Developing the Exoplanet Mass Measurement Method Using Space Based Observations

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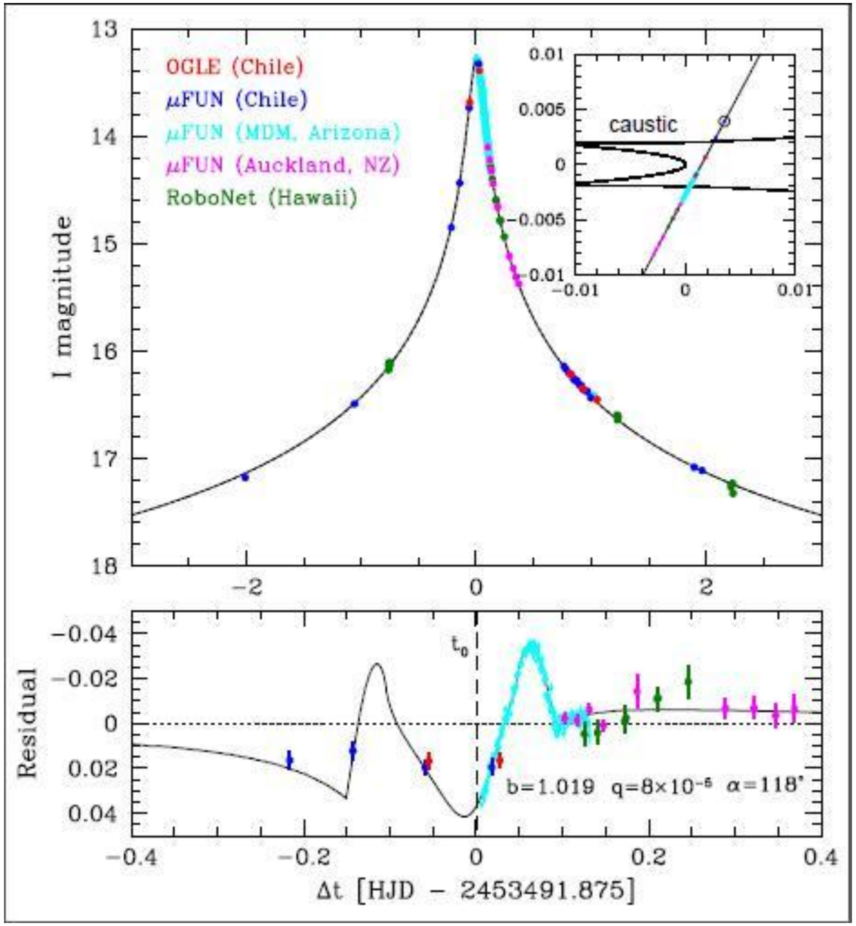
OGLE-2005-BLG-169 Discovery Paper



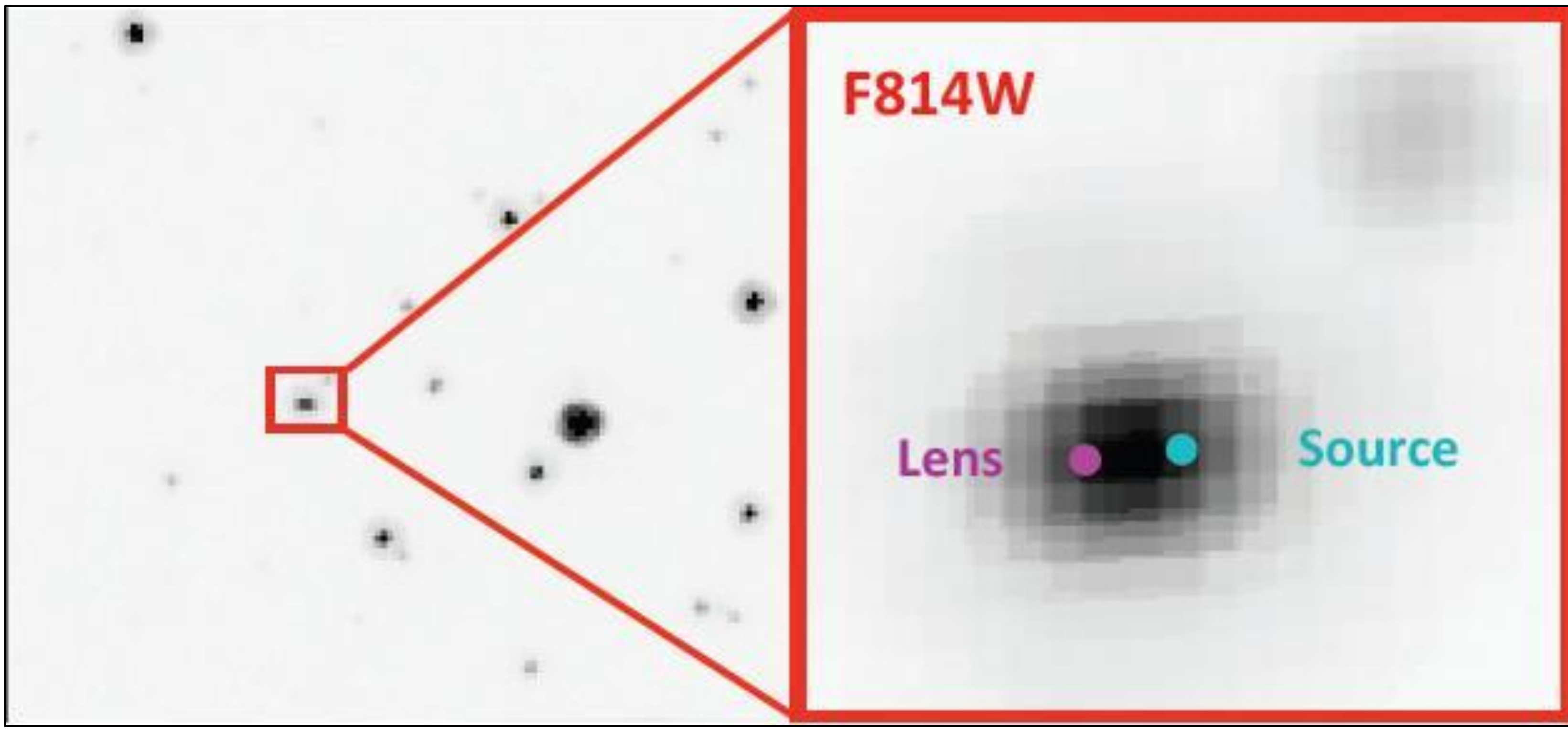
Gould et al (2006, ApJ, 644L,37G)

q (planet – host star mass ratio) determined, but planet host star mass and their separation in physical coordinates not determined

space based follow up observations needed

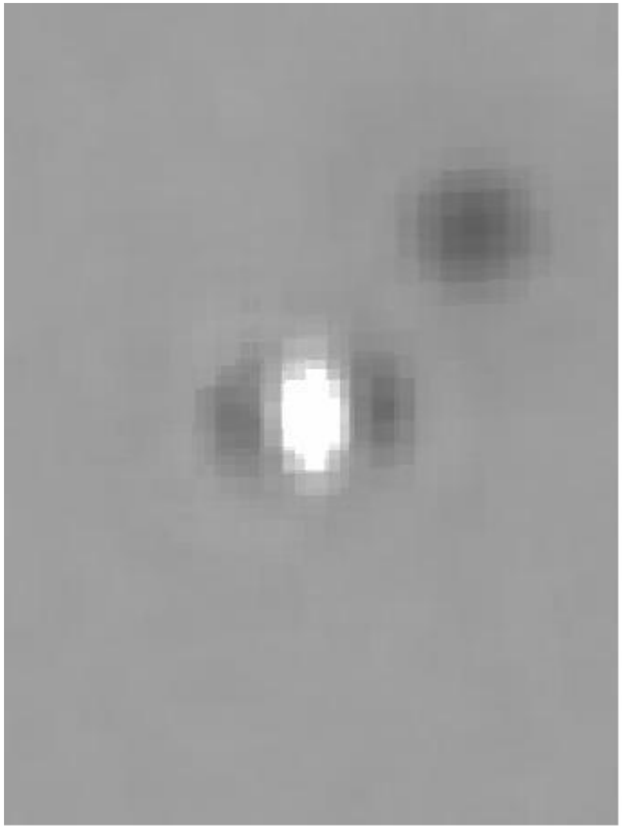
HST Observations & PSF fitting

Elongated target object OGLE-2005-BLG-169 observed in 2012 – 6.5 years after discovery



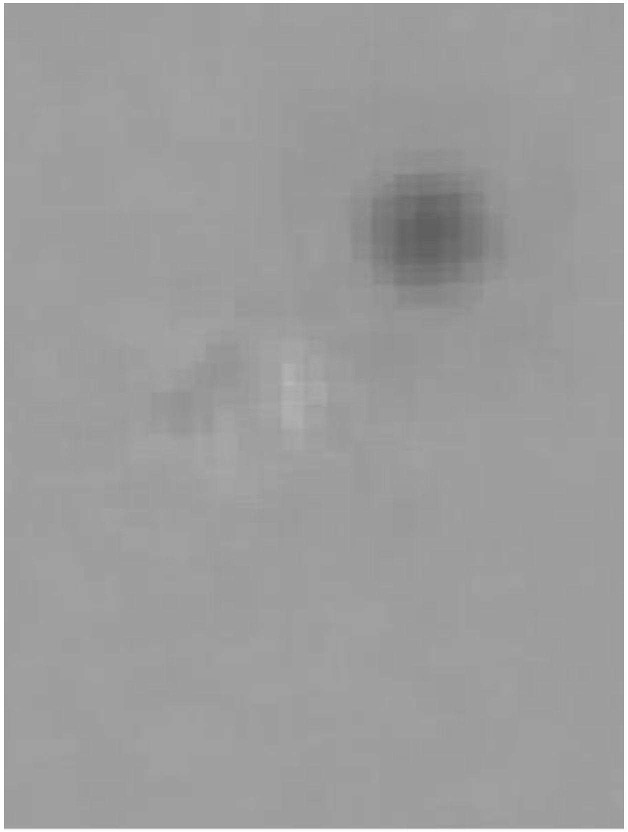
HST Observations & PSF Fitting

Single Star Fit Residual



Vs

Dual Star Fit Residual



HST Observations & PSF Fitting

How to know which star is Source?

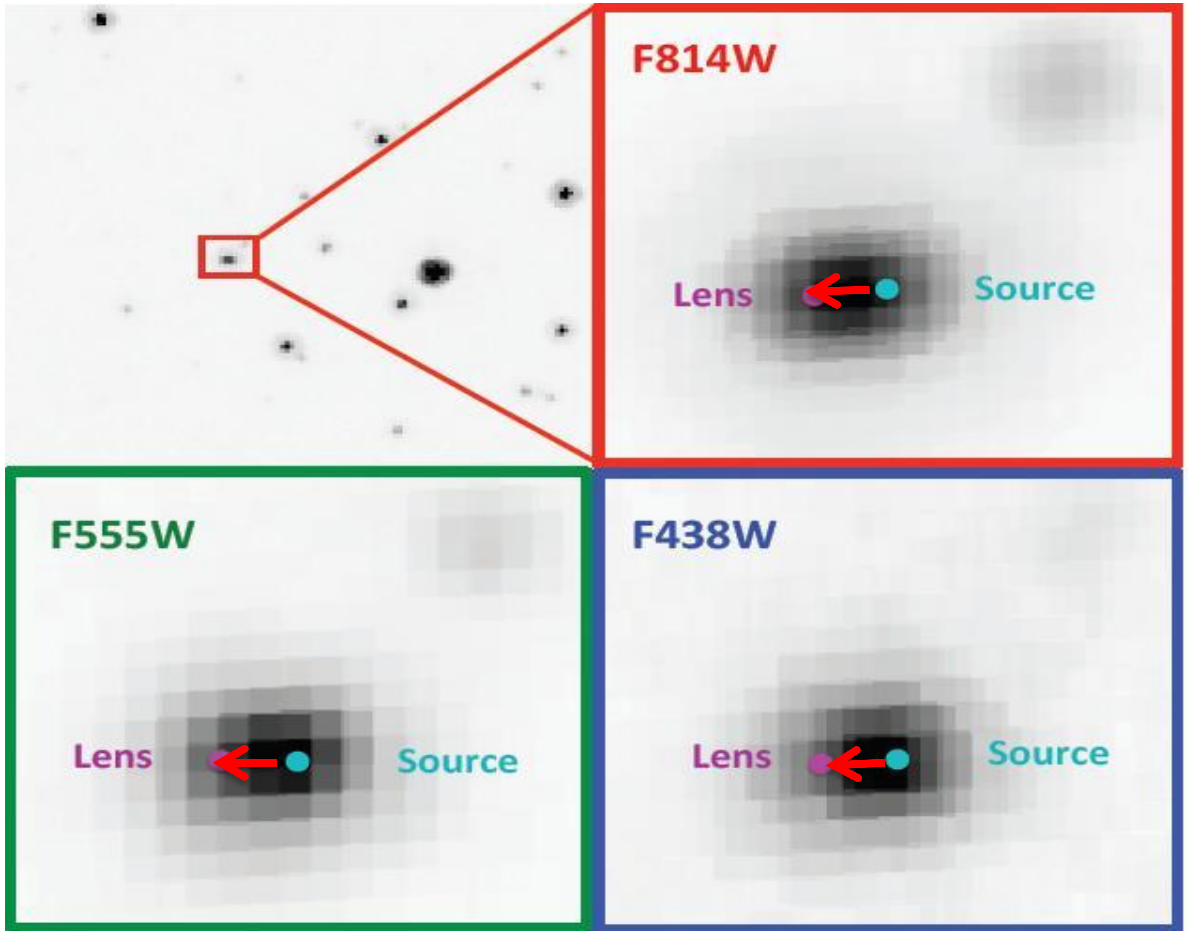
- In I band both stars have same magnitude – since lens in nearer than the main sequence source so it should be redder than Source - hence Lens is fainter in V and B band

  (see next slide)

- CTIO V band Source magnitude matches with brighter star of HST V band, hence confirming the source

HST Observations & PSF Fitting

μ_{rel_l} =
7.39 ± .20
mas/yr
μ_{rel_b} =
1.33 ± .23
mas/yr



Lens Source brightness similar in I band indicating Lens redder than source hence Lens is also fainter in V and B band

First Direct Relative (Lens-Source) Proper motion of Planetary Microlens Host Star Measured

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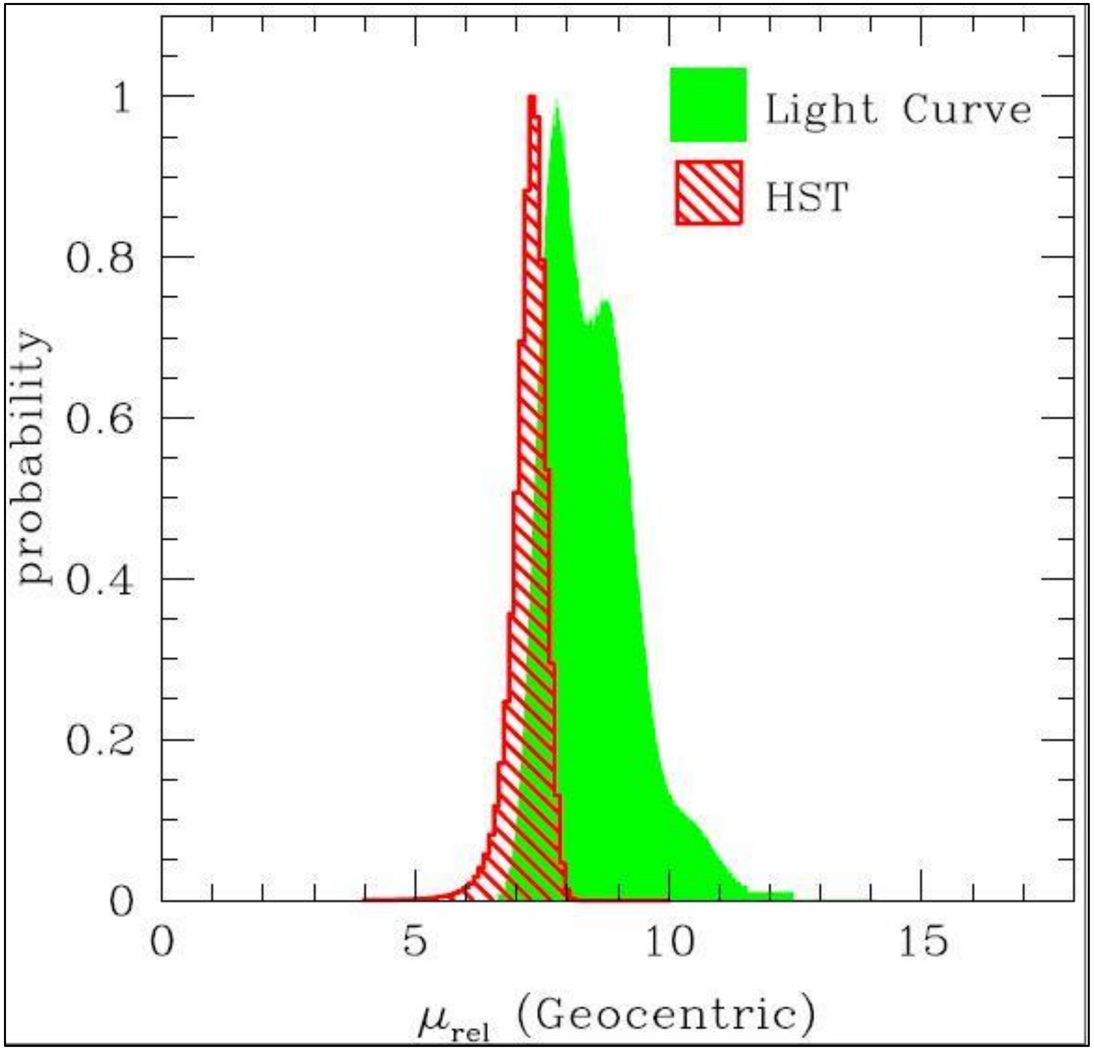
Proper Motion : Confirmation of Microlensing Planet

- HST: μ_{relG} = 7.2 ± 0.4 mas/yr
- $\mu_{rel,H}$ changed to μ_{relG} using probability distribution of (D_L/D_S) from a galactic model[1]

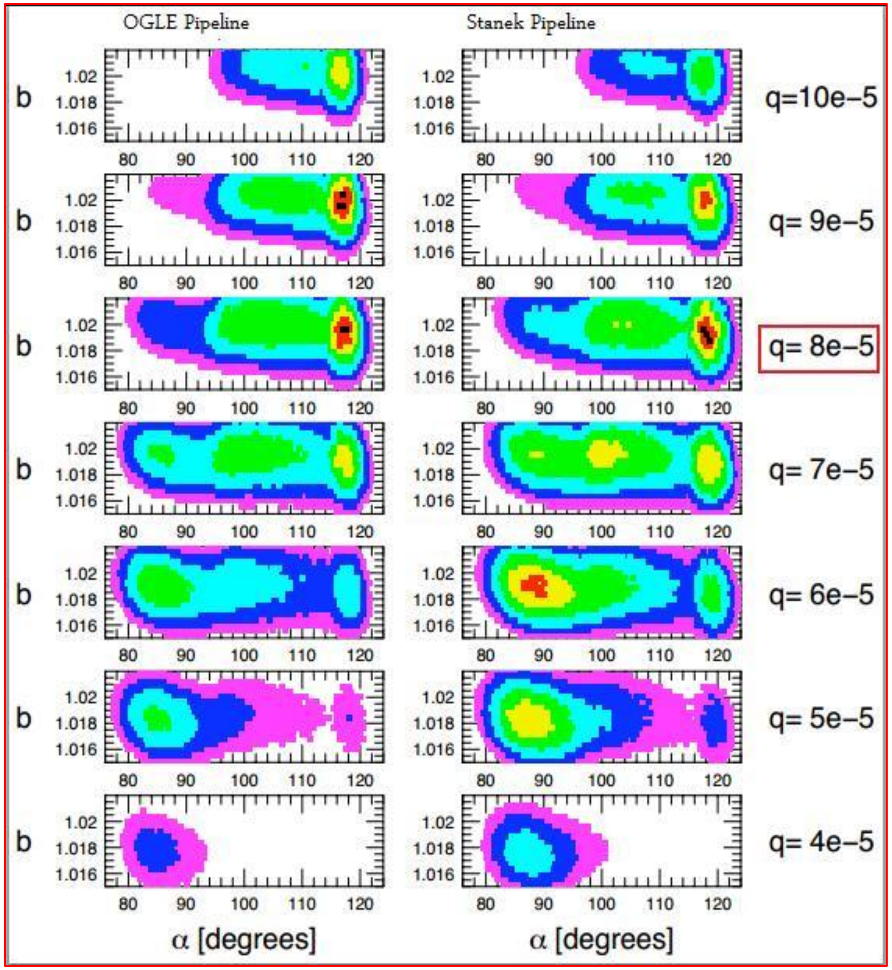
- First Confirmation of Microlens Planet Signal



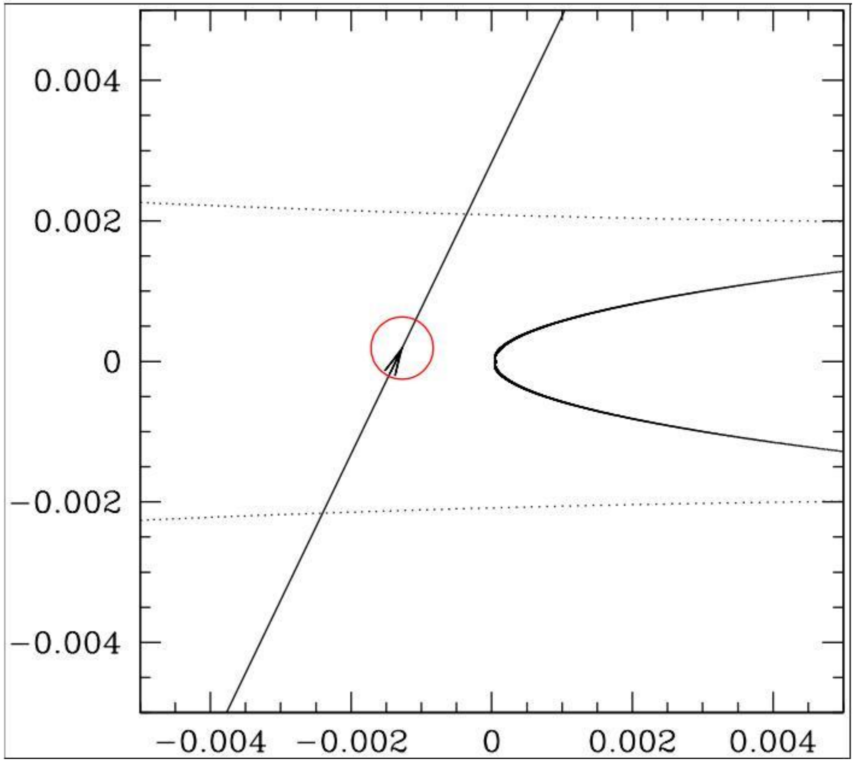
1. D.Bennett et al. 2014 ApJ 785, 155

Proper Motion: Constrains Star - Planet Mass Ratio

- Before:



$\mu_{relG} = \frac{\theta_*}{t_*}$. θ_* **is unchanged. So** t_* **smaller means** μ_{relG} **higher.**

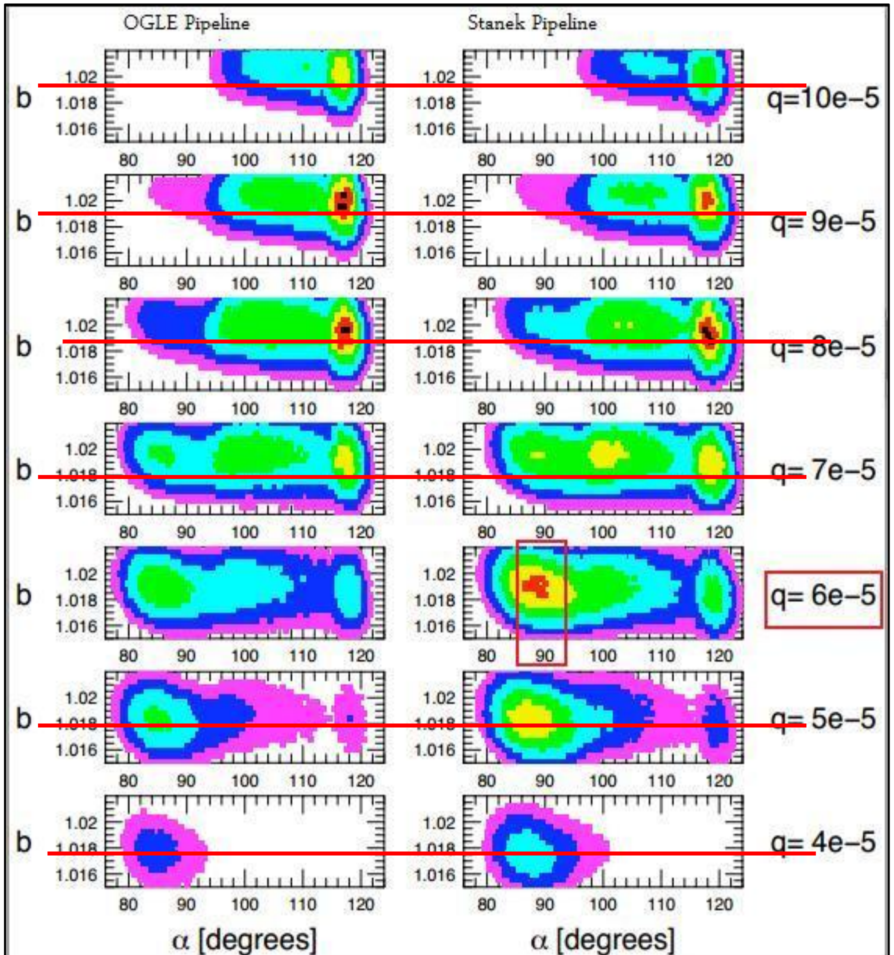


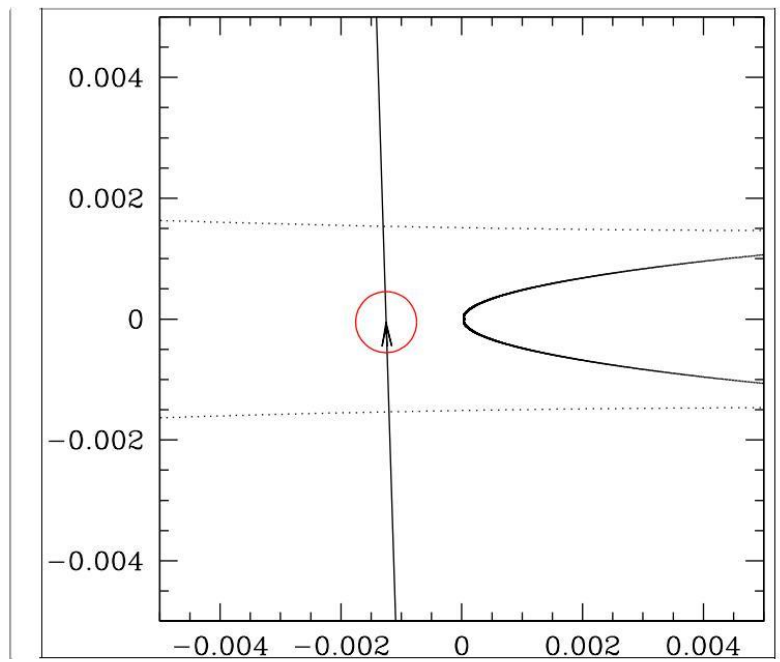
1. **Gould et al (2006, ApJ, 644L,37G)**

Proper Motion: Constrains Star - Planet Mass Ratio

- HST Analysis removes uncertainty in light curve fit parameters

$\mu_{relG} = \frac{\theta_*}{t_*}$. θ_* **is unchanged. So** t_* **higher means** μ_{relG} **smaller.**

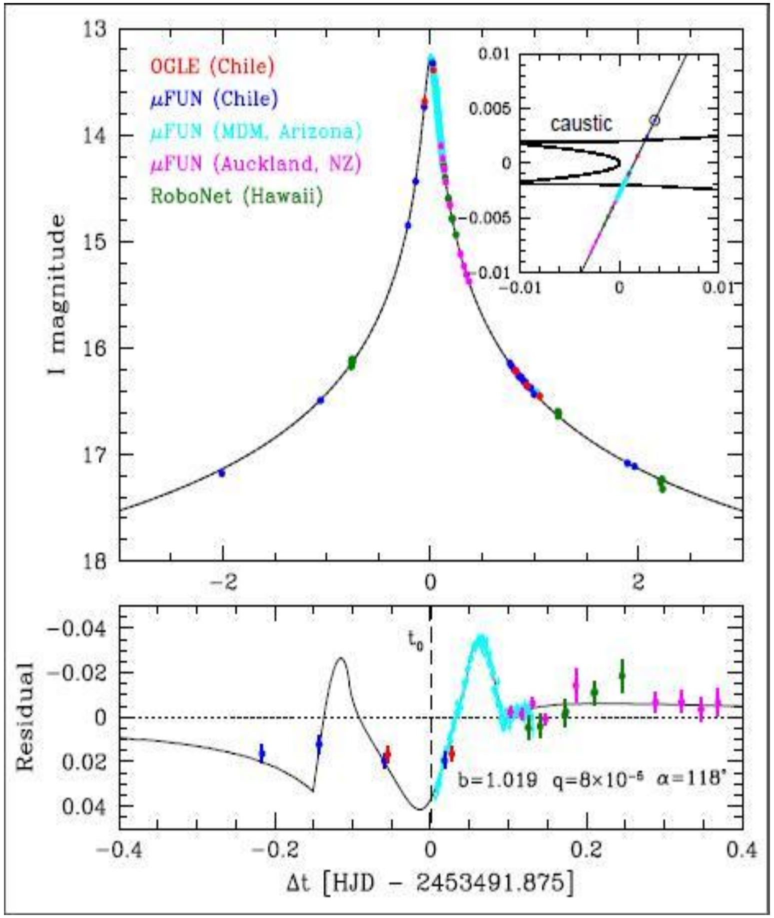




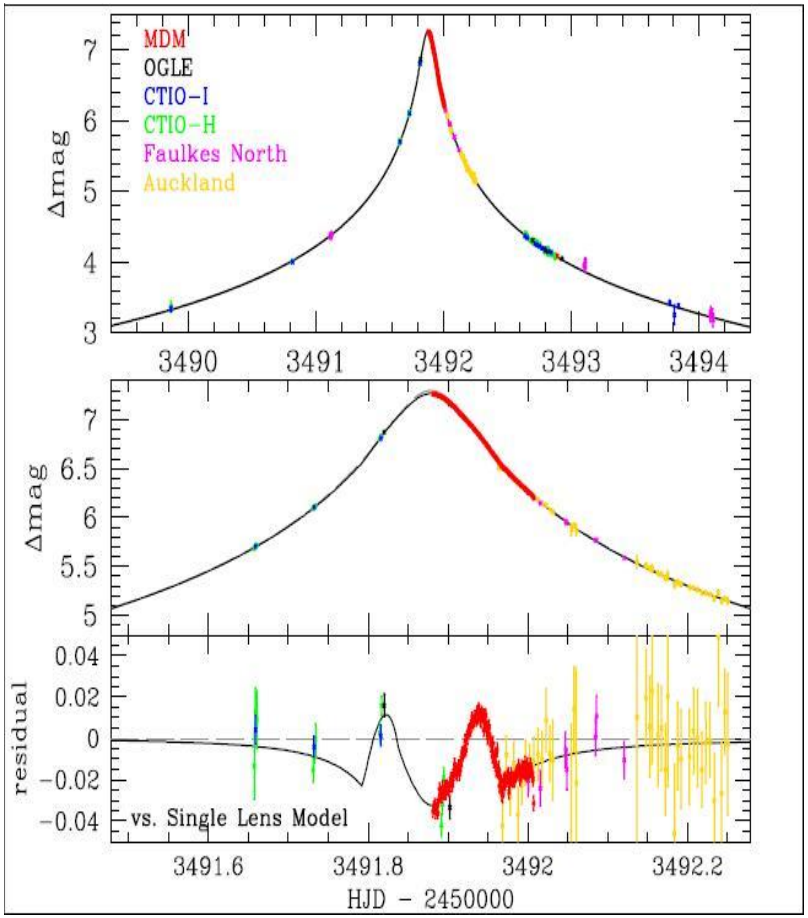
1. Gould et al (2006, ApJ, 644L,37G)

Comparing Results(1):Discovery and Follow Up

Discovery paper light curve[1]



Light curve consistent with HST



1. Gould et al (2006, ApJ, 644L,37G)

Determination of Host Star and Planet Mass

$$\theta_E^2 = \frac{4GM_L(D_S - D_L)}{c^2 D_S D_L}$$

Mass – Luminosity

(Henry,McCarthy[1];
Delfosse et al[2];
Henry et al[3];
Kenyon,Hartmann[4])

Constrains I_s and total target brightness

$M_P/M_H = q = 6\times10^{-5}$

M_H

D_L/D_S

$D_S \sim 8$ kpc
$a_\perp = \theta_E\, b\, D_L$ (2D)

Final Results

M_P

Projected separation $a_\perp$

1. Henry and McCarthy (1993, AJ, 106, 773)
2. Delfosse et al (2000 A&A 364, 217)
3. Henry et al (1999, ApJ, 512, 864)
4. Kenyon and Hartmann (1995, ApJS, 101, 117)

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Comparing Results(2): Discovery and Follow Up

Discovery paper [1]

- $\mu_{relG} = 8.4 \pm 1.7$ mas/yr
- $\alpha \sim 120^\circ$, $q = 8\times10^{-5}$
- Host mass:

  $0.49^{+0.23}_{-0.29} M_\odot$
- Planet Mass:

  $\sim 13\ M_\oplus$
- $D_L = 2.7^{+1.6}_{-1.3}$ kpc
- Projected Separation($a_\perp$):

  2.7 AU(2d)

HST [2]

- $\mu_{relG} = 7.2 \pm 0.4$ mas/yr
- $\alpha \sim 90^\circ$, $q = 6\times10^{-5}$
- Host mass:

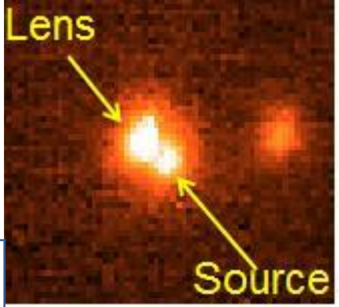
  $0.687 \pm .021\ M_\odot$
- Planet Mass:

  $14.1 \pm 0.9\ M_\oplus$
- $D_L = 4.1 \pm 0.4$ kpc
- Projected Separation($a_\perp$):

  3.5 ± 0.3 AU(2d)

1. Gould et al (2006, ApJ, 644L,37G)
2. Bennett D, Bhattacharya A , Anderson J et al in prep 2015

Comparing Results (3): HST & Keck



HST vs Keck

8.3 years after discovery[1]

Consistent

Look for Virginie Batista's Talk in afternoon

1. Batista et al - in preparation

Future Work and Improvements (1)

- With the magnitudes of Source and Lens known, stars similar in color to Source and Lens (instead of overall target) can be found to extract PSF and fit the target with new PSF model
- Eliminating the effect of nearby bright stars in PSF fitting of target.

Example – MOA -2008-BLG-379

(Follow next 2 slides)

Future Work and Improvements (2)

MOA-2008-BLG-379

From Discovery paper[1]:

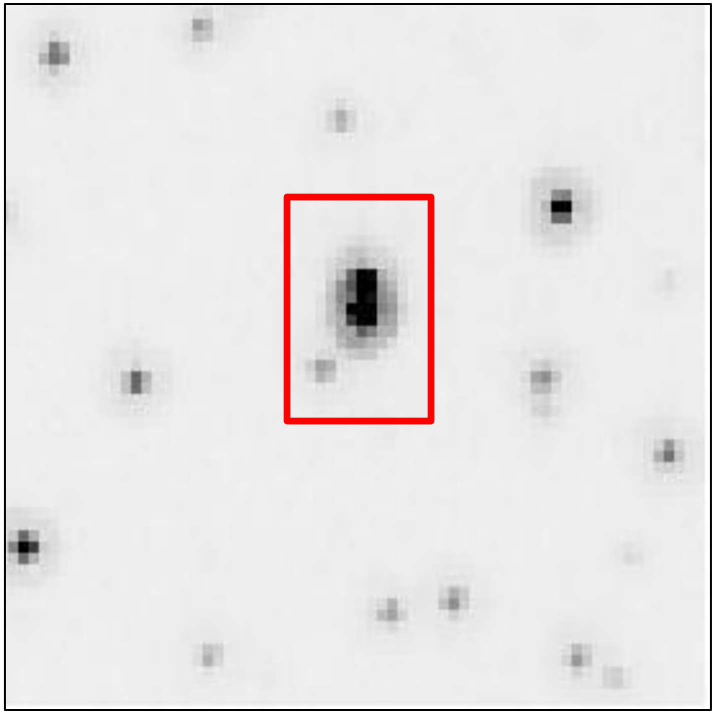
$\mu = 7.8 \pm 1.6$ mas/yr

Predicted separation for observations by late 2013:

37.8 ± 8.3 mas

(~ 1 HST pixel)

HST Observation of MOA-2008-BLG-379

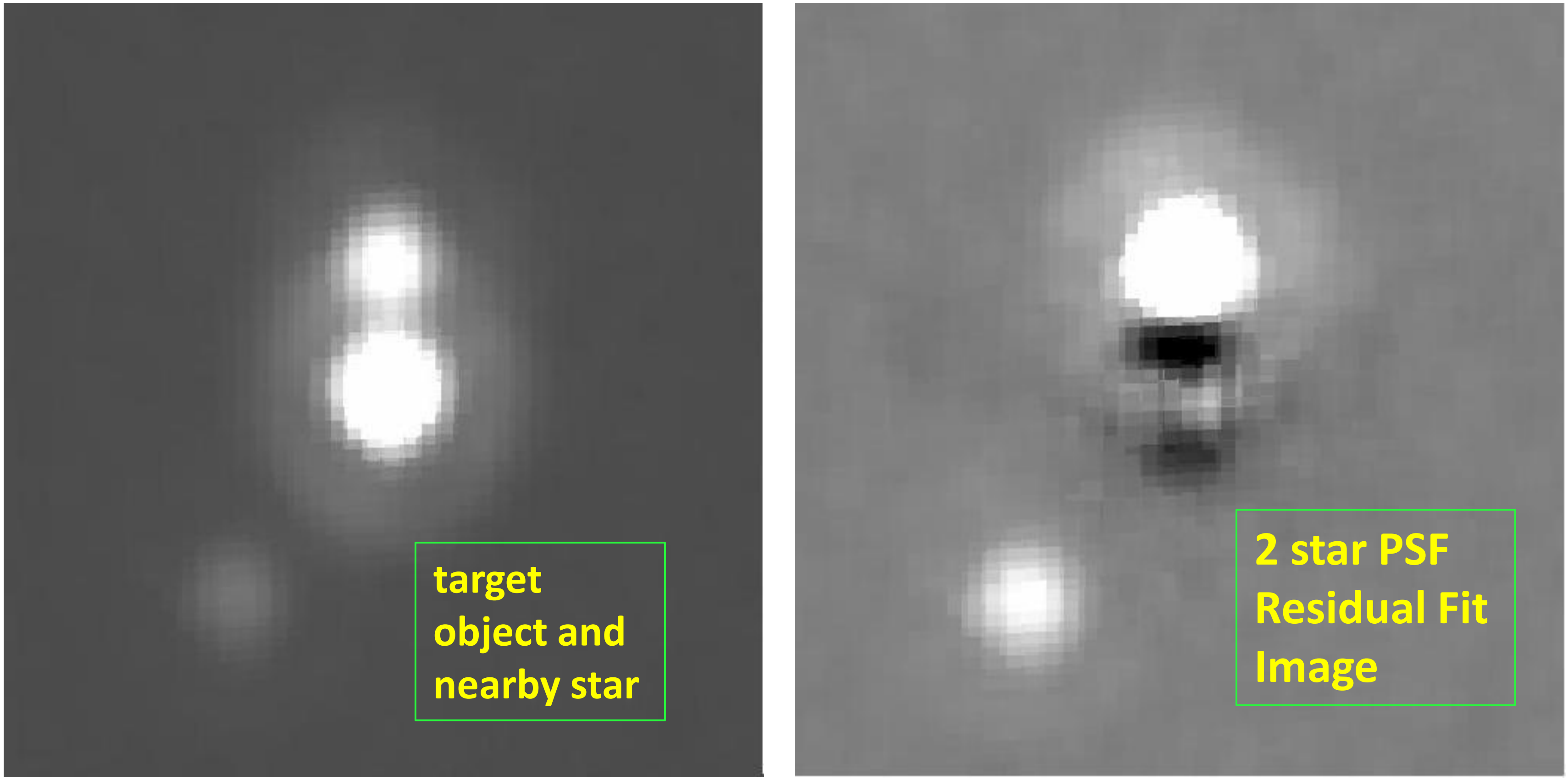


1. D.Suzuki et *al*. 2014 ApJ 780 123

Future Work and Improvements (1): Contamination from Nearby star

MOA-2008-BLG-379

Two star PSF fit close up



Probable Solution: Fit 3 star PSF model

Future Work and Improvements (2)

MOA-2008-BLG-310

- From Discovery paper[1]:

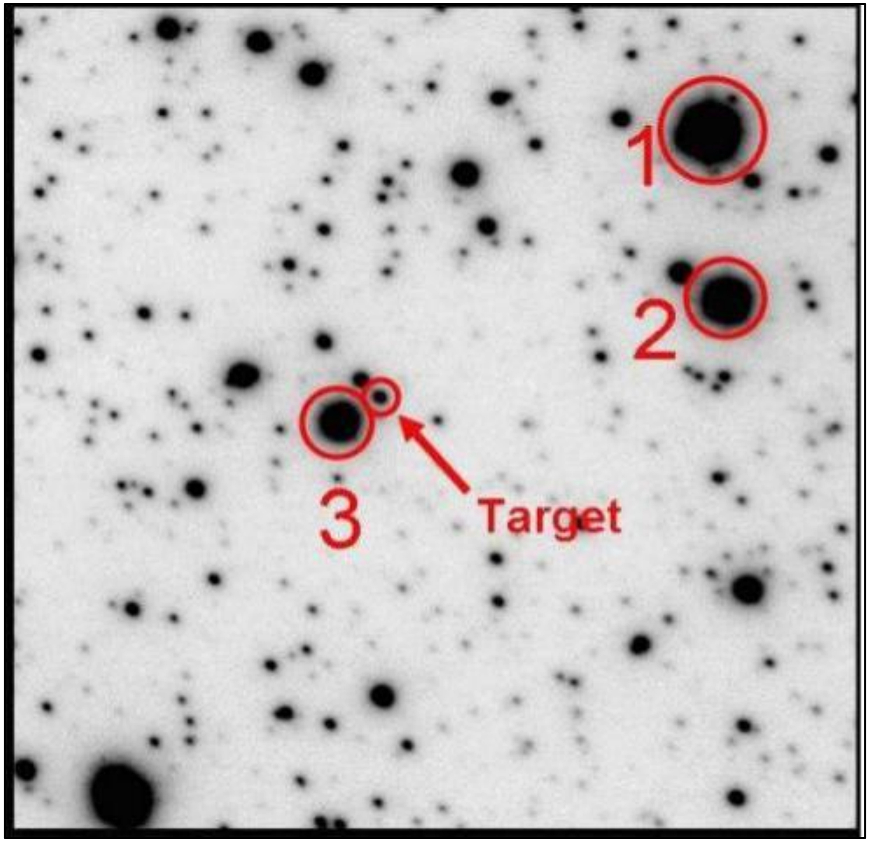
  $q = (3.3\pm0.3) \times 10^{-4}$

  Sub Saturn mass planet

  $\mu_{relG} = 5.1 \pm 0.3$ mas/yr

- Excess flux in H band (NACO Data)

Image from NACO VLT data



1. J. Janczak et al 2010 ApJ 711 731

Future Work and Improvements (2):

Reasons for extra flux from Discovery paper[1]

MOA-2008-BLG-310

Possible Reasons for Excess Flux on Source

- Excess flux due to Lens system
  (Unlikely as it requires Lens to be at 300 pc)
- Due to unrelated star
  (Unlikely ~5.1% chance)
- Due to Source Companion
  (Unlikely ~7% chance)
- Due to Lens Companion
  (Unlikely ~4% chance)

We need space based data to determine if excess flux is from Lens

1. J. Janczak et al 2010 ApJ 711 731

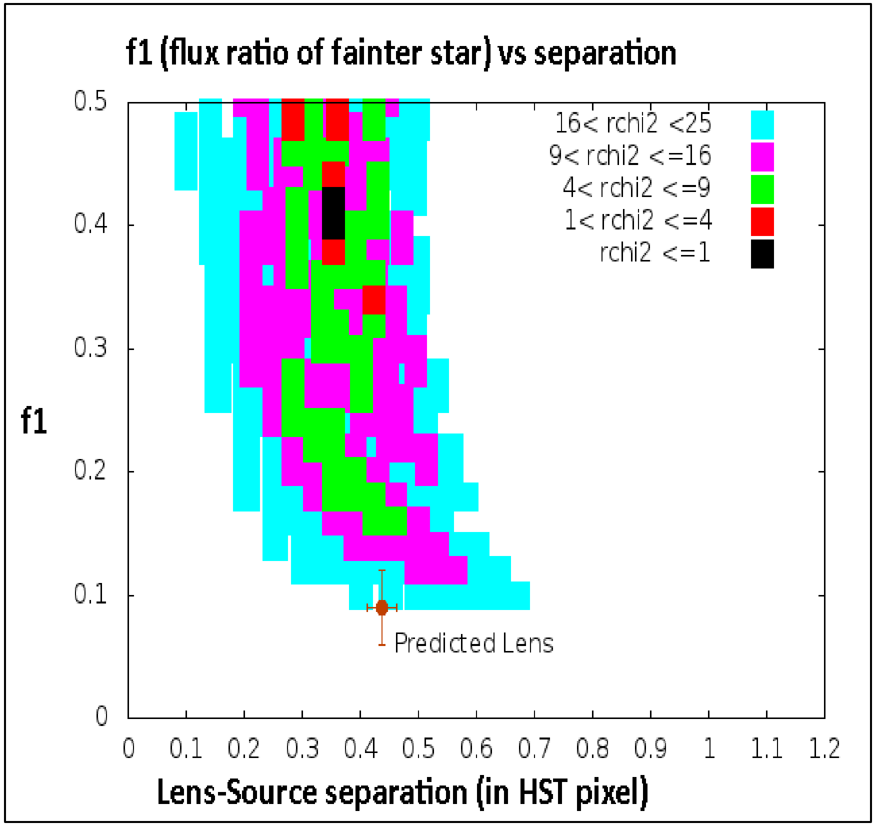
Future Work and Improvements (2):

Two star fit chi^2 contour

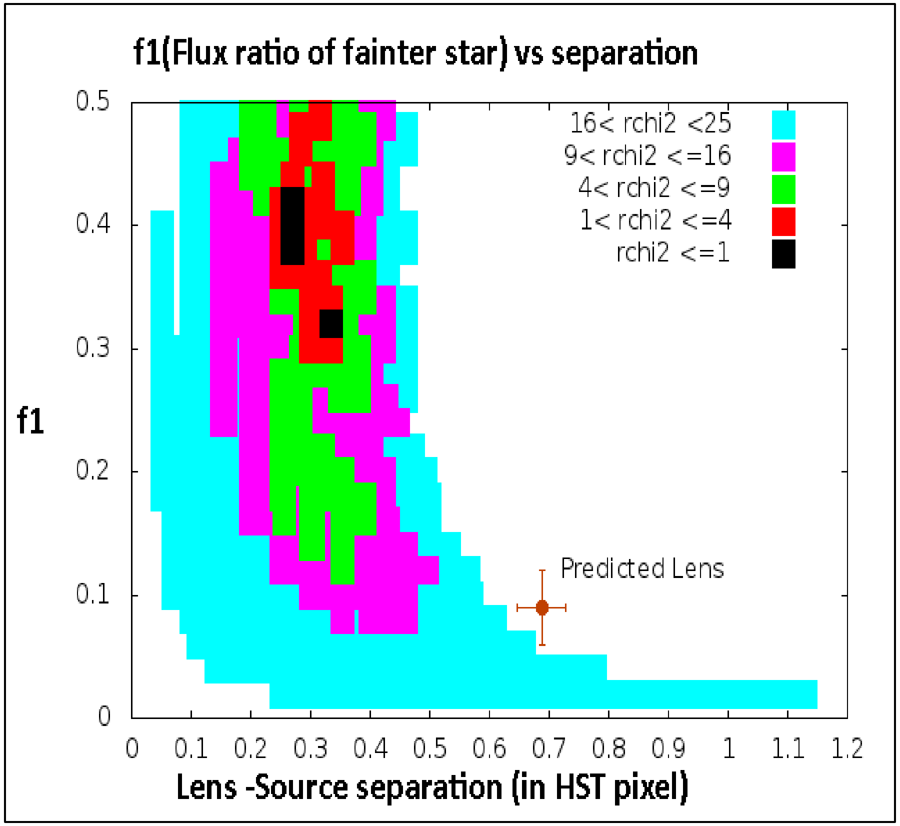
PRELIMINARY

MOA-2008-BLG-310

HST WFC3 I band data from Feb, 2012 (3.5 years after peak magnification)



HST WFC3 I band data from Feb, 2014 (5.5 years after peak magnification)



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Future Work and Improvements (2):Next Step

MOA-2008-BLG-310

CHALLENGE!! To determine if excess flux is due to lens and learn about lens system

Future procedure:

1. Analyze V band data and compare
2. Calibrate with ground based data to check if there is extra flux
3. Check PSF in HST WFC3 data analysis
4. Run PSF fit with constraint on Source magnitude

Conclusions & Future Work

- Space based data provides host star and planet mass, their separation, lens distance and First confirmation of Microlens planetary signal.

Prepares us to deal with future WFIRST microlensing data

- Demonstrates WFIRST Mass Measurement Method
- Resolved degeneracy in planetary models
- Many such measurements will build statistics for planetary mass function depending on host star mass and distance
- Similar techniques will be used to analyze HST WFC3 IR data which is more like WFIRST

THANK YOU