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High-Resolution Follow-up of Microlensing Planets

Partners in crime : V Batista J.B. Marquette (IAP), A. Fukui (Okayama), D. Bennett & A. Bhattacharya (Goddard), A. Cole J. Blackman (UTAS), C.S. Lee (NAOJ), P Fouqué (CFHT), C. Henderson, Y. Shvartzvald, C. Beichman M. Ygouf (CALTECH), N. Koshimoto, T. Sumi (Osaka)

High angular resolutions: 3 examples

- Detection lens flux without resolving lens/source
- Resolving source & lens, measuring rel proper motion
- Hunting for a dark lens (free-floating candidate)

Getting physical parameters

Mass ratios & projected separations are well known

- Mass ratio $q = M_p/M_*$
- Planet/star separation in Einstein Ring radius units
- Timescale t_E

We need mass-distance relations to get physical parameters:

- Masse-distance relation from Einstein ring radius measurements

  Easy to get, when you have caustic crossings

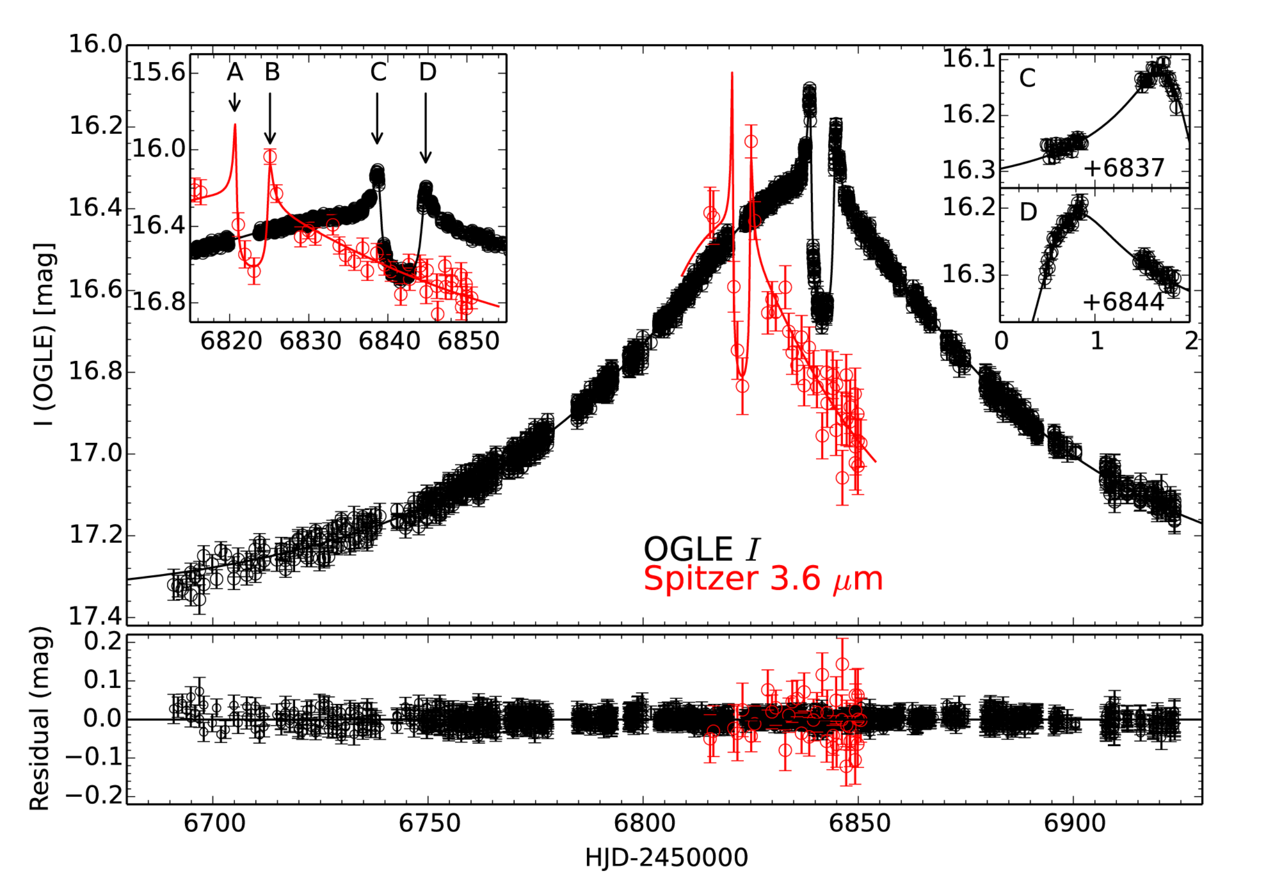
- Masse-distance relation from Parallax measurements

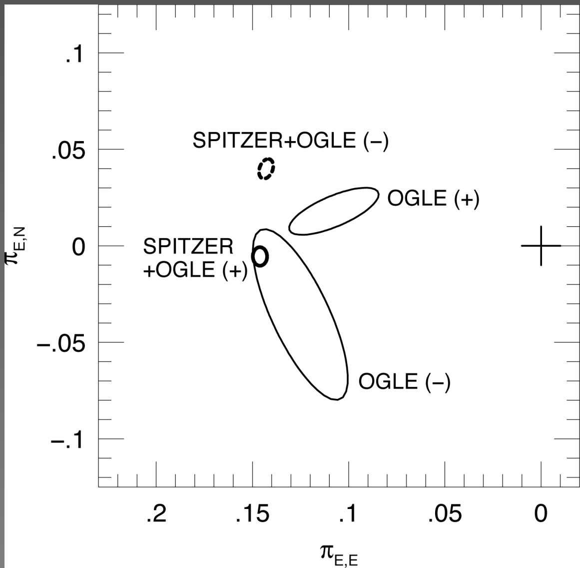
  Ground only is often problematic. Ideal with good-old-Spitzer /K2 !

- Masse-distance relation from high angular resolution observations

  With KECK AO: it is cheap (15-30 min) to constraint light from lens.
  Resolving source/lens is more tricky (~60 mas)

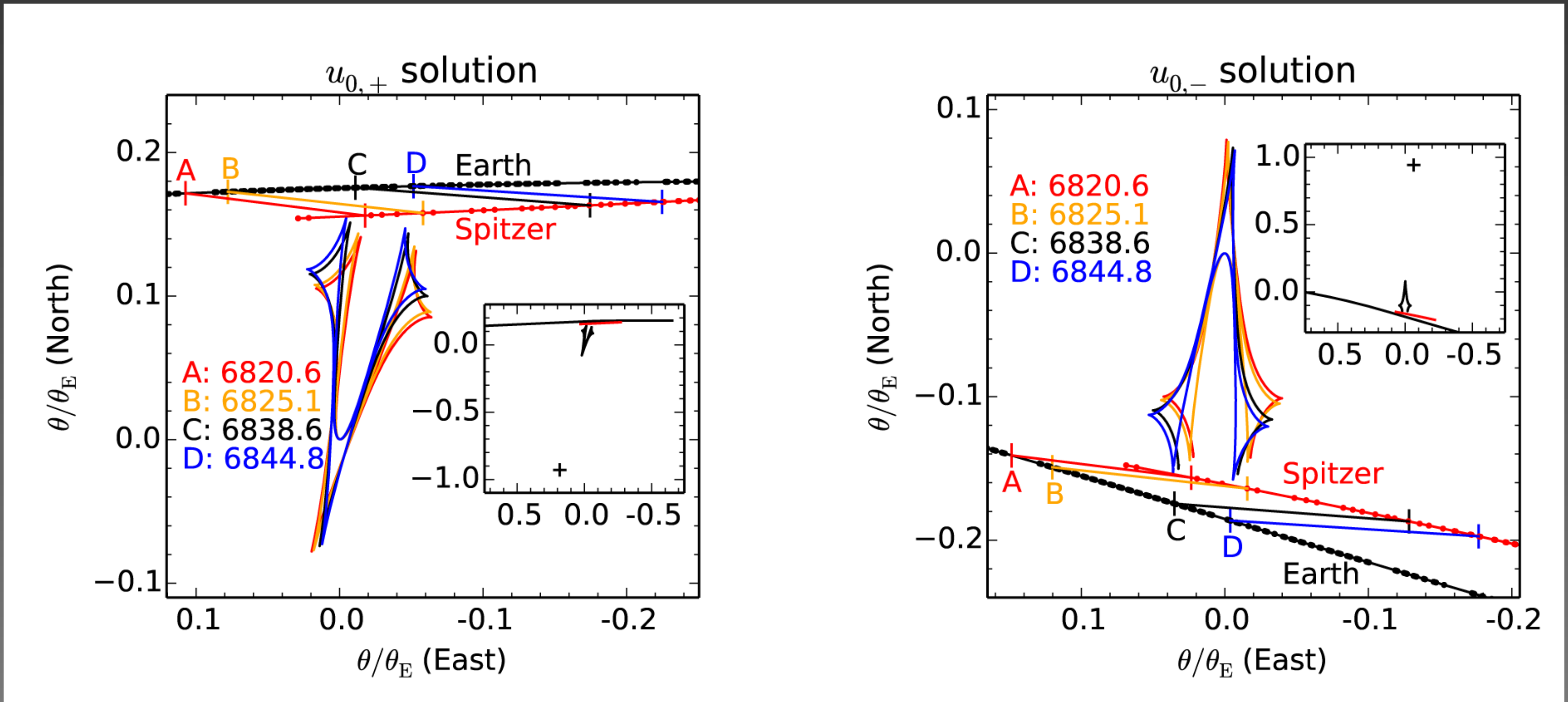
Ogle 2014-BLG-124: ground- Spitzer parallax

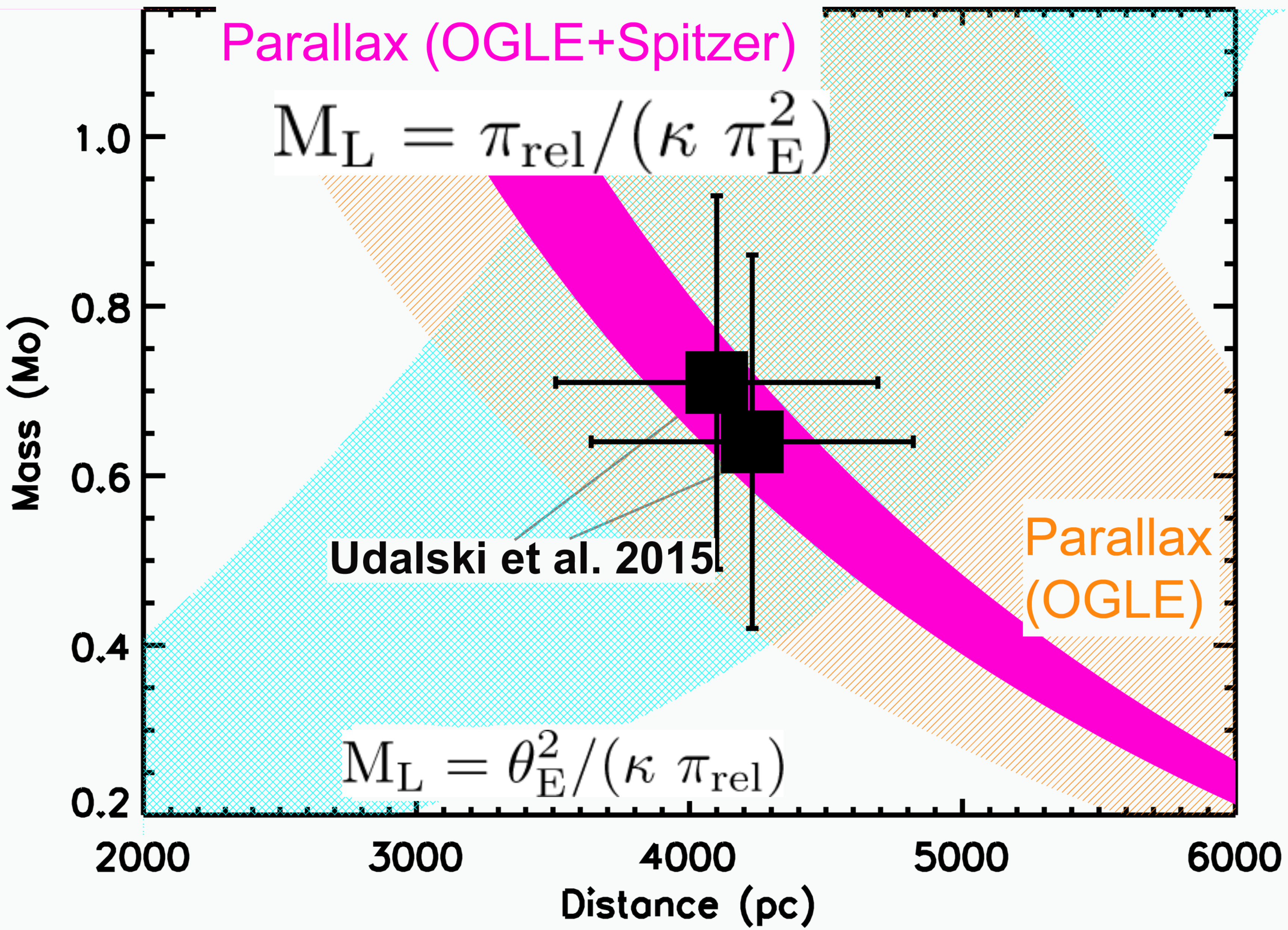




Udalski et al. 2015, Yee et al. 2016

Well constrained Parallax, but no caustic crossing !



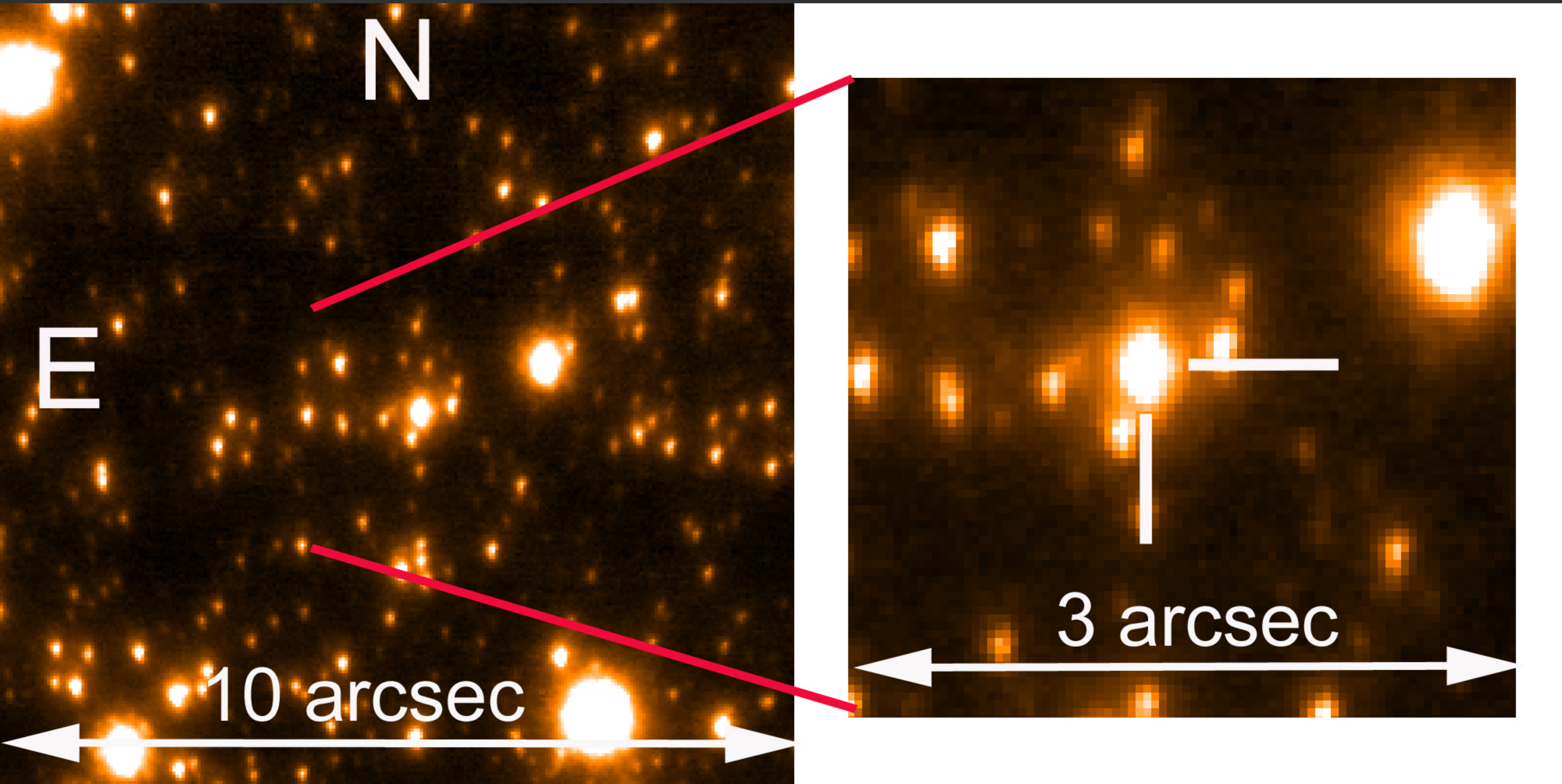


$$\pi_{rel} = (AU)(D_S - D_L)/(D_S\ D_L)$$

Source & lens are aligned

Source predicted H=17.04 ±0.05

Source +blend measured at H=15.95 ±0.03, So the blend is H=16.46 ±0.06



Is all the excess light coming from the lens ?

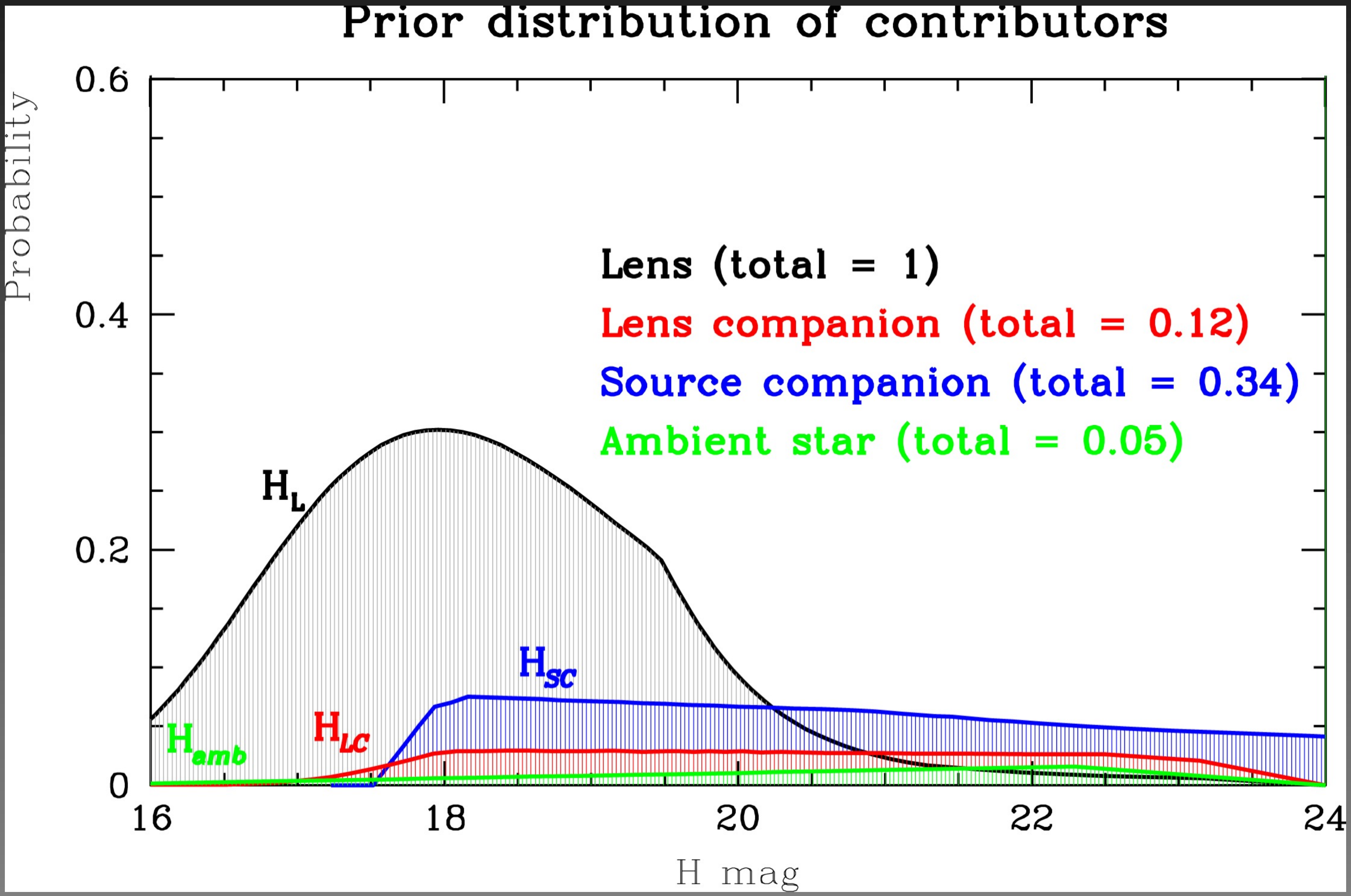
Study by Naoki Koshimoto and Virginie Batista.

Flux excess is an upper limit.

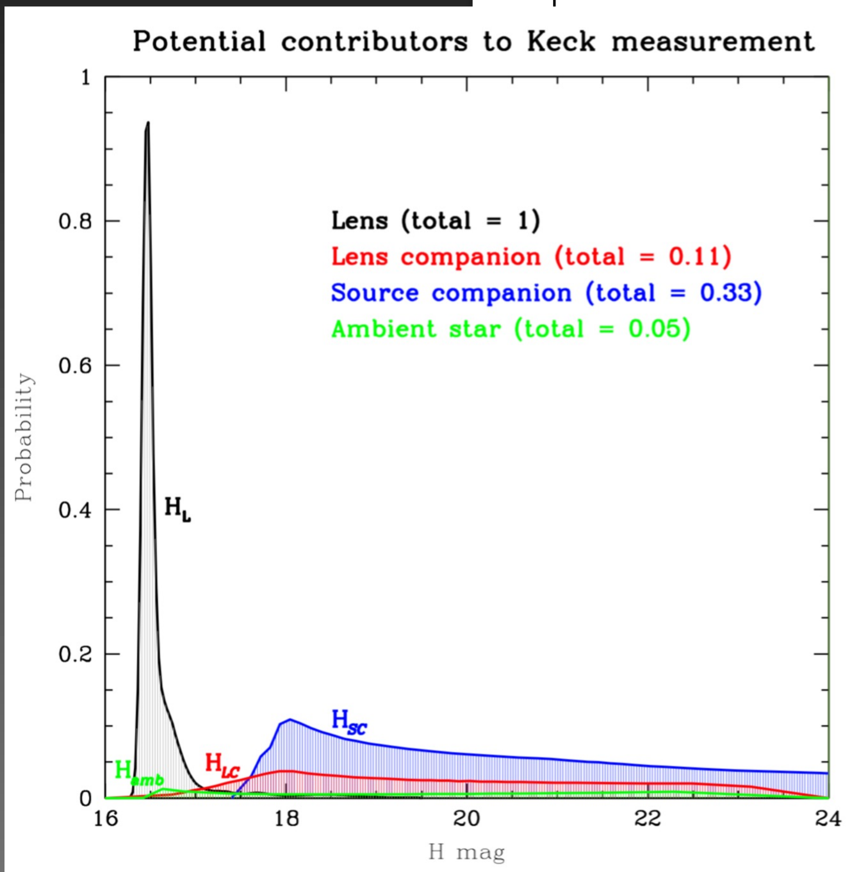
Within 100 mas, several scenarii. Which one is the more probable:

1/ Blend = lens
2/ Blend = lens + chance aligned star
3/ Blend = lens + companion to the lens (not affecting the light curve)
4/ Blend = lens + companion to the source
(and any combination of 2, 3, 4)

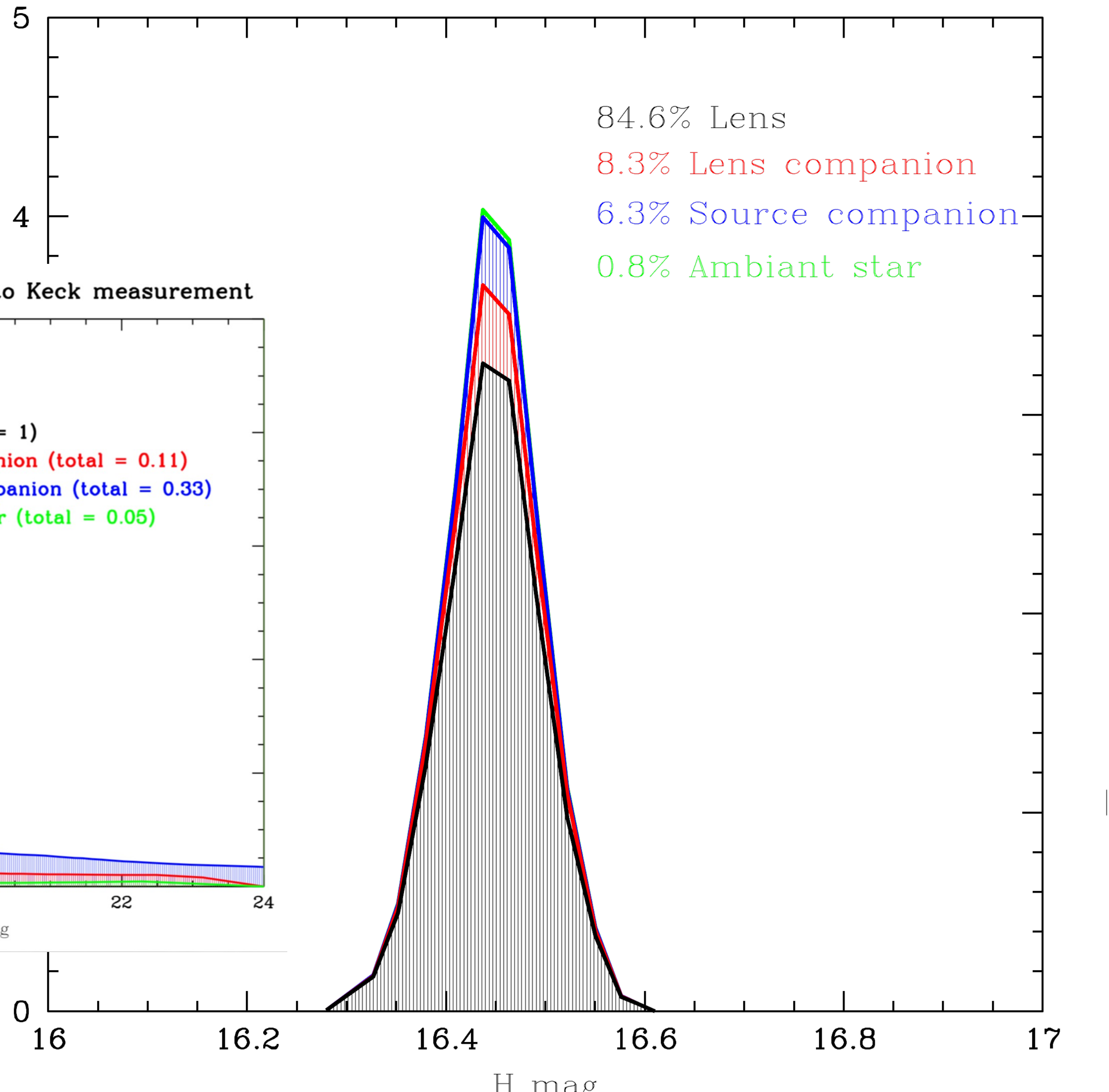
Rule of thumb:
- Bright sources, maybe some contamination by faint target (could be few % effect)
- with faint sources and faint lenses, extra caution.



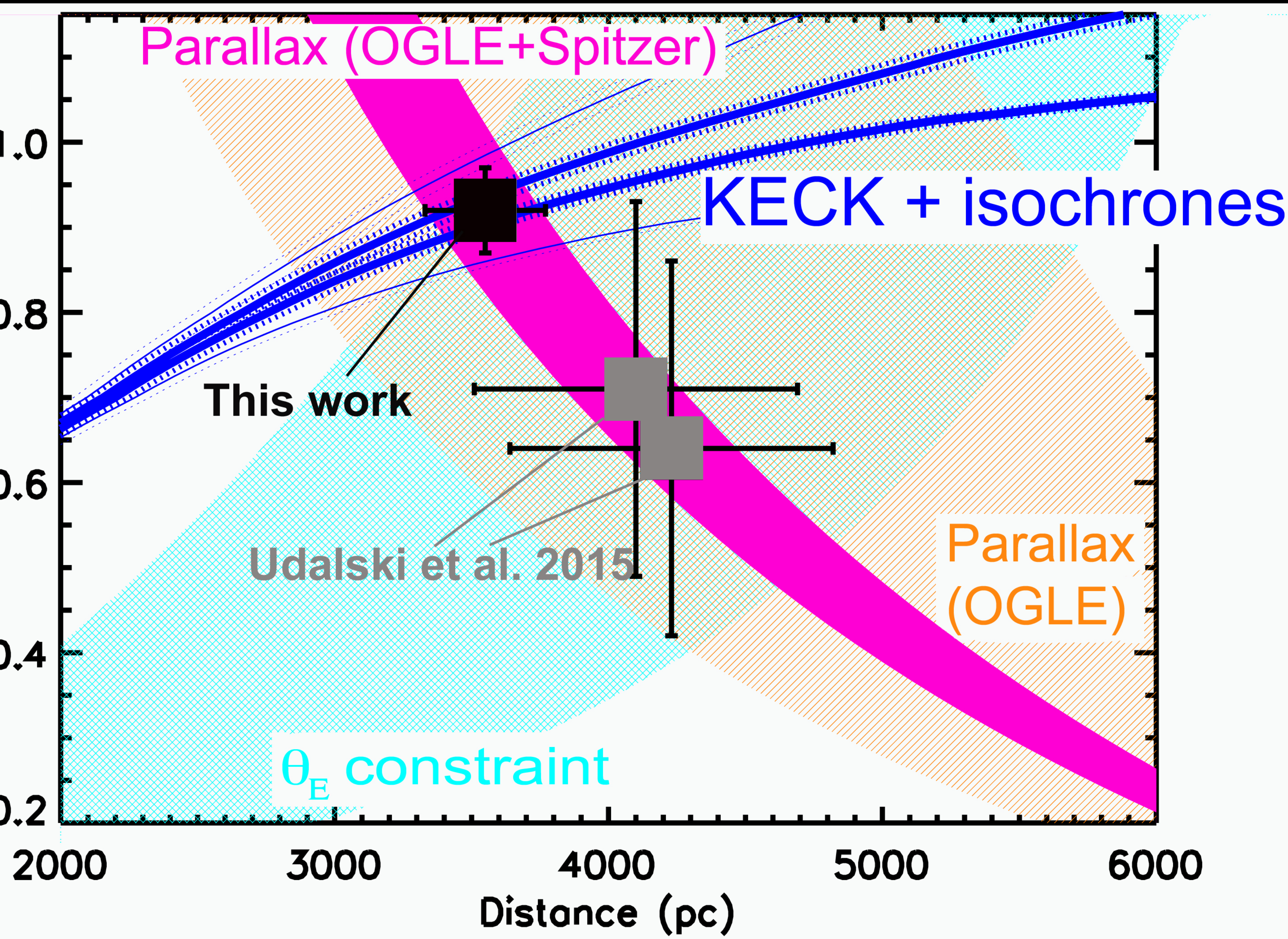
Prior distribution of contributors
Probability
0.6
0.4
0.2
0
16
18
20
22
24
H mag
Lens (total = 1)
Lens companion (total = 0.12)
Source companion (total = 0.34)
Ambient star (total = 0.05)
H_L
H_{SC}
H_{LC}
H_{amb}



Potential contributors to Keck measurement
Lens (total = 1)
Lens companion (total = 0.11)
Source companion (total = 0.33)
Ambient star (total = 0.05)
Probability
H mag

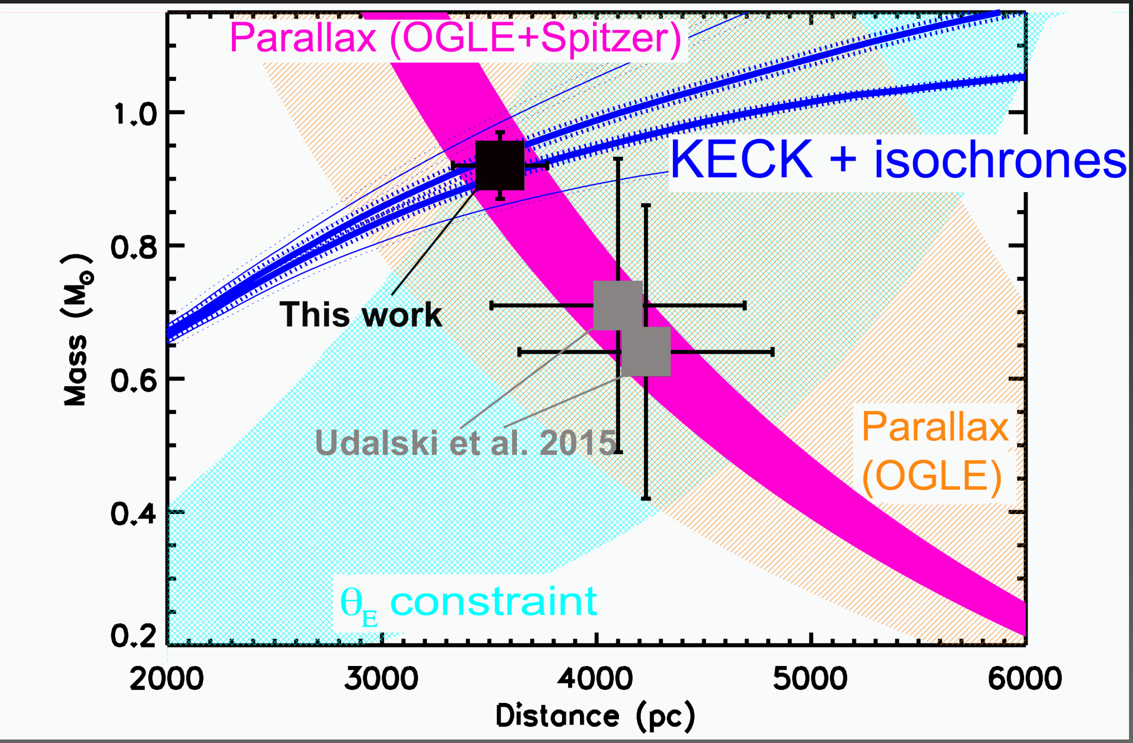


84.6% Lens
8.3% Lens companion
6.3% Source companion
0.8% Ambiant star
H mag



Parallax (OGLE+Spitzer)
KECK + isochrones
This work
Udalski et al. 2015
Parallax (OGLE)
θ_E constraint
1.0
0.8
0.6
0.4
0.2
2000
3000
4000
5000
6000
Distance (pc)

Most likely,
~80 % of the excess light is the lens



Udalski et al. 2015

Host star mass: 0.80 ± 0.20 M☉

0.74 ± 0.20 M☉

Planet mass: 0.63 ± 0.18 $M_{Jupiter}$

0.53 ± 0.16 $M_{Jupiter}$

Distance D_L: 4.92± 0.69 kpc

4.25± 0.72 kpc

Proj. Separation: 3.16 ± 0.46 AU

3.13 ± 0.47 AU

Beaulieu et al. 2017 ApJ

Host star mass: 0.89 ± 0.06 M☉

Planet mass: 0.64 ± 0.04 $M_{Jupiter}$

Orbit: 3.48 ± 0.22 AU

Distance: 3.6 ± 0.2 kpc

If 100 % of the light is the lens:

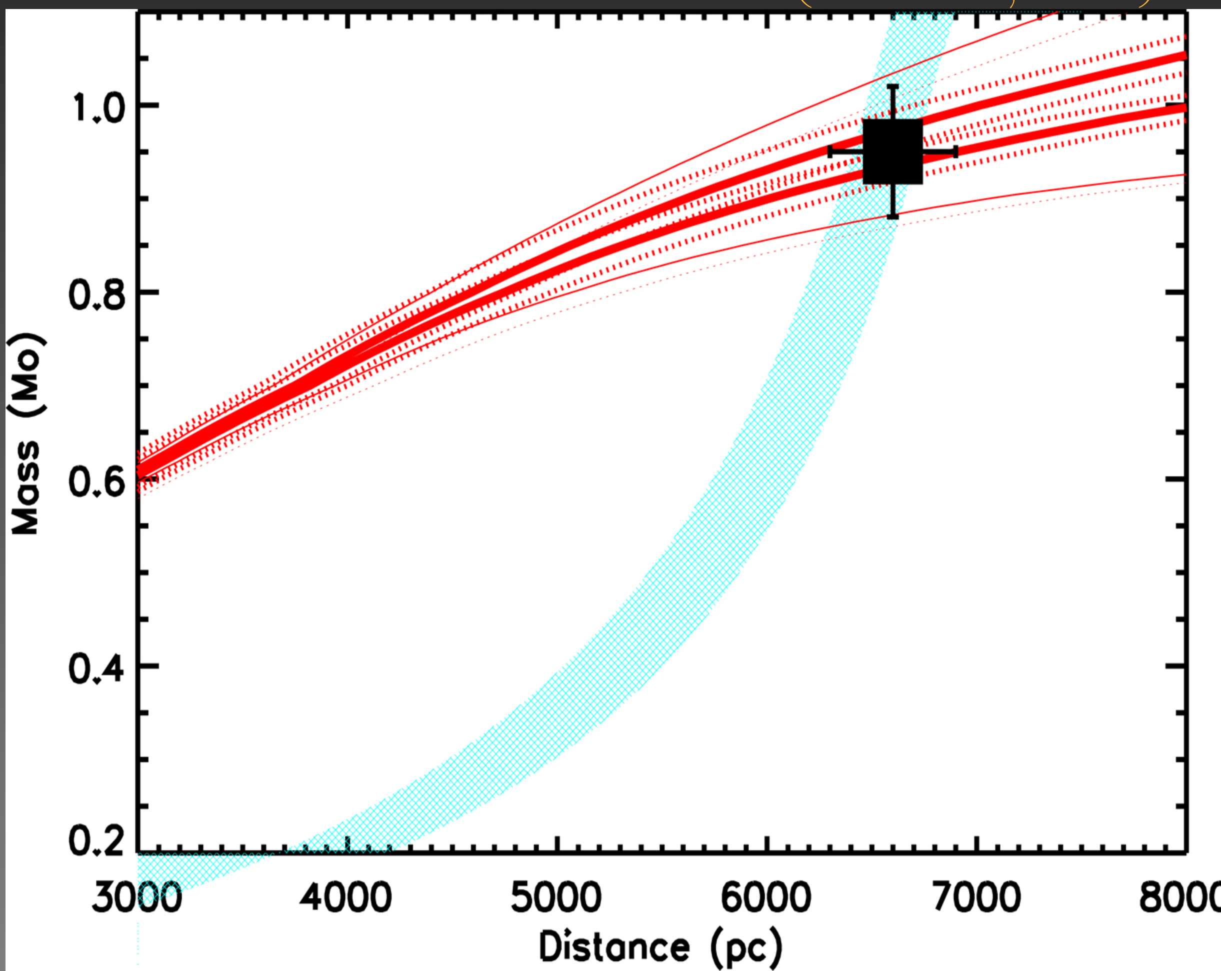
Host star mass: 0.91 ± 0.06 M☉

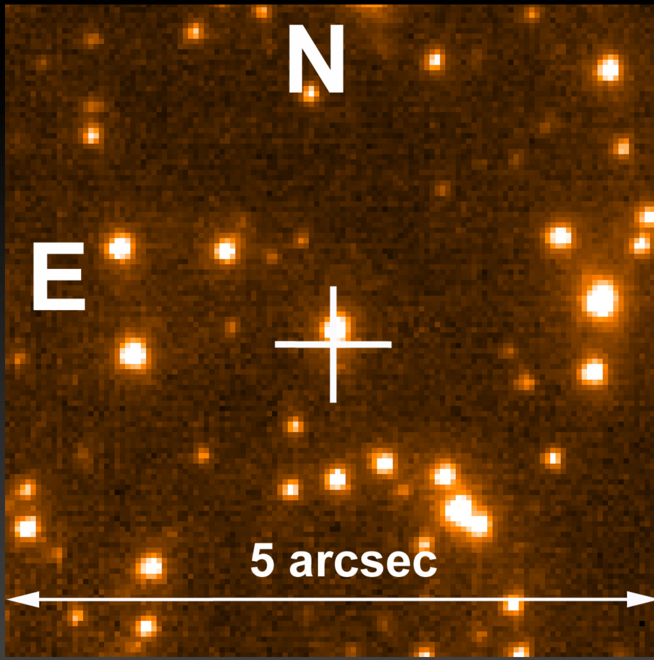
Planet mass: 0.65 ± 0.04 $M_{Jupiter}$

MOA-2013-BLG-220, a massive gazous planet

Mass ratio 3.01 ± 0.02 10-3,
good Einstein ring radius 0.456 ± 0.003 mas

(Yee et al., 2014)



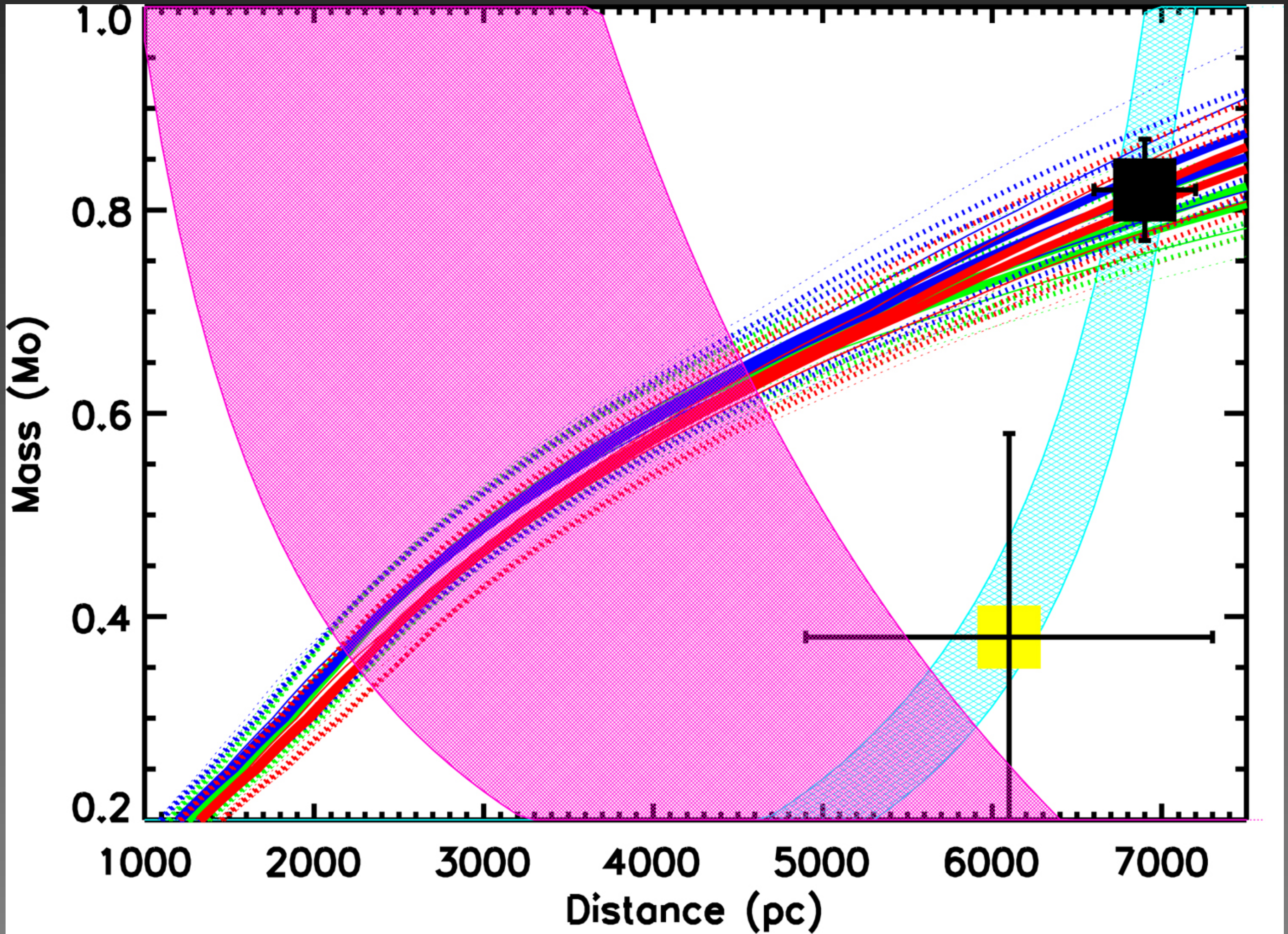


If all the light is the Lens, then
Mass : 0.96± 0.07 Mo
Distance: 6.55 ±0.5 kpc

A sub-Saturn orbiting a K or M dwarf ?

Before: Mass 0.38 ± 0.2 Mo ; Distance 6.1 ± 0.3 kpc Mp ~50 Mearth

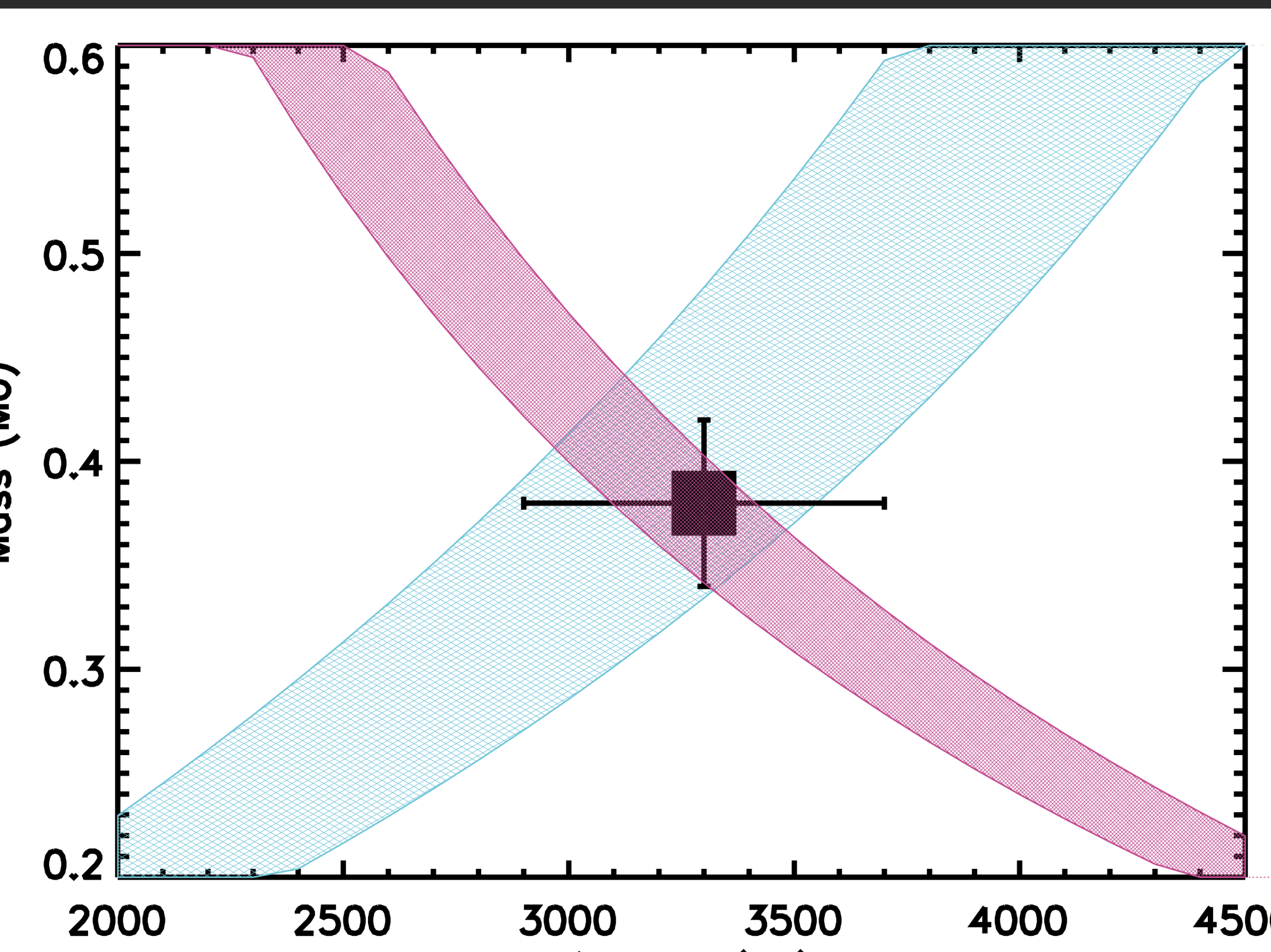
After: Mass 0.82 ± 0.05 Mo ; Distance 6.9 ± 0.3 kpc ; Mp~ 108 MEarth



Miyake et al., 2014

OGLE-2015-BLG-966, excellent Spitzer parallax

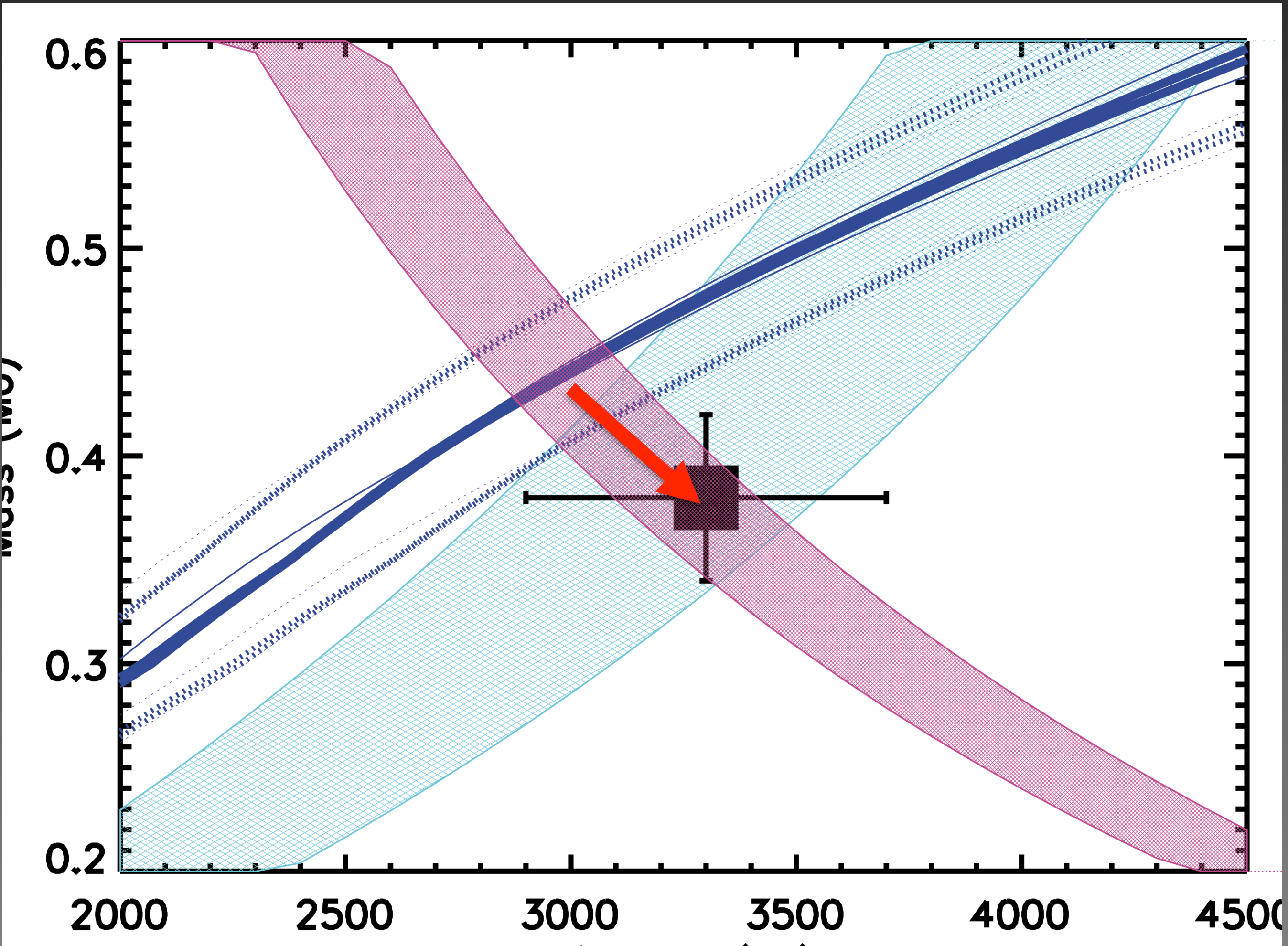
Cold Neptune orbiting a 0.38 Mo, at 2.5-3.3 kpc (Street et al., 2016)



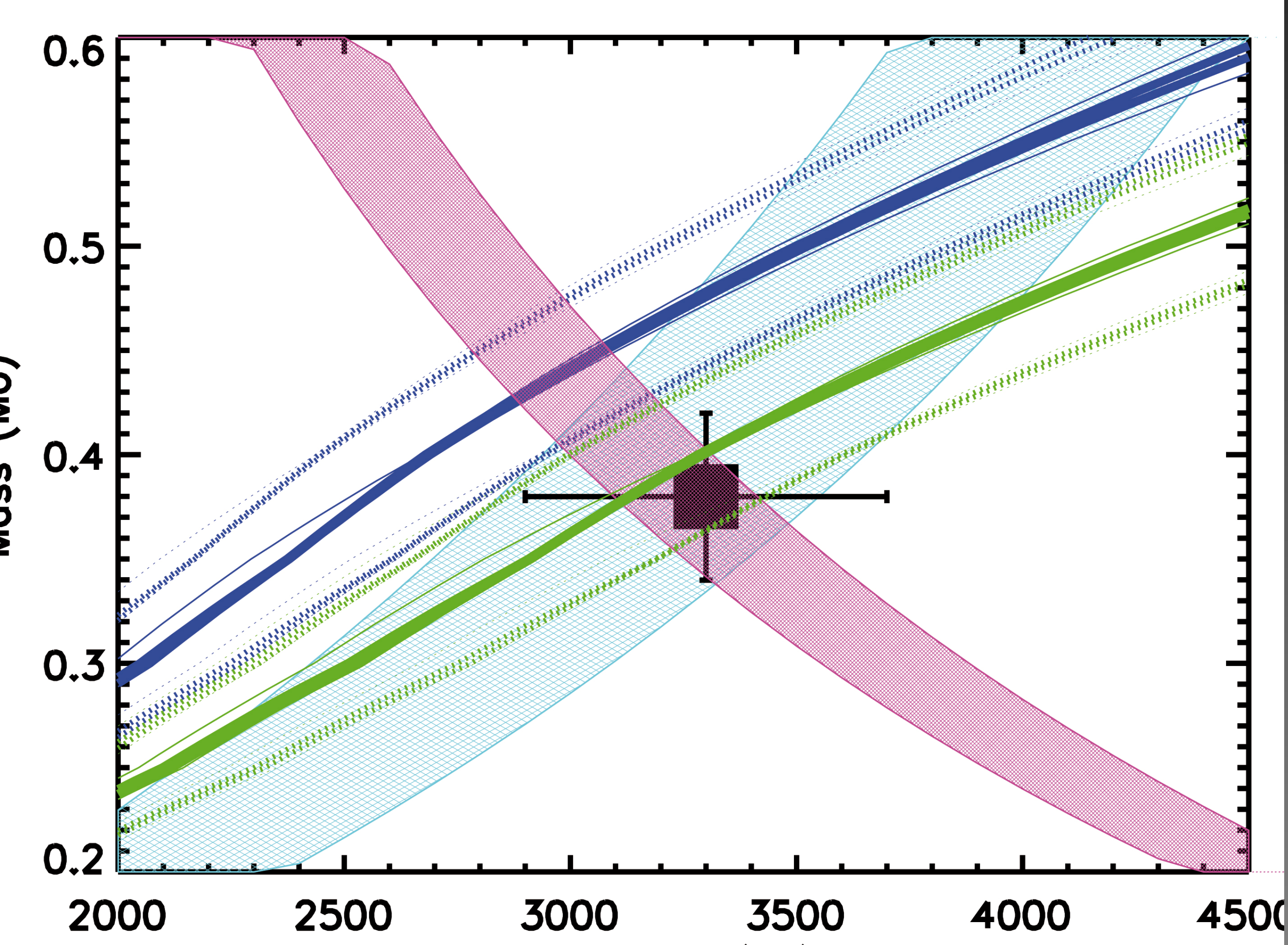
Detection of the blended flux at KECK

KECK observations by C. Henderson & Y. Schvartzvald.

Source + blend, H=16.92 ± 0.05 ; Source estimate: 17.14



A companion at H=20 to source/lens?



STOP

Let’s take a deep breath

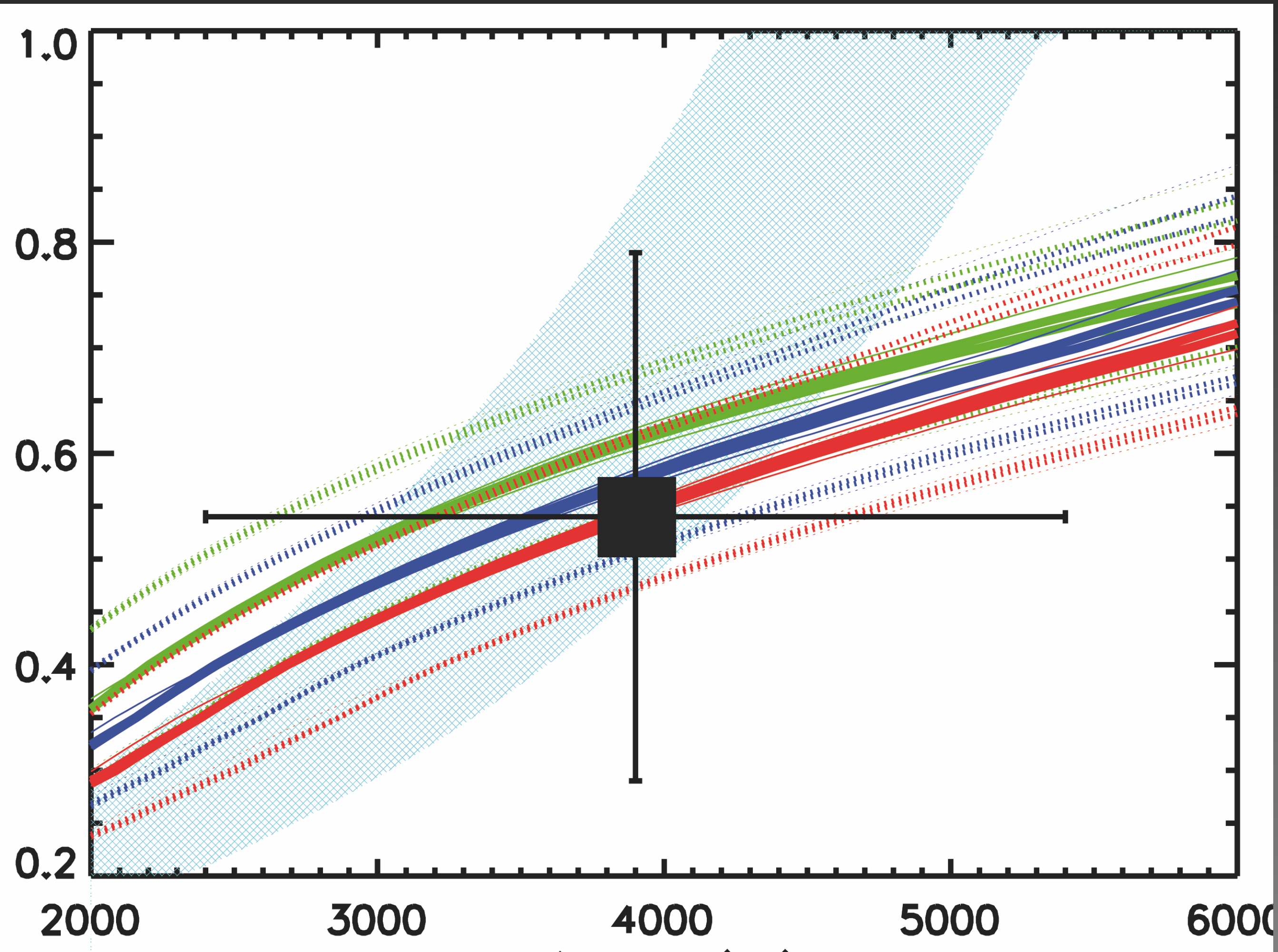
As you can see small errors on the color, extinction, AO measurements has a significant consequences.

So let’s be cautious, do parallel analysis of the same data by 2 groups.

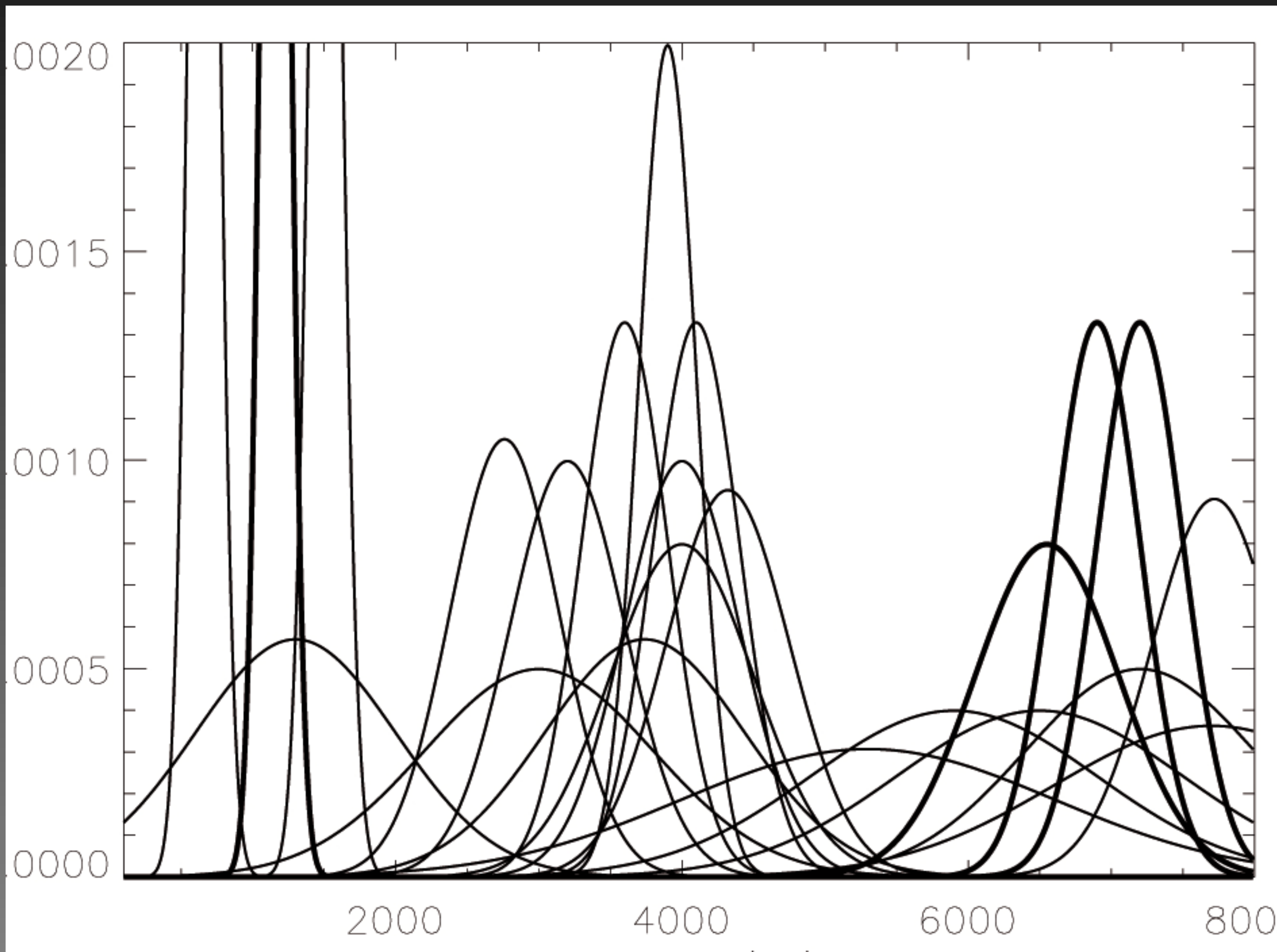
Calen & Yossi, there is some work to do on 966 ☺

It has to start with re-measuring the colors.

From time to time, it seems to work just fine !
OGLE-2013-BLG-132

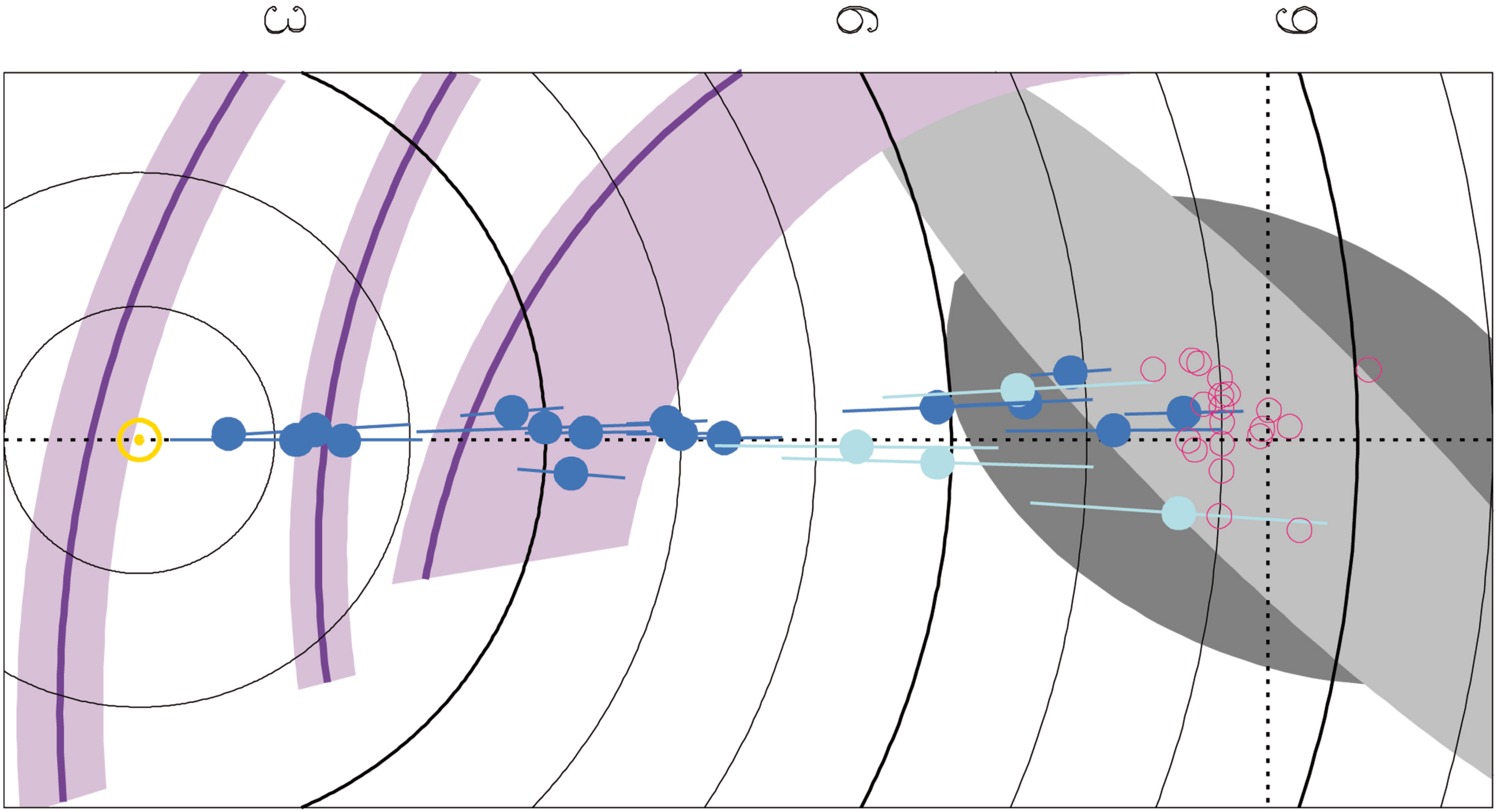


Lens distances with high angular resolution observations constraints



Distribution of lenses, preliminary

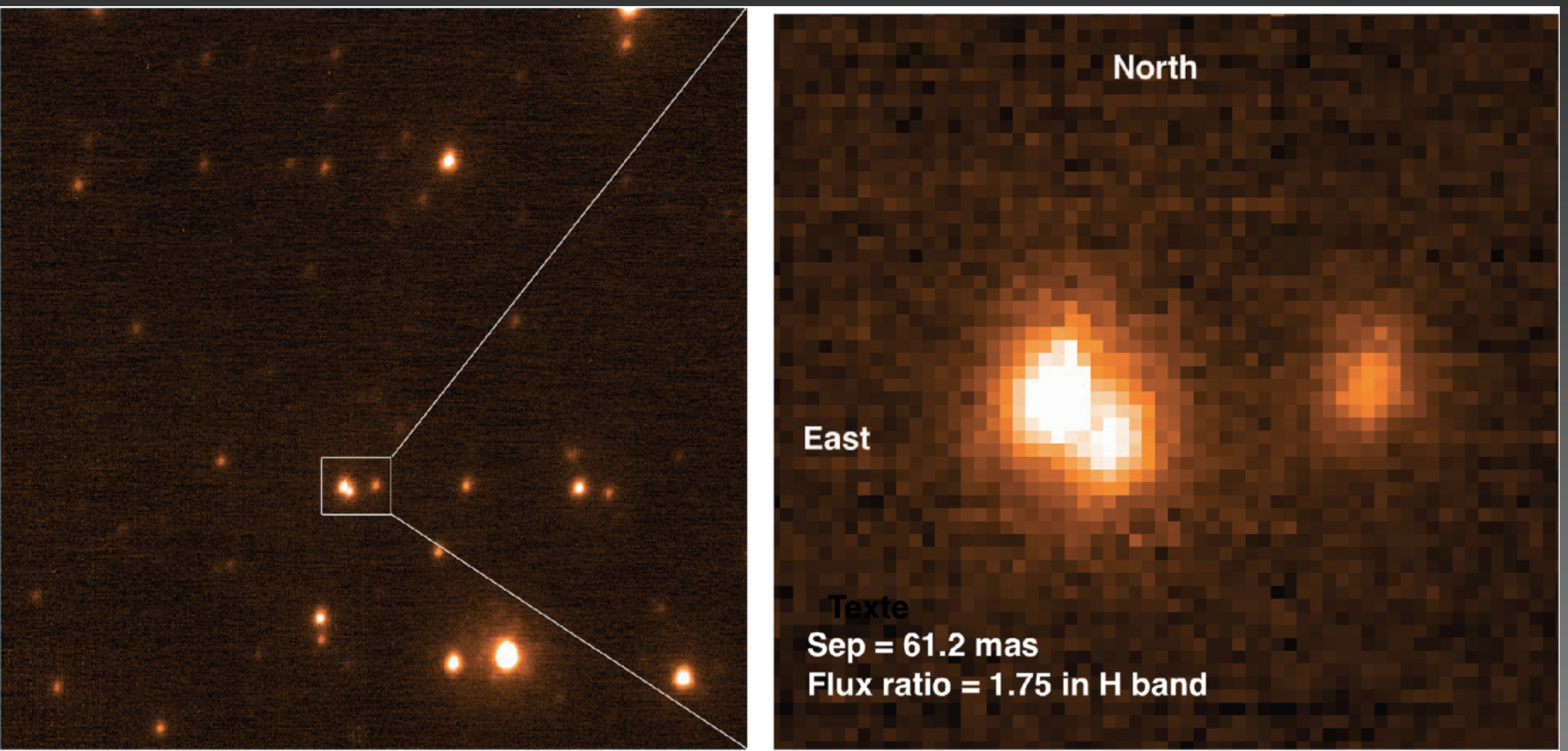
Well measured distances → systems associated with spiral arms or bar



OGLE-2005-BLG-169Lb : Resolving source & lens

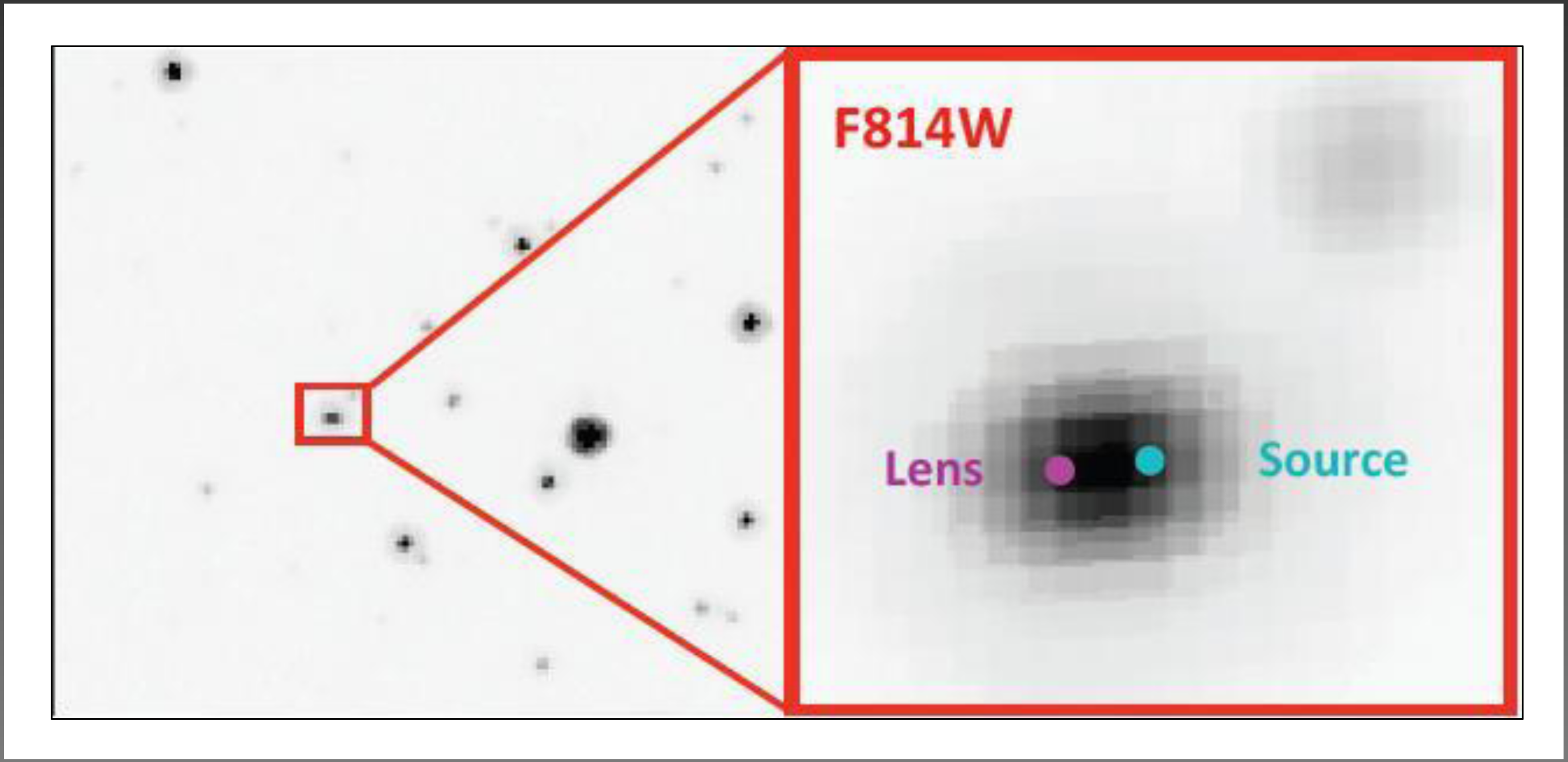
With KECK, detecting the lens in 2013
Measuring proper motion

Batista et al., 2015



HST : 6.5 years after the event

Bennett et al., 2015



Detecting source & lens, measuring proper motion

Initial paper & preductions

Gould et al. 2006

Relative proper motion ~ 7-9 mas/yr
Host star mass 0.5 ±0.3 $M_{\odot}$
Planet mass ~ 13 $M_{jupiter}$
Distance D_L=2.7 ± 1.6 kpc
Projected separation ~ 2.7 AU

HST Bennett et al. 2015

μ_{rel_l} = 7.39 ± 0.2 mas/yr
μ_{rel_b}= 1.33 ± 0.23 mas/yr

Host star mass: 0.69 ± 0.02 $M_{\odot}$
Planet mass: 14.1 ± 0.9 M_{earth}
Distance D_L = 4.1± 0.4 kpc
Projected separation 3.5 ± 0.3 AU

KECK Batista et al. 2015

μ_{rel_l} = 7.28 ± 0.12 mas/yr
μ_{rel_b}= 1.54 ± 0.12 mas/yr

Host star mass: 0.65 ± 0.05 $M_{\odot}$
Planet mass: 13.2 ± 1.5 M_{earth}
Distance D_L = 4.0± 0.4 kpc
Projected separation 3.4 ± 0.3 AU

In agreement with Gould et al., 2006, but more accurate results.

MACHO-95-BLG-3, a free-floating planet ?

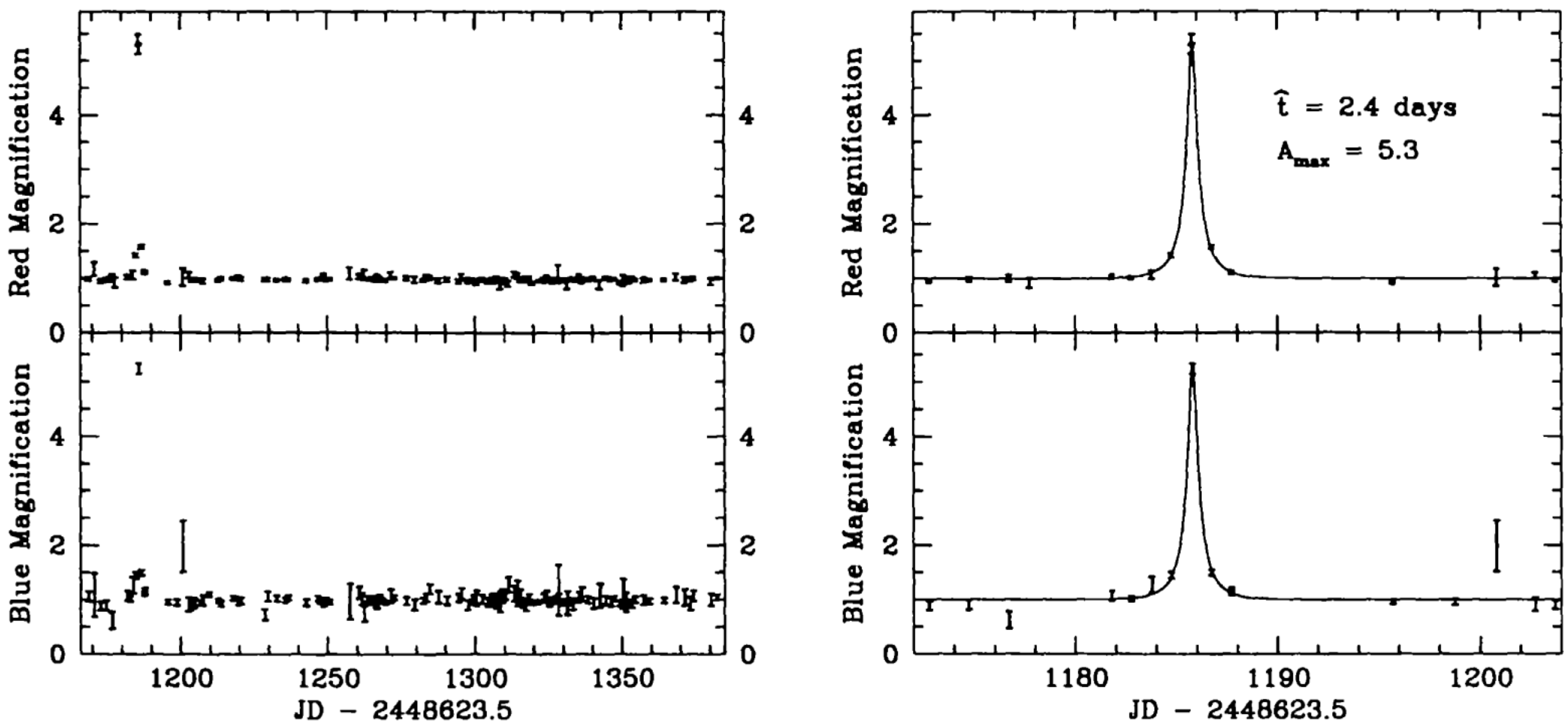
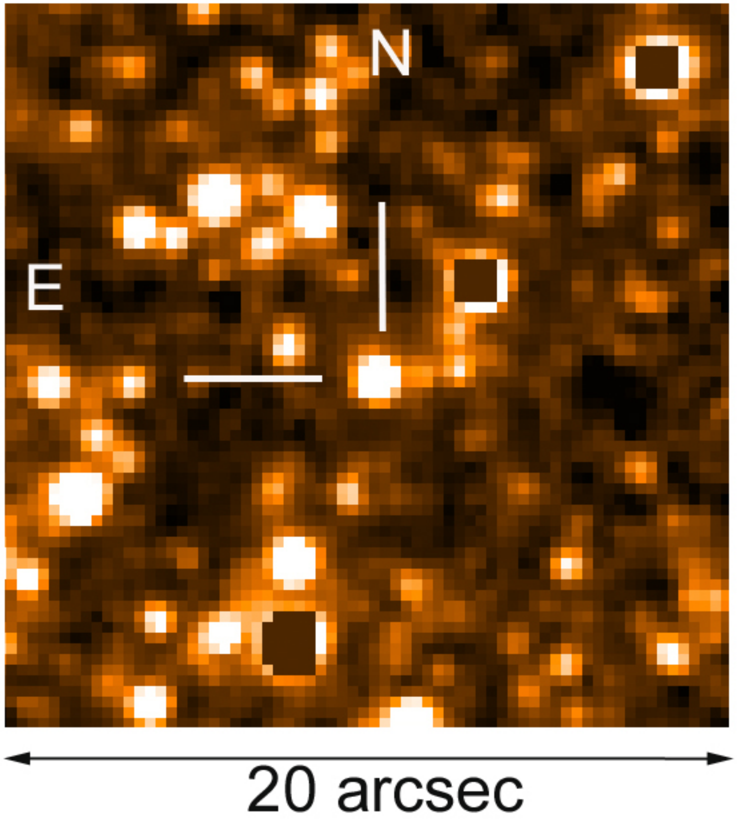
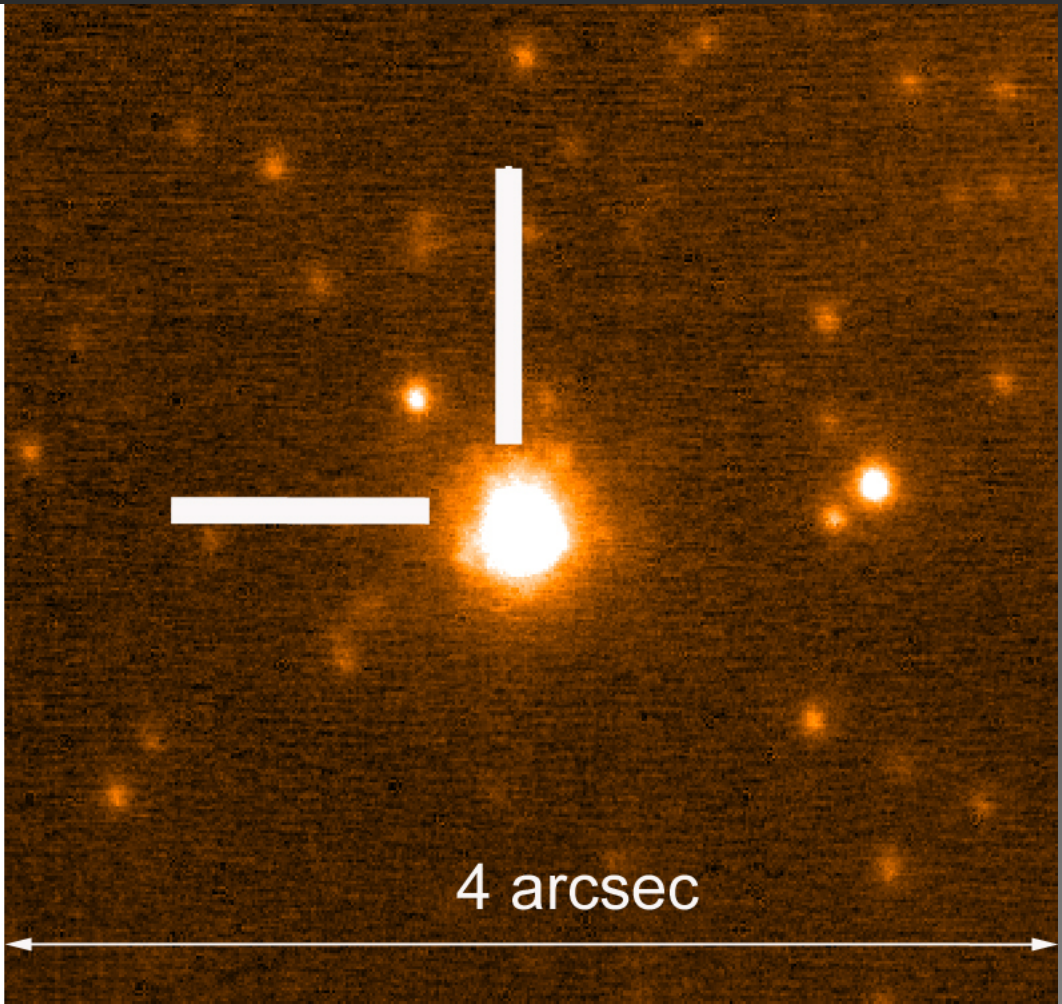


Figure 2. The dual-color light curve of event 95-BLG-3 during the 1995 Galactic bulge season and a close-up of the light curve showing the lens fit.

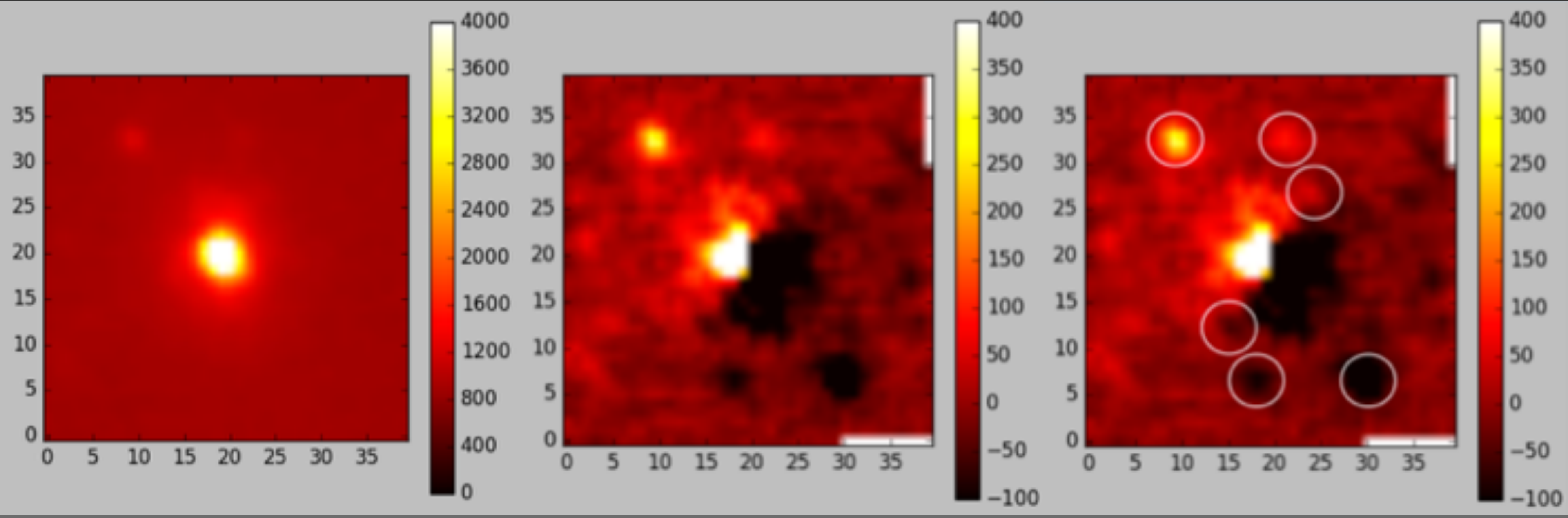
MACHO-95-BLG-3





3 companions, 0.6, 0.4, 0.3 arcsec

With Marie Ygouf, CALTECH



Free-floating planet ? Probably not...

What we need in papers

- Source flux I and colour V-I, with errorbars.
- Source distance and extinction, with errorbars.
- If H band data available, give estimate of source flux in H,

  with errorbars.

- Do not hesitate to double check these numbers, and to measure them again from the images.
- If you write discovery papers, why not asking around if there are high angular resolution observations available ?
- Is it fair game to publish models using H band data and not publishing the source flux ?

Do your duty as a co-author or a referee !

Observing cookbook

- Adaptive optics on 8m+ telescope (KECK, SUBARU, VLT, GEMINI)
- Natural Guide Star or Laser Guide Star
- Dithering, but not too big steps (few arcsec max)
- Take sequence of images at each dithering position
- Do not hesitate to overkill (a bit) prediction of the exposure calc
- Take a sky obs (same as people working on galactic center)
- Attempt to measure relative source-lens proper motion only in very good seeing condition (60 mas or better), preferably K band.
- Suite of tools from Astr*O*matic.net, Sextractor, Swarp, Scamp, PSFEx), starfinder (IDL) ,GAIA, topcat
- Calibration (astrometry, photometry) using reprocessed VVV data.
- Aperture photometry (for flux calibration purposes).
- PSF fitting: extracare needed, weird shape & variable.

To keep in mind

- Important to be cautious with high angular resolution.
- Measuring fluxes in AO, ok at 5% level, from time to time 2%.
- Unresolved source/lens: Procedure to estimate contamination by blends, companions to source & to lens (AO, Euclid, WFIRST)
- Centroid shift due to source/lens: Procedure to estimate contamination by blends, companions to source & to lens (AO, Euclid, WFIRST)
- Refining AO strategy to measure source-lens centroid shifts.
- Feedback from direct detection people

Conclusion

High Angular Resolution observations :

- Detect flux aligned with the source (AO)
- Measure source-lens relative proper motion
    - resolving source and lens with AO
    - measuring variation of centroid of PSF (HST, WFIRST, Euclid)

It is cheap to do (30-60) min per target.

About 30+ systems observed to date and 15 free-floating planet candidates

Derived physical parameters can be very different from Bayesian analysis

Distribution of planets is not uniform

Spiral arms and bar planetary systems...

Time to speak about the planets from the Bar
rather than planets from the Bulge ?

3 papers heading for submission to ApJ within a month