THEIA

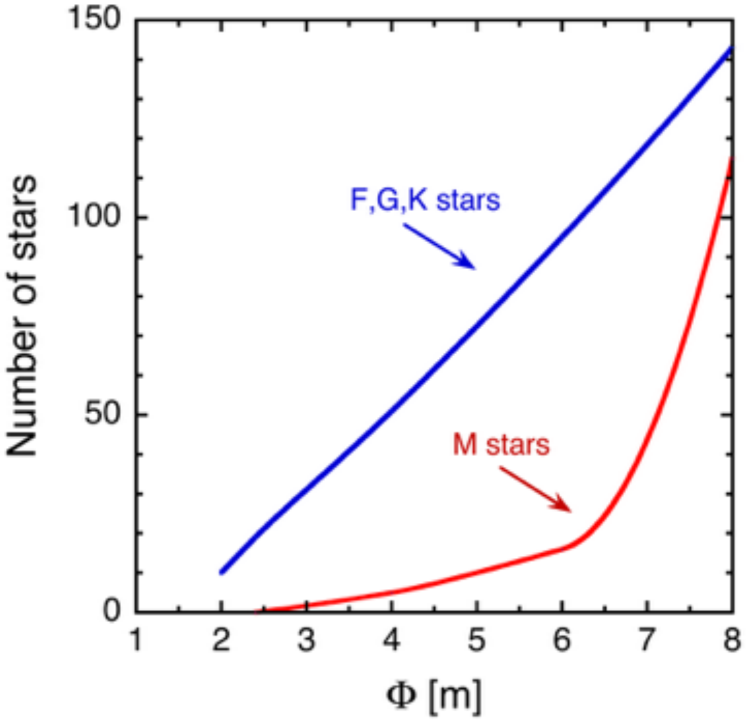
Microarcsecond Astrometric Observatory

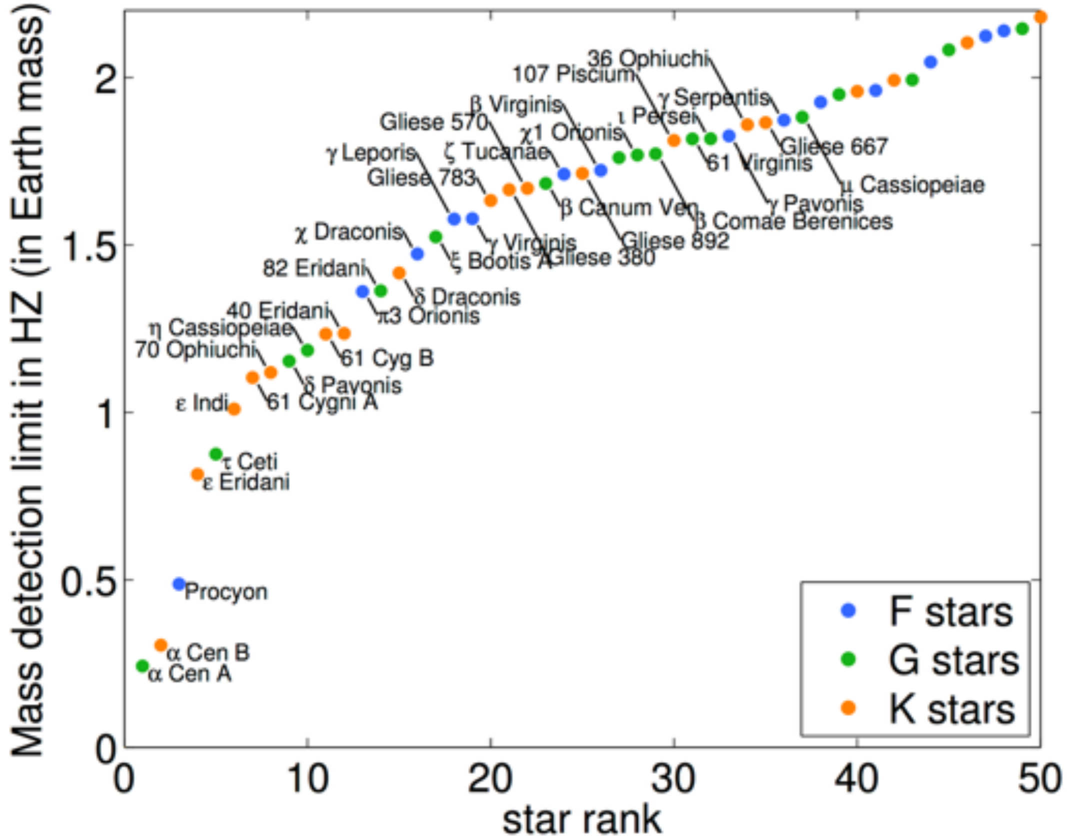
From Dark Matter to Compact Objects and Nearby Earths

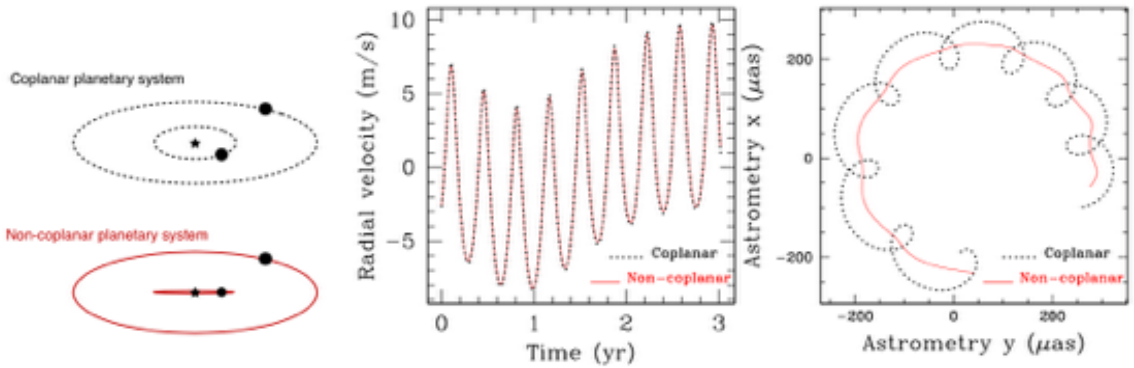
Science objectives

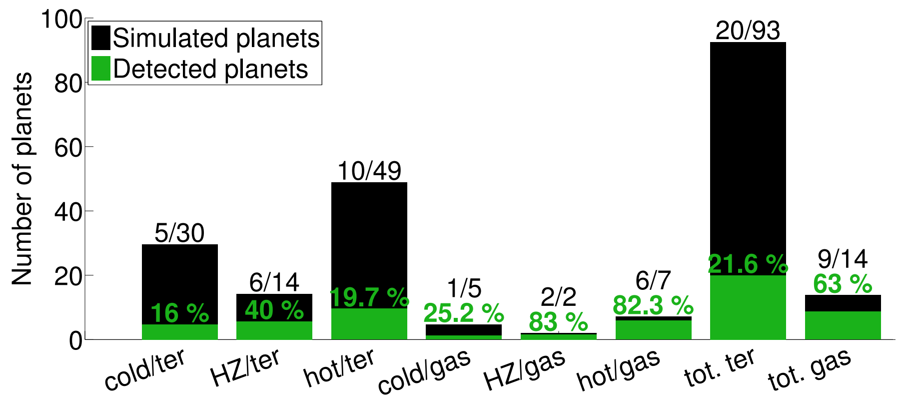
- Particle physics
  - The existence of Quark Stars
  - The nature of Dark Matter: Self-interacting dark matter? Warm dark matter?
- Exoplanets
- Young Stellar Clusters
- Following up on Gaia’s Results
- Open Time Observations

Nearby Habitable Exoplanets





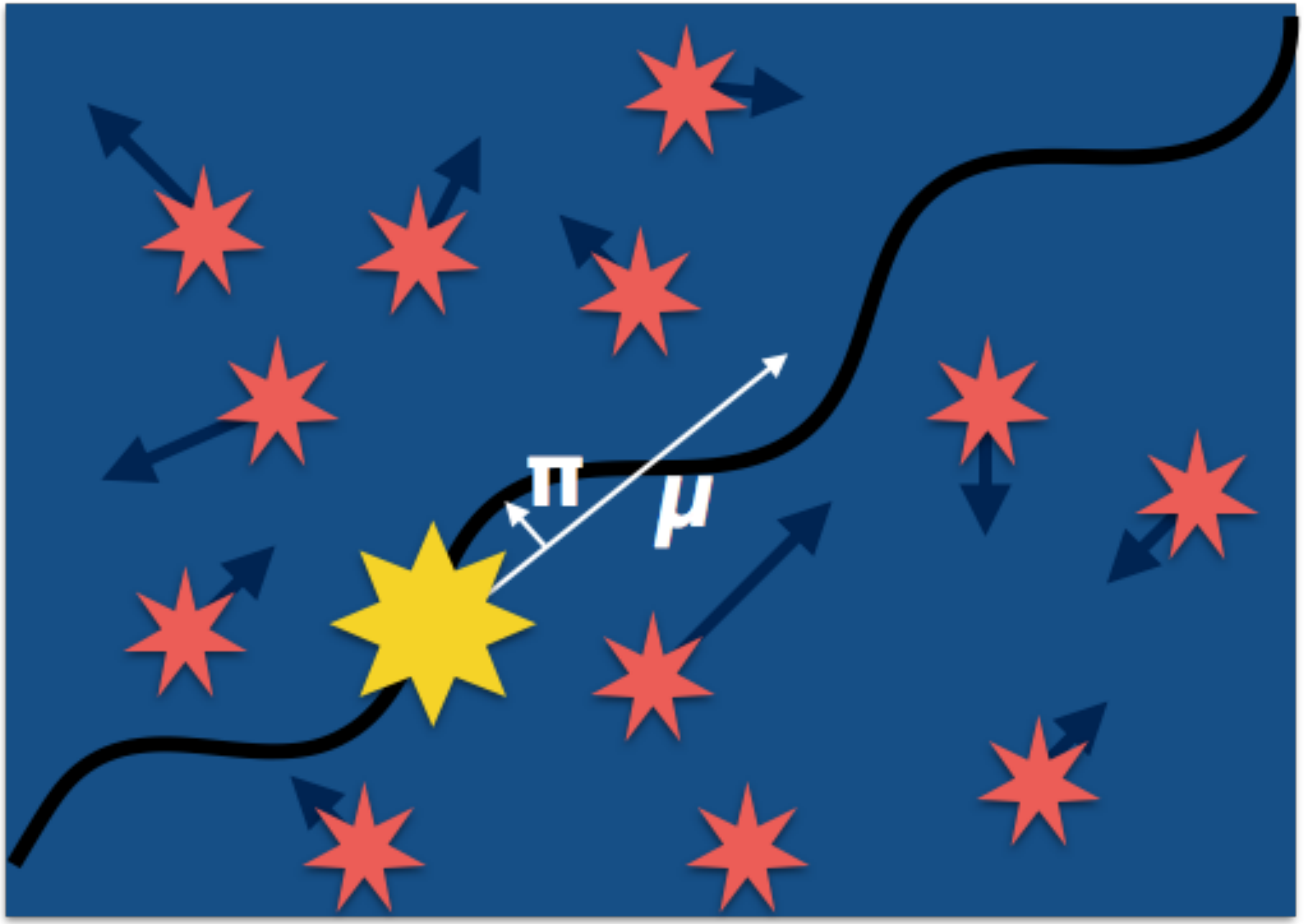




Scientific Requirements

- Measurement Principle : Differential astrometry
- Calibration Strategy
- Top Level Requirements
- Derived Technical Specifications
- Derived accuracy

Measurement Principle : Differential astrometry



Derived Technical Specifications

– Telescope : D~ 0,8 m with a 0.5 deg field of view diffraction-limited (scaled down version of Euclid optics and platform)

– commercially available 10µm pixels,

– reproducible centroid precision at better than **10^{-5} pix** are under way at NEAT/ CNRS/CNES testbed (R1A and R2A).

– CMOS detectors with windowed fast-readout modes yields data transfer rate < 3Mbits/s and less than 5 hr/day of antenna time.

– Calibration every 60s using a **laser fringe pattern** coming from M3.

– The position of each pixel against the fringe pattern will be calibrated down to 10^{-5} pix/hr.

– An orbit around L2, enhanced thermal shielding compared to Euclid, sun-avoidance angle of 45 deg, use of **low-thermal expansion optics (Zerodur) and structural components (carbon-carbon fiber tubes)** are proposed to achieve TLRs R4A and R4B (pointing, reproducibility) and TLR R5B (technology readiness), together with 150 mK thermal stability using Gaia-like thermal control technology (**thermal shielding between solar panels and telescope/ platform not present in Euclid**)

Expected accuracy

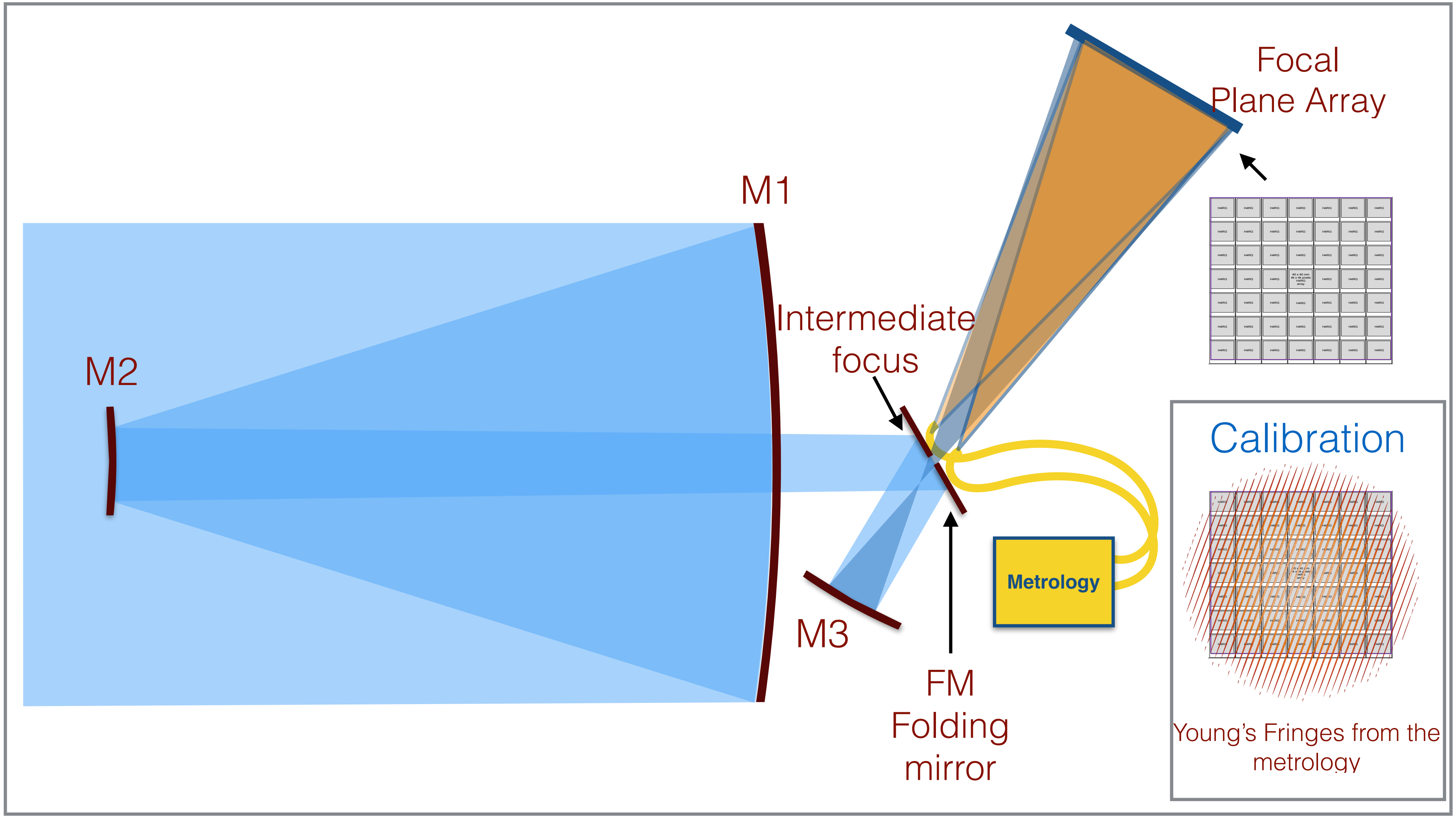
Summary of science cases with most stringent performance requirements set in each case. $\mu^{N\rightarrow\infty}$ is the 0 systematic noise floor in proper motions caused by systematics errors in the reference frame. It strongly depends on the FOV and characteristics of the target (eg. distance).

Program	Used time (h)	Mission fraction	Nb of objects per field	Benchmark target R mag (and range)	EoM precision (at ref. mag.)	Ref. frame accuracy $\mu_0^{N\rightarrow\infty}$
Dark matter	8 000	0.34	10^3–10^6	20 (14–22)	10 μas	$2-5$ μas/yr
Ultra-compact objects	2 600	0.11	20	17 (13-20)	8 μas	2 μas/yr
Nearby Earths	4 000	0.17	$<$20	5 (1–14)	0.15 μas	(none)
Young stellar clusters	2 600	0.11	10^3-10^5	20 (15-25)	35 μas	5 μas/yr
Gaia follow-up	2 600	0.11	10-10^6	10 (5-21)	1.0 μas	$2-5$ μas/yr
Open time	4 000	0.17	10-10^6	6 (1-25)	1.0 μas	$2-5$ μas/yr
Overall requirements	23 800	1.00	10^1-10^6	6 (1-25)	0.15 μas	$2-5$ μas/yr

Differential Measurement Astrometric uncertainty as a function the magnitude of target star for δt_{visit} = 10 hr and N_{visit} = 10 compatible with specification in deep field mode. The value of σ_π is a proxy for the end-of-mission astrometric precision.

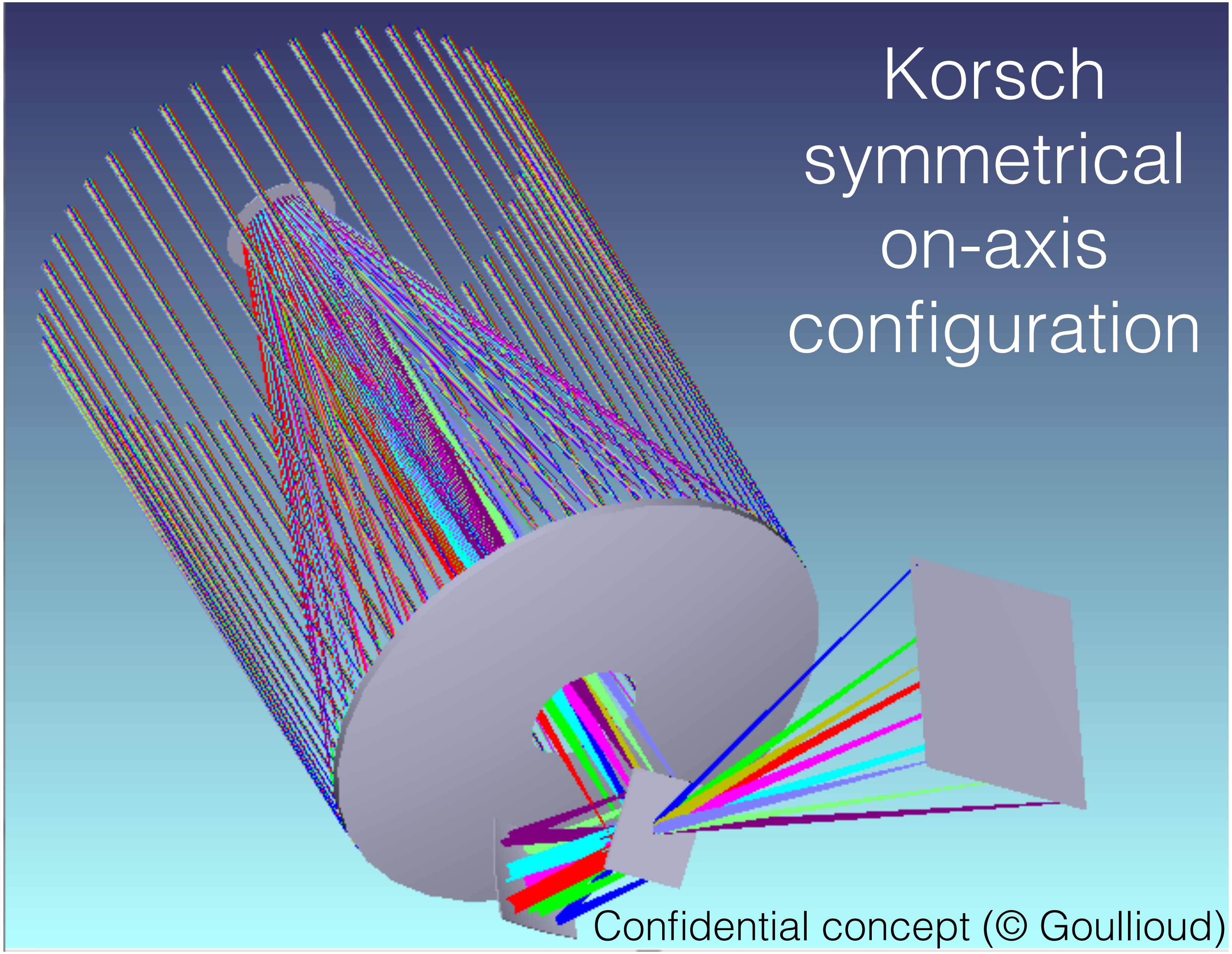
R (mag)	10	15	20	21	22	24	25
σ_μ (μas)	0,15	1.0	10	18	27	75	135
σ_π (μas/yr)	0,30	2.0	20	35	55	150	270

Instrumental concept

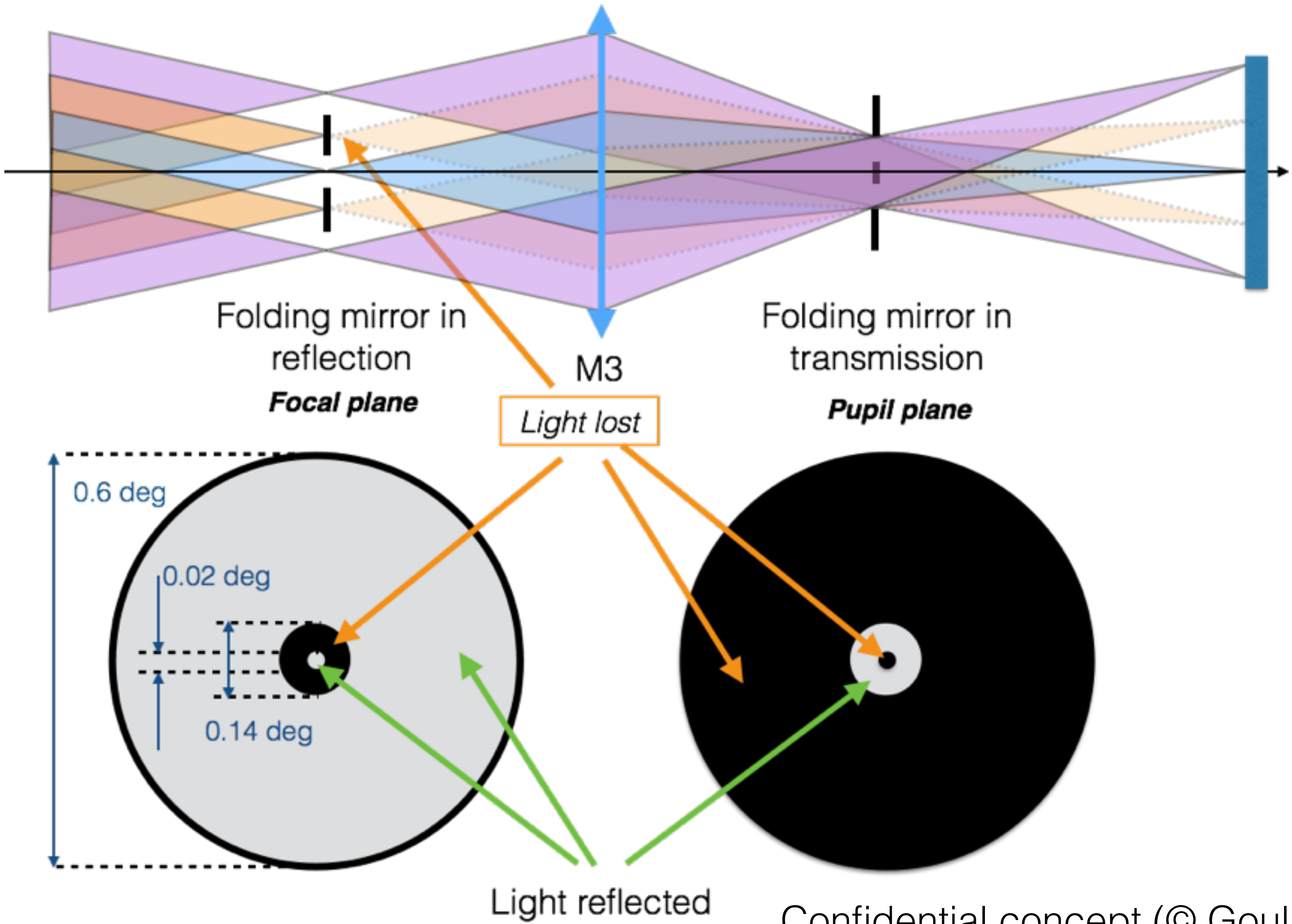


Confidential concept (© Goullioud)

3D optical concept



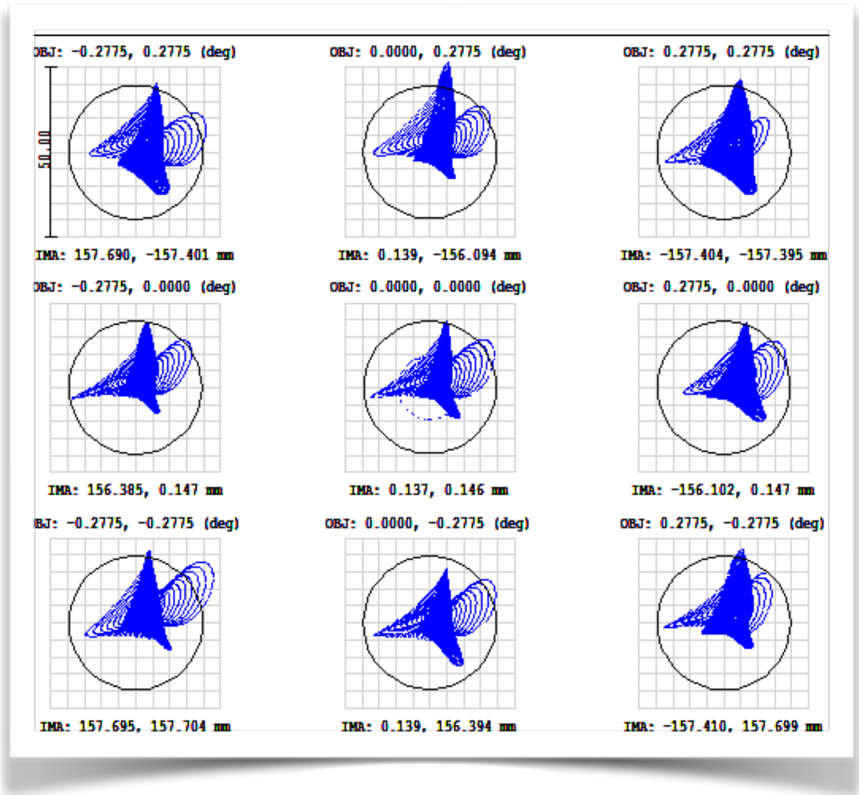
Korsch symmetrical on-axis configuration



Confidential concept (© Goullioud)

An example of real telescope

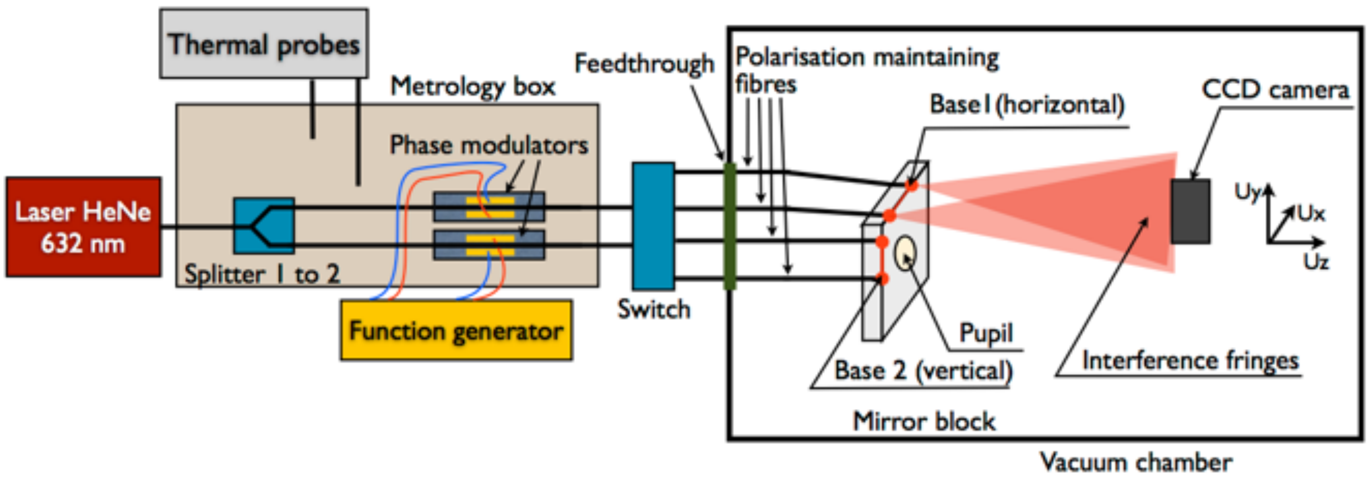
- Assuming a 5-DoF mechanism on M2,
  - about +/- 1 µm error in position after calibration, few arcsec in tip/tilt (set 2 µm in X,Y and 2,5 arcsec in RX,RY)
  - Z(M1M2) = +/- 1 µm
- Assuming very good mastering of M1 machining/AIT/flight :
  - WFE aberration of M1 : Z4-Z15, ~equi-partition, so that :
  - WFE at image = 20 nm rms at center of FOV, 25 nm rms at edge (excluding high frequencies)
- M3 : no positioning error (not very influent)
- M2, M3 assumed negligible / M1 for the moment

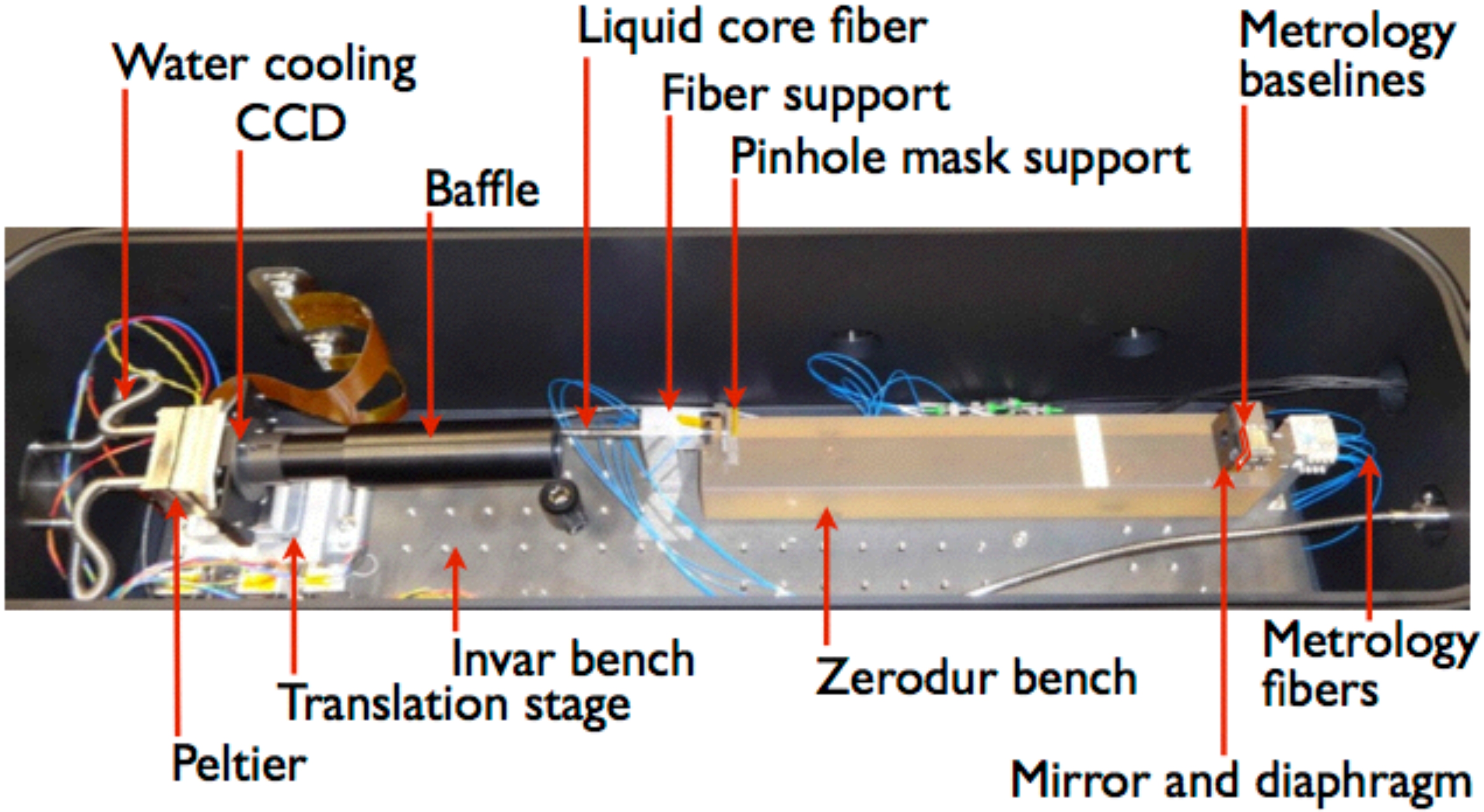


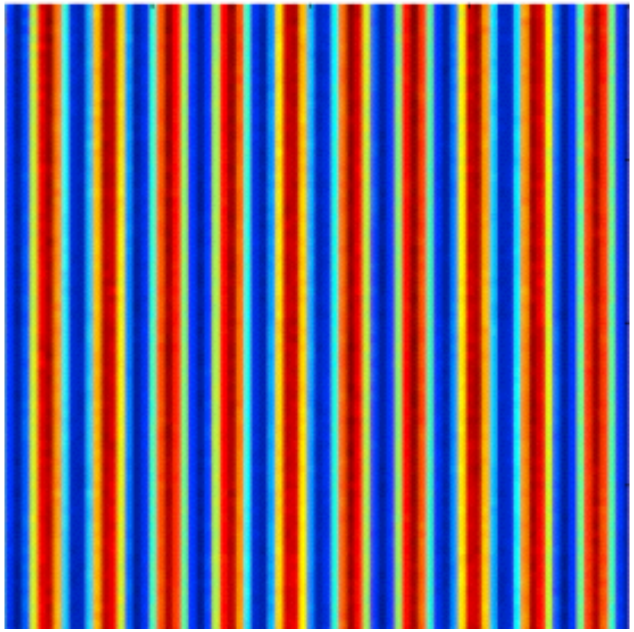
➡ **quite symmetric behavior, but some slight deviations**,

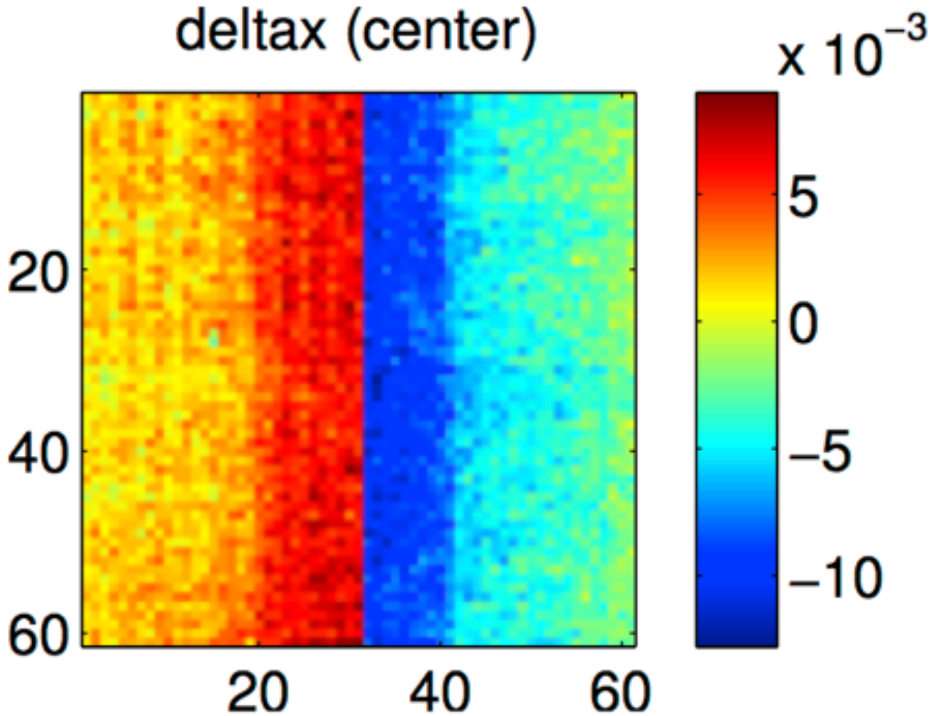
➡ importance of M2 lateral position combined with M1 coma.

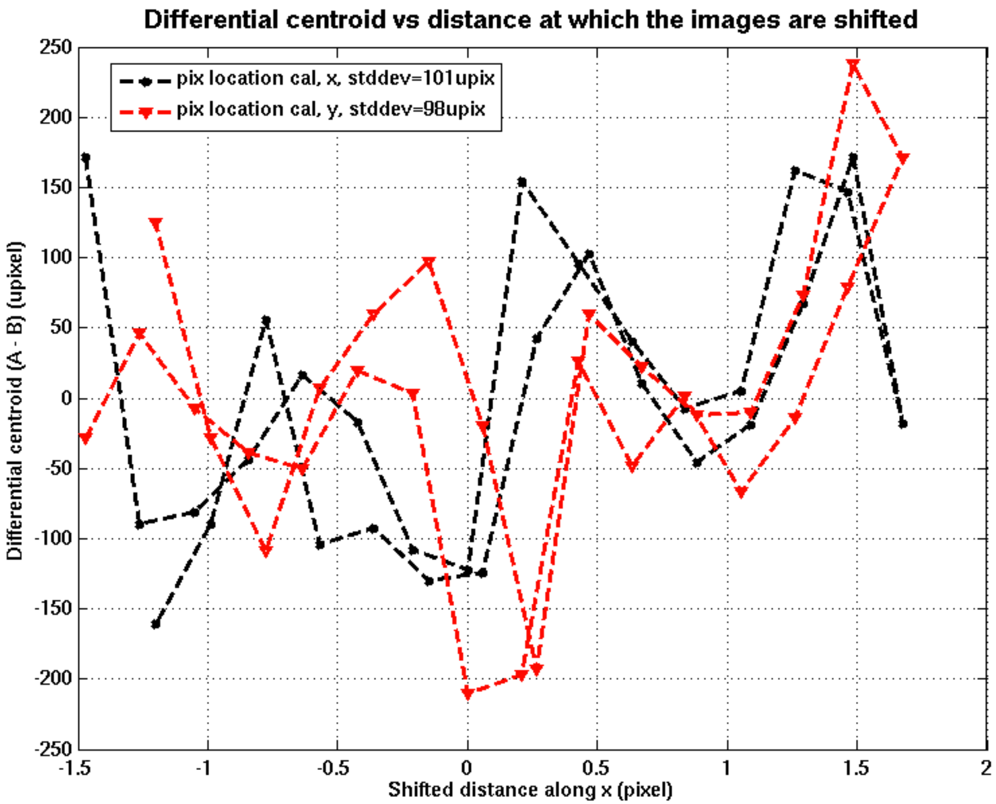
Detector Calibration unit









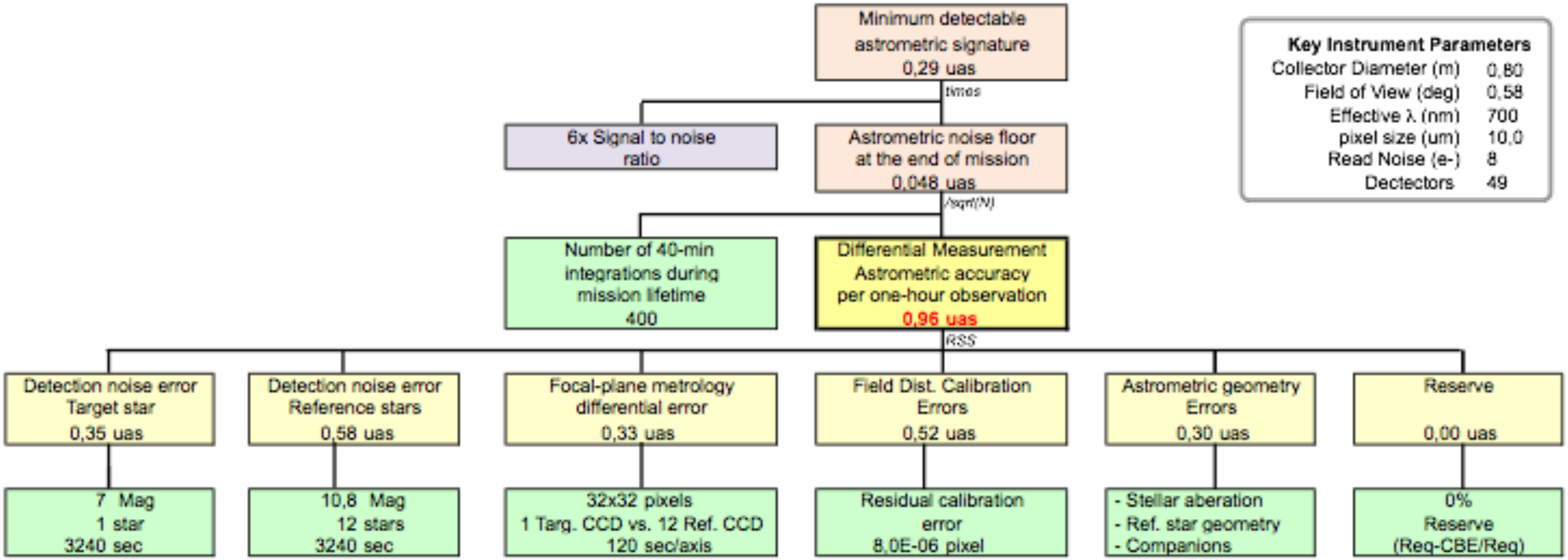


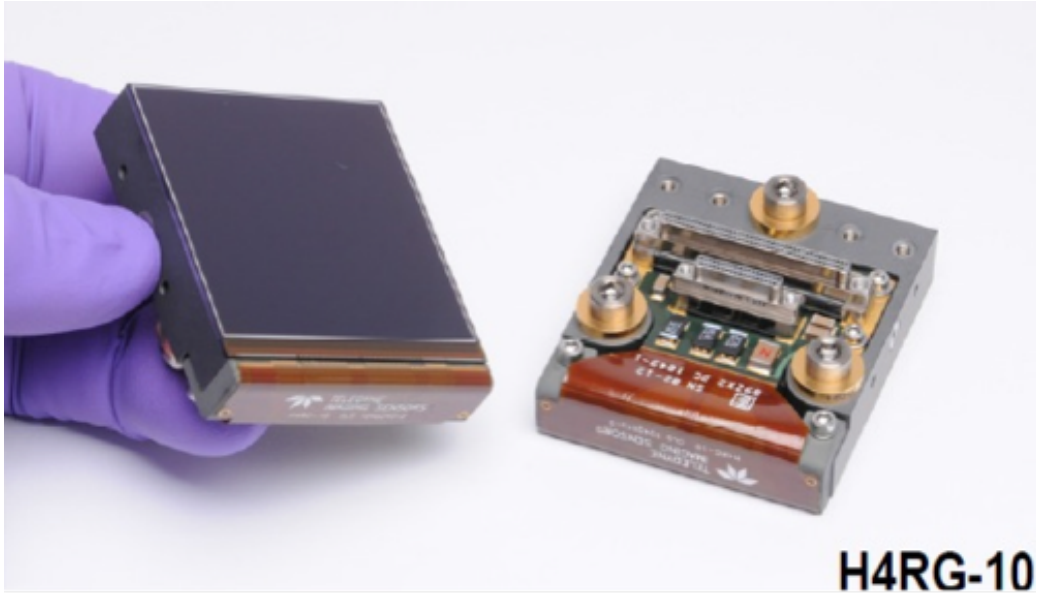
Best results so far:

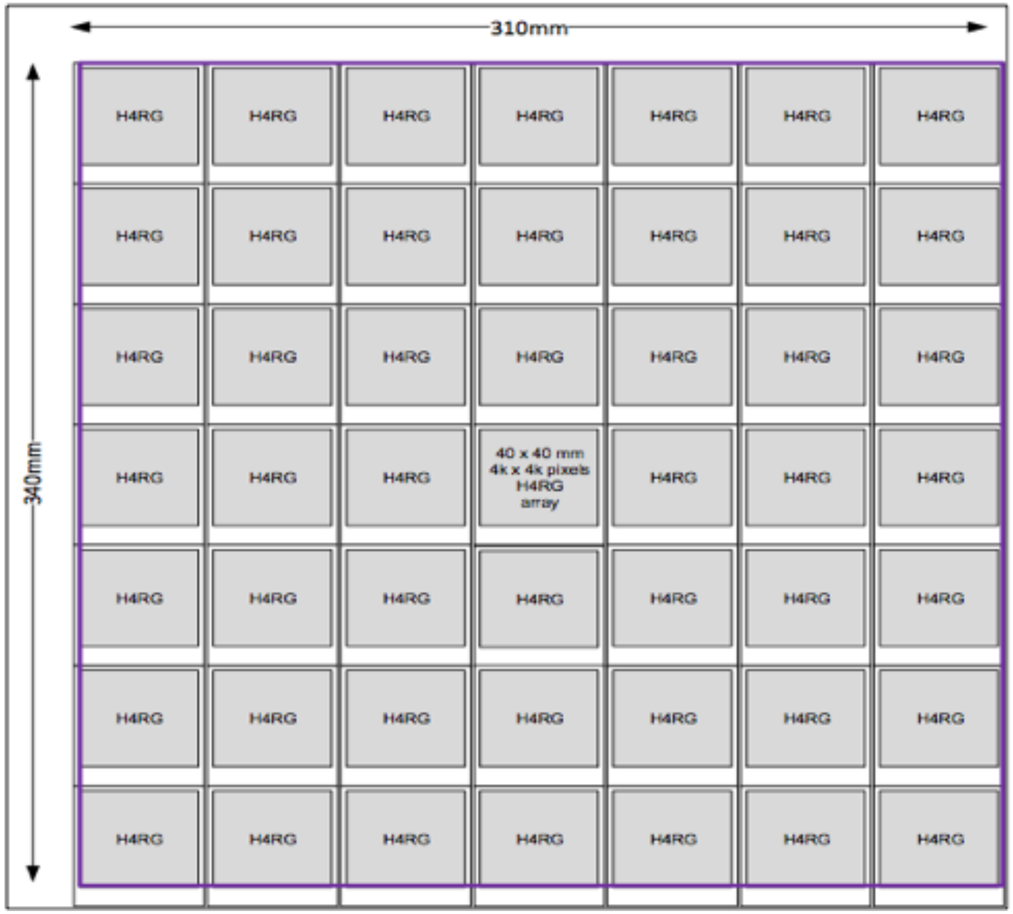
- IPAG/CNES: 2.8 10^{-4} pixels
- JPL/VESTA: 10^{-4} pixels

Proposed strategy to reach 10^{-5} pixel calibration:
100 independent positions, a space of ~ 40 × 40 pixels for Nyquist-sampled centroids

Performance assessment and error budget







Focal Plane Array Dectectors

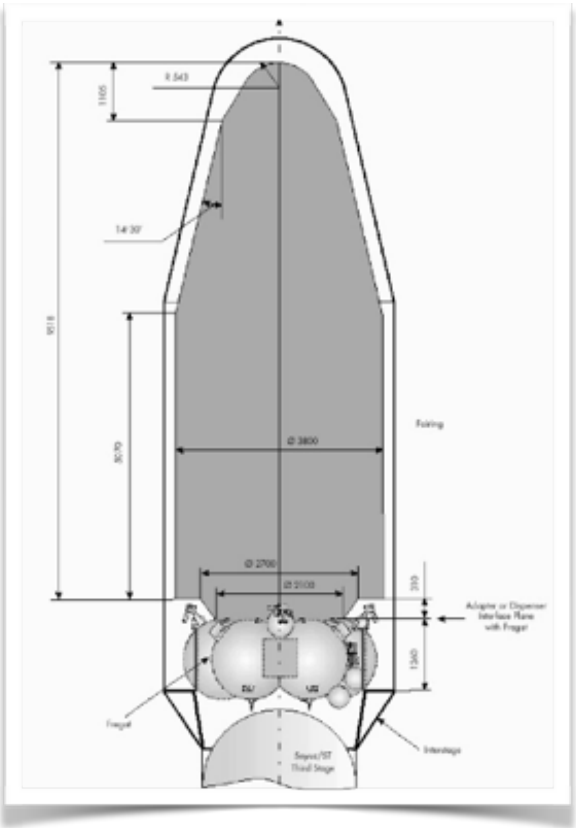
ITEM	VALUE
Pixel Number	4096 x 4096
Optical format	44 x 50 mm
Pixel size	10 x 10 um
Full well charge	100 Ke
QE	> 90%
Number of outputs	1, 4, 16, 32 or 64
Max Pixel rate readout rate	up to 5MHz
Full frame rate (fast mode)	19 fps w 64 outputs @ 5Mpix/s/output
Dark Current (room temperature)	5-10 nA/cm
Readout noise	< 10 e

Proposed mission profile

- **Mission Orbit**: large Lissajous or Halo orbit at L2.
- **Launcher** : Soyuz with the enhanced capacity version Fregat MT for the upper stage.
- **Duration**: 3.5 years with a possible extended science operation (1yr)

Main mission characteristics

Launch date	No constraints, allowing launch date in 2025
Orbit	Large Lissajous in L2
Lifetime	• 3 years of nominal science operations • Technical operations: orbit transfer (3m), instrument commissioning (1m overlap +1m), decommissioning (1m)
Concept	Single spacecraft
Communication architecture	5Mbits/s, twice a week during a total of 4h



A scalable mission

Mission name	Mirror diameter	Focal length	Field of view diameter	Focal Plane size	Ref. star mean magnitude	DMA in 1h	# targets for a given mass limit		
	(m)	(m)	(deg)	(cm)	(R mag)	(µas)	$0.5M_\oplus$	$1\ M_\oplus$	$5\ M_\oplus$
STEP	1.2	50	0.45	40	11.5	0.7	**7**	**100**	**200**
NEAT	1.0	40	0.56	40	11	0.8	**5**	**70**	**200**
Theia	0.8	30	0.71	35	10.5	1.0	**4**	**50**	**200**
EXAM	0.6	20	0.85	30	10.1	1.4	**2**	**35**	**200**
							$1M_\oplus$	$10\ M_\oplus$	$50\ M_\oplus$
µNEAT (*)	0.3	12	0.6	15	11	10.2	**2**	**25**	**200**

DMA = Differential astrometric Measurement Accuracy (rms); (*) centroiding requirement relaxed to 4e-5

Small reduction of diameter would reduce cost and science but would NOT kill science, e.g. number of stars studied,…

What to improve ?

- Better define the requirements on the science objectives (e.g. the calibration precision)
- Optical design: investigate refractive optics or at least some glass plate (Ritchey-Chretien design)
- Publish calibration results