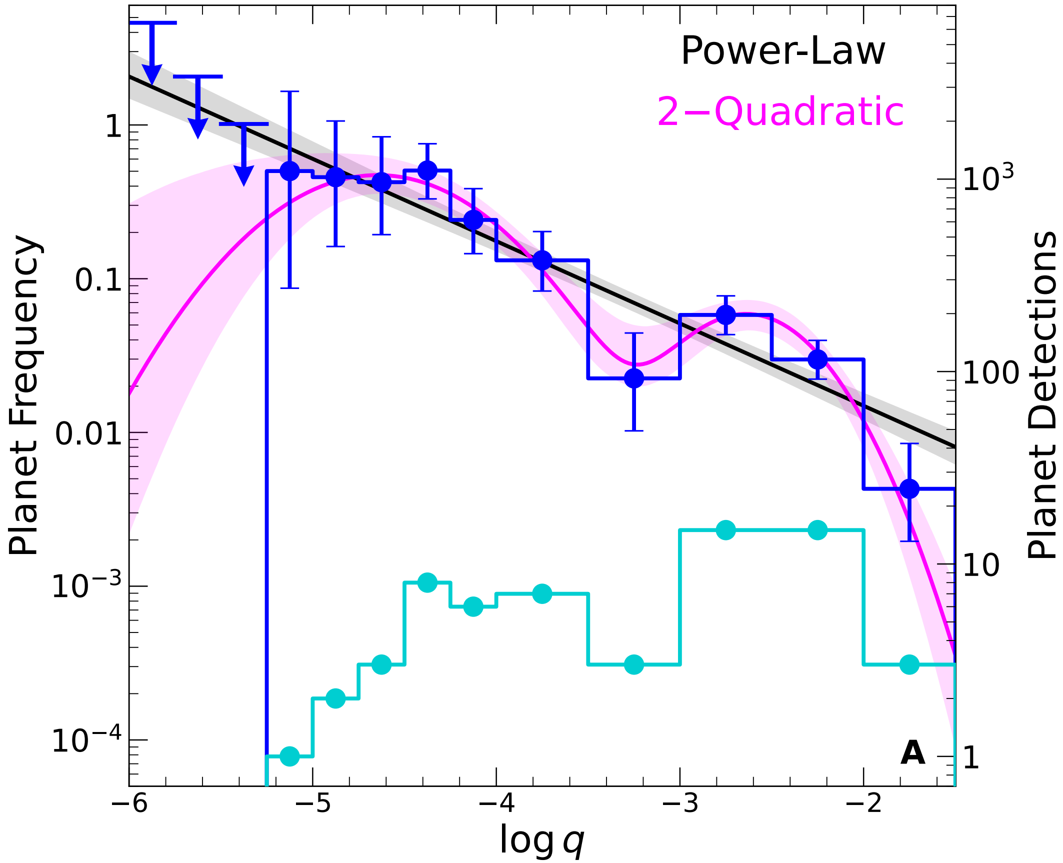
Mass-ratio function from the KMT survey



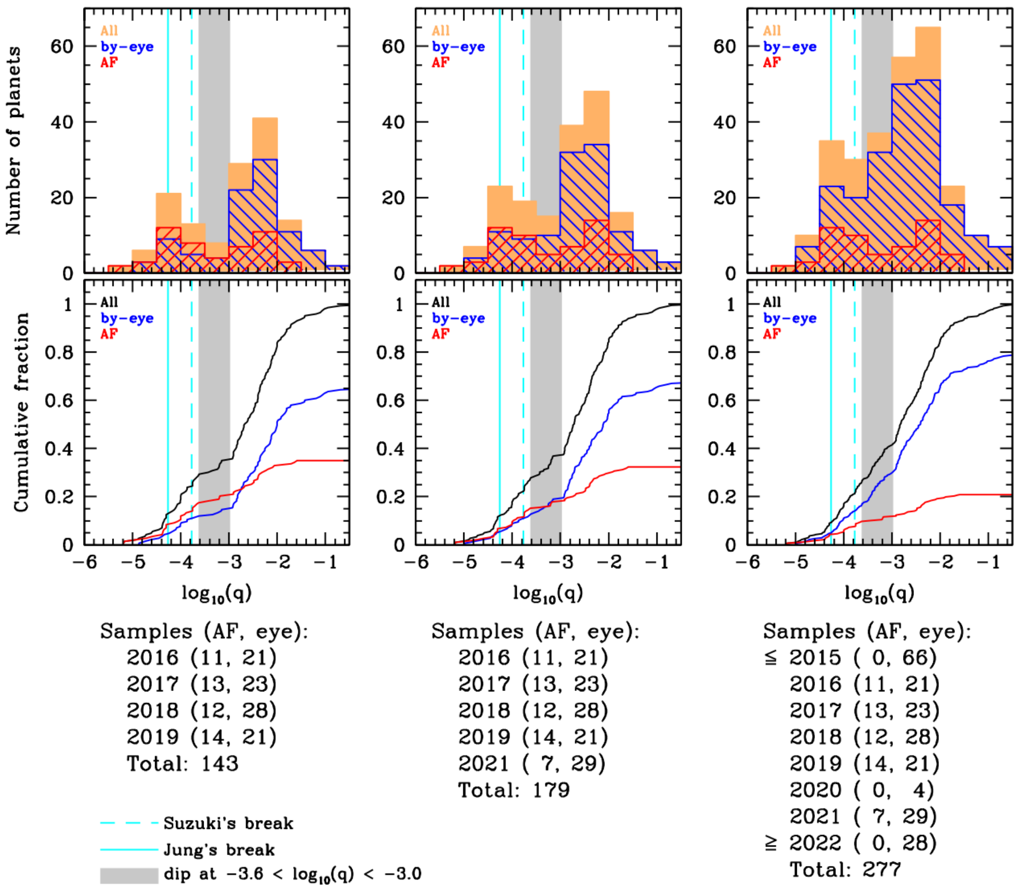
Zang+25

- 63planets from 2016-2019
- Possible dip at ~5x10^-4
- Which is almost Saturn mass assuming $0.5M_{Sun}$
- Which is not seen in the previous works

Mass-ratio function from the KMT survey



Zang+25



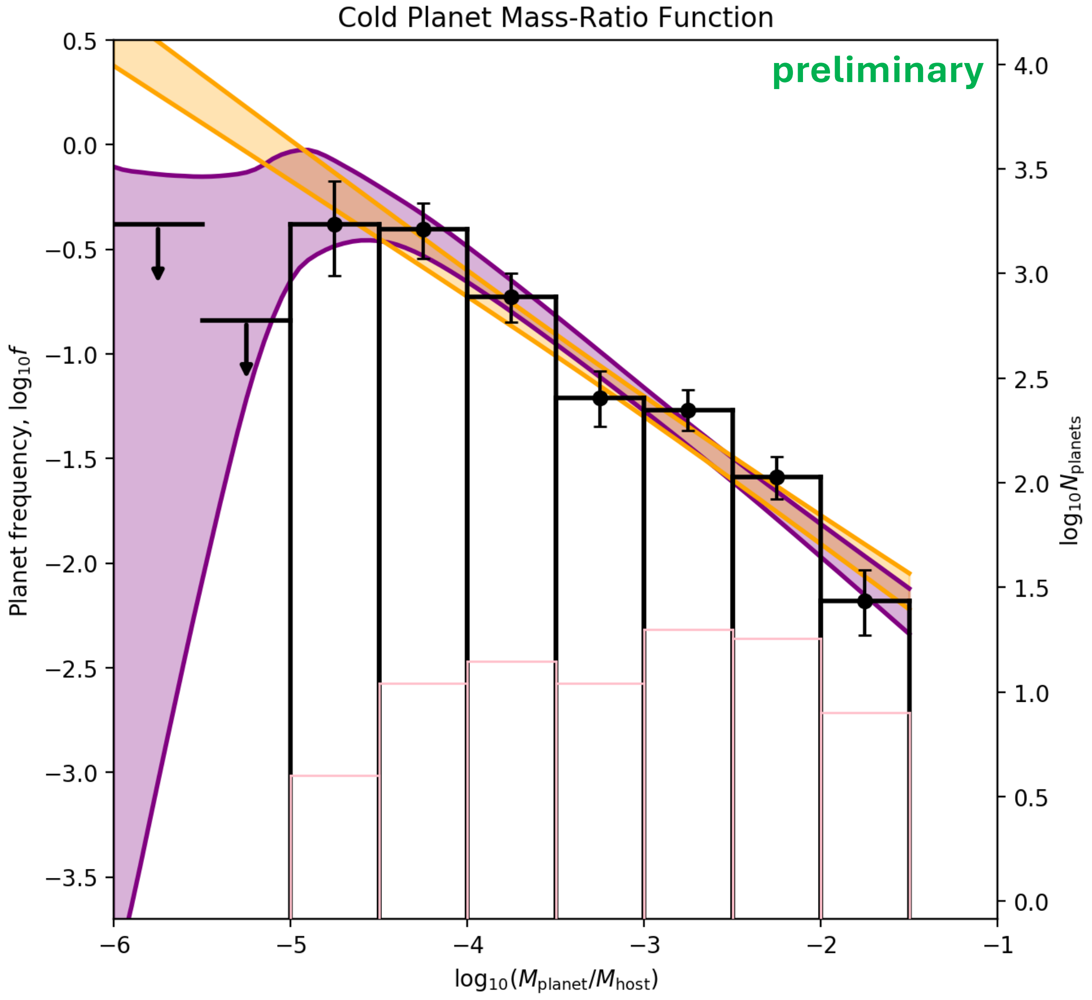
Samples (AF, eye):
2016 (11, 21)
2017 (13, 23)
2018 (12, 28)
2019 (14, 21)
Total: 143

Samples (AF, eye):
2016 (11, 21)
2017 (13, 23)
2018 (12, 28)
2019 (14, 21)
2021 (7, 29)
Total: 179

Samples (AF, eye):
≦ 2015 (0, 66)
2016 (11, 21)
2017 (13, 23)
2018 (12, 28)
2019 (14, 21)
2020 (0, 4)
2021 (7, 29)
≧ 2022 (0, 28)
Total: 277

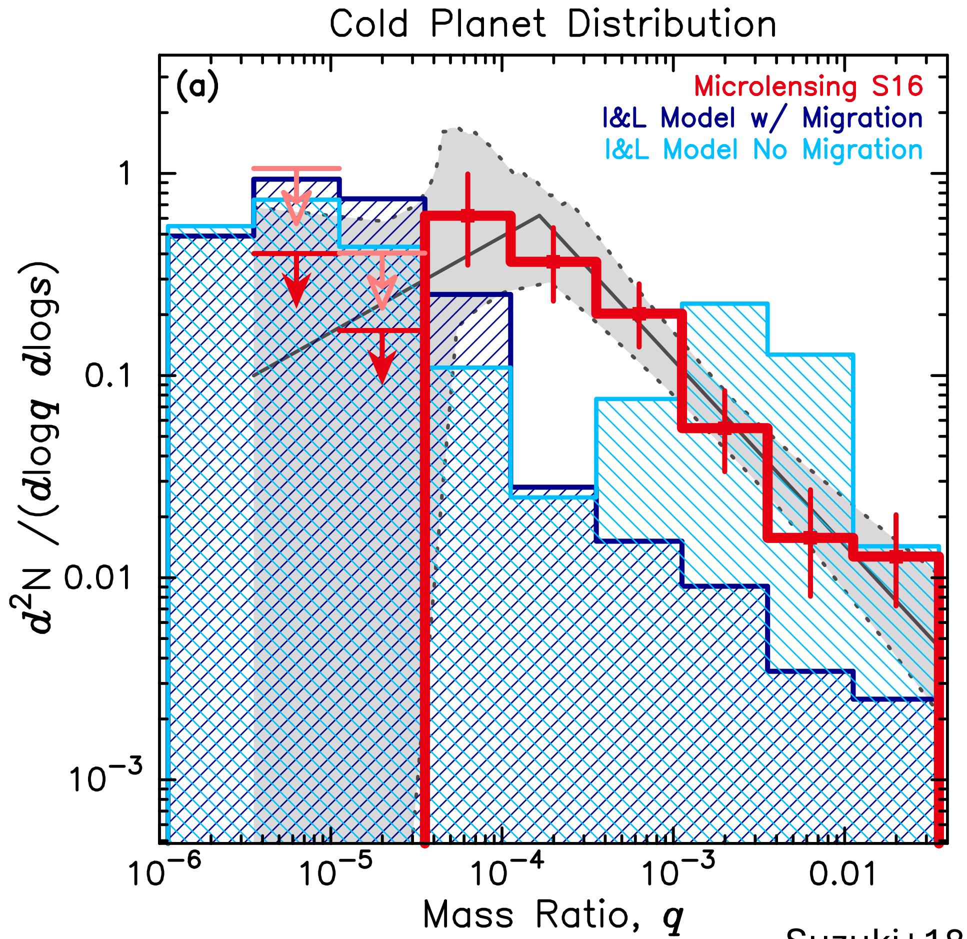
Shin+26

KMT+ MOA combined sample

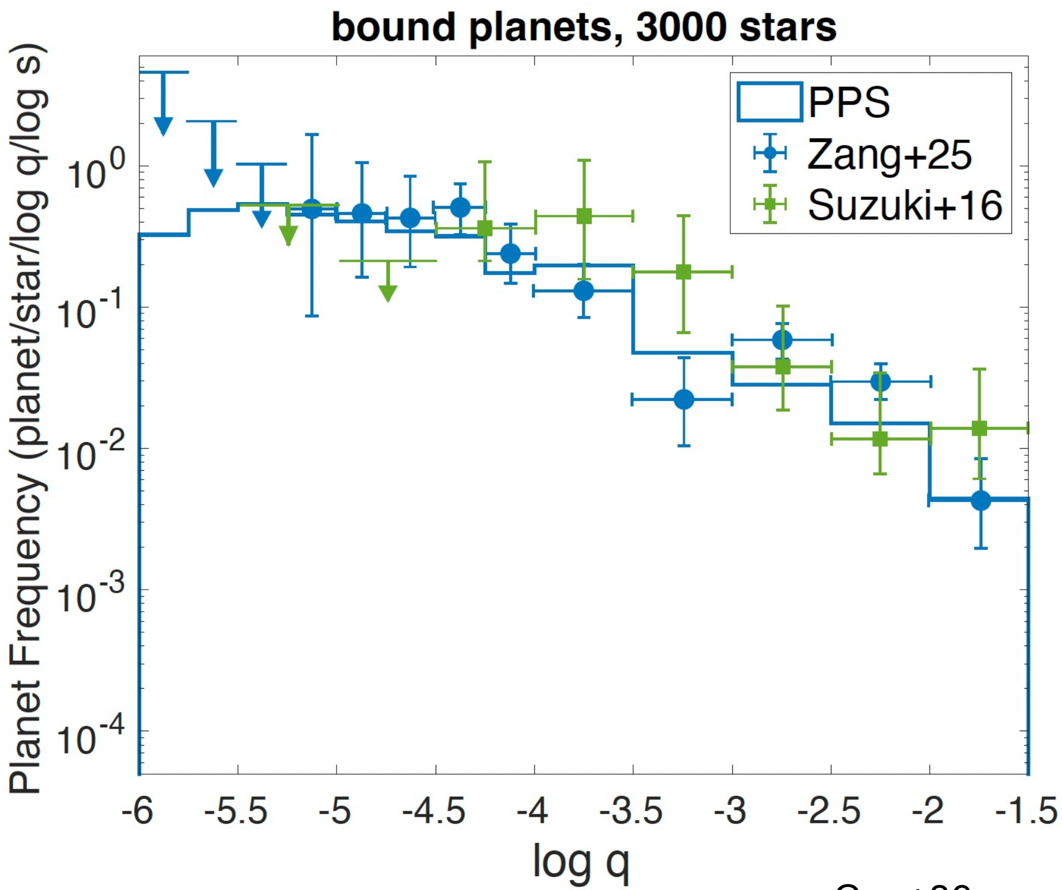


- Combined Suzuki+16 sample (30 planets) with Zang+25 sample (55 planets from 2018 and 2019)
- Total 85 planets are used.
- The dip at 5×10^{-4} disappeard.
- Broken power law is slighty favored.

Comparison to the theory (core accretion population synthesis model)

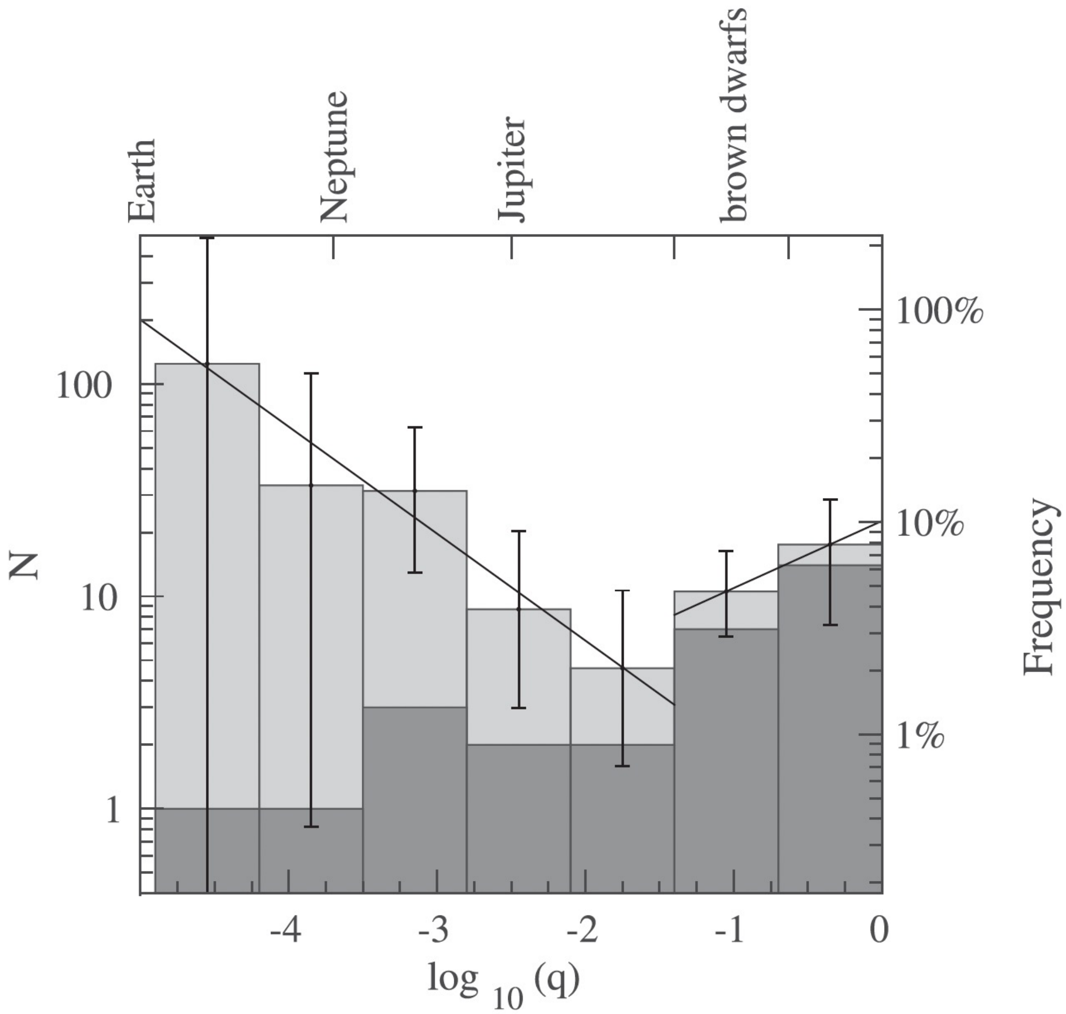


Suzuki+18



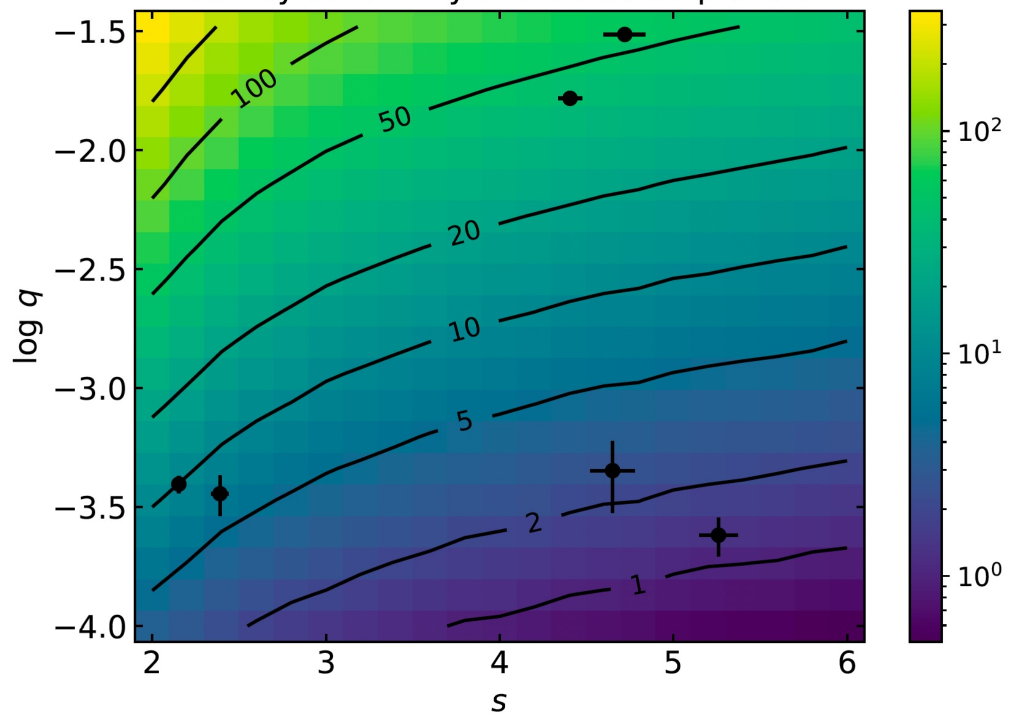
Guo+26

Gap between planets and brown dwarfs

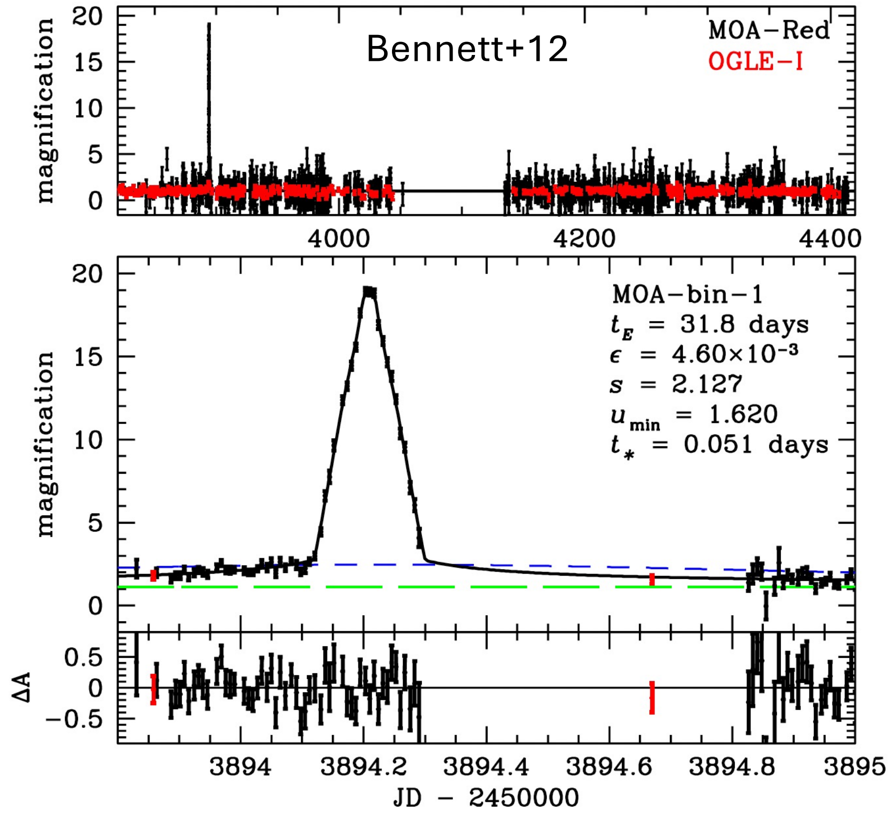


- Shvartzvald et al. 2016 estimated mass-ratio function from the planetary to stellar companion regime by using the MOA, OGLE and Wise survey data.
- We see the two population clearly and the deficit would be an analog of brown-dwarf desert found by RV around solar type stars.

Discussion: very wide planets?

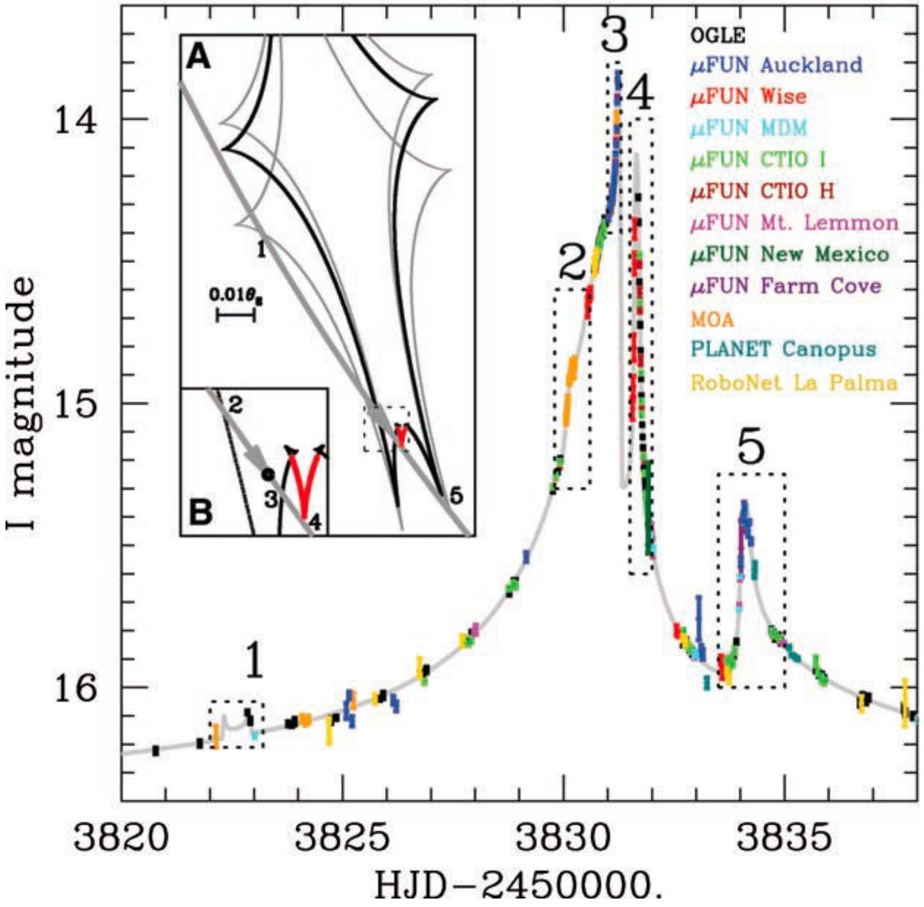


Poleski et al. 2021 estimated the occurrence of wide μlens planets, which is 2.4σ higher than Suzuki+16 estimate.

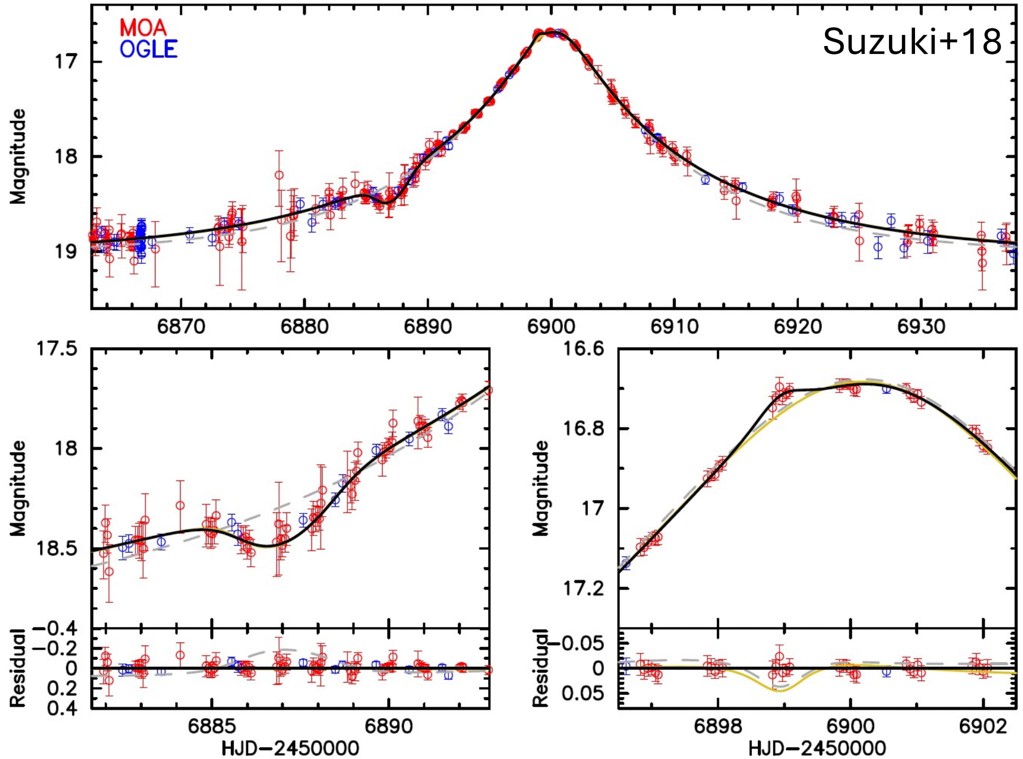


A wide planet detected only the anomaly signal: no magnification by the host.

Discussion: multiplicity?

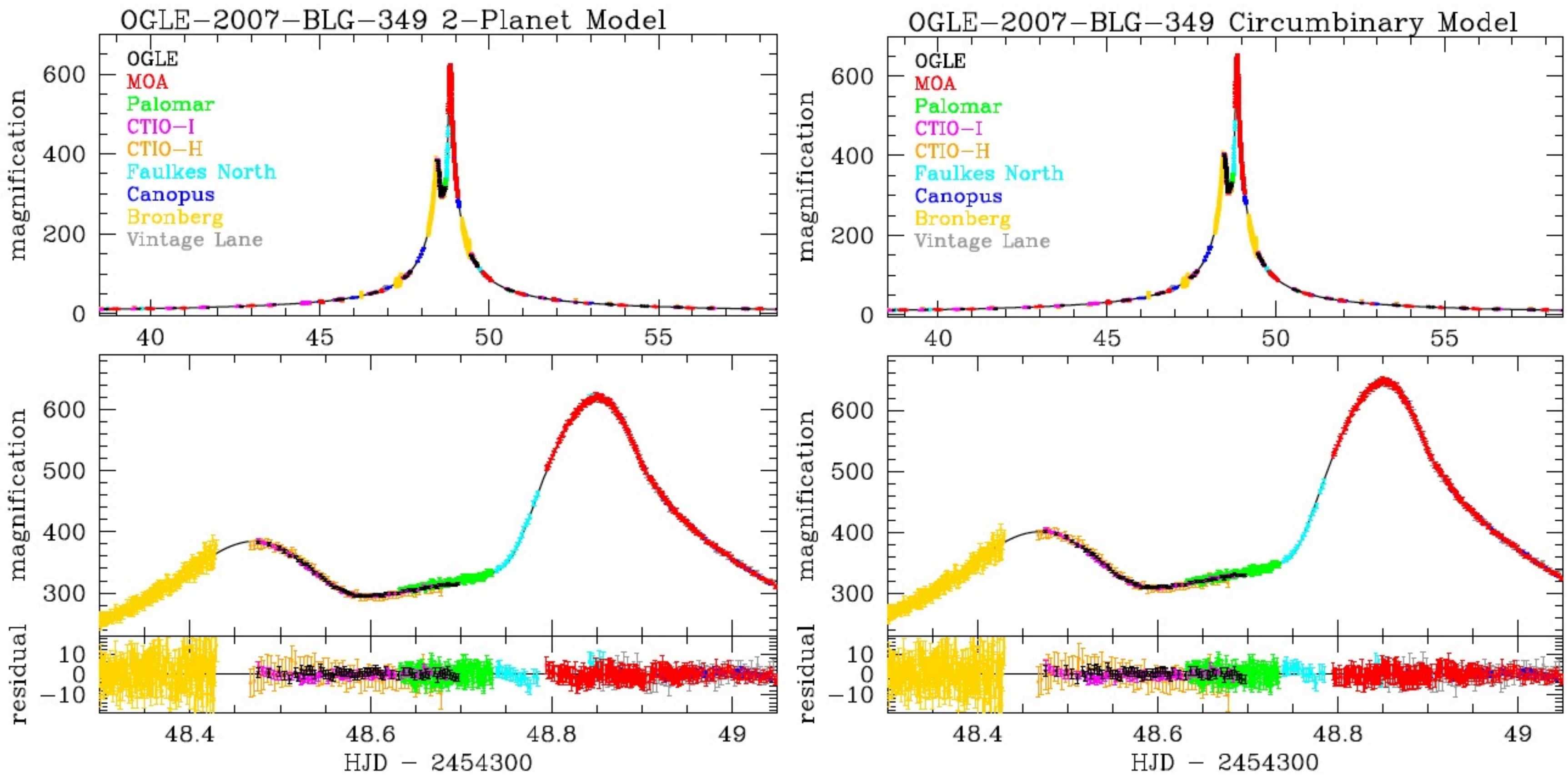


Gaudi+08, Bennett+10



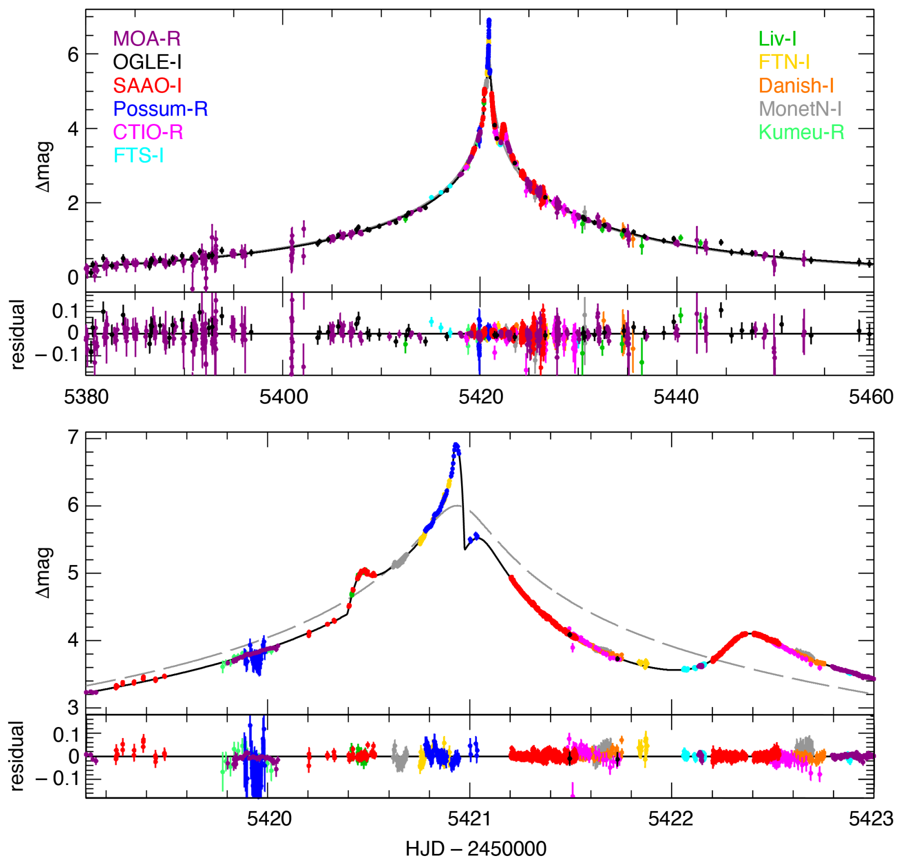
These are both two gas-giant system.
Assuming the extrapolation of the detection efficiency, the occurrence of two gas-giant system is estimated as η_{multi} = 0.06±0.02

Discussion: binary systems?

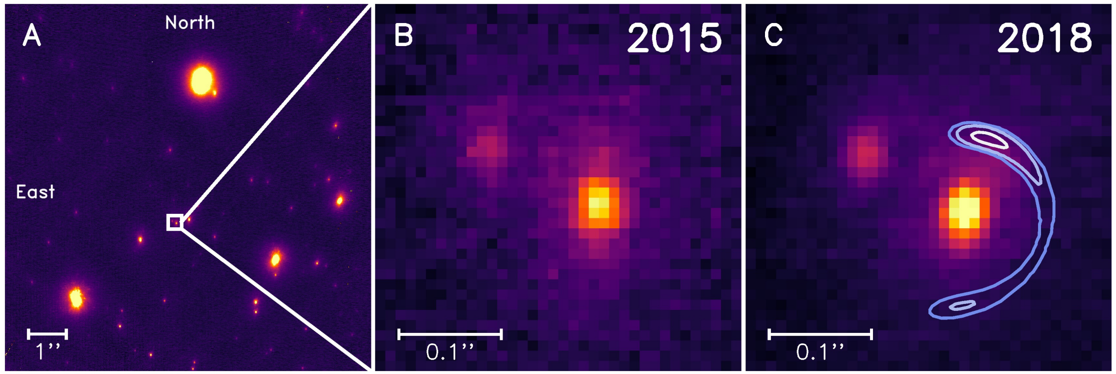


Bennett et al. 2016 found that the HST data is only consistent with the circumbinary model.
This event is inclueded in the Suzuki+16 sample, as the light curve shape is not dominated by the stellar binary lens.

Discussion: white dwarf hosts?

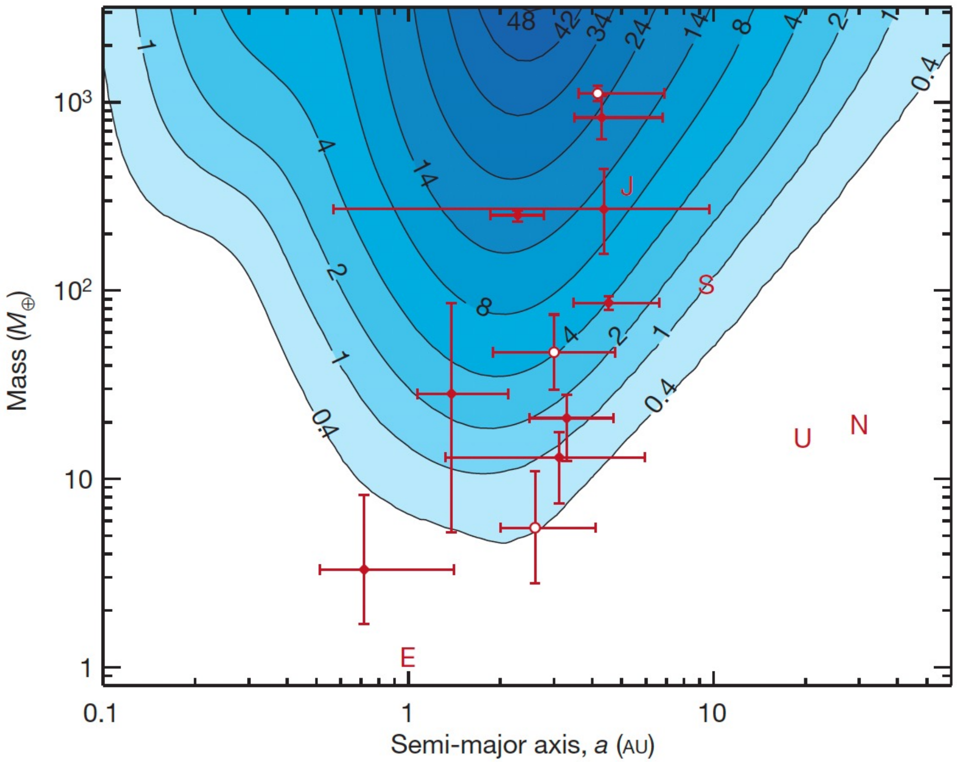


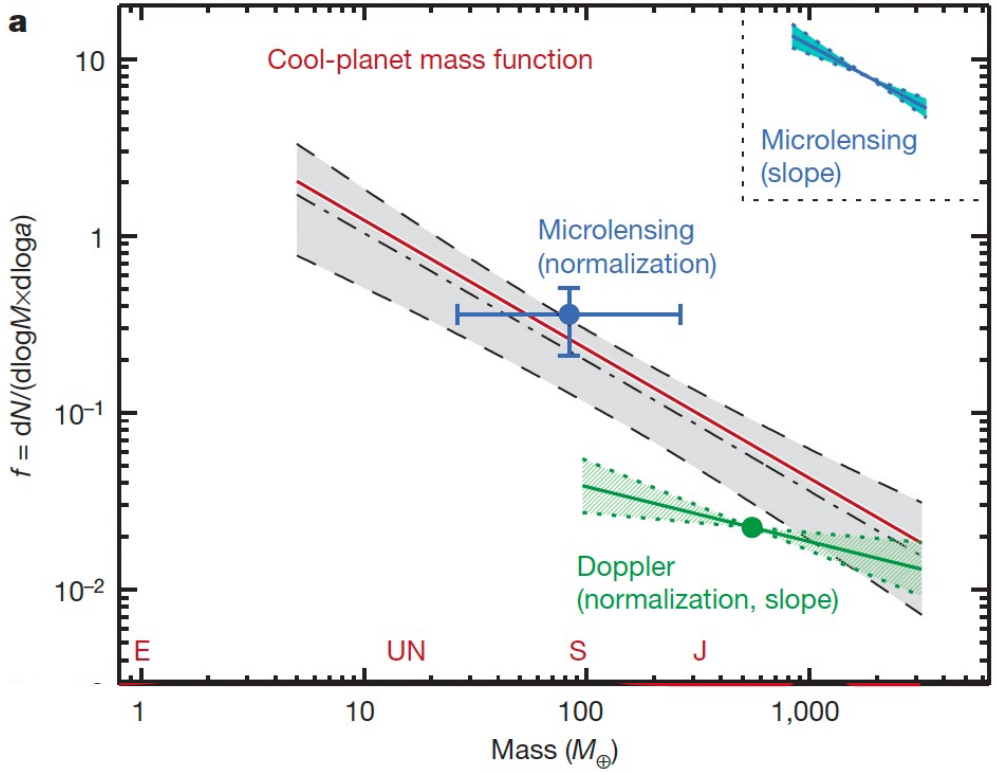
Blackman+21



- Suzuki+16 includes at least one (probably another one) white dwarf planet(s) that is about 4-9% of the selected sample.
- This is not super surprising. But, with the ground based data, it will be hard to measure the planet coccurce around the white dwarf.

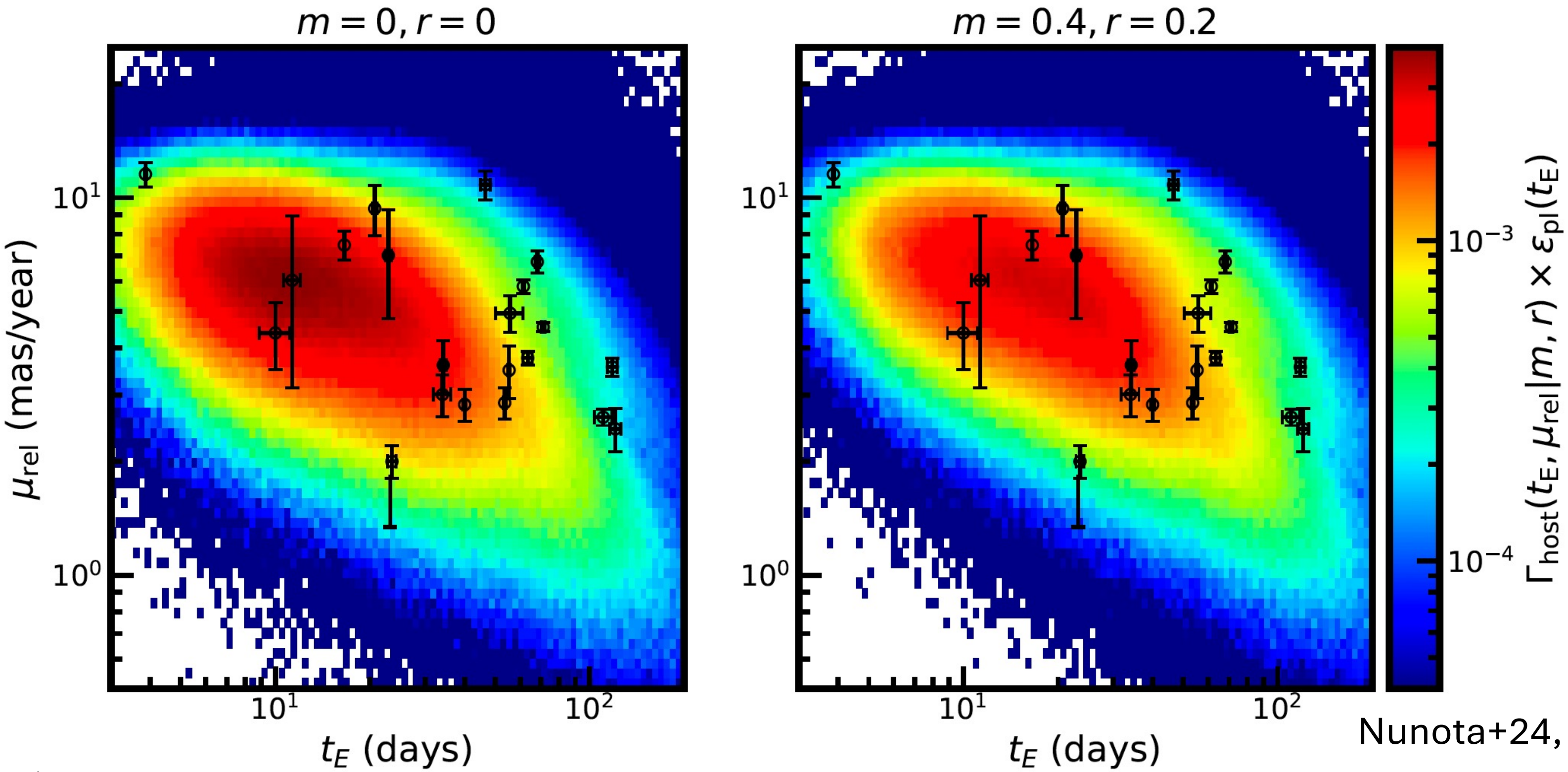
Mass function (Cassan+12)





- They calculated the detection efficiency in ε(log s, log q)
- Then, converted it to ε(log a, log M) using the Galactic model
- Which assumes that planet occurrence dose not depend on the host parameters (Mass, Distance)

On the host star mass / distance



Nunota+24, Koshimoto+21

Kansuke Nunota

- $\eta \propto M^m R^r$
- $m = 0.50^{+0.90}_{-0.70}$
- $r = 0.10^{+0.51}_{-0.37}$

$q < 10^{-3}$: $m = -0.08^{+0.95}_{-0.65}$

$q > 10^{-3}$: $m = 1.25^{+1.07}_{-1.14}$

Summary

- ➢Microlensing studies have constrained cold planet occurrence rate.
- ➢Many open questioins remain;
  - Mass-ratio break, wide planet occurrence, super-jupyter/brown dwarf desert, multiplicity, binary system, white dwarf hosts, etc
- ➢These issues will be addressed by the Roman data

Rmoan is not just x1000 faster surveyor for the GBTDS, not just increasing the planet sample.

Roman will add a lot of new information that cannot be obtained from the ground, enabling a much better planet occurrence.