Constraining Physical Properties of a Microlens

Subo Dong
Institute for Advanced Study

Angles!

$$\pi = \frac{AU}{D}$$

$$\mu = \frac{v_{proj}}{D}$$

Angles!

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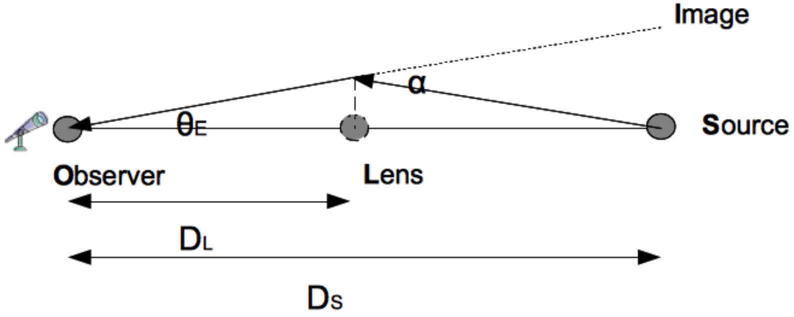
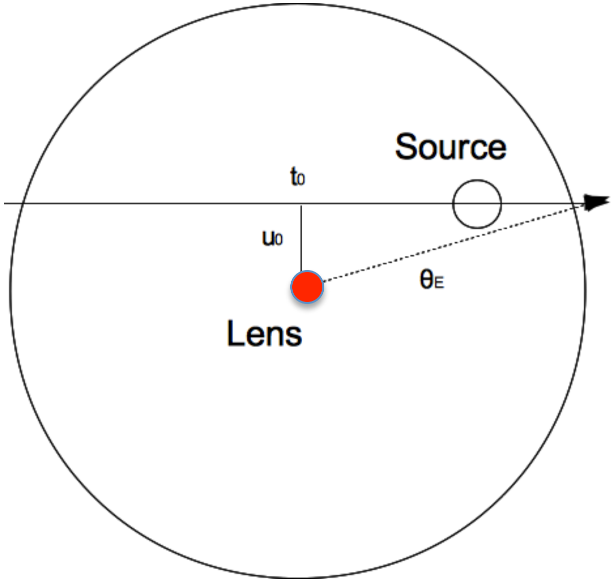
$$\mu = \frac{v_{proj}}{D}$$

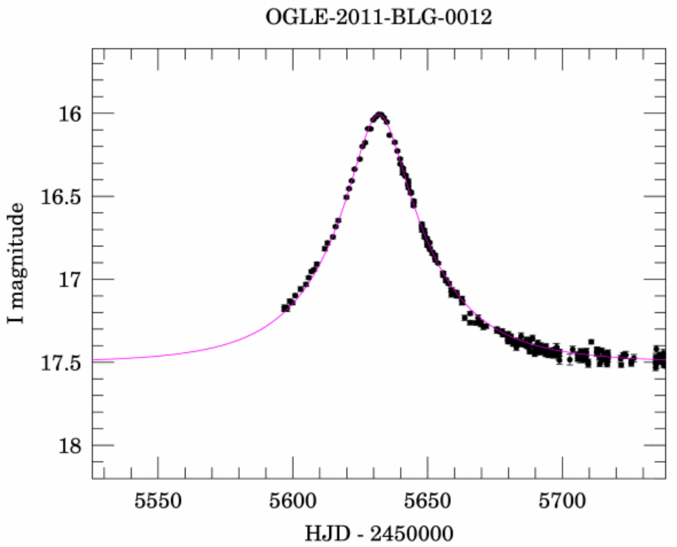




$$t_E = \frac{\theta_E}{\mu_{rel}}$$

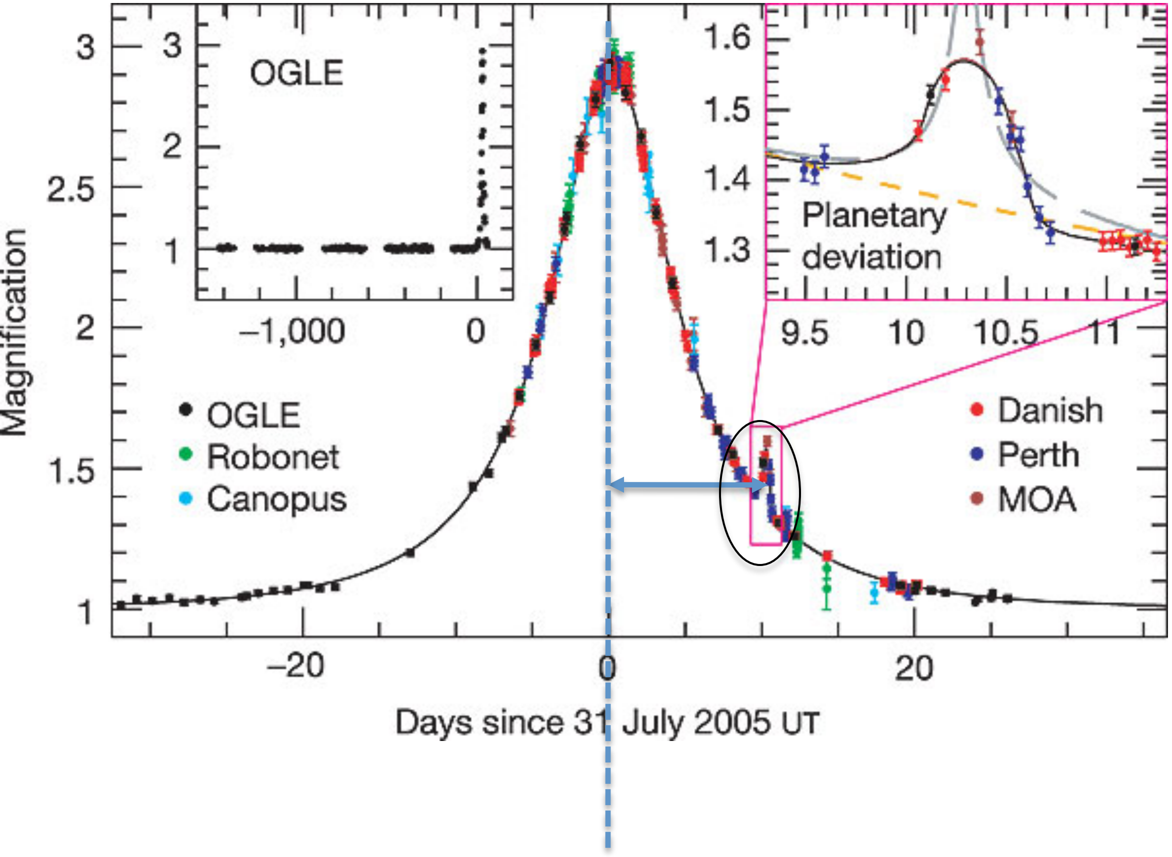
$$\theta_E = \sqrt{\kappa M_L \pi_{rel}}$$

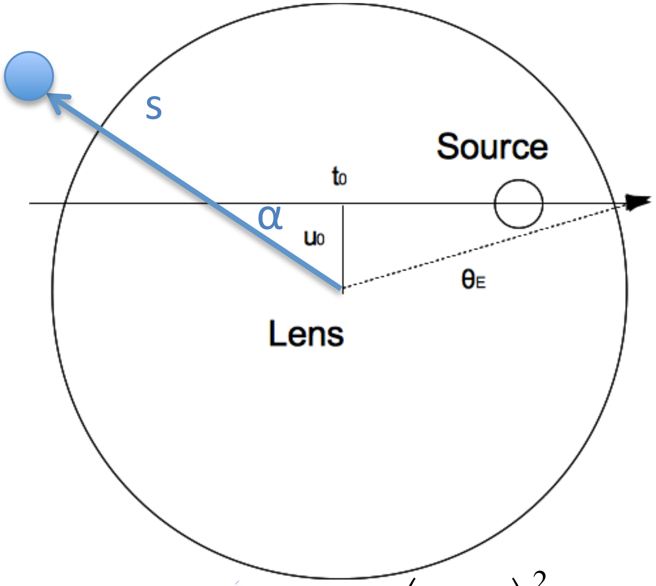
$$where, \kappa = 8.14 \frac{mas}{M_{sun}}, \pi_{rel} = \frac{AU}{D_L} - \frac{AU}{D_S}$$



What can be directly learned about the planet from the light curve?

Key scale: Einstein radius



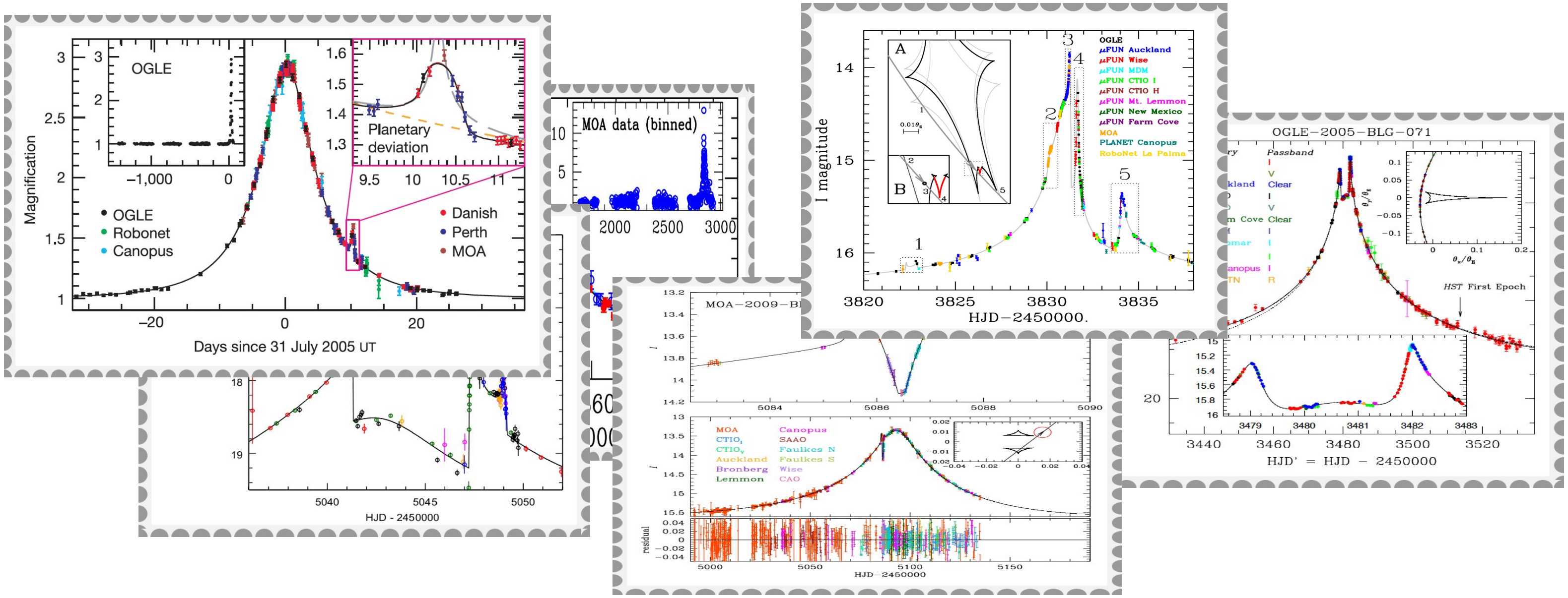


Mass ratio $q = \left(\frac{\theta_{E,P}}{\theta_E} \right)^2$

Projected separation s in θ_E

Trajectory angle α

How do we get host/planet mass and distance?



q,
s

?

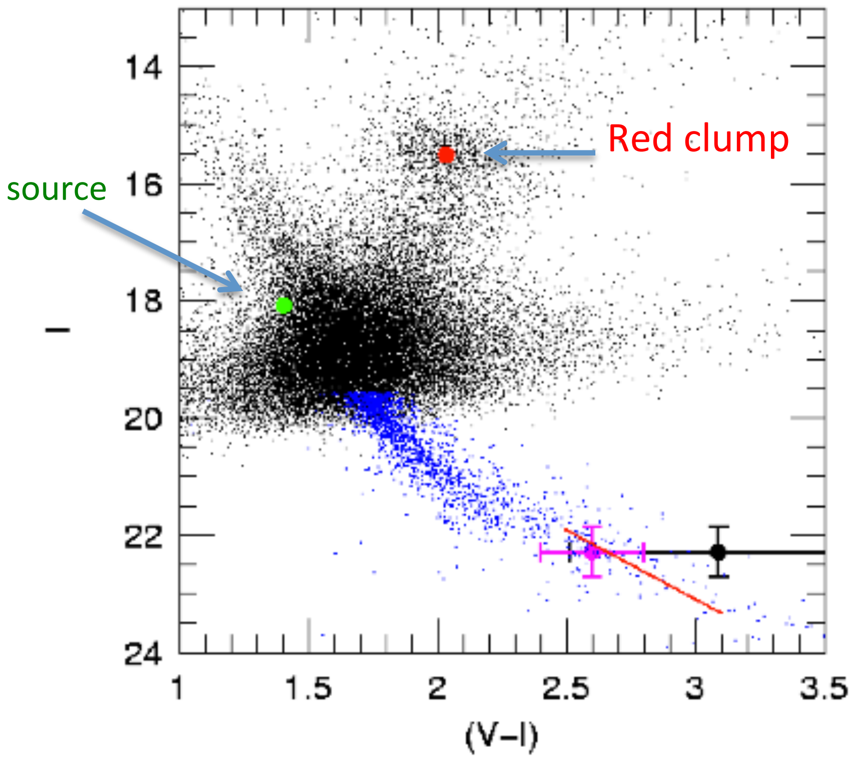
M_p,
r_{proj} in AU

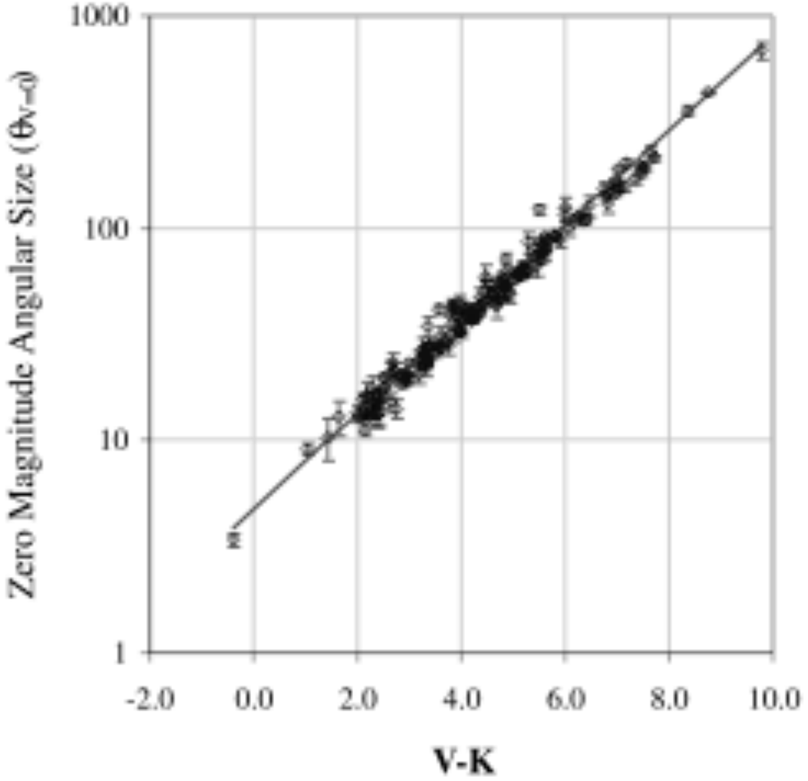
Need to know lens mass M and physical size of Einstein radius r_E

Ruler 1: Source Star Angular Size

- Angular size of the star can be derived from its de-reddened color and magnitude (Albrow et al., 1999; Yoo et al., 2004)

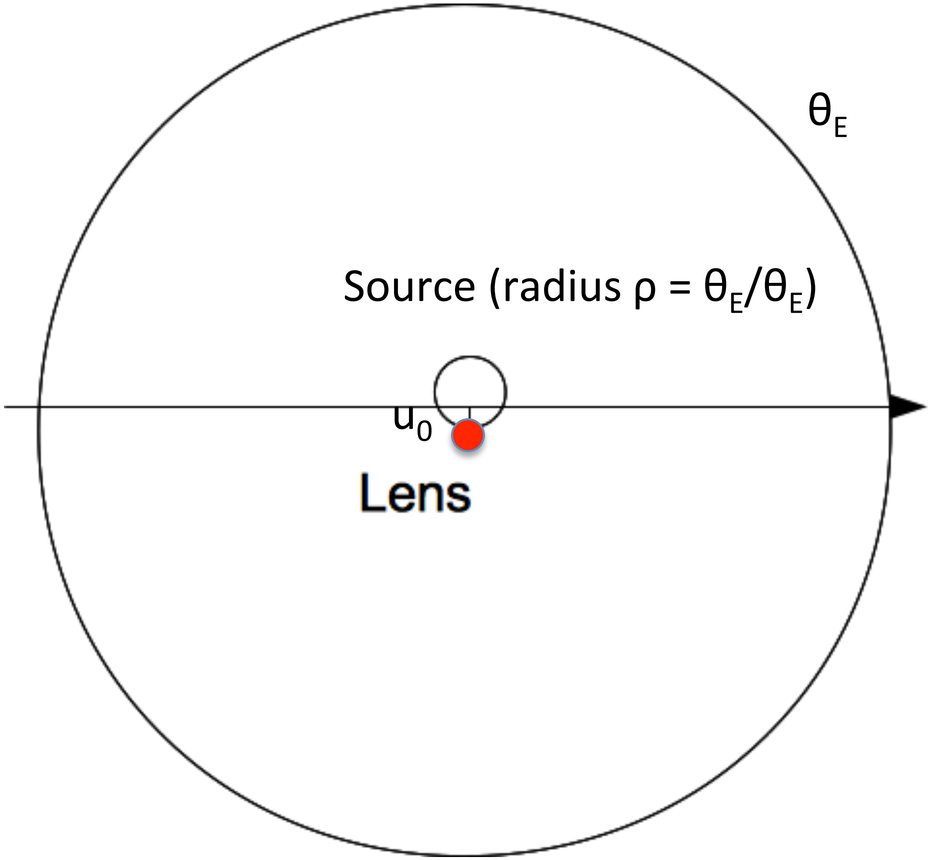
OGLE-2004-BLG-343





van Belle, G. T. 1999, PASP, 111, 1515

also, Kervella P., et al. 2004, A&A, 428, 587



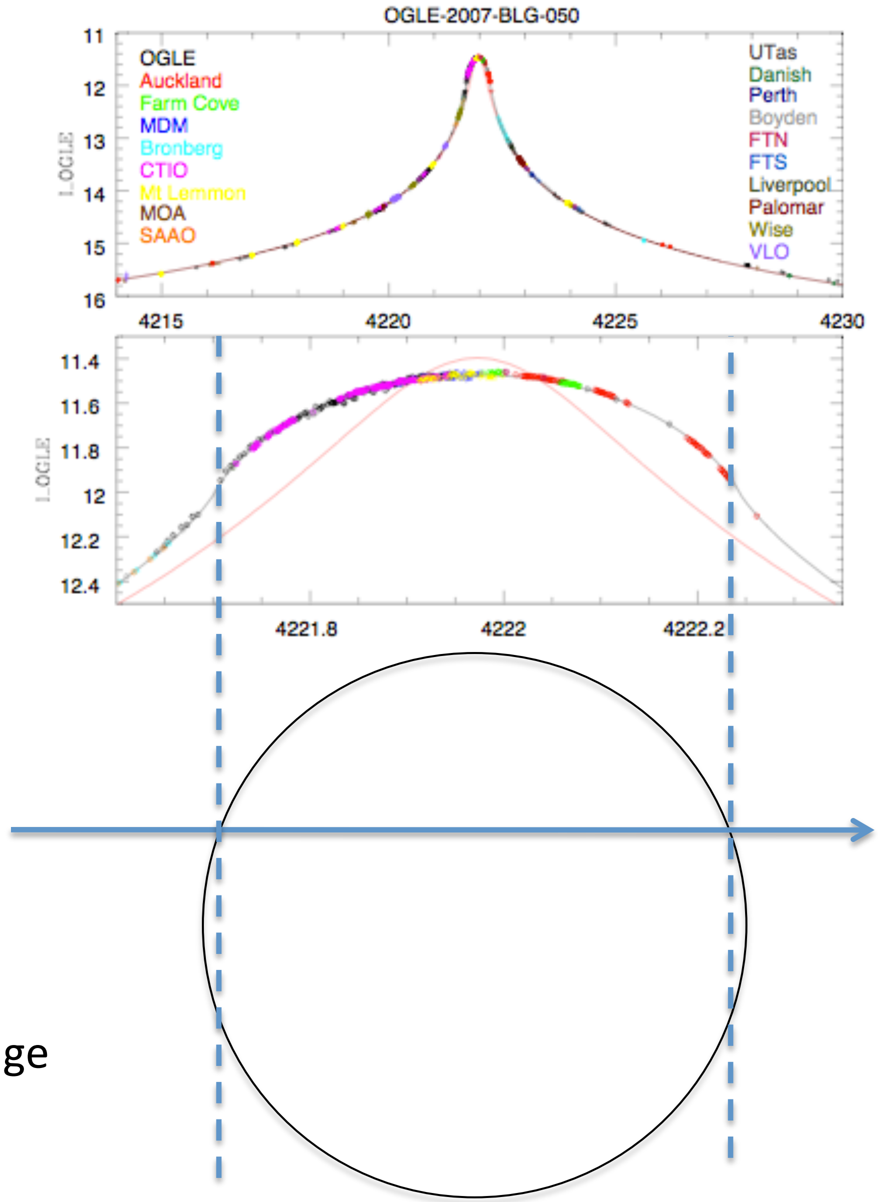
θ_E

Source (radius $\rho = \theta_E/\theta_E$)

u_0

Lens

Finite-source: Angular Einstein Radius (High-mag)



Lens passage

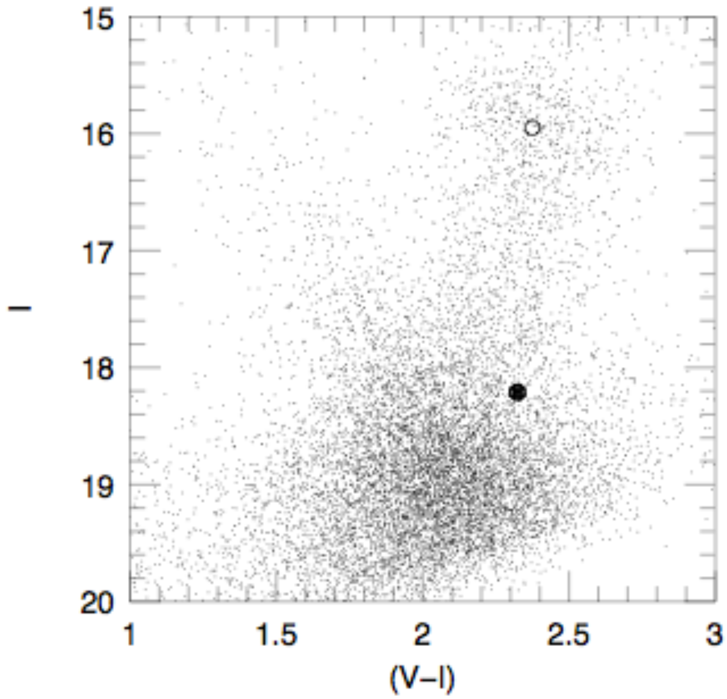
Source star

$u0 = 0.002$
$\rho = 0.0045$

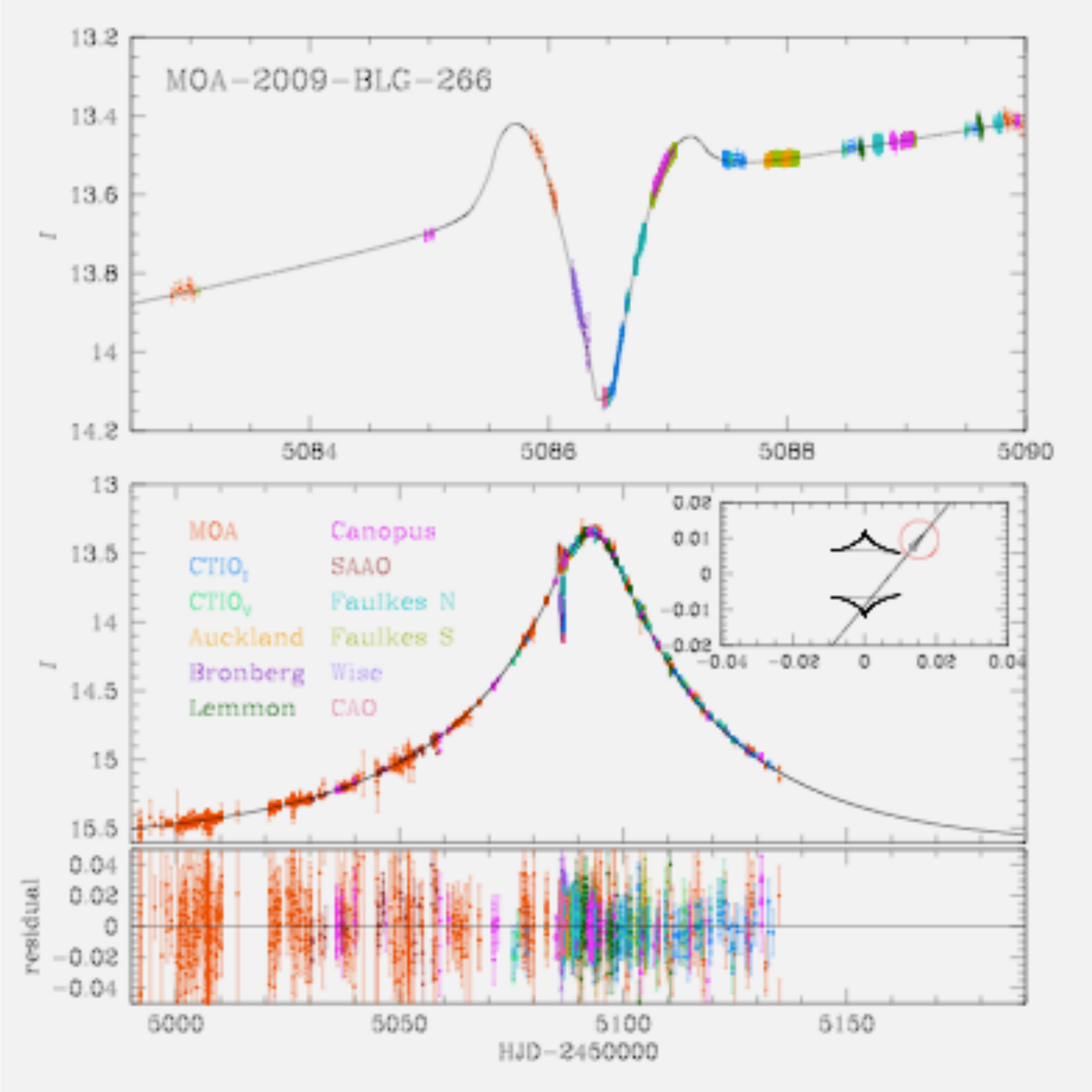
$\theta_* = 2.20 \pm 0.06\ \mu\text{as}$

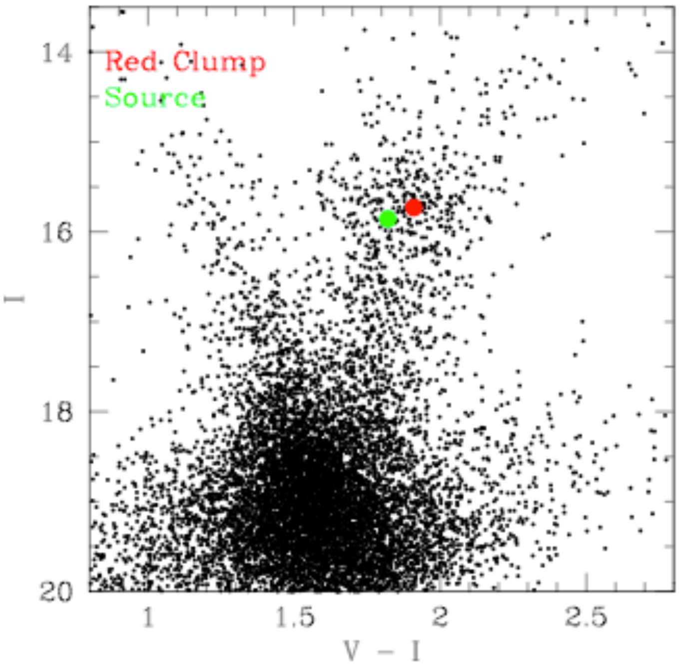
$\theta_E = \theta_* / \rho = 0.48 \pm 0.01\ \text{mas}$
$= \theta_*/t_* {*} t_E$

Batista, V., et al., 2009, A & A, 508, 467



Finite-source: Angular Einstein Radius (Binary/Planetary)





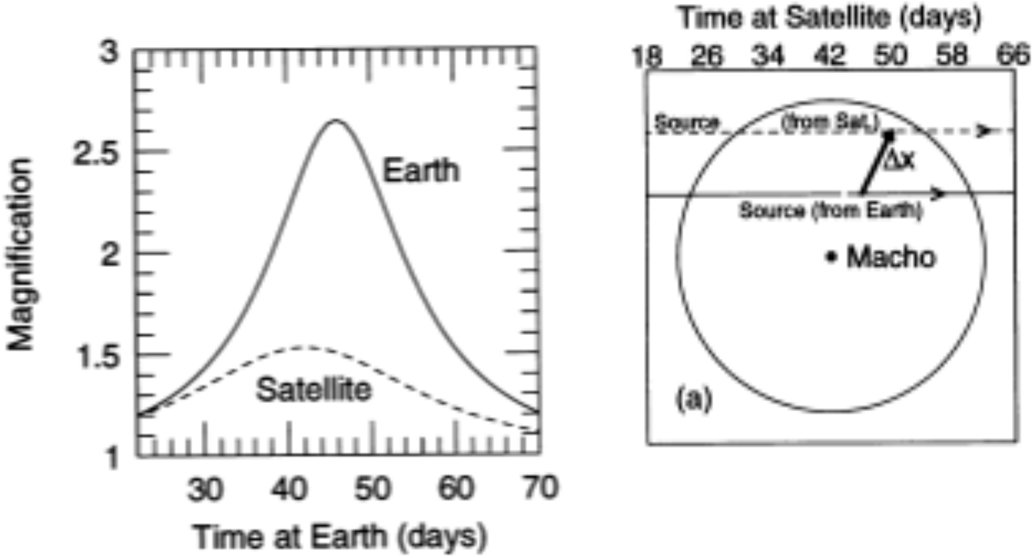
$\theta_\star = 5.2 \pm 0.2$ μas.

$\theta_E = 0.98 \pm 0.04$ mas

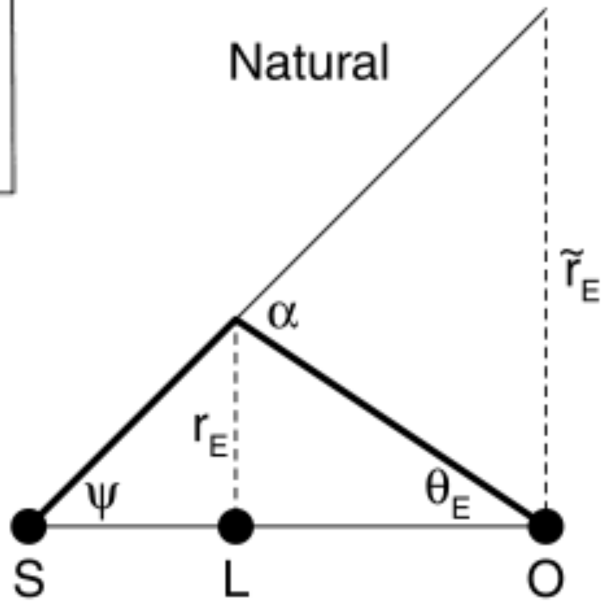
Muraki et al., 2011, ApJ, accepted

Ruler No. 2 on the observer plane

- Microlens parallax:

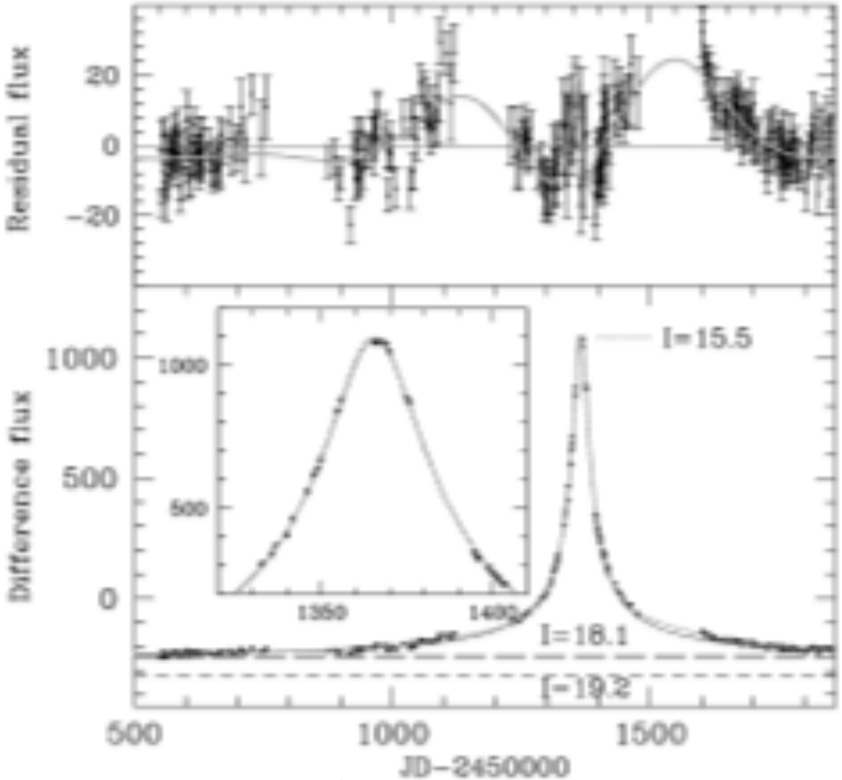


Gould, 1994, ApJ, 421, 75

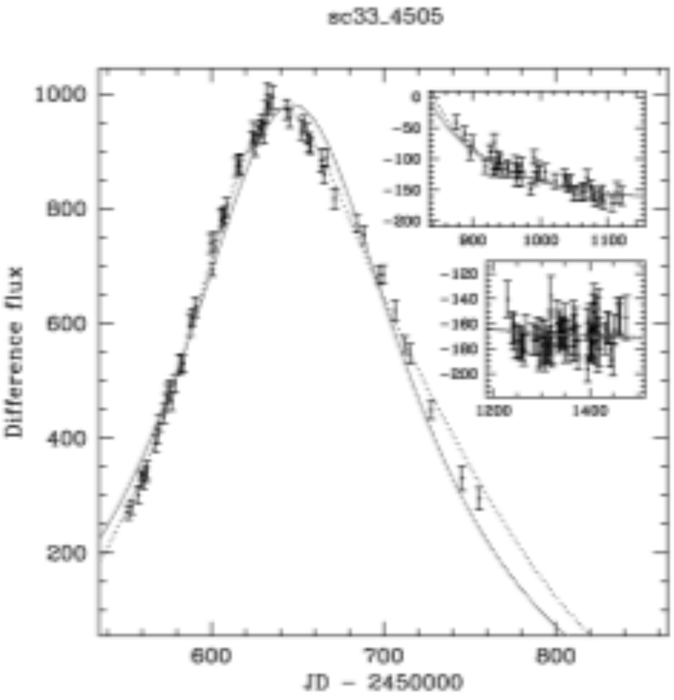


Ruler No. 2 on the observer plane

- Microlens Orbital parallax:
  Earth orbit as the ruler:
  Measuring Projected Einstein radius on the observer plane



Mao, S., et al., 2002, MNRAS, 329, 349



Smith, et al, 2002, MNRAS, 332, 962

Ruler No. 2 on the observer plane

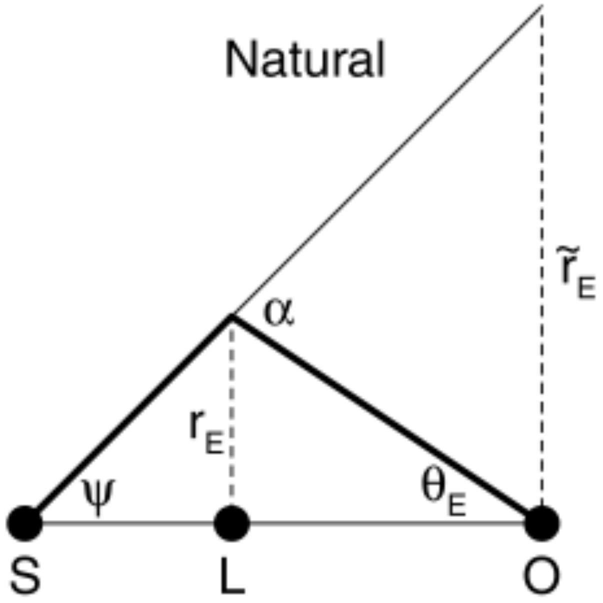
- Microlens Orbital parallax:
  Earth orbit as the ruler:
  Measuring Projected Einstein radius on the observer plane

$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

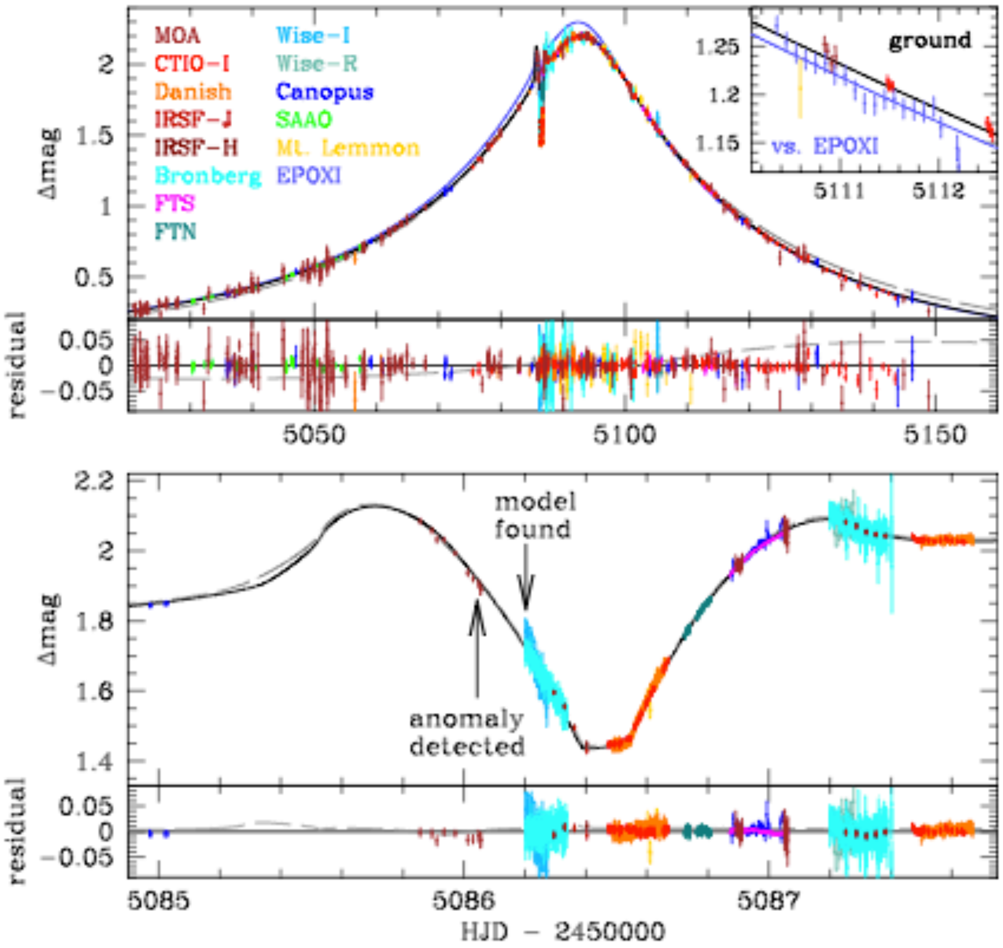
$$\theta_E = \alpha - \psi = \frac{\tilde{r}_E}{D_l} - \frac{\tilde{r}_E}{D_s} = \frac{\tilde{r}_E}{D_{rel}}$$

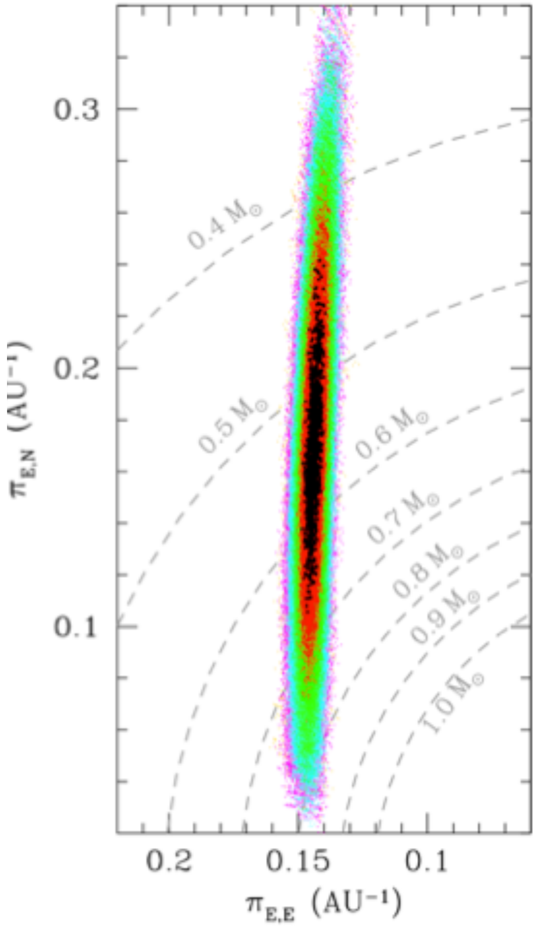
$$\pi_E \theta_E = \pi_{rel} , \quad \pi_E \equiv \frac{\mathrm{AU}}{\tilde{r}_E}$$

Gould, A, 2000, ApJ, 542, 785



Parallax + Finite Source



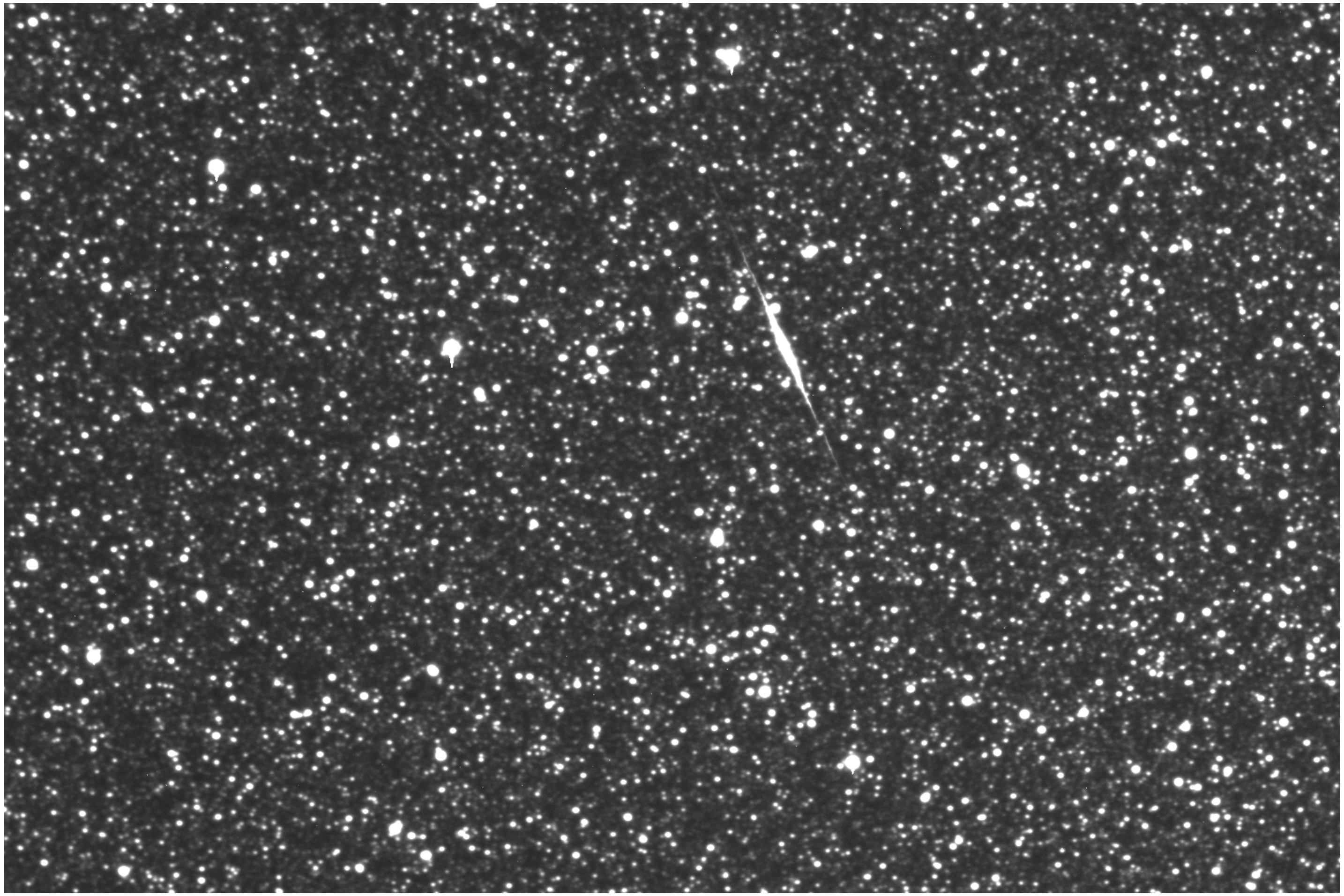


$$M_L = \frac{\theta_E c^2 \mathrm{AU}}{4G\pi_E} = \frac{\theta_E}{(8.1439\,\mathrm{mas})\pi_E} M_\odot \approx 0.57 M_\odot \qquad D_L = \frac{\mathrm{AU}}{\pi_E \theta_E + \pi_S} \approx 3.2\ \mathrm{kpc}$$

$m_p = 10.4 \pm 1.7 M_\oplus \quad a = 3.2^{+1.9}_{-0.5}$ AU

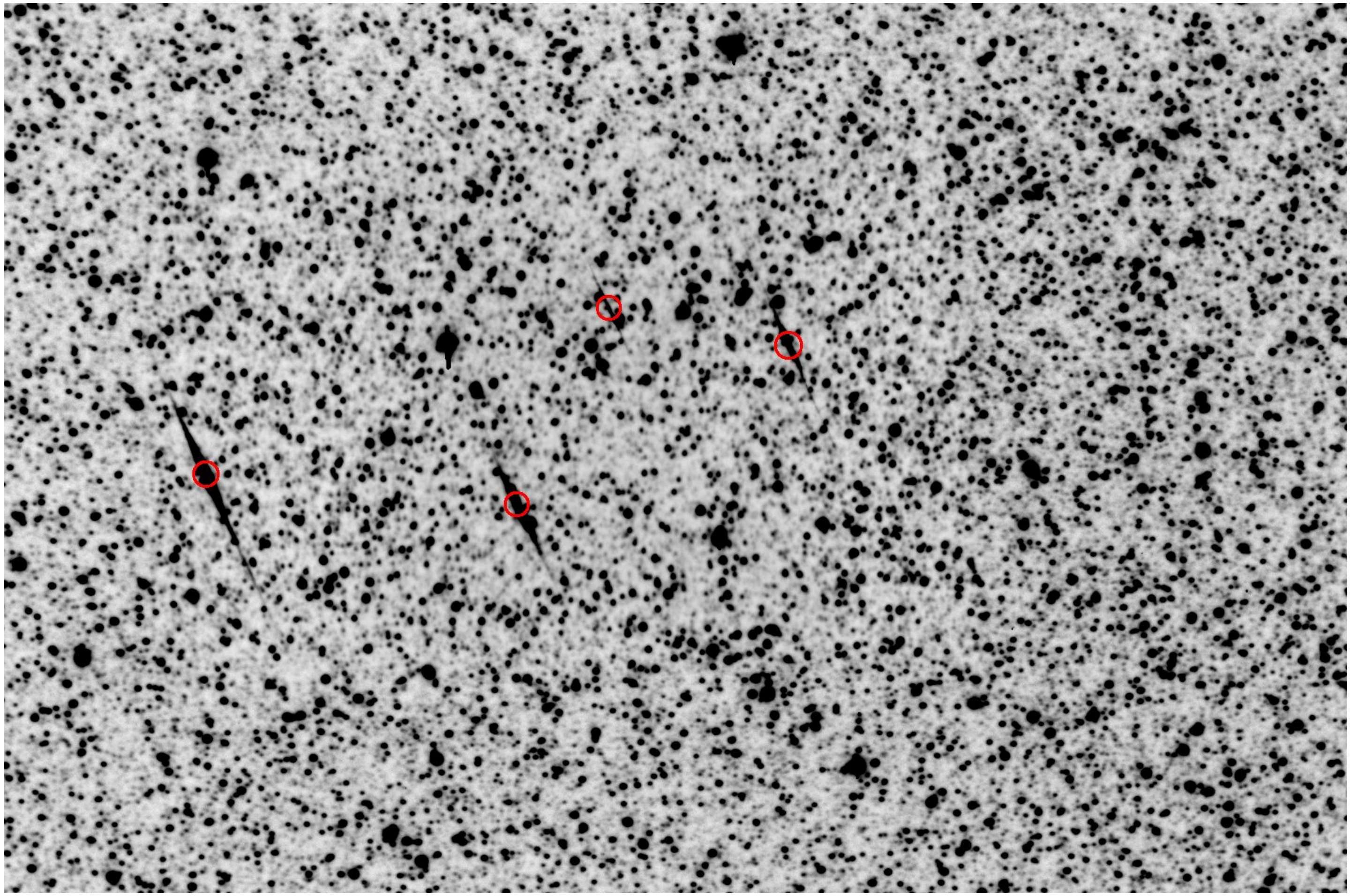
Muraki et al., 2011, accepted

MicroFUN



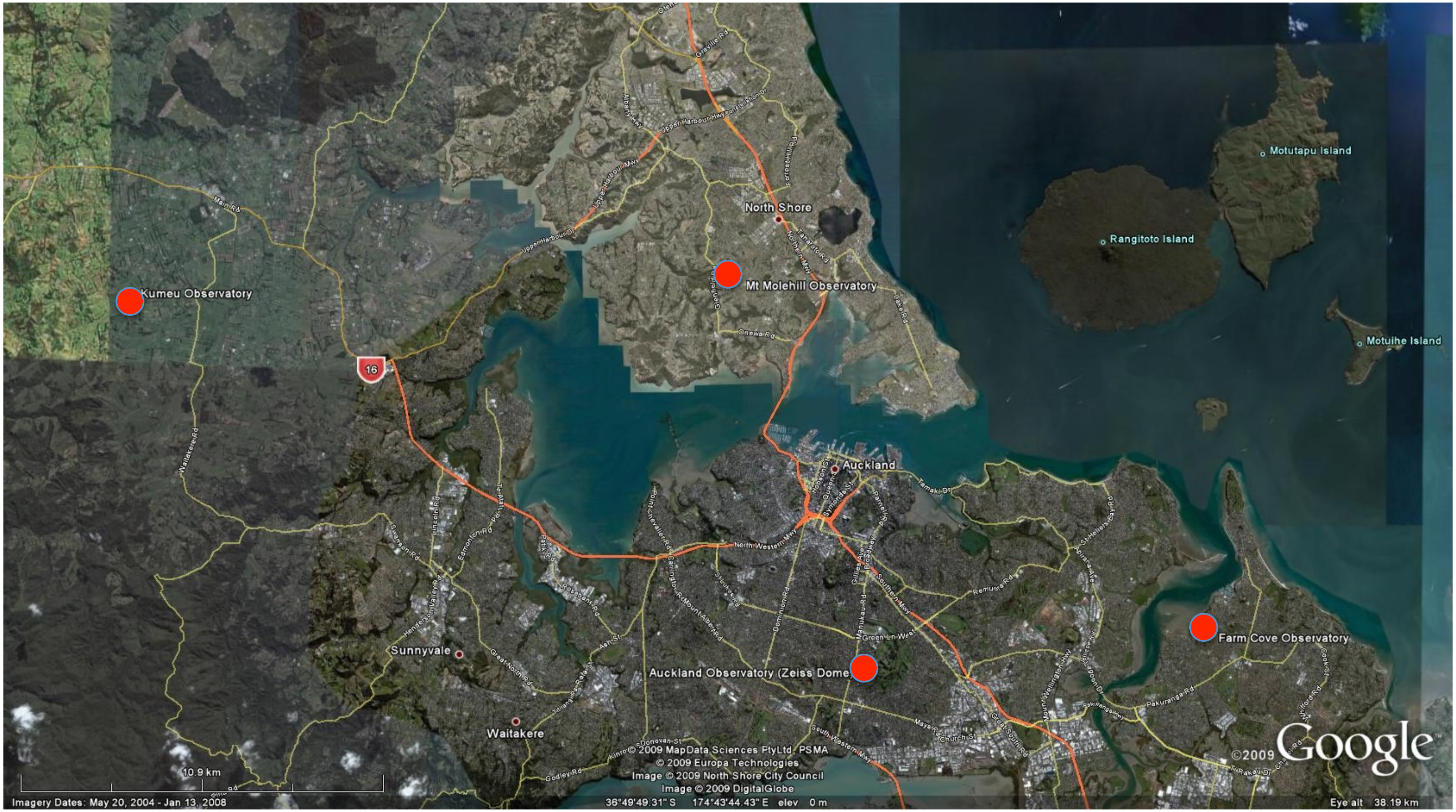
From Jennie McCormick, Farm Cove, New Zealand

Fun with multi-site observations



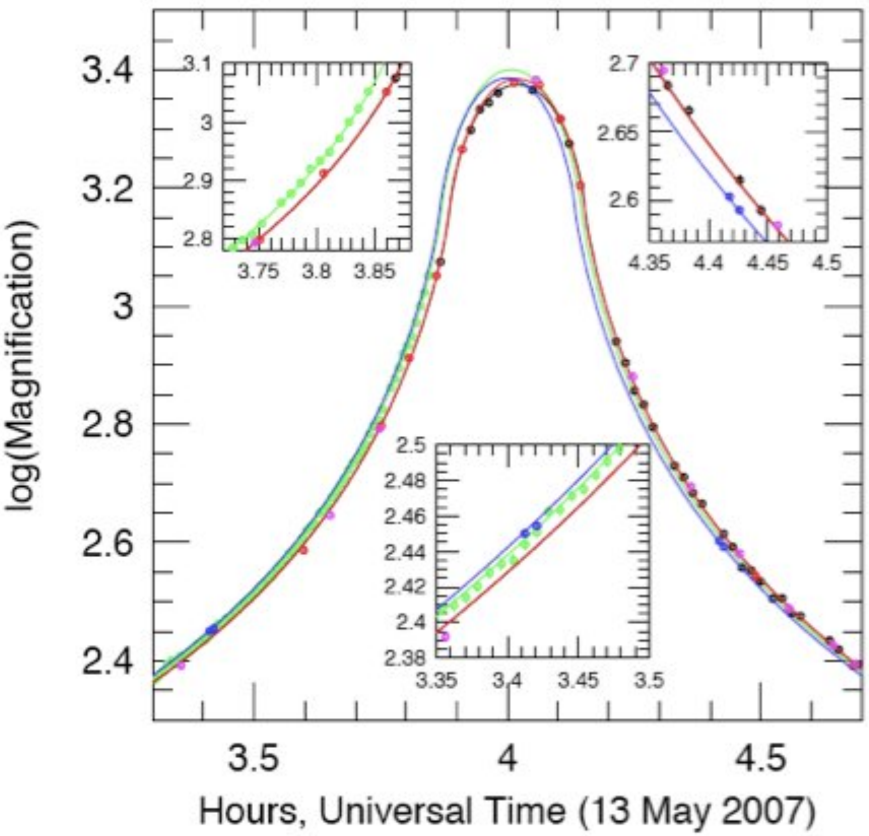
Credit: Grant Christie

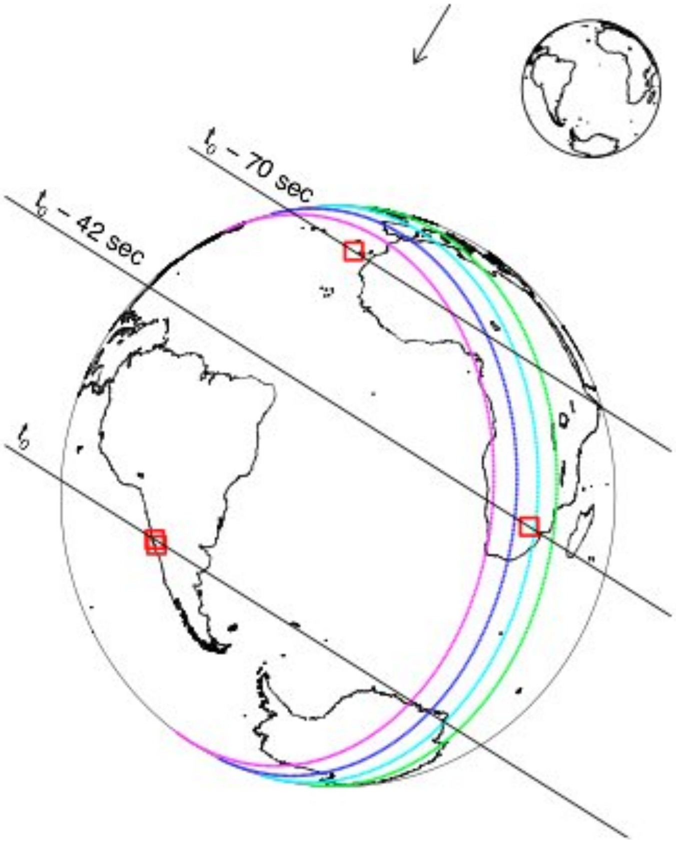
Terrestrial Parallax



COSMOS 1490 Earth altitude: 19110.4734 km

OGLE-2007-BLG-224, An old thick-disk brown dwarf





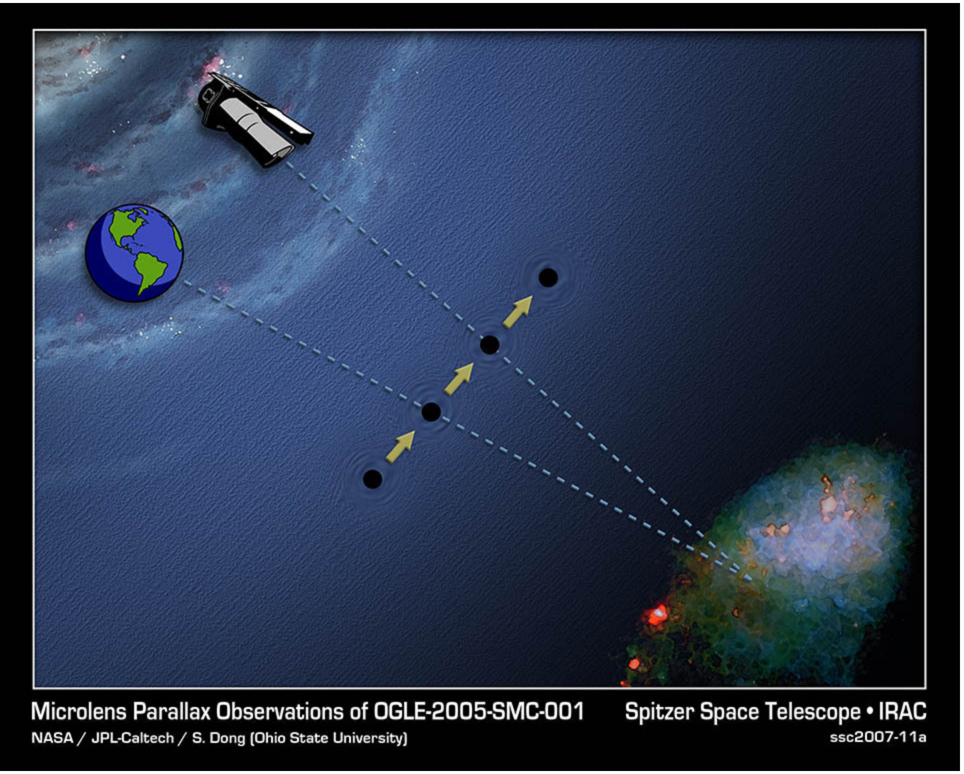
M=0.056 +/- 0.004 Msun; D = 525 +/- 40 pc

Old Thick-disk Brown dwarf?

Expected: H ~ 25.7 mag

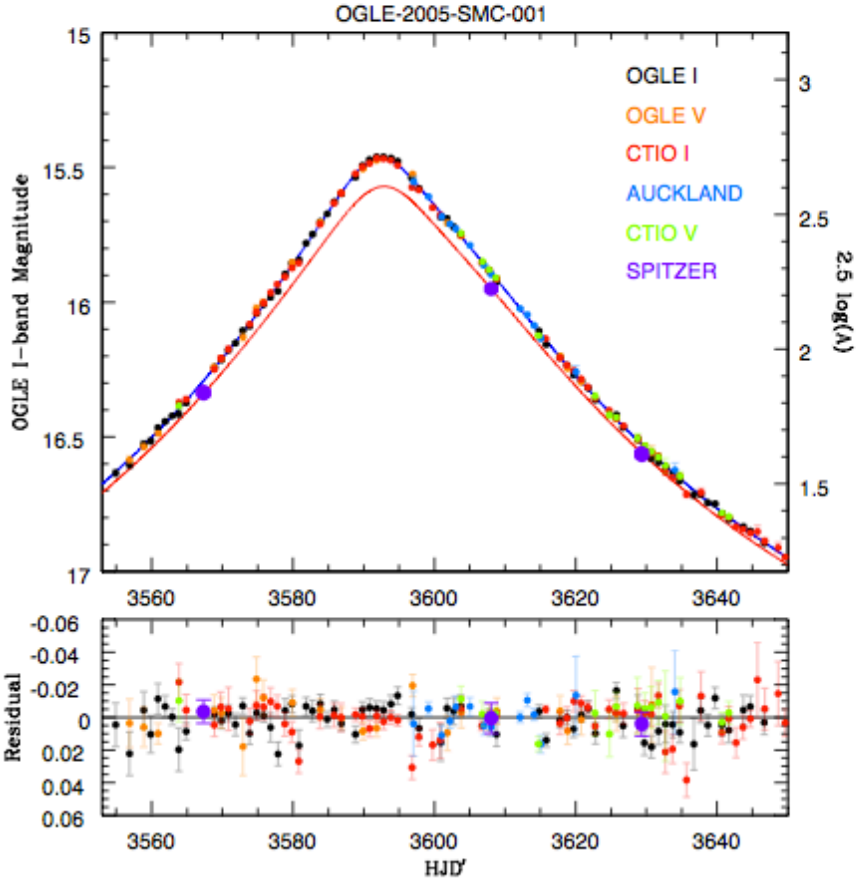
Gould, A., et al., 2009, ApJL, 698, L147

Space-based Microlens Parallax



Microlens Parallax Observations of OGLE-2005-SMC-001 Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / S. Dong (Ohio State University) ssc2007-11a



Dong, S., et al., 2007, ApJ, 664, 862

WFIRST will be at L2, suitable for measuring microlens parallax for Earth-mass planet:

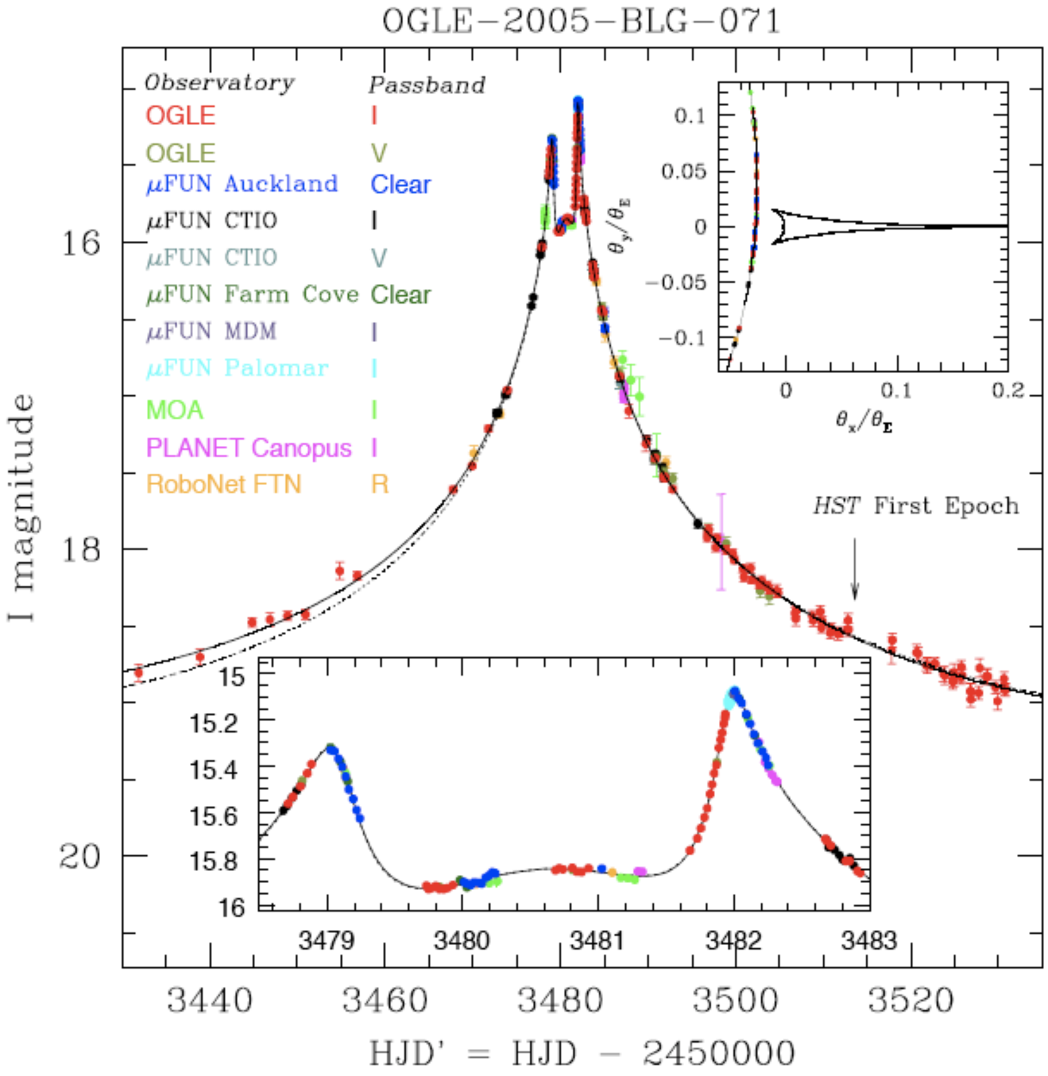
$$d_{\rm sat} \sim \sqrt{\frac{4GM_{\oplus}\,{\rm AU}}{c^2\,\pi_{\rm rel}}} = 0.025\,{\rm AU}\left(\frac{\pi_{\rm rel}}{40\,\mu{\rm as}}\right)^{-1/2}$$

Gould, Gaudi, & Han, 2003, ApJL, 591, L53

Seeing the lens with high-res imaging

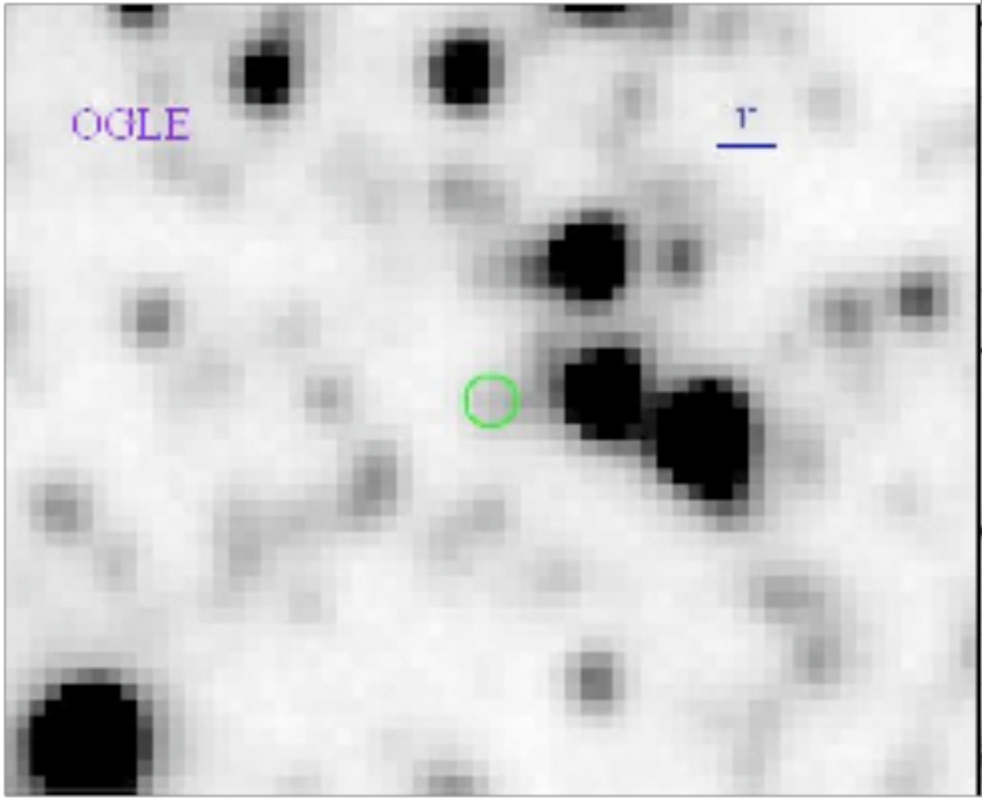
- Flux = F_{source} x A + F_{blend}
  - – F_{blend}: Lens + Other stars in the PSF (~1”) <-> Bulge Field is very crowded!
  - – High-res imaging is needed
    - Hubble Space Telescope
    - Adaptive Optics in IR from the ground (Keck, VLT)
- Constrain brightness (and color) of the lens
- θ_E or π_E yields a mass-distance constraint

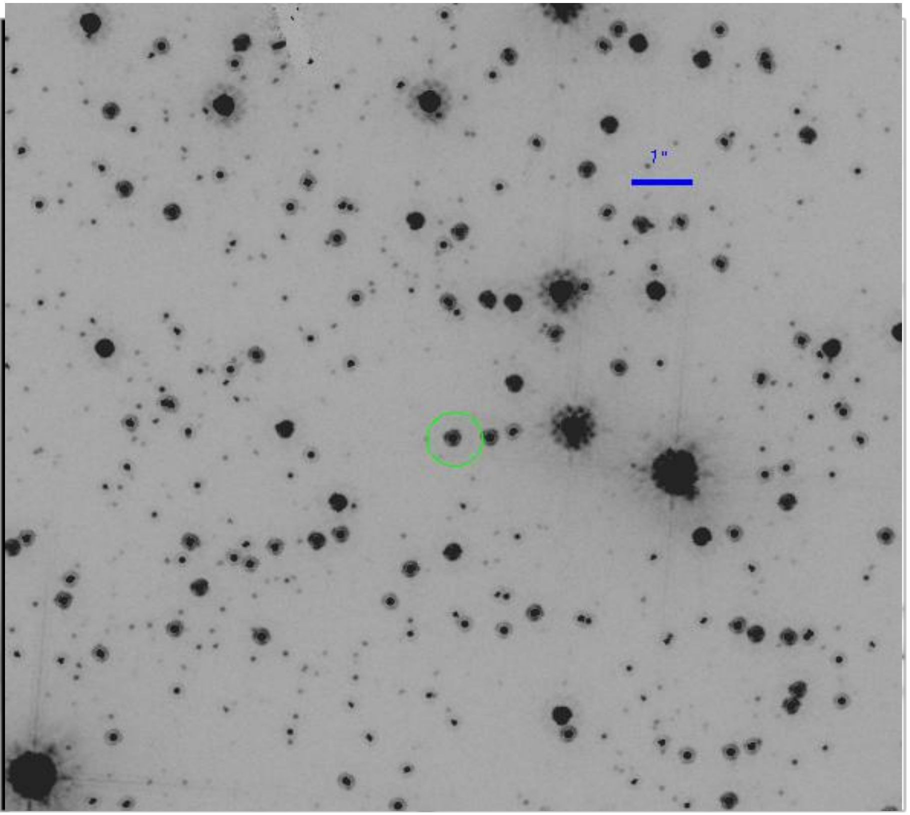
OGLE-2005-BLG-071Lb

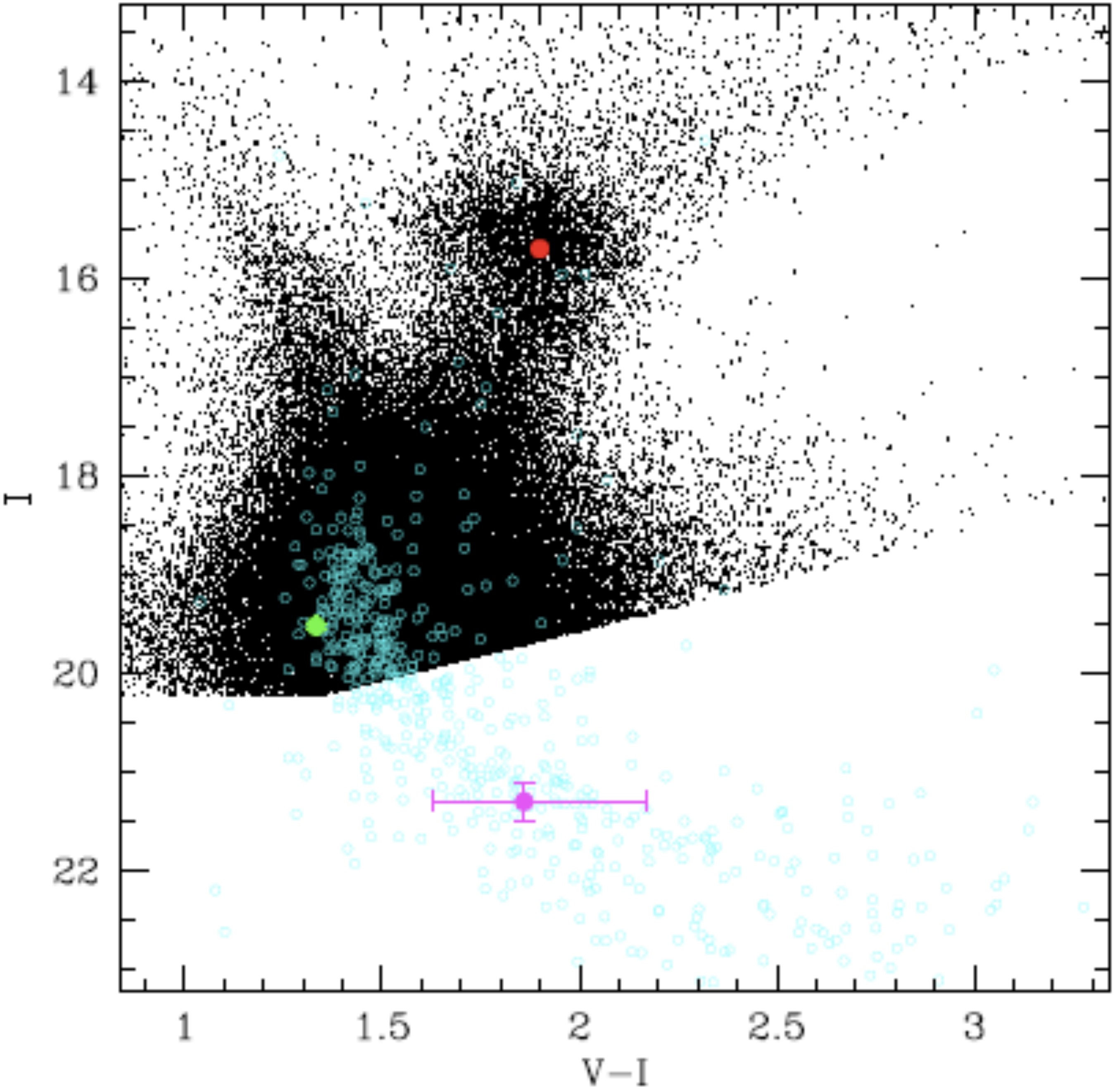


Dong, S., et al. 2009, ApJ, 698, 1826

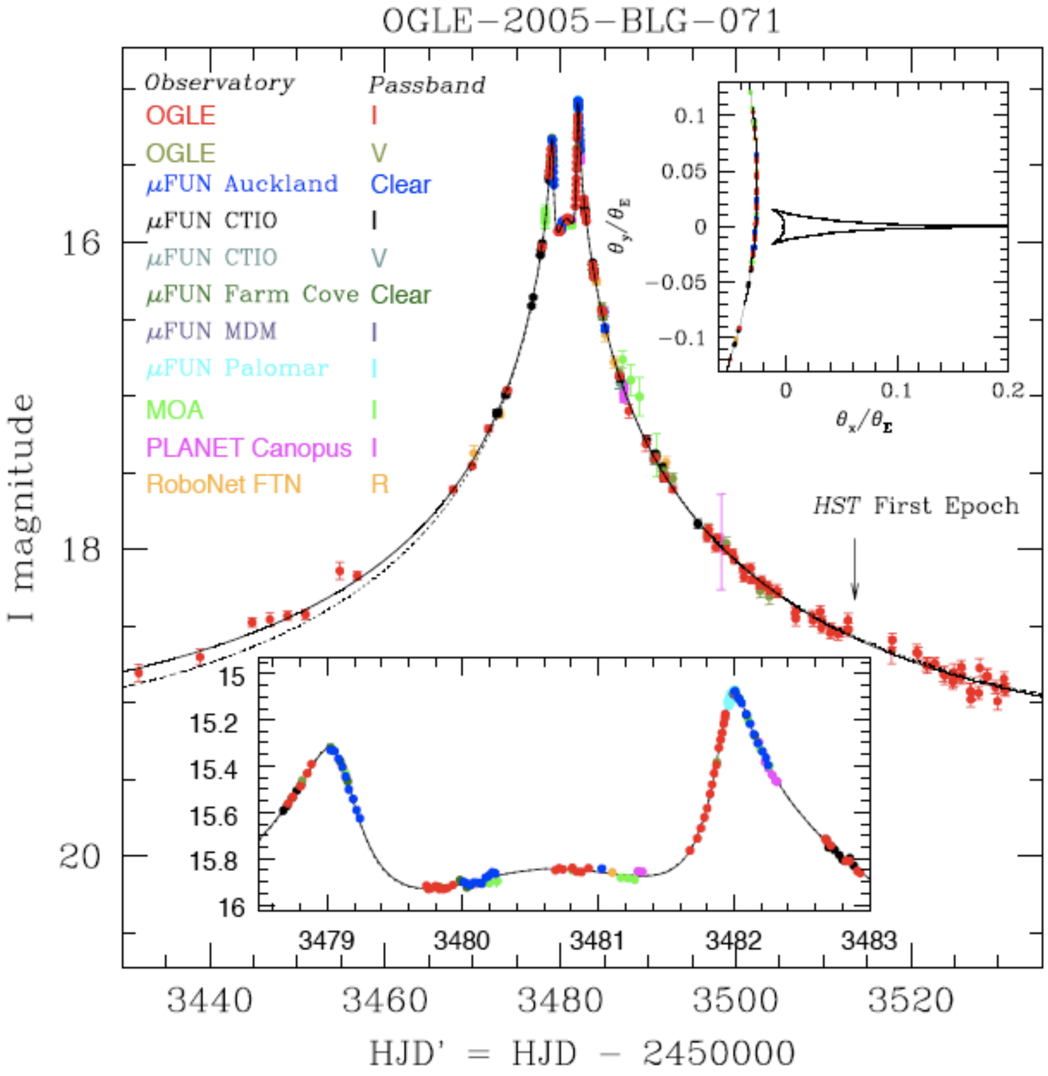
Ground v.s. Space

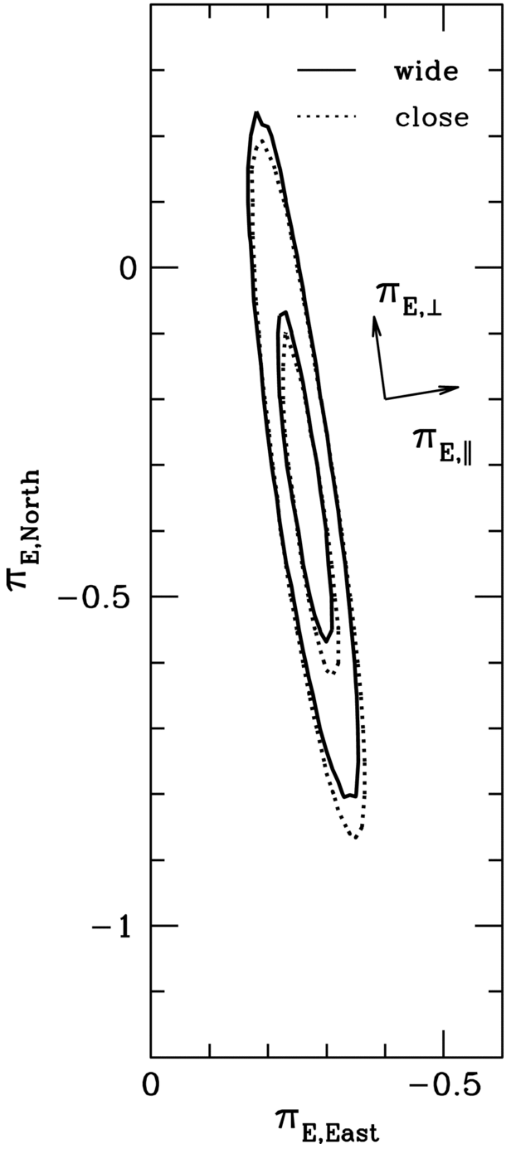




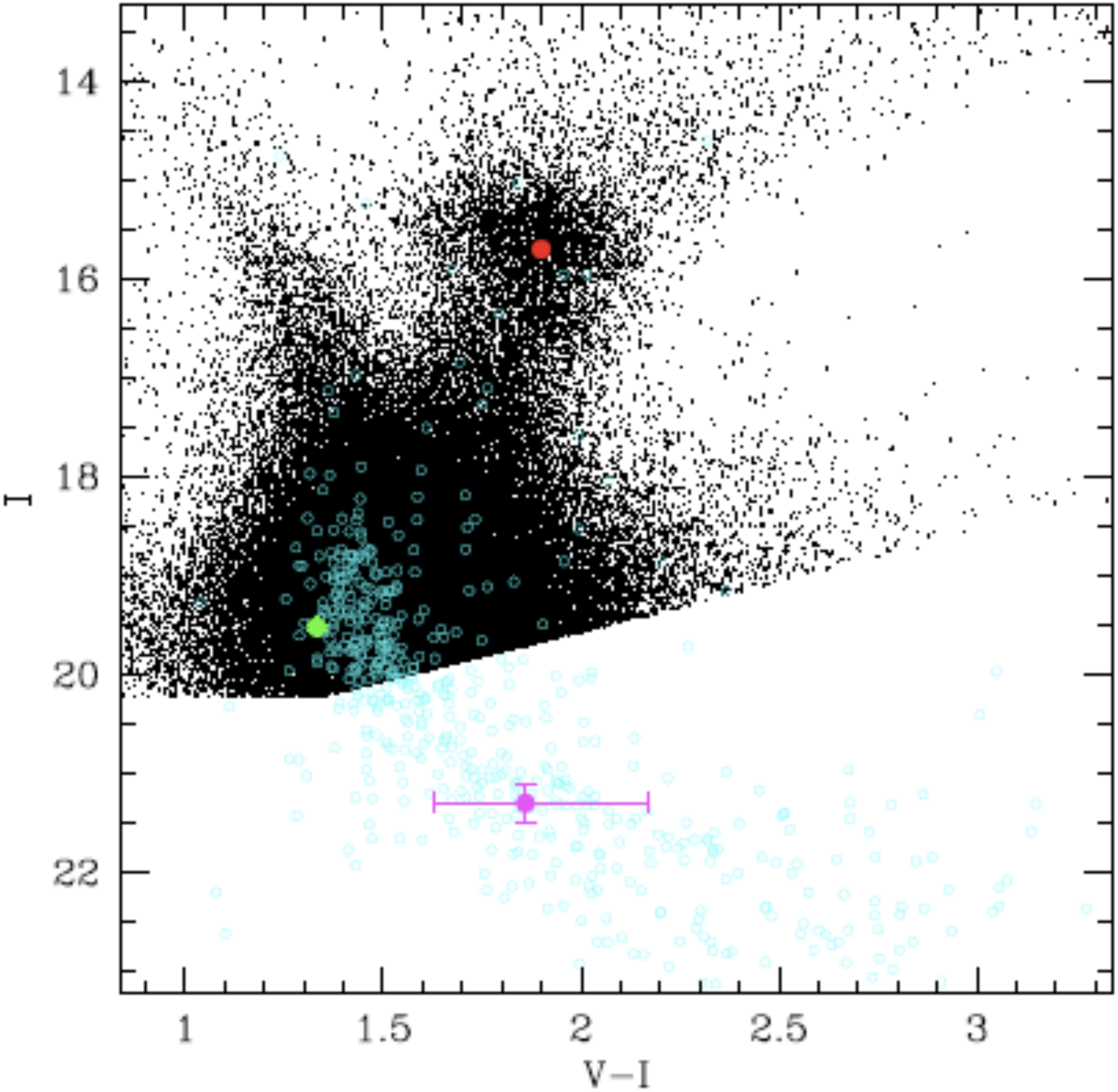

14
16
18
20
22
I
1
1.5
2
2.5
3
V−I

OGLE-2005-BLG-071Lb





Dong, S., et al. 2009, ApJ, 698, 1826


14
16
18
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I
1
1.5
2
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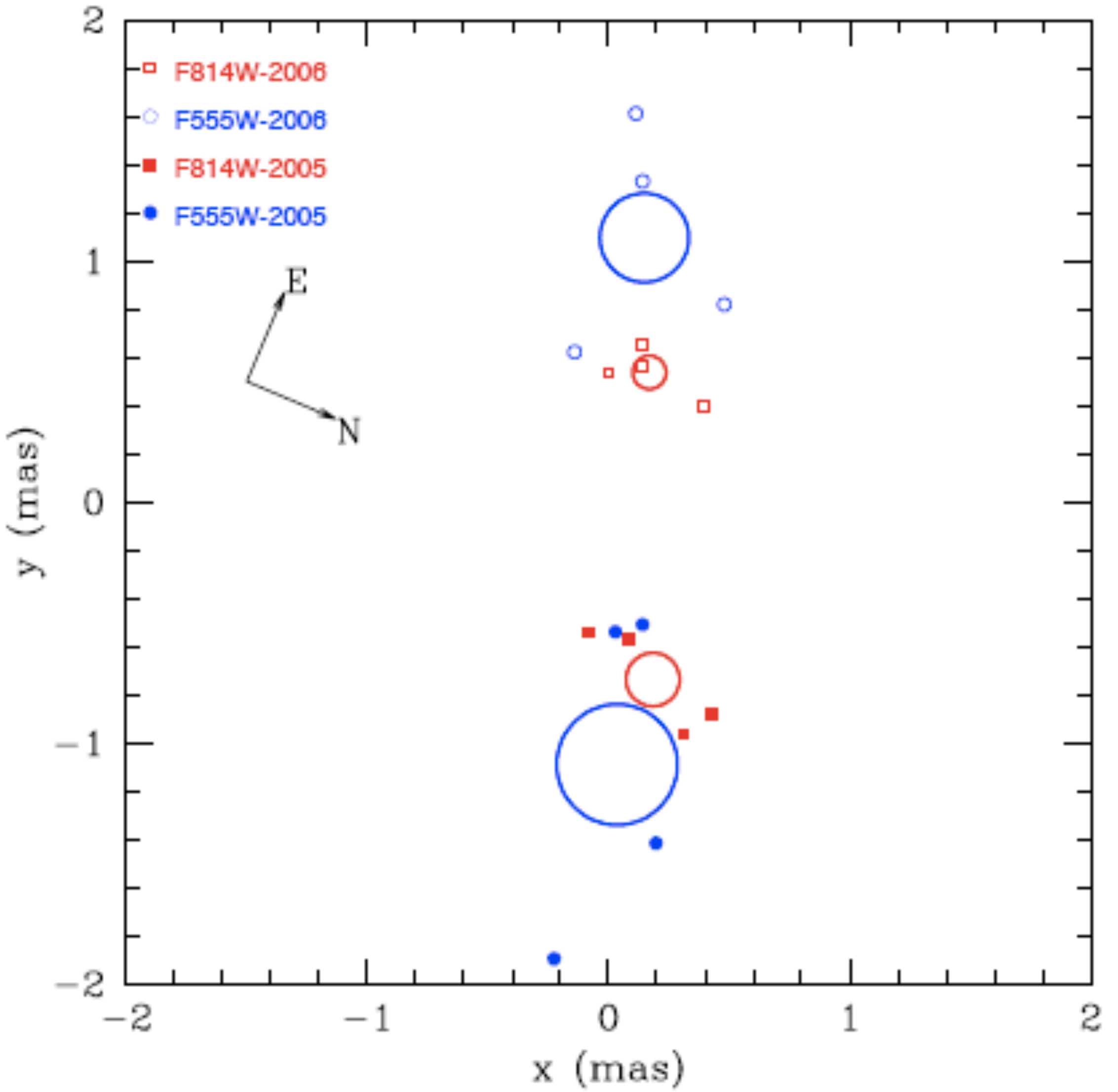
3
V−I

Even marginal astrometry signal!



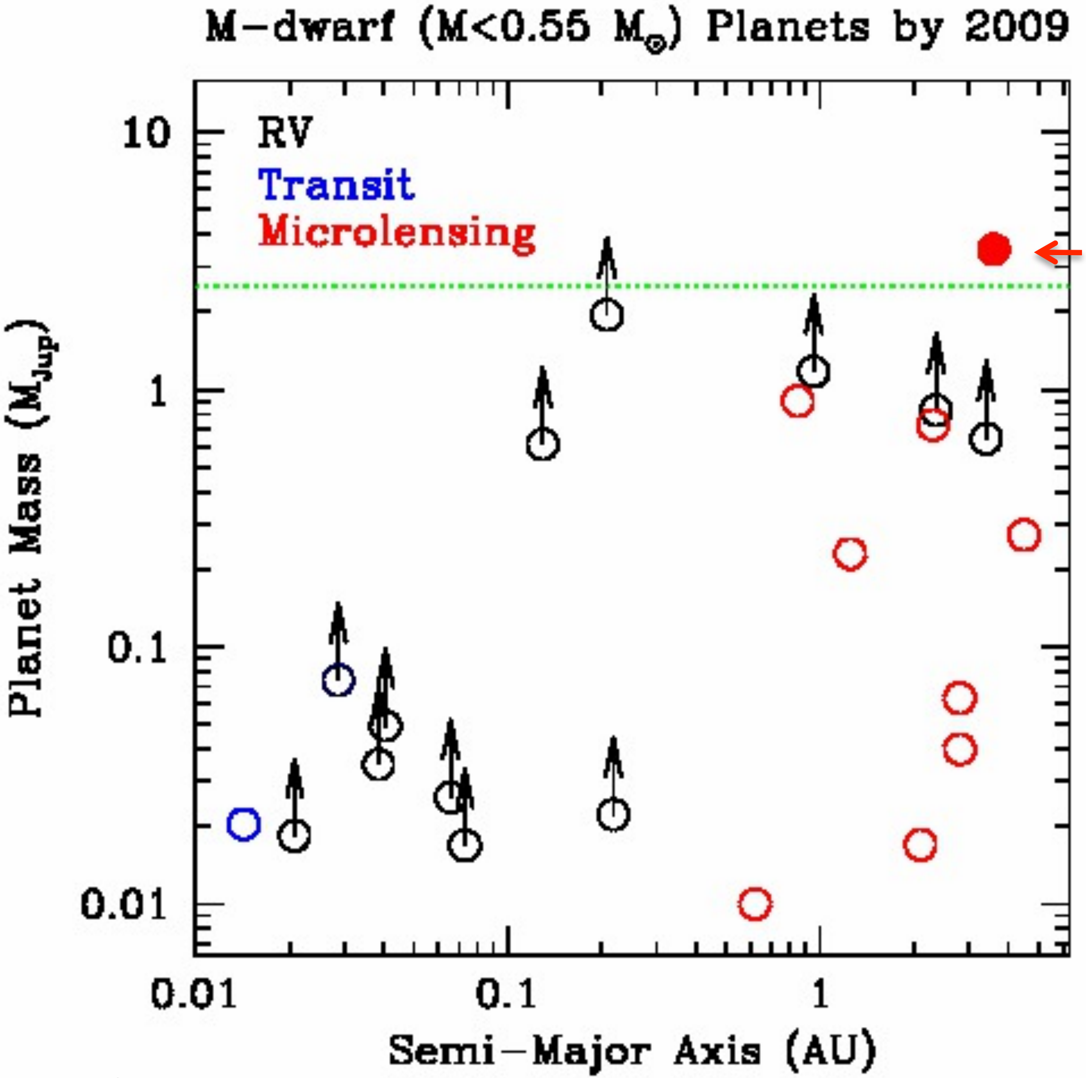
The most massive M-dwarf planet?

- V, I-band photometry
- Microlens Parallax
- Constraint on Finite-source effects
- Astrometry

$M \sim 0.46\ M_\odot$ $D_{\rm lens} \sim 3.2$ kpc

$M_p \sim 3.8\ M_J$ at 3.6 AU

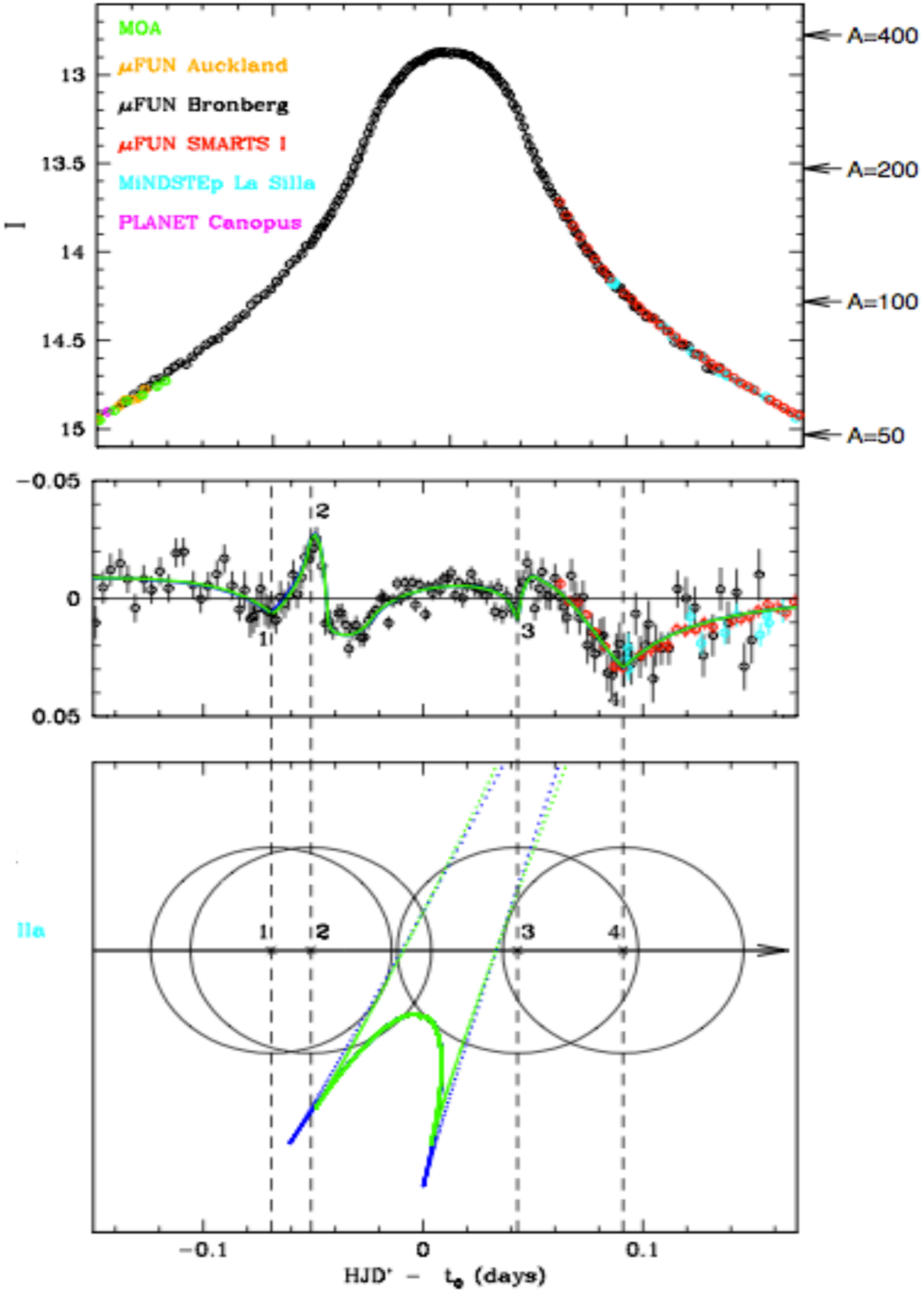
Dong, S. et al. 2009, ApJ, 695, 970

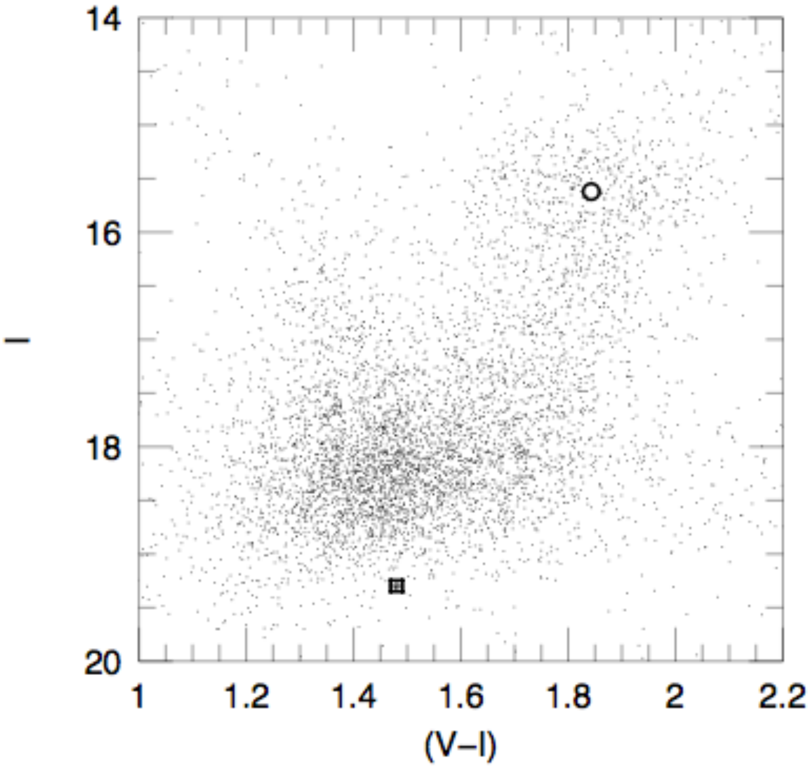


←OGLE-2005-BLG-071Lb

Too massive to form easily for M-dwarfs in core-accretion (Laughlin 2004; Kennedy & Kenyon 2008)

MOA-2008-BLG-310





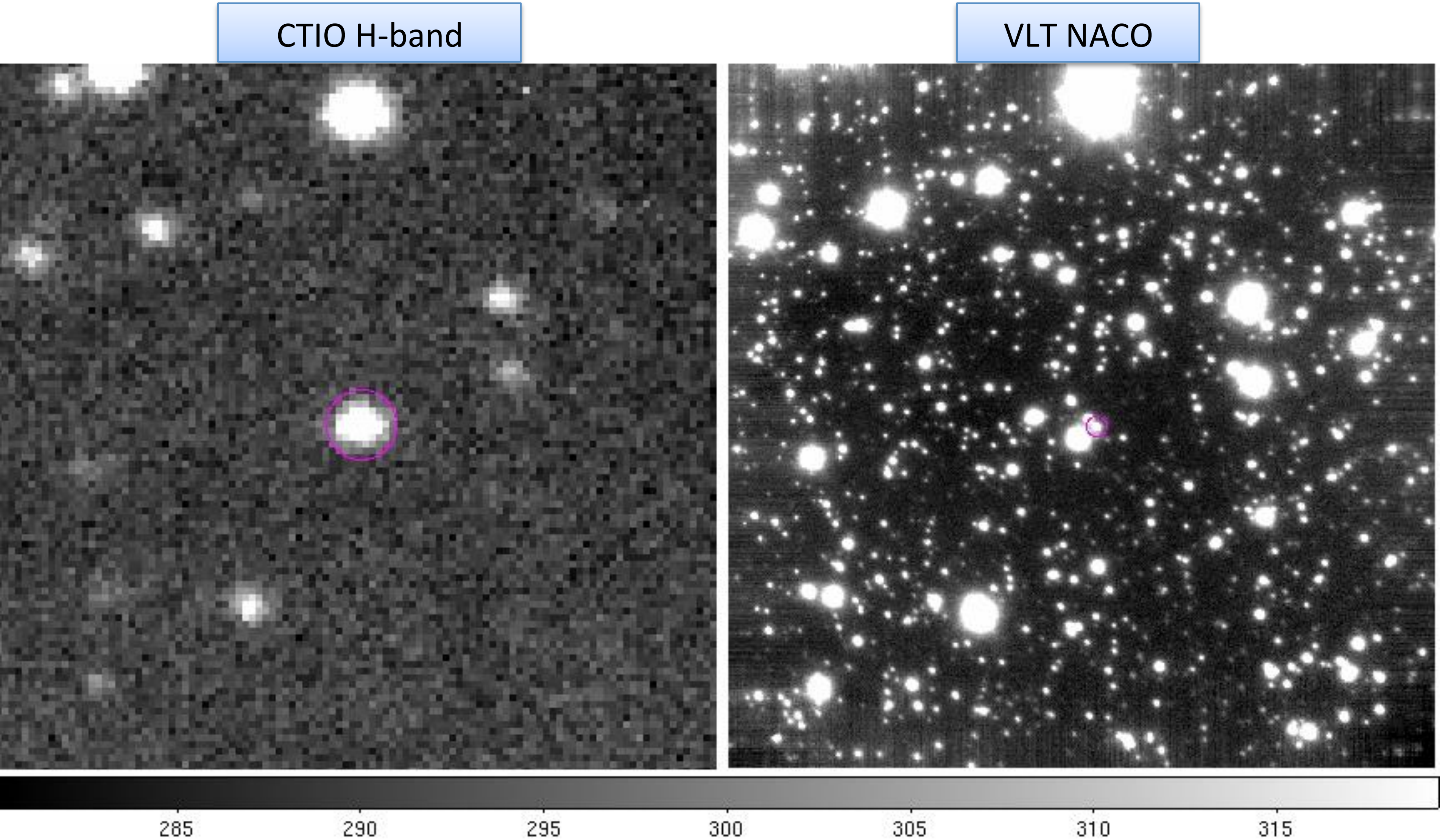
q=(3.3 ± 0.3)x10^{-4}

$\theta_* = 0.76 \pm 0.05\ \mu\text{as}$,

ρ = 0.0049

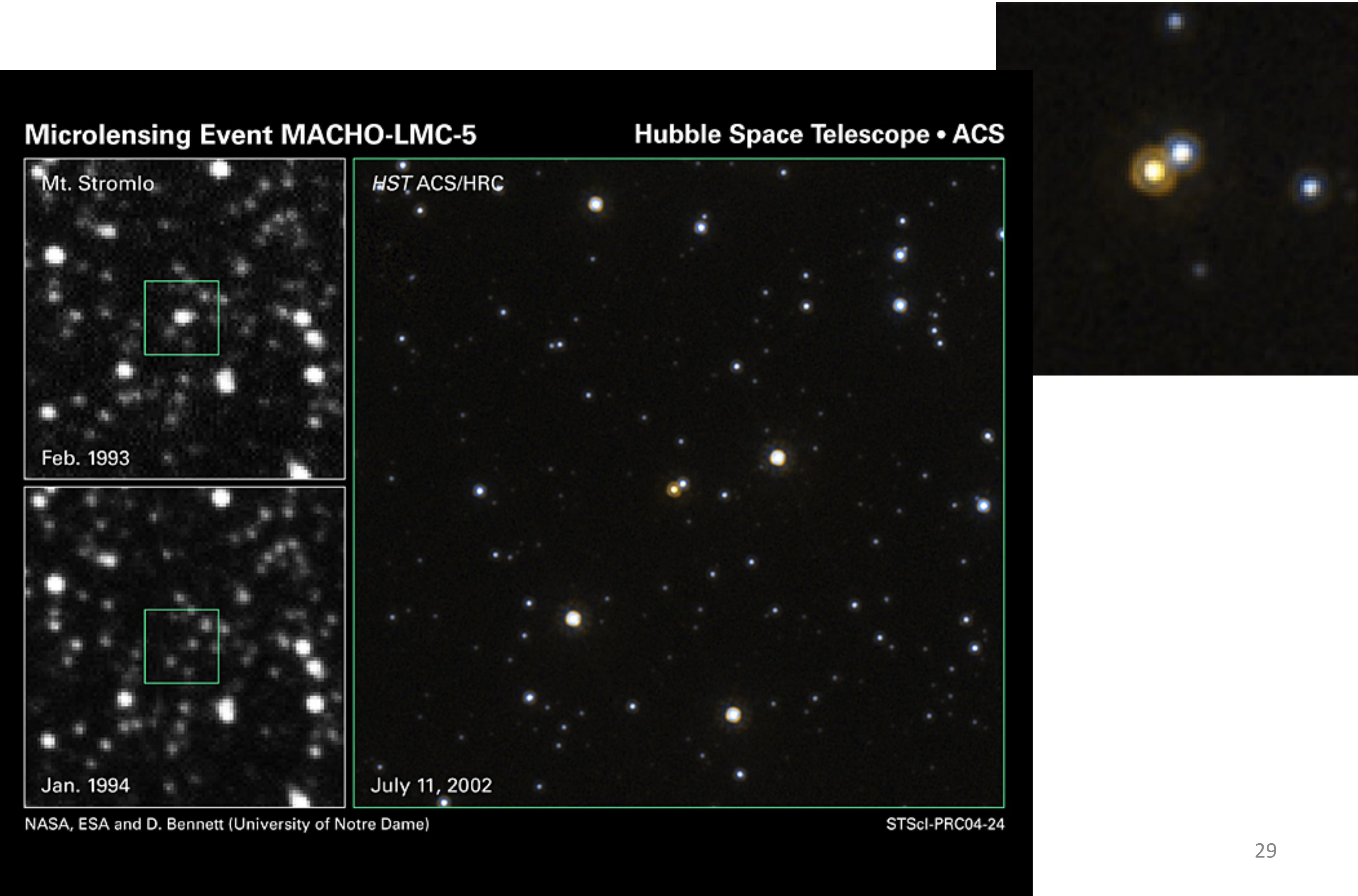
θ_E = 0.155 ± 0.011 mas

Janczak, J., et al., 2010, ApJ, 711, 731



- $\theta_E = 0.14$ mas, $\pi_{rel} = 1/D_{Lens} - 1/D_{Source} = 2.4$ uas $(M/M_{Sun})^{-1}$
- A planet in the bulge? *VLT: $M_L \sim 0.67\ M_{sun}$*

Many years after the event



NASA, ESA and D. Bennett (University of Notre Dame)

STScI-PRC04-24

Summary

- Extra information (finite-source, microlens parallax, high-res imaging, etc.) is needed to constrain mass and distance of the lens (and the planetary companion)
- Angular Einstein radius is usually measured for planetary event
- High-res imaging can constrain the lens flux as well as proper motion
  - See Jay Anderson, Justin Crepp & J.P. Beaulieu’s talks

Gould (2010) High-mag sample

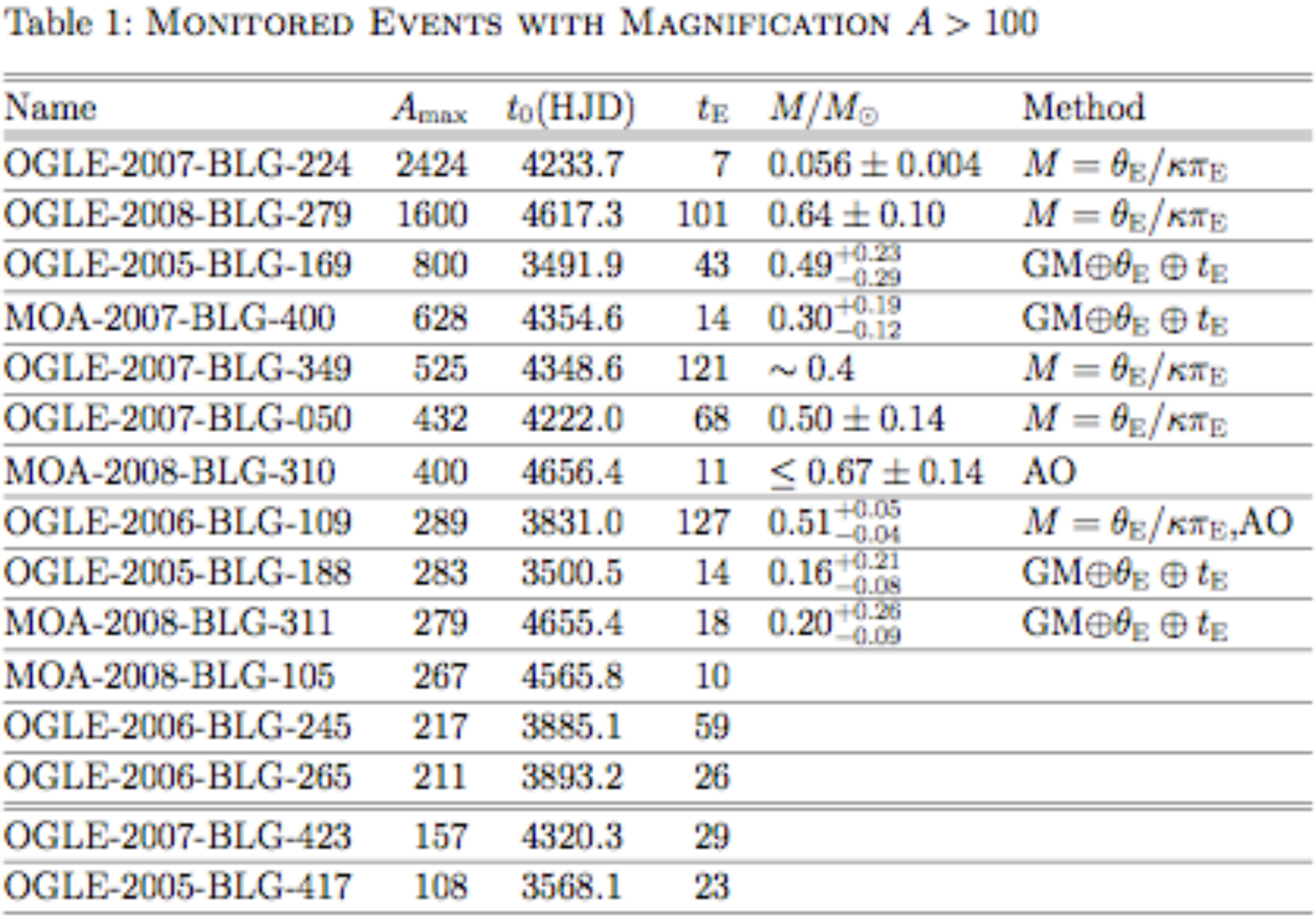
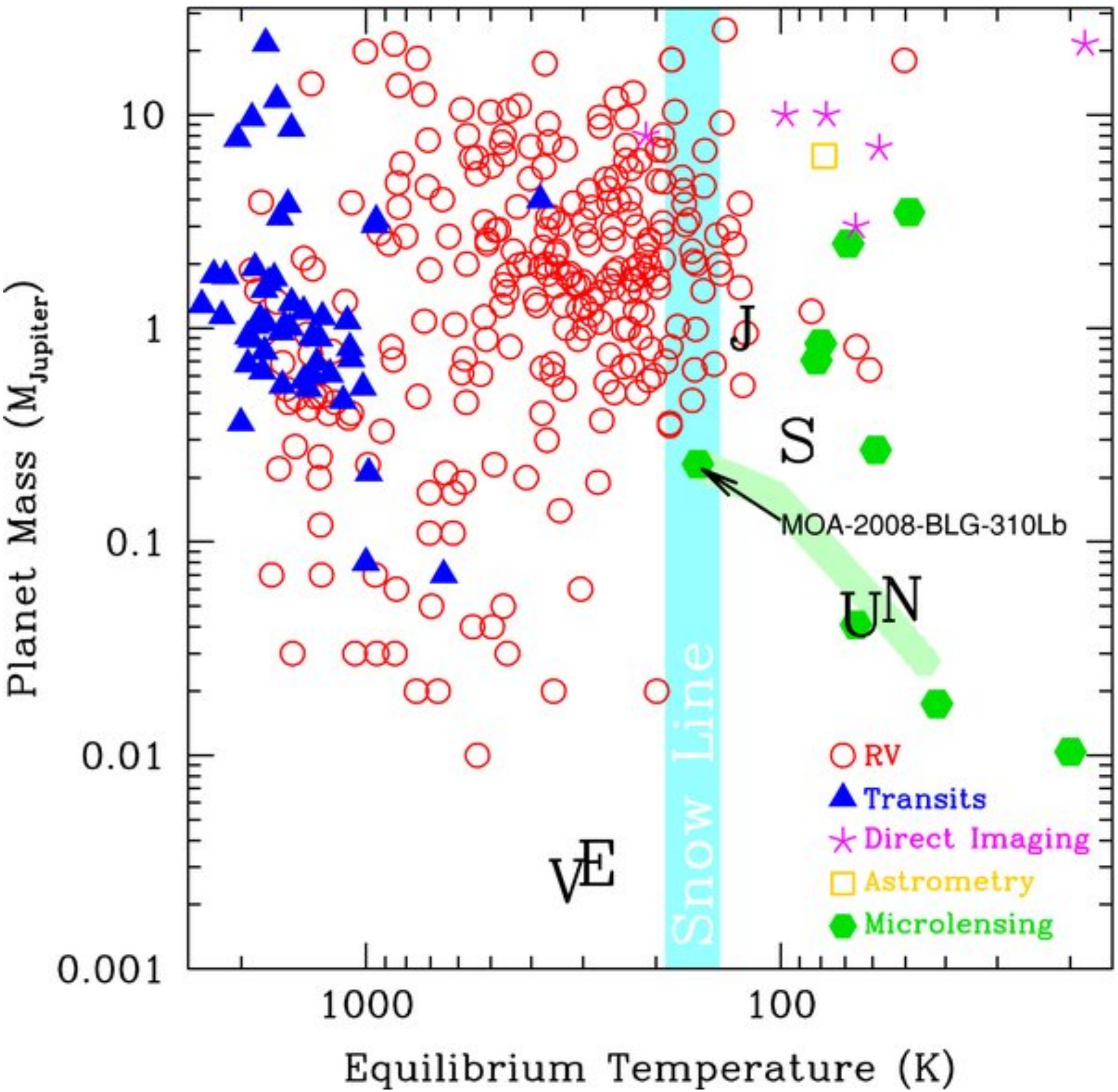


Table 1: MONITORED EVENTS WITH MAGNIFICATION $A > 100$

Name	$A_{\rm max}$	t_0(HJD)	$t_{\rm E}$	$M/M_\odot$	Method
OGLE-2007-BLG-224	2424	4233.7	7	0.056 ± 0.004	$M = \theta_{\rm E}/\kappa\pi_{\rm E}$
OGLE-2008-BLG-279	1600	4617.3	101	0.64 ± 0.10	$M = \theta_{\rm E}/\kappa\pi_{\rm E}$
OGLE-2005-BLG-169	800	3491.9	43	$0.49^{+0.23}_{-0.29}$	GM$\oplus\theta_{\rm E} \oplus t_{\rm E}$
MOA-2007-BLG-400	628	4354.6	14	$0.30^{+0.19}_{-0.12}$	GM$\oplus\theta_{\rm E} \oplus t_{\rm E}$
OGLE-2007-BLG-349	525	4348.6	121	~ 0.4	$M = \theta_{\rm E}/\kappa\pi_{\rm E}$
OGLE-2007-BLG-050	432	4222.0	68	0.50 ± 0.14	$M = \theta_{\rm E}/\kappa\pi_{\rm E}$
MOA-2008-BLG-310	400	4656.4	11	$\lesssim 0.67 \pm 0.14$	AO
OGLE-2006-BLG-109	289	3831.0	127	$0.51^{+0.05}_{-0.04}$	$M = \theta_{\rm E}/\kappa\pi_{\rm E}$,AO
OGLE-2005-BLG-188	283	3500.5	14	$0.16^{+0.21}_{-0.08}$	GM$\oplus\theta_{\rm E} \oplus t_{\rm E}$
MOA-2008-BLG-311	279	4655.4	18	$0.20^{+0.26}_{-0.09}$	GM$\oplus\theta_{\rm E} \oplus t_{\rm E}$
MOA-2008-BLG-105	267	4565.8	10		
OGLE-2006-BLG-245	217	3885.1	59		
OGLE-2006-BLG-265	211	3893.2	26		
OGLE-2007-BLG-423	157	4320.3	29		
OGLE-2005-BLG-417	108	3568.1	23		


Planet Mass ($M_{Jupiter}$)
Equilibrium Temperature (K)
10
1
0.1
0.01
0.001
1000
100
Snow Line
J
S
U
N
V
E
MOA-2008-BLG-310Lb
RV
Transits
Direct Imaging
Astrometry
Microlensing