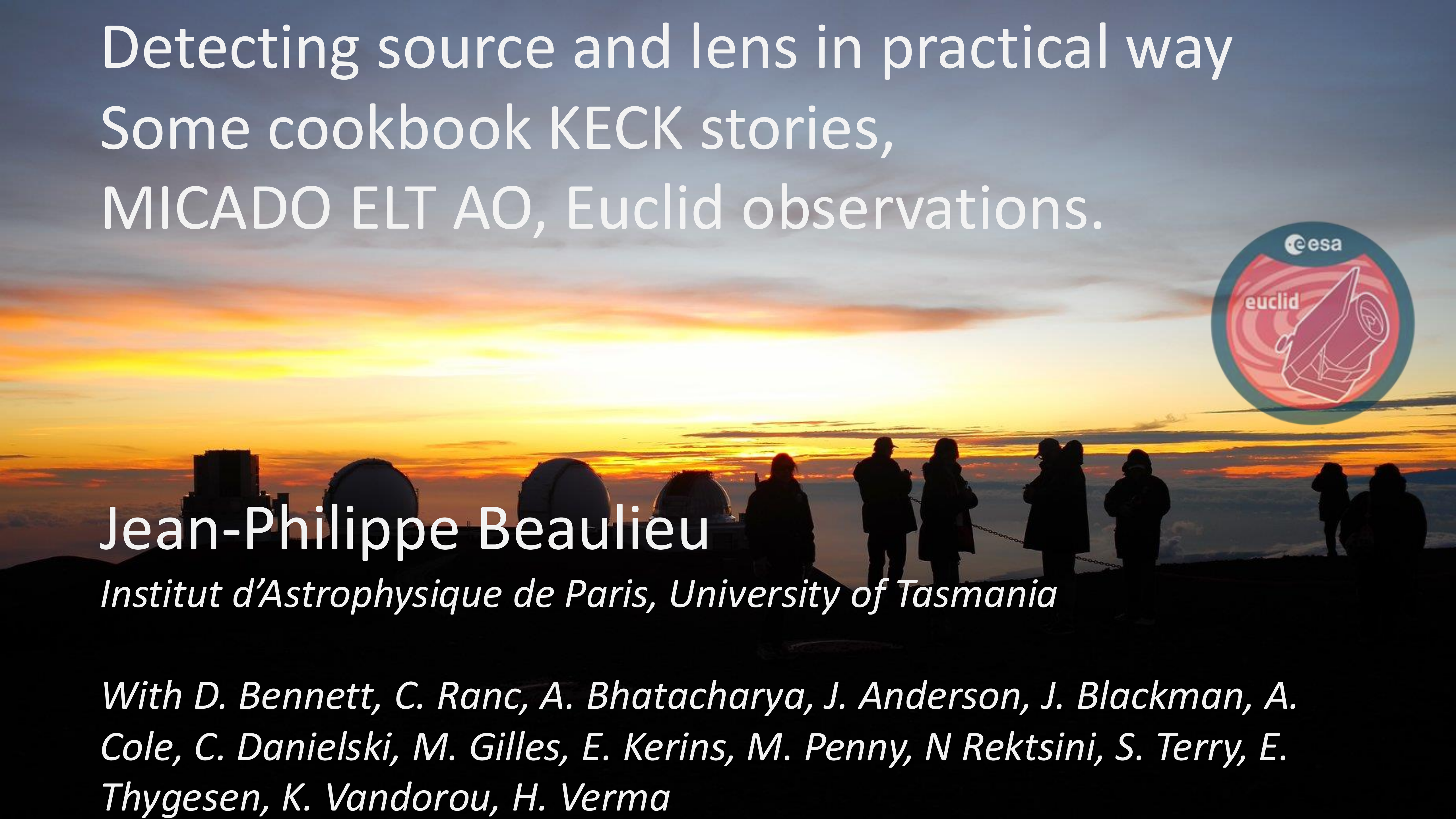


Detecting source and lens in practical way
Some cookbook KECK stories,
MICADO ELT AO, Euclid observations.

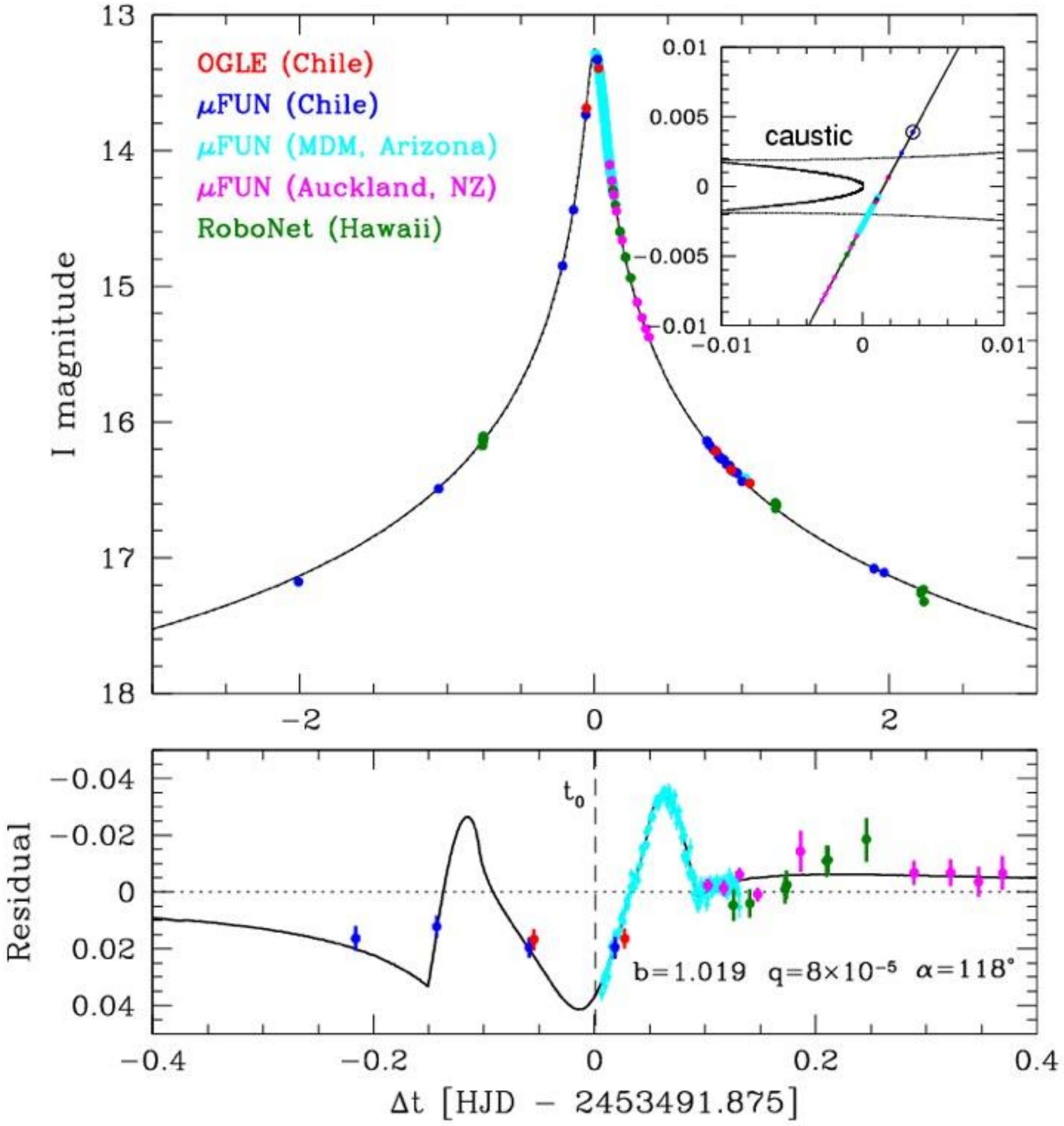
Jean-Philippe Beaulieu

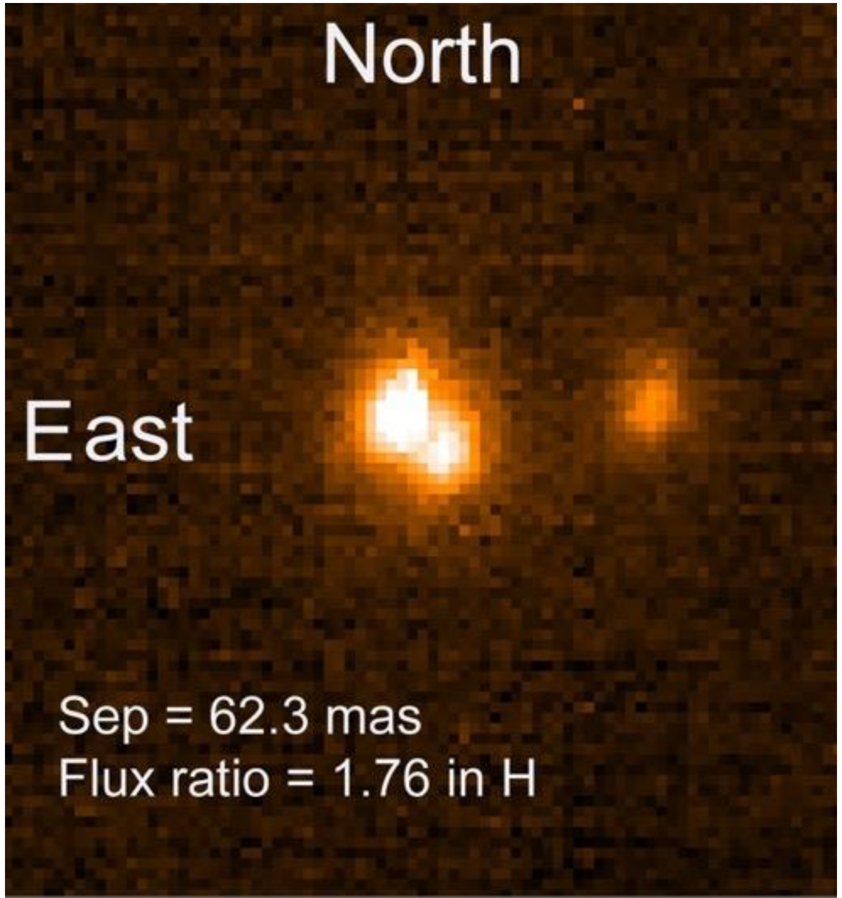
Institut d'Astrophysique de Paris, University of Tasmania

With D. Bennett, C. Ranc, A. Bhatacharya, J. Anderson, J. Blackman, A. Cole, C. Danielski, M. Gilles, E. Kerins, M. Penny, N Rektsini, S. Terry, E. Thygesen, K. Vandorou, H. Verma

Photo Nour Skaf, July 2021

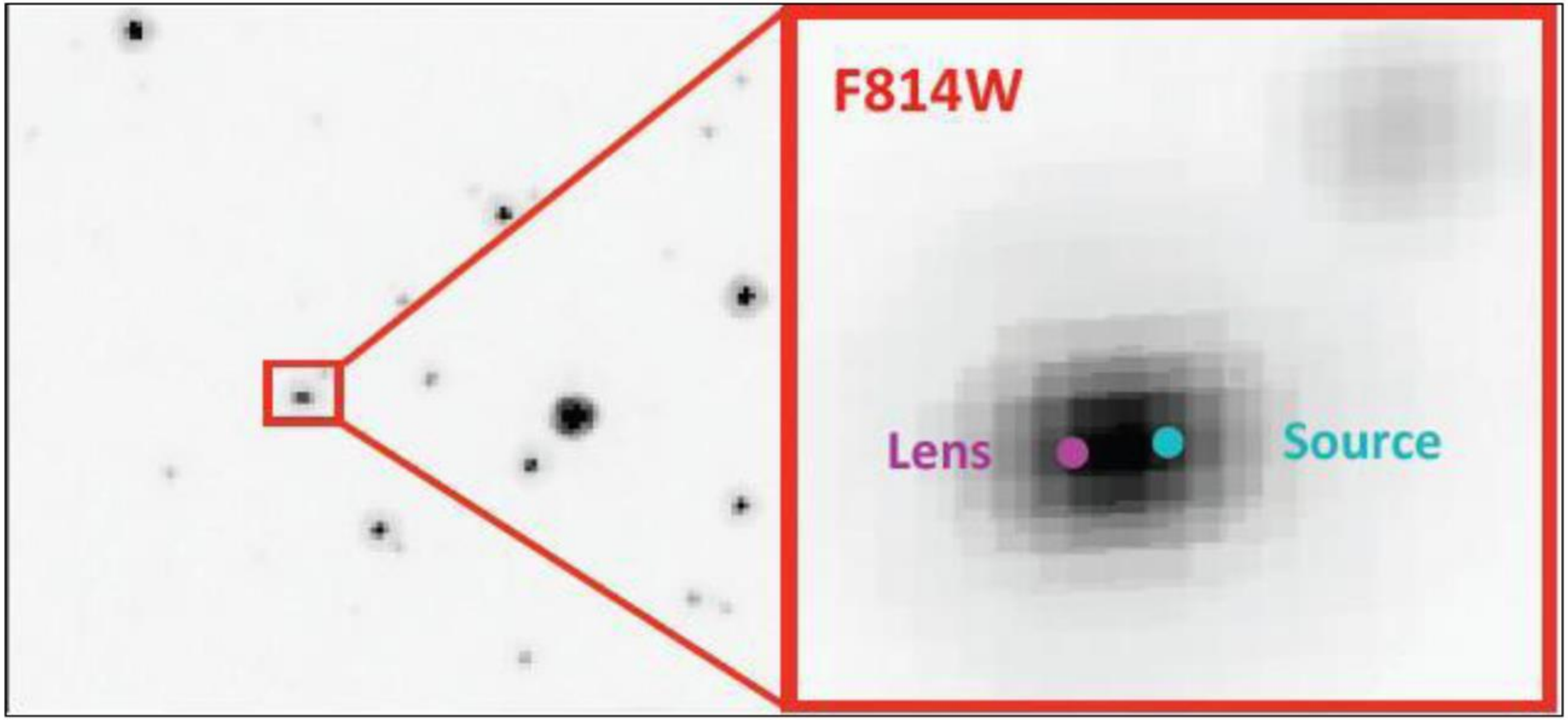
With 10 meters KECK telescope and adaptive optics, Resolving source and lens. Measuring proper motion



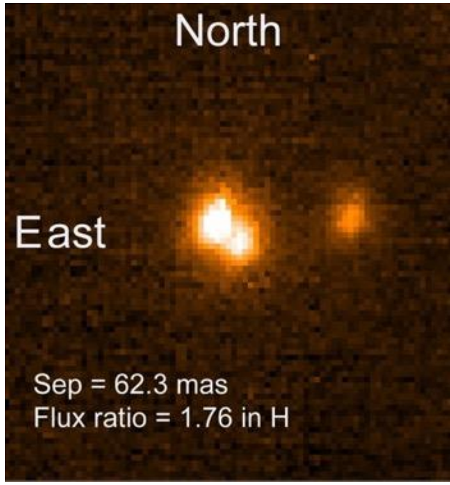


HST : 6.5 years after the event

Bennett et al., 2015



Detecting source & lens, measuring proper motion



Gould et al. 2006

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

HST Bennett et al. 2015

μ_{rel_l} = 7.39 $\pm$ 0.2 mas/yr
μ_{rel_b}= 1.33 $\pm$ 0.23 mas/yr

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

KECK Batista et al. 2015

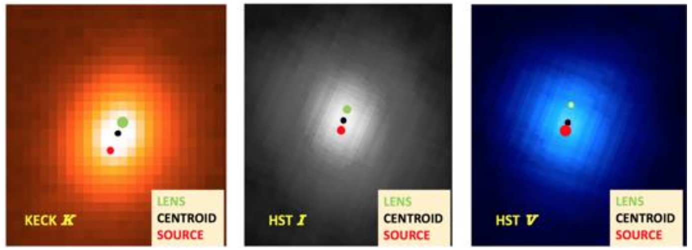
μ_{rel_l} = 7.28 $\pm$ 0.12 mas/yr
μ_{rel_b}= 1.54 $\pm$ 0.12 mas/yr

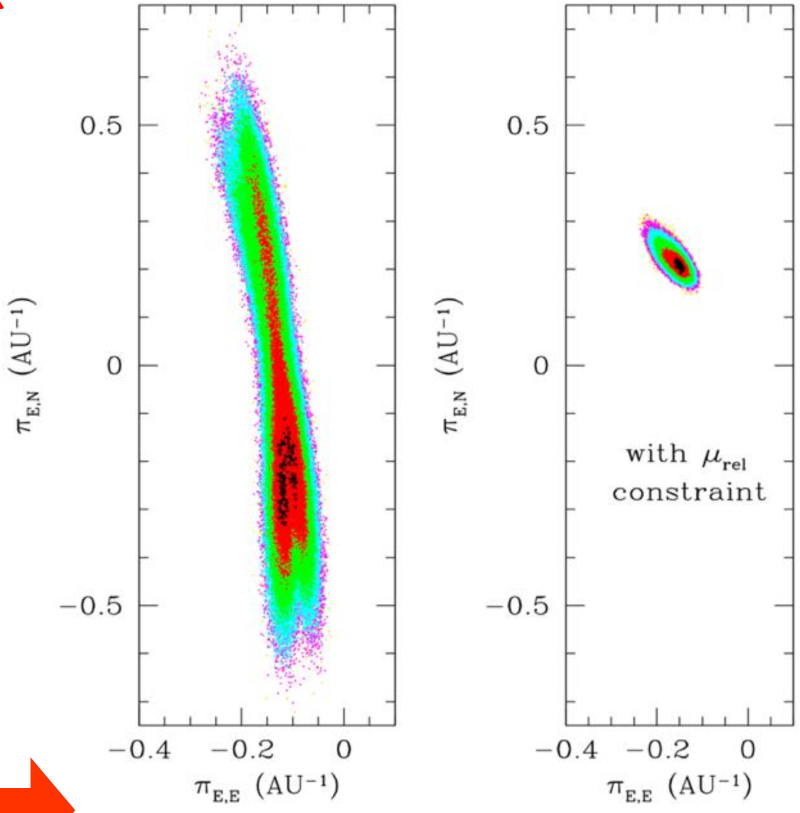
Host star mass: 0.65 $\pm$ 0.05 $M_{\odot}$
Planet mass: 13.2 $\pm$ 1.5 M_{earth}
Distance D_L = 4.0$\pm$ 0.4 kpc
Projected separation 3.4 $\pm$ 0.3 AU

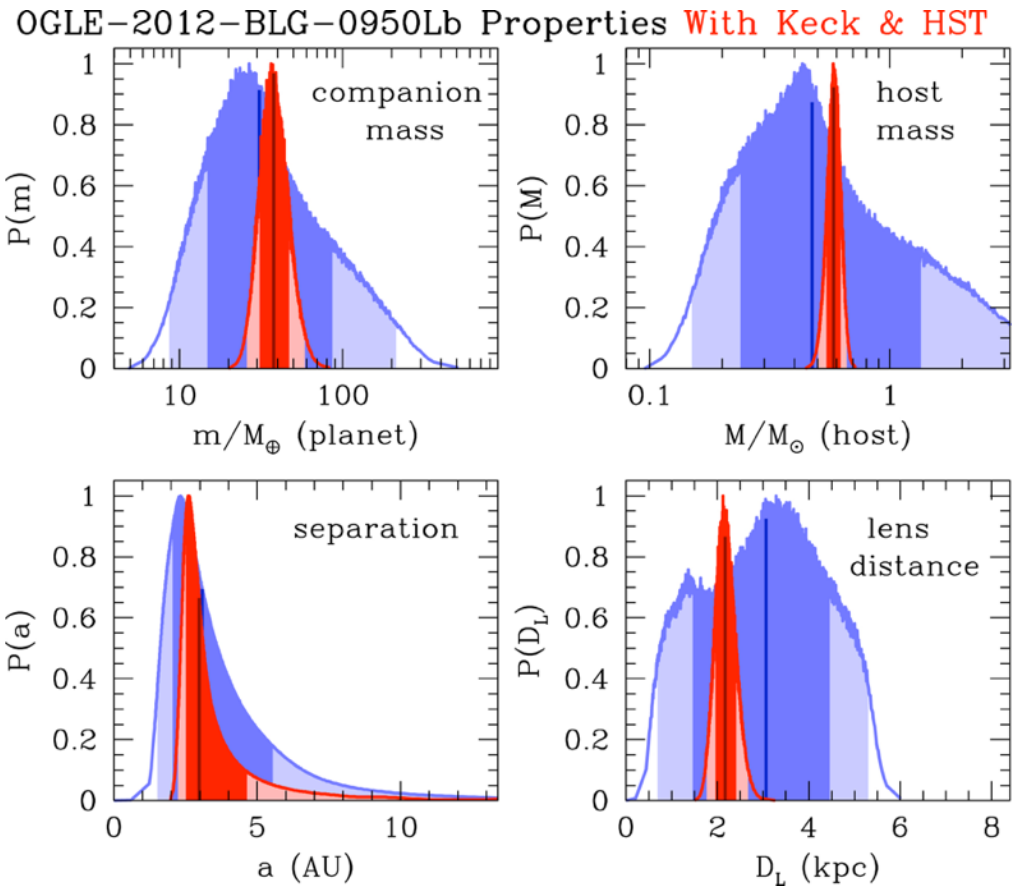
Constraining source-lens proper motion + lens flux

Initial study $M^* = 0.56^{+0.12}_{-0.16}$ Mo

$M_p = 35^{+17}_{-9}$ Mearth



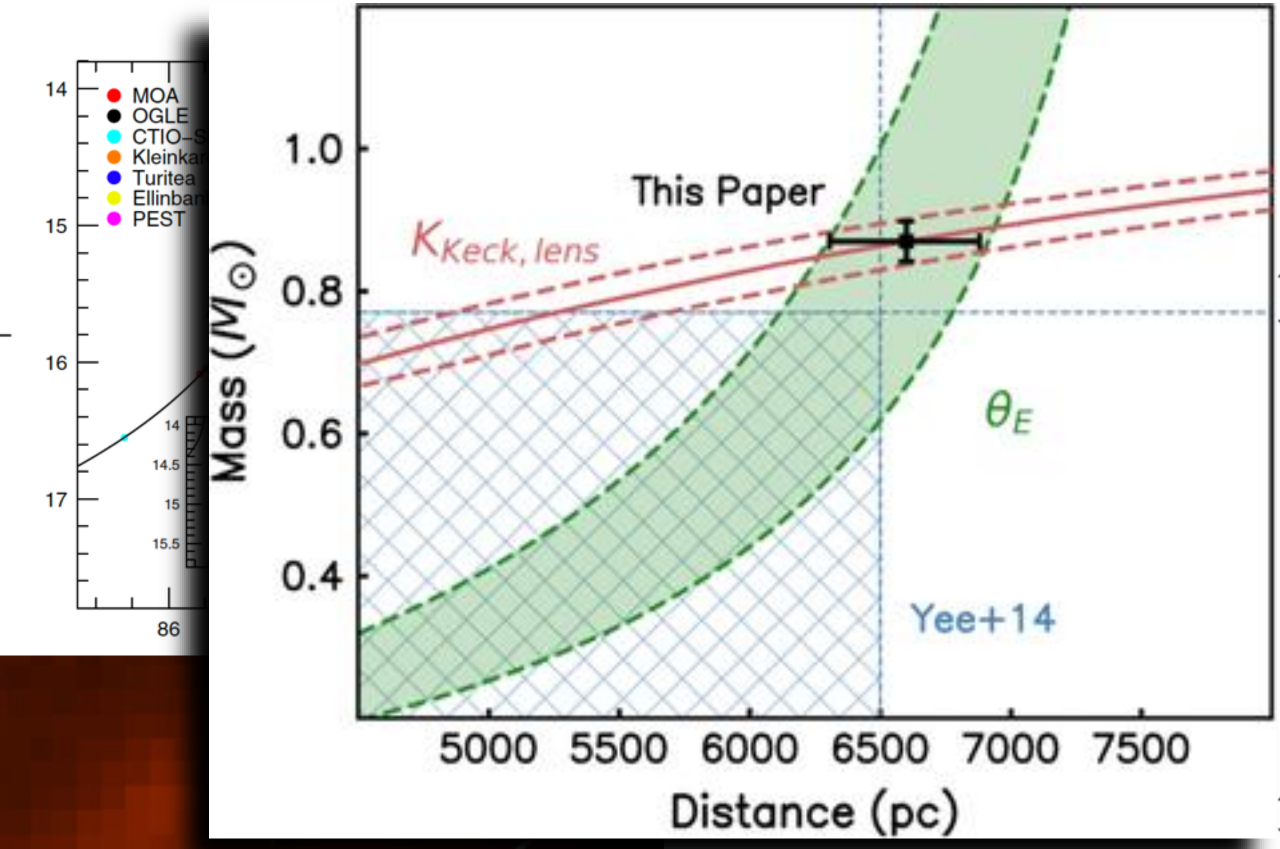


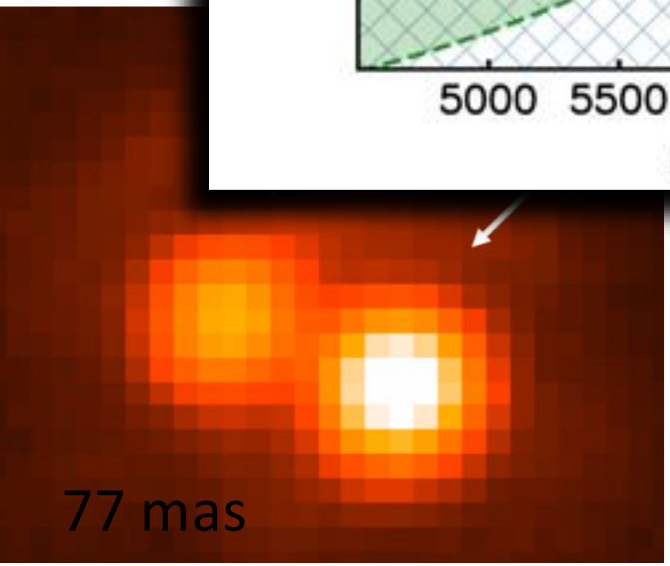


parameter	units	values & RMS	2-σ range
Host star mass, M_*	$M_\odot$	0.58 ± 0.04	0.51–0.67
Planet mass, m_p	$M_\oplus$	39 ± 8	26–59
Host star - Planet 2D separation, $a_\perp$	AU	2.54 ± 0.23	2.13–3.03
Host star - Planet 3D separation, a_{3D}	AU	$3.0^{+1.7}_{-0.5}$	2.2–10.8
Lens distance, D_L	kpc	2.19 ± 0.23	1.77–2.68

Bhatacharya+ 2018

Constraining source-lens proper motion + lens flux





Vandorou+ 2020

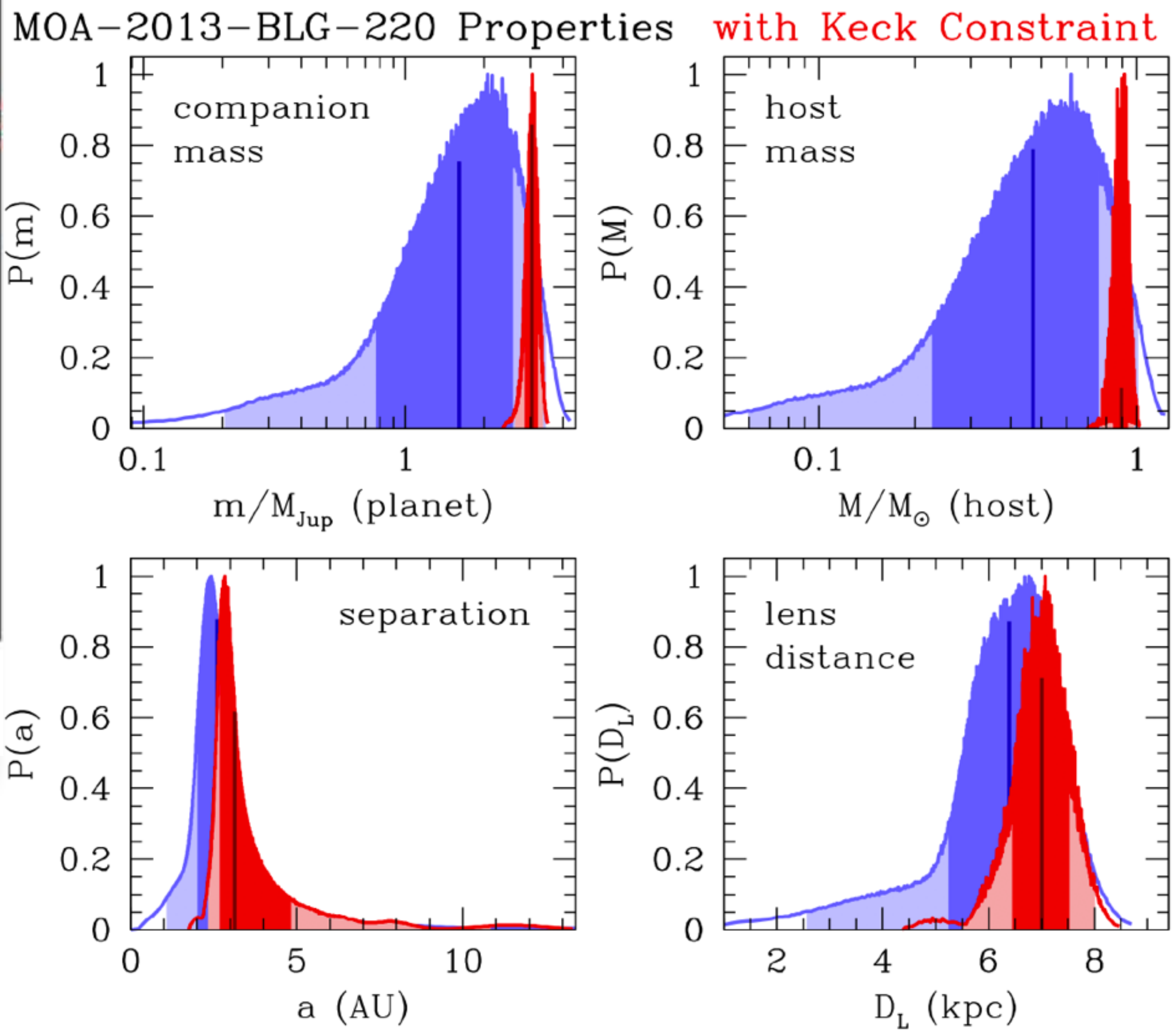
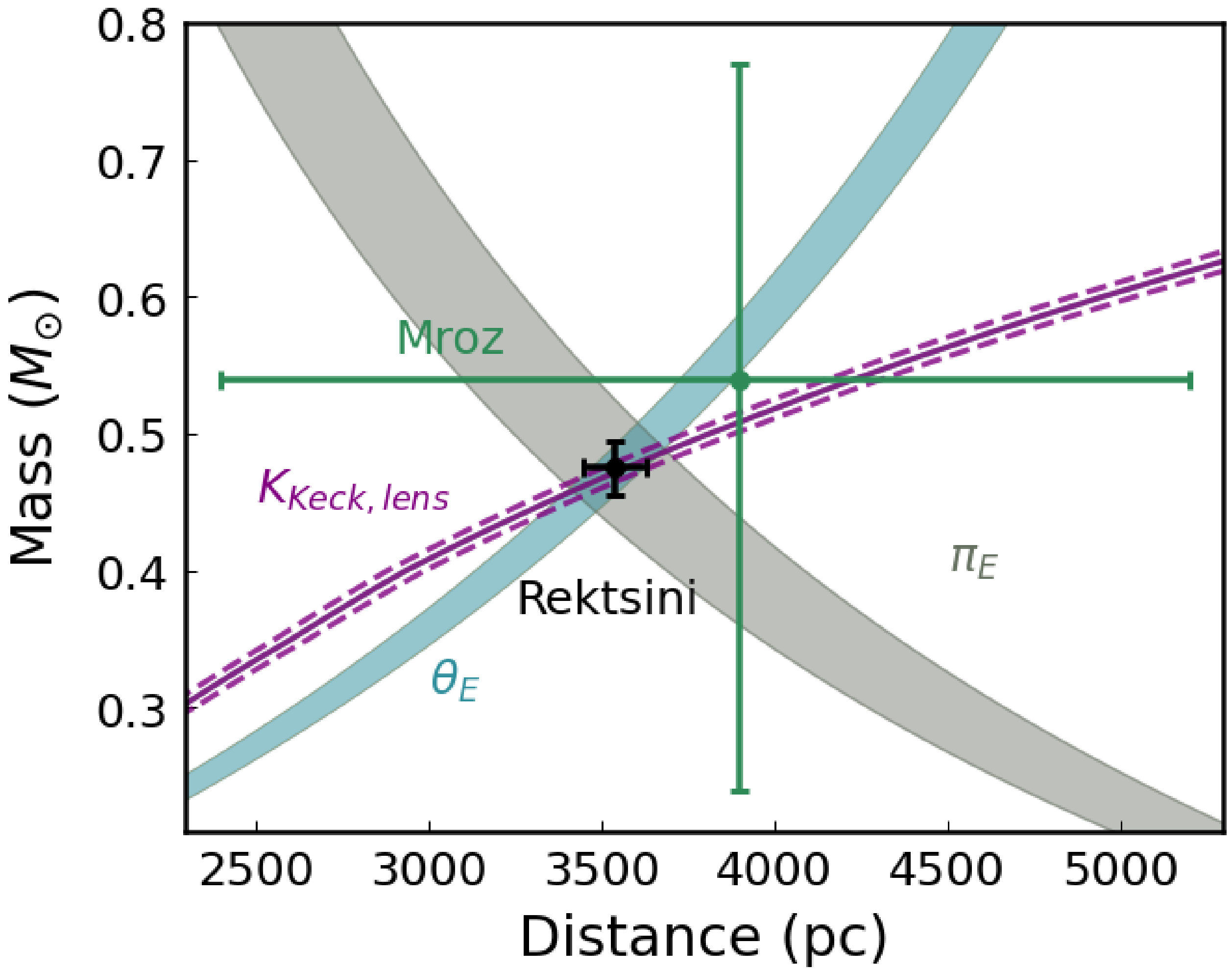
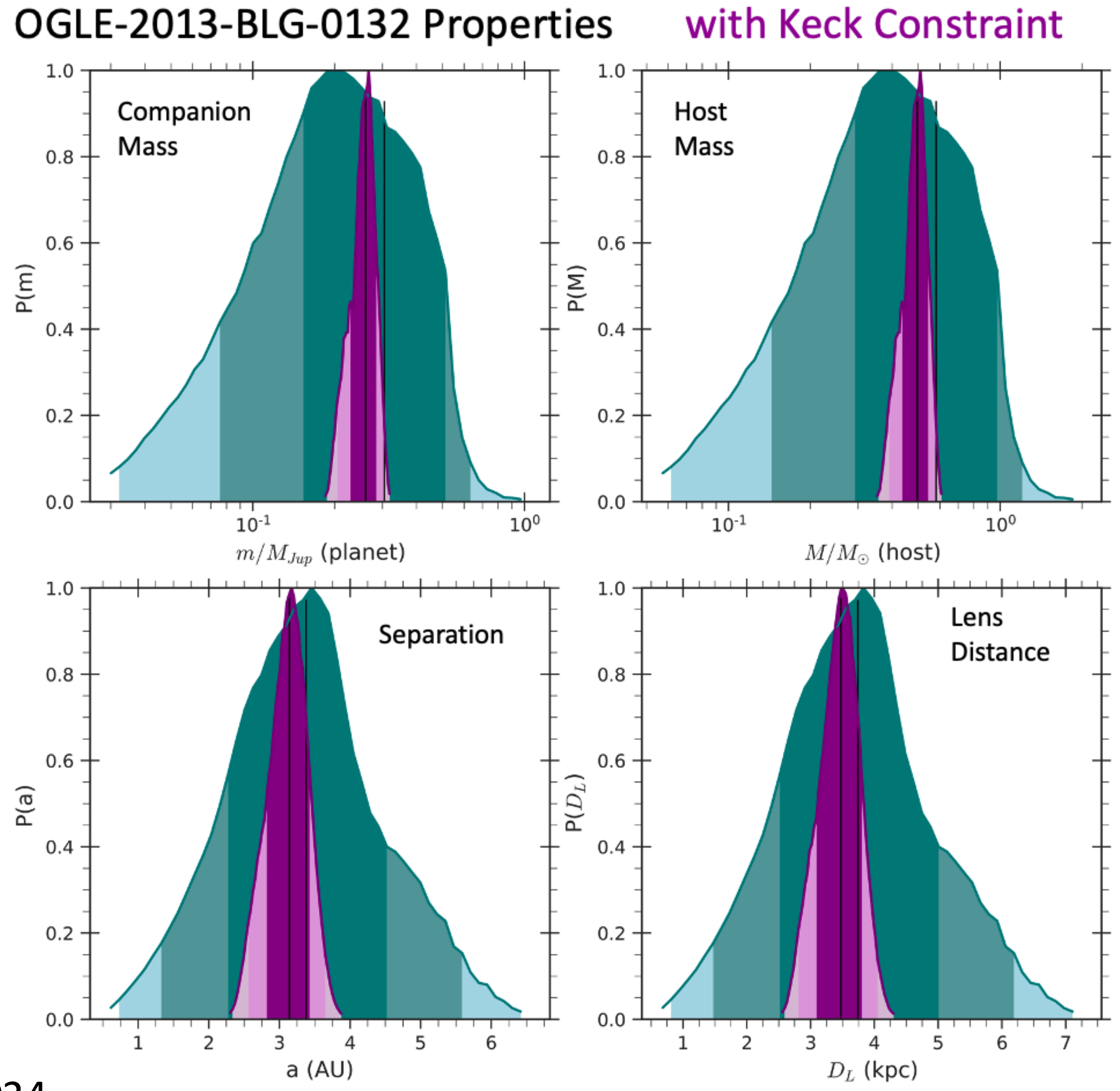


Figure 3. Distributions for the Bayesian posterior probability for the planetary and host star mass, their separation and the distance to the lens. These are shown with only light curve data (blue) and with additional constraints from Keck (red). The central darker shades represent the 68.3% of the distributions, and the lighter shades the 95.4% of the distributions. The black vertical line indicates the median of the probability distribution for each parameter

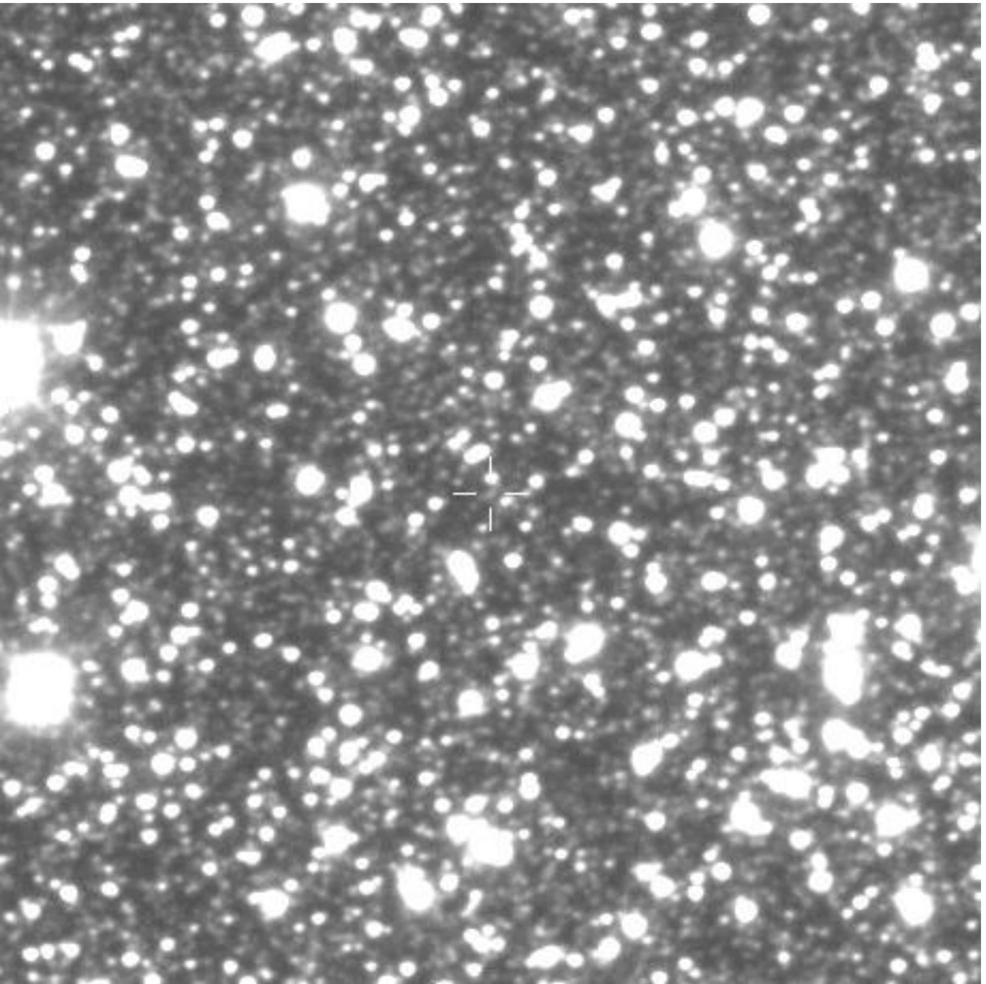
A Saturn-mass planet orbiting an M-dwarf

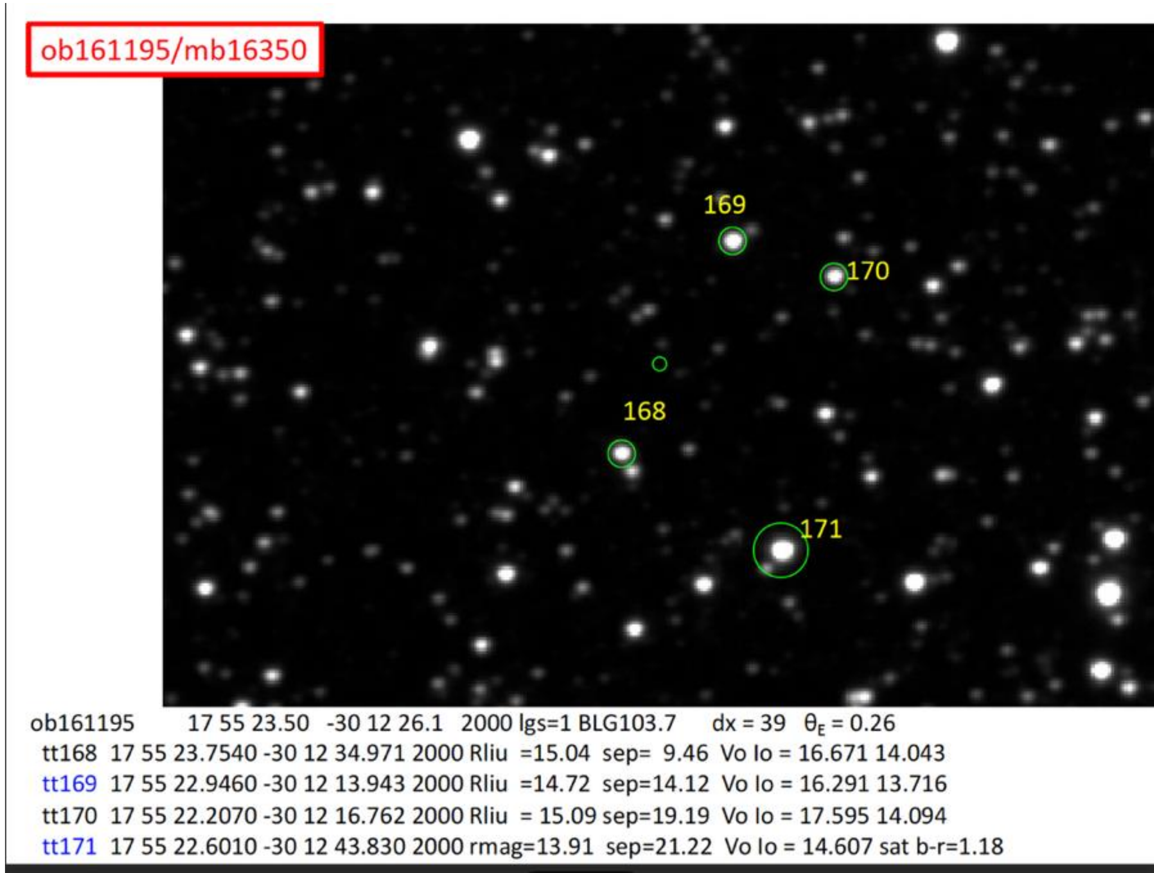




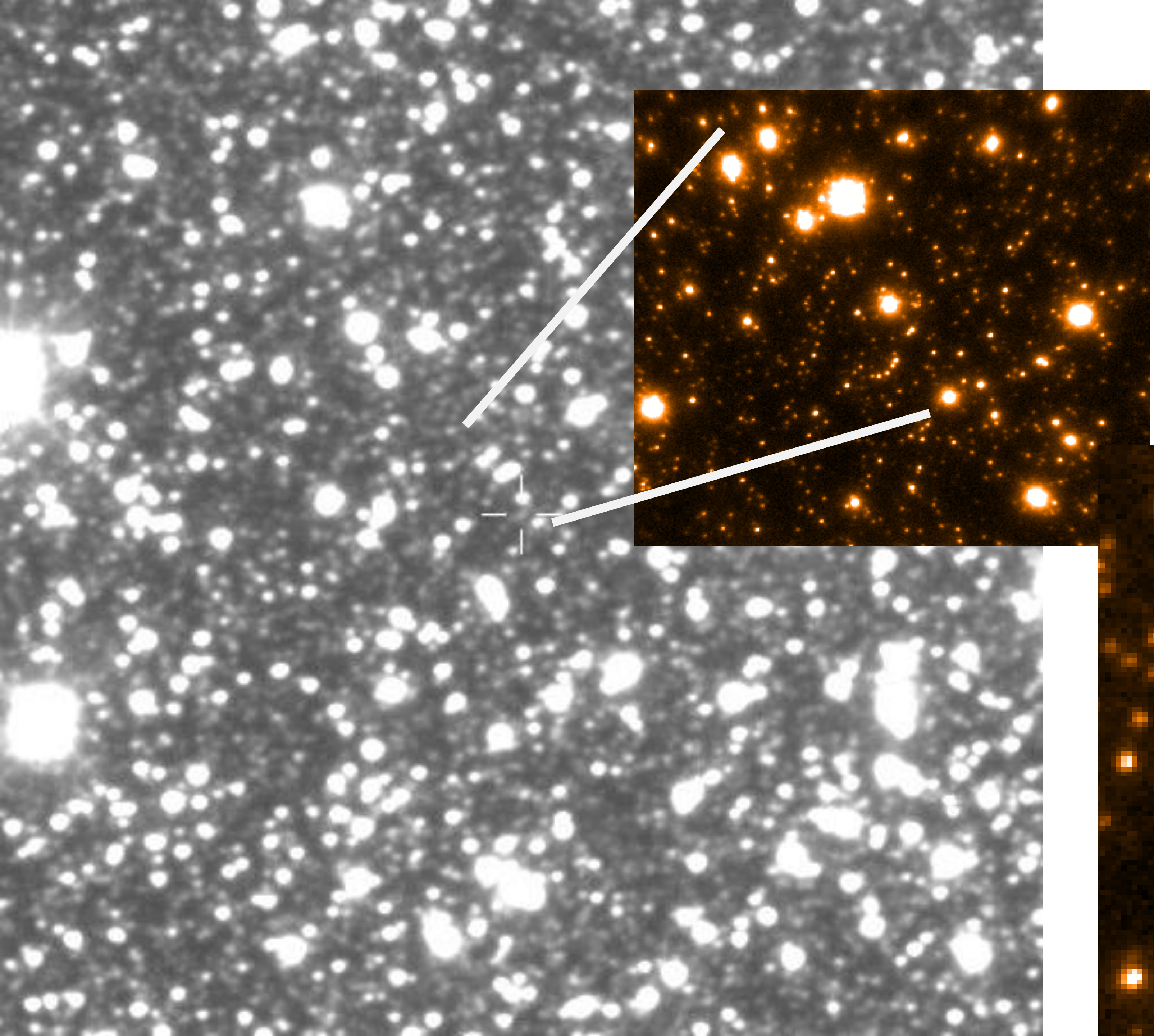
Rektsini et al 2024

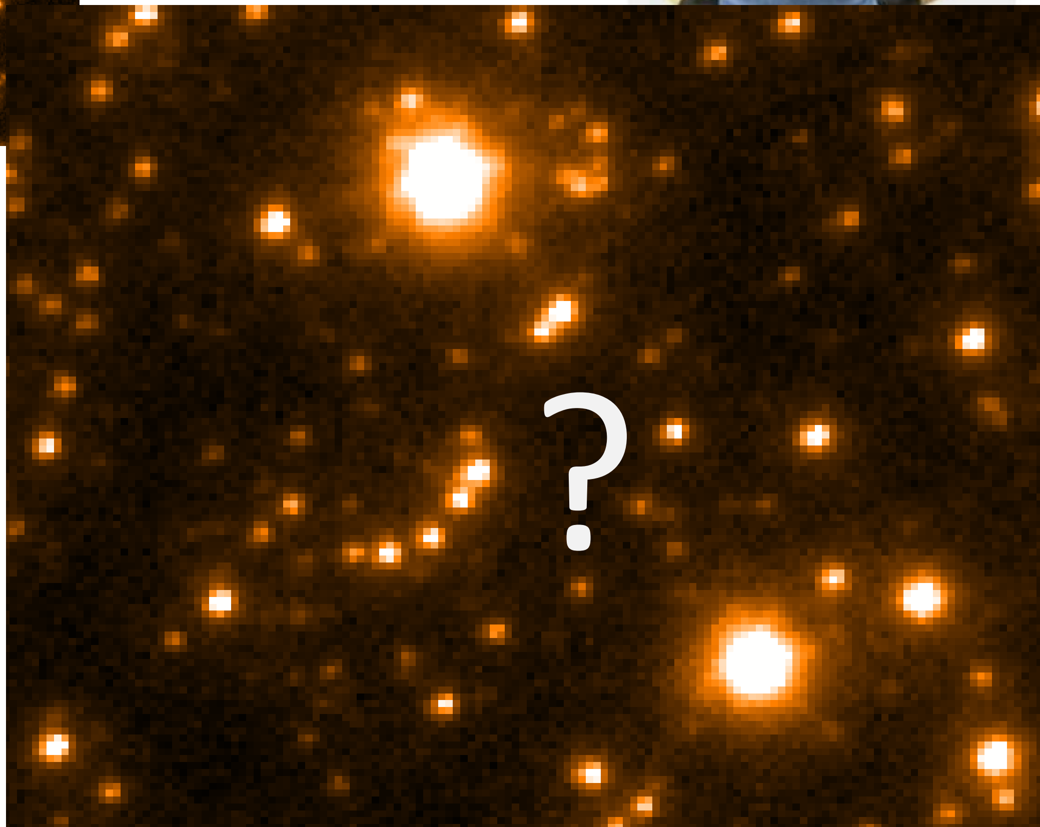
Observing at KECK, getting your tilt-tip star right



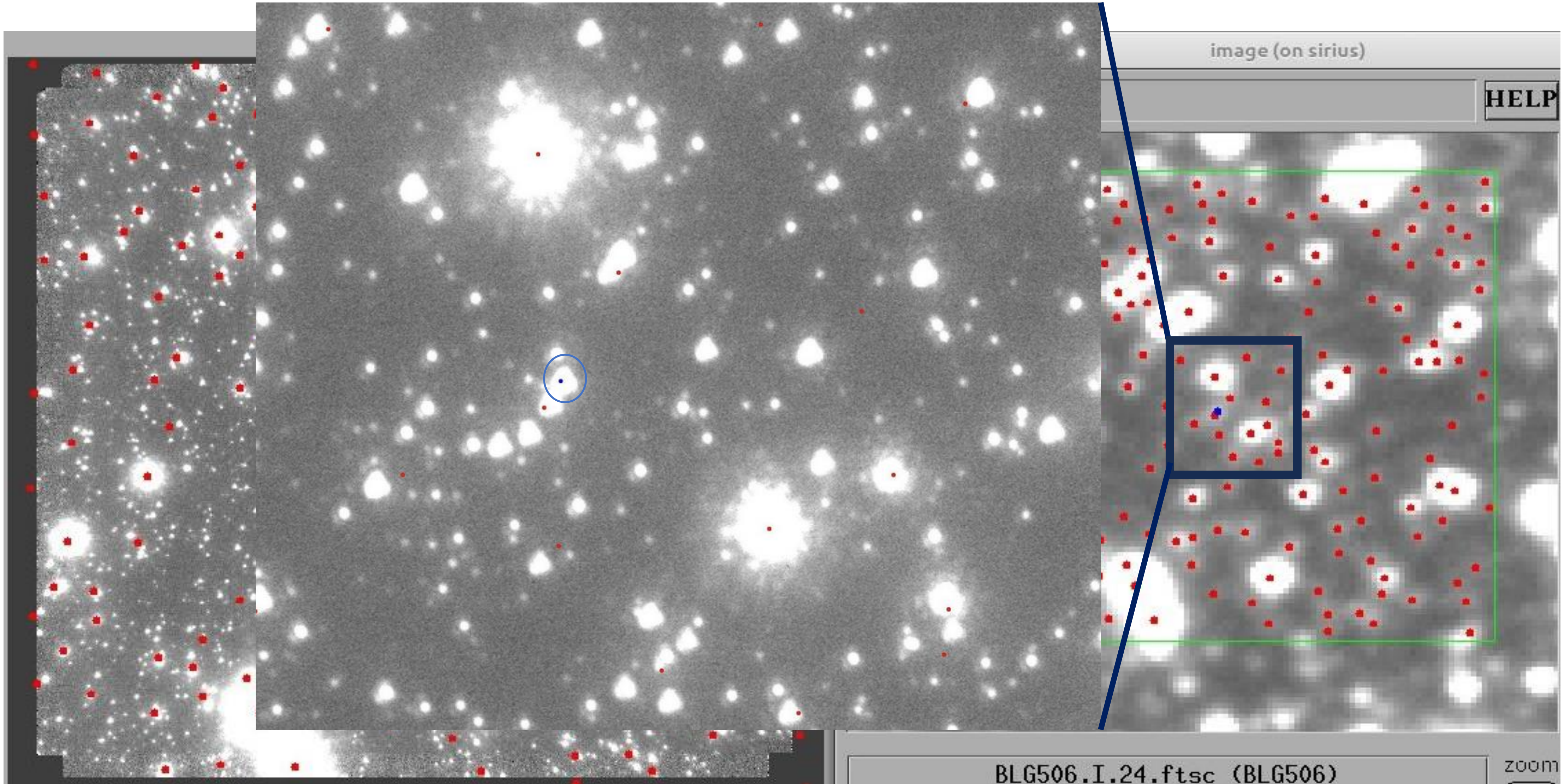


Where is the source ?

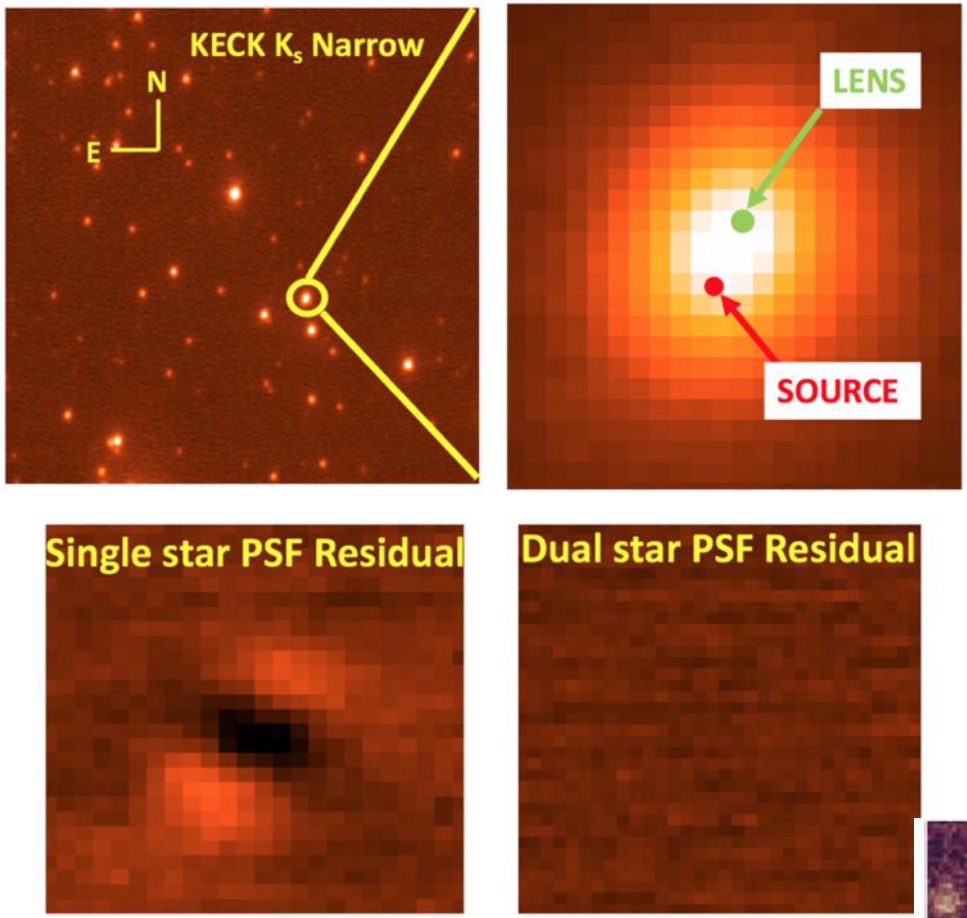




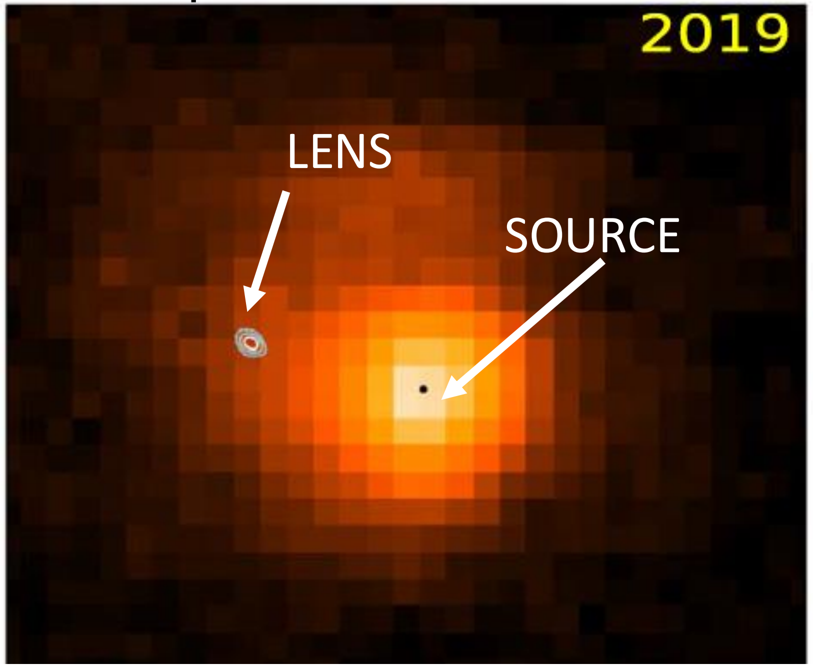
Where is the source ? Using OGLE data



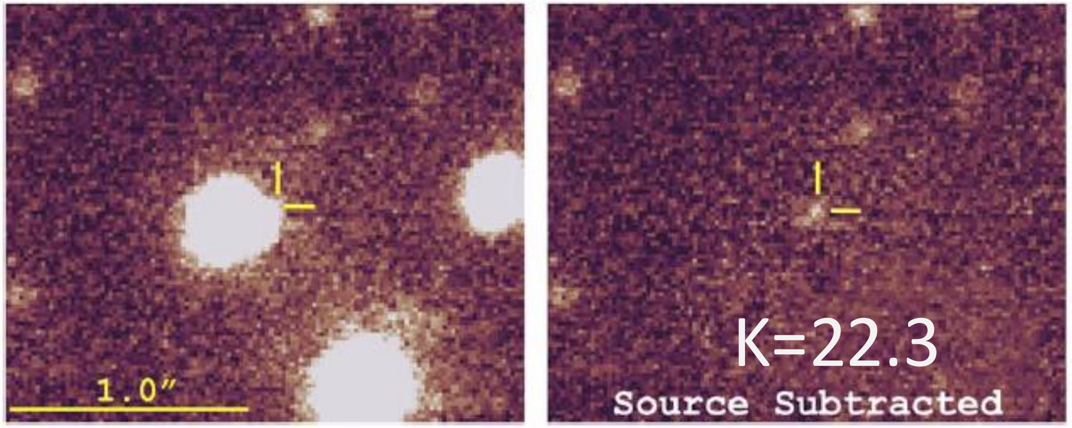
Not always easy to see the lens... if it is there



Separation = 67 mas



MOA-2009-BLG-319, Terry+ 2021



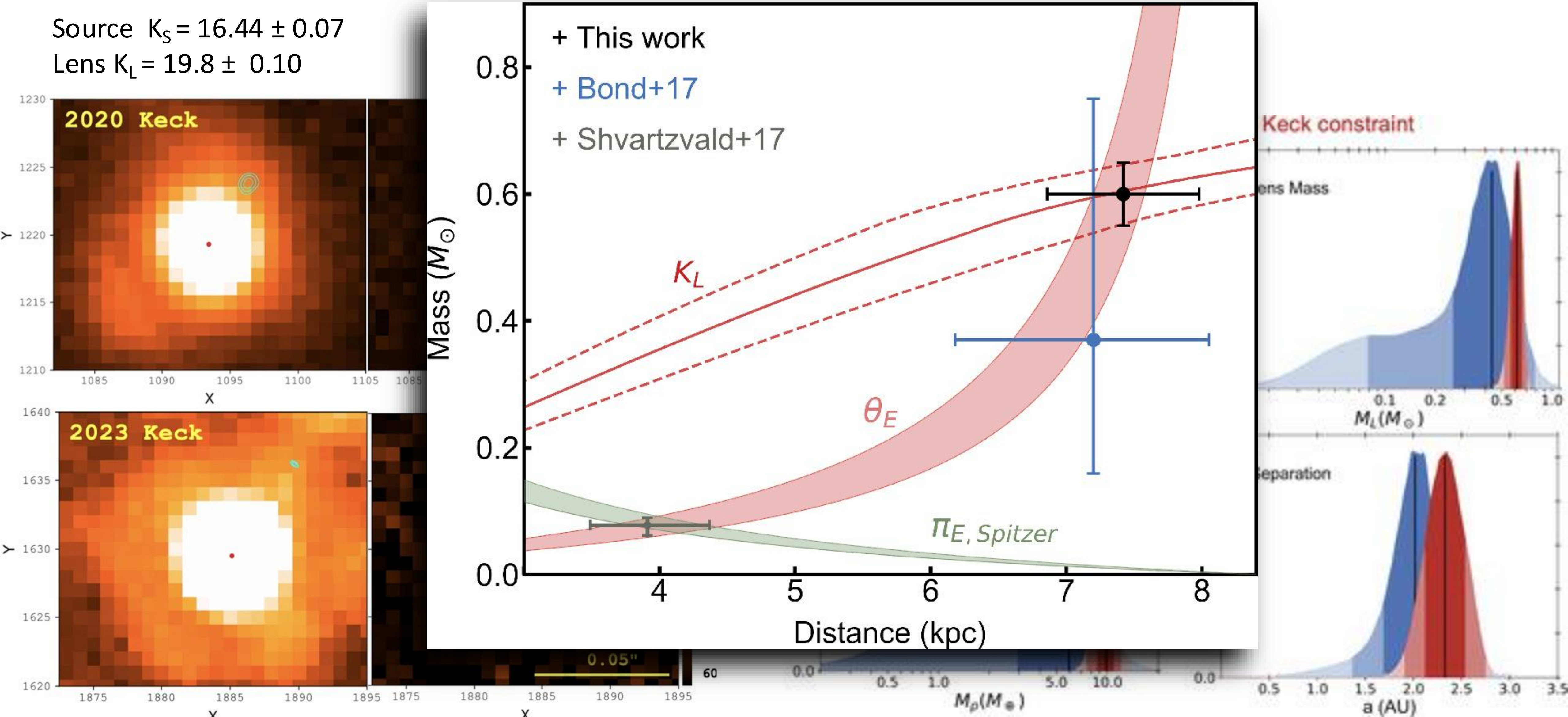
Terry+ 2025

A Sub-Neptune Beyond the Snow Line of an M-dwarf

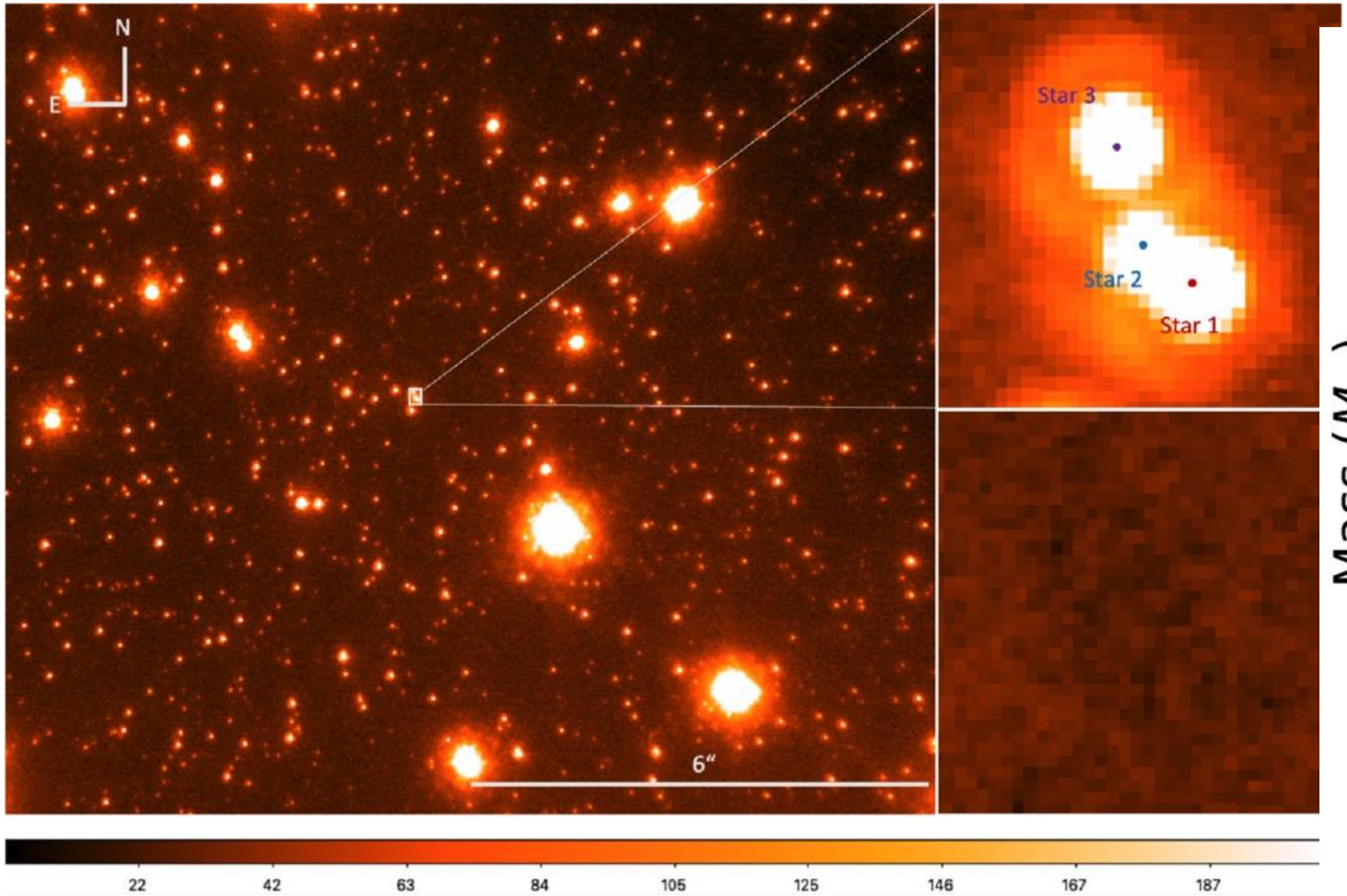
OGLE-2016-BLG-1195Lb, Vandorou+ 2025

Source $K_S = 16.44 \pm 0.07$

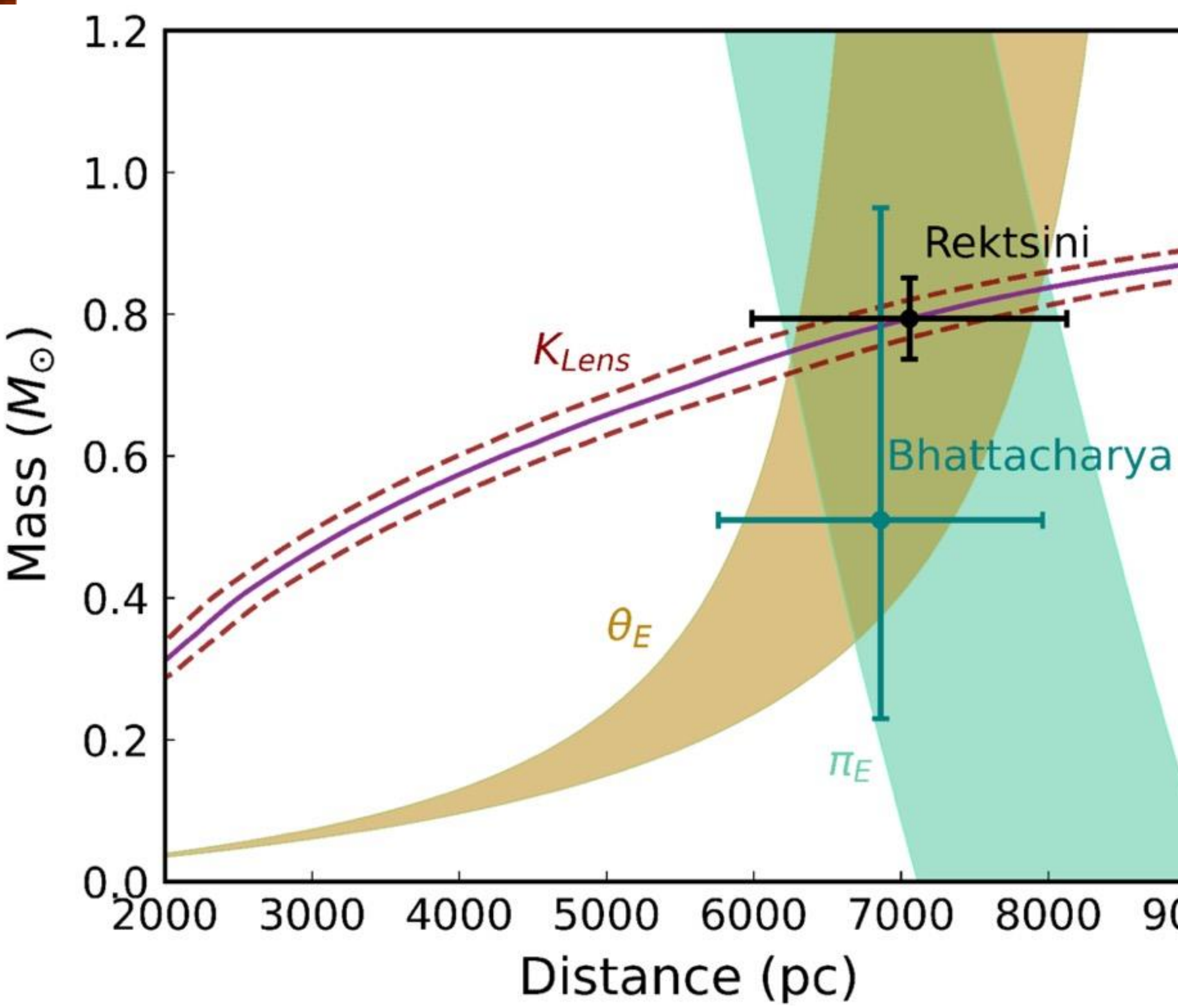
Lens $K_L = 19.8 \pm 0.10$



A Jupiter–Sun Analogue Residing in the Galactic Bulge



Rektsini+ 2025

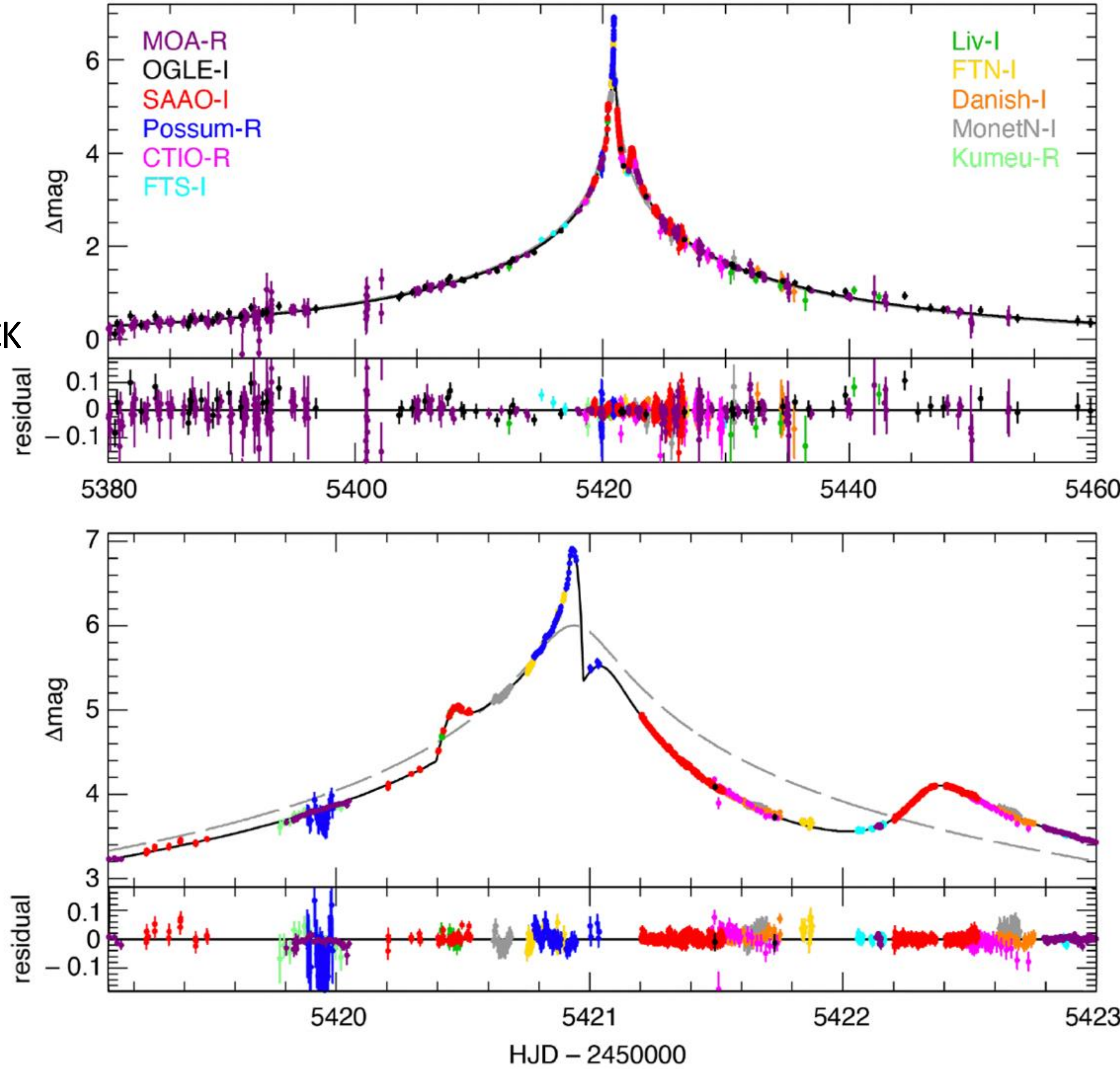


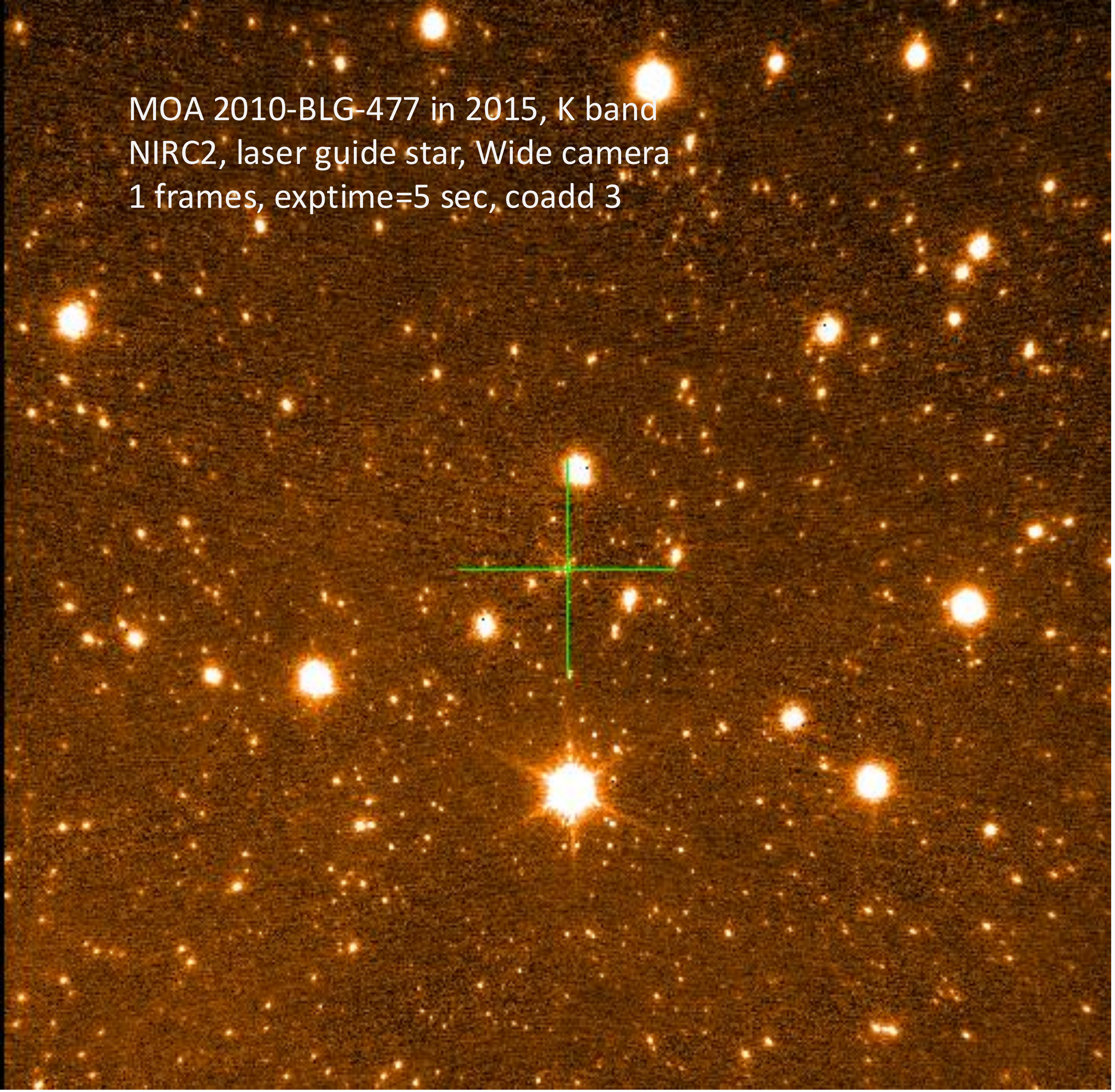
MOA-2010-BLG-477

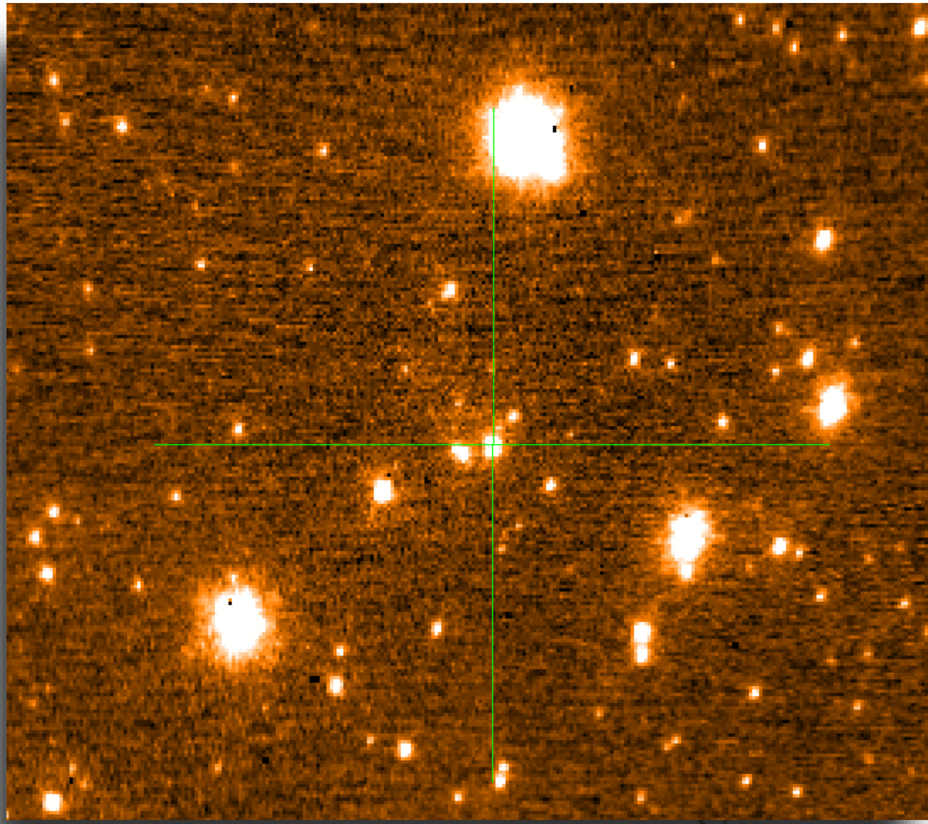
Bachelet+ 2012 : a Jupiter orbiting a ~ 0.6 Mo

The host should be H=14-19, detectable with KECK

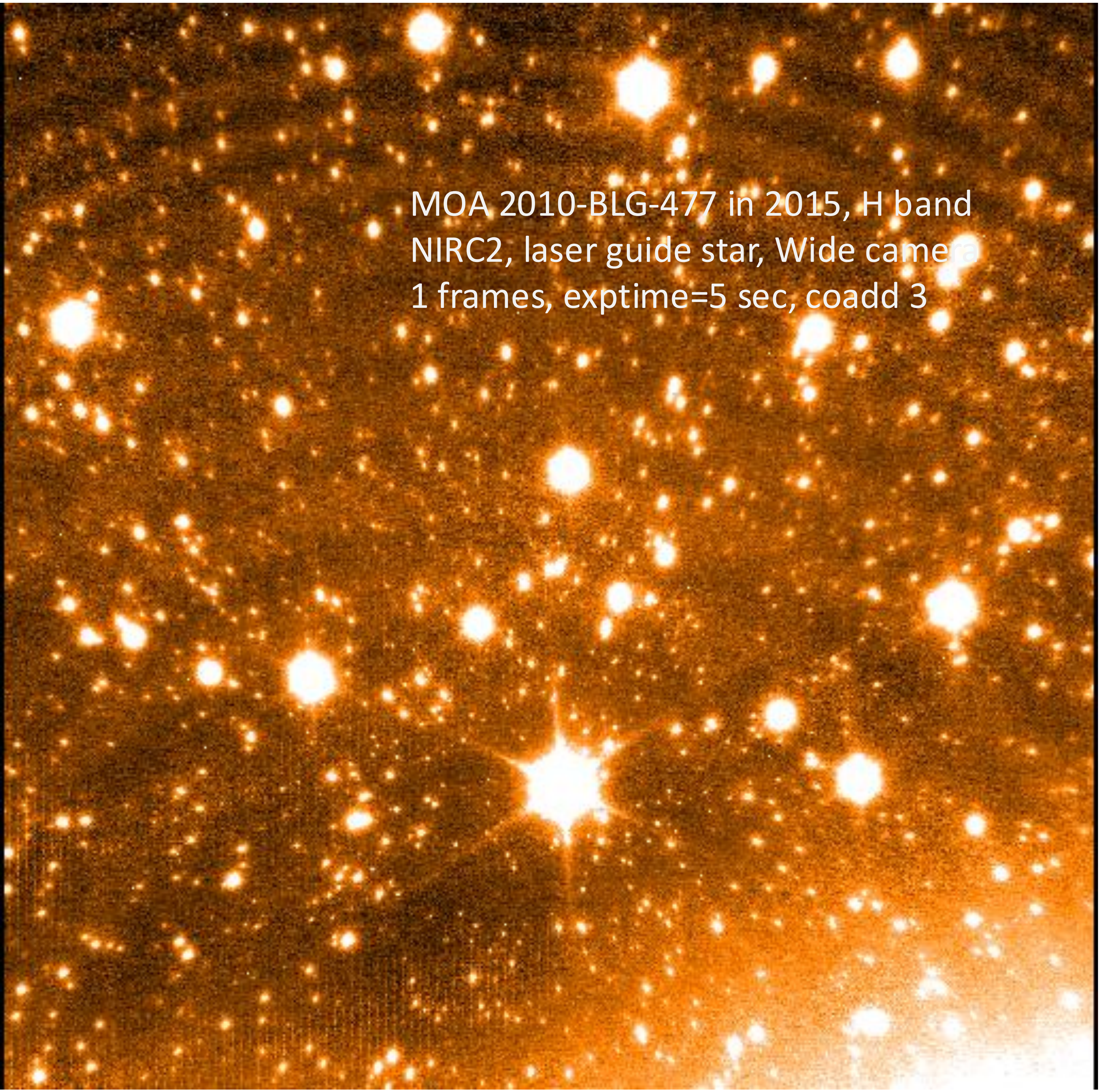
Source/lens proper motion 10 mas/yr



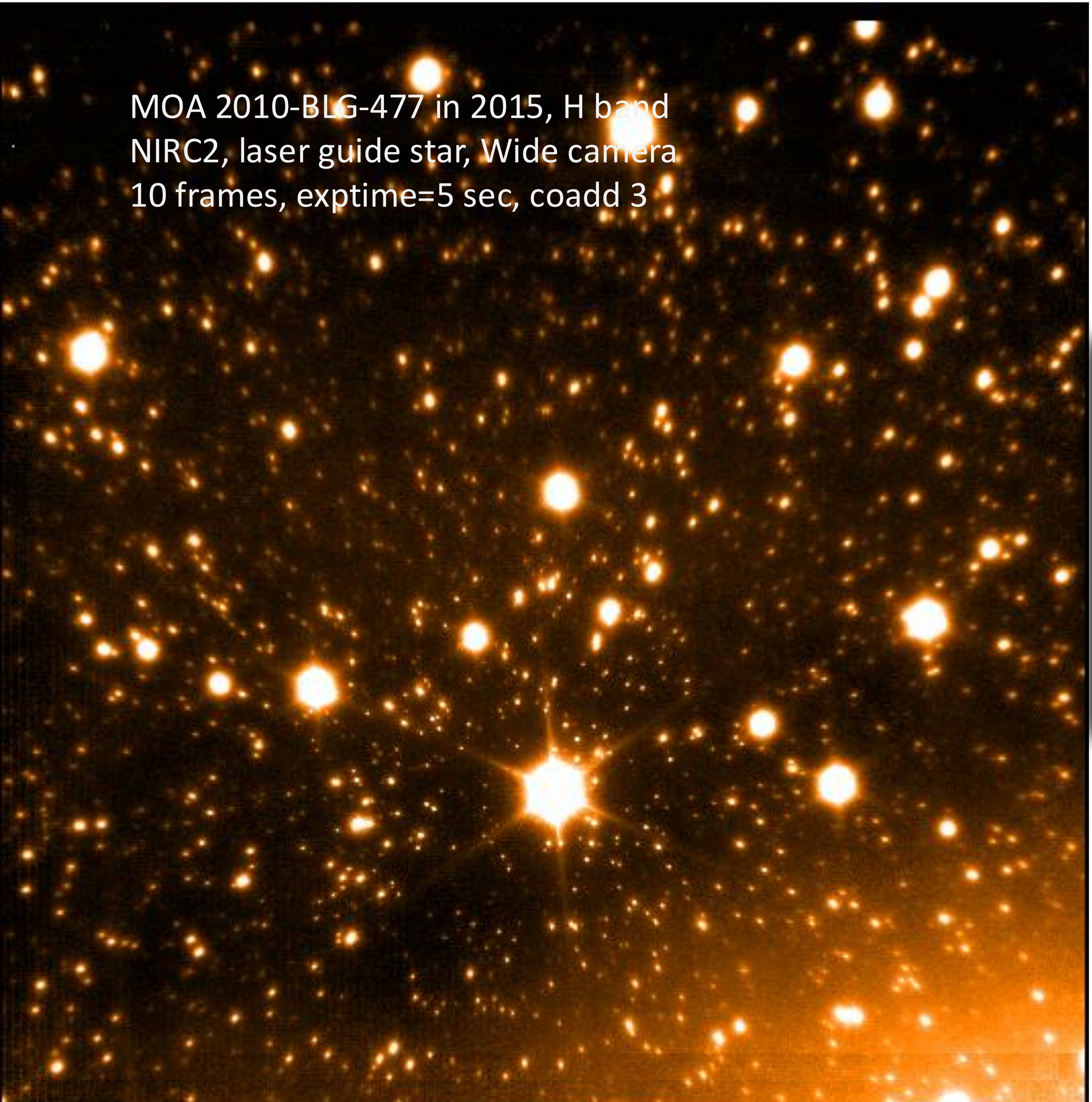


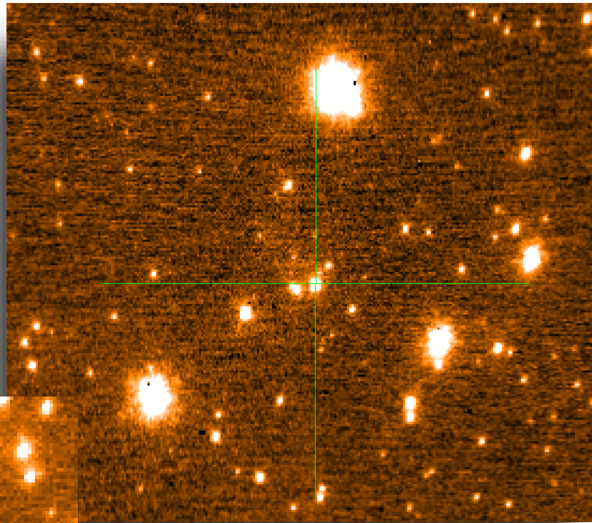


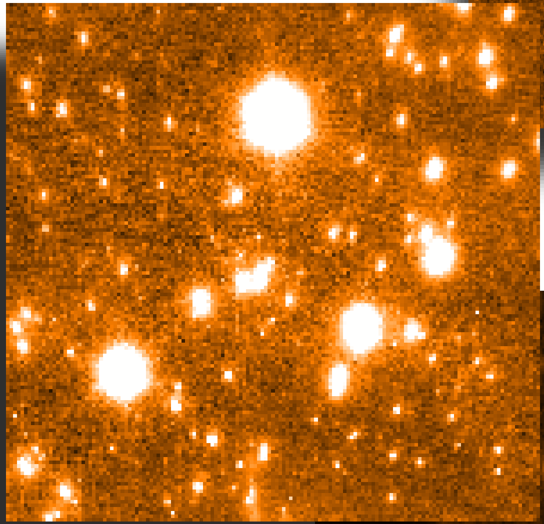
Do not forget to get enough photons...
If it is end of night,
ok, do your best...

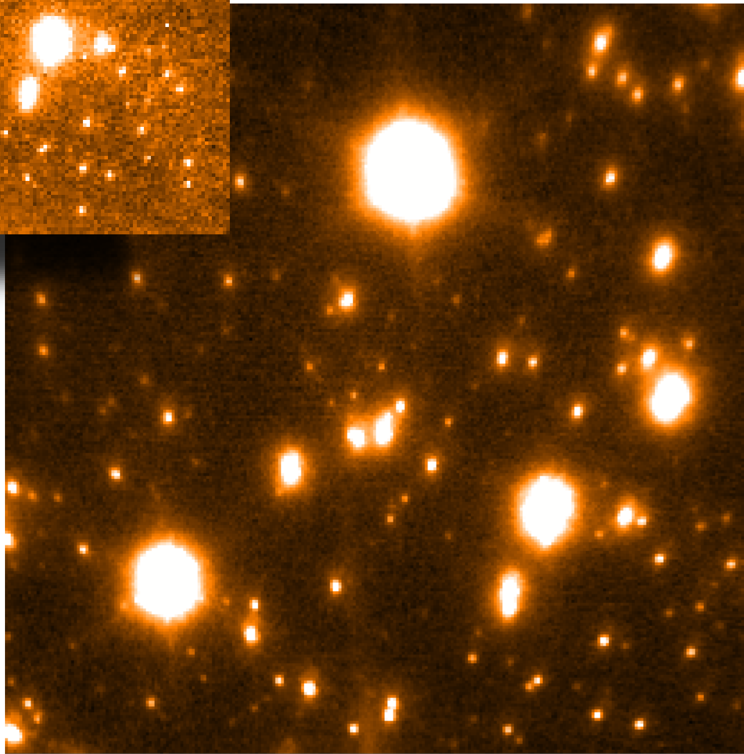


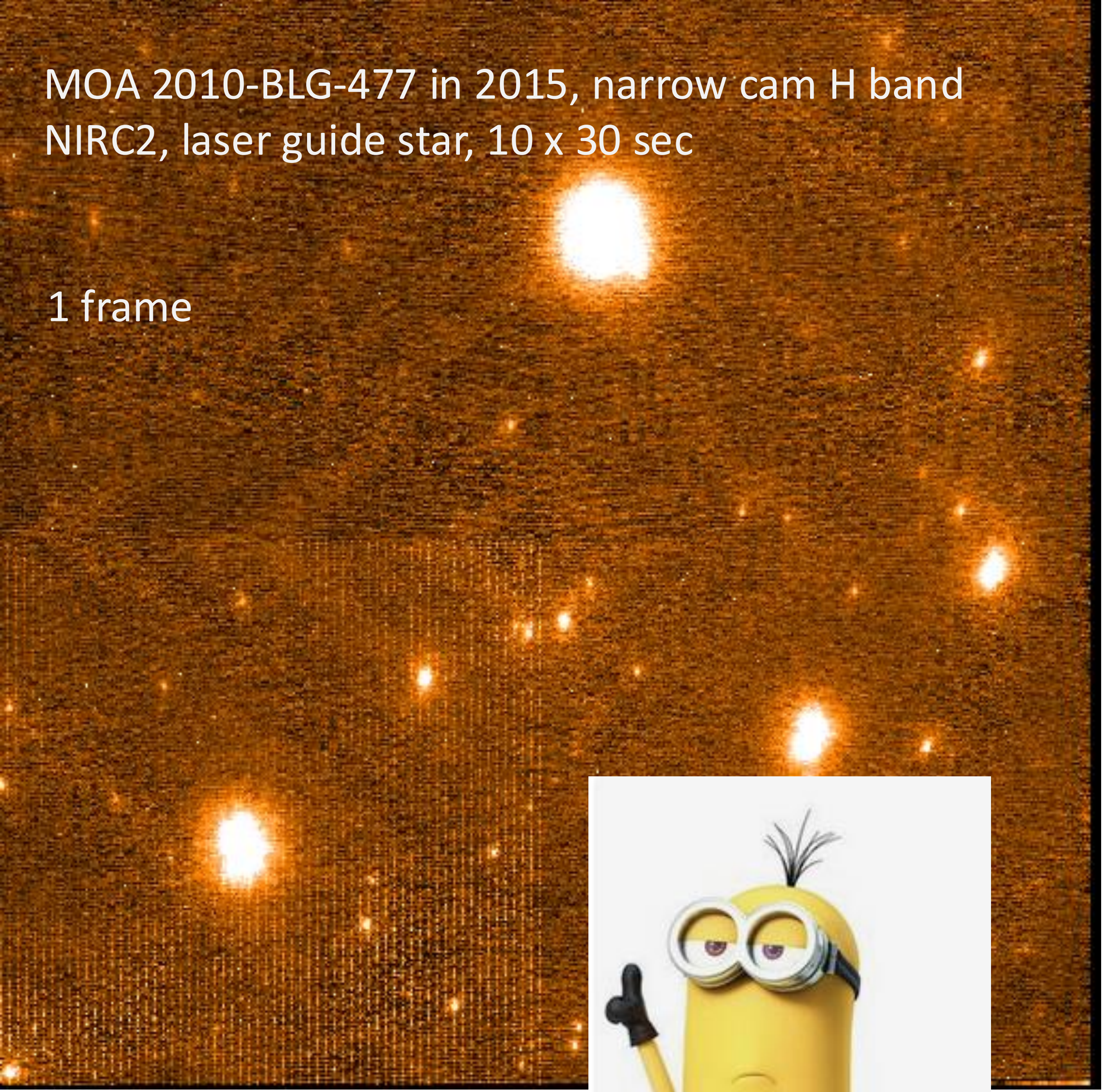
Look at the background… to correct for this, get a proper measurement of the sky
And point to avoid the bright star at the south

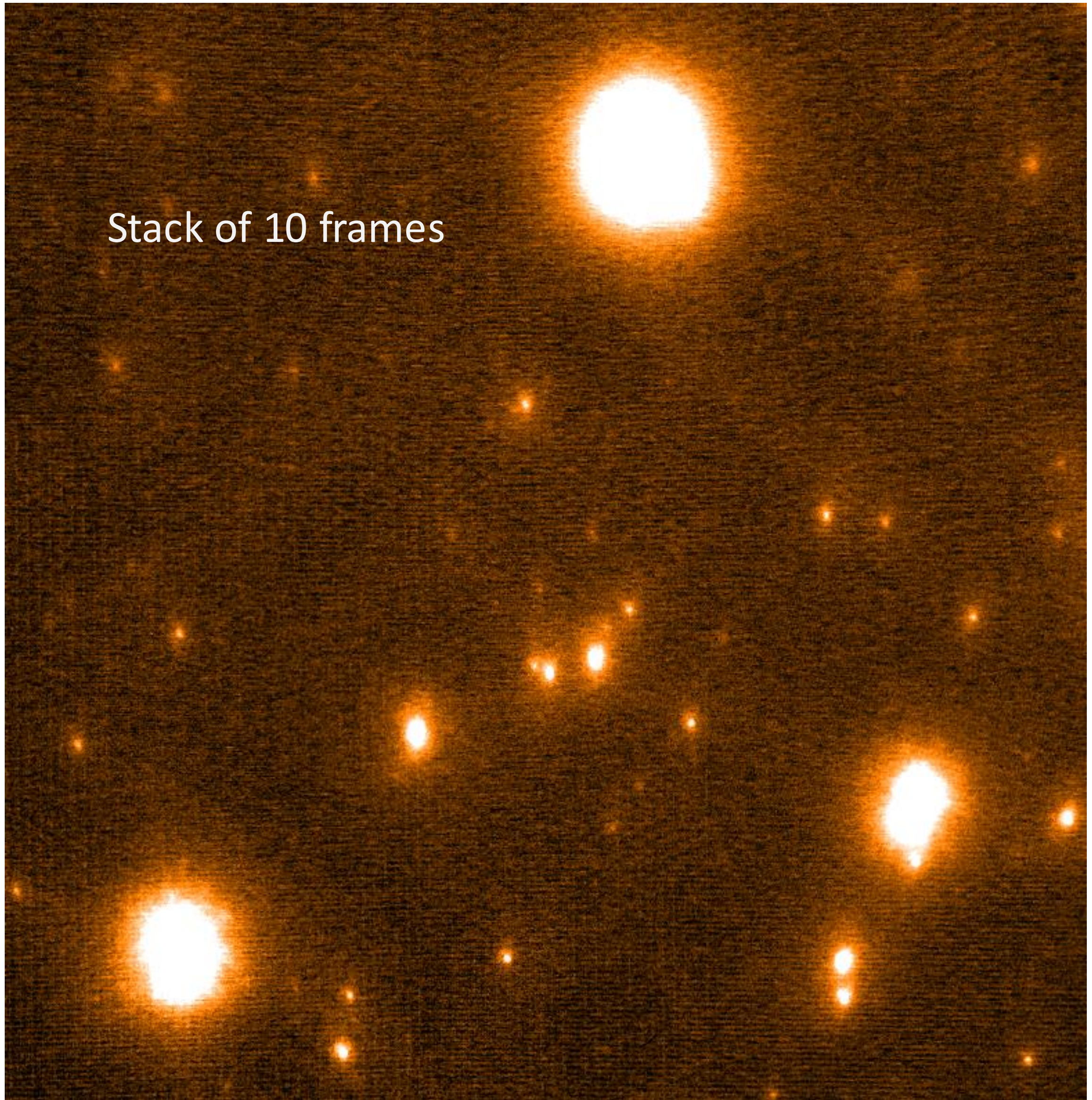

MOA 2010-BLG-477 in 2015, H band
NIRC2, laser guide star, Wide camera
10 frames, exptime=5 sec, coadd 3



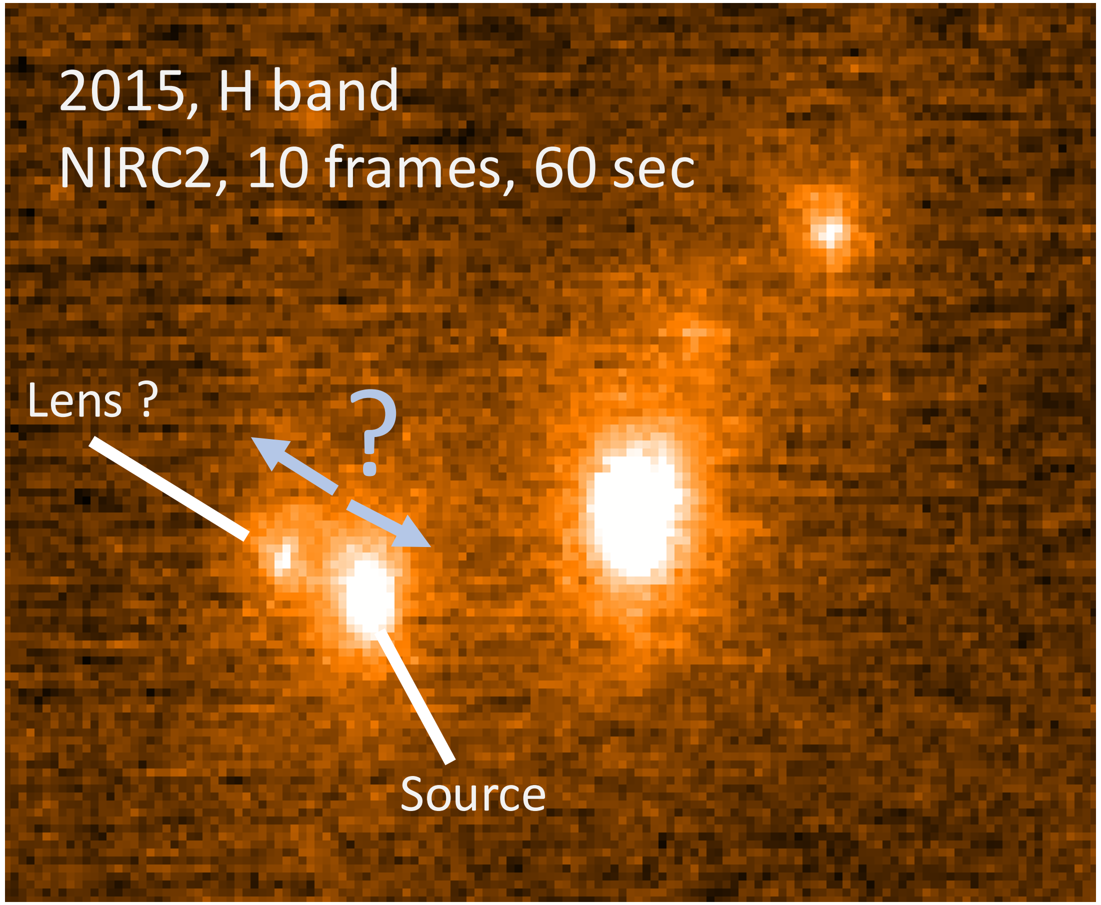


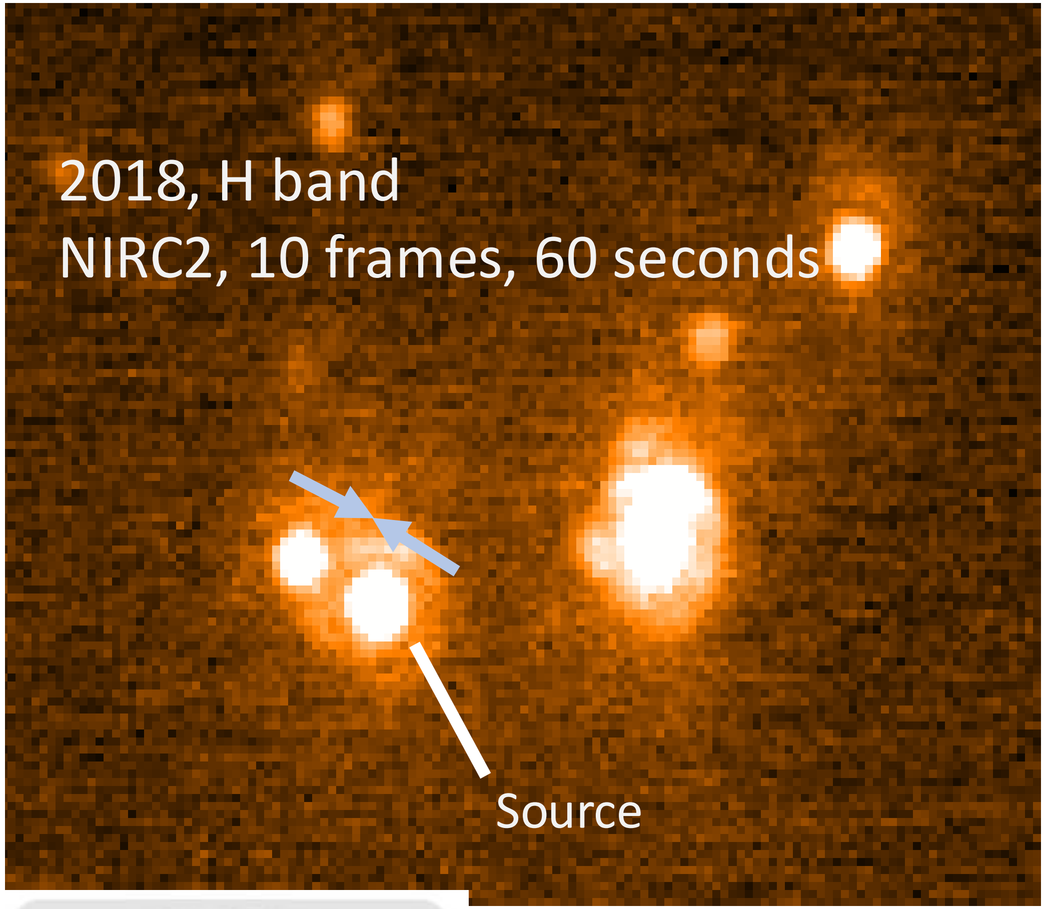






If one quadrant is bad,
do not center your target.





Is it the lens ?
Flux ok
Separation 2x

Not the lens !

Where is the lens ?

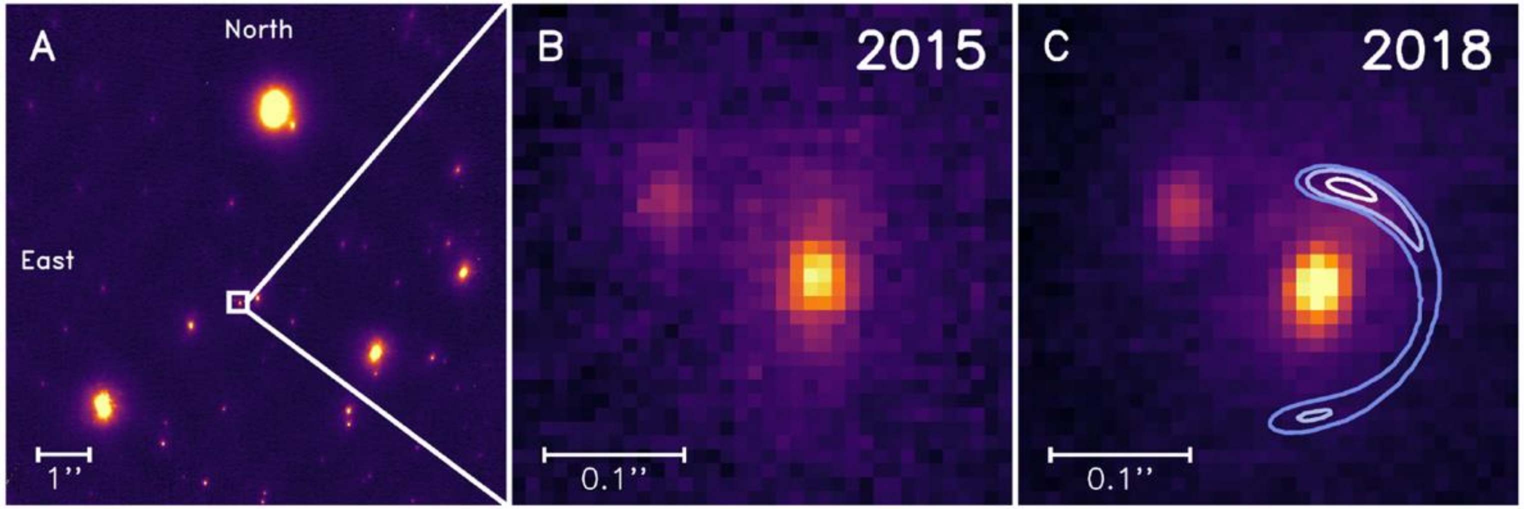
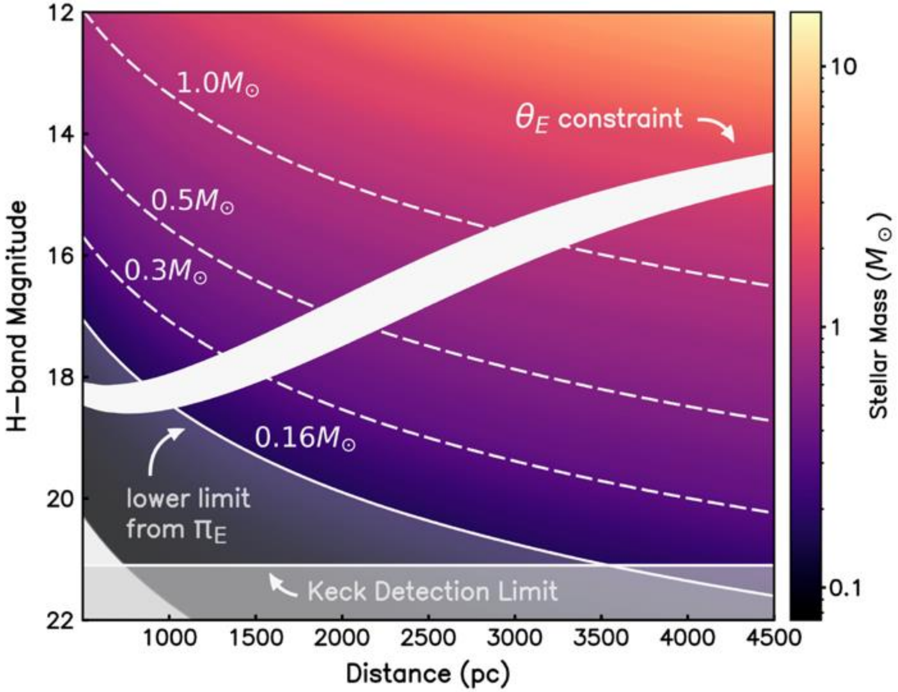


Figure 1. H-band adaptive optics imaging of MOA 2010-BLG-477 from the KECK observatory a. A crop of a narrow-camera H-band image obtained with the NIRC2 imager in 2015 centered on MOA 2010-BLG-477 with an 8 arcsec field of view. **b.** A 0.36 arcsec zoom of the same image. The bright object in the center is the source. To the north-east (the upper left) is an unrelated $H = 18.52 \pm 0.05$ star 123 mas from the source. **c.** The field in 2018. The contours indicate the likely positions of a possible main sequence host (probability of 0.393, 0.865, 0.989 from light to dark blue) using constraints from microlensing parallax and lens-source relative proper motion.

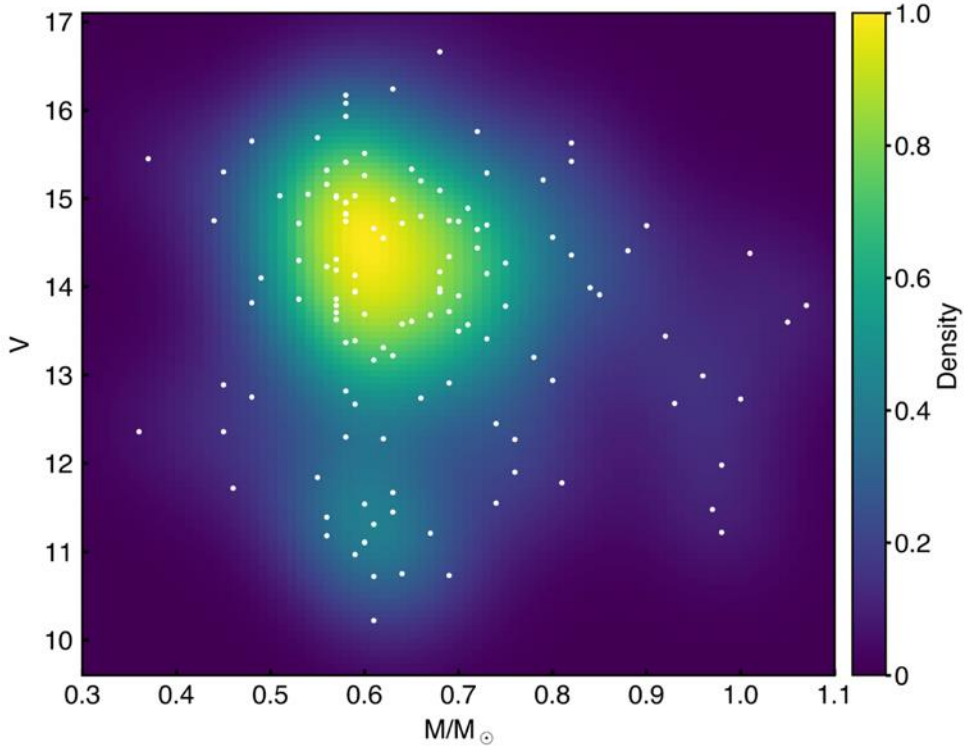


- Bachelet+ 2012 : a Jupiter orbiting a ~ 0.6 Mo
- The host should be H=14-19, detectable with KECK
- Nothing down to H=21 at predicted position.

White dwarf mass luminosity

Distance modulus = 11.5 mag

HST to search the lens at V 25-29 ?



Blackman et al.

Table 1. System Parameters of MOA 2010-BLG-477Lb

Parameter	Units	Value ($\pm 1\sigma$)	2σ range
White Dwarf Lens Distance	D_L (kpc)	1.99 ± 0.35	1.31–2.69
White Dwarf Lens Mass	M_L ($M_\odot$)	0.53 ± 0.11	0.32–0.74
Planet Mass	m_p (M_J)	1.43 ± 0.30	0.87–2.03
Source Star Distance	D_S (kpc)	7.8 ± 1.3	5.5–10.2
2D star-planet separation	$a_\perp$ (AU)	2.8 ± 0.5	1.9–3.7
3D star-planet separation	a (AU)	$3.4^{+1.8}_{-0.8}$	2.1–12.1
Mass Ratio	q (10^{-3})	2.61 ± 0.03	2.55–2.67
White Dwarf Host V_L	mag	26.92 ± 1.80	23.38–29.44
White Dwarf Host J_L	mag	24.83 ± 0.91	22.80–26.41

We can detect it with JWST or ELT.

AO observing cookbook, for visiting astronomers

The afternoon before observations, double check everything, build scenario of how the night would be knowing the weather. This is the moment to think and talk, at the telescope, it will be the action.

Get your finding chart right before the observations, choose tip-tilt stars, learn your field and your target
- choose also your fields for taking the sky.

- If laser cannot be used, have your natural guide stars.
-For your dither pattern, do not take too big steps, few arcsec
- Personnally, always series of 5 images. Example, NIRC2 Camera Narrow coadd 3, 5 images of 60 sec at each dither, and 5 dither, by 1 arcsec.

If you are at the telescope, be ready to adjust strategy as a function of your targets.
- If I can do 80 mas images, I do the target where I do need 80 mas, not the one where I need 50 mas.
- If I need 50 mas, I wait to have 50 mas no matter how cool my target is.

- Rule of thumbs, it will take you 5-10 min to arrive to new target, acquire the laser etc
- You usually start with tip-tilt star, close the loop and offset to target.
- Do check that indeed, you really offseted to target.
- In otherwords, do look at your images during acquisition… yes, do look at them !
- Make sure you have enough images to get your science out. If not 100 % sure, just spend a bit more time

AO data reduction comments

The Keck AO Imaging (KAI) data reduction pipeline
or
Using flat-fielded/dark subtracted data from KECK archive + home-made pipeline
Some tools : Sextractor (source extraction), Swarp (stack images), wcstools, gaia, Daophot

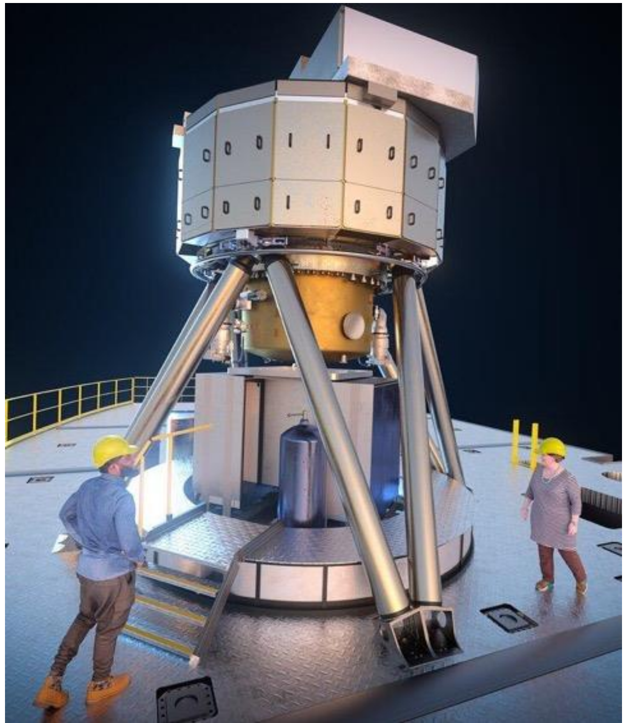
- Make sure you have identified the right target in the field (more tricky than what you would think)
- Using Vista 4m telescope data for calibration (VVV)
- Extra care in choosing calibration stars

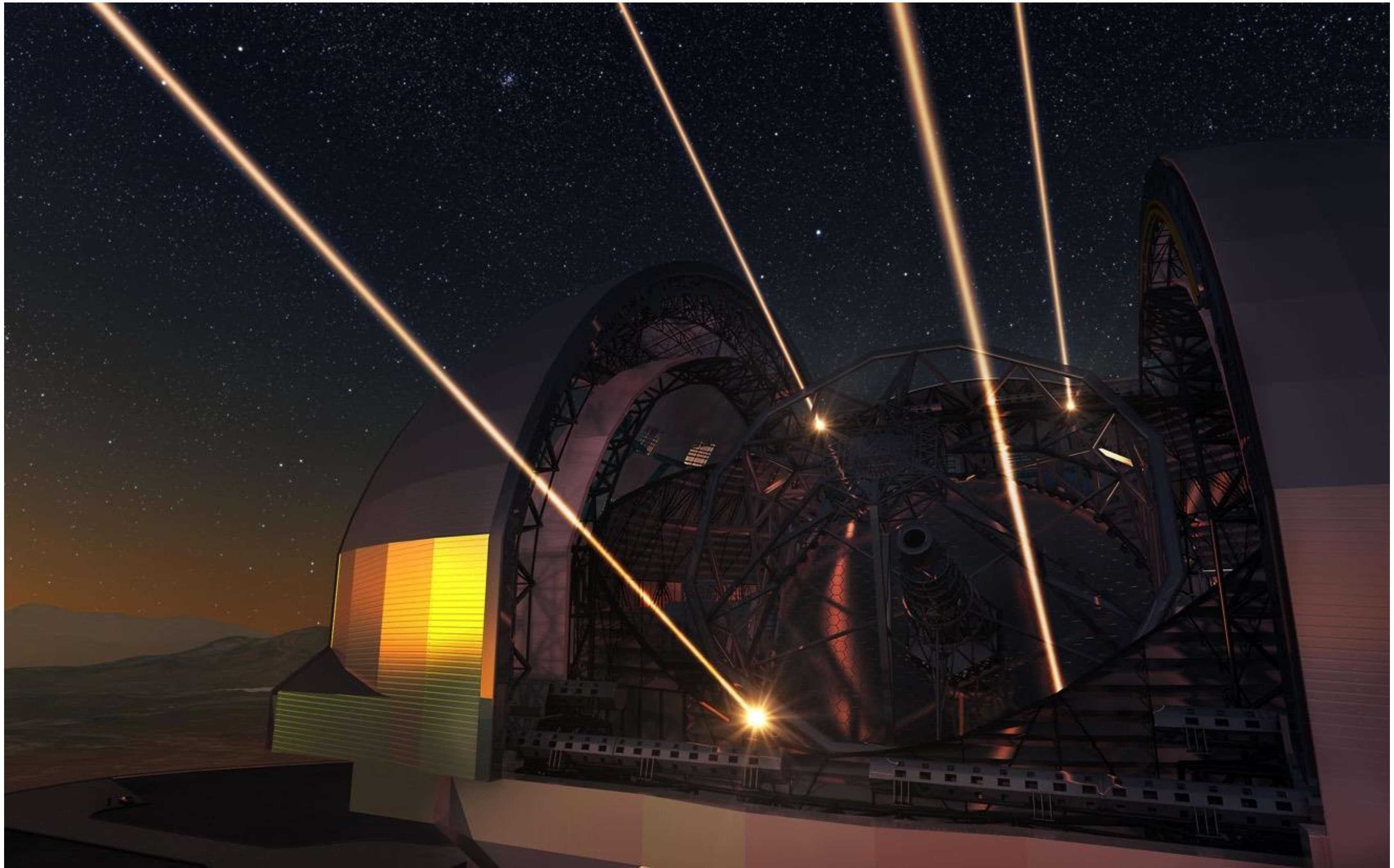
- Variable PSF in AO field, different from observing run to observing run.
    Aperture photometry to start, to measure fluxes.
    Calculating PSF models to resolve source/lens (daophot + others)

- If you measure flux excess at the position of the source -> upper limit on the flux of the lens.
- Companion to the source, companion to the lens, chance aligned stars ?
- If you detect a lens candidate… double check its proper motion few years later
-


MICADO
Soon…

Multi-conjugate AO (MCAO), providing a **uniform correction over a large (~50") field** with moderate-to-high Strehl on ELT



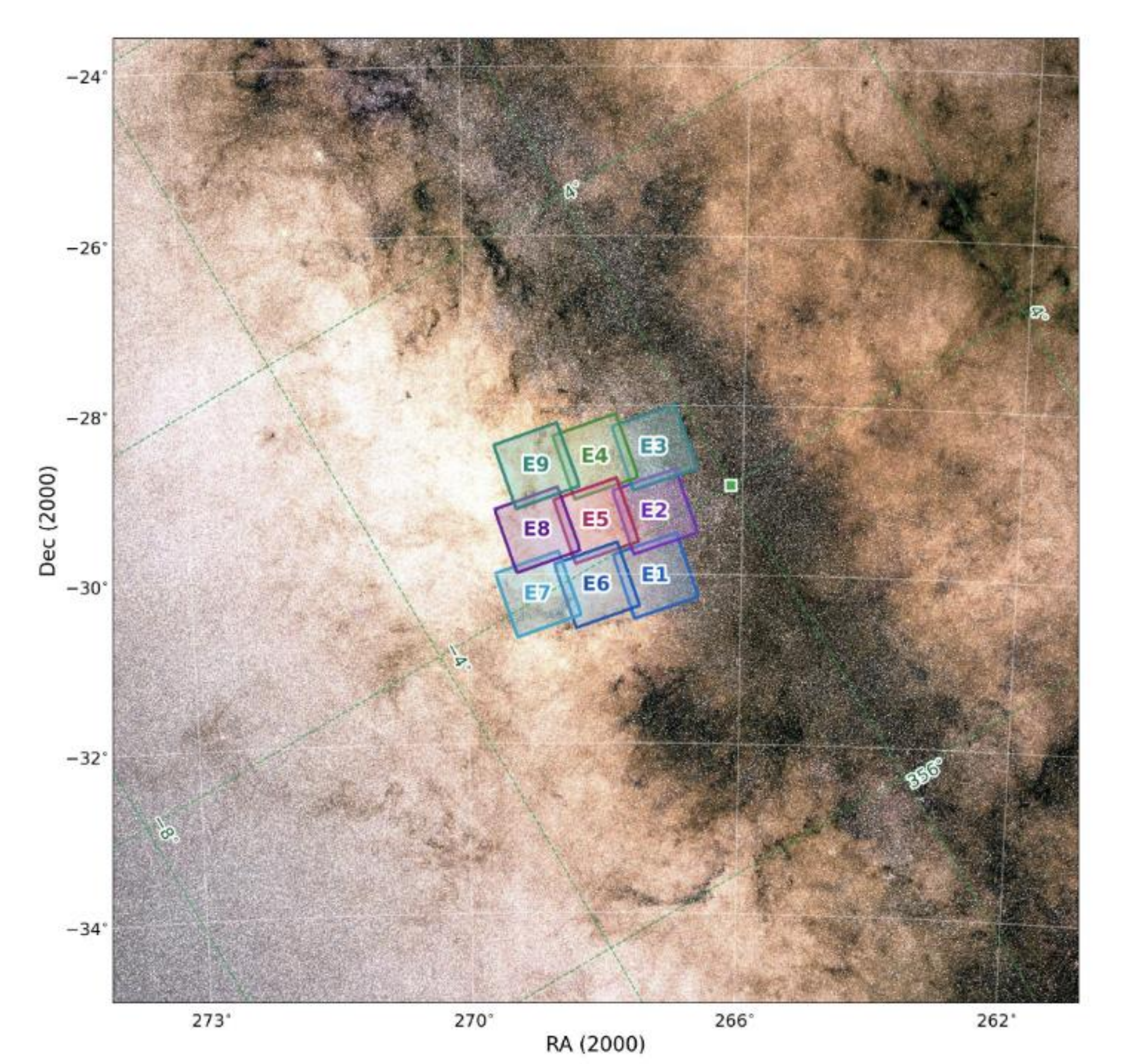


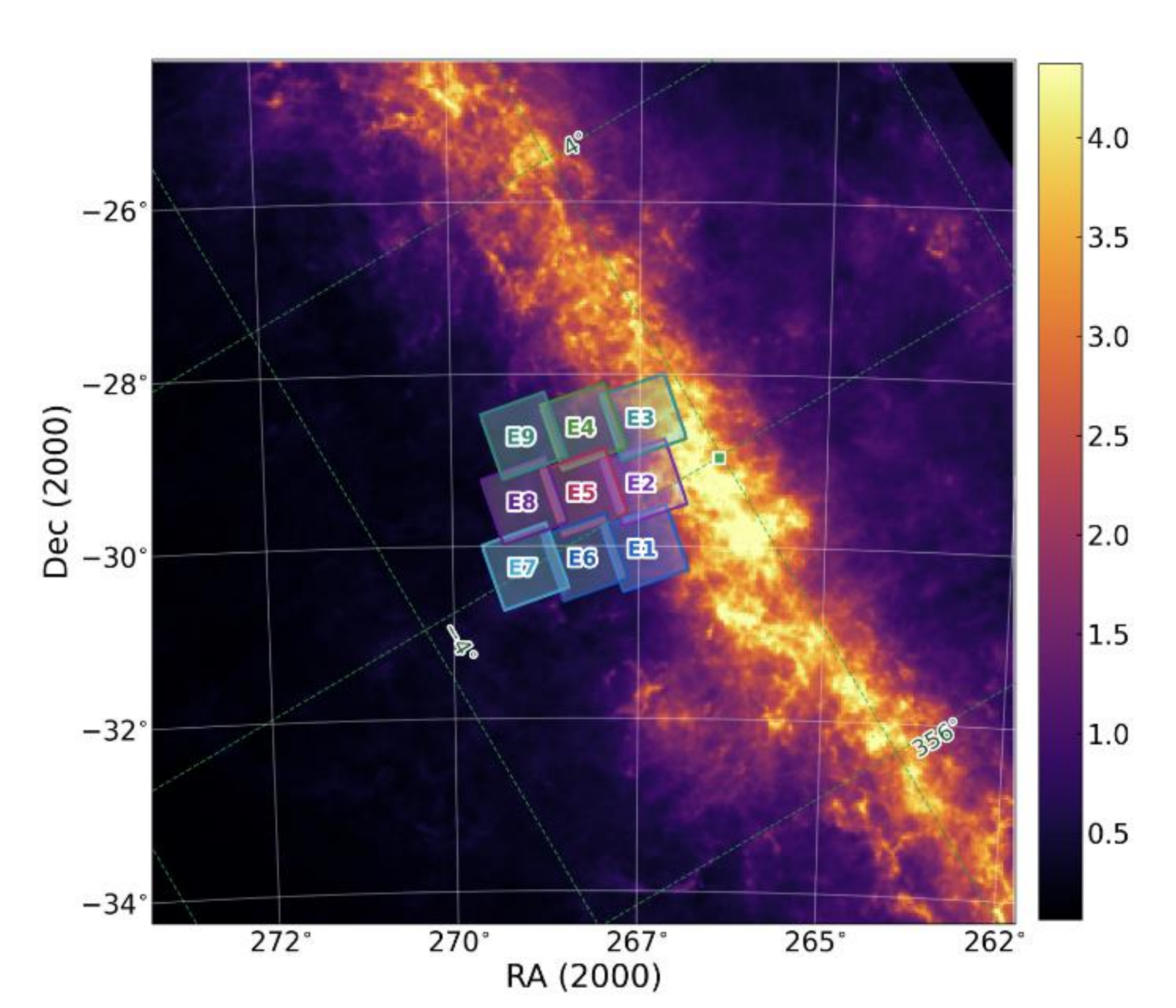
Instruments	MICADO (ELT)	OSIRIS Imager (Keck II)	GMTIFS
Telescope	ELT (39 m)	Keck II (10 m)	GMT (25.4m)
Wavelength	0.8–2.4 μm	1.0–2.5 μm	1.0–2.5 μm
Pixel scale	4 mas/pixel (wide), 1.5 mas/pixel (HR)	20 mas/pixel	5 mas/pixel
Field of view	50.5″ × 50.5″ (wide)	20.4″ × 20.4″	20.4″x20.4″
Detector	9 × H4RG (≈150 Mpix)	1024 × 1024 Hawaii-1	2 × H4RG (16.8 Mpix)
AO	MORFEO MCAO / SCAO	Keck NGS/LGS AO	
Astrometry	~50 μas design goal	0.5–2 mas after distortion calibration	~100–300 μas
Diffraction limit (K)	14 mas (3.5 pix/FWHM)	55 mas (2.7 pix/FWHM)	22 mas (4.2 pix/FWHM)
Typical useful Strehl	30–60% (expected)	15–40%, depending on conditions	60–70% (expected)
	MORFEO MCAO/SCAO	Keck NGS/LGS AO	LTAO or NGS AO

MICADO ELT versus OSIRIS KECK
4× sharper images, 5× finer sampling (or 13× in the astrometric mode),
2.5× larger linear field (about 6× the area), ~15× greater collecting area,

ELT is perfect to hunt for White Dwarf lenses… and astrometry for black holes, but not only !

Euclid galactic Bulge Survey, EGBS, Q2 data release





Beaulieu+ 2026 [Euclid Quick Data Release (Q2) -- The Euclid Galactic Bulge Survey]

Euclid galactic Bulge Survey, EGBS, Q2

- **Providing precursor high signal to noise observations of future microlensing events to be discovered by Roman during its survey**

- 9 fields, 4 ROS each (with 400 sec exp), VIS only
  + 2 calibration fields (lower density)
- 4.8 square degrees in 28 hours.
- 45+ million sources per dither

Observations done on March 2025

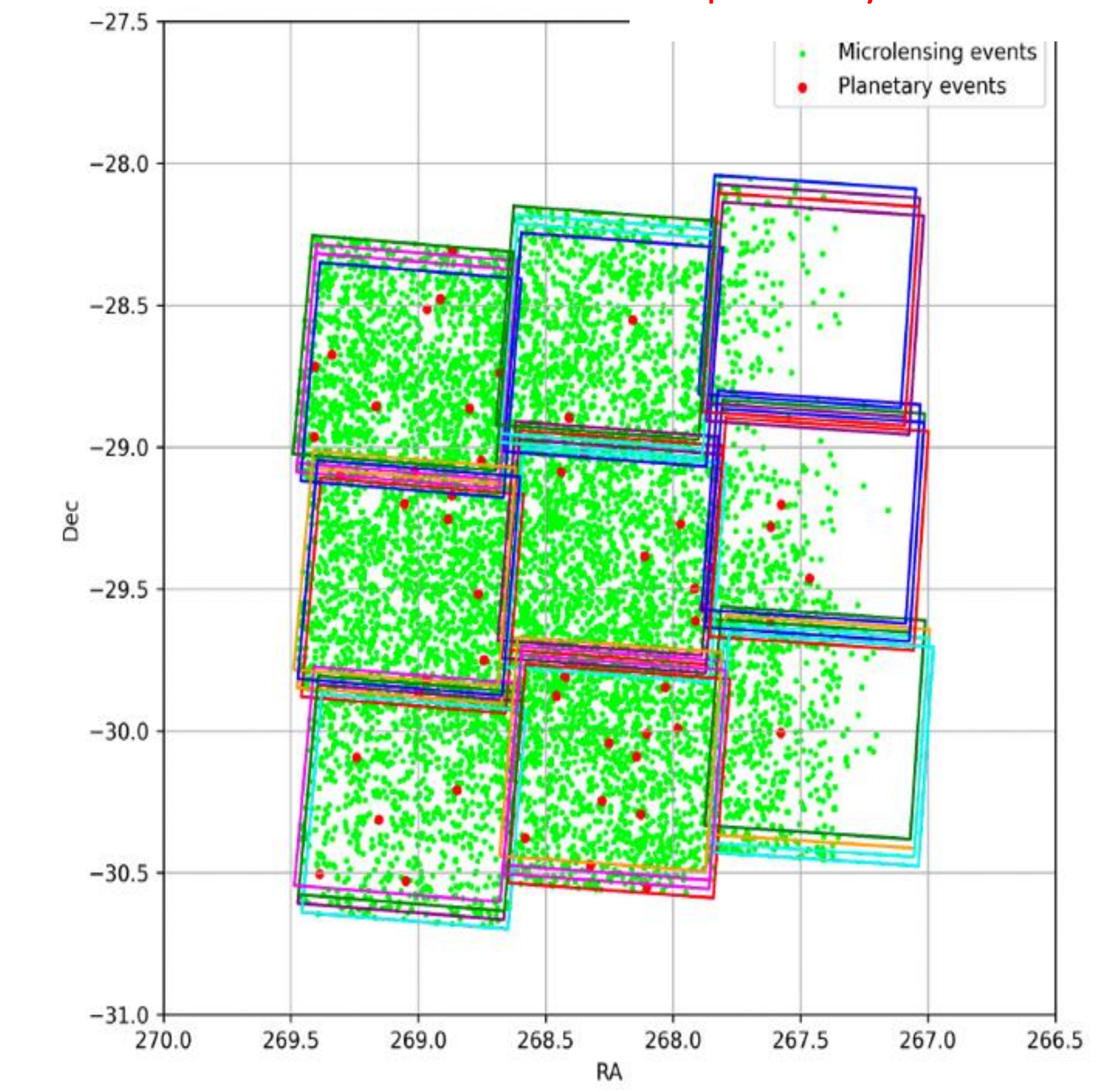
Released to consortium February 2026

Public release June 24, 2026

Bozza et al., 2026, under review

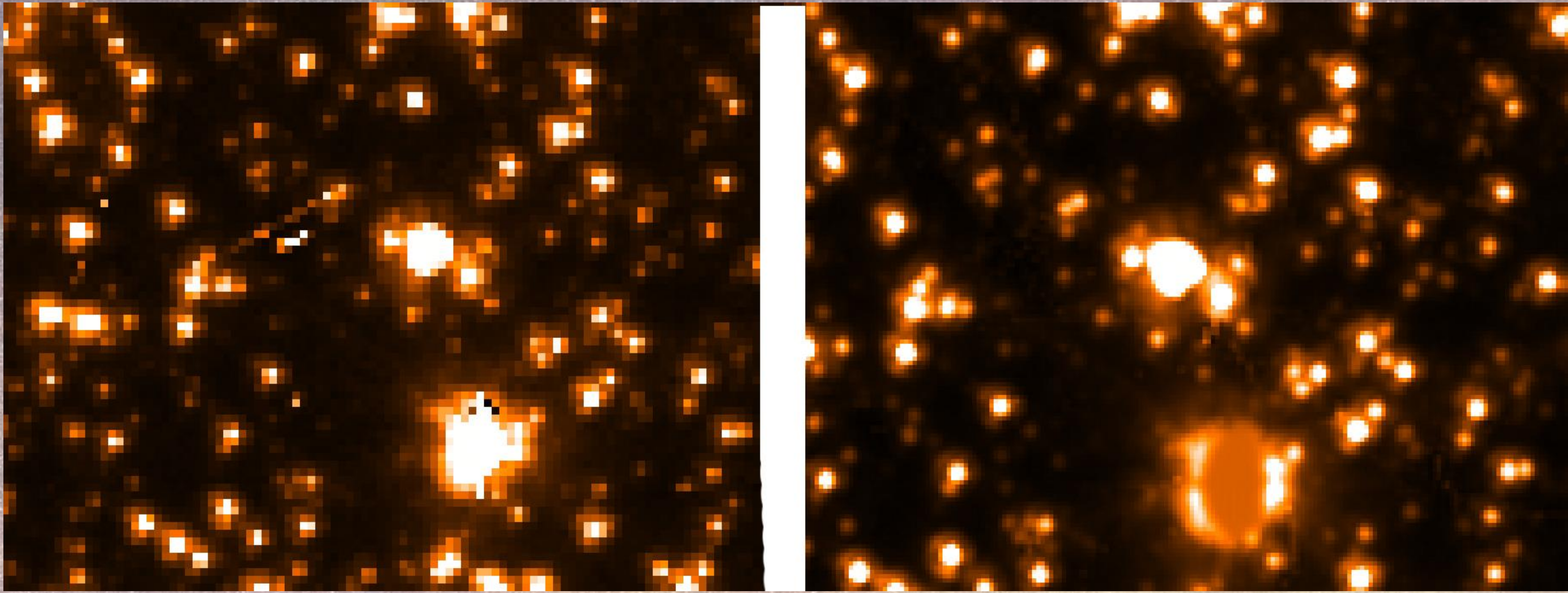
8081 single lens

51 planetary lens



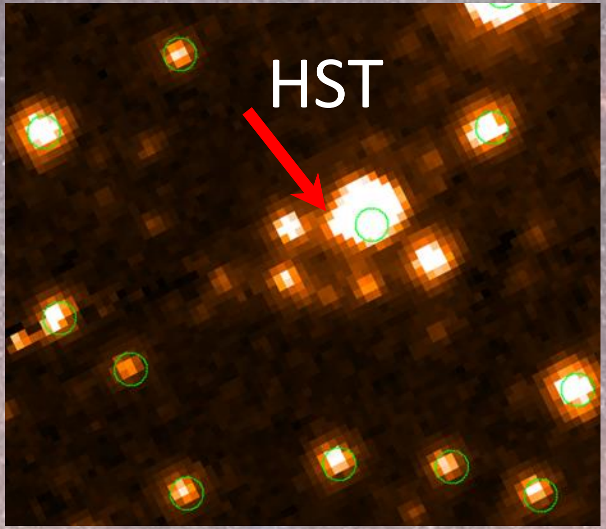
One dither, versus the stack

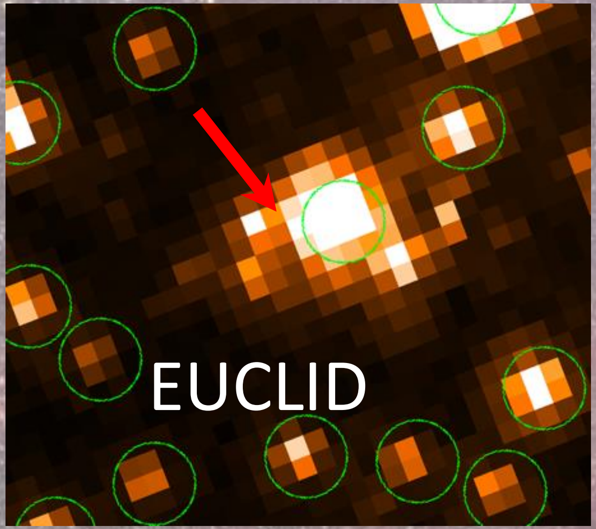
(courtesy E. Bachelet)

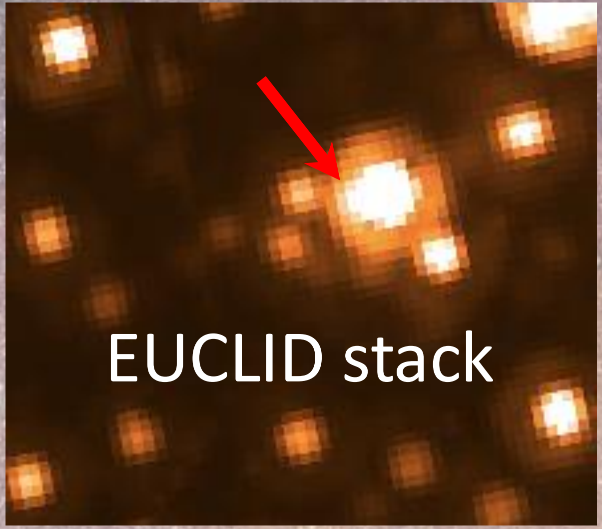


Examples, OGLE-341, a planetary microlensing from 2013

Telescope	Lens/source flux ratio	Measured separation	Proper motion
KECK 2020	0.86 in K band	78.54 mas	10.47 mas/yr
HST 2025		120 mas	10 mas/yr
Euclid 2025 (one dither)	0.14 ± 0.02 mas	126 ± 11 mas	10.51 ± 0.9 mas/yr





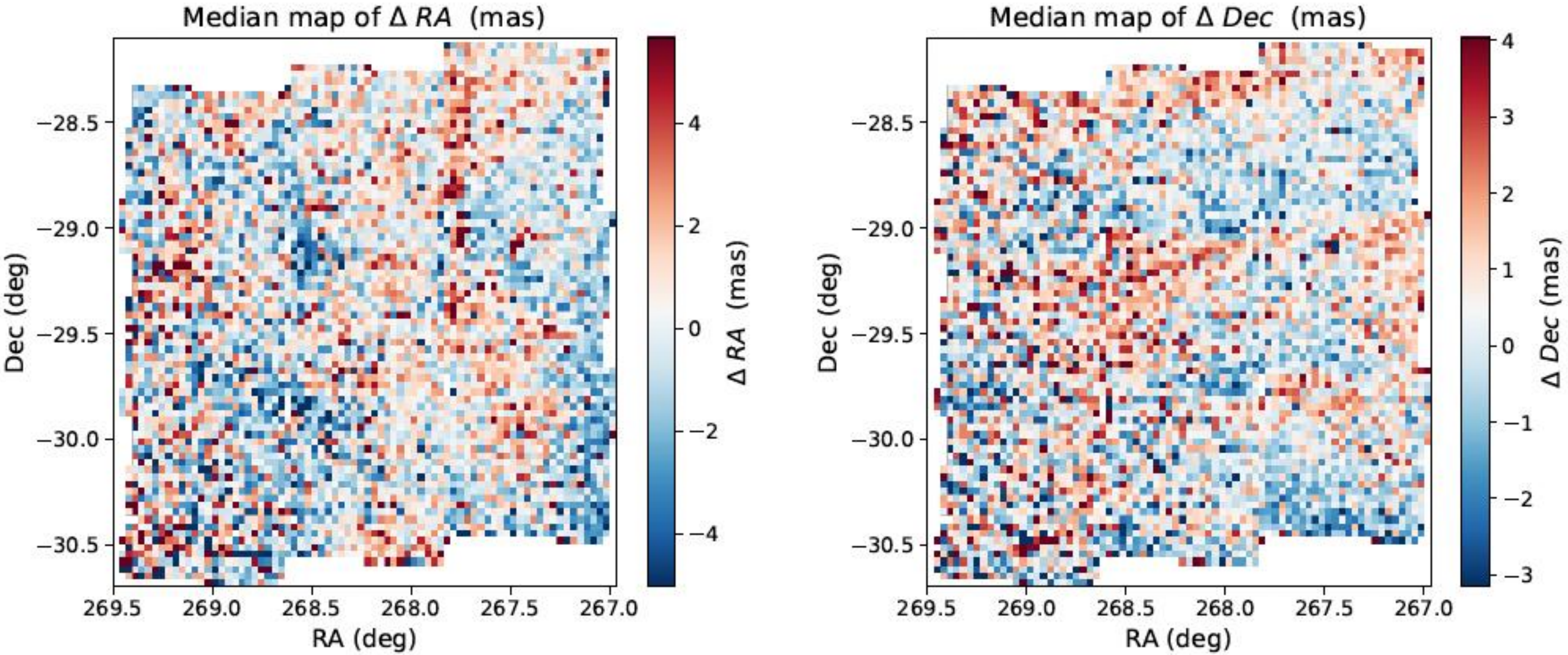


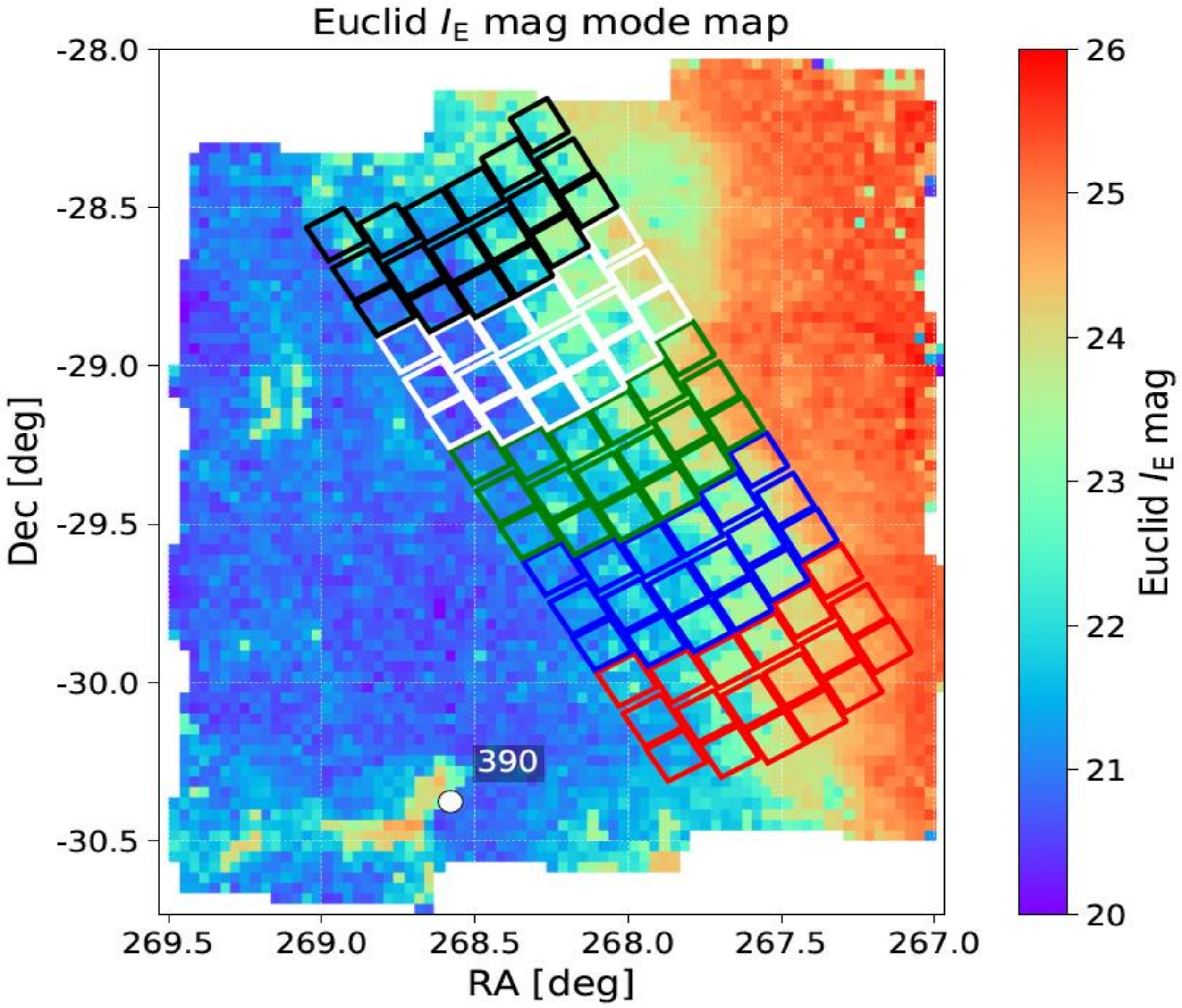
Excellent data quality of the VIS.
Currently testing on selected line of sight with HST and KECK data.

On going, testing with PSF from calibration field, and SHE PSF

Contribution led by Rektsini (IAP), Bachelet (Besançon)

Checking the astrometry

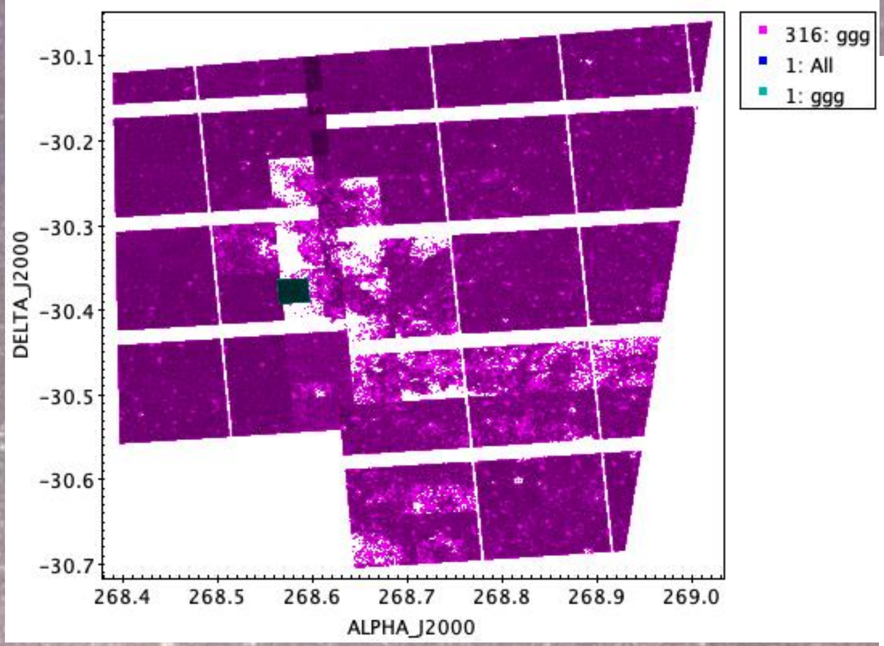


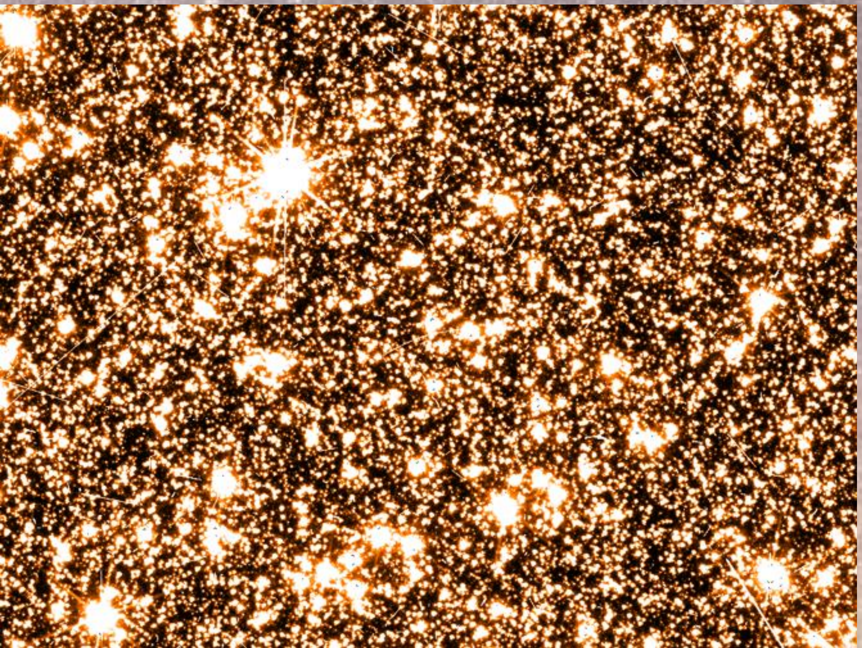


These catalogues are incomplete, but useful for calibrations

Zero point at 1.5 %, astrometry at ~ 3 mas

Example of limitation from Q2 catalogues





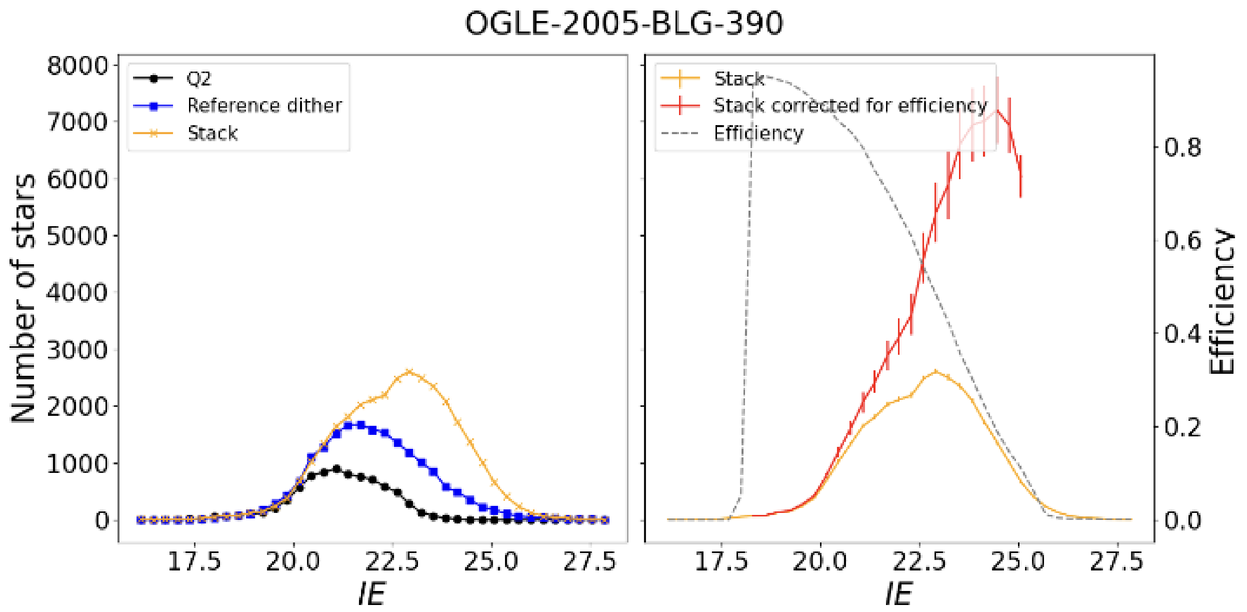
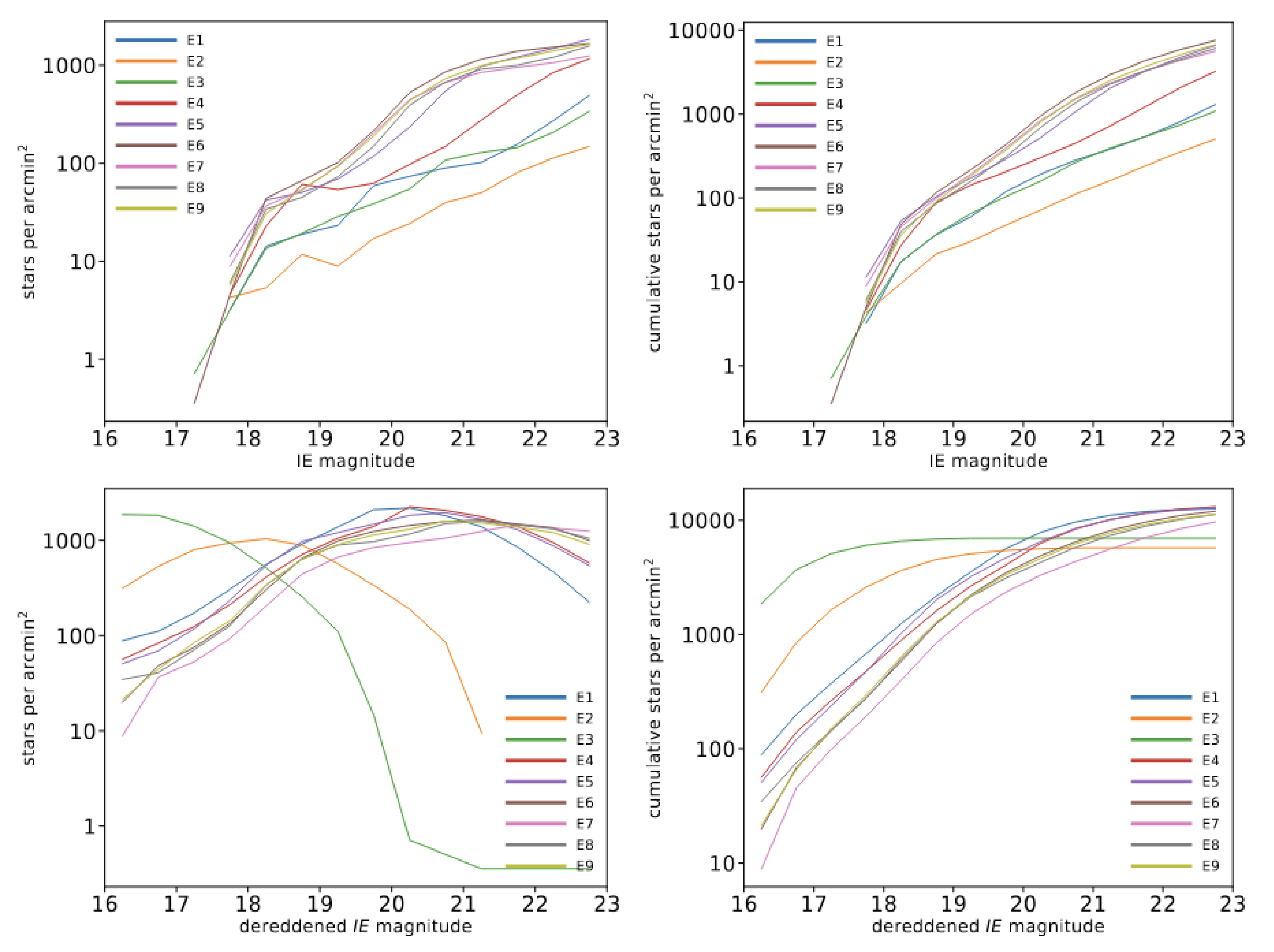
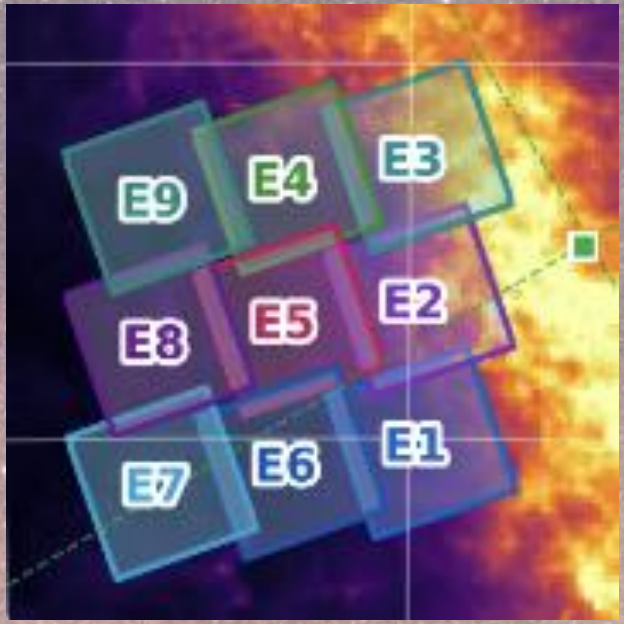
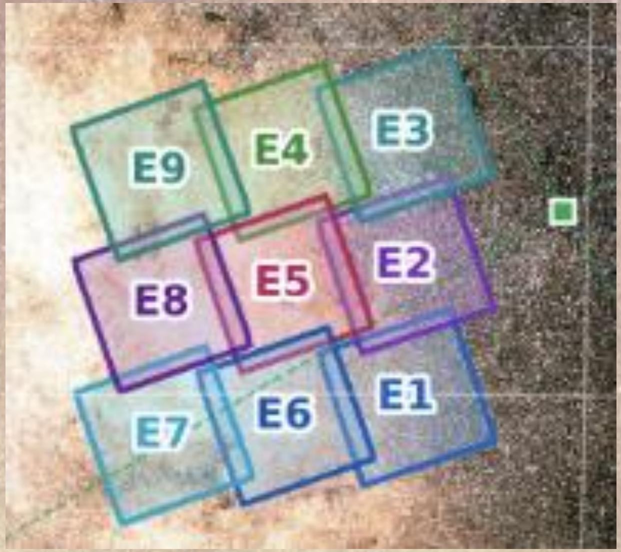


Fig. 16. *Left:* Number of stars detected in a 100.′5 × 100.′5 cutout centred around OGLE-2005-BLG-390Lb. In black are the magnitude distributions of detections available from the Q2 catalogue (7962 sources), while the blue and orange curves are detections using `DAOStarFinder`, on the reference dither (18 792 sources) and the stack (31 693 sources). *Right:* The red curve shows distribution of counts in the stack corrected for the detection efficiency (shown as the grey-dashed curve).

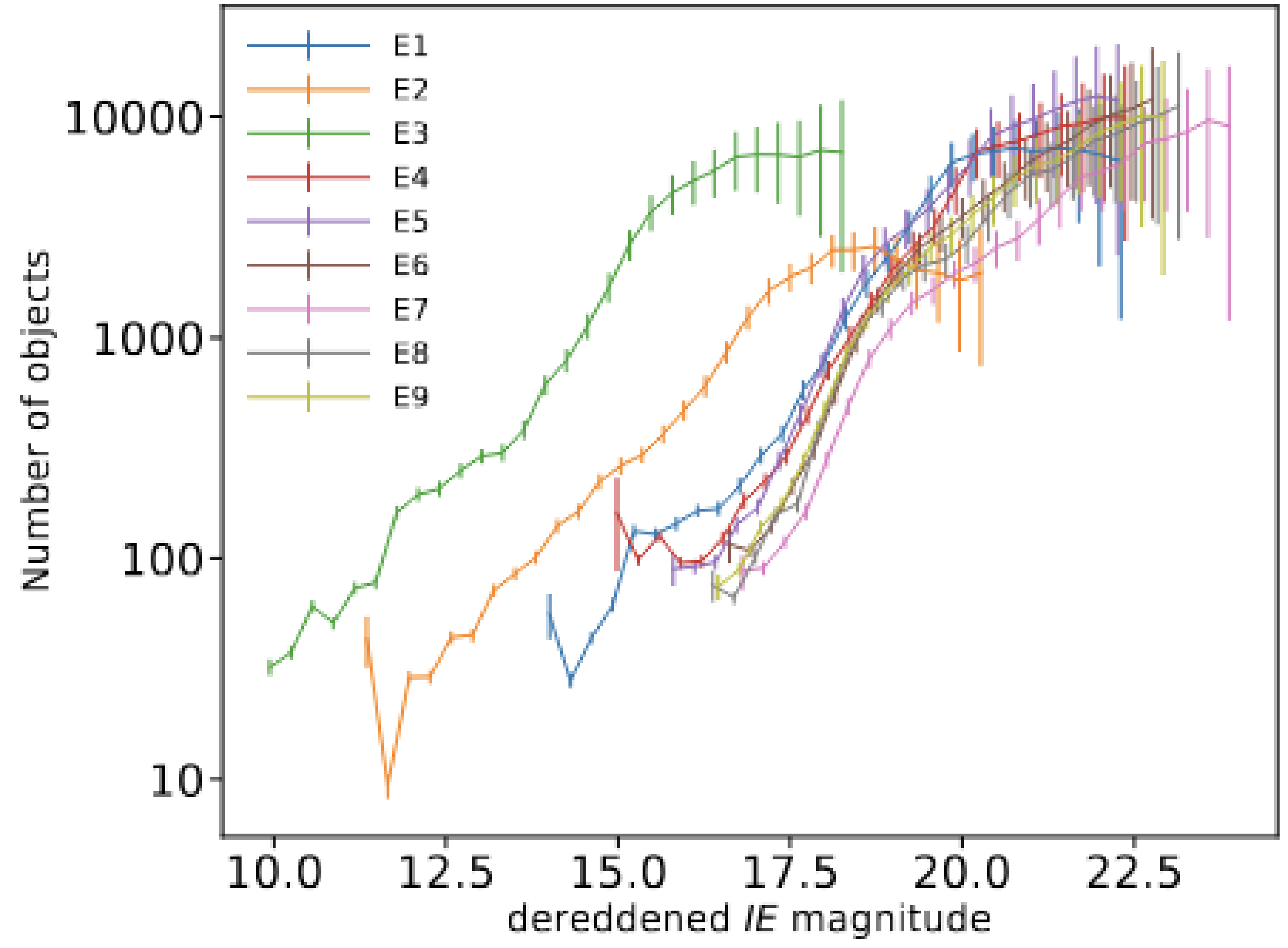
Observed luminosity functions in the center of the 9 fields

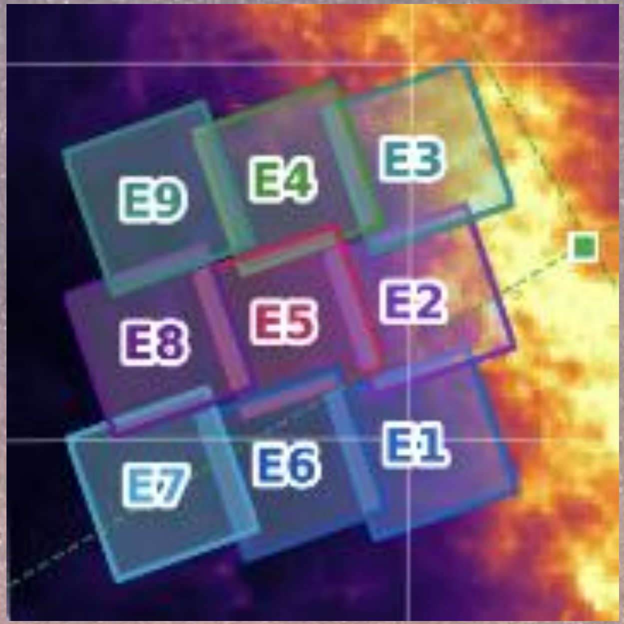


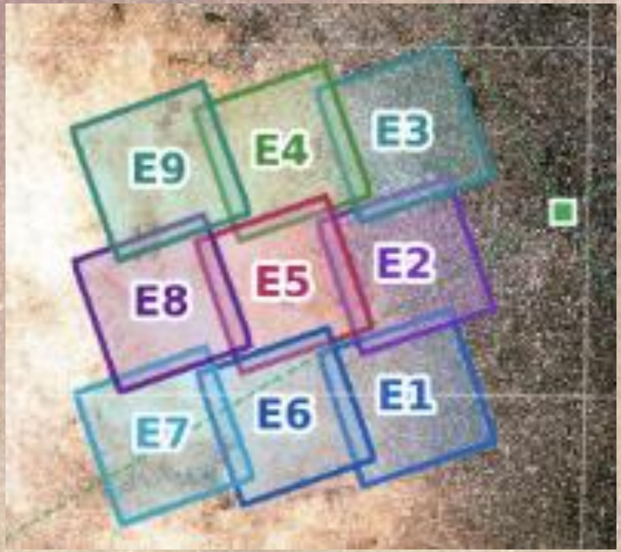




Luminosity function corrected for extinction

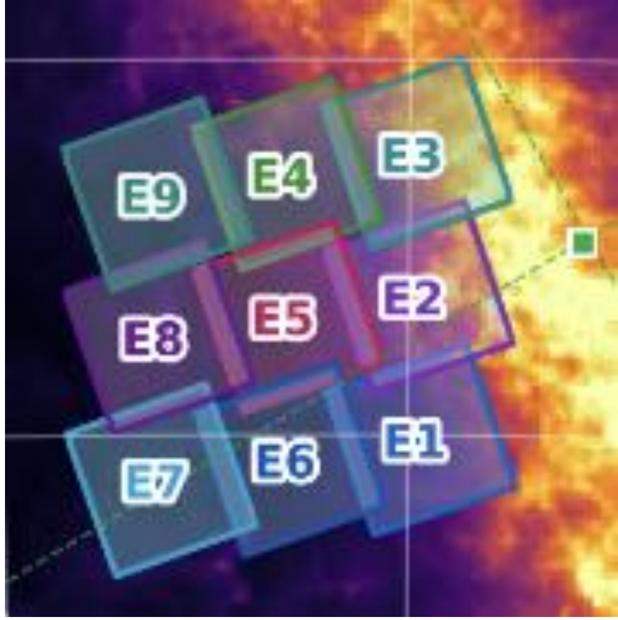




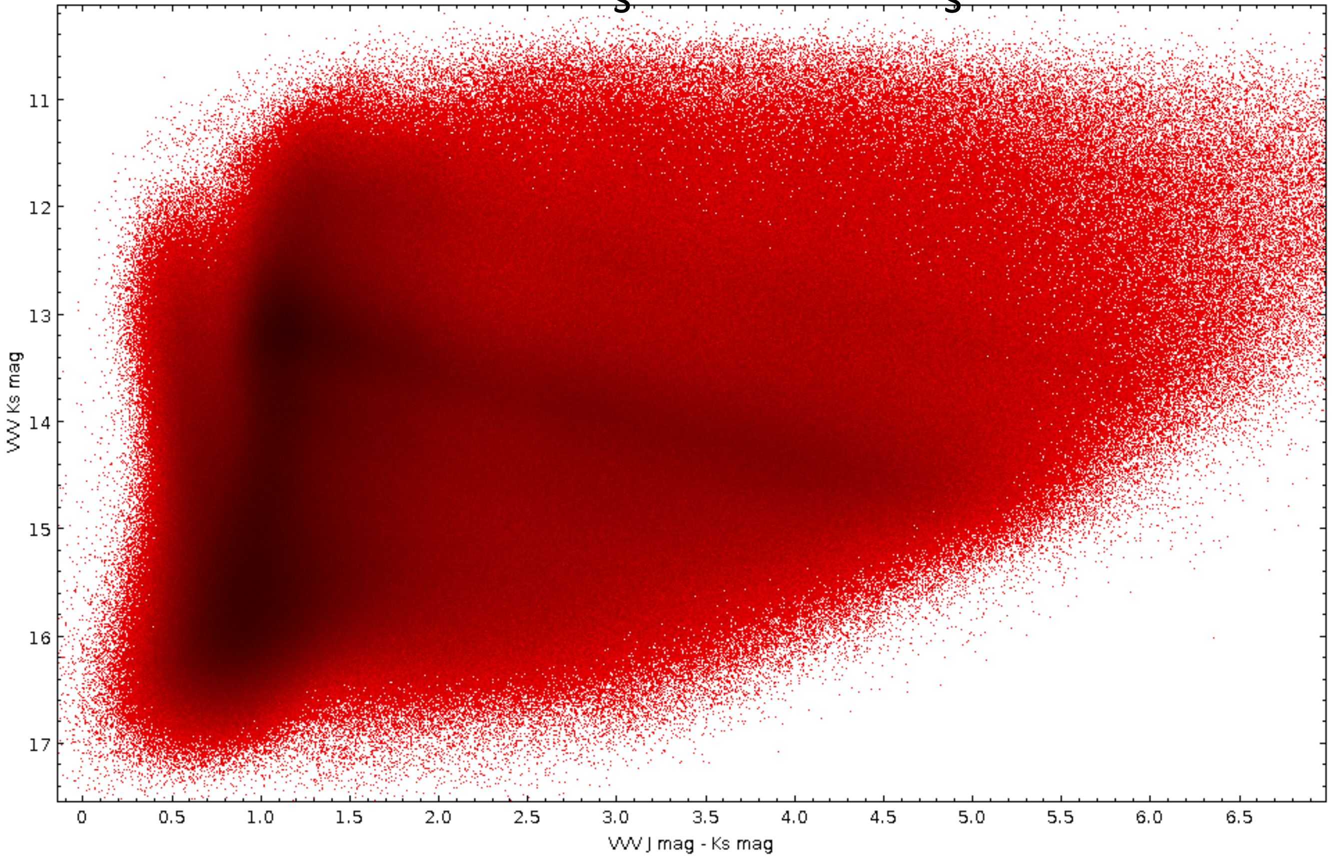


Reprocessed VISTA 4m telescope in JHK, deep OGLE V I, deep CFHT ugri' covering Euclid field

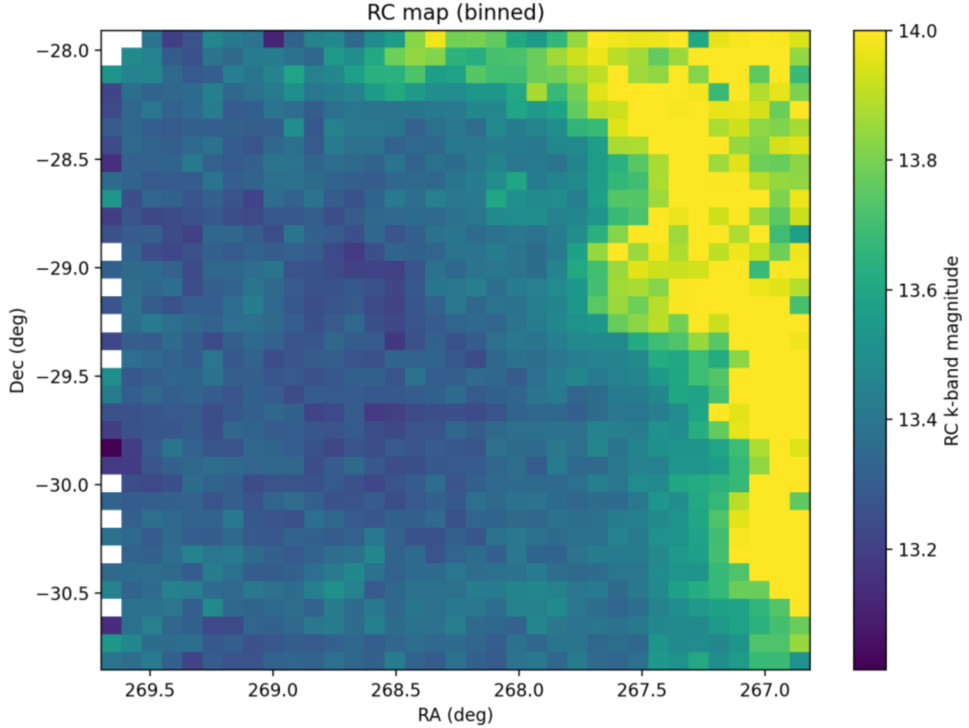
Led by Erica Thygesen



K_s versus J-K_s



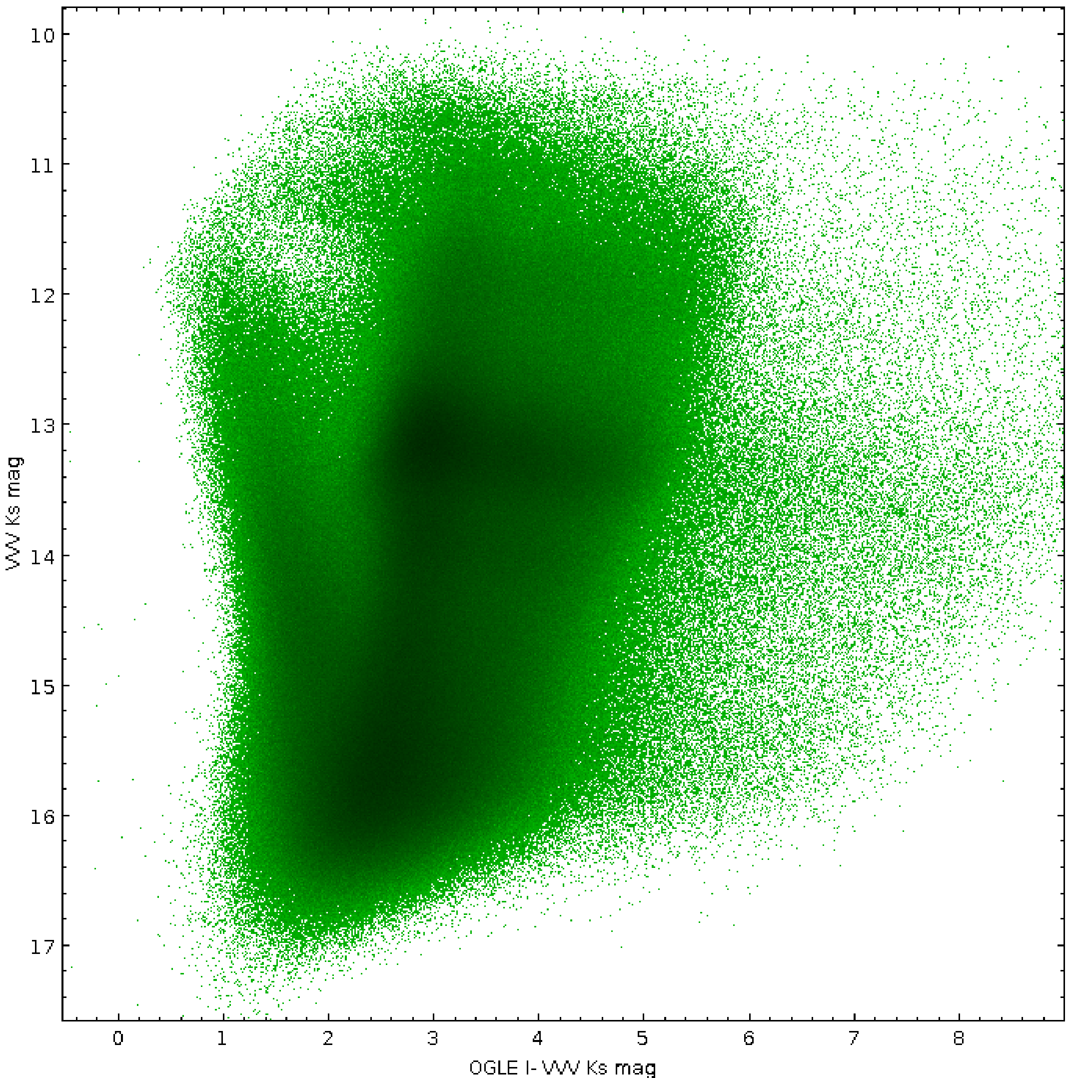
Red clump magnitude in K_s

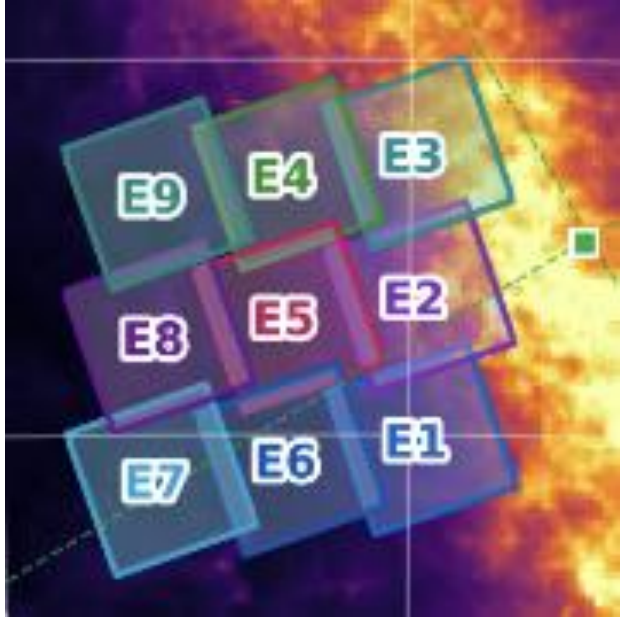


OGLE and VISTA 4m

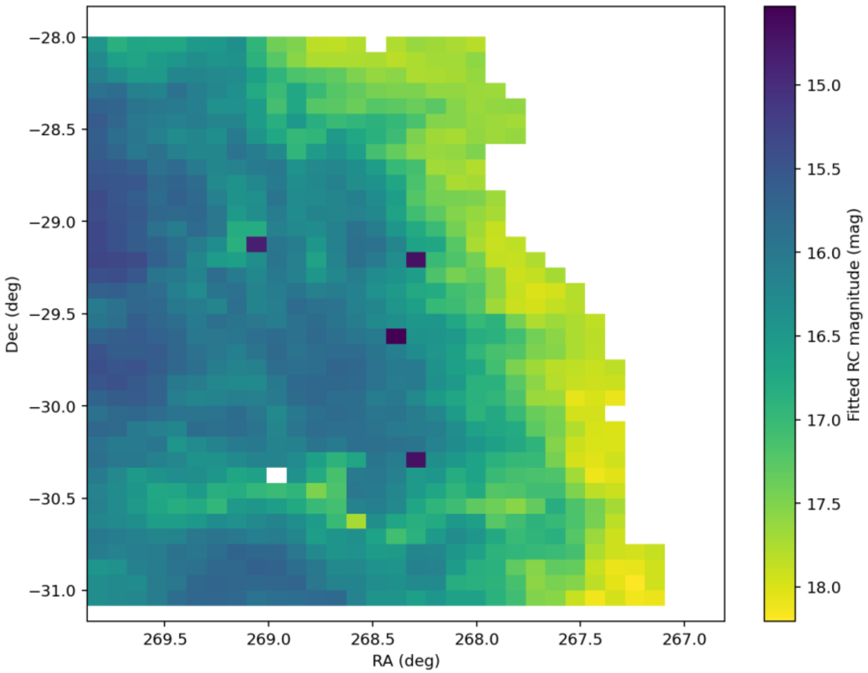
K_s versus I-K_s

Led by Erica Thygesen





Red clump magnitude in I



Searching for rogue Earths

~ 100 rogue planets per month for a 2 deg^2 field.

Bachelet+ 2022, [Euclid-Roman joint microlensing survey: Early mass measurement, free floating planets, and exomoons]()

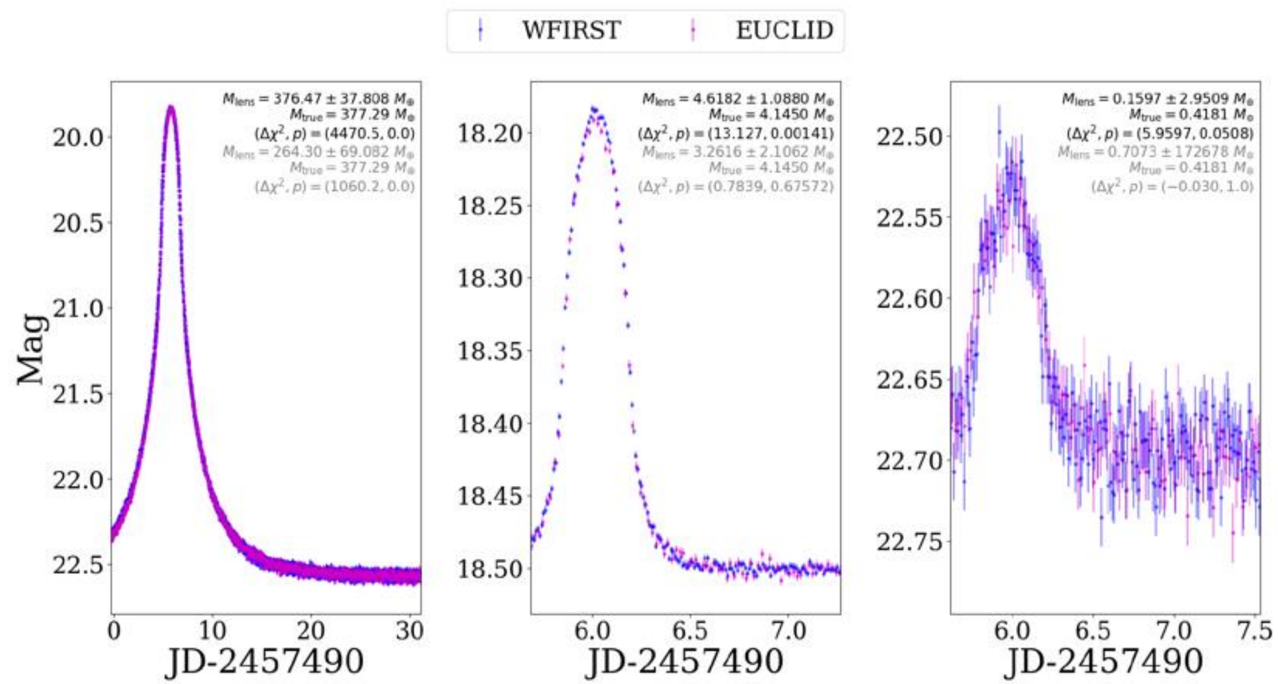
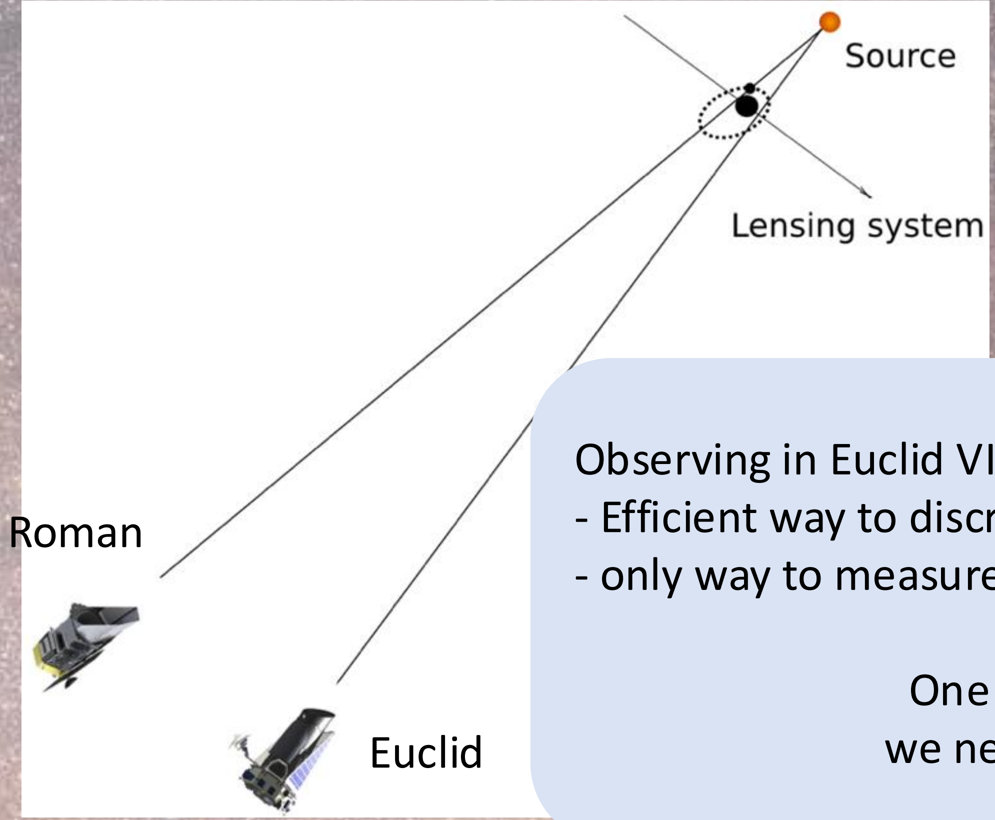
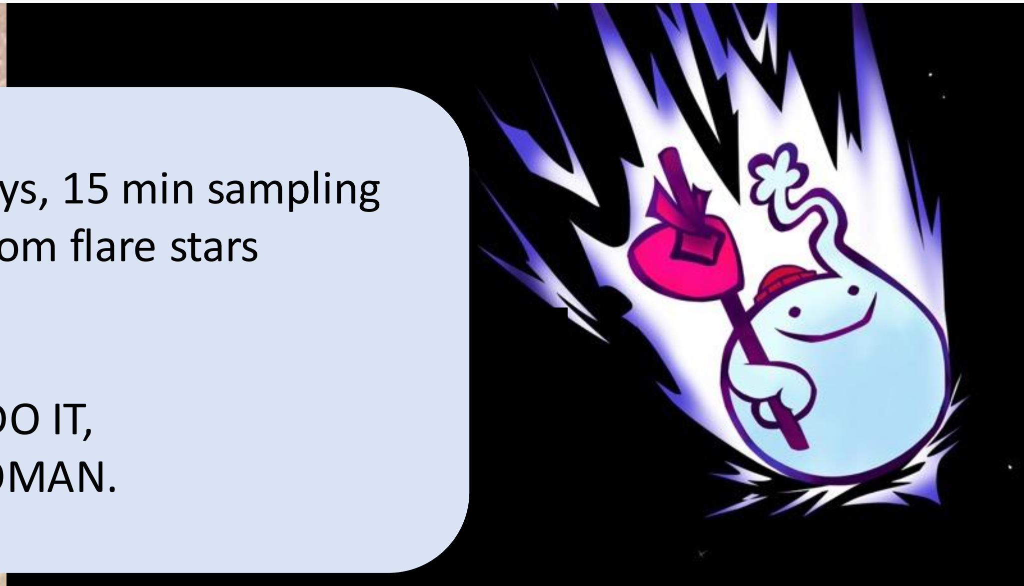


Fig. 1. Three simulated examples of microlensing events due to FFP lenses as seen by EUCLID and ROMAN. Best-fit parameters based only o
data are presented in gray in the top-right of each figure, while shown in black are best-fit solutions using both datasets. Note that the shif
and magnification due to the parallax are too small to be visible. Magnitudes are artificially aligned to the ROMAN system for the plotting



Observing in Euclid VIS and Roman IR for 20 days, 15 min sampling
- Efficient way to discriminate rogue planets from flare stars
- only way to measure masses by parallax

One satellite alone CANNOT DO IT,
we need BOTH EUCLID AND ROMAN.



Take away points, Euclid.

- 9 fields in the Galactic Bulge, very dense, strong extinction, VIS only
- images processed by VIS-PF are excellent (incl. Astrometry and zero points)
- PSF from calibration fields with same solar angles is different from Q1/DR1 PSF.

- *Catalogues in very crowded fields are not to be trusted.*

- Tool in datalab to extract data-cubes (typical 100 x 100 arcsec) developed by Manon Gilles
- Stacking Euclid VIS images
- Some microlensing papers underway (Bozza et al., Rektsini et al.)
- Luminosity function of the fields and star counts (EWG)
- Tool in preparation to built stacks of these cubes (Etienne Bachelet, Himanshu Verma)
- Ground based catalogues CFHT+OGLE+VISTA ugriVIJHK (soon available, Theigessen et al.)

- Long lasting legacy of the EGBS for all microlensing surveys.
- 25 hours of Euclid gives mass measurements for planets to be detected by Roman from 2027
- post-Q2, a time domain survey of the Q2 field for 20 days, simultaeously to Roman is the unique way to measure masses of Rogue Earths.
- Catalogue of 5.2 Sq degree with ugri (CFHT 4m), VI (OGLE), JHK (VISTA) underway.

Some recent papers & Data

Rektsini+2025 **OGLE-2014-BLG-1760: A Jupiter–Sun Analogue Residing in the Galactic Bulge**

Terry+, 2025 **A Candidate High-velocity Exoplanet System in the Galactic Bulge**

Vandorou+, 2025 **MOA-2010-BLG-328: Keck and HST Expose the Limits of Occams Razor in Microlensing**
Vandorou+, 2025 **OGLE-2016-BLG-1195Lb: A Sub-Neptune Beyond the Snow Line of an M-dwarf Confirmed by Keck Adaptive Optics**

Bachelet+ 2022 **Euclid-Roman joint microlensing survey: Early mass measurement, free floating planets, and exomoons**
Beaulieu+ 2026 **Euclid Quick Data Release (Q2) -- The Euclid Galactic Bulge Survey**

Euclid Q2 data release from June 2024

Catalogue of 5.2 sq degree with ugri (CFHT 4m), VI (OGLE), JHK (VISTA) underway (Thygesen+ 2026).