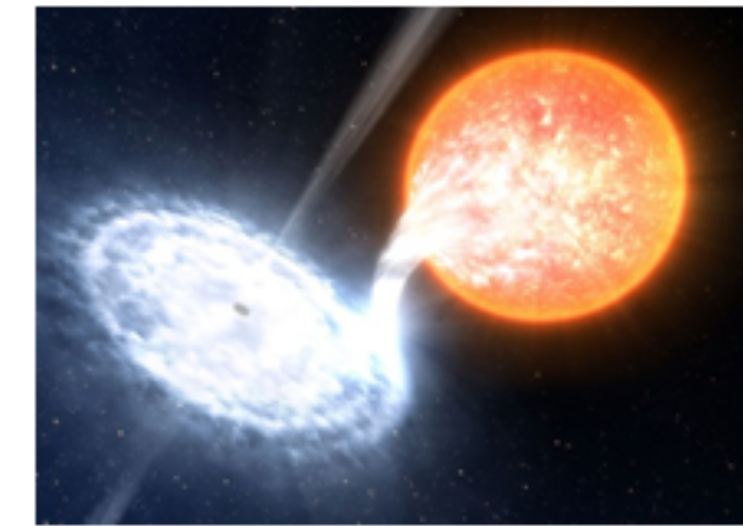
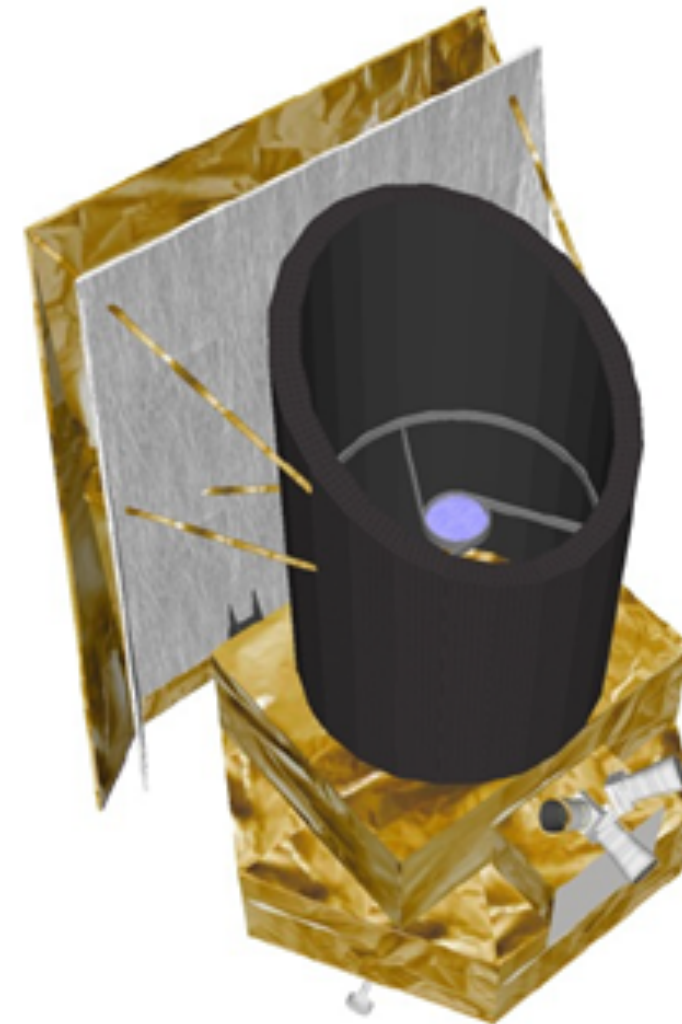
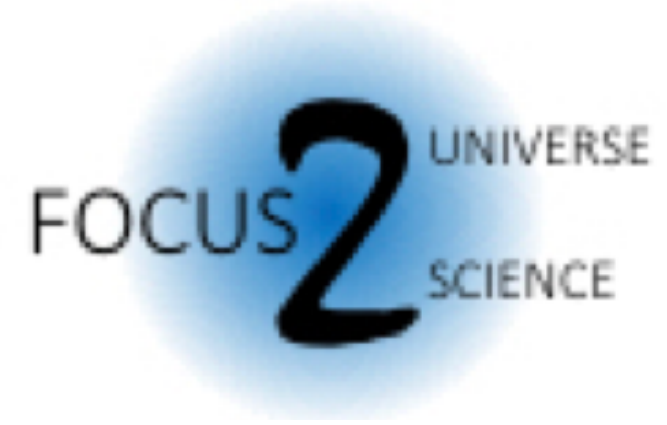
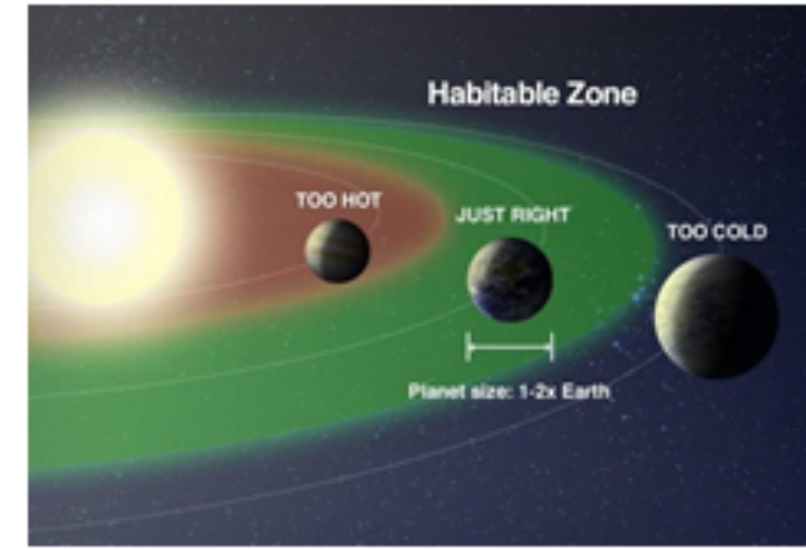




THEIA

Microarcsecond Astrometric Observatory



Exploration des architectures des systèmes exoplanétaires proches par astrométrie spatiale à haute précision

Fabien MALBET

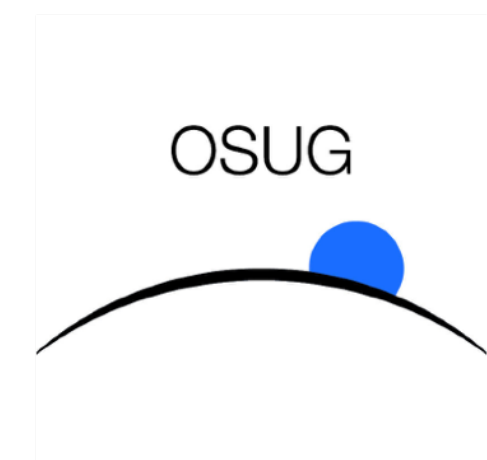
IPAG / Univ. Grenoble Alpes / CNRS

and trie Theia collaboration



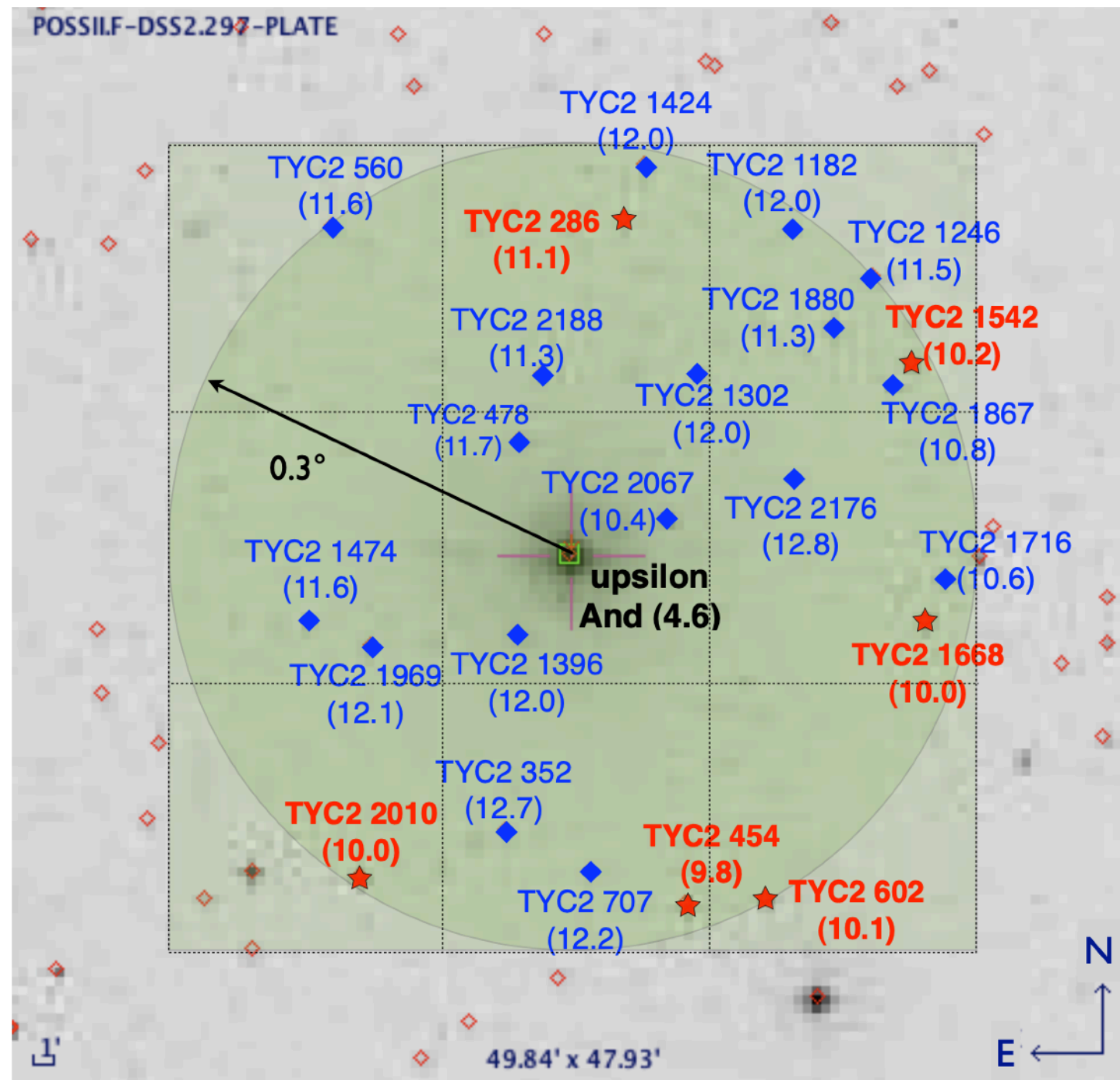
+ Manon Lizzana, Fabrice Pancher, Thierry Lépine, Alain Léger, Gary Mamon and Theia collaboration

Atelier Exosystèmes IV - Lyon 31 janvier - 1 février 2024

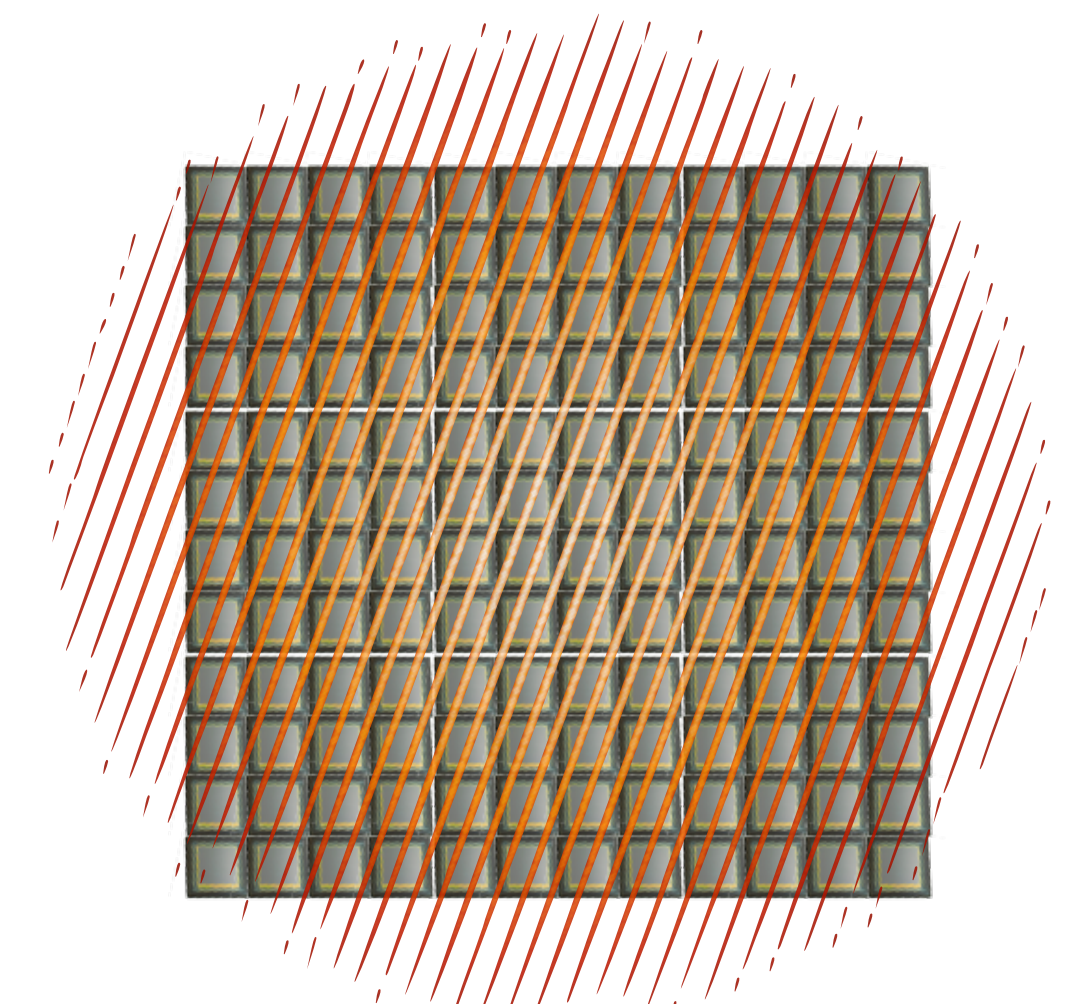
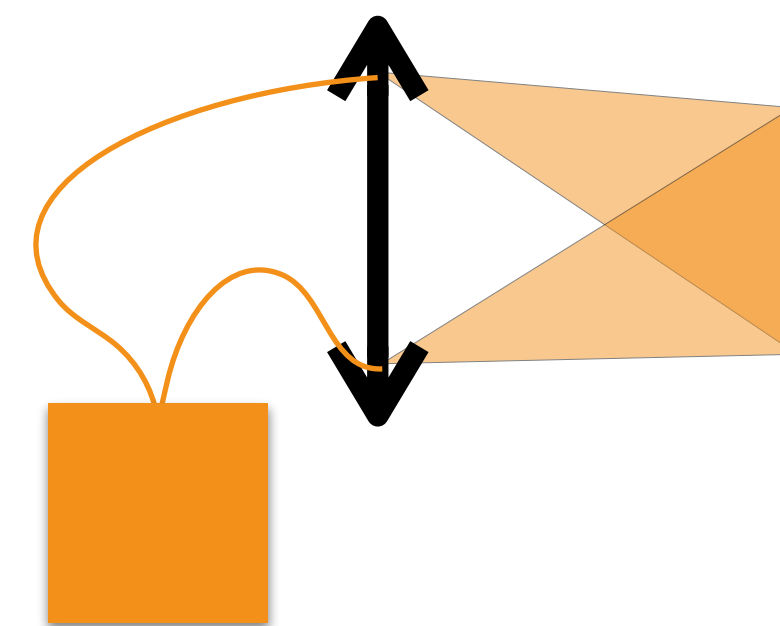
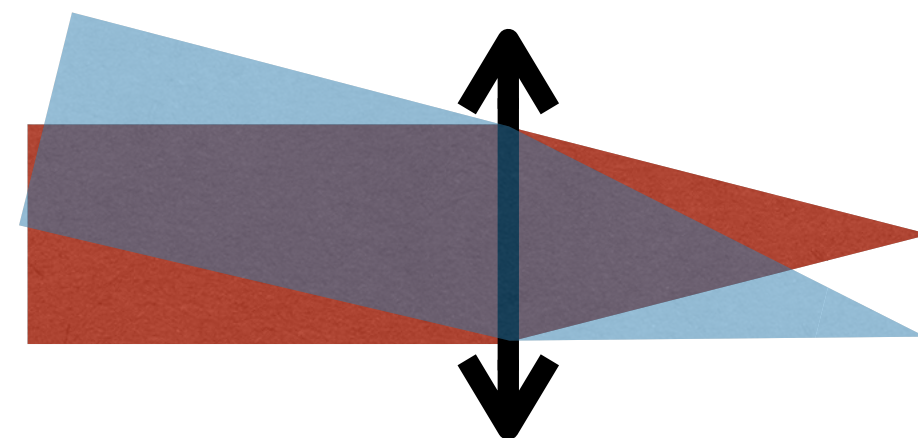


TERRE & UNIVERS

Principle of Theia : relative and precise differential astrometry

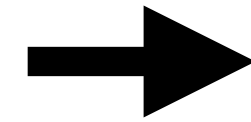


- ✓ The science target is at the center of the FOV
- ✓ We measure the offset angles between the target object (in **black**) and the reference stars (other stars in **red** and **blue**)
- ✓ The single measurement is repeated several times over the mission lifetime to reach the required accuracy on the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

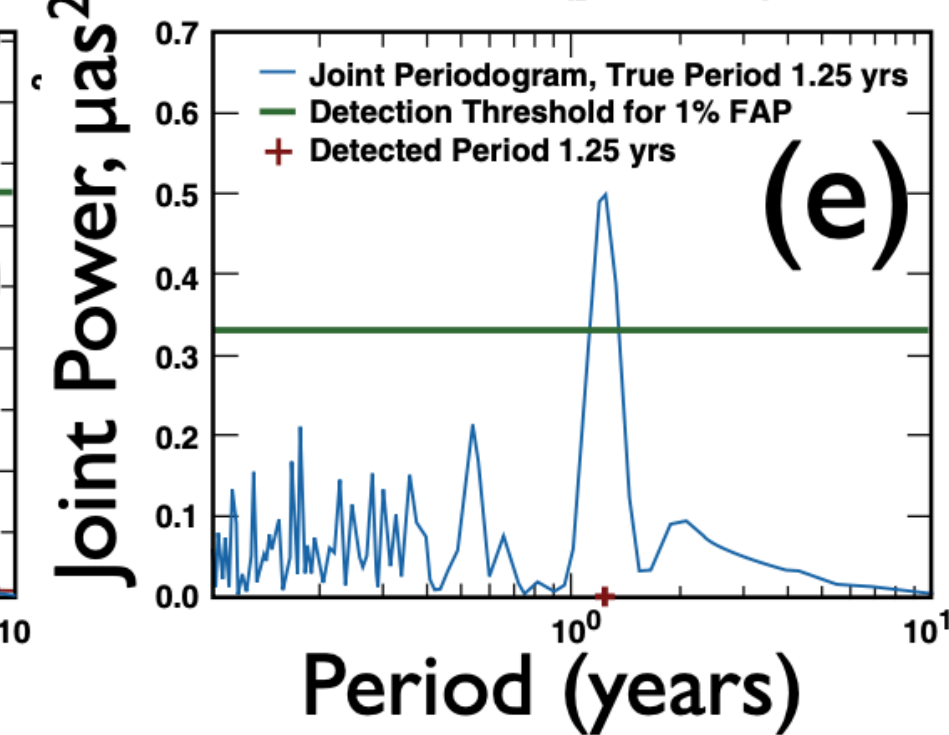
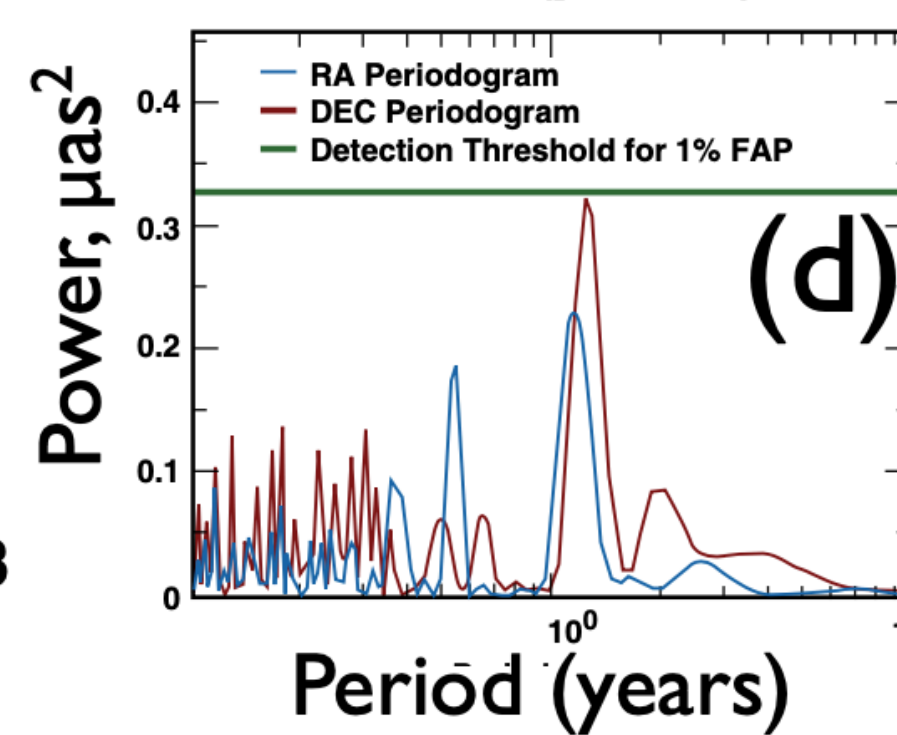
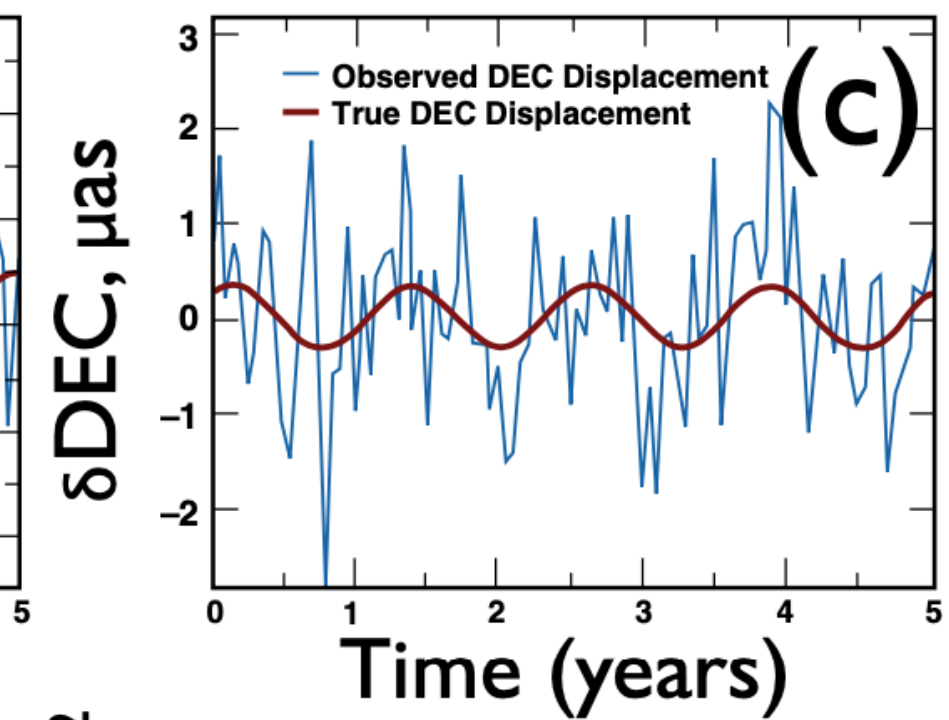
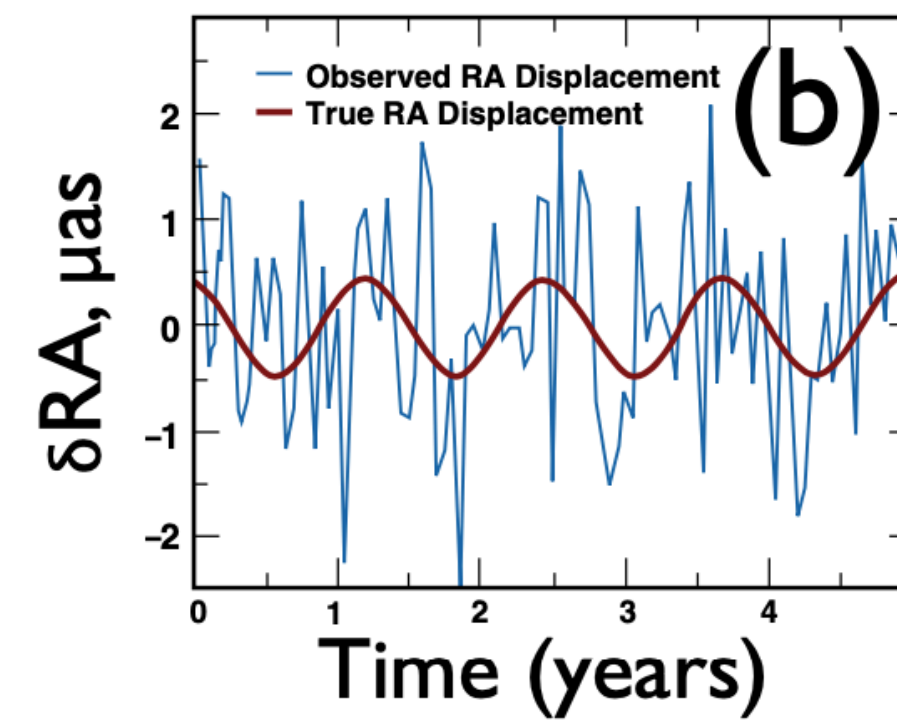
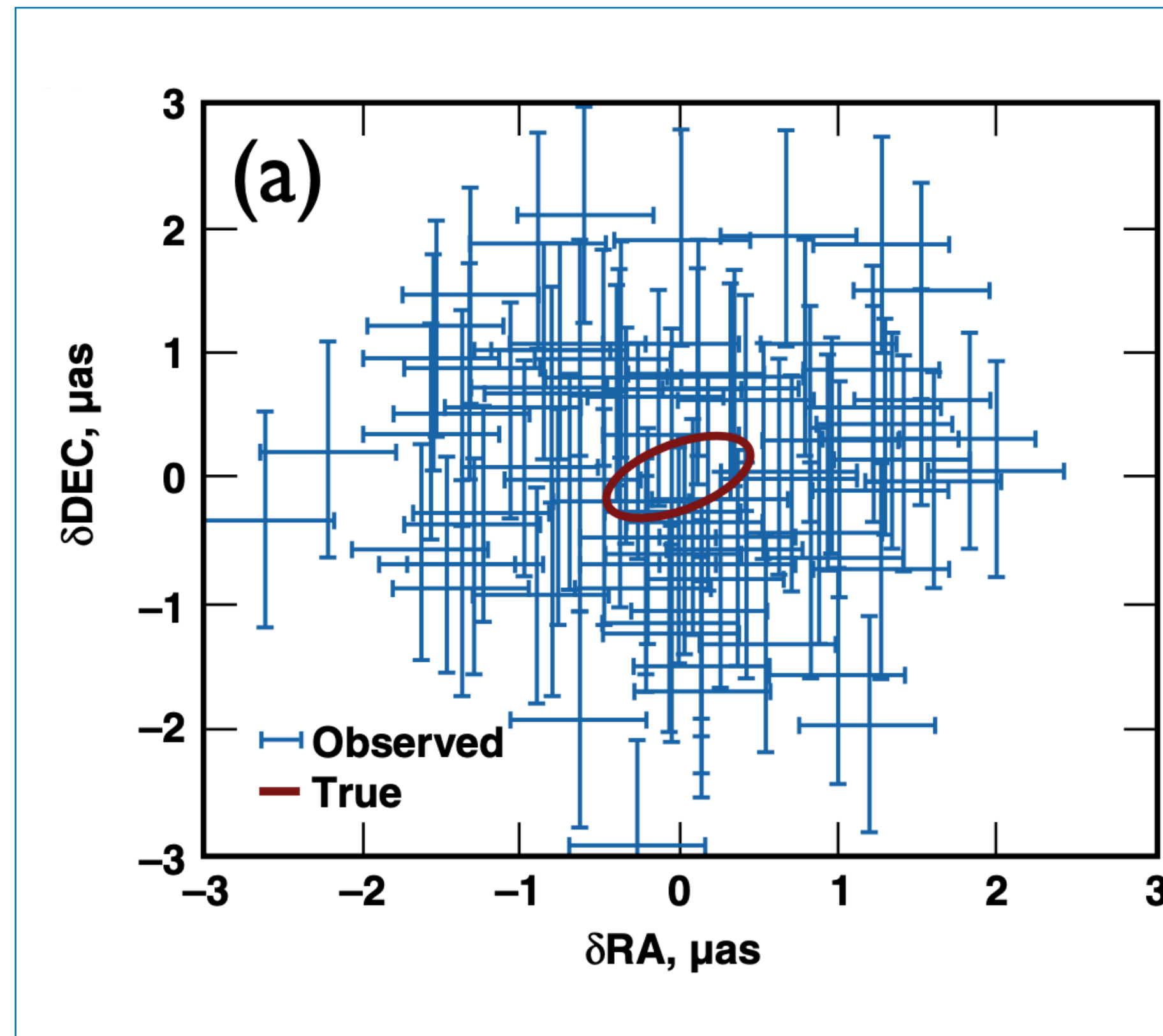
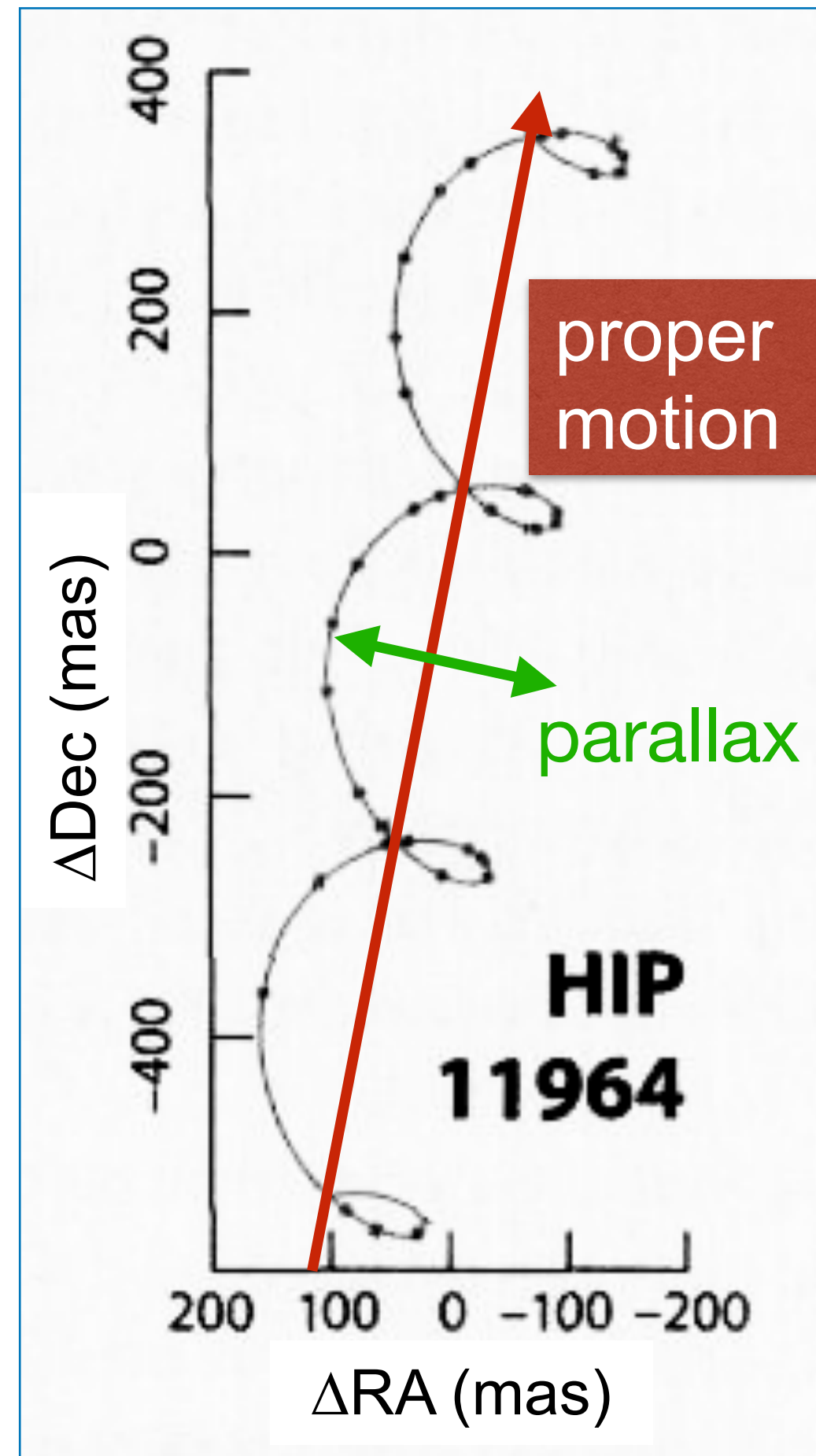


Astrometry: parallax, proper motion and reflex motion

Proper Motion + Parallax



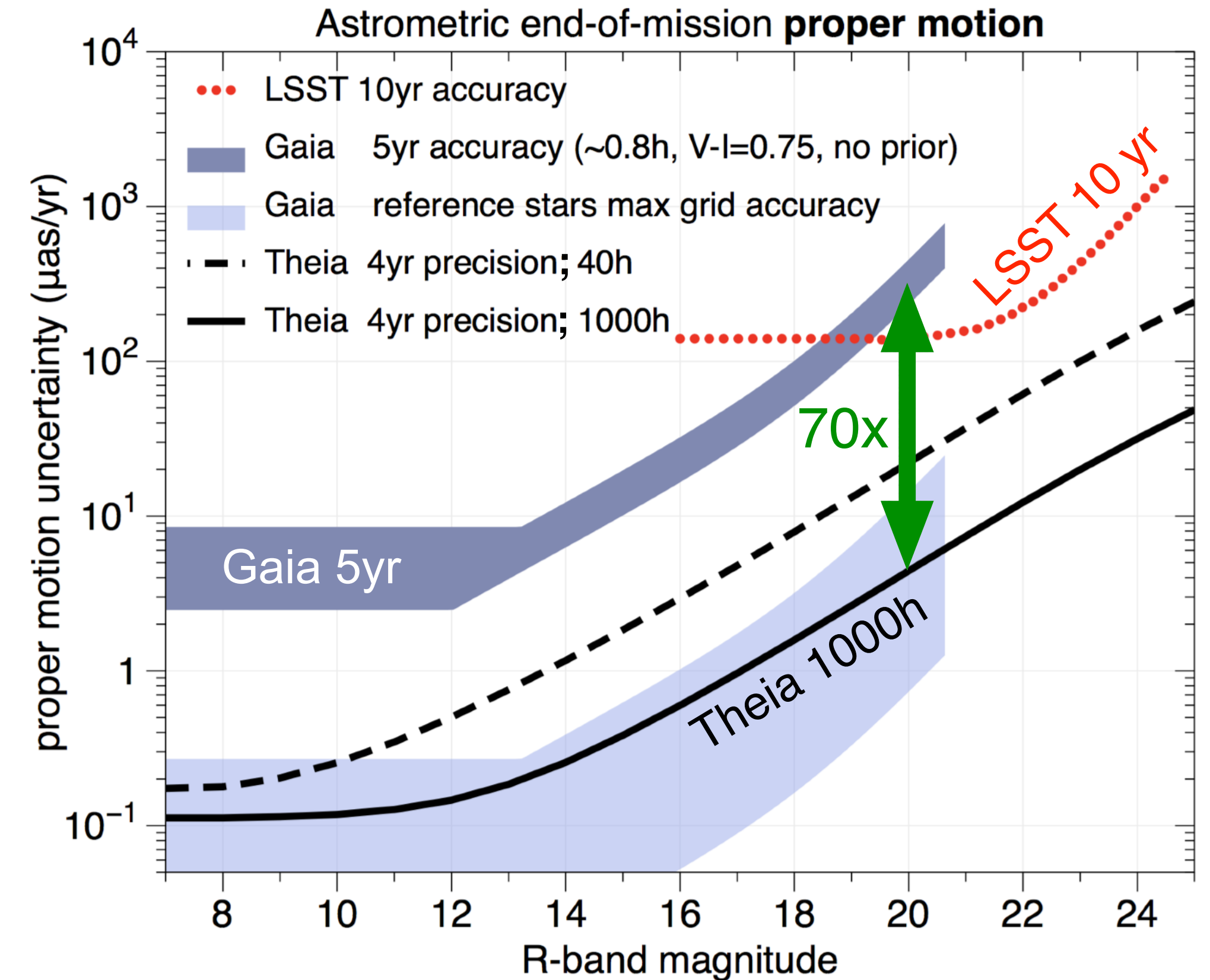
Residuals where (a) plots RA and DEC positions while (b,c) are positions with time and (d, e) are period-gram for each direction



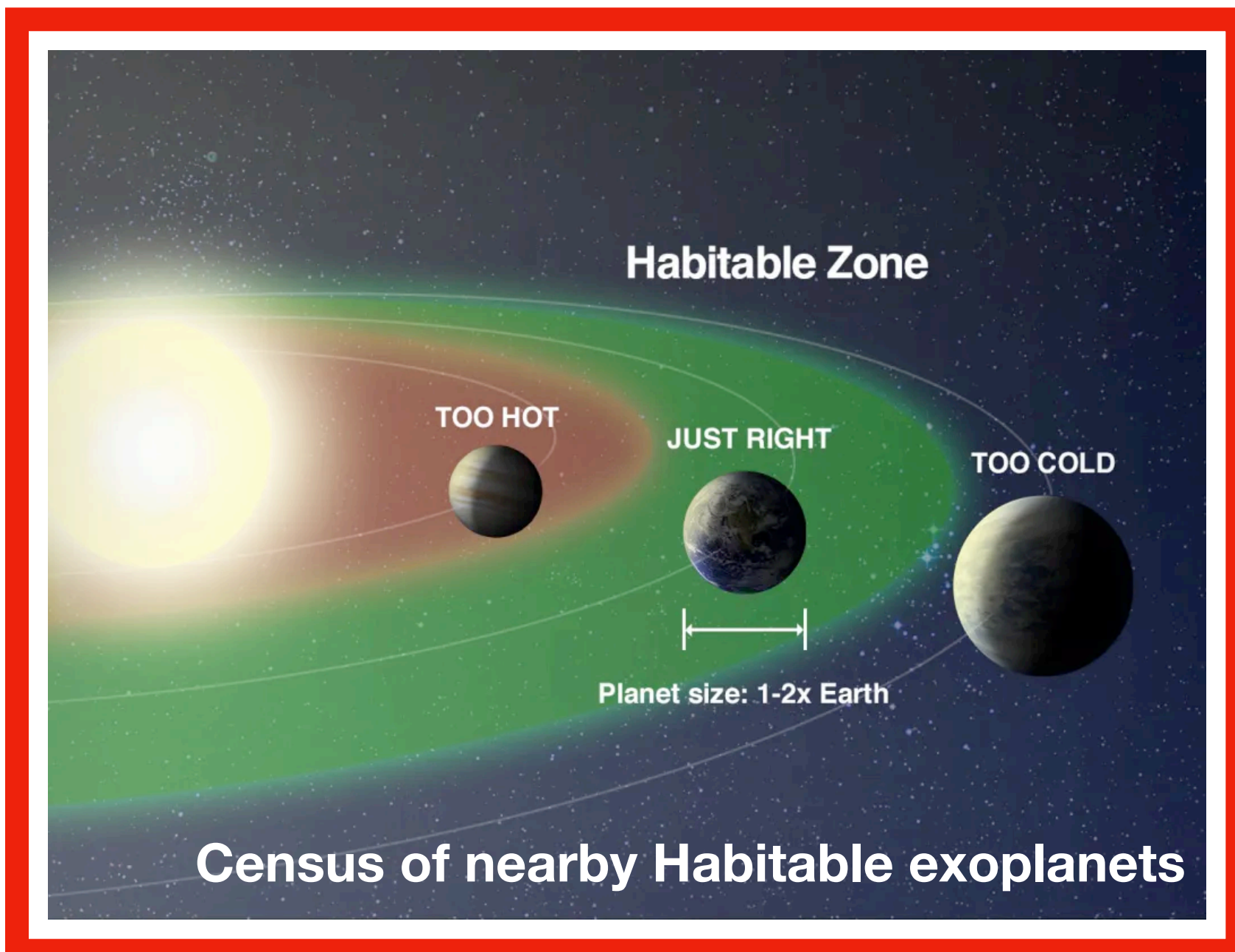
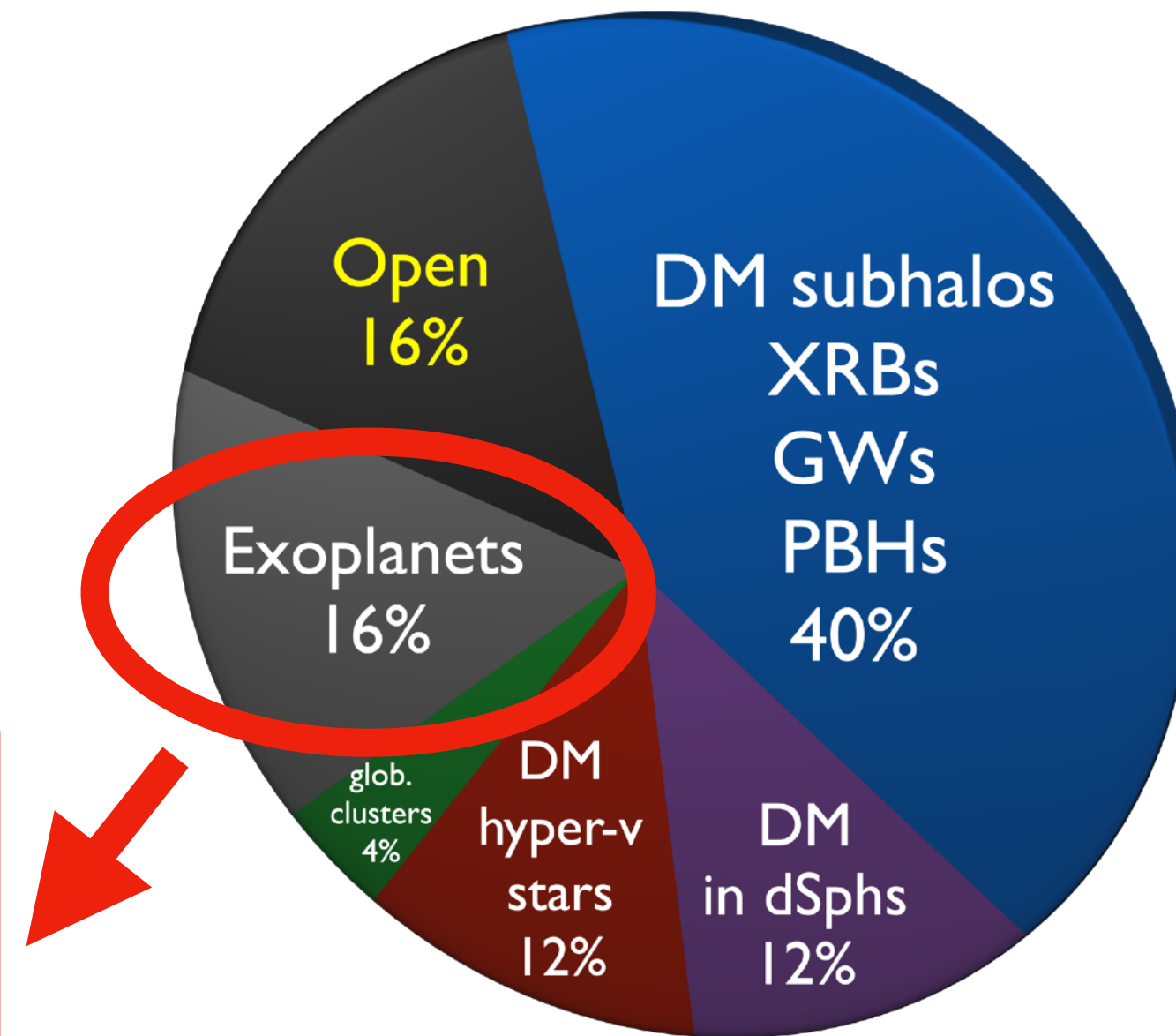
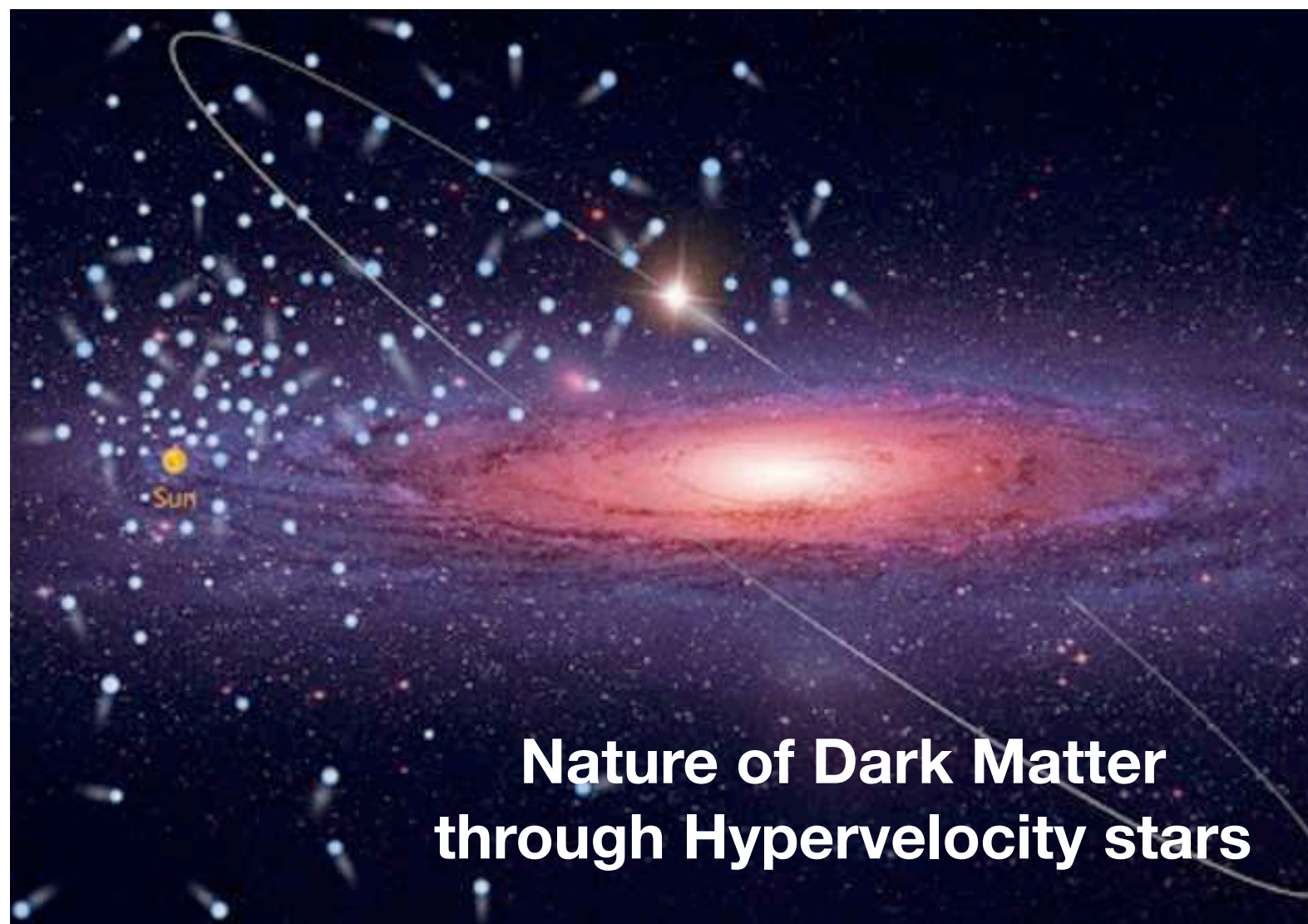
Unwin et al. (2008) ; Malbet et al. (2012)

Improvement compared to Gaia

| | Gaia post-launch | Theia | improvement |
|-------------------------------------|---|---------------------------|-------------|
| Telescope Aperture | 1.49 x 0.54 = 0.80 m ² | 0.8 → 0.50 m ² | 0.62 |
| Field of view | | 0.5 deg | |
| Coverage | Survey | <i>Pointed</i> | |
| Astrometry | Global | <i>Differential</i> | |
| Exposure time per field | 76 x 9 (CCD) x 4.4 sec = 0.84 hr | 25 x 40 hr = 1000 hr | 1200 |
| Additional factors | 2D vs 1D astrometry: 1.4, Gaia Stray light: 1.9 | | |
| Proper motion accuracy G=10 star | 3.5 μas/yr | 0.11 μas/yr | 30 |
| Proper motion accuracy G=15 star | 14 μas/yr | 0.4 μas/yr | 35 |
| Proper motion accuracy G=20 star | 330 μas/yr | 5 μas/yr | 66 |

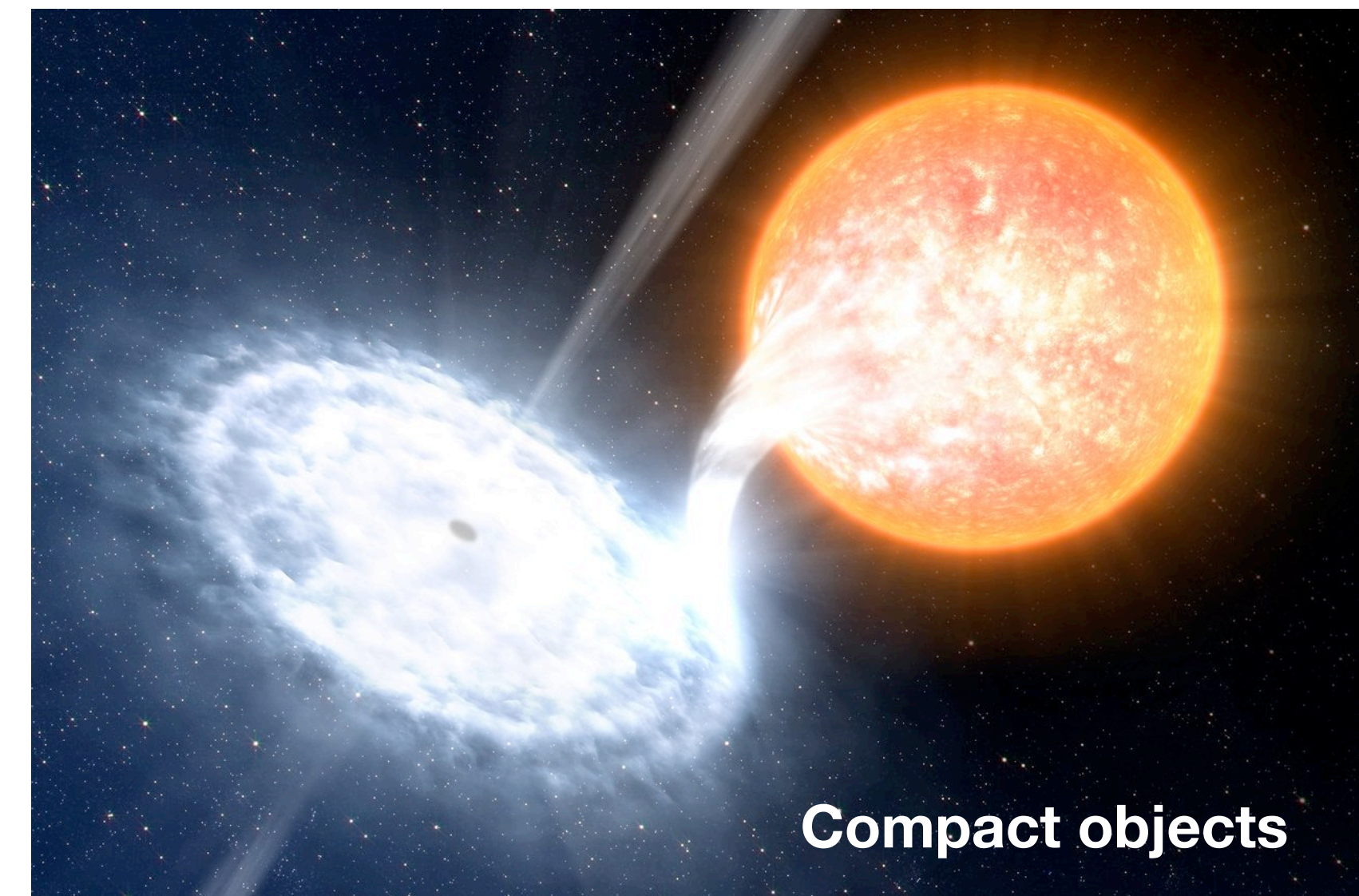


Theia's main science based on high precision astrometry



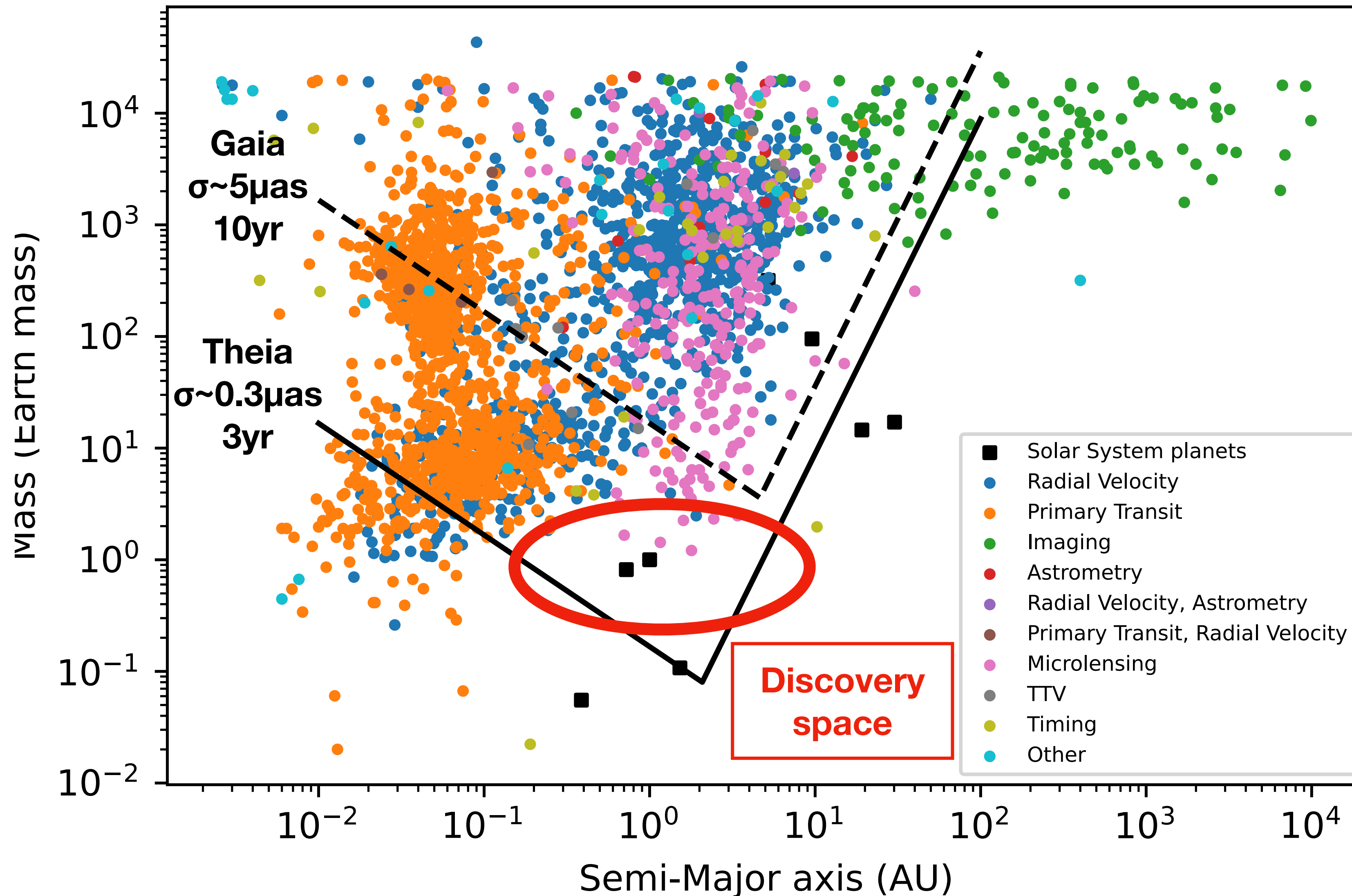
Two main observing modes:

- Faint star mode
- Bright star mode

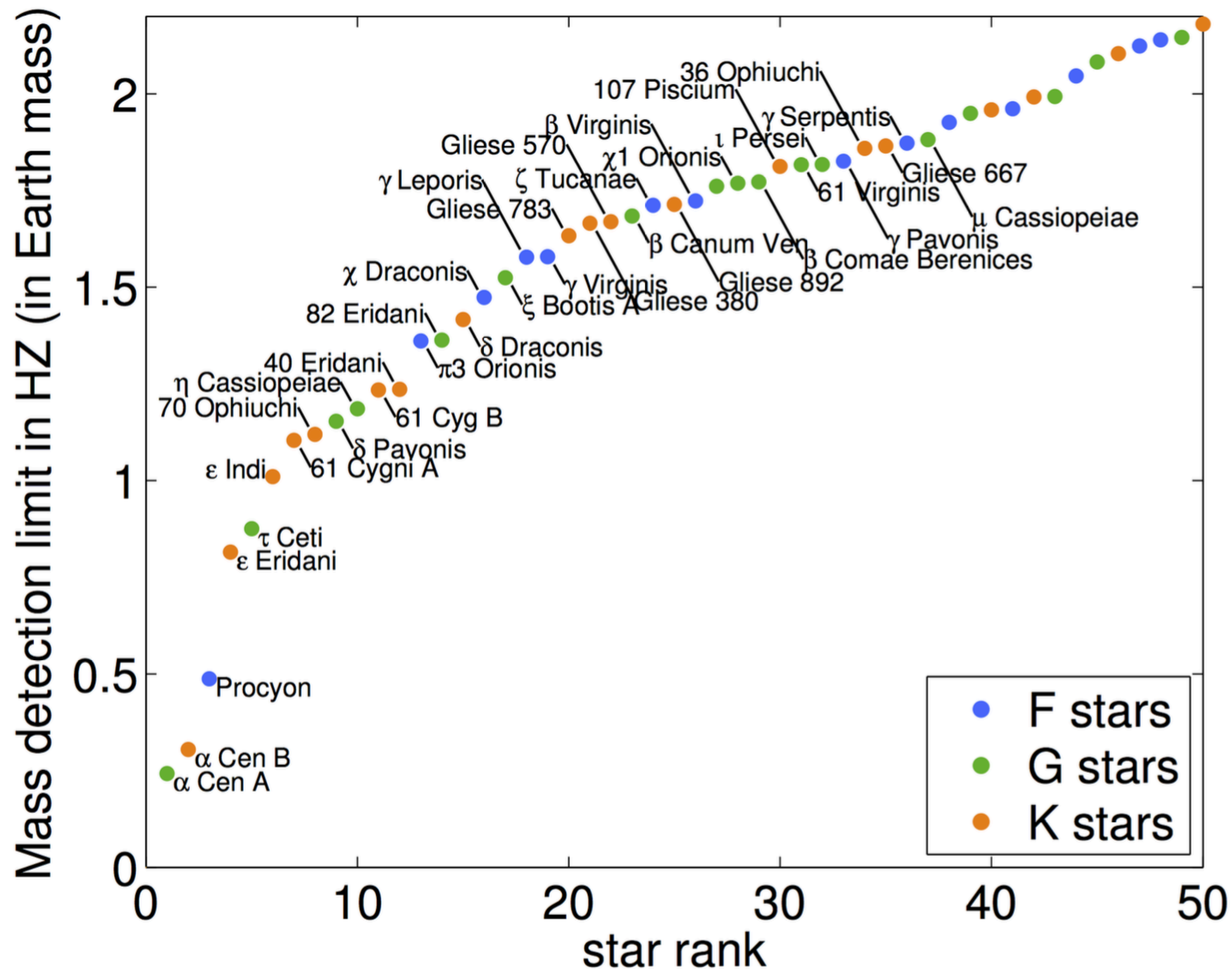


Exoplanets discovery space

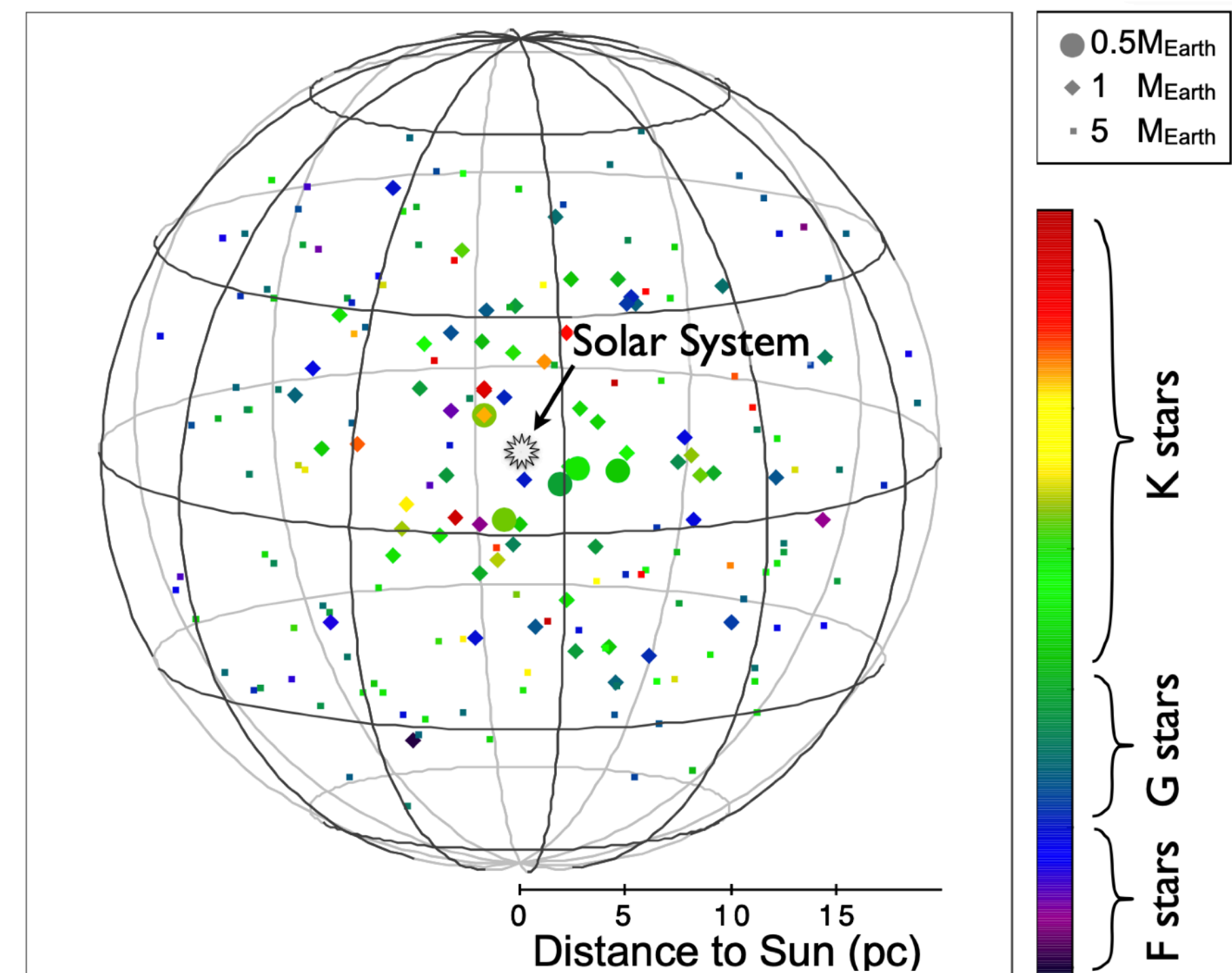
Mass vs Semi-Major Axis Diagram (from exoplanet.eu)



Exoplanets primary goal : Earth-mass planets in HZ in the vicinity of the Sun

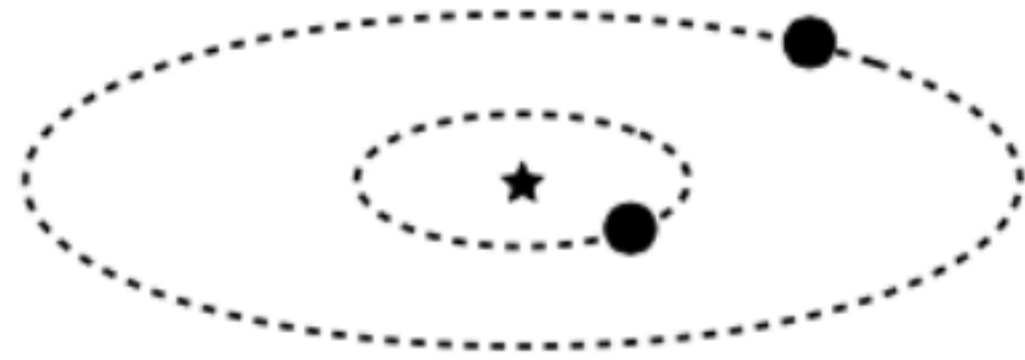


Complete census of exo-Earths, superEarths and mini-Neptune ($M < 5 M_{\text{Earth}}$) orbiting our 50 nearest Solar-type stars

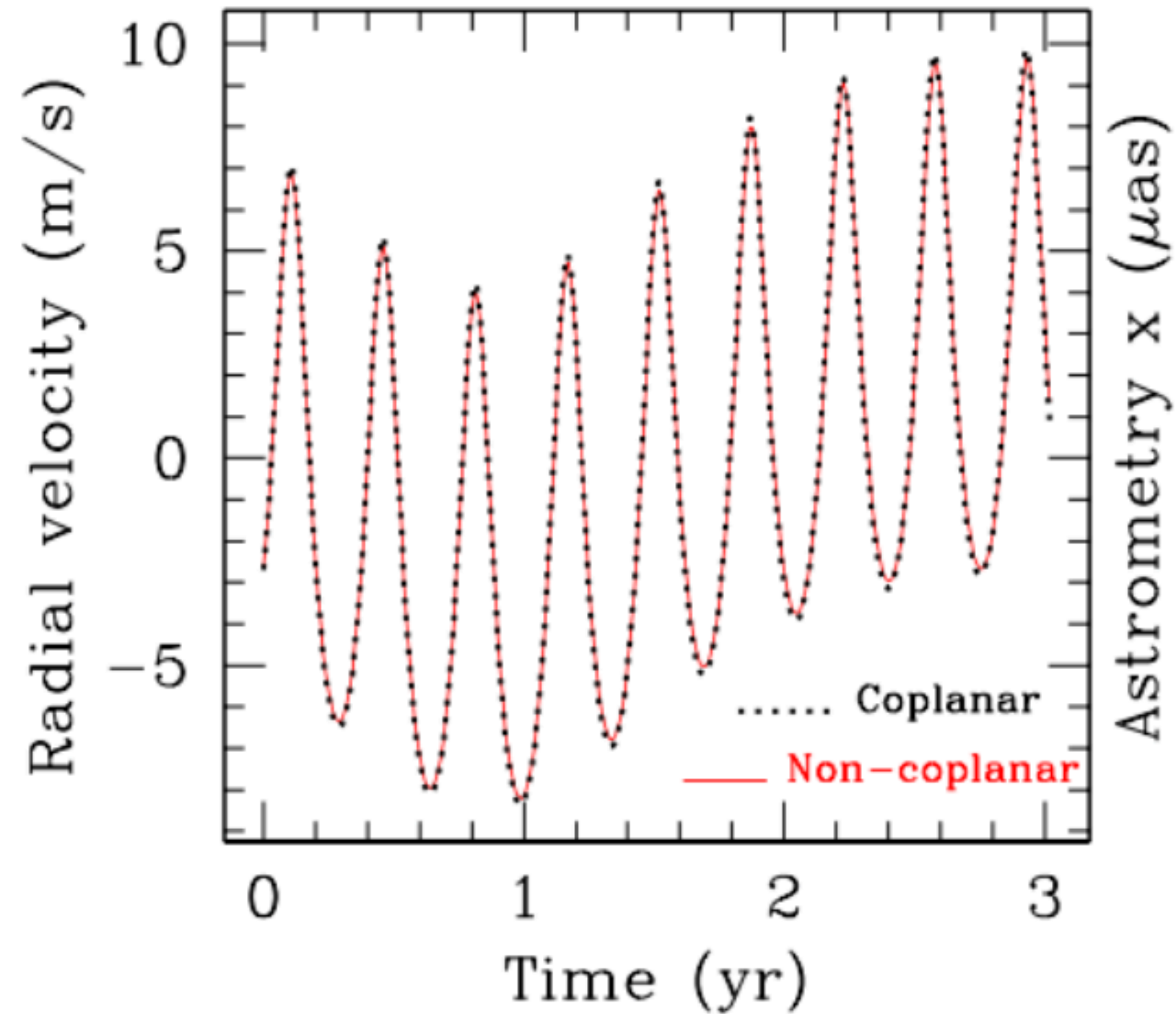
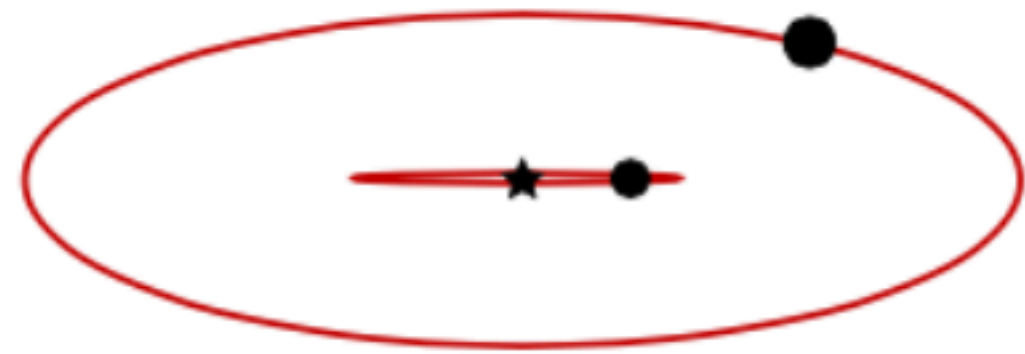


Astrometry breaks some orbit degeneracy: an example

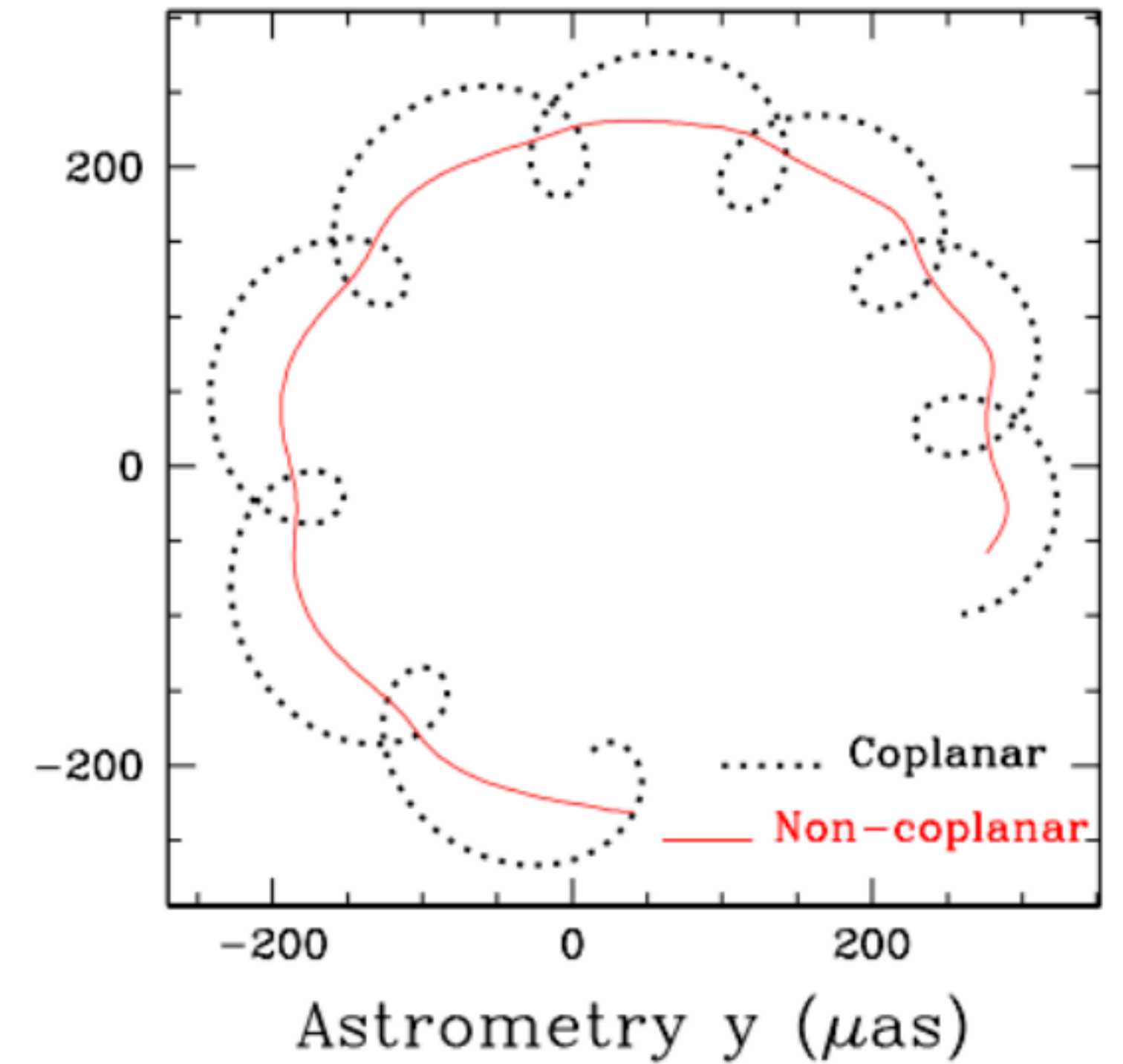
Coplanar planetary system



Non-coplanar planetary system



Radial velocity



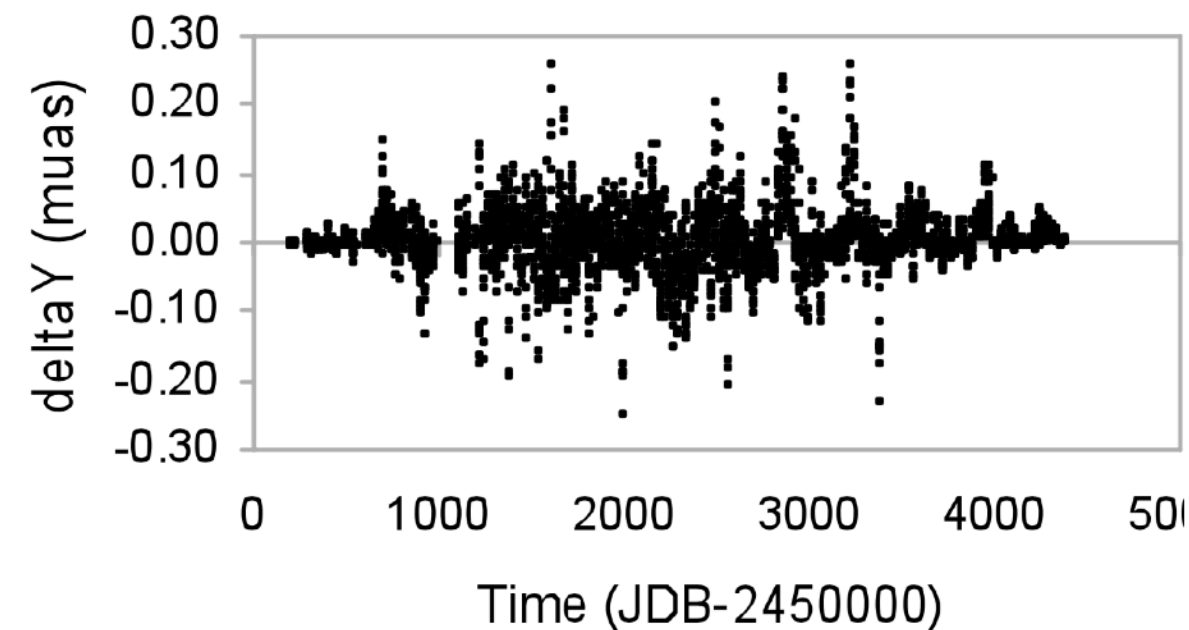
Astrometry

Two simulated planetary systems around a solar-type star at 10 pc, with two Jupiter-like planets at 0.5 and 2.5 AU

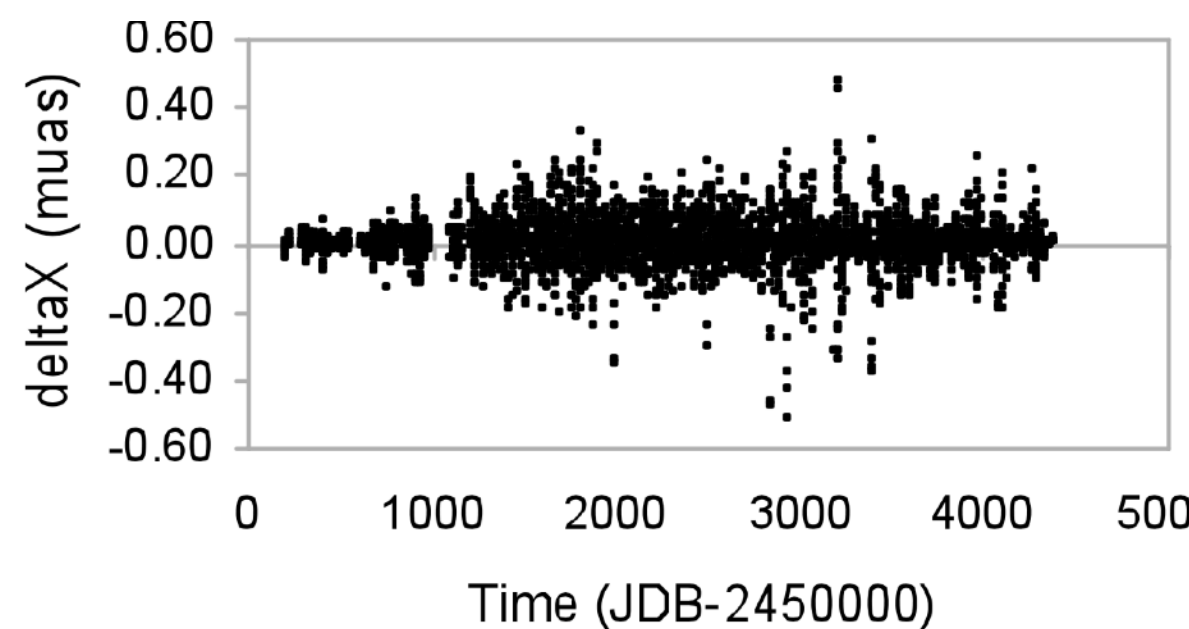
Malbet et al. (2021)

Astrometry less sensitive to stellar activity than RV

Sun's astrometric position due to activity (1996-2007)

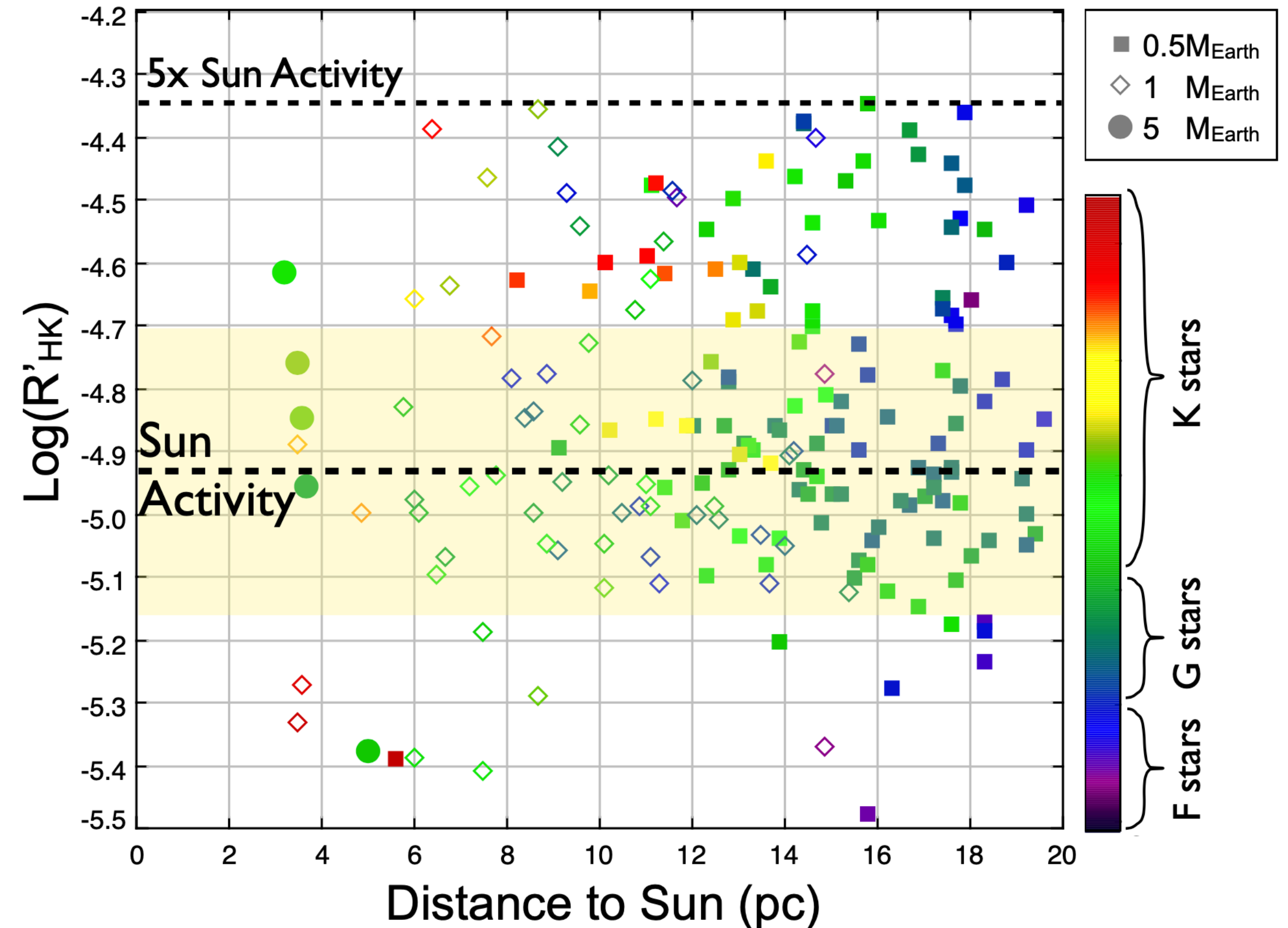


Earth astrometric signature @10pc



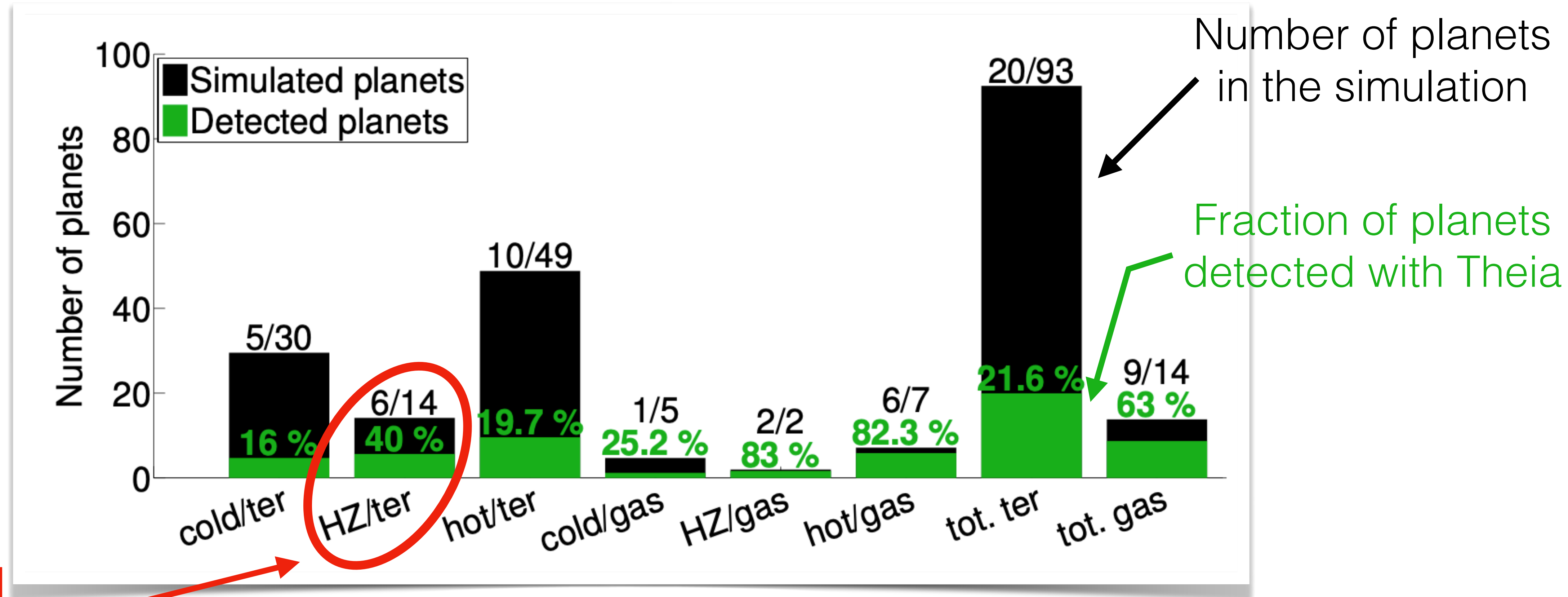
Earth astrometric signature @10pc

Detection limits have been revisited by Meunier & Lagrange (2023) through a blind test method and found lower detection limits, except for a handful of stars, **showing that it is probably possible to reach lower masses.**



Activity index $\log(R'_{HK})$ of the Theia targets as a function of the distance. The symbols represent the different detection threshold.

Expected detection rate from Kepler exoplanet population



Theia main objective

Averaging 10000 random exoplanets distributions around the 50 target stars (Crouzier 2014).

Theia instrumental concept

Specifications:

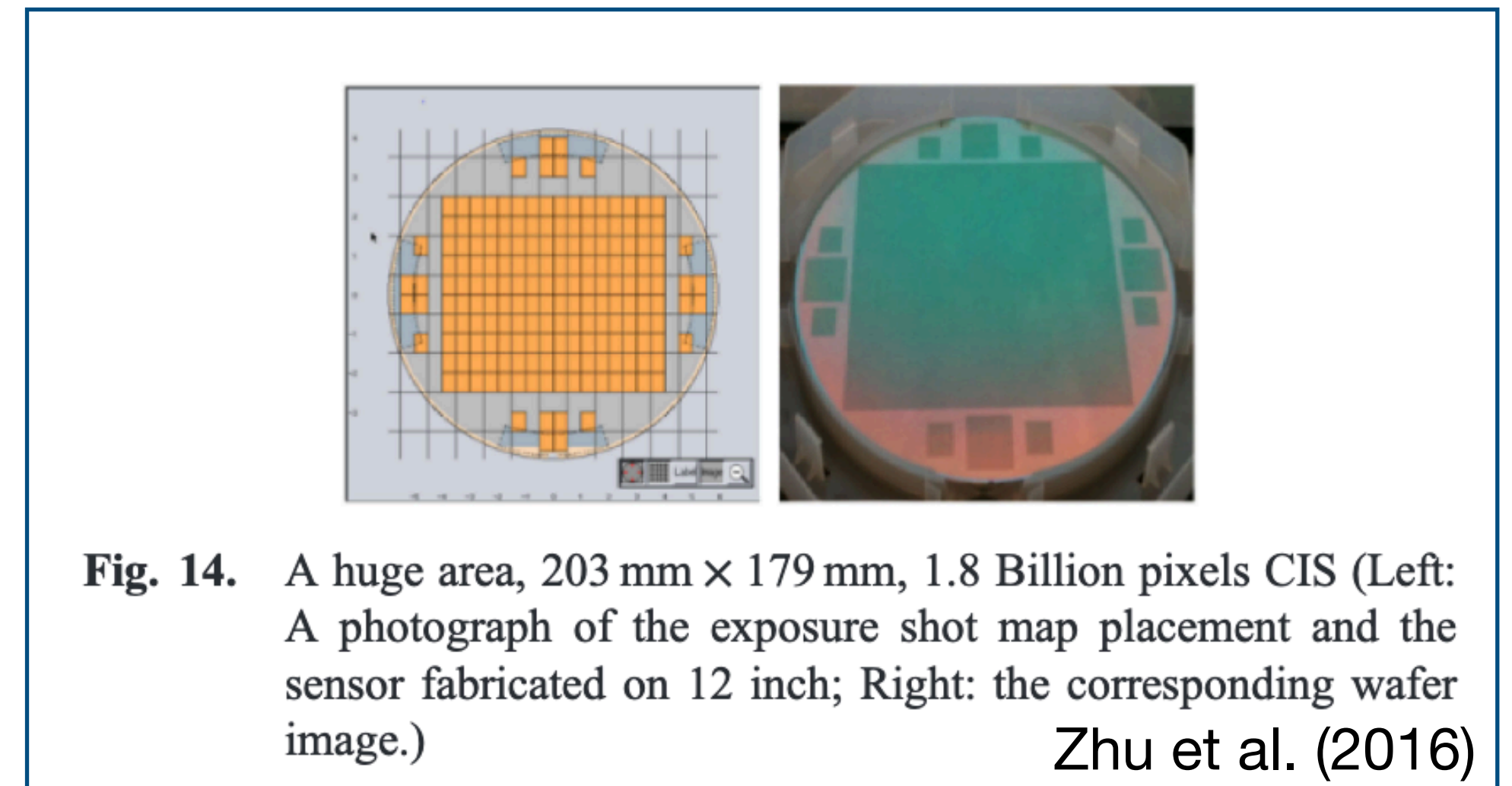
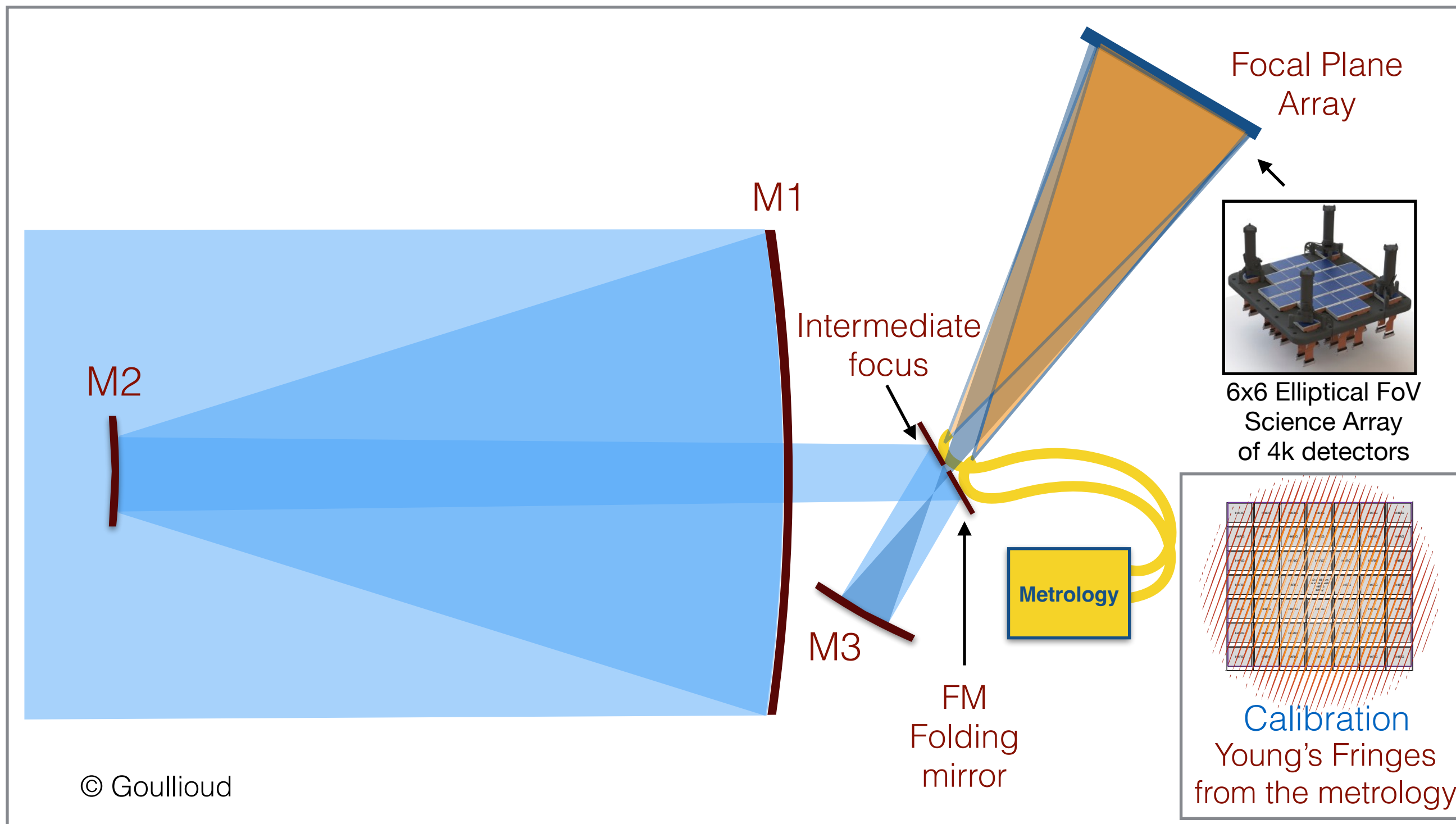
Diffraction-limited 0.5° FOV

$\sim 30,000 \times 30,000$ pixels

≤ 1 billion pixels

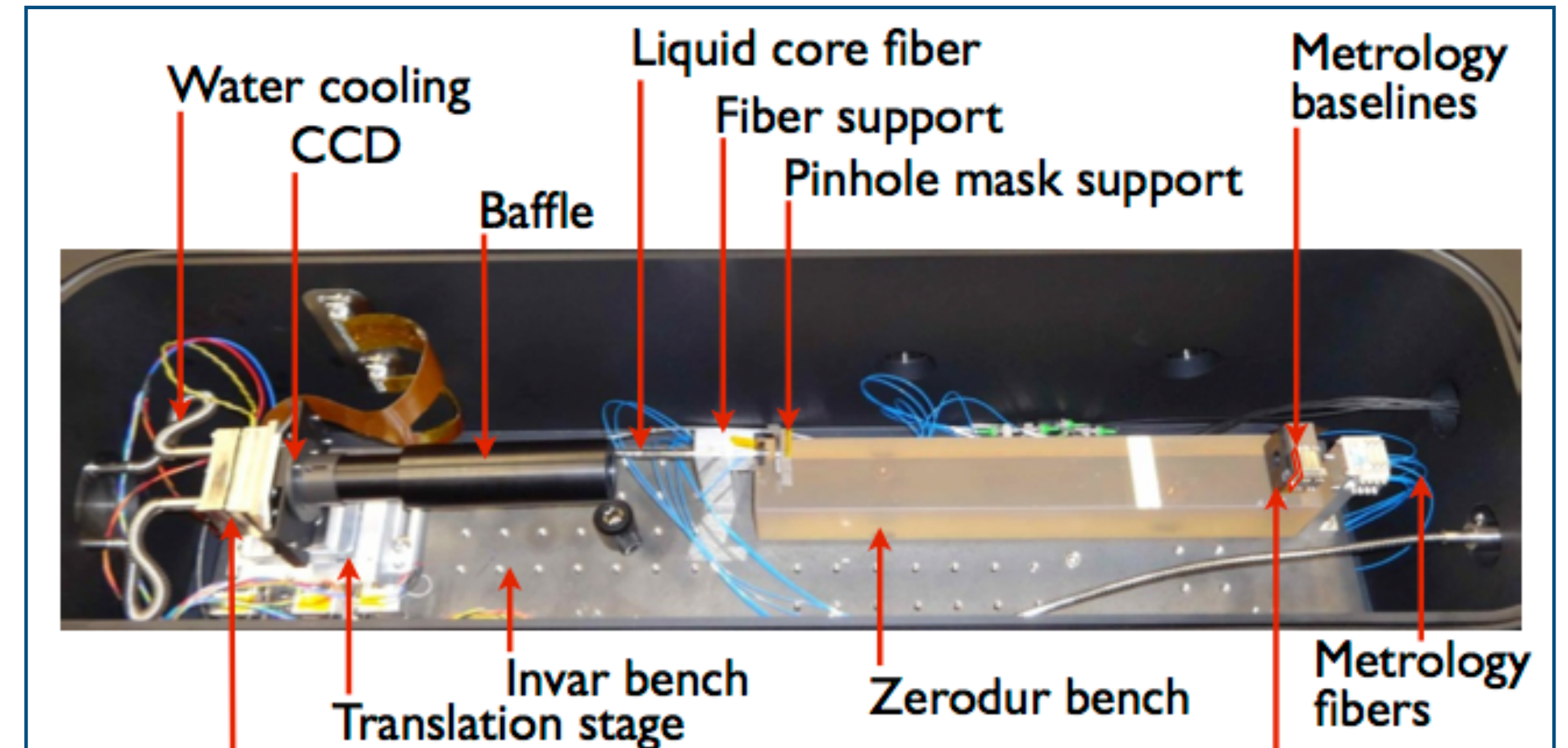
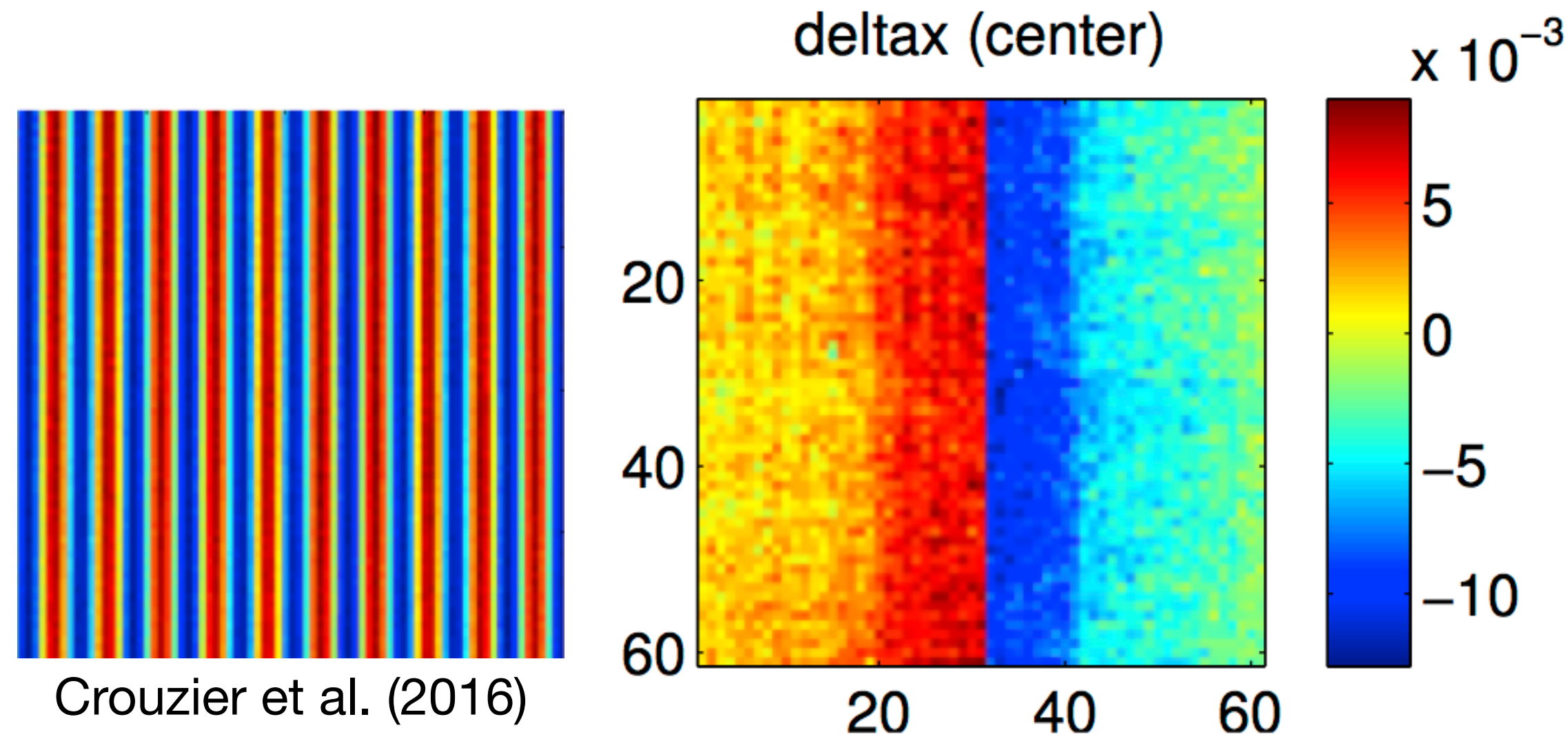
But new large CMOS detectors with smaller pixels !

Proposed implementation (M7)

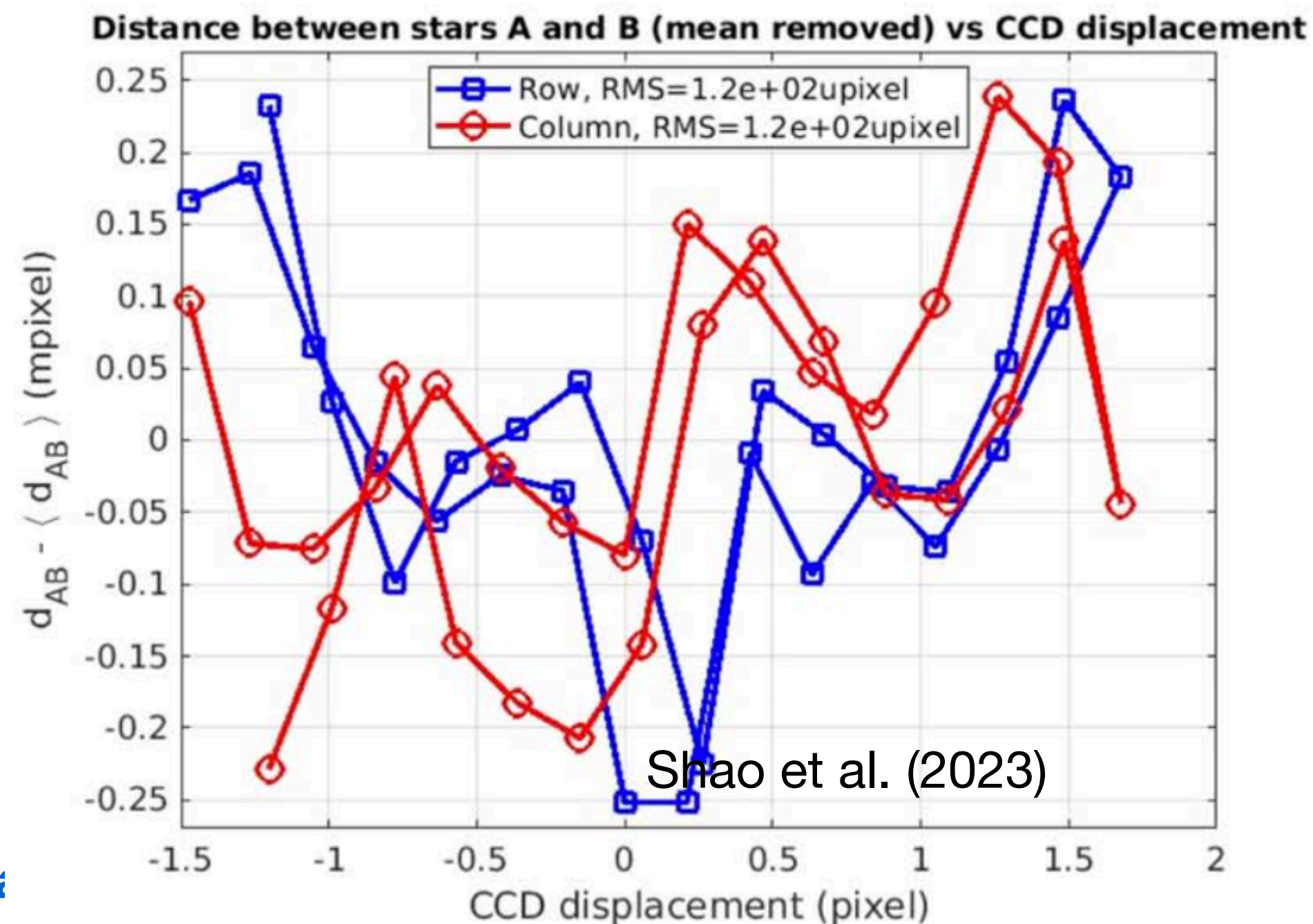


Pixels of $\sim 4\mu\text{m}$
 \Rightarrow array of 12 cm x 12 cm,
(ie. 30k x 30k detector)
can be manufactured on a wafer of
12" (300mm)

Detector calibration: laboratory results



Crouzier et al. (2016)



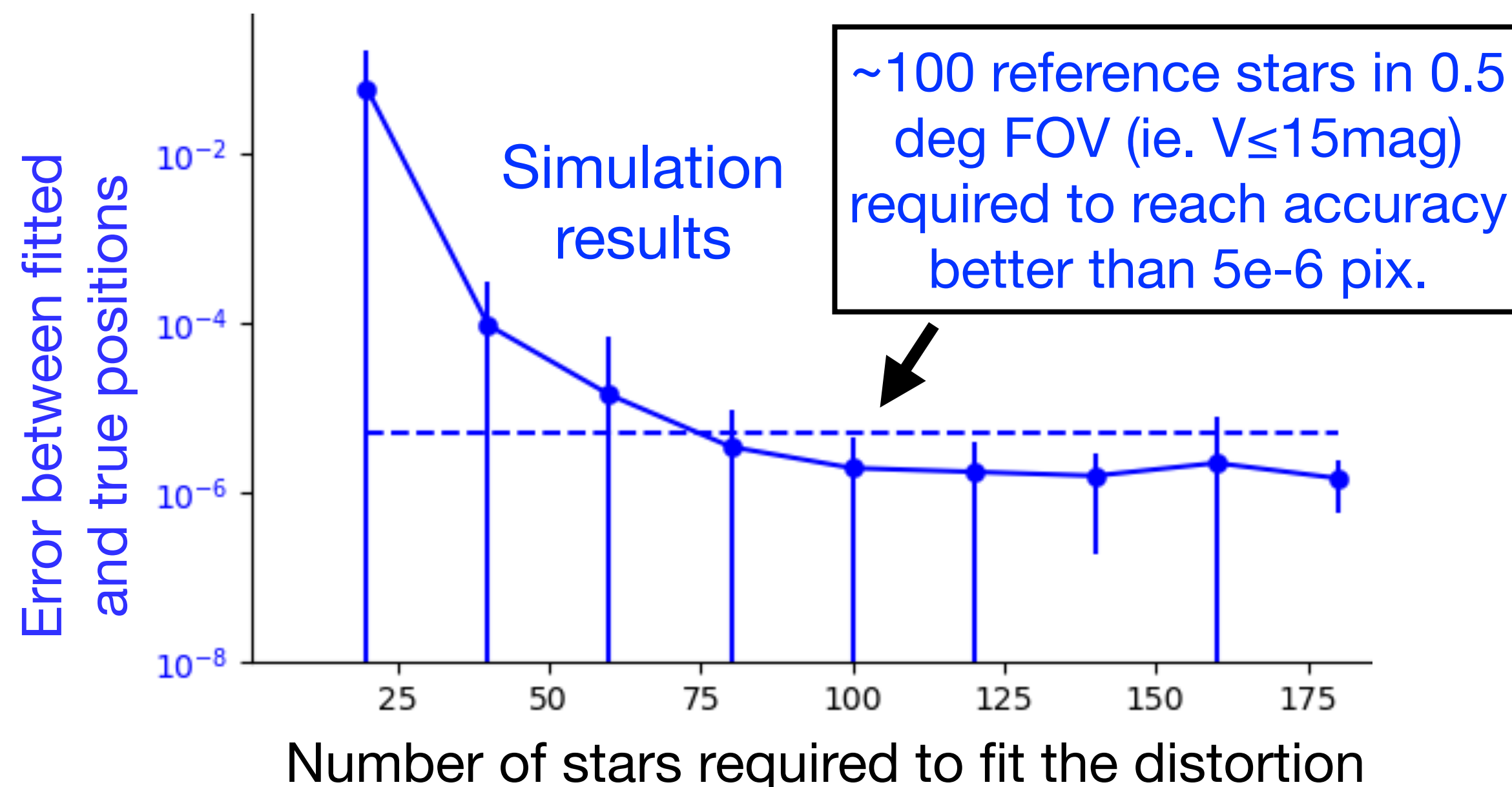
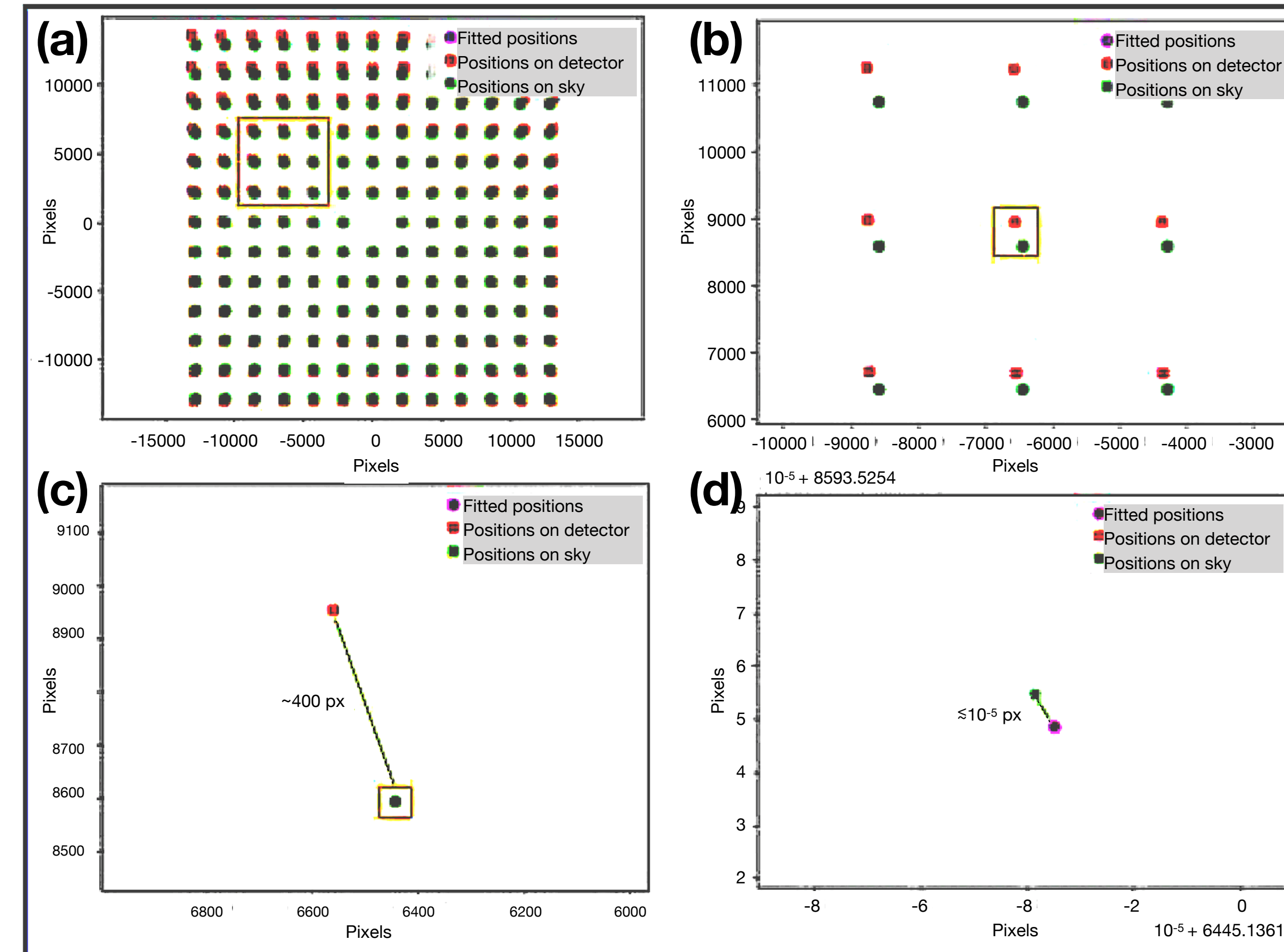
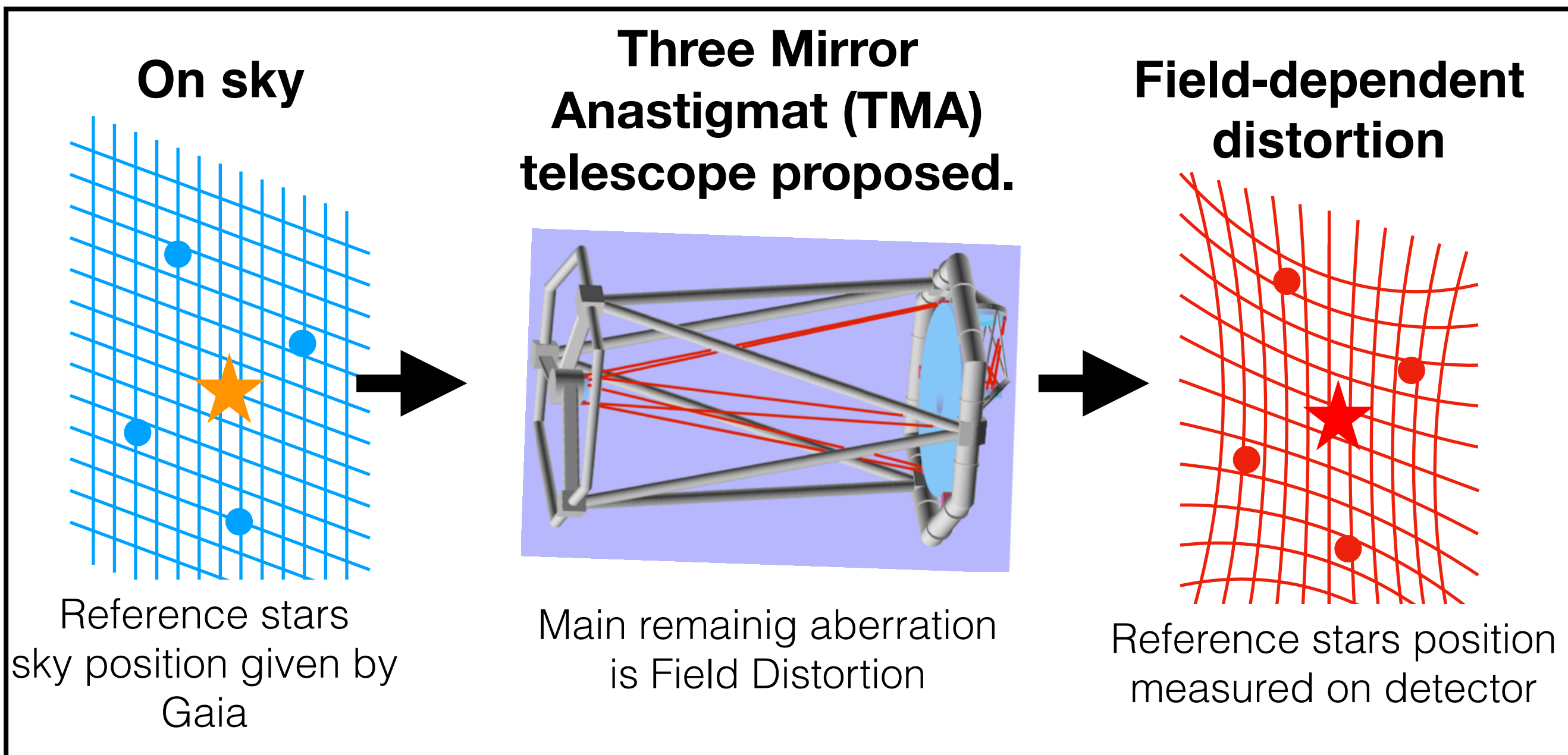
Best results so far:

- IPAG/CNES: 6×10^{-5} pixels (Crouzier et al. 2016)
- JPL/VESTA: 3×10^{-5} pixels (Shao et al. 2023)

Telescope calibration : using reference stars to monitor the distortion

See Manon Lizzana's poster

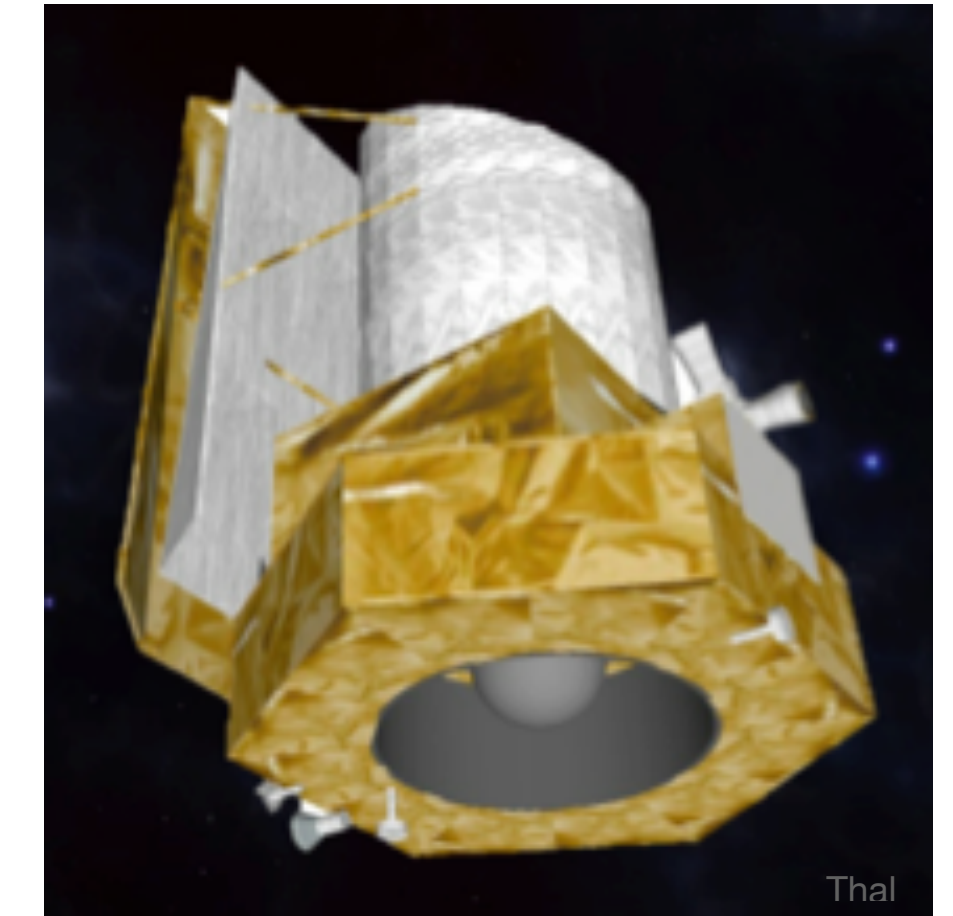
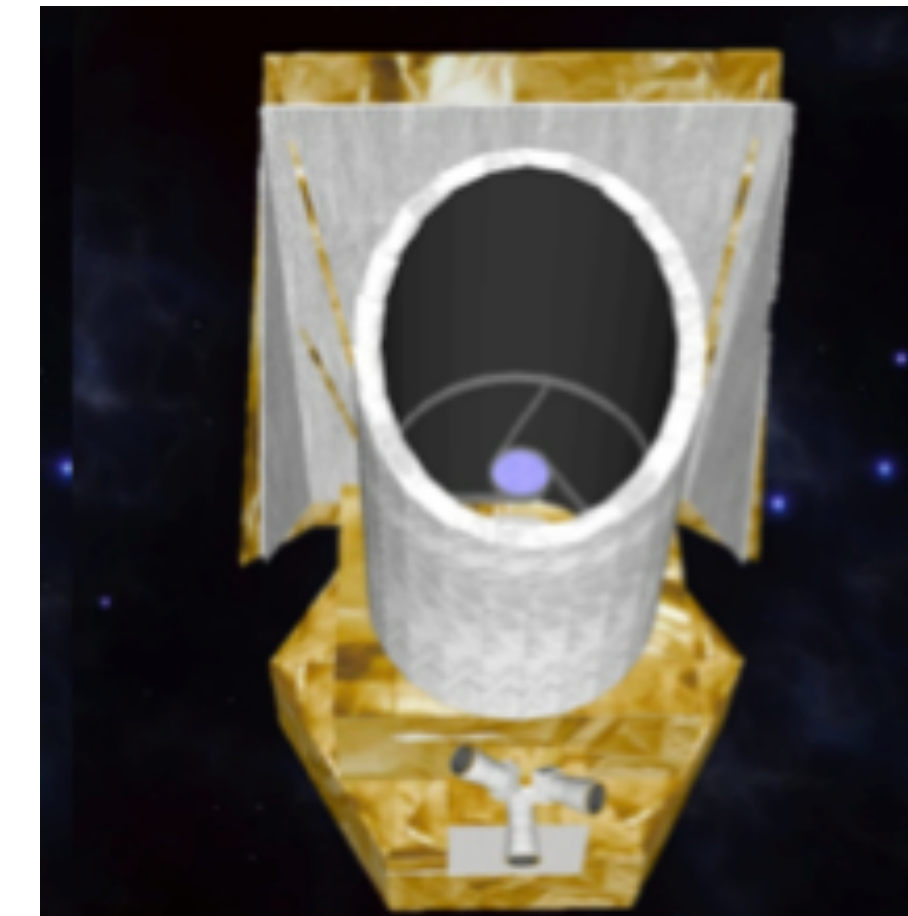
Distortion can be corrected by fitting the transformation (Sky \rightarrow Detector) as calculated by Ray-tracing (Zemax) by a 2D polynomial



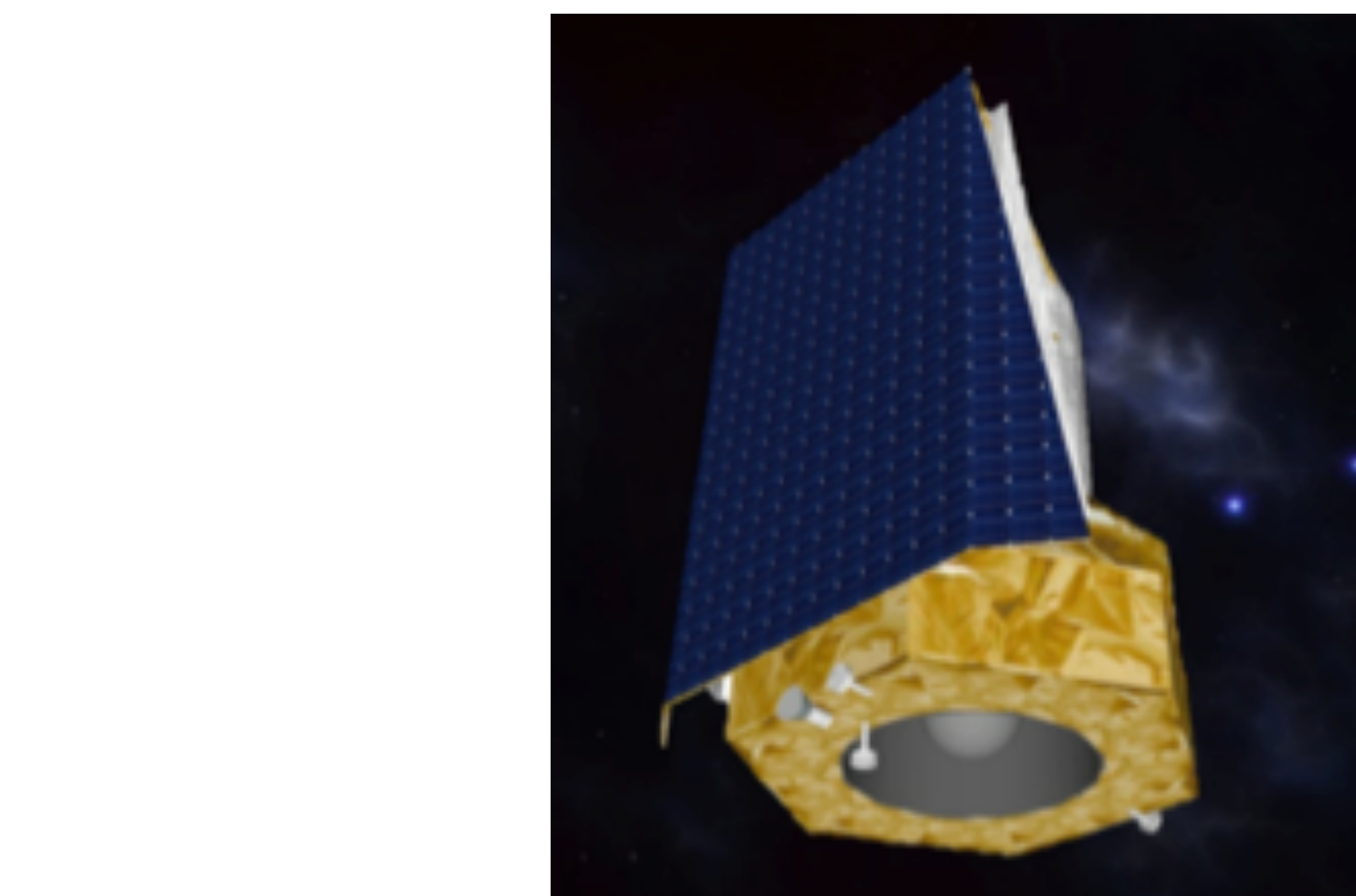
Simulated field-dependent distortion and fitted position

Theia mission profile

- **ESA-led, ESA-operated mission with consortium funded payload** (this is the normal type of ESA mission)
- Submitted for the **ESA M7 call** as an Ariane 6.02 launch
- Spacecraft dry mass with margin: 1063 kg. Total launch Mass: 1325 kg



Thal



| | |
|-----------------------------------|--|
| Launch date | No constraints, allowing launch date in 2037 |
| Orbit | Large Lissajous in L2 |
| Lifetime | <ul style="list-style-type: none"> • 4 years of nominal science operations • Technical operations: 6 months orbit transfer plus instrument commissioning and 1 month decommissioning |
| Concept | Single spacecraft, single telescope in the PLM, single camera in the focal plane, metrological monitoring of PLM |
| Communication architecture | 75 Mbps, 4h/day |

Conclusion and perspectives

- One of Theia main science objectives is to identify planets down to the Earth mass ($M \leq 5 M_{\text{Earth}}$) exoplanets in the habitable zone of Solar-type stars in the vicinity of the Sun ($d \lesssim 30 \text{ pc}$)
- Astrometry allows planet masses to be measured even for stars with stellar activity
- Pointed differential astrometry allows the number of exposures to be increased compared to global astrometry allowing to reach sub-microarcsecond accuracy
- Synergy with RV for long period and massive planets should allow us to identify Solar-type exo planetary systems
- Technical challenges are the focal plane array and mitigation of the optical distortion of the telescope: new detectors and new calibration strategy are under investigation with lab test benches.
- **Science Theia workshop planned for mid 2024** (stay tuned!)