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# High angular resolution imaging of microlensing

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# Cook book references:

Bennett, Anderson, Gaudi, 2007, ApJ 660, 781 (method)
Kubas et al. 2011, A&A in press (MOA 192 final analysis)

*Bennett et al. 2007, ApJ 684, 663 (MOA 192 detection super earth)*
*Dong et al. 2009, ApJ 695, 970 (OGLE 71 final analysis cold jupiter)*
*Janczak et al. 2010, ApJ (MOA 310, Bulge saturn mass planet*)
*Sumi et al., 2010, ApJ 710, 1641 (OGLE 368, Neptune planet)*

Tools :

-Dophot, Daophot, starfinder (PSF fitting code)
(http://www.eso.org/sci/publications/messenger/archive/no.100-jun00/messenger-no100-23-27.pdf)

- Jitter/Eclipse infrared data reduction package :
(http://www.eso.org/sci/software/eclipse/)
- skycat/gaia (astrometry http://starlink.jach.hawaii.edu/starlink)
-Topcat (catalogue manipulation http://www.star.bris.ac.uk/~mbt/topcat/)
- 2MASS catalogue (calibration http://www.ipac.caltech.edu/2mass/)

# Menu

**1/ Why we need AO or HST images ?**

***2/ Example of MOA 192 (in details)***

***3/ Some remarks about other events (MOA 310, OGLE 266, etc)***

# "Seeing" the lens

Observed light curve flux:

Amplification due to lens

$$F(t) = F_S A(t) + F_B$$

unlensed source flux

blend flux

$$F_B = F_{lens} + F_{Background}$$

**Idea: separate event from unrelated background**
**using space-based or AO high resolution imaging (ideally at 2 epochs)**
**-> using the lens model, the lens (planet host star) flux can be measured.**
**-> Improves accuracy of physical lens parameters by an order of magnitude!**

# Detection light from the lens & measuring direction of proper motion

1/ If relative lens proper motion μrel is known, while the angular Einstein ring is

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

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

It is a mass distance relation for the lens !

2/ We adopt a mass-luminosity relation

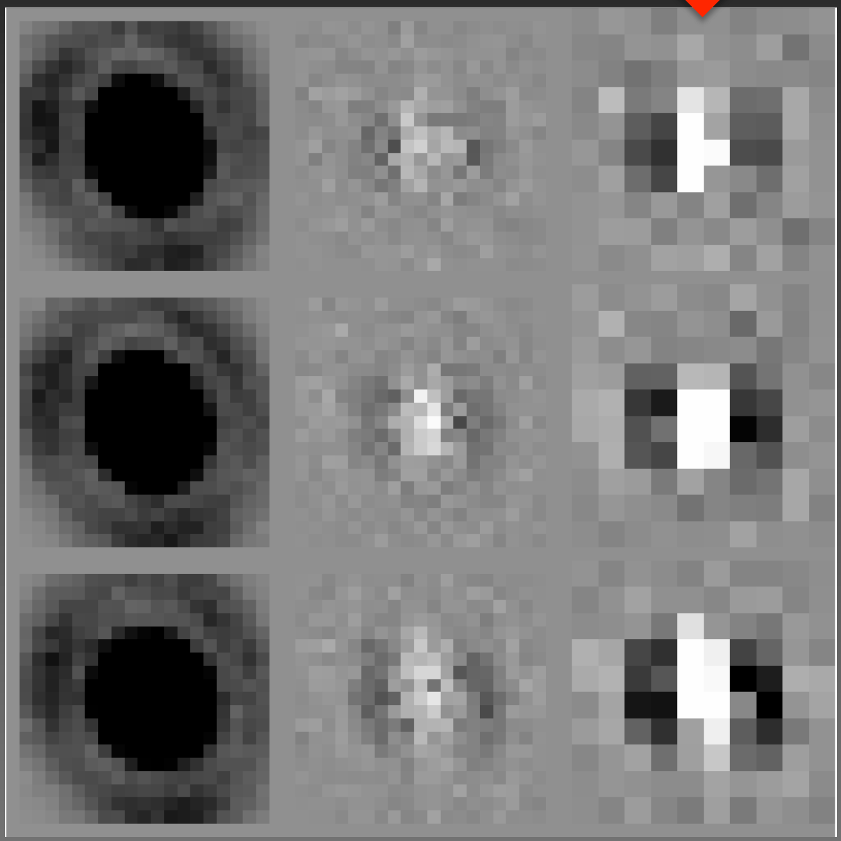
3/ We need to constraint light from the lens (AO obs + model)

Measure F(t1) and F(t2) with A(t1) > 1 and A(t2)=1

# Simulations by Anderson for OGLE 169

HST, ACS, F814W

Residual due to lens moving out



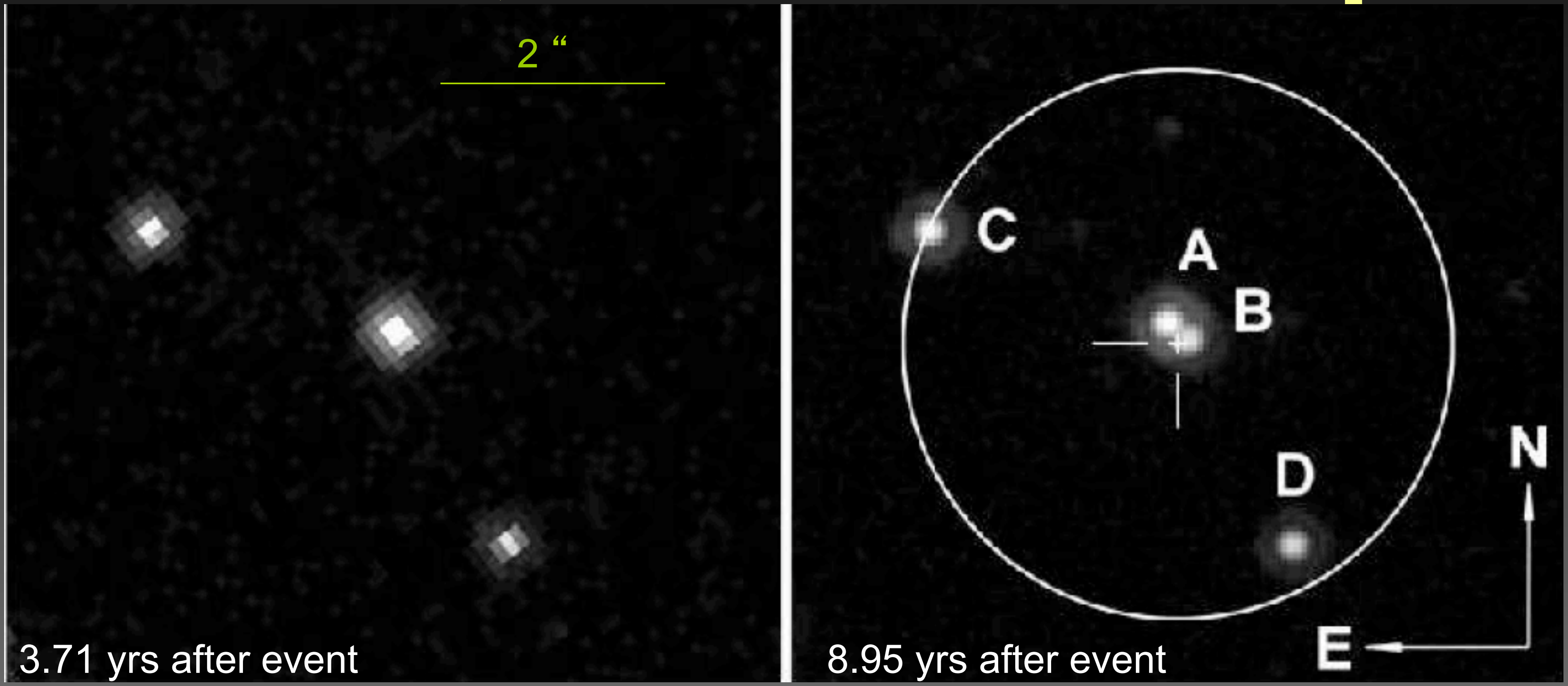
M*=0.08 Mo

M*=0.35 Mo

M*=0.63 Mo

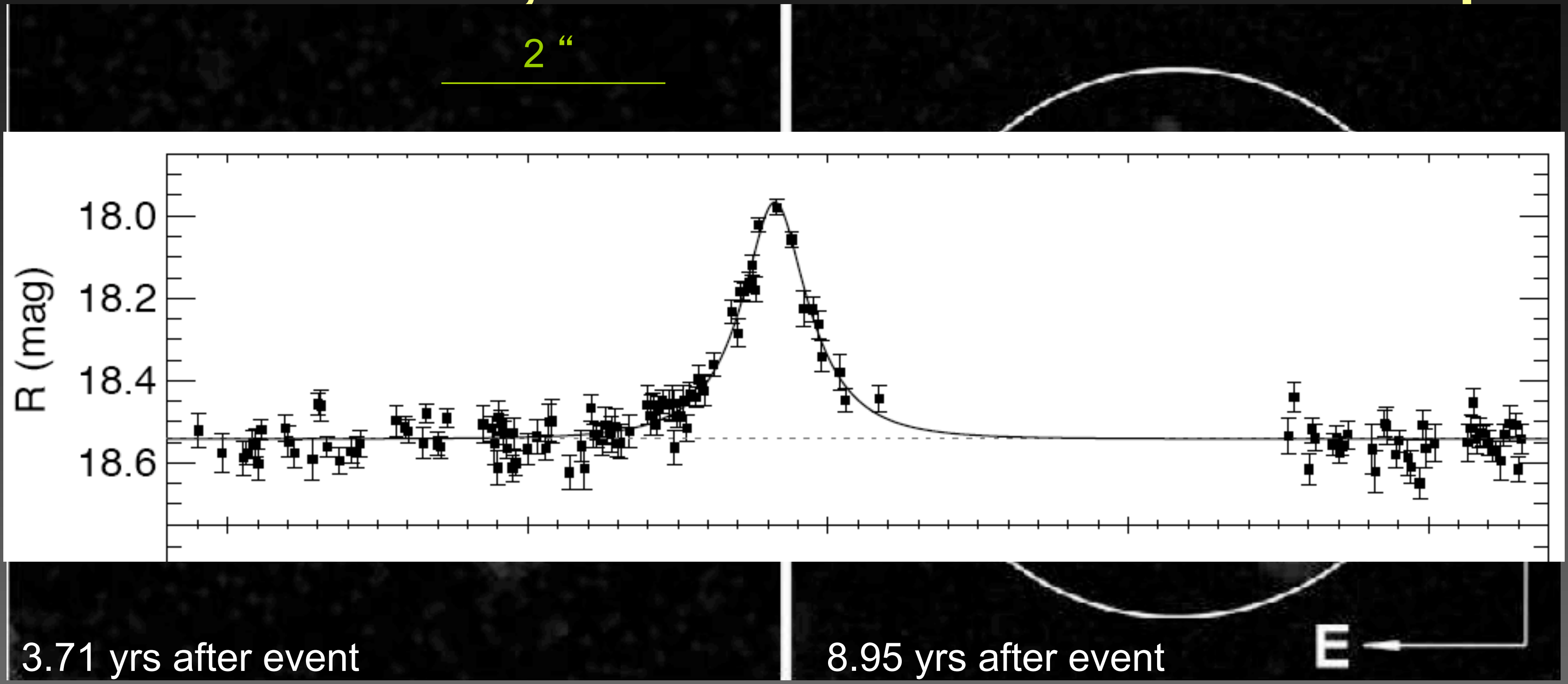
Detecting light from the lens, direction and amplitude of proper motion

# First detections by HST [Alcock et al 2001, Kozlowski et al 2007]



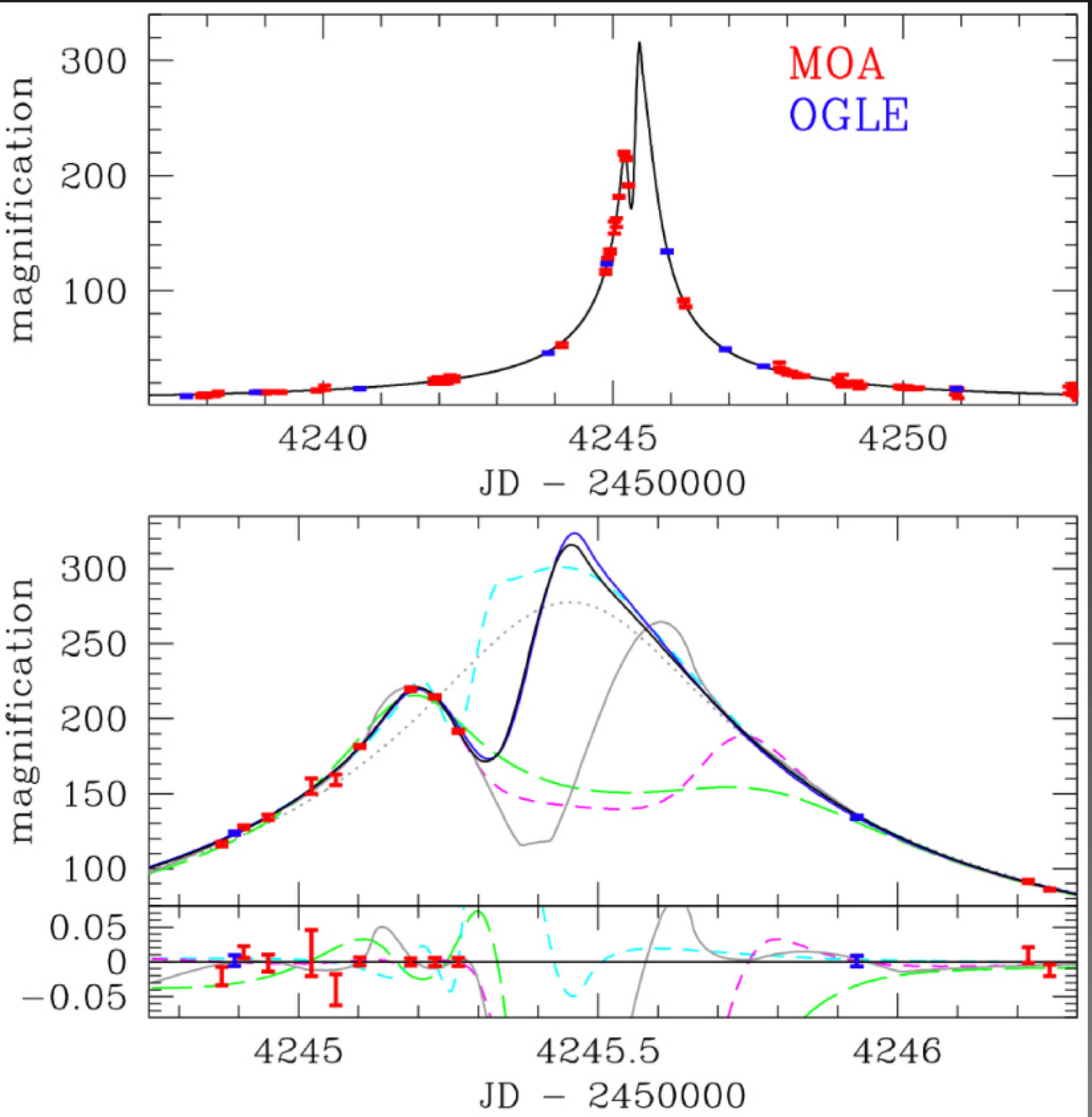

Macho-1995-blg-37 (Kozlowski et al 2007)

# First detections by HST [Alcock et al 2001, Kozlowski et al 2007]



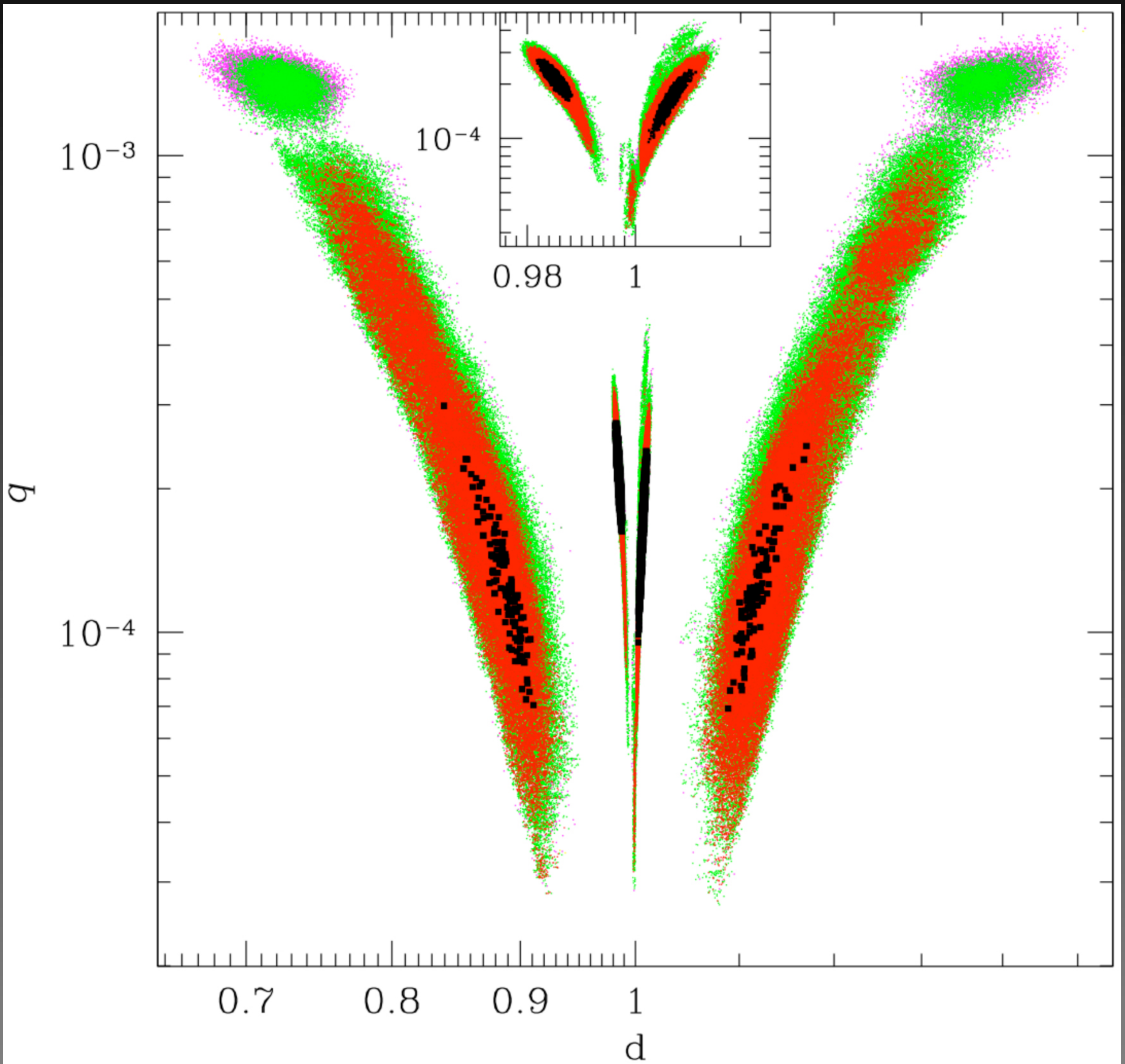

Ok, it works, let’s do it on planetary microlensing events!

# MOA 2007-BLG-192



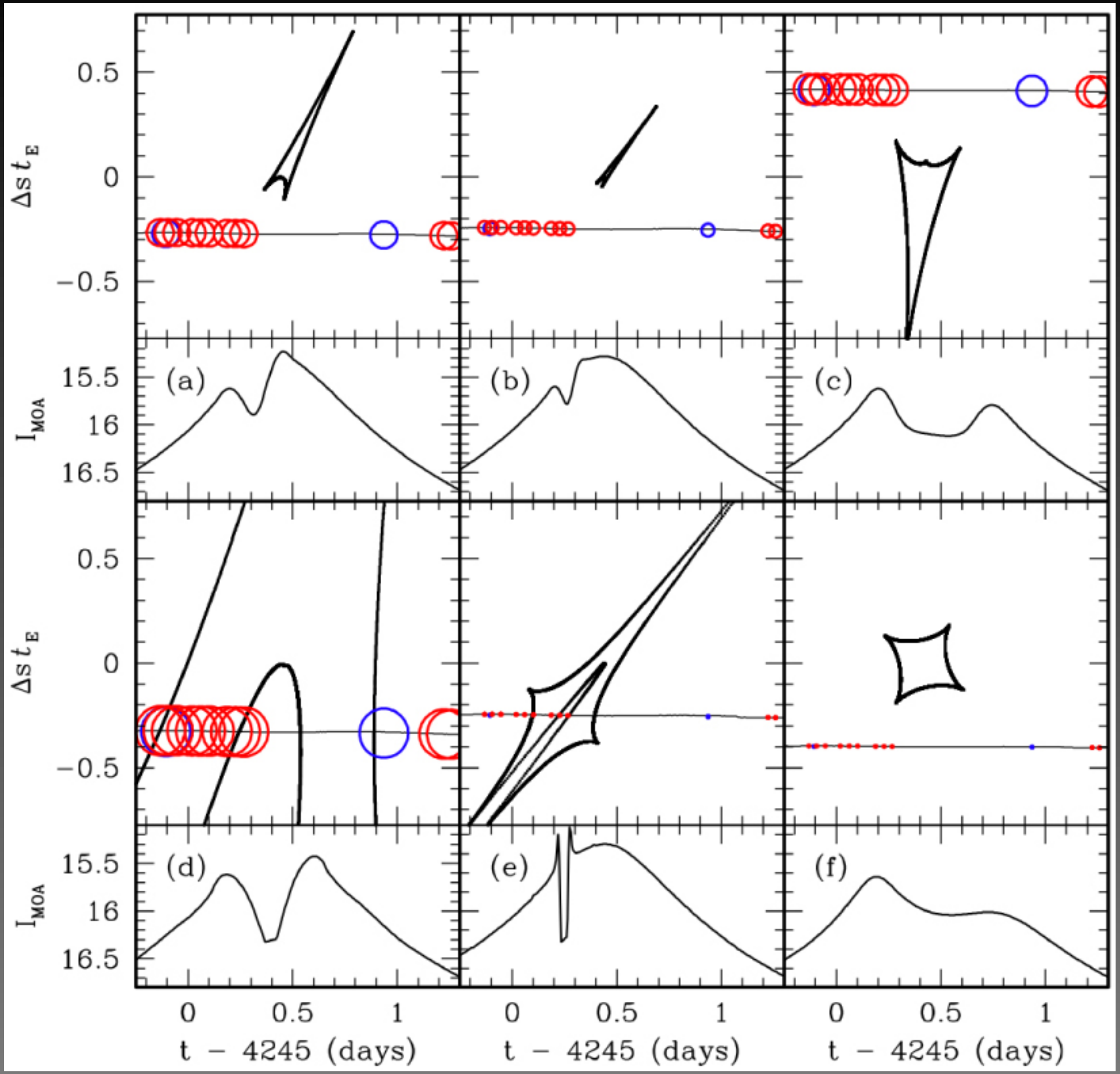

*Bennett et al., 2008 ApJ*

# Parameter space exploration of MOA 192




*Bennett et al., 2008 ApJ*

# The different caustic structures of MOA 192




*Bennett et al., 2008 ApJ*

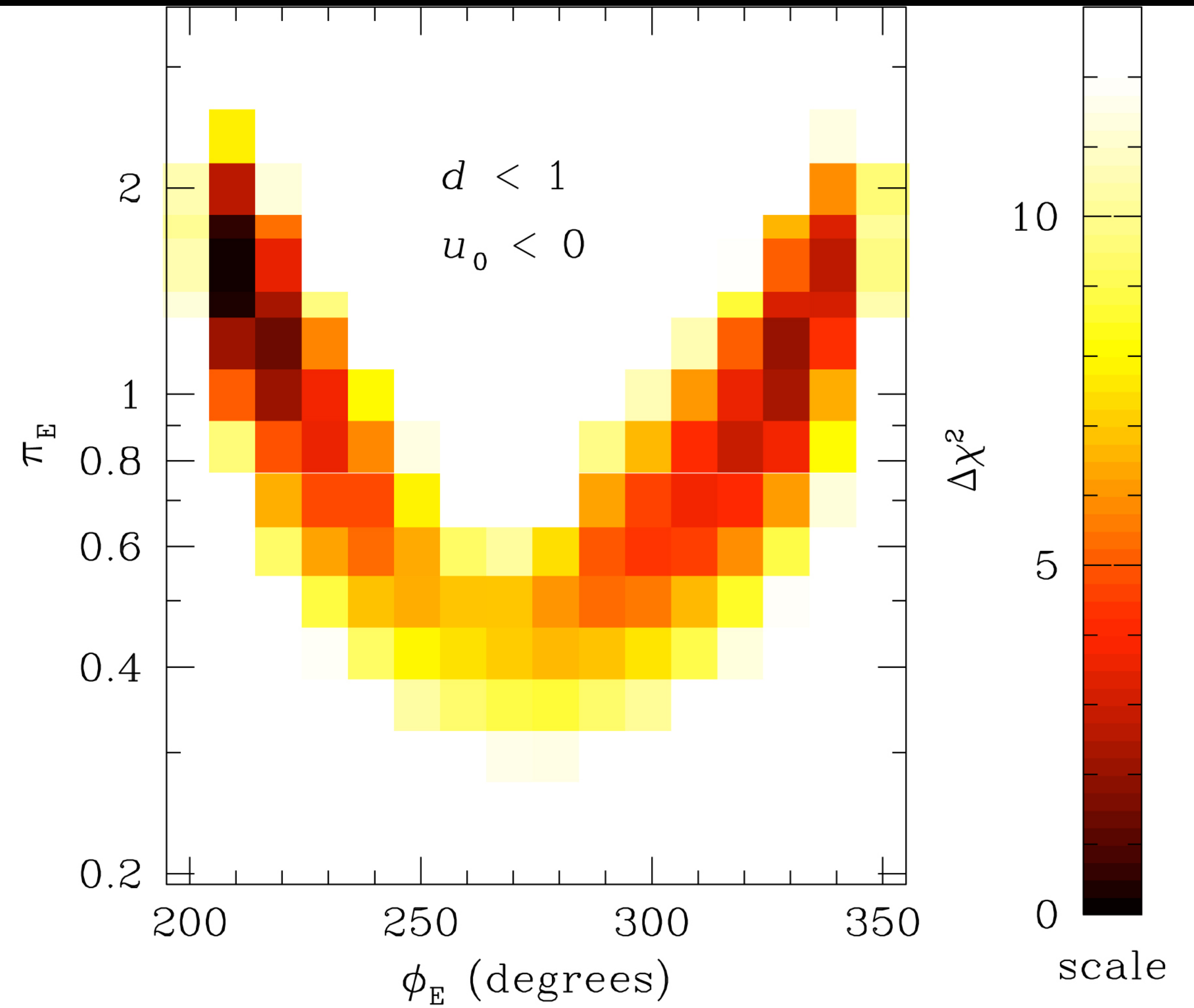



Fig. 8.— The regions of microlensing parallax parameter space that are consistent with the MOA-2007-BLG-192 light curve are indicated by the distribution of $\Delta\chi^2$ from the best fit model. The $\pi_E$ and $\phi_E$ values that are not shown and those that are indicated by white squares all give $\Delta\chi^2 > 12$ larger than the minimum value.

*Bennett et al., 2008 ApJ*

*Getting direction of proper motion would be cool !*

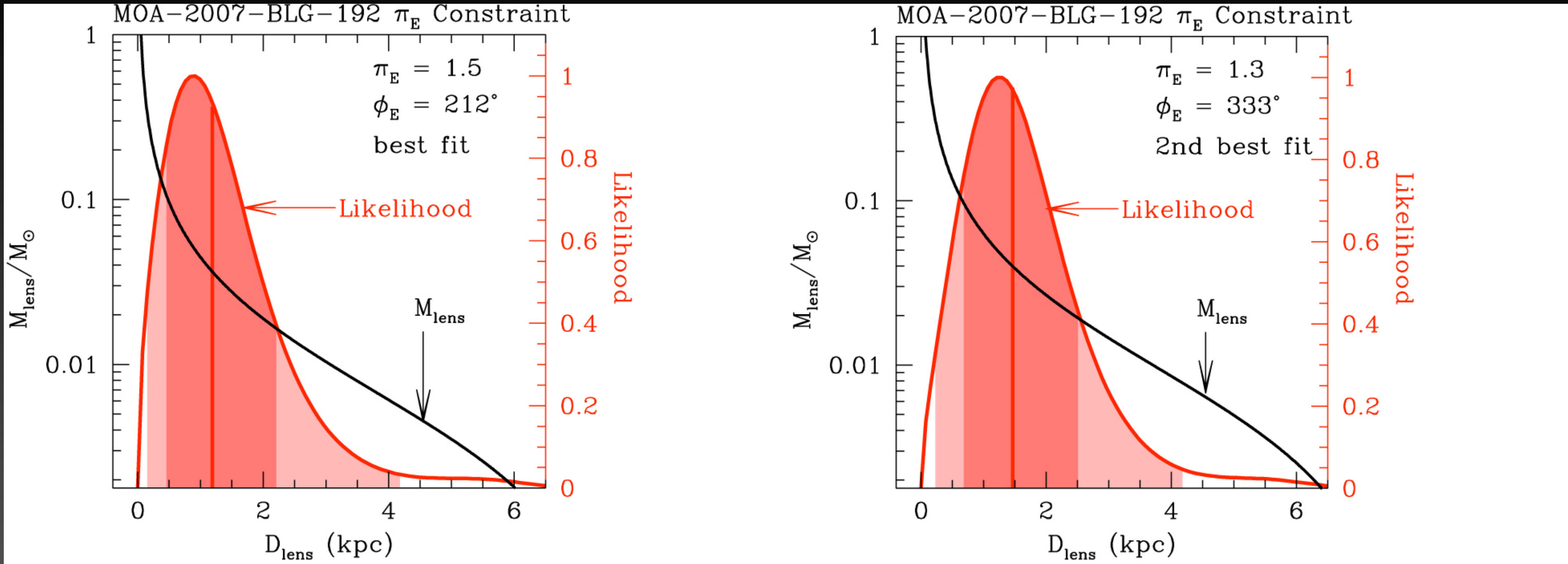
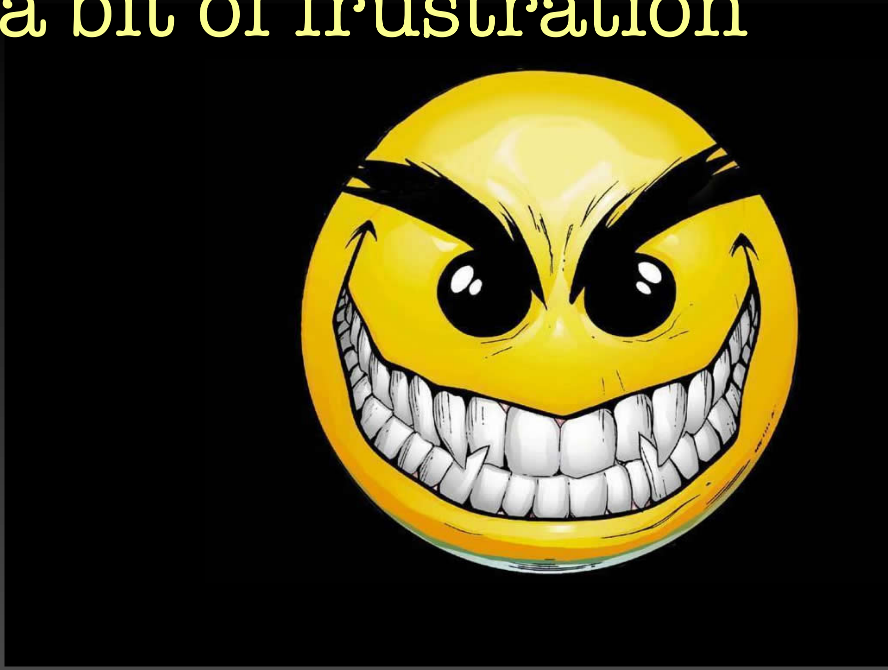



Fig. 9.— The mass-distance relations are plotted in black for the two local minima in the microlensing parallax parameter $\chi^2$ surfaces shown in Fig. 8. The red curves show the probability distributions from a Bayesian analysis that compares the $\tilde{\mathbf{v}}$ for each model to a standard Galactic model. The vertical red lines indicate the median distance and lens primary mass and the light red shaded regions indicate the 1-$\sigma$ and 2-$\sigma$ limits on the lens distance and mass. The median and 1-$\sigma$ limits for the lens star mass are $M = 0.036^{+0.057}_{-0.020} M_\odot$ and $M = 0.039^{+0.051}_{-0.020} M_\odot$ for the best and 2nd best fits, respectively. The 2-$\sigma$ ranges are $0.005 M_\odot \leq M \leq 0.36 M_\odot$ and $0.007 \leq M \leq 0.31 M_\odot$.

~3.3 $M_\oplus$ orbiting a~0.06 Mo star ? MOA 2007-BLG-192

| parameter | value | 2-$\sigma$ range |
|---|---|---|
| $M$ | $0.060^{+0.028}_{-0.021} M_\odot$ | $0.024$–$0.128 M_\odot$ |
| $m$ | $3.3^{+4.9}_{-1.6} M_\oplus$ | $1.0$–$17.8 M_\oplus$ |
| $a_\perp$ | $0.62^{+0.22}_{-0.16}$ AU | $0.33$–$1.14$ AU |
| $D_L$ | $1.0 \pm 0.4$ kpc | $0.5$–$2.0$ kpc |
| $I_S$ | $21.44 \pm 0.08$ | $21.31$–$21.61$ |
| $q$ | $1.8^{+1.9}_{-0.8} \times 10^{-4}$ | $0.5$–$7.1 \times 10^{-4}$ |

# MOA 2007-BLG-192 : a bit of frustration



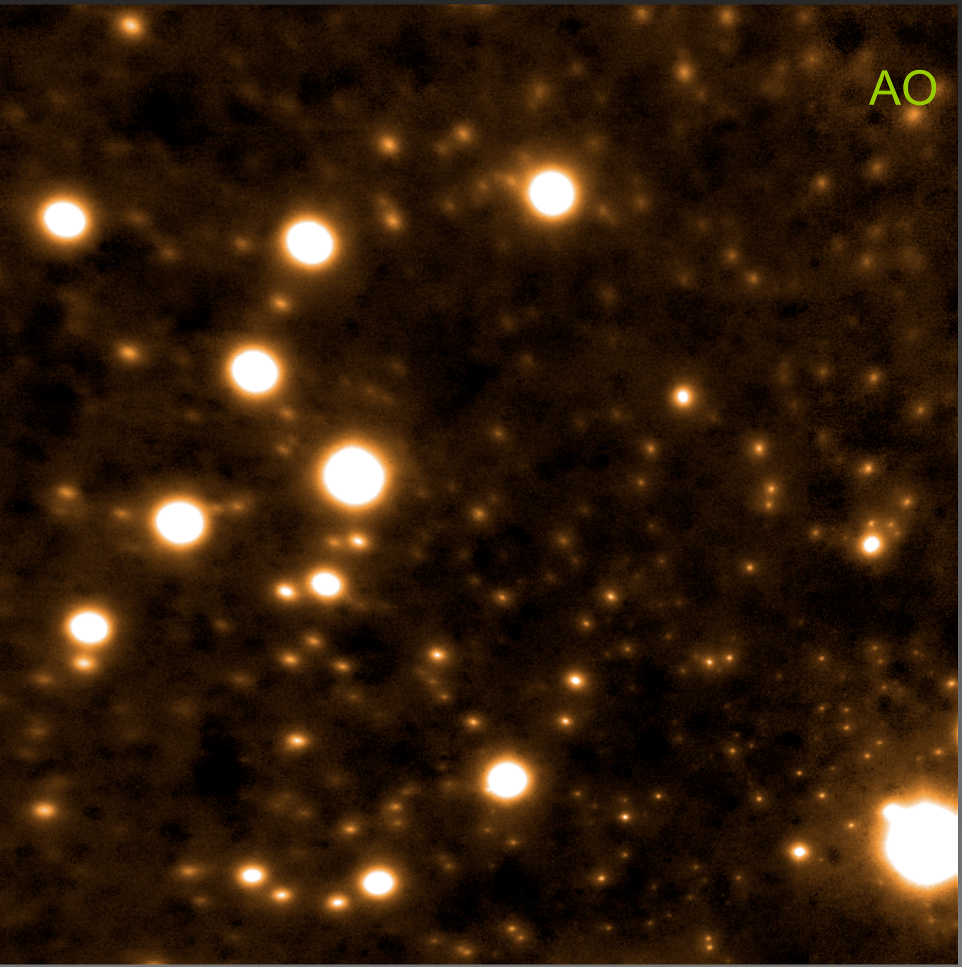
Incomplete light curve coverage -> degeneracy in lens models
Lack of strong contraint on source radius -> poorly known RE

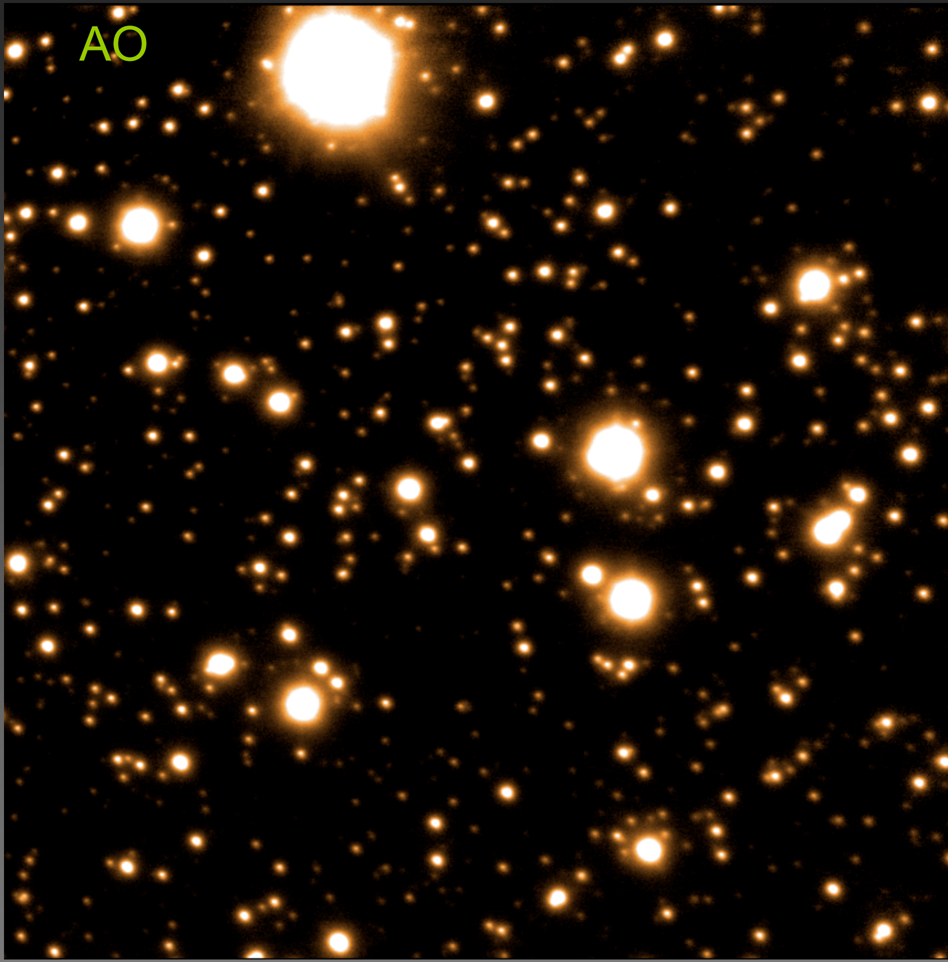
Therefore, large uncertainty in physical parameters.

# Can VLT/NACO  see the lens ?

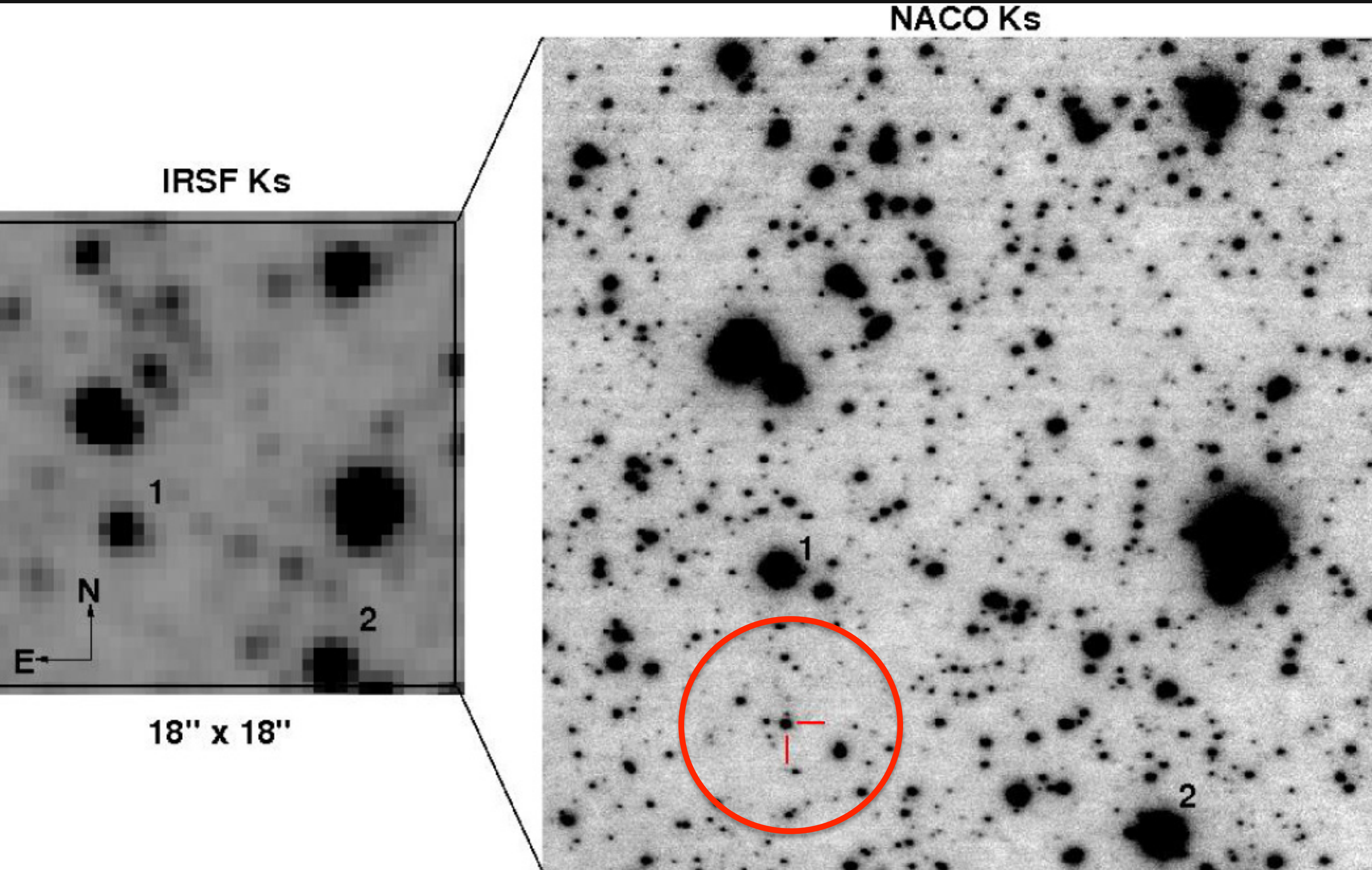
# AO photometry is "tricky"

- PSF is not analytical and space+time variant + skybackground varies too in NIR






NACO, 28 x 28", H band



IRSF Ks
NACO Ks
1
2
N
E
18'' x 18''

# MOA 2007-BLG-192 :

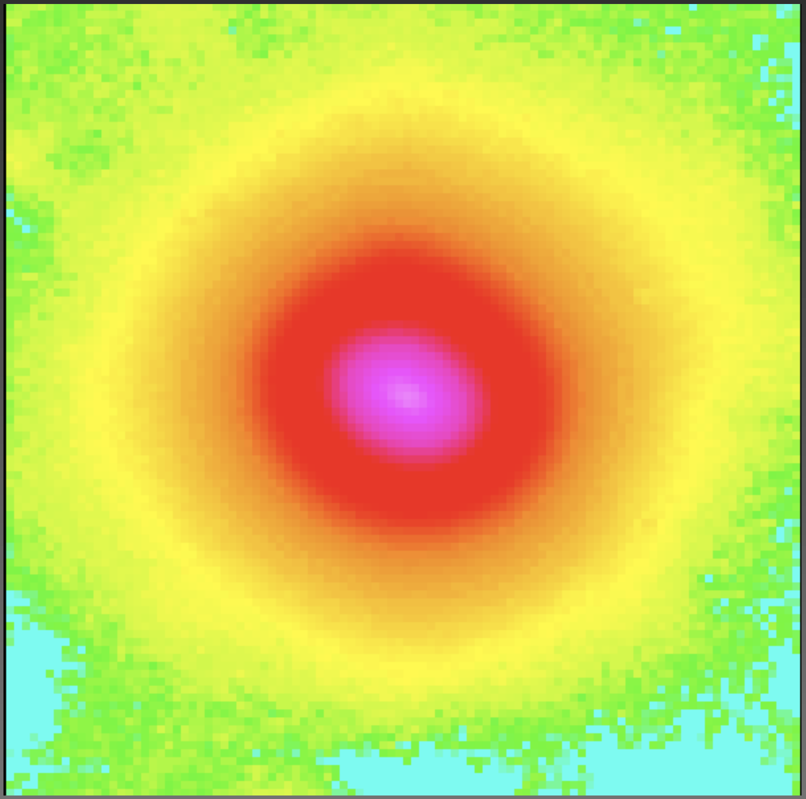
-2 VLT NACO epoch in JHK : 27”x27” with pixels of 0.02715”
-Jitter mode (10”) + Natural Guide star

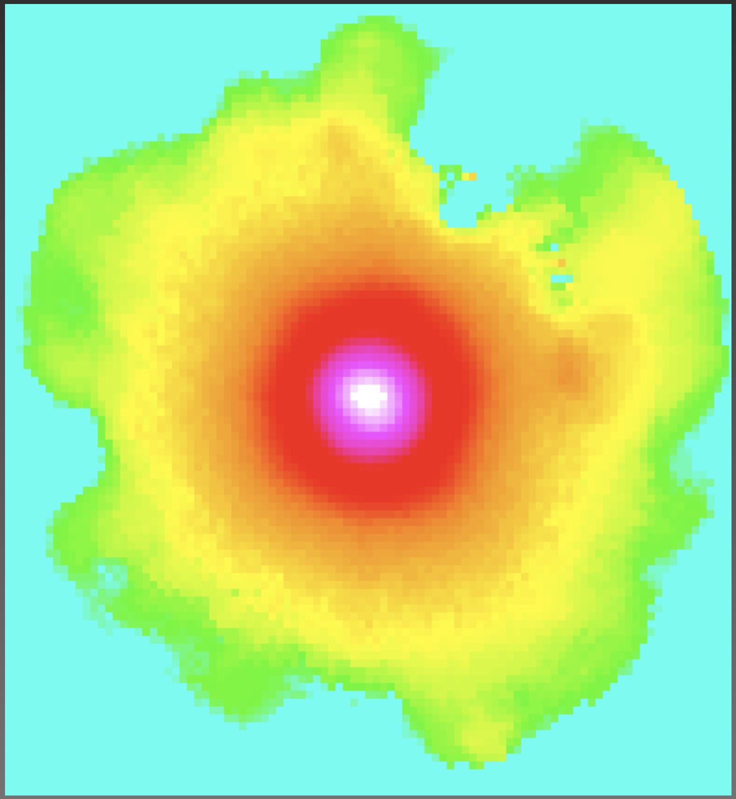
-IRSF (1.4m in Sout Africa) in JHK 8’x8’ with pixels of 0.45”

| Band | $n \times$ Exp [s] | MJD | Airmass | FWHM [″] |
|---|---|---|---|---|
| | | *Epoch 1* | A=1.23 | |
| J | $6 \times 60$ | 54350.00781250 | 1.005 | 0.14 |
| H | $20 \times 25$ | 54350.02734375 | 1.023 | 0.19 |
| Ks | $10 \times 25$ | 54349.98828125 | 1.002 | 0.09 |
| | | *Epoch 2* | A=1.0, baseline | |
| J | $23 \times 60$ | 55036.08593750 | 1.015 | 0.34 |
| H | $22 \times 30$ | 55036.06640625 | 1.034 | 0.29 |
| Ks | $24 \times 30$ | 55015.10156250 | 1.088 | 0.10 |

# Using Starfinder [Diolaiti et al. 2002]

Creating numerical psf-template to fit from stars in the fov

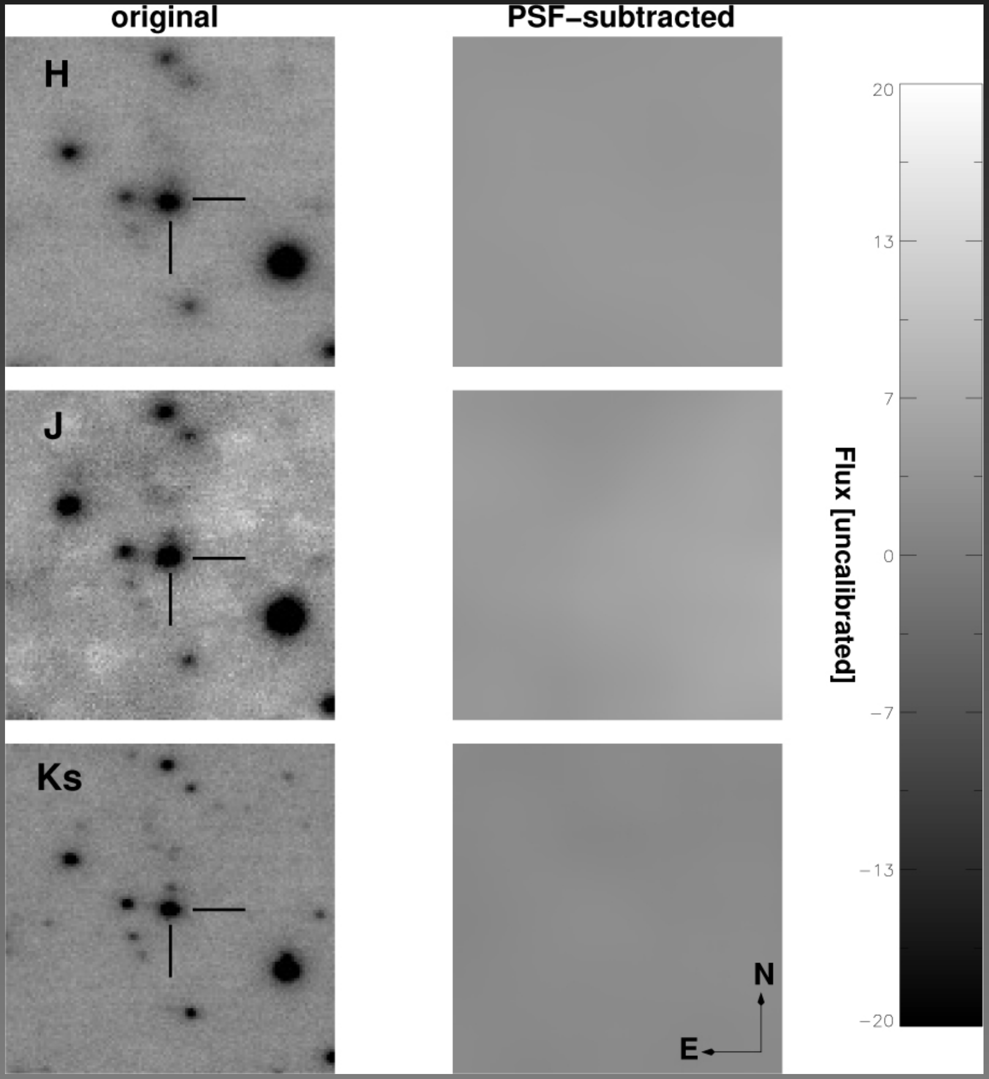


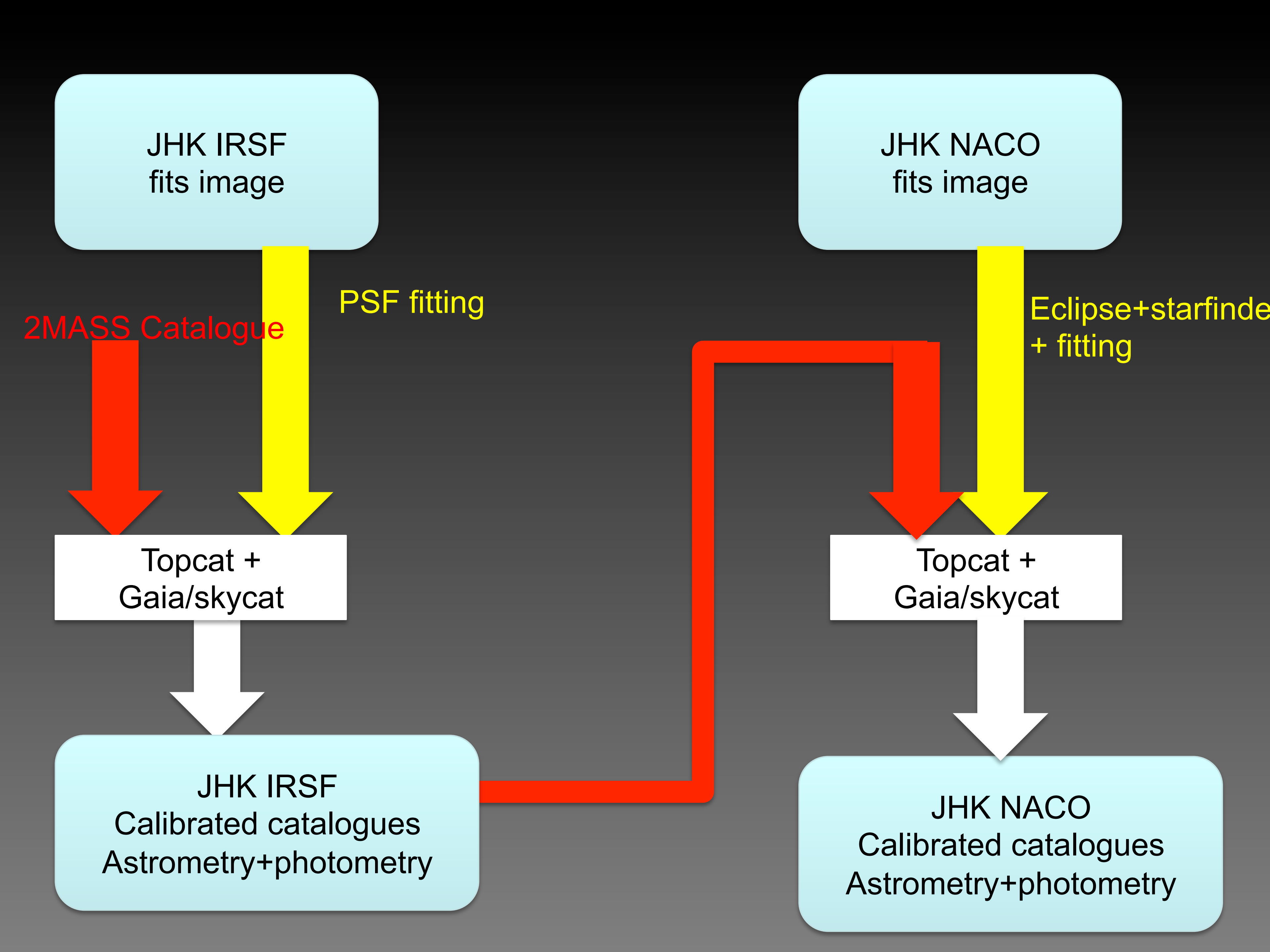


Remaining problem  photometric calibration!

std zps too “expensive” and different in sky/ background/ time

# STARFINDER processing




JHK IRSF
fits image
JHK NACO
fits image
PSF fitting
2MASS Catalogue
Eclipse+starfinde
+ fitting
Topcat +
Gaia/skycat
Topcat +
Gaia/skycat
JHK IRSF
Calibrated catalogues
Astrometry+photometry
JHK NACO
Calibrated catalogues
Astrometry+photometry

# Some cooking basics

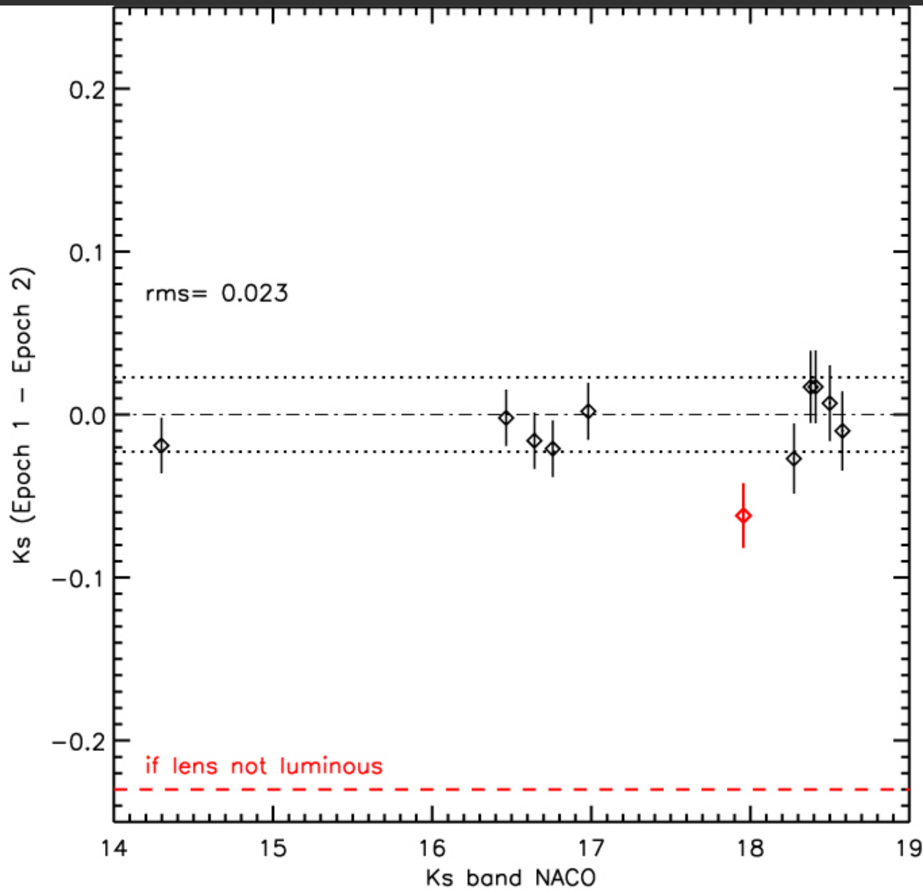
- STARFINDER can handle spatially variant PSFs to correct for the anisoplanatism. (Daophot, Dophot don't)

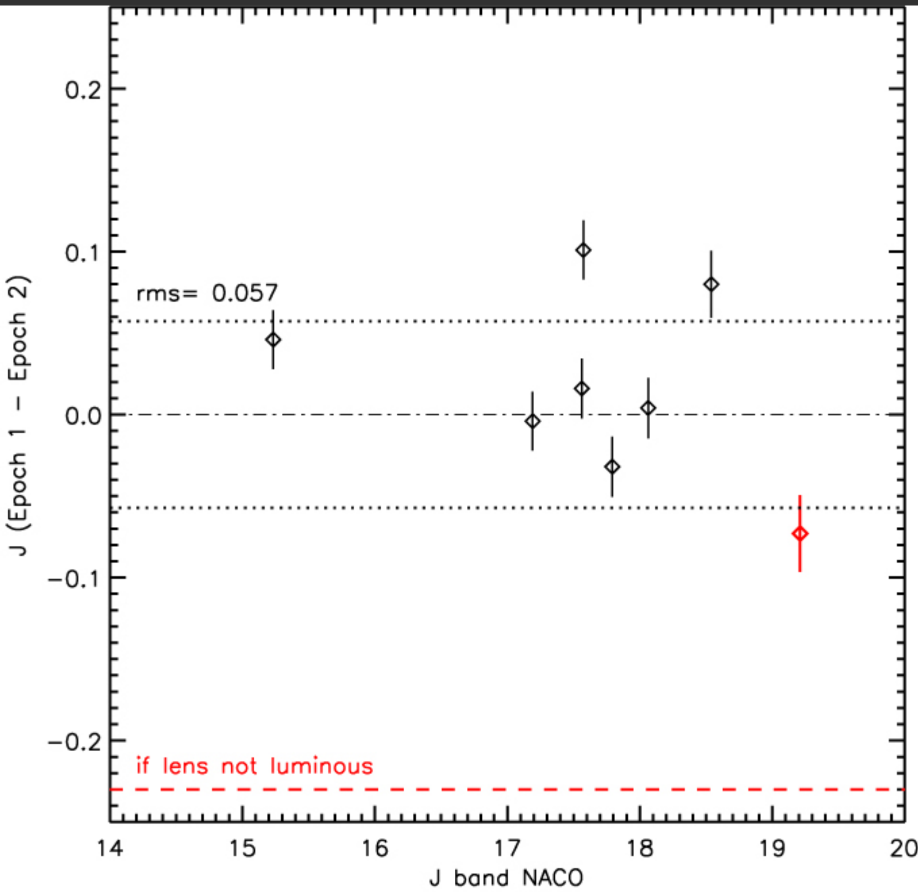
-For calibration : check crowding 1 2MASS star could be several IRSF stars

- Calibration stars could be variable (check with MOA and OGLE)

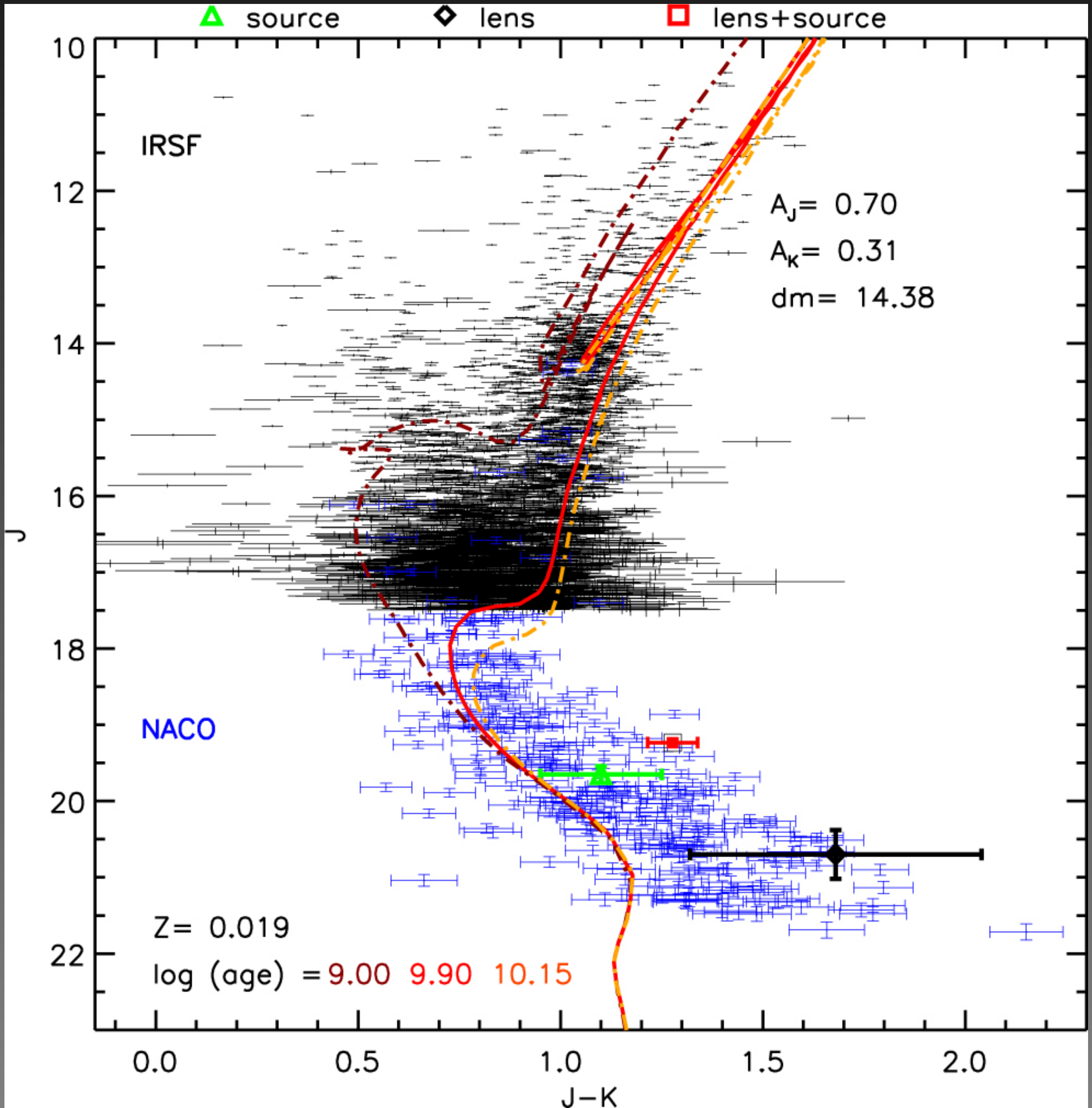
-Do, re-do, get your mates to double check, do again the calibration.

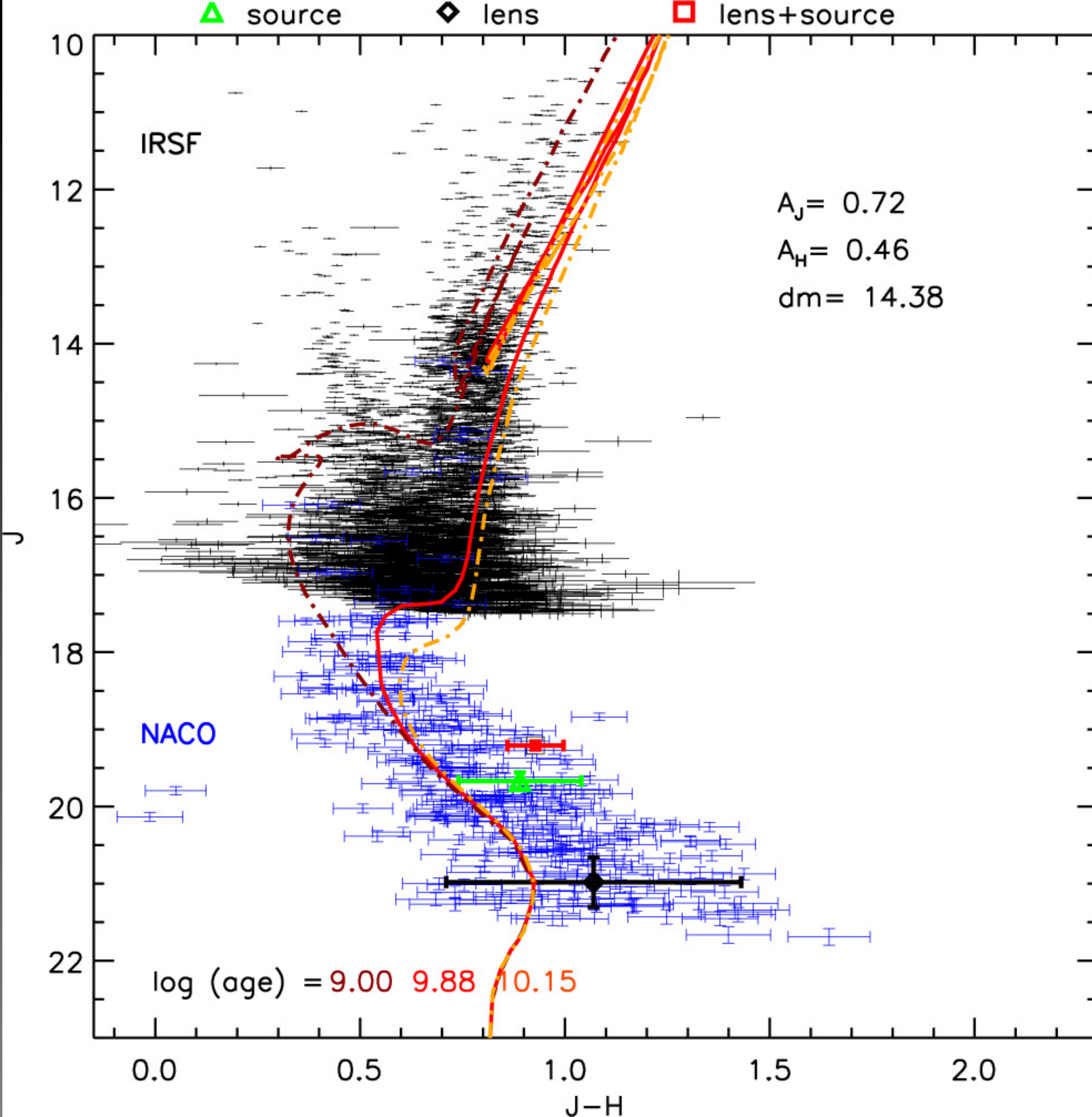
# NACO Epoch 1- 2 epoch 2



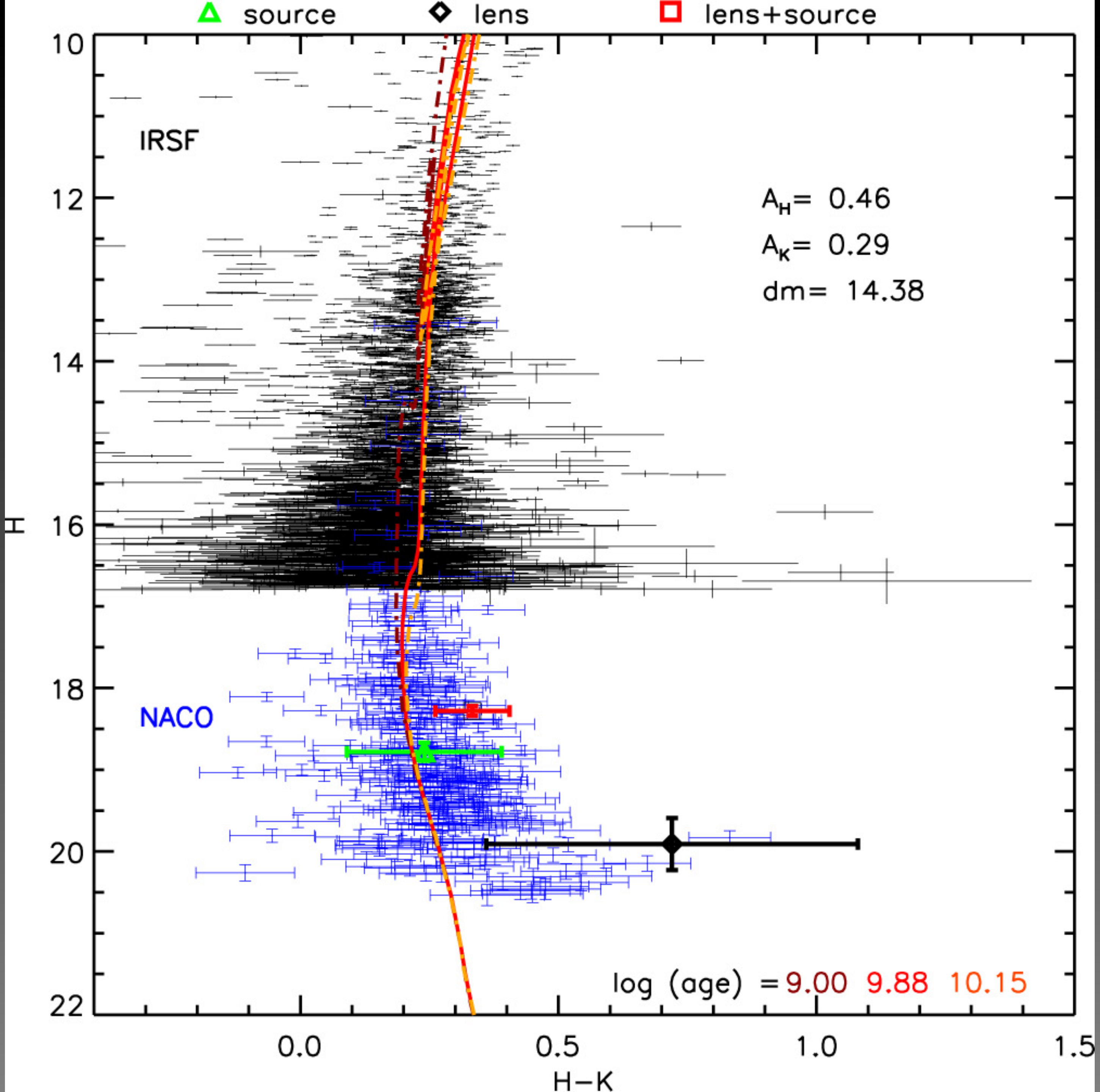



# MOA 2007-BLG-192 :
# Hunting for the source and the lens in J, H, K.





source
lens
lens+source
IRSF
NACO
A_J= 0.72
A_H= 0.46
dm= 14.38
log (age) = 9.00 9.88 10.15
J
J−H
10
12
14
16
18
20
22
0.0
0.5
1.0
1.5
2.0

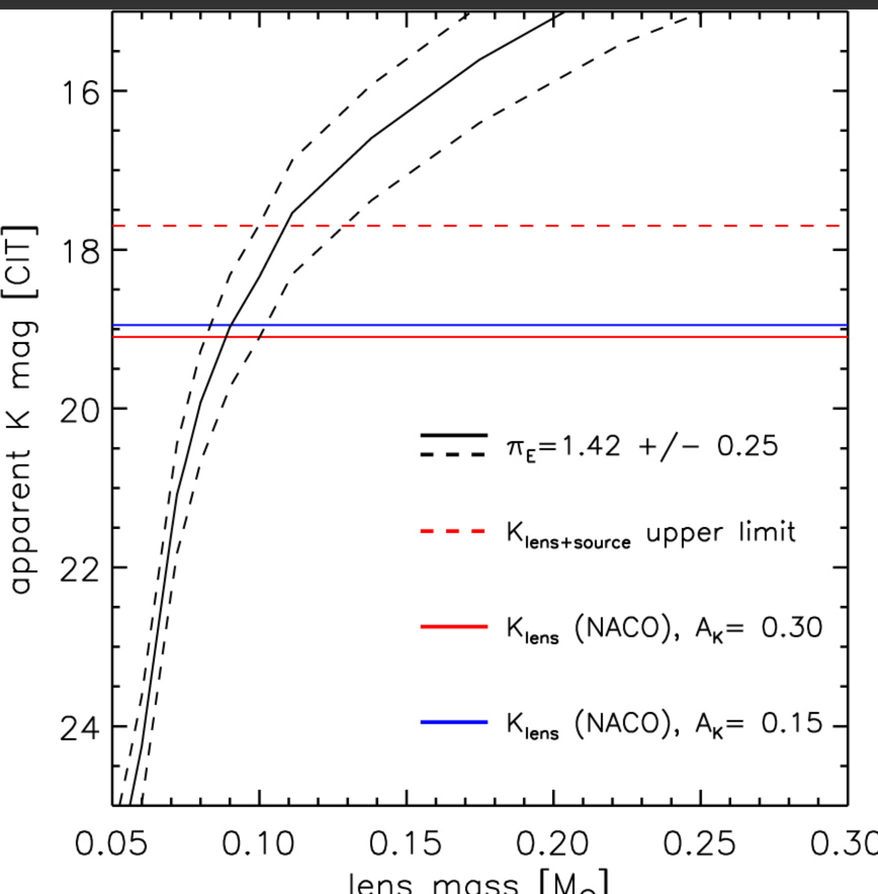


source
lens
lens+source
IRSF
NACO
A_H= 0.46
A_K= 0.29
dm= 14.38
log (age) = 9.00 9.88 10.15
H
H−K
10
12
14
16
18
20
22
0.0
0.5
1.0
1.5

# MOA 2007-BLG-192 :

A star, $0.084^{+0.015}_{+0.012}$ $M_\odot$ at $660^{+100}_{-70}$ pc

A planet, $3.2^{+5.2}_{-1.8}$ $M_\oplus$ at $0.82^{+0.51}_{-0.22}$ AU




Previous results

| parameter | value | 2-σ range |
|---|---|---|
| $M$ | $0.060^{+0.028}_{-0.021} M_\odot$ | $0.024$–$0.128 M_\odot$ |
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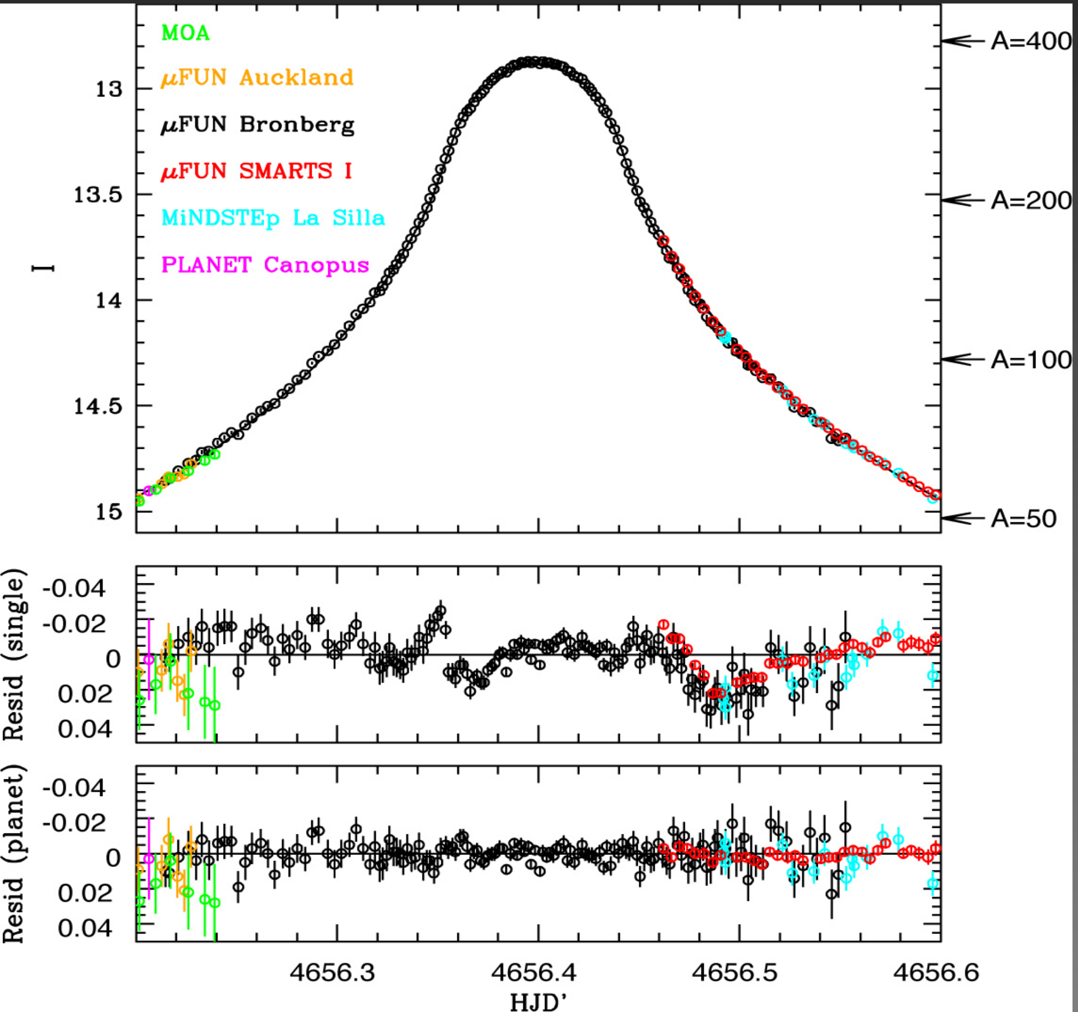
| $q$ | $1.8^{+1.9}_{-0.8} \times 10^{-4}$ | $0.5$–$7.1 \times 10^{-4}$ |

# MOA 2007-BLG-192 : lens detected

But it is not enough ! We need to detect direction of proper motion...

Stay tune, HST program to do it (Bennett et al., cycle 20)

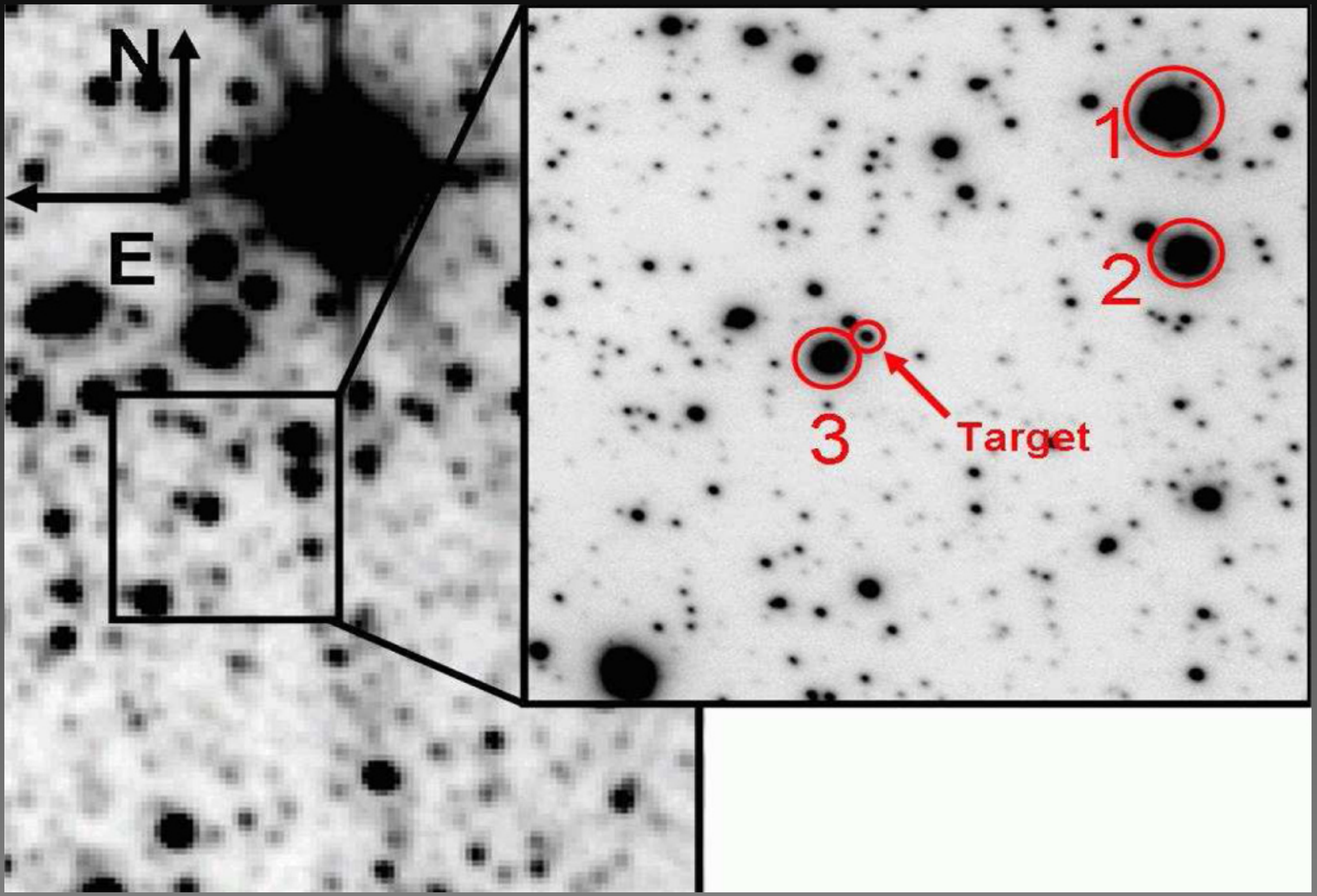
# A 74 ±17 $M_{\oplus}$ planet at 1.25 ±0.19 AU of a 0.67±0.14 $M_{\odot}$ star in the Bulge



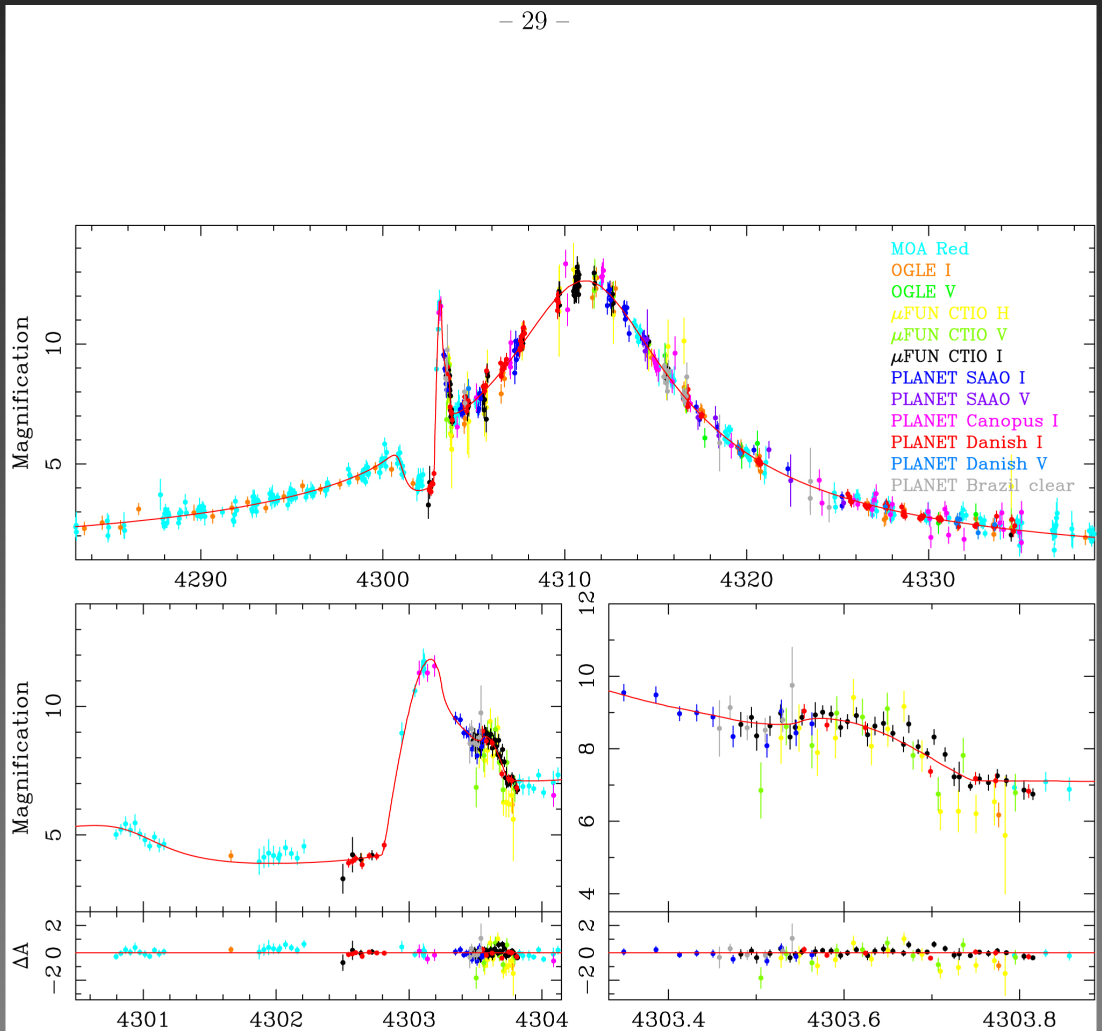

Amateur with 40 cm used to Trigger the VLT NACO

*Janczak et al., 2009*

# Light detected from the lens

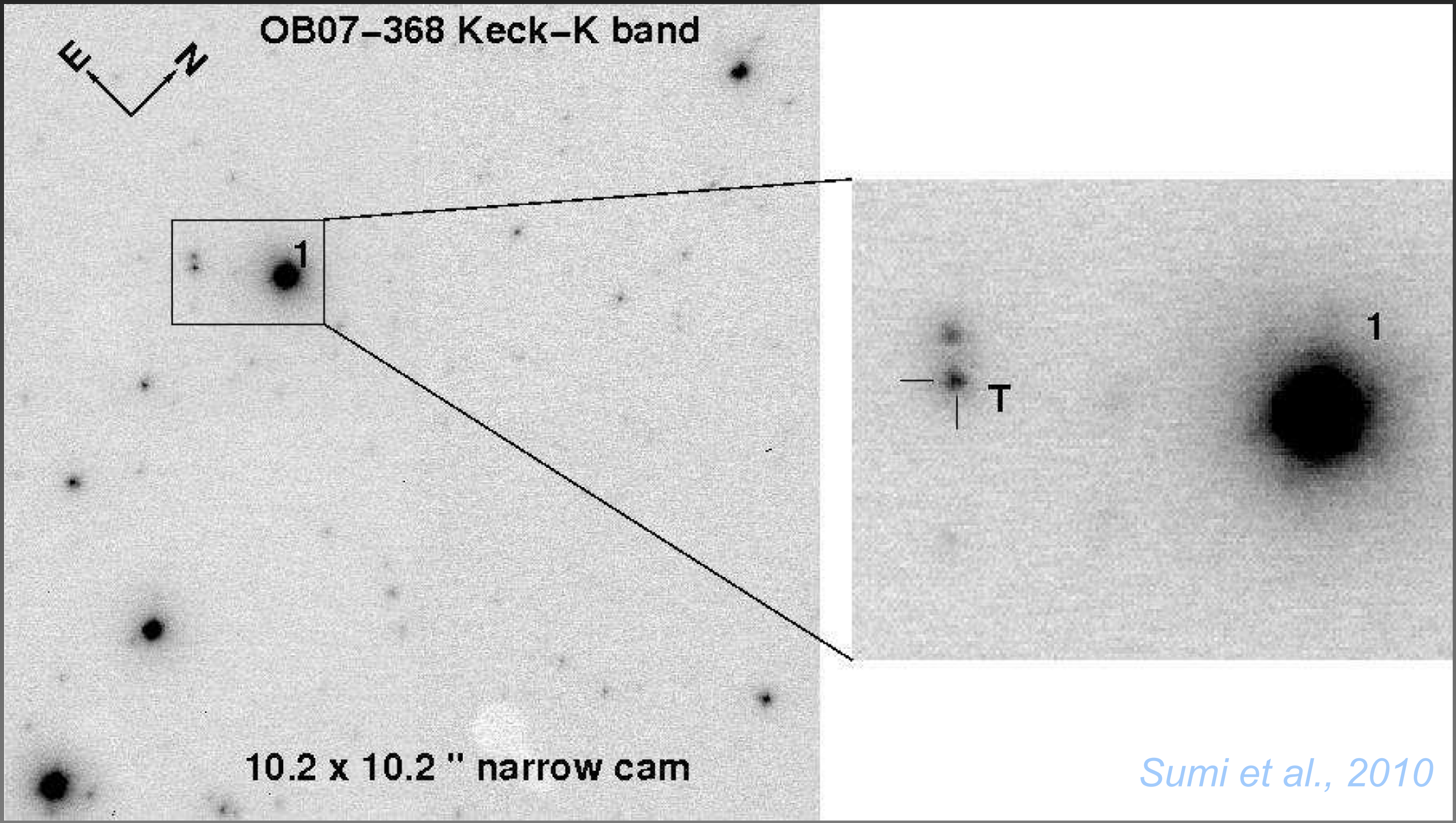


# A 20$^{-7}_{-8}$ M$_\oplus$ planet at 3.3$^{+1.4}_{-0.8}$ AU of a 0.64$^{-0.24}_{-0.26}$ M$_\odot$ star in the Bulge



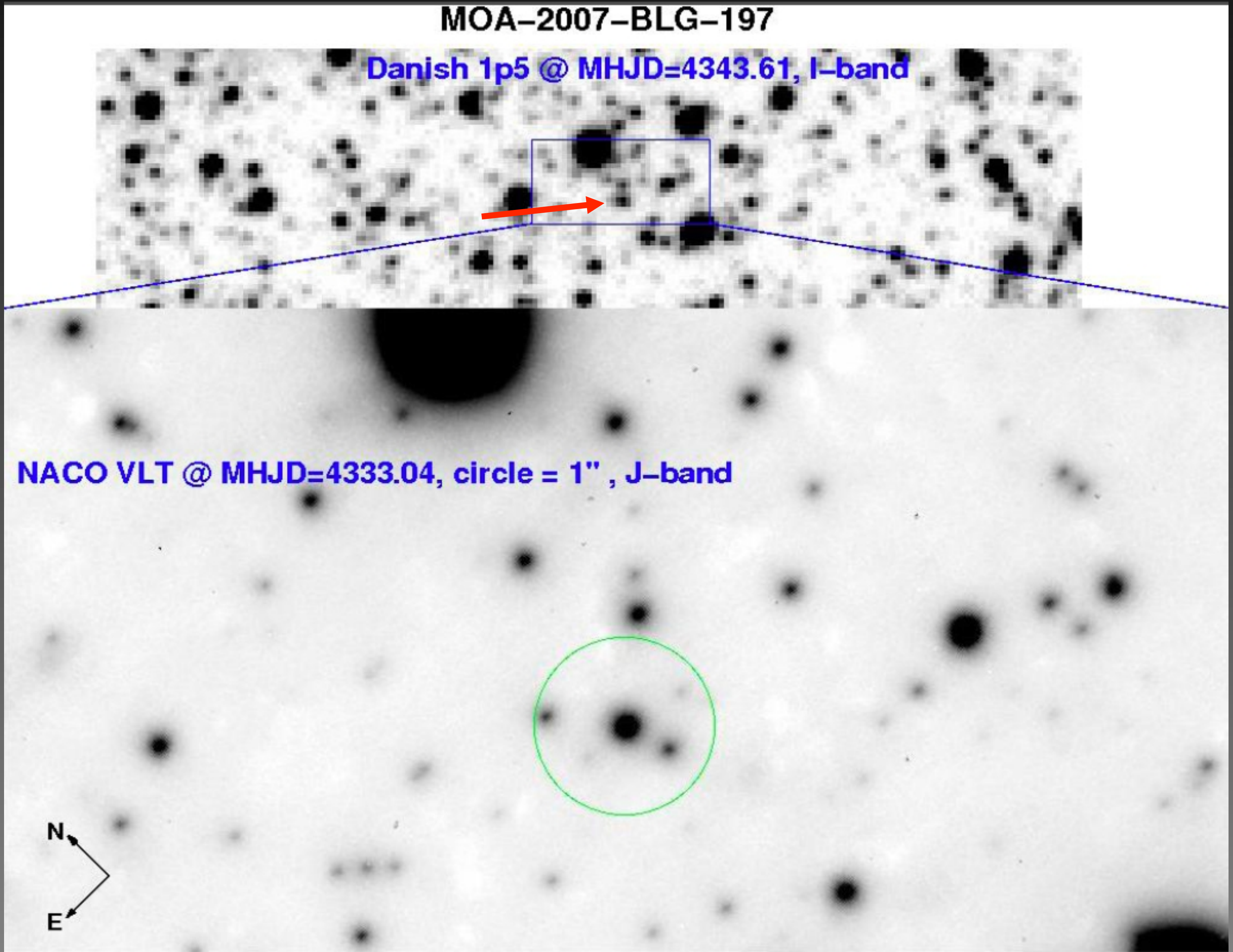

*Sumi et al., 2010*

# An upper limit on light from the lens magK > 18.1 at 3 sigma




Sumi et al., 2010

# NACO images of MOA-2007-BLG-197



# Conclusion:

-Important to get HR image to detect/constraint light from lens.
- Read Anderson, Bennett, Gaudi, 2007 and Kubas et al. 2011

- Get cross checks for calibrations
-Several steps (2MASS, IRSF, VLT/KECK/SUBARU/GEMINI et al.)
- Absolute photometry on AO image is not easy, but few percent is doable.
-Do double blind analysis to get secure numbers
- Detecting light from lens with AO (2 epochs).
- Detecting centroid shift is more for HST.

We need telescope time VLT, KECK, GEMINI, SUBARU, HST

We need you to swamp the time allocation comitees !