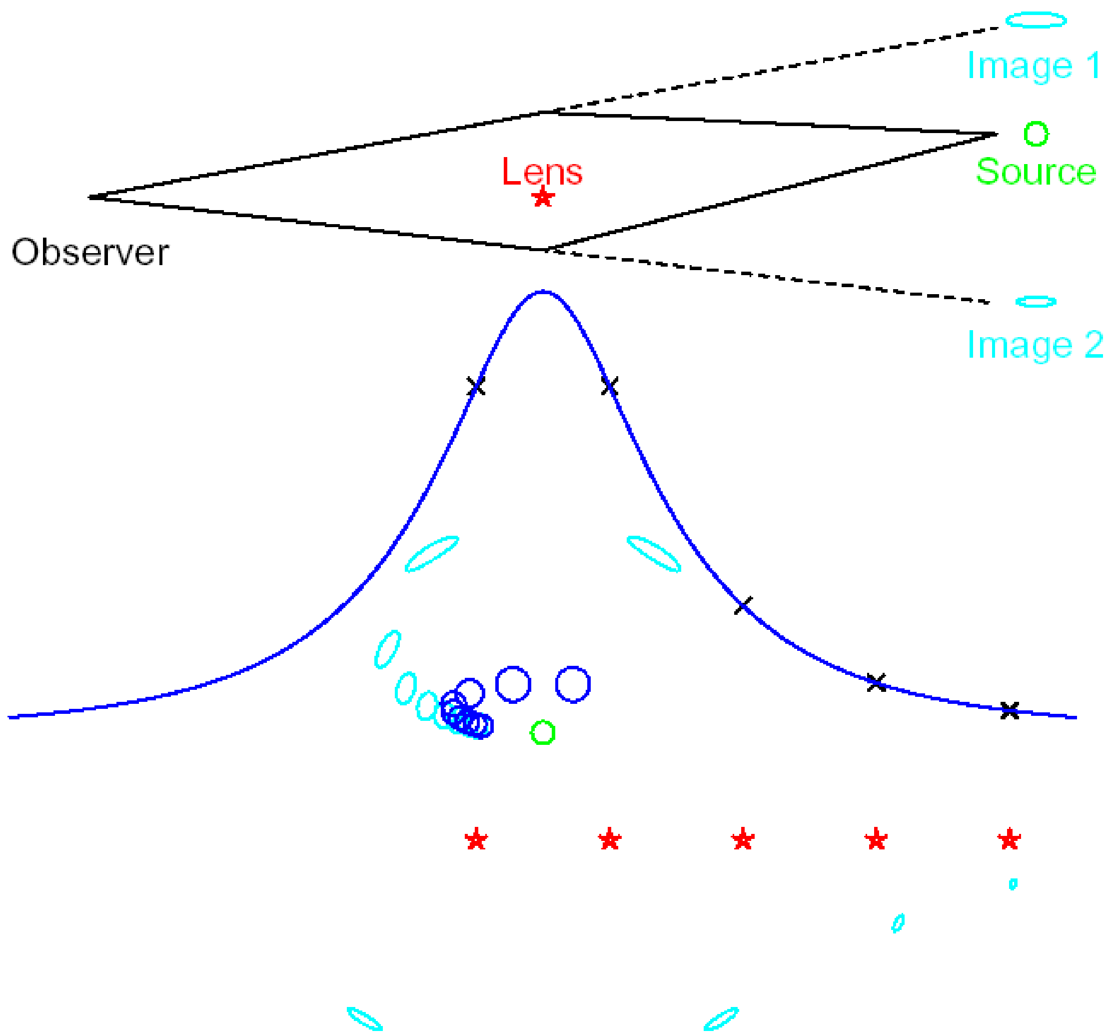
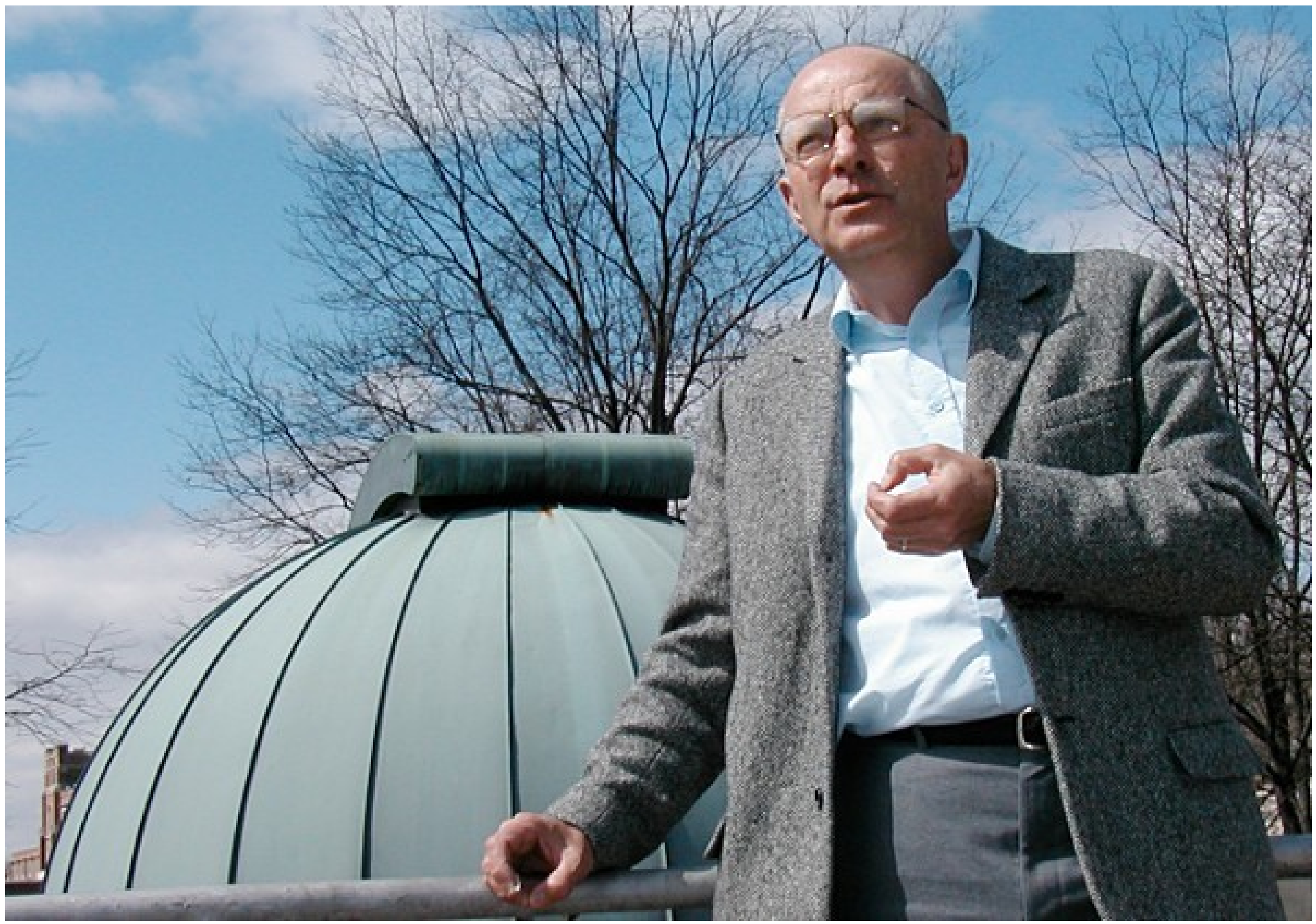
Microlensing VI:
Frontiers of Microlensing
Andy Gould (Ohio State)



Frontiers I:
Surveys

- 1993-1999 MACHO: 0.5 deg^2 ; 1.5m Aus
  - 40 events/year
- 1993-2001 EROS: 1.0 deg^2 ; 1.0m Chile
  - 20 events/yr
- 1992-1998 OGLE: 0.06 deg^2 ; 1.0m Chile
  - Few events/yr

All 3 Inspired by Bohdan Paczynski



Phases of OGLE

- OGLE-II (0.36 deg^2 ; 1.3m)
  - 1998: 41 events
  - 1999: 48 events
  - 2000: 78 events

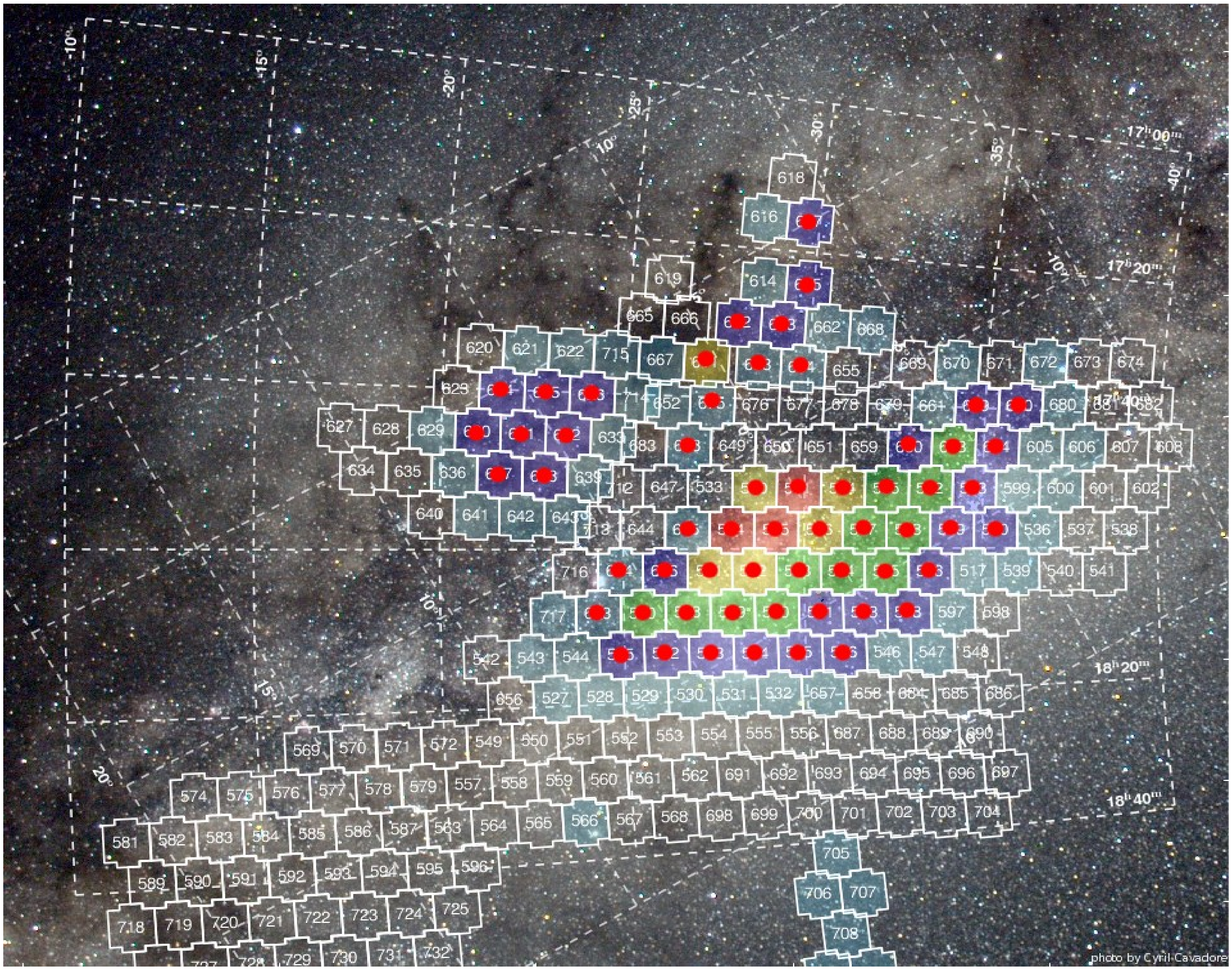
Phases of OGLE

- OGLE-III (0.36 deg^2 ; 1.3m)
  - 2002: 350 events
  - 2003: 450 events
  - 2004: 600 events
  - 2005: 550 events
  - 2006: 550 events
  - 2007: 600 events
  - 2008: 650 events

Phases of OGLE

- OGLE-IV (1.44 deg^2 ; 1.3m)
  - 2011: 1500 events
  - 2012: 1700 events
  - 2013: 2000 events
  - 2014: 2000 events

OGLE-IV Observing Strategy



Phases of MOA

- MOA-I (0.6m, NZ)
  - 2000-2005 (about 60 events/yr)
- MOA-II (1.8m, 2.2 deg^2)
  - 2006-present (about 650 events/yr)

Wise Survey

- 2011-present (1.0m; 1 deg^2; Israel)
  - Cross-identify few hundred OGLE/MOA events

Korean Microlensing Telescope Network (KMTNet)

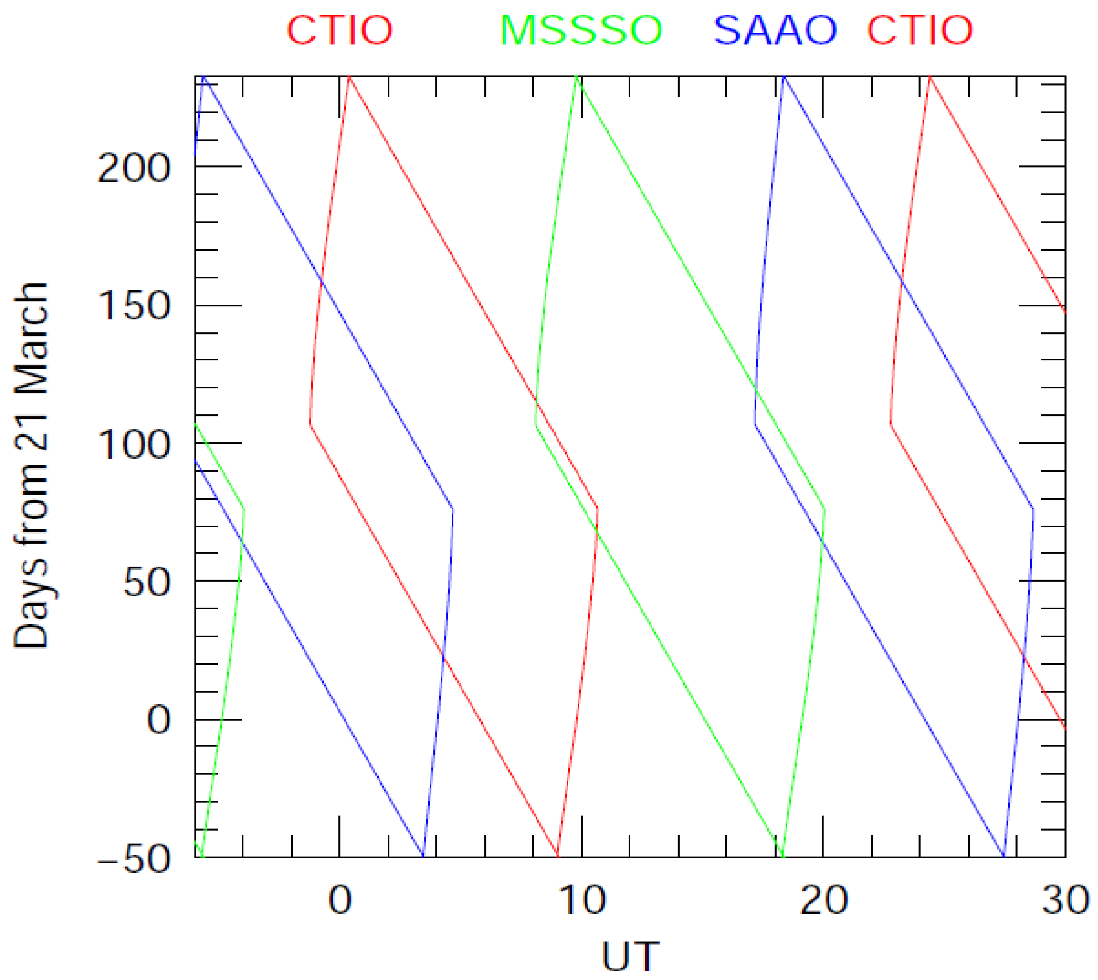
From Design ...

... To Construction

Main KMTNet Features

- 3 Telescopes
  - Chile
  - South Africa
  - Australia

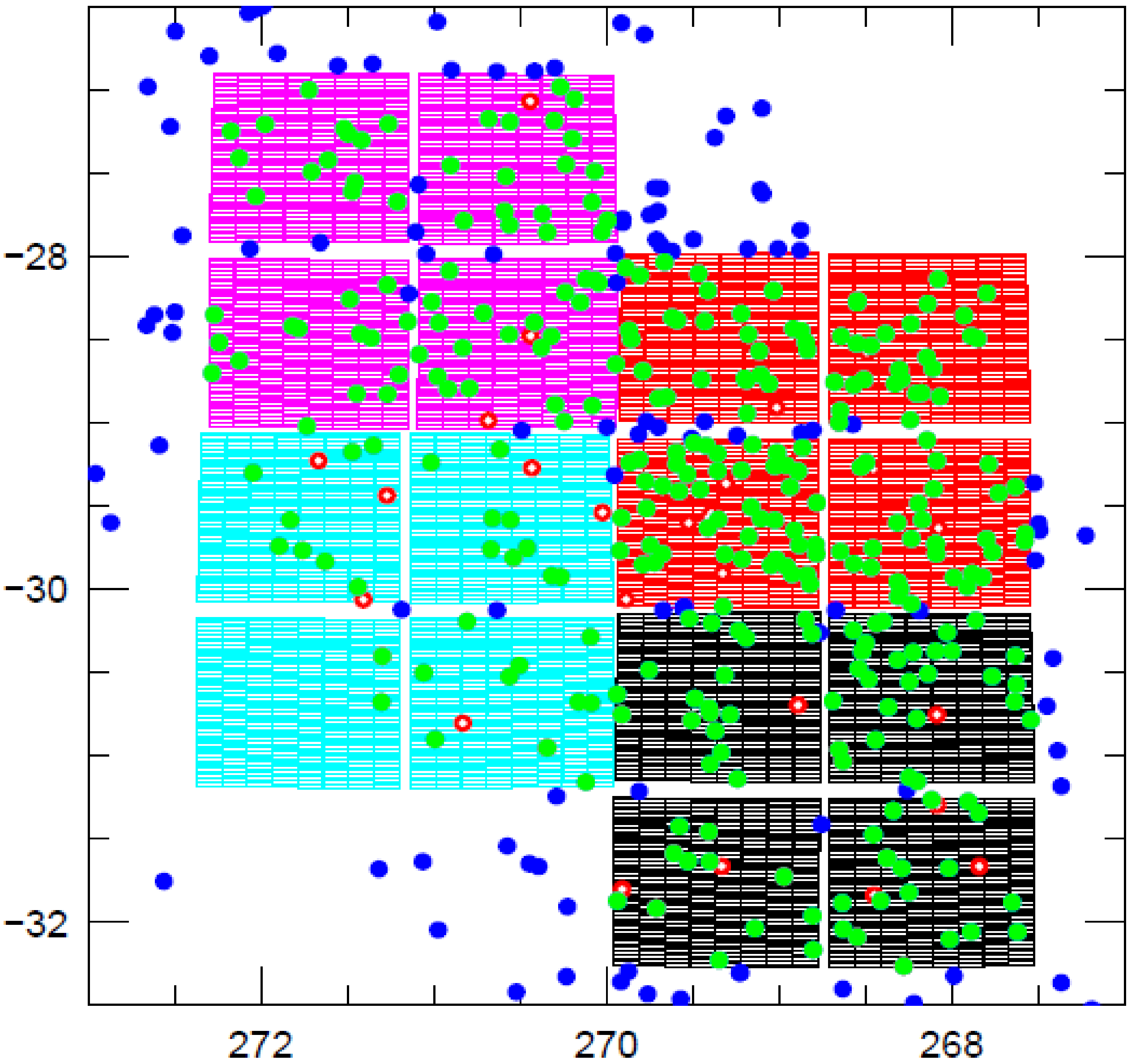
The Bulge Never Set on KMTNet
(at least in June)



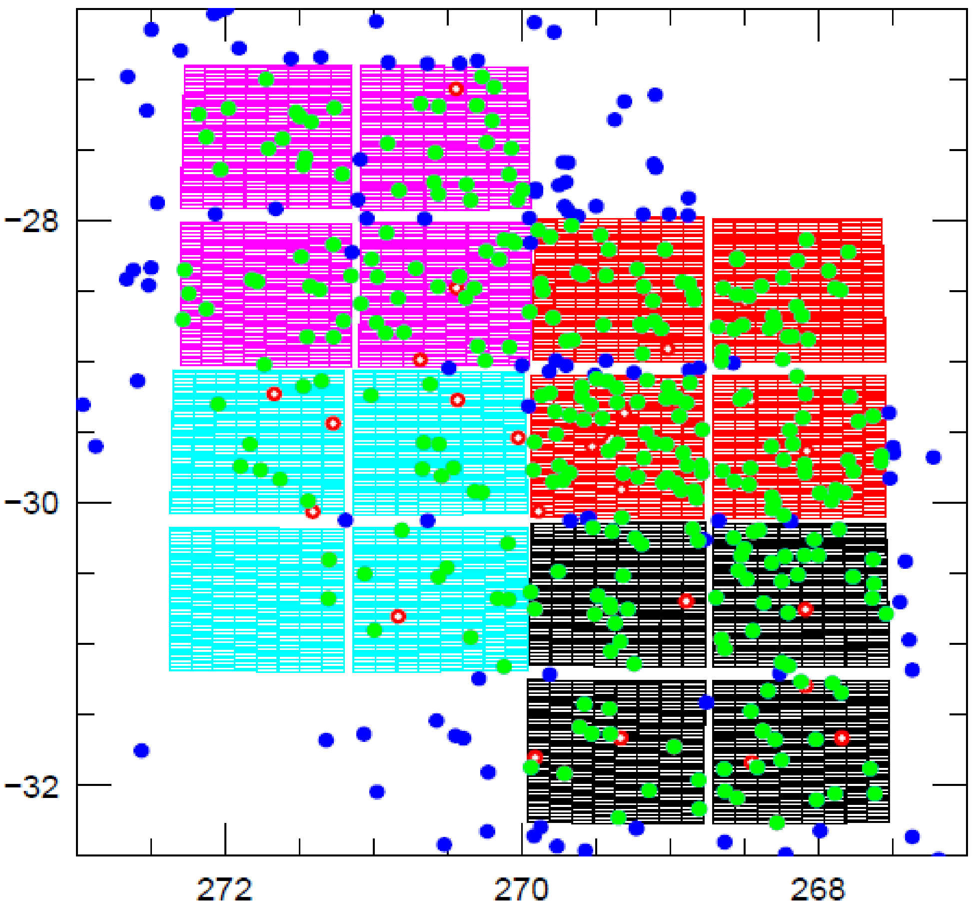
Main KMTNet Features

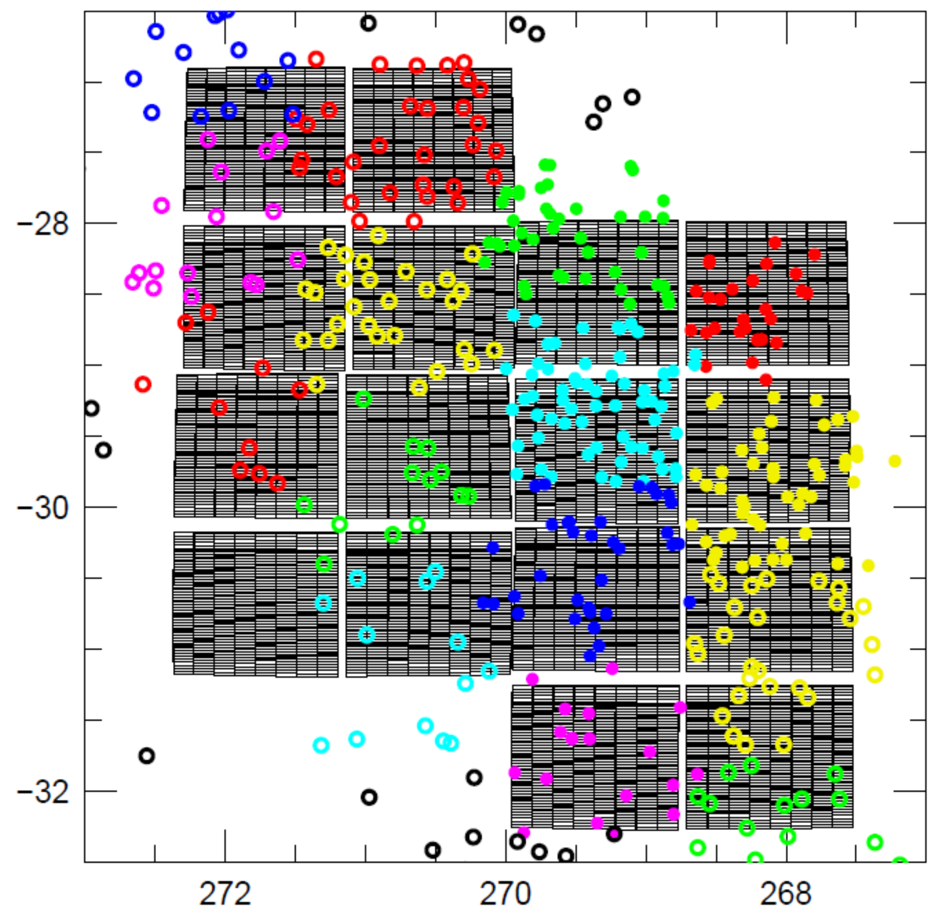
- 3 Telescopes
- Large Field of View
  - 4 deg^2

4 Main KMT Fields



4 Main KMT Fields





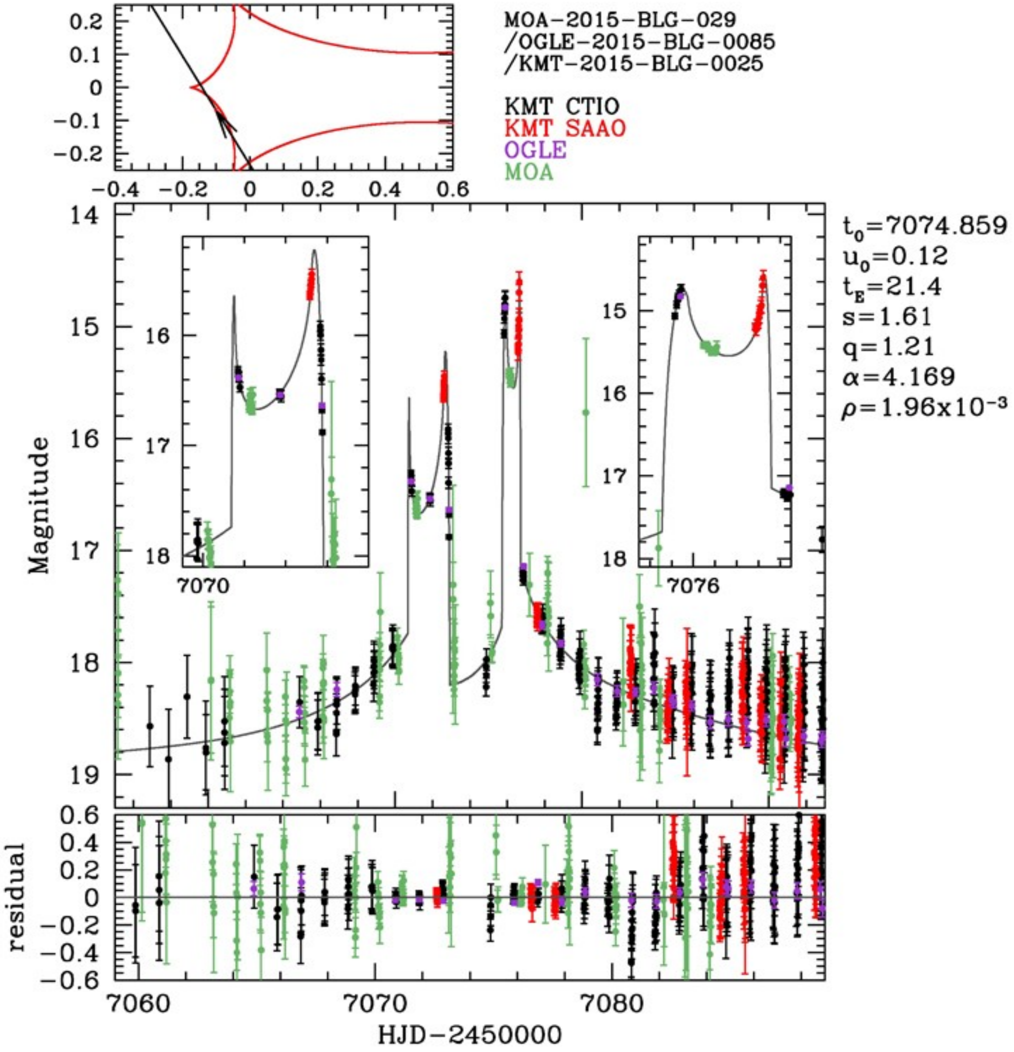
Main KMTNet Features

- 3 Telescopes
- Large Field of View
- Relatively Large Aperture
  - 1.6 m

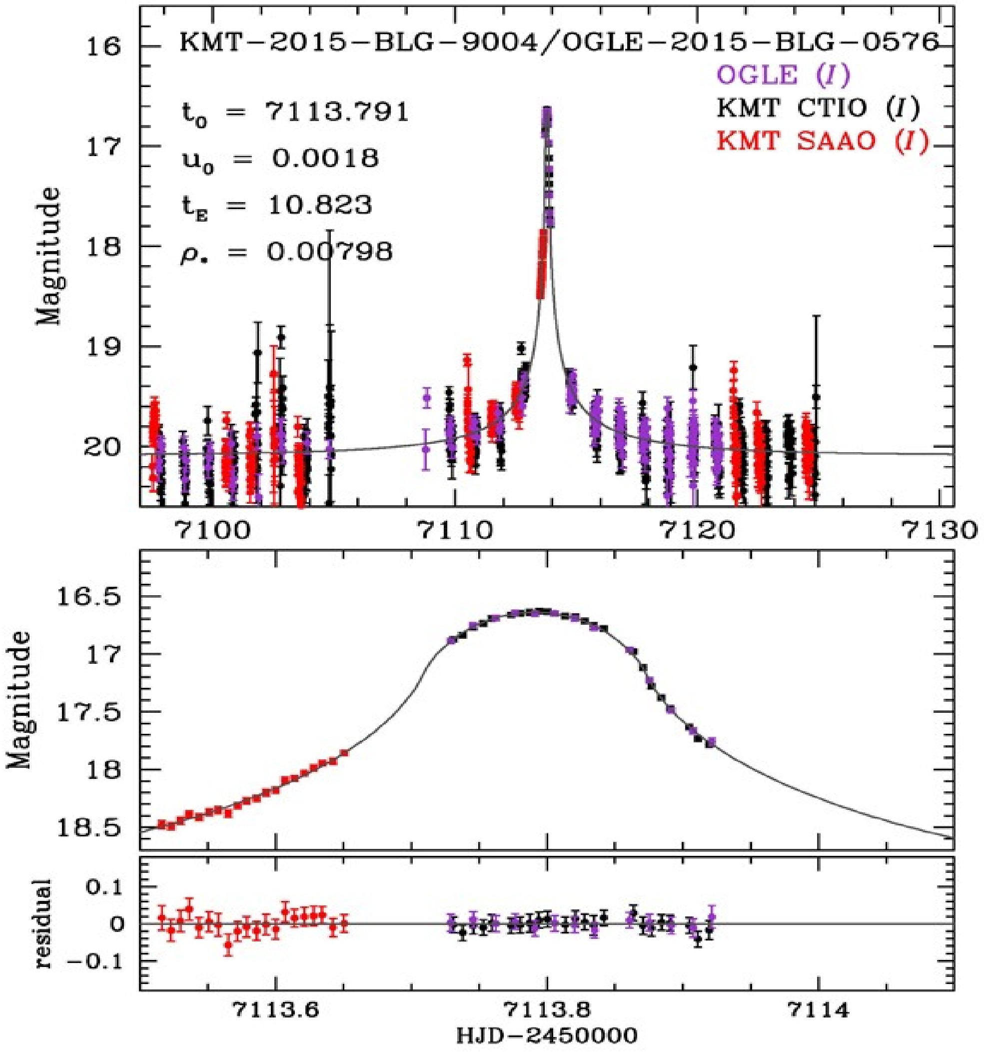
Main KMTNet Features

- 3 Telescopes
- Large Field of View
- Relatively Large Aperture
- ==> Fast Cadence
  - <10 min cycles of 4 fields

Example (early season)



Another Example



Frontiers II

Planet Frequencies

- Biggest Sample So Far ...

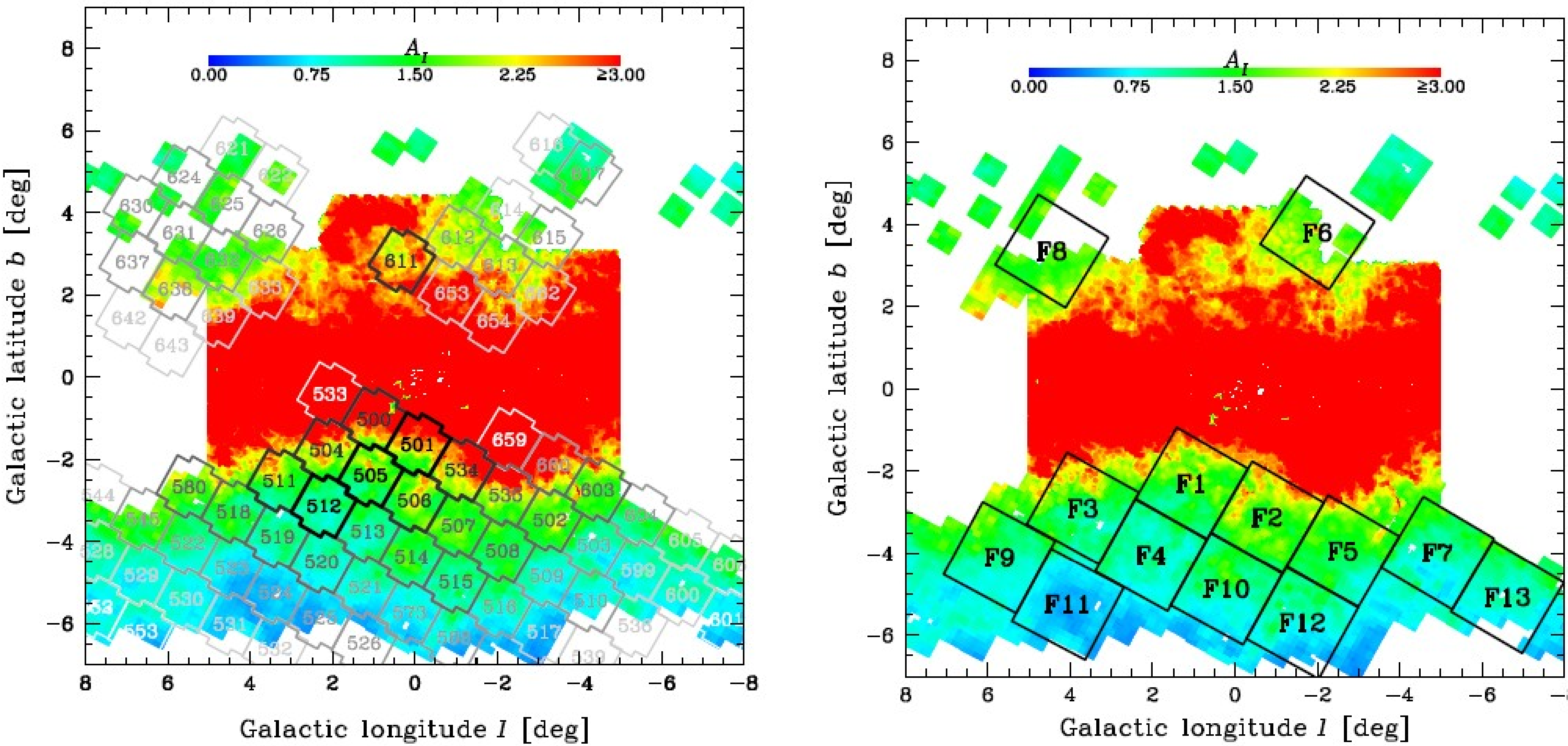
Table 1
Monitored Events with Magnification $A > 100$

Name	A_{max}	t_0(HJD)	t_E	$M/M_\odot$	Method
OGLE-2007-BLG-224	2424	4233.7	7	0.056 ± 0.004	$M = \theta_E/\kappa\pi_E$
OGLE-2008-BLG-279	1600	4617.3	101	0.64 ± 0.10	$M = \theta_E/\kappa\pi_E$
OGLE-2005-BLG-169	800	3491.9	43	$0.49^{+0.23}_{-0.29}$	GM$\oplus\theta_E \oplus t_E$
MOA-2007-BLG-400	628	4354.6	14	$0.30^{+0.19}_{-0.12}$	GM$\oplus\theta_E \oplus t_E$
OGLE-2007-BLG-349	525	4348.6	121	∼0.6	$M = \theta_E/\kappa\pi_E$
OGLE-2007-BLG-050	432	4222.0	68	0.50 ± 0.14	$M = \theta_E/\kappa\pi_E$
MOA-2008-BLG-310	400	4656.4	11	$\leqslant 0.67 \pm 0.14$	AO
OGLE-2006-BLG-109	289	3831.0	127	$0.51^{+0.05}_{-0.04}$	$M = \theta_E/\kappa\pi_E$, AO
OGLE-2005-BLG-188	283	3500.5	14	$0.16^{+0.21}_{-0.08}$	GM$\oplus\theta_E \oplus t_E$
MOA-2008-BLG-311	279	4655.4	18	$0.20^{+0.26}_{-0.09}$	GM$\oplus\theta_E \oplus t_E$
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		

Frontiers II
Planet Frequencies

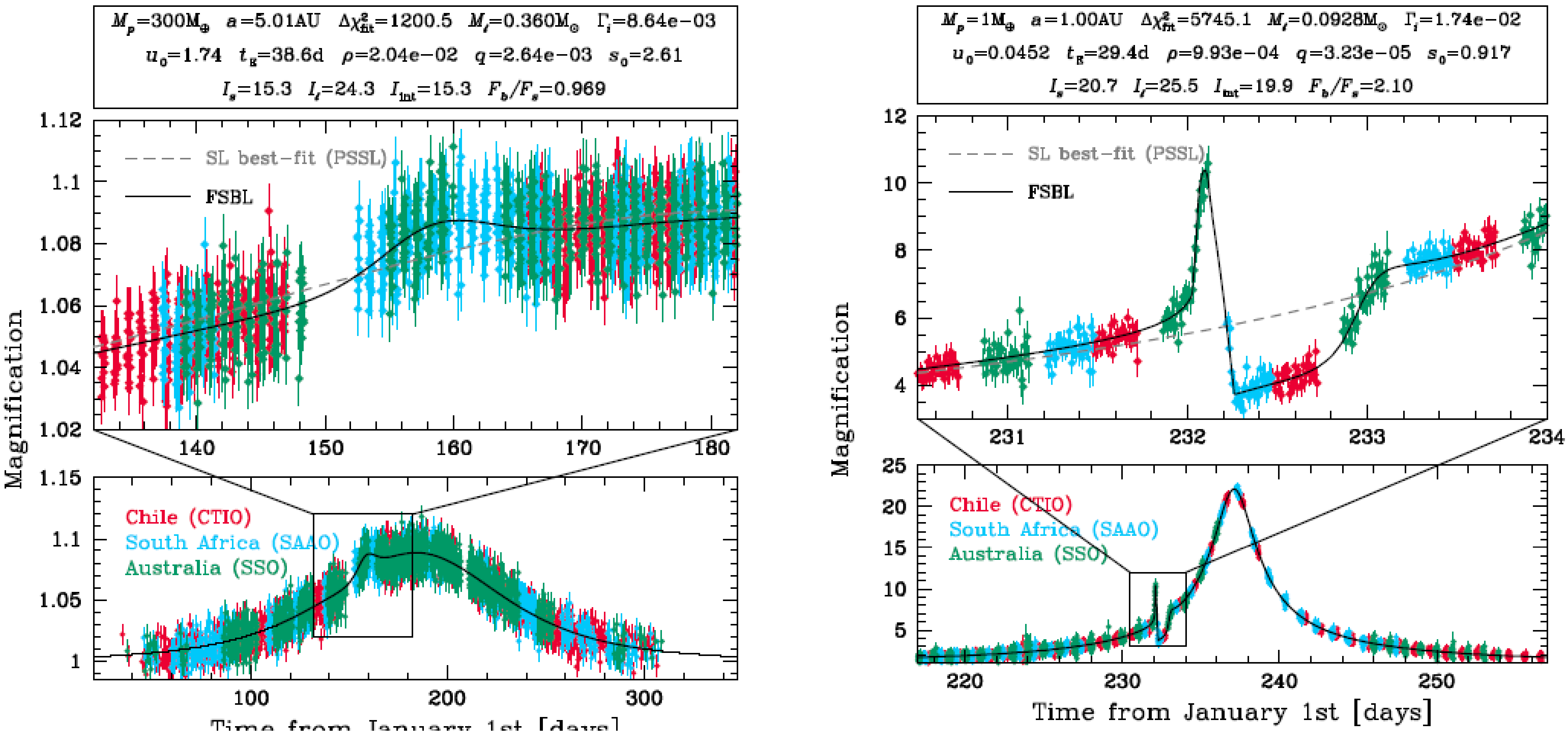
- Biggest Sample So Far ...
- Gould+ 2010 [6 planets]
- MOA Analysis (in prep) ...
  - 20 planets?

KMTNet Predictions



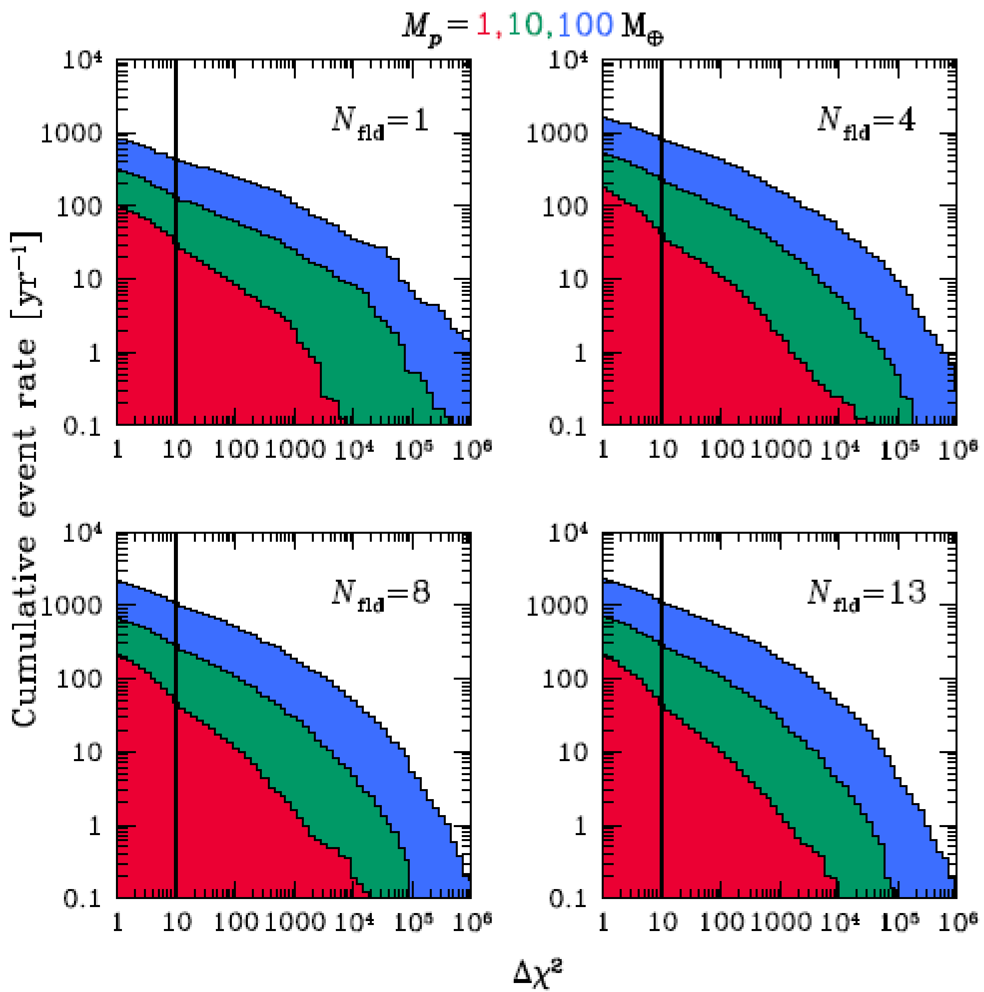
Henderson et al. 2014, ApJ, 794, 52

KMTNet Predictions



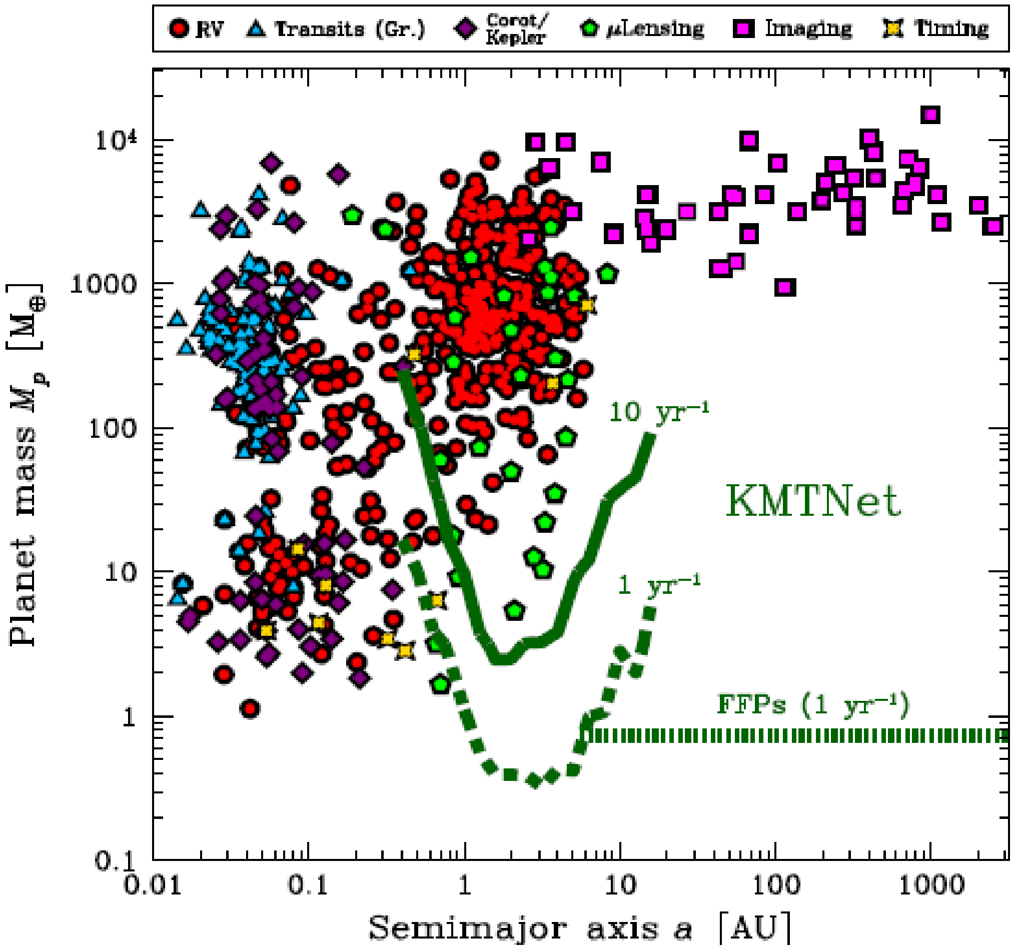
Henderson et al. 2014, ApJ, 794, 52

KMTNet Predictions



Henderson et al. 2014, ApJ, 794, 52

KMTNet Predictions



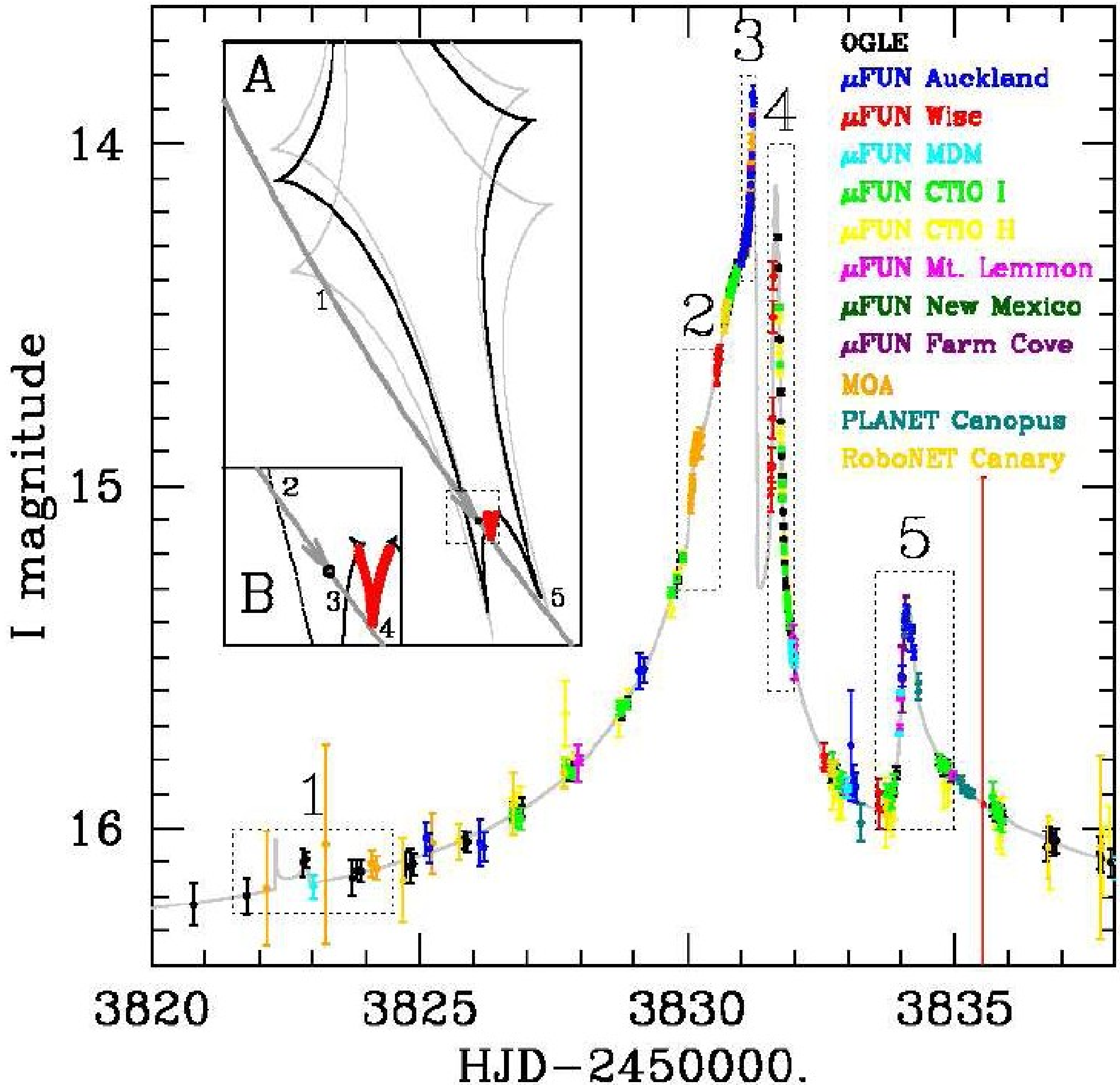
Henderson et al. 2014, ApJ, 794, 52

Frontiers III

3(+) Bodies

OGLE-2006-BLG-109

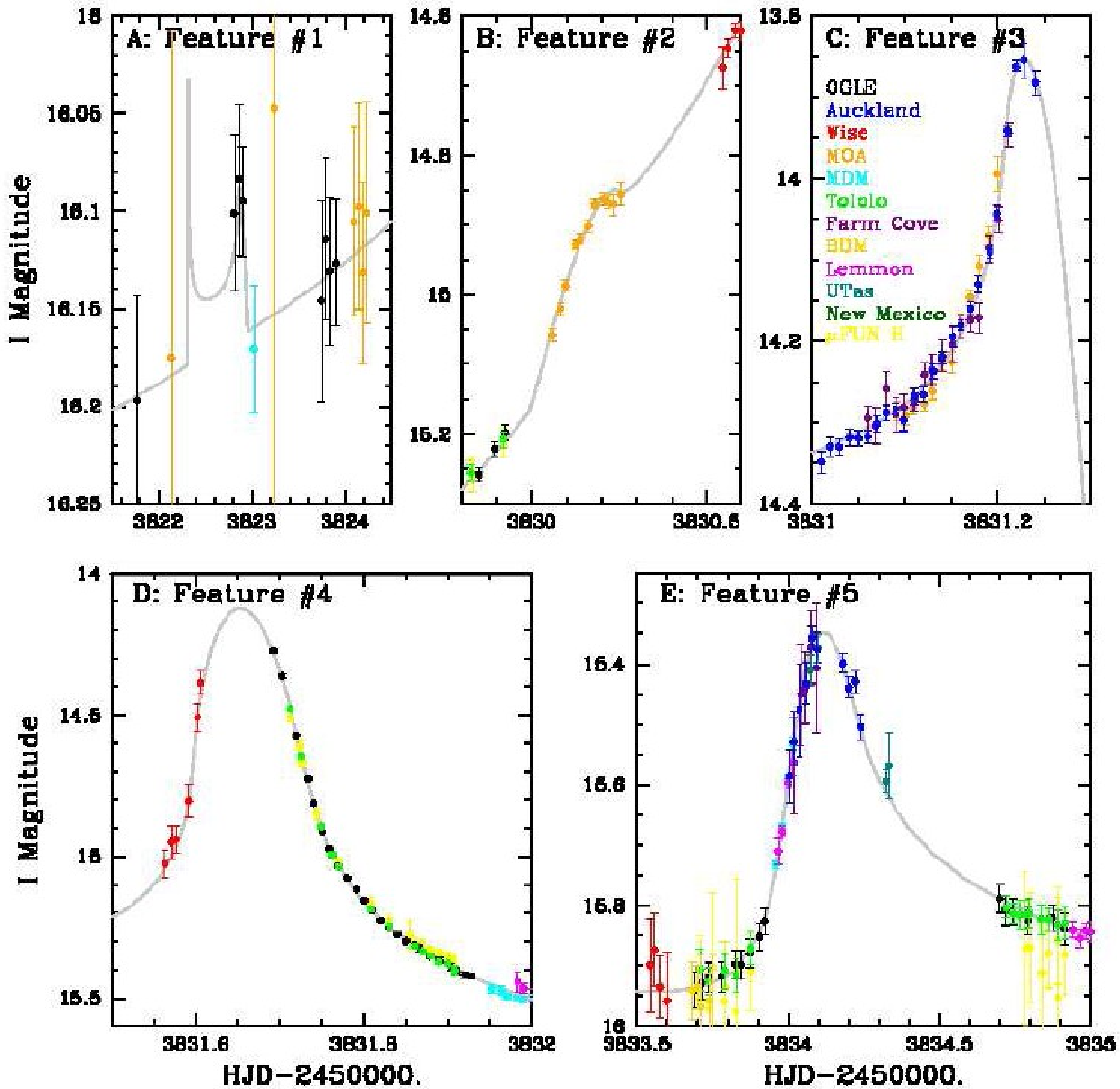
1 Star + 2 Planets



Gaudi et al. 2008, Science, 319, 927

Five Lightcurve Features

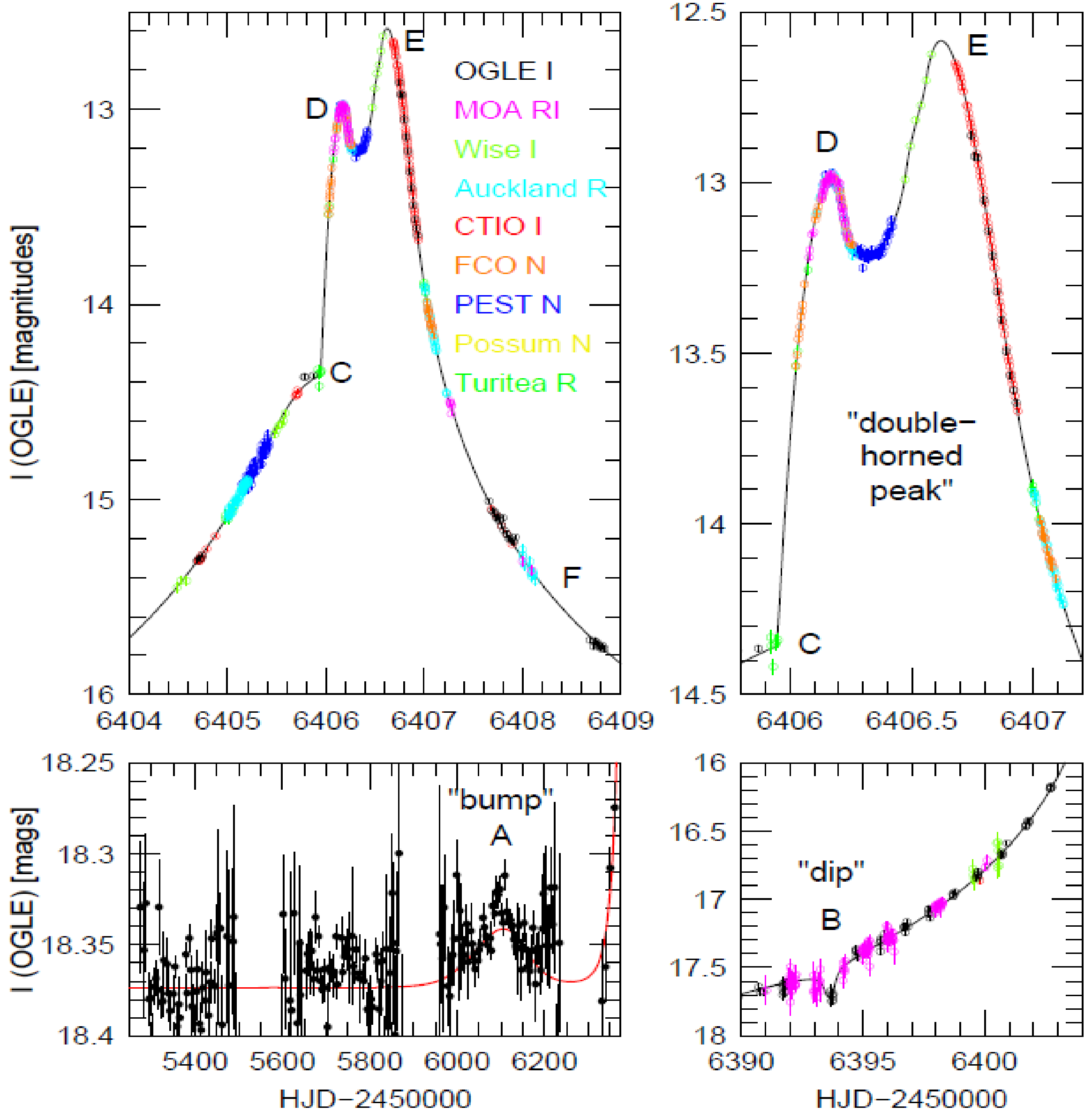
1+2+3+5=Saturn 4=Jupiter



OGLE-2013-BLG-0341

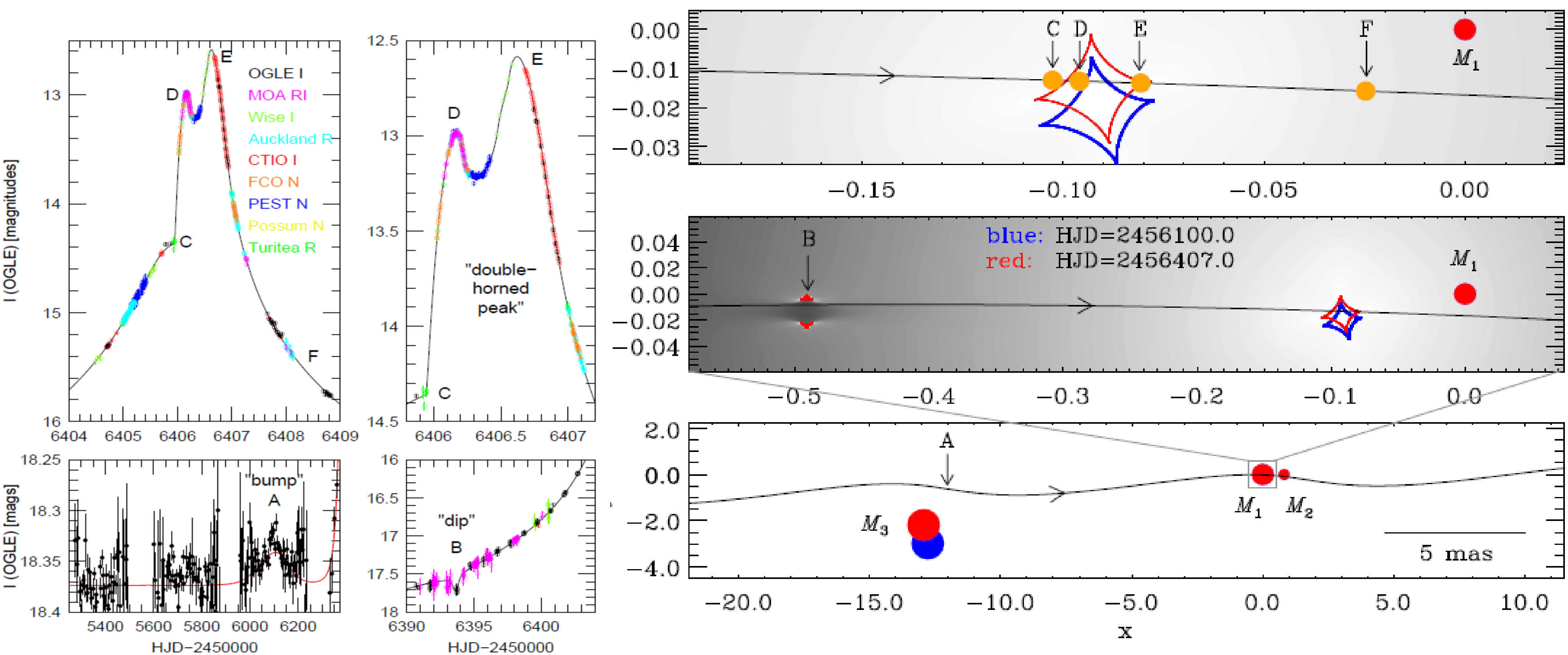
2 Stars + 1 Planet

($2\text{-}M_{Earth}$ Planet at 1AU)



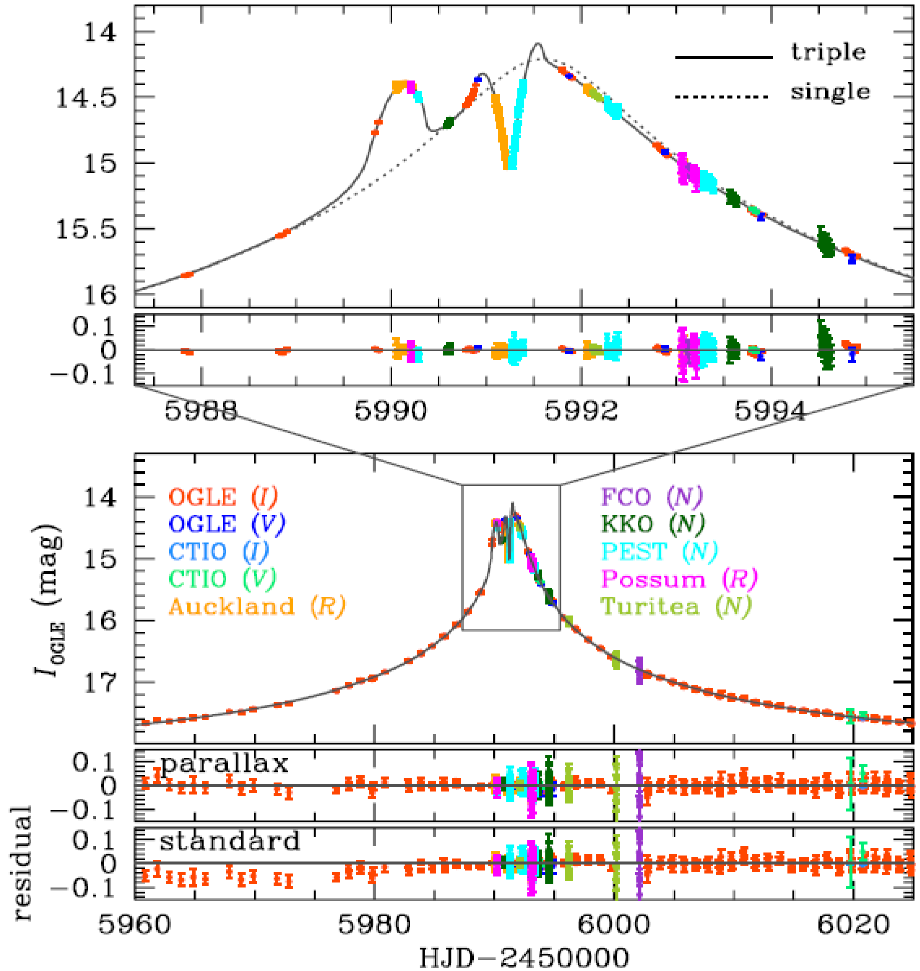
OGLE-2013-BLG-0341: Binary+Planet at 1AU

(Gould et al. 2014, Science, 345, 46)



OGLE-2012-BLG-0026

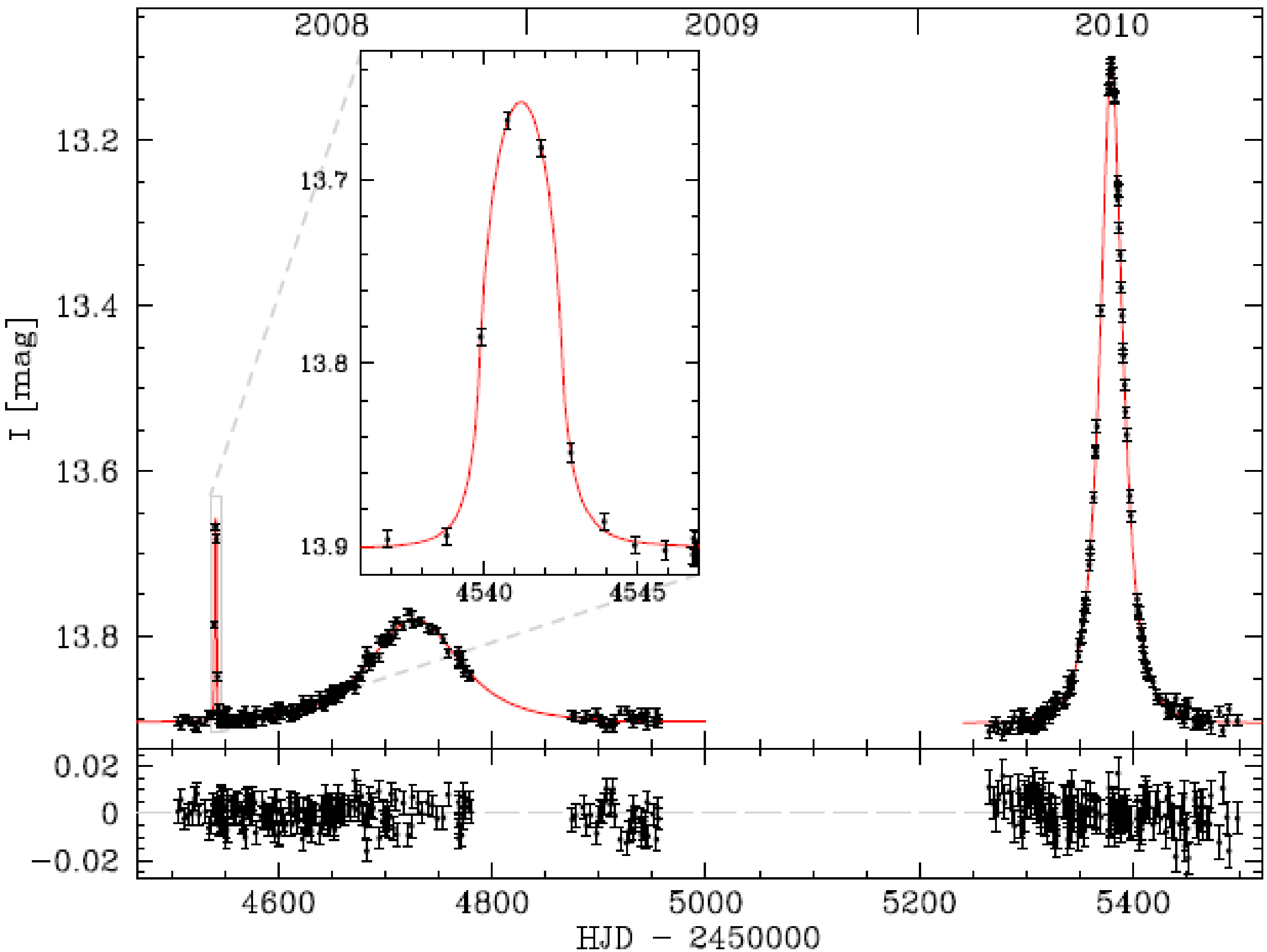
1 Star + 2 Planets



Han et al. 2013, ApJ, 762, L28

OGLE-2008-BLG-092

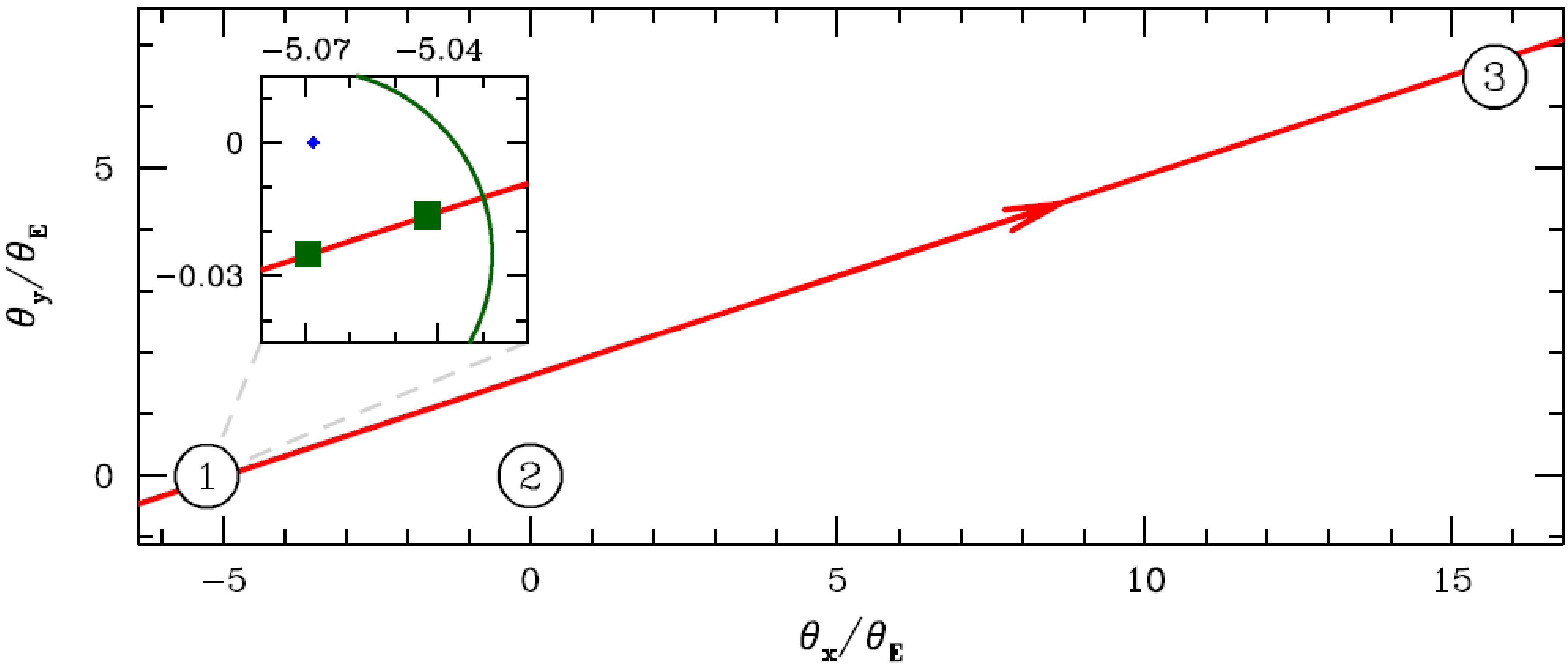
2 Stars + 1 Planet



Poleski et al. 2014, ApJ, 795, 42

OGLE-2008-BLG-092

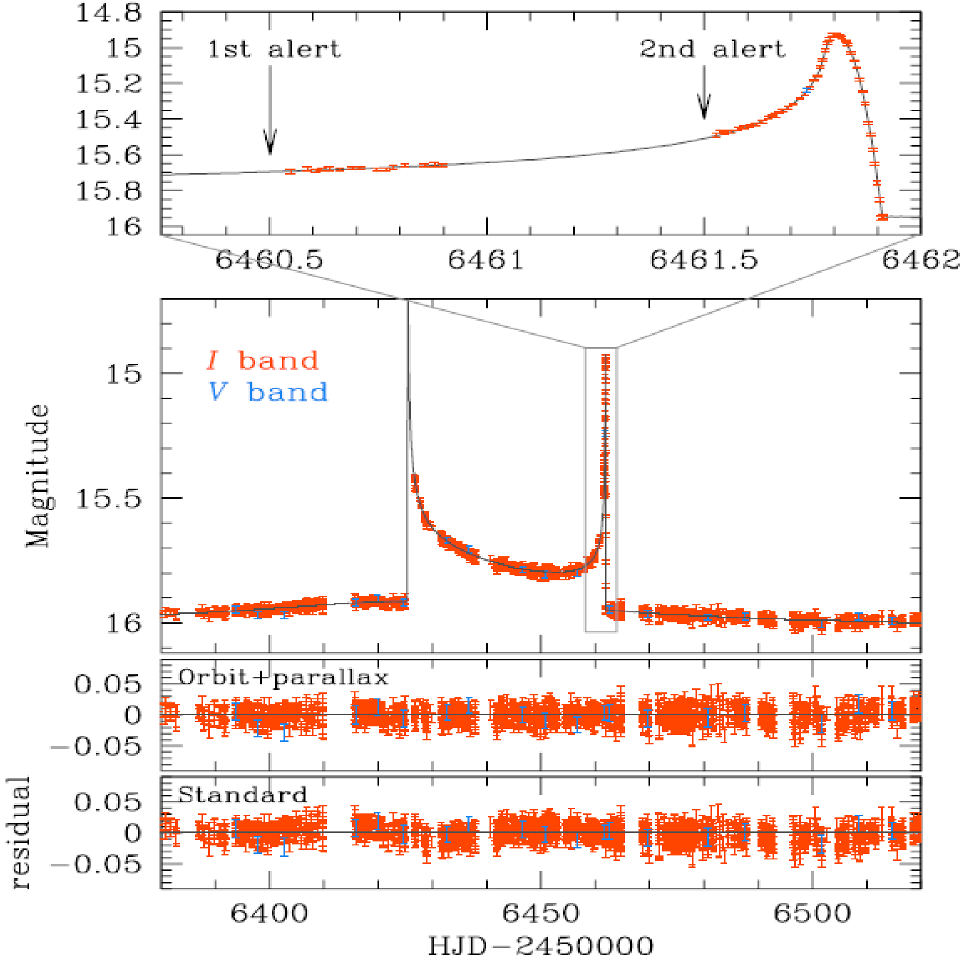
2 Stars + 1 Planet

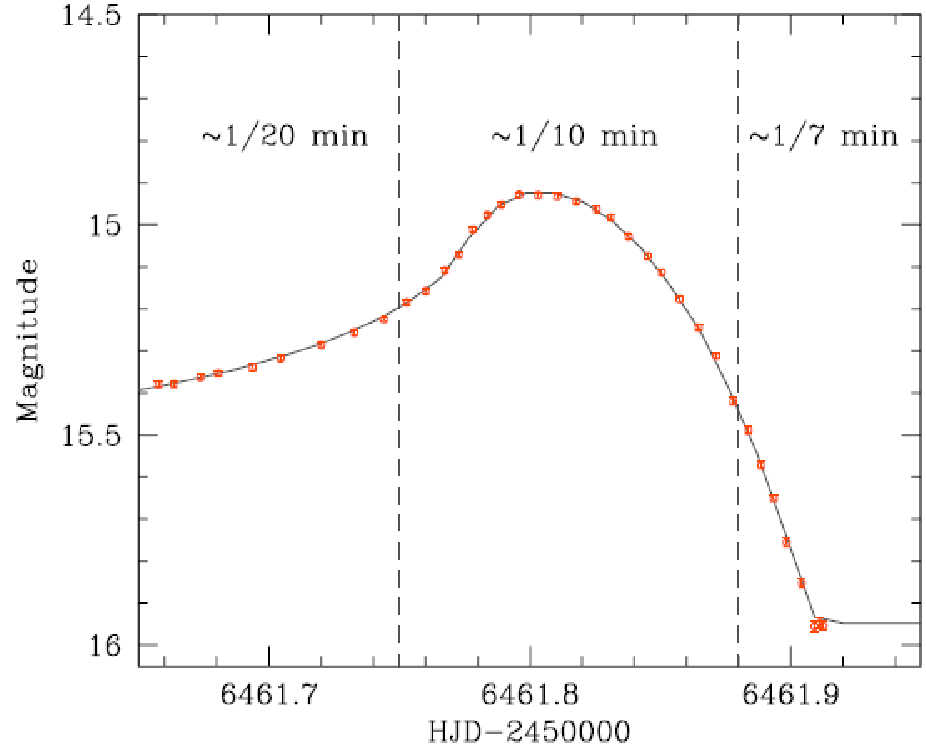


Poleski et al. 2014, ApJ, 795, 42

OGLE-2013-BLG-0578

2 Stars





Park et al. 2015, ApJ, in press

OGLE-2013-BLG-0578

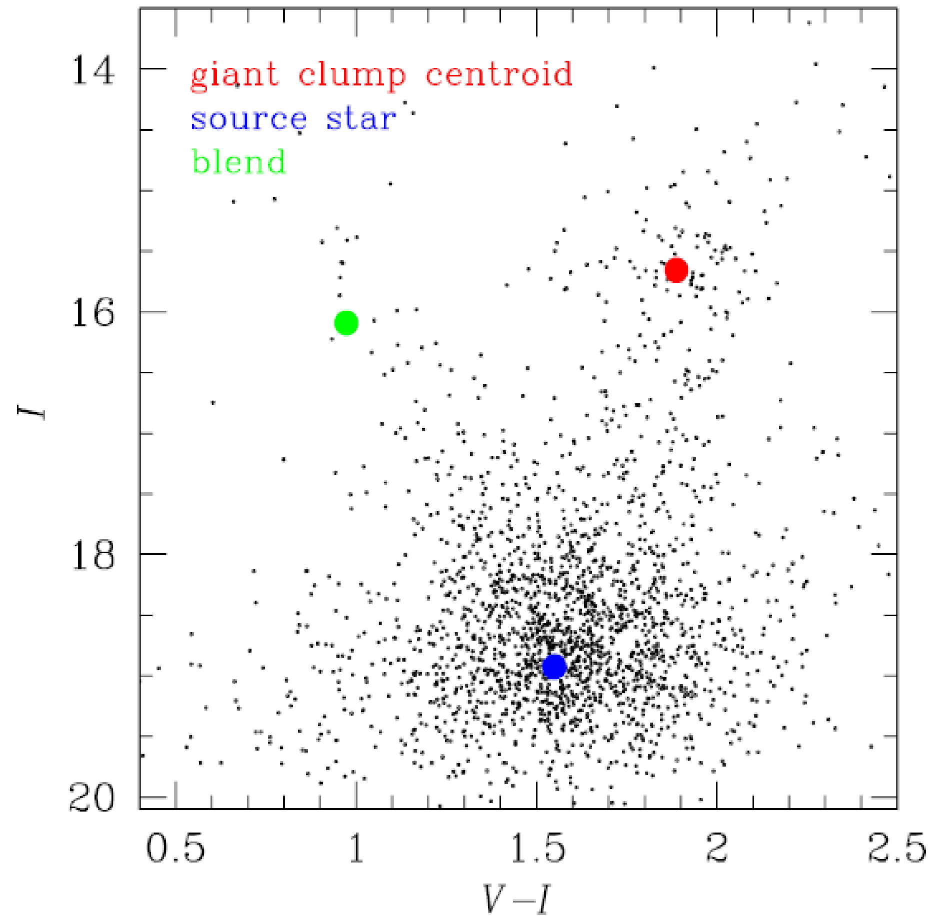
Well, actually: 1 BD + 1 M Dwarf

Parameter	$u_0 > 0$	$u_0 < 0$
Einstein radius (mas)	0.97 ± 0.07	0.96 ± 0.07
Geocentric proper motion (mas yr^{-1})	4.90 ± 0.35	4.96 ± 0.35
Heliocentric proper motion vector (mas yr^{-1})	$(0.72 \pm 0.05, 3.70 \pm 0.26)$	$(0.77 \pm 0.05, -2.63 \pm 0.18)$
Total mass ($M_\odot$)	0.156 ± 0.017	0.133 ± 0.011
Mass of primary ($M_\odot$)	0.124 ± 0.014	0.107 ± 0.009
Mass of companion ($M_\odot$)	0.032 ± 0.004	0.026 ± 0.002
Distance (kpc)	1.16 ± 0.11	1.02 ± 0.08
Projected separation (AU)	1.16 ± 0.11	1.02 ± 0.08
$(KE/PE)_\perp$	0.48 ± 0.20	0.32 ± 0.07

Park et al. 2015, ApJ, in press

OGLE-2013-BLG-0578

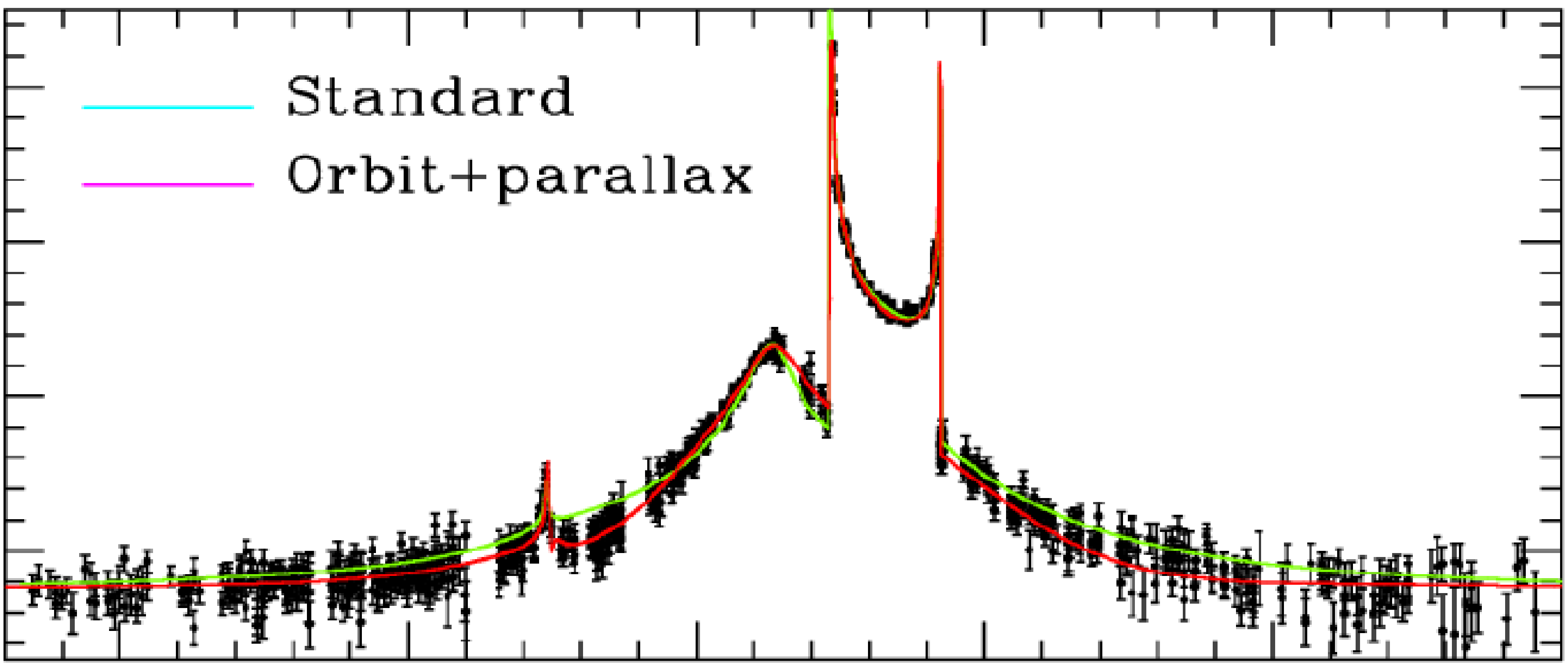
Err... 1 BD + 1 M Dwarf ...
+ 1 K Dwarf (?)



Park et al. 2015, ApJ, in press

OGLE-20XX-BLG-NNNN

2 Stars + 1 Planet

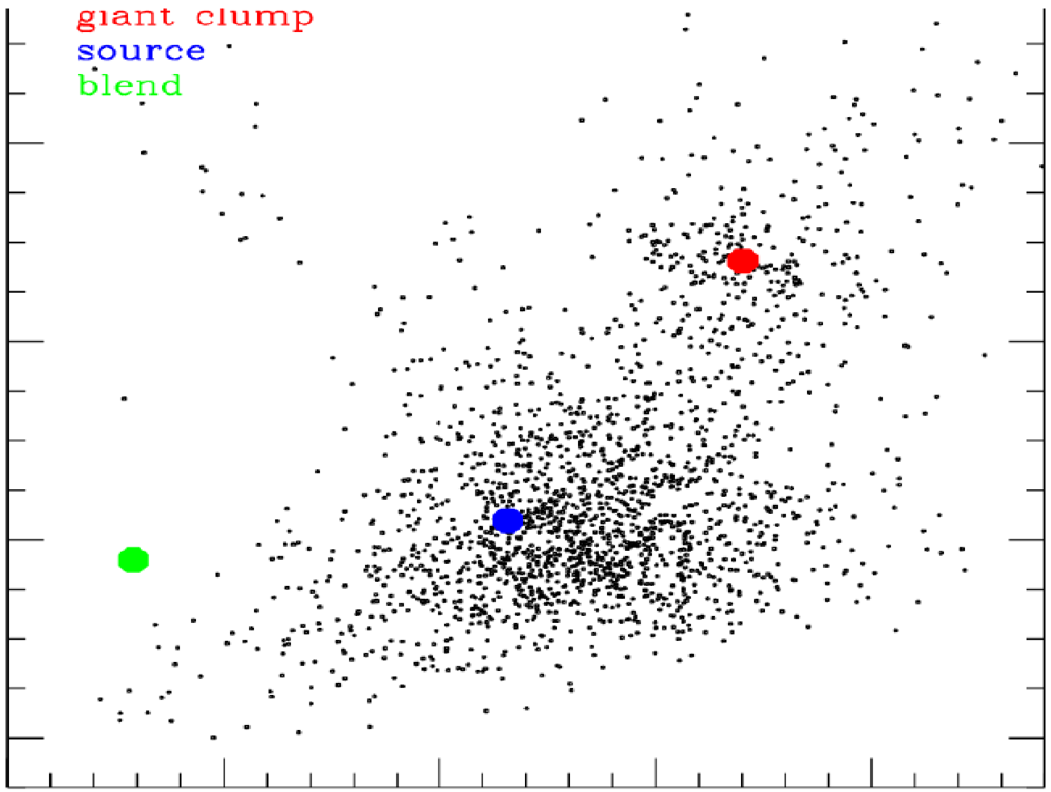


XXX et al. 2015, in prep

OGLE-20XX-BLG-NNNN

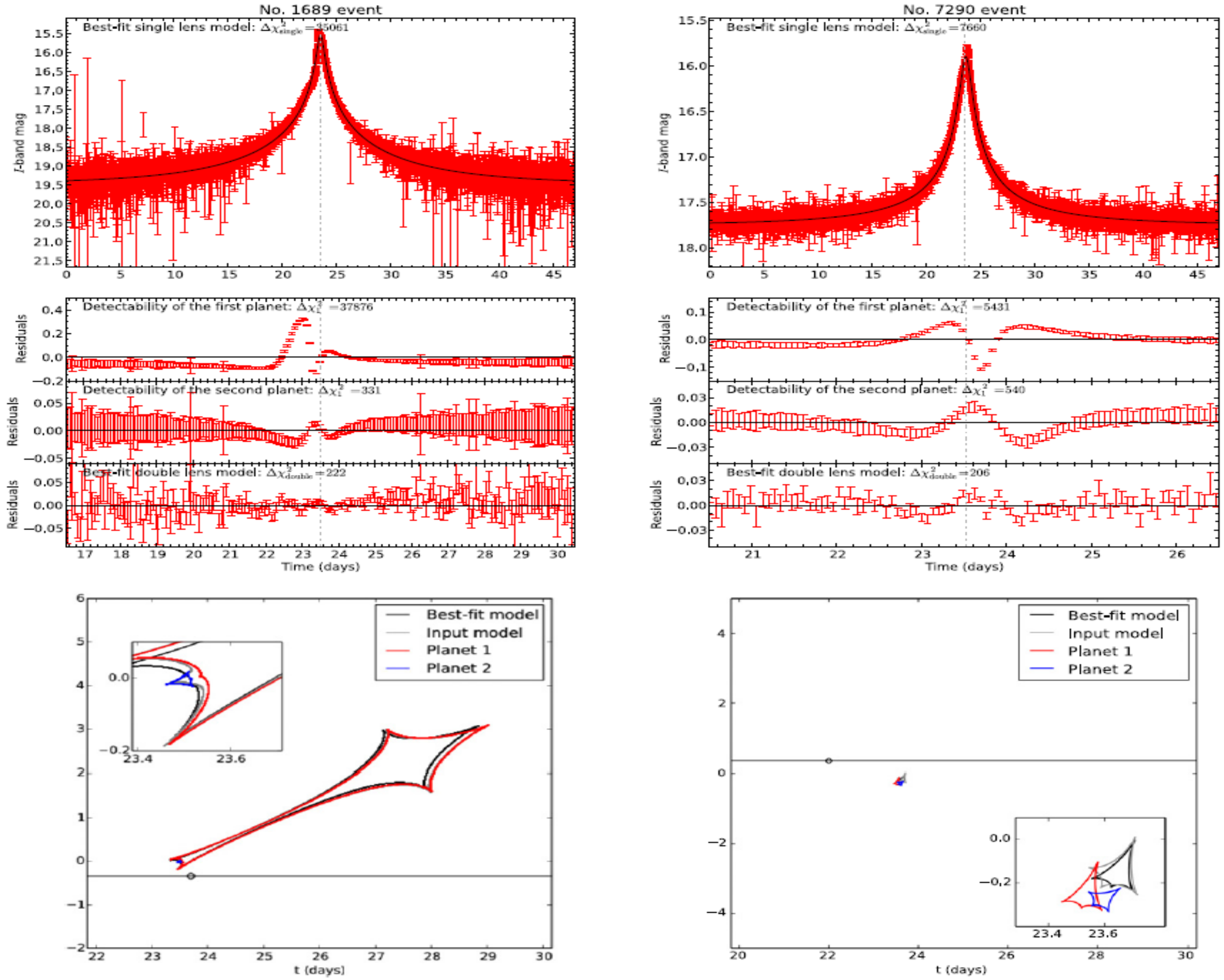
2 Stars + 1 Planet ...

+ 3rd Star (?)



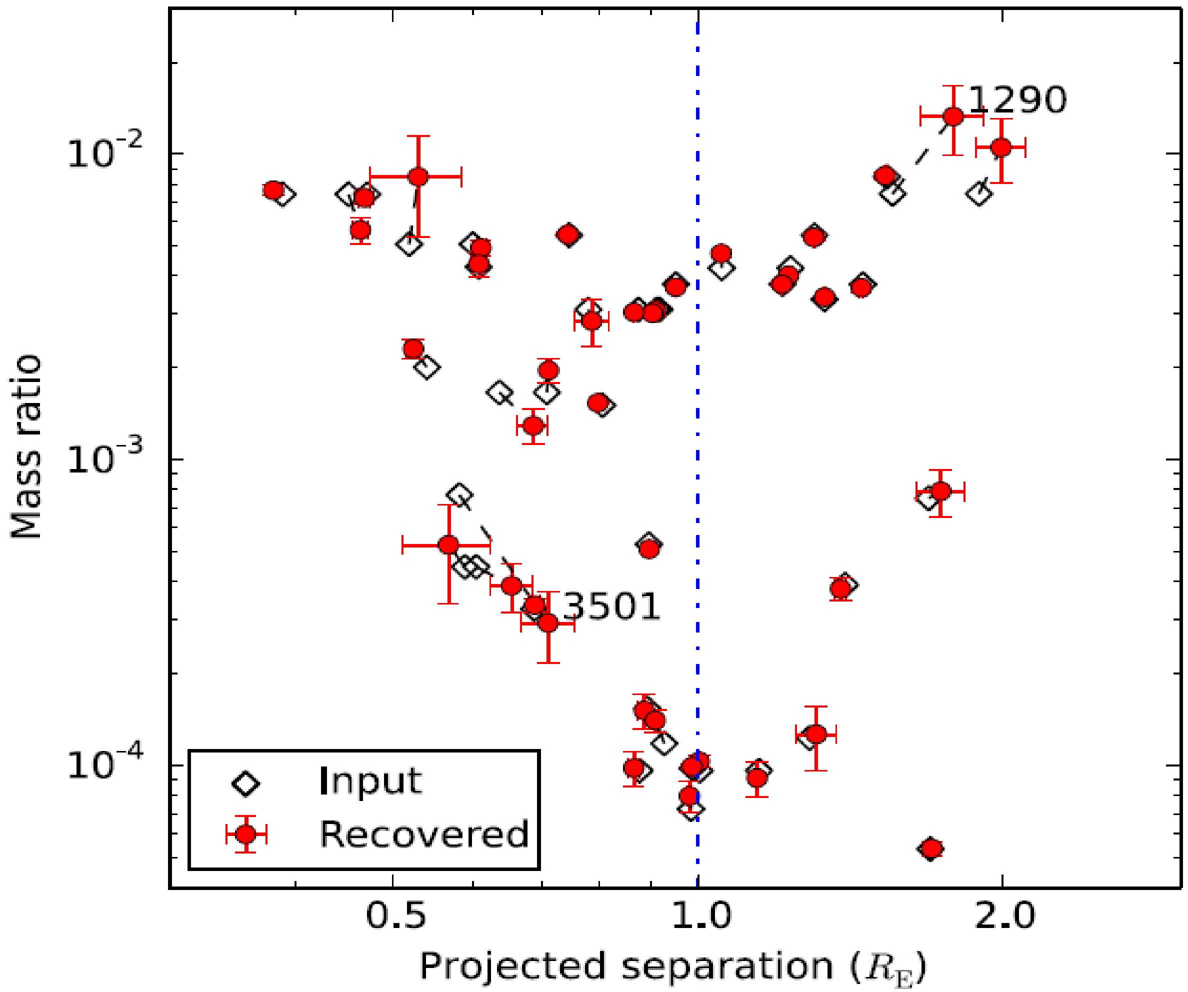
XXX et al. 2015, in prep

Only 1 Theoretical Study of 3-body Detections



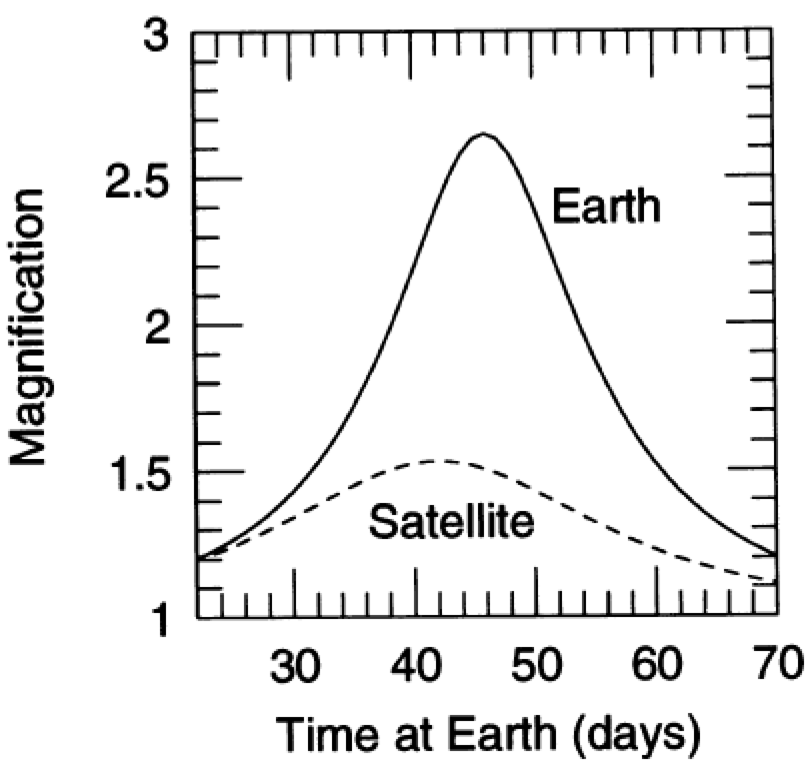
Zhu et al. 2014, ApJ, 794, 53

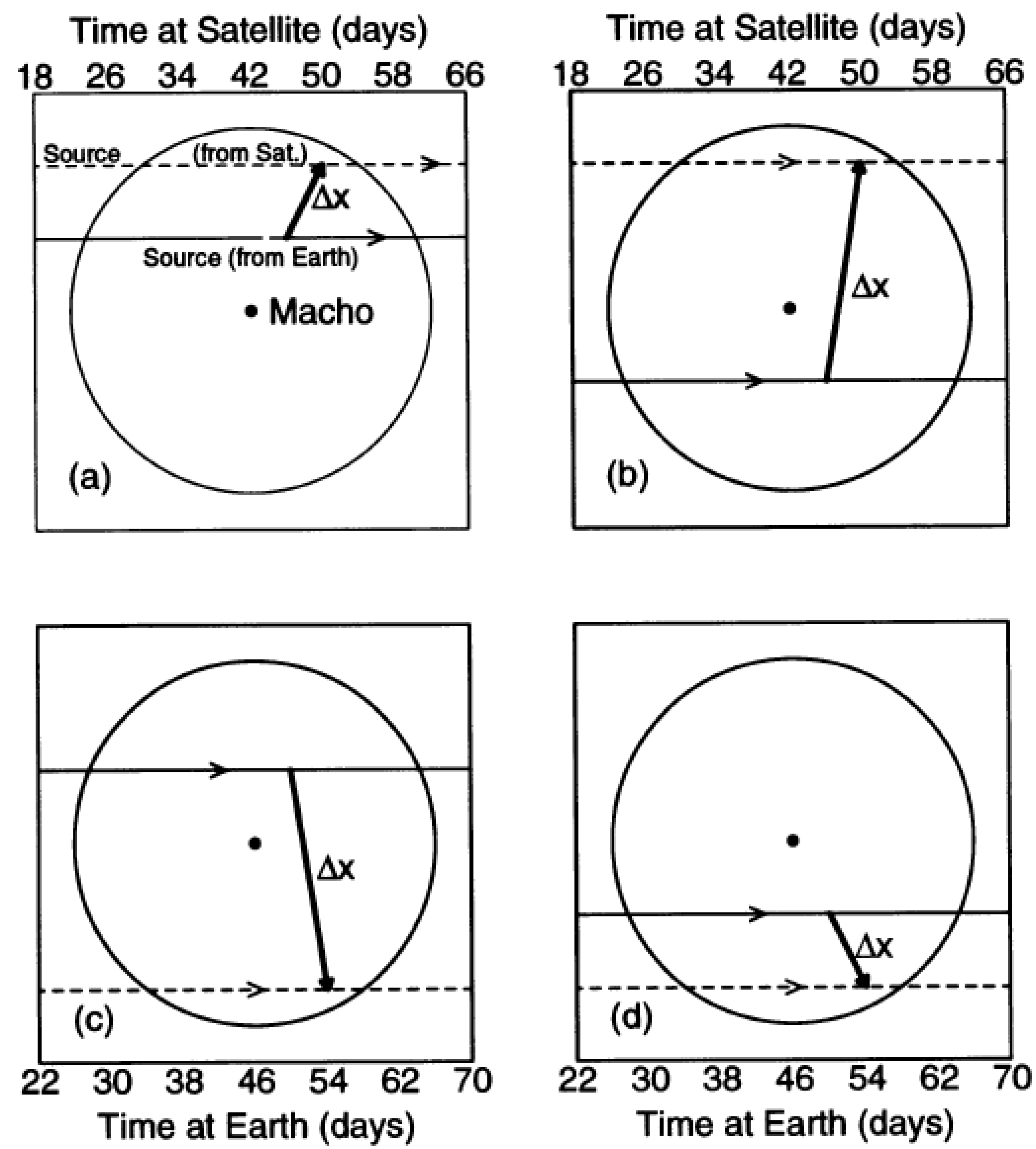
Only 1 Theoretical Study of 3-body Detections

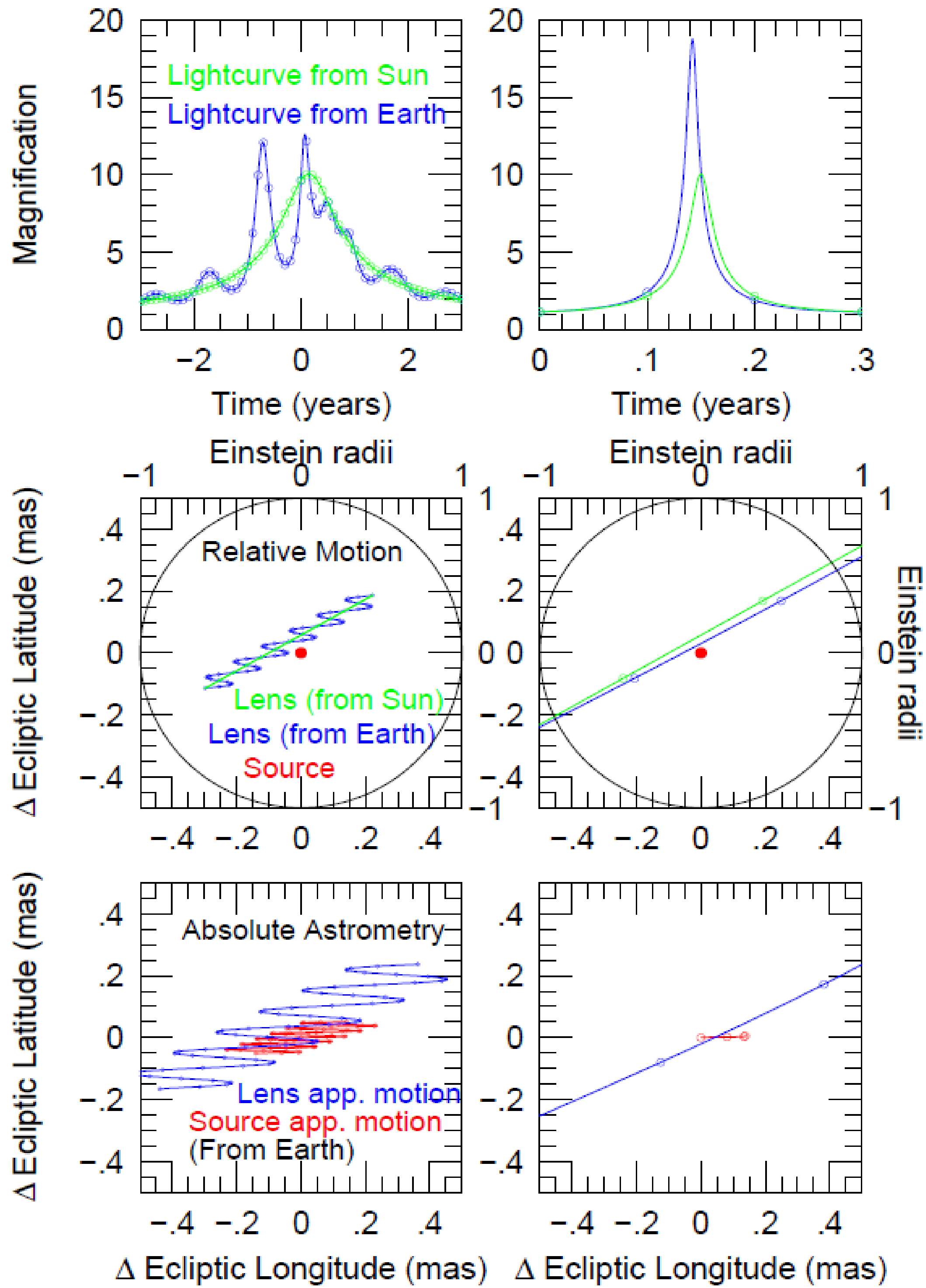


Zhu et al. 2014, ApJ, 794, 53

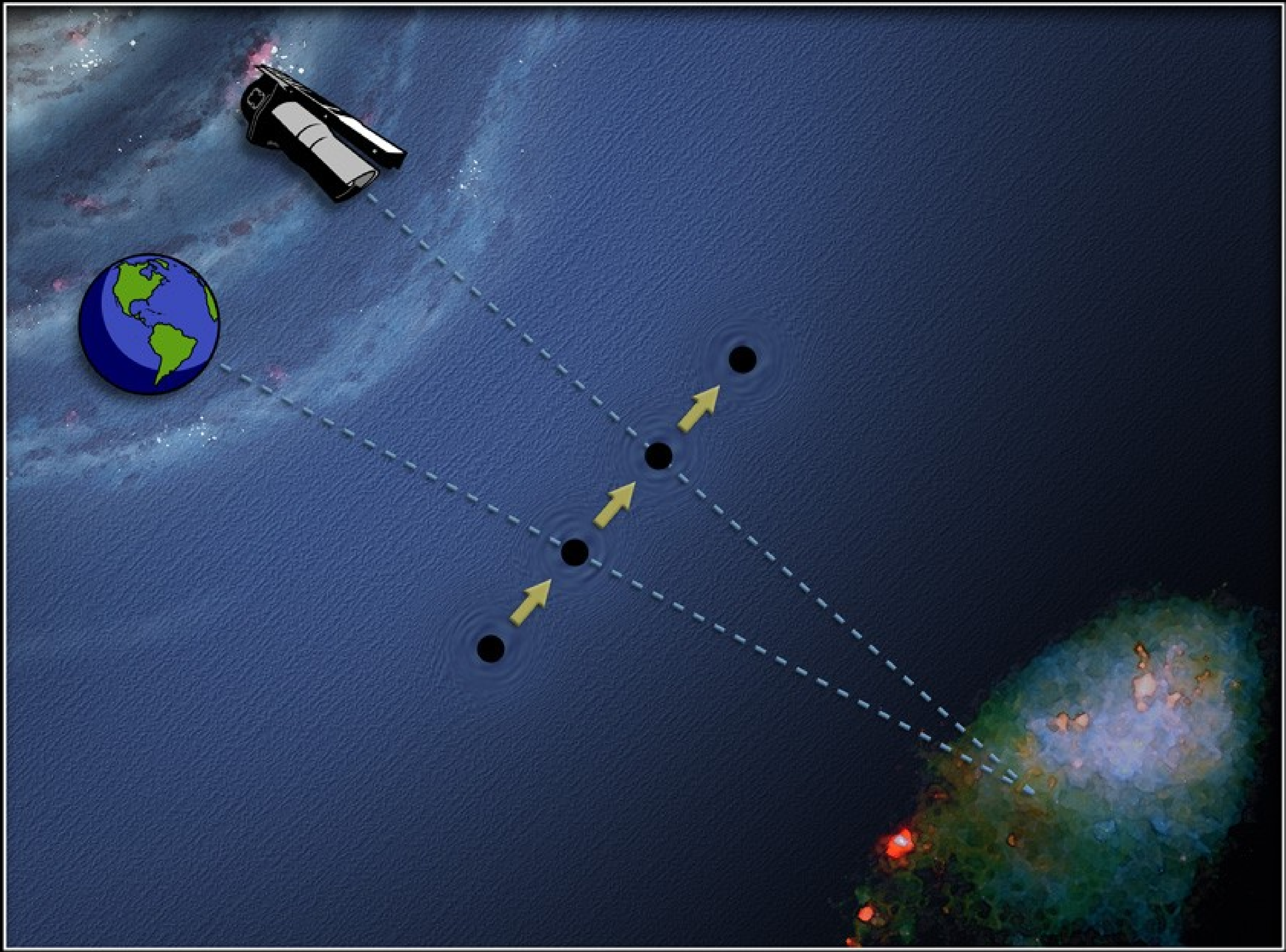
Frontiers IV:
Space-Based Parallaxes







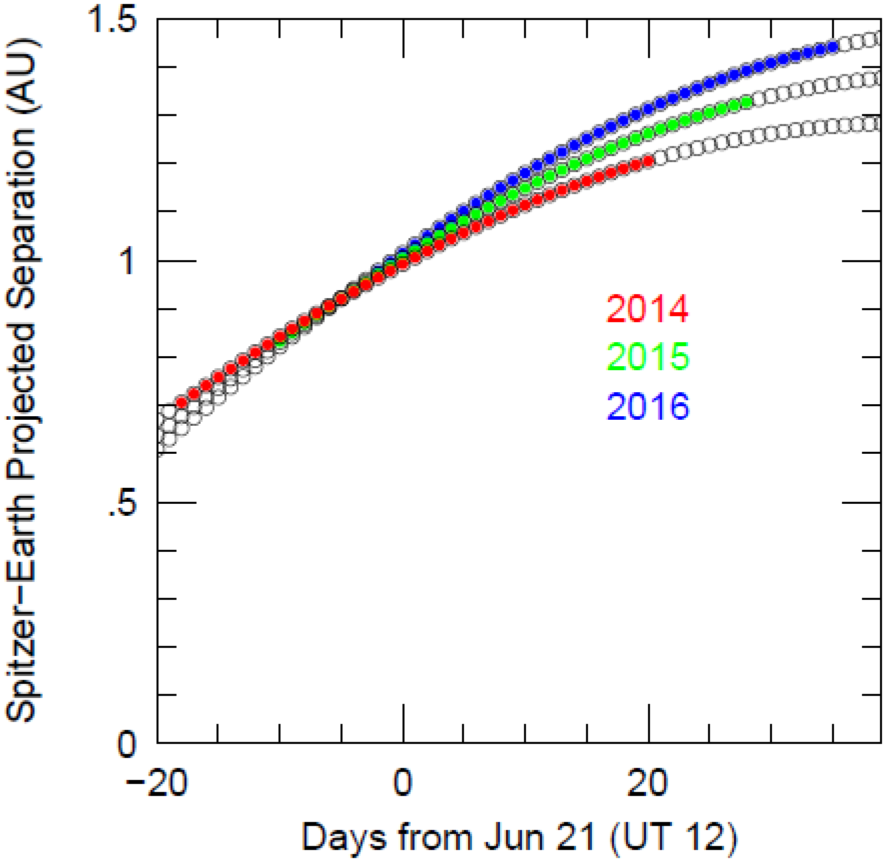
Magnification
Lightcurve from Sun
Lightcurve from Earth
Time (years)
Time (years)
Einstein radii
Einstein radii
Relative Motion
Lens (from Sun)
Lens (from Earth)
Source
Δ Ecliptic Latitude (mas)
Einstein radii
Absolute Astrometry
Lens app. motion
Source app. motion
(From Earth)
Δ Ecliptic Latitude (mas)
Δ Ecliptic Longitude (mas)
Δ Ecliptic Longitude (mas)

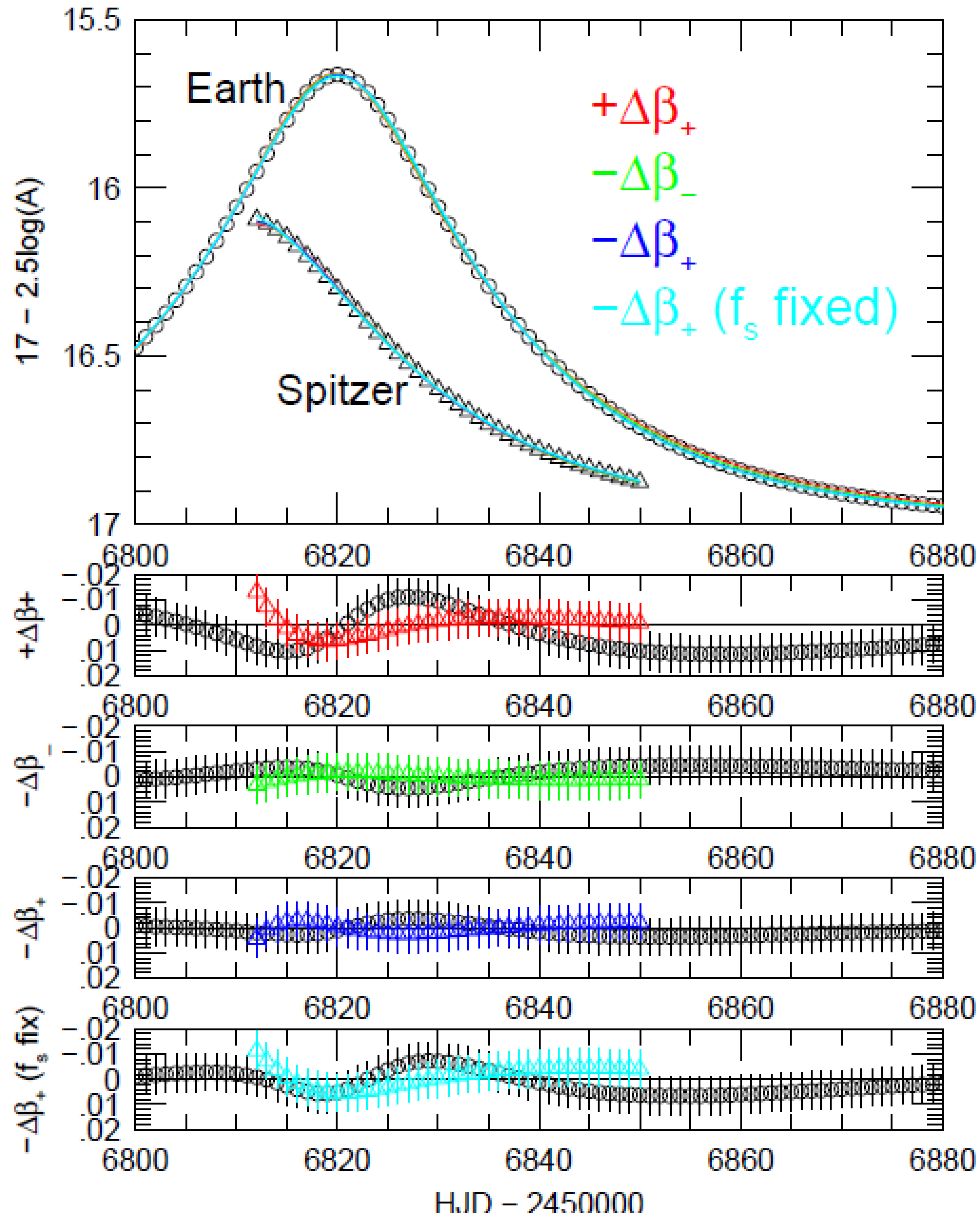


Microlens Parallax Observations of OGLE-2005-SMC-001 Spitzer Space Telescope • IRAC

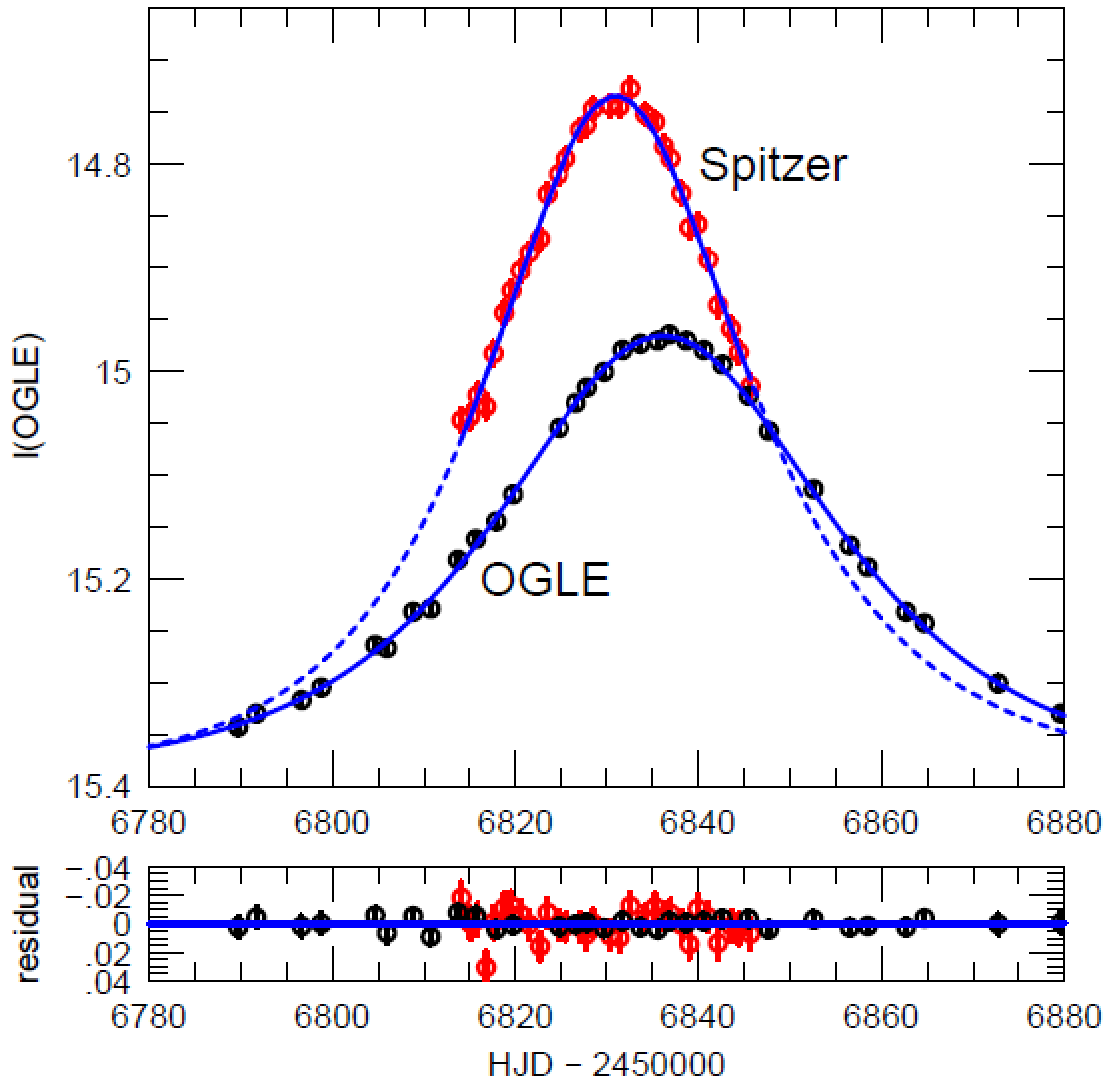
NASA / JPL-Caltech / S. Dong (Ohio State University) ssc2007-XX

100-Hr Spitzer Feasibility Study 2014



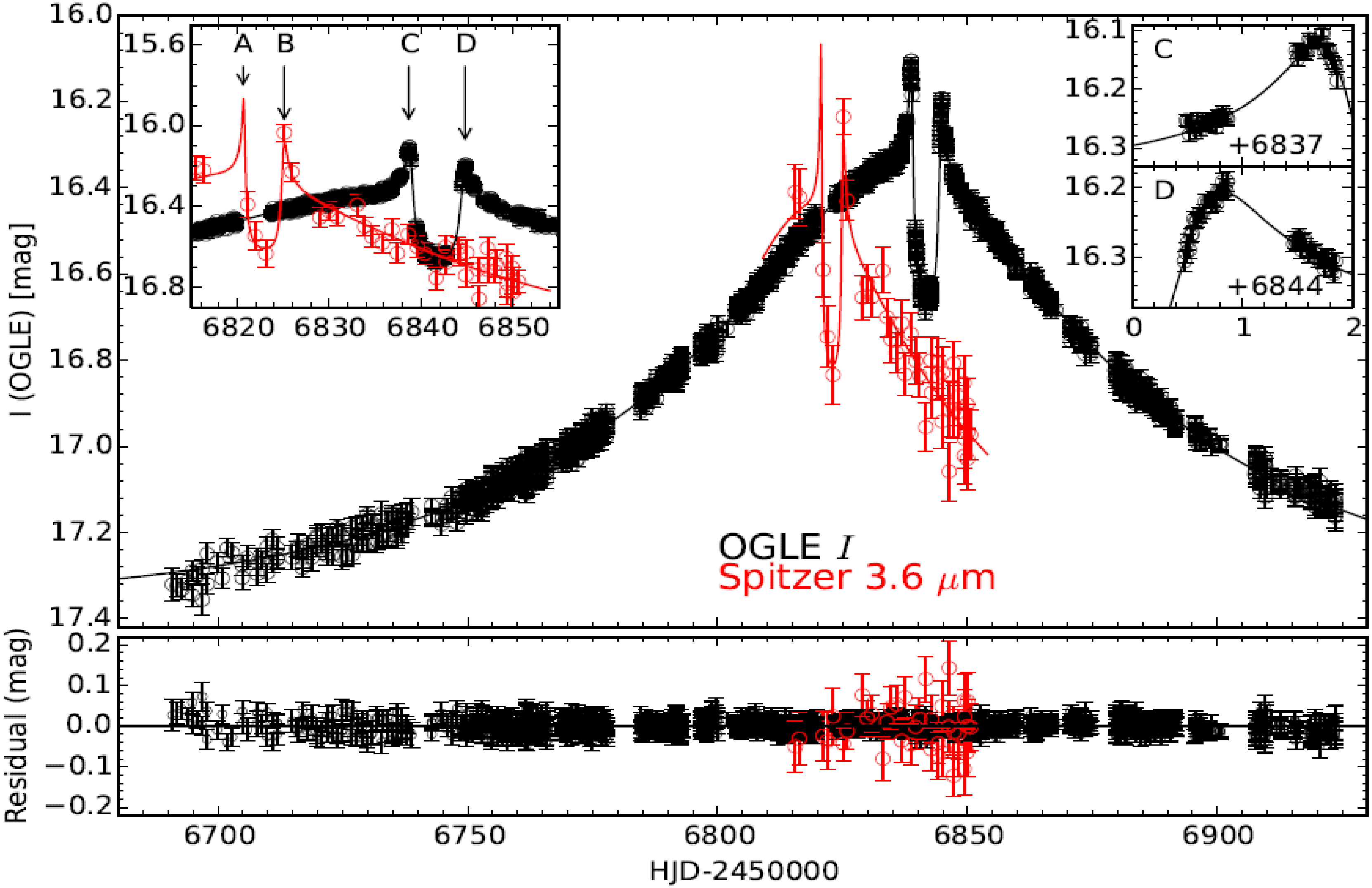


OGLE-2014-BLG-0939:
First Isolated Lens with Spitzer Parallax



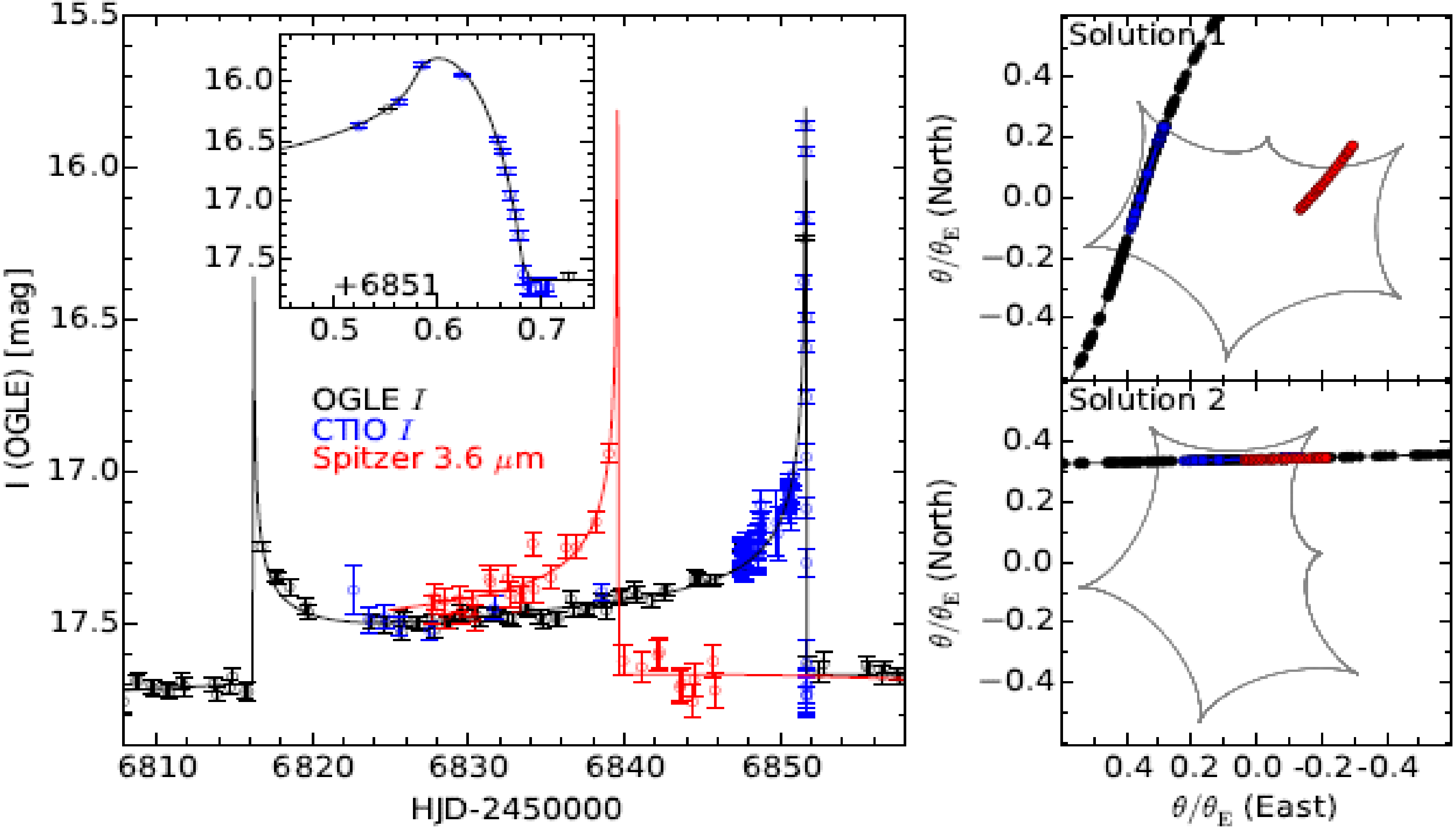
Yee et al. 2015, ApJ, 802, 76

OGLE-2014-BLG-0124:
First Microlens Planet with Spitzer Parallax



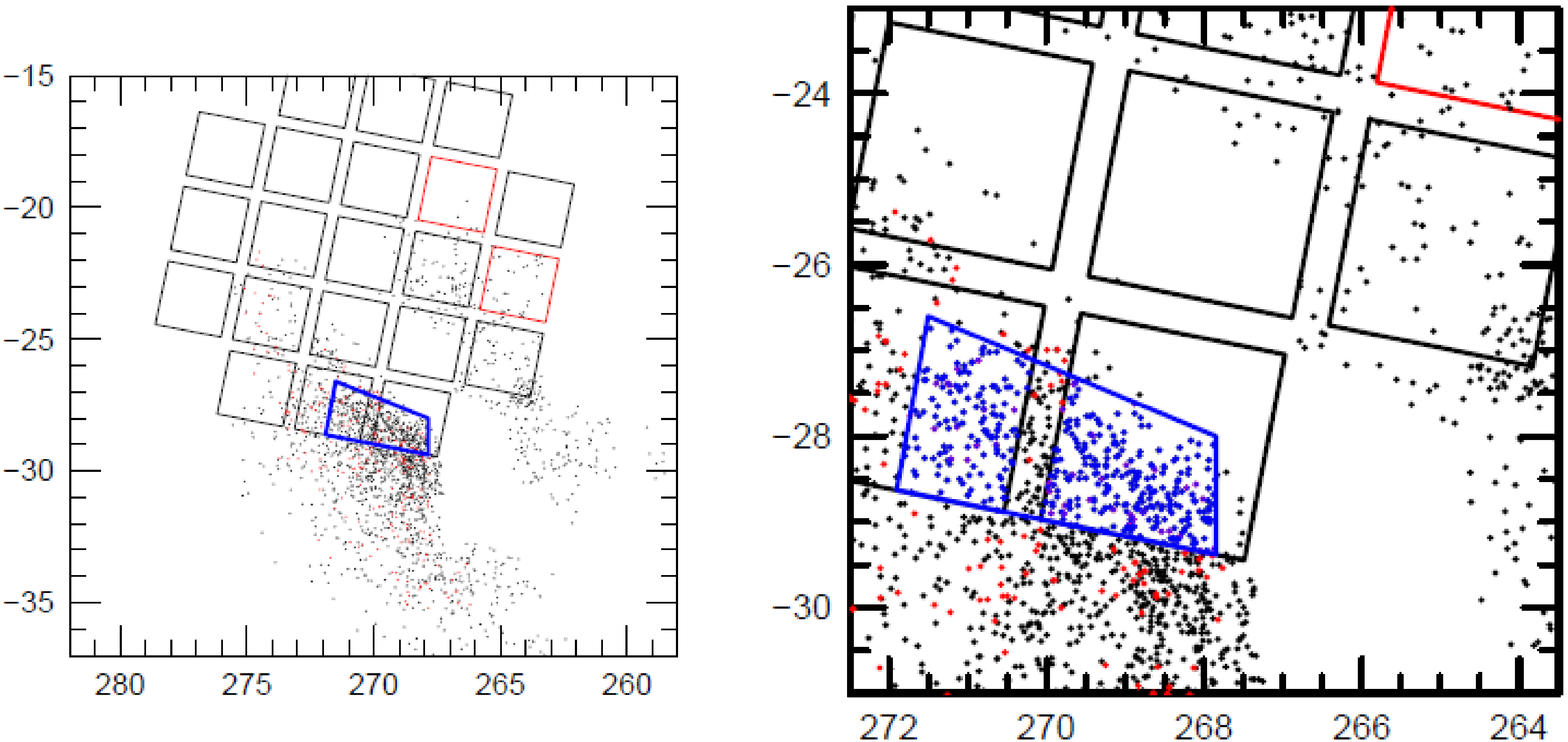
Udalski et al. 2015, ApJ, 799, 237

OGLE-2014-BLG-1050: First Binary Caustic Crossing From Space



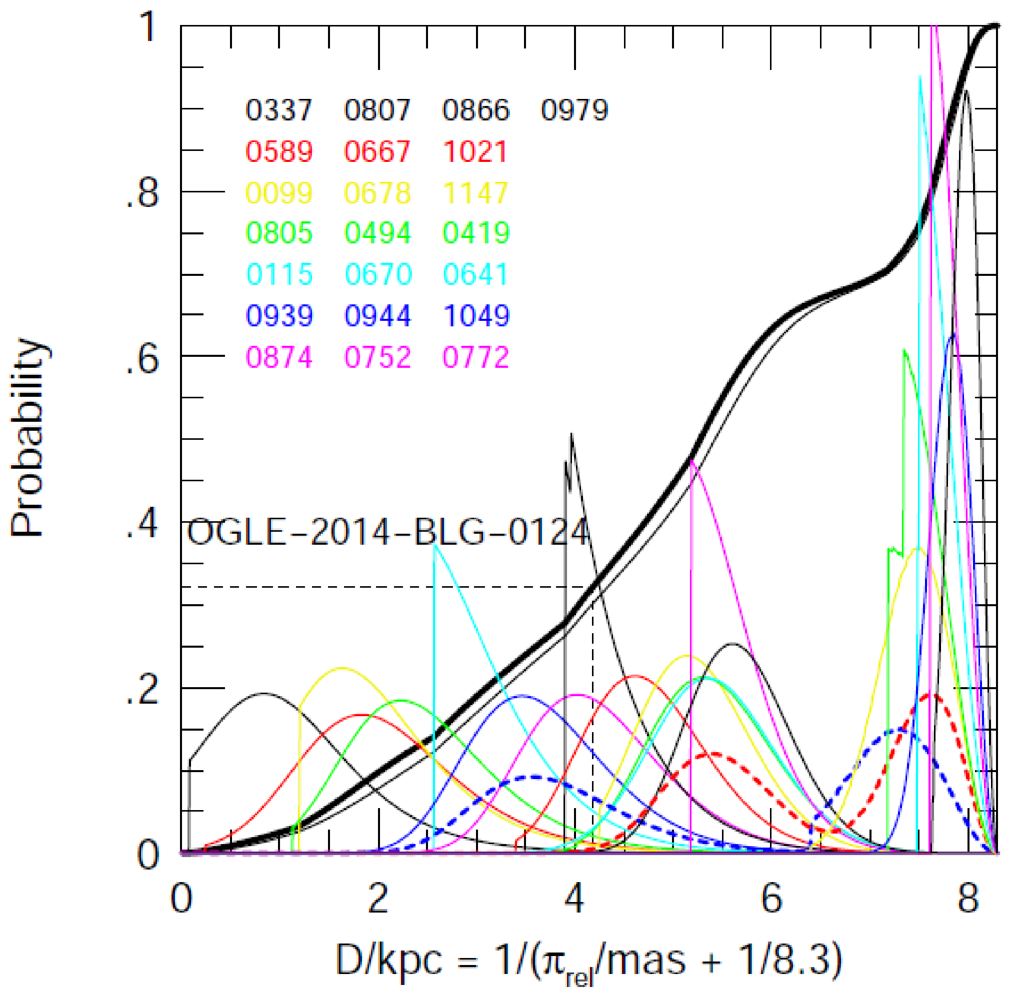
Zhu et al. 2015, ApJ, in press

Proposal: K2 Field9 5.3 Mpxl



Gould, Horne, Street 2014, K2 White Paper

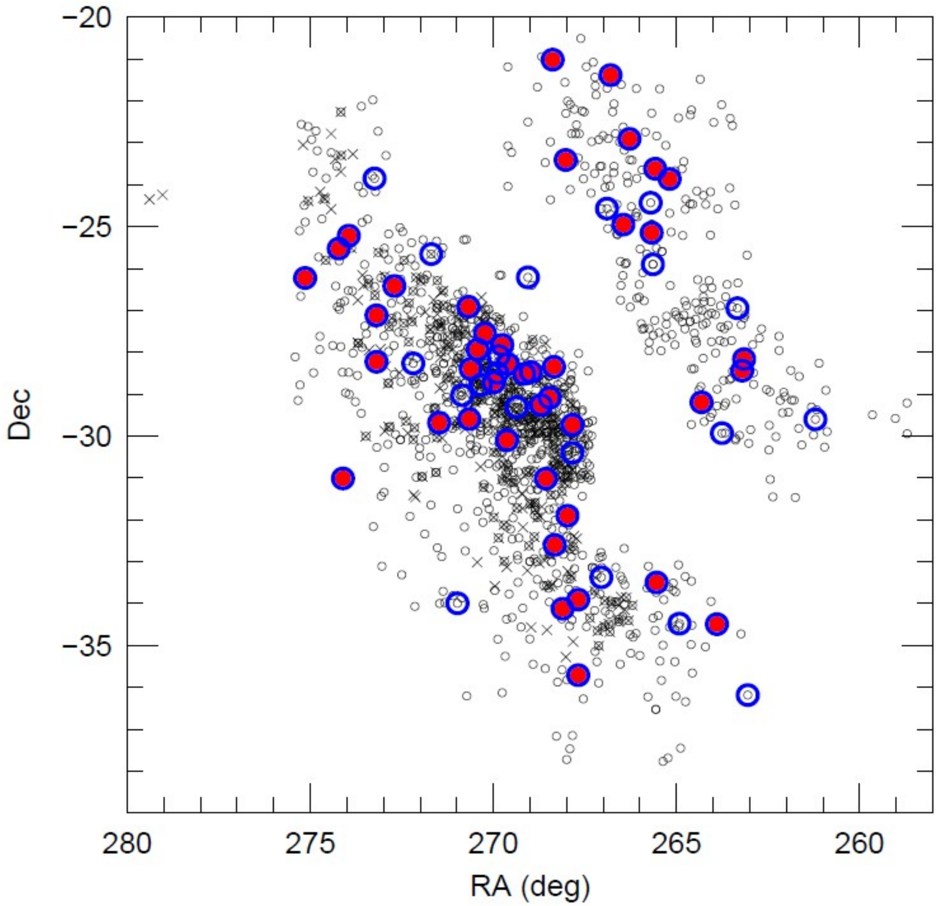
22 Point-Lens Spitzer Parallax Measurements
Versus 1 Planet



Calchi Novati et al. 2015, ApJ, 804, 20

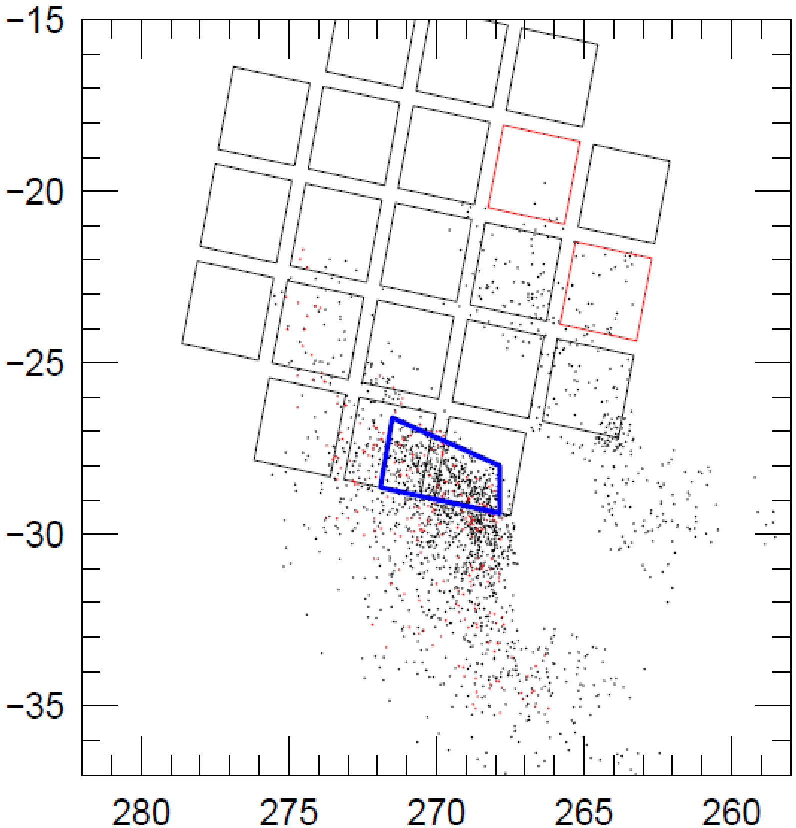
Spitzer

- Alert Each Event

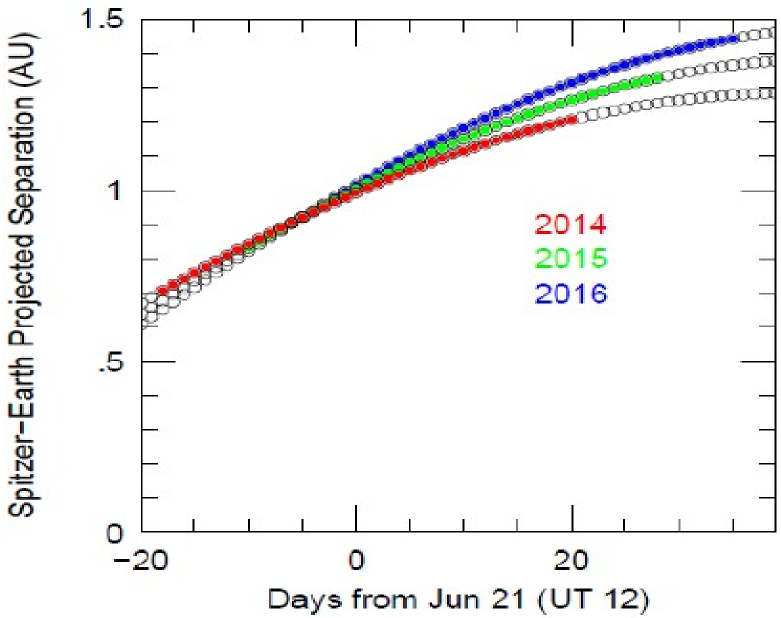


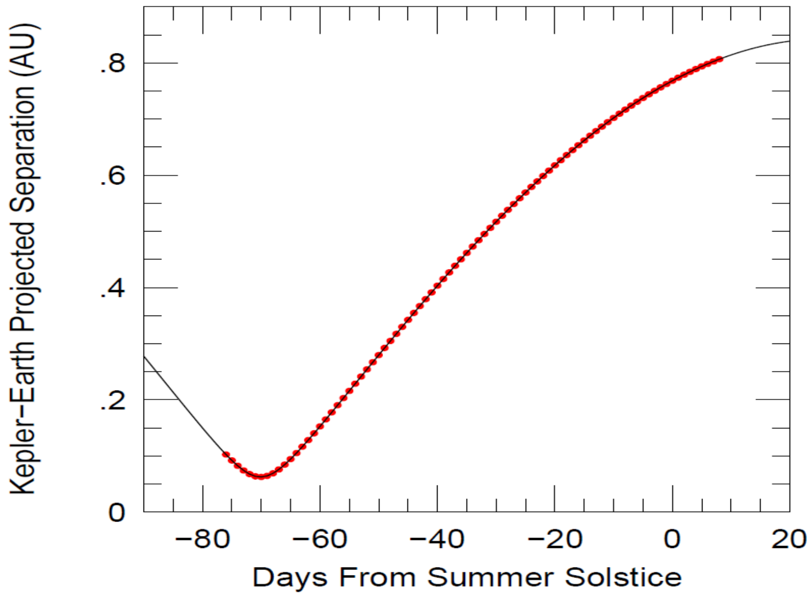
K2

- Contiguous Field

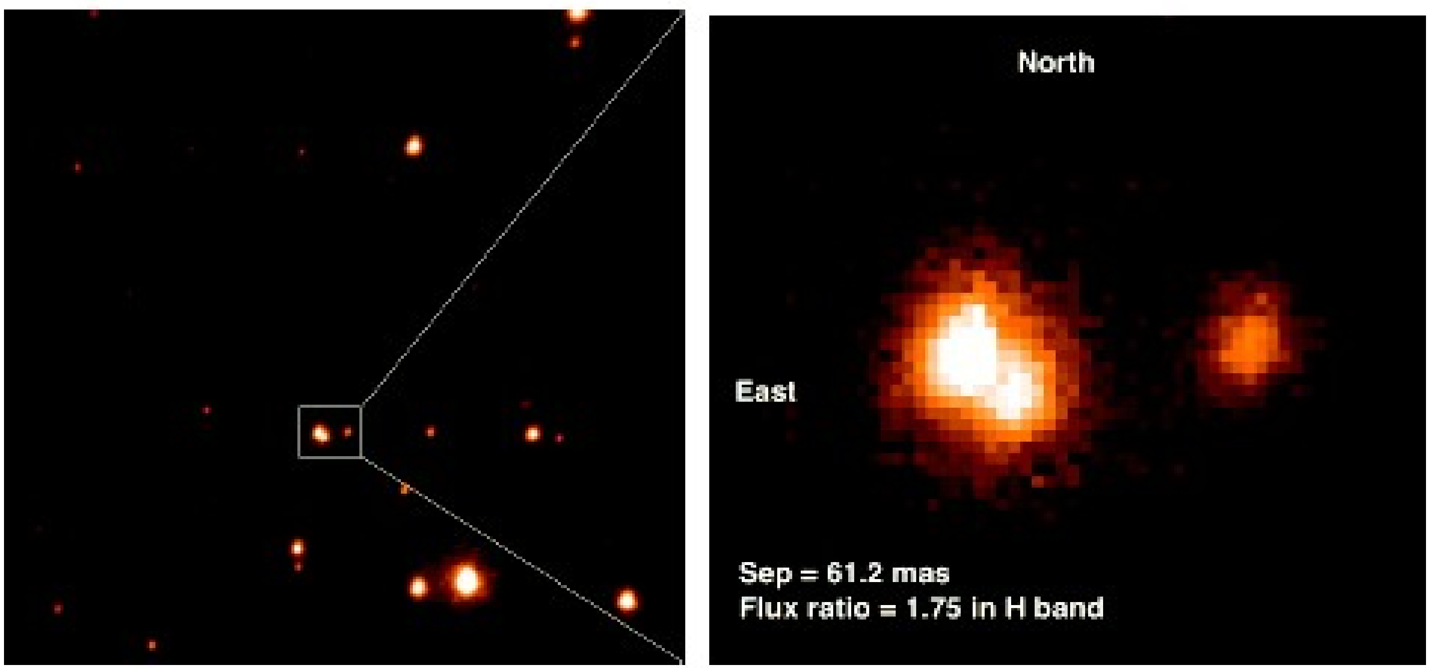


Spitzer	K2
Alert Each Event	Contiguous Field
3-9 Day Delay	No Delay
~1.0 AU Proj Sep	0.1-1.0 AU ProjSep



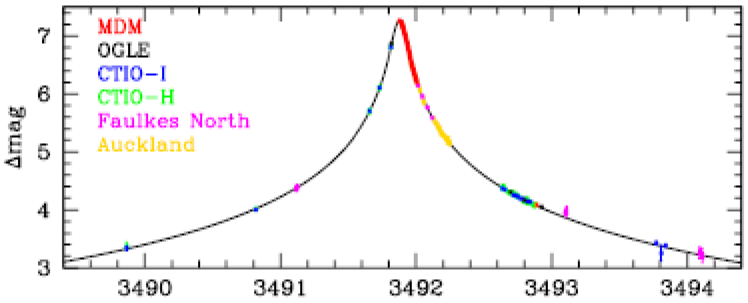


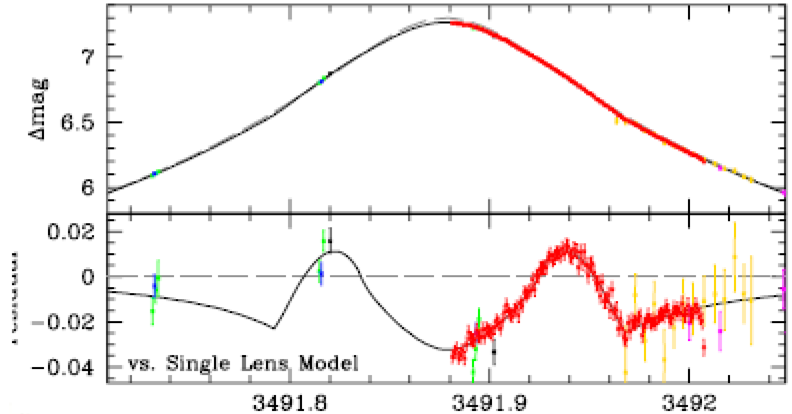
Frontiers V:
High-Resolution Imaging

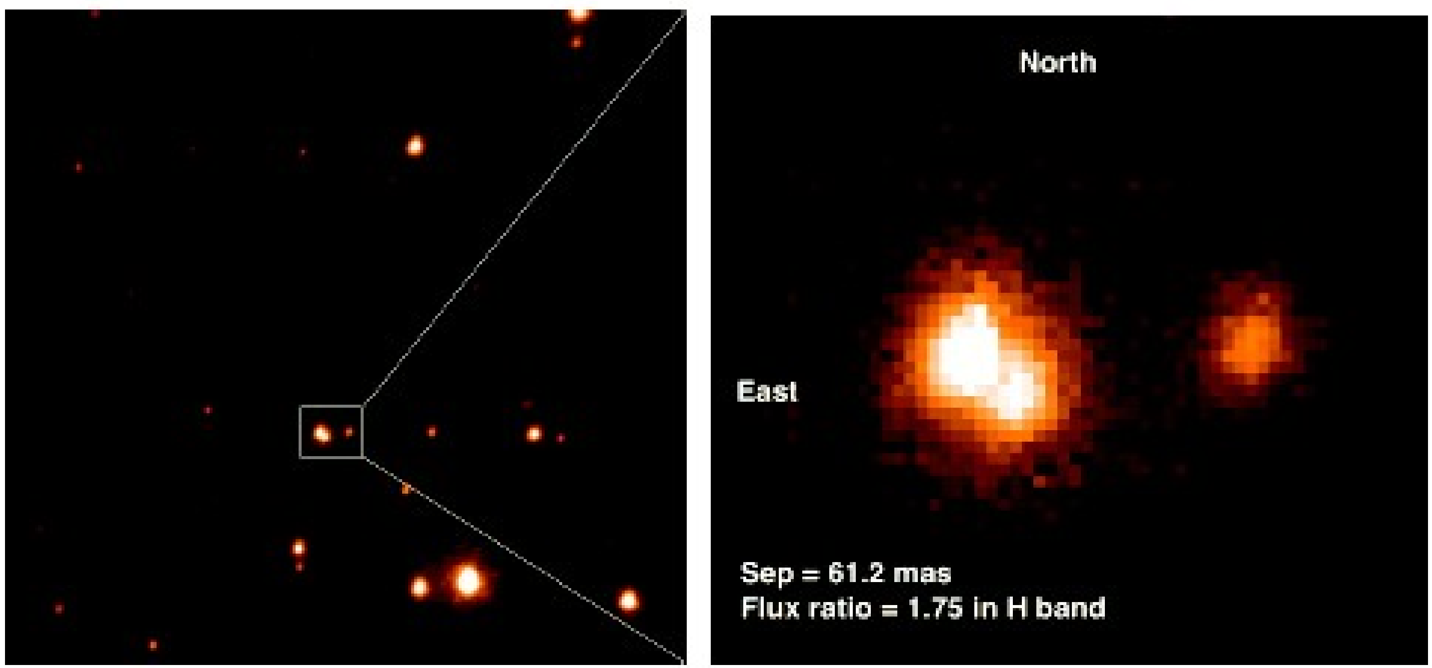


8 Years After Event ...

Keck Imaging of OGLE-2005-BLG-169



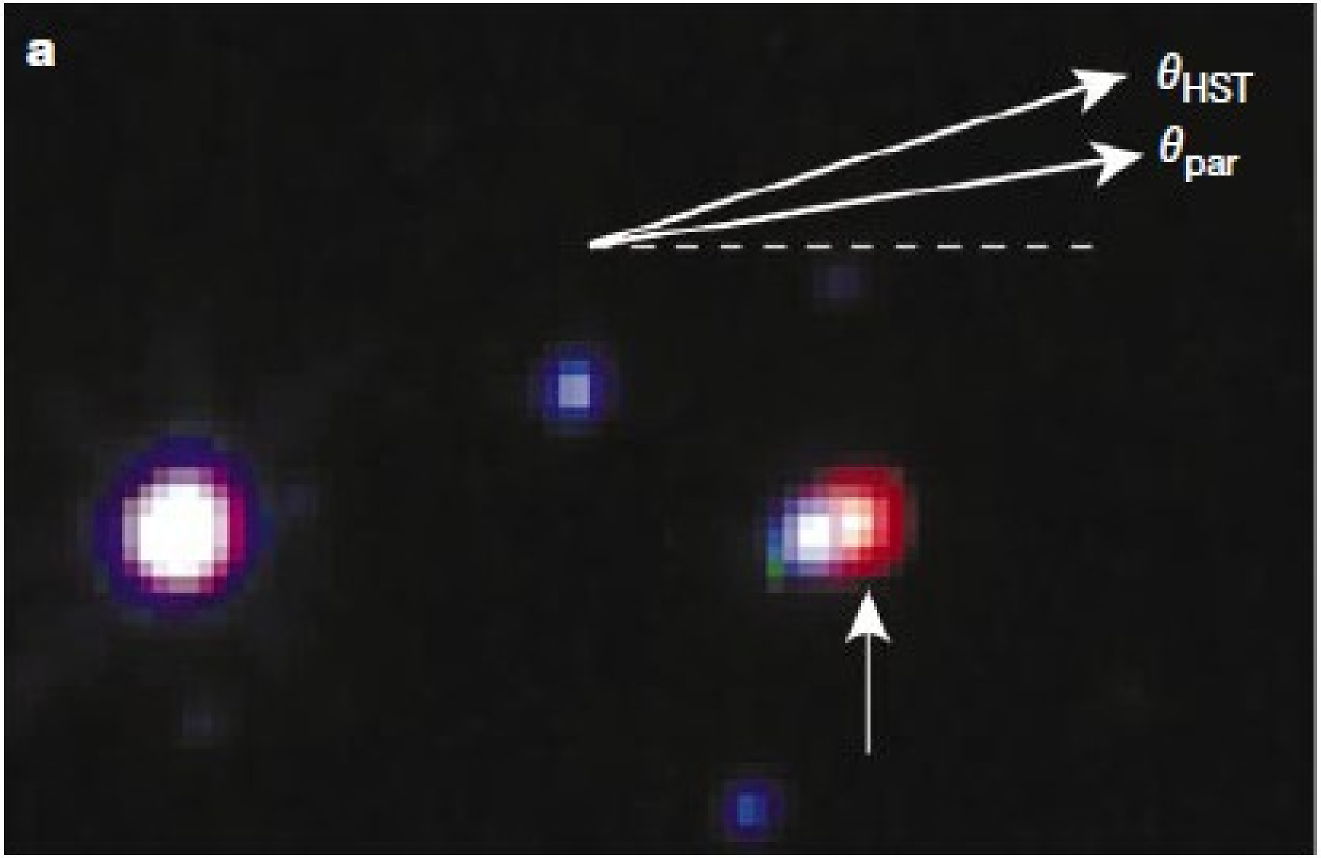




Batista et al. 2015, ApJ, submitted

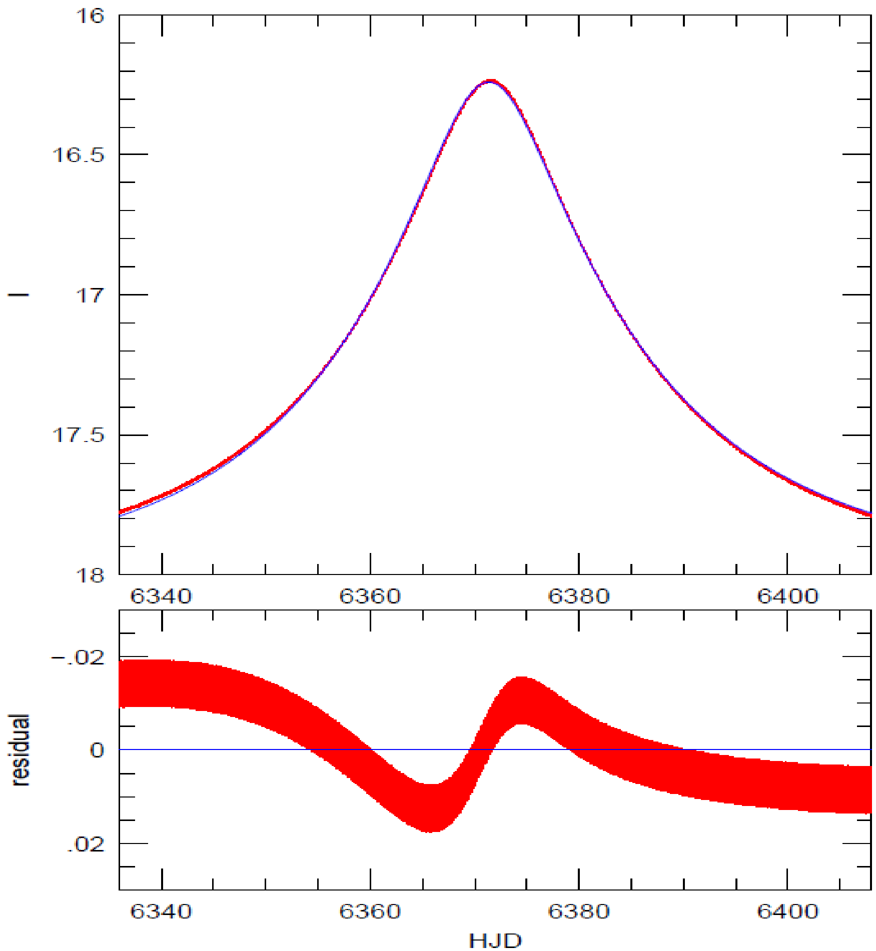
HST image at t_0 + 6.3 yrs

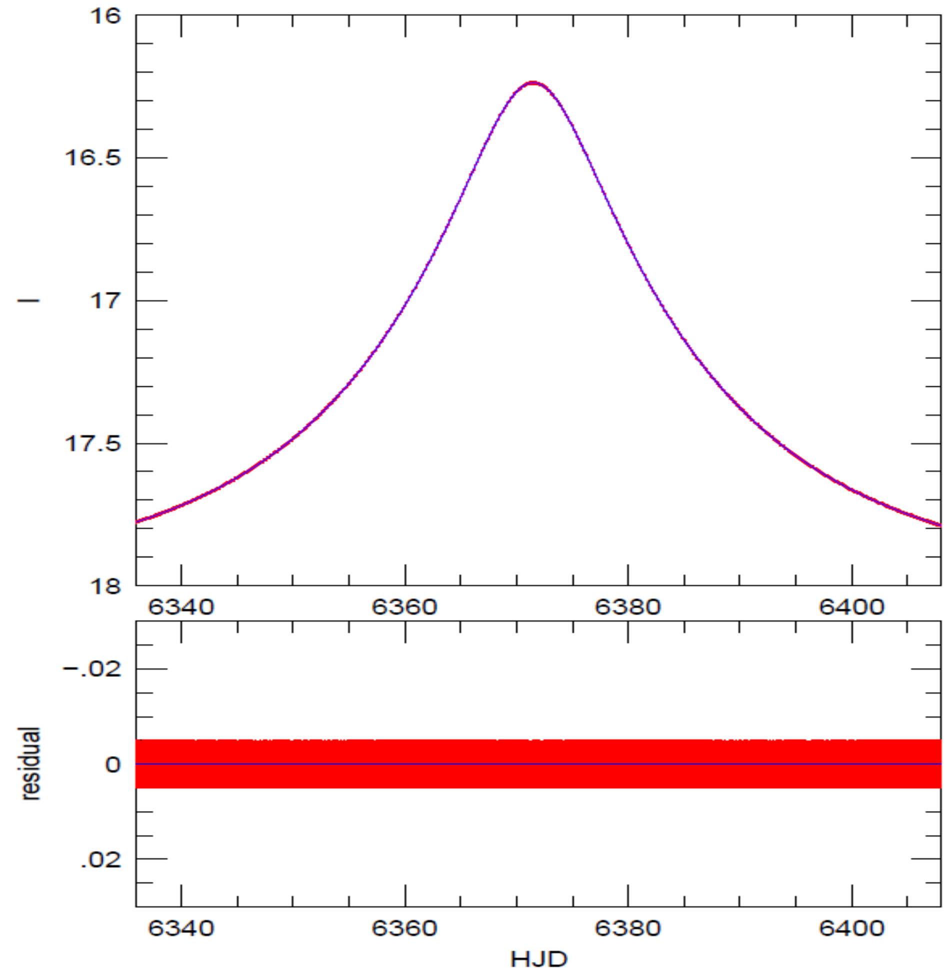
MACHO-LMC-5



Alcock et al. 2001, Nature, 414, 617

1-D parallaxes common ...

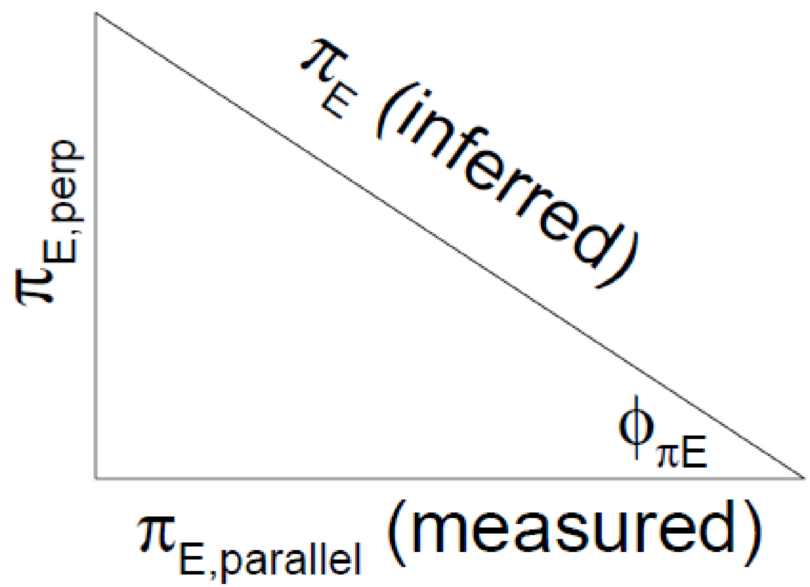




Turn 1-D parallax into 2-D

(Plus, measure θ_E)

- Measure $\pi_{E,\text{parallel}}$ (robust)
- Measure direction of μ (ϕ_μ)
- Infer direction of π_E ($\phi_{\pi E} = \phi_\mu$)
- Derive magnitude of $\pi_E = \pi_{E,\text{parallel}}/\cos(\phi_{\pi E})$



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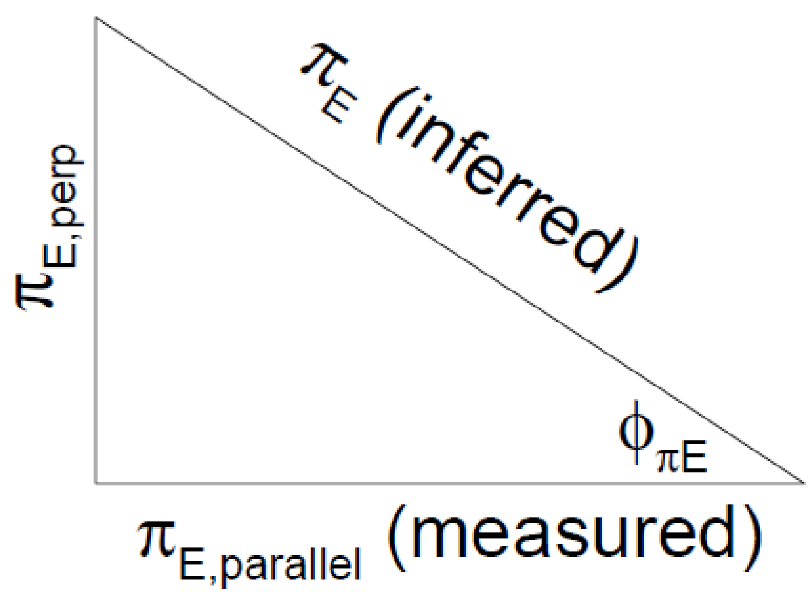
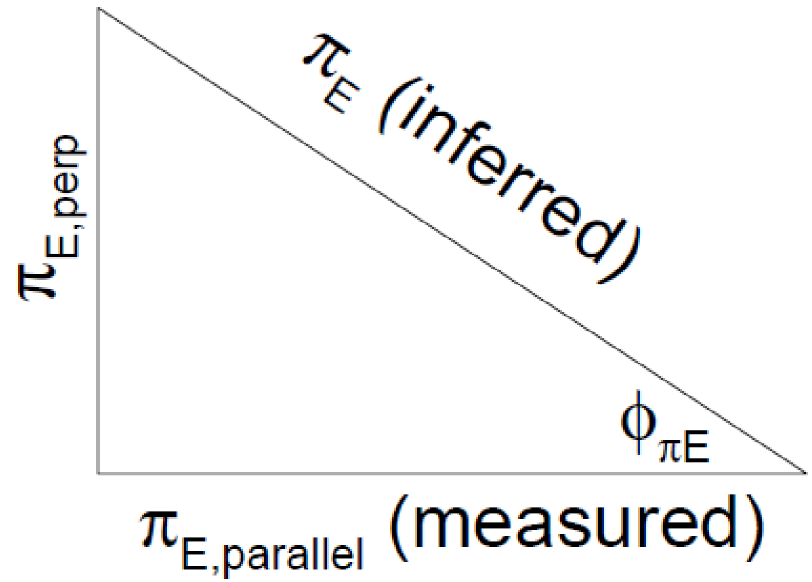
- Measure $\pi_{E,\text{parallel}}$ (robust)
- Measure direction of μ (ϕ_μ)
- Infer direction of π_E ($\phi_{\pi E} = \phi_\mu$)
- Derive magnitude of $\pi_E = \pi_{E,\text{parallel}}/\cos(\phi_{\pi E})$



Turn 1-D parallax into 2-D

... err ... not quite ...

- Derive magnitude of $\pi_E = \pi_{E,\mathrm{parallel}}/\cos(\phi_{\pi E})$



$$\mu_{\rm hel} = \mu_{\rm geo} + \mu_\oplus \pi_{\rm rel} = \frac{\theta_{\rm E}}{t_{\rm E}}\frac{\pi_{\rm E,geo}}{\pi_{\rm E}} + \mu_\oplus \pi_{\rm E}\theta_{\rm E} \qquad \mu_\oplus \equiv {\rm v}_{\oplus,\perp}/{\rm AU}$$

$$\tan\phi \equiv \frac{\mu_{\rm hel,\perp}}{\mu_{\rm hel,\|}} = \frac{\pi_{\rm E,\perp} + \theta_{\oplus,\perp}\pi_{\rm E}^2}{\pi_{\rm E,\|} + \theta_{\oplus,\|}\pi_{\rm E}^2}\ ; \quad \theta_\oplus \equiv \mu_\oplus t_{\rm E}$$

$$A\pi_{\rm E,\perp}^2 - \pi_{\rm E,\perp} + C = 0 \qquad A \equiv \theta_{\oplus,\|}\tan\phi - \theta_{\oplus,\perp}\ ; \quad C \equiv A\pi_{\rm E,\|}^2 + \pi_{\rm E,\|}\tan\phi$$

Turn 1-D parallax into 2-D

... err ... not quite ...

- Derive magnitude of $\pi_E = \pi_{E,\rm parallel}/\cos(\phi_{\pi E})$

$$\boldsymbol{\mu}_{\rm hel} = \boldsymbol{\mu}_{\rm geo} + \boldsymbol{\mu}_\oplus \pi_{\rm rel} = \frac{\theta_{\rm E}}{t_{\rm E}} \frac{\boldsymbol{\pi}_{\rm E,geo}}{\pi_{\rm E}} + \boldsymbol{\mu}_\oplus \pi_{\rm E} \theta_{\rm E} \qquad \boldsymbol{\mu}_\oplus \equiv \mathbf{v}_{\oplus,\perp}/\mathrm{AU}$$

$$\tan\phi \equiv \frac{\mu_{\rm hel,\perp}}{\mu_{\rm hel,\parallel}} = \frac{\pi_{\rm E,\perp} + \theta_{\oplus,\perp}\pi_{\rm E}^2}{\pi_{\rm E,\parallel} + \theta_{\oplus,\parallel}\pi_{\rm E}^2} \;; \quad \boldsymbol{\theta}_\oplus \equiv \boldsymbol{\mu}_\oplus t_{\rm E}$$

$$A\pi_{\rm E,\perp}^2 - \pi_{\rm E,\perp} + C = 0 \qquad A \equiv \theta_{\oplus,\parallel}\tan\phi - \theta_{\oplus,\perp} \;; \quad C \equiv A\pi_{\rm E,\parallel}^2 + \pi_{\rm E,\parallel}\tan\phi$$

$$\pi_{\rm E,\perp} = \frac{1 \pm \sqrt{1-4AC}}{2A}$$

$$\pi_{\rm E,\perp} = C(1 + AC + \ldots) \qquad (4AC \ll 1)$$

$$\pi_{\rm E,\perp} = \frac{1}{A} - C + \ldots \qquad (4AC \ll 1, \quad \text{alternate})$$

Gould 2014, JKAS, 47, 153

$$\theta = 1.22\ \lambda/D$$

Keck K-band

50 mas

$$\theta = 1.22\ \lambda/D$$

Keck K-band

50 mas

GMT J-band

11 mas

$$\theta = 1.22\ \lambda/D$$

Keck K-band

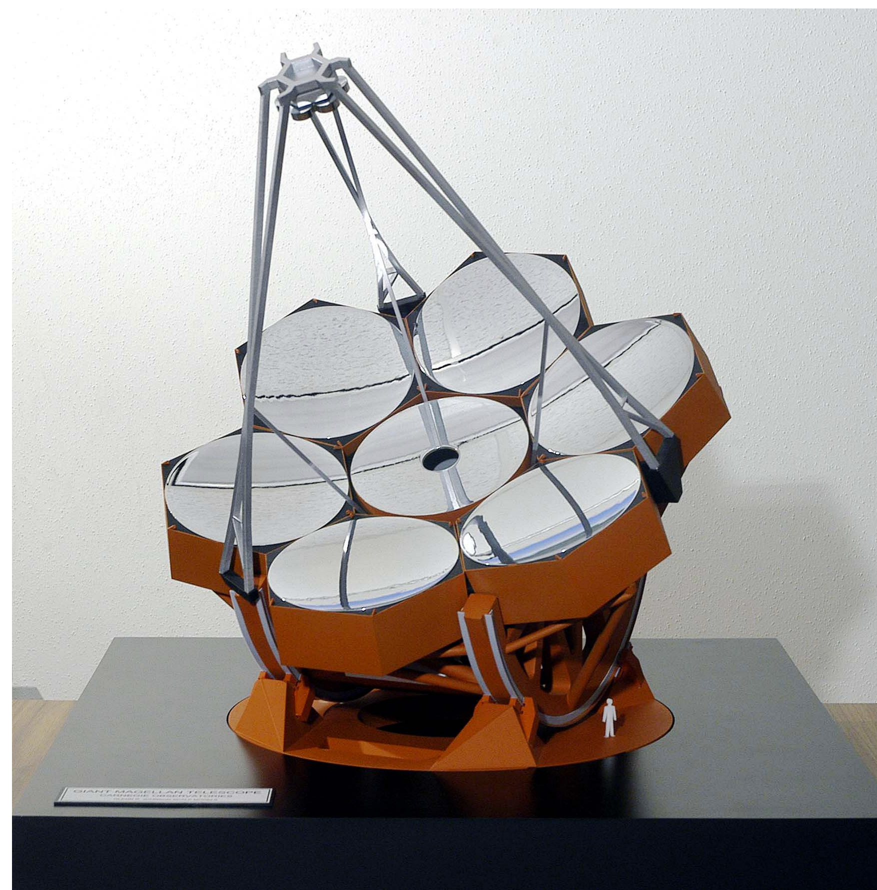
50 mas

25 years

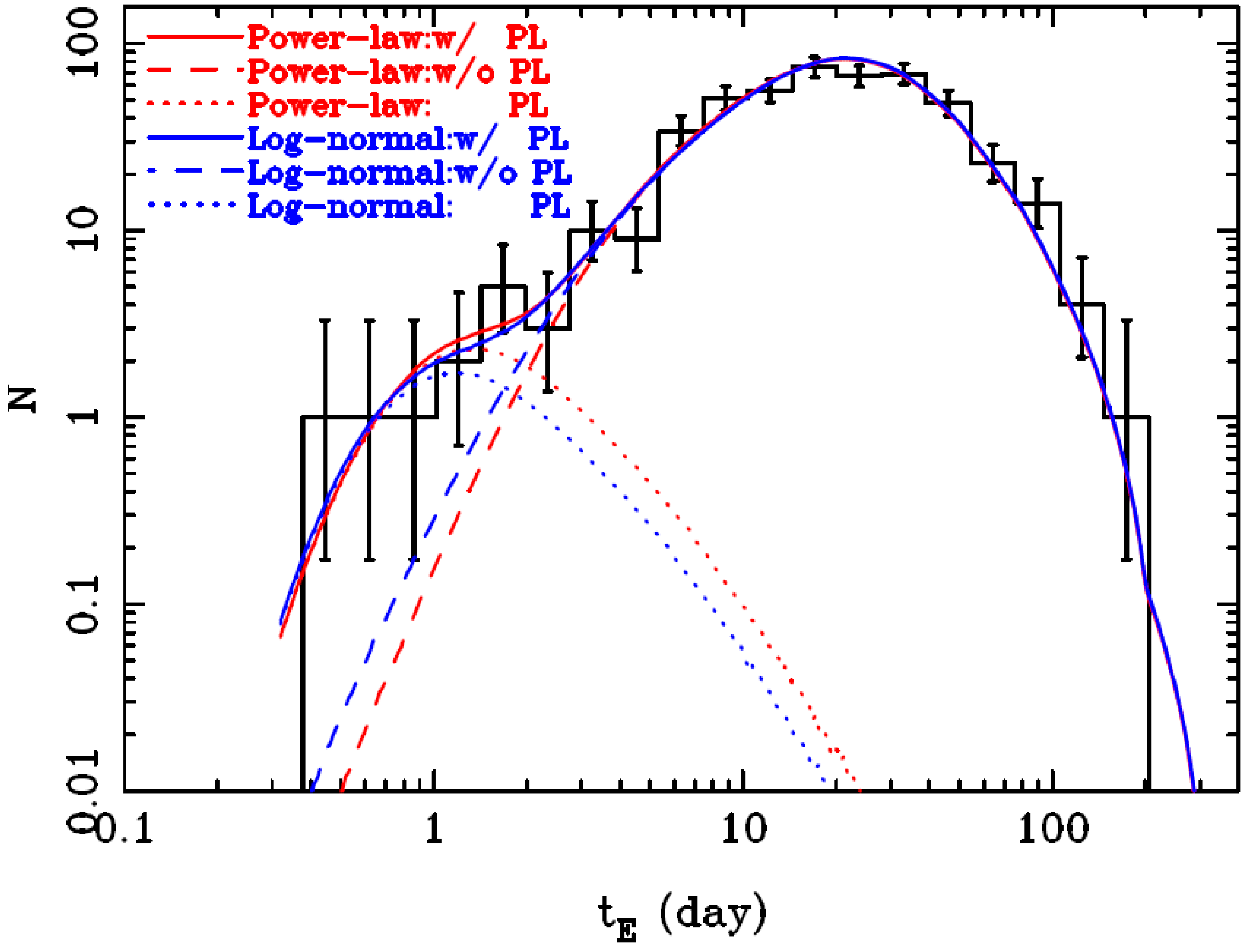
GMT J-band

11 mas

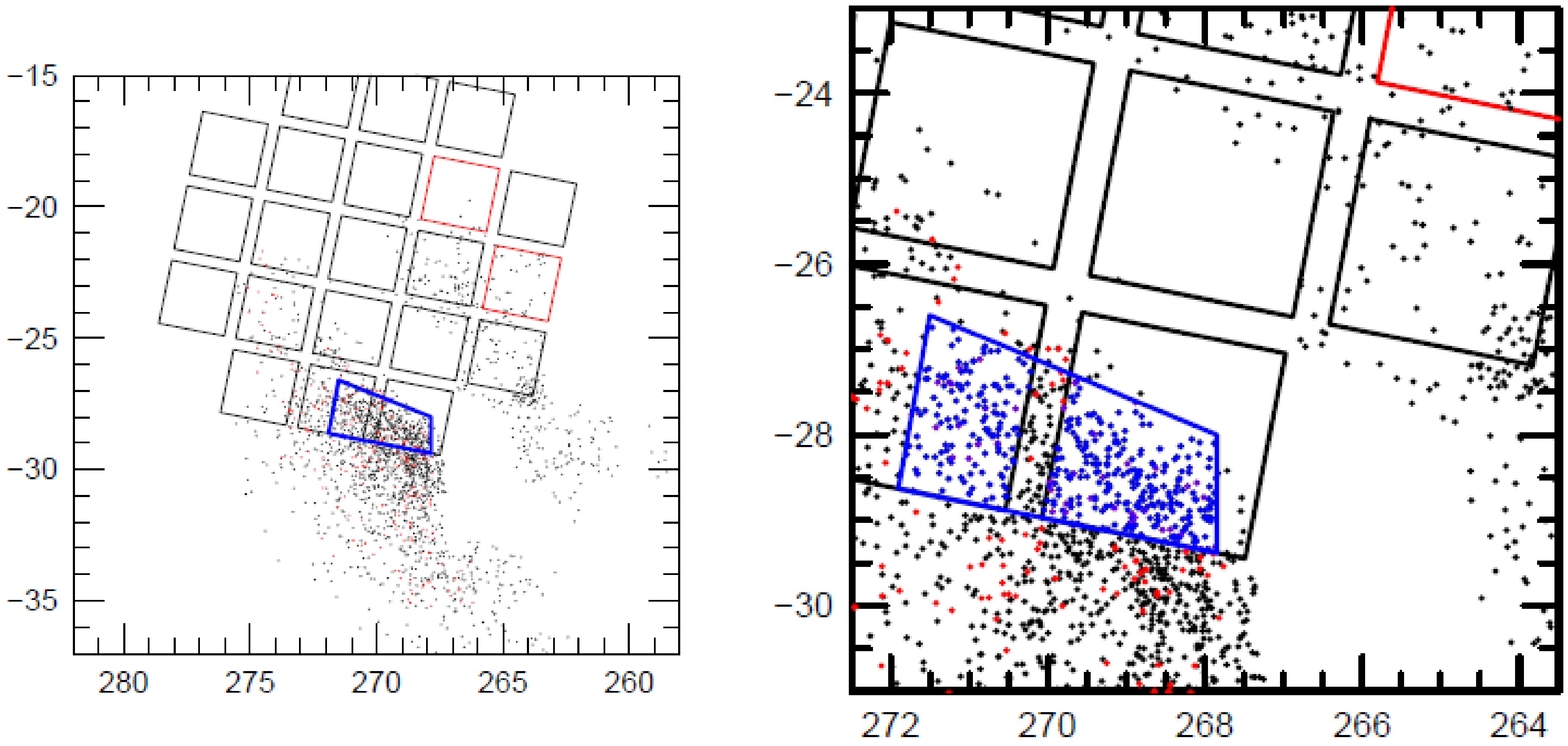
6 years



Frontiers VI:
Free-Floating Planets

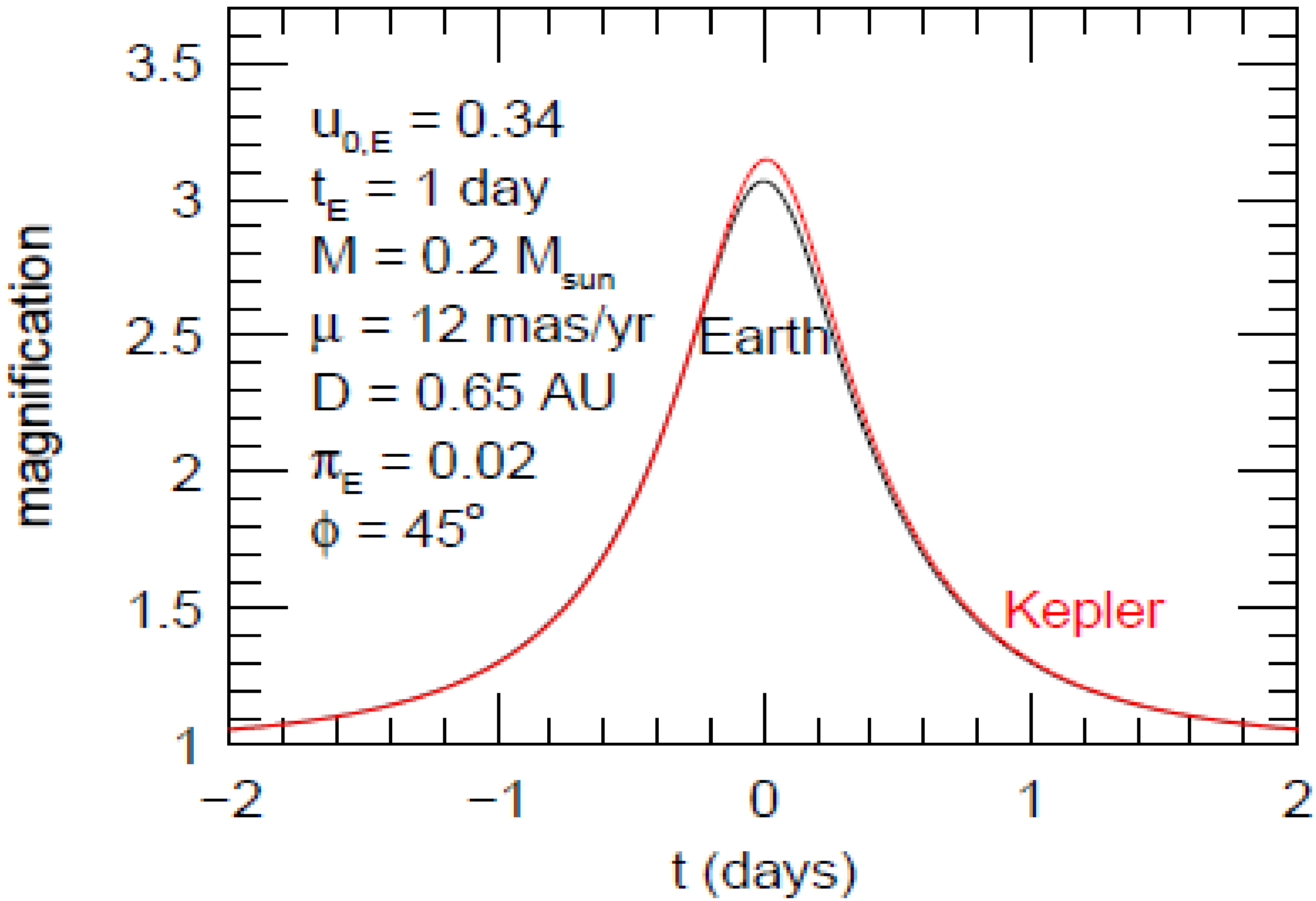


Proposal: K2 Field9 5.3 Mpxl



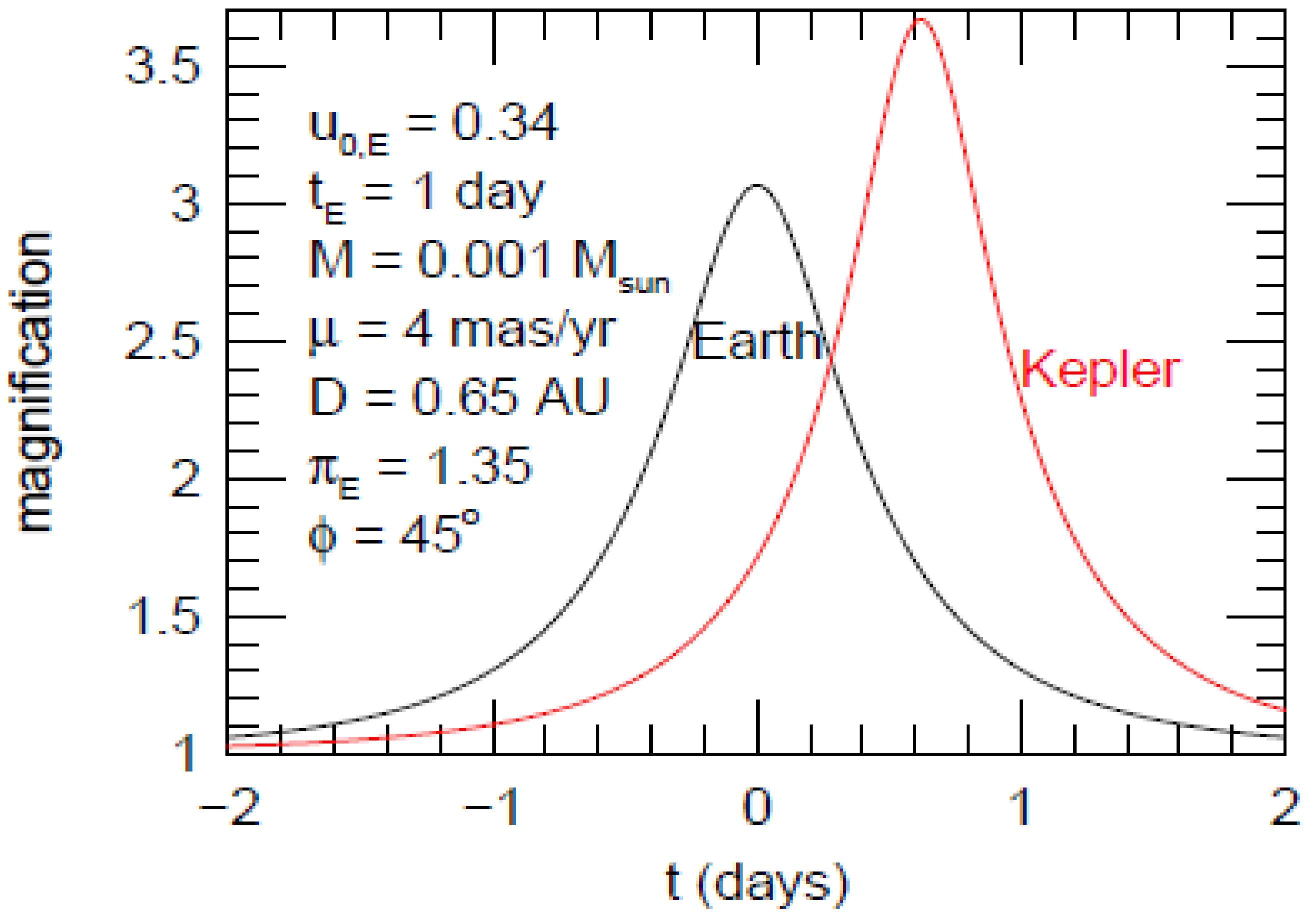
Gould, Horne, Street 2014, K2 White Paper

K2 Microlensing Science:
Short Event: If lens is a star



Gould, Horne, Street 2014, K2 White Paper

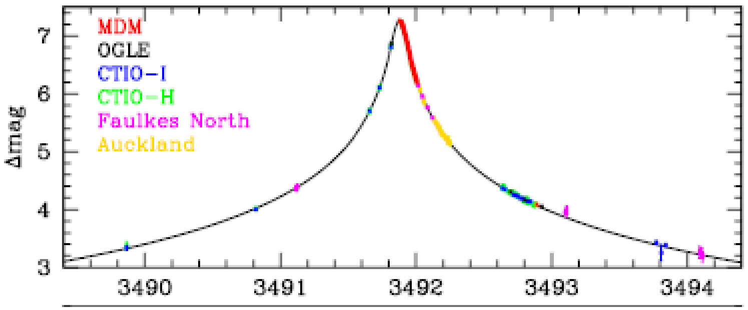
K2 Microlensing Science:
Short Event: If lens is an FFP

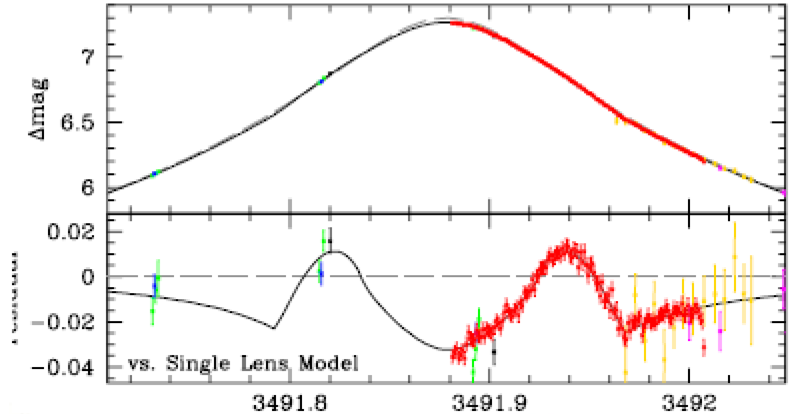


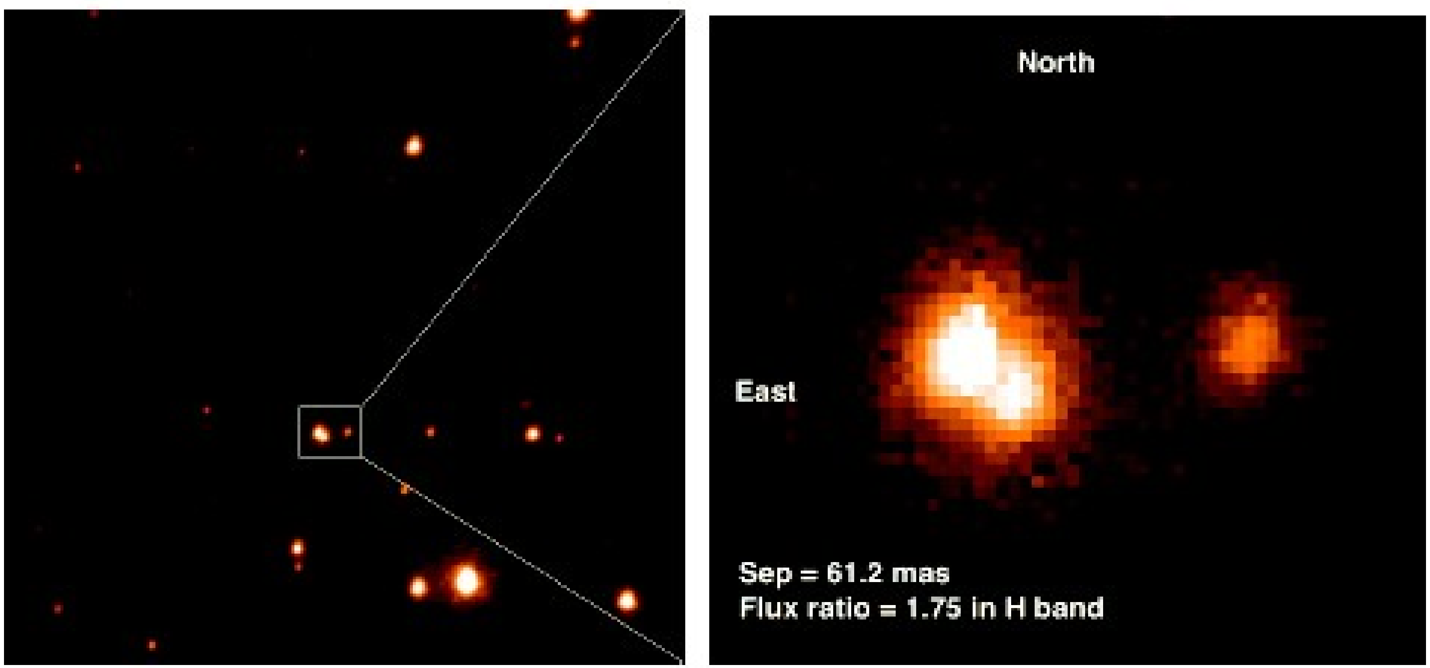
Gould, Horne, Street 2014, K2 White Paper

8 Years After Event ...

Keck Imaging of OGLE-2005-BLG-169

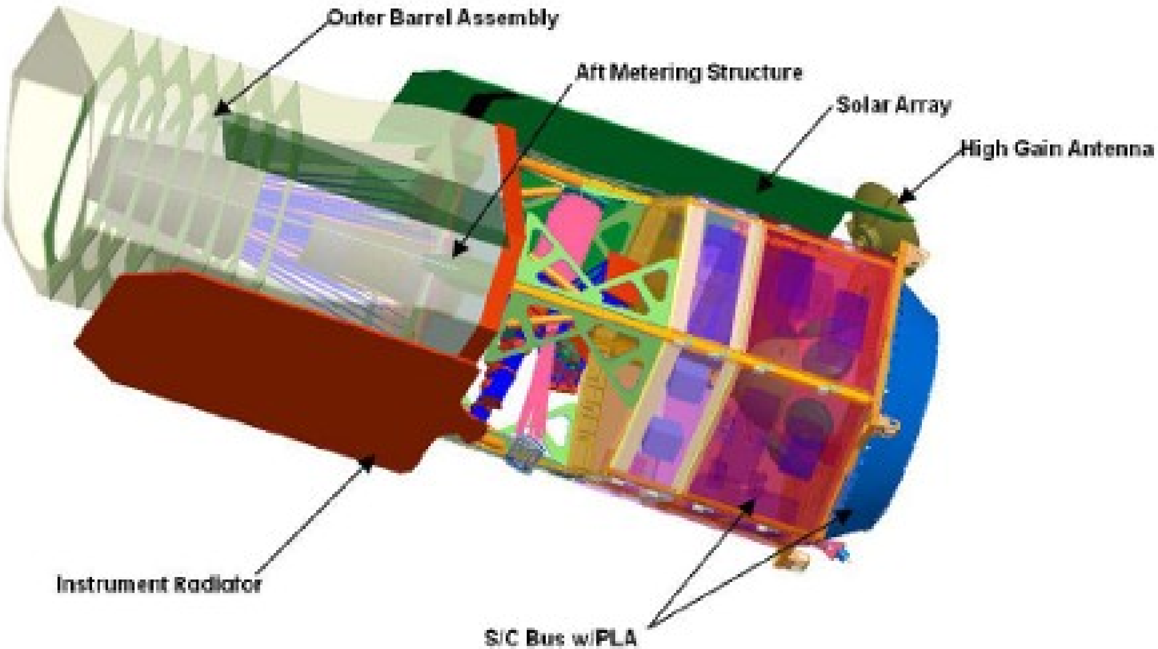




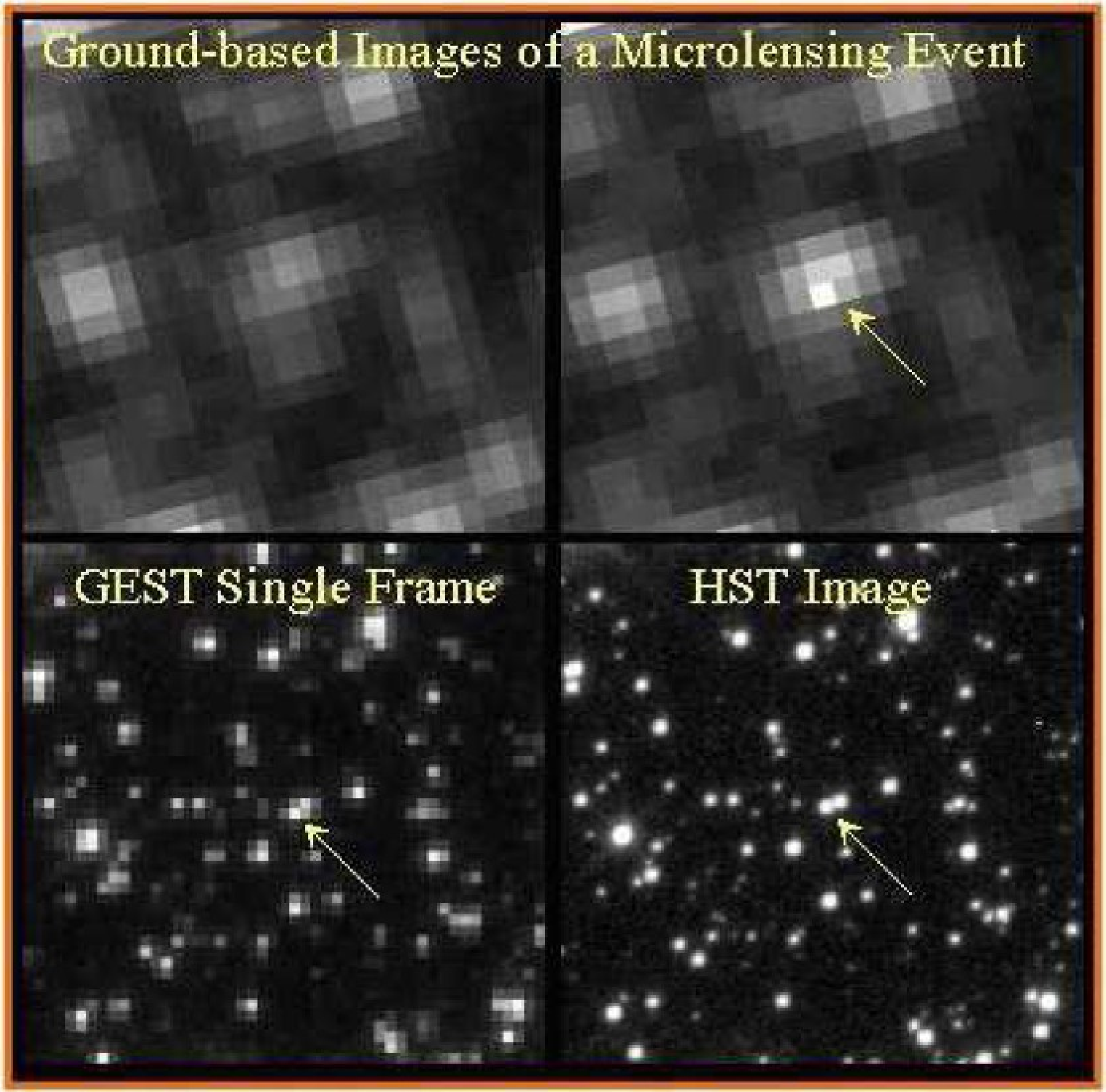


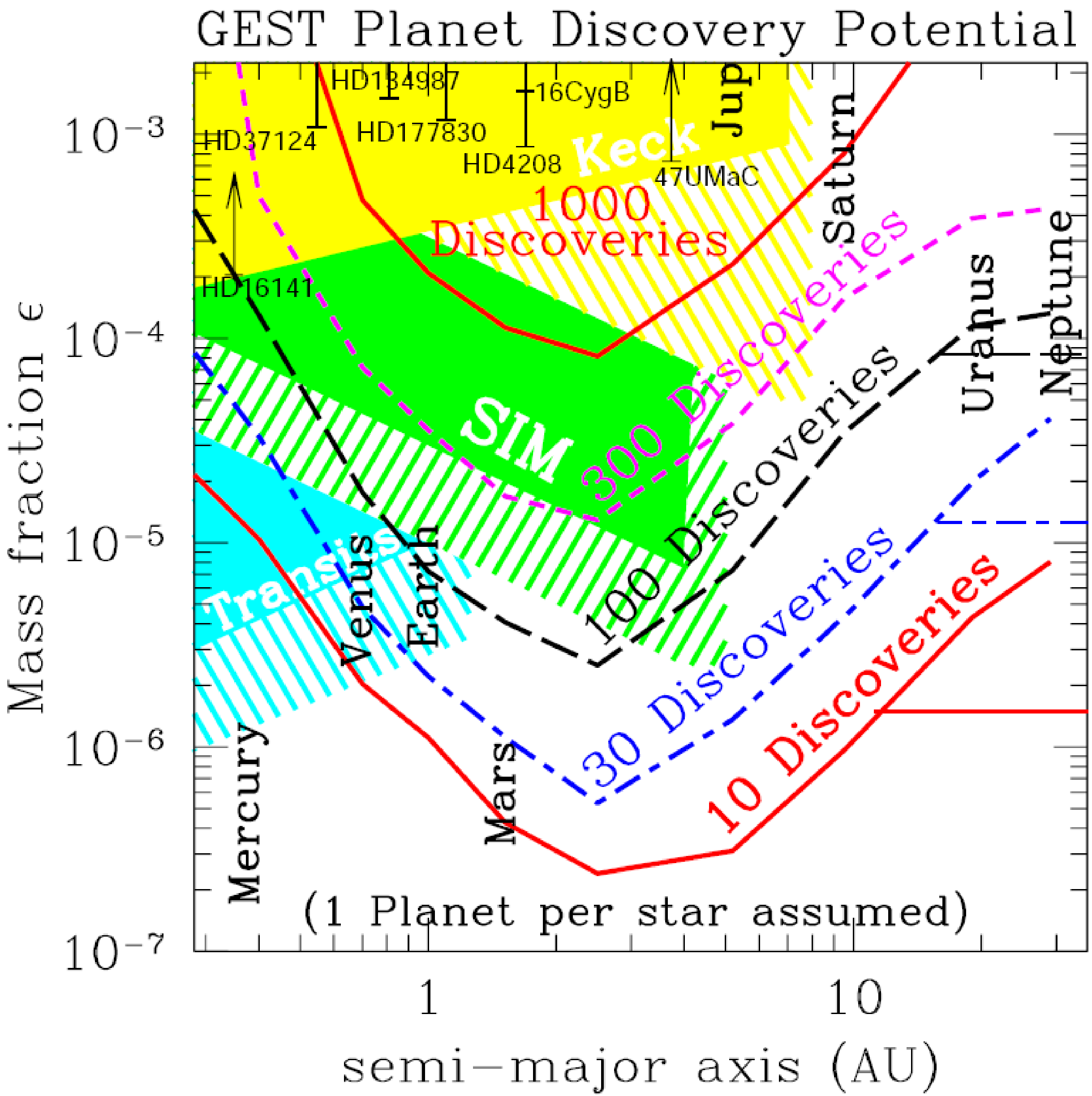
Batista et al. 2015, ApJ, submitted

Frontiers VII:
WFIRST



Seeing Better In Space (also weather)





Bennett & Rhie 2002, ApJ, 574, 985