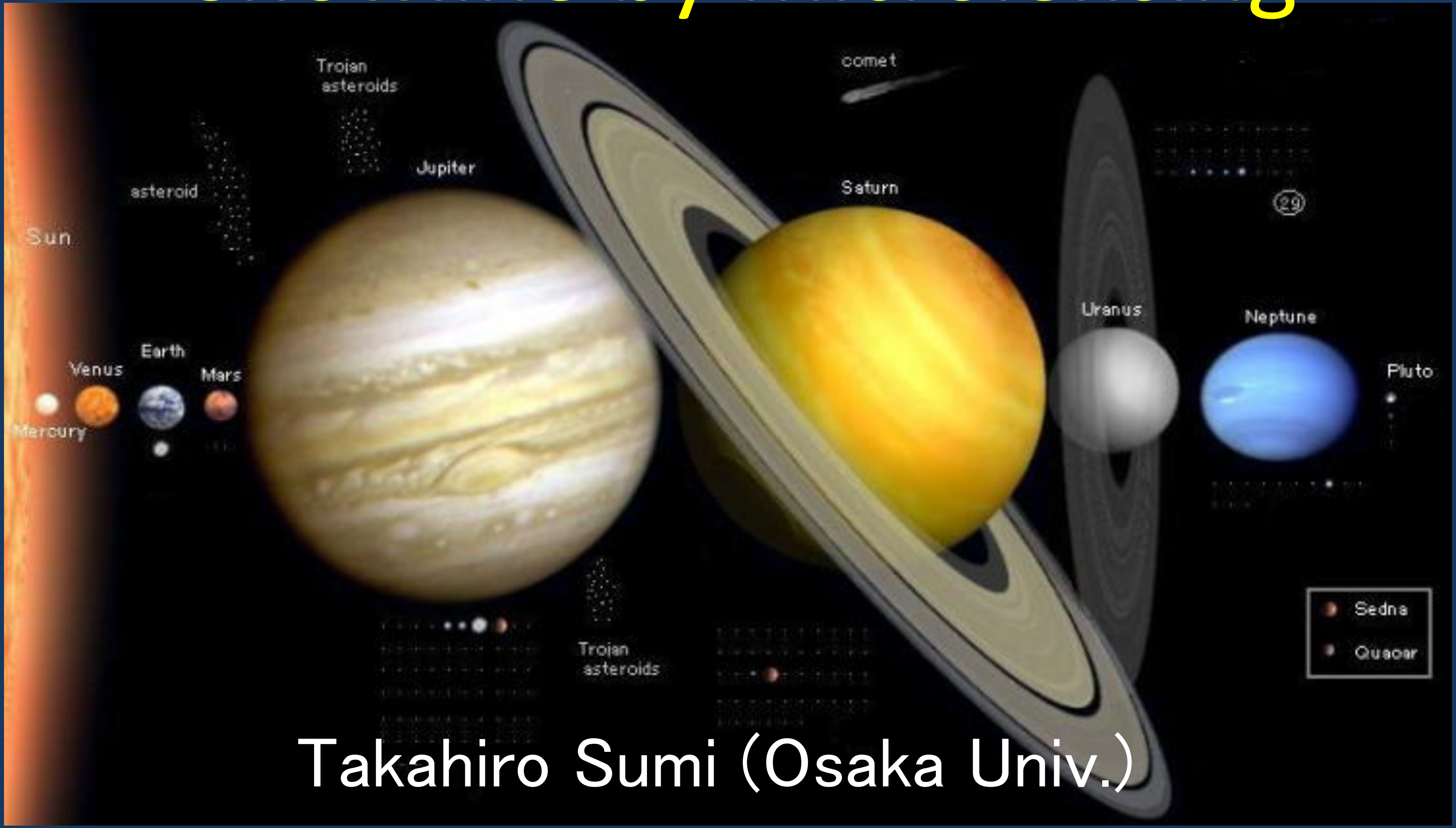
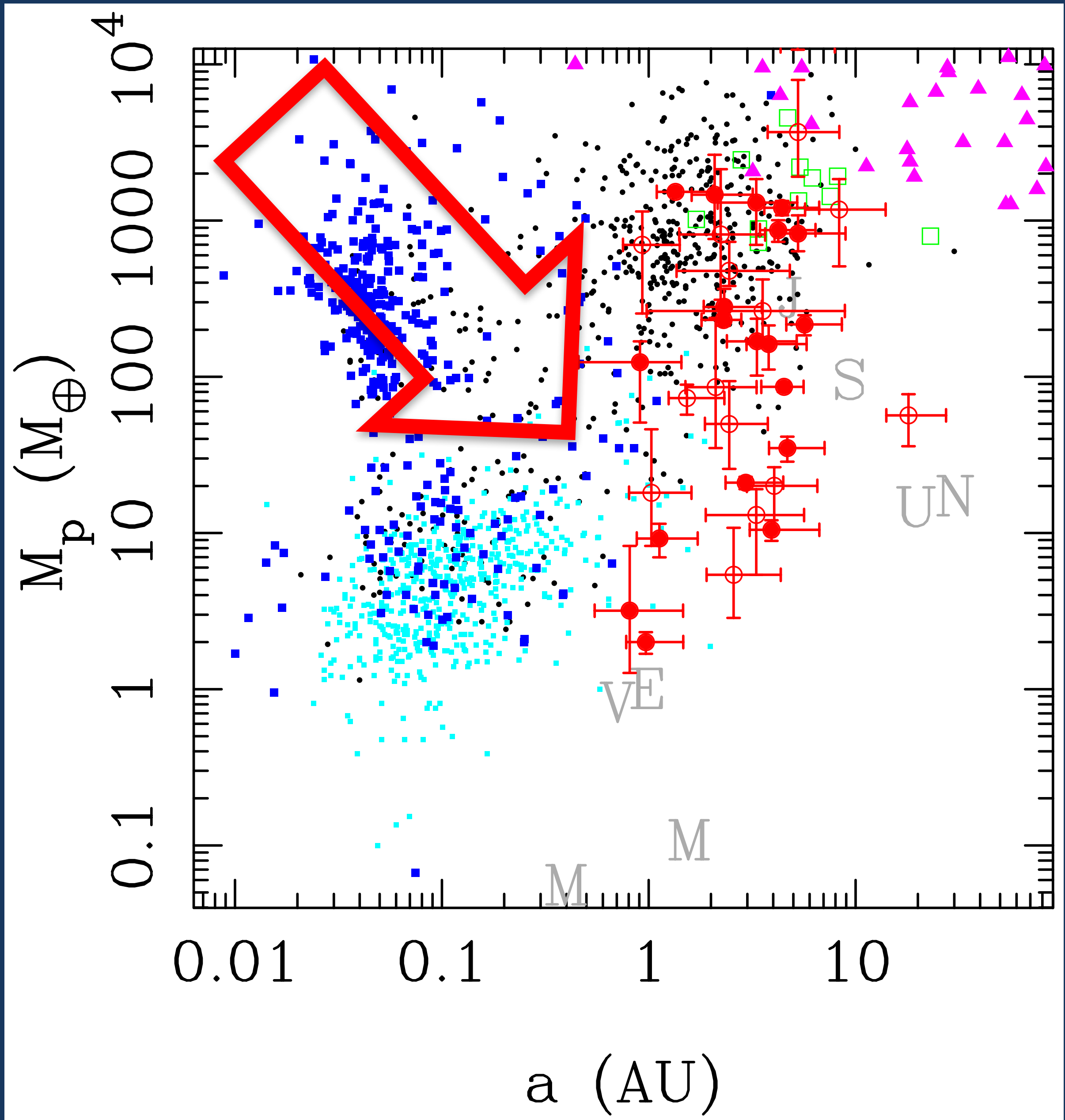
Planet distribution outside Snowline by Microlensing



Takahiro Sumi (Osaka Univ.)

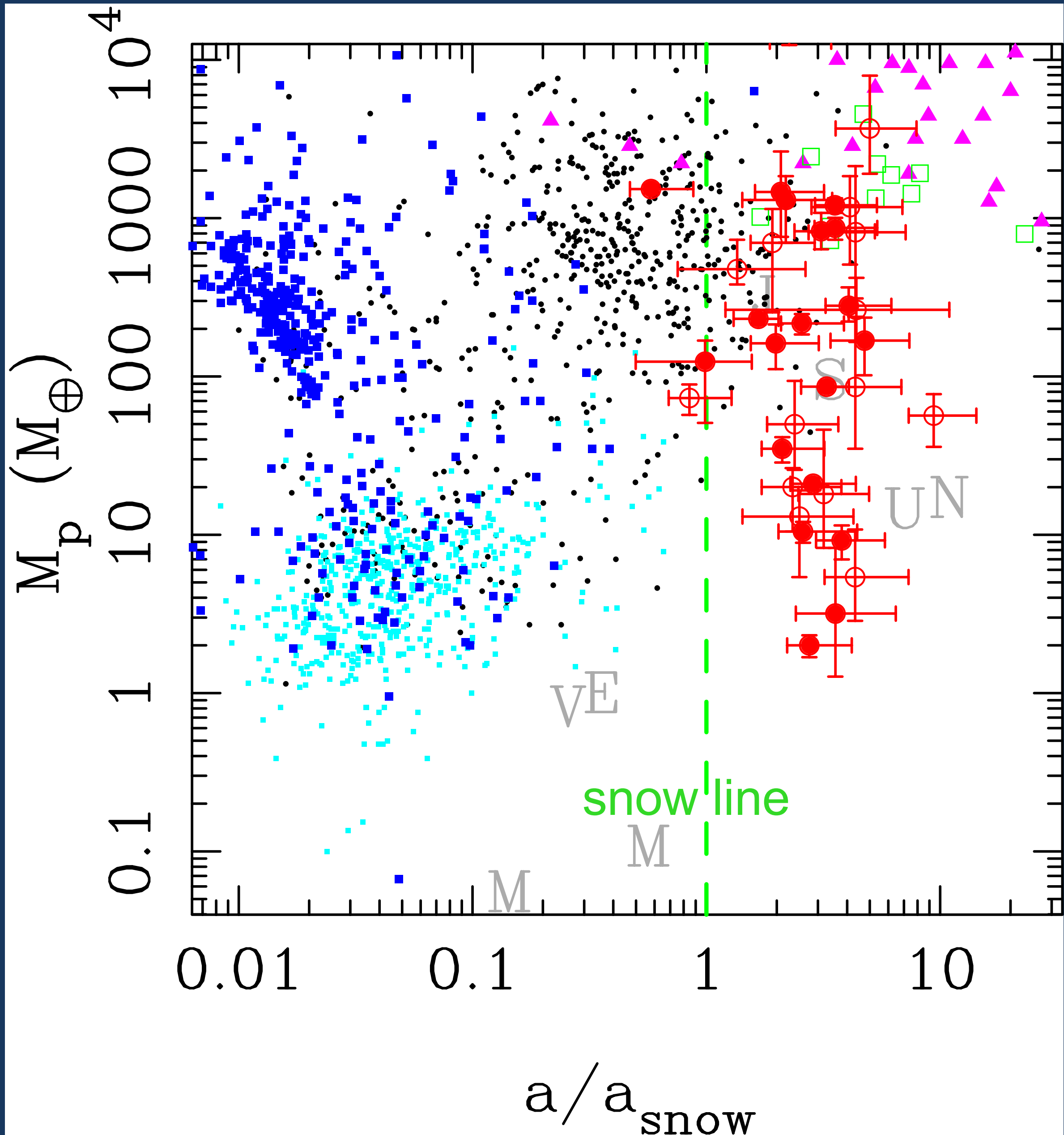
RESCEU/Planet International Symposium "Planet Formation around Snowline" @U Tokyo 2017/11/28

Discovered exoplanets (M_p-a)



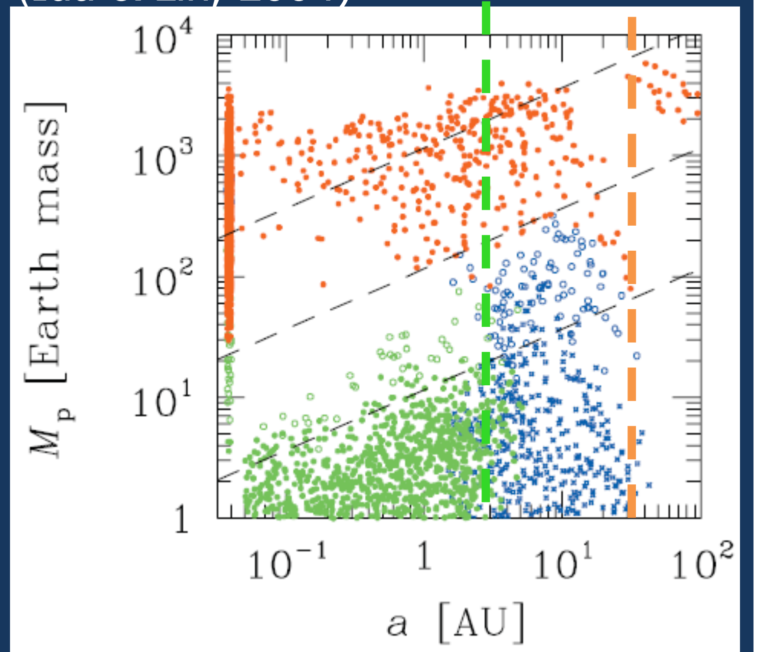
- RV
- Transit (Kepler)
- Direct image
- Microlensing
  - Mass measurements
  - Mass by Bayesian

Discovered exoplanets (M_p-a/a_{snow})

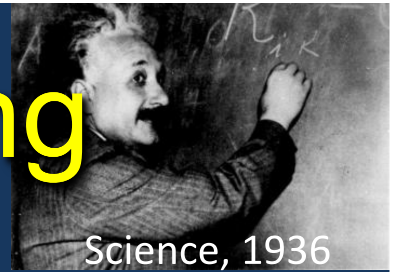


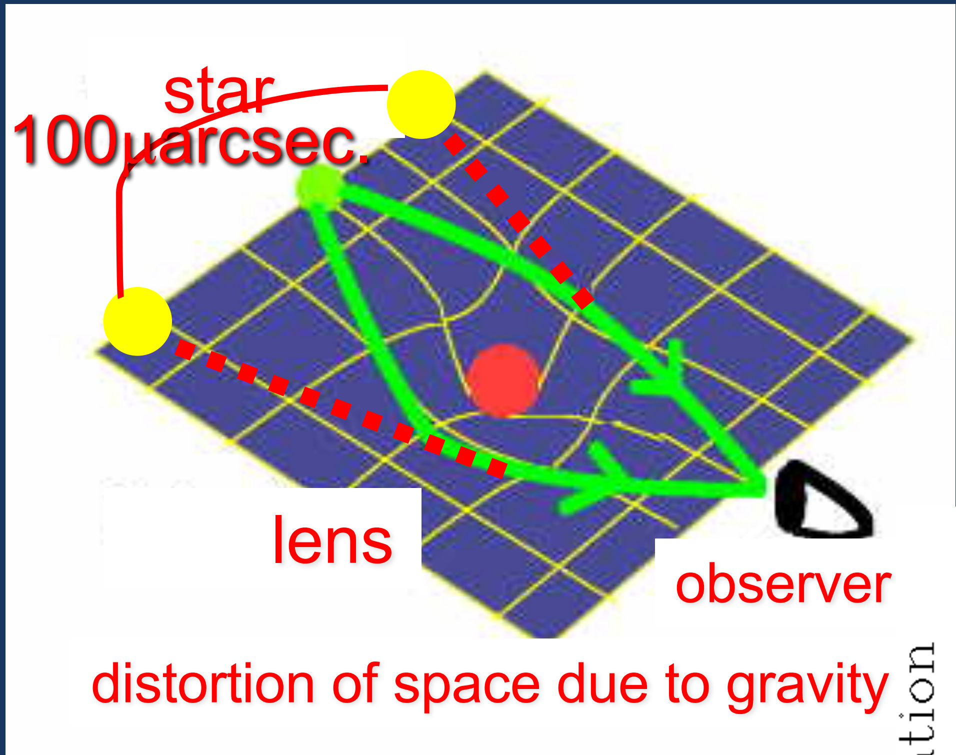
- RV
- Transit (Kepler)
- Direct image
- Microlensing
  - ● Mass measurements
  - ○ Mass by Bayesian

Theory
(Ida & Lin, 2004) 、snow line $10a_{snow}$



Gravitational Microlensing

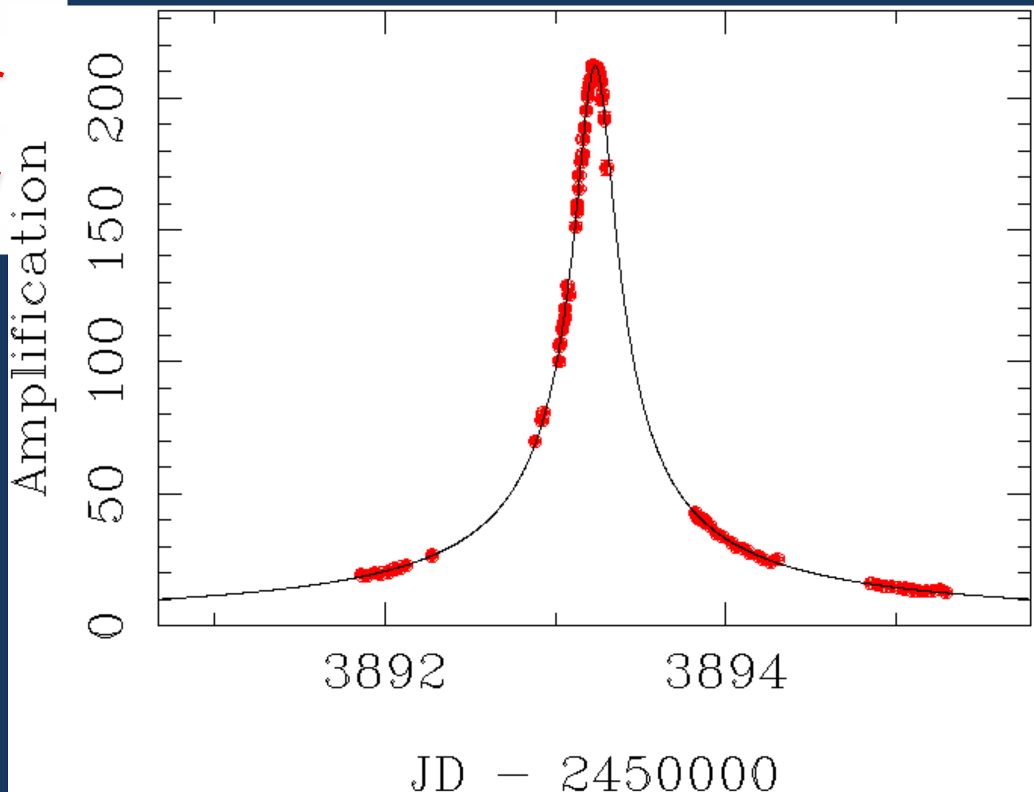




✧If a lens is a star, elongation of images is an order of 100μarcsec.

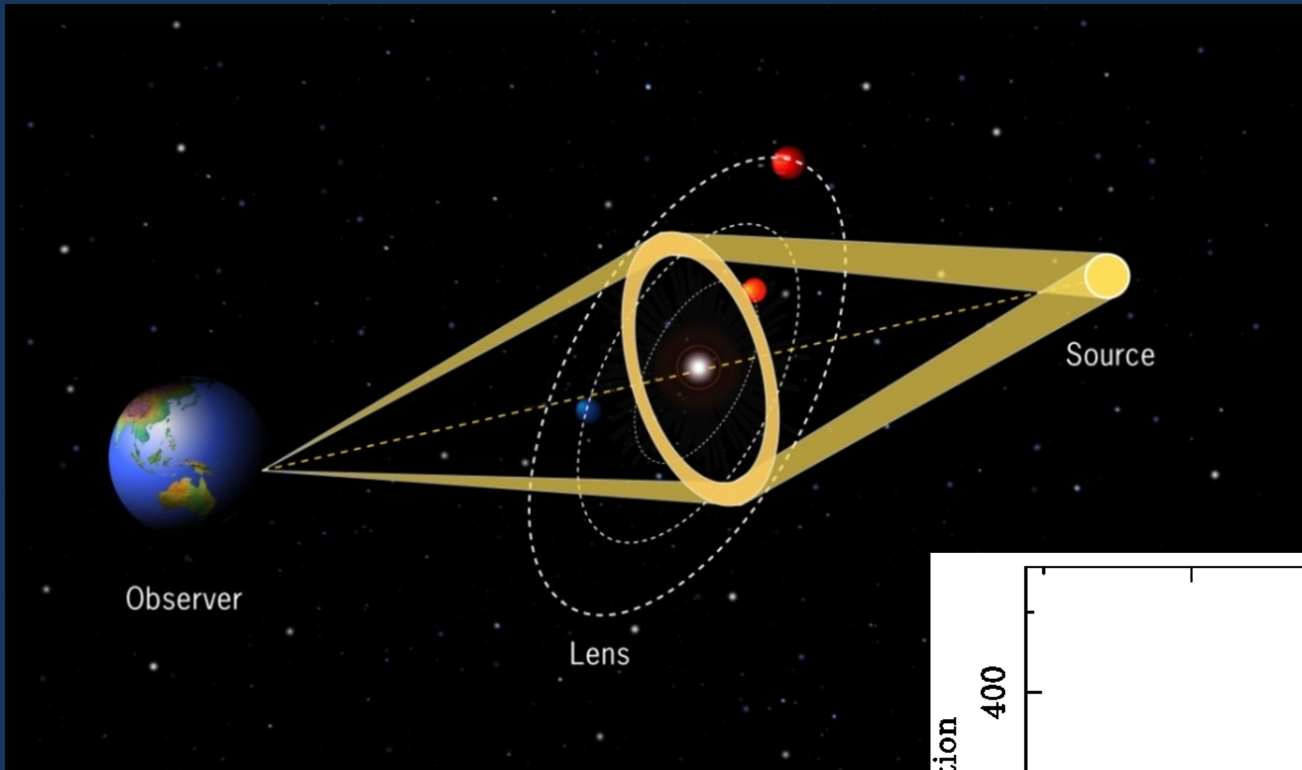
✧Just see a star magnified

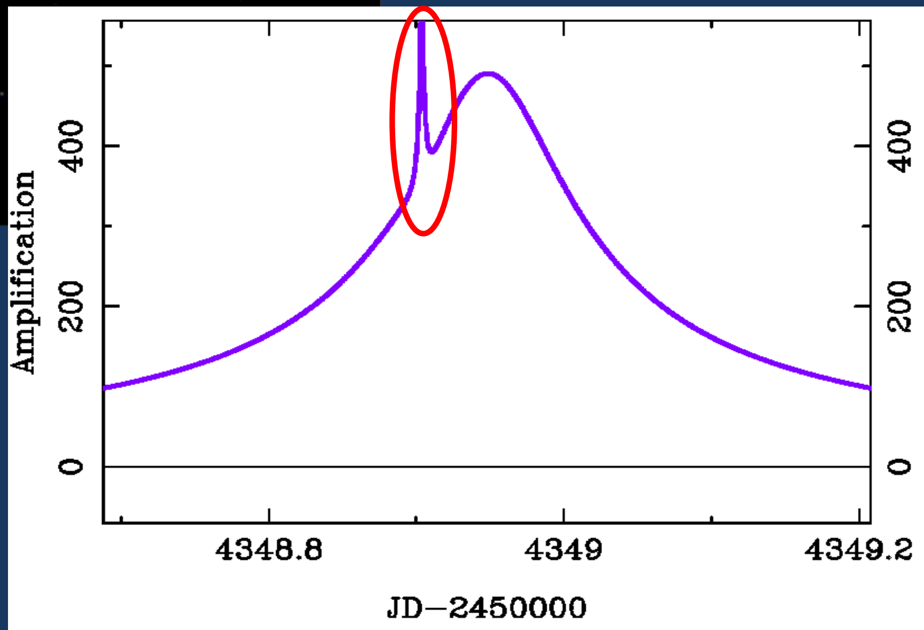
✧Einstein predicted 1936, but concluded impossible to observe. Event rate is 1/1M



- 1986
  Watch Millions stars
  Paczynski

planetary microlensing

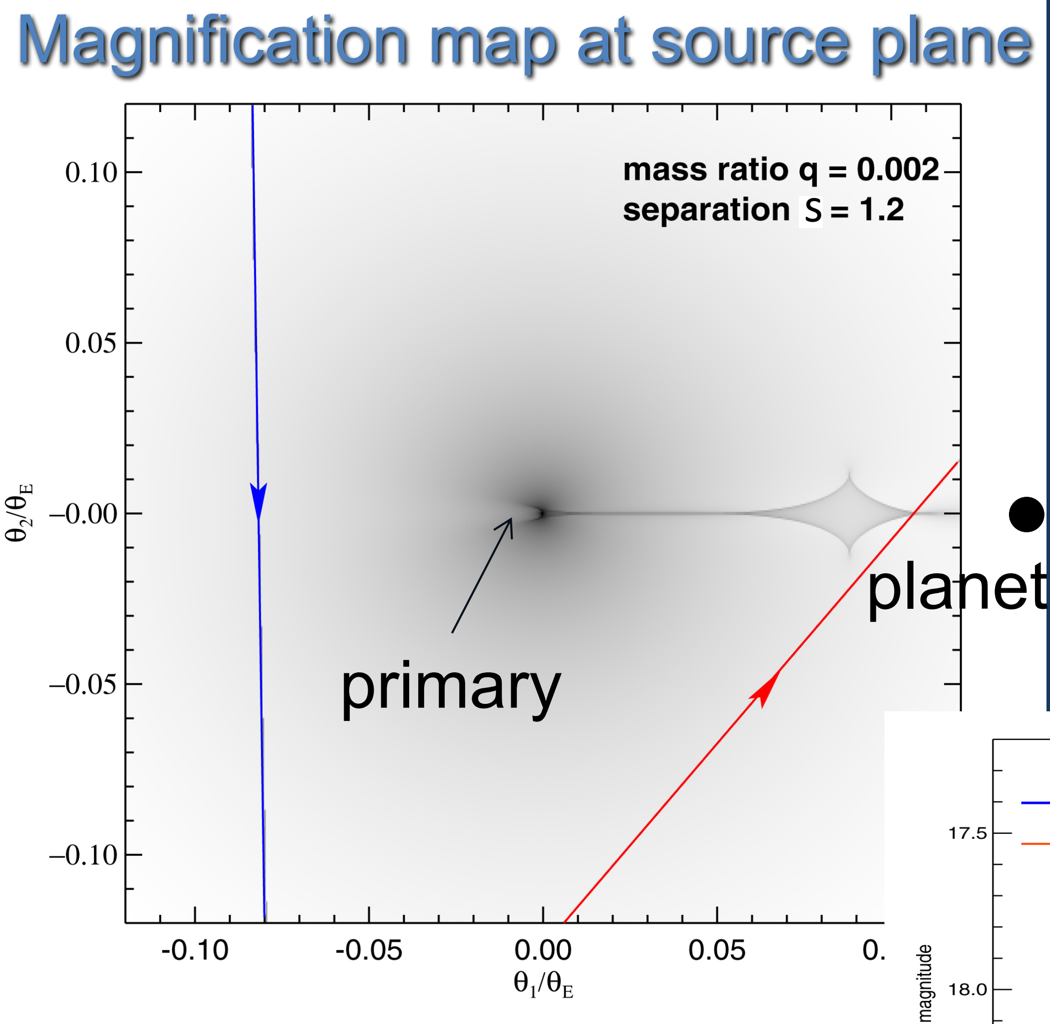




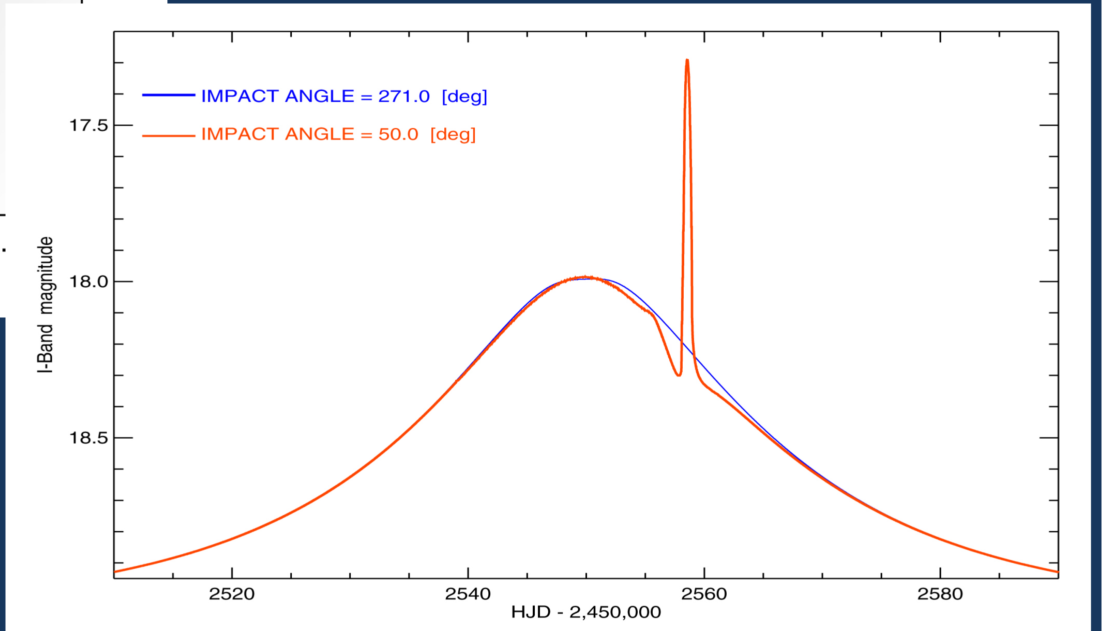
Time scale: $t_p \sim M^{1/2} \sim 1 \mathrm{day}(M_J)$

Sensitive to Cold planets outside of snowline ($\sim 3a_{snow}$)

How to detect/miss a planet orbiting a microlens star



low−mass planet signals are rare and brief,
but not weak→
Need large sample with moderate precision, high cadence

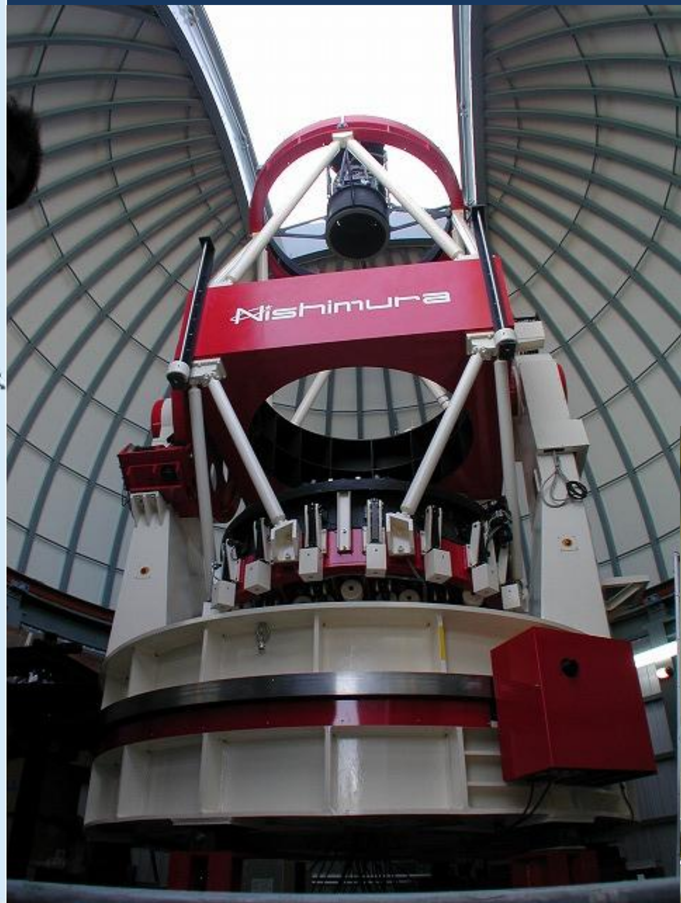


Light curve modeling give us
mass ratio: $q=M_p/M_*$
Projected separation: s (R_E)

MOA (since 1995)

(Microlensing Observation in Astrophysics)

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

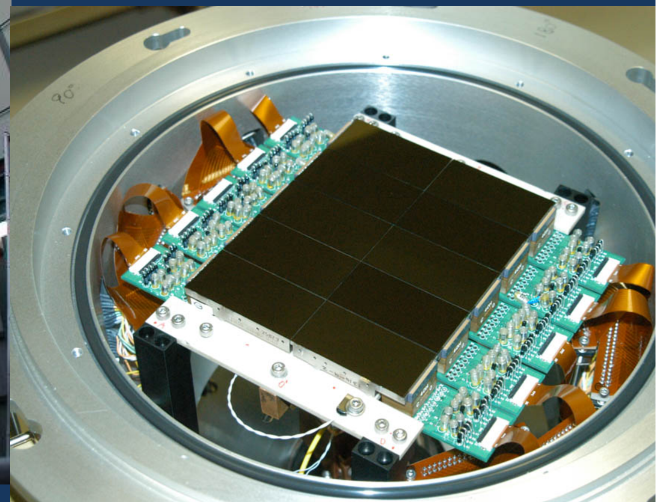


Mirror : 1.8m

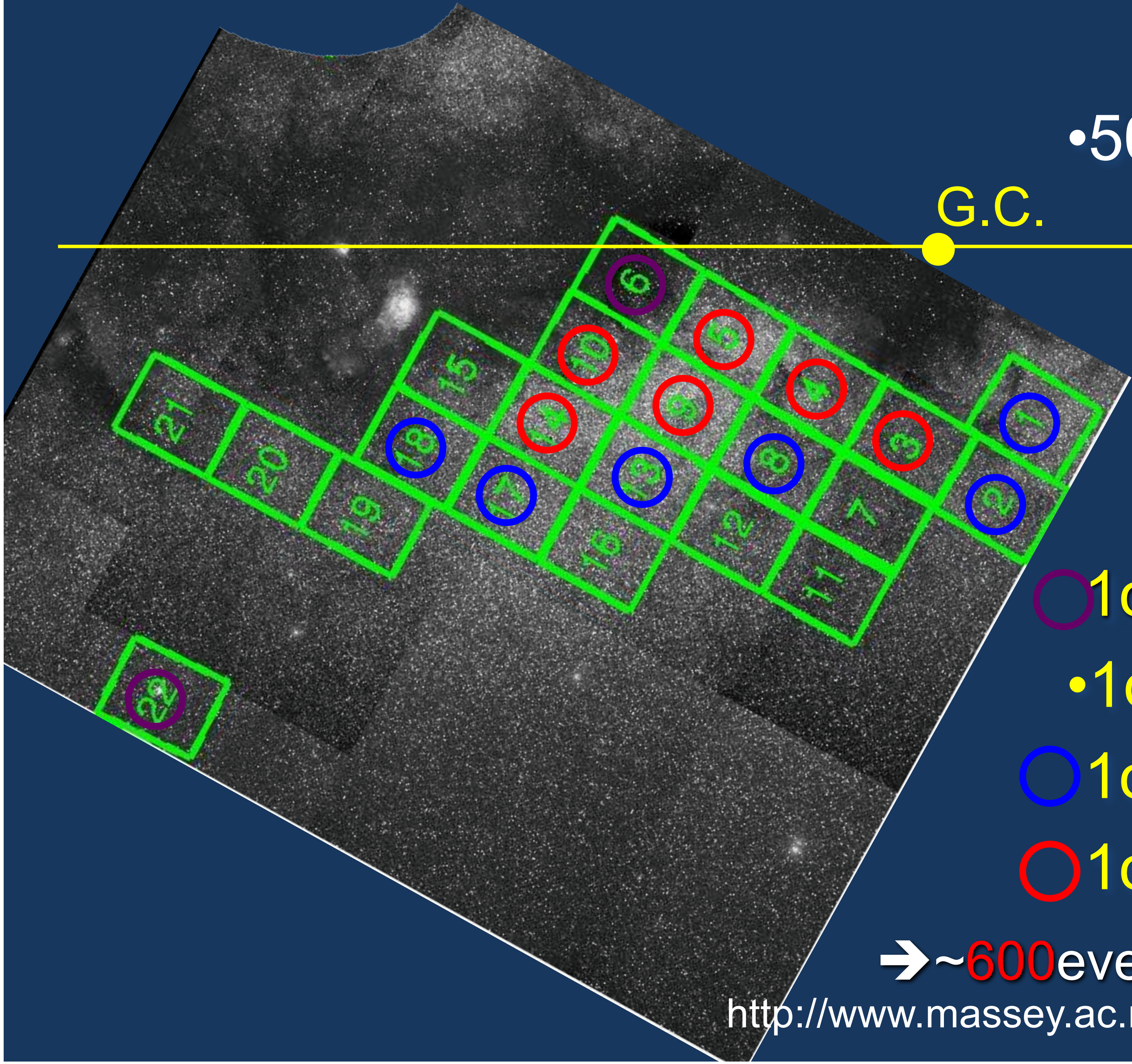
CCD : 80M pix.

FOV : 2.2 deg.^{2}

cadence: 15-50 min.



Observation by MOA



- 50 deg.^{2}(20Mstars)

- ○ 1obs./night.(>M_{Jup})
- •1obs./95min.(M_{jup})
- ○ 1obs./47min. (M_{nep})
- ○ 1obs./15min. ($M_{\oplus}$)

➔~600events /yr

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

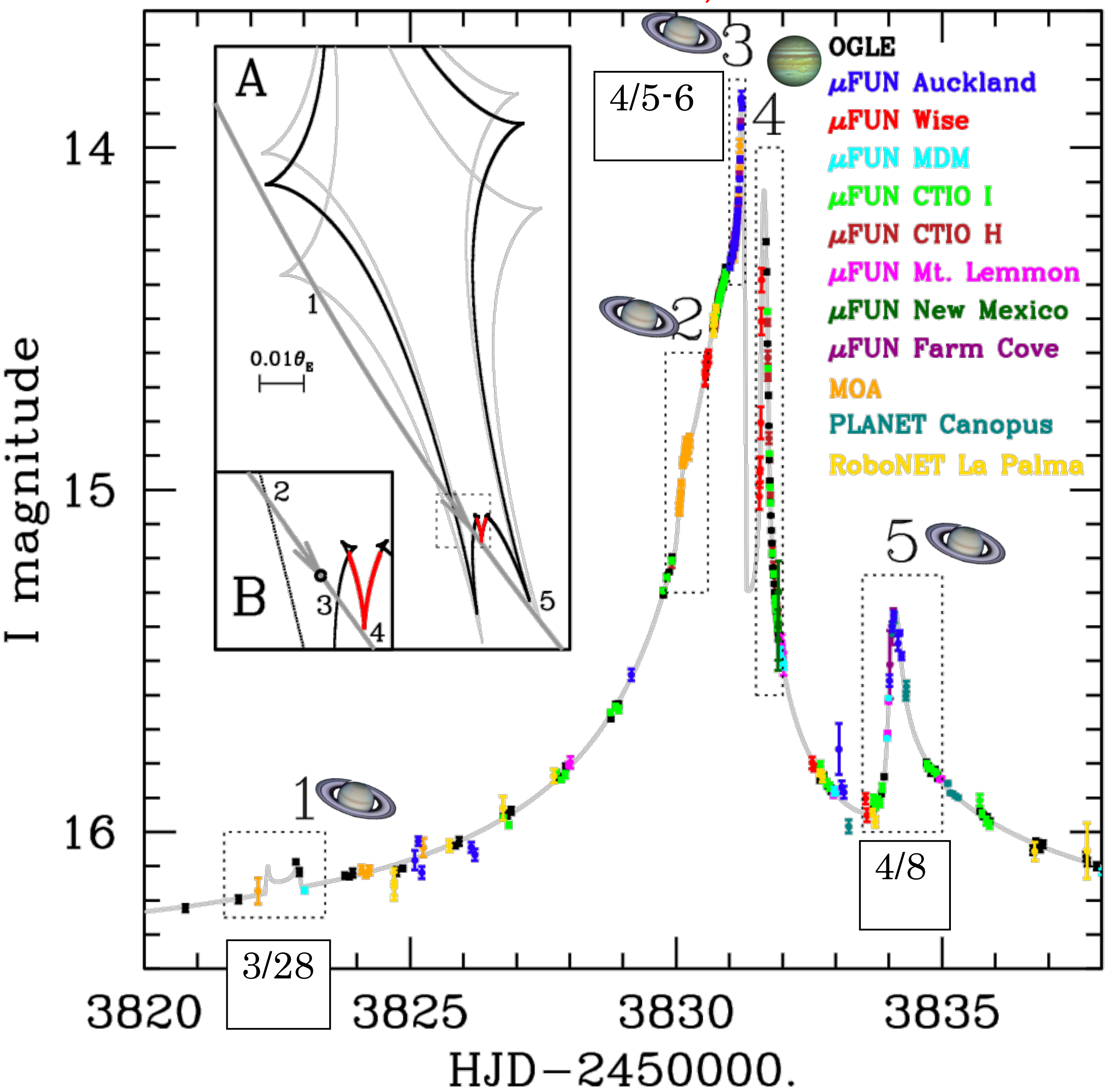
Jupiter/Saturn analog : OGLE-2006-BLG-109L

- 5 distinct planetary features
- Feature #4 requires an additional planet
- Half size of Sun/Jupiter/Saturn in terms of mass & separation

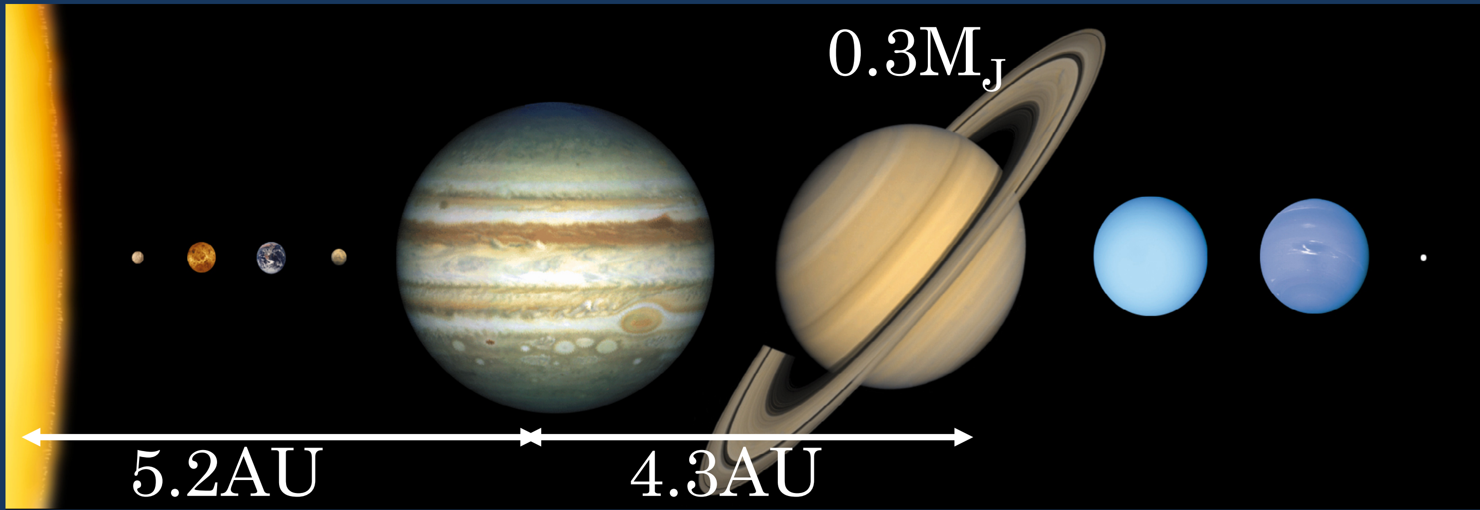
constrains four and weak constrain 5th of the six parameters that are needed to describe the planetary orbit.

TMT, EELT may confirm by RV

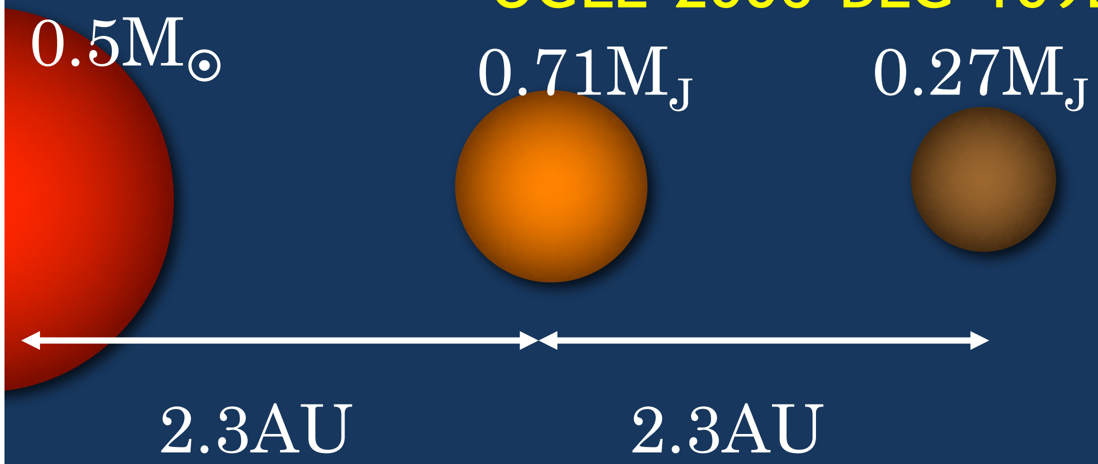
Gaudi et al. 2008, Bennett et al. 2010



Comparison to solar Jupiter/Saturn



OGLE-2006-BLG-109L



$m_b/M_* = 1.35\text{x}10^{-3}$, ($M_j/M_\odot = 1\text{x}10^{-3}$)

$m_c/m_b = 0.37$, ($m_s/m_j = 0.3$)

$a_b/a_c = 0.50$, ($a_j/a_s = 0.55$)

$T_b = 85K$ ($\sim 0.7 \times T_J$)

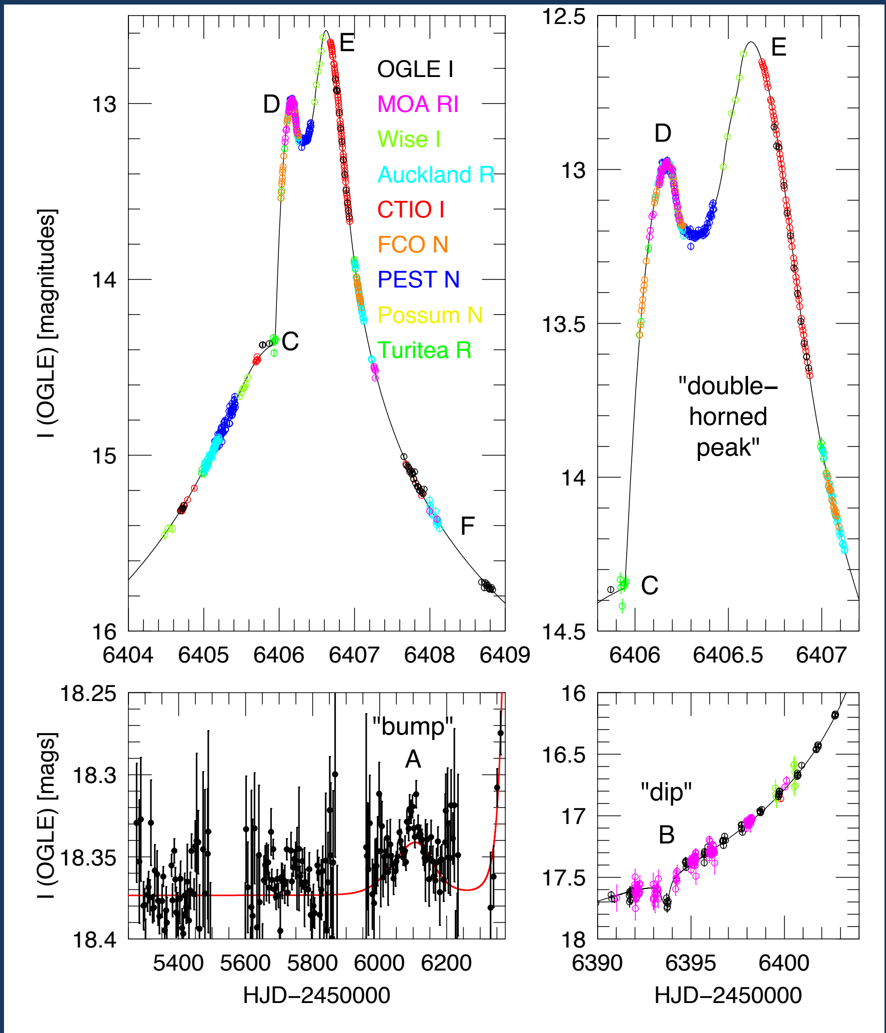
$T_c = 60K$ ($\sim 0.7 \times T_S$)

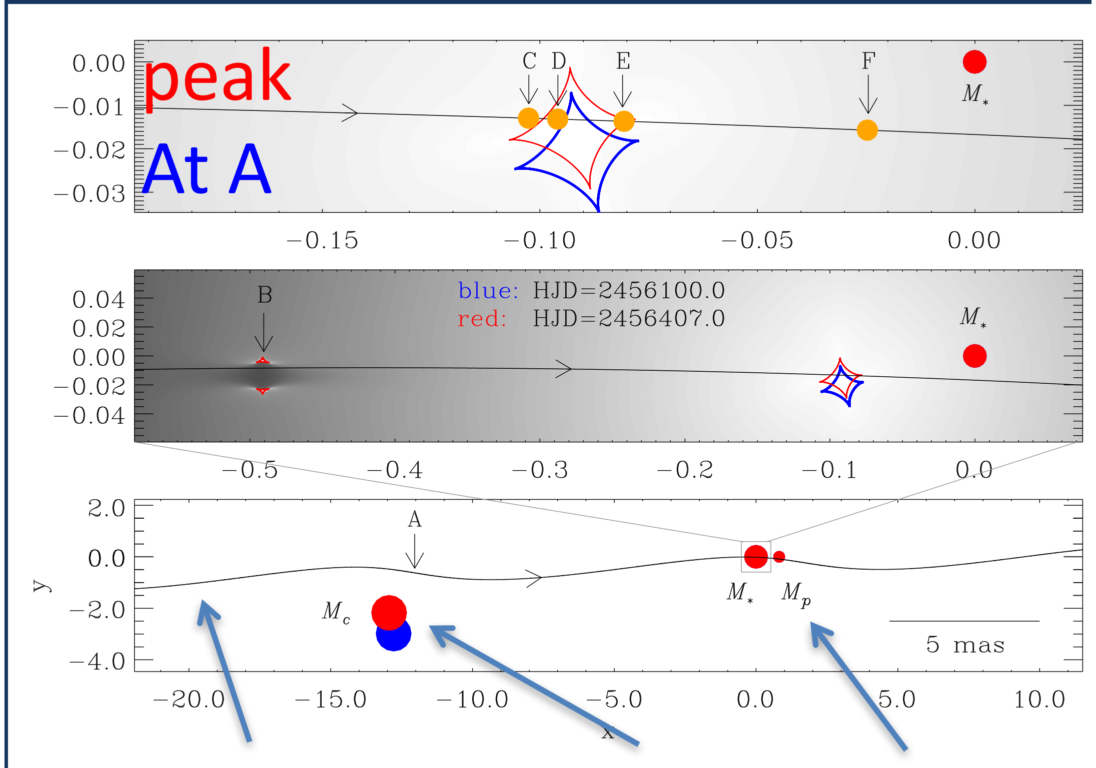
1.7 Earth-mass planet in a binary system

OGLE-2013-BLG-0341/MOA-2013-BLG-260

D_l=911.00±0.07kpc
M_c=0.121±0.009$M_\odot$
M_h=0.113±0.009$M_\odot$
M_p=1.66±0.18 M_E
a=0.70±0.02AU

Gould+2014





Source trajectory

companion

Planetary system

Linear approximation of orbit

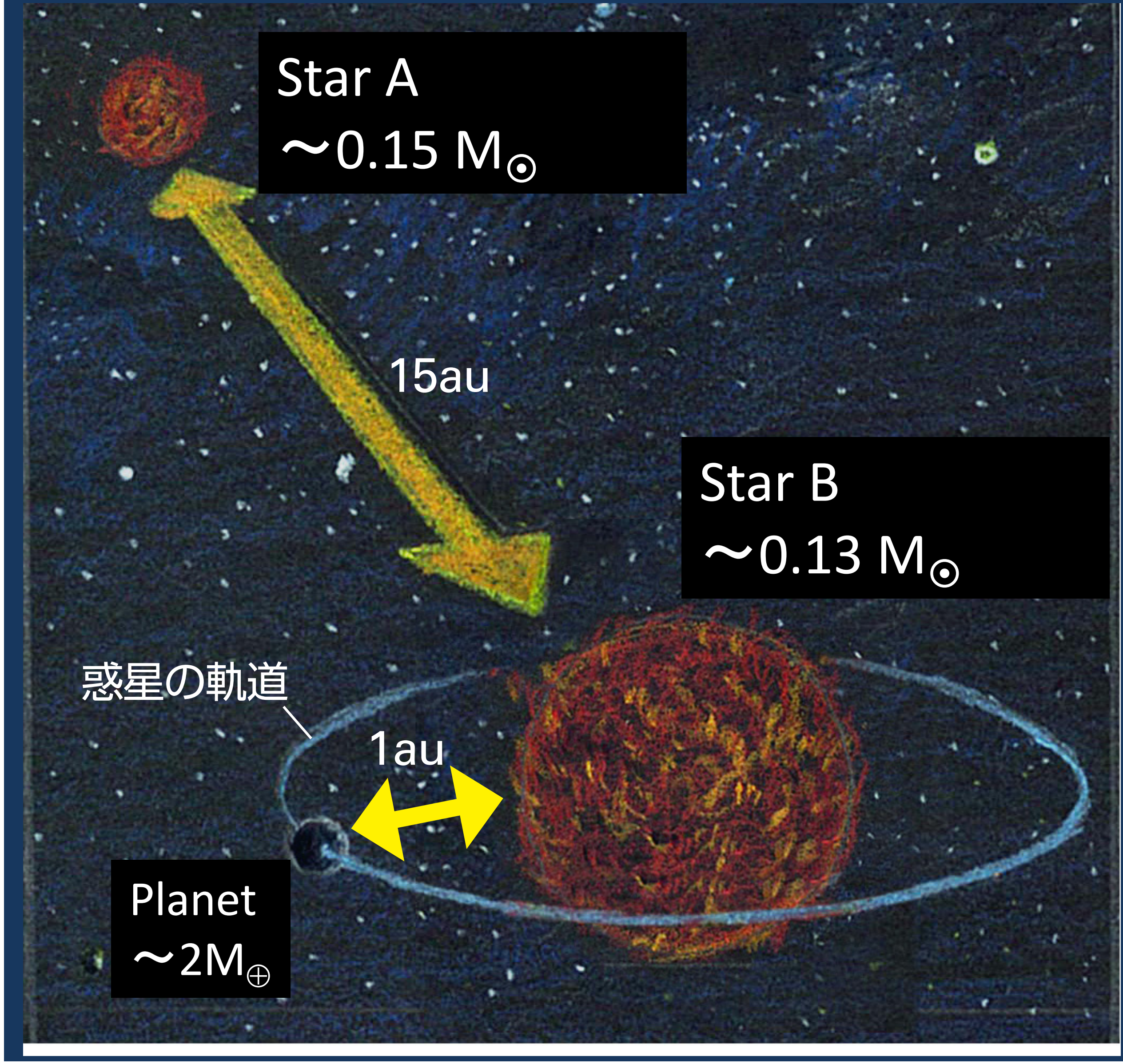
$\alpha(t)=\alpha_0+d\alpha/dt(t-t_{fix})$

$s(t)=s_0 \quad +ds/dt(t-t_{fix})$

$$\left(\frac{KE}{PE}\right)_\perp = \frac{(r_\perp/\mathrm{AU})^3}{8\pi^2(M/M_\odot)}\left[\left(\frac{1}{s}\frac{ds}{dt}\right)^2+\left(\frac{d\alpha}{dt}\right)^2\right]$$ <1 to be bound

2 Earth-mass planet at 1 AU

OGLE-2013-BLG-0341 /MOA-2013-BLG-260

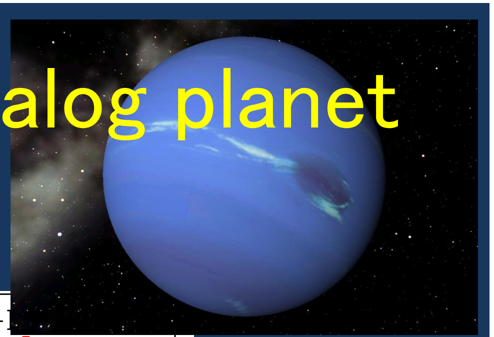


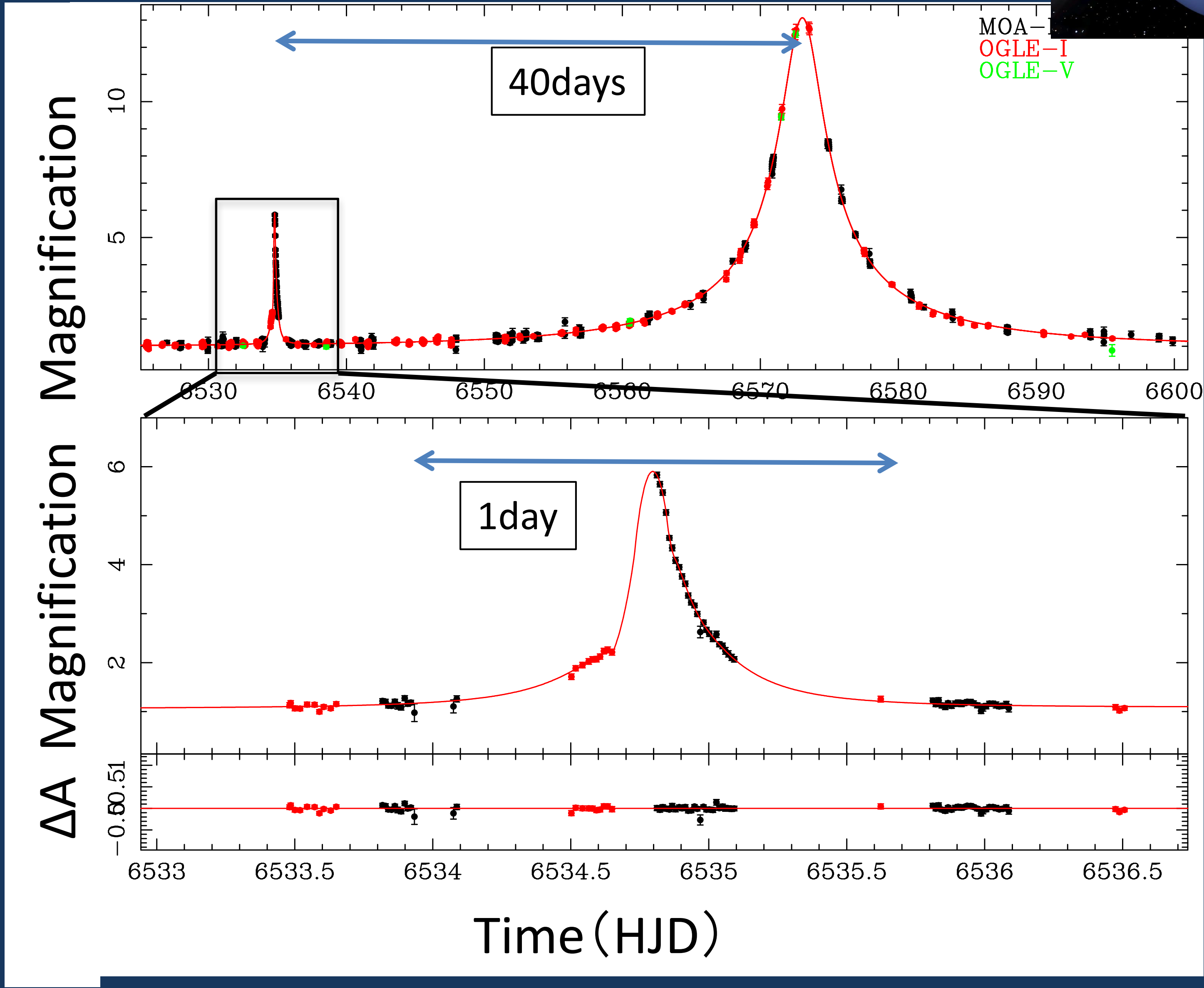
However, planet temperature is much lower, T < 60 K, because the host star is only 0.13±0.03 $M_\odot$, 400 times less luminous than the Sun.

MOA-2013-BLG-605: the Neptune analog planet

$q=3\times10^{-4}$, $s=2.3$,

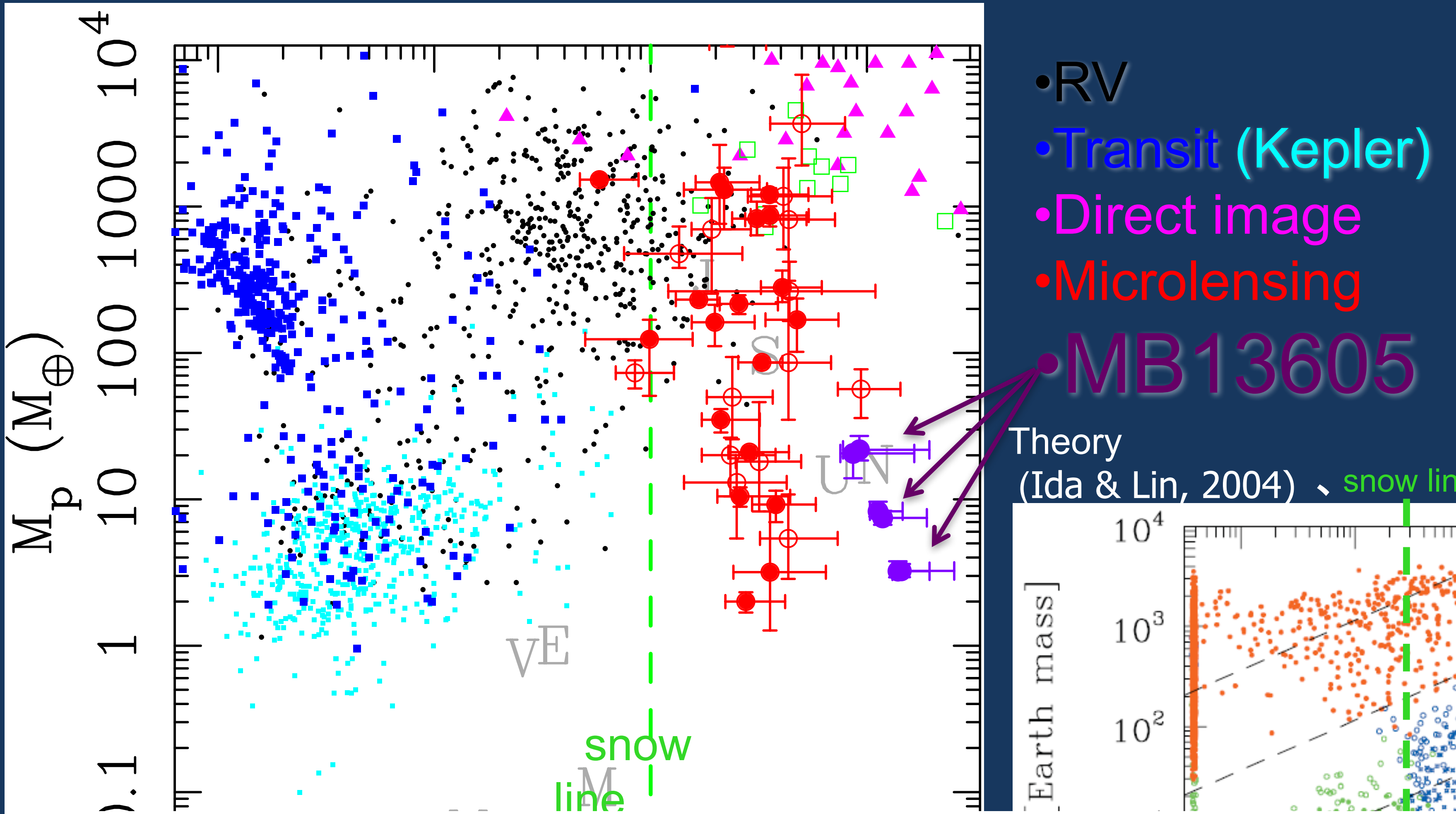
Neptune or super Earth around Brown-dwarf



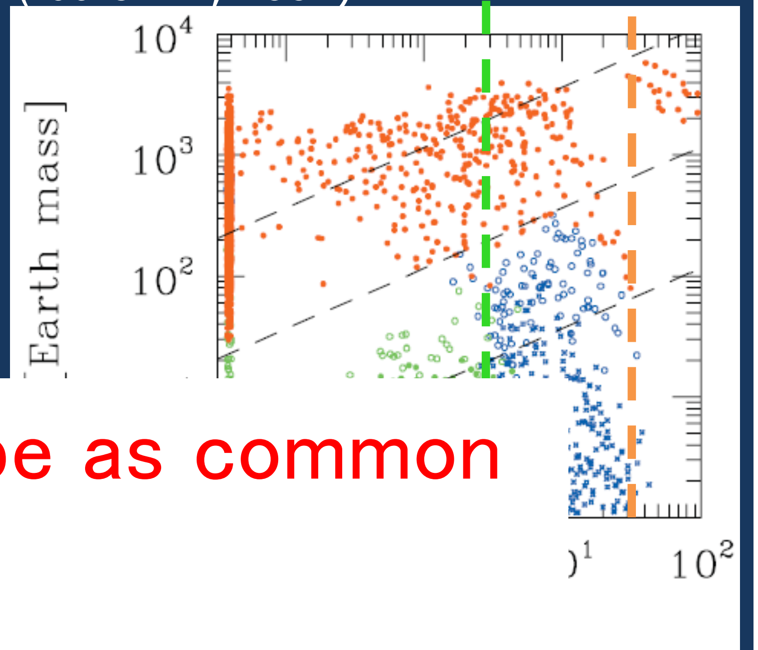


TS+2016

Discovered exoplanets (M_p-a/a_{snow})



Theory (Ida & Lin, 2004) 、snow line $10a_{snow}$



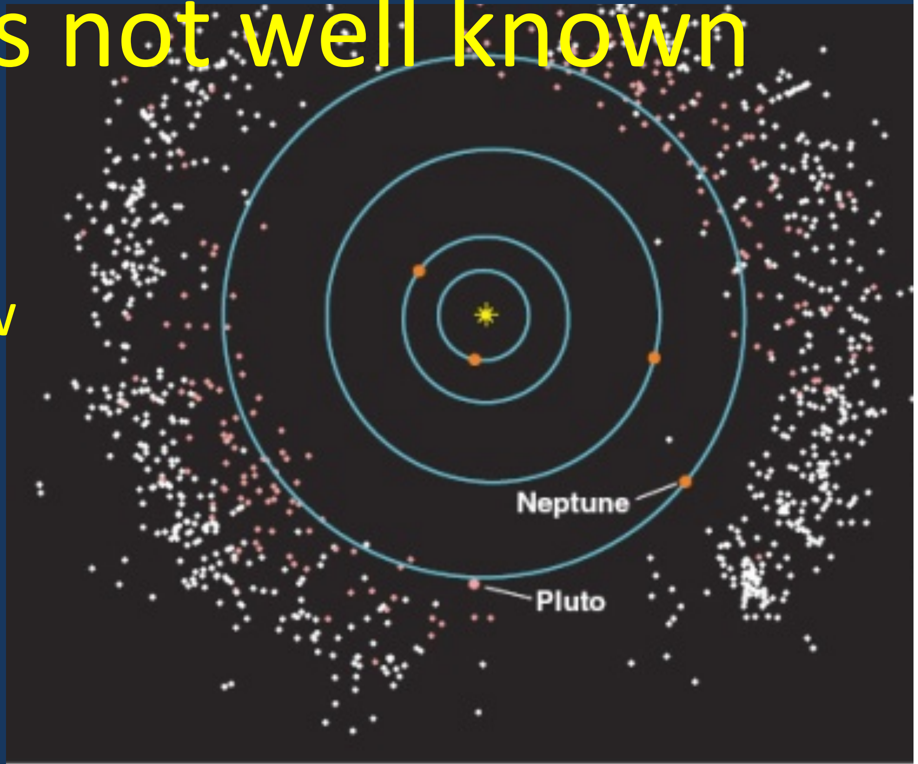
neptunes at a～$10a_{snow}$ could be as common as ones at a～$3a_{snow}$

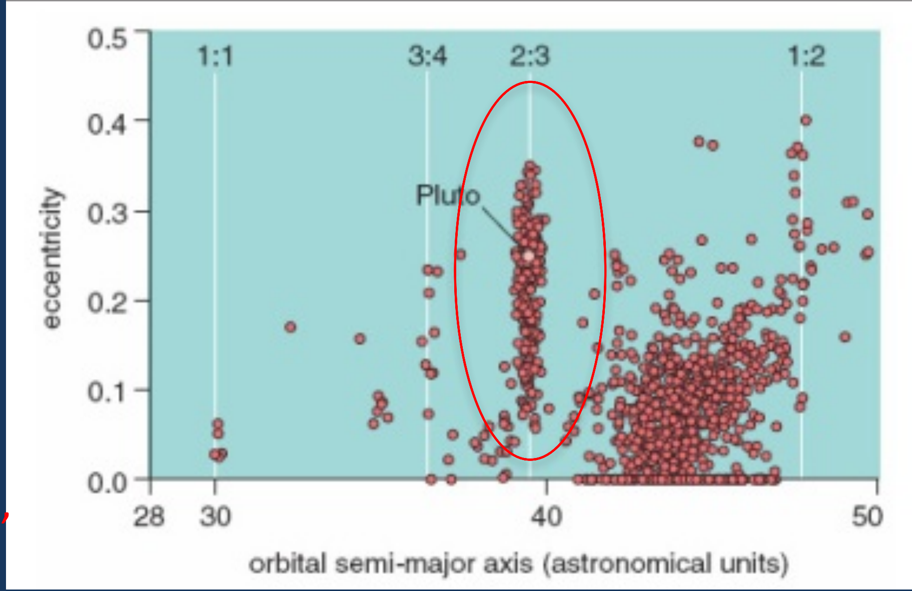
Neptune formation is not well known

- Core accretion model cannot form ice giants like Uranus and Neptune at their current positions due to low density of planetesimals and slow evolution in these orbits (Pollack et al. 1996)

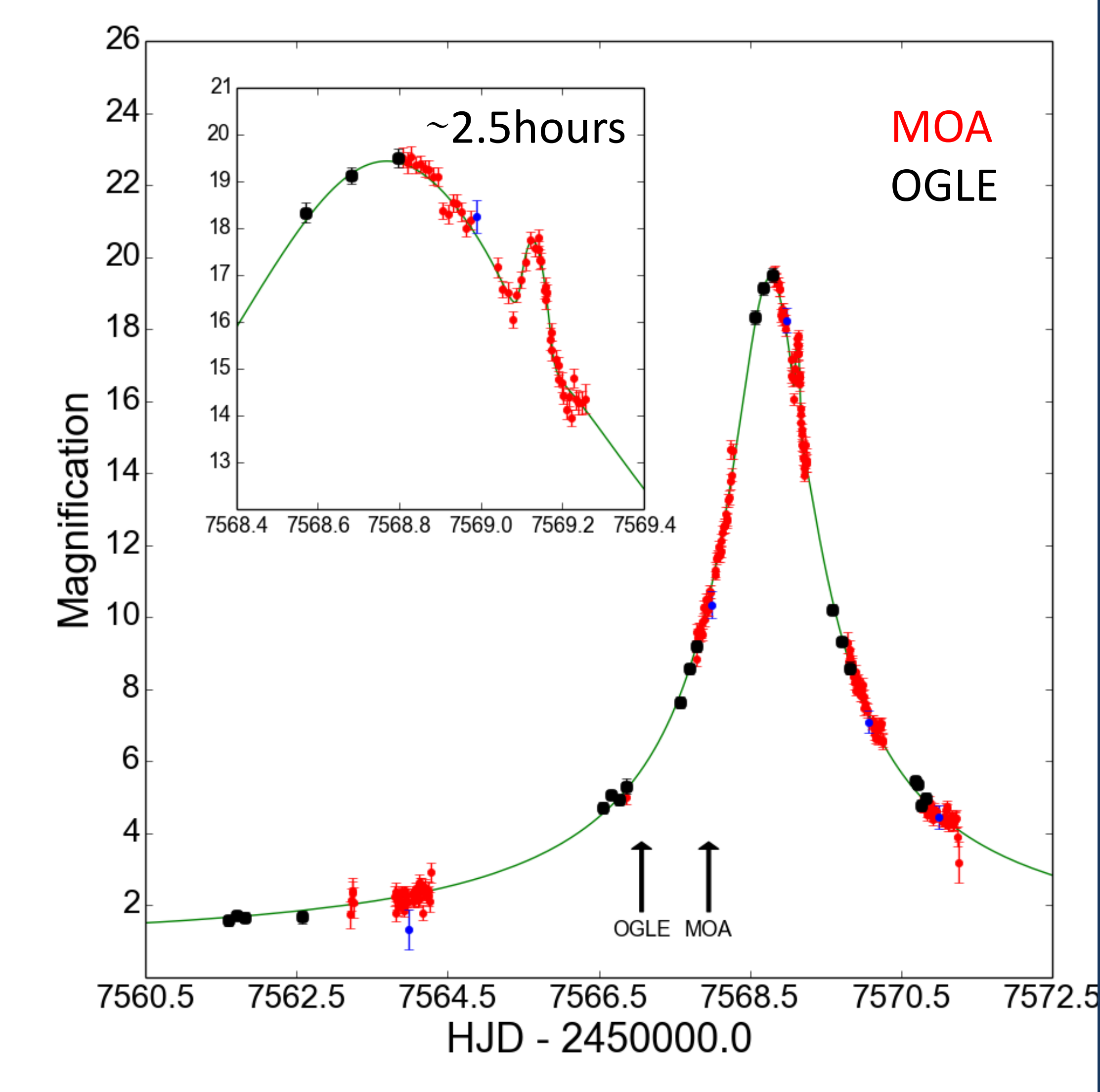
- Uranus/Neptune formed in the Jupiter-Saturn region and migrated

- Neptune should have moved 23AU→30AU to explain orbit of plutinos which are TNO in 2:3 resonance with Neptune. (Malhotra, R. 1993, The Origin of Pluto's Peculiar Orbit, Nature 365, 819)





The Lowest Mass Ratio Planetary Microlens: OGLE 2016-BLG-1195Lb



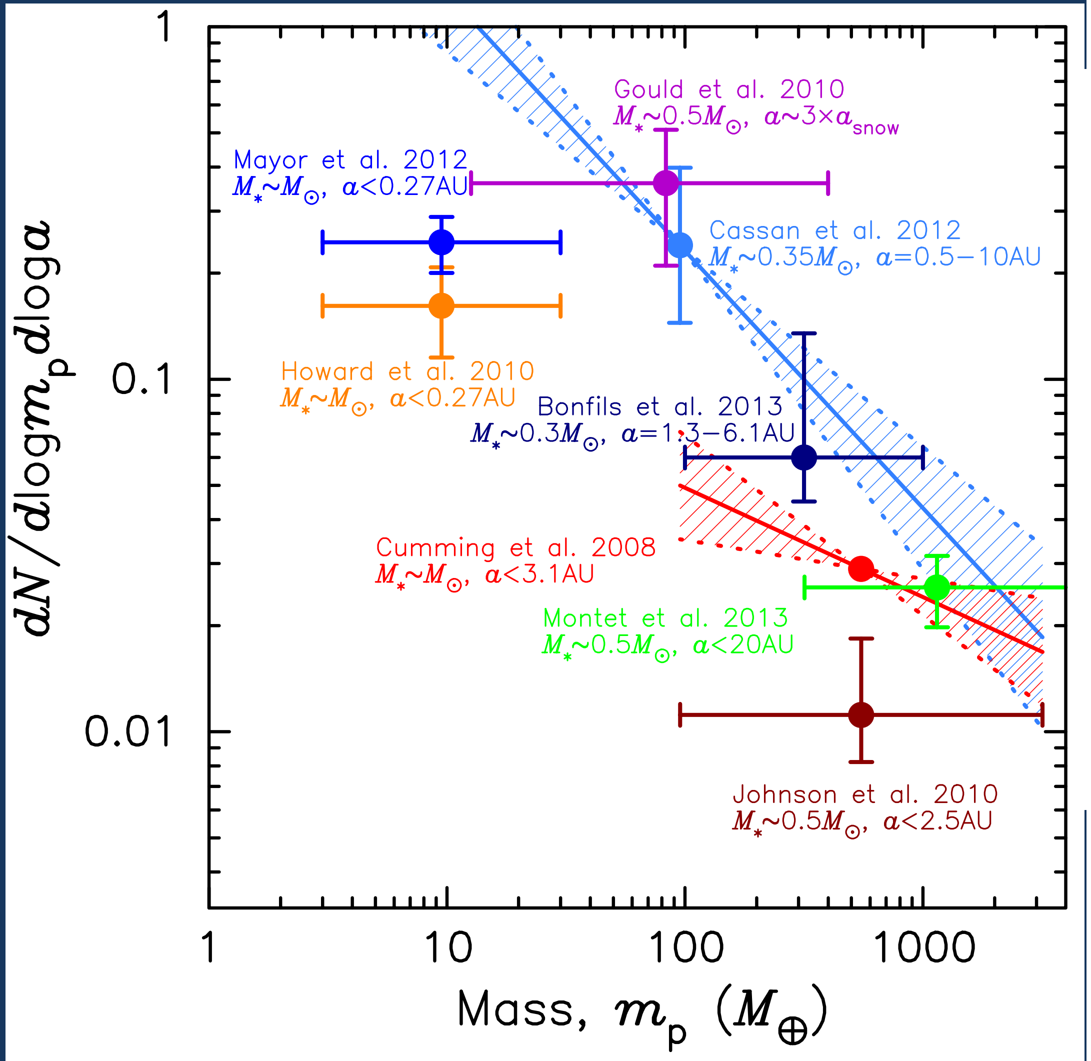
q=4.2±0.7×10−5
~3 $M_\oplus$ in
~2 AU wide orbit around
~ 0.2 $M_\odot$ star
at 7.1 kpc.(Bond+ 2017)

Combine Spitzer and
ground-based KMTNet
Earth-mass (1.32+0.41−0.28$M_\oplus$) planet
1.11+0.13−0.10 AU orbiting a round
0.072+0.014−0.010$M_\odot$ ultracool
dwarf, likely a brown dwarf.
at 4.20+0.29−0.34 kpc
(Shvartzvald+2017)

mass function from early microlensing results

#of planets used

- TS et al. 2010 (10)
  $f \propto q^{-0.68\pm0.2}$
- Gould et al. 2010 (6)
  0.36 ± 0.15 @ $q \sim 5\times10^{-4}$
- Cassan et al. 2012 (8)
  $10^{-0.62\pm0.22}(M/M_{Sat})^{-0.73\pm0.17}$



7x more cold Neptune than cold Jupiters.

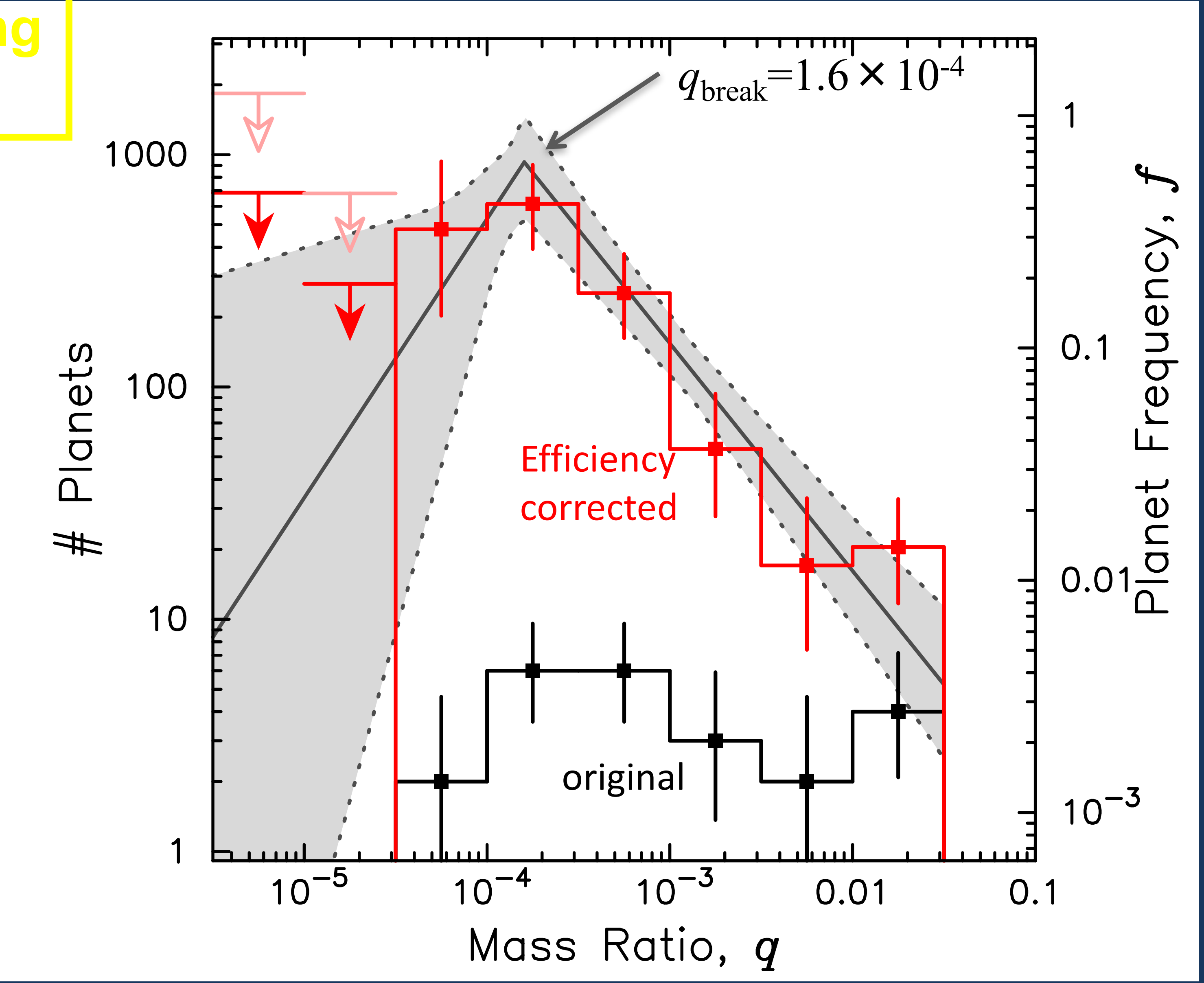
7x more planet than inner planets. (1 planet/tar.)

Efficiency Corrected mass ratio function

Suzuki+16

Full 30-event microlensing sample

- model with Broken power-law
- *Break at* q_{break}=1.6 × 10^{-4}
- Power of
-0.96 (q>q_{break})
0.94(q<q_{break})



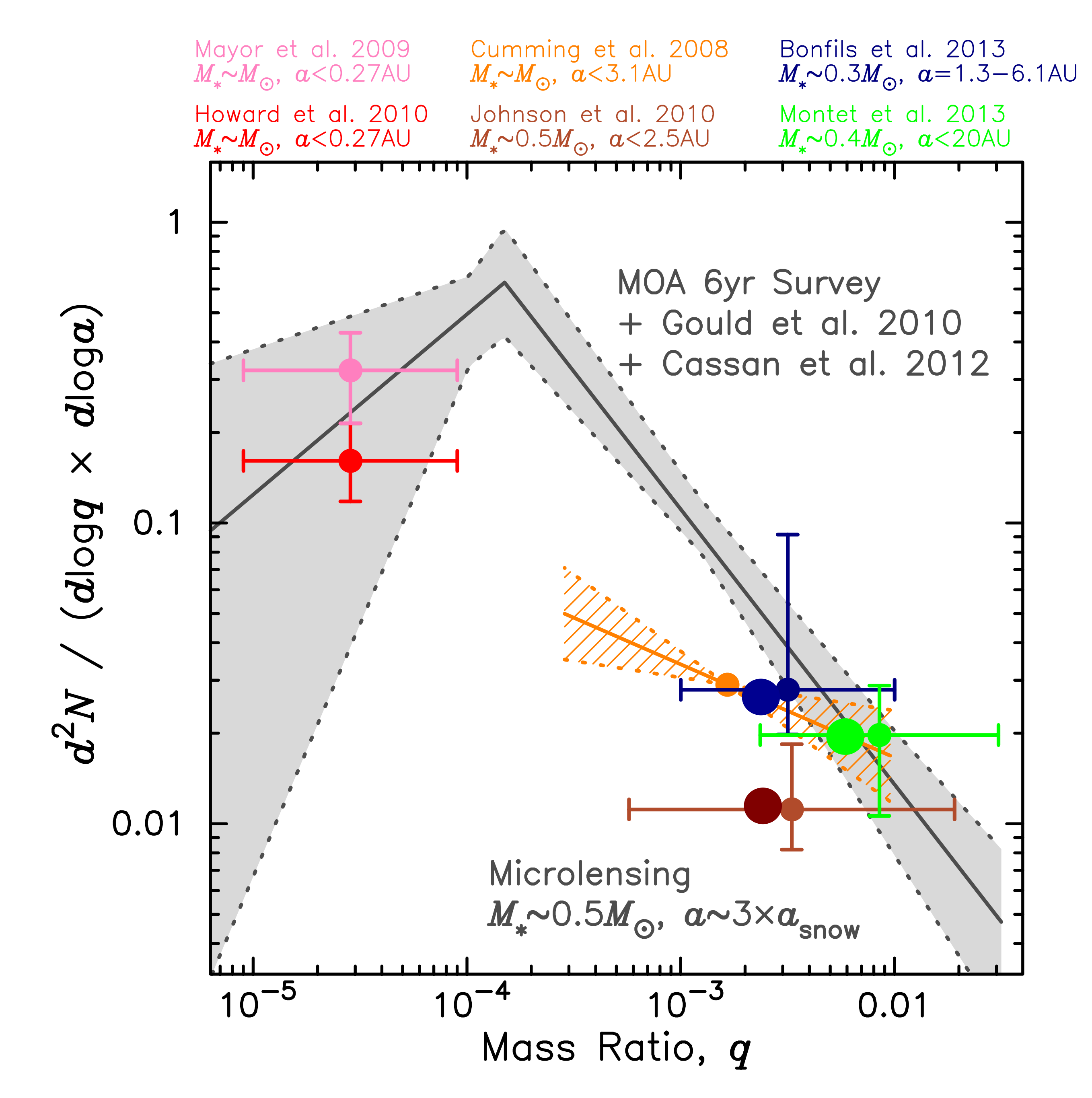
Microlensing vs RV Surveys

Suzuki+16

Full 30-event microlensing sample

- Ice Giants are ~8 times more common than Jupiters

Consistent with RV for cold Jupiter around M-dwarfs



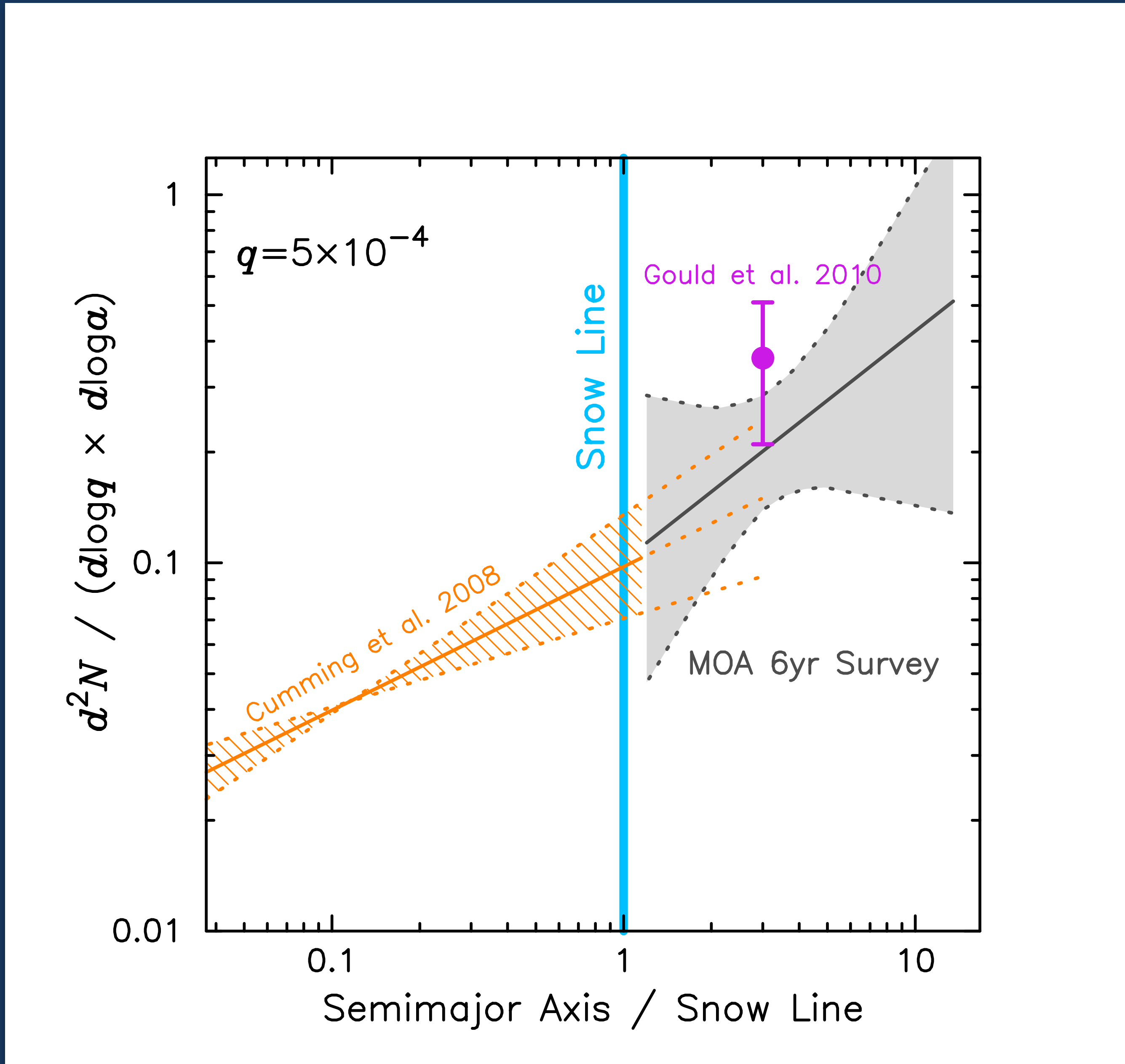
Planet Frequency vs Semi-Major Axis

Suzuki+16

MOA result is ~factor 2 lower than previous Gould et al. (2010) result.

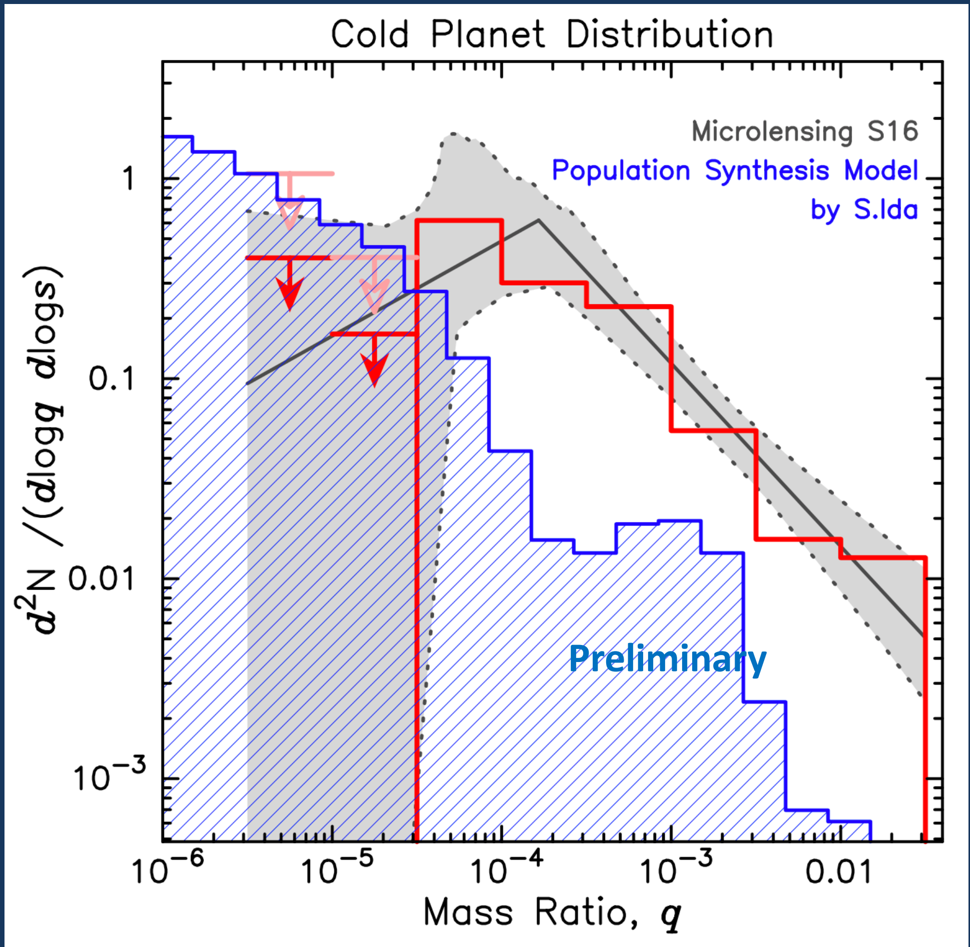
Planets beyond the snow line are 5x more common (per $\log a$) than planets inside the snow line.

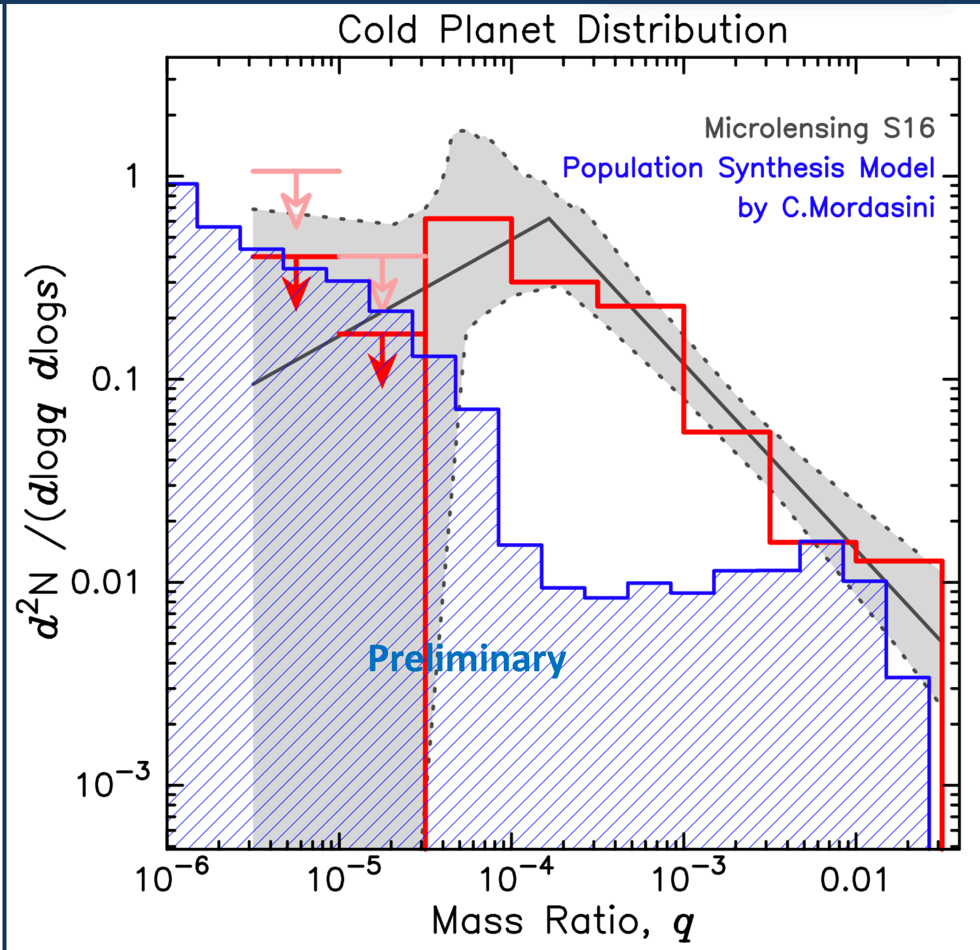
Along the line of the slope from inner planets.



Comparison to Population Synthesis

Suzuki+ in prep.



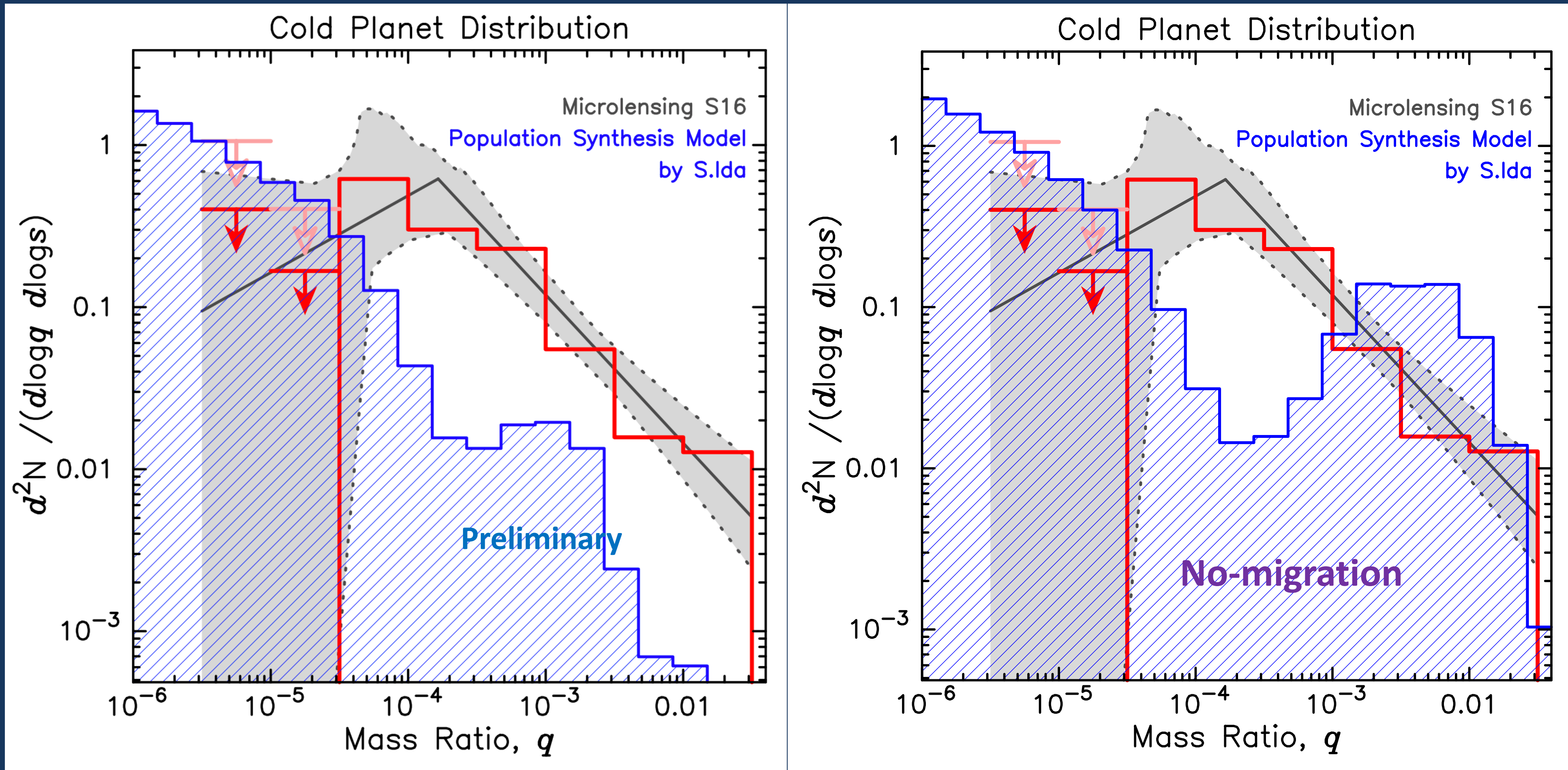


- Host mass for Ida-san's model log M = {-0.10, -0.25, …, -1.15, -1.30}
- Host mass for Mordasini's model log M = {0.00, -0.30, -0.60}

A huge gap around ~50 $M_{\rm Earth}$

Comparison to Population Synthesis

Suzuki+ in prep.



- Host mass for Ida-san's model log M = {-0.10, -0.25, …, -1.15, -1.30}

A huge gap around ~50 $M_{\rm Earth}$

PRIME (PRime-focus Infrared Mirolensing Experiment) Wide FOV 1.8m Telescope at SAAO

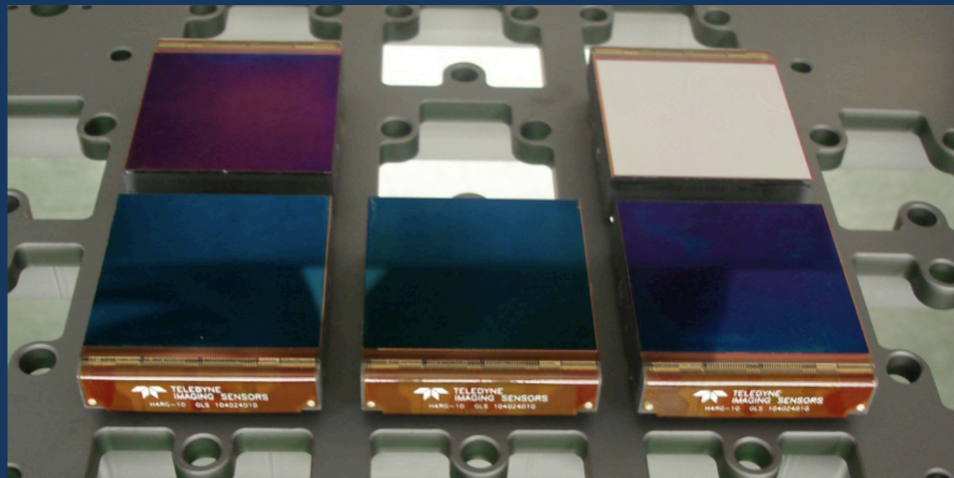
Alt. 1761m

Diameter: 1.8m, (f/2.29)

FOV:1.13° x1.13° =1.3deg^2(0.5"/pix)

(6xfull moon) World Largest FOV

H-band

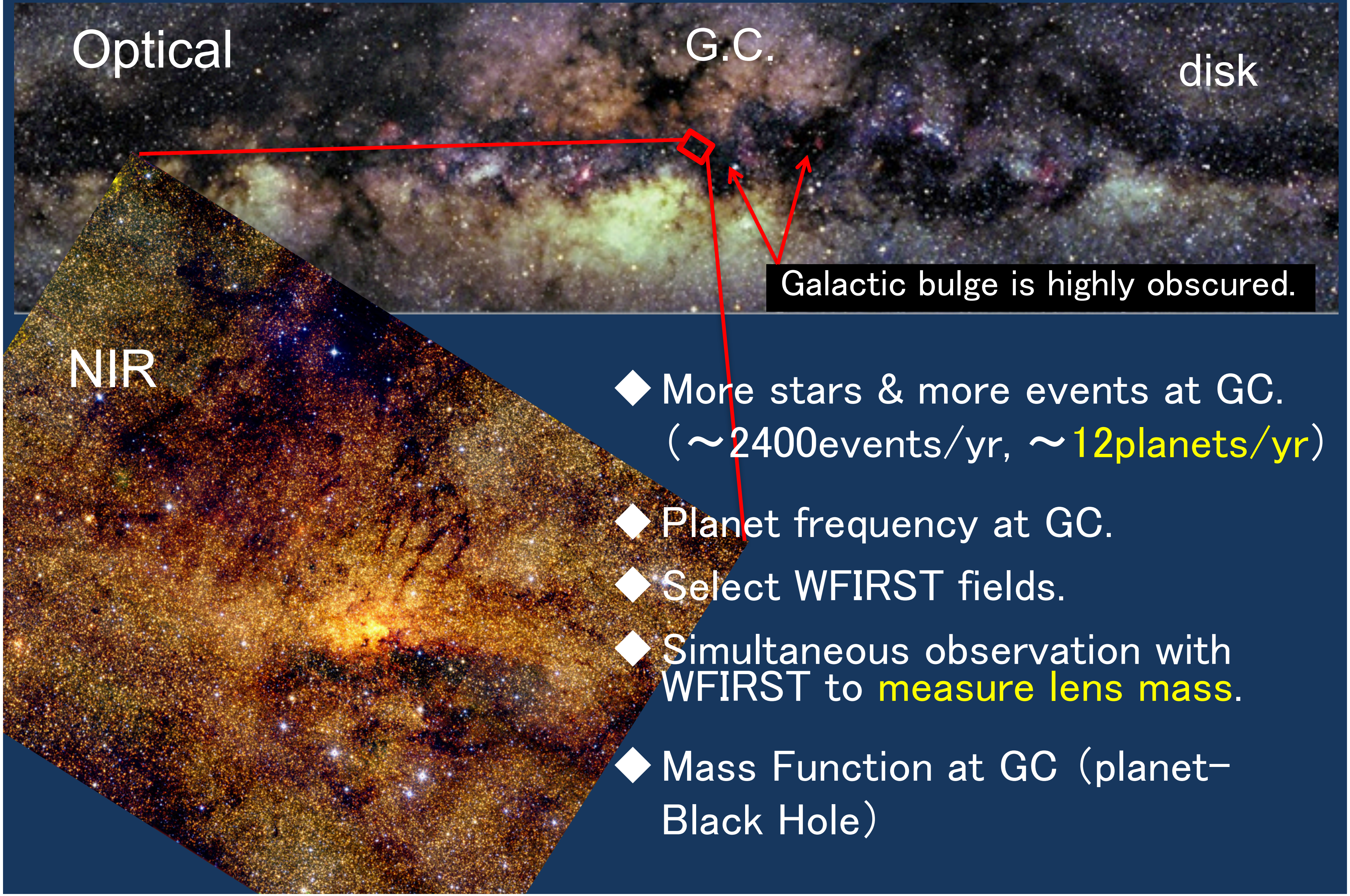


Loan Four Teledyne HgCdTe

4kx4k H4RG-10 (10μm pitch)

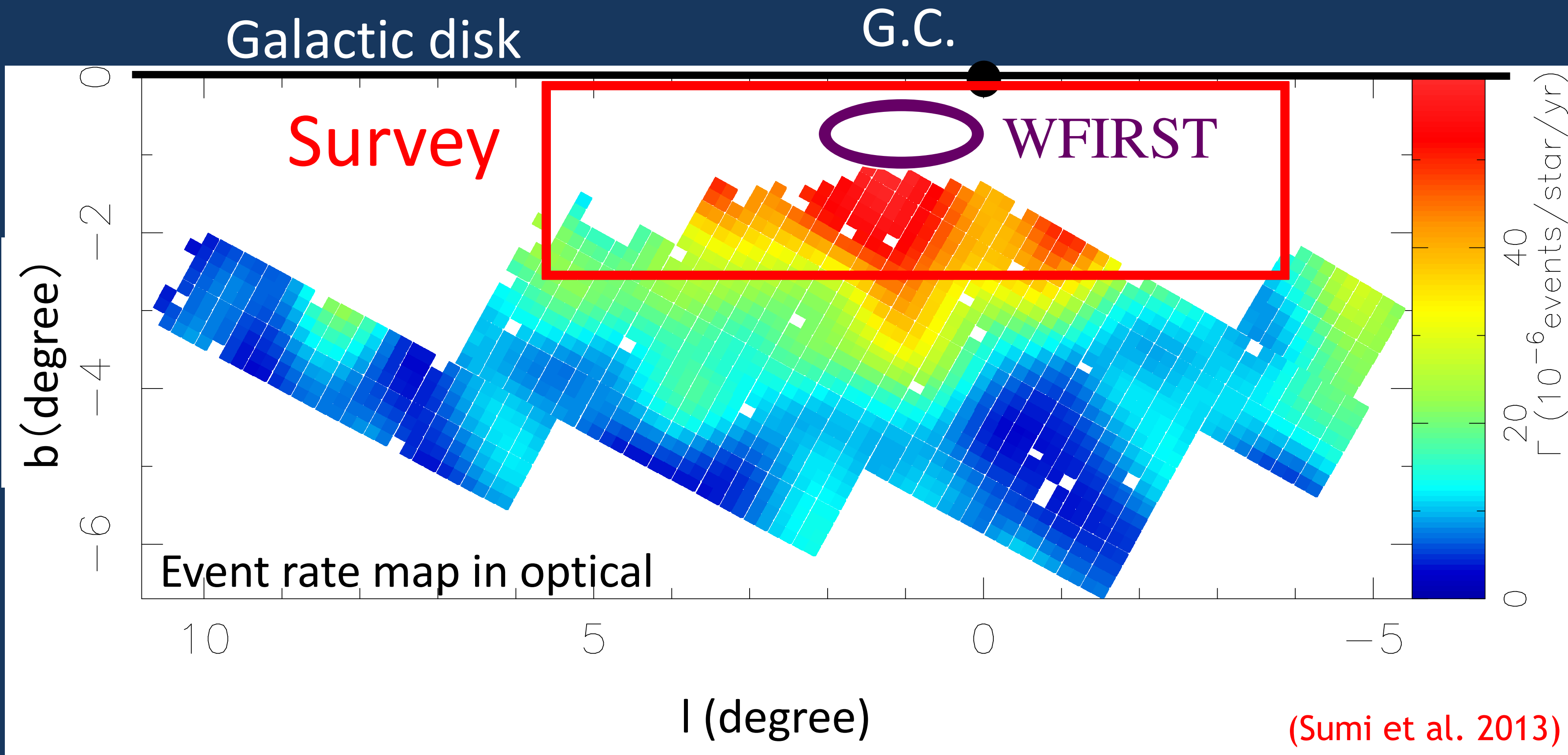
from WFIRST team (NASA)

More events & planets in NIR at G.C.

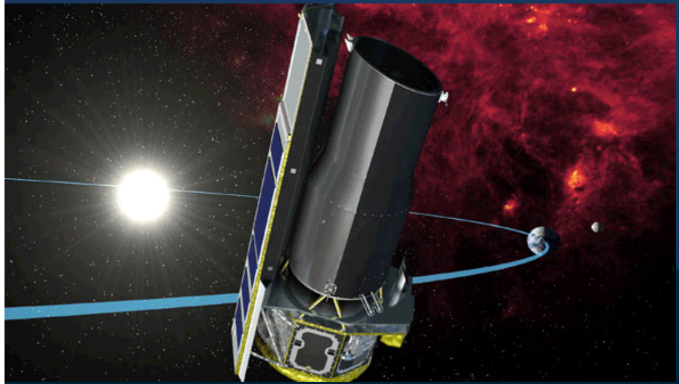


- More stars & more events at GC. (～2400events/yr, ～12planets/yr)
- Planet frequency at GC.
- Select WFIRST fields.
- Simultaneous observation with WFIRST to measure lens mass.
- Mass Function at GC (planet-Black Hole)

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



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

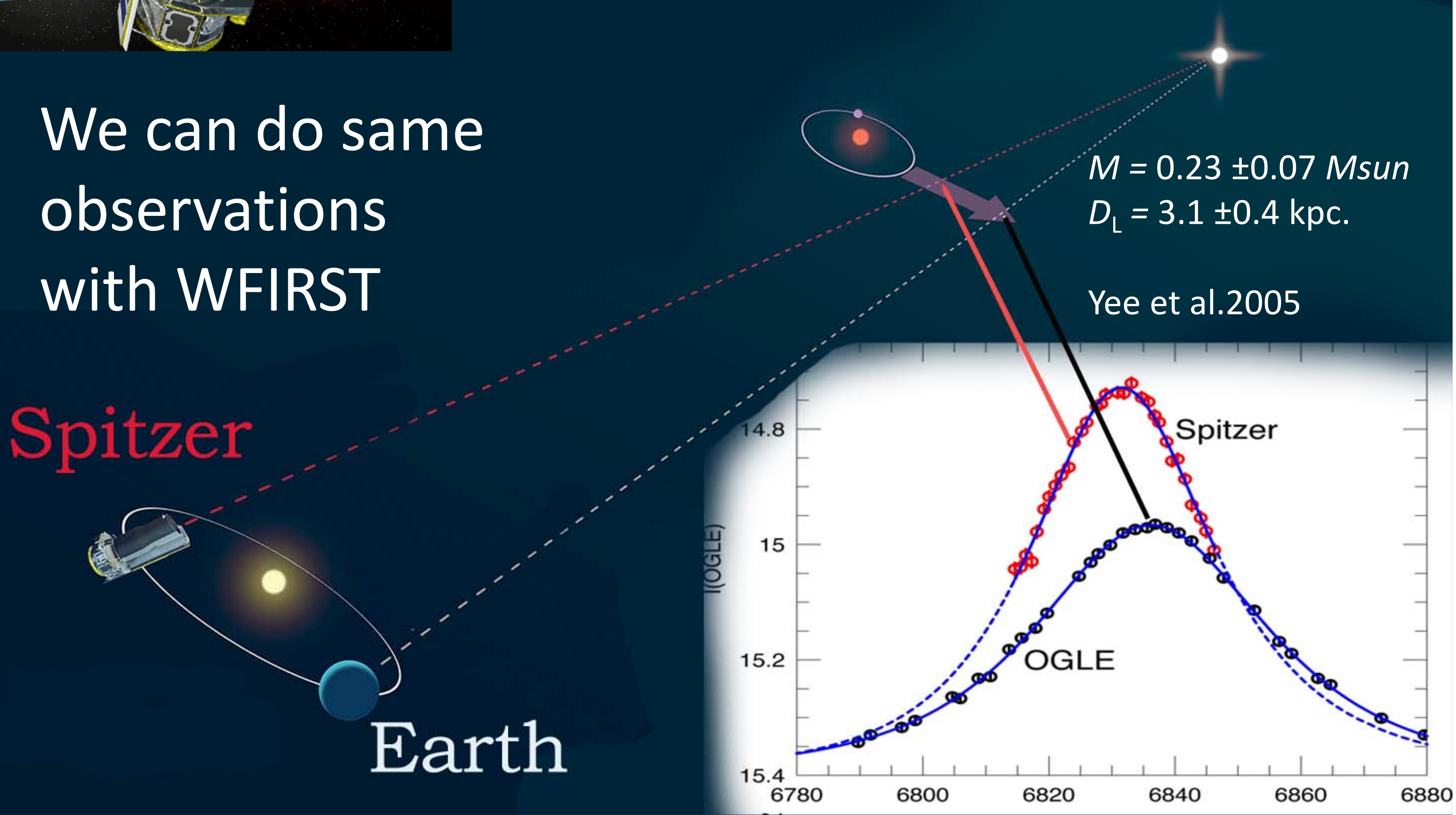


Simultaneous Ground-Space monitoring with Spitzer

We can do same observations with WFIRST

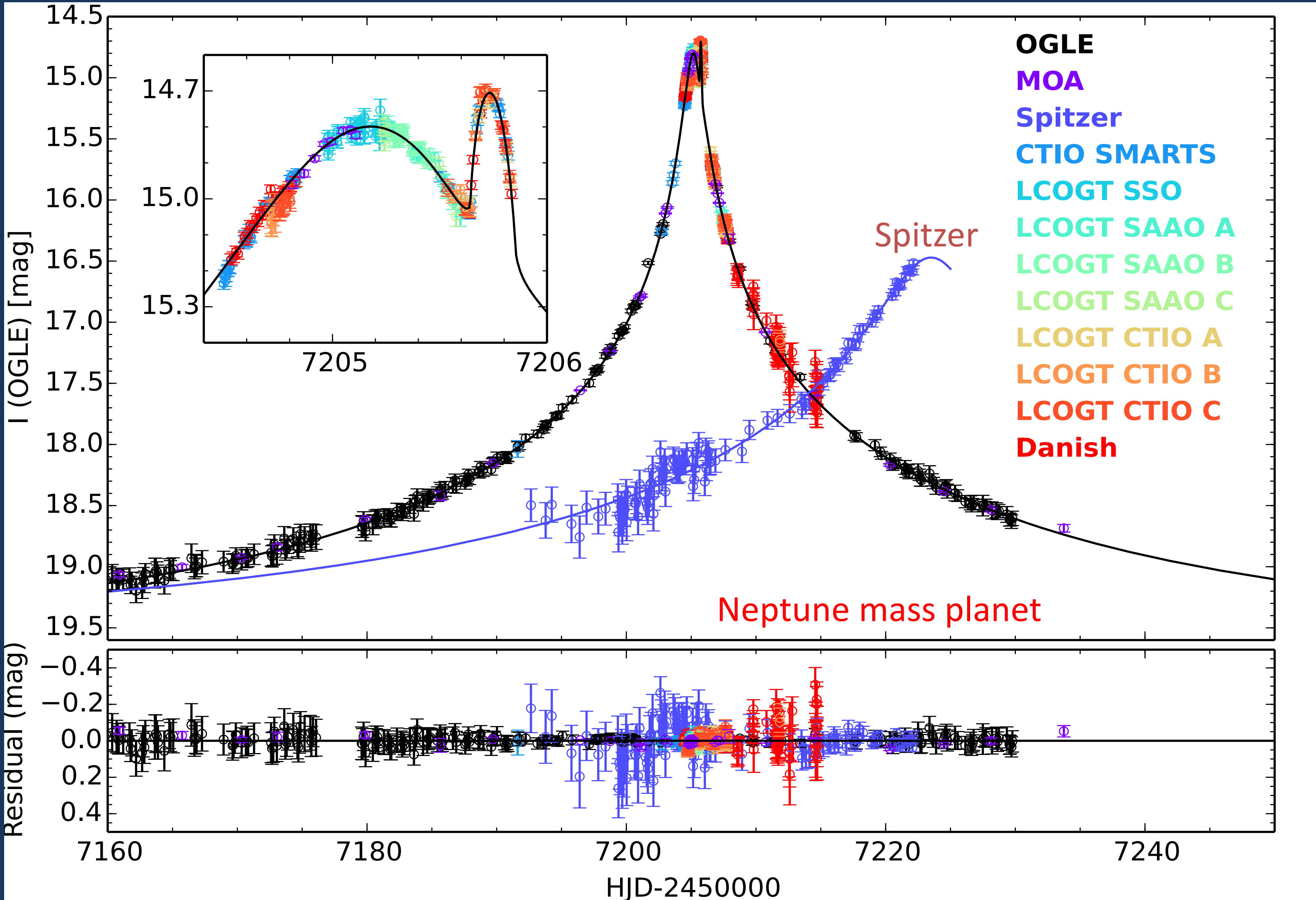
M = 0.23 ±0.07 *Msun*
D_L = 3.1 ±0.4 kpc.

Yee et al.2005



OGLE-2015-BLG-0966/MOA-2015-BLG-281

(Street et al. 2015)

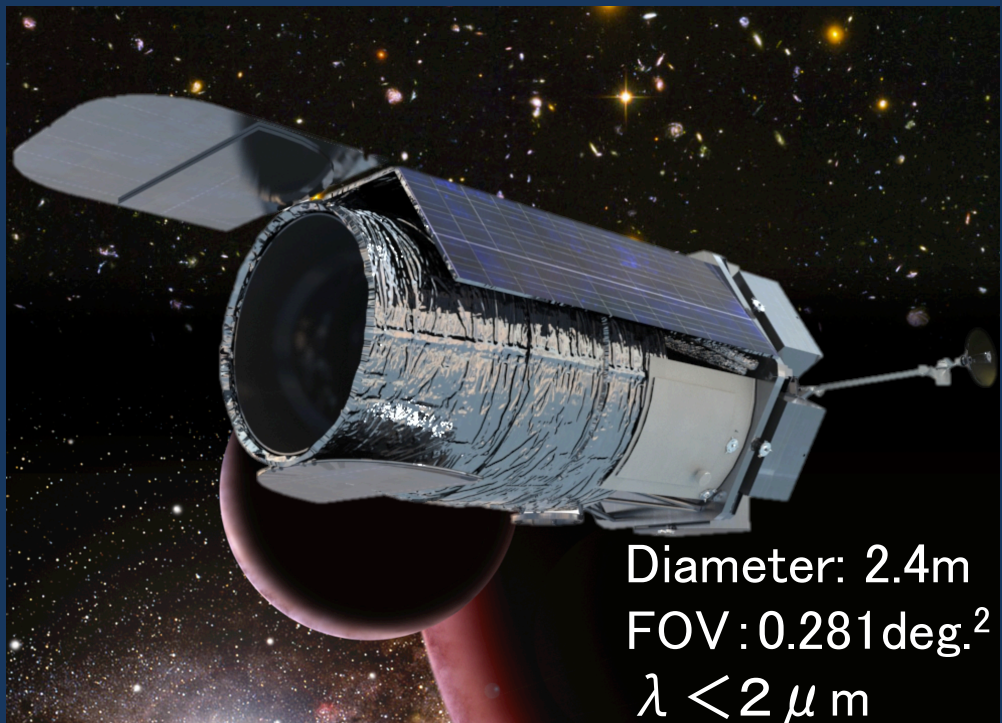


WFIRST

WFIRST Wide-Field Infra-Red Survey Telescope

(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
- Near Infrared Sky Survey
- Guest Observing Prog.

ISAS/JAXA WFIRST Working Group trying to join to the WFIRST

Channel field layout for AFTA-WFIRST wide field instrument

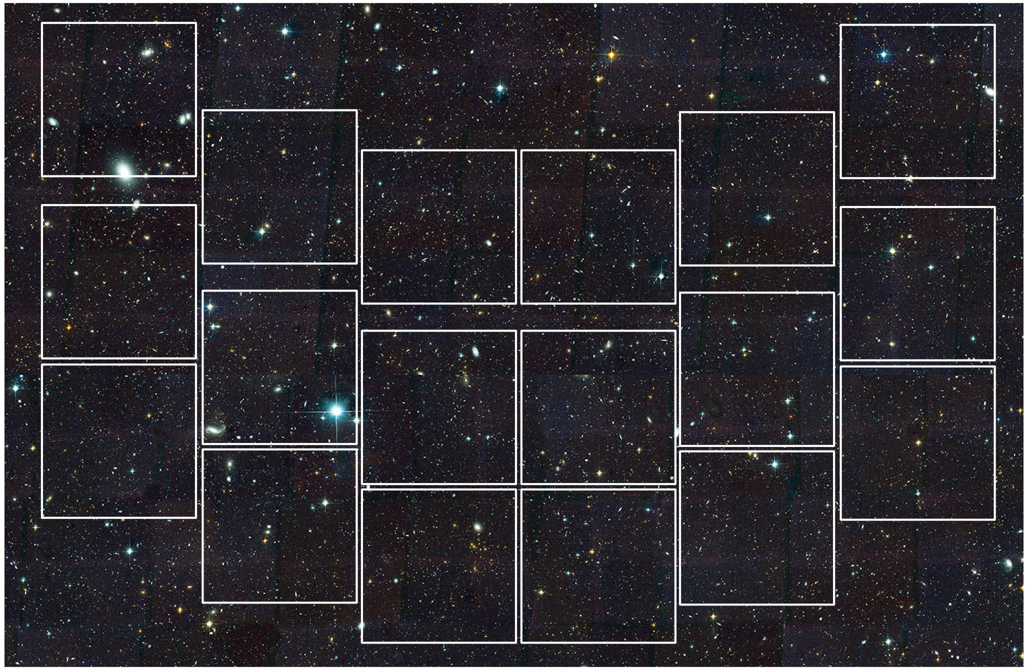
0.788° wide
0.427° high

X gaps 2.5mm
Y gaps 8.564mm

18 4k x 4k pixel H4RG-10 IR detectors

VOF: 0.28 deg^2 0.11 arcsec/pixel

Moon (average size seen from Earth)

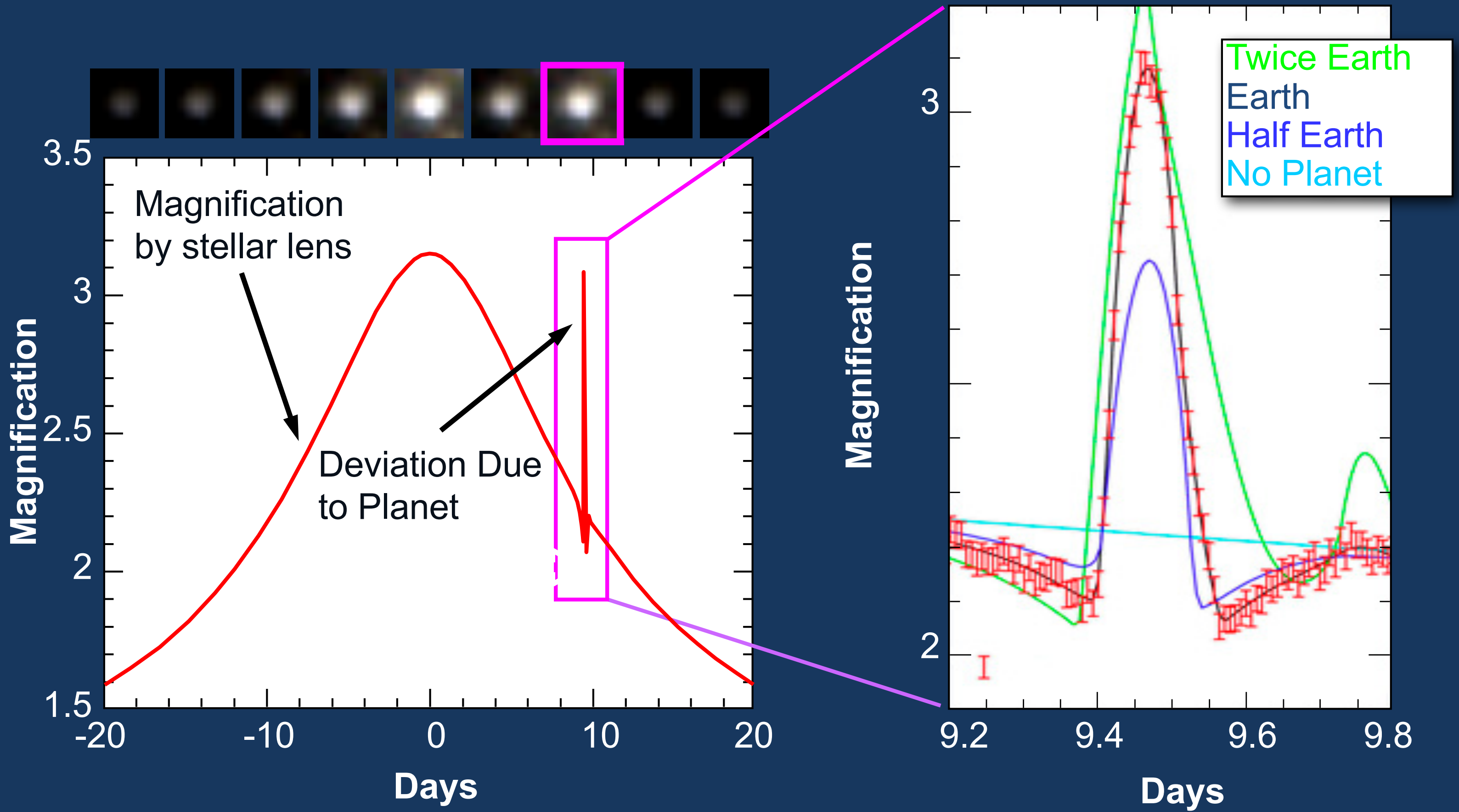


~90 × bigger than HST–ACS FOV,
~200 × bigger than IR channel of WFC3

Each square is a H4RG-10
4k x 4k, 10 micron pitch
288 Mpixels total

Slitless spectroscopy with grism in filter wheel
R_θ ~ 100 arcsec/micron

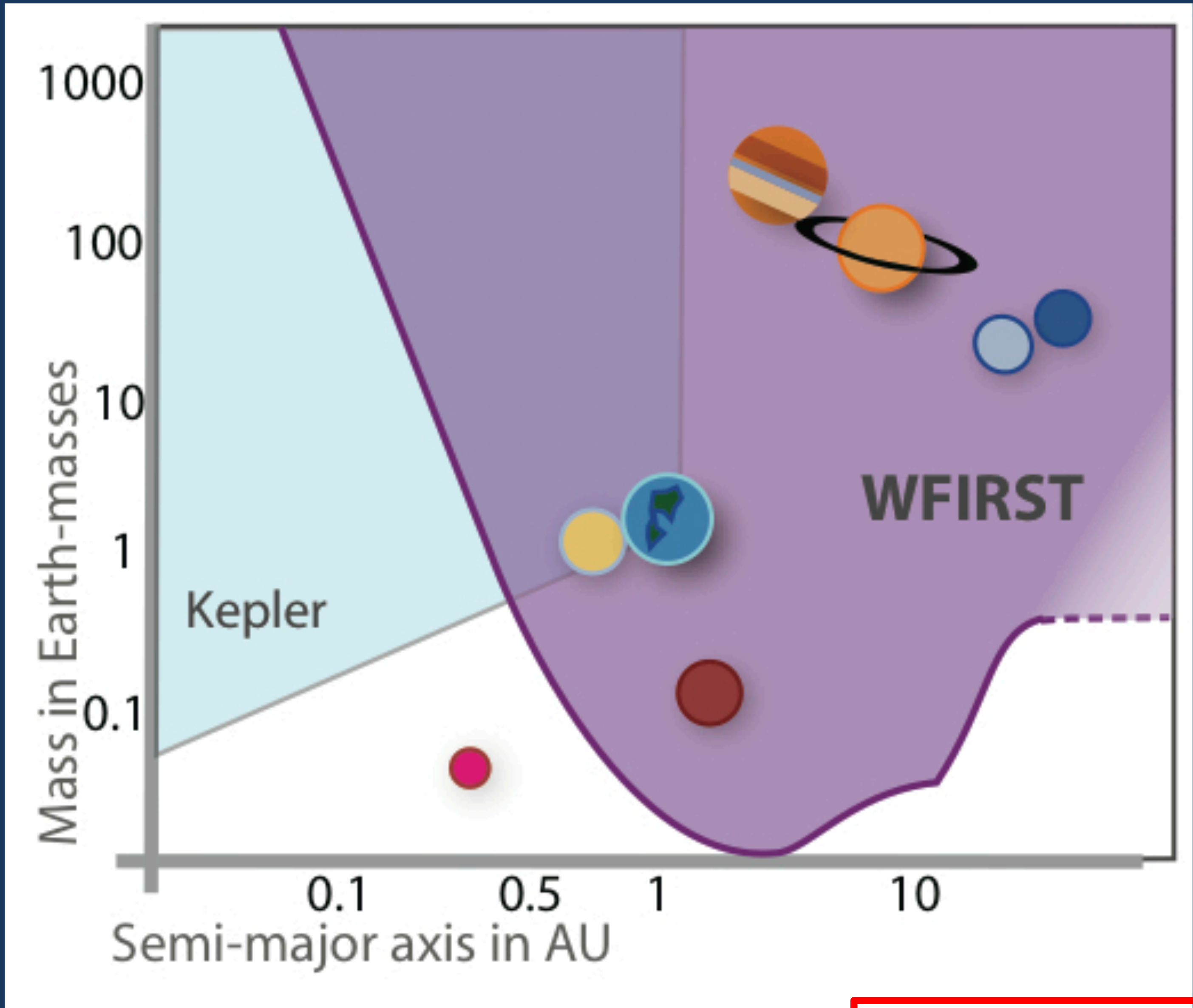
Simulated Exoplanet Signal



Monitor 3 billion stars in 2.8 deg.^{2} every 15 minutes with 0.2-1% precision for six 72-day continuous observation, 432days in total

Detect 3000 exoplanets including 200 sub-Earth mass planets.

Complete the census of planetary systems



- WFIRST can detect all solar system planet analog except Mercury.

•3000 bound planet, 200 (< 1 $M_\oplus$)

Summary

- neptunes at a～10a$_{snow}$ could be as common as ones at a～3a$_{snow}$
- Planets outside of snowline: Broken power-law, break $@q_{break}=1.6\times10^{-4}$
- Significant gap from pop. synthesis.
- PRIME will increase the samples.
- WFIRST can complete the statistical census outside of snowline