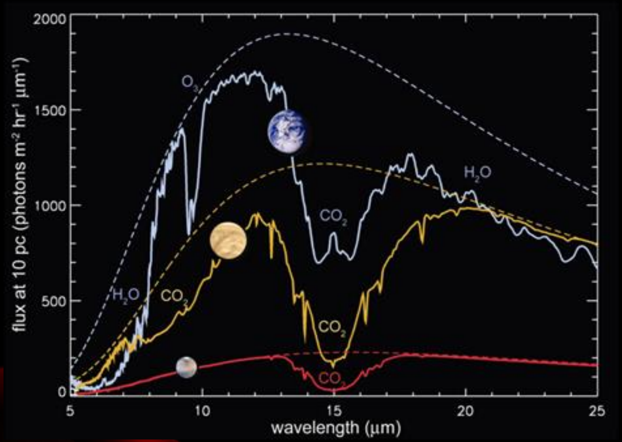
PUSHING THE LIMITS OF SPACE-BASED ASTROMETRY: TECHNOLOGICAL ADVANCES AND TECHNICAL CHALLENGES

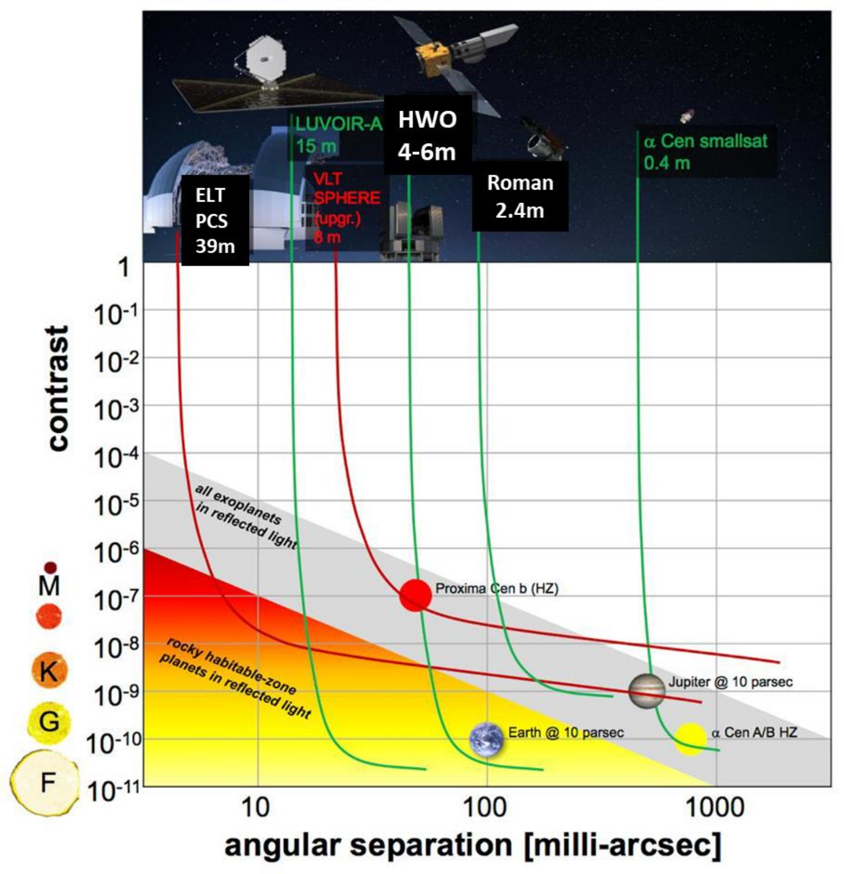
D. Busonero
INAF - Osservatorio Astrofisico di Torino

EARTH-*LIKE* PLANETS: THE ULTIMATE FRONTIER

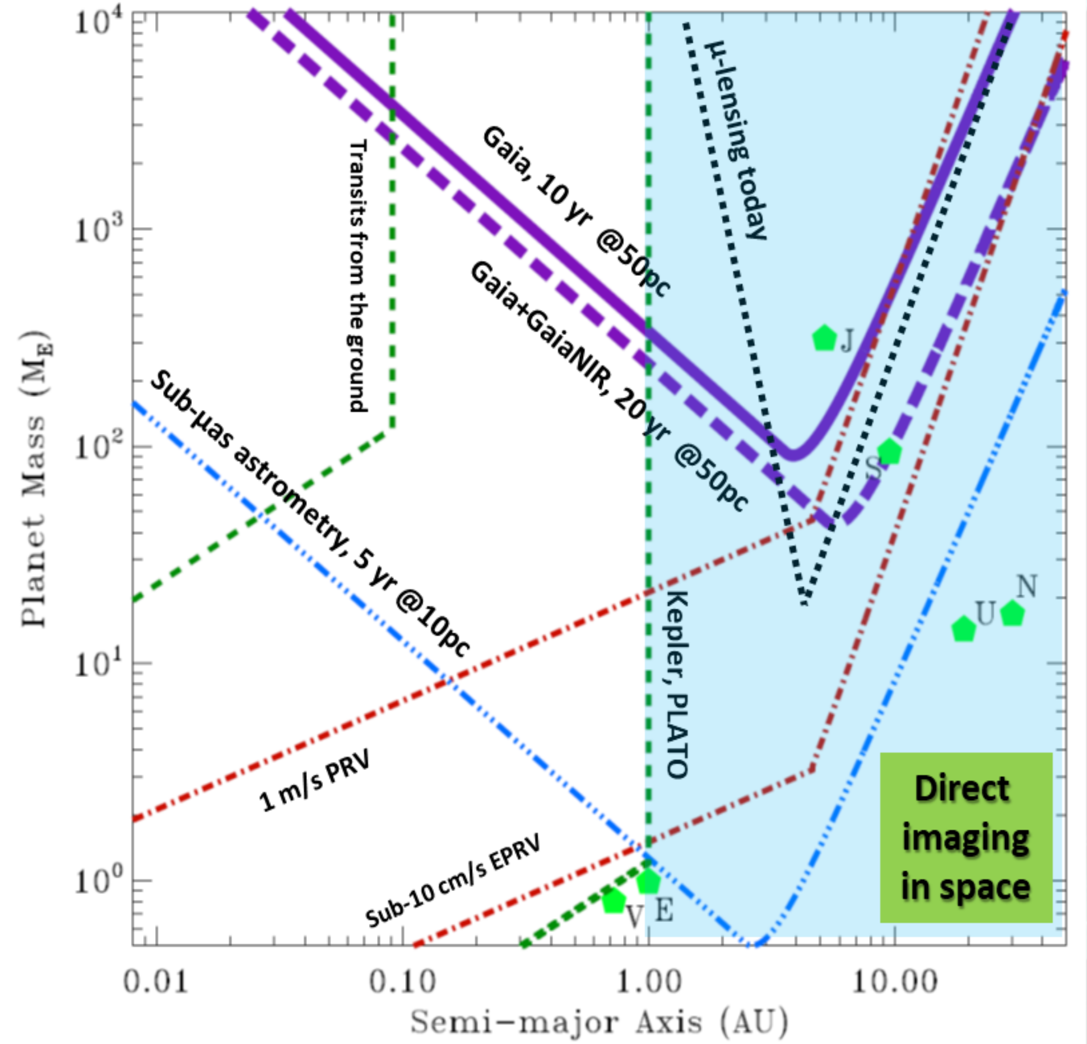
Habitability and atmospheric biosignatures of temperate terrestrial exoplanets around *solar-type* stars within 20 pc from the Sun



Finding the targets FIRST is mandatory in order to maximize science return



Finding the Nearest Earth analogs



Transits:

P_t (1yr) = 4.6x10^{-3} : super-low!

RVs:

True Earth twin: K = 9 cm/s

Stellar activity-induced RV jitter: between a few and 10-15 m/s (from >10 to > 100 times larger!)

Astrometry:

Earth twin@10 pc: α = 0.3 μas

Astrometric jitter:

active Sun @ 10 pc: 0.05 μas

RELATIVE ASTROMETRY IN SPACE IS BEST SUITED

- Current best on-ground results: few 10 μas on few arcsec field
- Limitation: atmospheric residual effects
- Challenge: PSF stability / calibration (MAVIS, MCAO @ VLT) [Taheri et al. 2024]
- Starvation on reference stars! (Not all HWO target stars will have low levels of stellar activity)
- Wide field + Gaia bootstrap approach: few mas - few 10 mas [Fortino et al. 2021]

For Earth-mass planets around FGK stars,
space-based astrometry might be only option

Astrometry: Post-Gaia Outlook

GaiaNIR (2045-2050)

- NIR global astrometry
- Gaia-like precision

Exoplanet demographics

Census of Jupiter+Saturn-like systems around stars of varied M, age, [Fe/H]

Frequency of true Solar-System analogs

Theia (2040+)

- Visible differential astrometry
- Precision 30x better than Gaia's

Exoplanet demographics

Census of temperate terrestrial planets around the nearest solar-type stars

Precursor science for HWO or LIFE to search for atmospheric biomarkers

And the new concept RAFTER

For binaries, TOLIMAN/SHERA

Or, using HWO itself, or both

CHALLENGE: SUB-μAS PRECISION ON SMALL TELESCOPES

Telescope class: 1 m diameter ⟹ ~100 mas resolution in the visible

Scaling factor: 1’000’000!

Compatible with photon limit on long exposures (many elementary images)

Issue: instrument response stability and/or calibration

ESA: lack of Technology Readiness!

Main driver: Exoplanets but requires very low systematics @ bright end → complicates the instrument (off-axis TMA ⟹ metrology)

Error sources at the μas level – Technical challenges

- Signal to Noise
- Focal plane array (ccd vs CMOS)
- Detector imperfections
- Optical field distortion of the telescope
- Observing very bright sources and much fainter reference stars at the same time

and possible mitigation

- New detectors
- Unconventional PSF (Toliman, AGP)
- Relaxation of the telescope tolerances (centered layout)
- Common Modes
- Opto-mech tricks for stability (reduction of DOF sensitivity)
- Optical simmetry

Error sources at the μas level - Technical challenges

- Signal to Noise
- Focal plane array (ccd vs CMOS)
- Detector imperfections
- Optical field distortion of the telescope
- Observing very bright sources and much fainter reference stars at the same time

Detector Calibration using focal plane metrology; reference stars grid and laser fringe metrology techniques

and possible mitigation

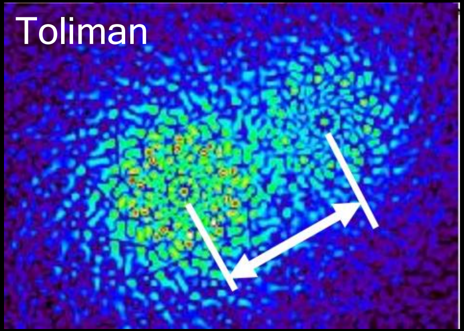
- New detectors
- Unconventional PSF (Toliman, AGP)
- Relaxation of the telescope tolerances (centered layout)
- Common Modes
- Opto-mech tricks for stability (reduction of DOF sensitivity)
- Optical simmetry

Error sources at the μas level – Technical challenges

- Signal to Noise
- Focal plane array (ccd vs CMOS)
- Detector imperfections
- Optical field distortion of the telescope
- Observing very bright sources and much fainter reference stars at the same time

Detector Calibration using focal plane metrology; reference stars grid and laser fringe metrology techniques

and possible mitigation



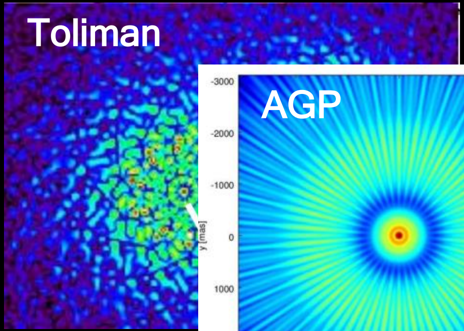
- New detectors
- Unconventional PSF (Toliman, AGP)
- Relaxation of the telescope tolerances (centered layout)
- Common Modes
- Opto-mech tricks for stability (reduction of DOF sensitivity)
- Optical simmetry

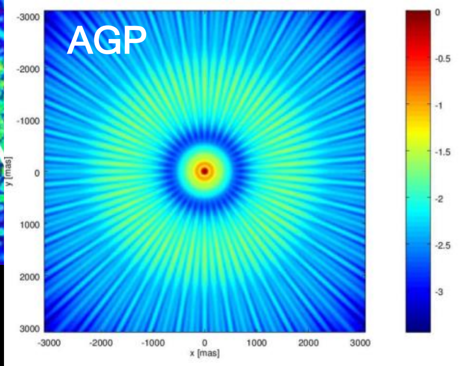
Error sources at the μas level - Technical challenges

- Signal to Noise
- Focal plane array (ccd vs CMOS)
- Detector imperfections
- Optical field distortion of the telescope
- Observing very bright sources and much fainter reference stars at the same time

Detector Calibration using focal plane metrology; reference stars grid and laser fringe metrology techniques

and possible mitigation





- N v detectors
- onventional PSF (Toliman, AGP)
- axation of the telescope tolerances (centered layout)
- nmon Modes
- o-mech tricks for stability (reduction of DOF sensitivity)
- ical simmetry

Error sources at the μas level – Technical challenges

- Signal to Noise
- Focal plane array (ccd vs CMOS)
- Detector imperfections
- Optical field distortion of the telescope
- Observing very bright sources and much fainter reference stars at the same time

and possible mitigation

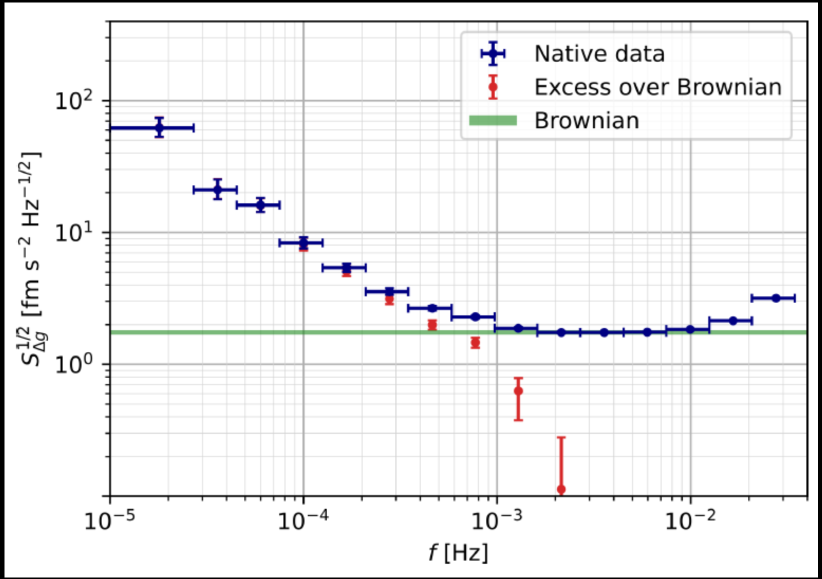
- New detectors
- Unconventional PSF (Toliman, AGP)
- Relaxation of the telescope tolerances (centered layout)
- Common Modes
- Opto-mech tricks for stability (reduction of DOF sensitivity)
- Optical simmetry

WHY METROLOGY?

Support to instrument calibration & monitoring

State of the art: LISA metrology, fm/s²/√Hz on Pathfinder, operating on million km distance [Armano et al., 2024]

Orders of magnitude better than our needs!



RAFTER concept requirements: nm precision on 1 m scale

Concept: INNOVATIVE TMA DESIGN

•On-axis telescope materialized by means of annular mirrors (rings)

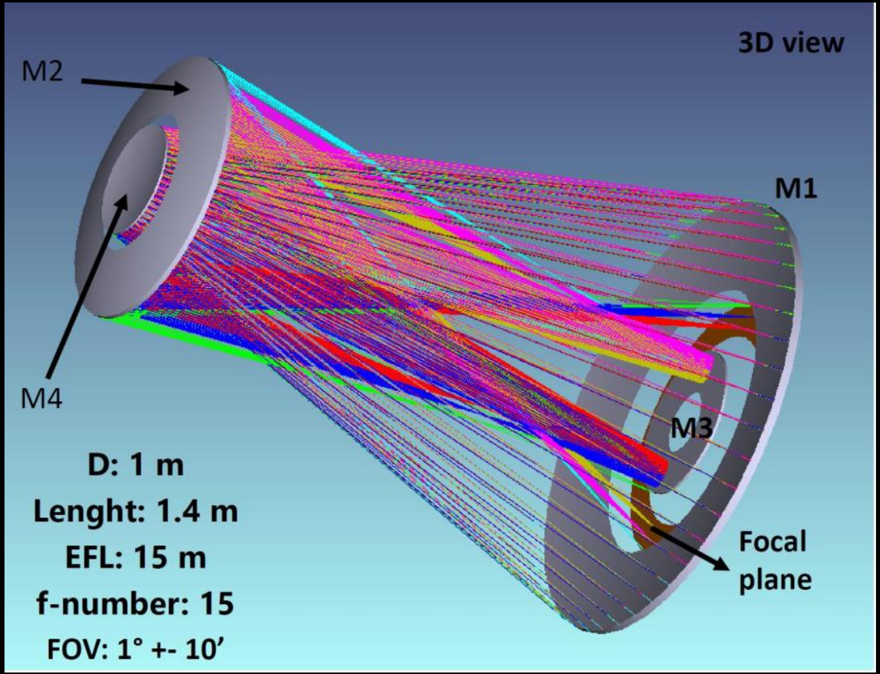
•Annular focal plane-> ring of detectors

Compact structure whole envelope: <2 m

- ❑ **Simmetry**
- ❑ **Simplified alignment of M1/M3-M2/M4 zones**

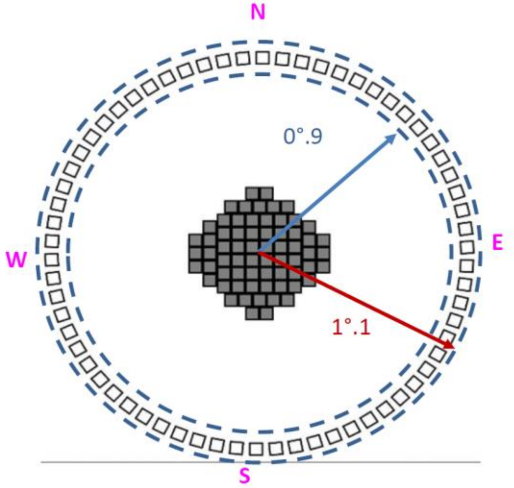
The tilting of the elements together are compensating

- ❑ The telescope is naturally split into two smaller optomechanical units, facing each other;
- ❑ mutual placement stabiliy of the nearby mirrors, relaxing the overall number of degrees of freedom and complexity;
- ❑ each mirror pair is subject to a common local thermal environment, including its thermo-elastic perturbations



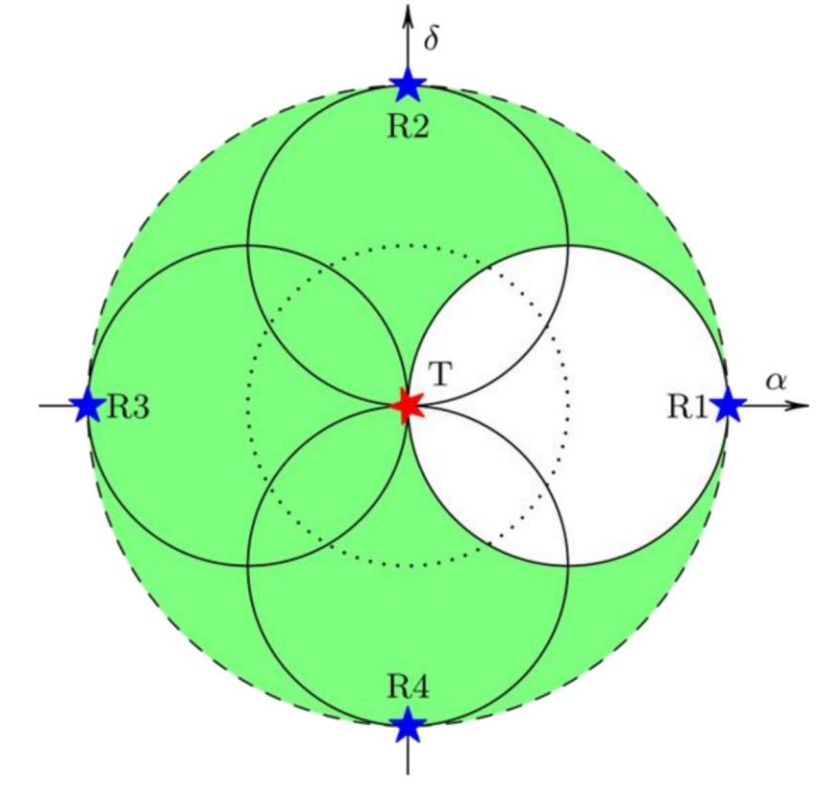
This configuration overcomes the issue of lack of reference stars

- Platescale 50 mas/pixel
- Compatible with 4-5 μm pixel CMOS detectors



Rings of 66 hypotetical detectors (4k x 4k)

(Same number of device arranged around optical axis for comparison)



METROLOGY ON RAFTER

Optional on-board simplified metrology system (just a tip-tilt measurement) as back-up and high performance support

Precision / accuracy goal: 1’000’000 times better than PSF size

Gai et al, using centroiding algorithms for differential astrometry on TESS science data, have demonstrated in-flight uncertainties of $\leq 1\times10^{-5}$ px on single frames and $\sim 2\times10^{-6}$ as collective performance for an observing sequence. (PASP 2022)

PSF variation reduced by 100× thanks to optical design (symmetry constrain)

Calibration approach based on large statistical sample demonstrated on Gaia

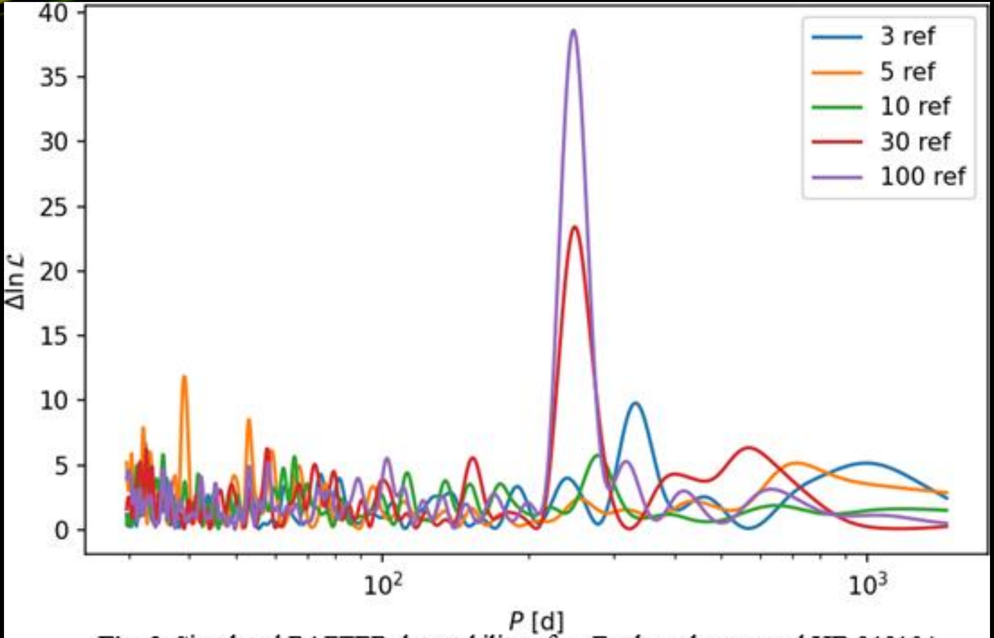


Fig. 3: Simulated RAFTER detectability of an Earth analog around HD 219134

Pinamonti et al. preliminary investigations based on a simplified observing scenario (100 2-d observations evenly spread over 4 years) for the nearby star solar-type star HD 219134 indicate that the astrometric signal of a HZ Earth-like planet could be detected by RAFTER with high statistical confidence (Delta-log-likelihood > 10) using > 30 reference stars with global reference frame astrometric precision similar to that expected for the Gaia DR5 catalog

CONCLUSIONS

Just *two* potential dedicated relative astrometry European mission concepts such as Theia and RAFTER now on the floor as the ultimate targets providers for future space missions such as HWO or LIFE.