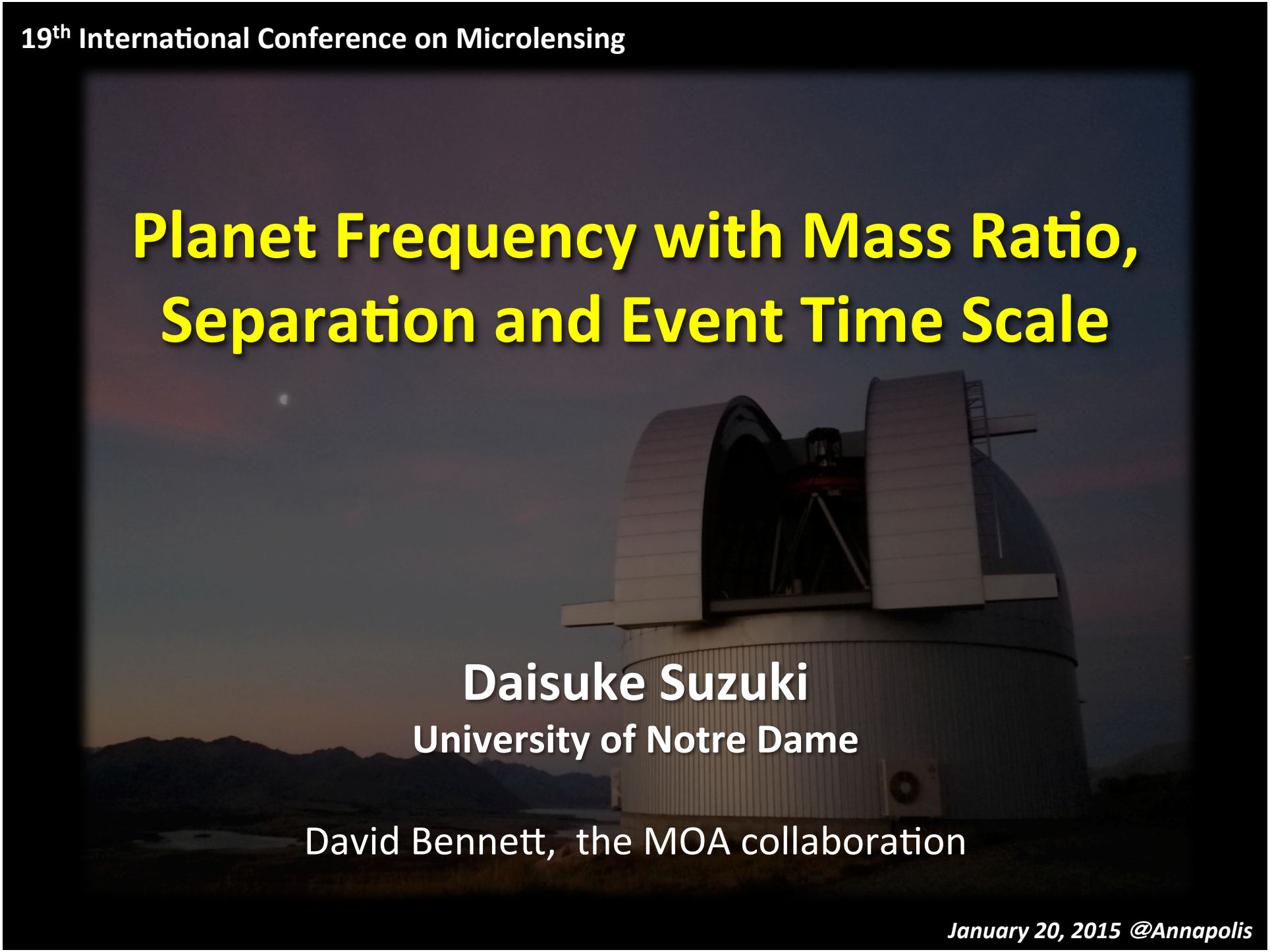
19th International Conference on Microlensing



Planet Frequency with Mass Ratio, Separation and Event Time Scale

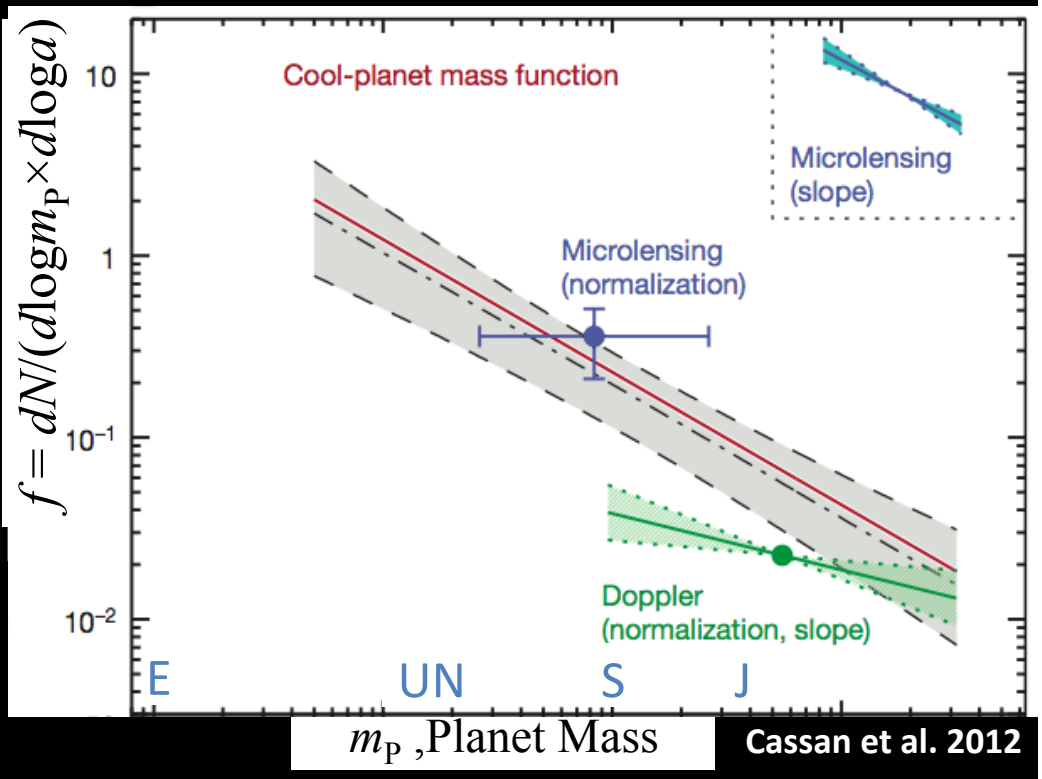
Daisuke Suzuki
University of Notre Dame

David Bennett, the MOA collaboration

January 20, 2015 @Annapolis

Statistics from Microlensing

- Sumi et al. 2010
  - $f \propto q^{-0.68\pm0.2}$
- Gould et al. 2010
  - 0.36 ± 0.15 @ $q \sim 5\times10^{-4}$
- Cassan et al. 2012
  - $10^{-0.62\pm0.22}(M/M_{\rm Sat})^{-0.73\pm0.17}$



Cassan et al. 2012

This work: focus on planet frequencies with

q: mass ratio

s: separation

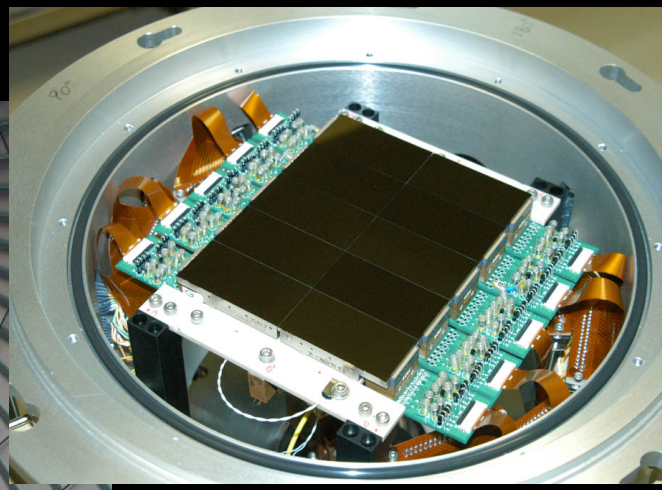
$t_{\rm E}$: event time scale

using MOA data in 2007-2012

MOA (since 1995)

（Microlensing Observations in Astrophysics）

（ New Zealand/Mt. John Observatory, Latitude：44˚S, Alt:　1029m ）



Mirror: 1.8m

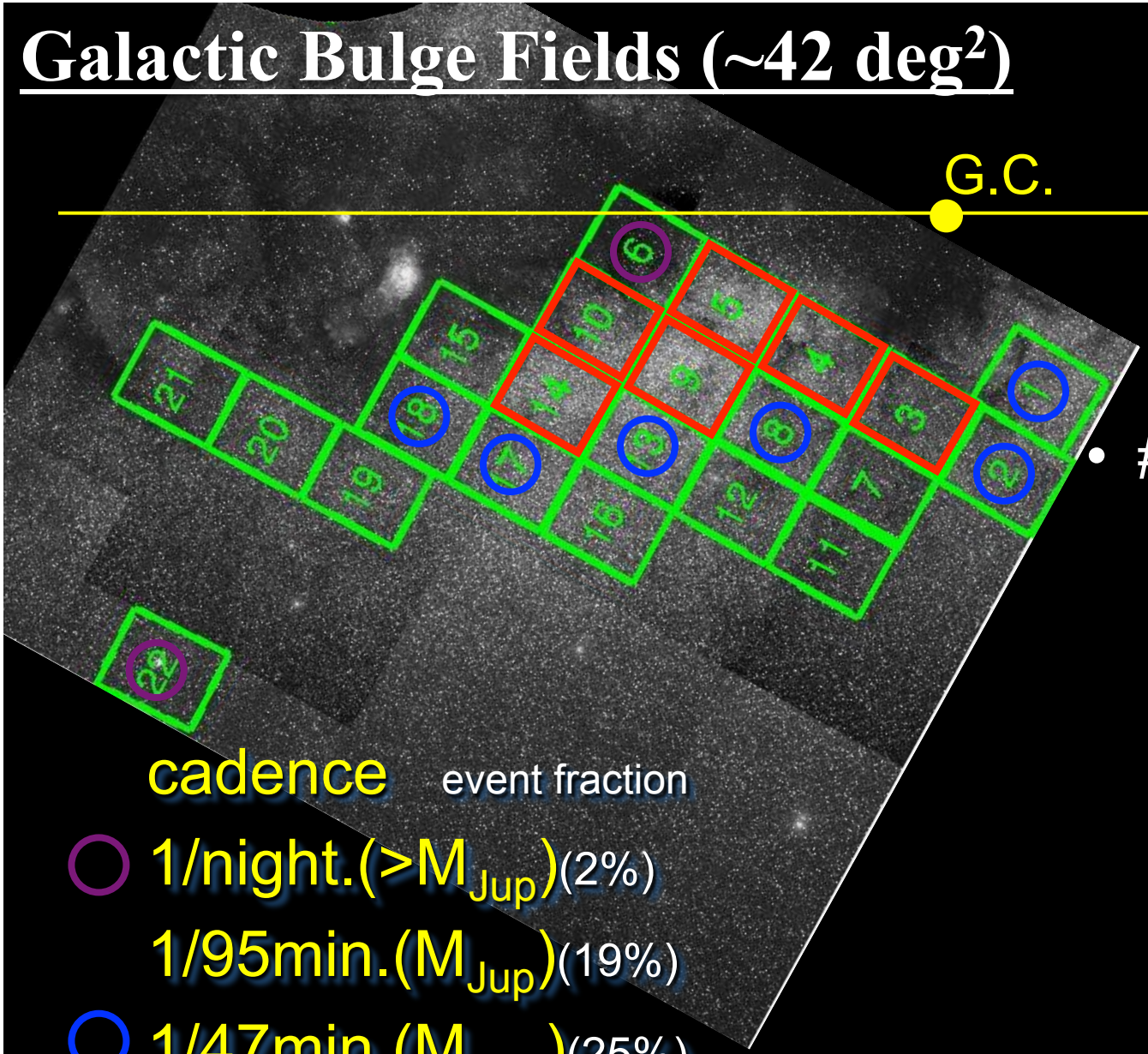
CCD　: 80M pix.

FOV　: 2.2 deg.^{2}

Filter : MOA-Red

(R + I)

Galactic Bulge Fields (~42 deg^2)



cadence event fraction

- 1/night.(>M_{Jup})(2%)
- 1/95min.(M_{Jup})(19%)
- 1/47min.(M_{Nep})(25%)
- 1/15min. ($M_{\oplus}$) (54%)

- # of μlens alerts
  - 2007: 488
  - 2008: 477
  - 2009: 563
  - 2010: 607
  - 2011: 485
  - 2012: 680
  - 2013: 668
  - 2014: 621

3300 events in 6 yrs

http://www.massey.ac.nz/moa

Event Selection

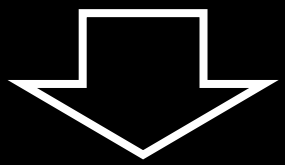
To construct a sample of well defined single and planetary events, we reject …

1. Non-microlensing events (CVs, moving objects, …)
2. Stellar binaries: $q > 0.03$
3. Events with insufficient data points

For, planetary events

Detection : MOA survey data

Characterization : All available data



Remaining events are 1316 events (from 3300 events/6yrs)

1291 single lens, 22 planetary, 3 ambiguous

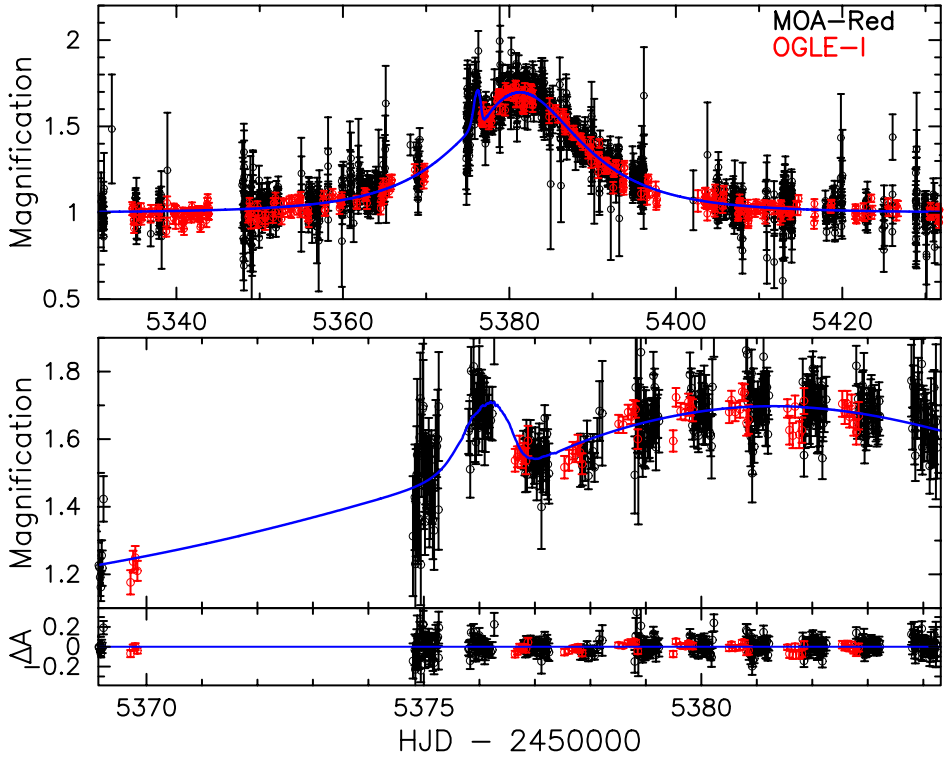
22 Planetary Events

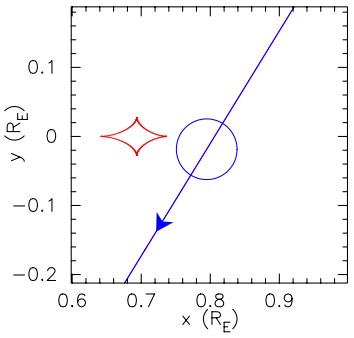
Event	Paper	Event	Paper
MB07192	Bennett+2008	MB10477	Bachelet+2012
OB07368/MB07308	Sumi+2010	MB11028/OB110203	Skowron+ in prep.
OB07349/MB07379	Dong in prep.	OB110265/MB11197	Skowron+ 2014
OB08355/MB08288	Koshimoto+2014	MB11262/OB110703	Bennett+2014
MB08379	Suzuki+2014	MB11291	Bond+ in prep.
MB09266	Muraki+2011	MB11322/OB111127	Shvartzvald+2014
MB09319	Miyake+2011	MB12006/OB120022	
MB09387	Batista+2011	OB120563/MB12288	Fukui+ in prep.
MB10117	Bennett+ in prep.	MB12355	
MB10328	Furusawa+2013	MB12505	MOA in prep.
MB10353	Rattenbury+ in prep.	OB120950/MB12527	Koshimoto+ in prep.

4 planets found in the analysis of online data, 5 planets in 2012

New Planets in 22 Planetary Events

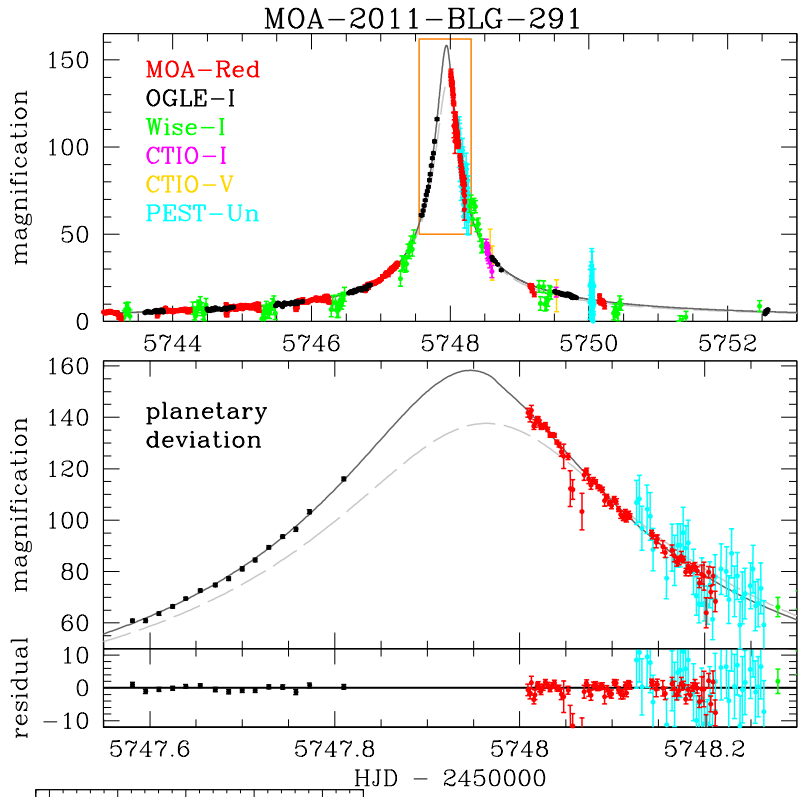
MOA-2010-BLG-353

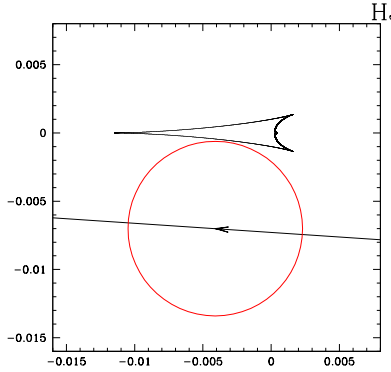




$t_E = 11$ days
$q = 1.3 \times 10^{-3}$
$s = 1.5$
Rattenbury et al. in prep.

MOA-2011-BLG-291

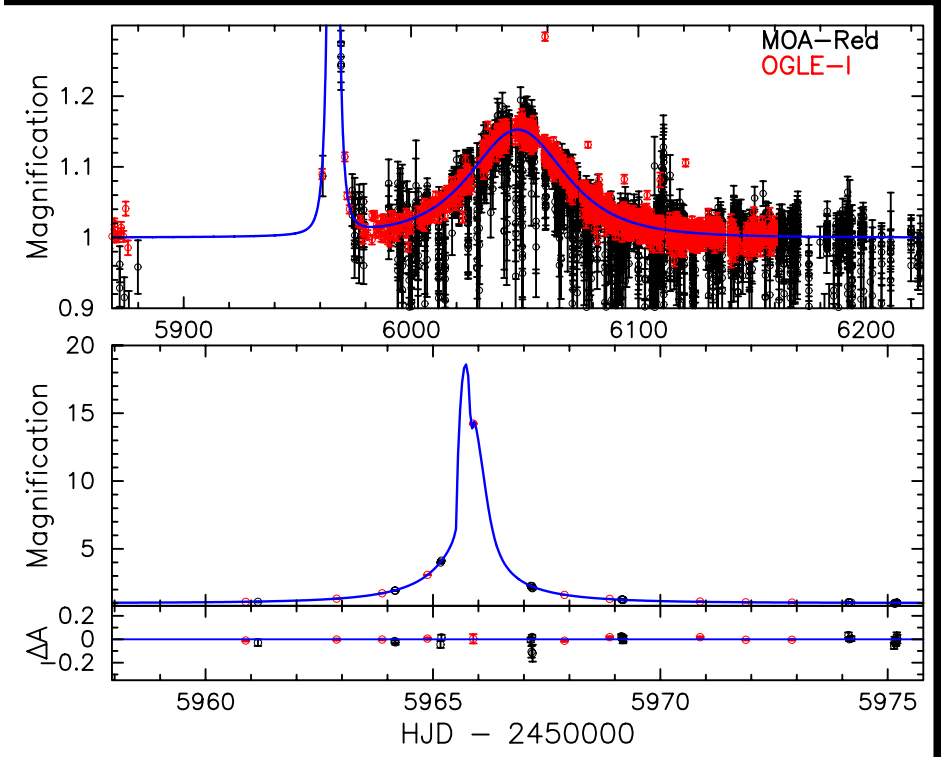


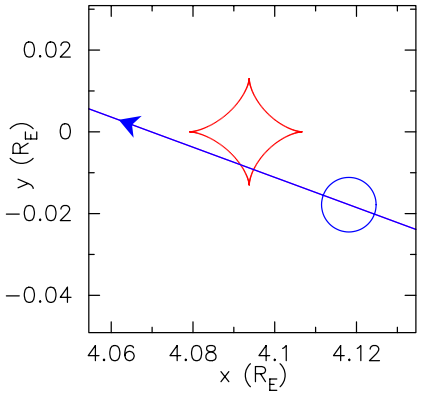


$t_E = 24$ days
$q = 4.2 \times 10^{-4}$
$s = 1.2$
Bond et al. in prep.

Planets in 2012 Season

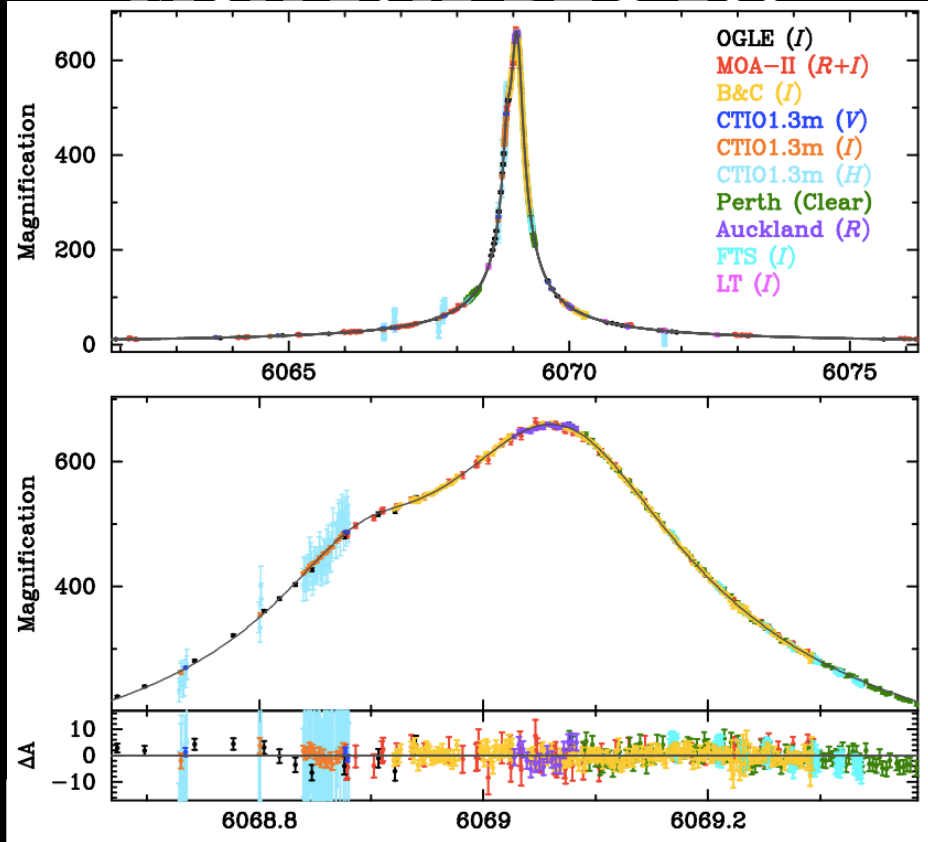
MOA-2012-BLG-006 / OGLE-2012-BLG-0022

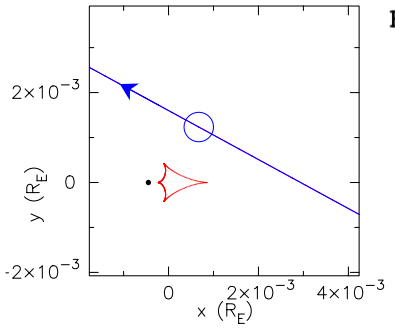




$t_E = 21$ days
$q = 1.6\times10^{-2}$
$s = 4.3$

OGLE-2012-BLG-0563/ MOA-2012-BLG-288

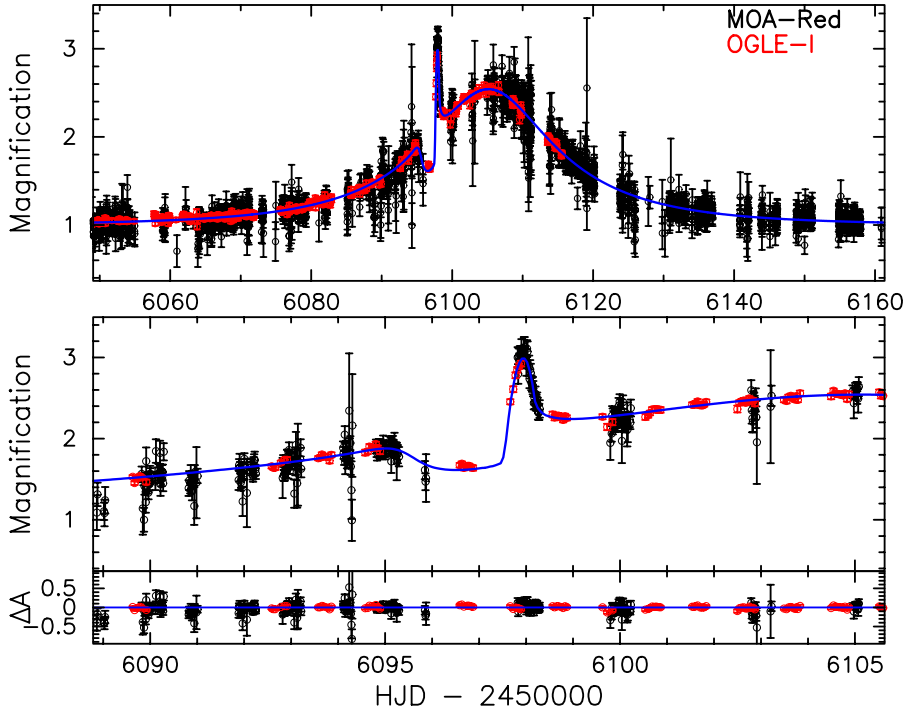


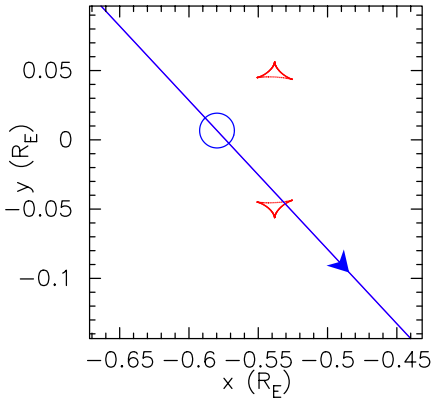


$t_E = 78$ days
$q = 1.1\times10^{-3}$
$s = 0.4$ or 2.4
Fukui et al. in prep.

Planets in 2012 Season

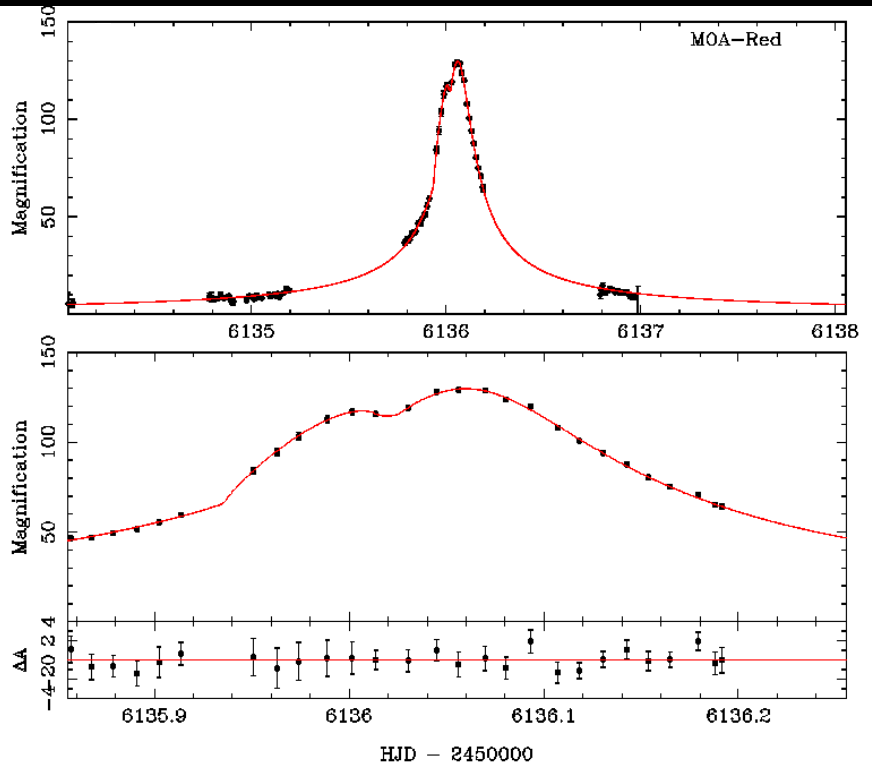
MOA-2012-BLG-355

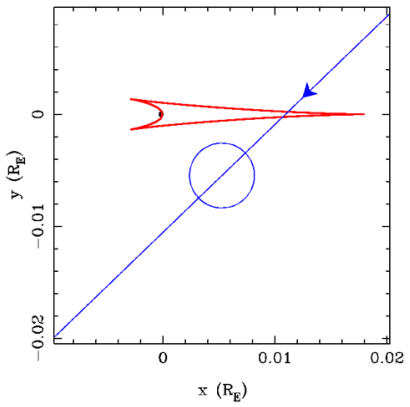




$t_E = 22$ days
$q = 7.3 \times 10^{-4}$
$s = 0.77$

MOA-2012-BLG-505



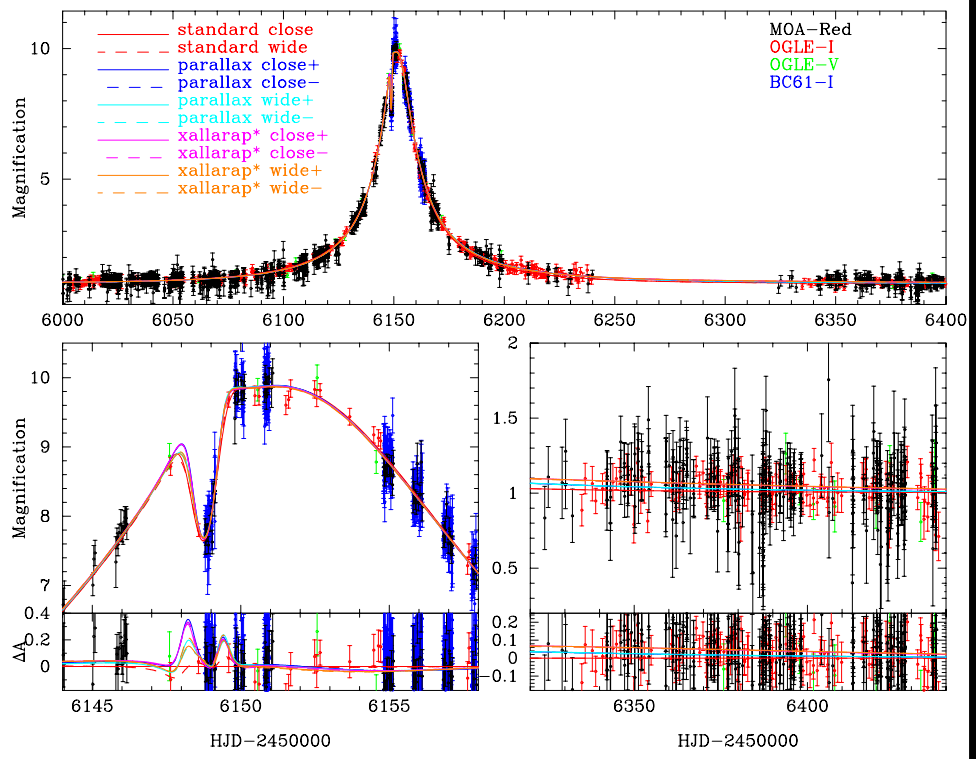


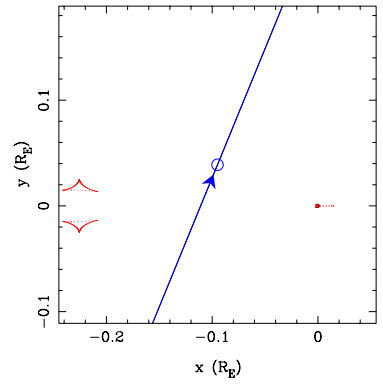
$t_E = 10$ days
$q = 2.0 \times 10^{-4}$
$s = 0.9$ or 1.1

Figures by Namba

Planets in 2012 Season

OGLE-2012-BLG-0950 / MOA-2012-BLG-527





$t_E = 67$ days

$q = 2.3 \times 10^{-4}$

$s = 0.9$ or 1.0

Koshimoto et al. in prep.

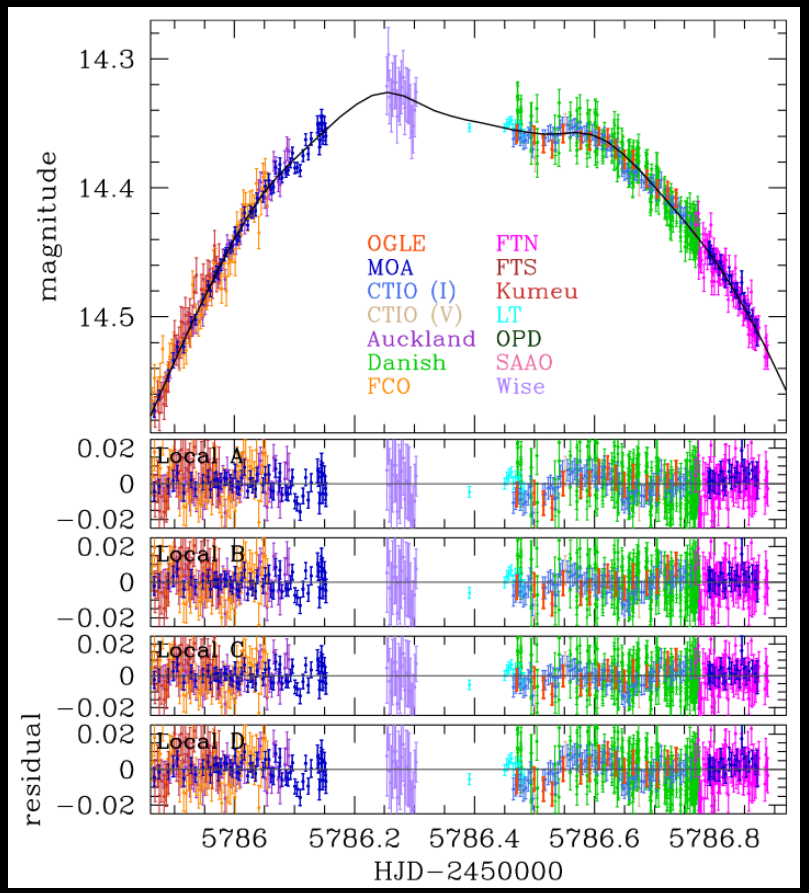
Short Summary

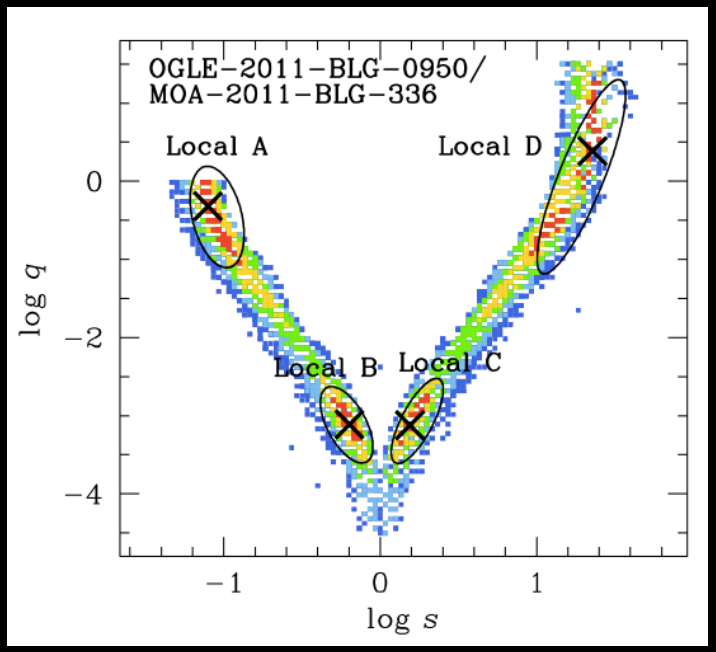
Event	Note
MB10353	Low-mag
MB11291	High-mag
MB12006/ OB120022	Low-mag, large s
OB120563/ MB12288	High-mag
MB12355	Low-mag, close to RR Lyrae
MB12505	High-mag, t_E=10
OB120950/ MB12527	Low-mag

3 Ambiguous (Planetary or Stellar Binary?)

- MB0789 / OB07141
- OB110950 / MB11336 (High-mag)
- MB12201 / OB120501

OB110950 / MB11336





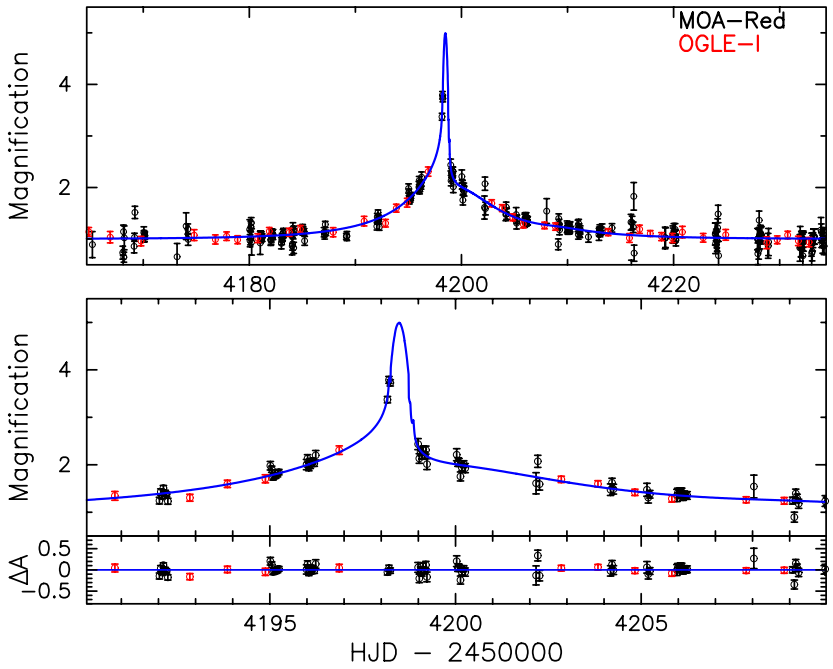
our result: $\chi^2_{SB} - \chi^2_{PL} = 18$

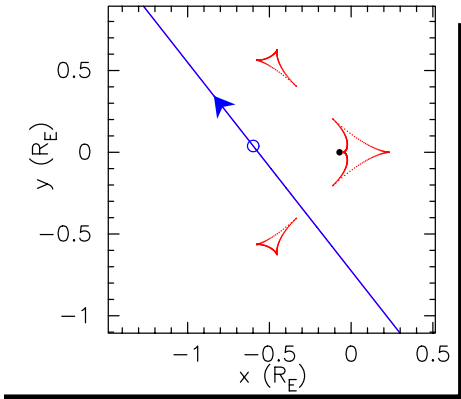
Choi et al. 2012

MB0789 / OB07141: Ambiguous Event

$\chi^2_{SB} - \chi^2_{PL} = -3$

Stellar Binary Model



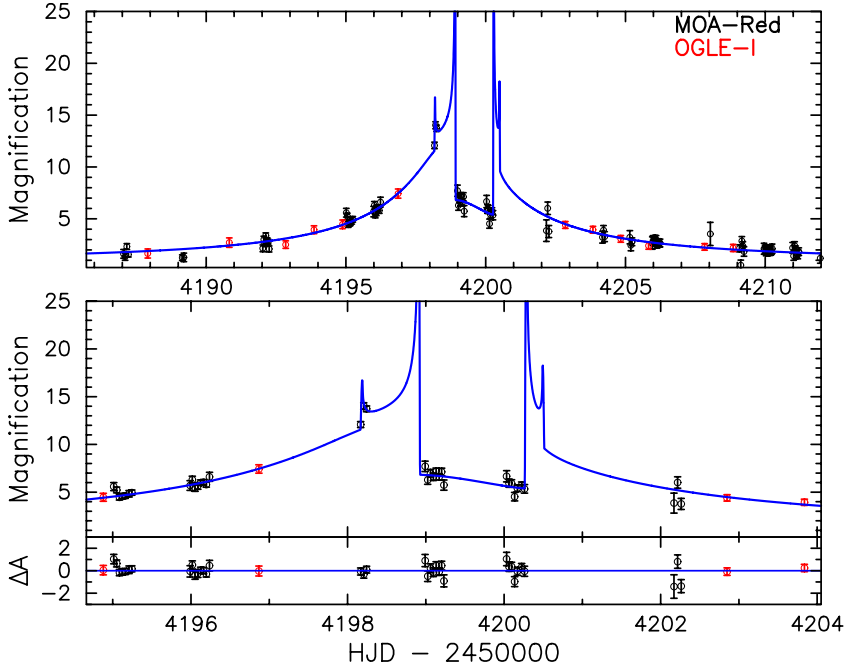


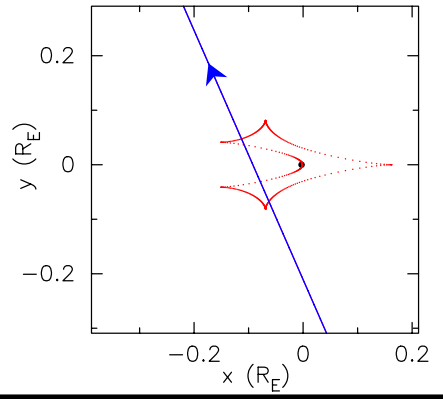
$t_E = 9.3$ days

$q = 1.0\times10^{-1}$

$s = 0.75$

Planetary Model





$t_E = 19$ days

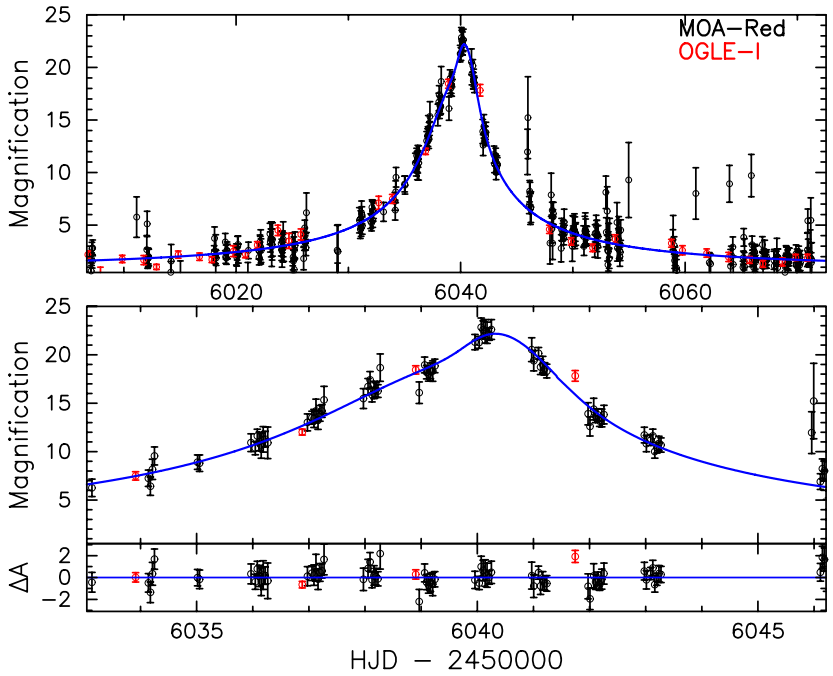
$q = 3.0\times10^{-3}$

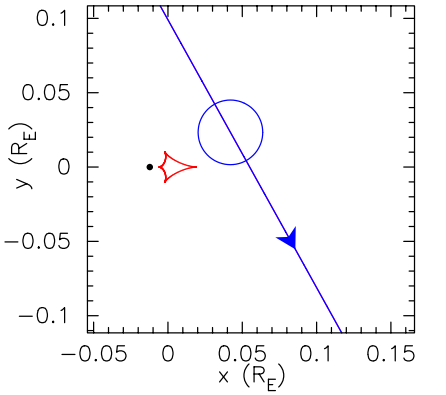
$s = 0.97$

MB12201 / OB120501: Ambiguous Event

$$\chi^2_{SB} - \chi^2_{PL} = 8$$

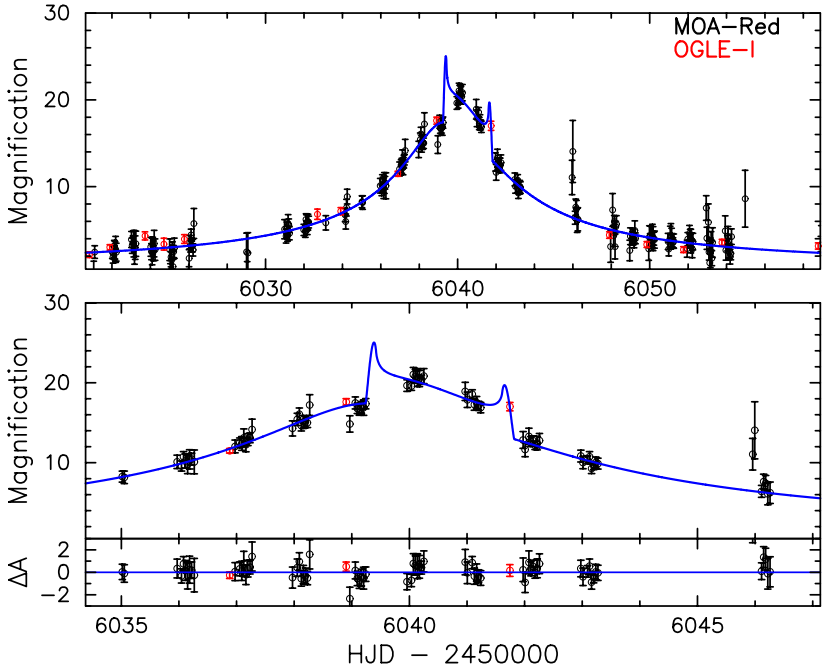
Stellar Binary Model

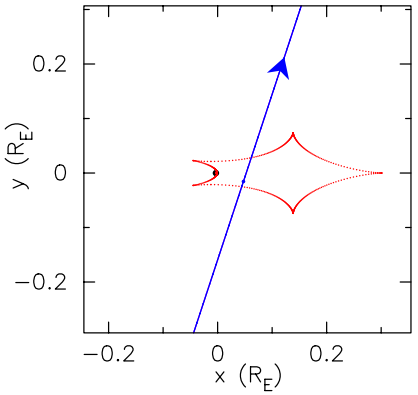




$t_E = 46$ days
$q = 3.3\times10^{-2}$
$s = 2.64$

Planetary Model

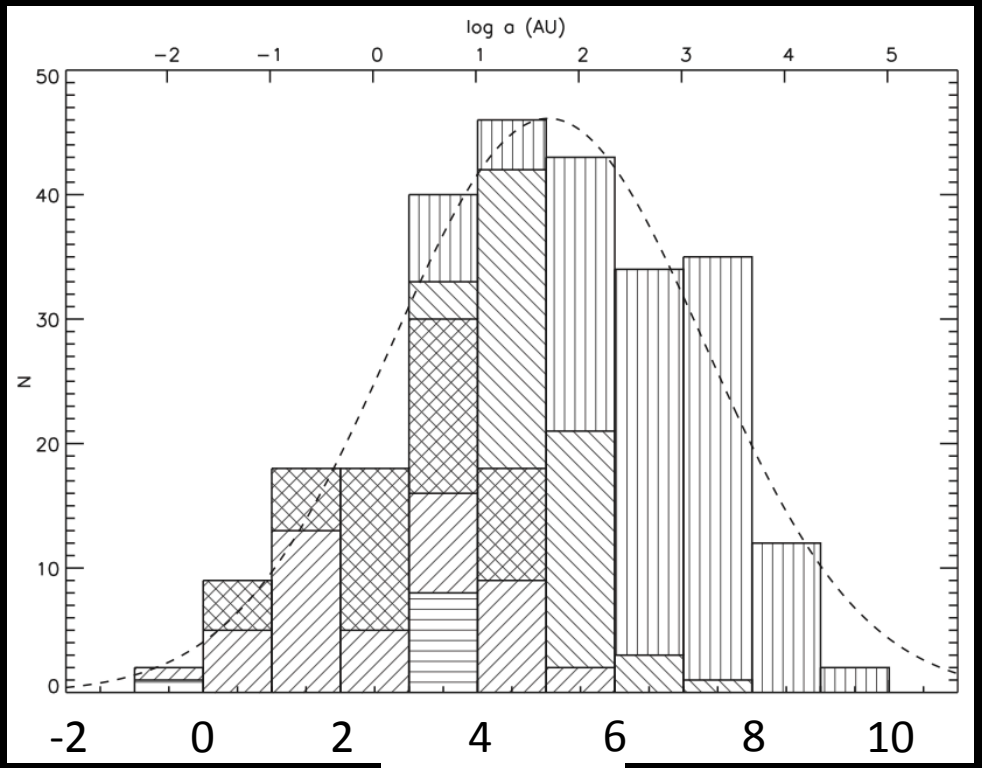




$t_E = 43$ days
$q = 3.4\times10^{-3}$
$s = 1.07$

Treating Ambiguous Events

1. $\Delta\chi^2$ between PL and SB model of light curve fitting
2. Prior probability of frequency for each companion
   - SB: Orbital period distribution (Raghavan et al. 2010), Mass ratio function (Duchêne & Kraus 2013)
   - PL: Our mass ratio function



Raghavan et al. 2010

# of planets
MB0789: 0.7
MB11336: 0.9
MB12201: 0.9

Detection Efficiency, $\varepsilon(\log s, \log q)$

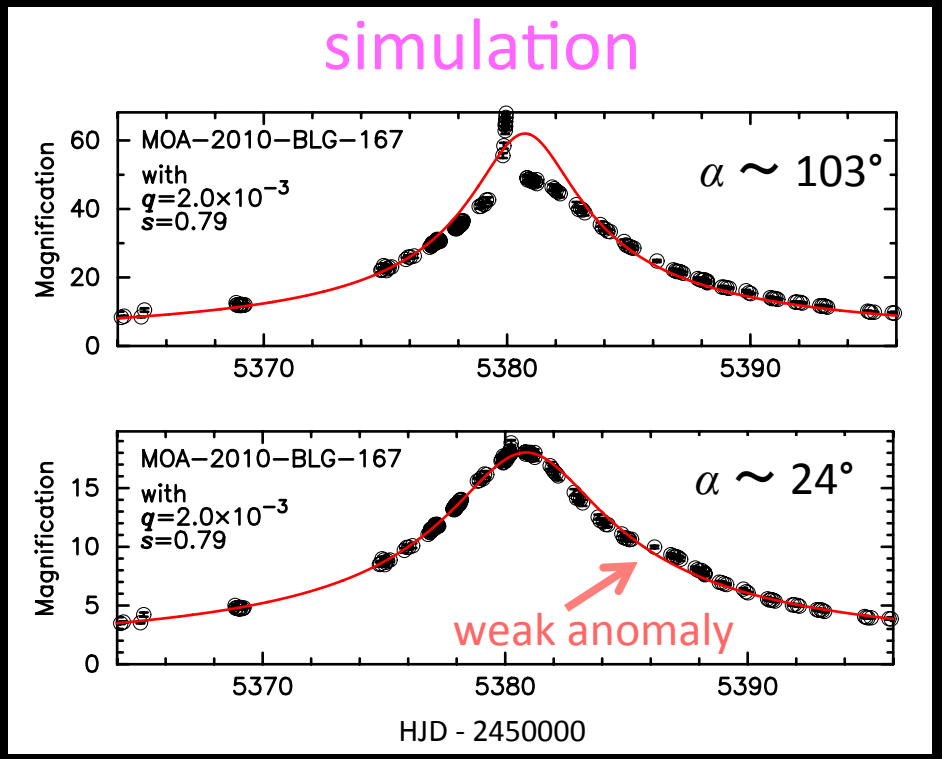
- q : mass ratio
- s : separation
- α : angle from the axis
- Data quality
- ρ : finite source effect

$\rho = \theta_* / (t_E \mu_{rel})$

θ_*: angular source star radius

$\mu_{rel} = <\mu_{rel}> = 5.2$mas/yr

(Rhie+2000, Holtzman+ 1998, Rattenbury+ 2007, Kervella & Fouqué 2008,)

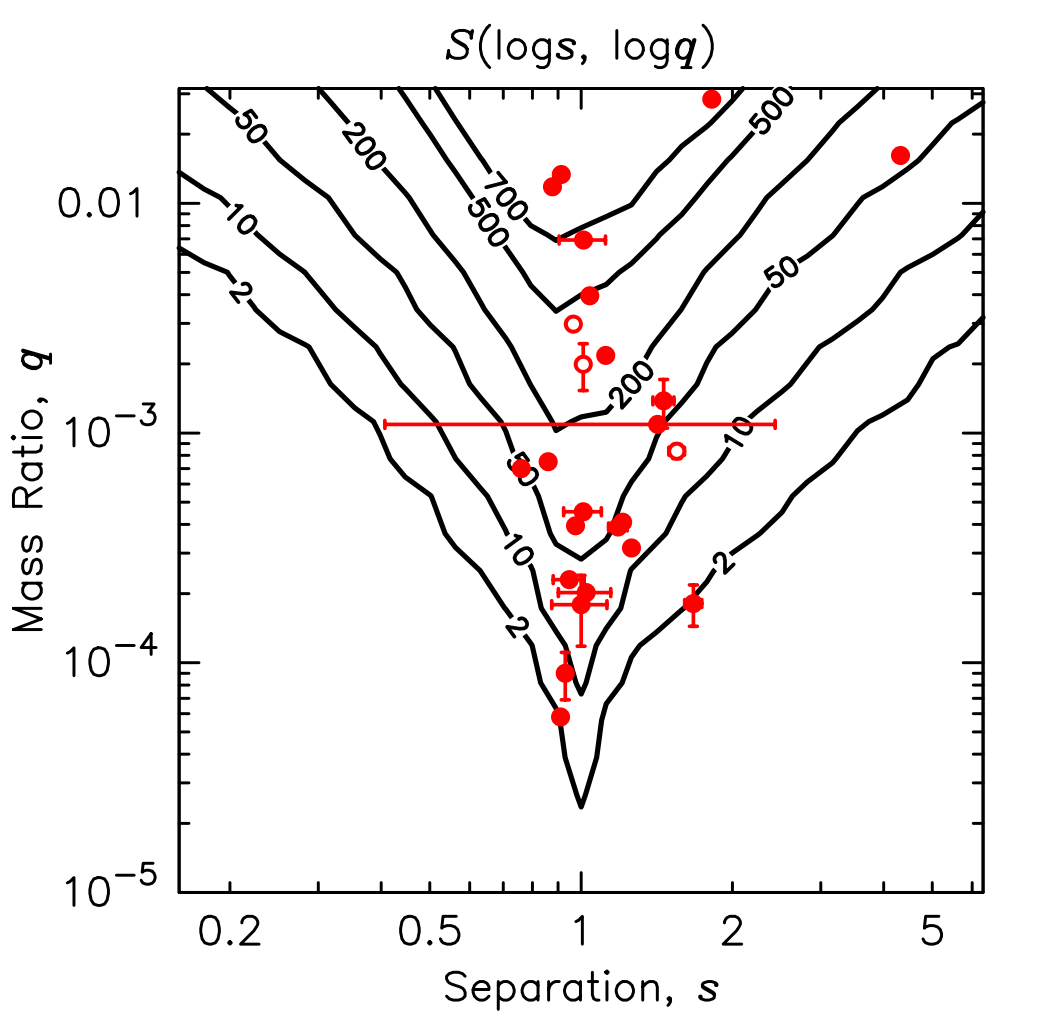


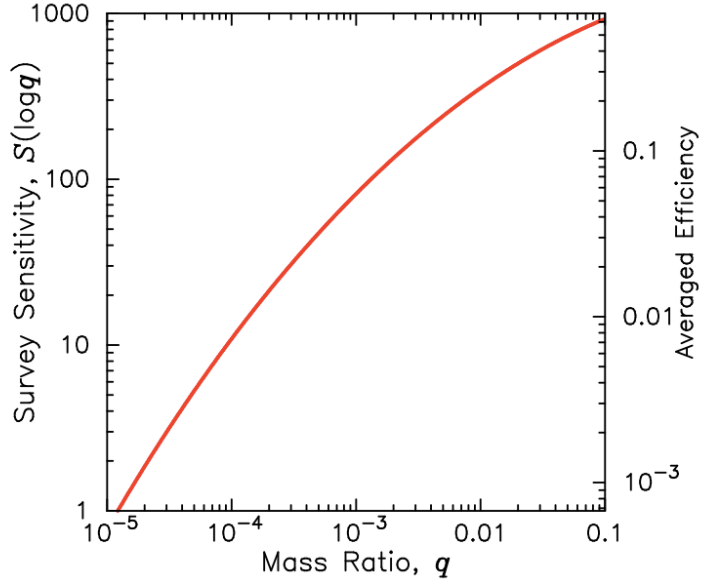
Detection:

$$\Delta\chi^2 = \chi^2_{\rm Single} - \chi^2_{\rm Binary} > 100$$

$\varepsilon(\log s, \log q)$:
Fraction of detections within $0 < \alpha < 2\pi$

Detection Efficiency on *s*-*q* Plane





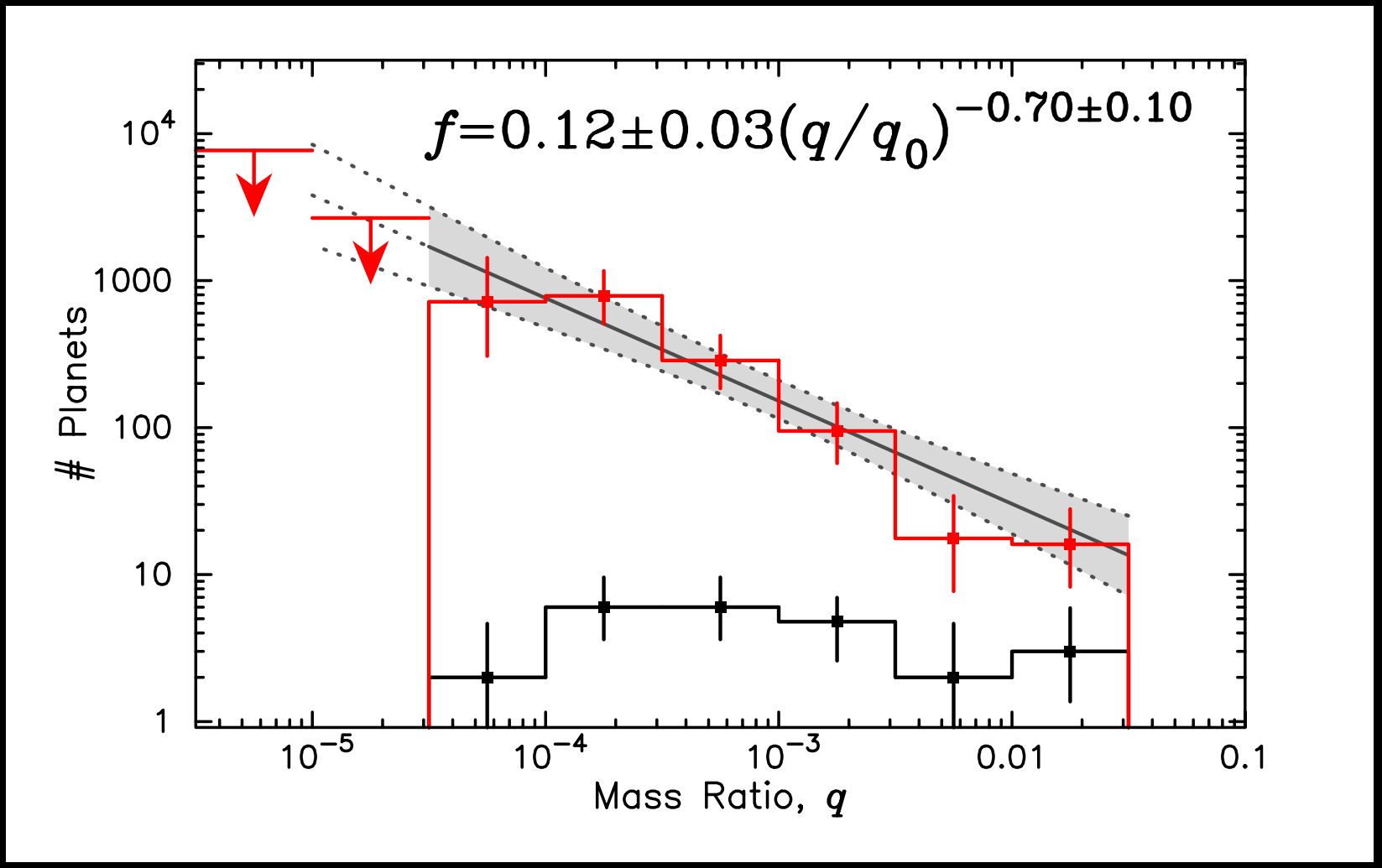
$$f \equiv \frac{dN}{d\log s \; d\log q} = A\left(\frac{q}{q_0}\right)^n$$

$$q_0 = 10^{-3}$$

$$L(A,n) = -N_{\rm exp} + \sum_i^{N_{\rm obs}} \ln f(q_i) S(\log q_i)$$

$$N_{\rm exp} = \int_{q-}^{q+} dq f(q) S(\log q)$$

Planet Frequency with Mass Ratio

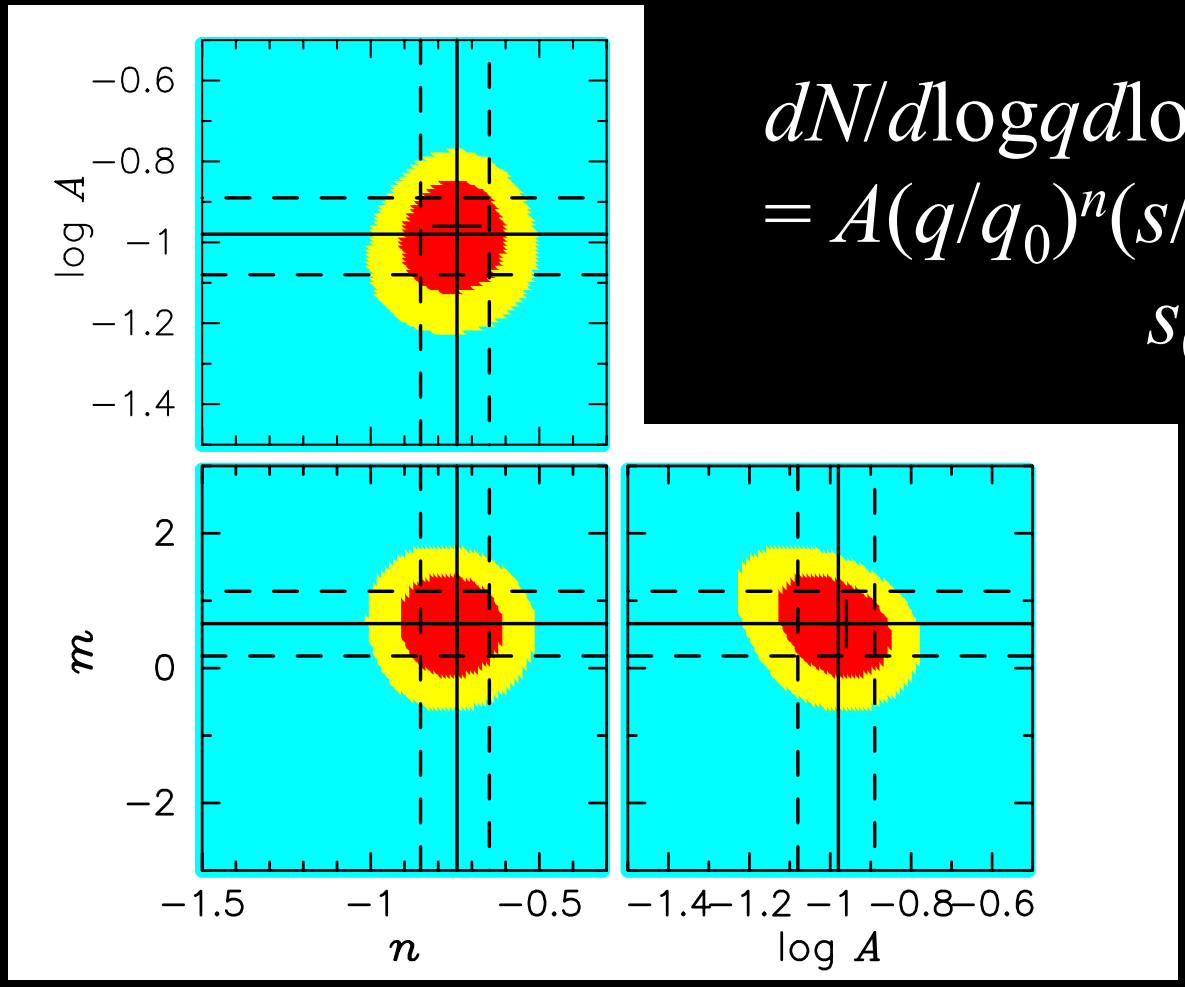


Cf. Sumi et al. 2010 : $f \propto (q/q_0)^{-0.68\pm0.20}$

Gould et al. 2010 : $N = 0.36\pm0.15$ @ $q = 5\times10^{-4}$

this work : $N = 0.20\pm0.06$ @ $q = 5\times10^{-4}$

Planet Frequency with *q* and *s*



$$dN/d\log q\, d\log s = A(q/q_0)^n (s/s_0)^m$$

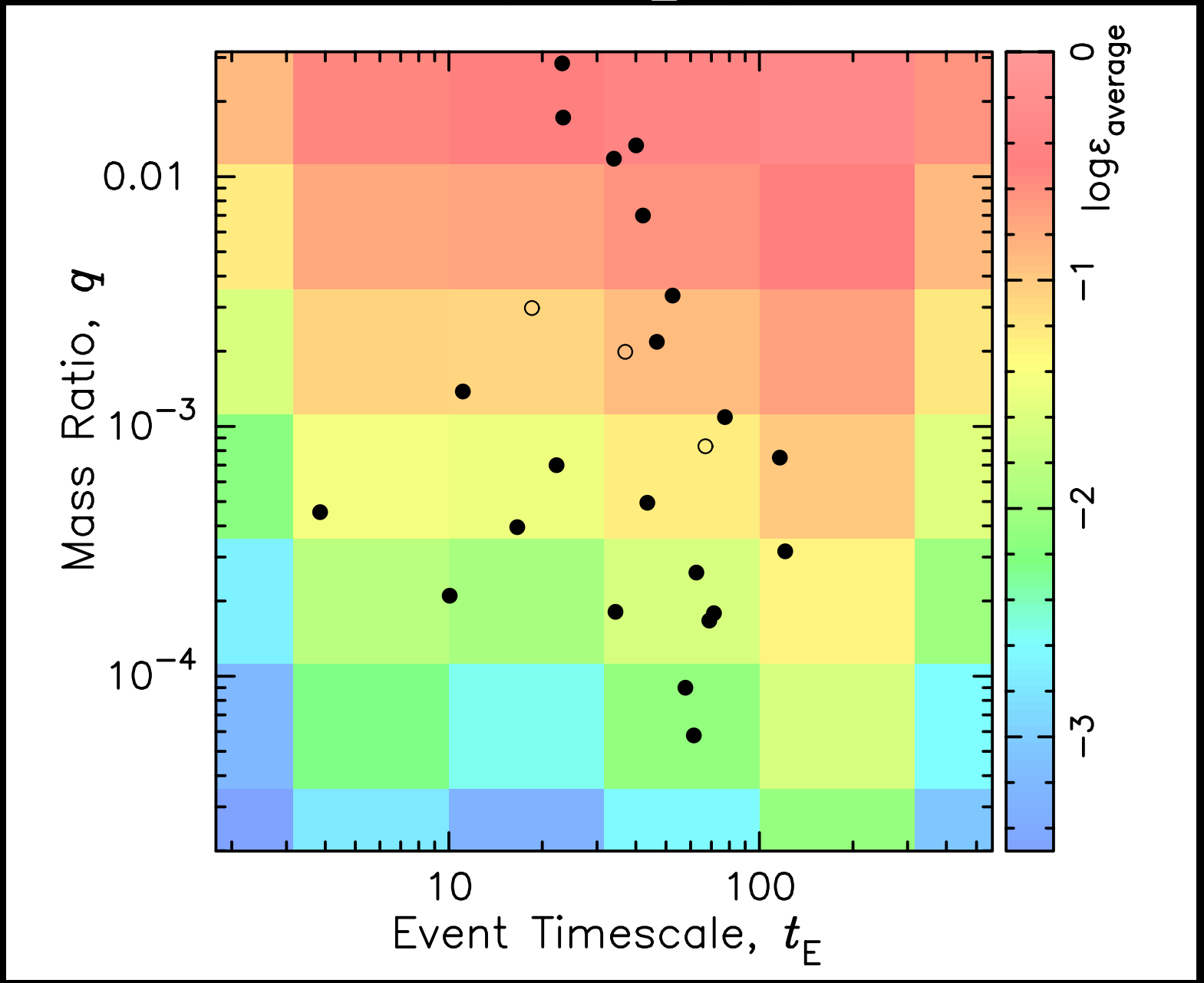
$$s_0 = 1.0$$

preliminary

$$F = 0.10\pm0.02 (q/q_0)^{-0.74\pm0.10} (s/s_0)^{0.66\pm0.48}$$

Cf. Cumming et al. 2008: $dN = CM^{\alpha}P^{\beta}\, d\ln M d\ln P$, $\beta = 0.26\pm0.10$

Detection Efficiency on t_E- q plane



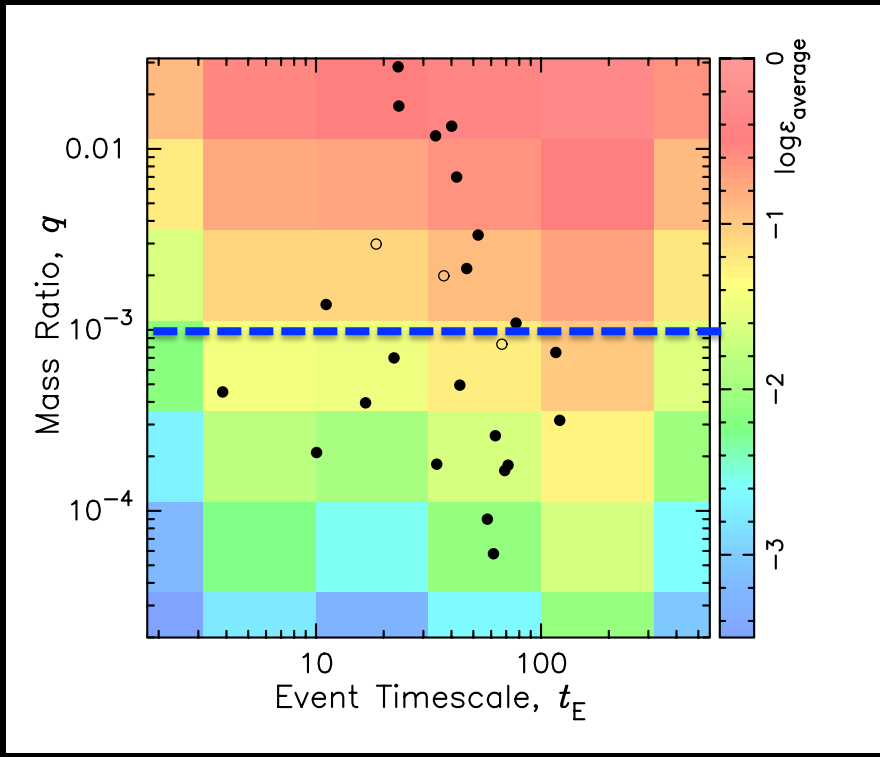
Planet Frequency with Event Time Scale

$F = C(t_E/t_{E0})^{\gamma}$

t_{E0} = 20 days

if $\gamma > 0$, planets favor

- Massive stars
- Nearby disk stars



Planet Frequency with Event Time Scale

$F = C(t_E/t_{E0})^{\gamma}$

t_{E0} = 20 days

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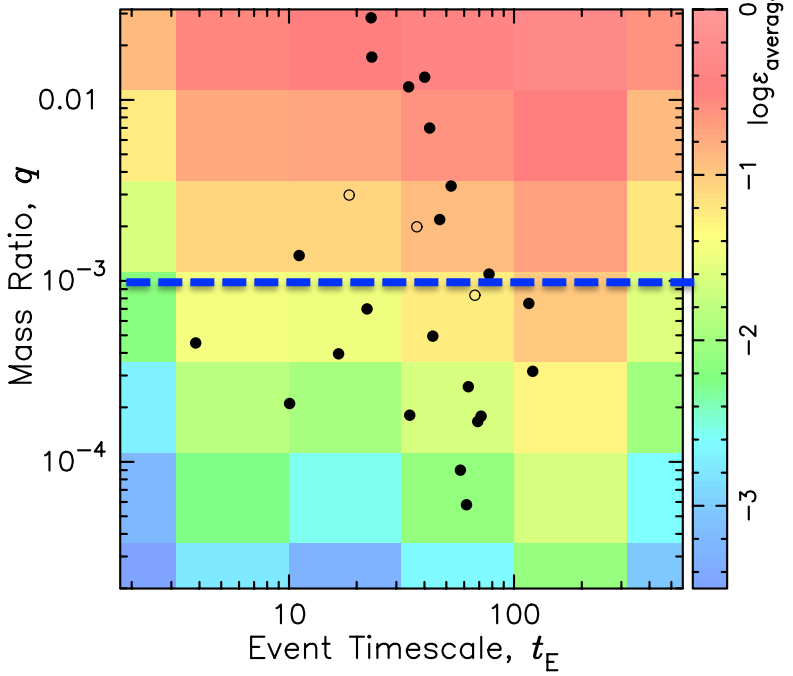

preliminary

For the planets with $q > 0.001$

$\gamma = 0.15 \pm 0.45$

For the planets with $q < 0.001$

$\gamma = 0.15 \pm 0.30$

Summary

From MOA survey in 2007-2012, 1291 single lens, 22 planetary and 3 ambiguous events are used

- $F = 0.12 \pm 0.03 (q/q_0)^{-0.70 \pm 0.10}$; $q_0 = 10^{-3}$
- $F = 0.10 \pm 0.02 (q/q_0)^{-0.74 \pm 0.10} (s/s_0)^{0.66 \pm 0.48}$; $s_0 = 1.0$
- Uncertainty in the slope and normalization are twice smaller than previous works' values
- $F \propto (t_E/t_{E0})^{\gamma}$; γ is consistent with 0; t_{E0}=20 days

Statistical exoplanet analysis of MOA-II survey data leads a way for the coming survey era