Recent Results from Gravitational Microlensing

- Bound planets
- Unbound/Distant planets

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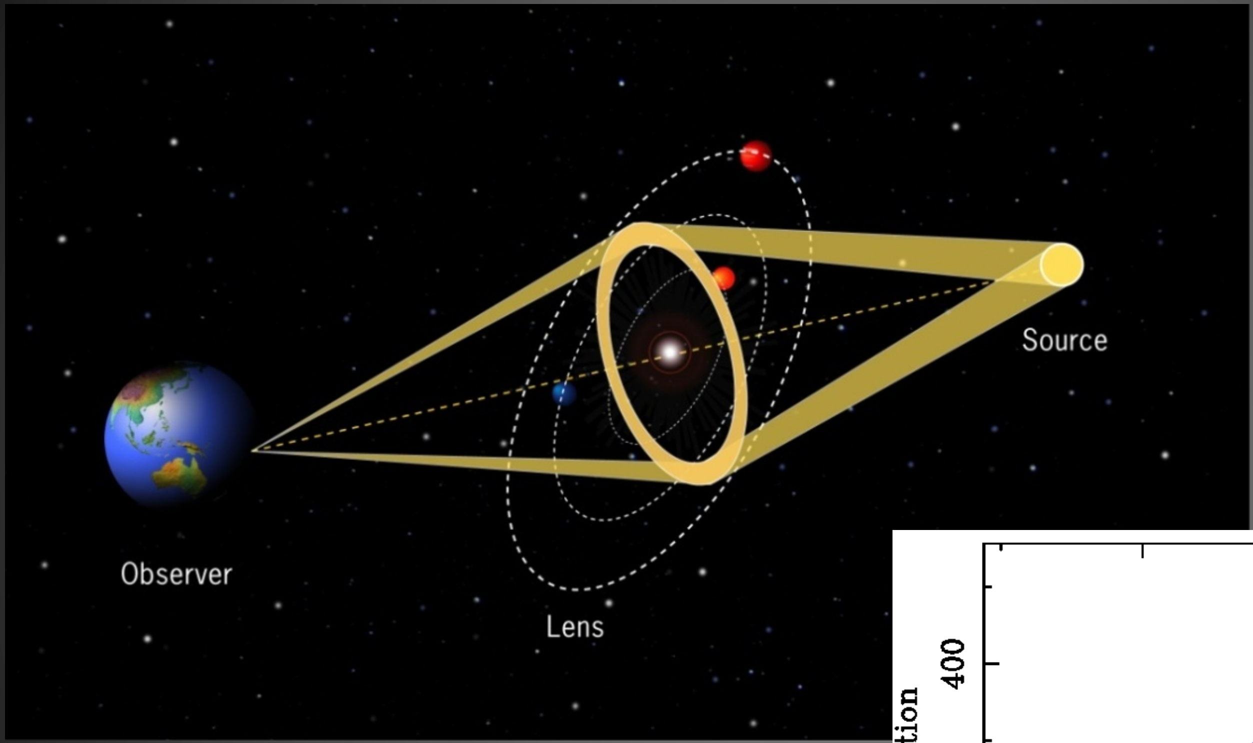
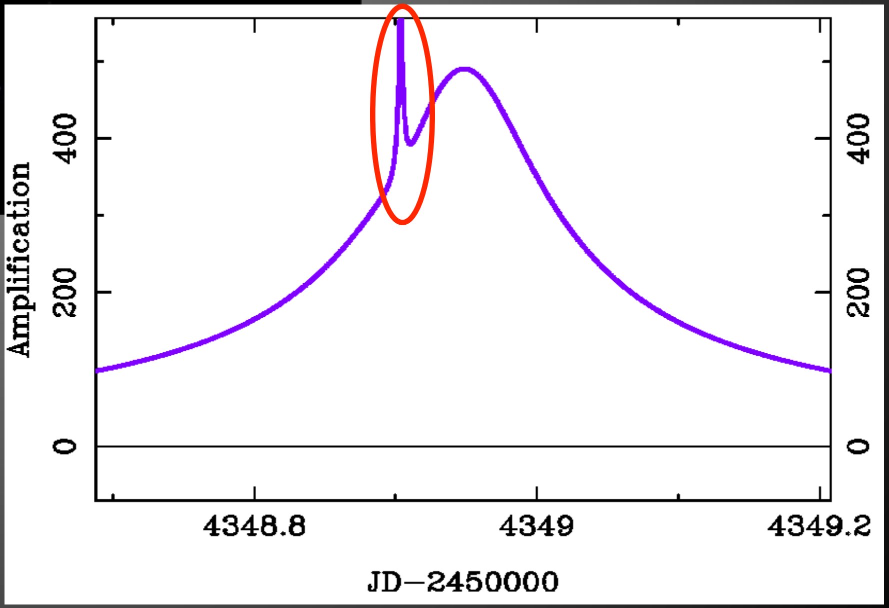
MOA collaboration

NASA/JPL-Caltech/R. Hurt

planetary microlensing





Microlensing observation global network

Survey Group

MOA(NewZealand)

OGLE(Chile),

- Wide field
- Low cadence

Micro lensing Alert →

Anomaly Alert ⇔

Follow-up Group

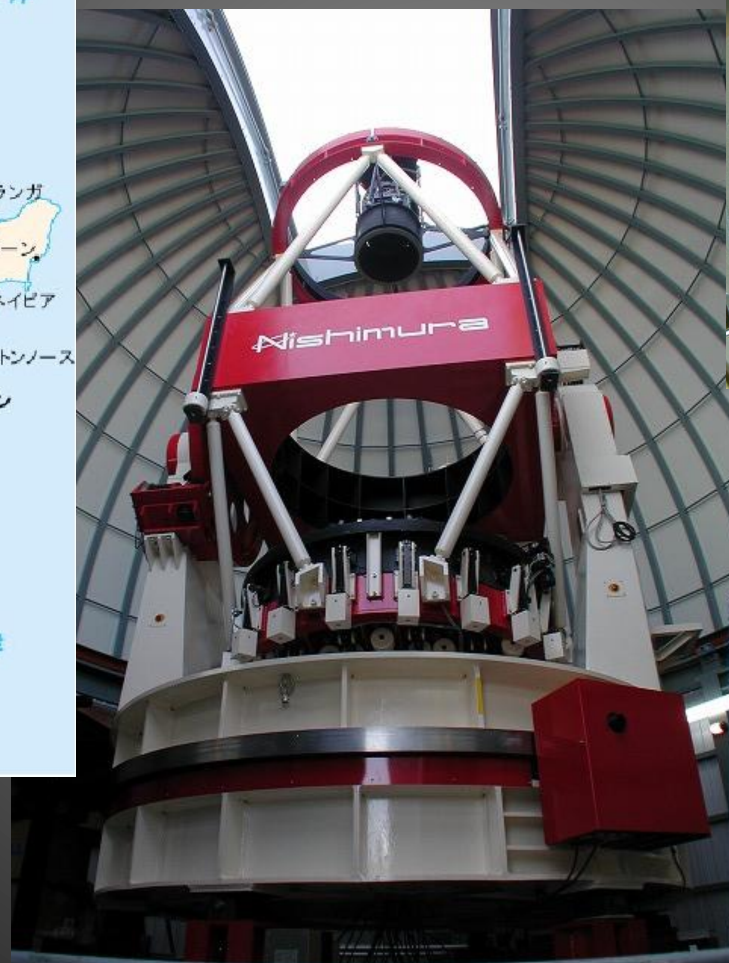
PLANET
μFUN
Robonet-II
MiNDSTEp

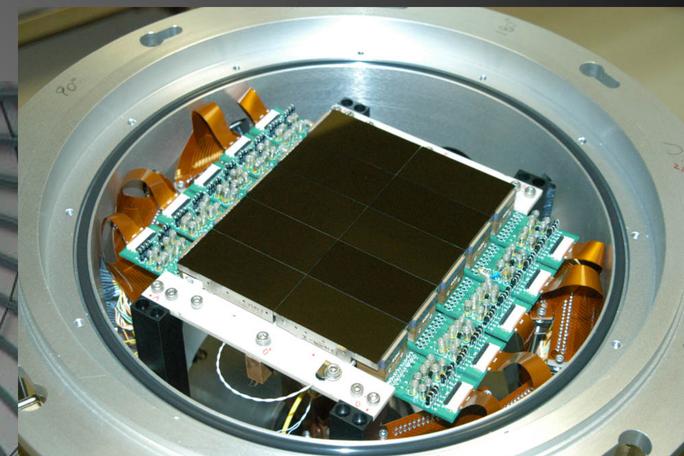
- Pointing each candidate
  High cadence

MOA (since 1995)

（Microlensing Observation in Astrophysics）

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





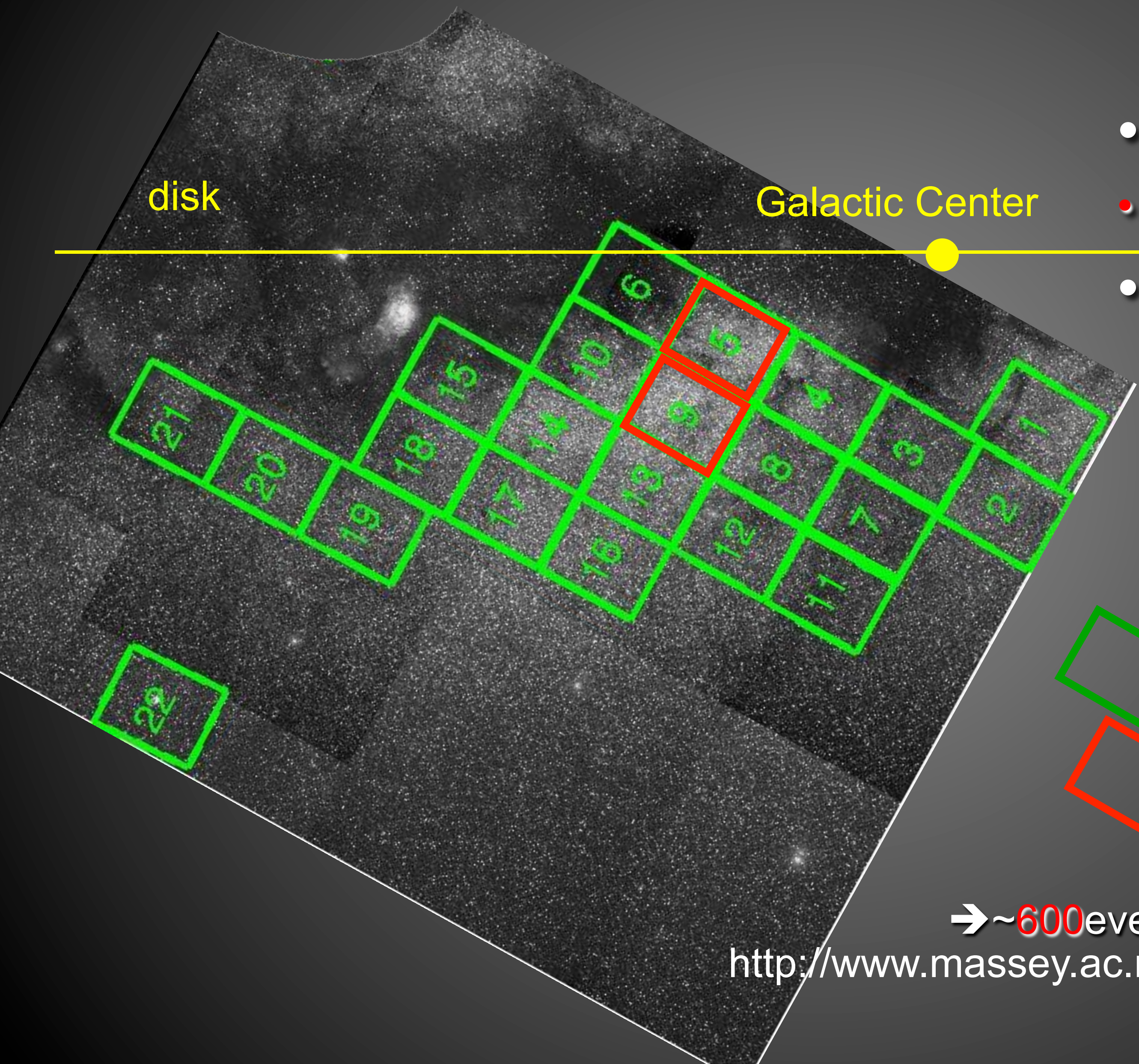
Mirror : 1.8m

CCD : 80M pix.(12x15cm)

FOV : 2.2 deg.^{2}

(10 times as full moon)

Observational fields



- 50 deg.^{2}
- (200x full moon)
- 50 M stars

1obs/1hr

1obs/10min.

➔~600events／yr

http://www.massey.ac.nz/~iabond/alert/alert.html

Mass measurement of the cold, low-mass planet MOA-2009-BLG-266Lb
Muraki et al. 2011

m_p = 10.4 +- 1.7 M_{Earth}

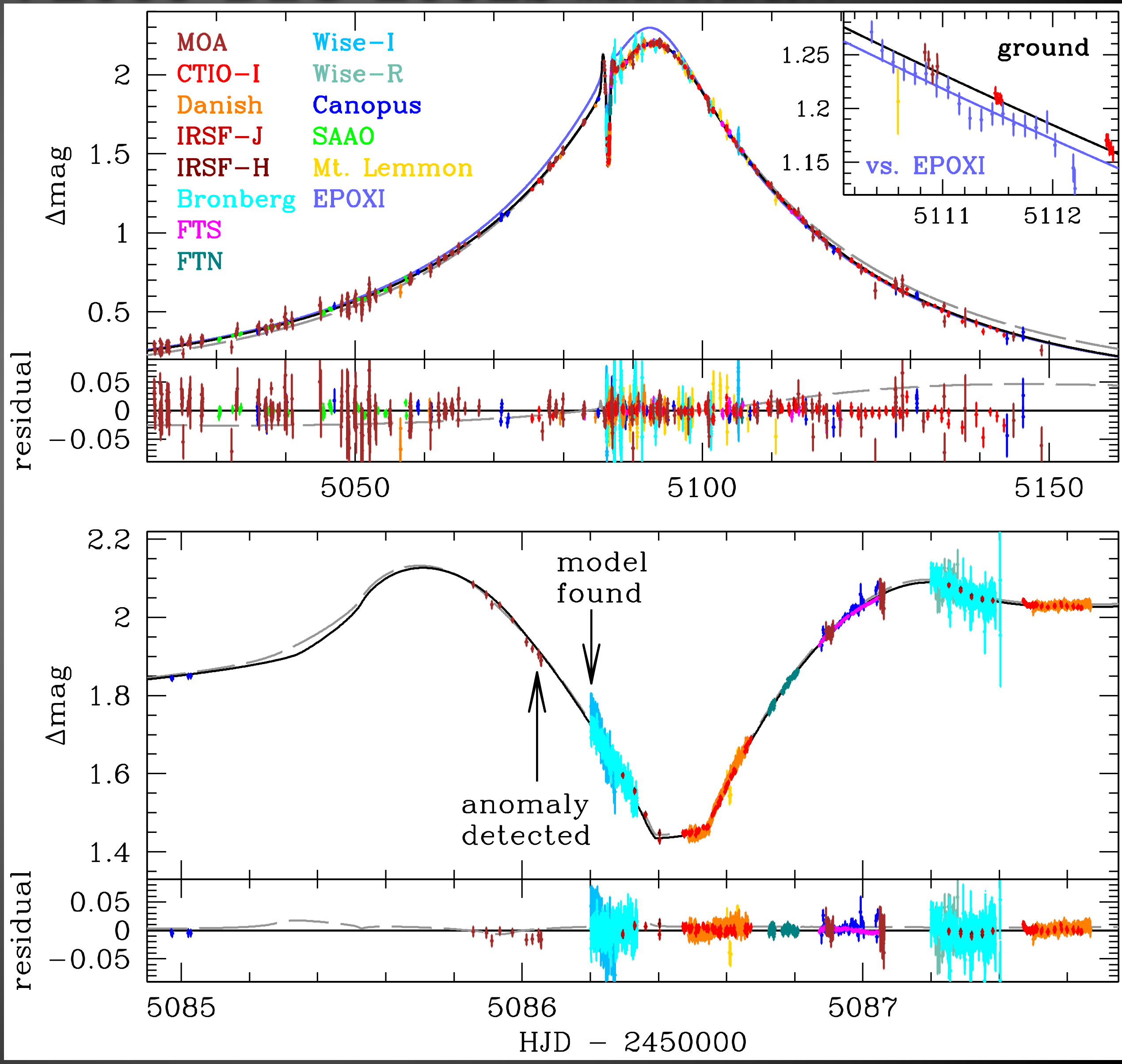
M_* = 0.56 +- 0.09 $M_\odot$

a = 3.2 (+1.9 -0.5) AU

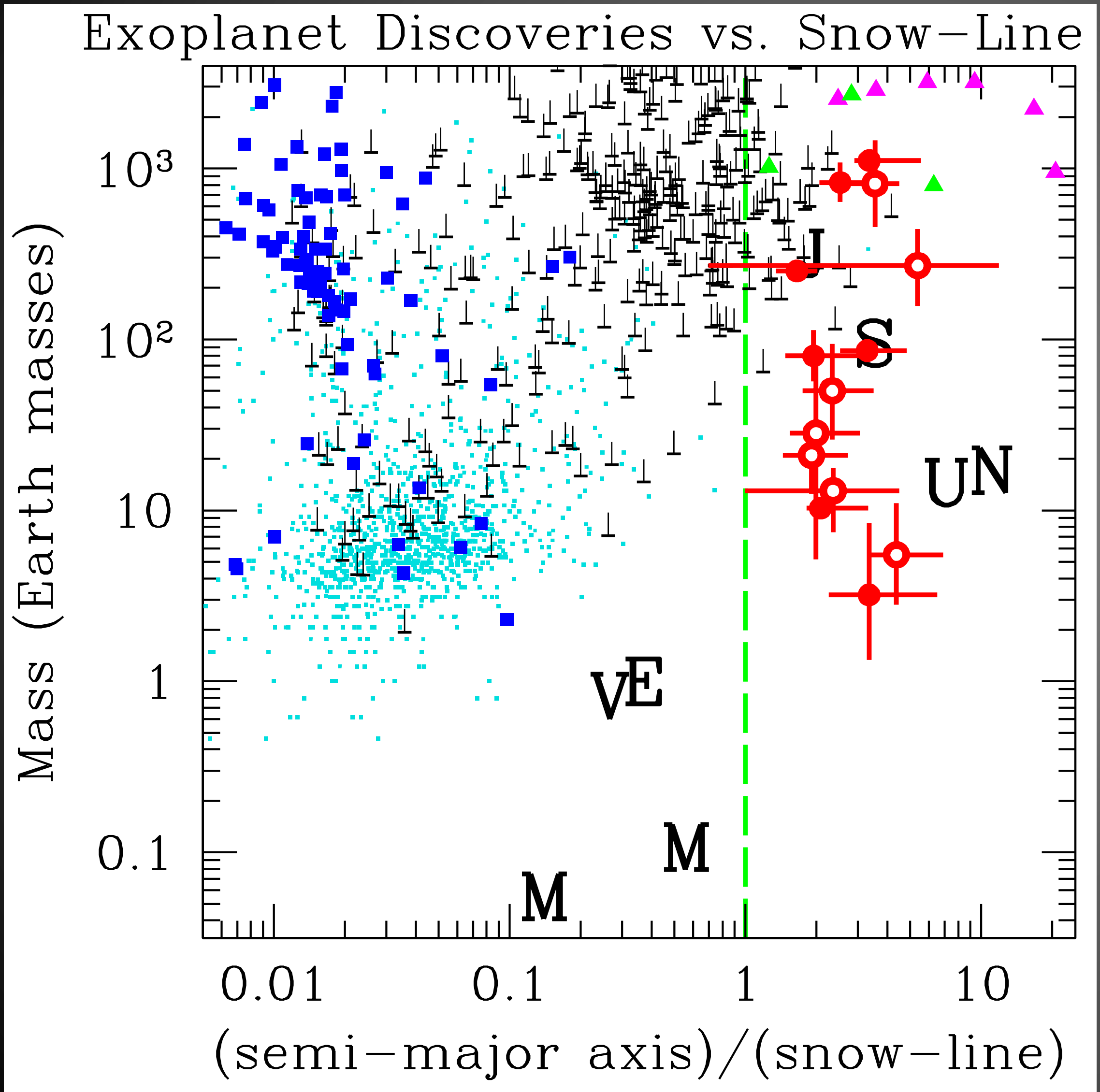
Orbital period:

P=7.6 (+7.7-1.5) yrs.

demonstrates the capability to measure microlensing parallax with the Deep Impact (or EPOXI) spacecraft in a Heliocentric orbit.

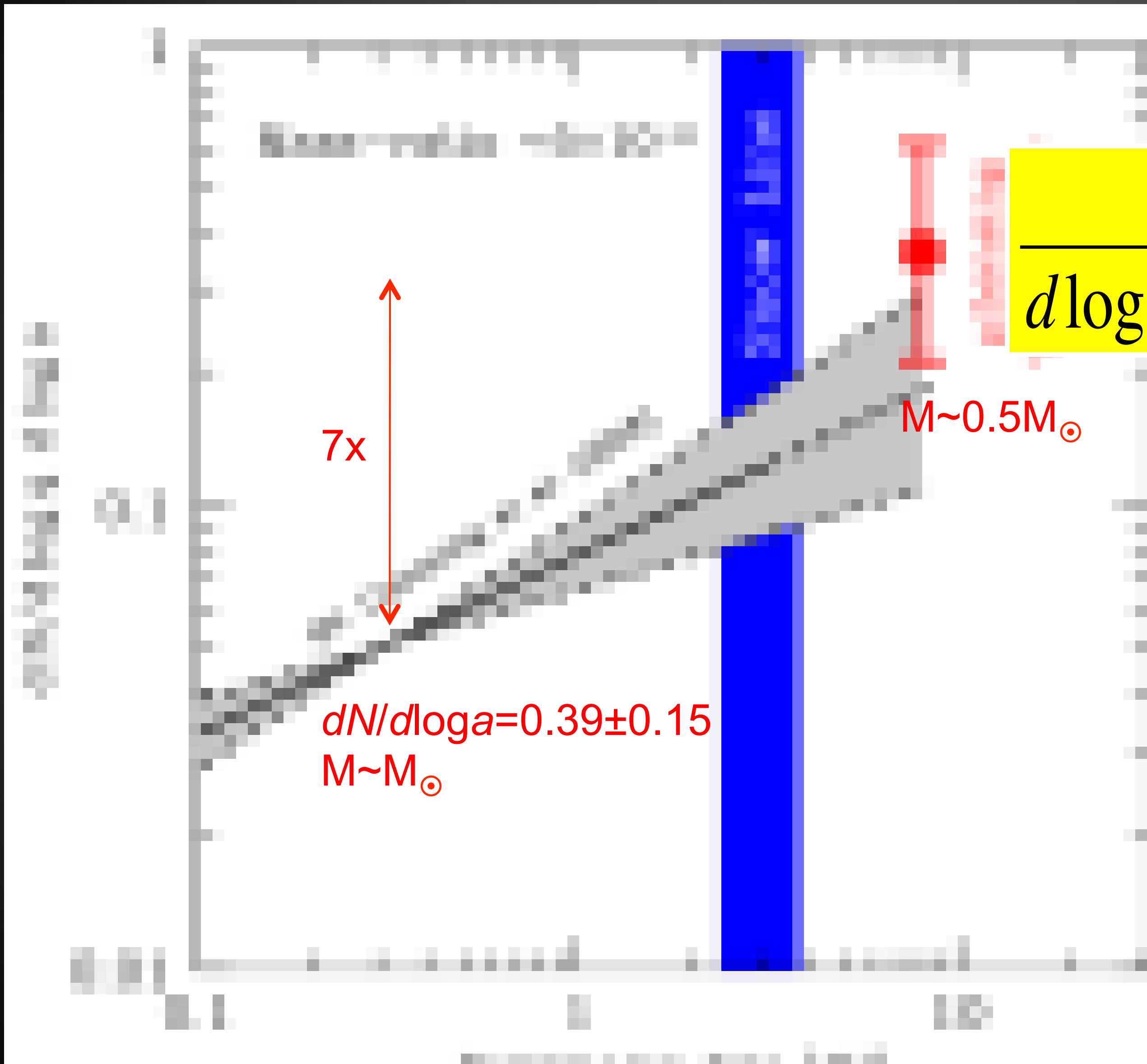


Summary of Planet candidates



- •RV
- •Transit (Kepler)
- •Direct image
- •Microlensing : 14planets
  - Mass measurements
  - Mass by Bayesian

Planet Frequency vs semimajor axis



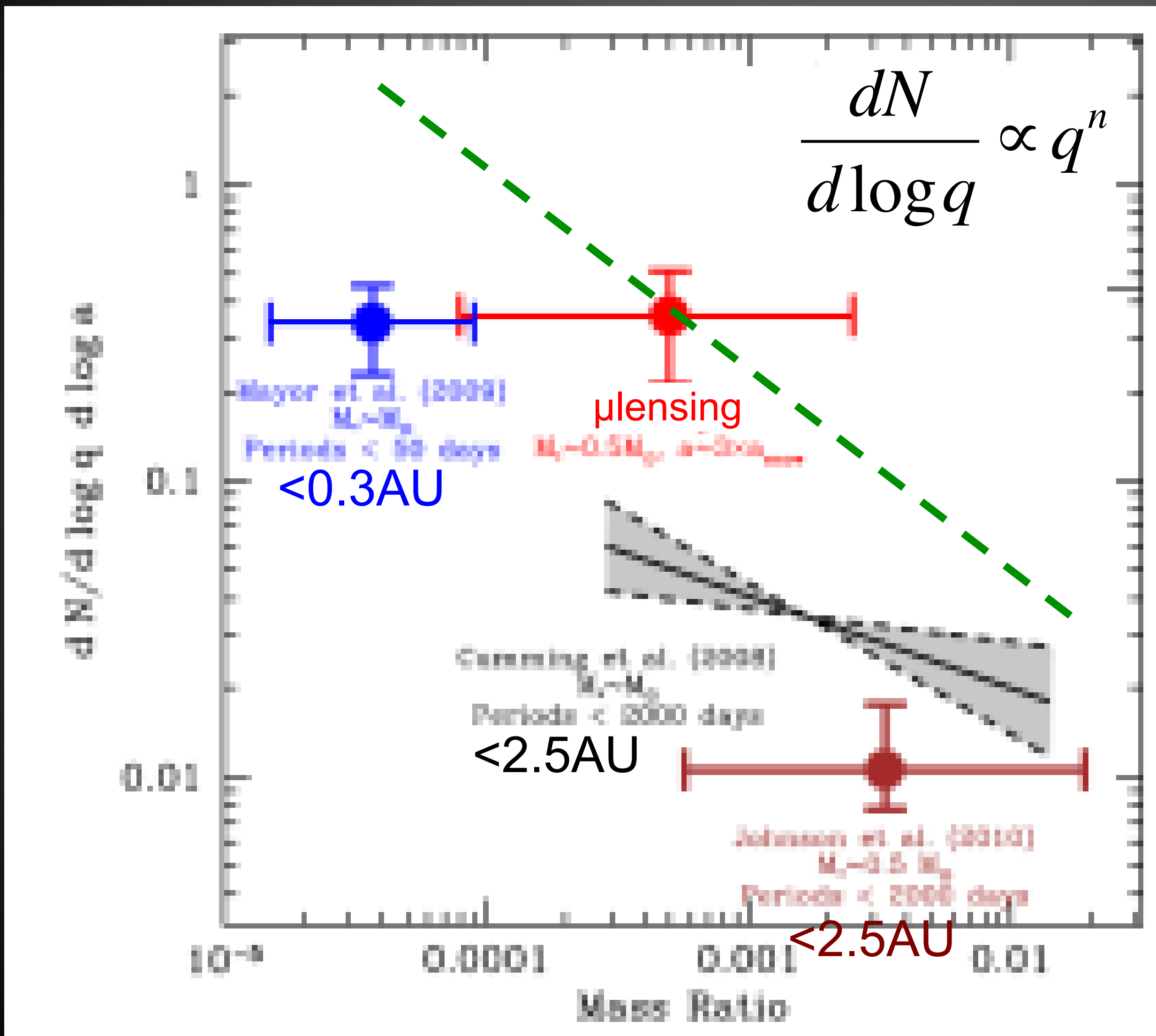
6planets

$$\frac{dN}{d\log q\, d\log s} = 0.36\ \mathrm{dex}^{-2}$$

- Most ice & gas giant planets do not migrate very far in K,M dwarf
- Amount of migration is a continuous parameter

Gould et al. 2010

Planet mass ratio function



4 Neptune,
1 sub-Saturn,
5 Jupiter

n = −0.68 ±0.20
(Sumi et al. 2010)
<-0.35(95%cl)

n = −0.31 ±0.20
(RV, solar-type stars, Cumming et al. 2008)

Cold Neptunes($q \sim 5\times10^{-5}$) are 7^{+6}_{-3} times more common than Jupiters ($q \sim 10^{-3}$), >2.8 times (95% cl) around K,M dwarfs

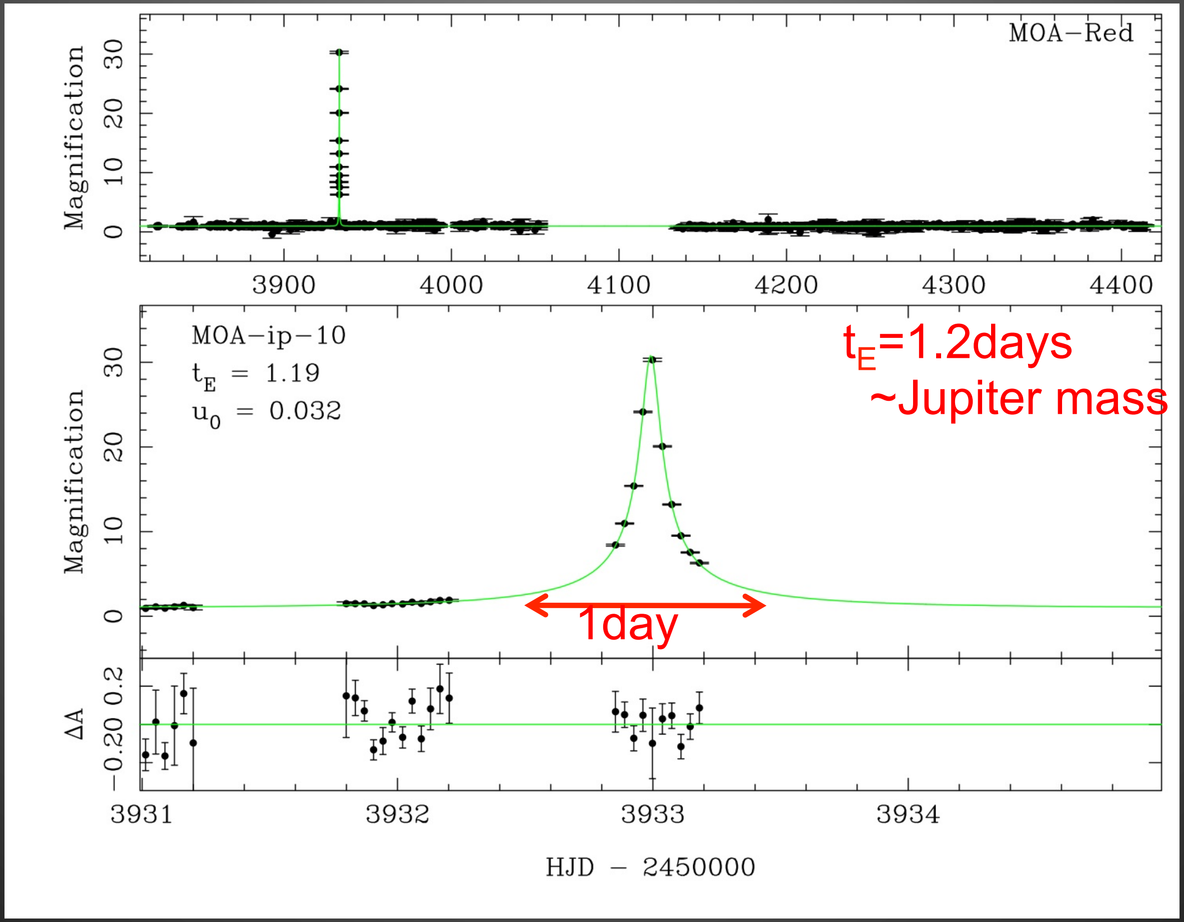
10 events with timescale t_E<2days

474events in 2 years

timescale: $$t_E = \frac{R_E(M,D)}{v_t} \sim \sqrt{M/M_J}\ day$$

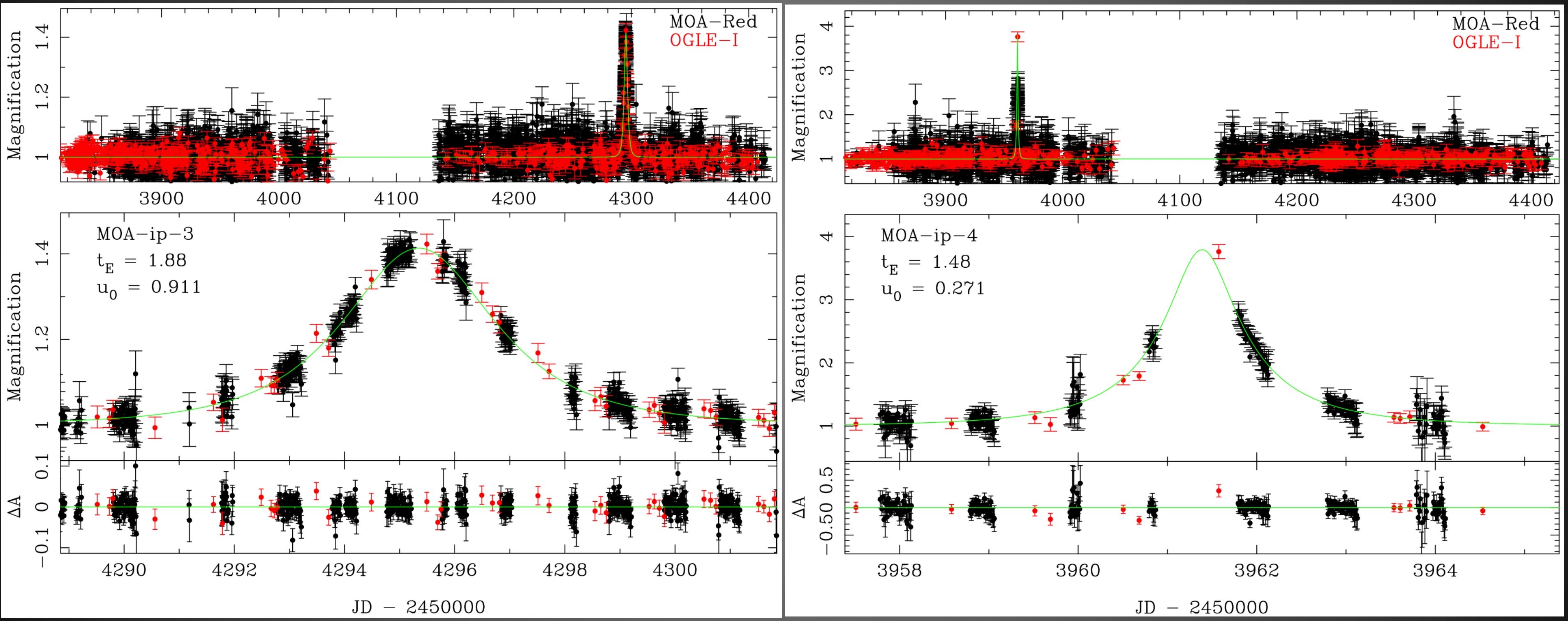
~20days for stars

M: lens mass
M_J: Jupiter mass
D: distance
v_t: velocity



10 events with t_E< 2 days from 2006-2007

(events 3, 4)



MOA data in black, confirmed by OGLE data in red

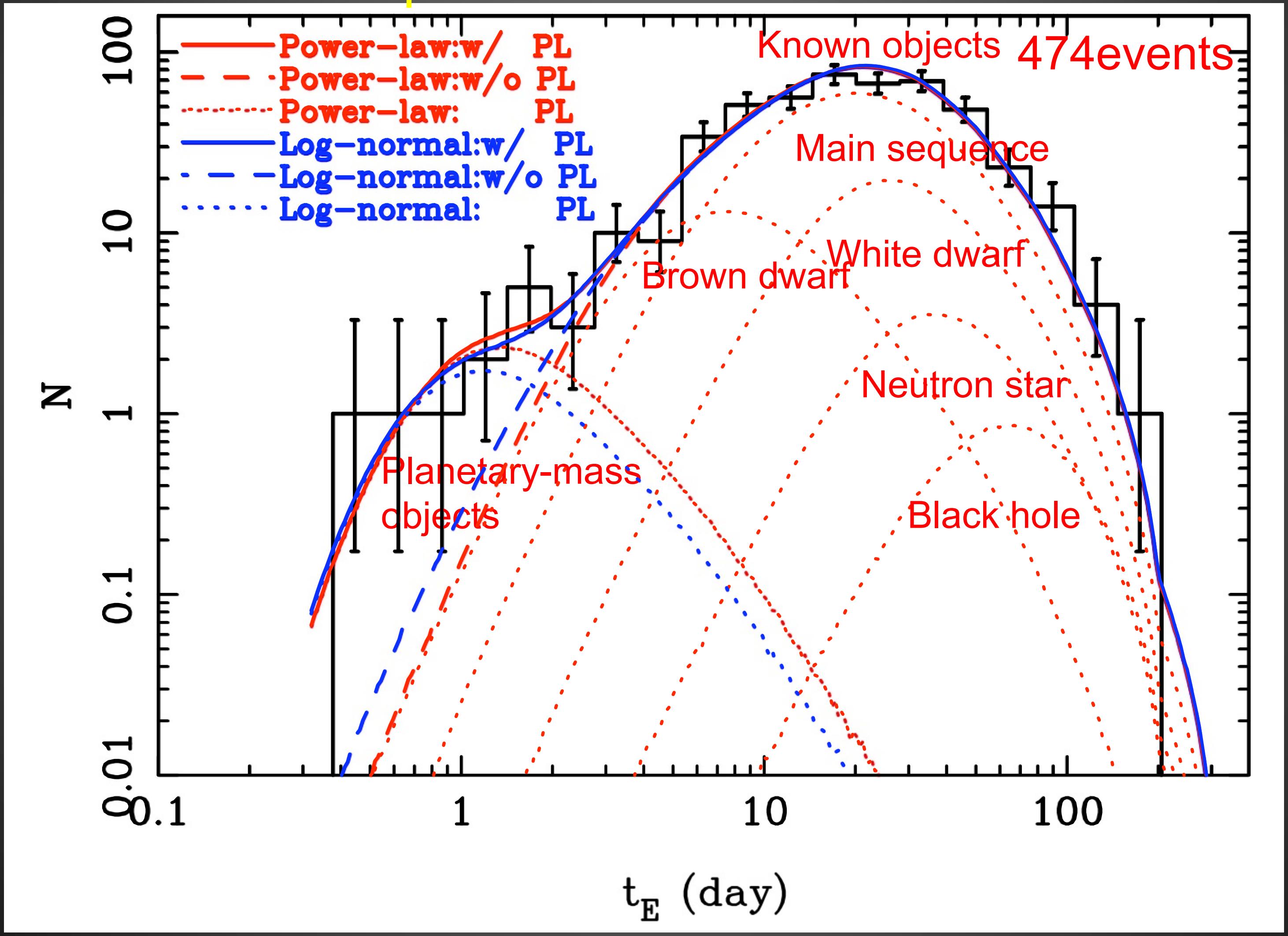
Timescale t_E distribution

abundance :~1.8 as common as stars

Mass : ～Jupiter mass

$$N_{planet} = 1.8^{+1.7}_{-0.8} N_{star}$$

$$M_{planet} = 1.1^{+1.2}_{-0.6} M_J$$

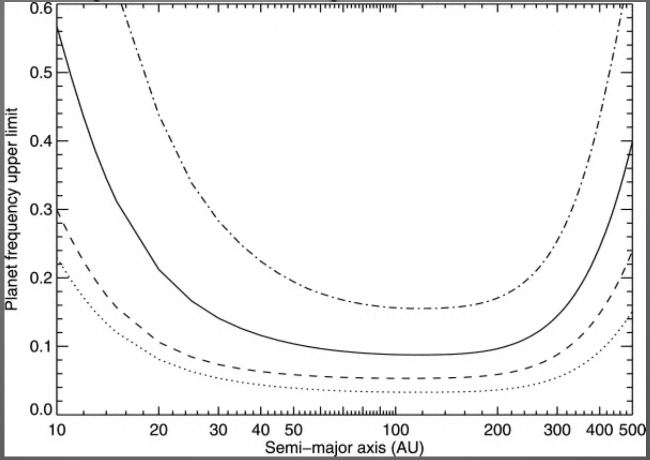


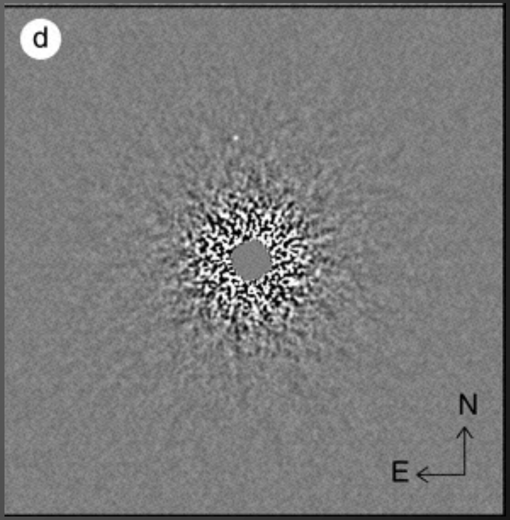
Sumi et al. 2011, Nature, 473, 7347, 349-352

Unbound or distant planets?

- Microlensing data only sets a lower limit on the separation: no host stars within 10AU
  - HST follow-up can set tighter limits or detect host

- 8m telescope, Direct imaging limits （Lafreniere et al. 2007)
  - < 40% of stars have 1 Jupiter-mass planet at 10 AU < *a* < 500 AU





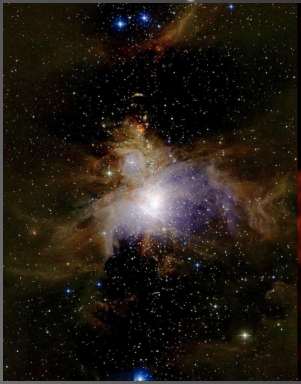
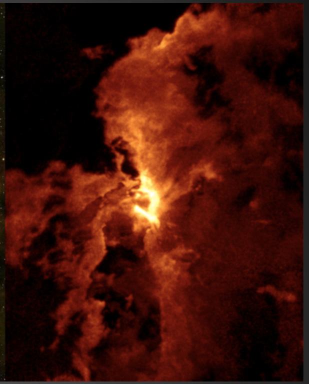
- We find 1.8 planets per star,

➔ so at least 1.4 planets per star (75%) should be free!

Formation Scenarios:

1. formed on their own through gas cloud collapse similar to star formation (sub brown dwarf)

- Hard to form Jupiter-mass objects
- Planetary-mass sub brown dwarf can explain only 1 or 2 short events.
- Abrupt change in mass function at Jupiter-mass do not support this scenario.

2. formed around a host star, and scattered out from orbit

Hot Jupiters orbiting hot stars have high obliquities (Winn et al. 2010, Triaud et al. 2010)

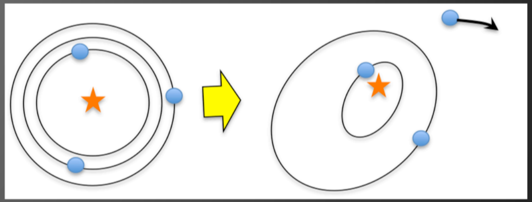
➔ evidence of gravitational interaction

Hot Jupiters are alone (Latham et al. 2011)

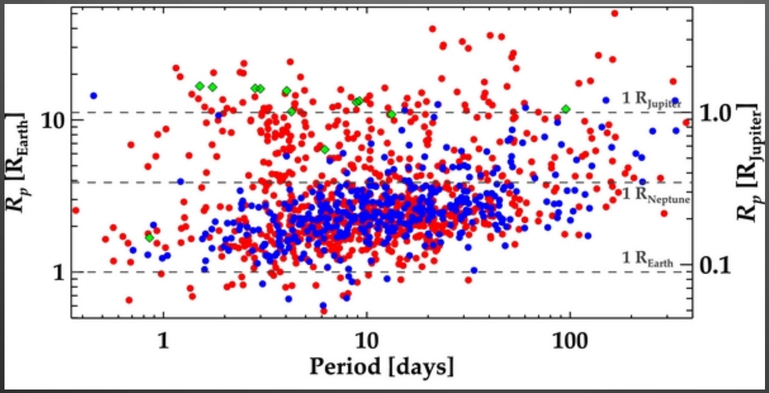
➔ evidence of gravitational interaction

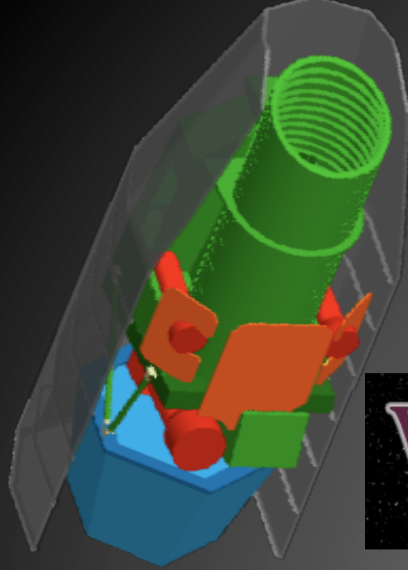
No desert for short-period super-earths (Howard et al. 2010)

planet-disk interactions are of secondary importance to planet-planet scattering



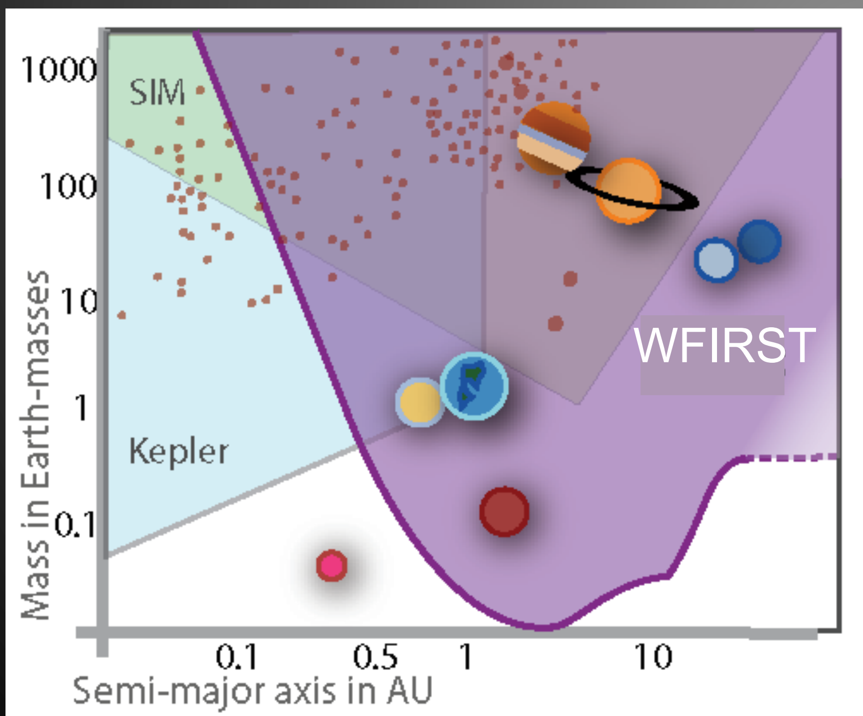
•Single-planet
•Multi-planet





The WFIRST Microlensing Exoplanet Survey:

Recommended by ASTRO 2010 Decadal report



~3000 exoplanets
~300 sub Earth-mass Planets,
>25 habitable planets
（0.5-10 M_{Earh}、0.72-2.0 AU）
around FGK stars

~2000 Free-Floating Planets!
~190 sub Eath-mass FFP!
(>30 Earth-mass FFP！)

Complete the census of planetary systems

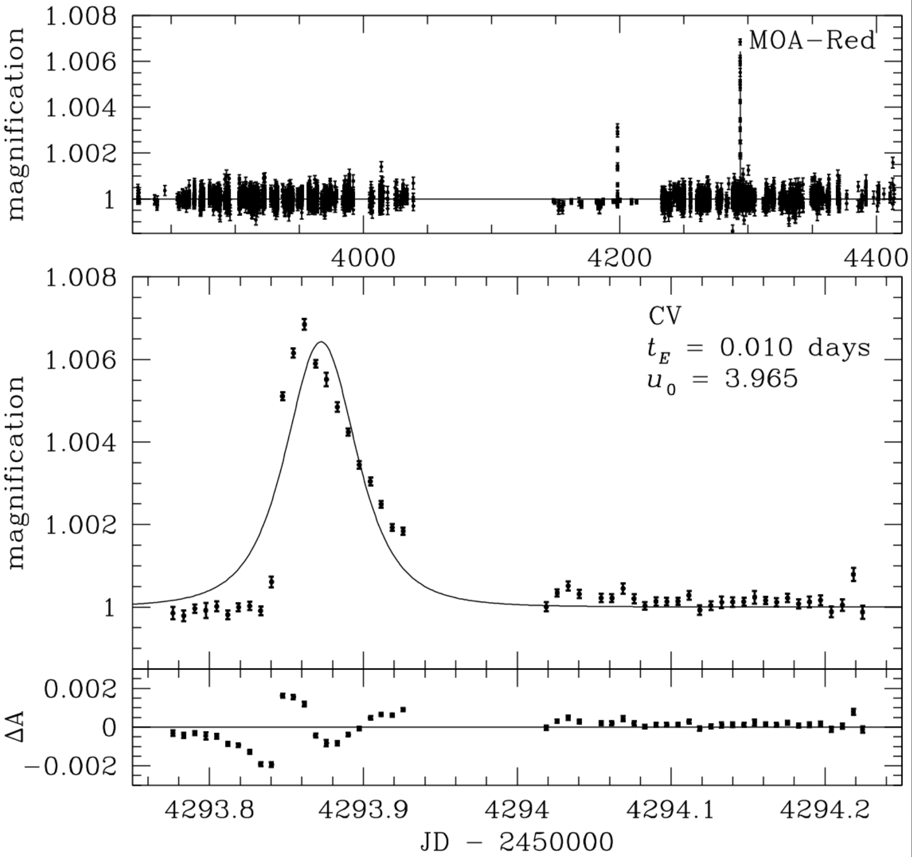
Summary

- *Mass-ratio function:* $\propto q^n$: $n=-0.7\pm0.2$, $n<-0.35$(95%cl) (>snow line)
  - ✧ Cold Neptune are 7x (or at least 3x) more common than Jupiters in K,M-dwarf
- Frequency: $dN/(d\log q\, d\log s)=0.36\,\mathrm{dex}^{-2}$ (>snow line)
  - ✧ 7x more than at a=0.3AU by RV (Consistent with slope in sep)
  - ✧ 10x more than core accretion model.
- Free-floating planets are 1.8 times as common as main sequence stars (at least same order)

  ->They inform us not only the number of planets that survived in orbit, but also planets that formed earlier and scattered.
- WFIRST will complete the census of planetary systems

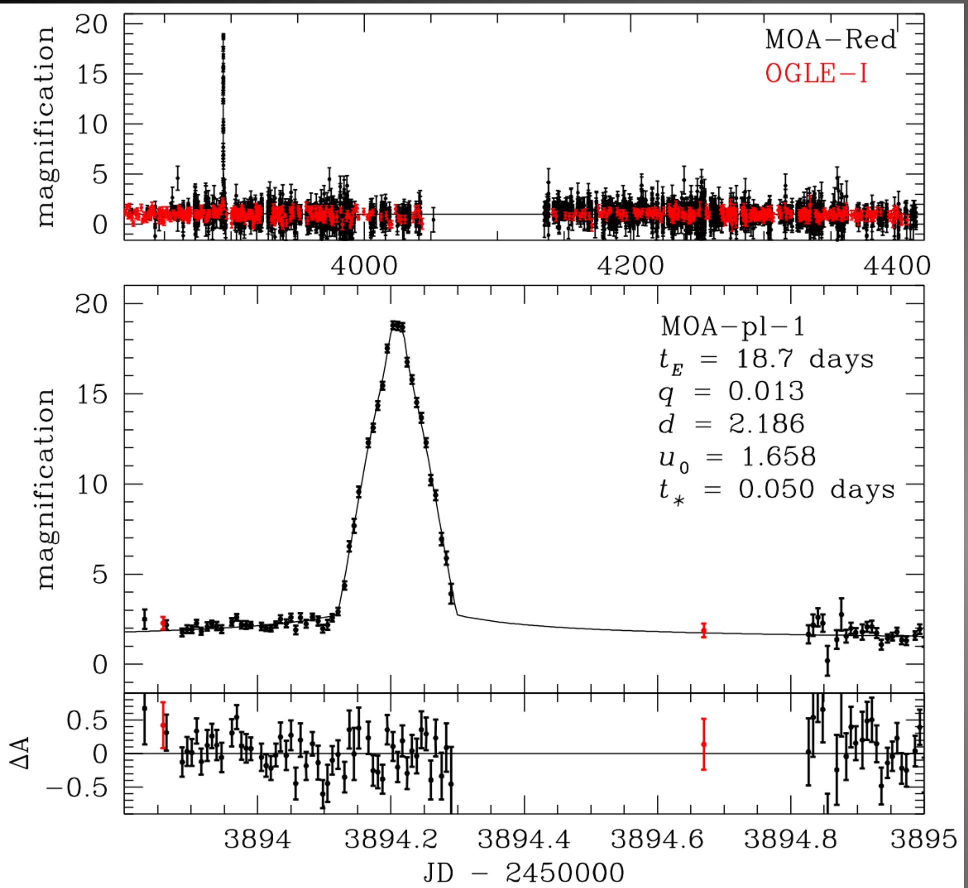
end

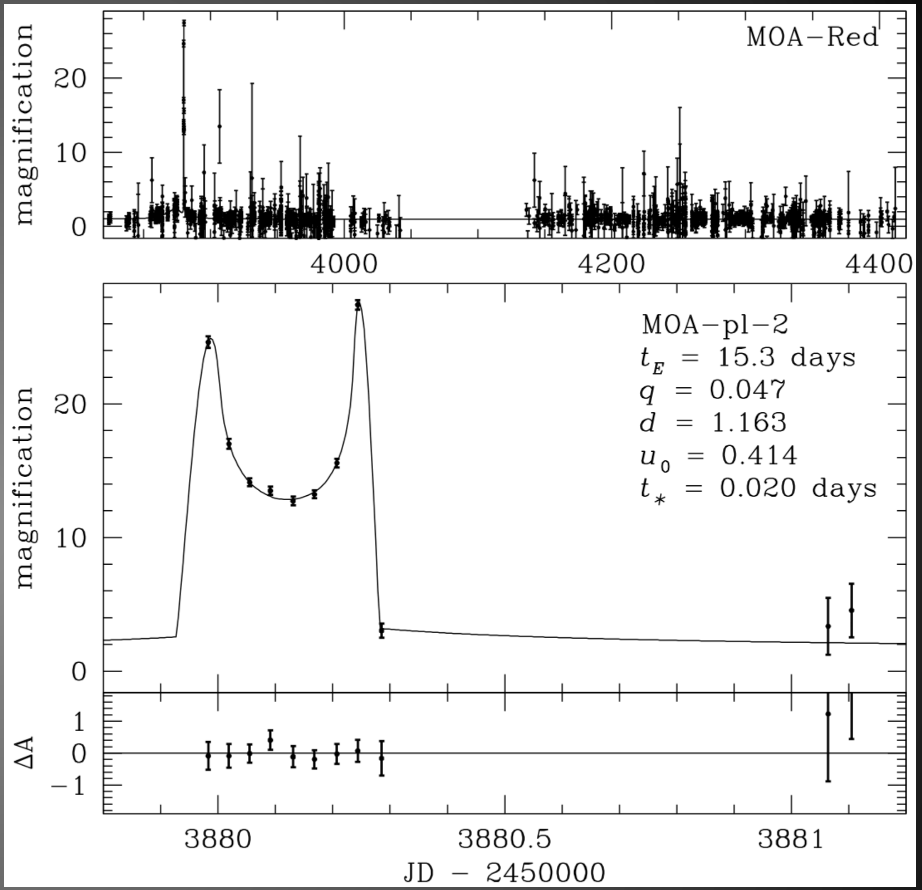
Background: CV

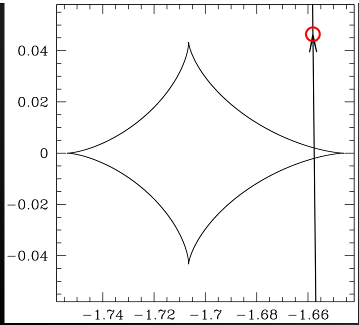


a CV gives a poor microlensing fit, often with low magnification and an unphysically bright source

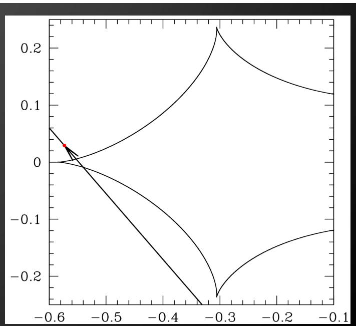
Background: Short Binary Events



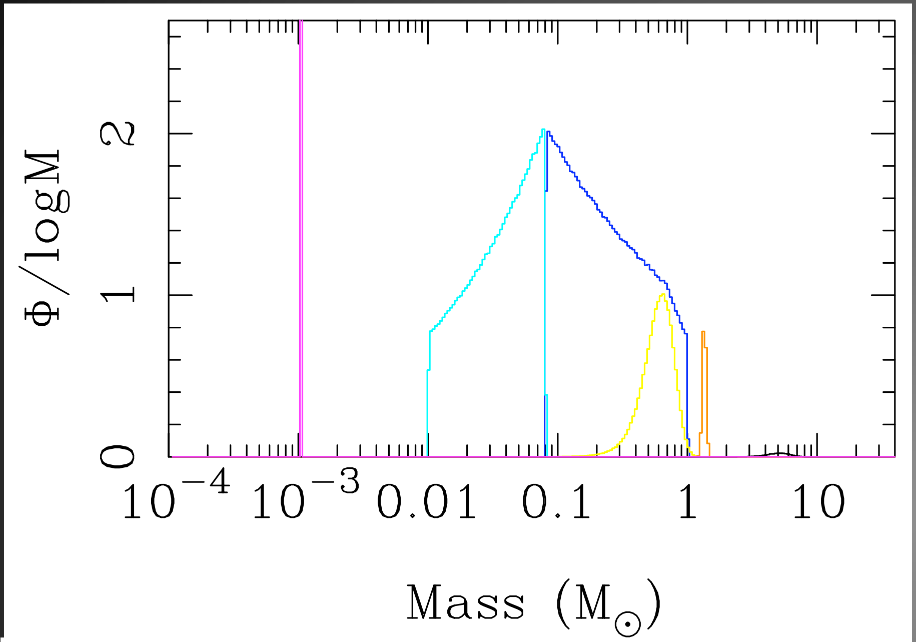


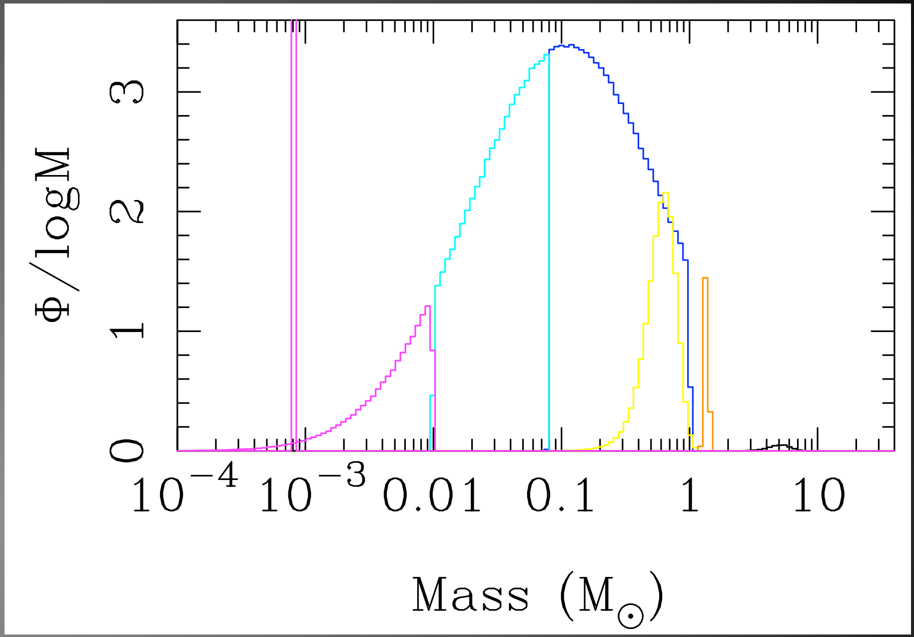


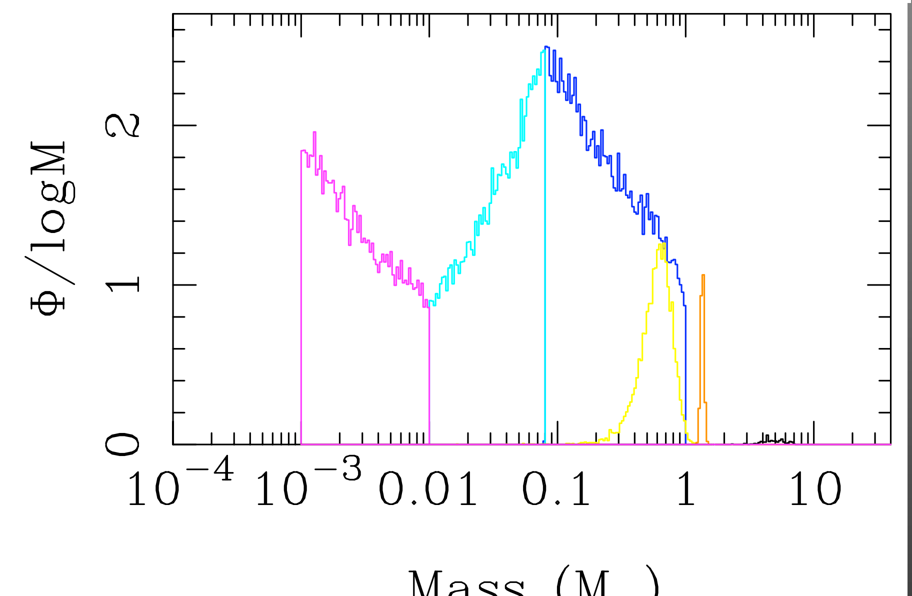
Wide-binaries (d = 2.2, 1.2) with planetary and brown dwarf mass ratios of q = 0.013 and 0.047



Mass-function

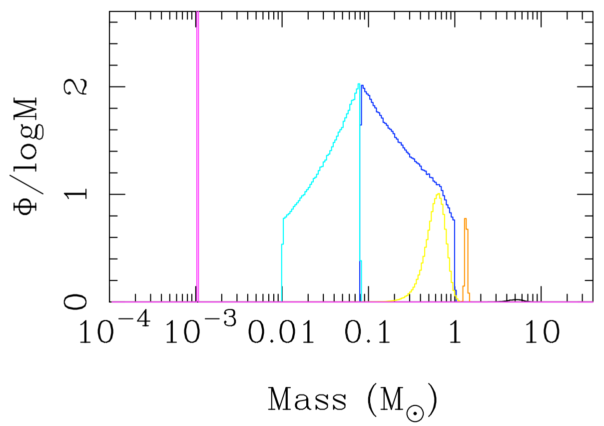






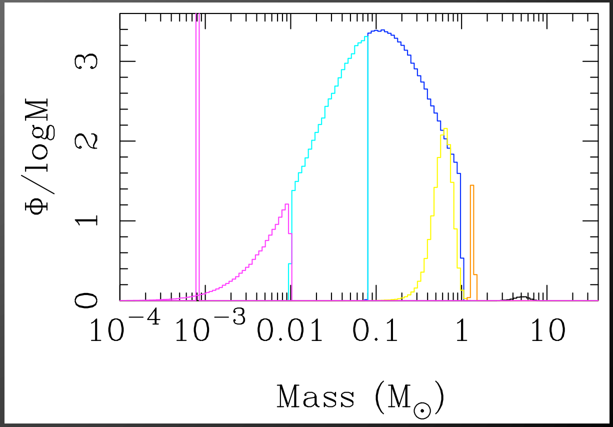
Mass Function Models

- Stars >1 $M_\odot$ have become stellar remnants
- Assume Salpeter-like slope (α = -2) for initial >1 $M_\odot$ stars
- Two choices at < 1 $M_\odot$



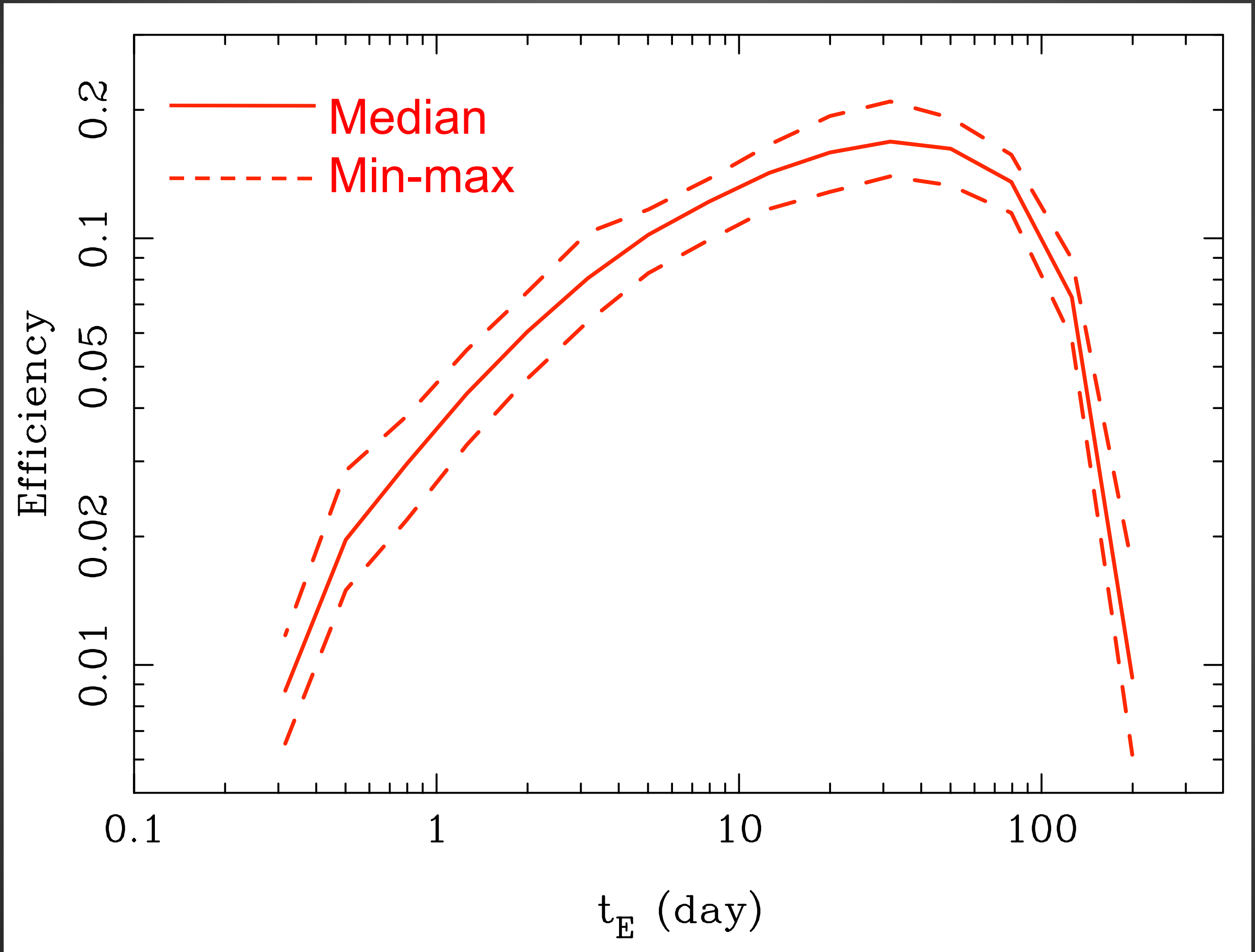
  – Broken power law
    - α = -2 for M > 0.7 $M_\odot$
    - α = -1.3 for 0.7 $M_\odot$ > M > 0.08 $M_\odot$
    - α = -0.52 for 0.08 $M_\odot$ > M > 0.01 $M_\odot$
  – Chabrier log-normal
    - M_c = 0.12 $M_\odot$, σ_c = 0.76

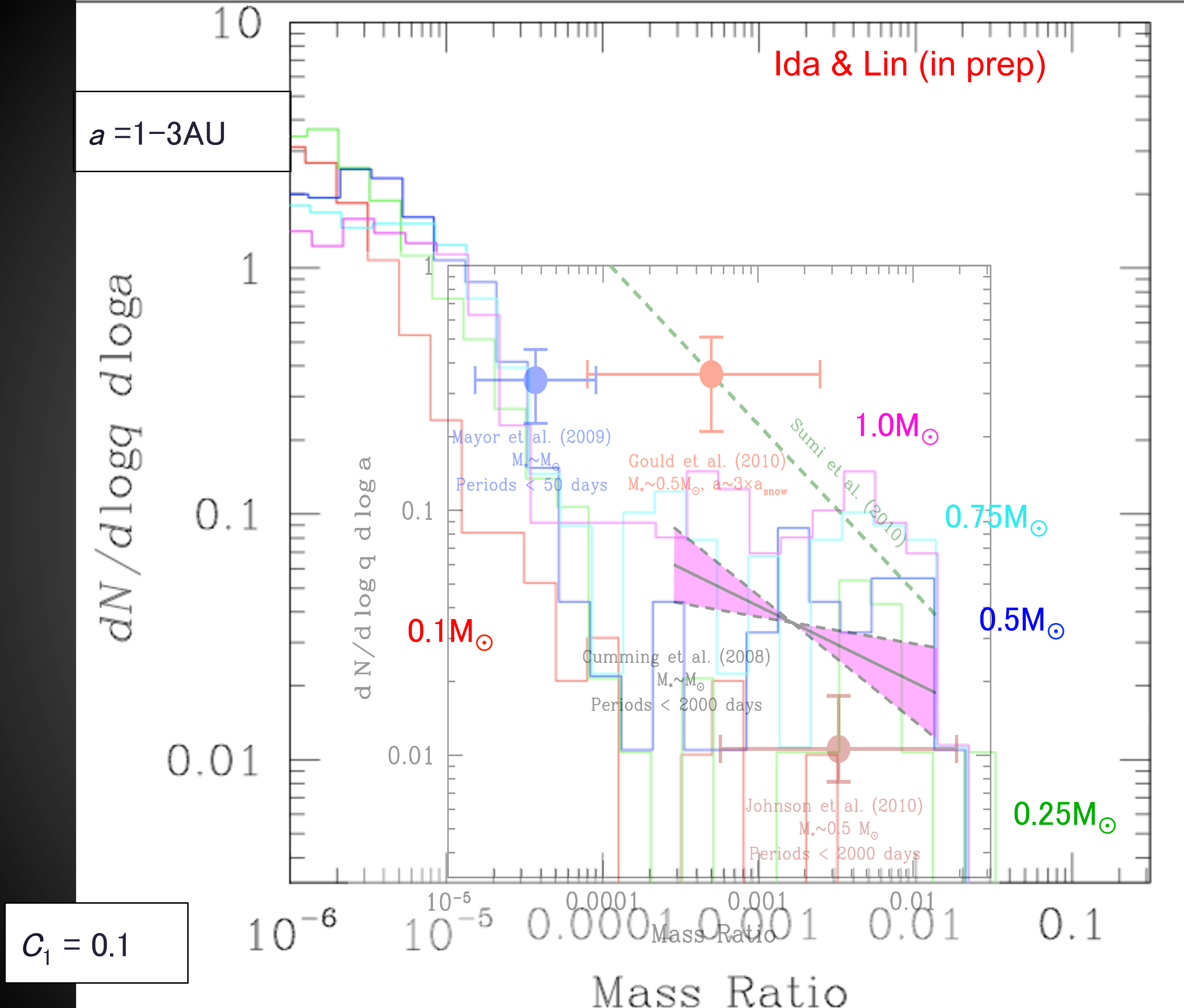
$$dN/d\log M = \exp[(\log M - \log M_c)^2/(2\sigma_c^2)]$$



- Planetary δ-function in mass
    - mass resolution limited by factor of 2-3 precision in t_E – mass relation

Detection Efficiency





Ida & Lin (in prep)
a =1−3AU
C1 = 0.1
dN/dlogq dloga
Mass Ratio
10
1
0.1
0.01
10−6
10−5
0.0001
0.001
0.01
0.1
1.0M⊙
0.75M⊙
0.5M⊙
0.25M⊙
0.1M⊙
Mayor et al. (2009)
M*~M⊙
Periods < 50 days
Gould et al. (2010)
M*~0.5M⊙, a~3×a_snow
Sumi et al. (2010)
Cumming et al. (2008)
M*~M⊙
Periods < 2000 days
Johnson et al. (2010)
M*~0.5 M⊙
Periods < 2000 days
dN/dlog q dlog a

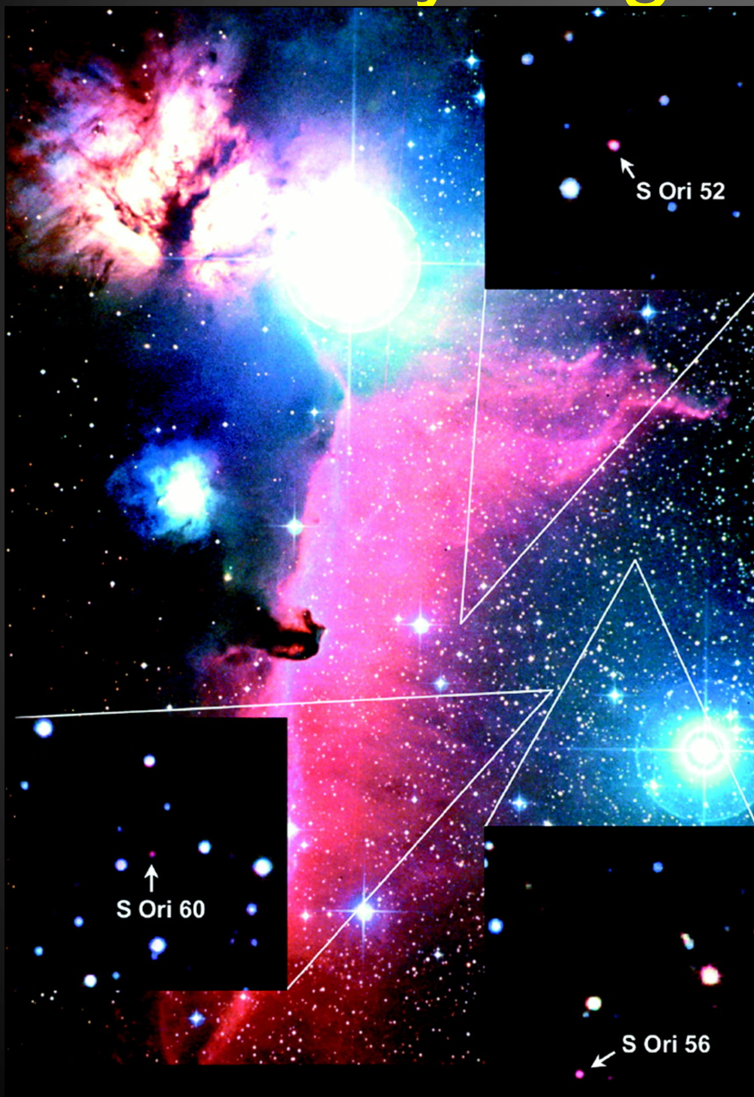
Isolated vs. Bound Planets

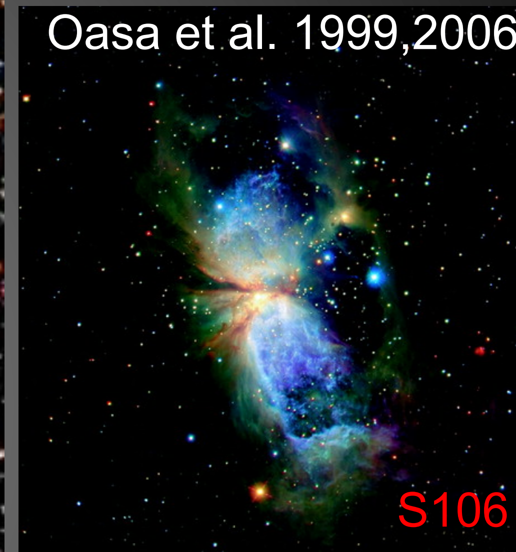
(Isolated means no detectable host – either free-floating or in a distant orbit > 7-45 AU depending on the event)

- Log-normal mass function implies 8 planets (plus 3 planetary mass brown dwarfs)
- Also, 5 planet+star events in the sample
  - So, a isolated:bound ratio of 8/5 = 1.6
- We can also compare to measurements of Cumming et al. (2008) and Gould et al. (2010) inside and outside the snow-line
  - Implies 1.2 Saturn-Jupiter mass planets per star at 0.03-10 AU
  - So, isolated:bound ratio ~ 1.8/1.2 = 1.5

- **More isolated planets than bound**
- **(At least comparable)**

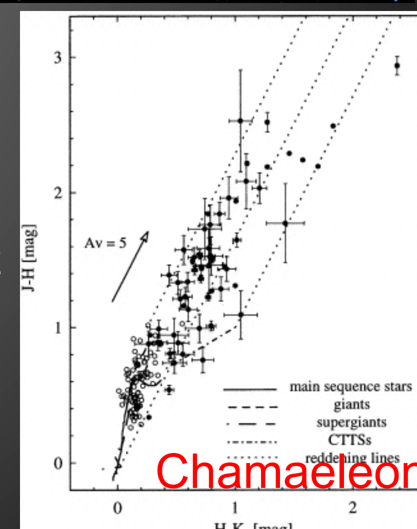
Free-floating planetary-mass objects in young star forming region



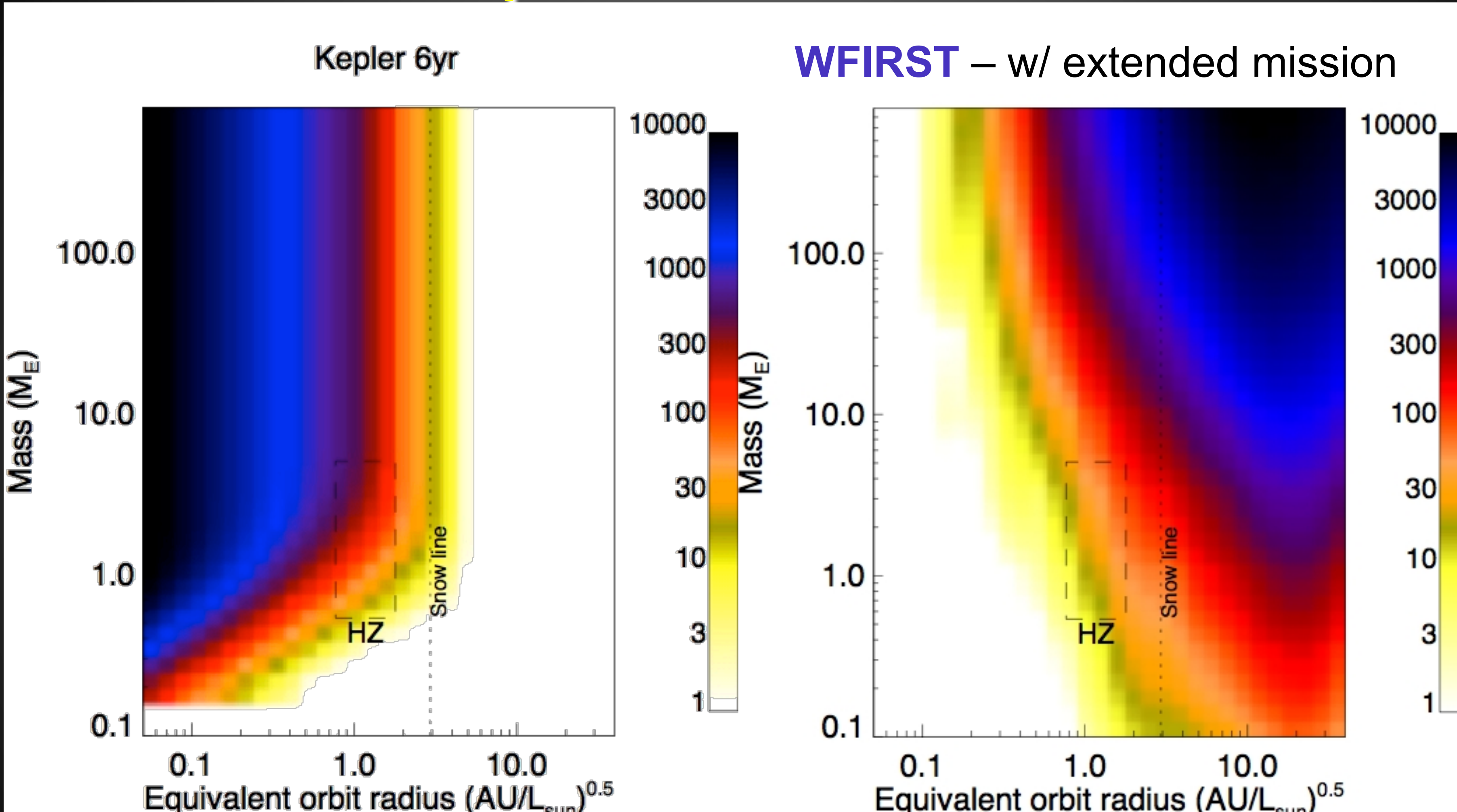


M~5-15 M_J

However, Large uncertainty in
- photometric mass measurement
- their abundance



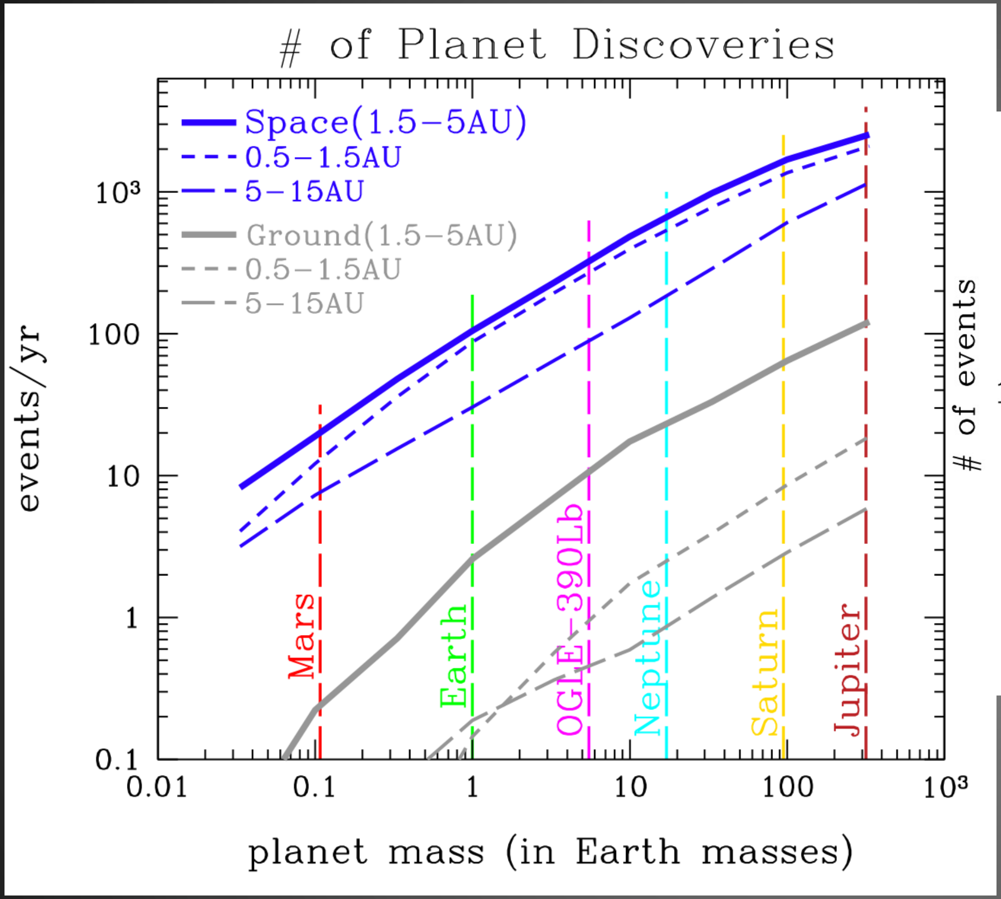
Kepler vs. WFIRST

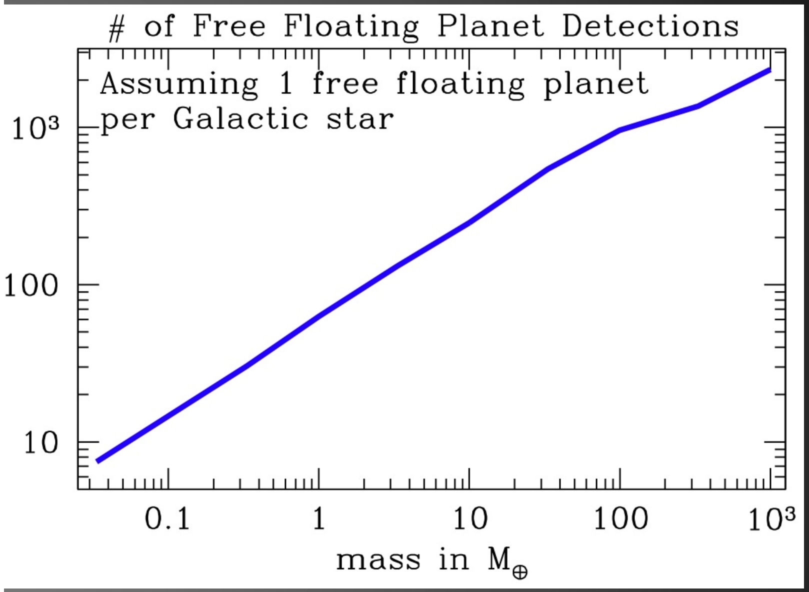


Figures from B. MacIntosh of the ExoPlanet Task Force

Complete the census of planetary systems in the Galaxy

WFIRST's Predicted Discoveries





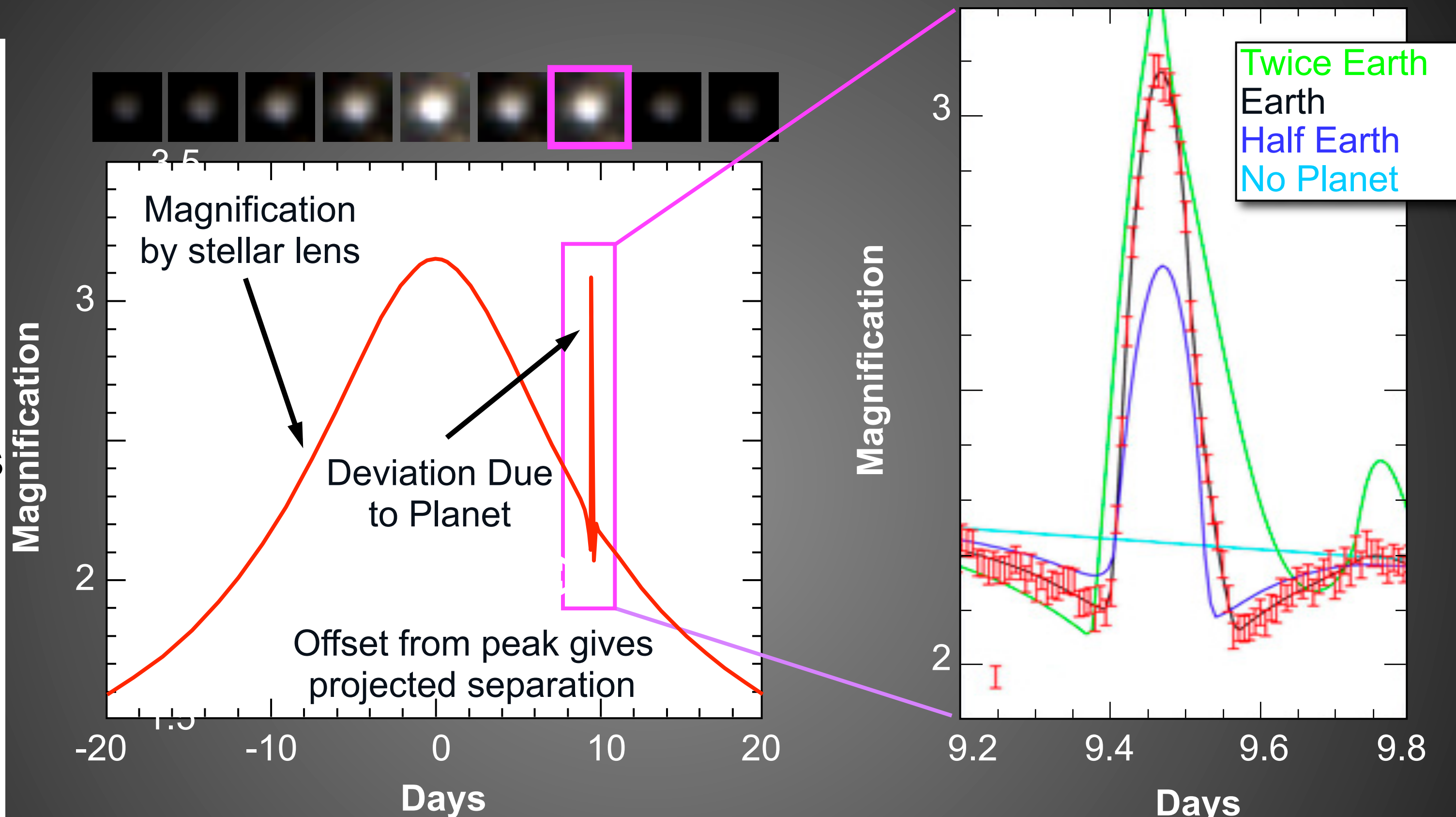
~2000 FFP！
~190 sub Eath-mass FFP!
(>30 Earth-mass FFP！)

~3000 exoplanets
~300 sub Earth-mass Planets,
>25 habitable planets
（0.5-10 M_{Earh}、0.72-2.0 AU）
around FGK stars

Free-floating rocky planets may have liquid water, Stevenson (1999)

Simulated **WFIRST** Planetary Light Curves

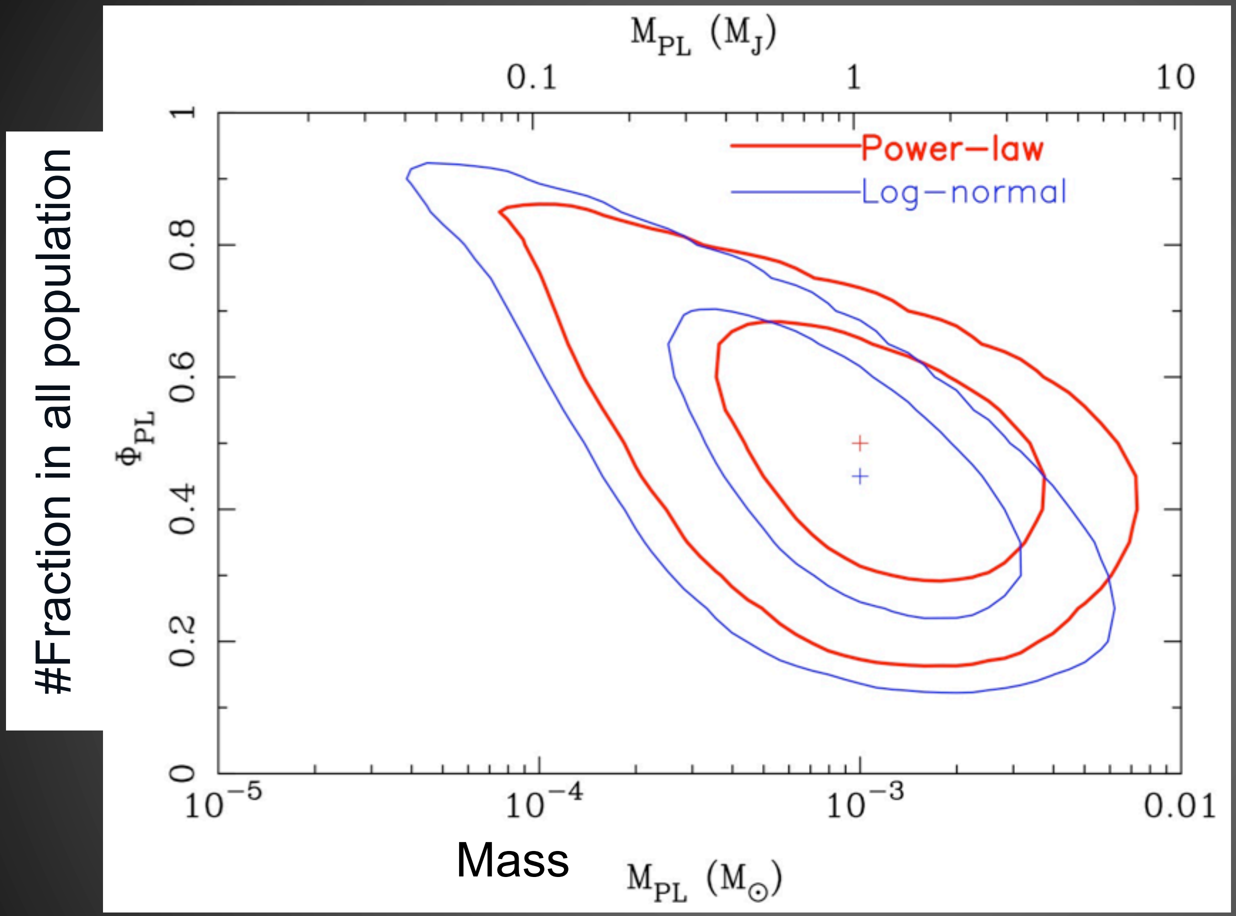
Time-series photometry is combined to uncover light curves of background source stars being lensed by foreground stars in the disk and bulge.



Planets are revealed as short-duration deviations from the smooth, symmetric magnification of the source due to the primary star.

Detailed fitting to the photometry yields the parameters of the detected planets.

Planetary Mass Function Parameters



68%, 90% contour

$$Power-law: M_{PL} = 1.1^{+1.2}_{-0.6} \times 10^{-3}, \quad \Phi_{PL} = 0.49^{+0.13}_{-0.13}, \Rightarrow N/N_* = 1.9 \pm 0.5$$

$$\log-normal: M_{PL} = 0.83^{+0.96}_{-0.51} \times 10^{-3}, \quad \Phi_{PL} = 0.46^{+0.17}_{-0.15}, \Rightarrow N/N_* = 1.8 \pm 0.6$$

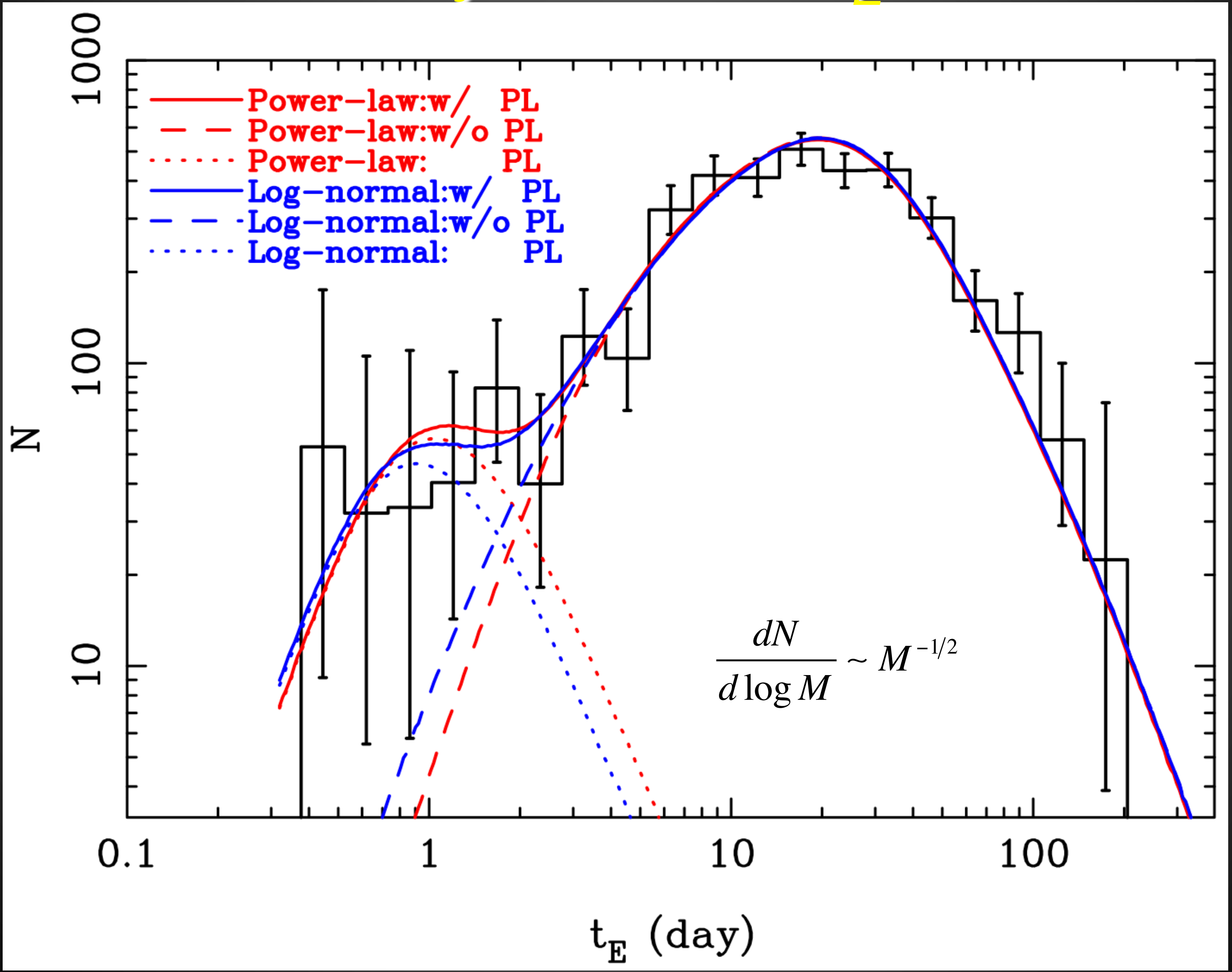
1.8 isolated planets per star!

Final Mass Function Models

Table S3. Mass Function

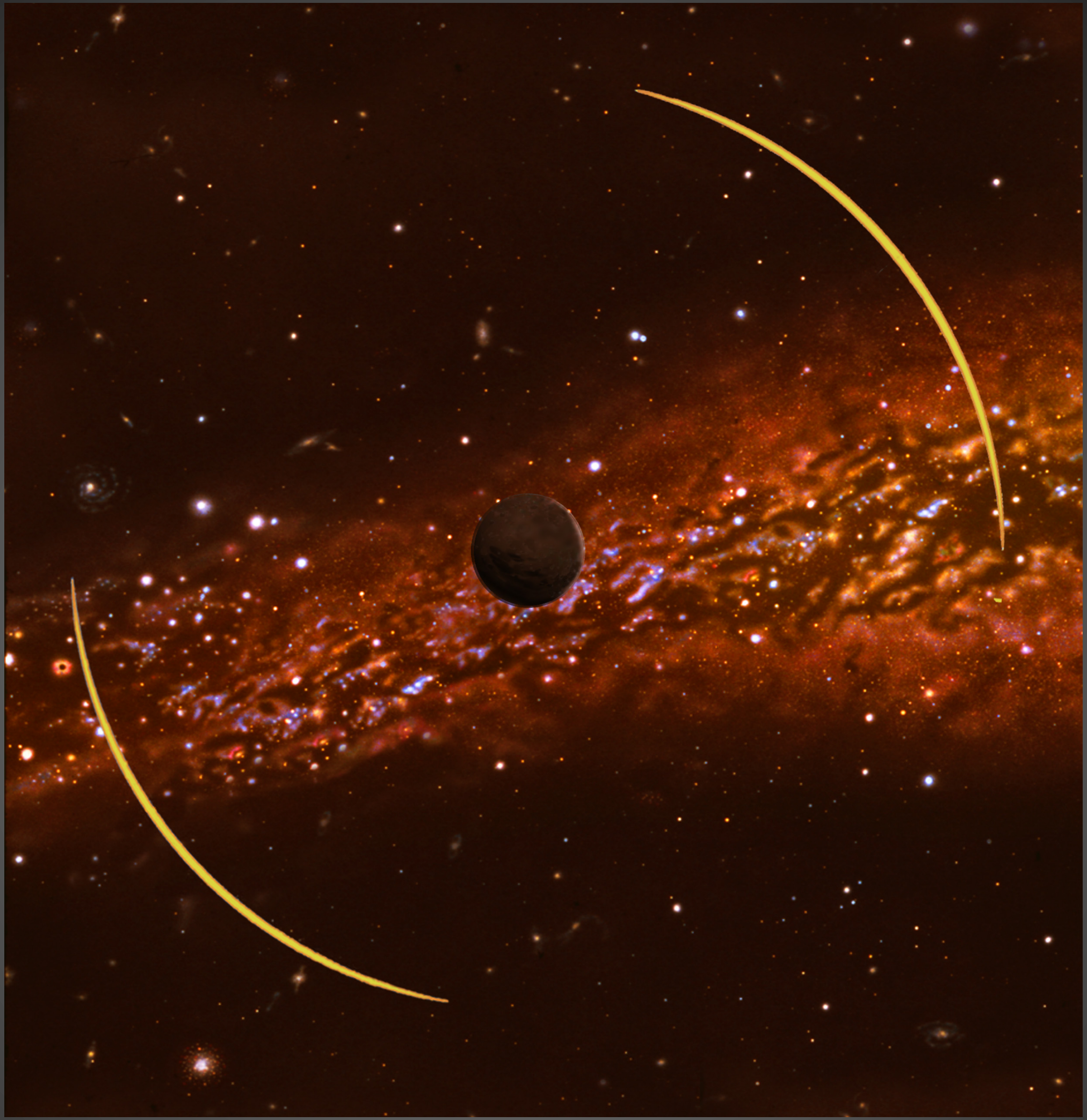
#	Mass ($M_\odot$)	Function	parameter (M and σ are in $M_\odot$)	Fraction (N_*)
1	$40.0 \leq M$	Gaussian	Black hole ($M_r = 5, \sigma_r = 1$)	0.0031
	$8.00 \leq M \leq 40.0$	Gaussian	Neutron star ($M_r = 1.35, \sigma_r = 0.04$)	0.021
	$1.00 \leq M \leq 8.00$	Gaussian	White dwarf ($M_r = 0.6, \sigma_r = 0.16$)	0.18
	$0.70 \leq M \leq 1.00$	Power-law	$\alpha_1 = 2.0$	1.0
	$0.08 \leq M \leq 0.70$	Power-law	$\alpha_2 = 1.3$	
	$0.01 \leq M \leq 0.08$	Power-law*	$\alpha_3 = 0.48^{+0.29}_{-0.37}$ w/o PL	$0.73^{+0.22}_{-0.19}$
	$0.01 \leq M \leq 0.08$	Power-law**	$\alpha_3 = 0.50^{+0.36}_{-0.60}$ w/ PL	$0.74^{+0.30}_{-0.27}$
	$M = M_{PL}$	δ-function**	$M_{PL} = 1.1^{+1.2}_{-0.6} \times 10^{-3}, \Phi_{PL} = 0.49^{+0.13}_{-0.13}$	$1.9^{+1.3}_{-0.8}$
2	$40.0 \leq M$	Gaussian	Black hole ($M_r = 5, \sigma_r = 1$)	0.0031
	$8.00 \leq M \leq 40.0$	Gaussian	Neutron star ($M_r = 1.35, \sigma_r = 0.04$)	0.021
	$1.00 \leq M \leq 8.00$	Gaussian	White dwarf ($M_r = 0.6, \sigma_r = 0.16$)	0.18
	$0.08 \leq M \leq 1.00$	Log-normal*	$M_c = 0.12^{+0.03}_{-0.03}$, $\sigma_c = 0.76^{+0.27}_{-0.16}$	1.0
	$0.01 \leq M \leq 0.08$	Log-normal*	$M_c = 0.12^{+0.03}_{-0.03}$, $\sigma_c = 0.76^{+0.27}_{-0.16}$	$0.70^{+0.19}_{-0.30}$
	$0.00 \leq M \leq 0.01$	Log-normal*	$M_c = 0.12^{+0.03}_{-0.03}$, $\sigma_c = 0.76^{+0.27}_{-0.16}$	$0.17^{+0.24}_{-0.15}$
	$M = M_{PL}$	δ-function***	$M_{PL} = 0.83^{+0.96}_{-0.51} \times 10^{-3}, \Phi_{PL} = 0.46^{+0.17}_{-0.15}$	$1.8^{+1.7}_{-0.8}$
3	$40.0 \leq M$	Gaussian	Black hole ($M_r = 5, \sigma_r = 1$)	0.00060
	$8.00 \leq M \leq 40.0$	Gaussian	Neutron star ($M_r = 1.35, \sigma_r = 0.04$)	0.0061
	$1.00 \leq M \leq 8.00$	Gaussian	White dwarf ($M_r = 0.6, \sigma_r = 0.16$)	0.097
	$0.50 \leq M \leq 1.00$	Power-law	$\alpha_1 = 2.3$	1.0
	$0.075 \leq M \leq 0.50$	Power-law	$\alpha_2 = 1.3$	
	$0.01 \leq M \leq 0.075$	Power-law	$\alpha_3 = 0.3$, $R_{HBL} = 0.3$	0.19
	$M = M_{PL}$	δ-function	$M_{PL} = 1.9^{+1.4}_{-0.9} \times 10^{-3}, \Phi_{PL} = 0.50^{+0.11}_{-0.10}$	$1.3^{+0.7}_{-0.4}$
4	$0.08 \leq M$		same as model (1)	
	$0.01 \leq M \leq 0.08$	Power-law**	$\alpha_3 = 0.49^{+0.24}_{-0.27}$ w/ PL	$0.73^{+0.17}_{-0.15}$
	$10^{-5} \leq M \leq 0.01$	Power-law**	$\alpha_{PL} = 1.3^{+0.3}_{-0.4}$ w/ PL	$5.5^{+18.1}_{-4.3}$

Fit to efficiency corrected t_E distribution



CV Background Rejection

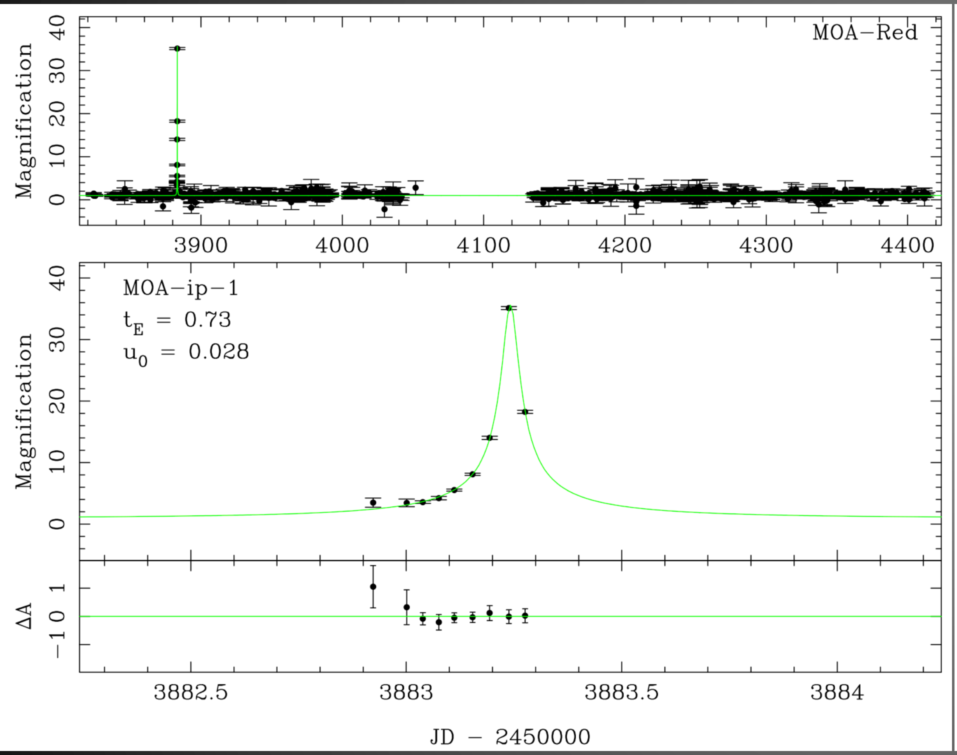
- Poor fit to microlensing event or unphysical source brightness
- Repeating
- 208 of 418 CV light curves in 2006-2007 data have a 2nd outburst in 2006-2010
  - Classified by eye from rejected events
  - 421 multiple outbursts fit to microlensing from multiple outburst events
  - All 421 failed to pass the cuts
- after analysis was complete, OGLE-III, II, I, and MACHO databases were checked
  - OGLE-III data confirms lens models for events 2, 3, 4, 6, 7, 8 and 9
  - OGLE-III 2002-2008 data shows no additional outburst back to 2002 for events 2, 3, 4, 5, 6, 7, 8, and 9
  - Events 3, 5, 6, and 8 show no outburst in 1990s – MACHO

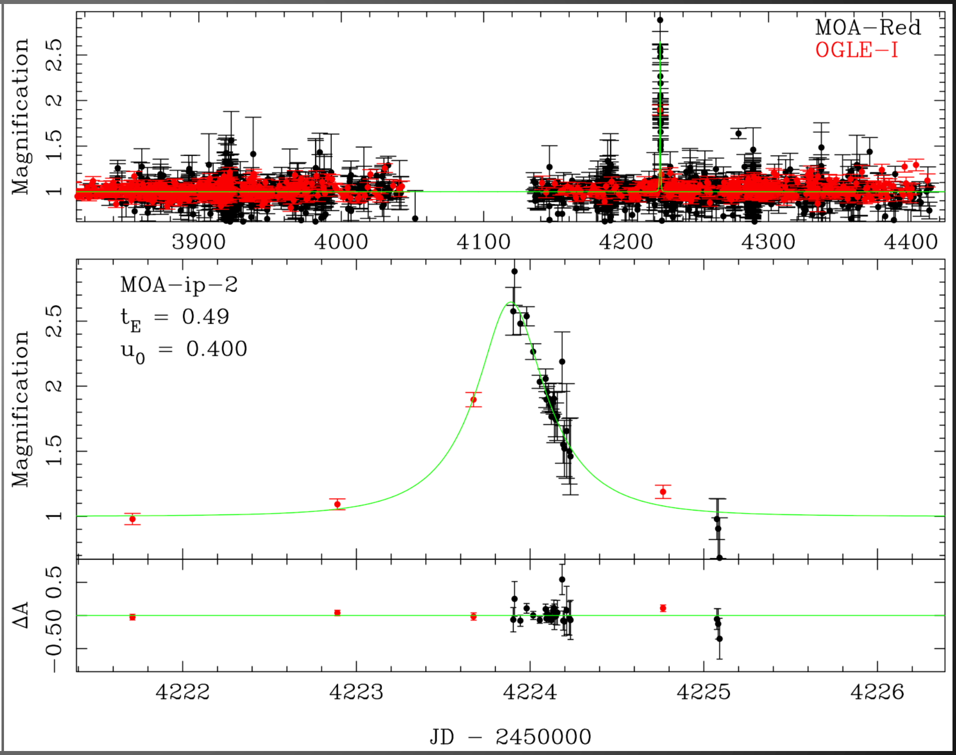


Far-infrared rendition of the Jovian-mass planet MOA-ip-10. It is either free-floating or extremely distant from its host star, and thousands of light-years away towards the galactic center. The planet's gravity creates Einstein arcs of a background star. Artwork by Jon Lomberg.

10 events with t_E< 2 days from 2006-2007

(events 1, 2)

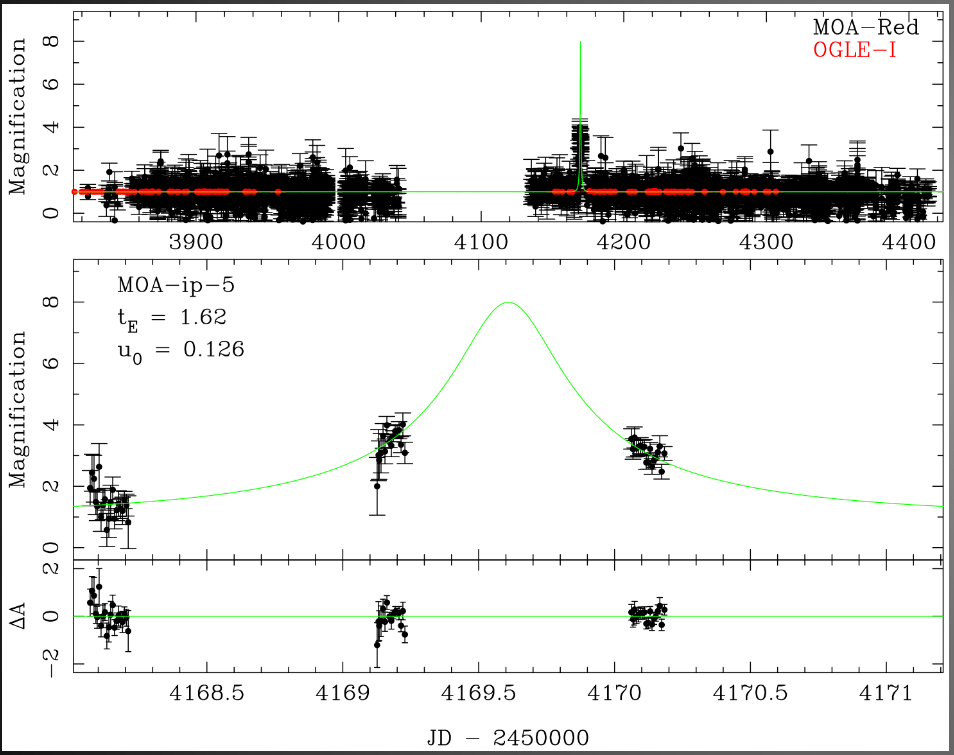


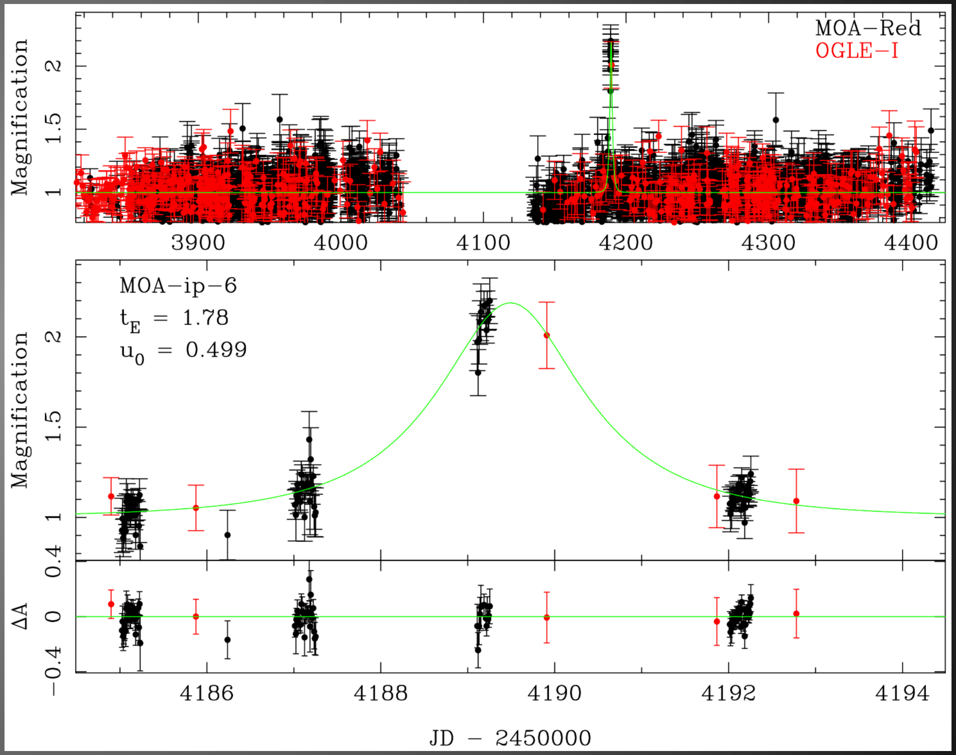


MOA data in black, confirmed by OGLE data in red

10 events with t_E< 2 days from 2006-2007

(events 5, 6)

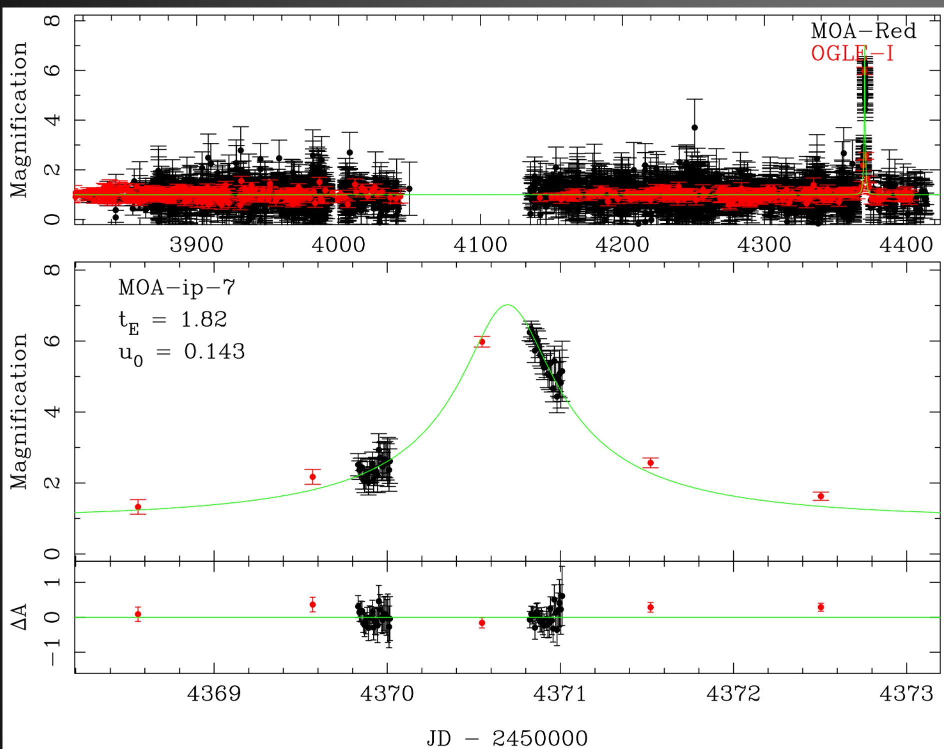


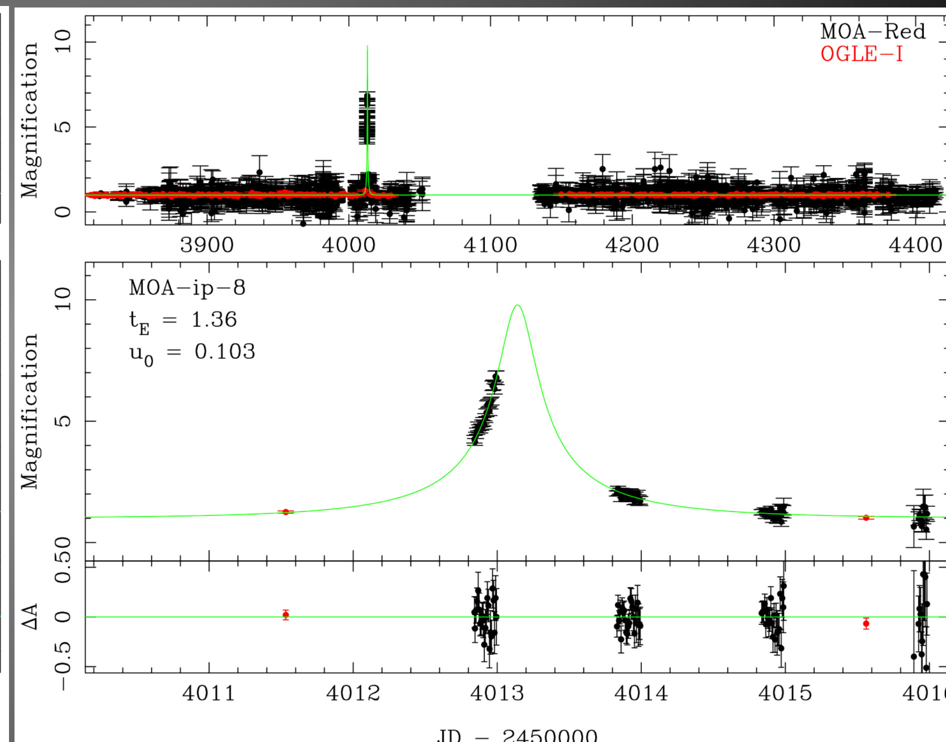


MOA data in black, confirmed by OGLE data in red

10 events with t_E< 2 days from 2006-2007

(events 7, 8)

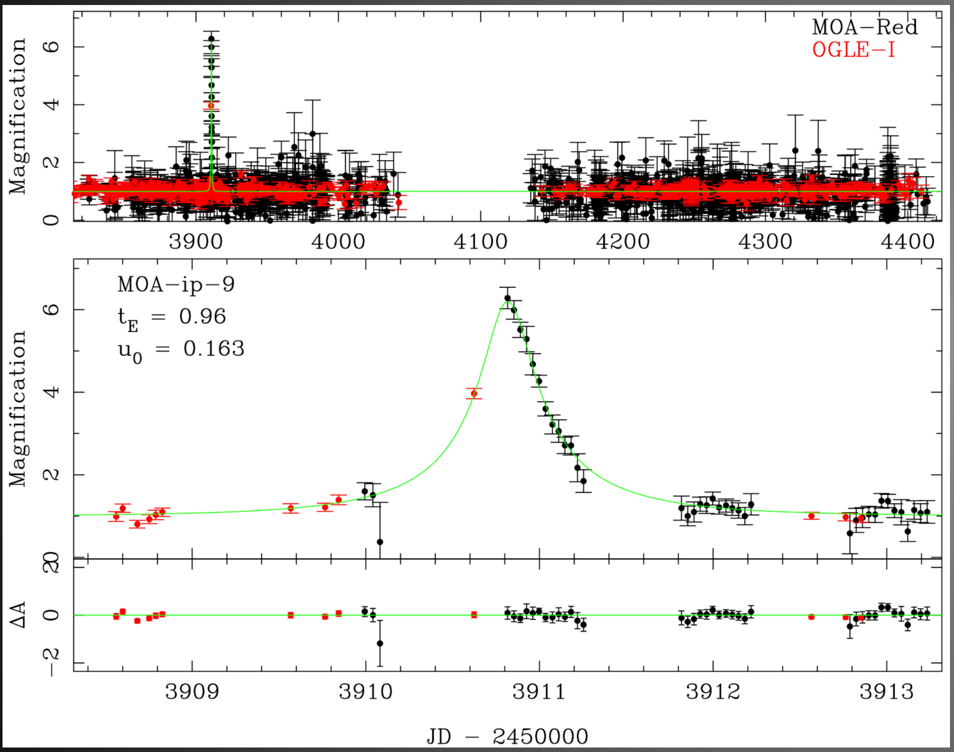


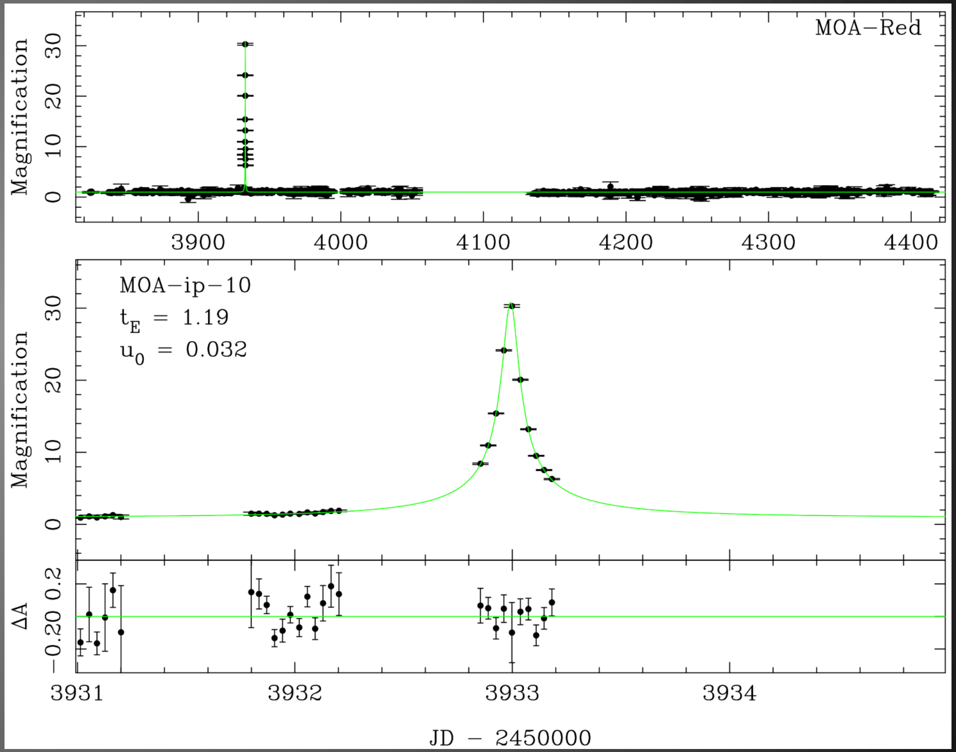


MOA data in black, confirmed by OGLE data in red

10 events with t_E< 2 days from 2006-2007

(events 9,10)

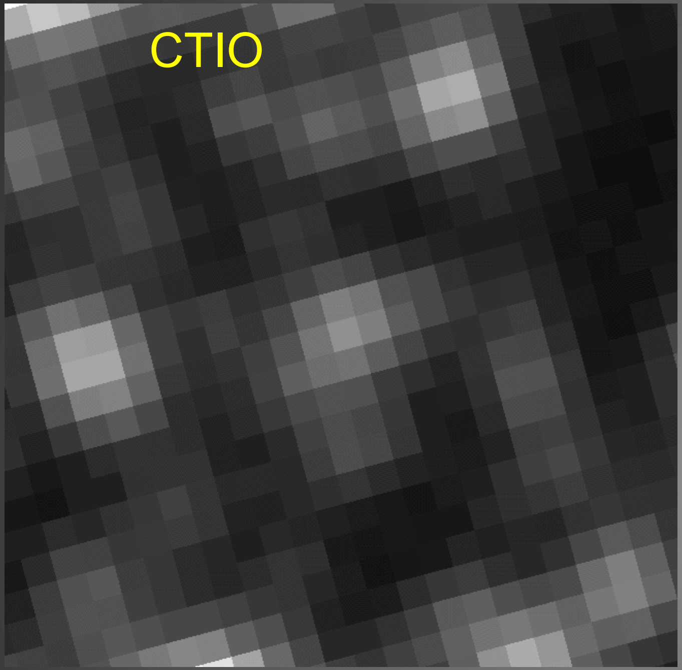


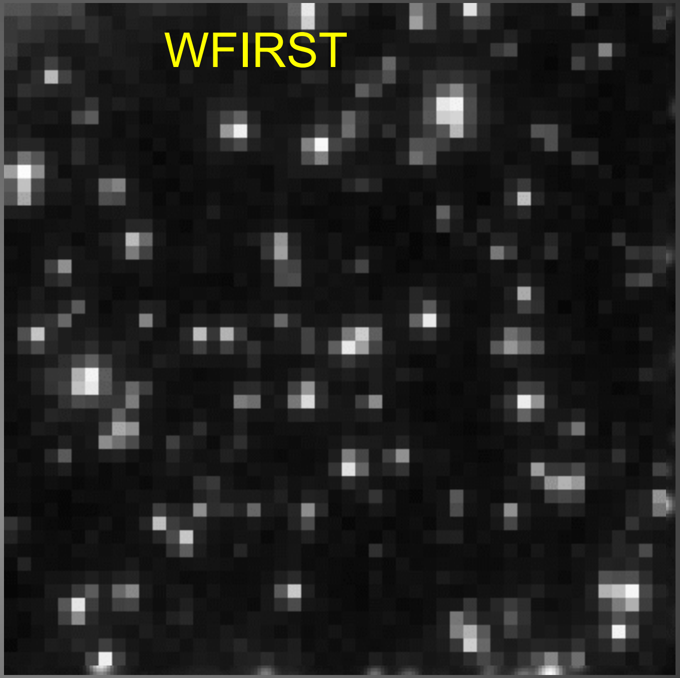


MOA data in black, confirmed by OGLE data in red

A_{max}= 30 event is separated from host star by > 15 R_E

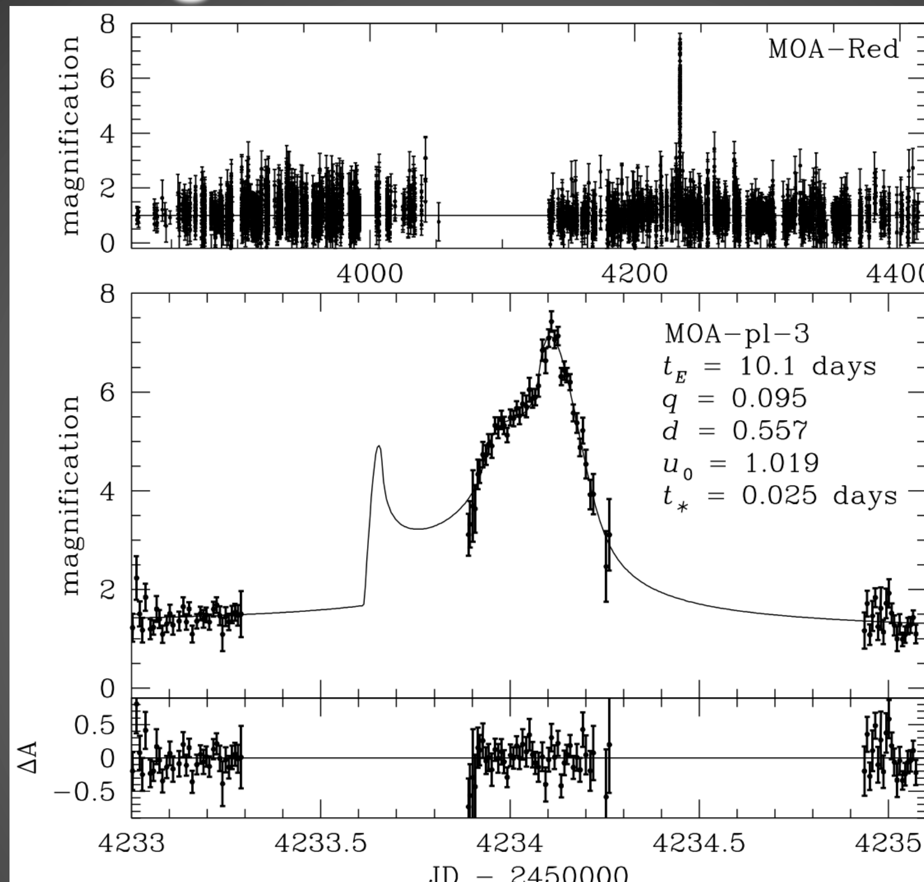
Ground-based confusion, space-based resolution

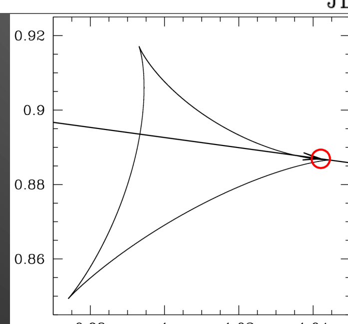




- Space-based imaging needed for high precision photometry of main sequence source stars (at low magnification) and lens star detection
- High Resolution + large field + 24hr duty cycle => Microlensing Planet Finder (MPF)
- Space observations needed for sensitivity at a range of separations and mass determinations

Background: Short Binary



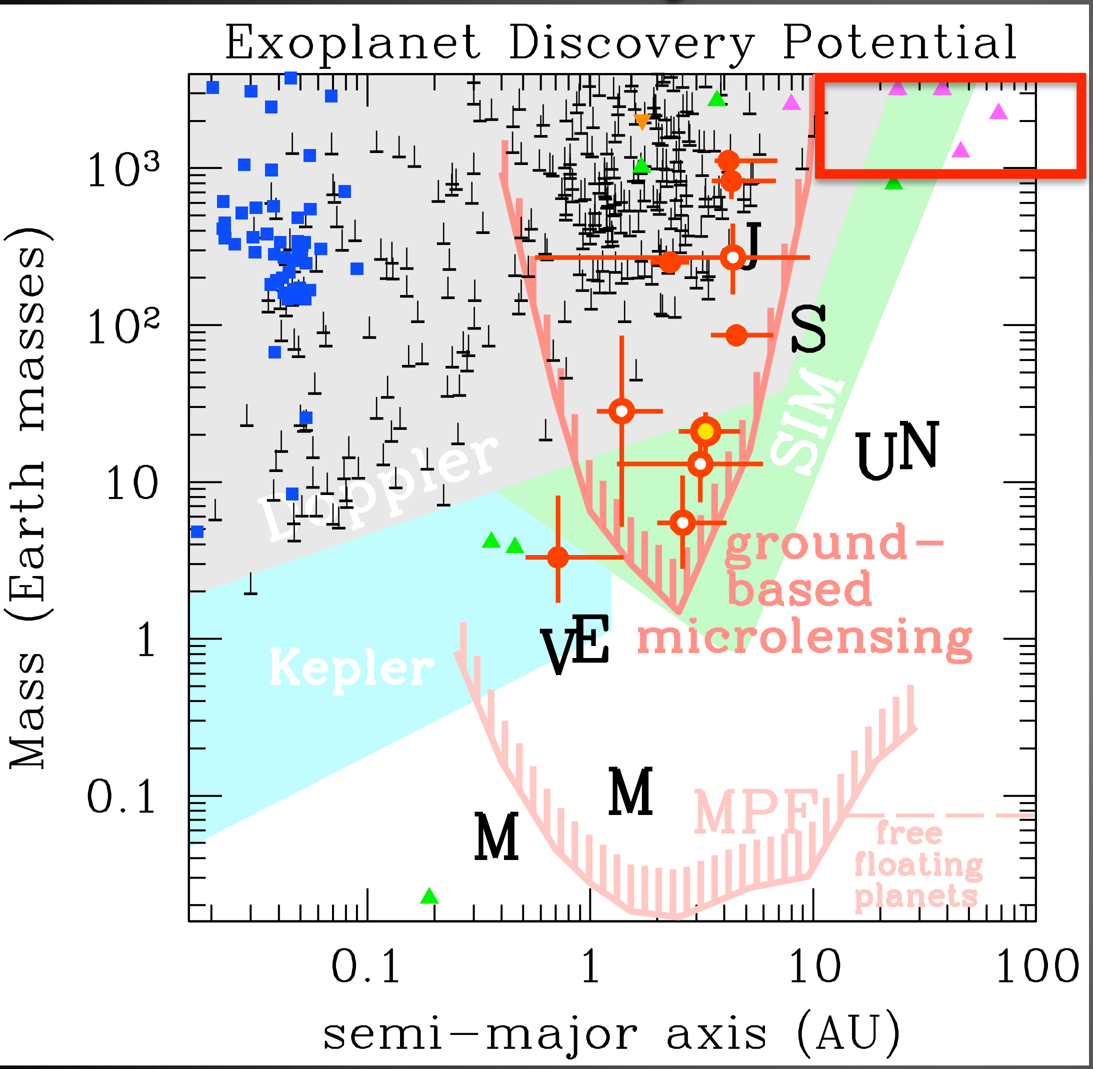


Close-binary (d = 0.56) with q = 0.095

Binary Lens Background Rejection

- Both close ($d < R_E$) and wide ($d > R_E$) binary lens events can give rise to brief microlensing magnifications
- All short events can be fit by a wide binary model, because a wide binary approaches a single lens as d -> ∞
  - host stars must be at a distance > 3-15 R_E, depending on the event
  - high magnification events have the tightest limits
  - 2 wide binaries fail light curve shape cuts
- Close binaries have small external caustics that can also give short events
  - 1 such event passed all cuts but the light curve fit.
  - Close binary models have different, usually asymmetric, light curves
  - Close binary models can be rejected for all t_E< 2 day events, except for event 5
  - Since only 1 of 13 short events is a close binary, event 5 is probably a single lens event

Sensitivity of various methods



- •RV
- •transit
- •Direct image
- •Microlensing : not rely on flux from host

- •1-6 AU : beyond snow line
- •small planet : down to Earth
- •Faint star :M-dwarf, brown dwarf
- •No host : free floating planet
- •Far system: galactic distribution

Free-floating planet

Planetary-mass objects that is not orbiting about any host star called :

- Free-floating planet
- Rogue planet
- Orphan planet
- Interstellar planet

Can we call them “Planet”? --- still in debate

- If they formed around a host star, and scattered out from orbit, then we may call them a planet.
- However, others believe that the definition of 'planet' should depend on current observable state, and not origin
- They may form on their own through gas cloud collapse similar to star formation; in which case they would never have been planets. →“planetary-mass object” or ” sub brown dwarf”

MOA-2009-BLG-387Lb: A massive planet orbiting an M dwarf Batistaet al. 2011

- $m_p = 2.6\ M_{Jupiter}$
- $M = 0.19\ M_{\odot}$.
- 3.5 kpc < *DL* < *7.9 kpc,*
- 1.1AU < *a* < *2.7AU,*
- *3.8 yr < P < 7.6 yr*