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Microlensing Mass Measurements Using Keck AO, Paving the Road for Euclid and WFIRST

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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

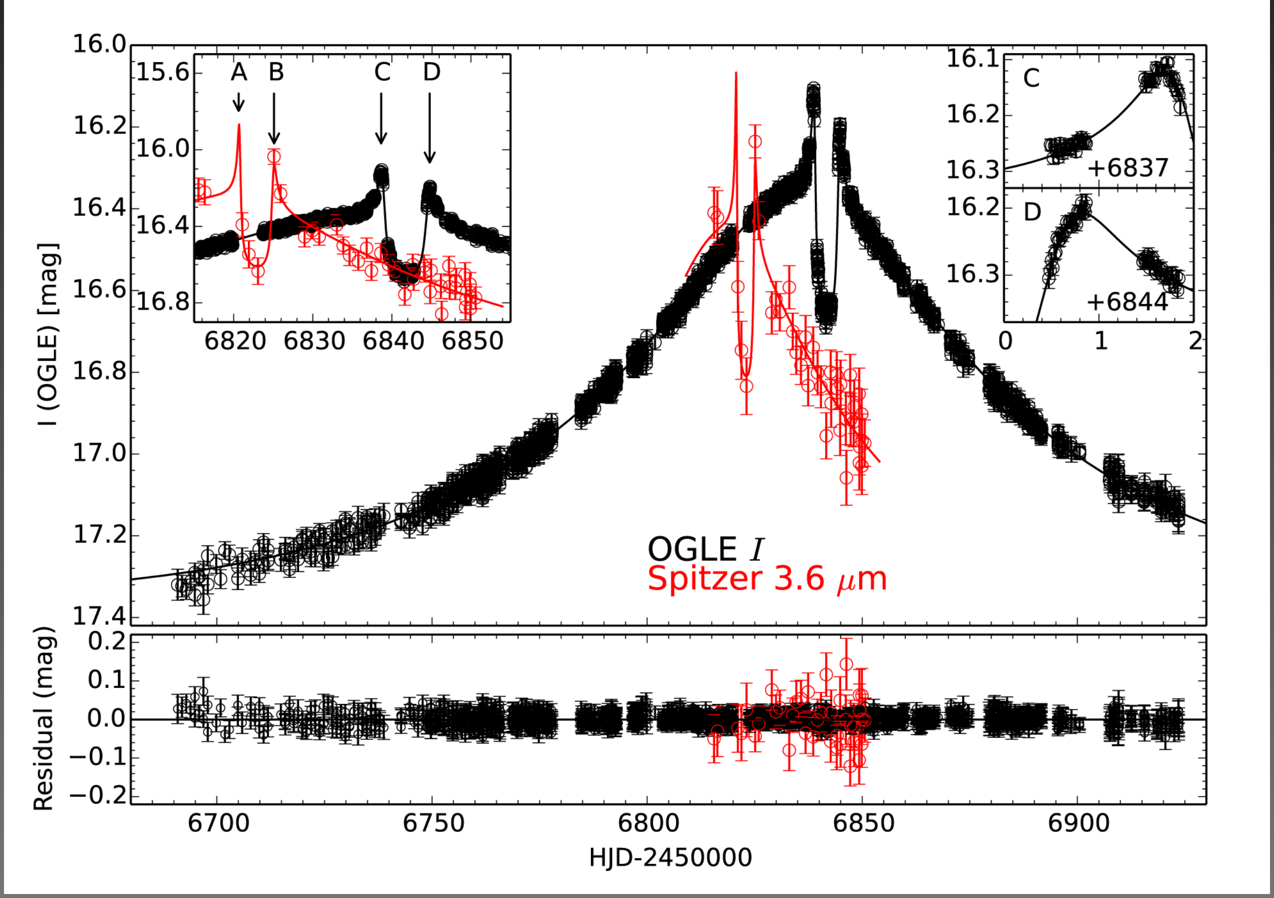
- Masse-distance relation from Parallax measurements

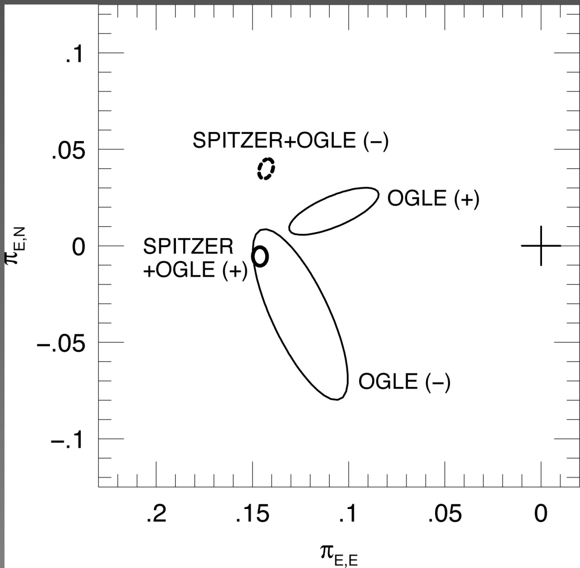
  Ground only is often problematic. Ideal with good-old-Spitzer /K2 !

- 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)

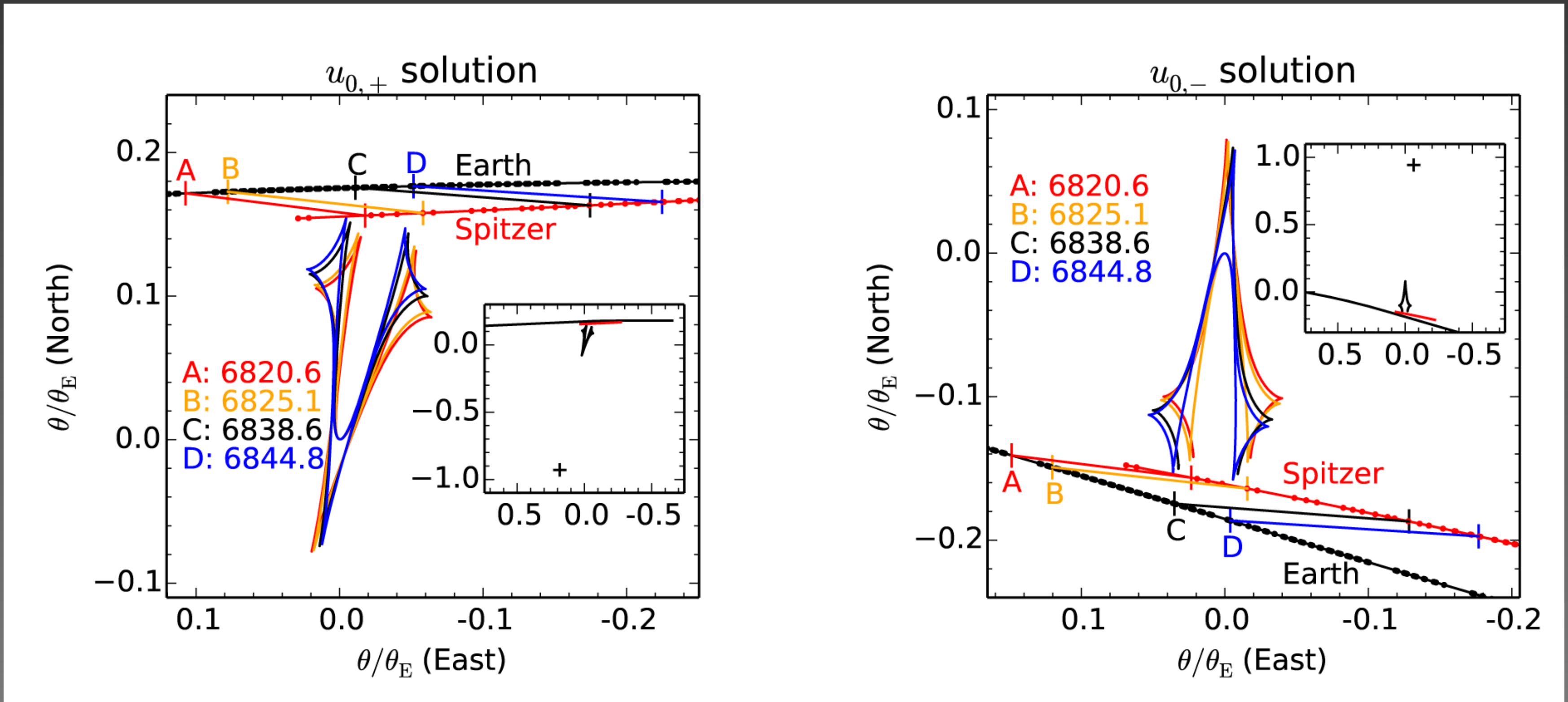
Ogle 2014-BLG-124: ground- Spitzer parallax

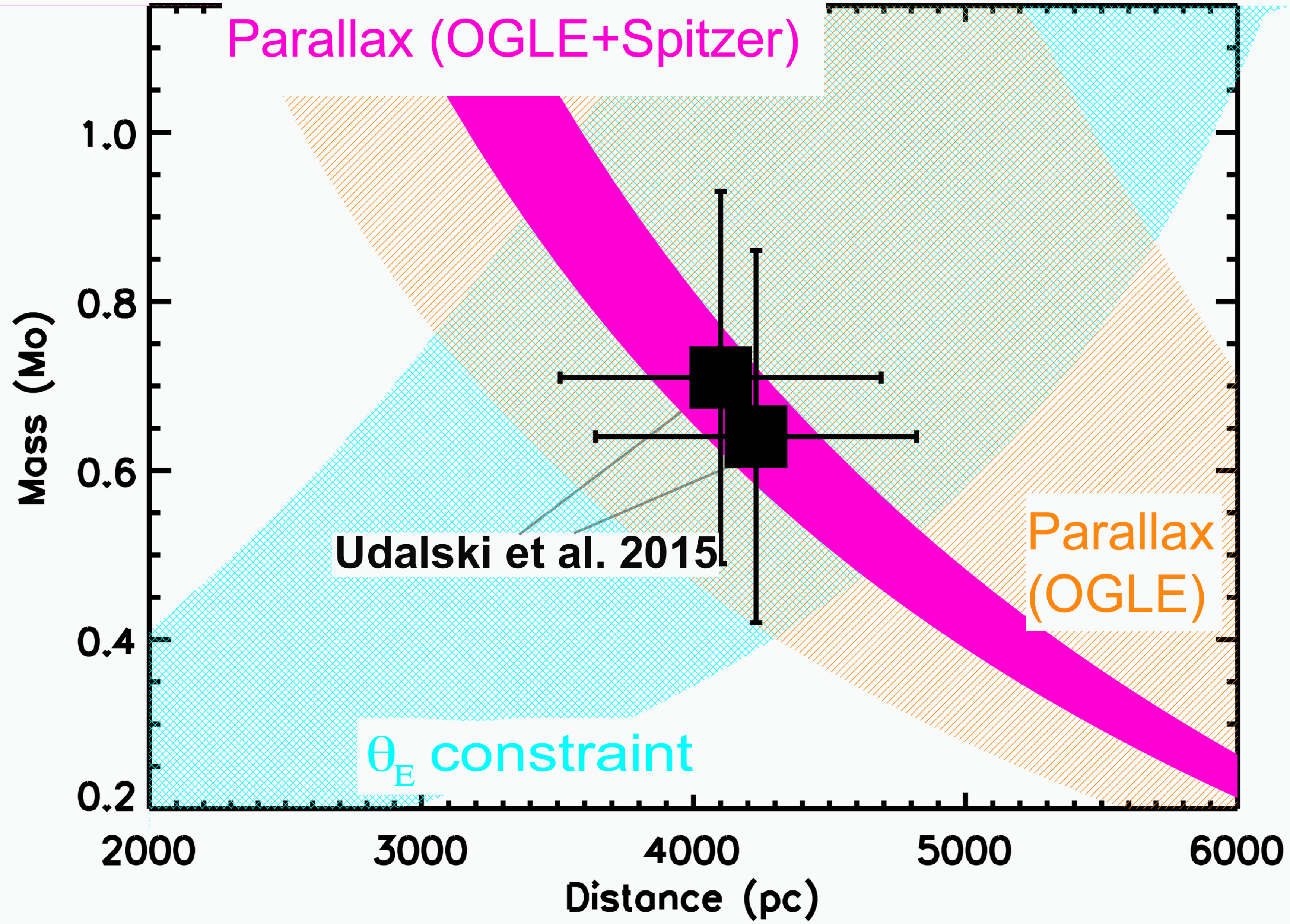




Udalski et al. 2015, Yee et al. 2016

Well constraint Parallax, but no caustic crossing !



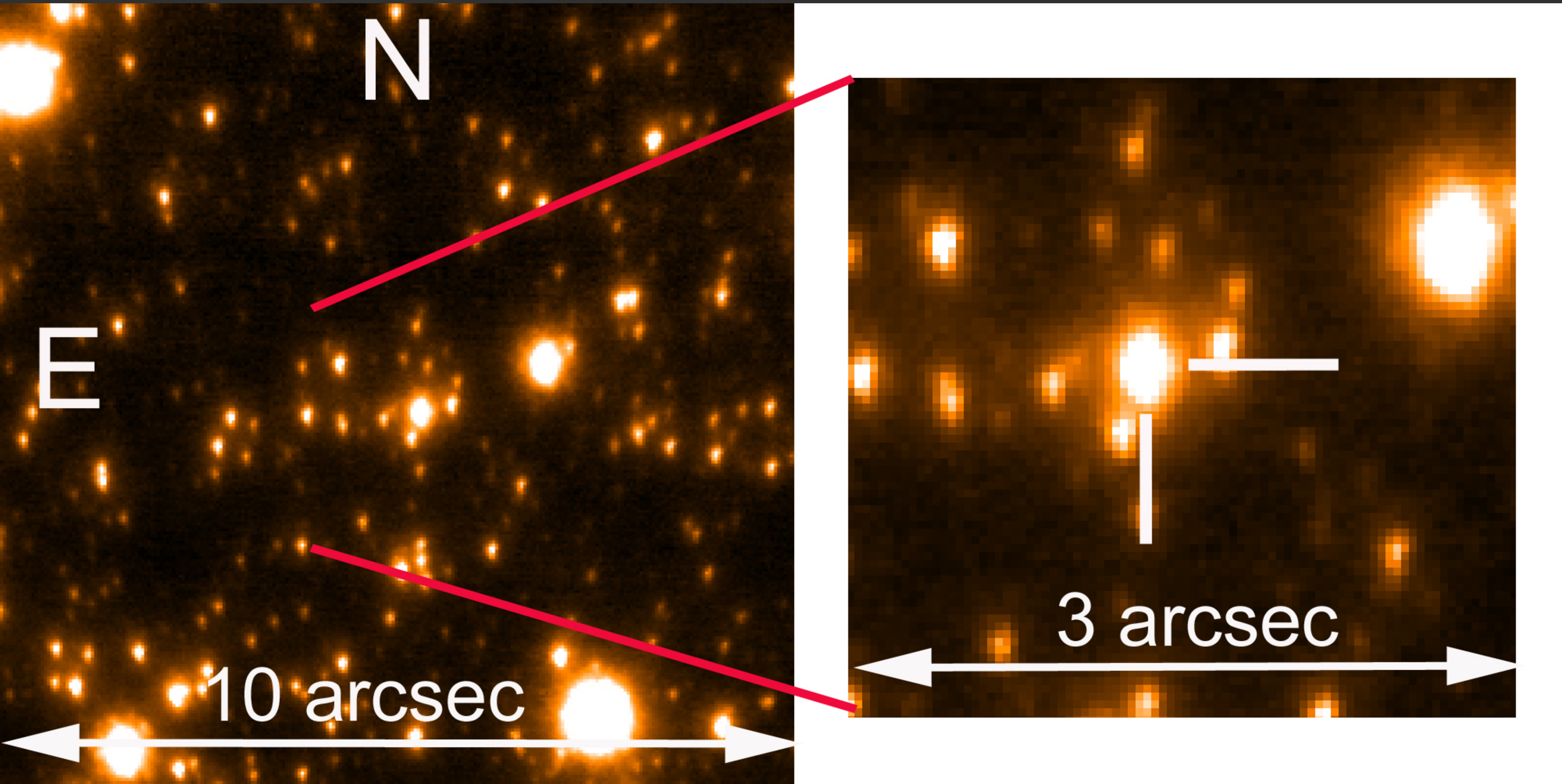


Parallax (OGLE+Spitzer)
1.0
0.8
0.6
0.4
0.2
Mass (Mo)
Udalski et al. 2015
Parallax
(OGLE)
θE constraint
2000
3000
4000
5000
6000
Distance (pc)

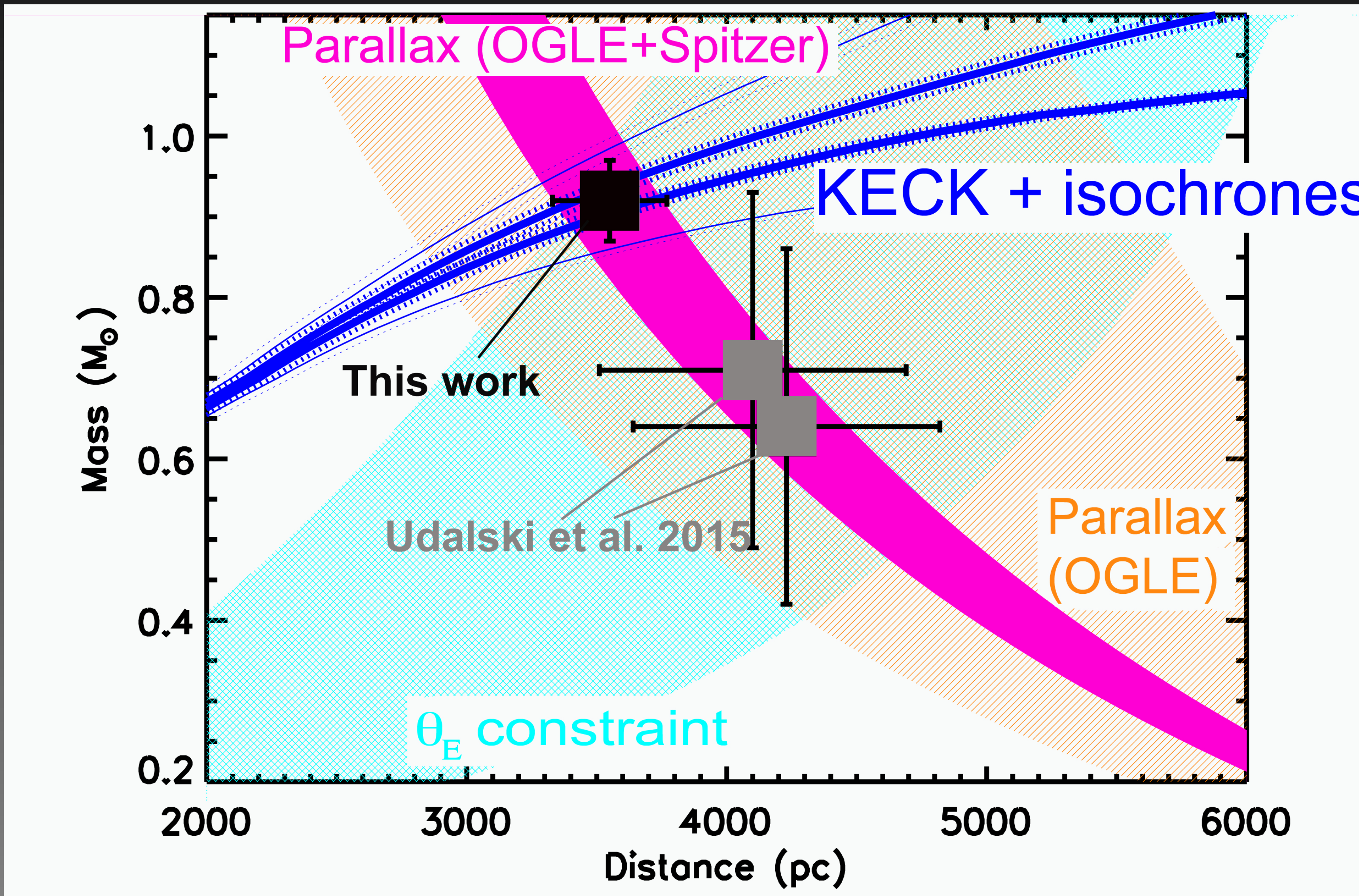
Source & lens are aligned

Source predicted H=17.04 ±0.05

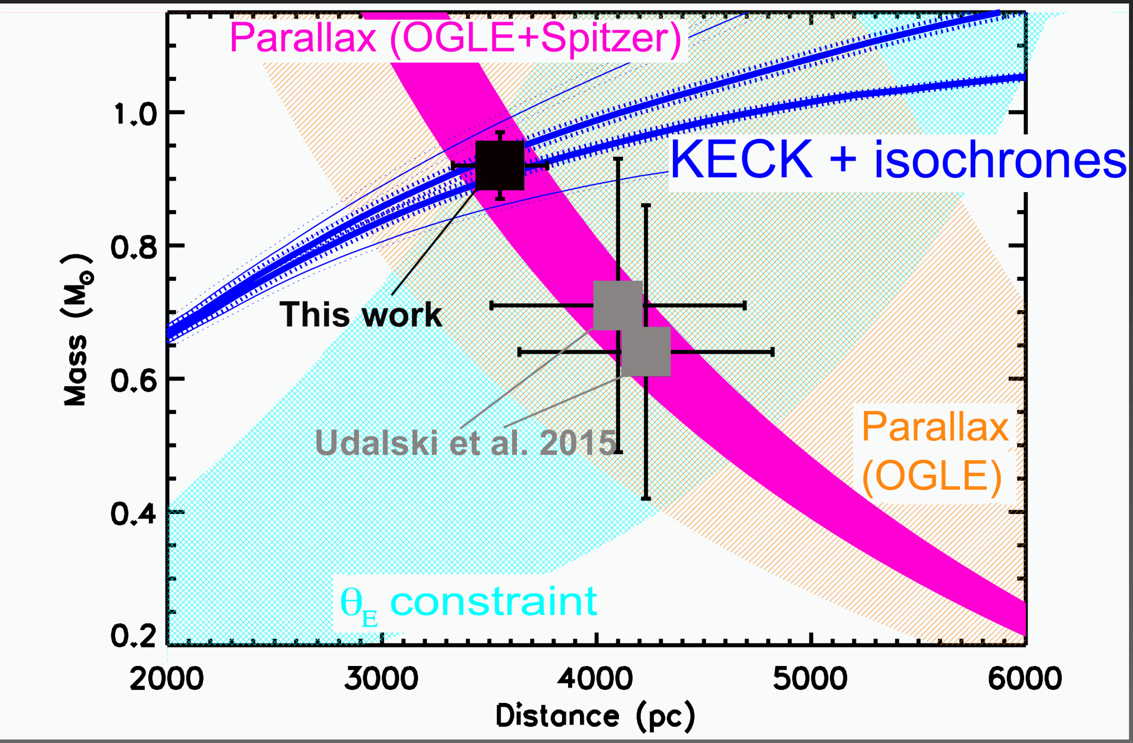
Source +blend measured at H=15.95 ±0.03, So the blend is H=16.45 ±0.06



Additional flux detected !
We have a new mass-distance relation



If all 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

Host star mass: 0.91 ± 0.05 M☉

Planet mass: 0.65 ± 0.06 $M_{Jupiter}$

Distance D_L = 3.5 ± 0.2 kpc

Is all the excess light coming from the lens ?

On going refined study by Virginie Batista.

Flux excess is an upper limit.

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

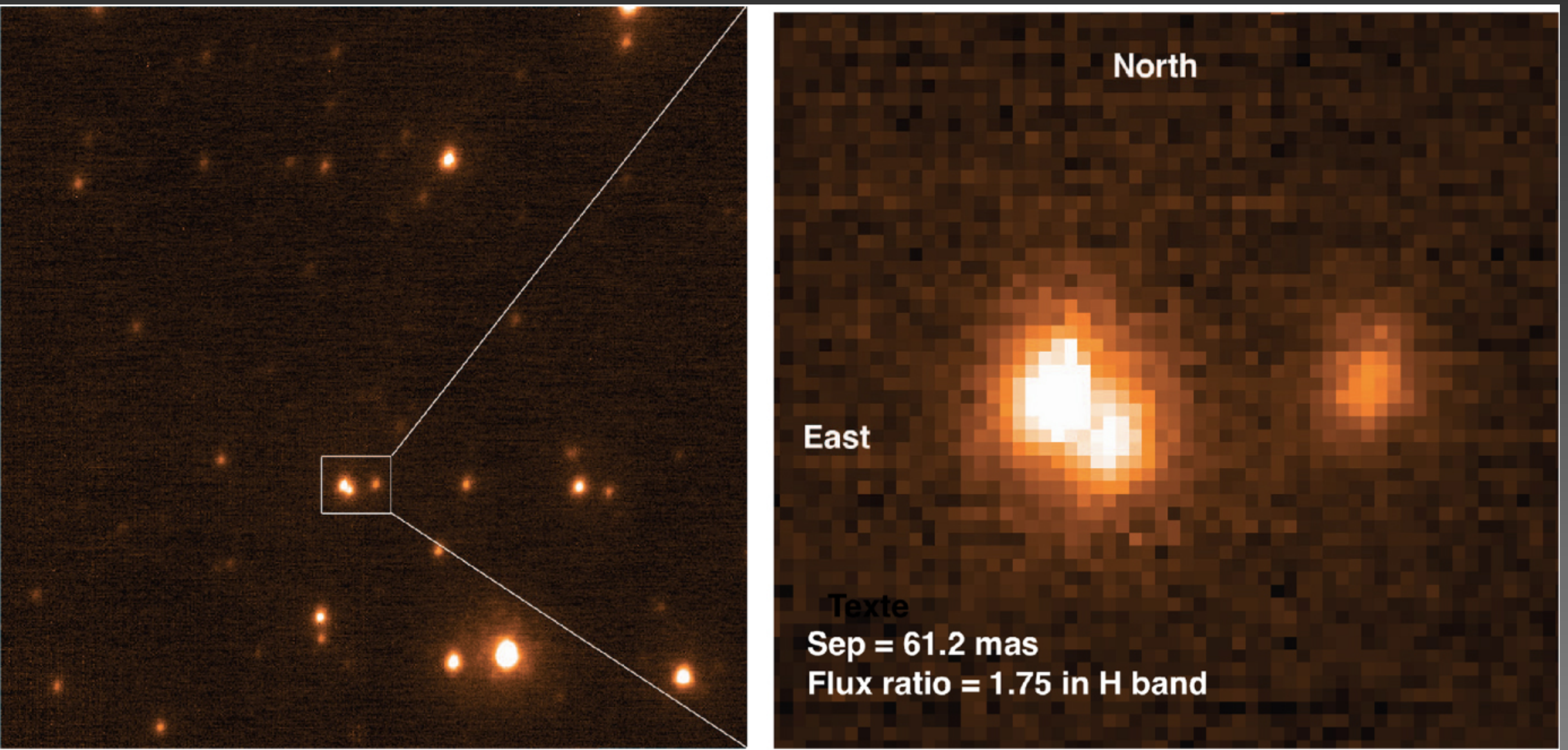
1/ Blend = lens
2/ Blend = lens + chance aligned star
3/ Blend = lens + companion to the lens (not affecting the light curve)
4/ Blend = lens + companion to the source
(and any combination of 2, 3, 4)

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

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

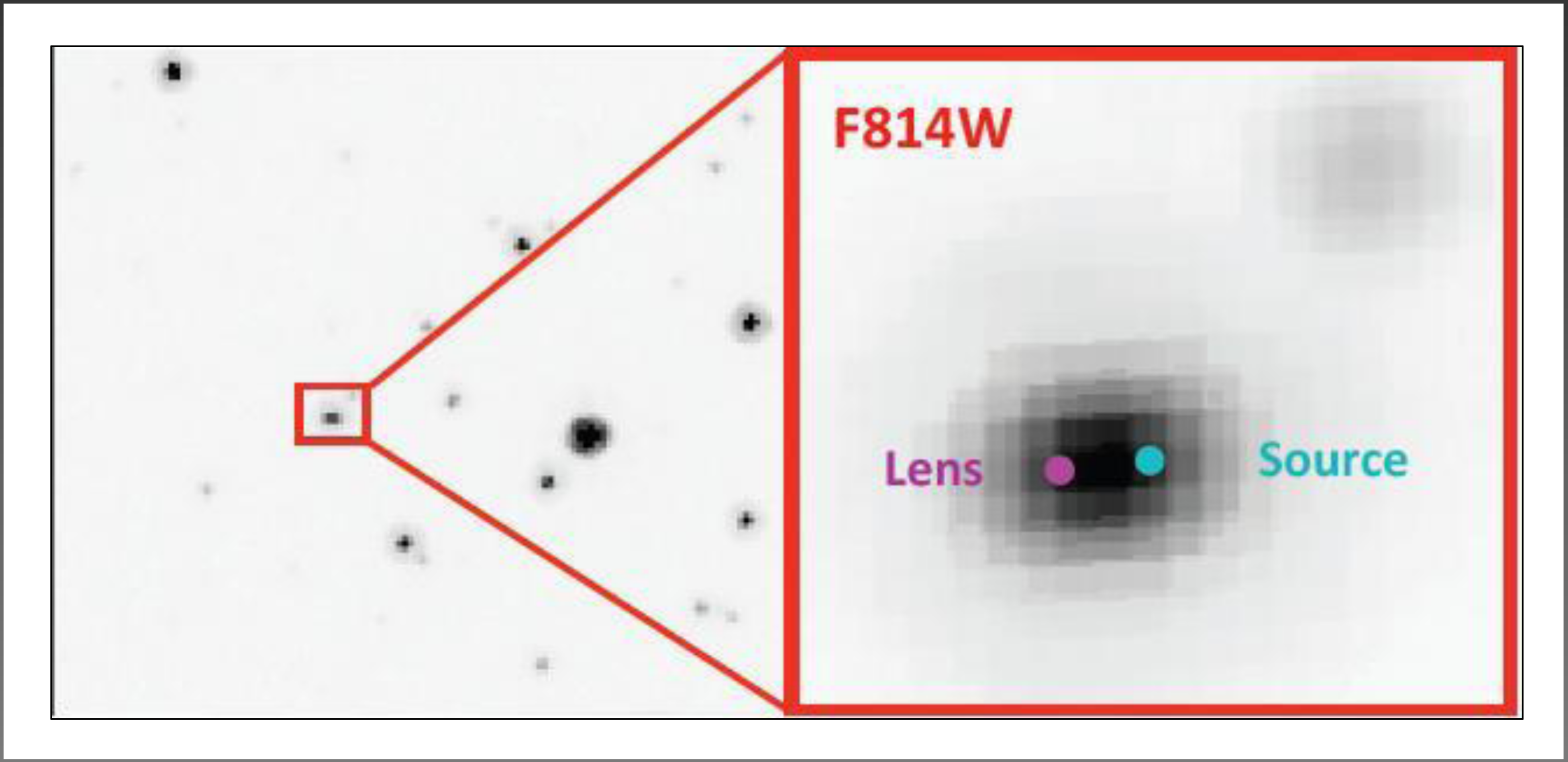
With KECK, detecting the lens in 2013
Measuring proper motion

Batista et al., 2015



HST : 6.5 years aftr the event

Bennett et al., 2015, Aparna's talk



Detecting source & lens, measuring proper motion

Gould et al. 2006

Initial paper & preductions

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 ?

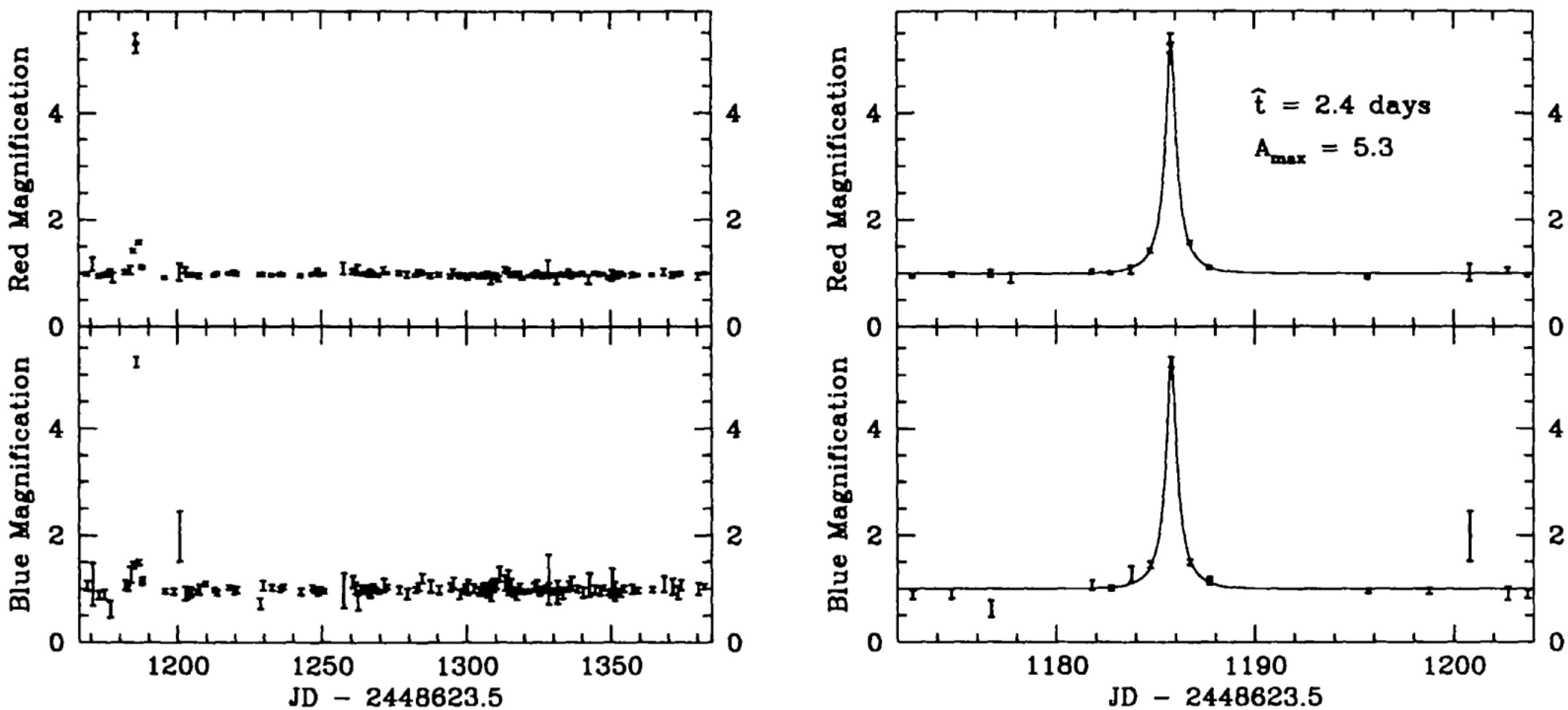
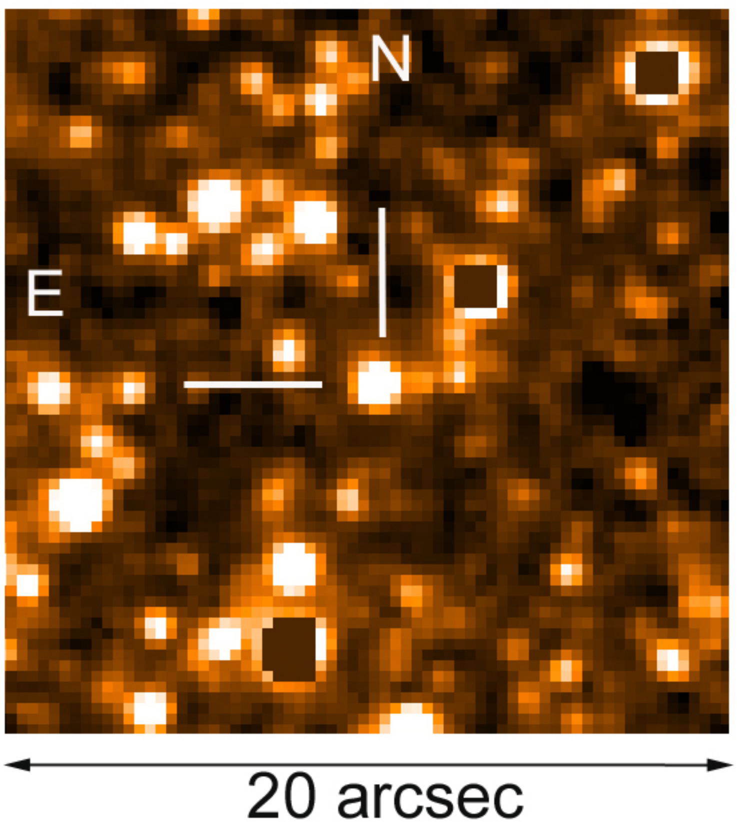
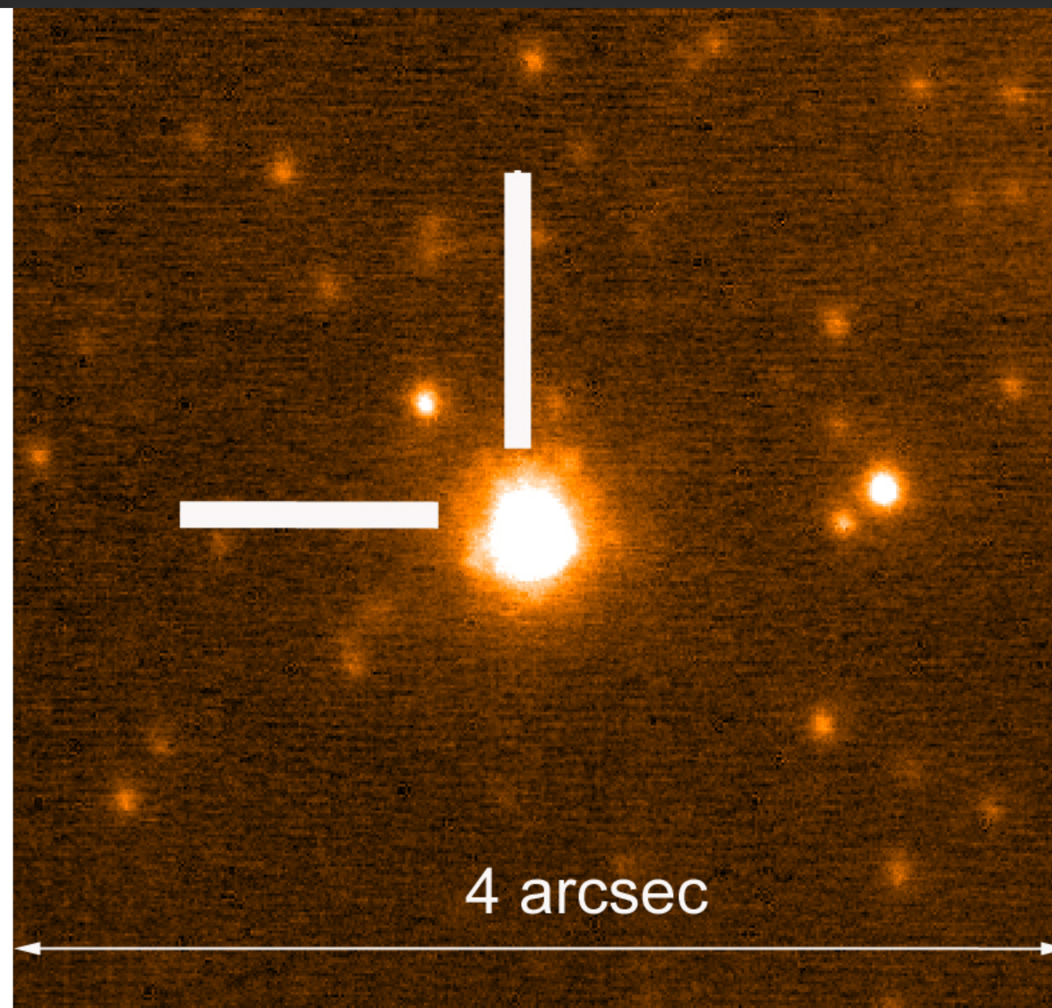


Figure 2. The dual-color light curve of event 95-BLG-3 during the 1995 Galactic bulge season and a close-up of the light curve showing the lens fit.

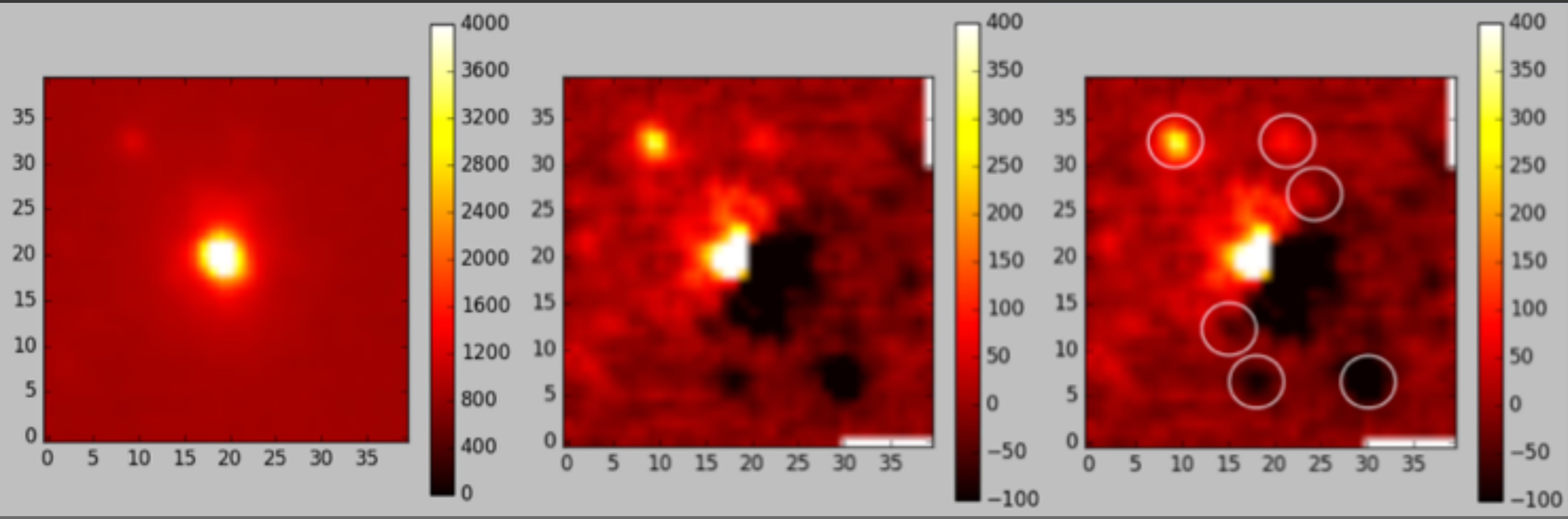
MACHO-95-BLG-3





3 companions, 0.6, 0.4, 0.3 arcsec

With Marie Ygouf, CALTECH



Free-floating planet ? Probably not...

Lessons / Work to do
KECK, SUBARU, Euclid, WFIRST

- It is numerology, so have 2 people reducing same datasets.
- 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

Euclid Microlensing survey

Beaulieu, Kerins, et al.

3 fields observed every 17 min in H, every 12 hours in VIS, J, Y.
Mini-survey during commissionning (24h), then 4 x 1 months survey

- Measuring cold Earth abundance and mass function

  ~35 planets / month (5 Earth / month, 15 Neptune / month)

- Getting constraints on free floating planets

  ~15 free-floating planets / month

- EUCLID/ML complements parameter space probed by RV and KEPLER

Measuring the cold planet mass function below 1 Earth mass.

- Possibility of simultaneous EUCLID-WFIRST in the extended mission 2026+
  (parallax between EUCLID and WFIRST to measure masses of Earth mass free floaters)

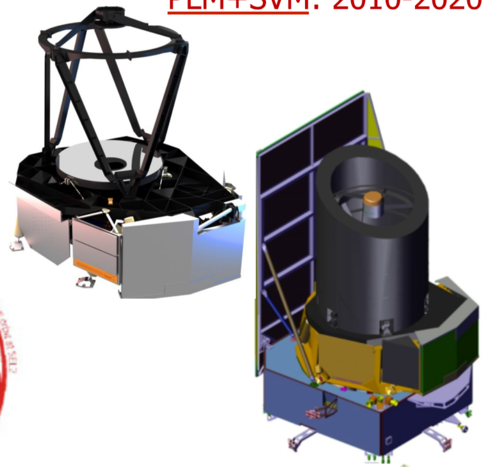
Penny et al., 2013 MNRAS 434, 2

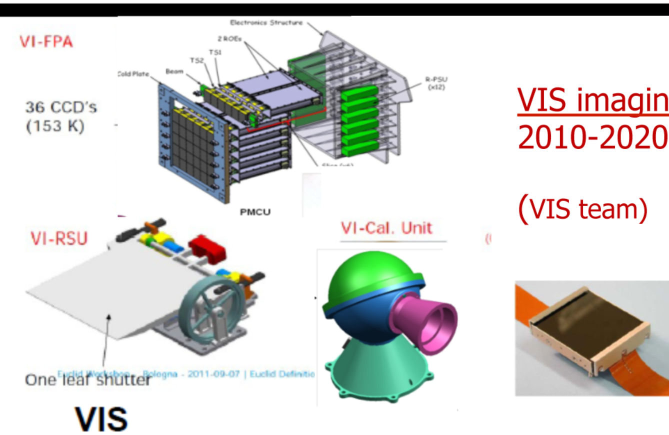
The ESA Euclid space mission

Soyuz@Kourou

Launch date: Dec 2020

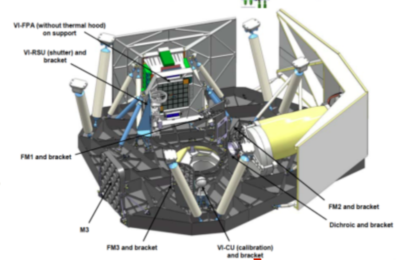
PLM+SVM: 2010-2020





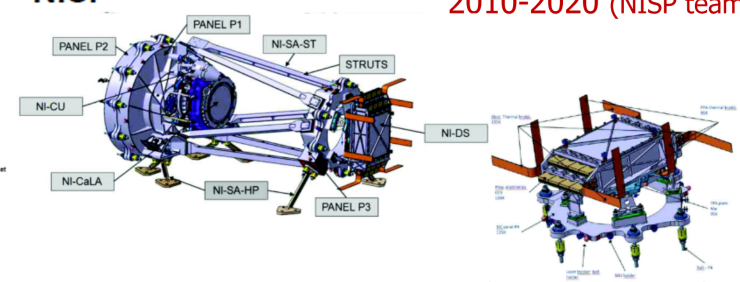
VIS imaging: 2010-2020

(VIS team)

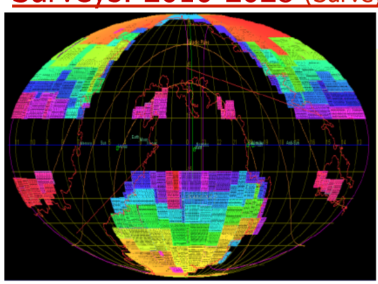


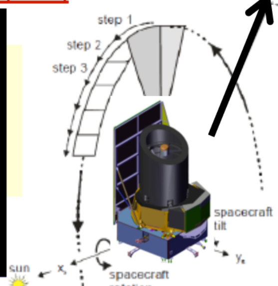
NIR spectro-imaging

2010-2020 (NISP team)



Surveys: 2010-2028 (Survey WG)





Survey duration: 6 yrs

15,000 deg²

Commisionning – SV

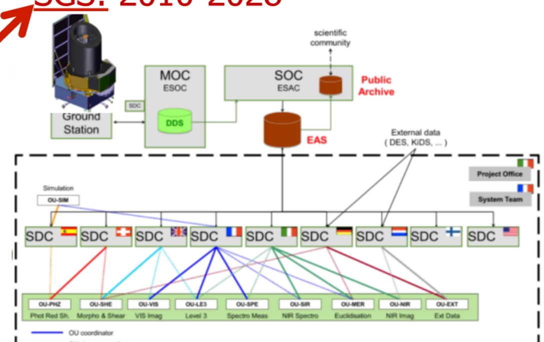
Euclid opération:

5.5 yrs:Euclid Wide+Deep

+: SNIa, mu-lens, MW?

Ground data

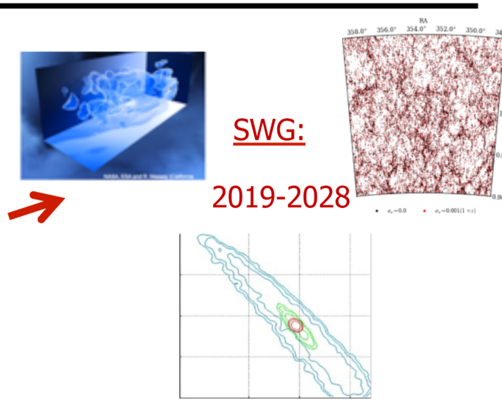
SGS: 2010-2028



~100 PB data processing (EC-SGS team)

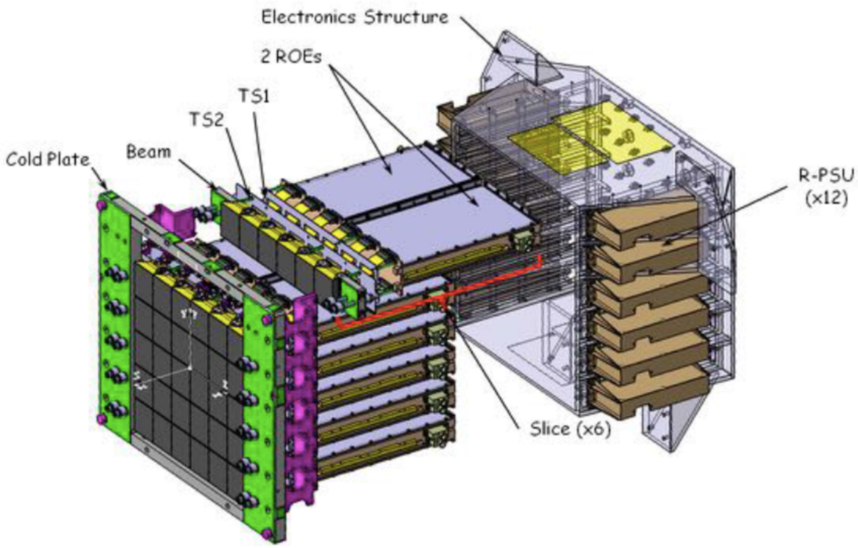
SWG:

2019-2028



Science analyses

VIS

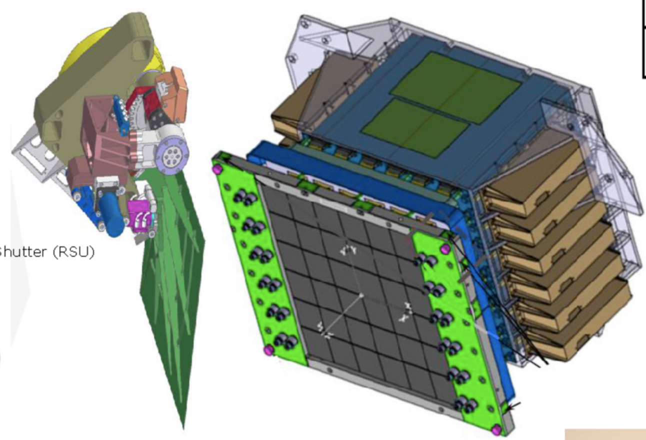


Courtesy: S. Pottinger, M. Cropper and the VIS team

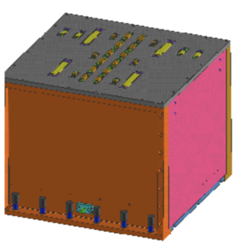
Table 1: VIS and weak lensing channel characteristics

Spectral Band	550 – 900 nm
System Point Spread Function size	≤0.18 arcsec full width half maximum at 800 nm
System PSF ellipticity	≤15% using a quadrupole definition
Field of View	>0.5 deg^2
CCD pixel sampling	0.1 arcsec
Detector cosmetics including cosmic rays	≤3% of bad pixels per exposure
Linearity post calibration	≤0.01%
Distortion post calibration	≤0.005% on a scale of 4 arcmin
Sensitivity	$m_{AB} \geq 24.5$ at 10σ in 3 exposures for galaxy size 0.3 arcsec
Straylight	≤20% of the Zodiacal light background at Ecliptic Poles
Survey area	15000 deg^2 over a nominal mission with 85% efficiency
Mission duration	6 years including commissioning
Shear systematic bias allocation	additive $\sigma_{sys} \leq 2 \times 10^{-4}$; multiplicative $\leq 2 \times 10^{-3}$

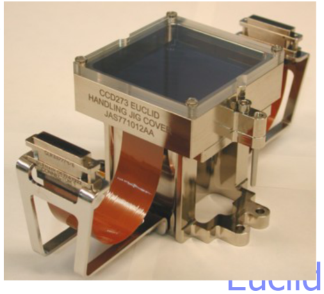
Cropper et al 2016.SPIE

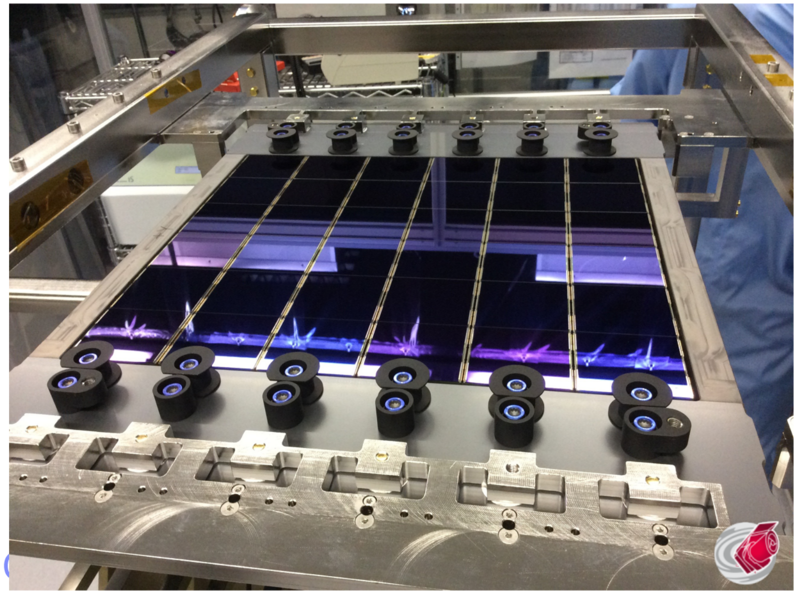


Warm Units in Service Module



Payload and Mechanism Control Unit (PMCU)

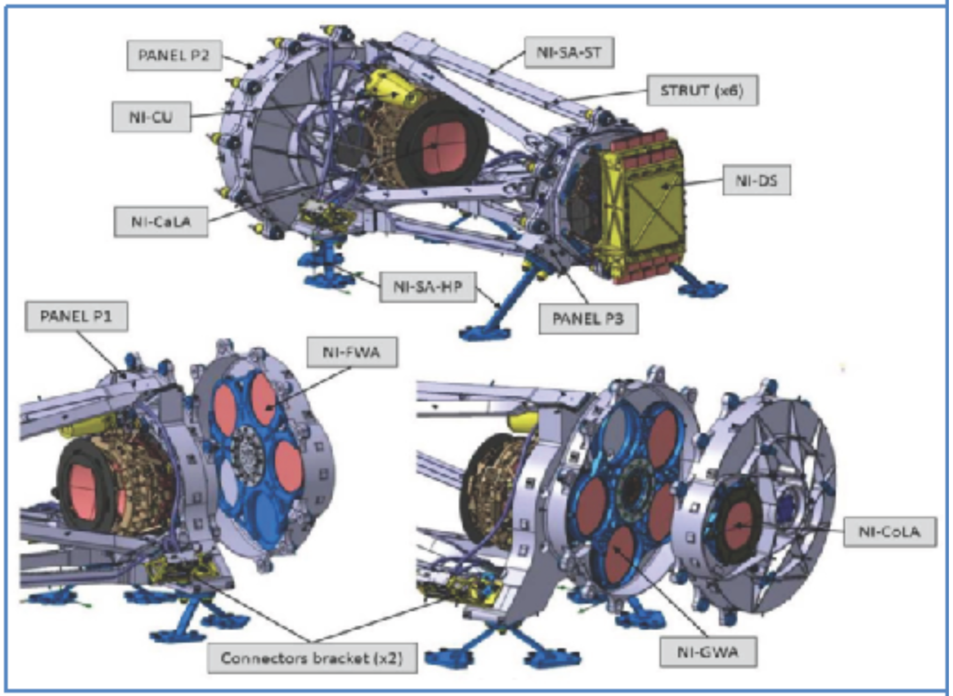


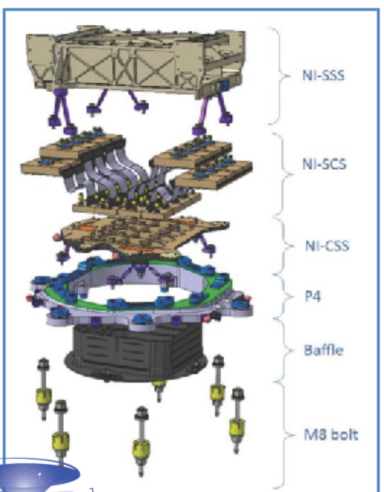


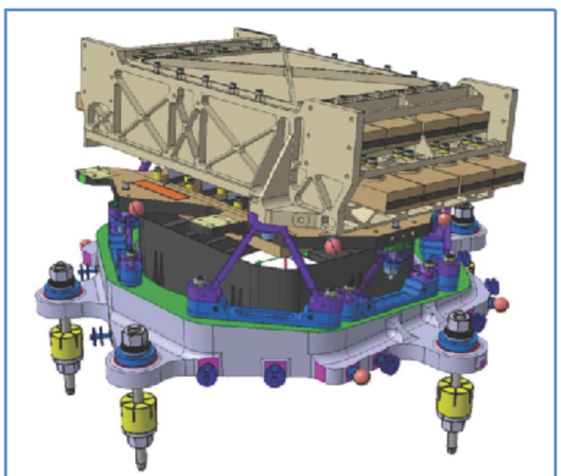
Euclid C

NISP

Courtesy: T. Maciaszek and the NISP team







- FoV: 0.55 deg^2
- Mass : 159 kg
- Telemetry: < 290 Gbt/day
- Size: 1m x 0.5 m x 0.5 m
- 16 2kx2K H2GR detectors
- 0.3 arcsec pixel on sky
- Limiting mag, wide survey AB : 24 (5 σ)
- **3 Filters**:
- Y (950-1192nm)
- J (1192, 1544nm)
- H (1544, 2000nm)
- **4 grisms**:
- 1B (920 – 1300) , 1 orientation 0°
- 3R (1250 – 1850), 3 orientations 0°, 90°, 180°

Maciaszek et al 2016:SPIE