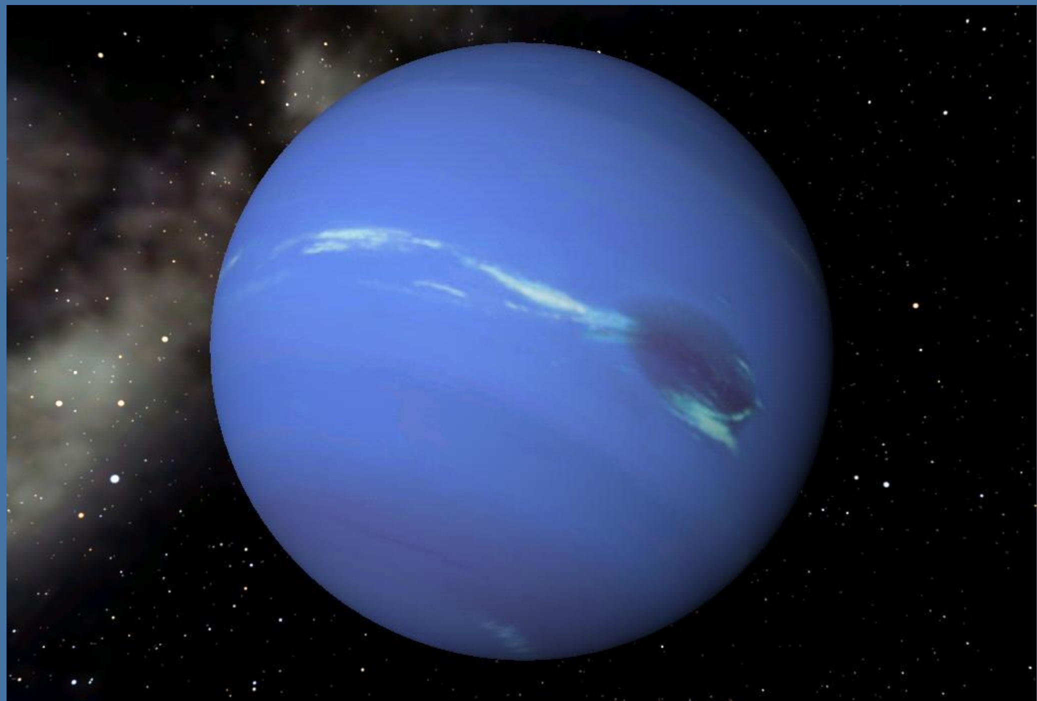
MOA-2013-BLG-605Lb: The Neptune Analog



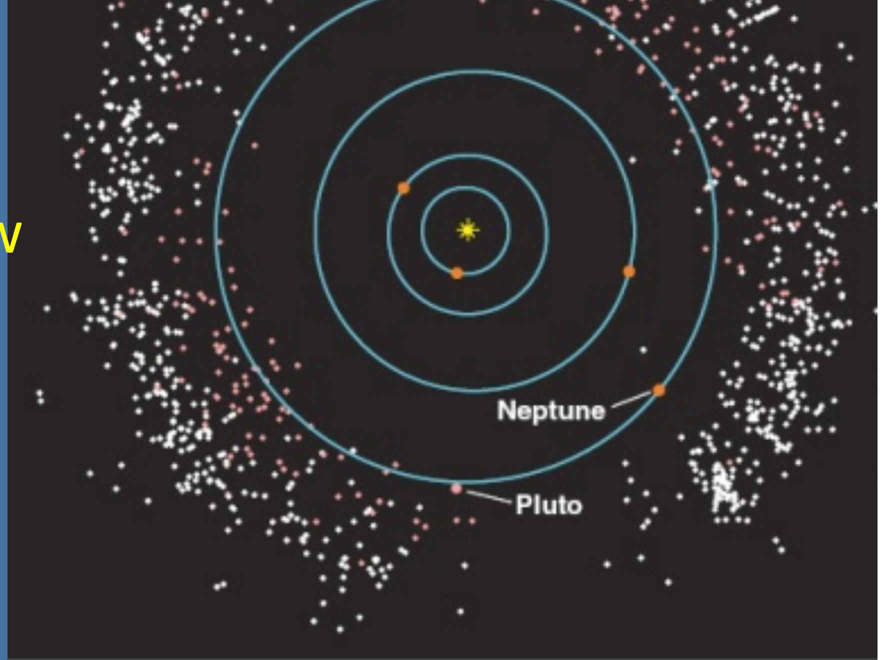
Takahiro Sumi (Osaka Univ.)
MOA collaboration in collaboration with OGLE

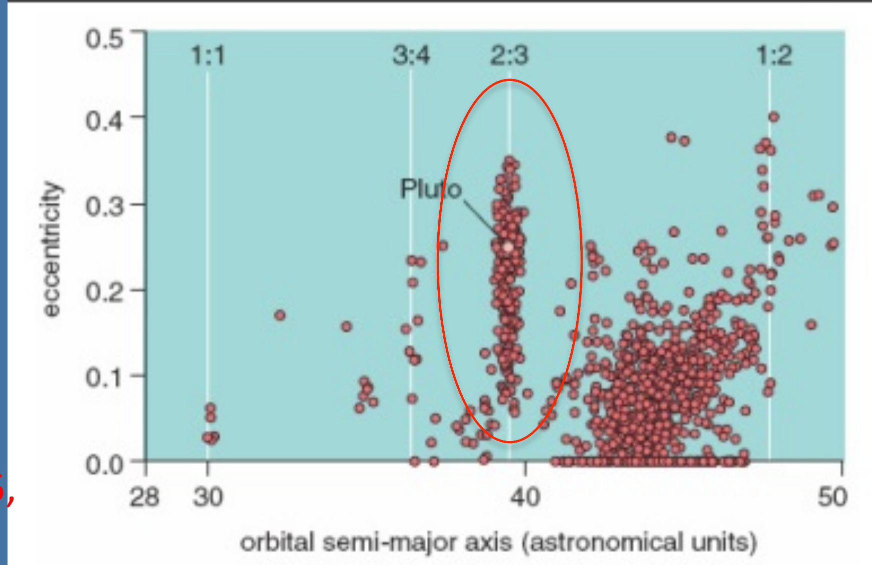
Neptune formation is not well known

- 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

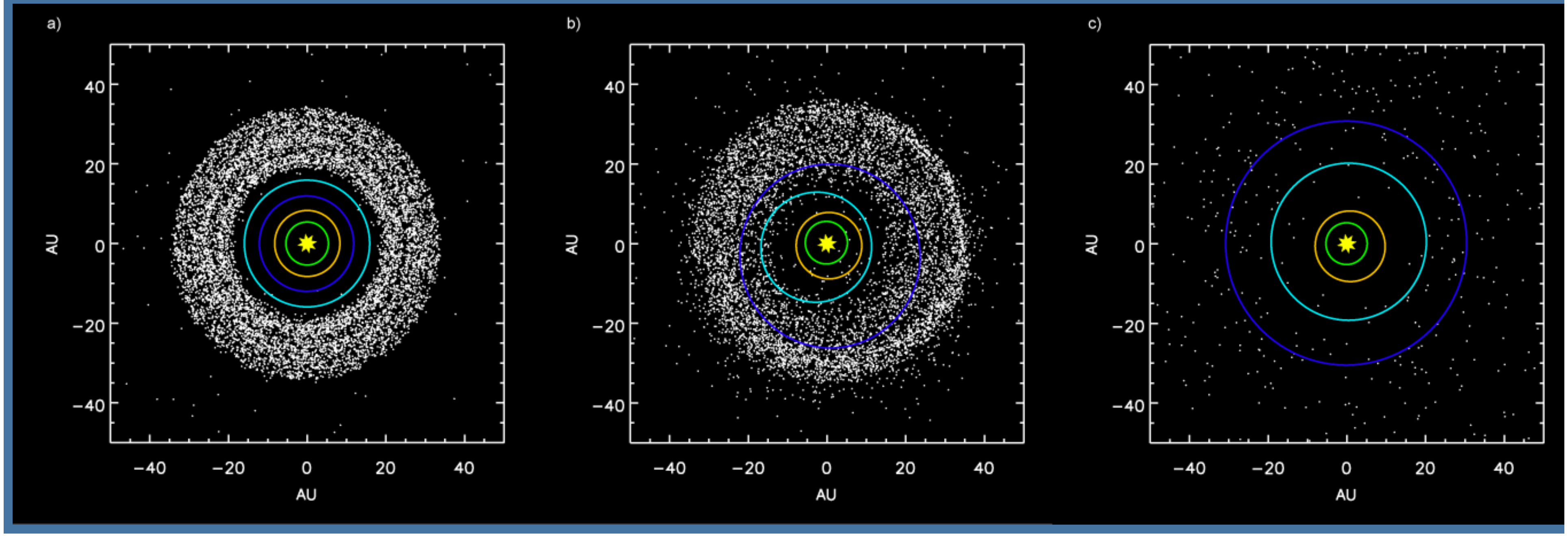
- Neptune should have moved 23AU→30AU to explain orbit of plutinos which are TNO in 2:3 resonance with Neptune. (Malhotra, R. 1993, The Origin of Pluto's Peculiar Orbit, Nature 365, 819)



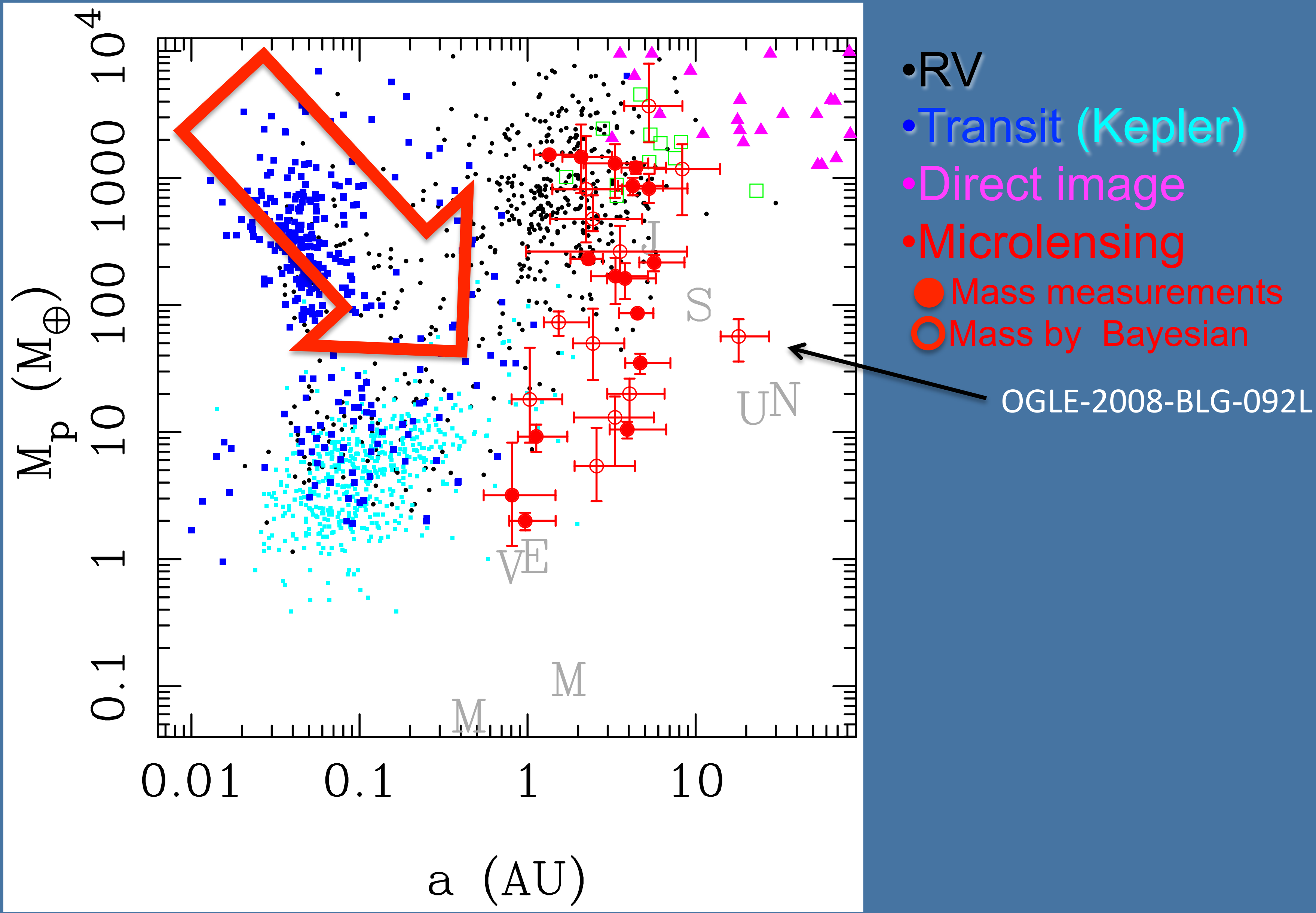


Neptune formation is not well known

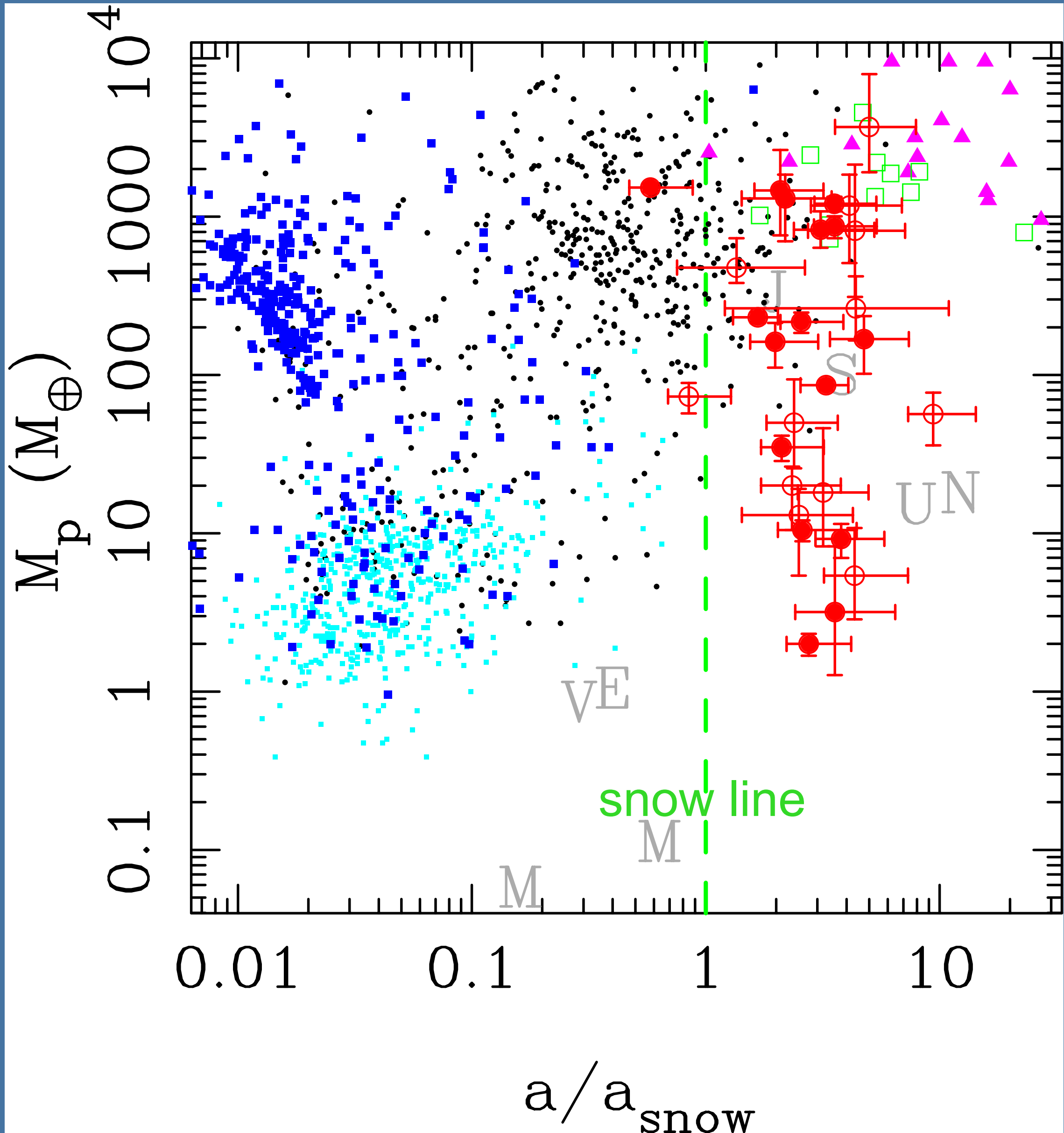
- They can move by the exchange of orbital angular momentum with planetesimals, (Fernandez, J. A.; Ip, W.-H. 1984, Icarus 58, 109)
- When Jupiter and Saturn pass 1:2 mean-motion resonance they gravitationally scattered Uranus and Neptune outwards to their current position (Thommes, Duncan & Levison 1999; Helled & Bodenheimer 2013)



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

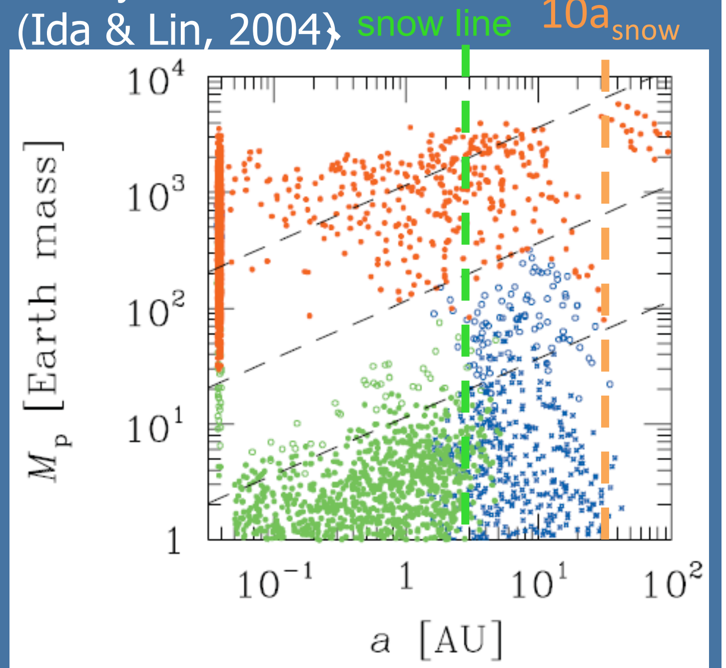


Discovered exoplanets (M_p-a/a_{snow})

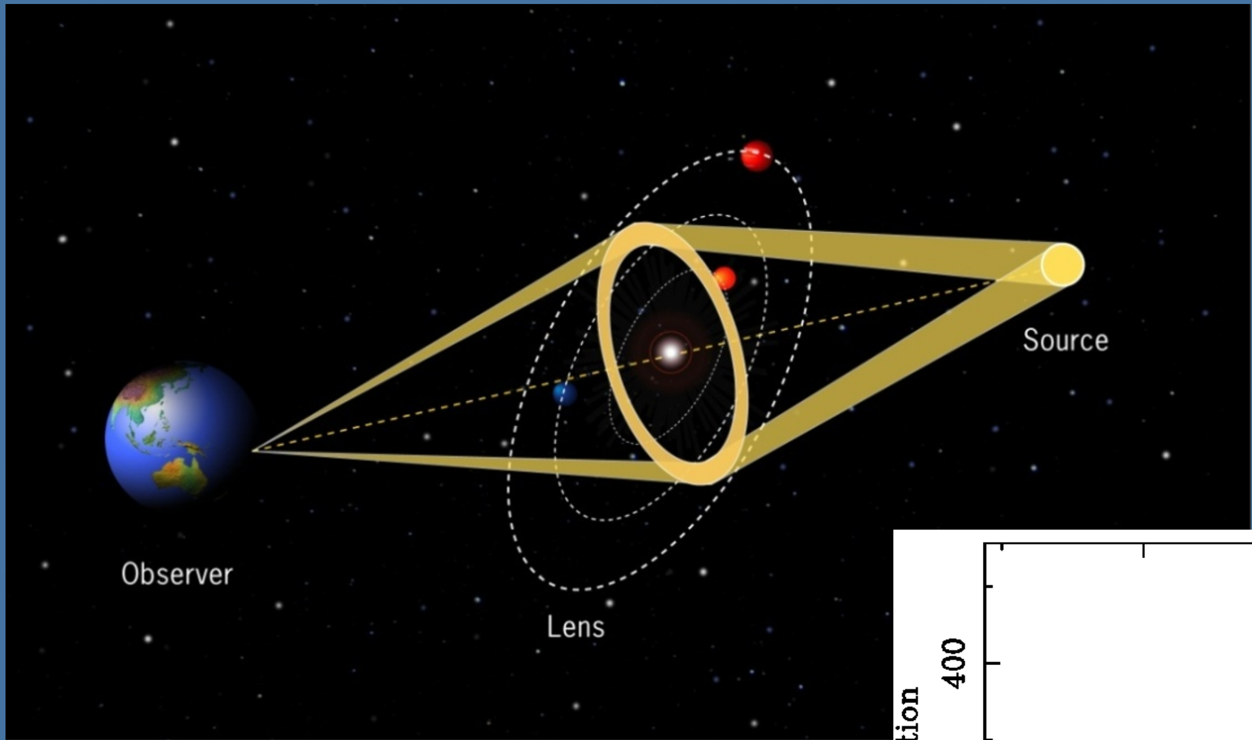


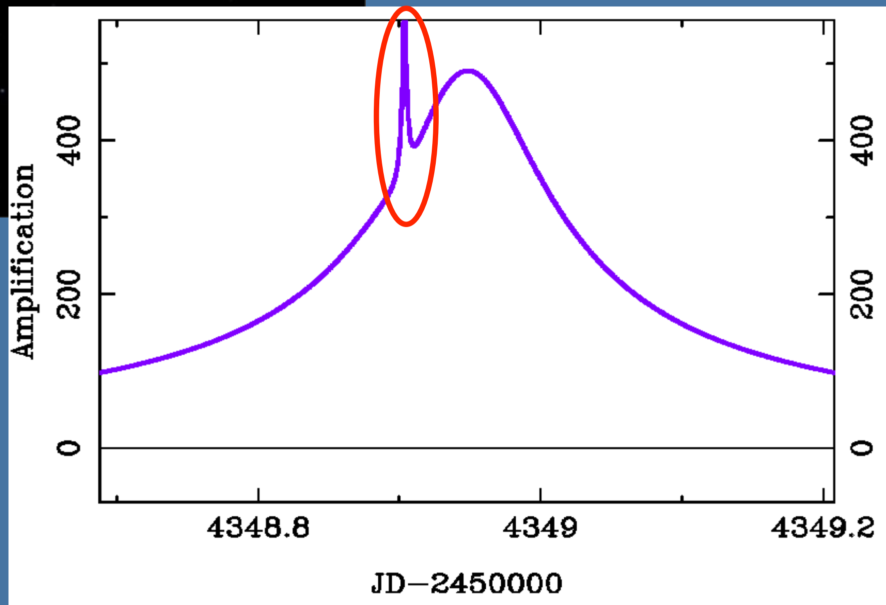
•RV
•Transit (Kepler)
•Direct image
•Microlensing
Mass measurements
Mass by Bayesian

Theory
(Ida & Lin, 2004)



planetary microlensing





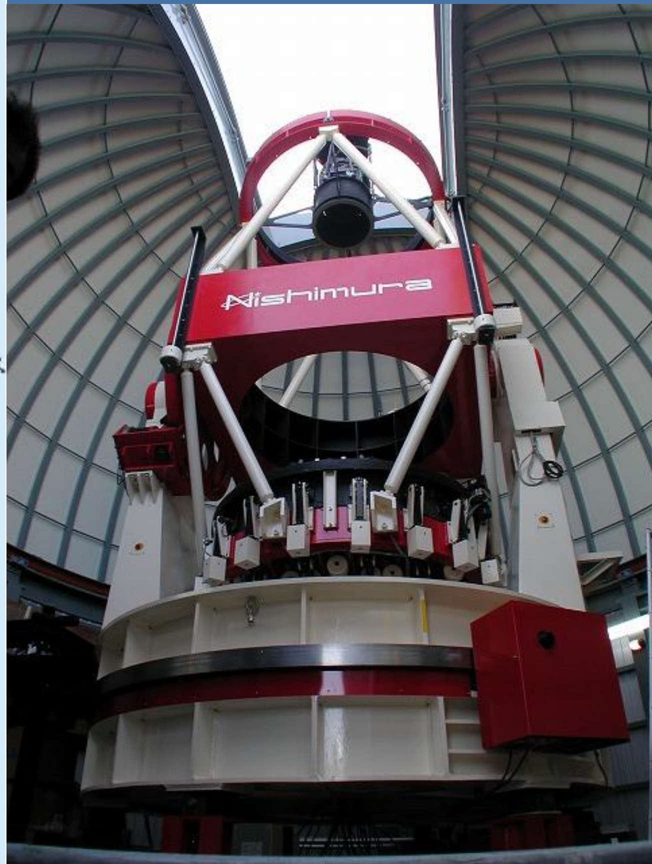
Time scale: $t_p \sim M^{1/2} \sim 1\text{day}(M_J)$

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

MOA (since 1995)

(Microlensing Observation in Astrophysics)

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

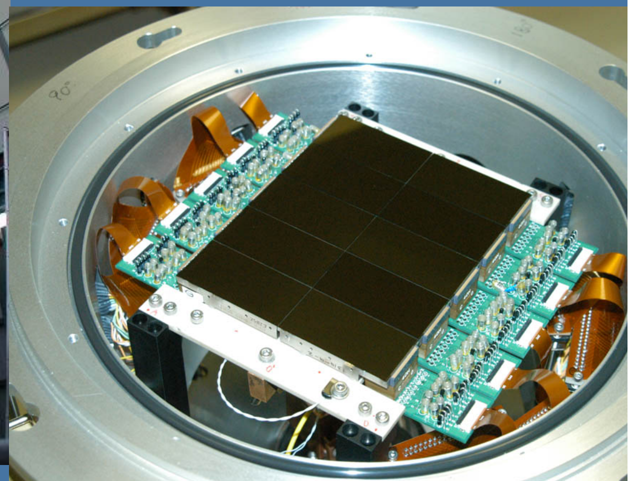


Mirror : 1.8m

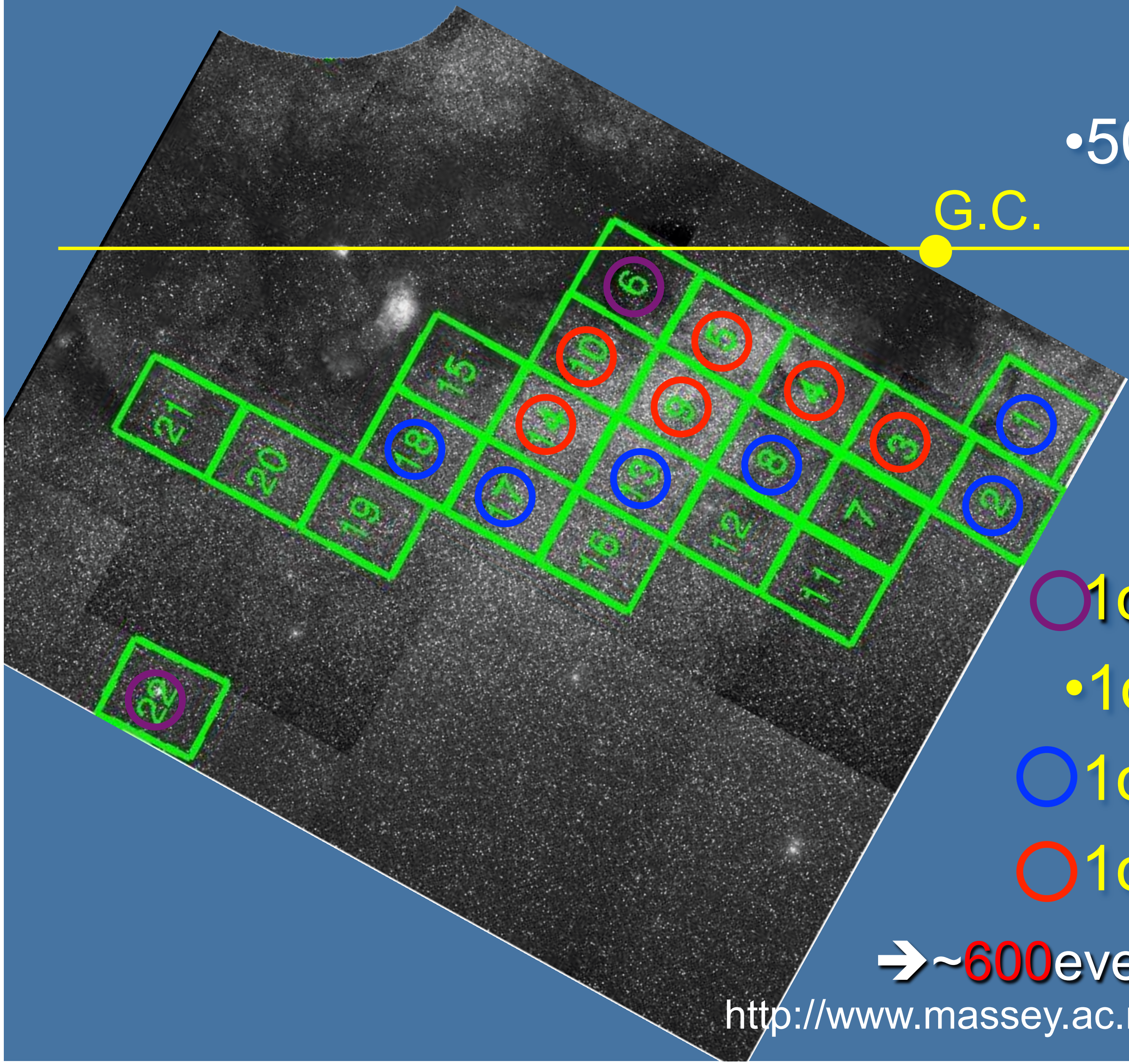
CCD : 80M pix.

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})

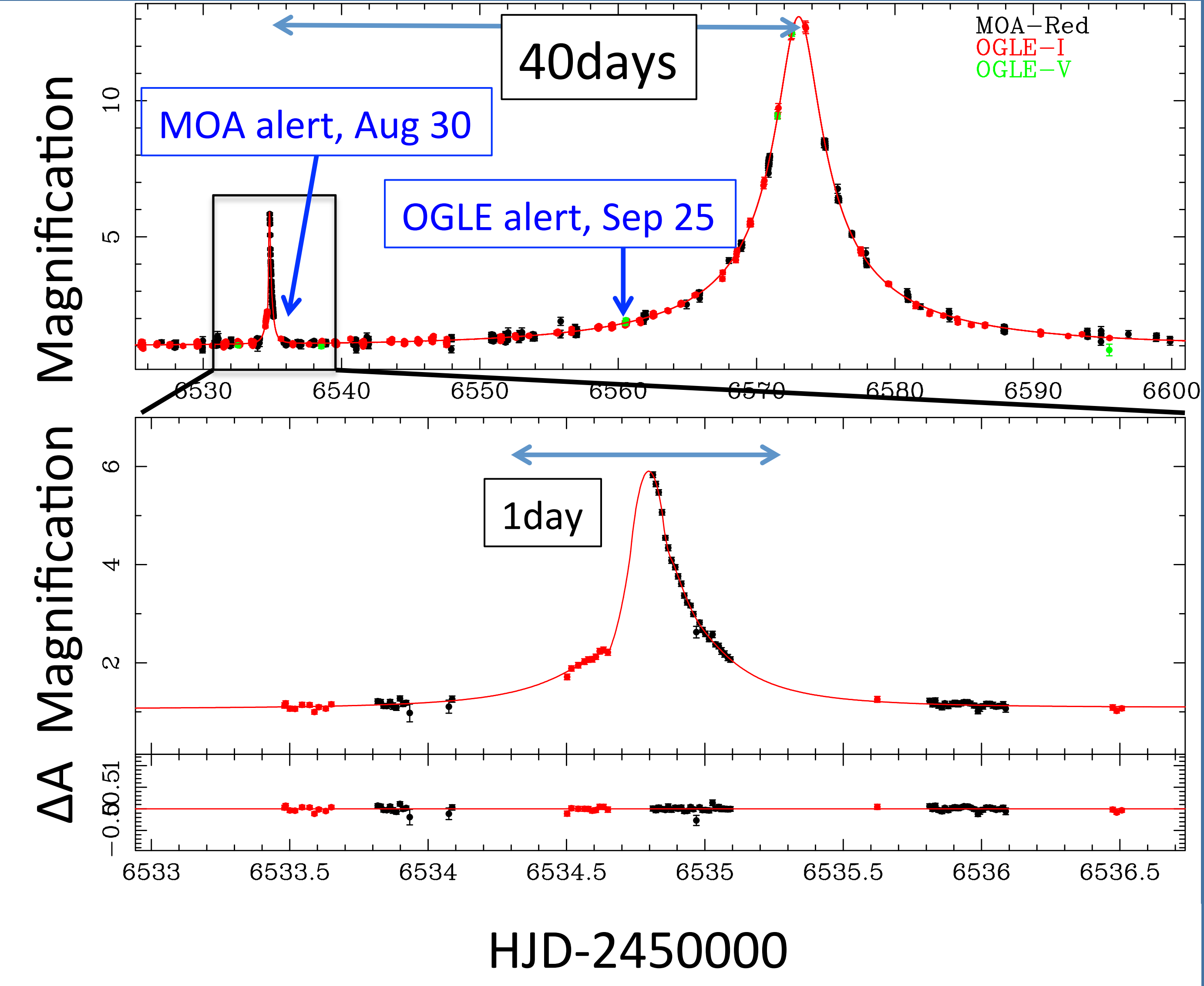
○1obs./15min. ($M_{\oplus}$)

➔~600events /yr

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

MOA-2013-BLG-605 light curve

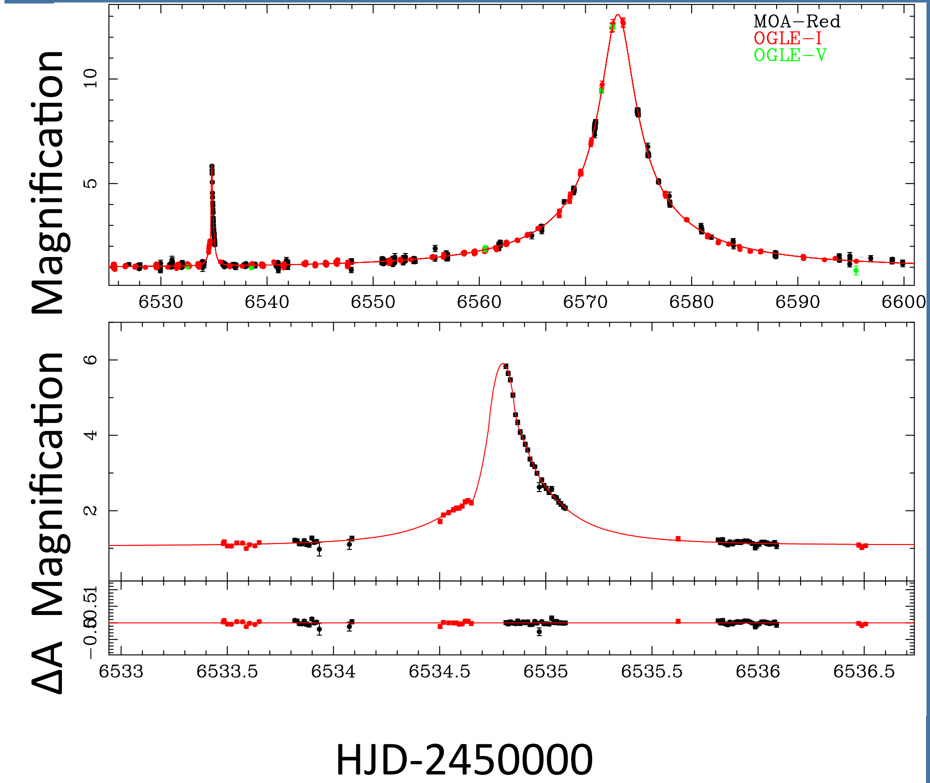
(OGLE-2013- BLG-1835)

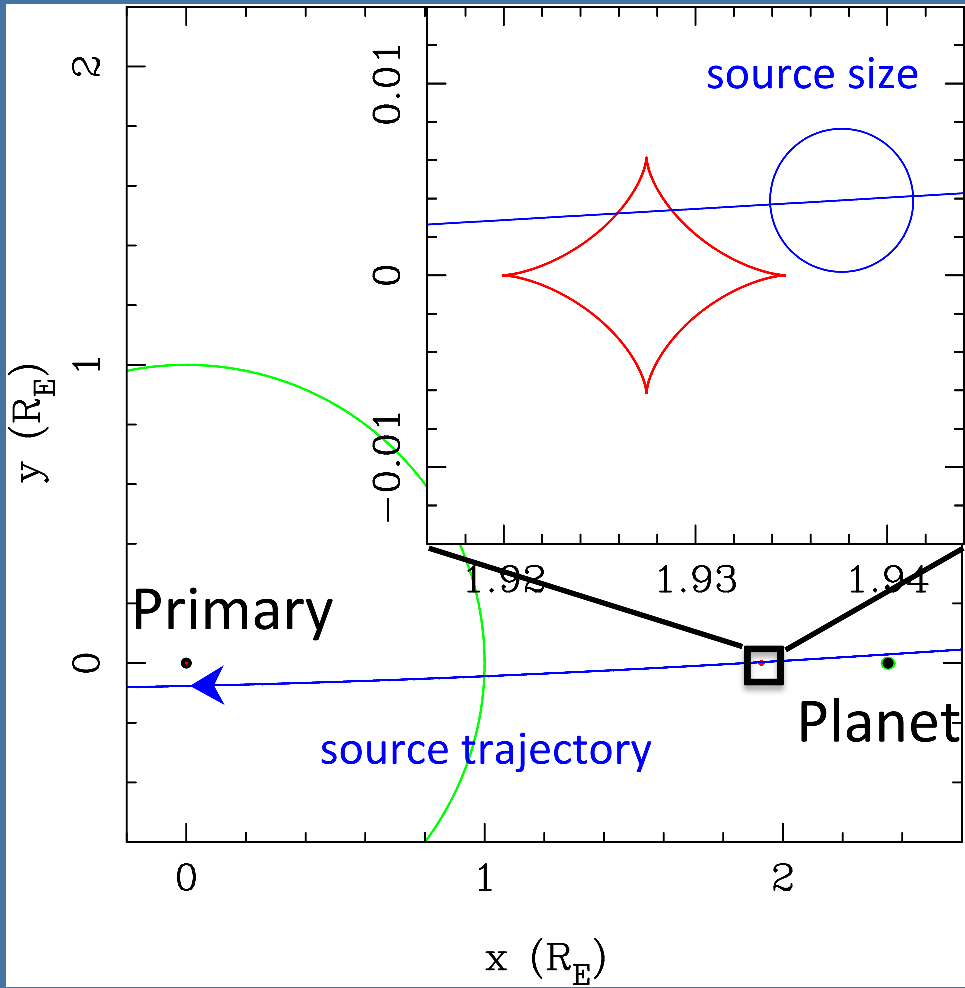


Lens geometry & Caustics

$q=3\text{x}10^{-4}$

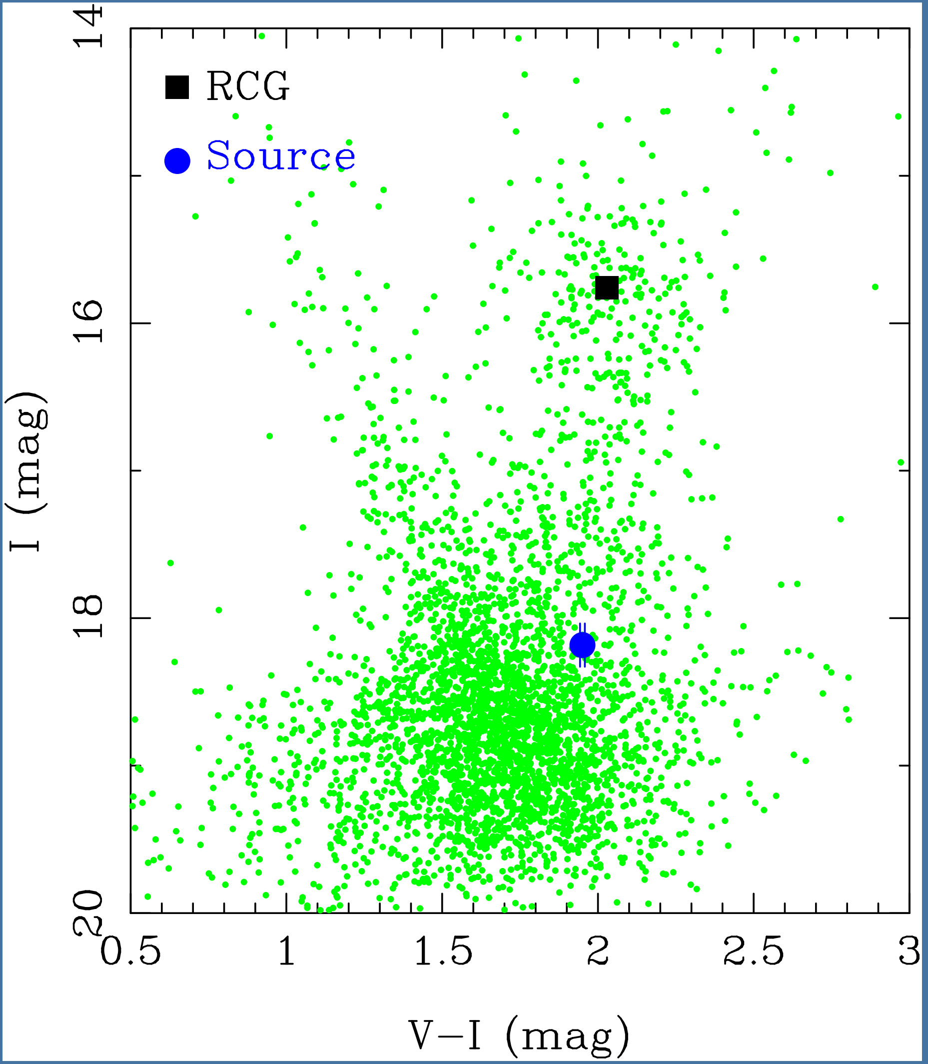
$s=2.3$





Finite source and
Parallax are detected

OGLE CMD & source radius



Source: K2 subgiant

$\theta_* = 1.8 \mu as$

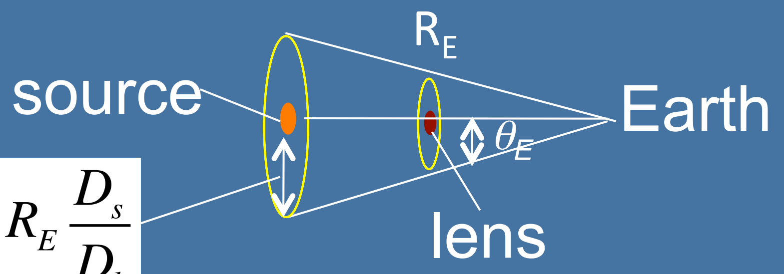
$\theta_E = 0.48 mas$

Finite Source Effects & Microlensing Parallax Yield Lens System Mass

θ_* :source star angular radius

D_L and D_S:lens and source distances

- Finite source effects: Angular Einstein radius $\theta_E = \theta_* / \rho$

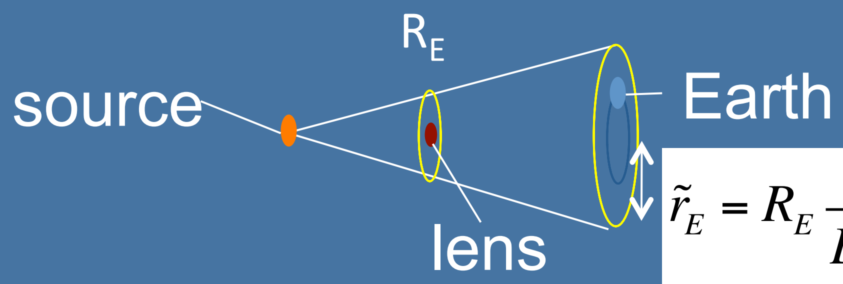


$$\hat{r}_E = R_E \frac{D_s}{D_l}$$

$$M_L = \frac{c^2}{4G} \theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

- Parallax: (Effect of Earth's orbital motion)

  Einstein radius projected to Observer

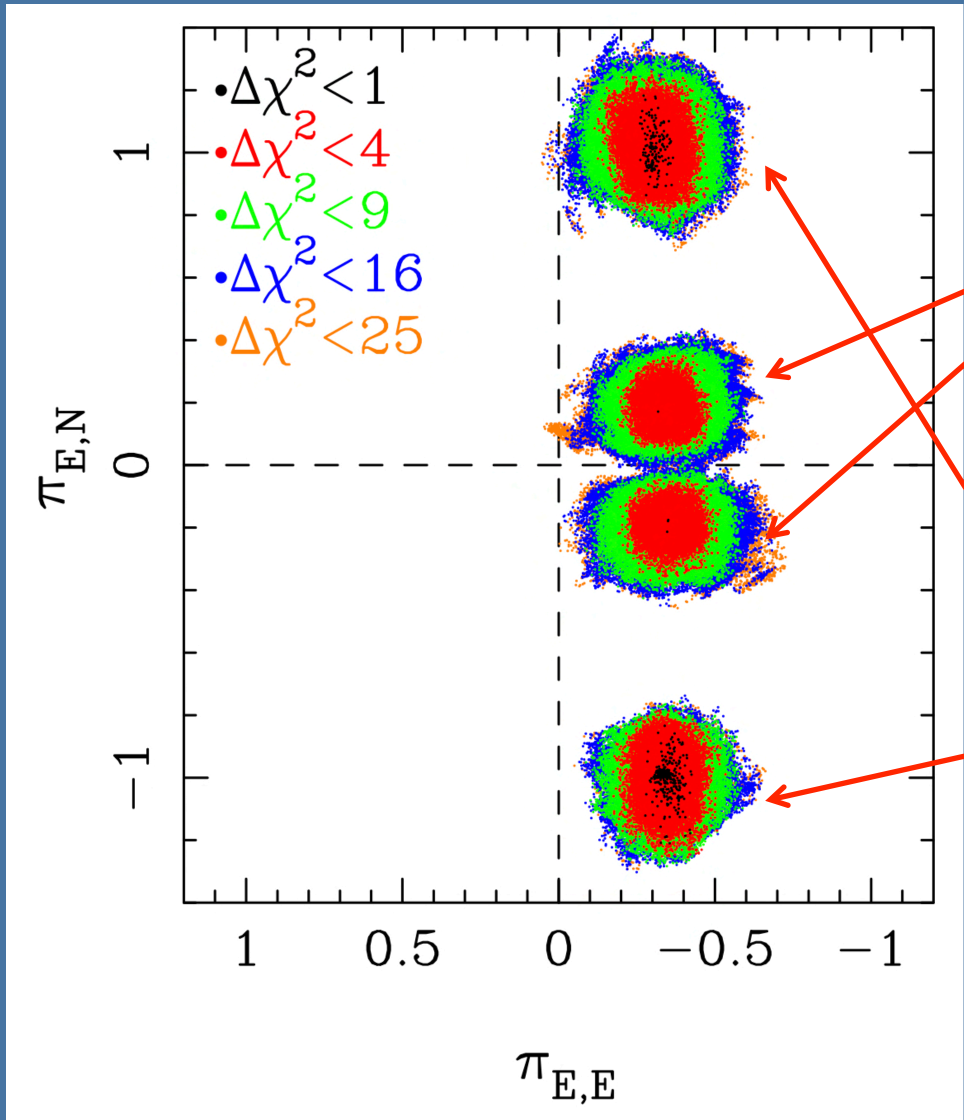


$$\tilde{r}_E = R_E \frac{D_s}{D_s - D_l}$$

$$M_L = \frac{c^2}{4G} \tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

$$M_L = \frac{c^2}{4G} \tilde{r}_E \theta_E$$

4 degenerate Parallax solutions



Small parallax:

M_h=0.16±0.05$M_\odot$

M_p=18±5$M_\oplus$

a =$4.6_{-1.1}^{+2.5}$AU

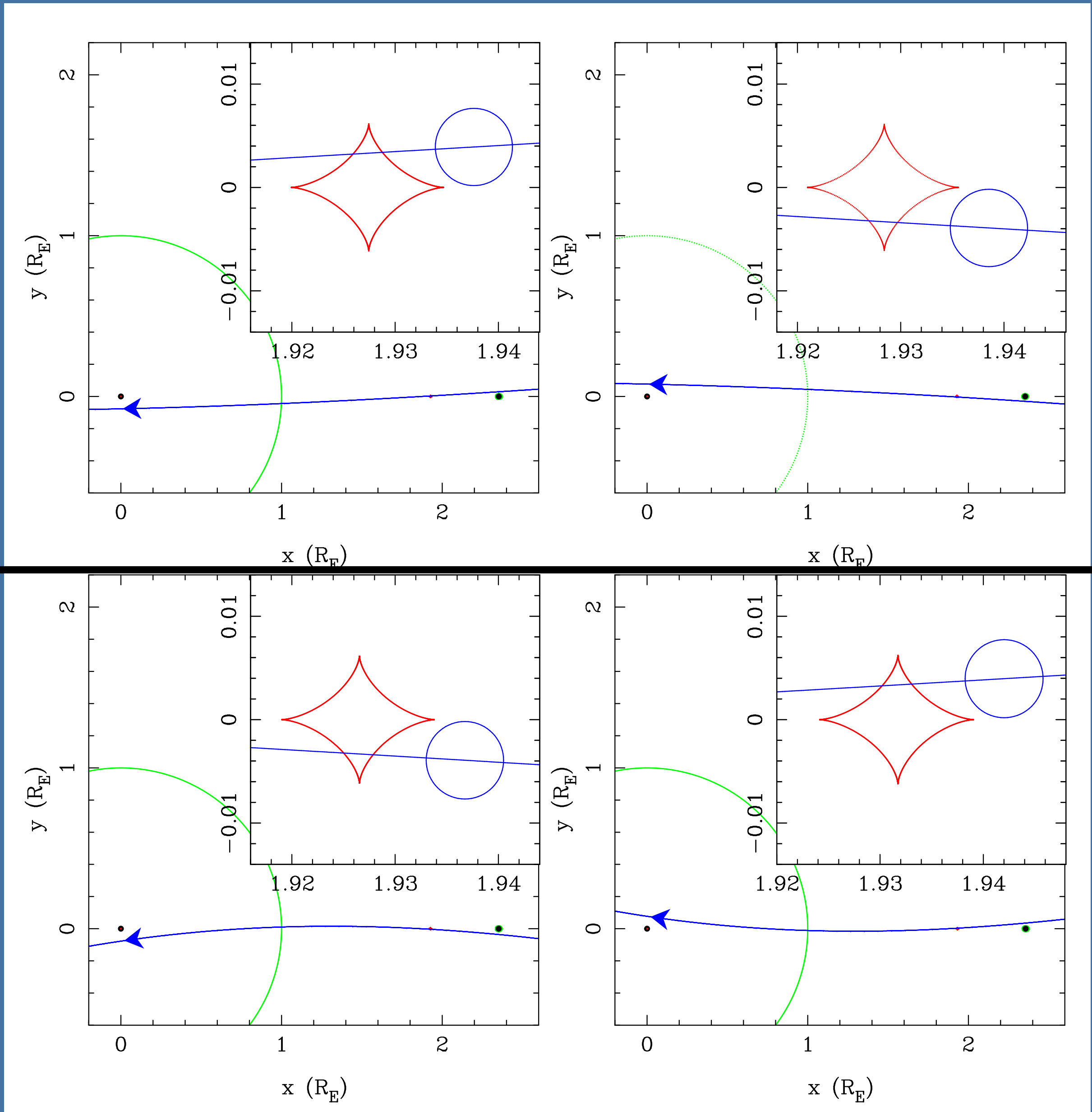
Large parallax:

M_h=0.06±0.01$M_\odot$

M_p=6.6±1.0$M_\oplus$

a =$2.2_{-0.4}^{+1.3}$AU

4 degenerate Parallax solutions



Small parallax:

$M_h = 0.16 \pm 0.05 M_\odot$

$M_p = 18 \pm 5 M_\oplus$

$a = 4.6_{-1.1}^{+2.5}$ AU

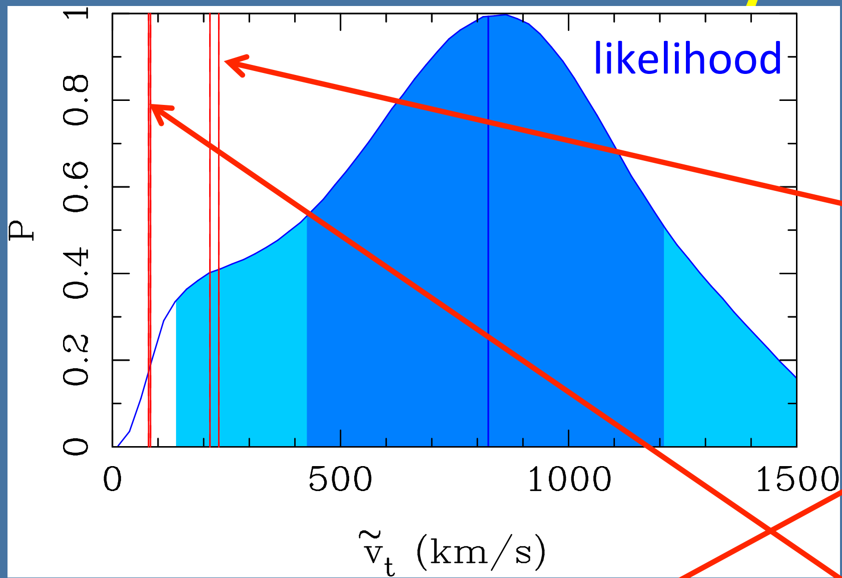
Large parallax:

$M_h = 0.06 \pm 0.01 M_\odot$

$M_p = 6.6 \pm 1.0 M_\oplus$

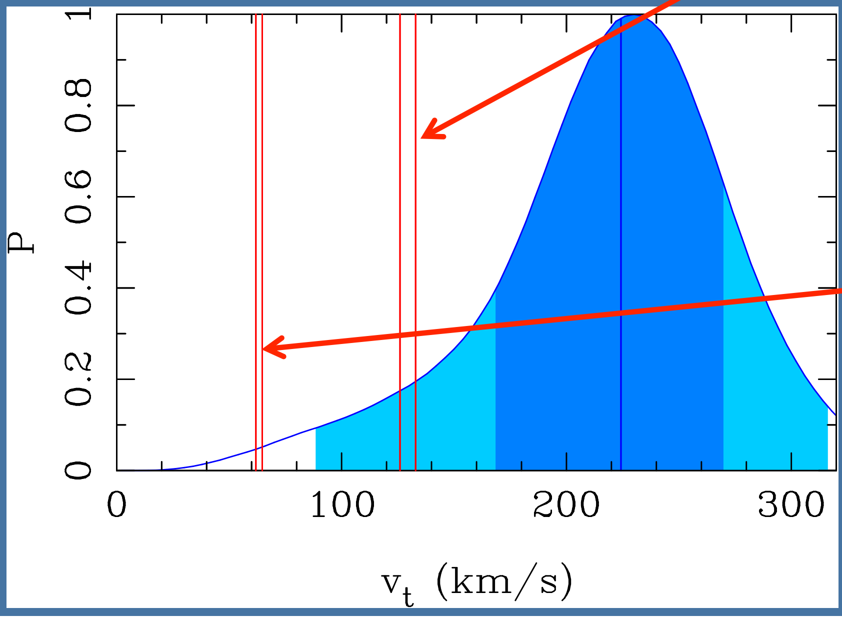
$a = 2.2_{-0.4}^{+1.3}$ AU

Small parallax (M-dwarf+Neptune) is more likely by Galactic model



2× more likely

3-4× more likely



Small parallax:

$M_h = 0.16 \pm 0.05 M_\odot$

$M_p = 18 \pm 5 M_\oplus$

$a = 4.6_{-1.1}^{+2.5}$ AU

$\tilde{v}_t = 220$, $v_t \sim 130$,

Large parallax:

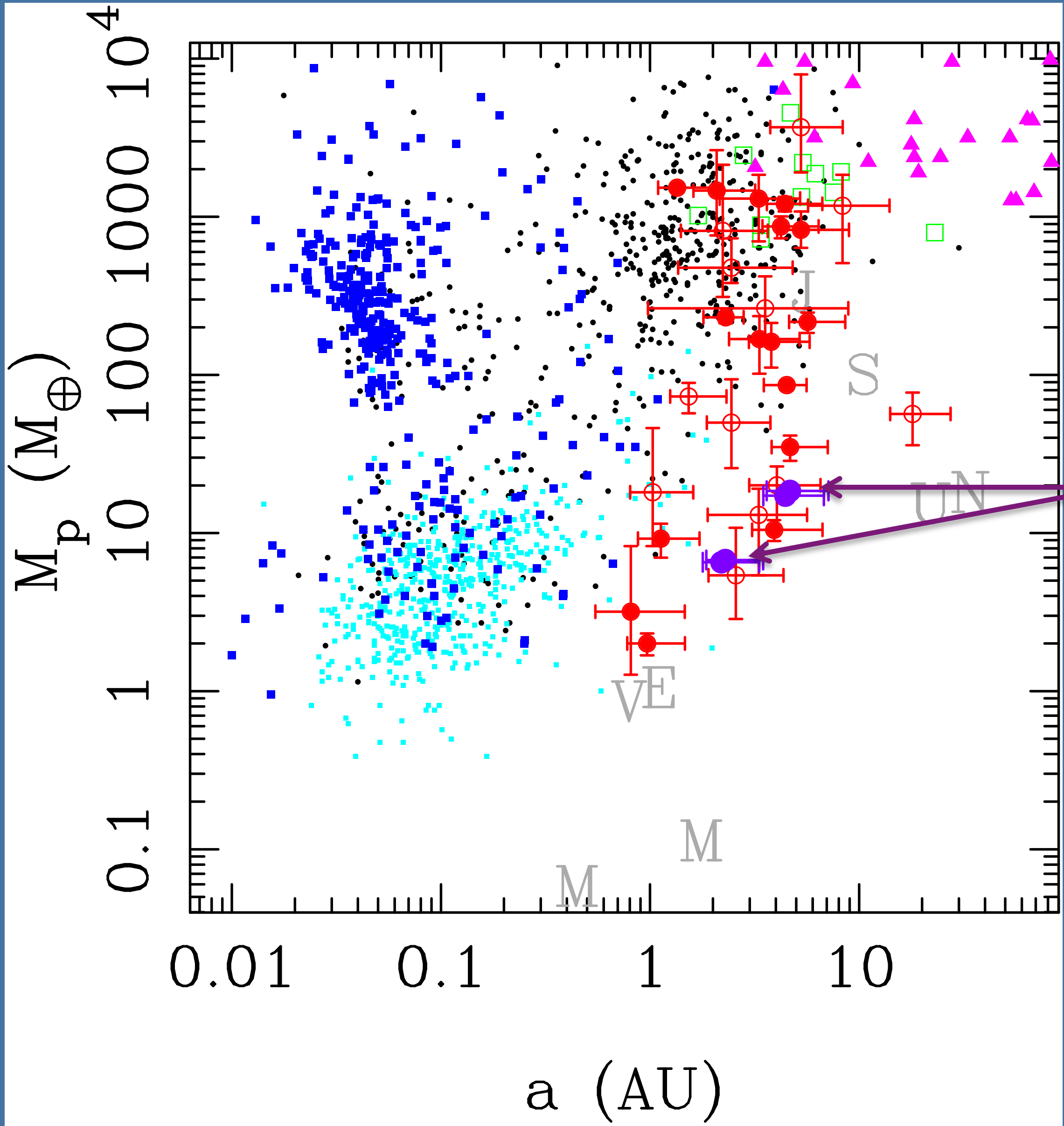
$M_h = 0.06 \pm 0.01 M_\odot$

$M_p = 6.6 \pm 1.0 M_\oplus$

$a = 2.2_{-0.4}^{+1.3}$ AU

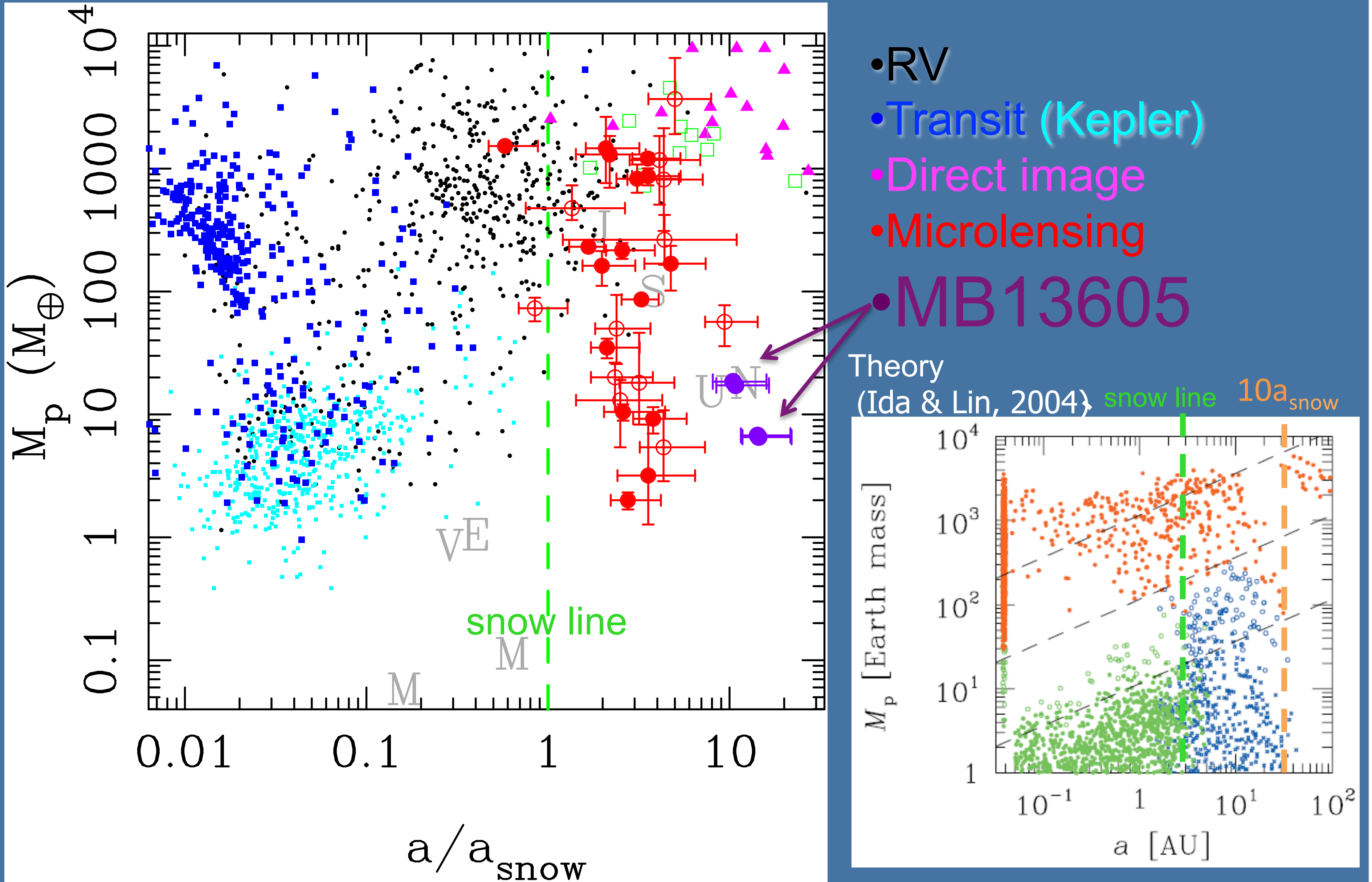
$\tilde{v}_t \sim 82$, $v_t \sim 64$

Discovered exoplanets (M_p-a)



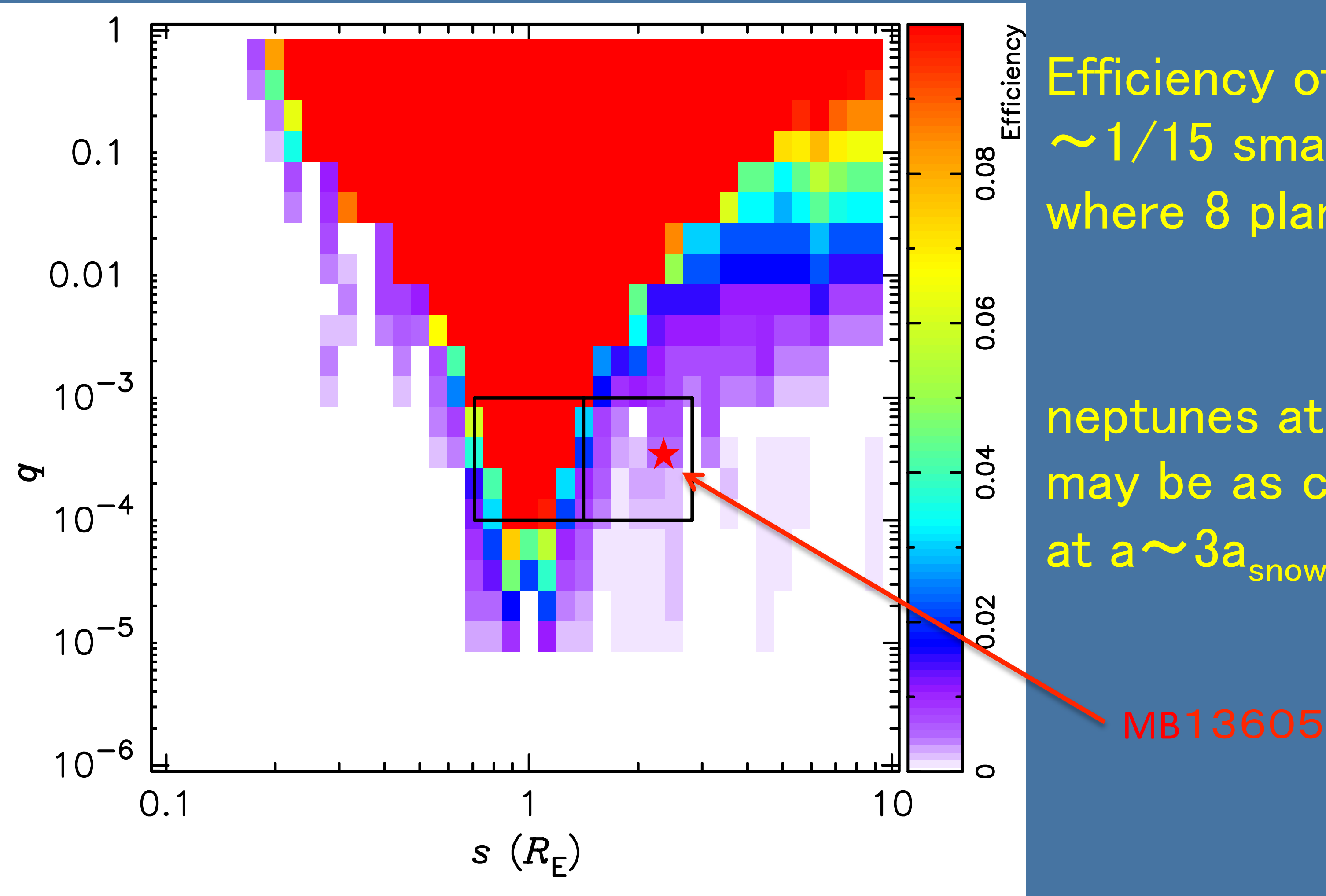
- RV
- Transit (Kepler)
- Direct image
- Microlensing
  - Mass measurements
  - Mass by Bayesian
- MB13605

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



Detection efficiency

Preliminary

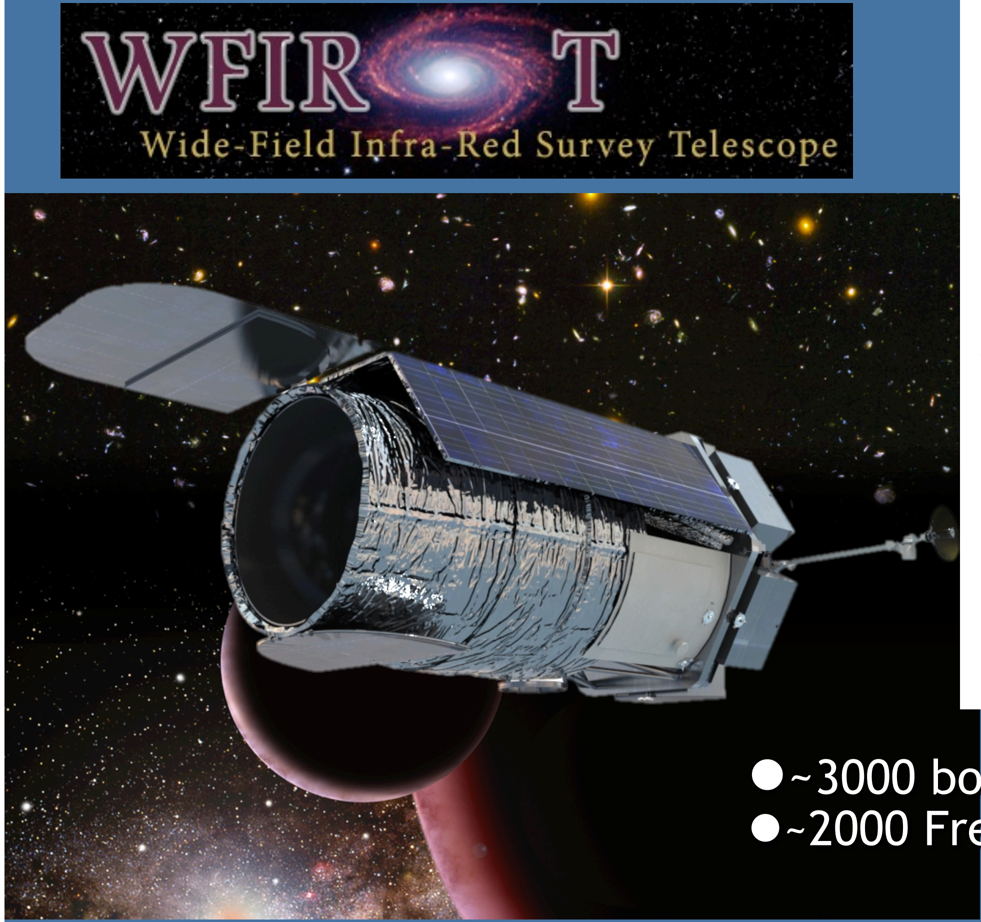


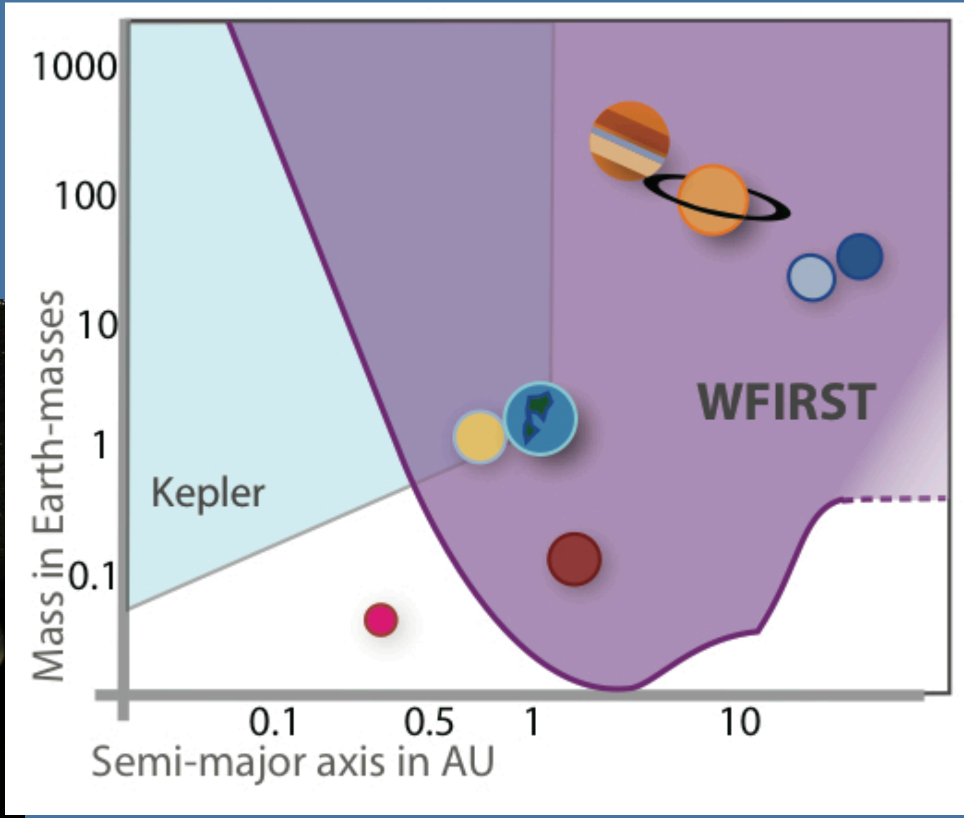
Efficiency of MB13605 is ～1/15 smaller than s～1 where 8 planets detected

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

Microlensing exoplanet search by WFIRST

D: 2.4m
FOV : 0.281deg.^{2}
$\lambda < 2\mu$m
15min cadence





- ~3000 bound exoplanets with ~200 w/ M < 1 $M_{\oplus}$,
- ~2000 Free-floating planets with ~100 w/ M < 1 $M_{\oplus}$

Summary

- MOA-2013-BLG-605Lb is the first Neptune analog
- neptunes at $a \sim 10a_{snow}$ could be as common as ones at $a \sim 3a_{snow}$

- Distribution of exo-neptunes is important to understand the formation of Neptune
- WFIRST can constrain the models.