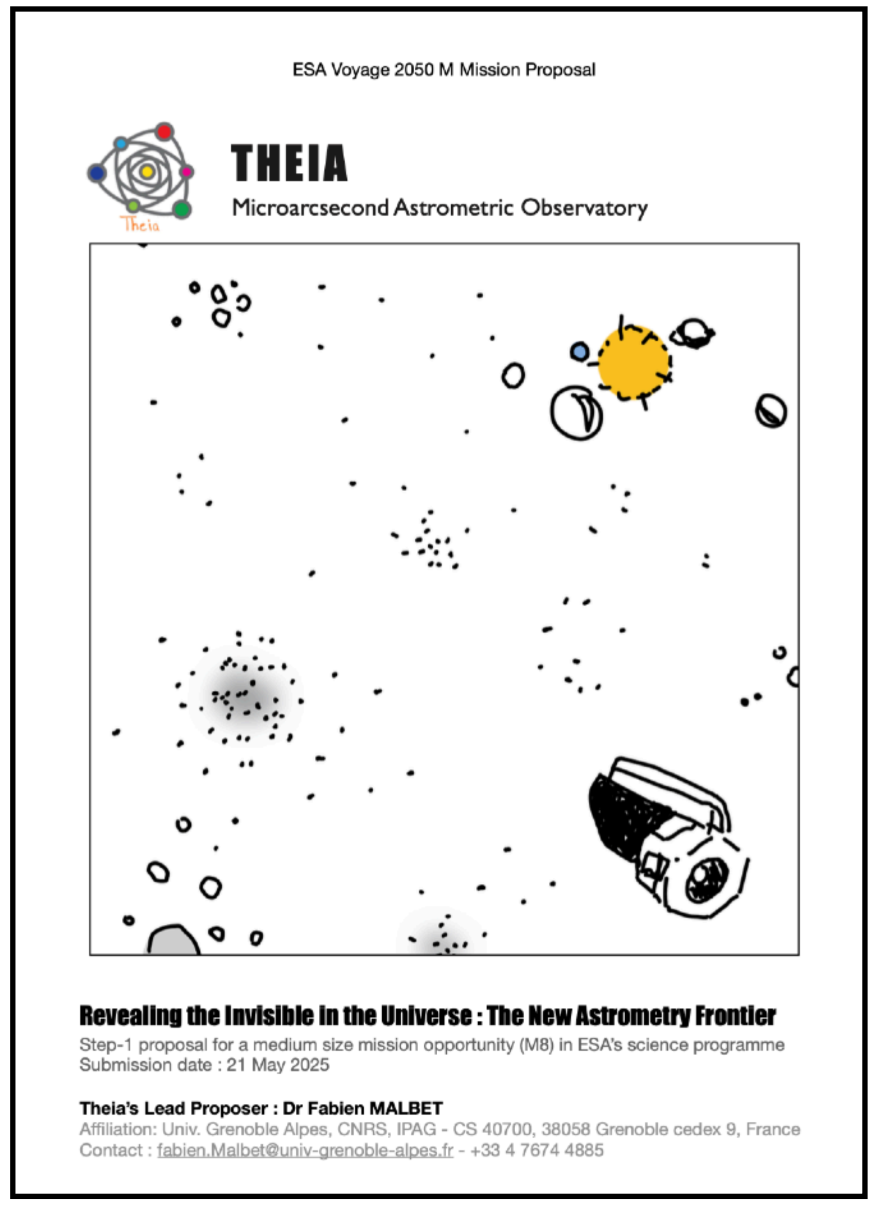
Metrology studies for high precision astrometry in Theia / HWO

Fabien MALBET
IPAG / Univ. Grenoble Alpes / CNRS

w*ith M. Lizzana, F. Pancher, S. Soler, H. Rousset, Y. Er-Rahmaouy, Y. Bakka @IPAG*
and A. Léger, (IAS) T. Lépine (IOGS/University. St-Etienne), A. Sozzetti (INAF Torino), L. Labadie (University. Köln)

Technical workshop of the Milky Way-Gaia Doctoral Network - Cambridge, 15/16 July 2025


ESA Voyage 2050 M Mission Proposal

THEIA

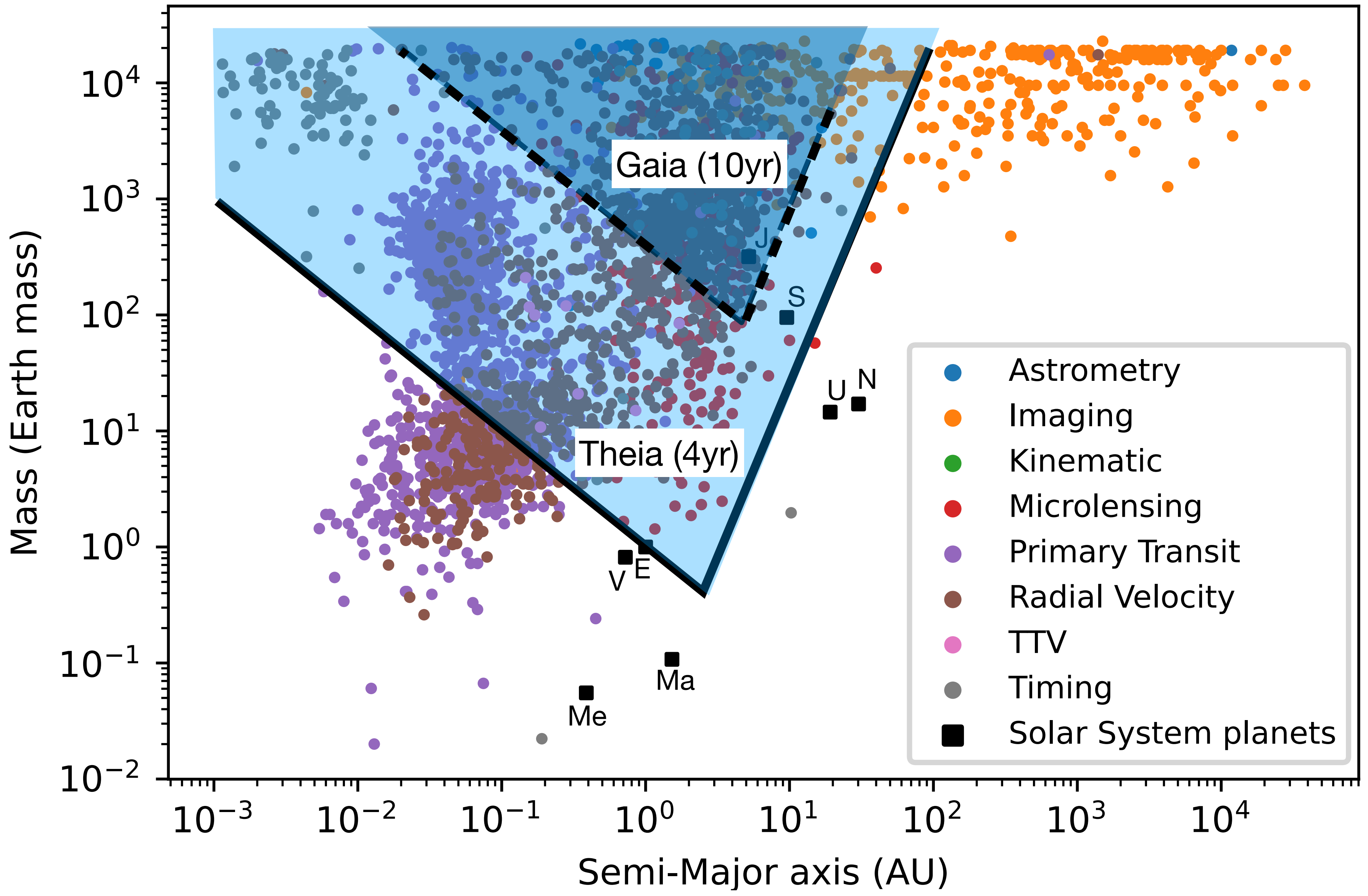
Microarcsecond Astrometric Observatory

Revealing the Invisible in the Universe : The New Astrometry Frontier

Step-1 proposal for a medium size mission opportunity (M8) in ESA's science programme
Submission date : 21 May 2025

Theia's Lead Proposer : Dr Fabien MALBET
Affiliation: Univ. Grenoble Alpes, CNRS, IPAG - CS 40700, 38058 Grenoble cedex 9, France
Contact : fabien.Malbet@univ-grenoble-alpes.fr - +33 4 7674 4885

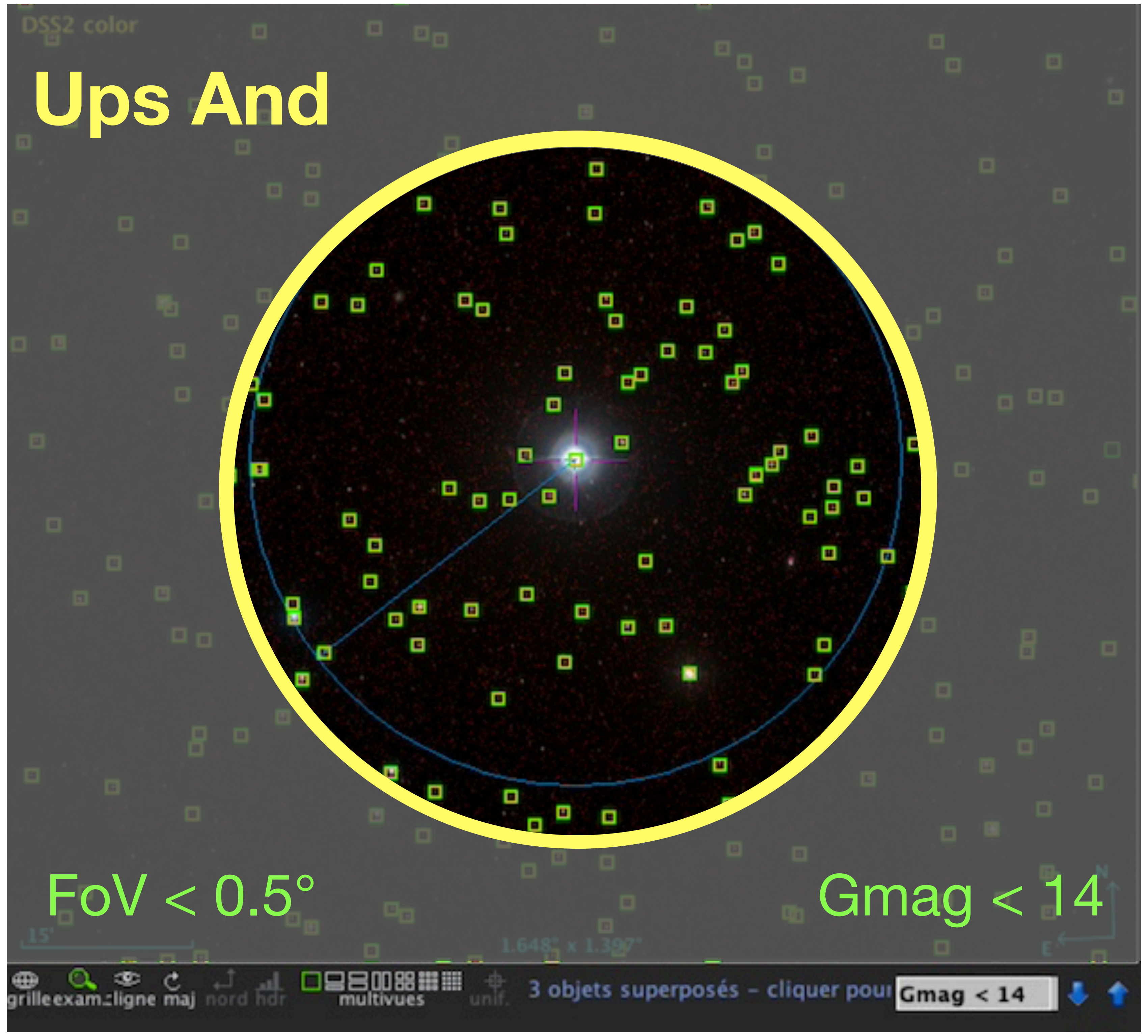
Theia proposal for ESA M8



Context of the studies

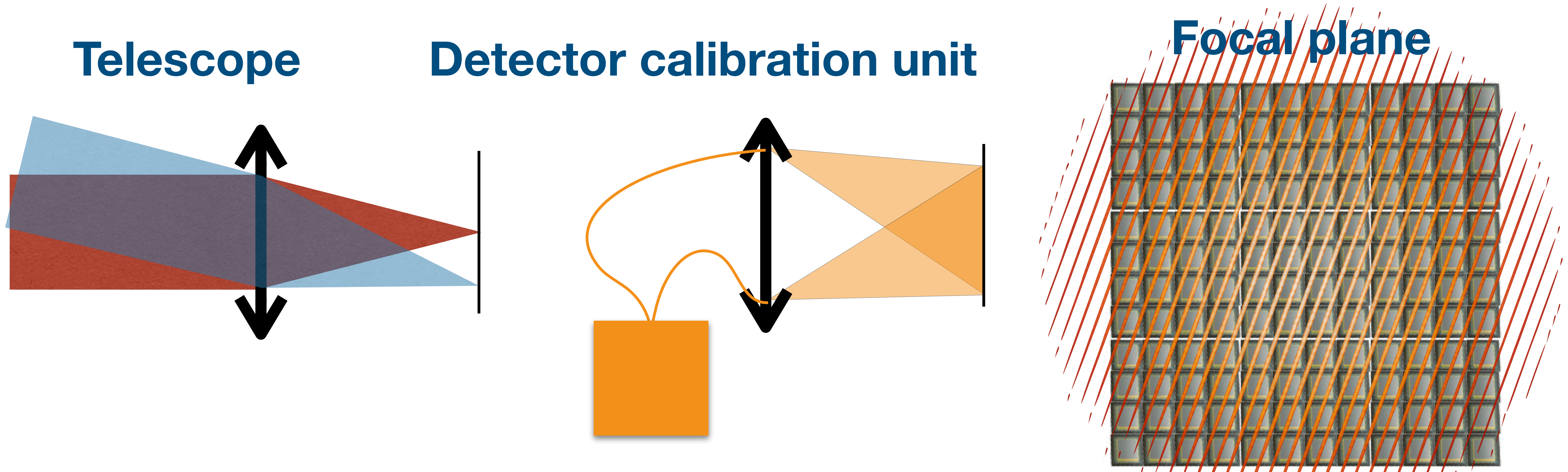
- **High precision space astrometry in the visible domain**
  - Earth-mass planets orbiting in the Habitable Zone of nearby solar-type stars => Bright star mode with requirement
  - Investigating the nature of Dark Matter through the shape of dwarf spheroidal galaxies (cored or cuspy ?), the kinematic disturbances for stars above/below Galactic plane, and the direction of proper motion for hypervelocity stars
- **Two application projects**
  - **Theia**: 0.8-m telescope with FoV of 0.7 degrees (ESA M8)
  - **HWO** 7-m telescope high resolution imager with 3'x2' FoV (NASA)
- **Differential pointed astrometry**
  - Gaia global astrometry allows data closure over the sky but is limited in exposure time and number of visits
  - Pointed astrometry allows optimization of exposure time and observing sequences, but fewer objects

Principle : relative and precise differential astrometry

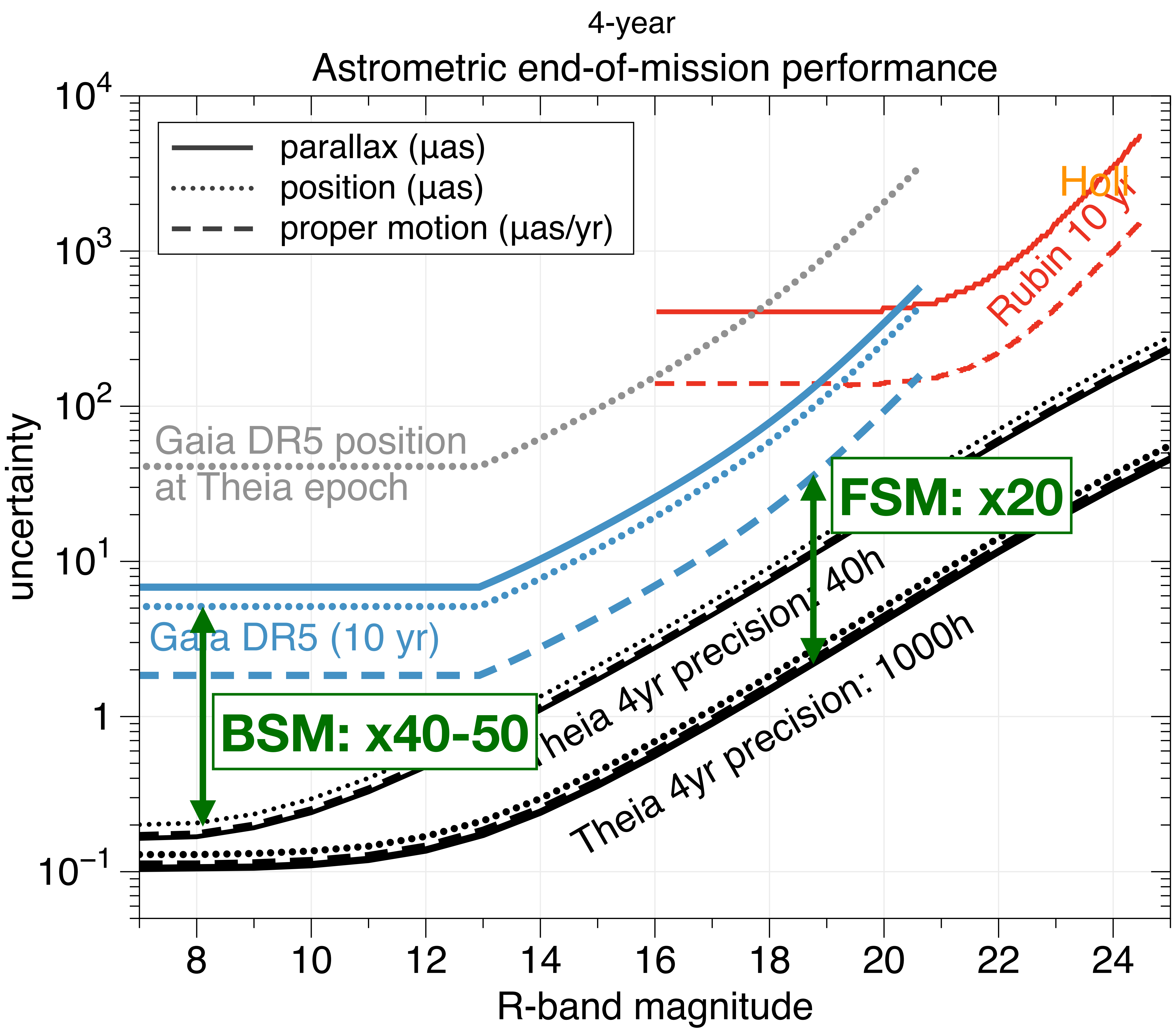


Gaia DR3 data

- ✓ The science target is at the center of the FOV
- ✓ We measure the offset angles between the target object (in the center) and the reference stars (other stars in green)
- ✓ The single measurement is repeated several times over the mission lifetime to reach the required accuracy on the target motion
- ✓ The detector calibration is done using interferometric modulated Young's fringes



Theia expected performances

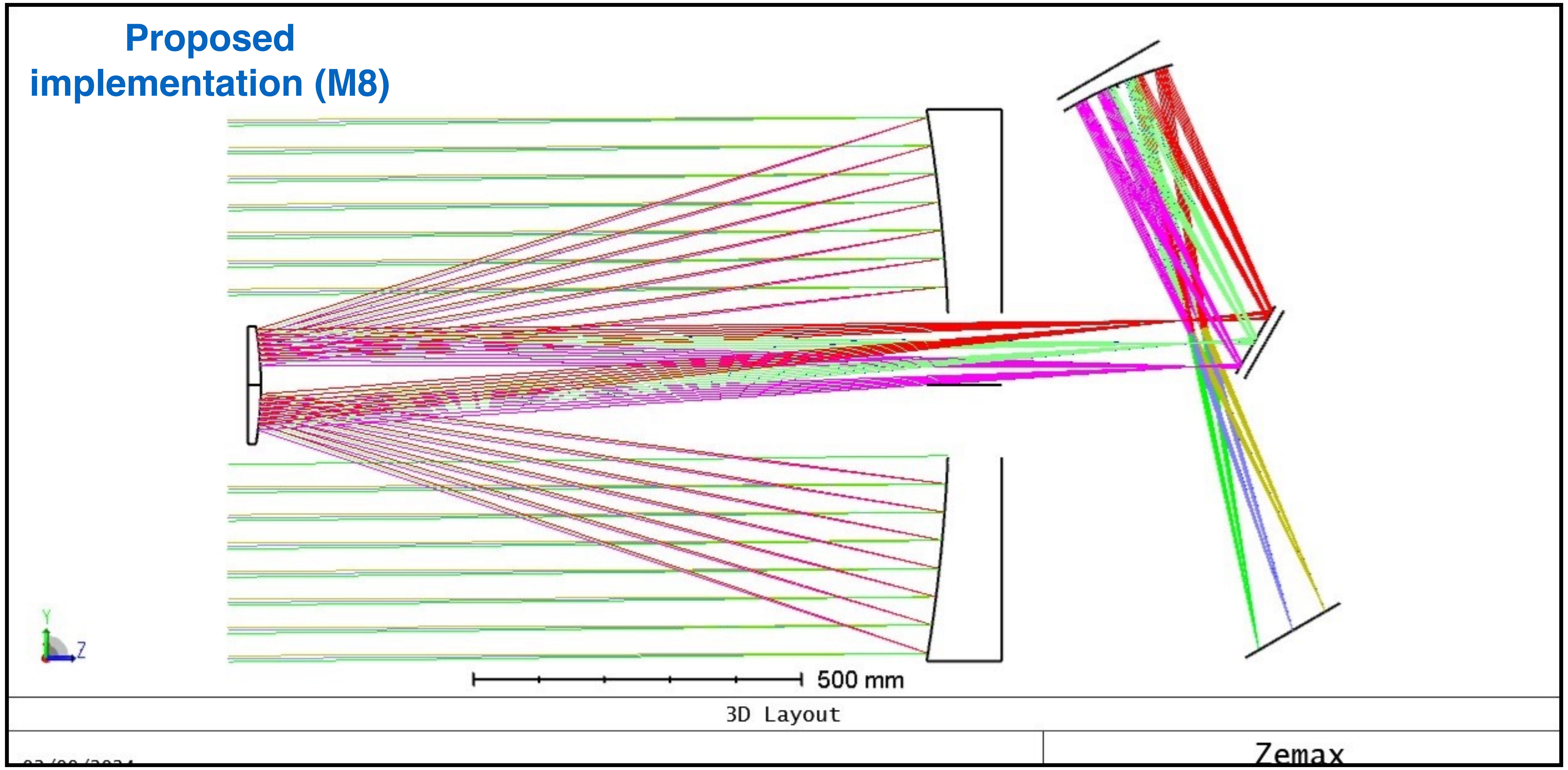


- **Faint Source Mode (FSM)** : 23 times the PM precision of Gaia (10yr) and 14 times that of HST (10yr)
- **Bright Source Mode (BSM)** Theia's 1µas precision in 1h integrations at the reference value R = 10mag exceeds that of Gaia by factor of ~40-50, Roman ~10-20 and VLTI/GRAVITY by ~30-100, and other missions/instruments (e.g. HST, JWST, ELT/MICADO, Rubin) by even larger factors.

Theia optical concept (ESA M8)

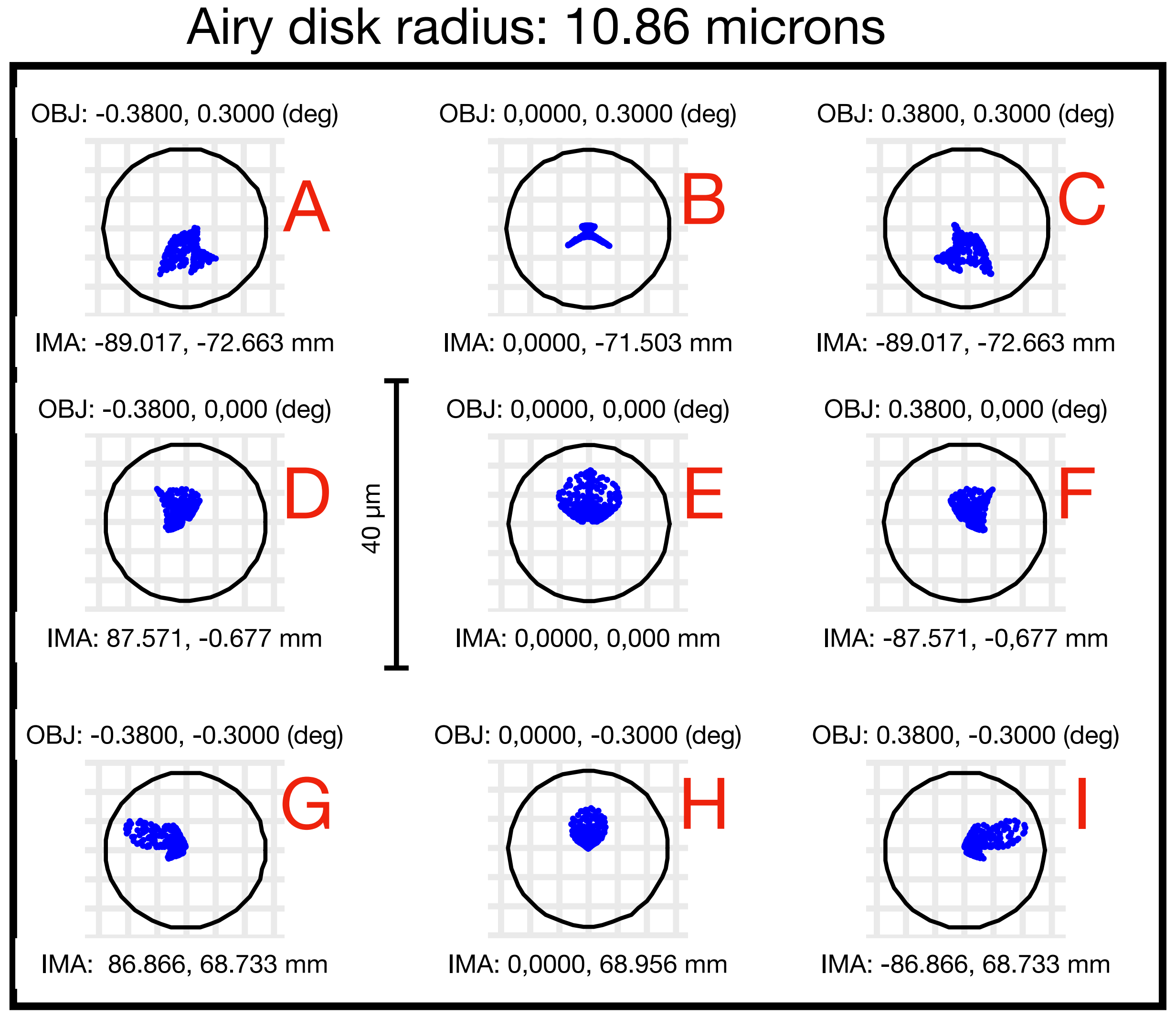
Theia characteristics :

- 0.8-m telescope diameter
- diffraction-limited 0.5° FOV

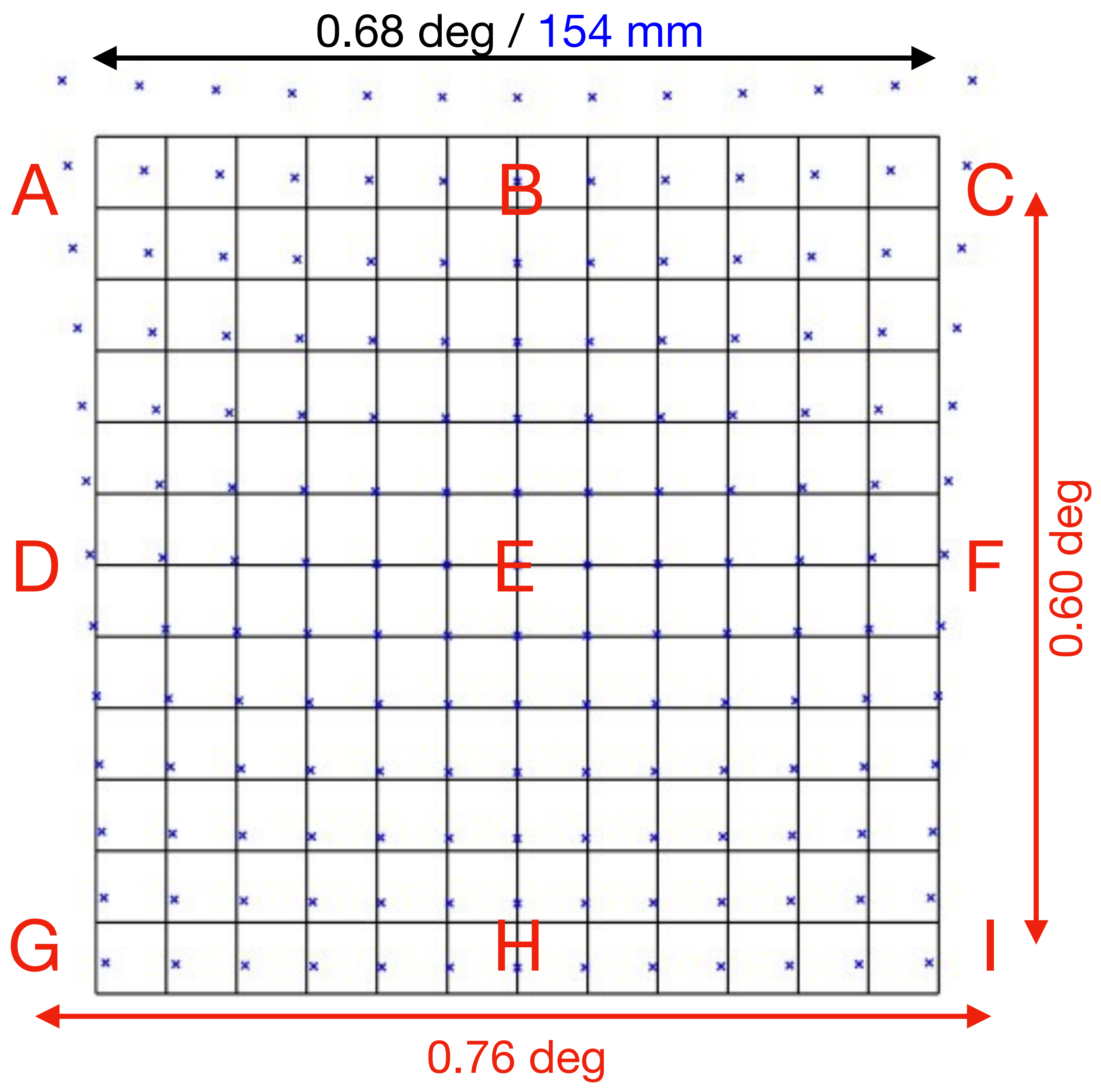


Three mirror anastigmat, Korsch design

Spot Diagram



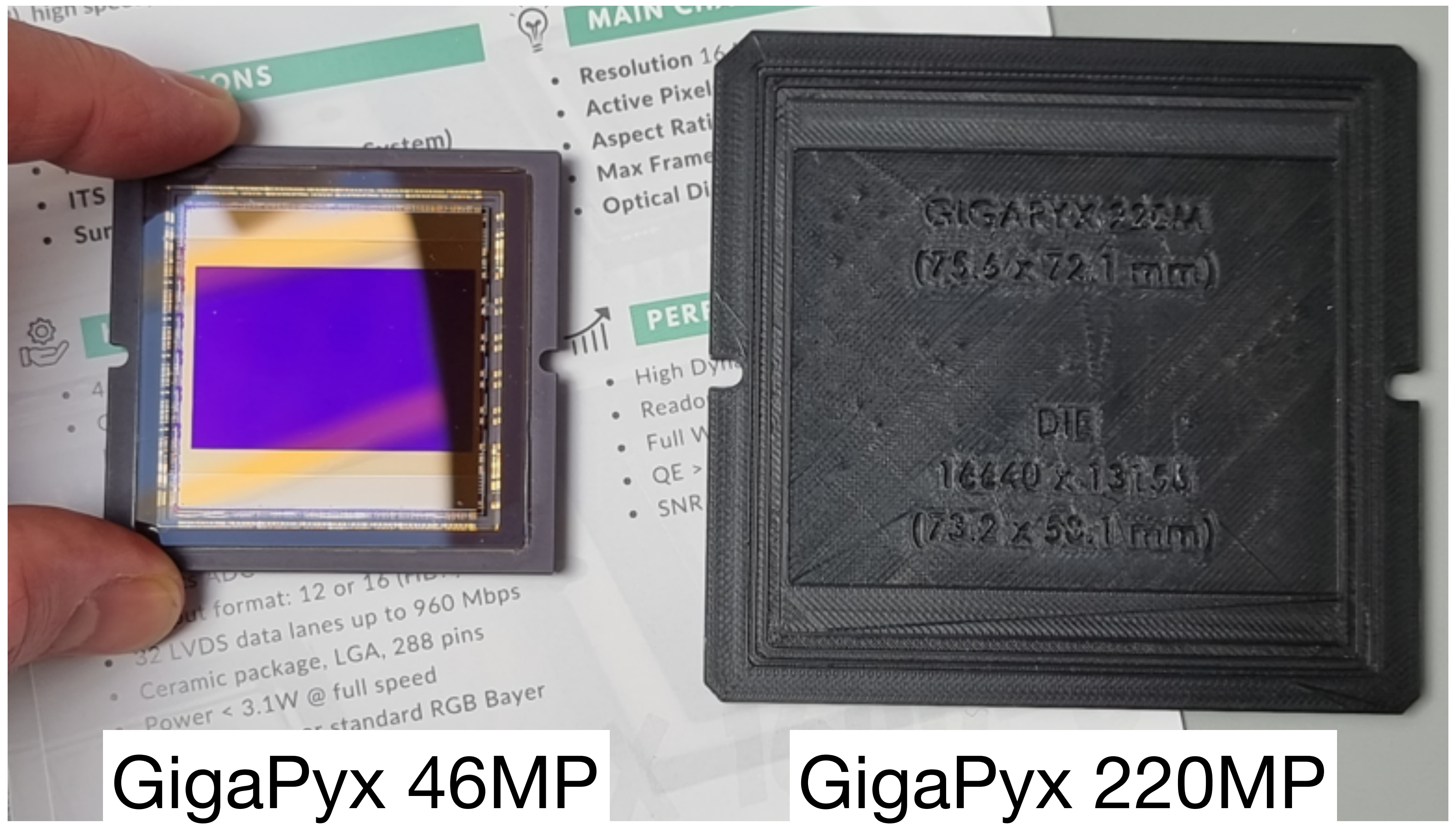
Distortion map 13x13



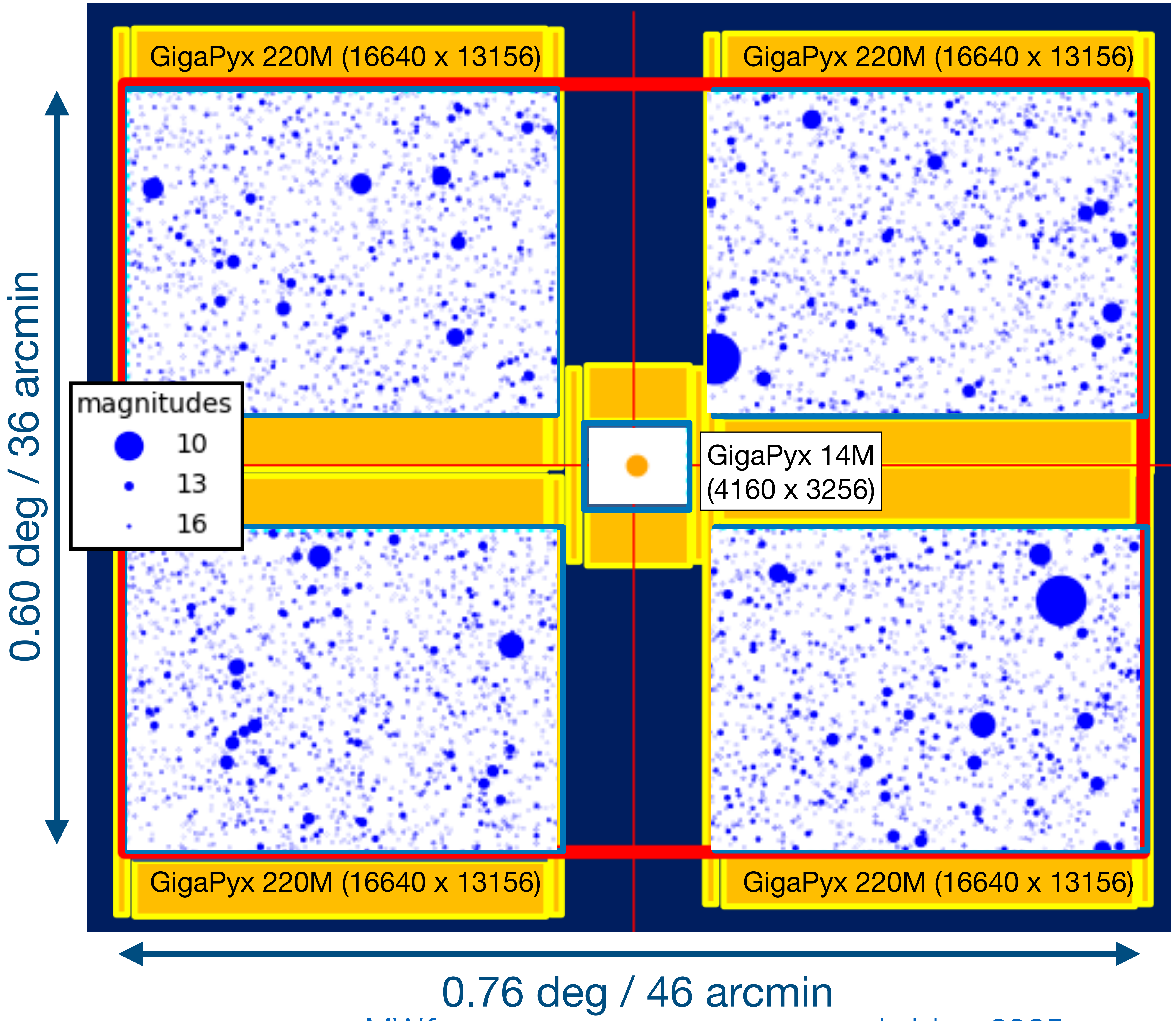
Focal plane for Theia

The Focal Plane uses 4 Pyxalis CMOS detectors GIGA220M (in development) +1 GIGA14M:

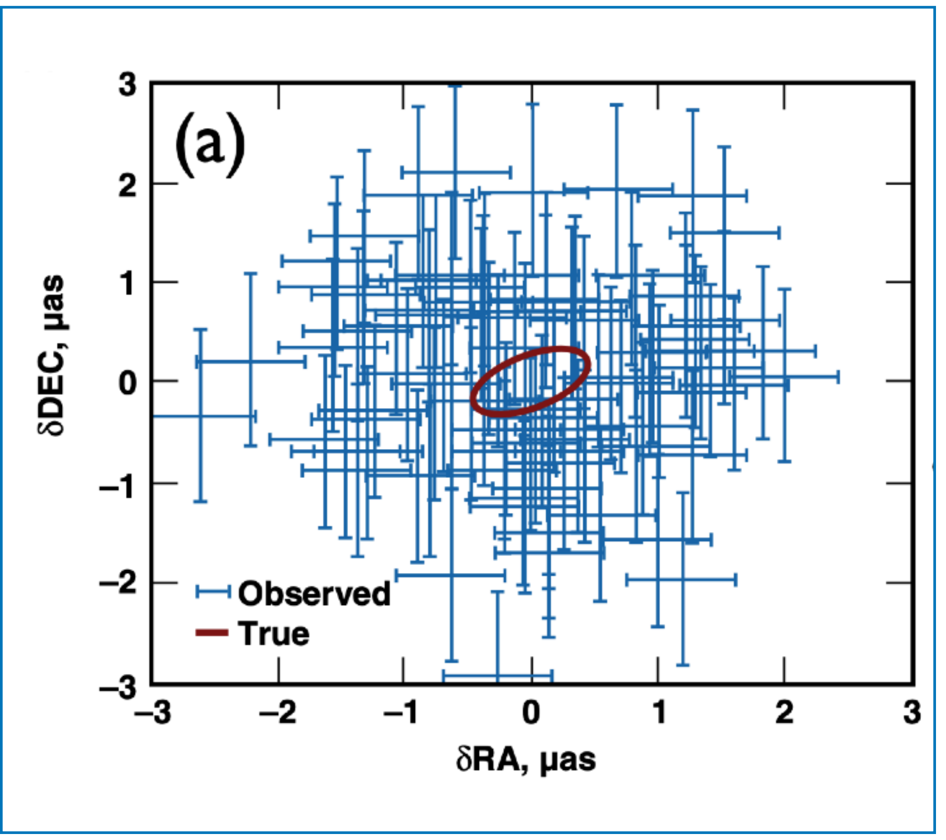
- 4x [16640 x 13156 pixels] (4 x 218 915 840 pixels) + 1 x [4160 x 3256 pixels] with 4,4 um pixel pitch
- Non buttable (~10 mm on 2 sides / ~2 mm on 2 sides): 27% loss of area
- Focal Plane 173 mm x 136 mm
  <=> 45.7 arcmin x 35.9 arcmin
  <=> 0.76°x0.60°
- **0.46 deg² total for 0.33 deg²** effective (881 Mpx), i.e. 27% loss

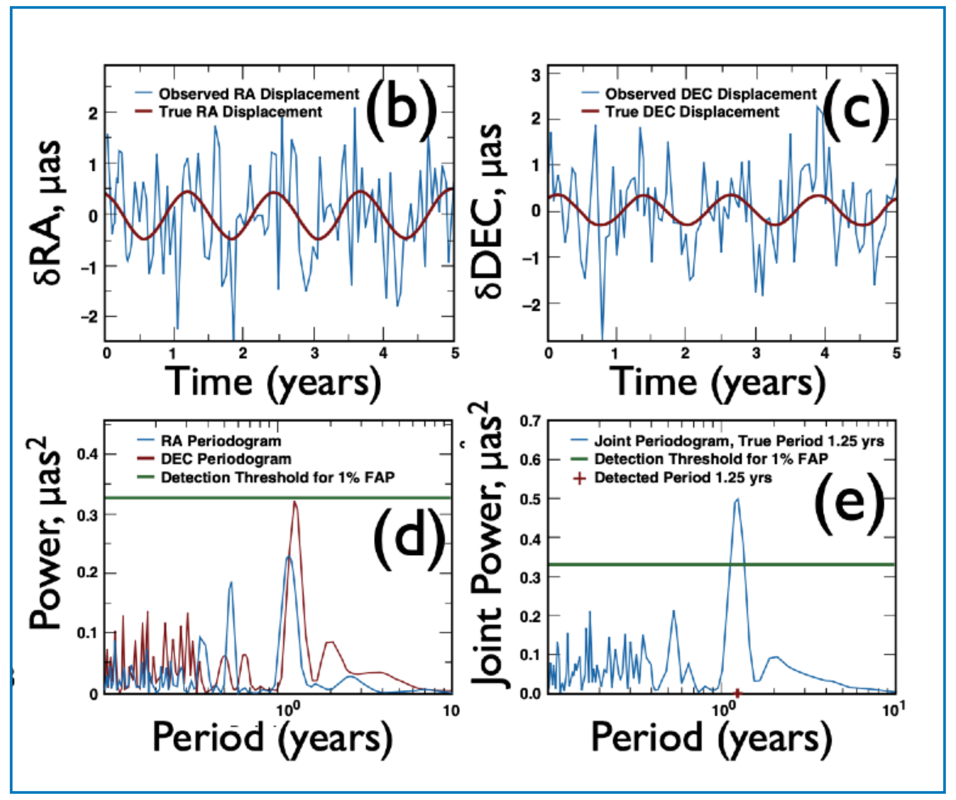


Field around ι Per (V = 4.05 mag, *d* = 10.58 pc, G0V)

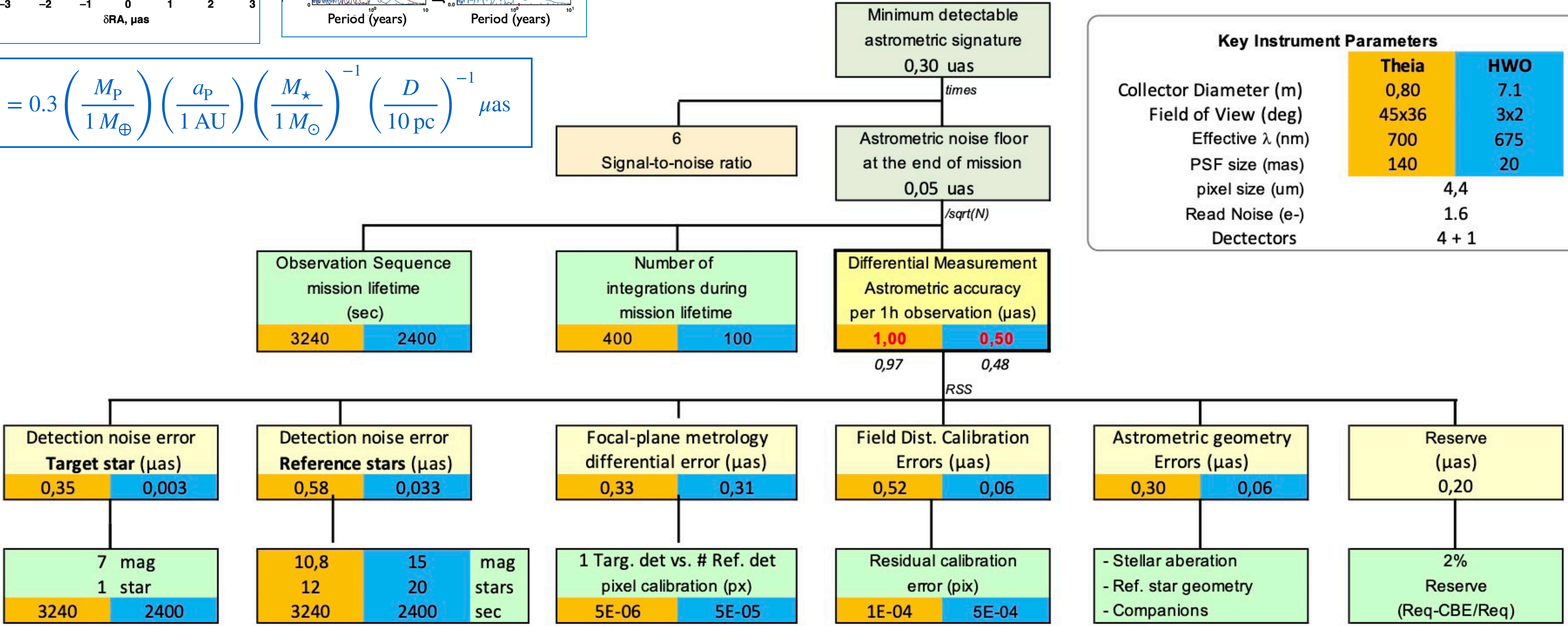


Astrometric error budget for bright targets with Theia and HWO





$$\alpha = 0.3 \left(\frac{M_P}{1\,M_\oplus}\right)\left(\frac{a_P}{1\,\mathrm{AU}}\right)\left(\frac{M_\star}{1\,M_\odot}\right)^{-1}\left(\frac{D}{10\,\mathrm{pc}}\right)^{-1} \mu\mathrm{as}$$

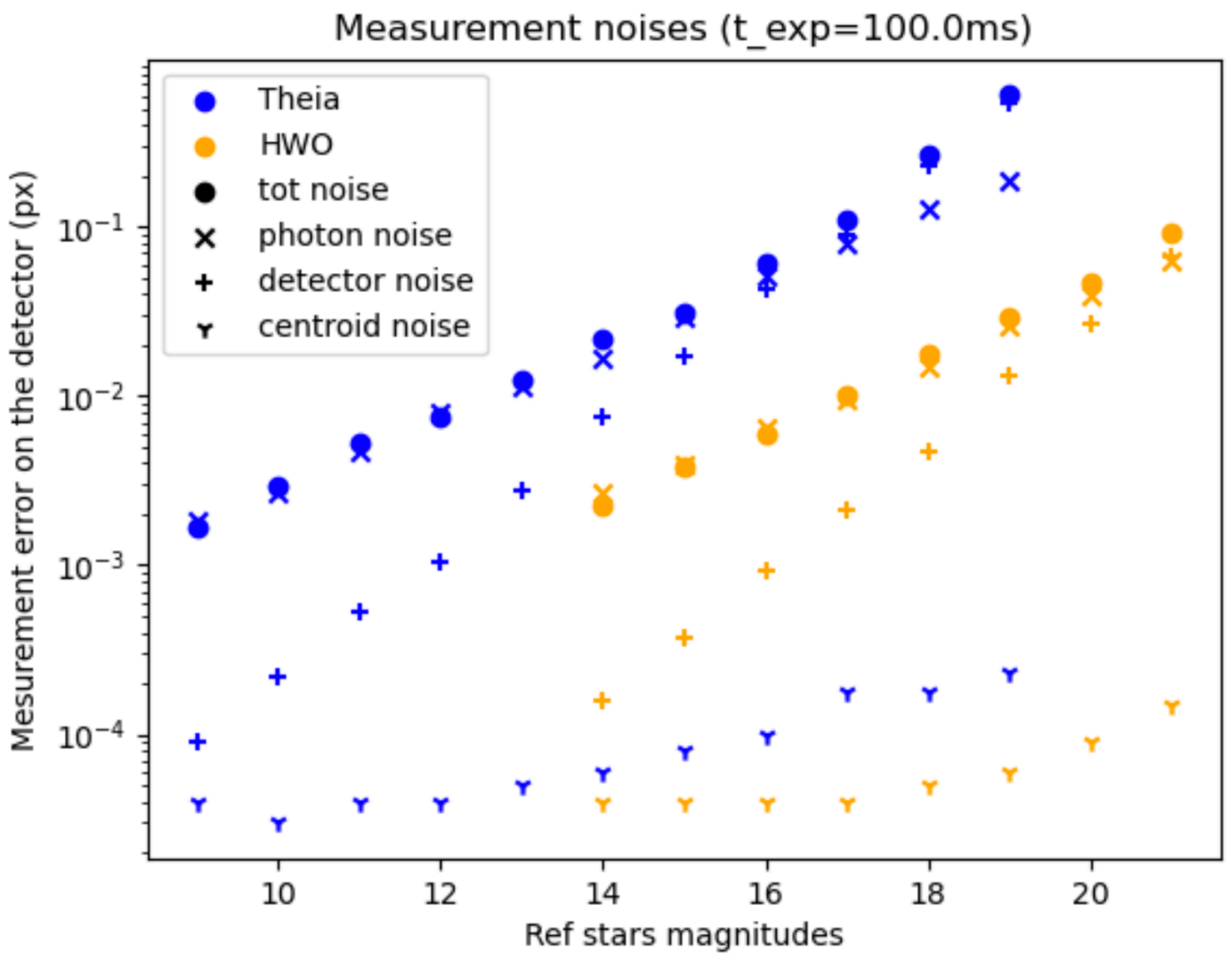


Key Instrument Parameters

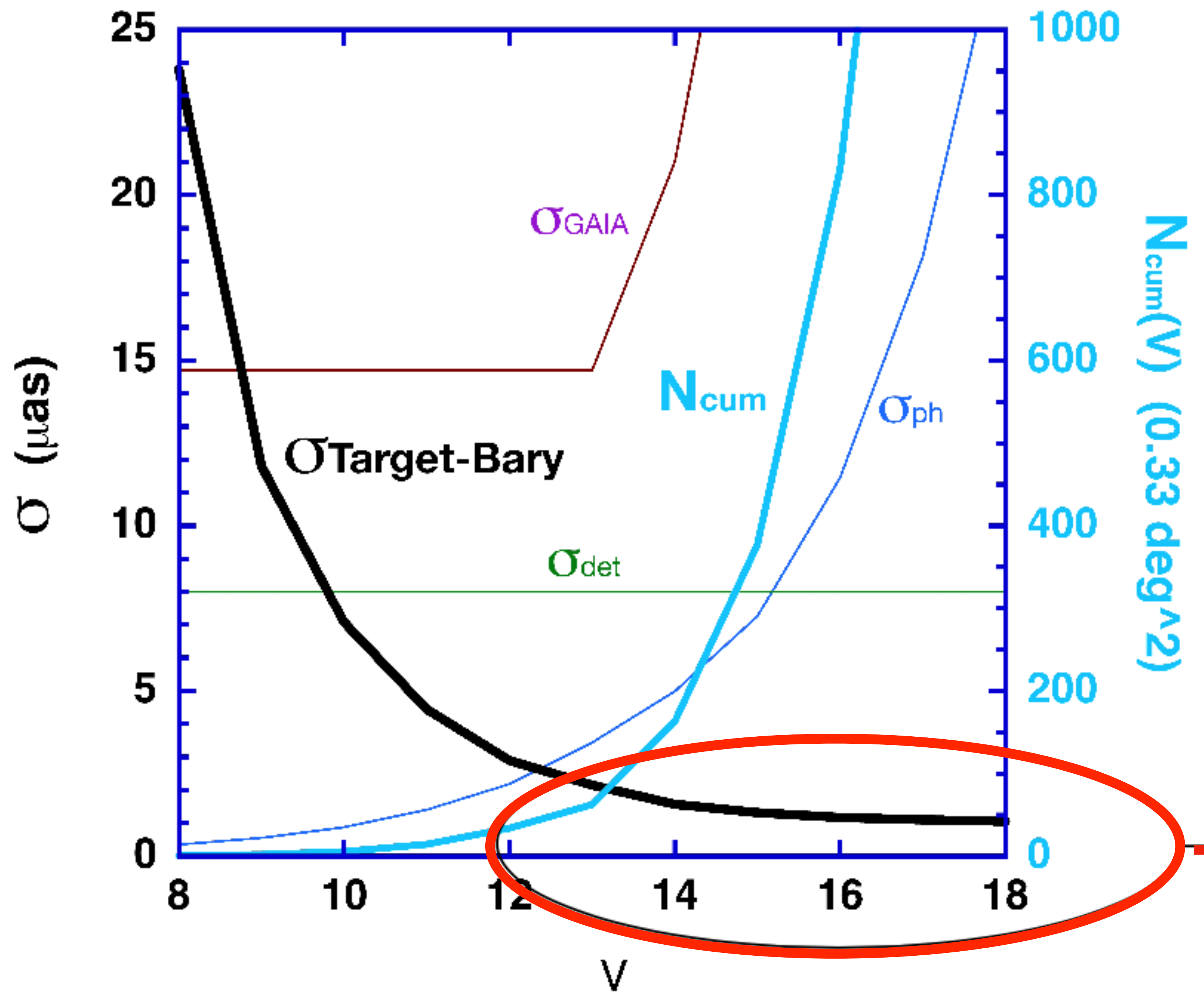
	Theia	HWO
Collector Diameter (m)	0,80	7.1
Field of View (deg)	45x36	3x2
Effective λ (nm)	700	675
PSF size (mas)	140	20
pixel size (um)	4,4	
Read Noise (e-)	1.6	
Dectectors	4 + 1	

The accuracy of target position increases with number of reference stars

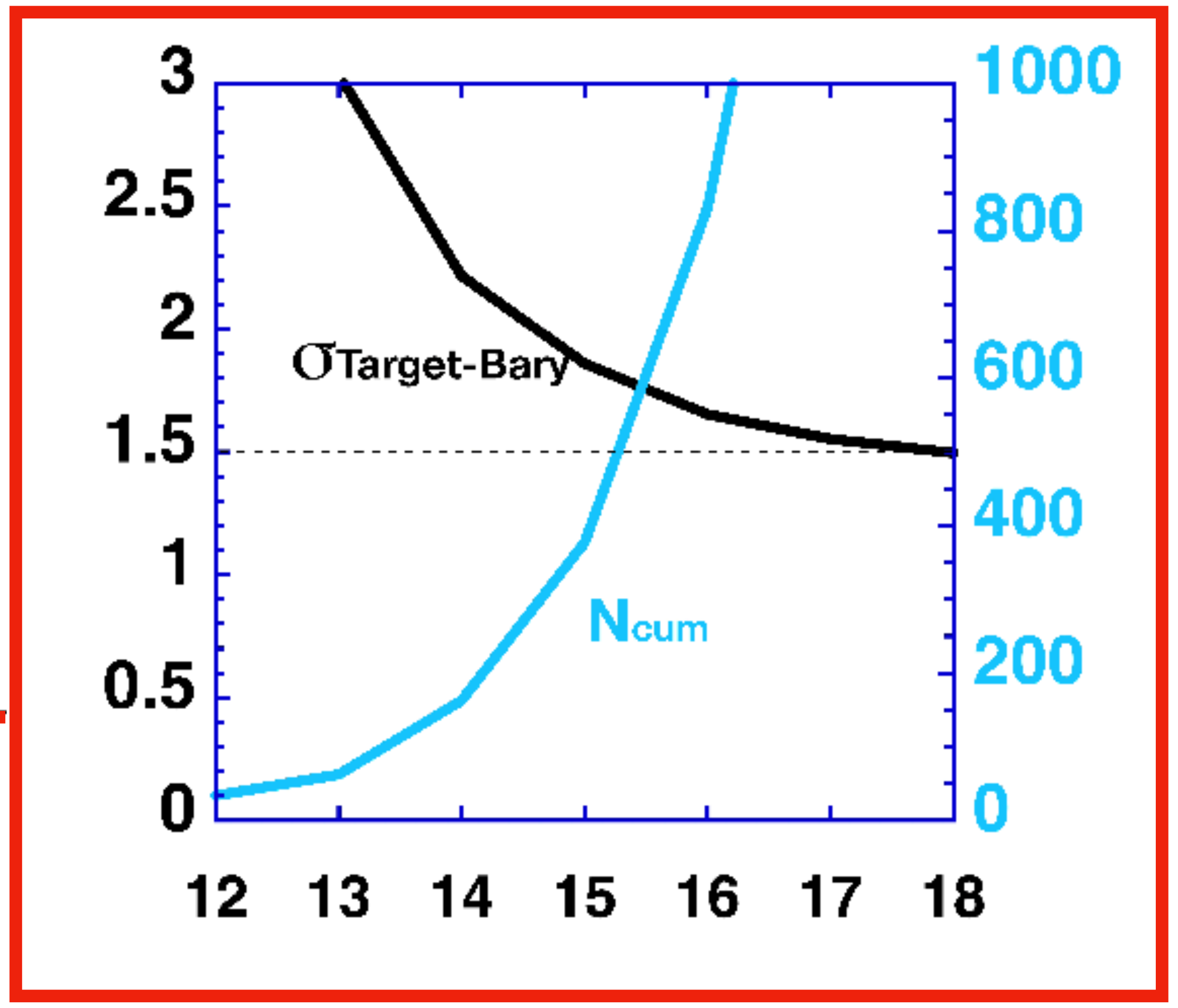
Uncertainties on reference position increases with flux, mostly limited by photon noise at the bright end and detector noise at the faint end.



Accuracy of Gaia position for after 20 years is not sufficient, but this can be solved by using multiple reference stars and decrease with the number of references.

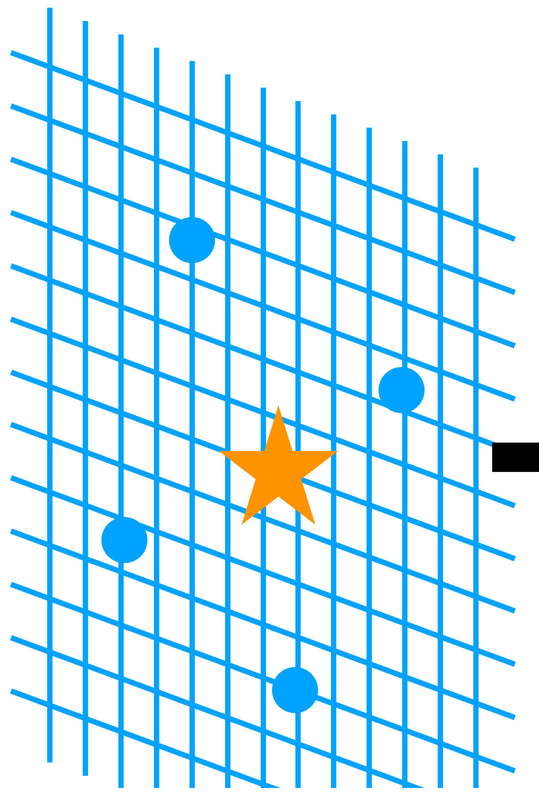


But number of reference stars increases exponentially. The final accuracy of the reference frame using Gaia data depends on each direction. However, the final precision will depend on teh current mission accuracy.



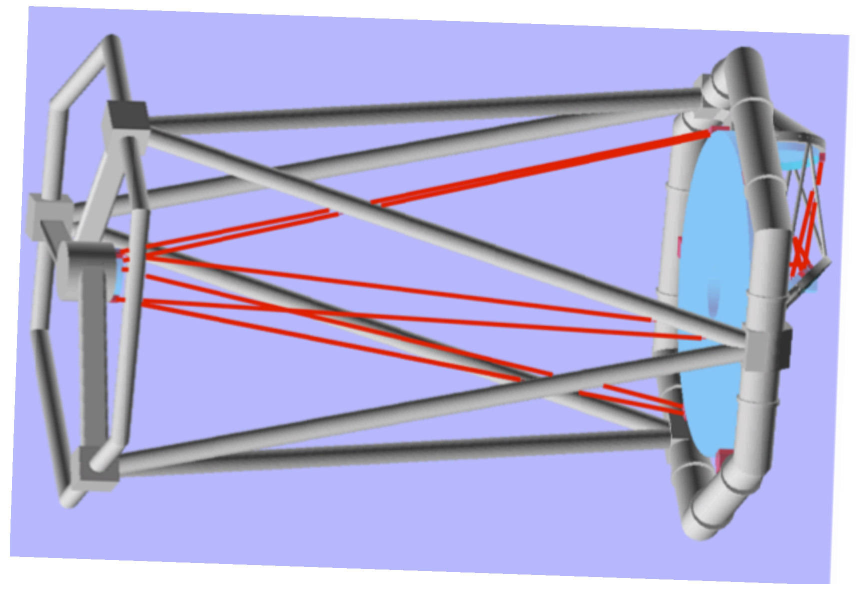
Telescope calibration : using reference stars to monitor the distortion

On sky



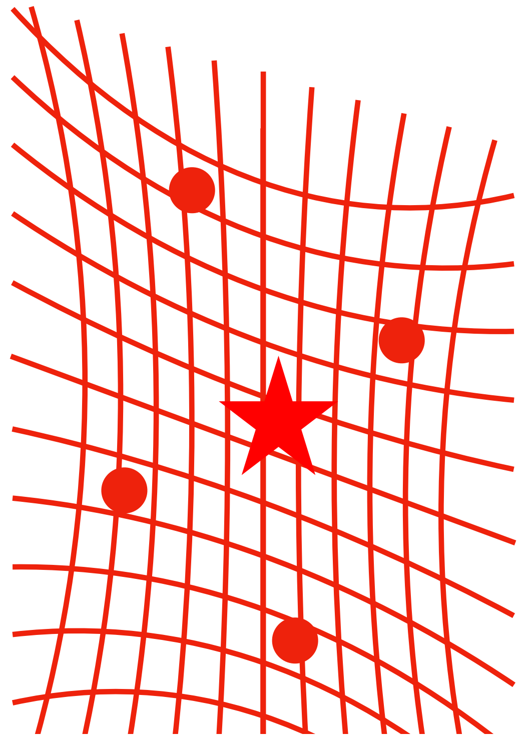
Reference stars sky position given by Gaia

Three Mirror Anastigmat (TMA) telescope proposed.



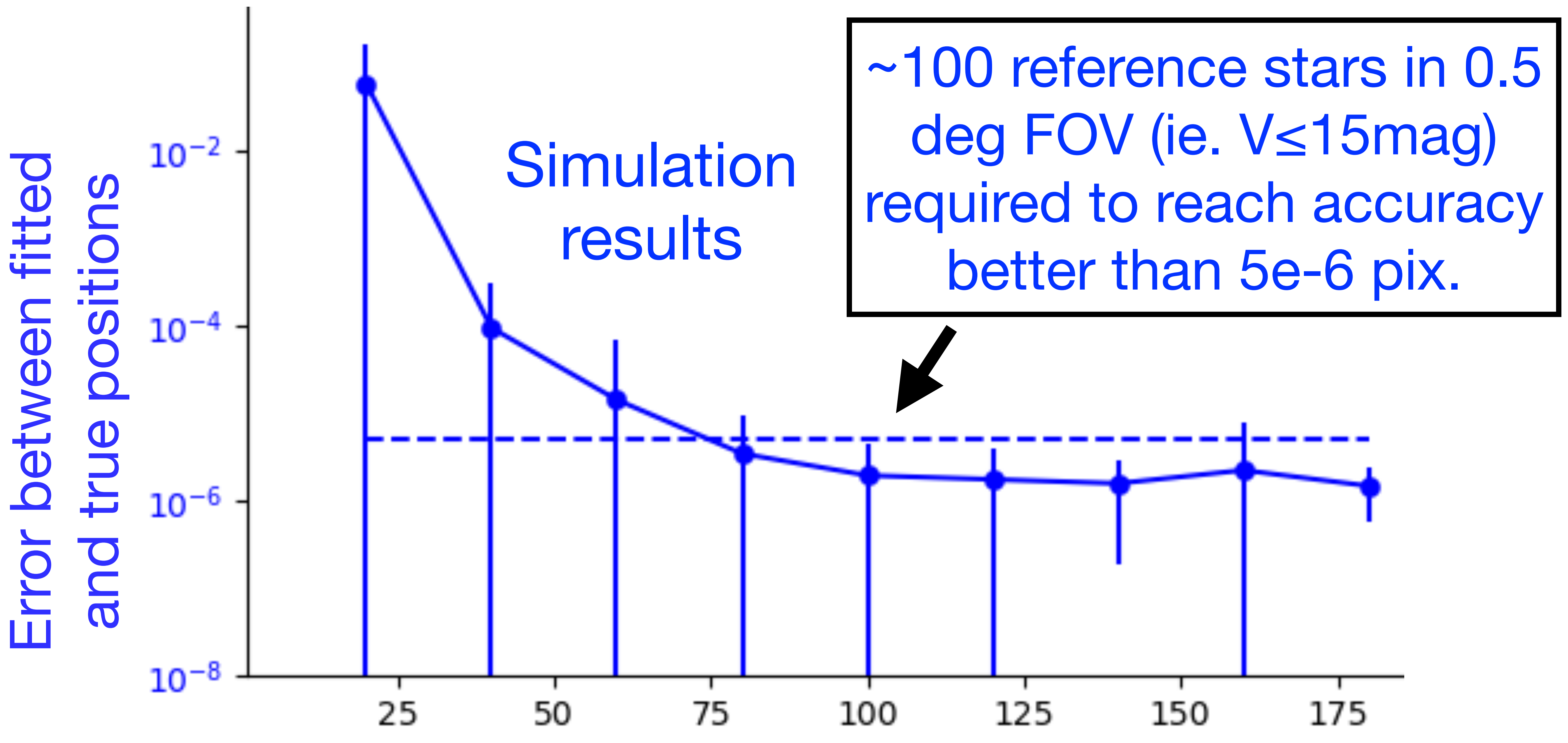
Main remainig aberration is Field Distortion

Field-dependent distortion

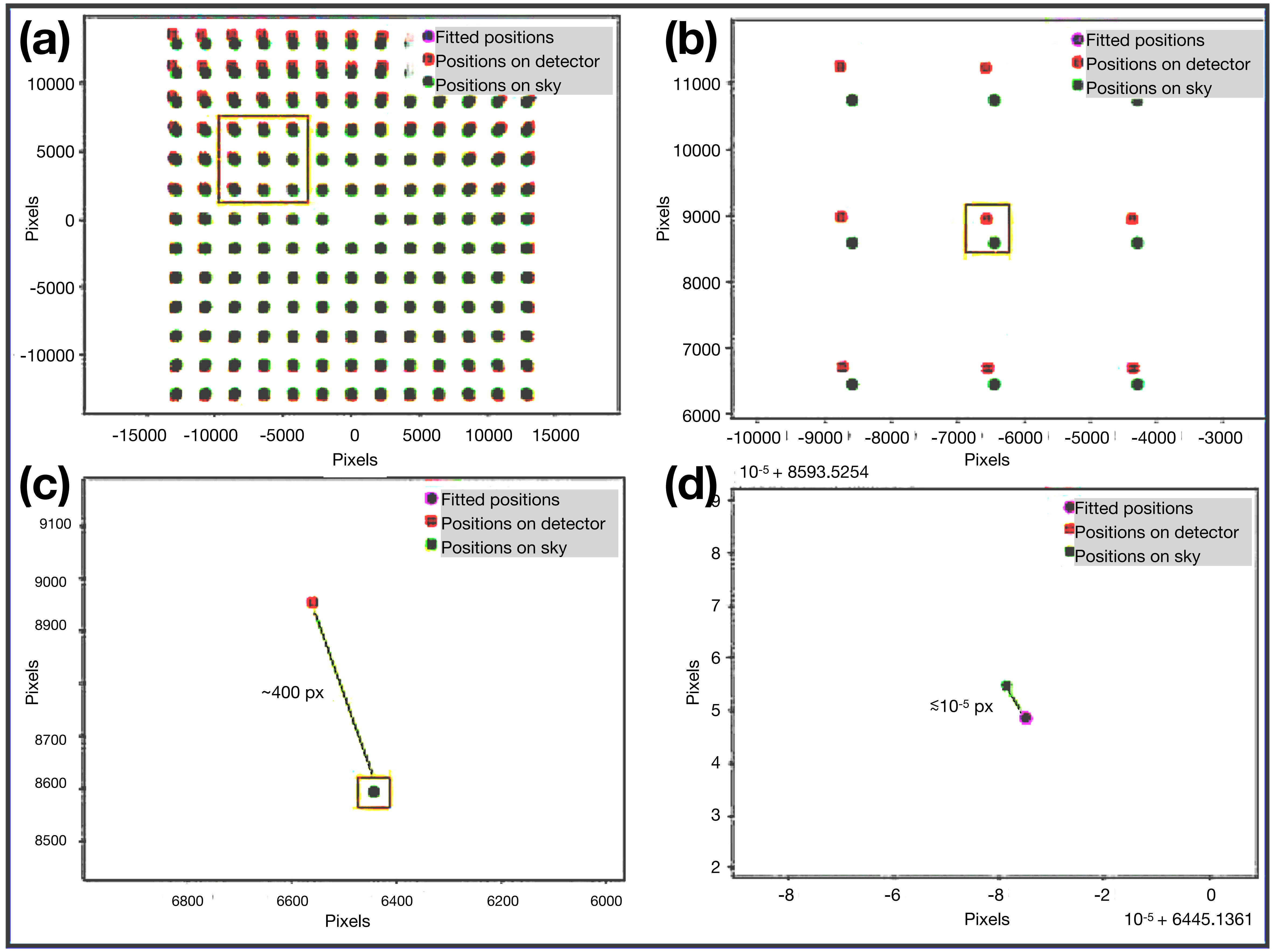


Reference stars position measured on detector

Distortion can be corrected by fitting the transformation (Sky -> Detector) as calculated by Ray-tracing (Zemax) by a 2D polynomial



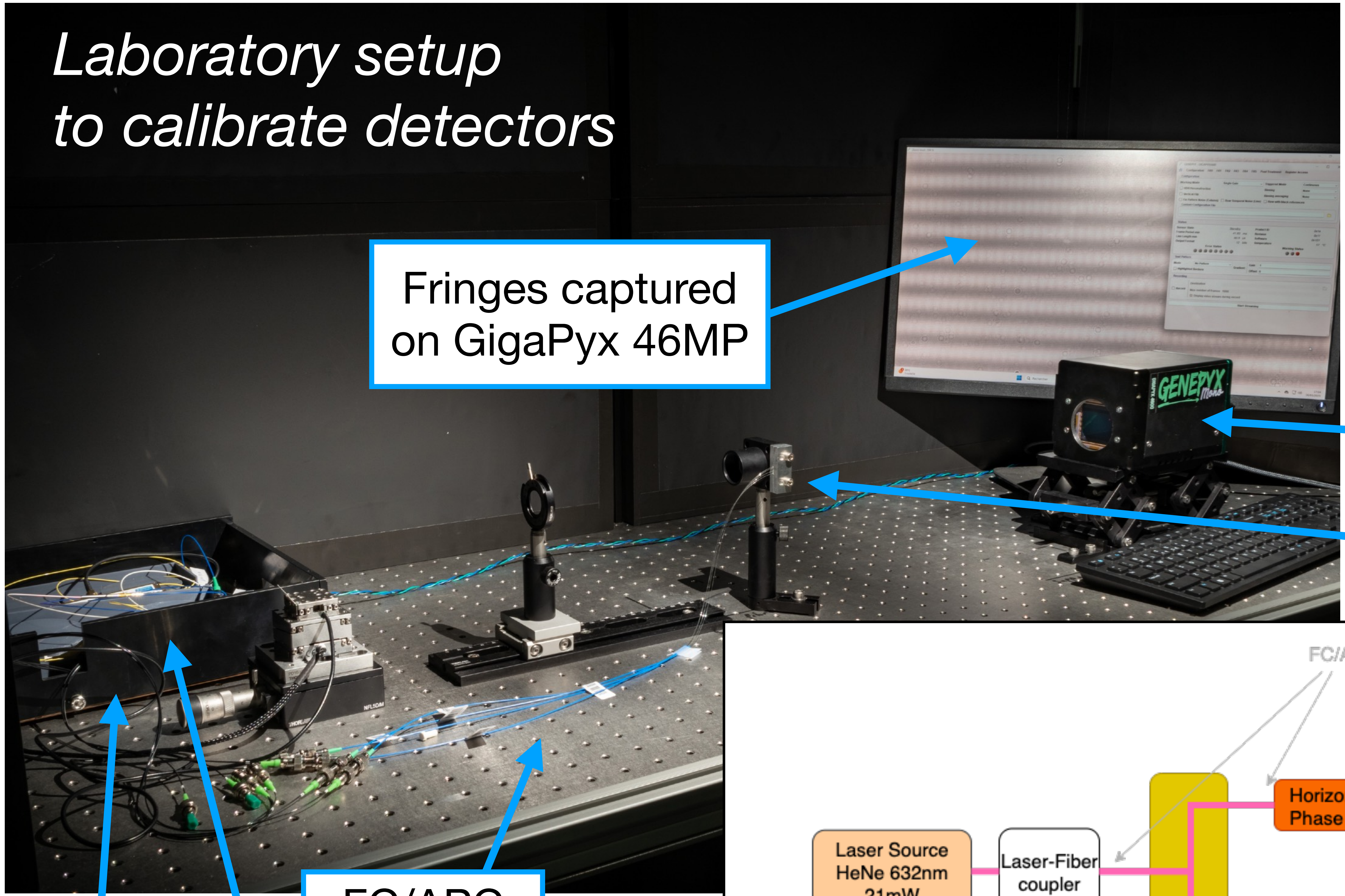
Number of stars required to fit the distortion



Simulated field-dependent distortion and fitted position

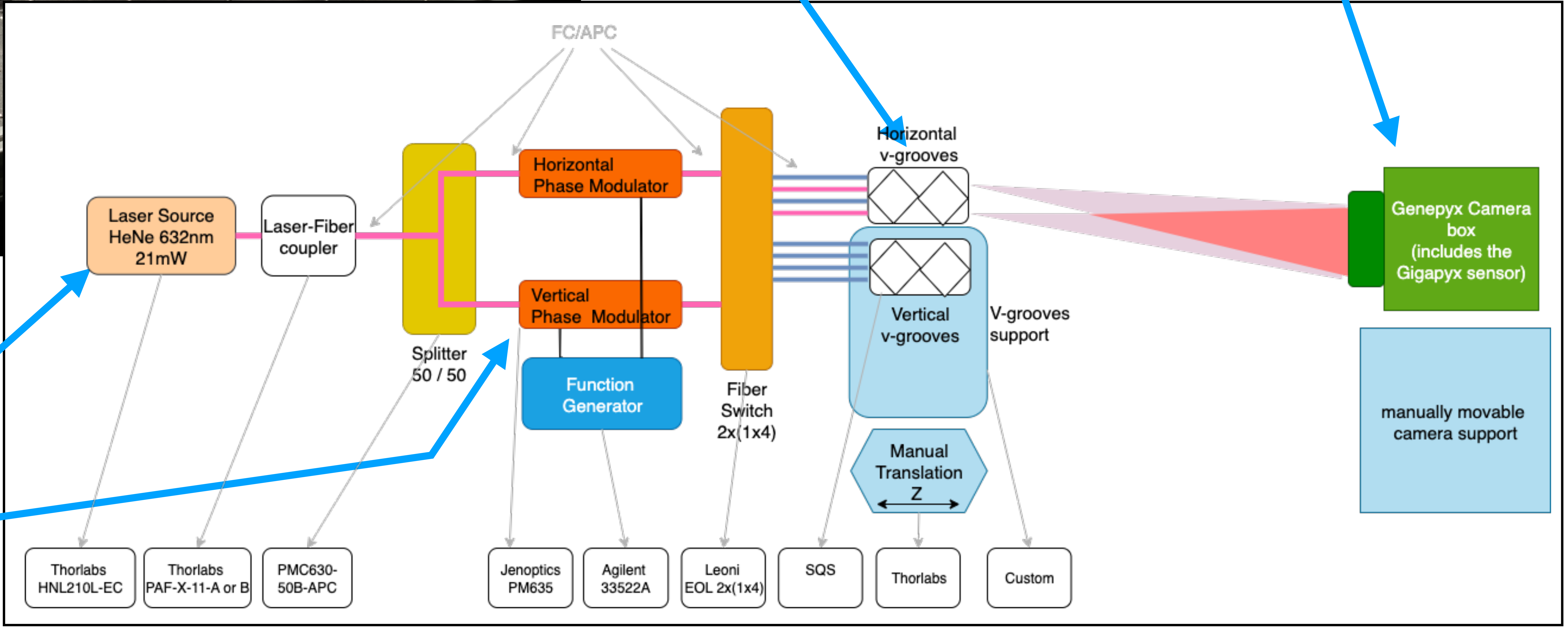
Current lab tests at IPAG

(FOCUS & CNES R&T)



GigaPyx 46MP detector

V-grooves



Detector radiometric performance measurements

GIGAPYX 4600

46 Megapixel, BSI Rolling Shutter
High Speed HDR CMOS image sensor

Ultimate video image quality
pyxalis
Your Image Sensor Solution




Key Performances

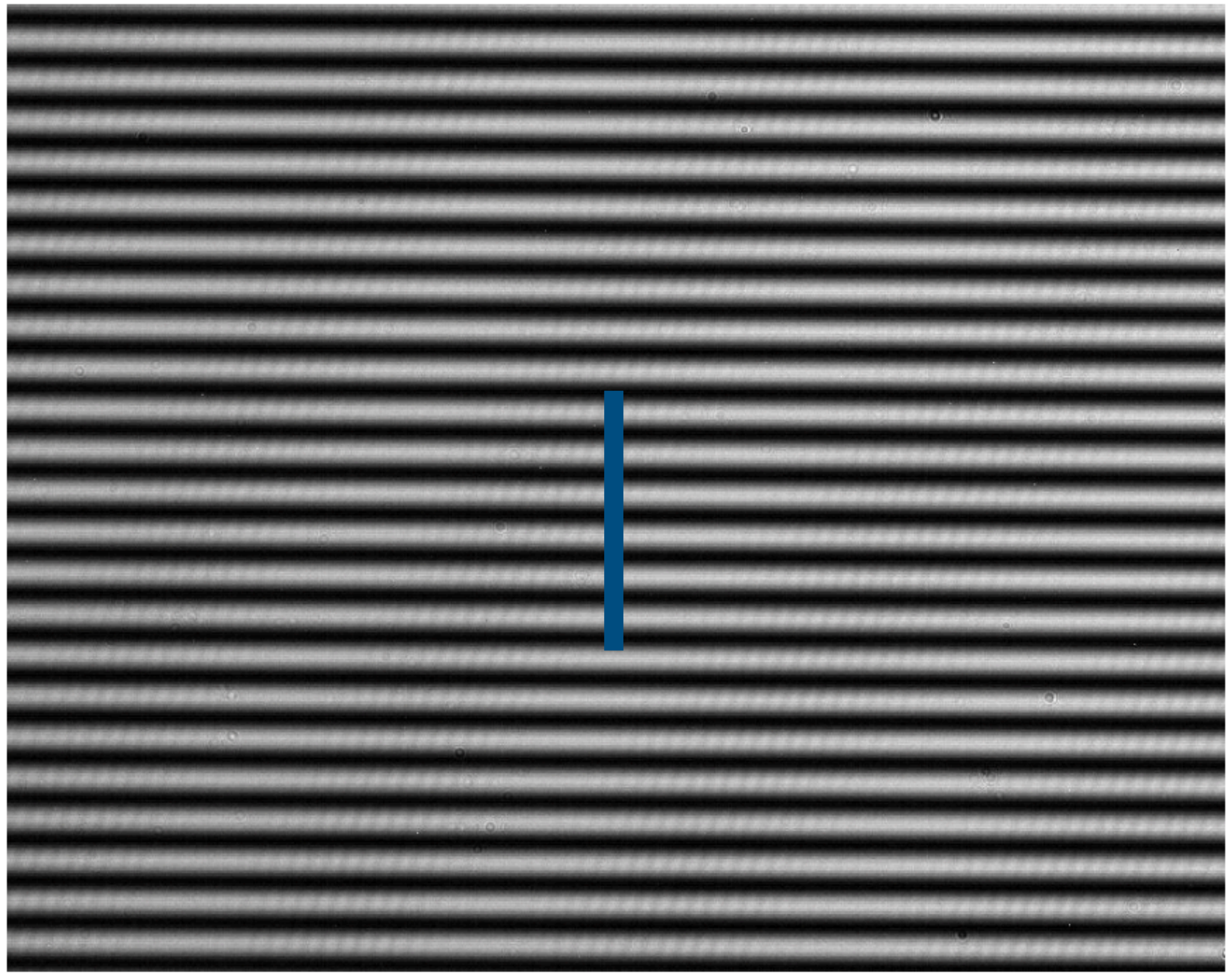
Parameter	Typical Value
Saturation Charge (linear), HG/LG	5 ke- / 50 ke-
Temporal Noise in darkness (HG) (1)	1.5 e- rms
Linearity Error, 5-95% $QSAT_{LIN}$	< 3%
Dynamic Range, HG (1)	70 dB
Dynamic Range, HDR (1)	90 dB
SNR at blending point in HDR	37 dB
Peak QE x FF, at 445 nm (mono)	80 %
Relative Illumination, up to ± 25°	> 90%
Dark-Current (1)	24 e-/s rms (@35°C)
Fixed-Pattern Noise (2)	14 DN
Photo-Response Non-Uniformity (2)	< 2%
Frame-rate, FF, 12 bits, HG/LG	152 FPS
Frame-rate, 8K, 12 bits, HG/LG	192 FPS
Frame-rate, FF, 13 bits, HDR	54 FPS
Frame-rate, 8K, 13 bits, HDR	63 FPS
Power-consumption, standby	< 150 mW
Power-consumption, full operation (3)	< 4.1W

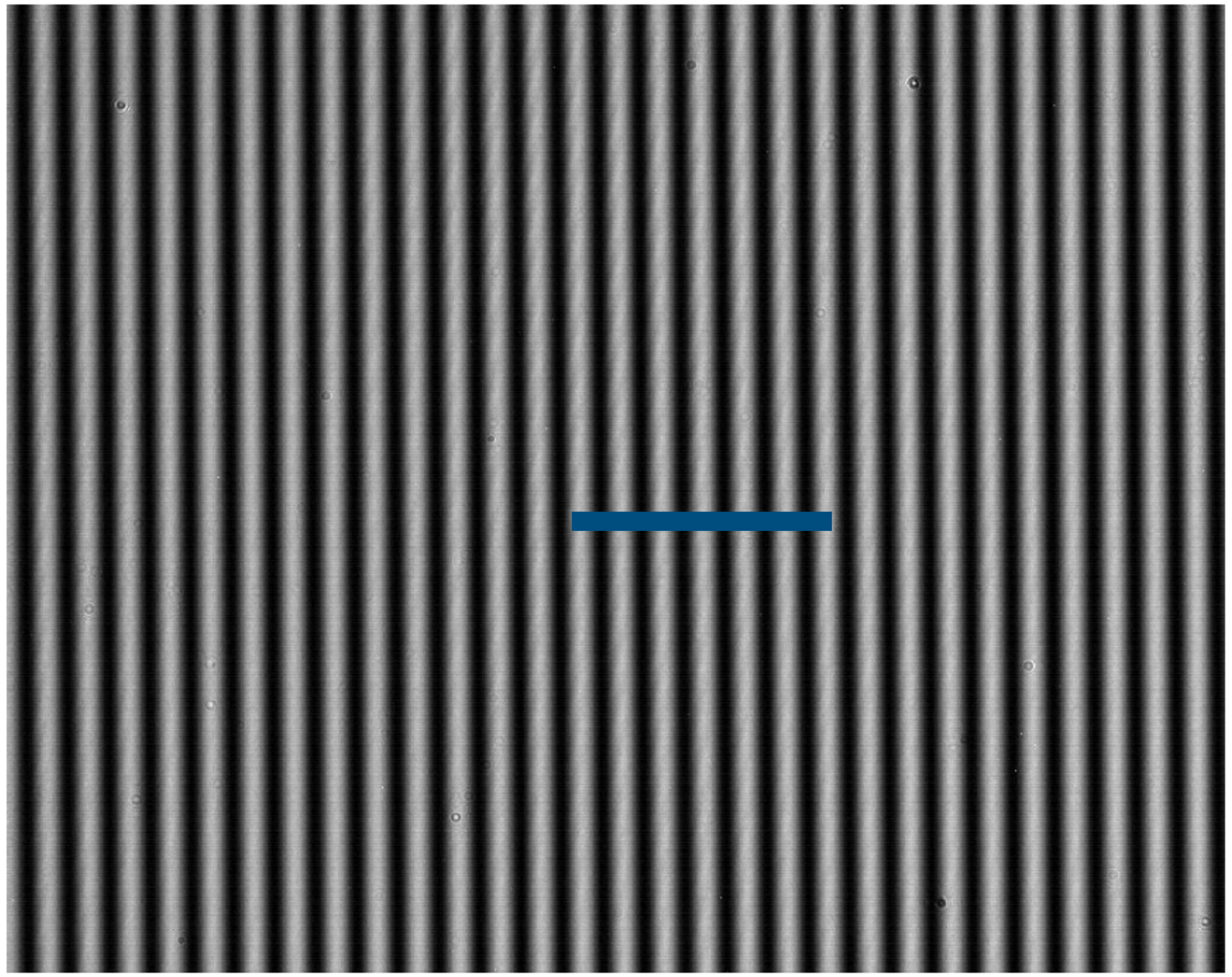
Our measurements

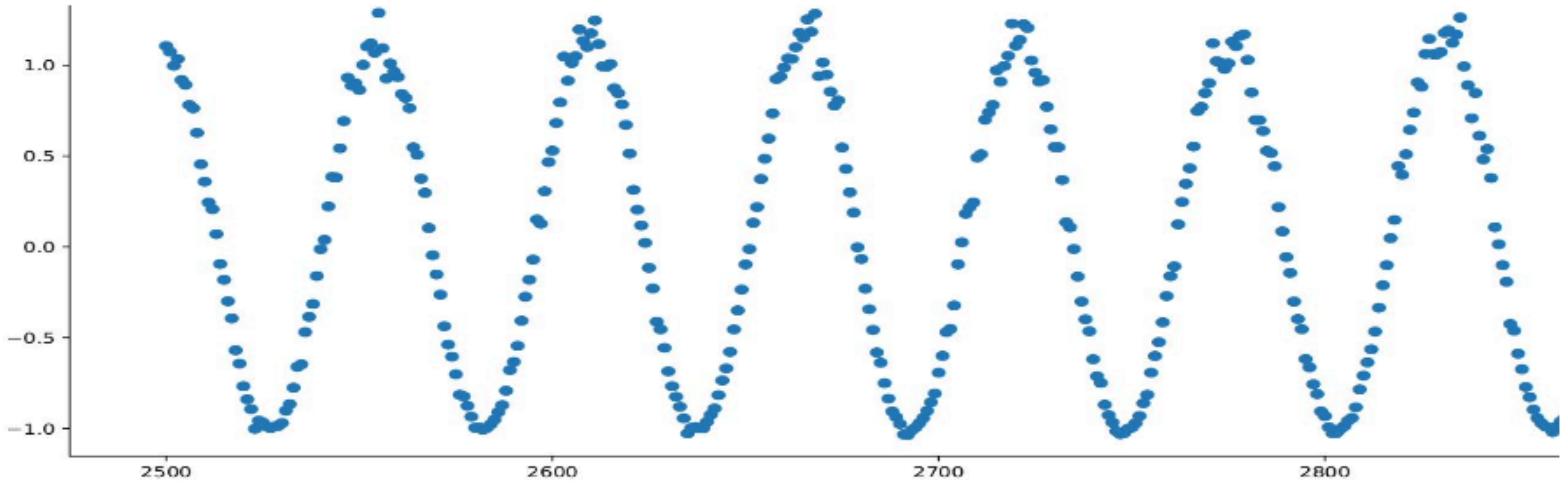
```
median_bias_(ADU): 377.0
std_bias_(ADU): 60.9961
median_dark_current_(ADU/ms): 0.0387
std_dark_current_interpx_(ADU/ms): 0.011
std_dark_current_1px_(ADU/ms): 0.0002
linearity_error_(%): 0.5154
median_roq_noise_(ADU): 0.7798
std_roq_noise_(ADU): 0.2203
median_gain_(ADU/e-): 0.7105
std_gain_(ADU/e-): 0.0359
PRNU_tot_(%): 2.2207
PRNU_center_(%): 1.7011
PRNU_HF_(%): 2.7931
```

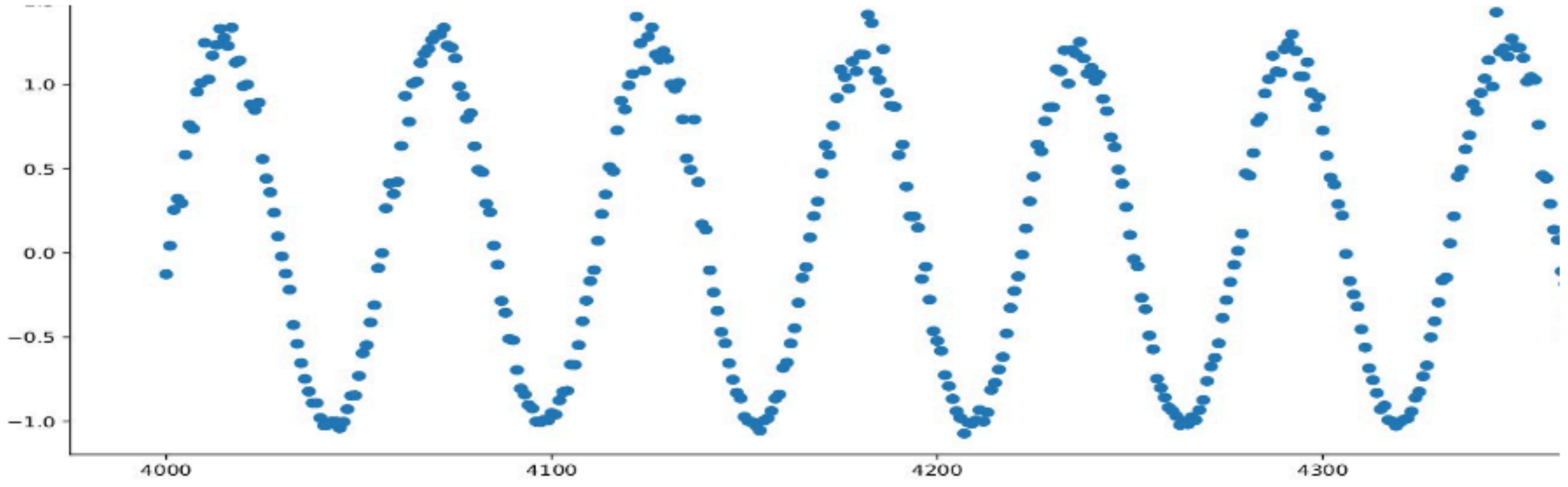
	PYXALIS	IPAG measurements	
	(e-)	(ADU)	(e-)
Conversion factor (ADU/e-)	0.7	-	0.71
Read-out noise	1.6		
Dark current (/ms)	24	39	27
PNRU	<2%	2.2%	

First fring measurements on a 46MP detector

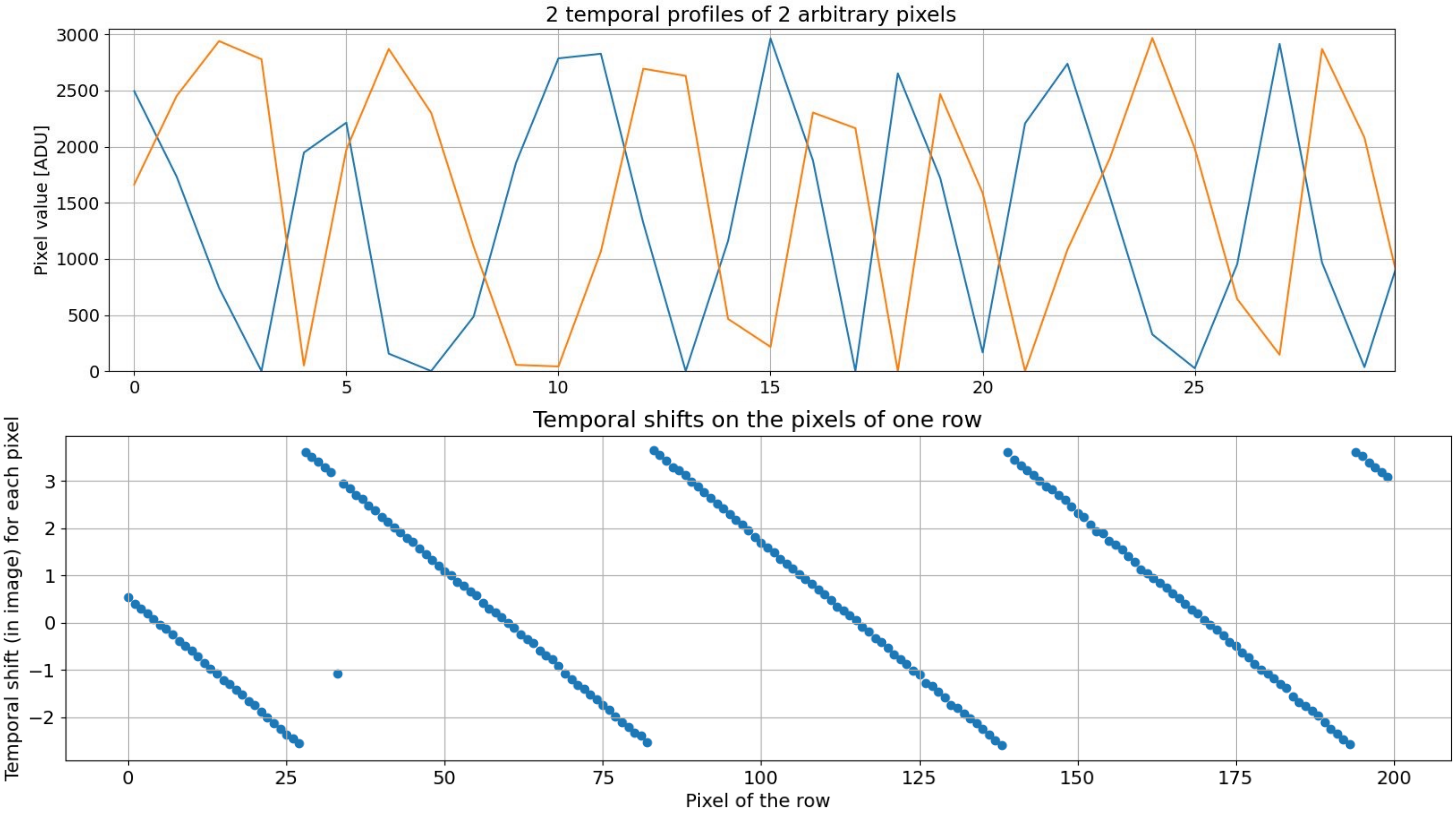








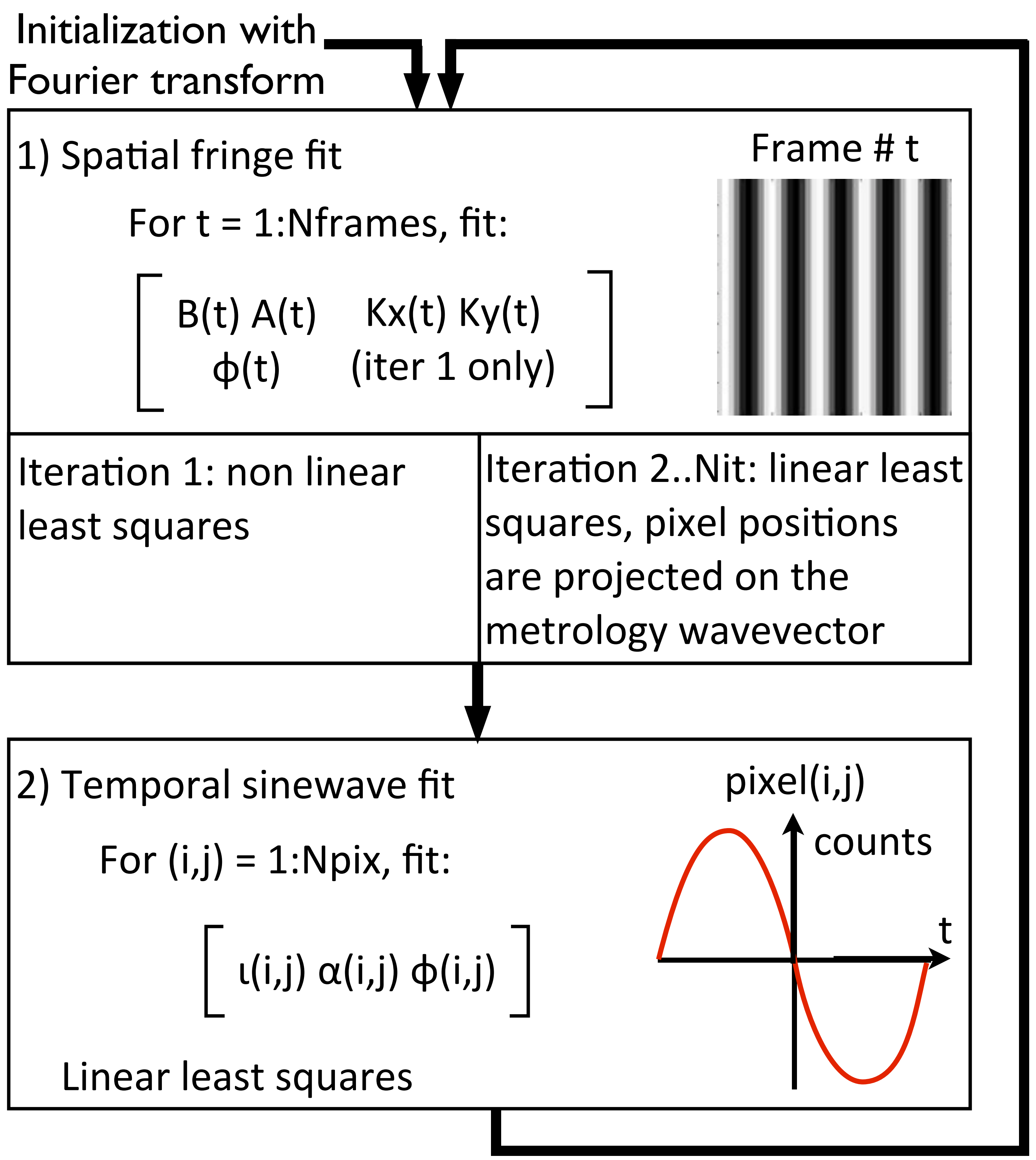
Temporal correlation of the interferometric signal



Retrieving pixel positions at sub-millipixel accuracy

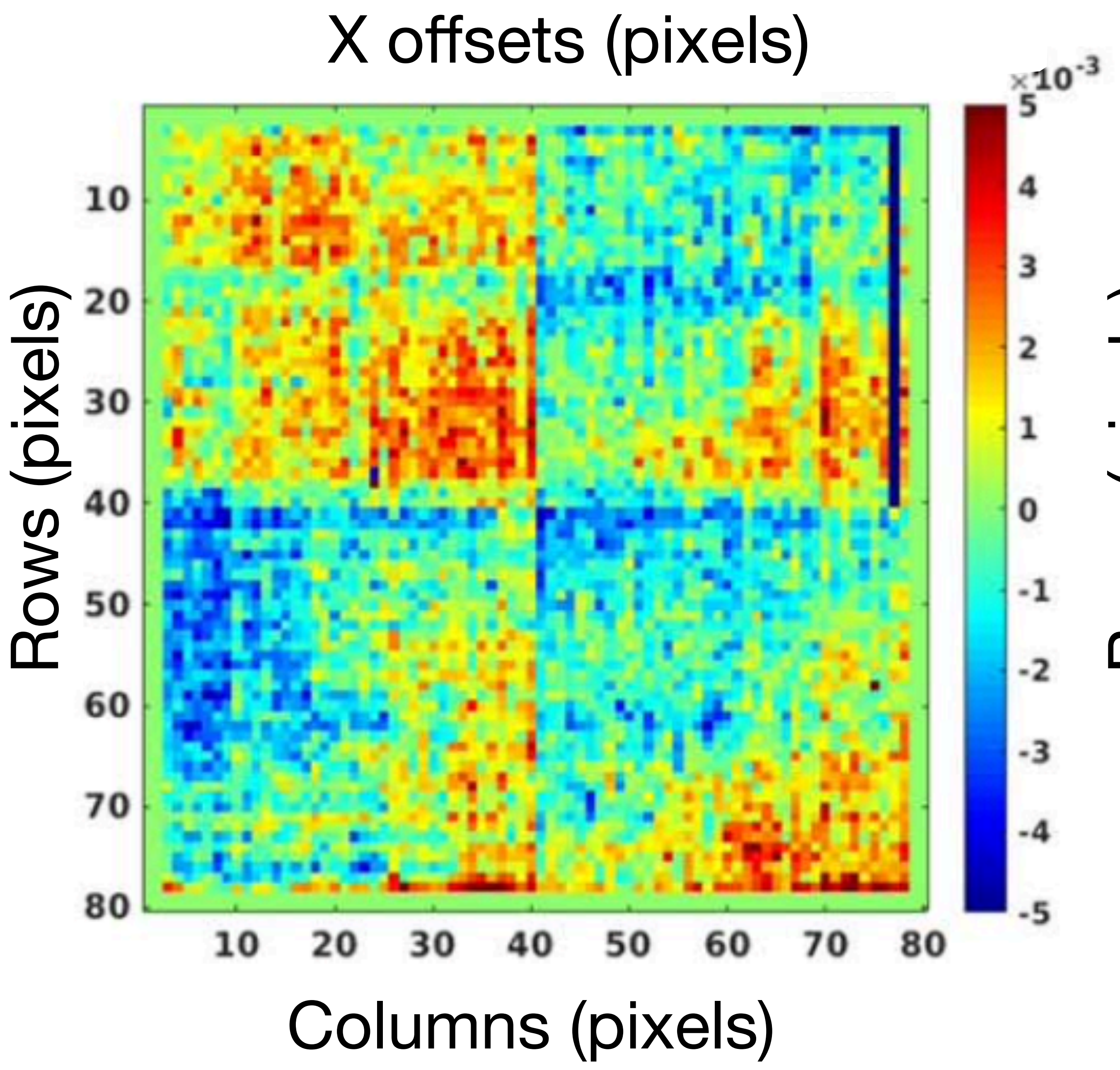
$$I_{ij}(t) = B(t)\ \iota_{ij} + A(t)\ \alpha_{ij}\ \sin\left[i\,K_x(t) + j\,K_y(t) + \phi(t) + \delta_{x,ij}\,K_x(t) + \delta_{y,ij}\,K_y(t)\right]$$

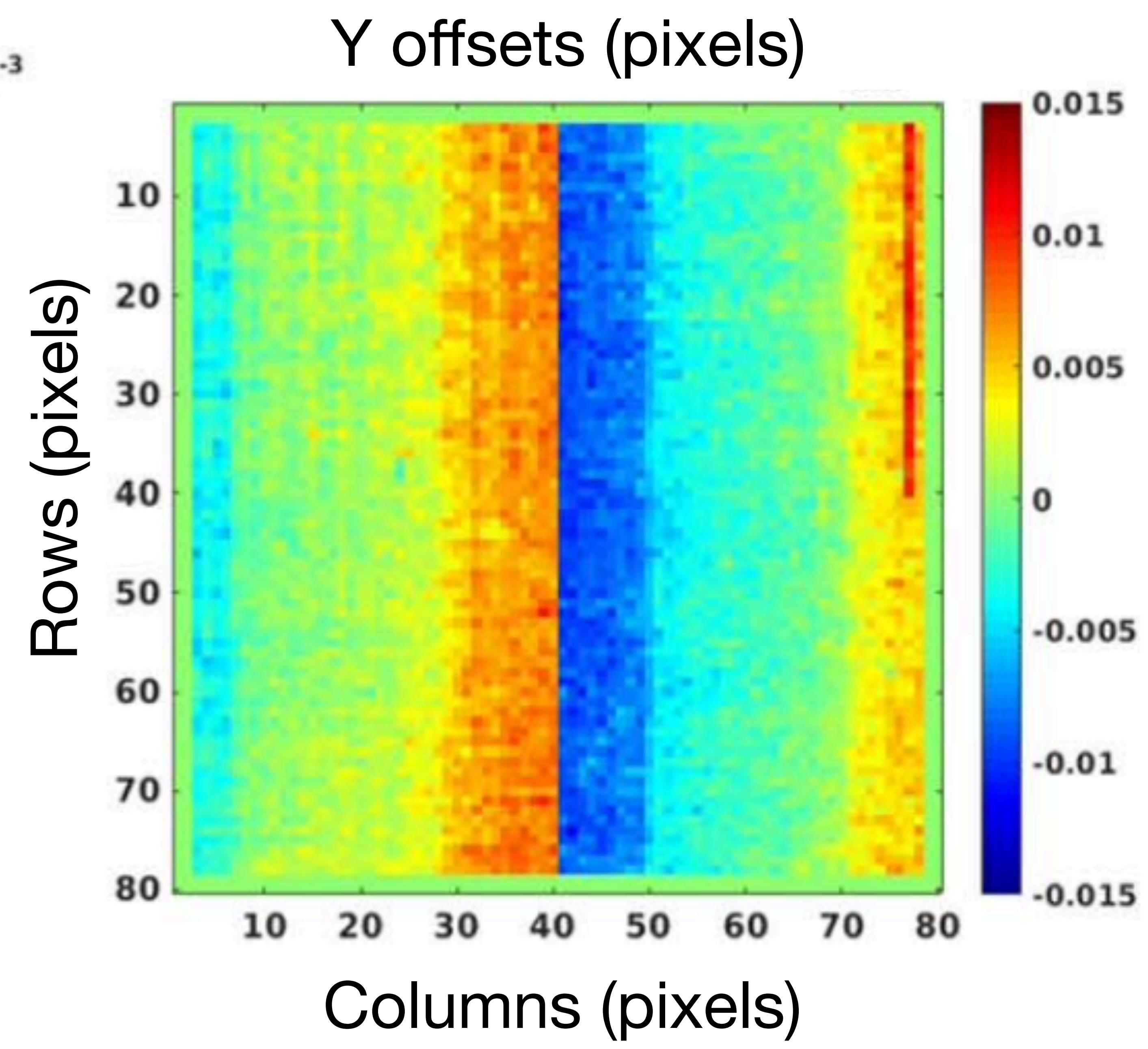
Notation	Name	Absorbed noises
$B(t)$	Average intensity	Laser flux, offset fluctuations
ι_{ij}	Intensity carrier	Photo response non uniformity (PNRU)
$A(t)$	Average fringe amplitude	Laser flux, polarisation fluctuations
α_{ij}	Fringe relative amplitude	Photo response non uniformity (PNRU)
$K_x(t), K_y(t)$	Metrology wavevector	Laser freq. fluctuation, thermal expansion
$\phi(t)$	Differential phase	Phase jitter (thermal and mechanical)
$\delta_{x,ij}, \delta_{y,ij}$	Pixel offsets (*x* and *y* directions)	-

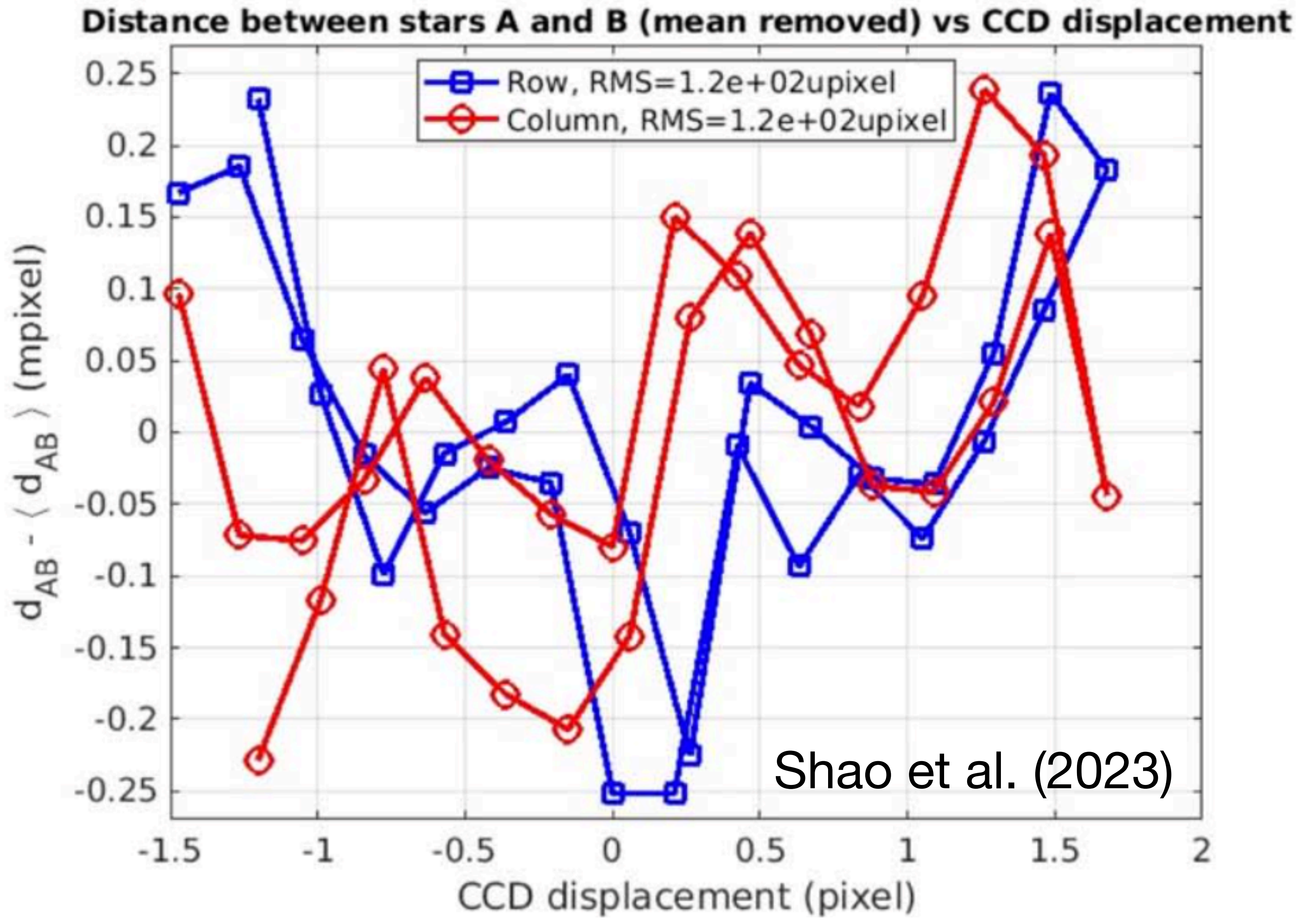


Crouzier et al. (2016)

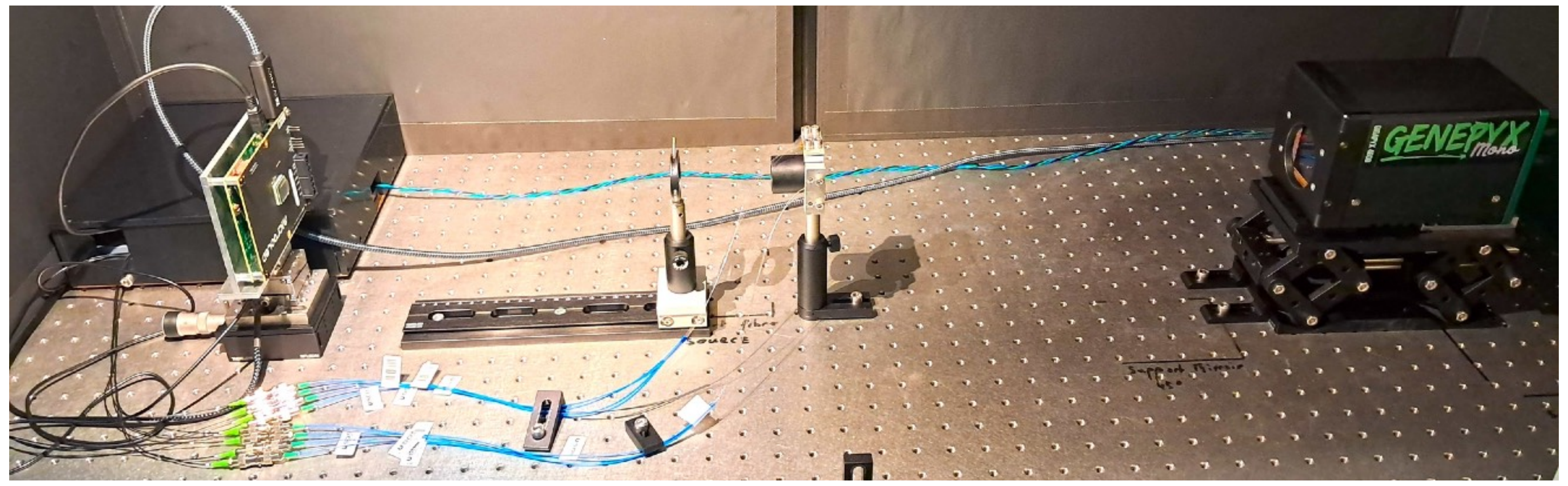
Detector interferometric measurements





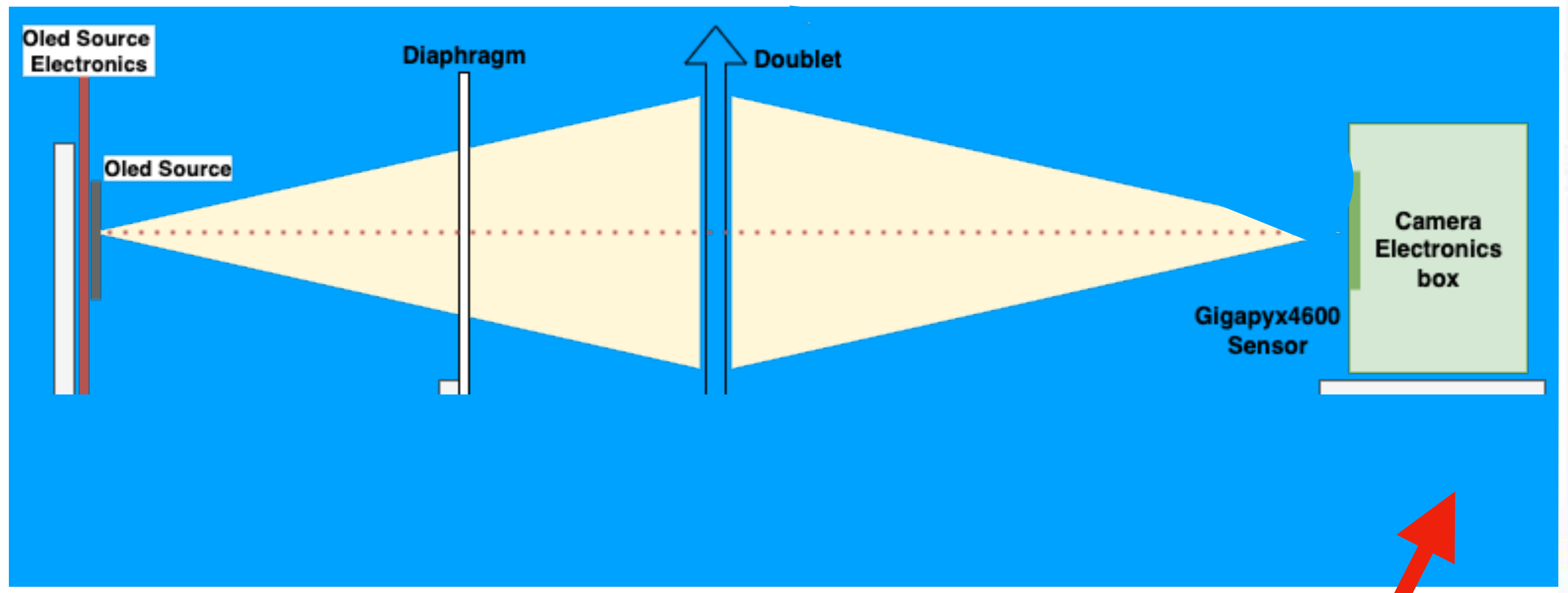


Best results so far:
- IPAG/CNES: 6 10^{-5} pixels (Crouzier et al. 2016, A&A 595, A108)
- JPL/VESTA: 3 10^{-5} pixels (Shao et al. 2023, PASP 135, 074502)



Optical calibration in the lab

On the OLED micro-display



On the GigaPyx 46MP detector

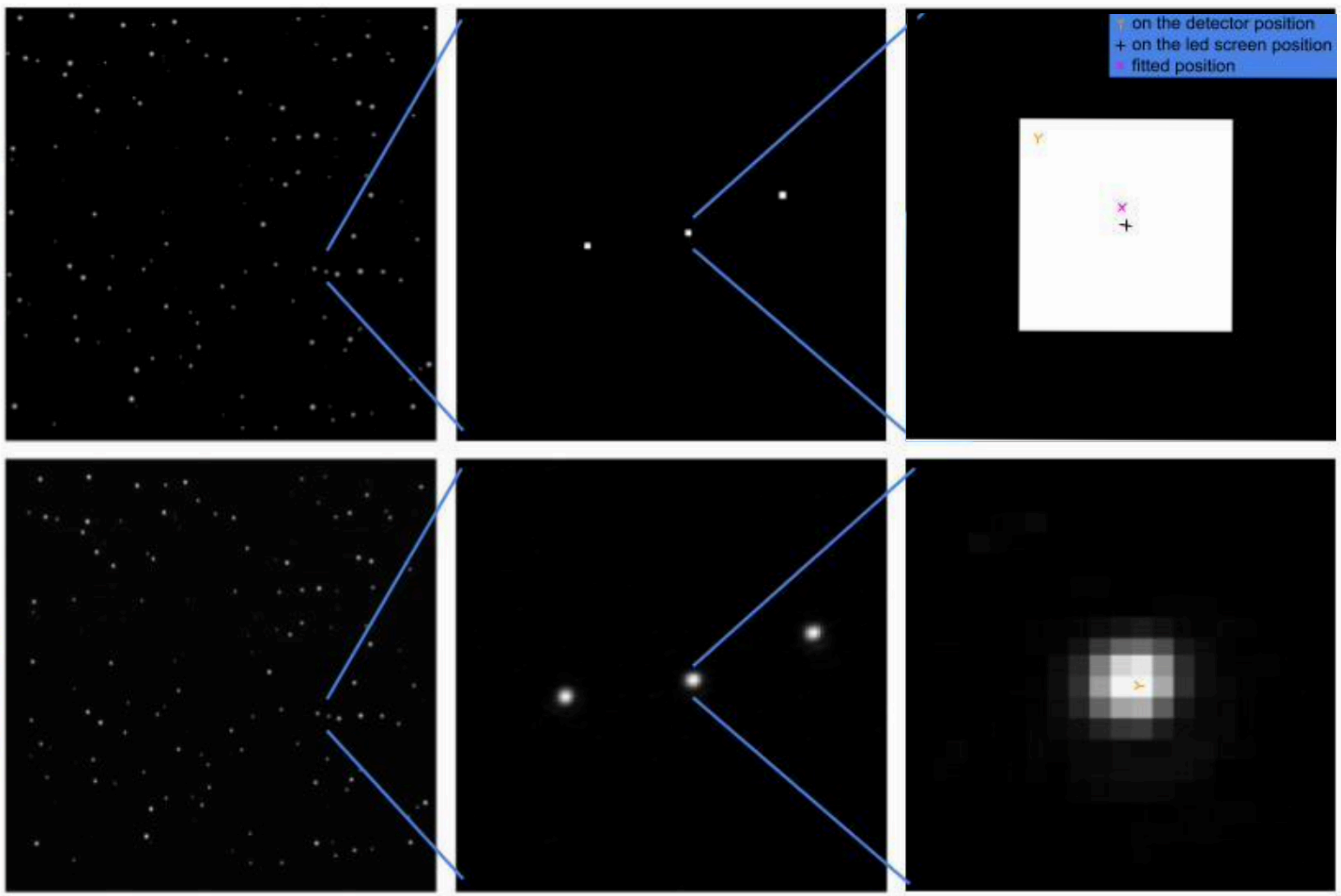
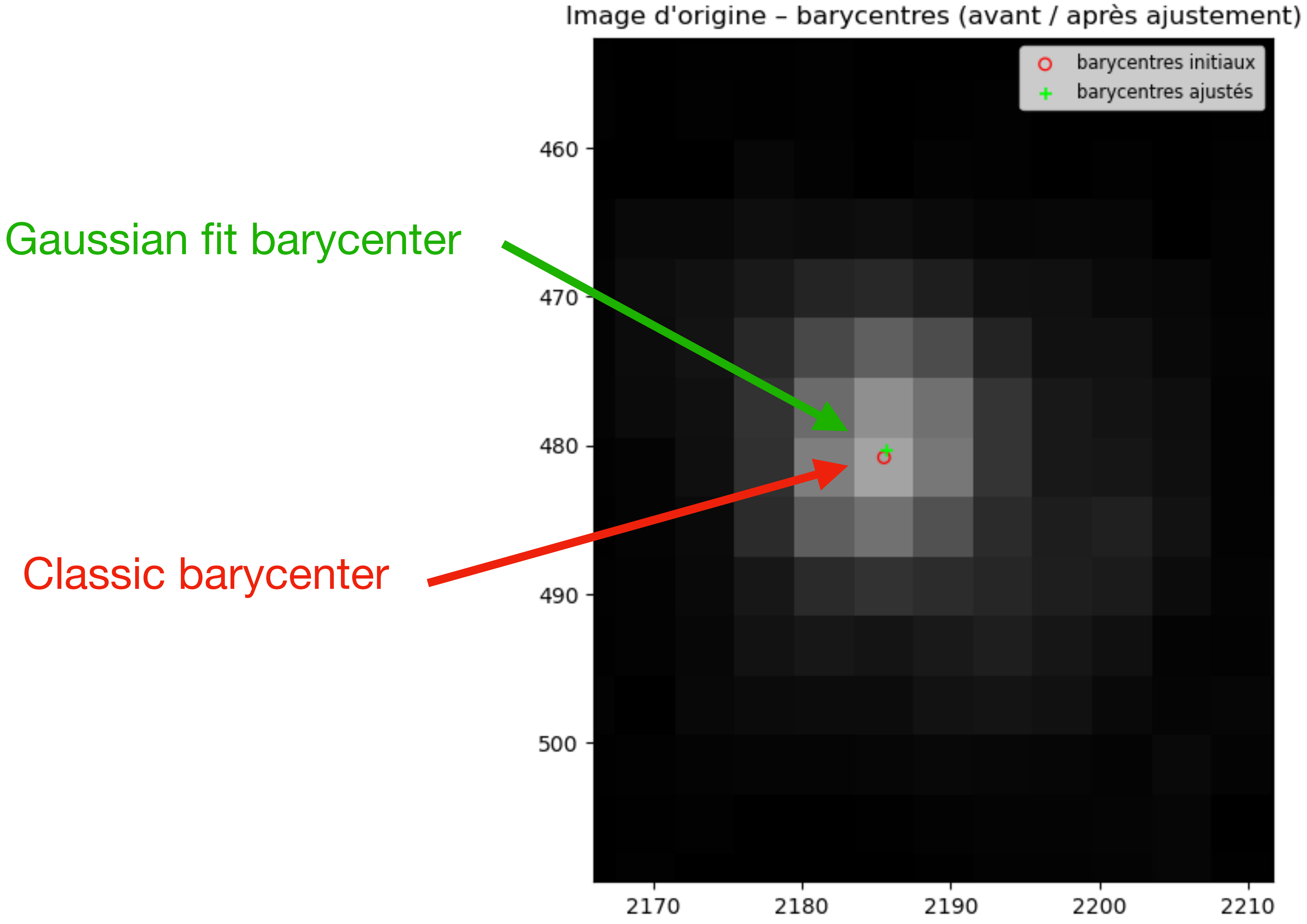
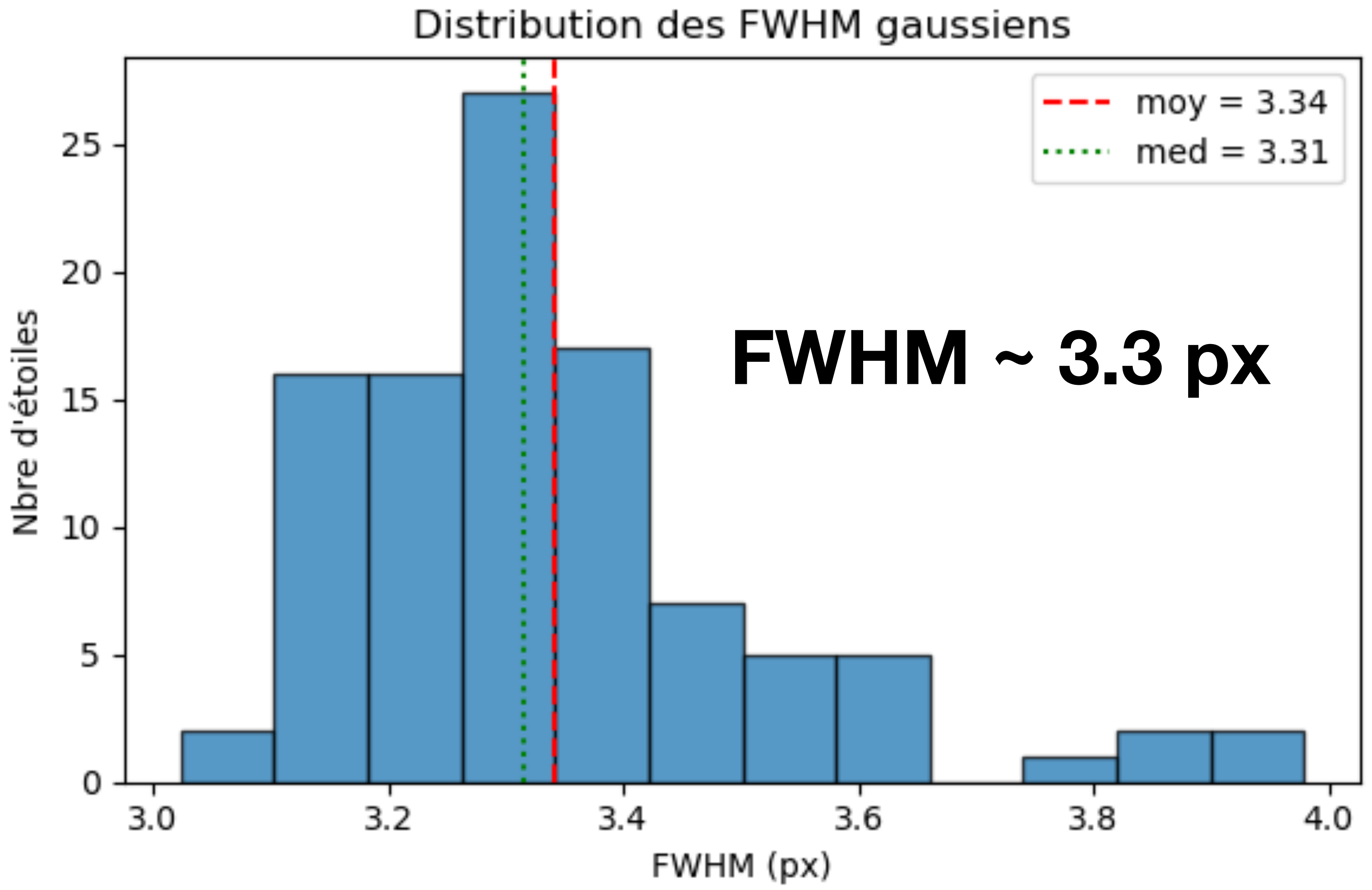
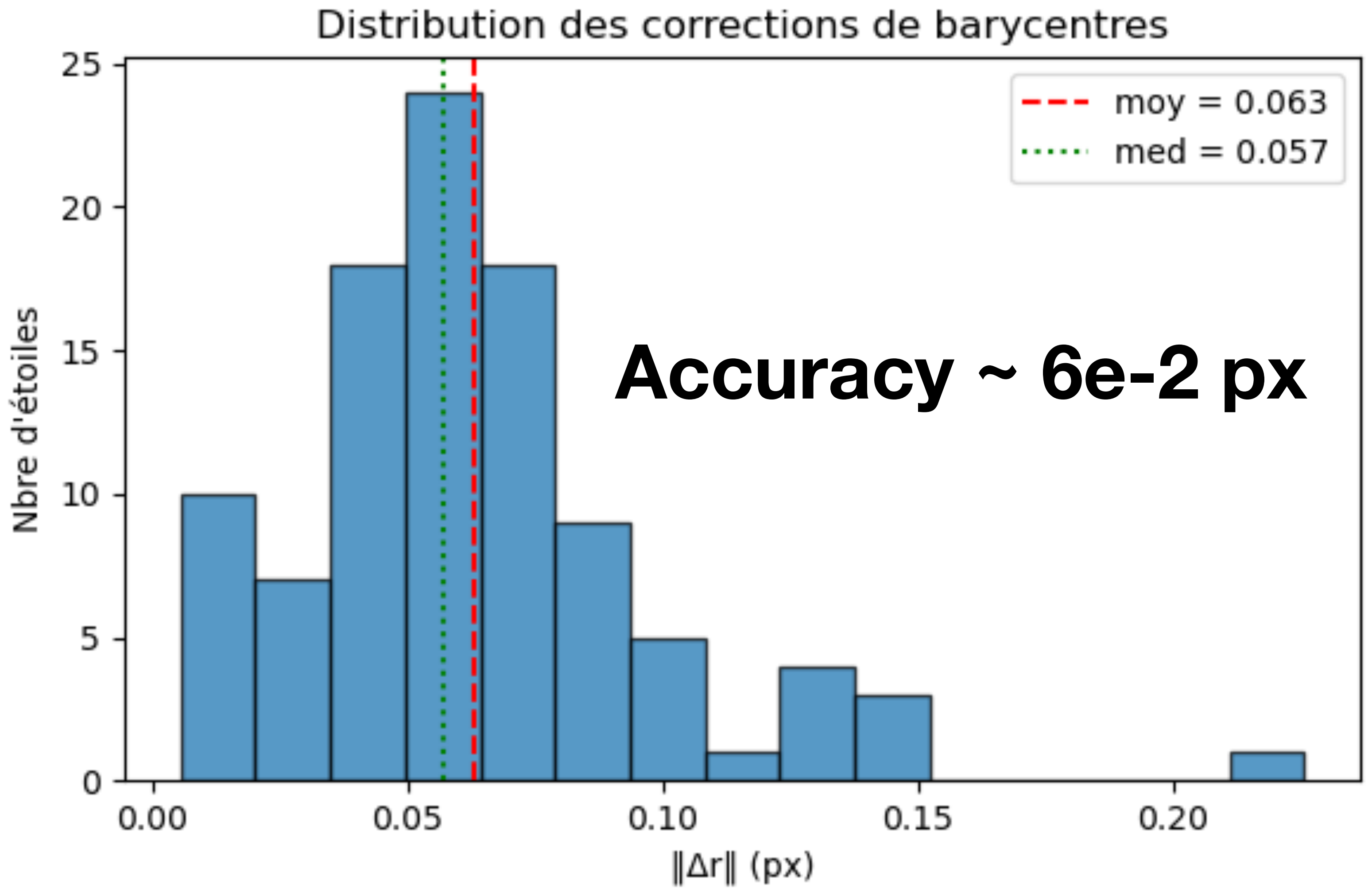


Image data processing







Quite promising ! We need to make sure that we are meeting the flux requirement.

Conclusion and perspectives

- We have shown that the CMOS 46MP Gigapyx should be a viable technology for high precision astrometry
- The lab measurements are reaching the company announced performance
- The test bench in the lab is operationnal
- We are measuring fringes and temporal modulation,but we are not yet at the pixel position calibration
- The lab simulation of optical distortion correction is working at 1e-2 level, but not yet reaching 1e-4 pixel;

- For GaiaNIR, the detector technology is different but the process is the same with other materials.