Free-floating planets from Microlensing

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MOA collaboration

NASA/JPL-Caltech/R. Hurt

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Free–floating planet

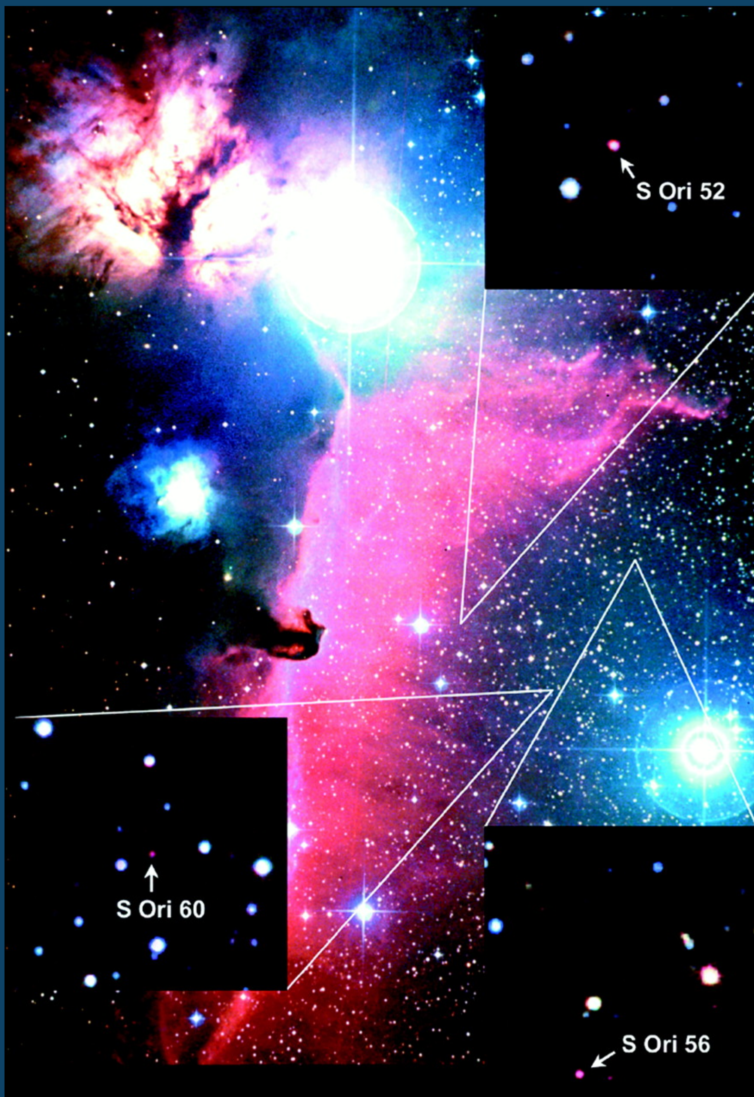
Planetary–mass objects that is not orbiting about any host star called:

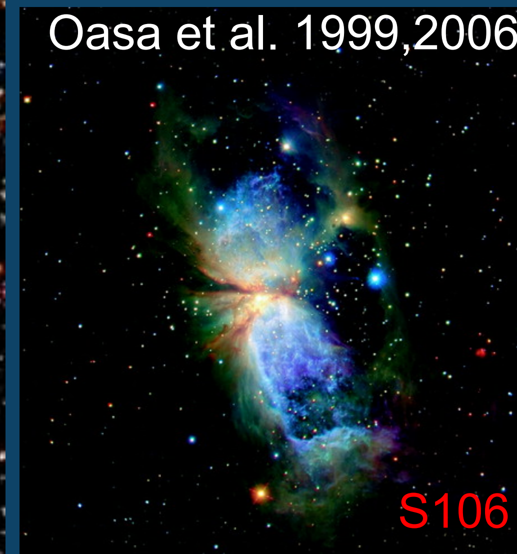
- Free–floating planet
- Rogue planet
- Orphan planet
- Interstellar planet

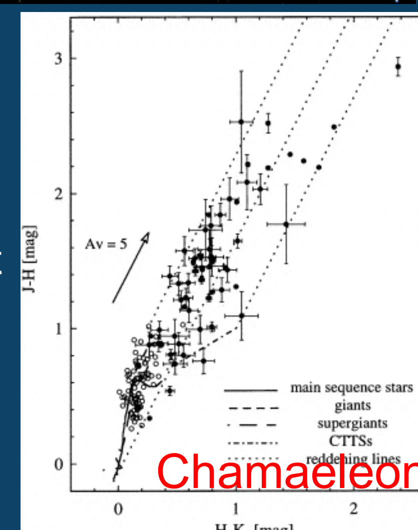
Can we call them "Planet"? ––– still in debate

- 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"

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



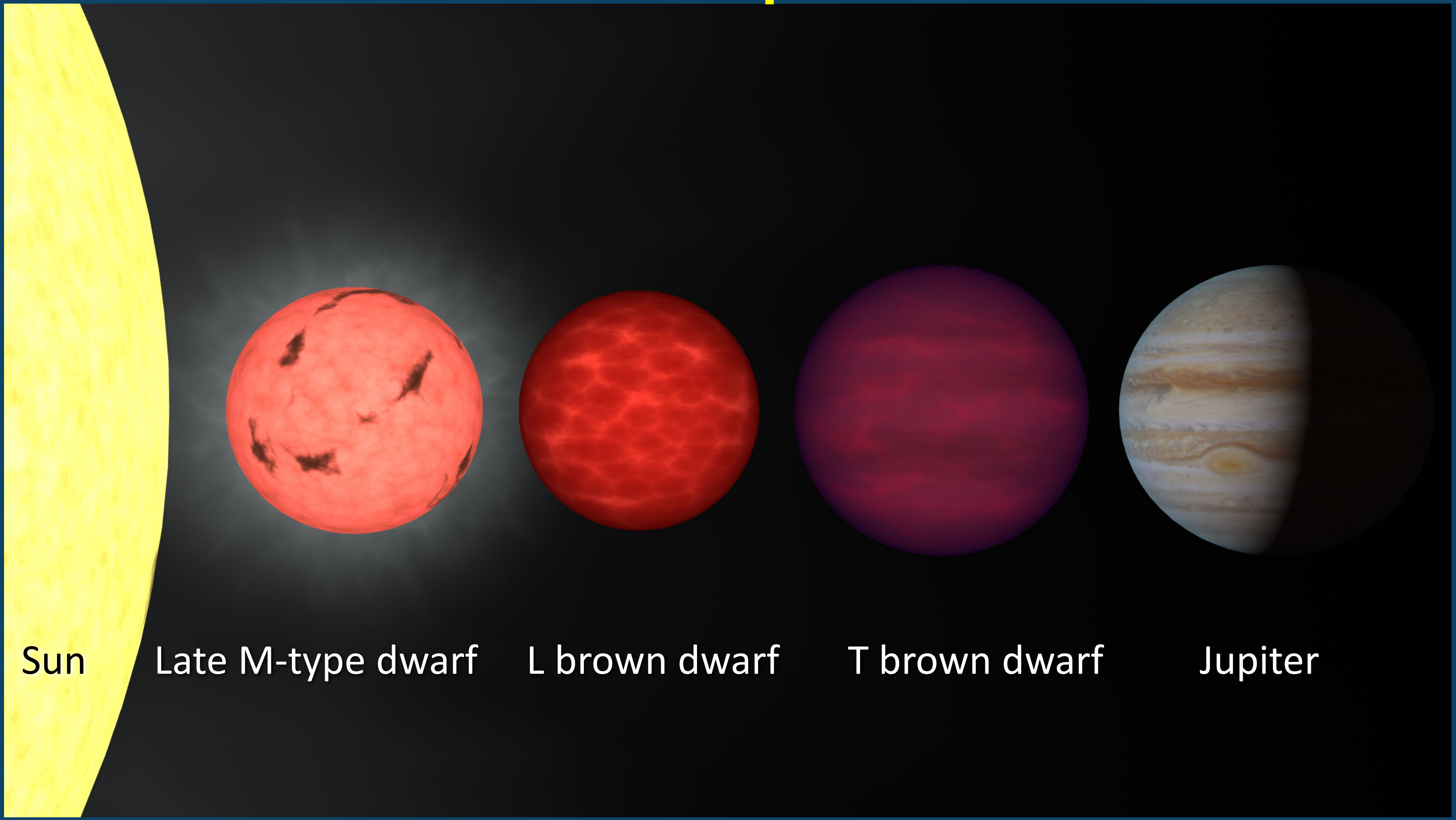




M~5-15 M_J

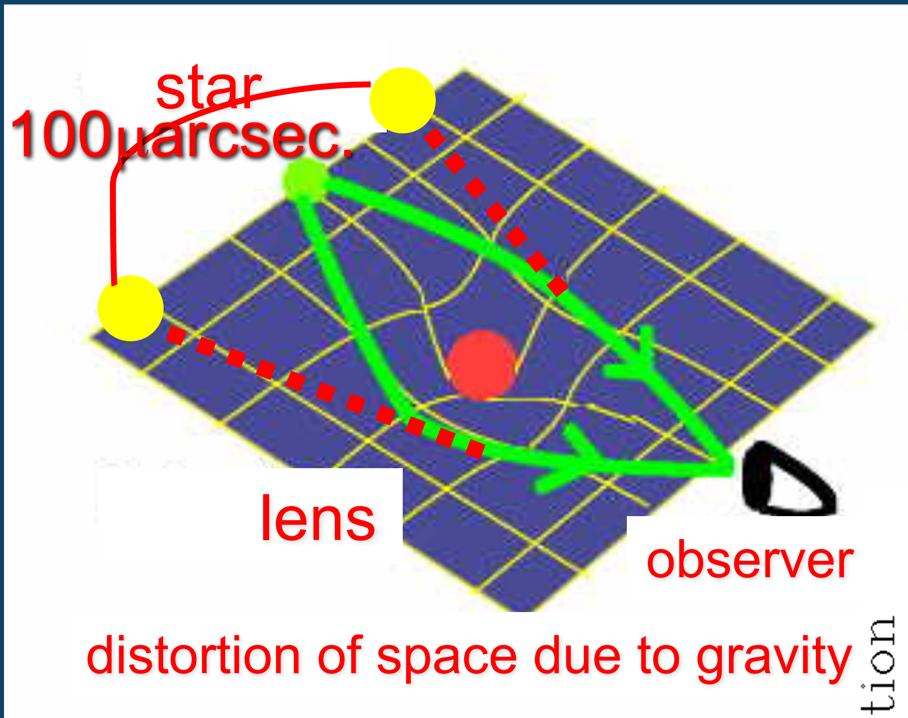
However, Large uncertainty in
- photometric mass measurement
- their abundance

Size comparison



Mass：1050　　75　　65　　30　　1(Jupiter mass)

Gravitational Microlensing

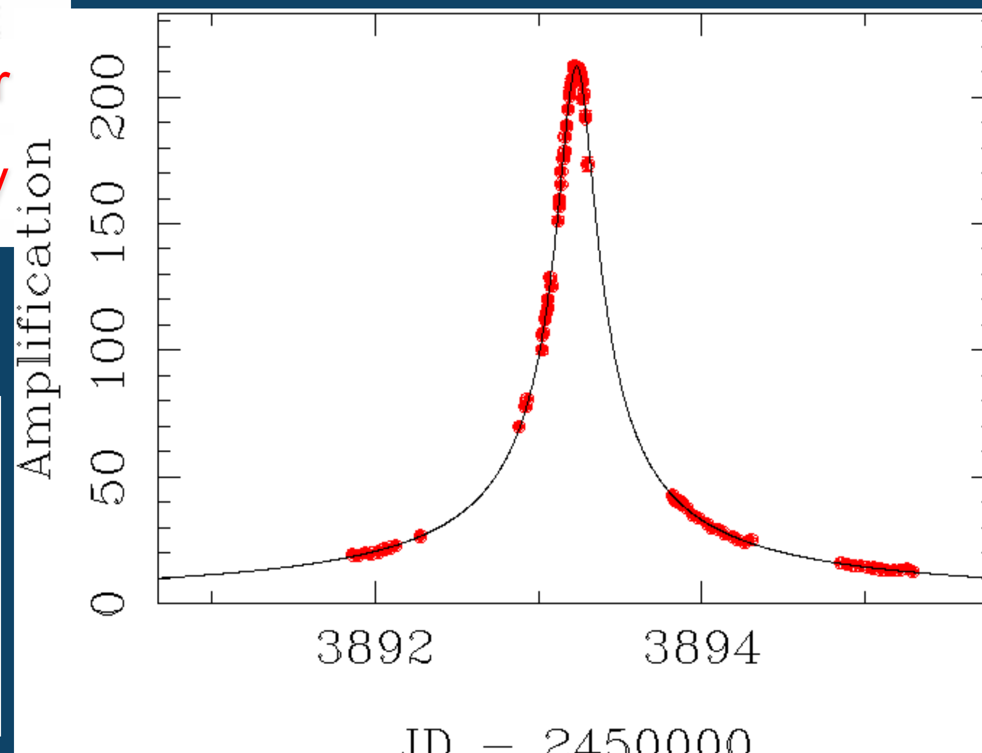


✧If a lens is a star, elongation of images is an order of 100μarcsec.

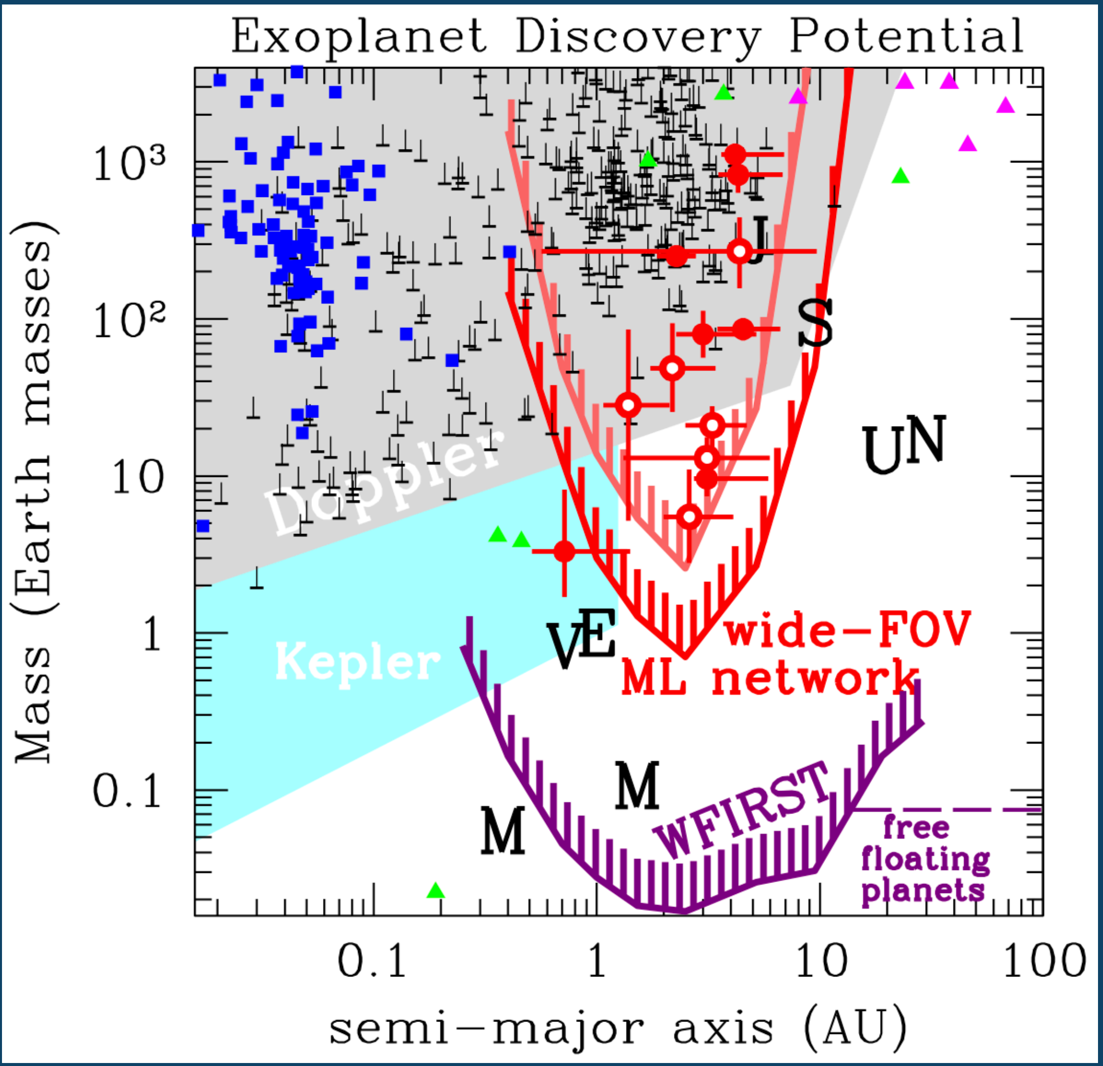
✧Just see a star magnified

✧Einstein predicted 1936, but concluded impossible to observe. Event rate is 1/1M

- 1986
Watch Millions stars
Paczynski



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

MOA (since 1995)

（Microlensing Observation in Astrophysics）

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

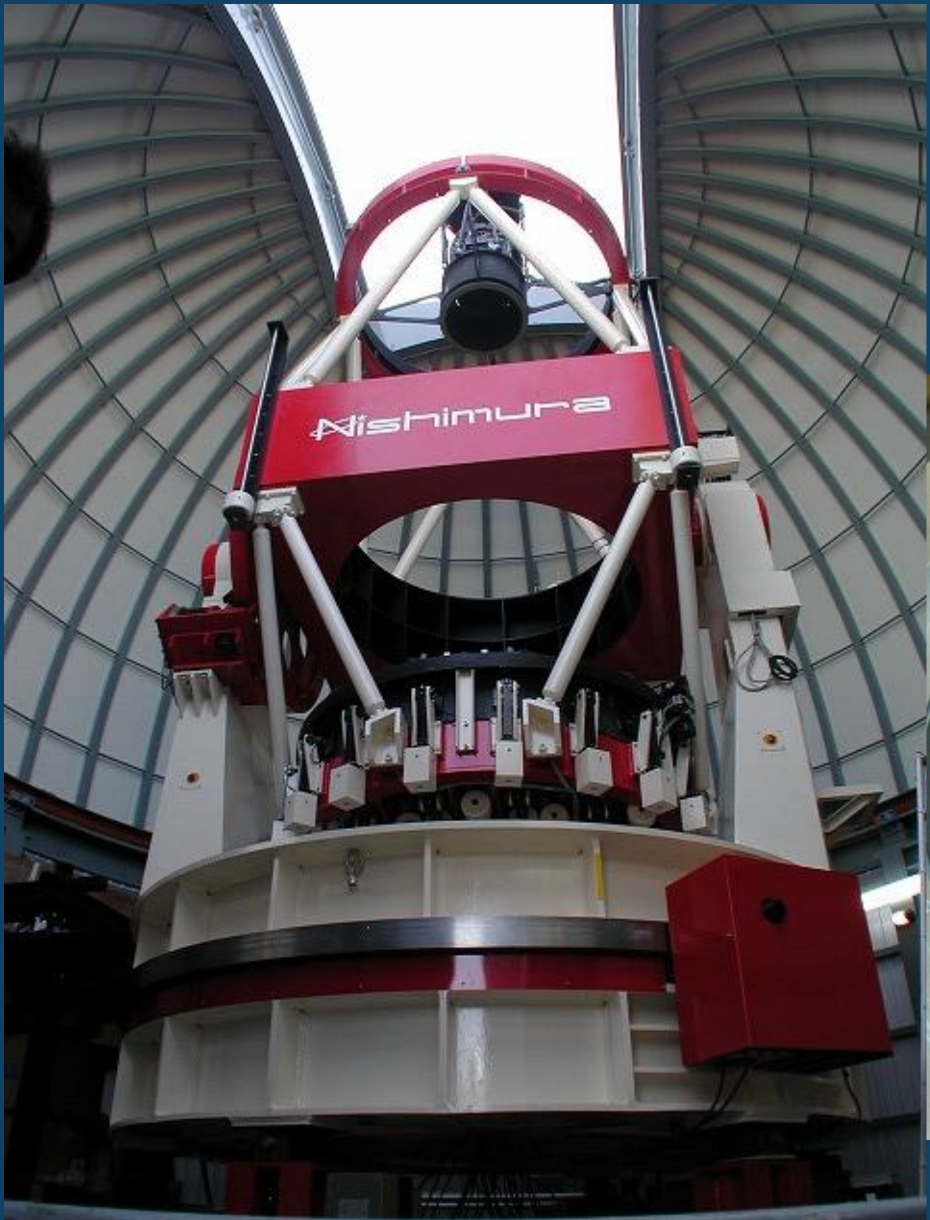
MOA (until ~1500)

(the world largest bird in NZ)

- height:3.5m
- weight:250kg
- can not fly
- Extinct 500 years ago

(Maori ate them)

MOA-II 1.8m

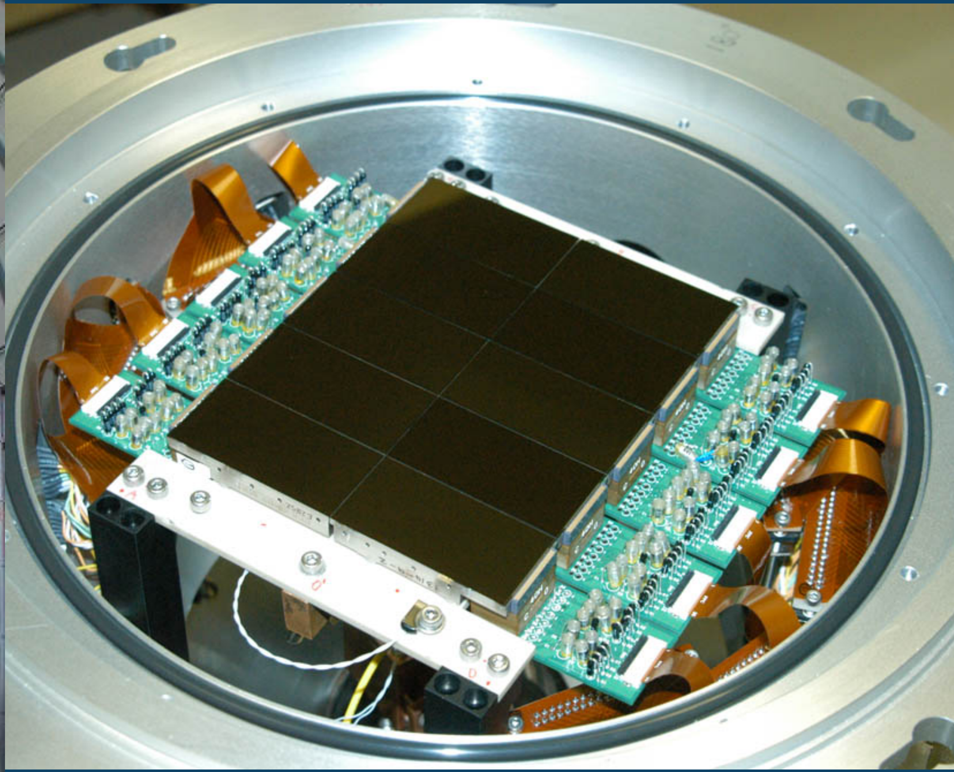


Mirror : 1.8m

CCD : 80M pix.(12x15cm)

FOV : 2.2 deg.^{2}

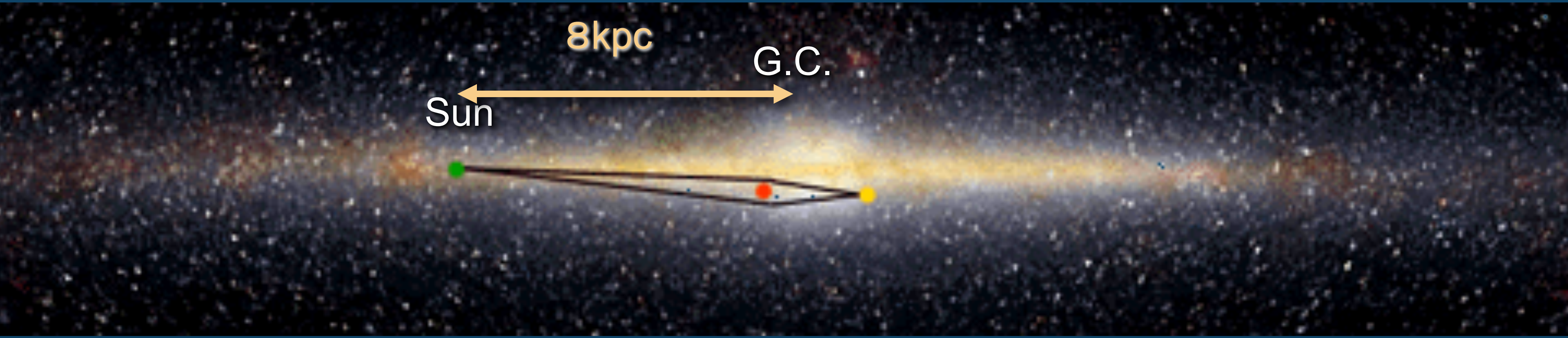
(10 times as full moon)



Survey towards the Galactic Bulge

✧ why ? ➔ Probability:
Microlensing : ~10^{-6} events/yr/star
Planetary event : ~10^{-2}

➔ need Wide Field for Many stars

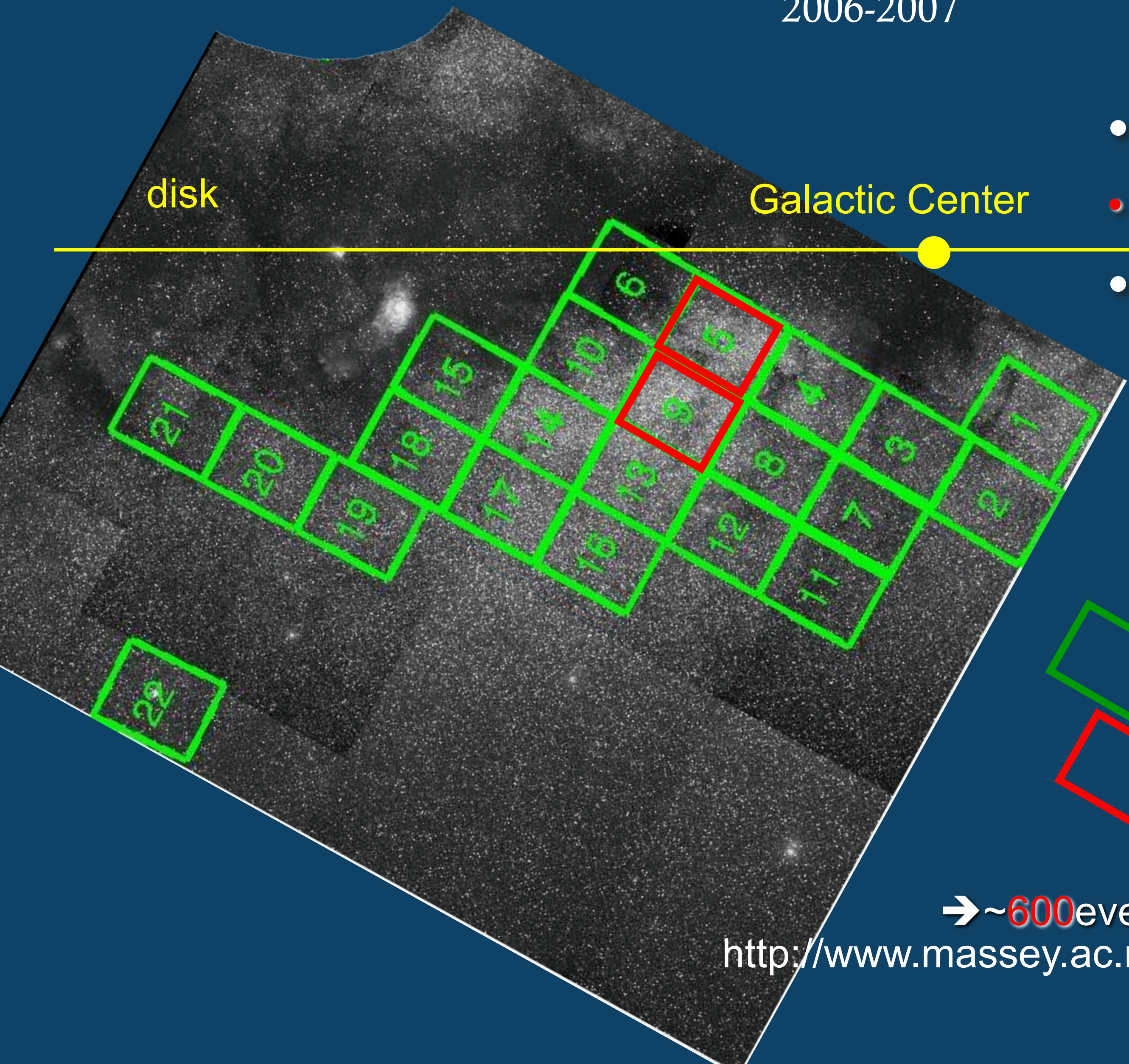


Time scale ~ 30days ($M_\odot$)
~ a few days (M_{Jup})
~ hours ($M_\oplus$)

➔ need high cadence

Observational fields

2006-2007



- 50 deg.^{2}
- (200x full moon)
- 20 Mstars

1obs/1hr

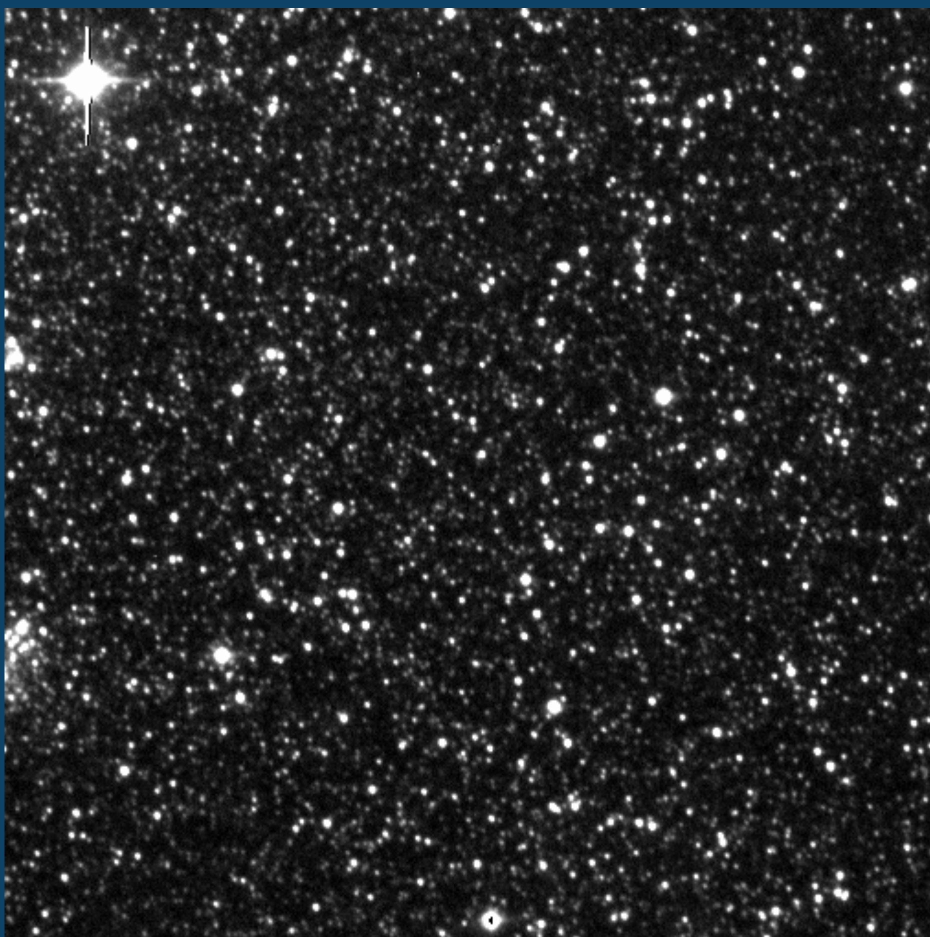
1obs/10min.

➔~600events／yr

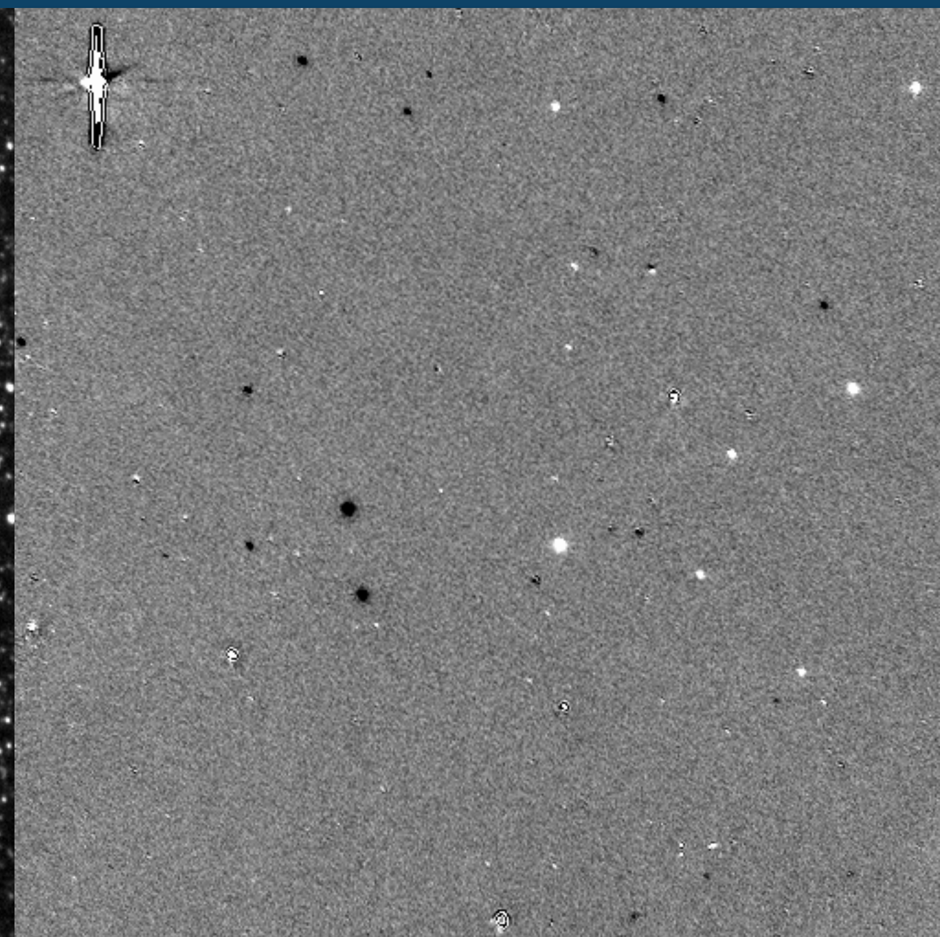
http://www.massey.ac.nz/~iabond/alert/alert.html

Difference Image Analysis (DIA)

Observed



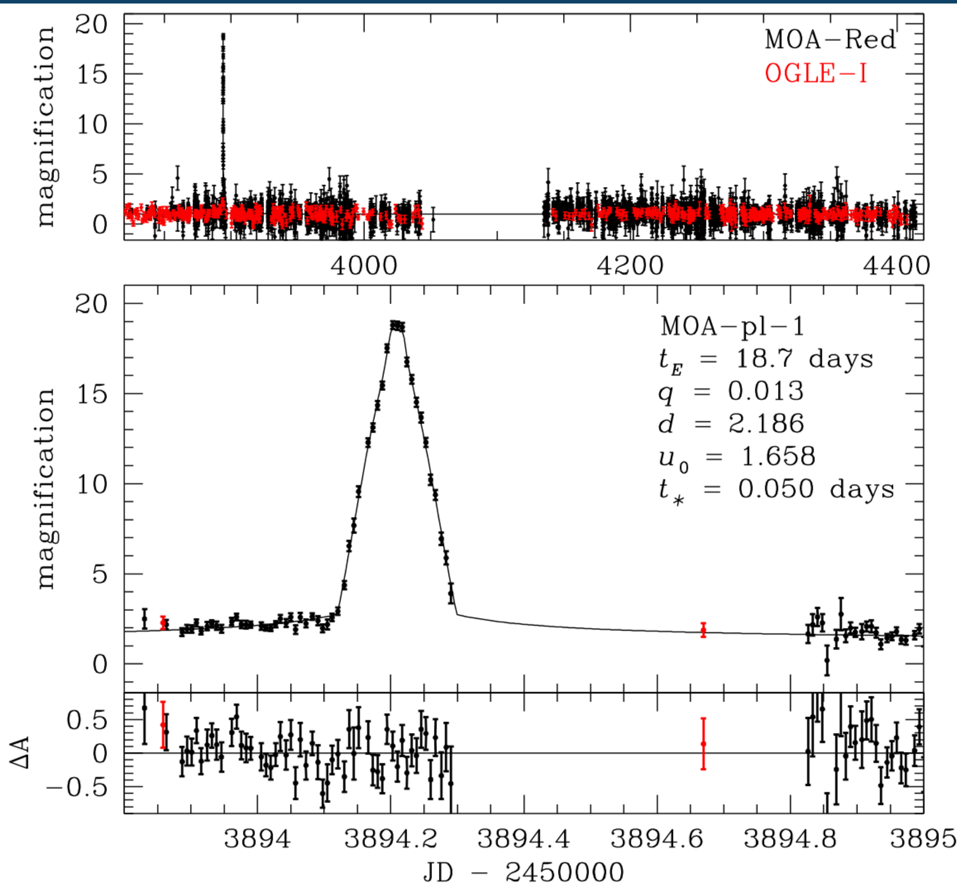
subtracted

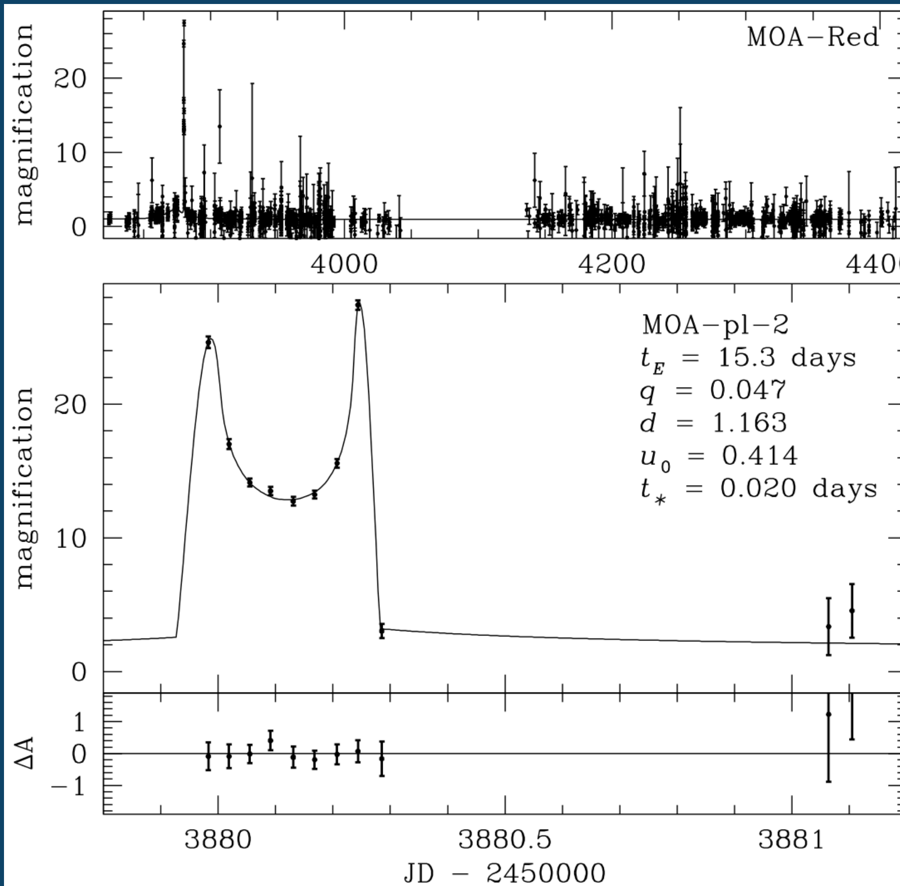


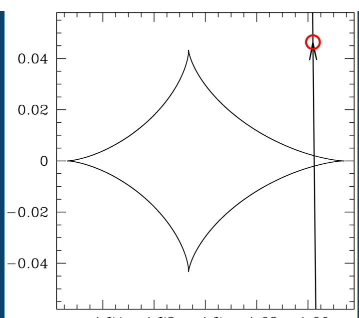
Binary Lens Background Rejection

- 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

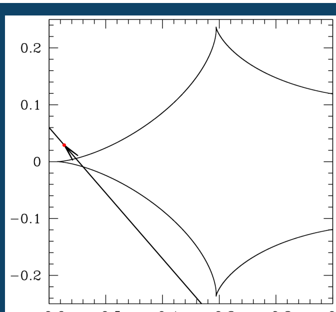
Background: Short Binary Events



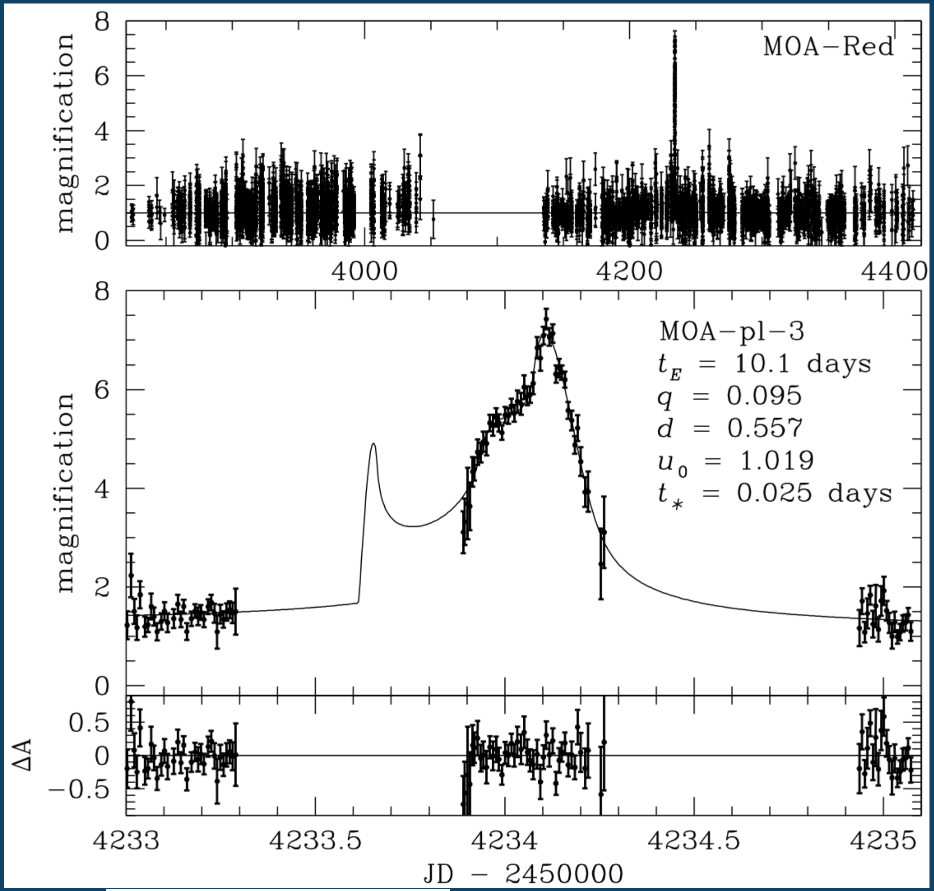


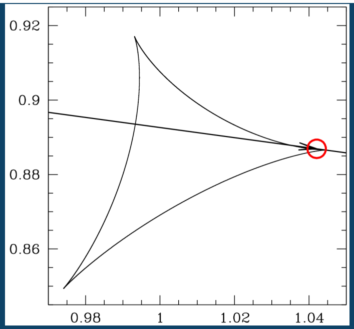


Wide-binaries (d = 2.2, 1.2) with planetary and brown dwarf mass ratios of q = 0.013 and 0.047



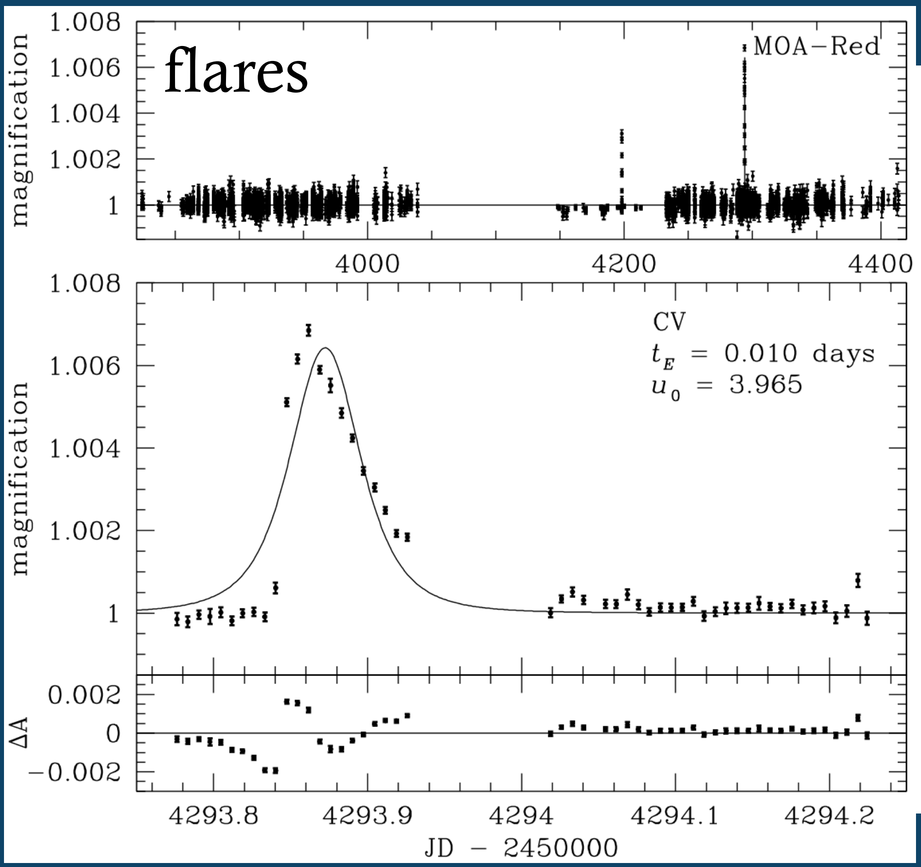
Background: Short Binary

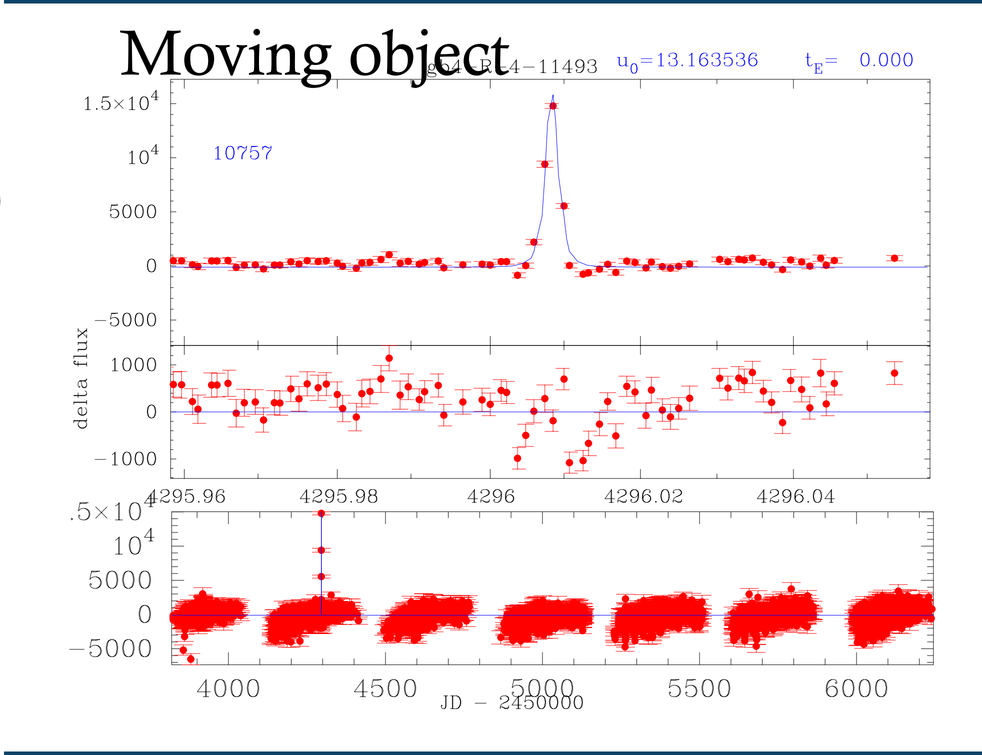




Close-binary (d = 0.56) with q = 0.095

Background: CV or moving objects





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

Moving object gives symmetric but unphysical microlensing fit, often with low magnification and an unphysically bright source

10 events with timescale t_E<2days

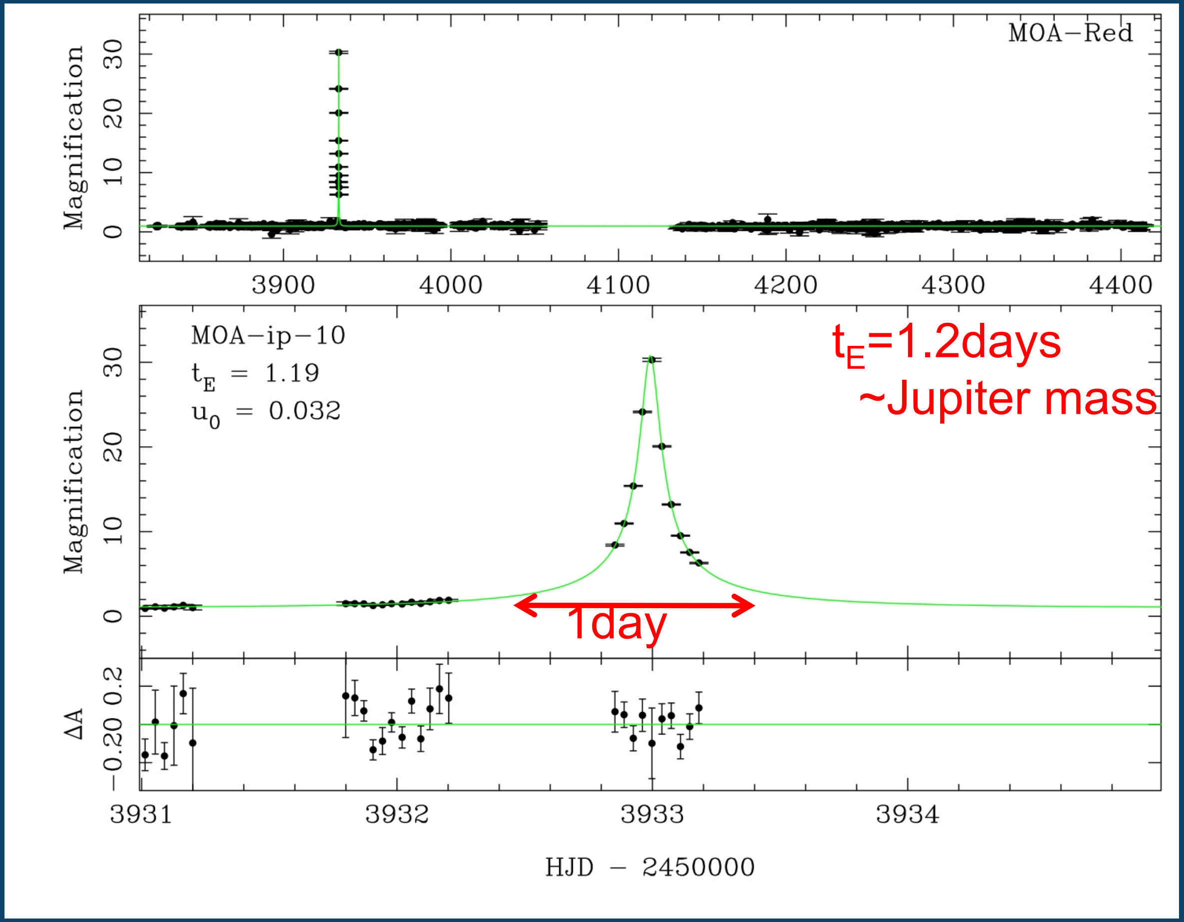
474events in 2 years

Einstein timescale:

$$t_E = \frac{R_E = \sqrt{\frac{4GM}{c^2}\frac{D_l(D_s - D_l)}{D_s}}}{v_t} \sim \sqrt{M/M_J}\ day$$

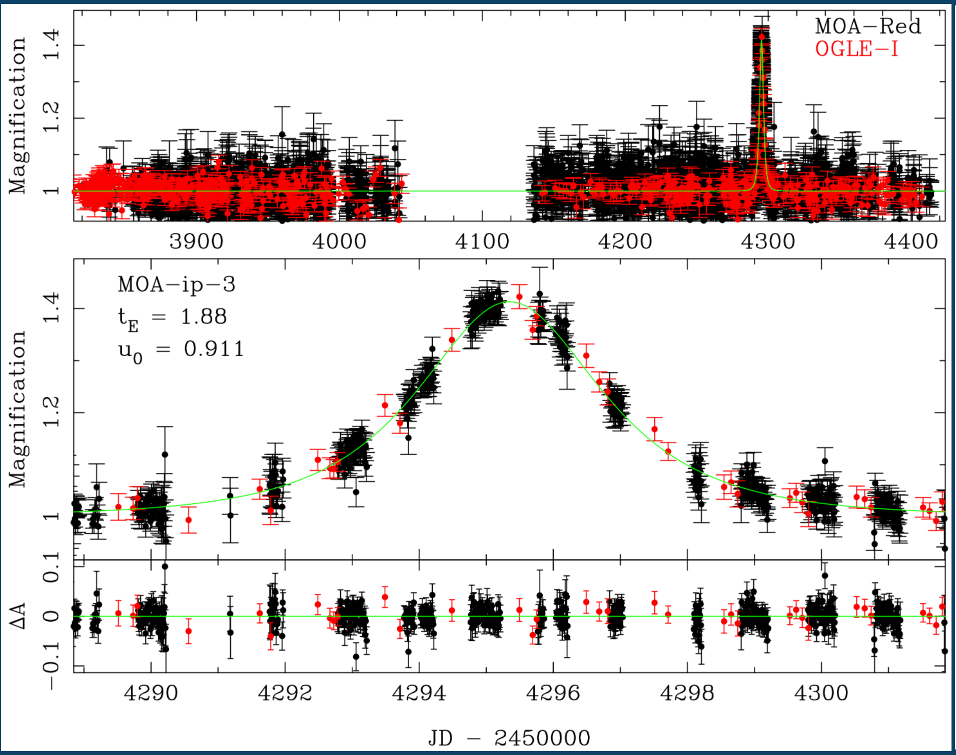
~20days for stars

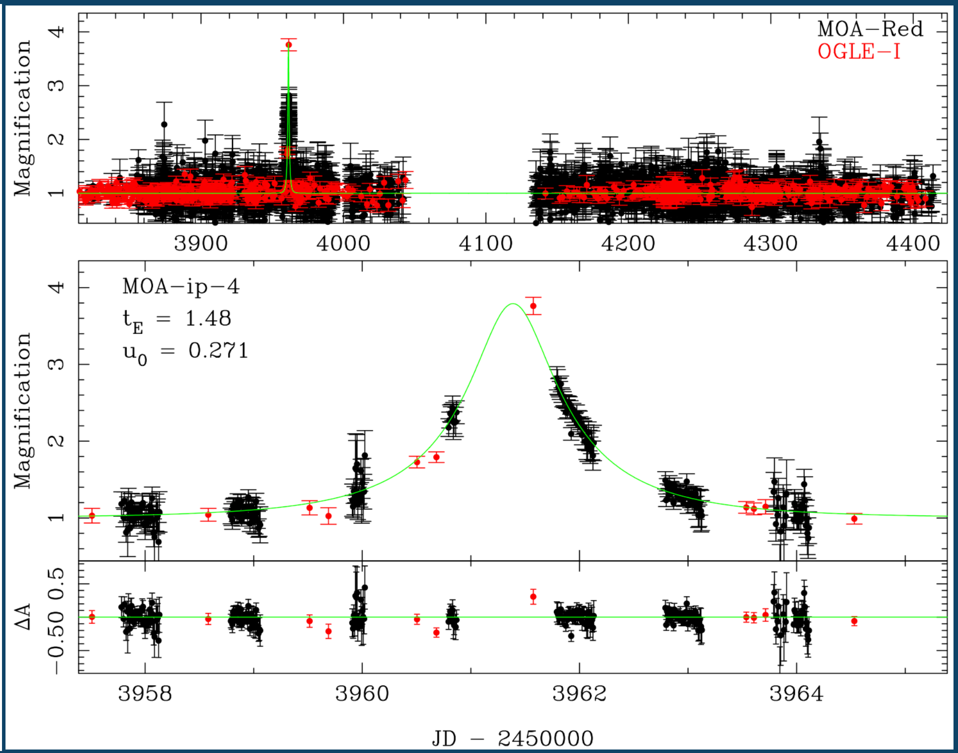
M: lens mass
M_J: Jupiter mass
D_l: lens distance
D_s: source distance
v_t: transverse velocity



10 events with t_E< 2 days from 2006-2007

(events 3, 4)





MOA data in black, confirmed by OGLE data in red

Einstein timescale

Table 4. Timescale t_E [d] for a grid of (D_ℓ, M_ℓ), assuming $\mu_{rel} = 4$ mas/yr (bulge lens)[a]

Bulge lens

Lens Type	M_ℓ $[M_\odot]$	D_ℓ **[kpc]**						
		1.0	2.0	3.0	4.0	5.0	6.0	7.0
Black hole	10					225.5	168.1	110.1
G Dwarf	1					71.3	**53.2**	34.8
M Dwarf	0.3					39.1	**29.1**	19.1
M Dwarf	0.1					22.6	16.8	11.0
Brown Dwarf	0.01					7.1	5.3	3.5
Jupiter	0.001					2.3	1.7	1.1

[a] Assuming a source star distance of $D_s = 8$ kpc.

Conceptual Themes for the 2017 Sagan Summer Workshop

Table 5. Timescale t_E [d] for a grid of (D_ℓ, M_ℓ), assuming $\mu_{rel} = 10$ mas/yr (disk lens)[a]

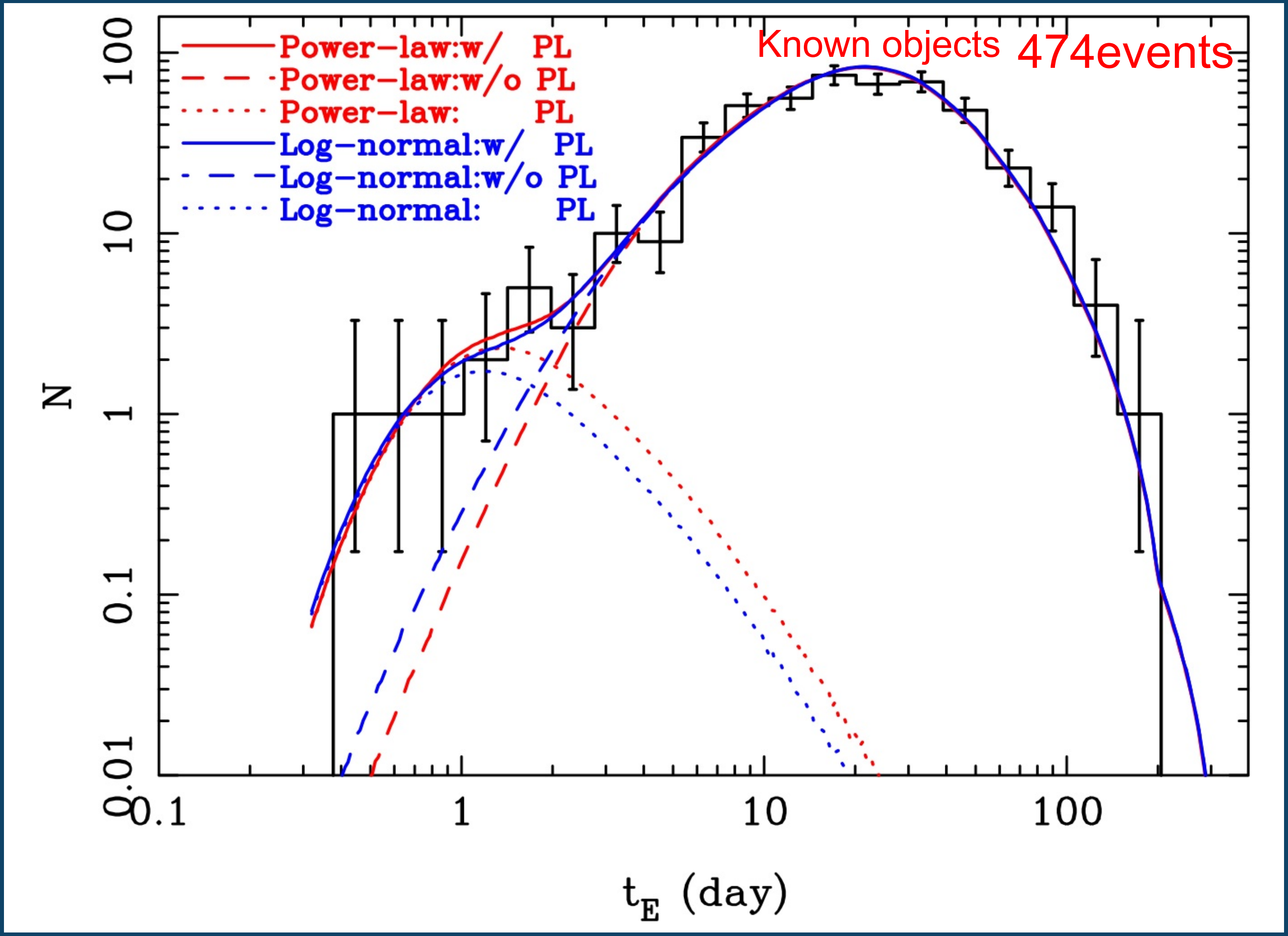
Disk lens

Lens Type	M_ℓ $[M_\odot]$	D_ℓ **[kpc]**						
		1.0	2.0	3.0	4.0	5.0	6.0	7.0
Black hole	10	308.1	201.7	150.4	116.5	90.2		
G Dwarf	1	97.4	63.8	47.5	**36.8**	28.5		
M Dwarf	0.3	53.4	34.9	26.0	**20.2**	15.6		
M Dwarf	0.1	30.8	20.2	15.0	11.6	9.0		
Brown Dwarf	0.01	9.7	6.4	4.8	3.7	2.9		
Jupiter	0.001	3.1	2.0	1.5	1.2	0.9		

[a] Assuming a source star distance of $D_s = 8$ kpc.

Timescale t_E distribution

474 events In 2006-2007



Sumi et al. 2011

Modeling t_E distribtution

The Einstein timescale t_E is the only observable in the regular single lens microlensing event and is given by

.

$$t_E = \frac{R_E(M,D)}{v_t}$$

Mass

Distance

Transverse velocity

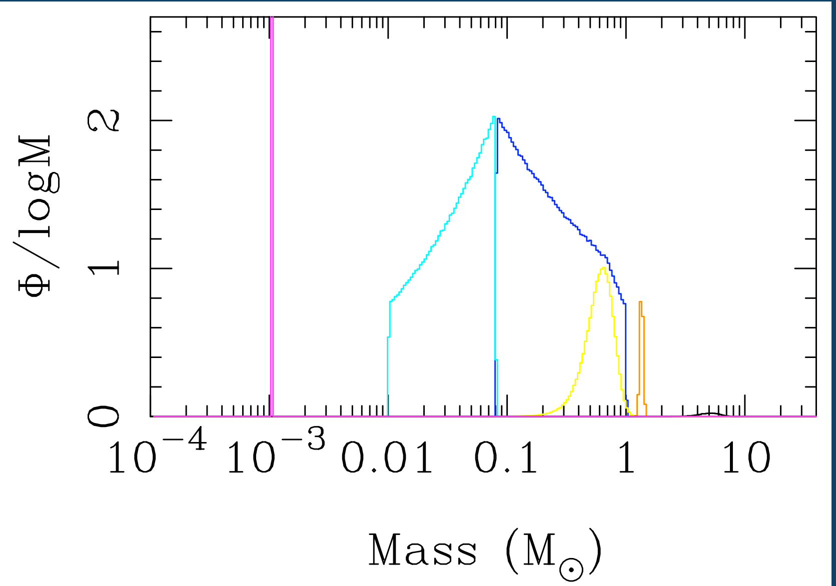
Although the physical parameters of the lens and source are degenerate, a model t_E distribution, Φ(tE), can be calculated using a Monte Carlo simulation for an assumed mass function with a standard galactic mass density and velocity model (Han,C.& Gould, 2003)

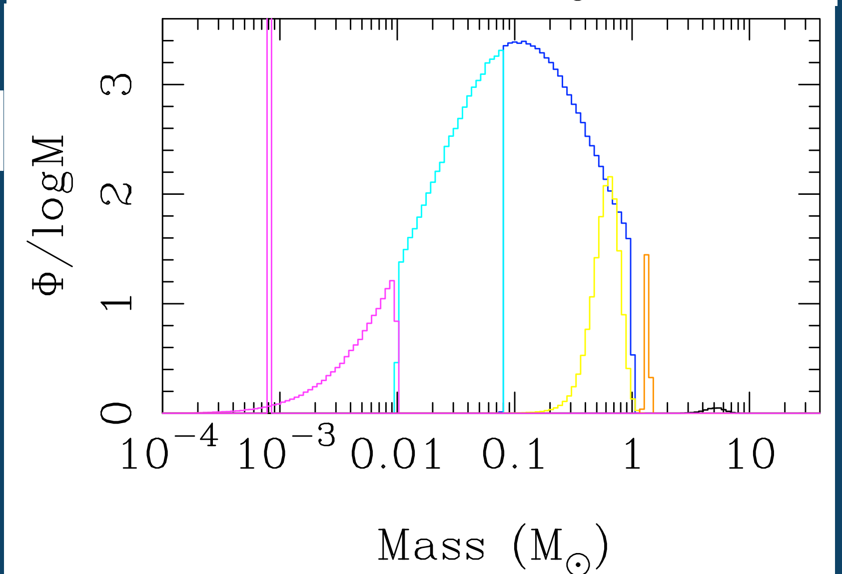
Mass Function Models

- Assume Salpeter-like slope (α = -2) for initial >1 $M_\odot$ stars → stellar remnants
- 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

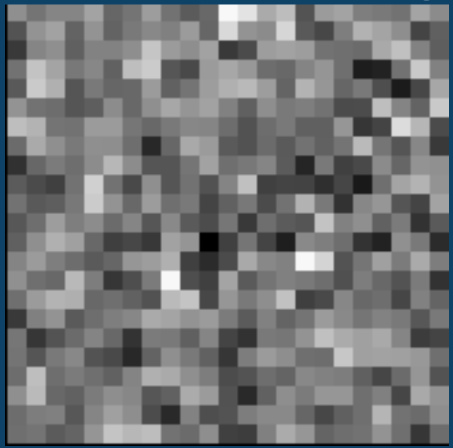




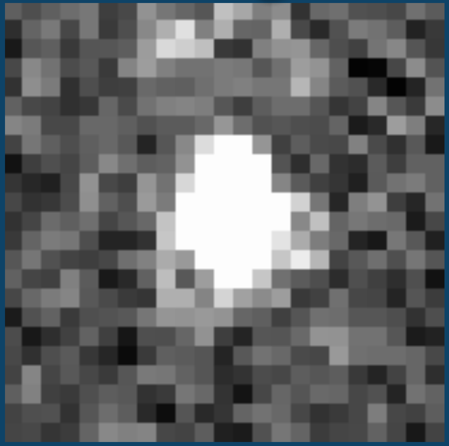
Simulation

Put artificial events on real images

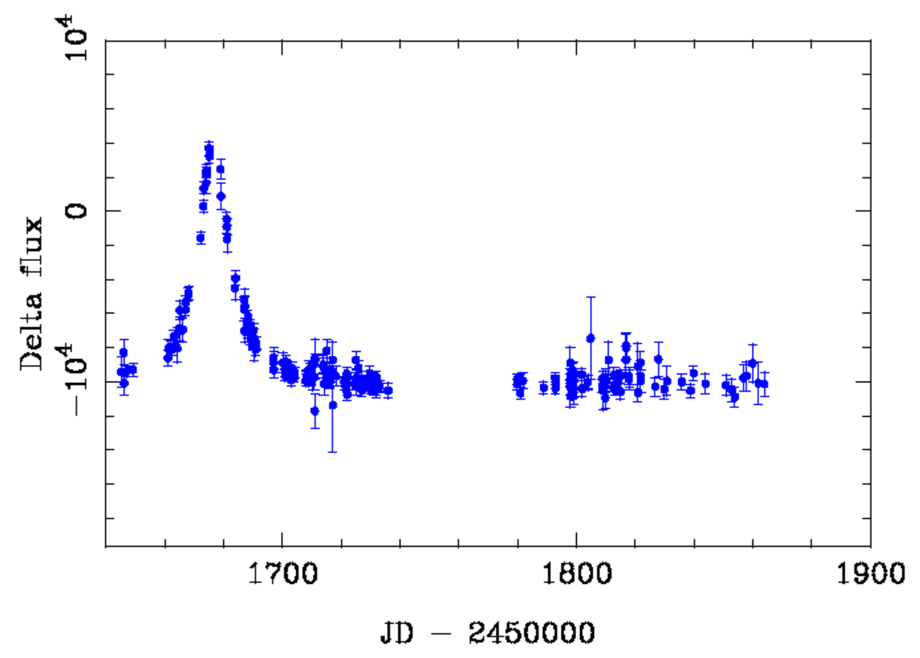
Subtracted image



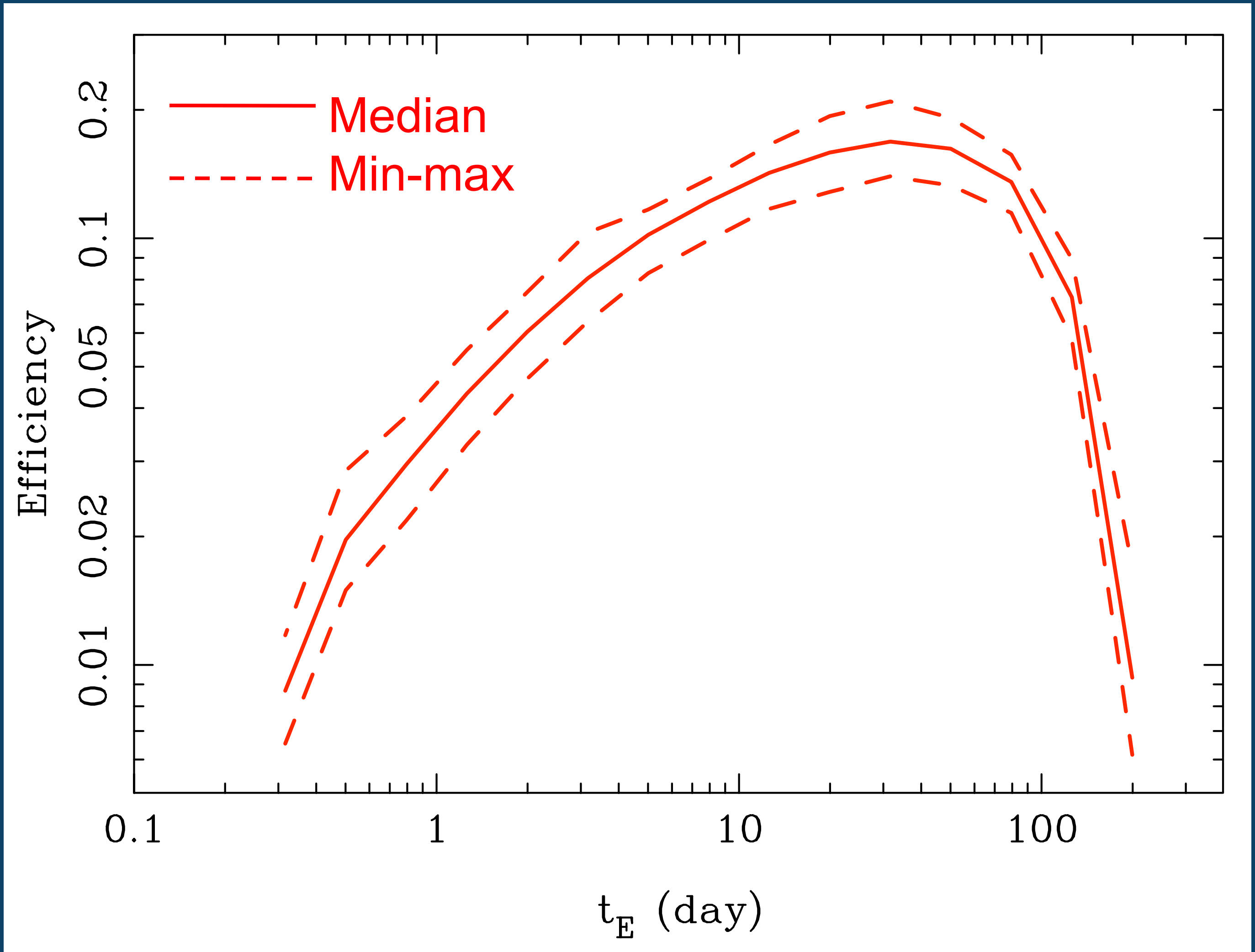
Art image



- Sampling
- noise
- Artifacts
- Nearby bright star,
- Nearby variable star
- Nearby high proper motion star
- Differential refraction

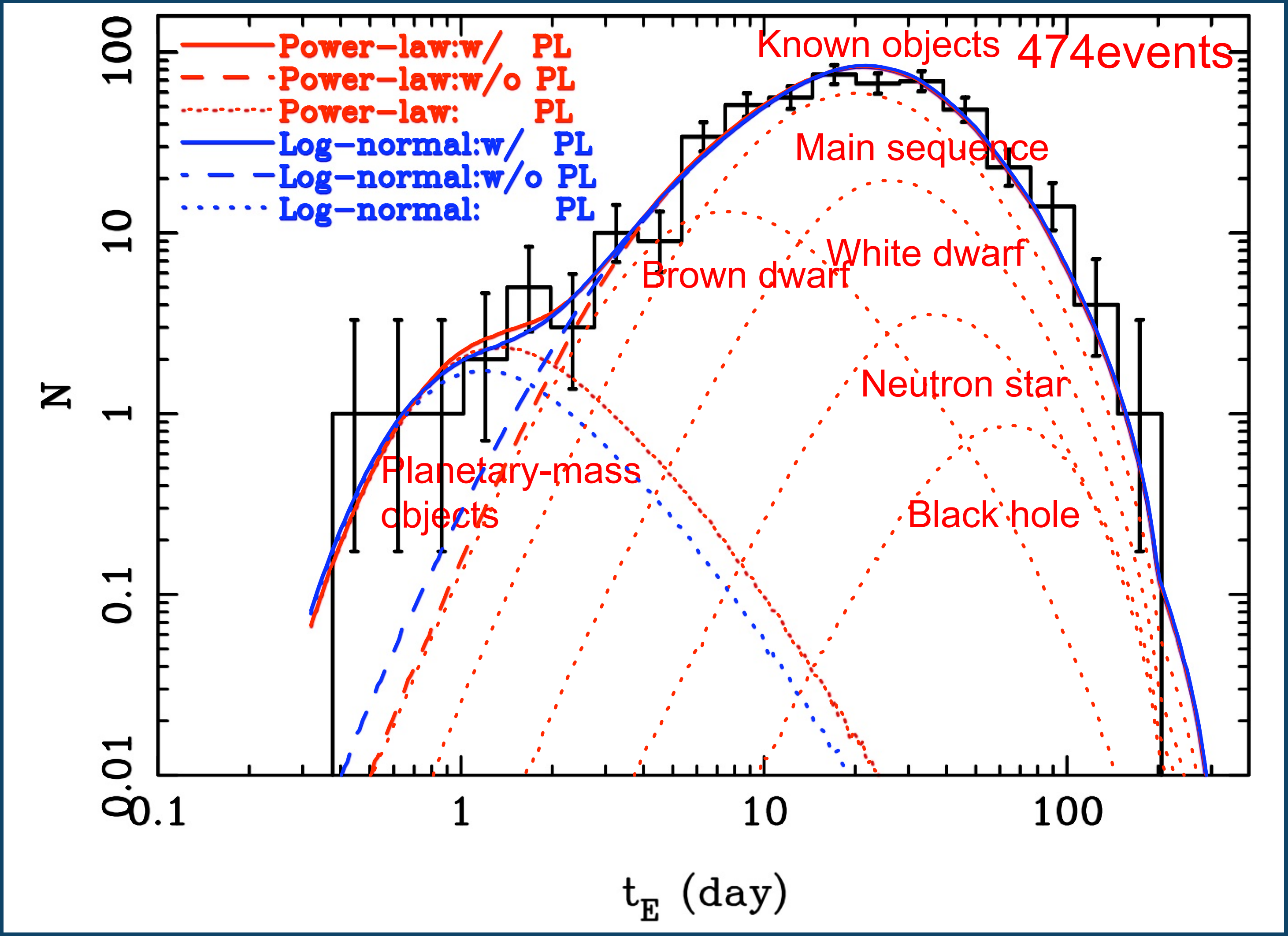


Detection Efficiency



Timescale t_E distribution

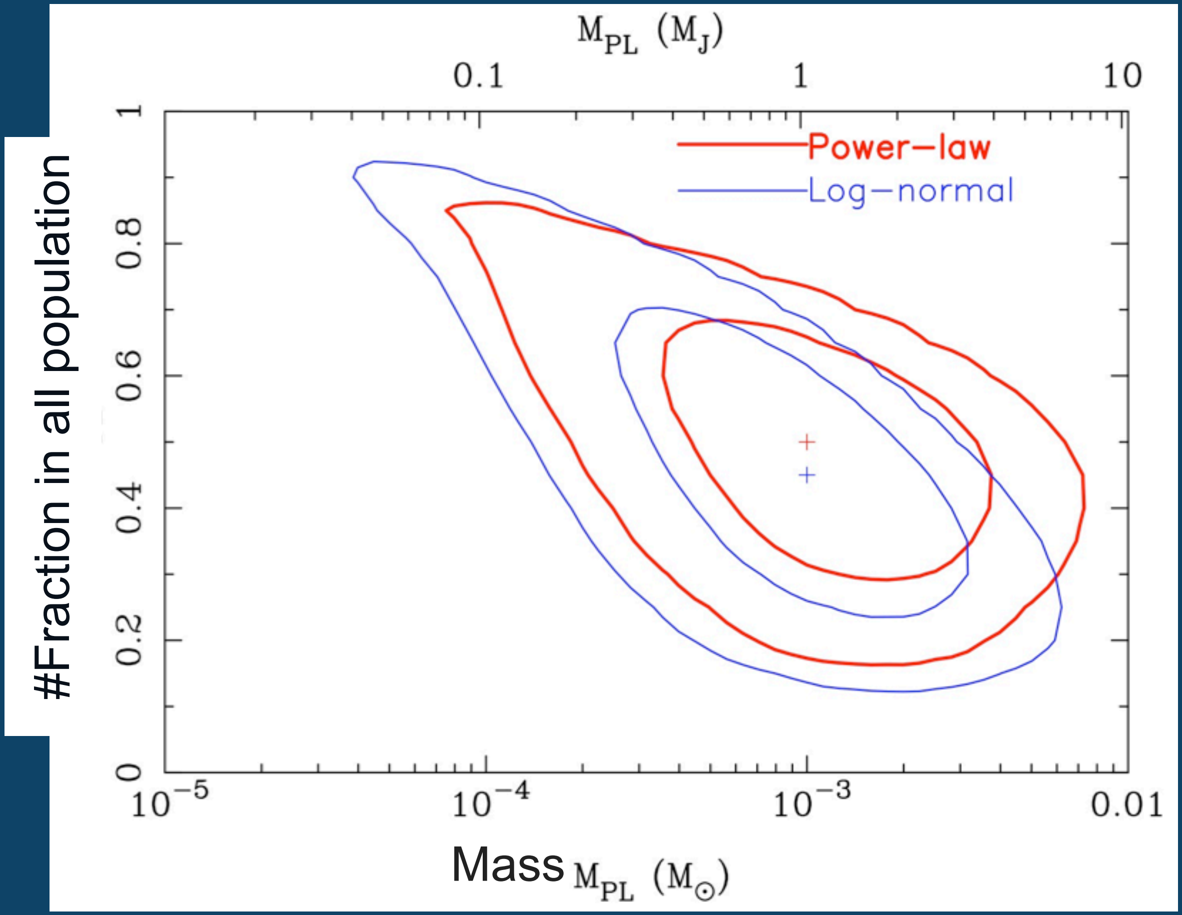
474 events In 2006-2007



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

Likelihood of Planetary Mass Function Parameters

68%, 90% contour

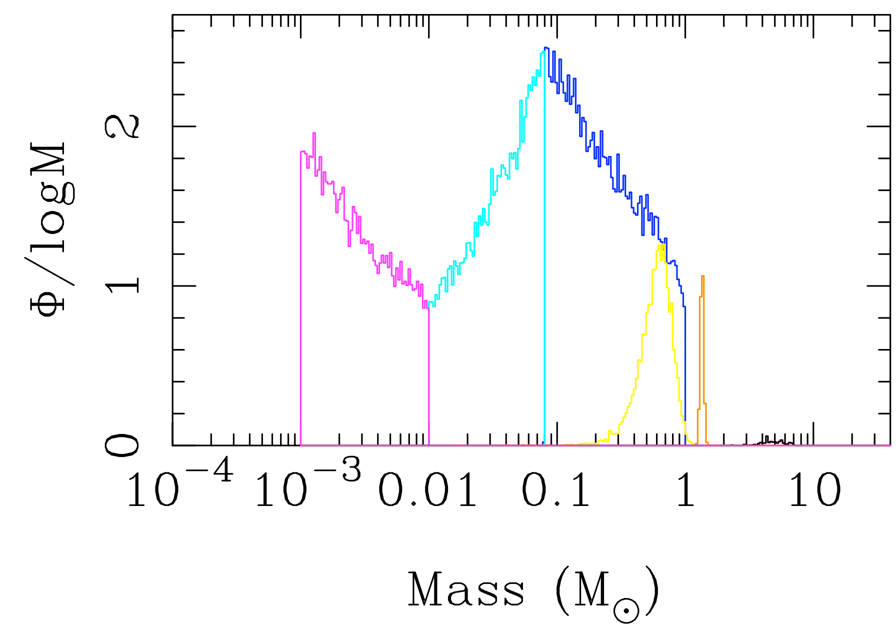


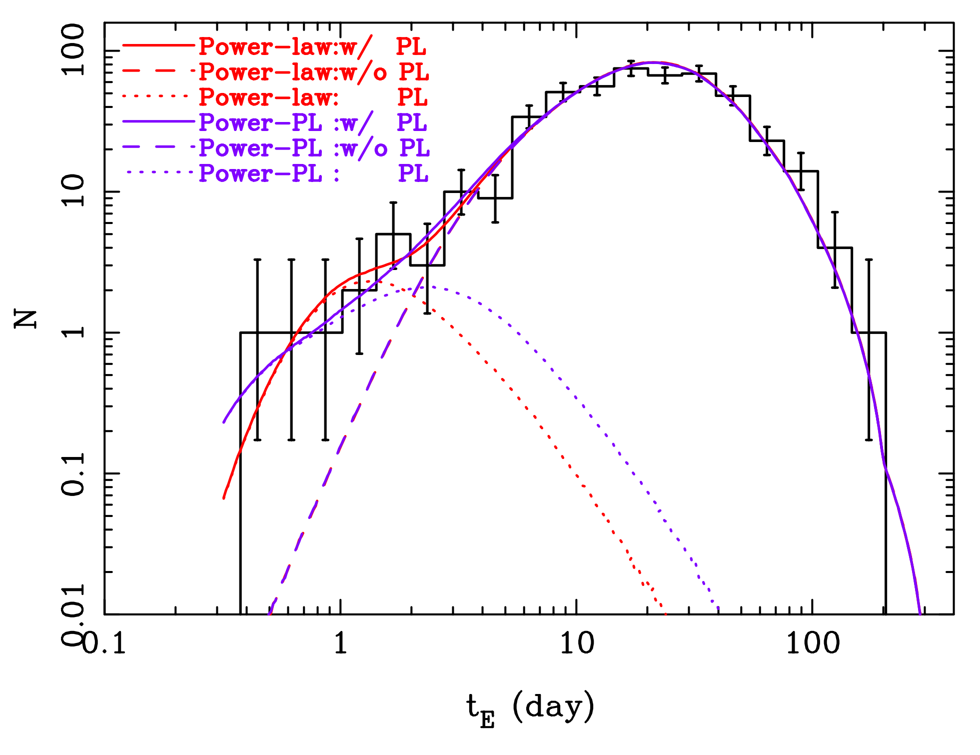
$$N_{planet} = 1.8^{+1.7}_{-0.8} N_{star}$$

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

0.2-3.5 isolated planets per star

Power law PL MF



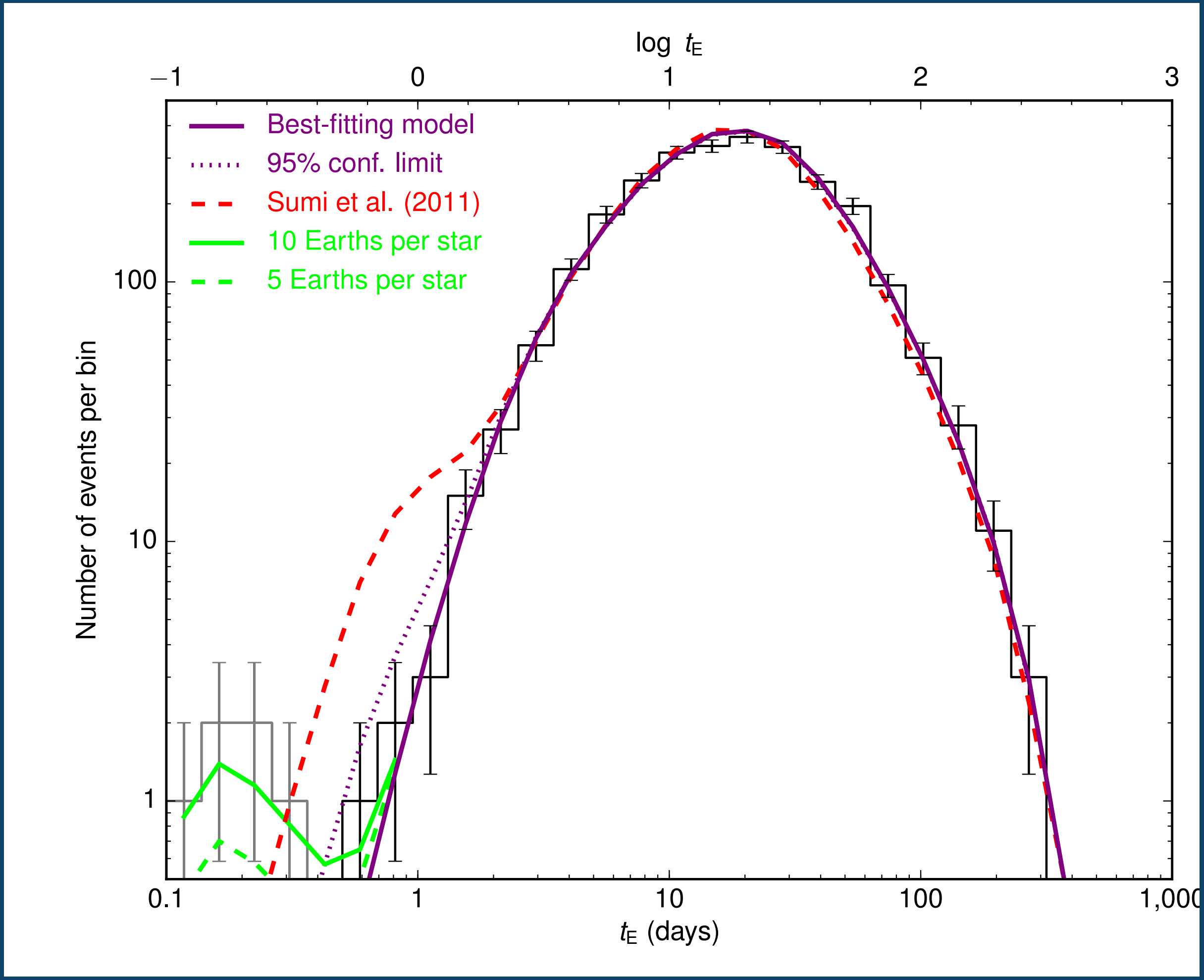


4	$0.08 \leq M$		same as model (1)	
	$0.01 \leq M \leq 0.08$	Power-law**	$\alpha_3 = 0.49^{+0.24}_{-0.27}$ w/ PL	$0.73^{+0.17}_{-0.15}$
	$10^{-5} \leq M \leq 0.01$	Power-law**	$\alpha_{PL} = 1.3^{+0.3}_{-0.4}$ w/ PL	$5.5^{+18.1}_{-4.3}$

Predict Many super Earth.

But still consistent with delta function

Recent OGLE-IV results



Mróz+2017

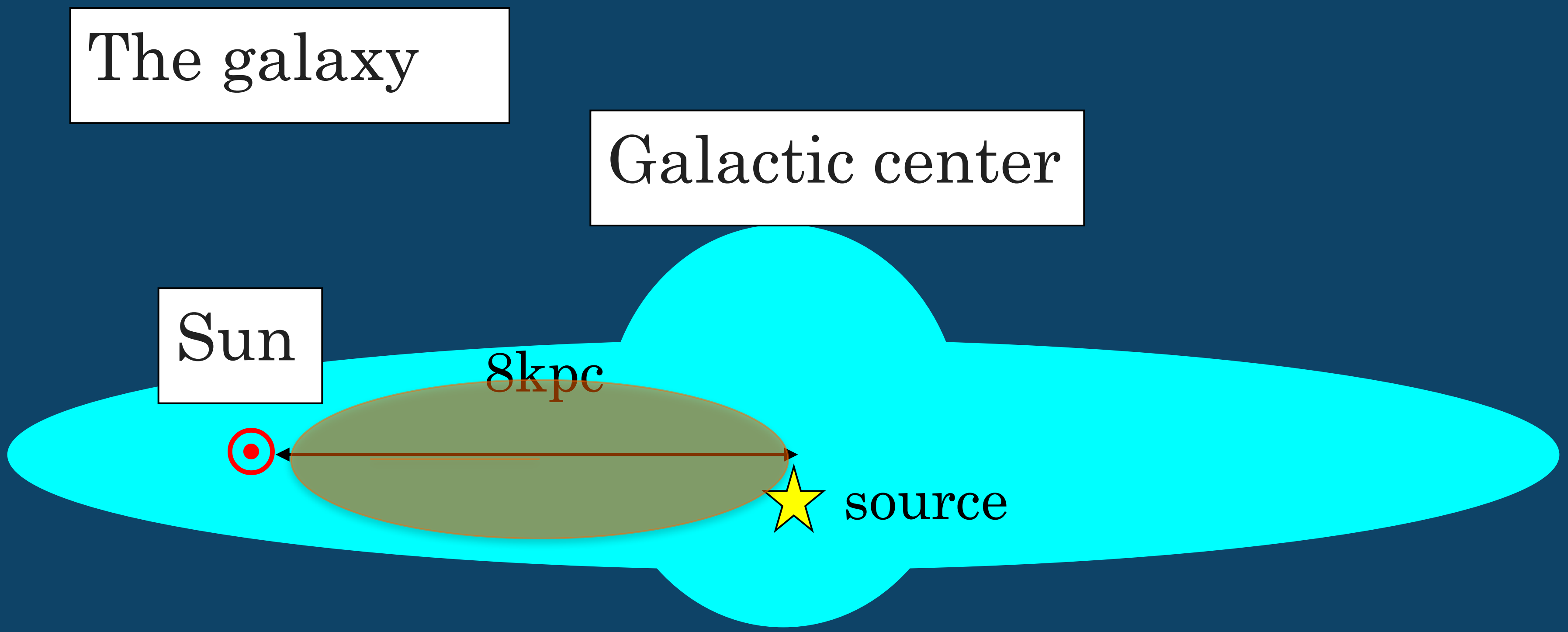
Jupiter mass lenses :
~0.05 x Main sequence
<1/4 of Main sequence

Six ultra short events
With t_E ~ 0.2days
Super Earth FFP?

Reasons of difference:

1. Statistic (2.5-3σ)
2. Uncertainty in t_E
3. Contamination of short binary
4. OGLE found more BD. 0.9 brown dwarf per MS star compared to 0.7 in MOA

Where are they?

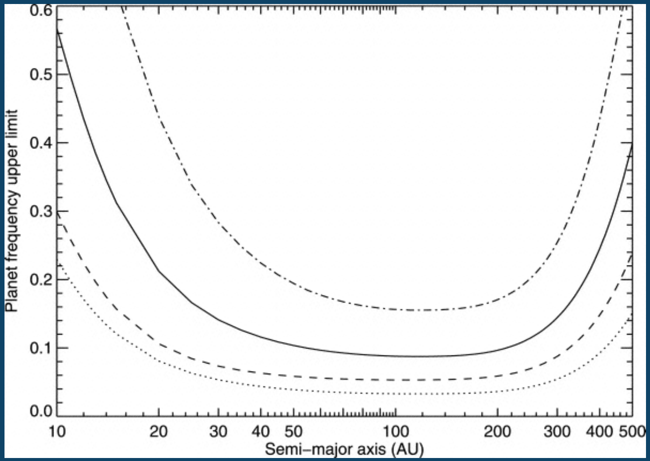


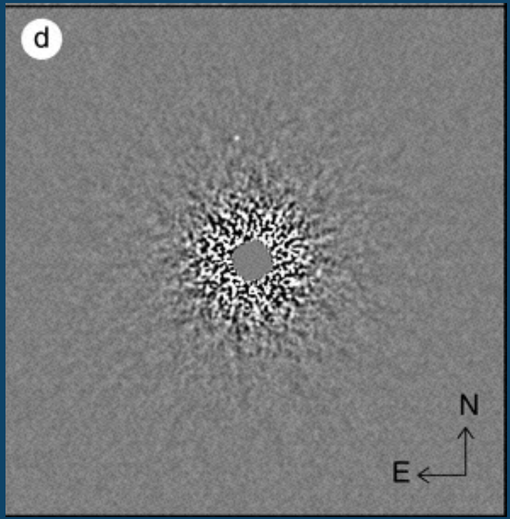
Somewhere between Sun and the galactic center

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

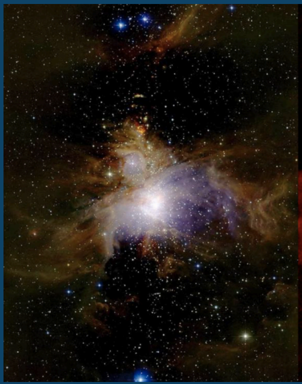


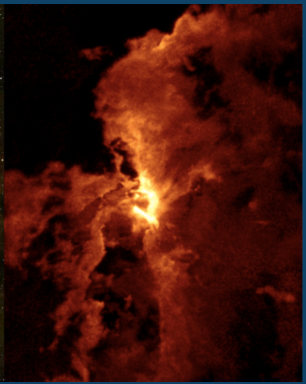


- < 10-16% for 1-13M_J at 10-100AU (Bowler,B.P.2015)
- They can be bound. But not nessesaly.

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）

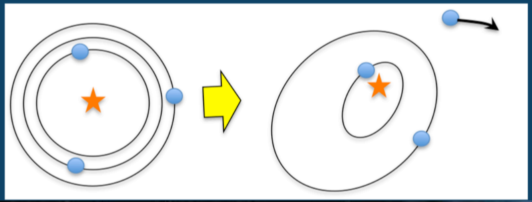
➔ evidence of gravitational interaction

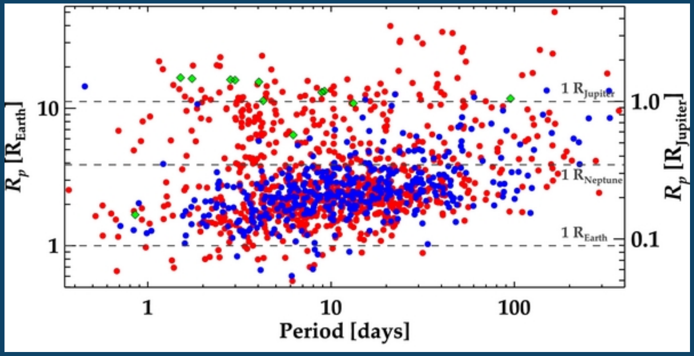
Hot Jupiters are alone (Latham et al. 2011)

➔ evidence of gravitational interaction

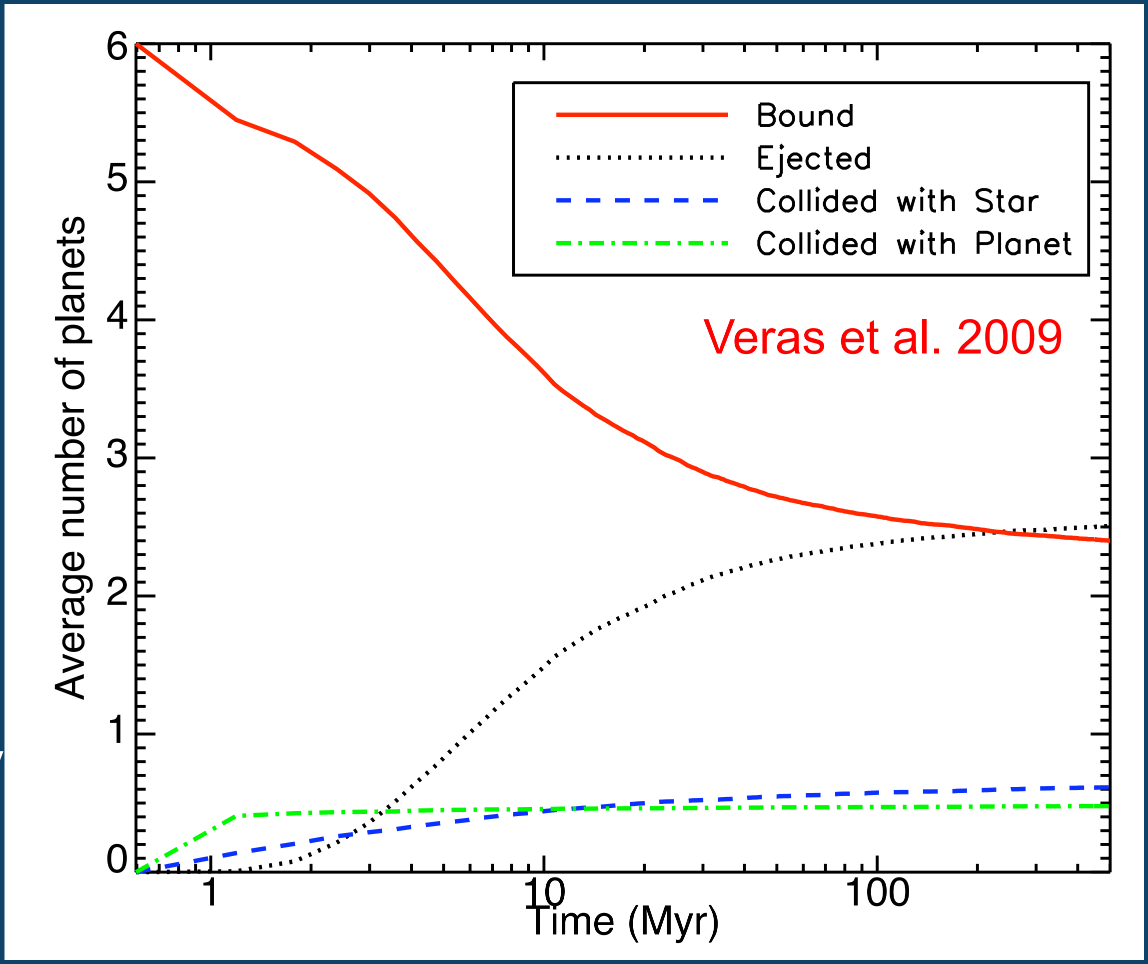
No desert for short-period super-earths (Howard et al. 2010)

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



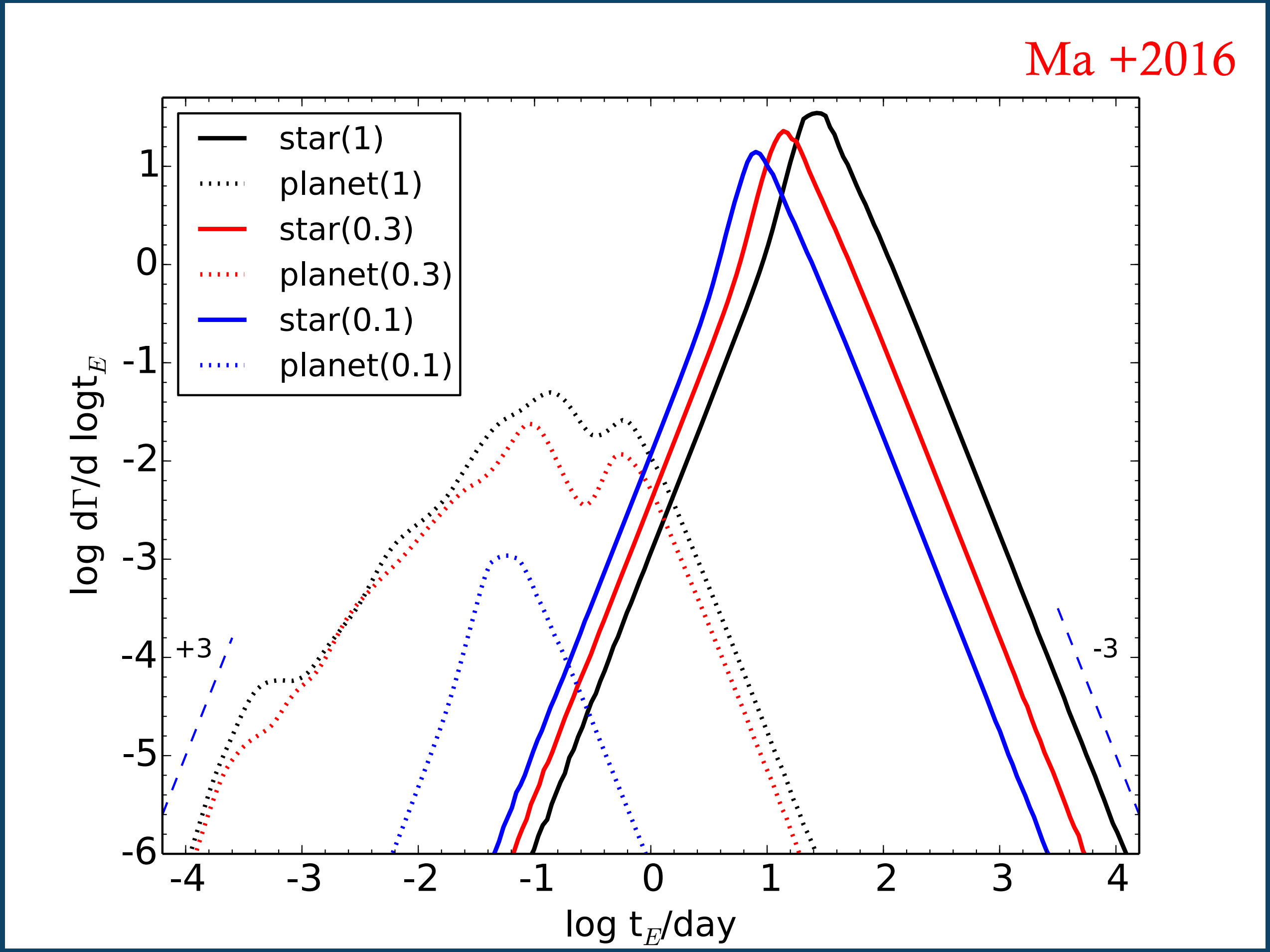


Simulation of the dynamical effect of planetary system



- half planets ejected after 10^7y
- Free floating
- Microlensing can find

The event rate as a function t_E of scattered planets

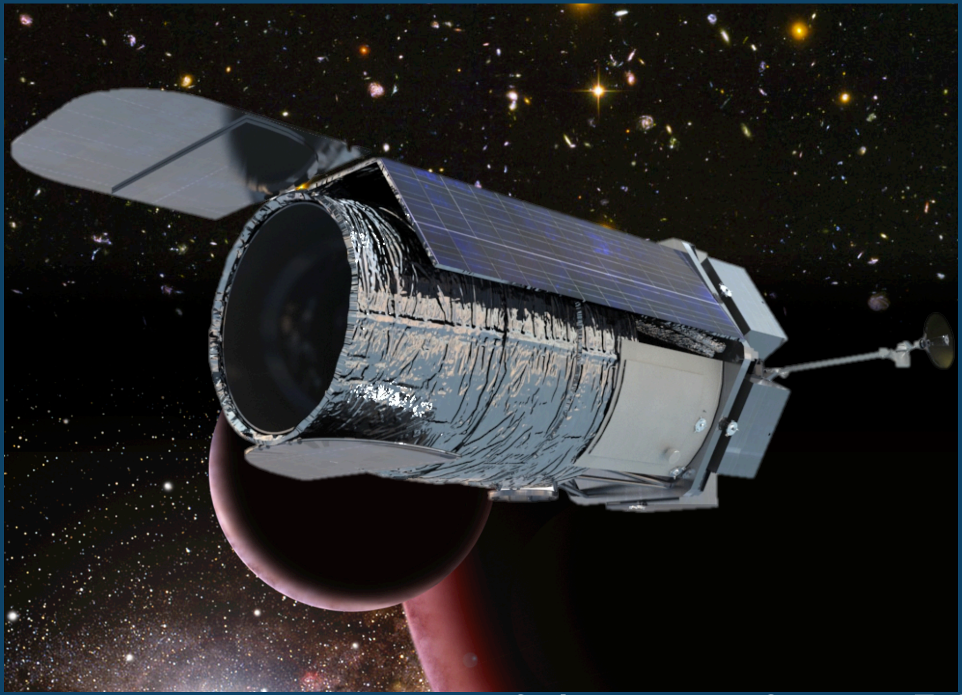


Use Population synsethis by Ida & Lin.
Simulated how many planets are scatted out.
The three solid curves are for the events produced by three stellar masses, 1, 0.3 and 0.1M⊙, respec- tively. The three corresponding planetary curves (dotted lines) are shown on the left.

WFIRST

(Wide Field Infra Red Survey Telescope)

Recommended by Decadal survey astro2010
NASA's flagship mission following HST, JWST



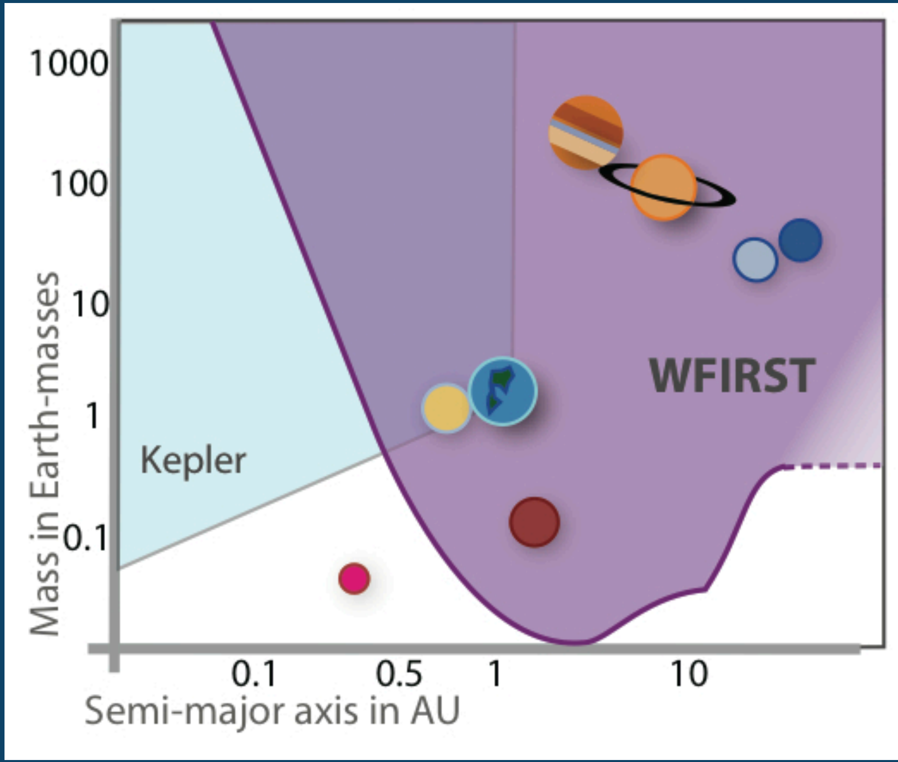
Launch in 2025

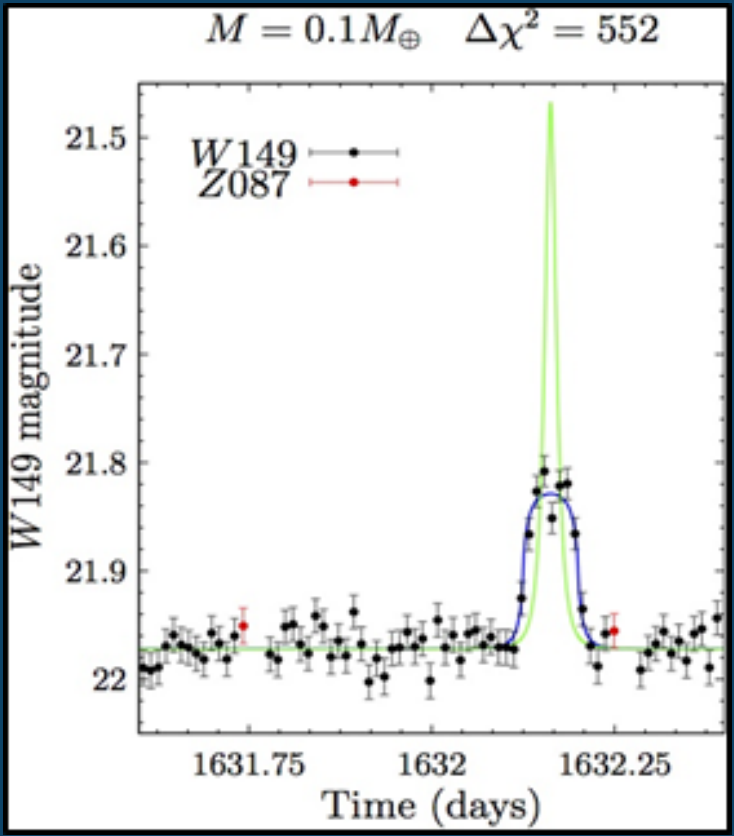
- Dark Energy
- Exoplanet Microlensing
- Exoplanet Coronagraph
- Near Infrared Sky Survey
- Guest Observing Prog.

Diameter: 2.4m given from NRO (National Reconnaissance Office)
$\lambda < 2\mu$m
FOV：0.281deg.^{2}

Complete the census of planetary systems

- WFIRST can detect all solar system planet analog except Mercury & FFP





Penny

- 3000 bound planet, 200 ($< 1\ M_\oplus$)
- 2000 free-floating planet, 100 ($< 1\ M_\oplus$)

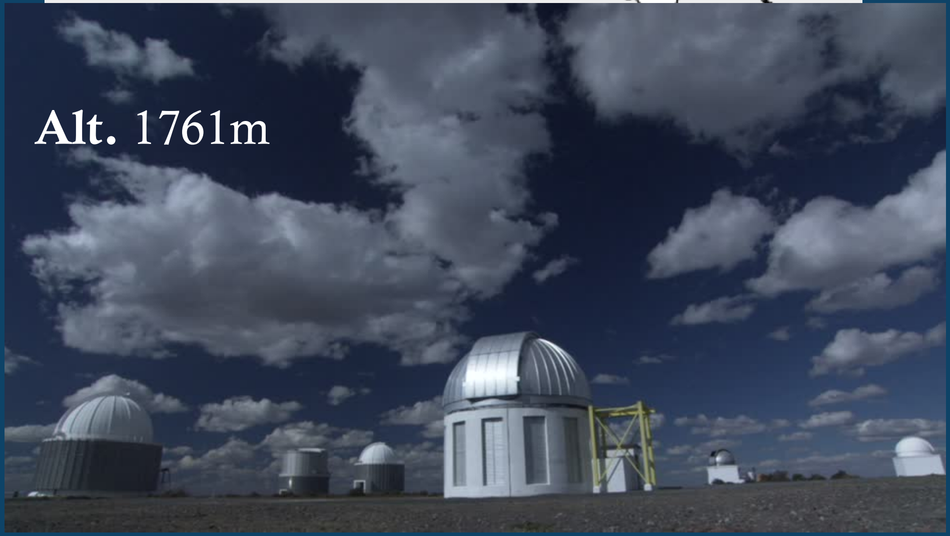
PRIME (PRime-focus Infrared Microlensing Experiment) 1.8m Telescope at SAAO

Diameter: 1.8m, (f/2.29)

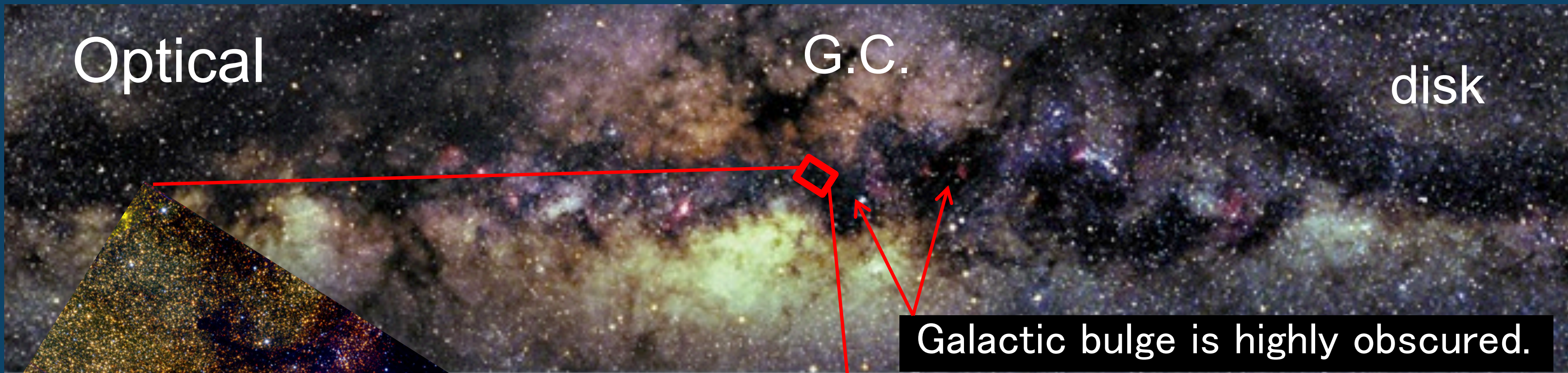
FOV:1.25° x1.25° =1.56deg^2(0.5”/pix)

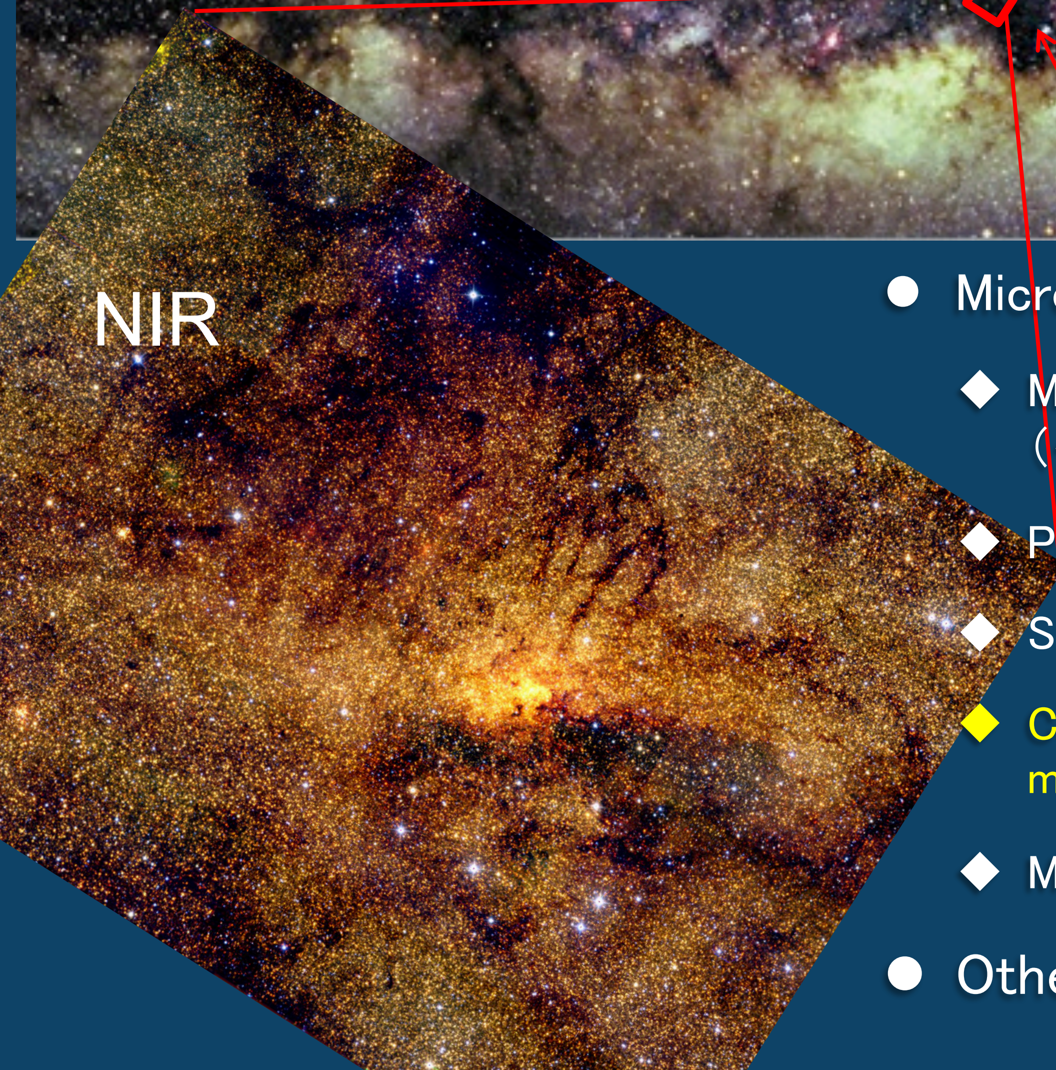
(6xfull moon) World Largest FOV

H-band



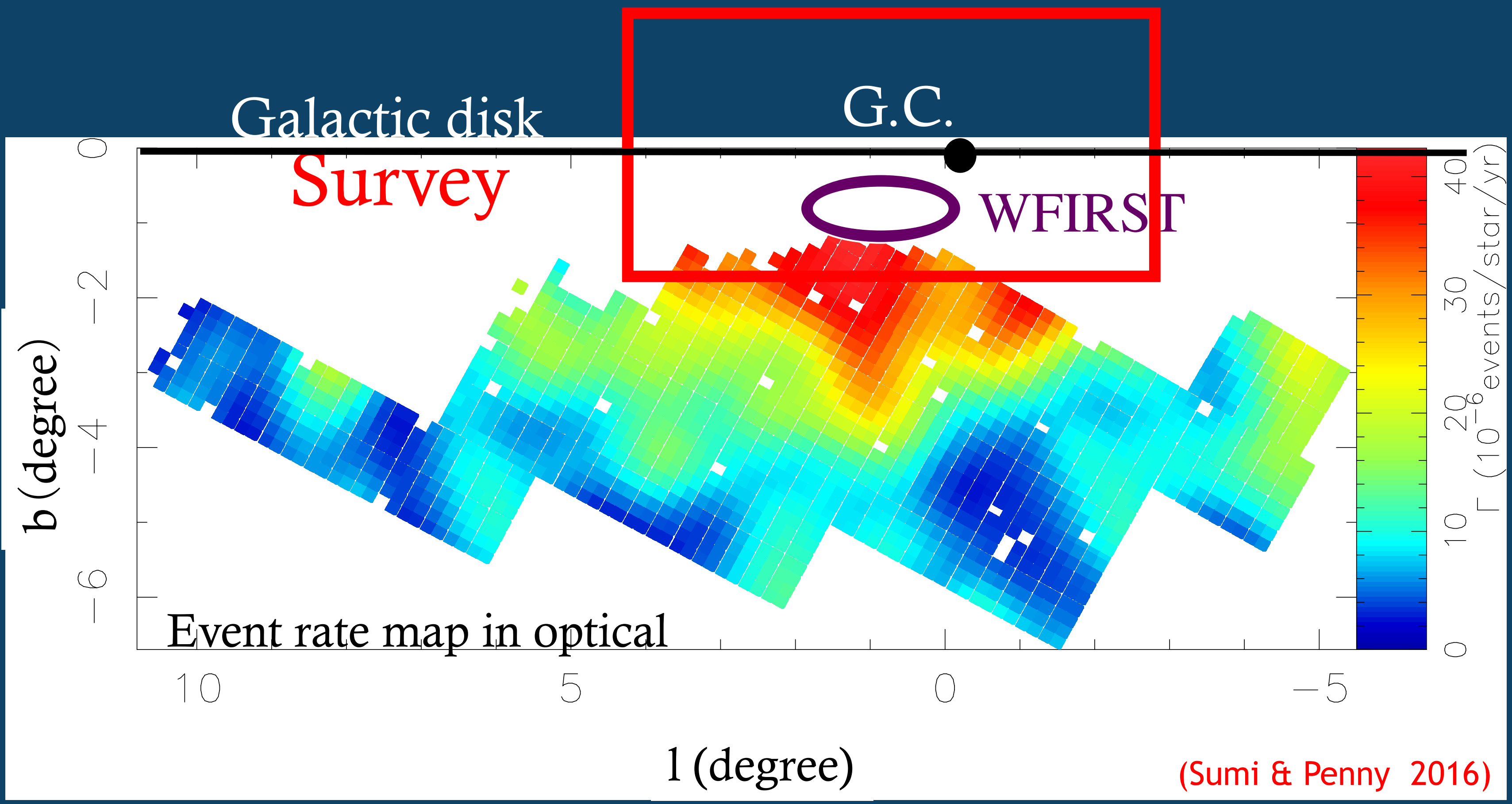
More events & planets in NIR at G.C.



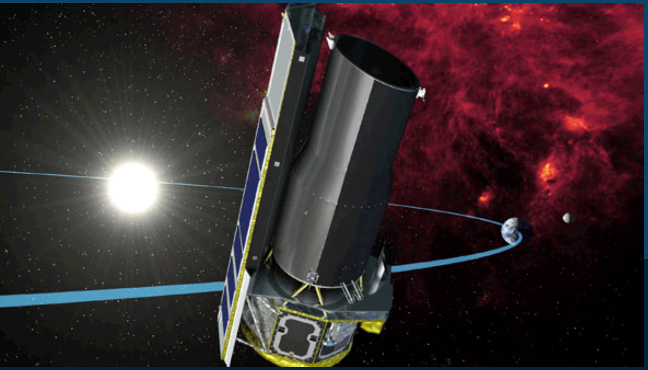


- Microlensing Exoplanets (～50%)
  - ◆ More stars & more events at GC. (～2400events/yr, ～12planets/yr)
  - ◆ Planet frequency at GC.
  - ◆ Select WFIRST fields.
  - ◆ Concurrent observation with WFIRST to measure lens mass.
  - ◆ Mass Function at GC (planet–Black Hole)
- Other sciences (～50%)

Study the galactic structure & Optimize WFIRST microlensing survey fields by mapping the event rate in NIR

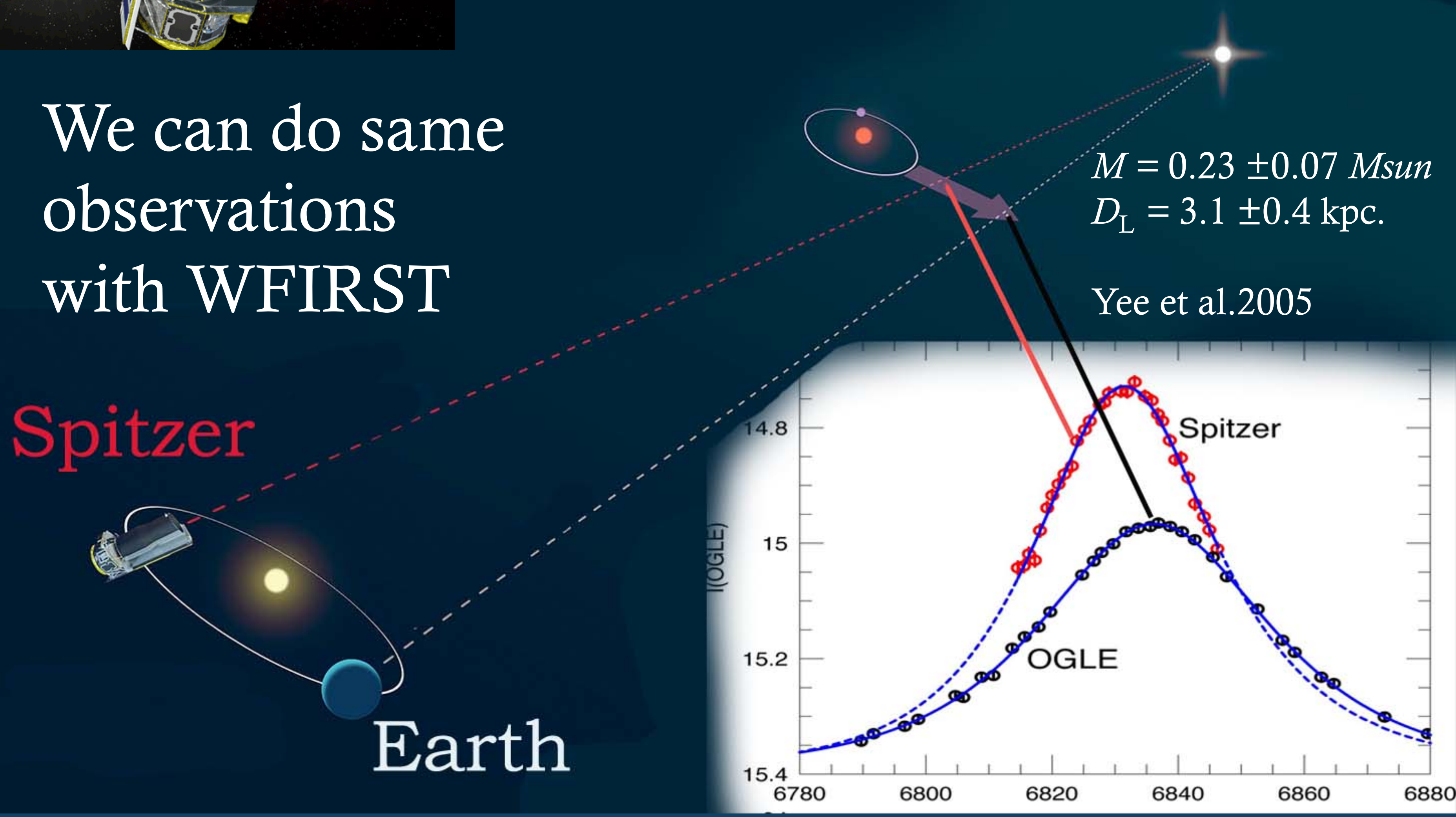


Event rate vary by a factor of 2 (peak is at l=1°)



Simultaneous Ground-Space monitoring with Spitzer

We can do same observations with WFIRST



Projected Einstein Radius

Earth-L2 separation.~0.01AU

Table 3. Projected physical Einstein radius $\tilde{r}_E$ [AU] for a grid of $(D_\ell, M_\ell)^a$

Lens Type	$\boldsymbol{M_\ell}$ **[$\boldsymbol{M_\odot}$]**	$\boldsymbol{D_\ell}$ **[kpc]**						
		1.0	2.0	3.0	4.0	5.0	6.0	7.0
Black hole	10	9.64	14.73	19.76	25.51	32.93	44.18	67.49
G Dwarf	1	3.05	4.66	6.25	**8.07**	10.41	13.97	21.34
M Dwarf	0.3	1.67	2.55	3.42	**4.42**	5.70	7.65	11.69
M Dwarf	0.1	0.96	1.47	1.98	2.55	3.29	4.42	6.75
Brown Dwarf	0.01	0.30	0.47	0.62	0.81	1.04	1.40	2.13
Jupiter	0.001	0.10	0.15	0.20	0.26	0.33	0.44	0.67

Conceptual Themes for the 2017 Sagan Summer Workshop

[a] Assuming a source star distance of $D_s = 8$ kpc.

WFIRST+PRIME can constrain the mass of FFP by space-base parallax

Summary

- Mricrolensing can detect Free-Floating planets
- Giant Free-floating planets are less than 1/4 of main sequence stars. (OGLE)
- Earth/Super Earth mass FFP may be common (OGLE)
- They inform us not only the number of planets that survived in orbit, but also planets that formed earlier and scattered.

  →important for planetary formation theory

- WFIRST will detect
  - ~3000 bound exoplanets with ~200 w/ $M < 1\ M_{\oplus}$,
  - ~2000 Free-floating planets with ~100 w/ $M < 1\ M_{\oplus}$
  - Constrain Mass of FFP by space-base parallax with PRIME