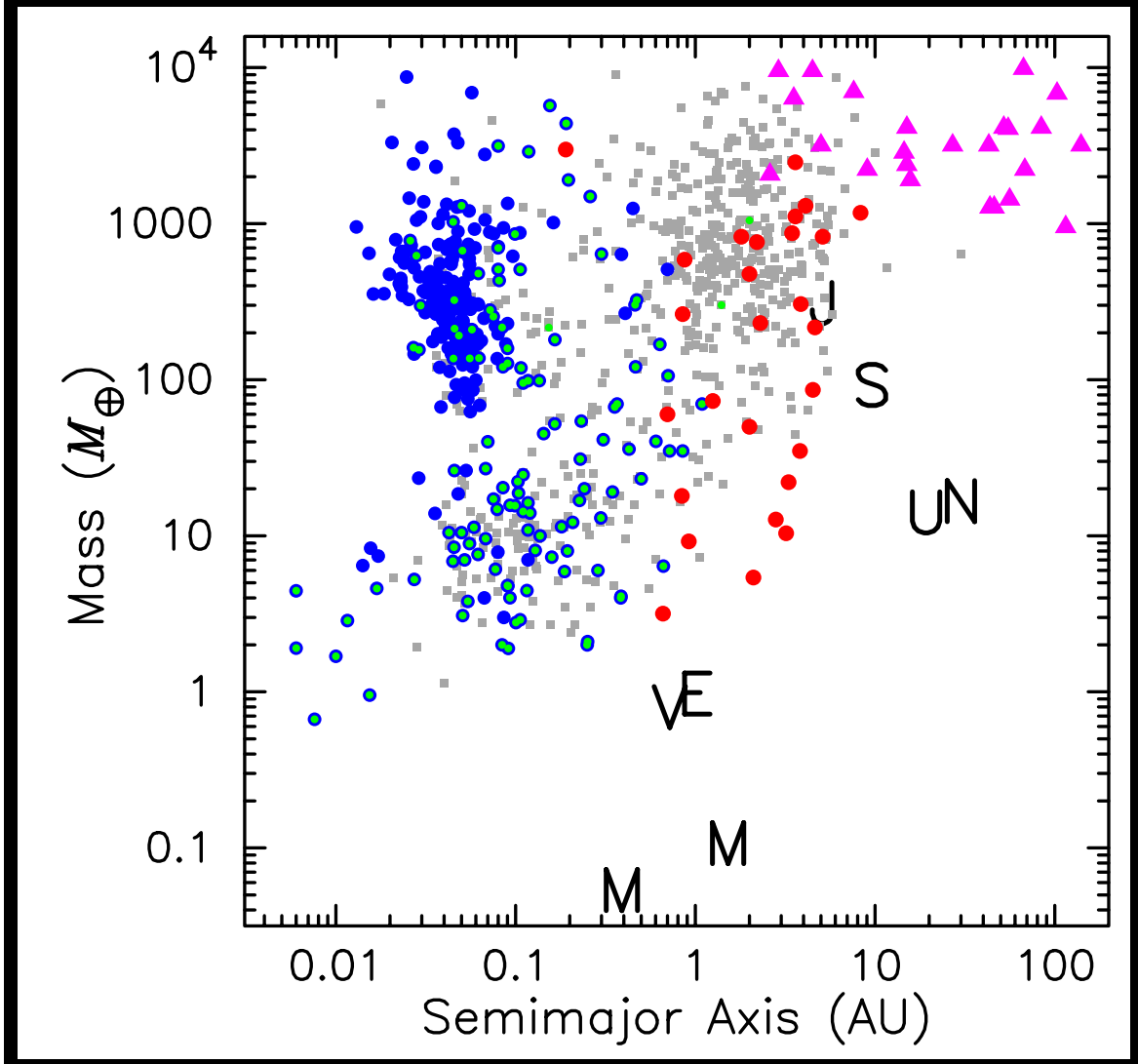
224th AAS Meeting
On the Shoulders of Giants: Planets Beyond the Reach of *Kepler* II: Demographics

Planet frequency beyond the snow line from MOA-II microlensing survey

Daisuke Suzuki
Osaka University

June 03, 2014 @Boston Westin Copley Place

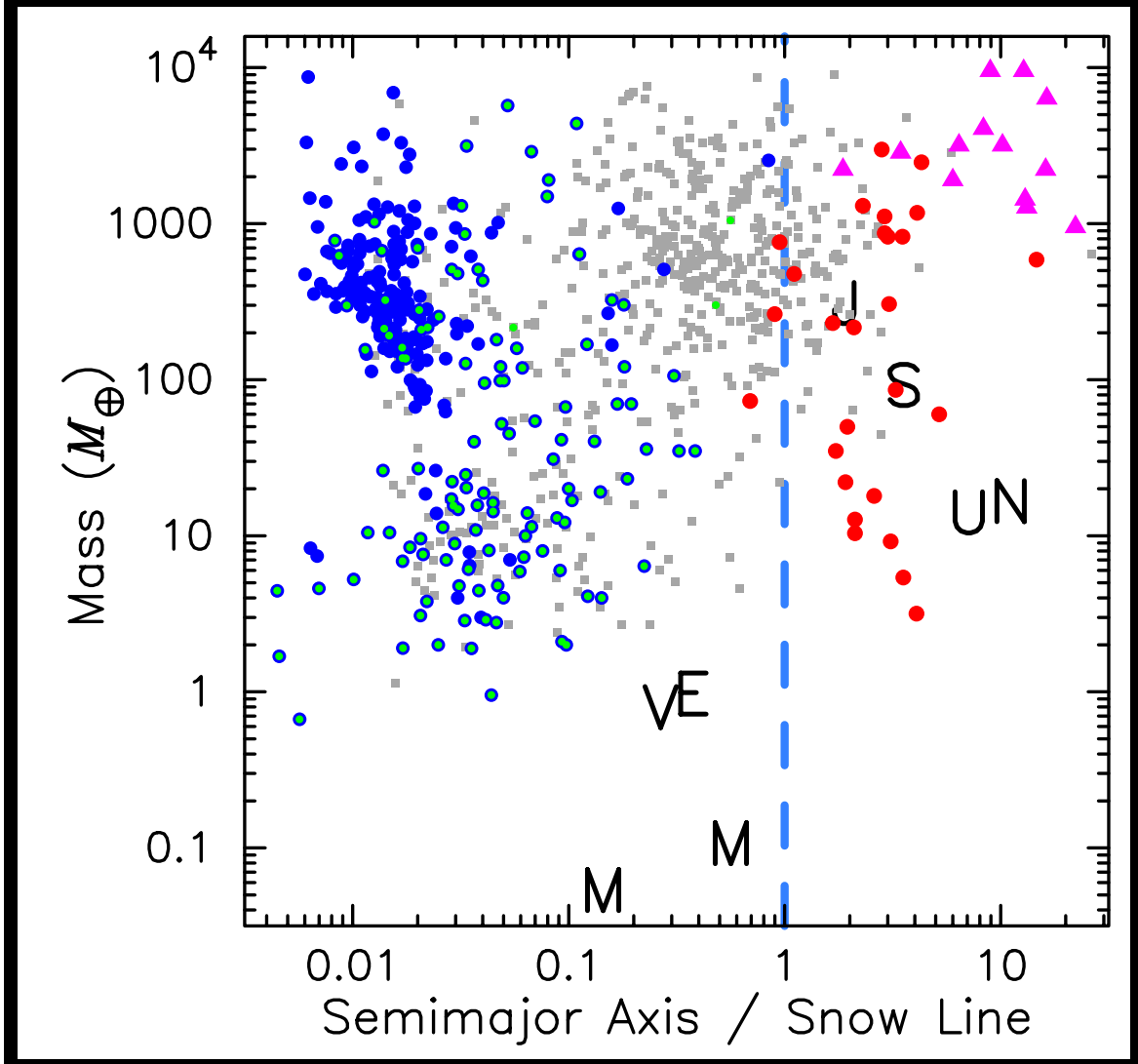
Exoplanets We Have Known



- Radial Velocity
  - A-M type stars
- Transit
  - FGK type stars
- Microlensing
  - KM type stars
- Direct Imaging
  - A-M type stars
- Kepler planets
  - G type stars

http://exoplanet.eu/

Exoplanets We Have Known



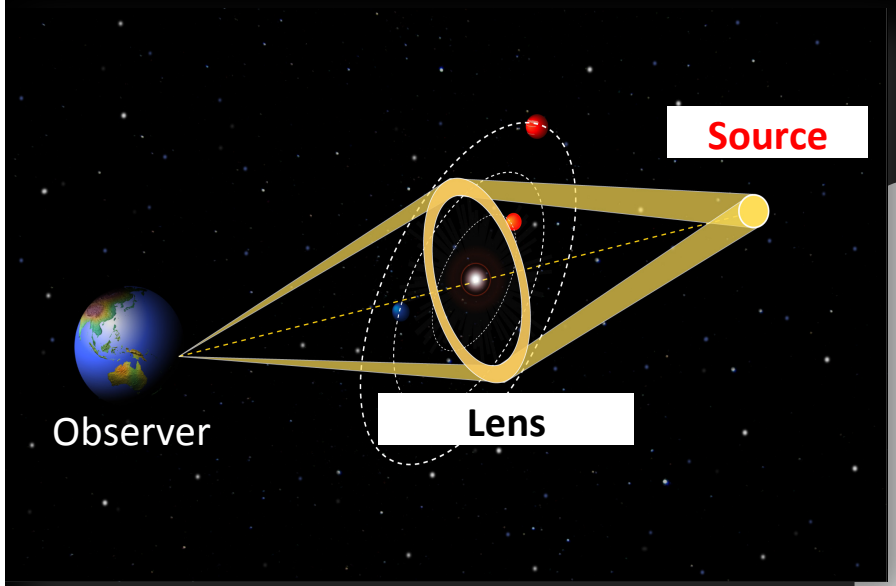
- Radial Velocity
  - A-M type stars
- Transit
  - FGK type stars
- Microlensing
  - KM type stars
- Direct Imaging
  - A-M type stars
- Kepler planets
  - G type stars

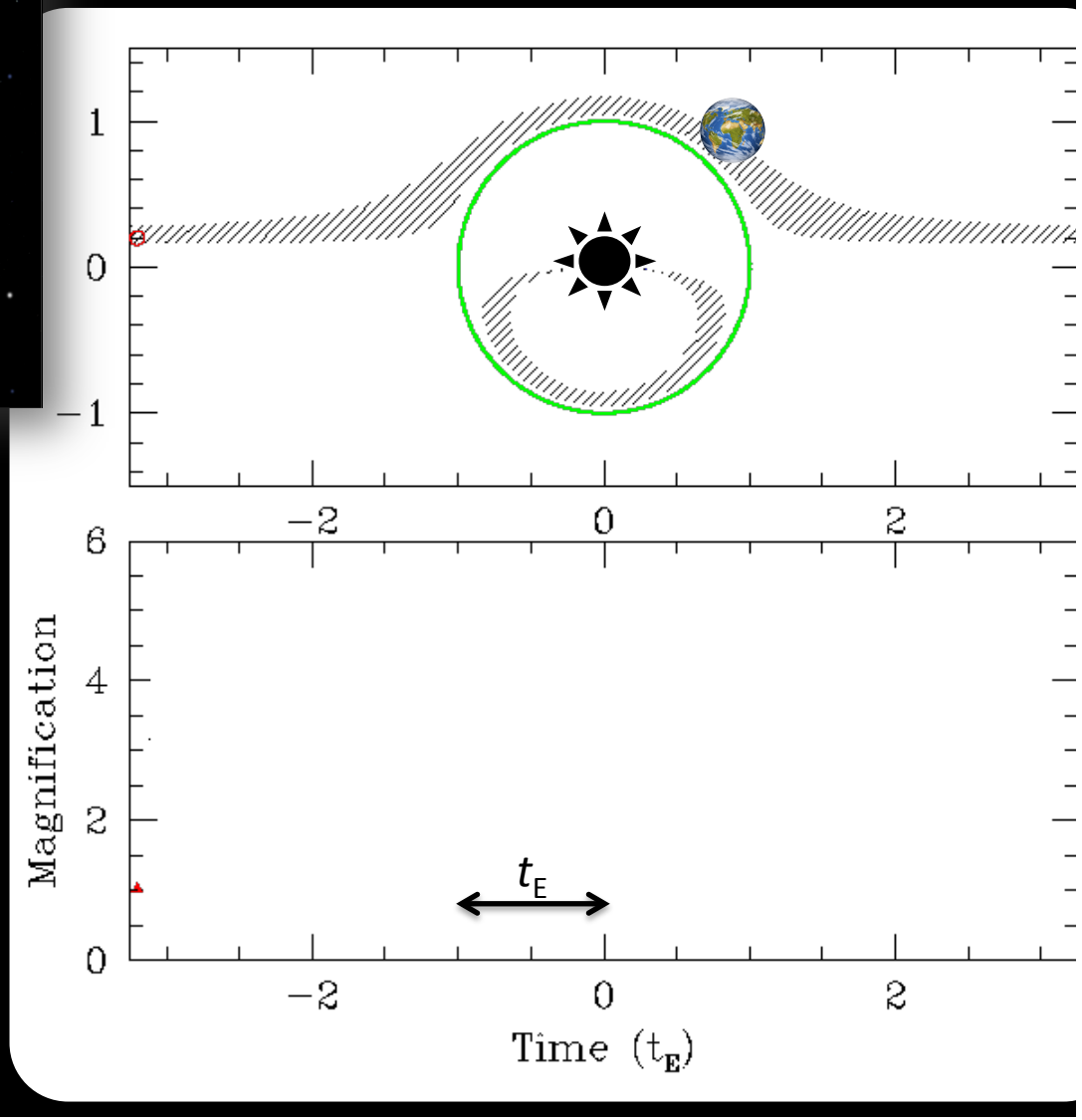
$$a_{\mathrm{snow}} = 2.7\ (M/M_{\mathrm{Sun}})\ \mathrm{AU}$$

http://exoplanet.eu/

Gravitational Microlensing

- Lens star
- Source star
- Einstein ring
- Images of the source star





Event timescale : t_E

$$t_E \propto \sqrt{M}$$

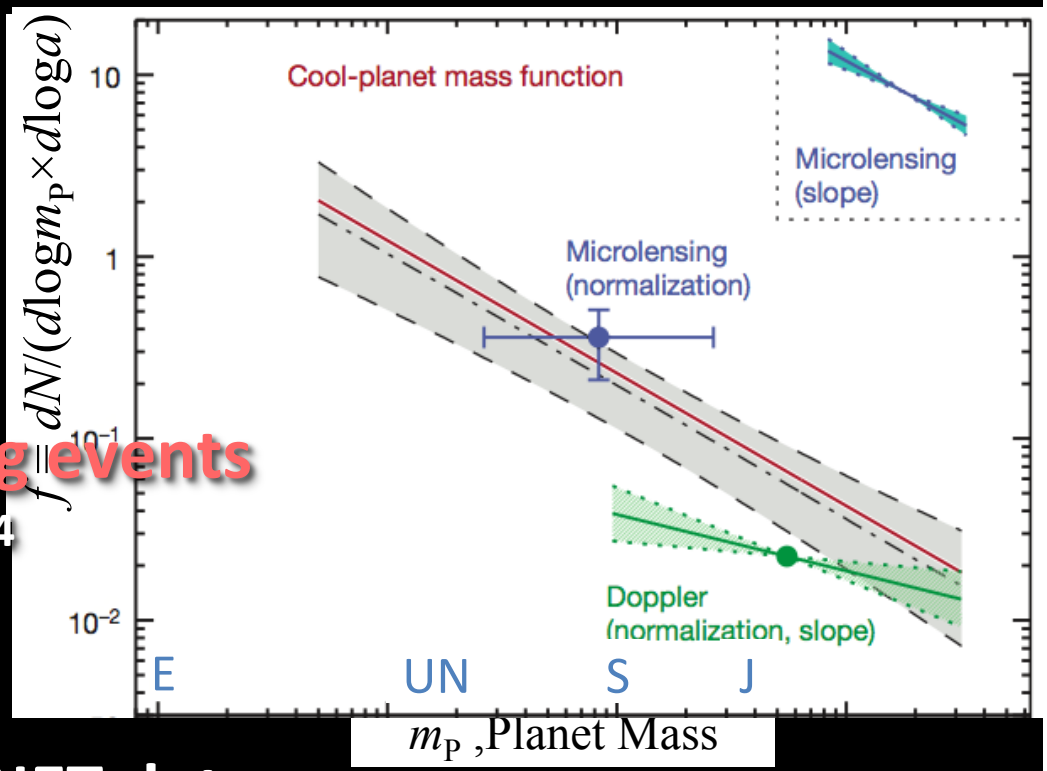
Solar mass ~ 30 days

Jupiter mass ~ a few days

Earth mass ~ a few hours

Cold Planet Mass Function from Microlensing

- Sumi et al. 2010
  - 10 planets, f $\propto q^{-0.68\pm0.2}$
- Gould et al. 2010
  - 6 planets in 13 high-mag events
  - 0.36±0.15 @ $q \sim 5\times10^{-4}$
- Cassan et al. 2012
  - 2002 – 2007 OGLE, PLANET data
  - 2 additional planets together with the above.



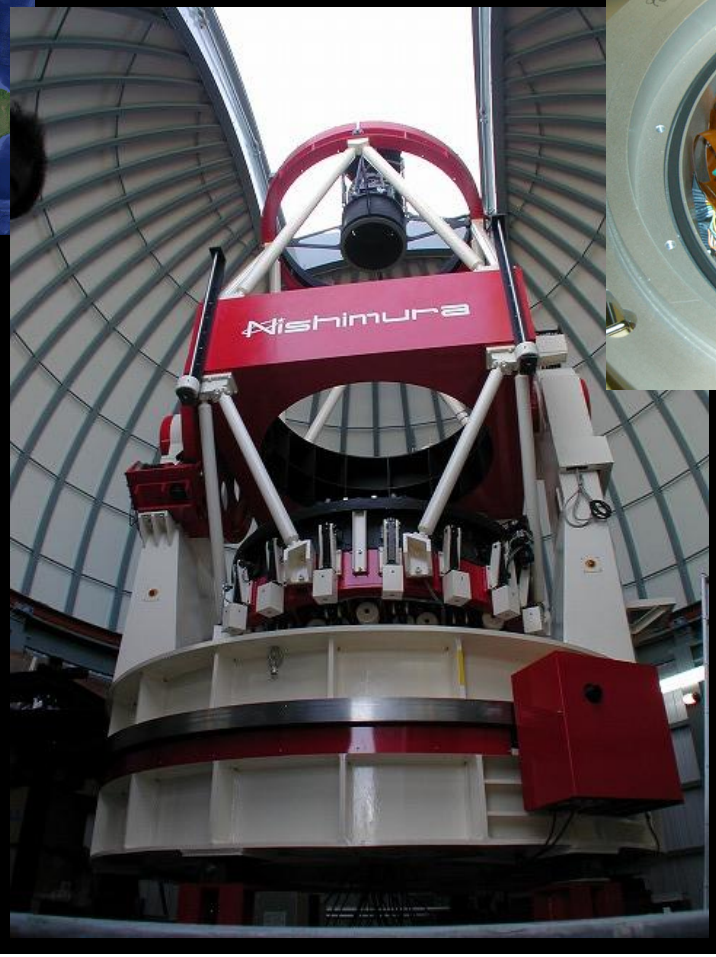
Cassan et al. 2012

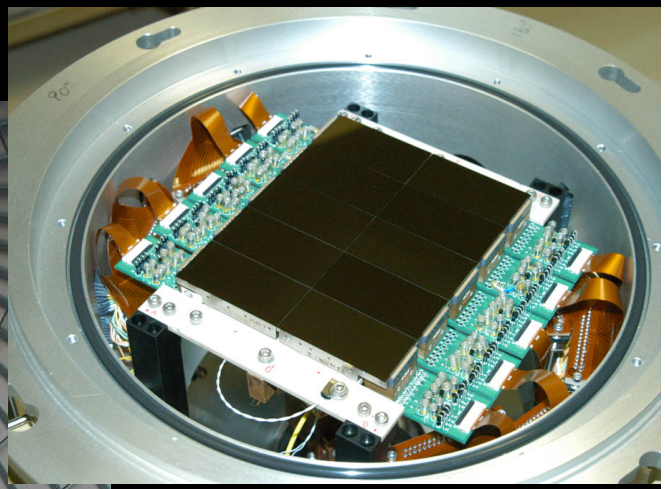
This work : derive planet frequency beyond the snow line from MOA-II observations in 2007-2012 including 21 planets.

MOA (since 1995)

（Microlensing Observations in Astrophysics）

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





Mirror: 1.8m

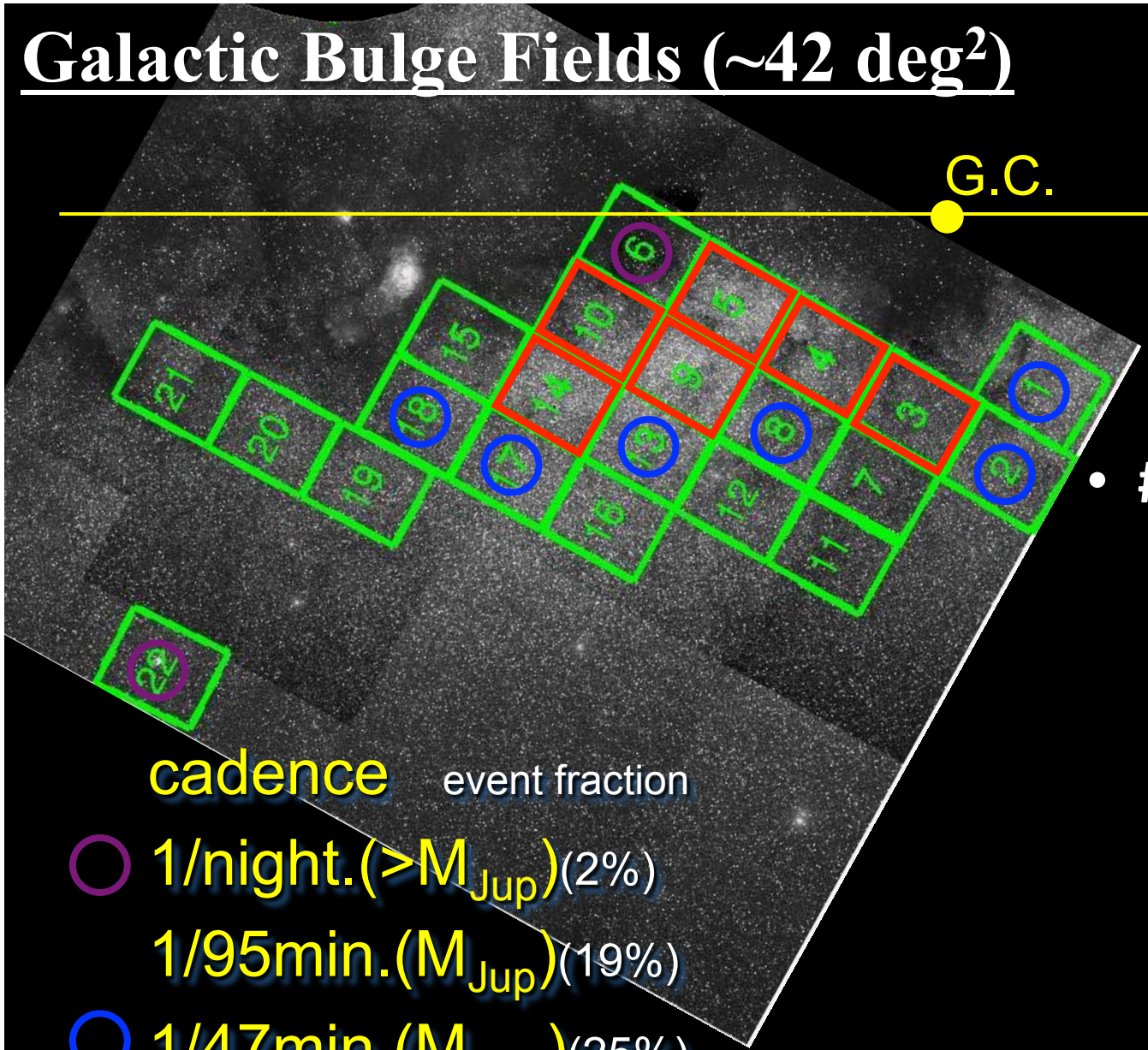
CCD　: 80M pix.

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

3300 events in 6 yrs

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

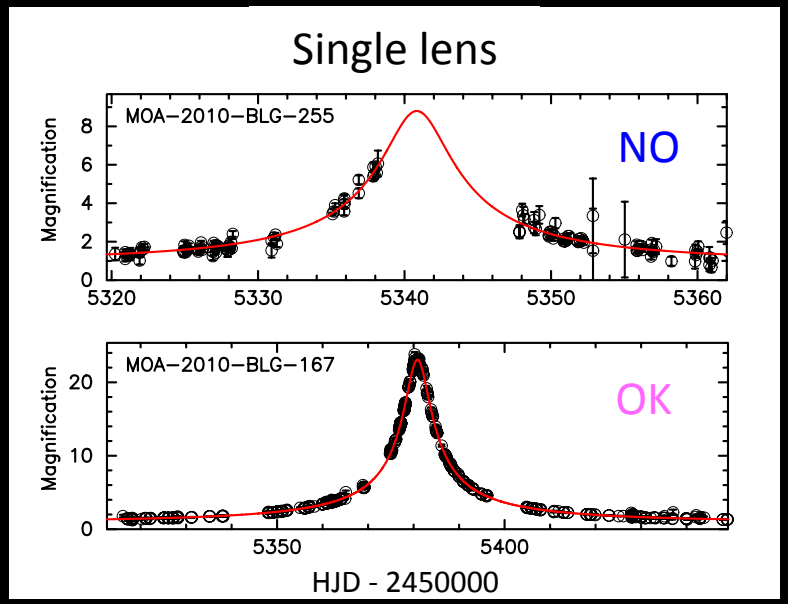
Event Selection

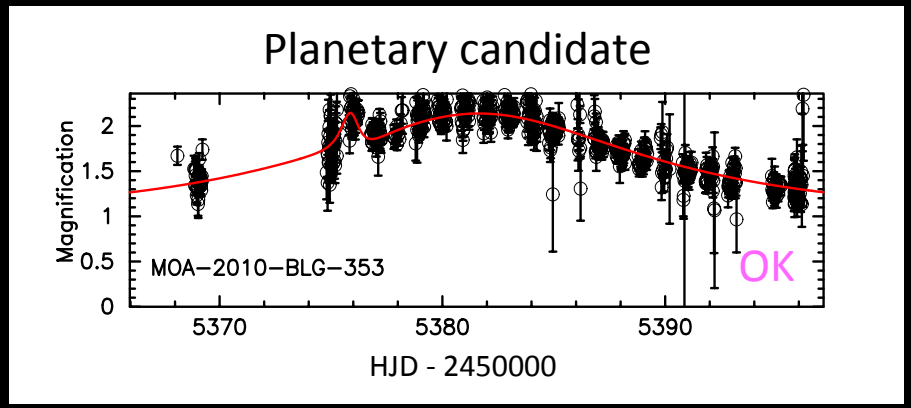
We reject …

1. Non-microlensing events (CVs, moving objects, …)
2. Non-planetary anomalies (stellar binary: q > 0.03)
3. Events with insufficient data points

Remaining events are

1471 single lens and 21 planetary candidate events

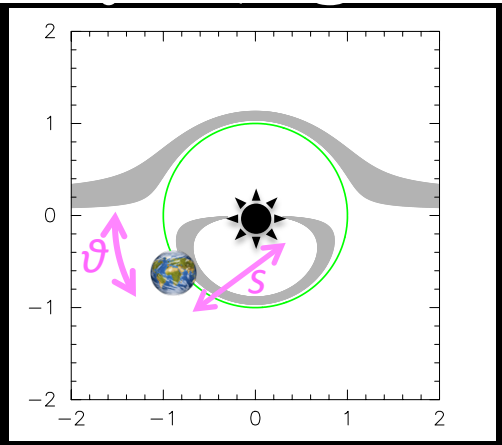




To derive planet frequency, we should consider detection efficiencies for planetary anomalies

Detection Efficiency, ε(logs, logq)

s : separation
q : mass ratio
ϑ : angle from the axis
ρ_*: source star size
Data quality…



Detection:

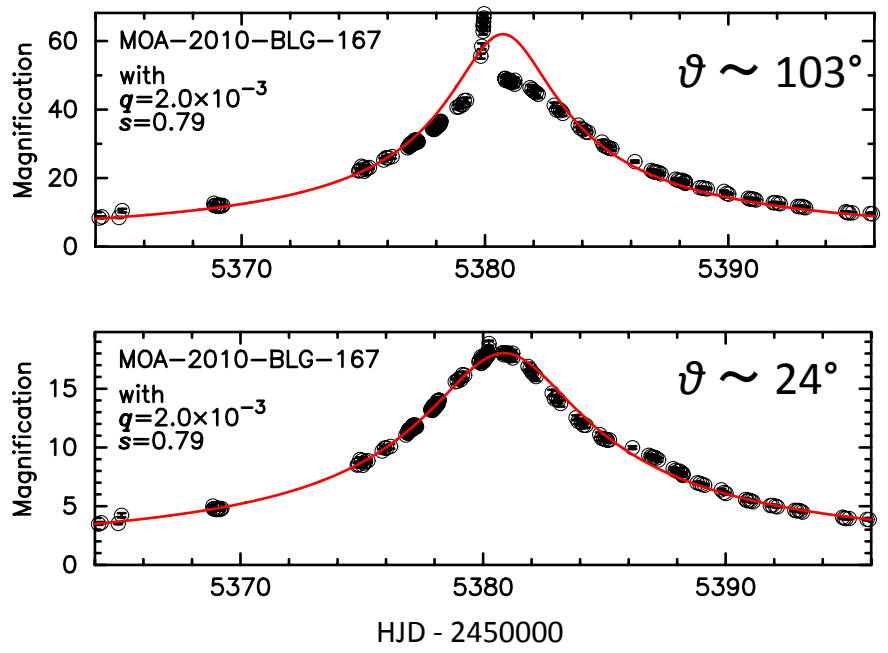
$$\Delta\chi^2 = \chi^2_{\rm Single} - \chi^2_{\rm Binary} > 100$$

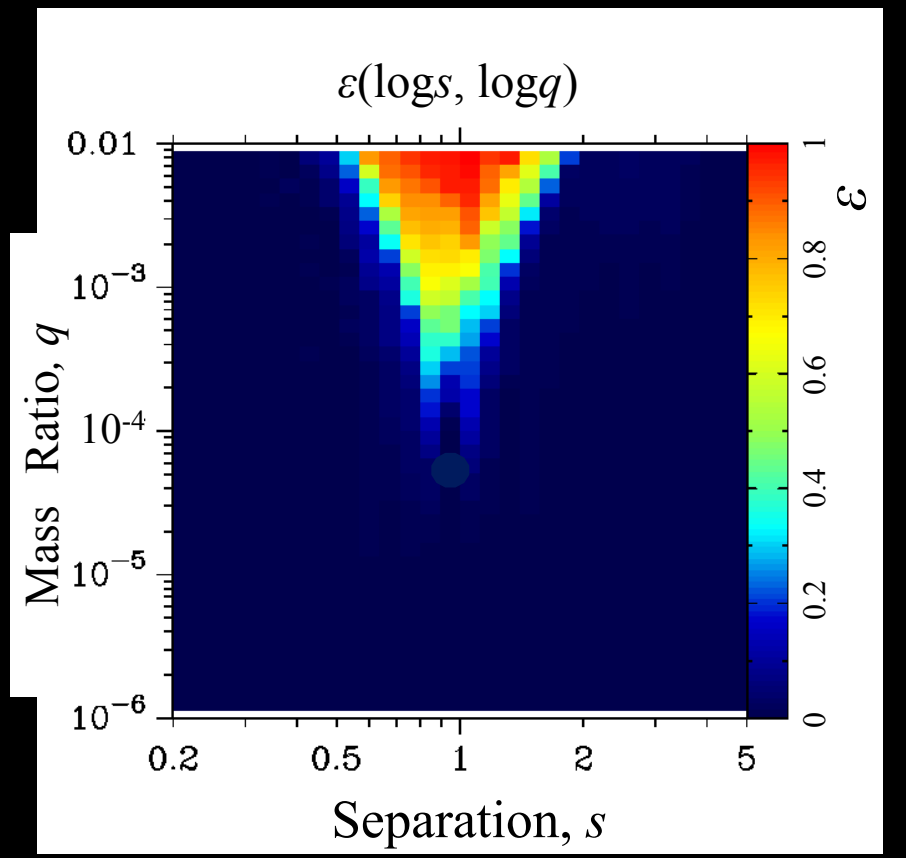
ε(logs, logq):

Fraction of detections within $0 < \vartheta < 2\pi$

Rhie et al. 2000

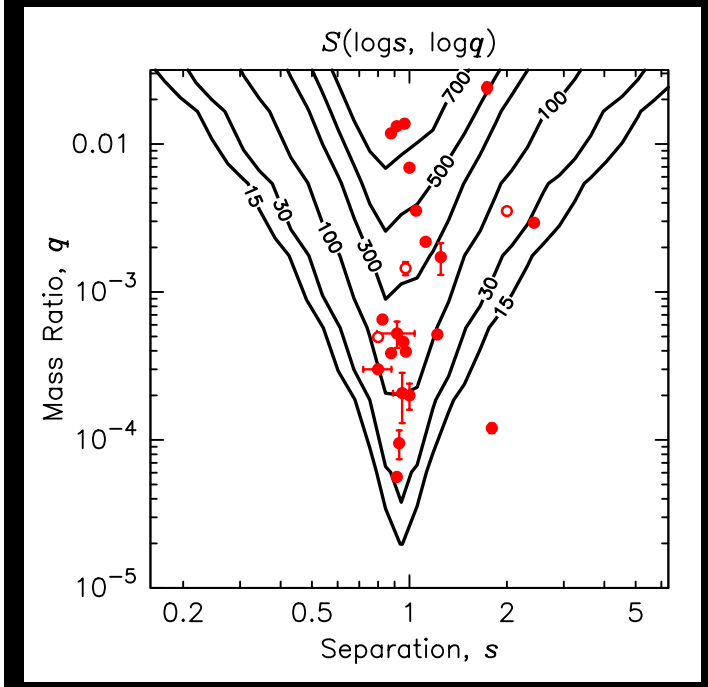
simulation

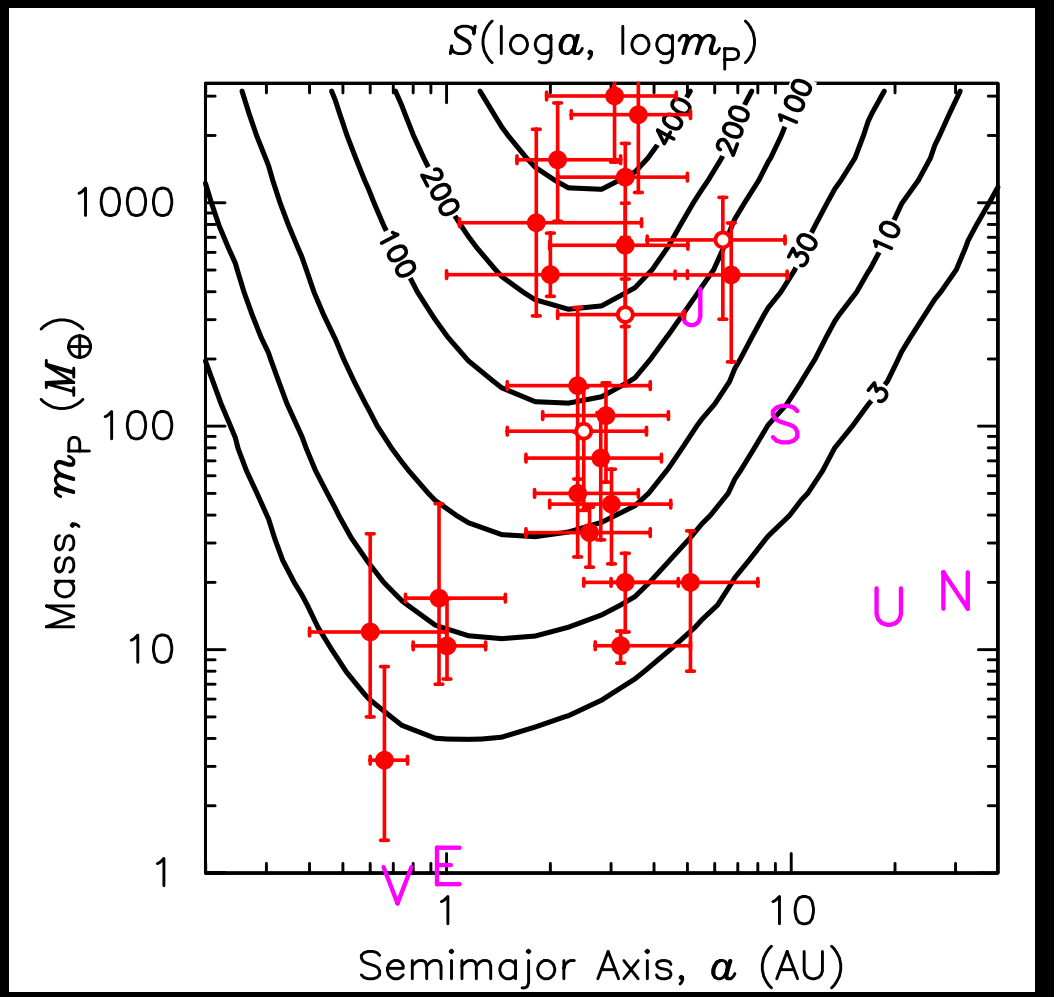




$S(\log s, \log q) \Rightarrow S(\log a, \log m_P)$

Sum of the detection efficiency in each event





$$M_{Lens} = 0.32^{+0.41}_{-0.23} M_{Sun}$$

Bayesian Estimate

- **Use t_E in each event**
- **With mass function (Sumi et al. 2011, Table3 model #1)**
- **With Galactic model (Han & Gould 2003)**

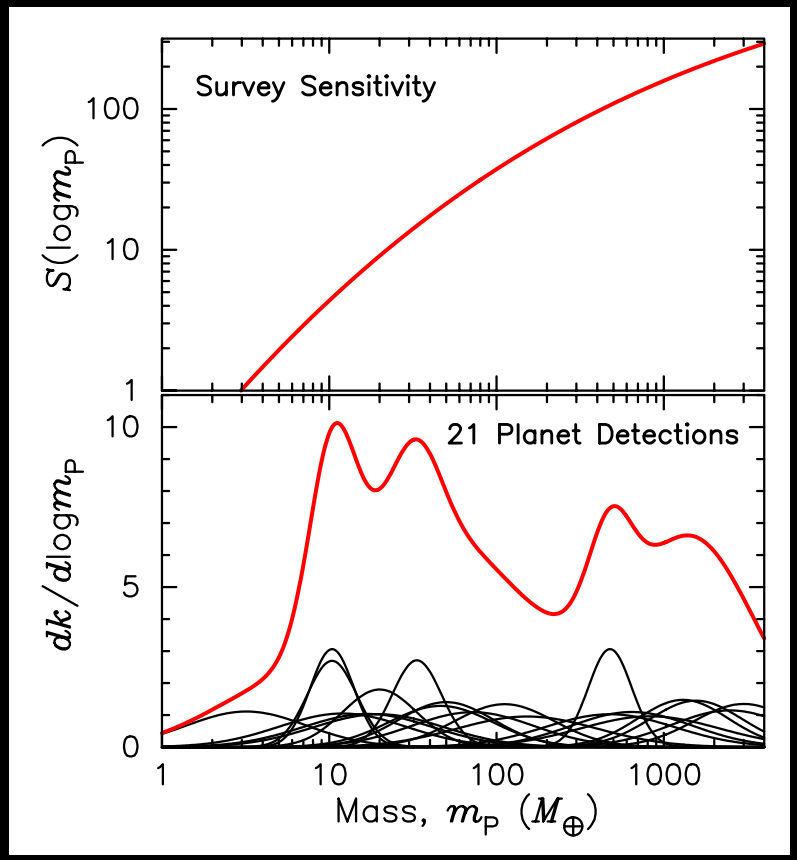
Likelihood Analysis

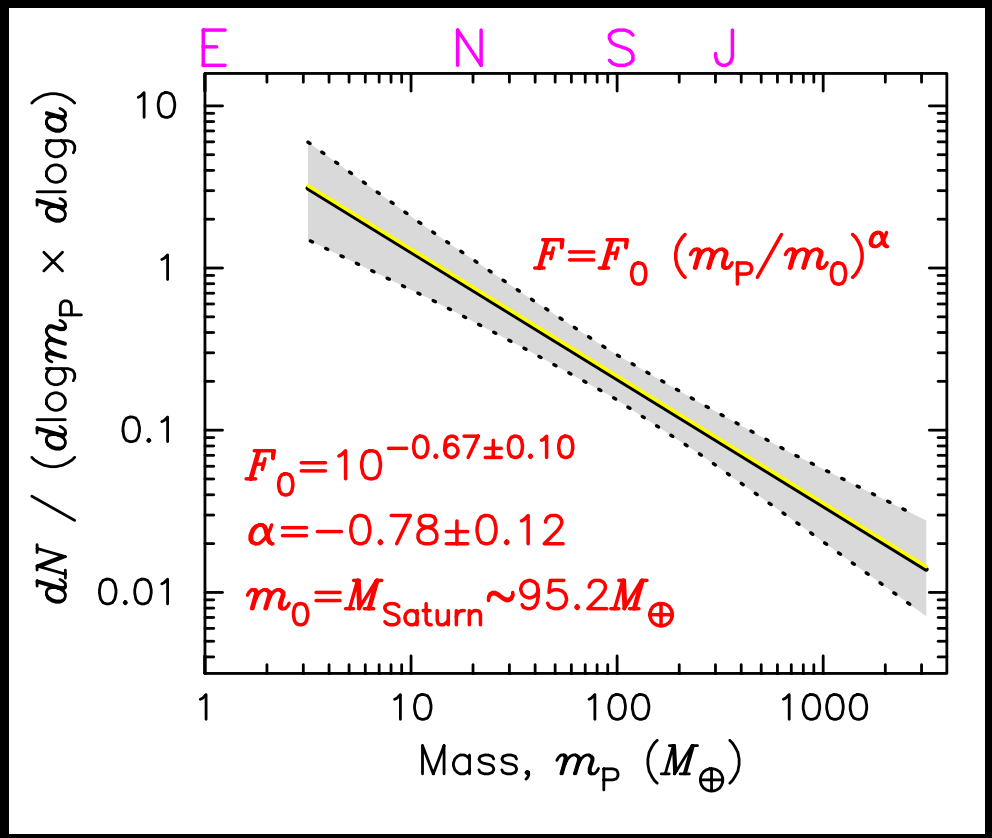
Planet mass function:

$$F \equiv \frac{dN}{d\log a\, d\log m_{\rm P}} = F_0 \left(\frac{m_{\rm P}}{m_0}\right)^{\alpha}$$

Likelihood:

$$\mathcal{L}(F_0, \alpha) = \prod_j P(k_j | E_j)$$





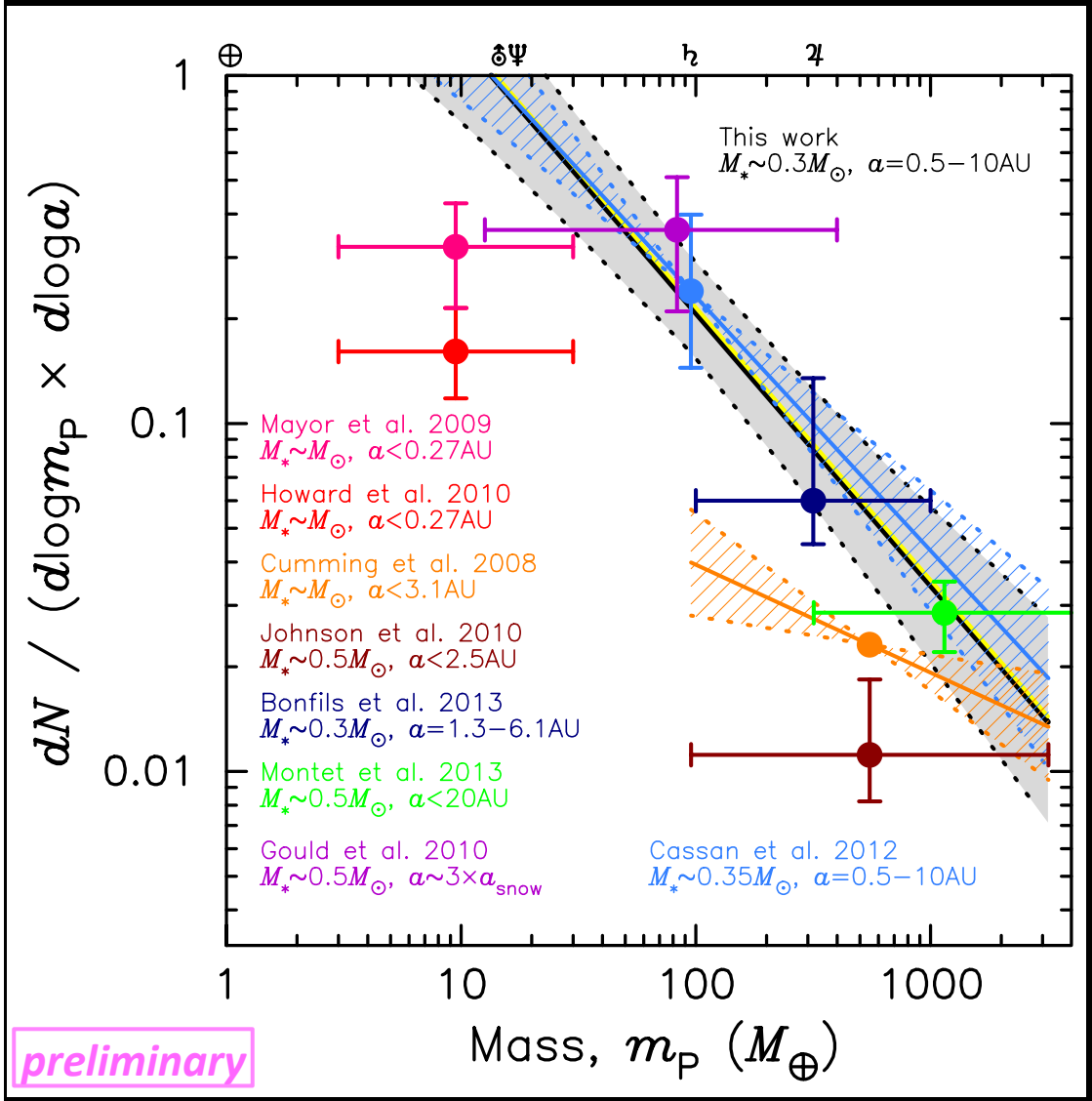
$$E = \iint S(\log a, \log m_{\rm P}) F(\log a, \log m_{\rm P}) d\log a\, d\log m_{\rm P}$$

Expected number of the detection with any given F

$$P(k|E) = \frac{E^k \exp(-E)}{k!}$$

Poisson distribution, k : # of planet detections

Planet Mass Function (Microlensing VS RV)



Consistent with previous microlensing results

N: Planet abundance

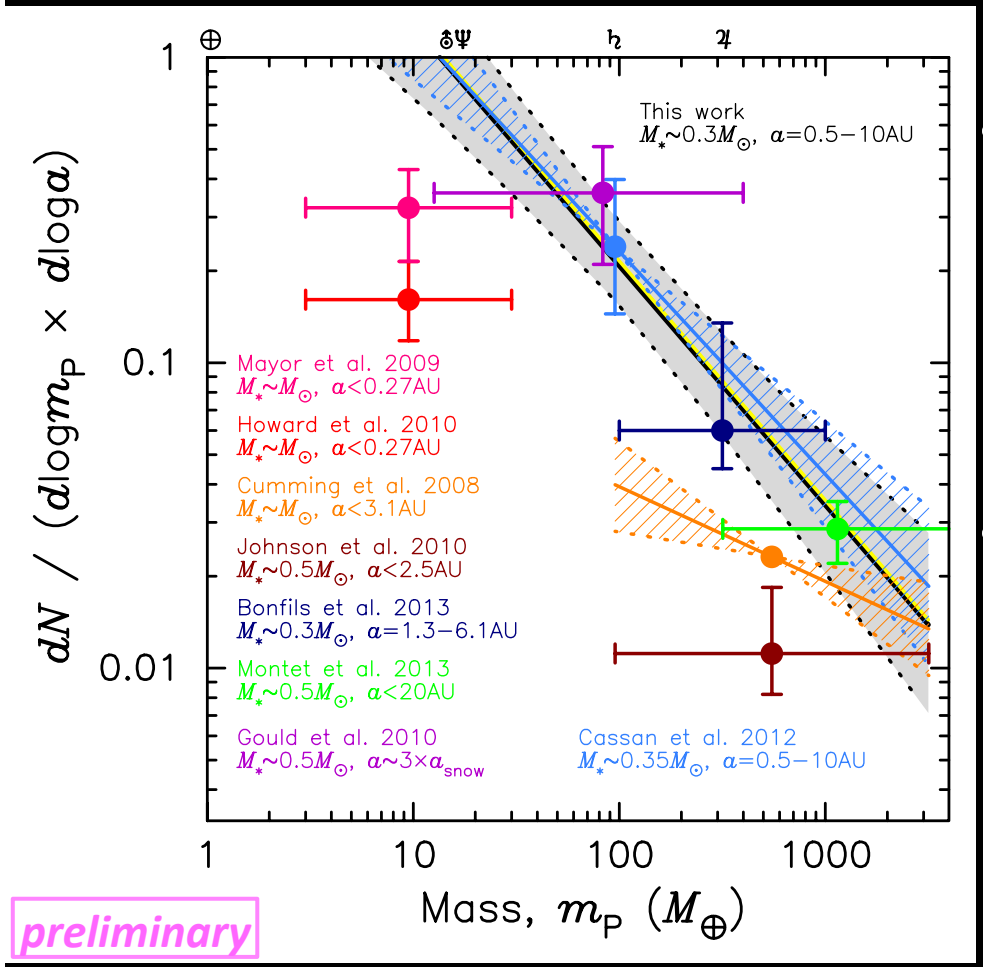
$$N = \iint F_0 \left(\frac{m_P}{m_0}\right)^{\alpha} d\log a \, d\log m_P$$

Within 0.5 – 10 AU

- **15^{+4}_{-3} %**
  (Giants: 0.3 M_{Jup} - 10 M_{Jup})
- **52^{+18}_{-15} %**
  (Neptunes: 10 M_{Earth} - 30 M_{Earth})
- **$1.6^{+0.52}_{-0.42}$ planets per star**
  (5 M_{Earth} - 10 M_{Jup})

Discussion

From MOA survey in 2007-2012,



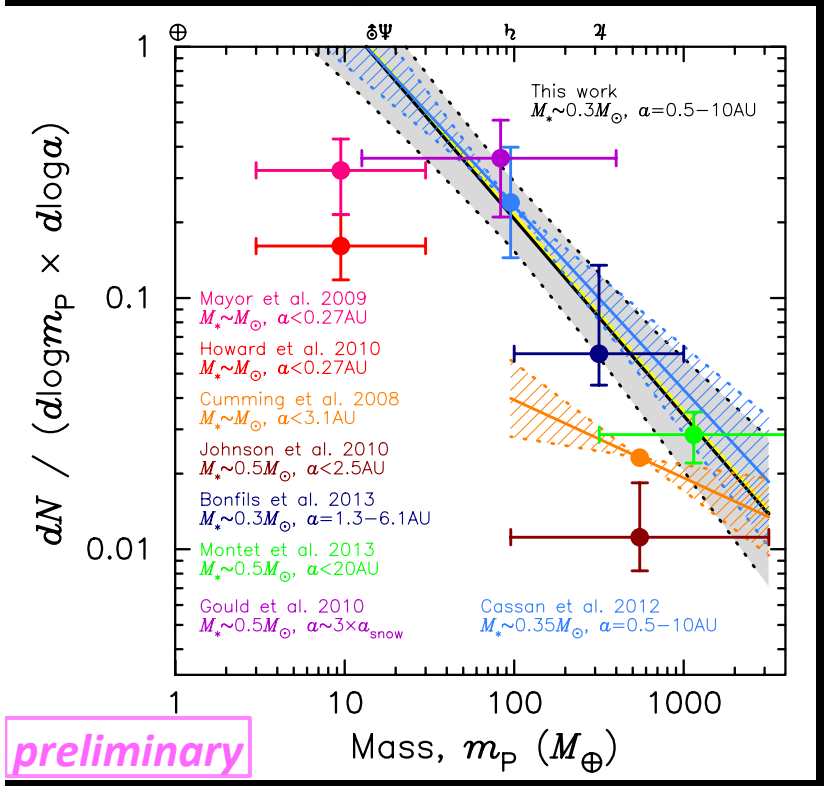
- Consistent with RV for long period giants around M dwarfs: **Bonfils+ 2013**, **Montet+ 2013**
- More cold giants than close-in Jupiters around M dwarfs: **Johnson+ 2010**

Future: to reduce the uncertainties in planet and host star masses

- Statistics of the events with mass measurements
  - MOA, OGLE, WISE, KMTNet (2nd gen. survey from ground)
  - WFIRST

Summary

From MOA survey in 2007-2012,



- $F = F_0(m_P/m_0)^\alpha$, $F_0 = 10^{-0.67\pm0.10}$, $\alpha = -0.78 \pm 0.12$
- Consistent with previous µlensing results
- Consistent with RV for long period giants around M dwarfs: **Bonfils+ 2013**, **Montet+ 2013**

- More cold giants than close-in Jupiters around M dwarfs: **Johnson+ 2010**
- Could be difficult to explain by core accretion theory
- Future: Statistics of the events with mass measurements