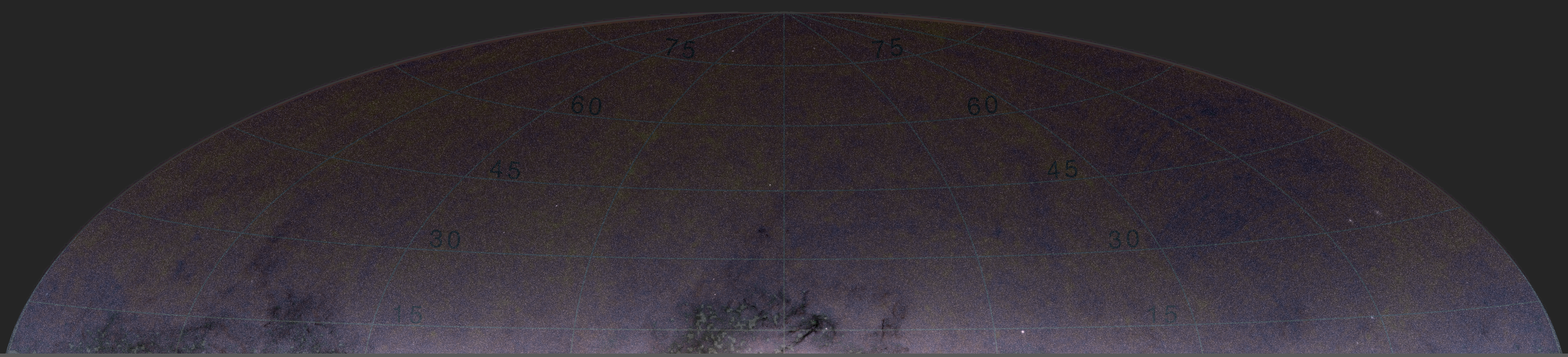
DIFFERENTIAL ASTROMETRY FOR EARTHS AT MICRO-ARCSECOND PRECISION

Alberto Krone-Martins
Donald Bren School of Information and Computer Sciences
University of California, Irvine



In this short talk…

What and why?

Challenges?

The future?

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ASTROMETRY?

- “All that part of astronomy which specifies reference coordinate systems and/or determines the coordinates of celestial bodies and their derivatives." H. Eichhorn

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ASTROMETRY AND EXOPLANETS

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  - Not strongly affected by stellar activity;
    - Telluric planets around FGK stars.

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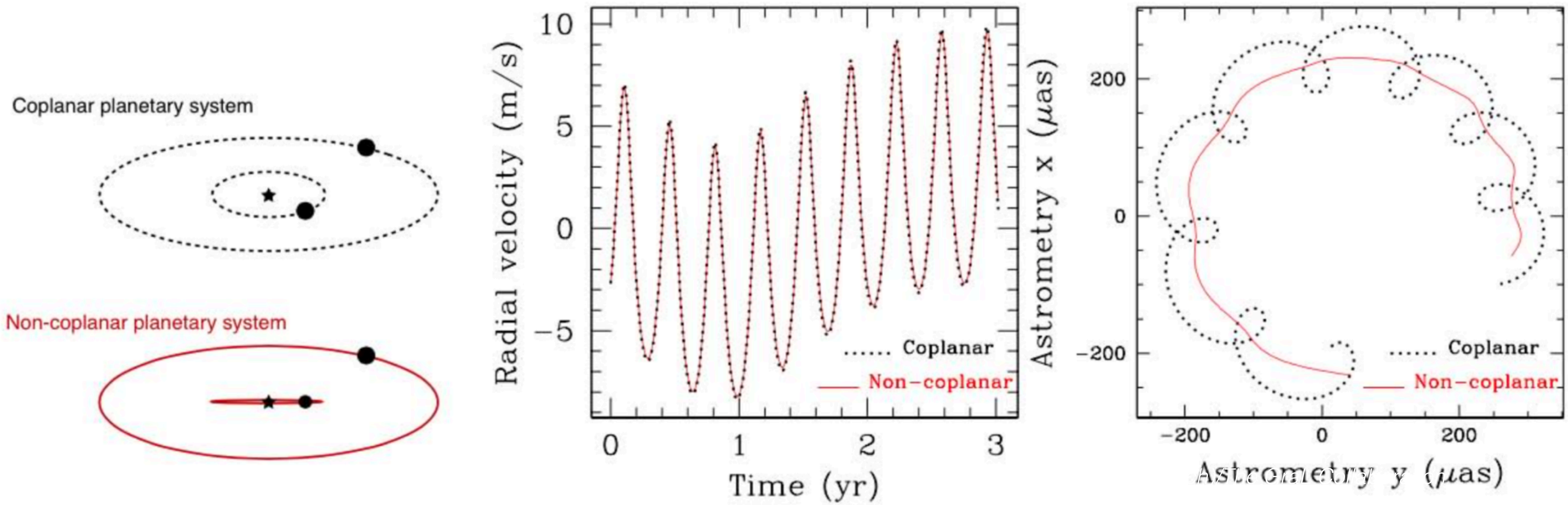

arXiv:1707.01348

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But very small effect!!

$$\Delta\theta = 3\left(\frac{M_{\rm p}}{M_{\oplus}}\right)\left(\frac{a_{\rm p}}{1{\rm AU}}\right)\left(\frac{M_{\star}}{M_{\odot}}\right)^{-1}\left(\frac{D}{1{\rm pc}}\right)^{-1}\mu{\rm as}$$

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Earth at 1 AU of a Sun at 10pc ~ 0.3 uas

ASTROMETRY AND EXOPLANETS

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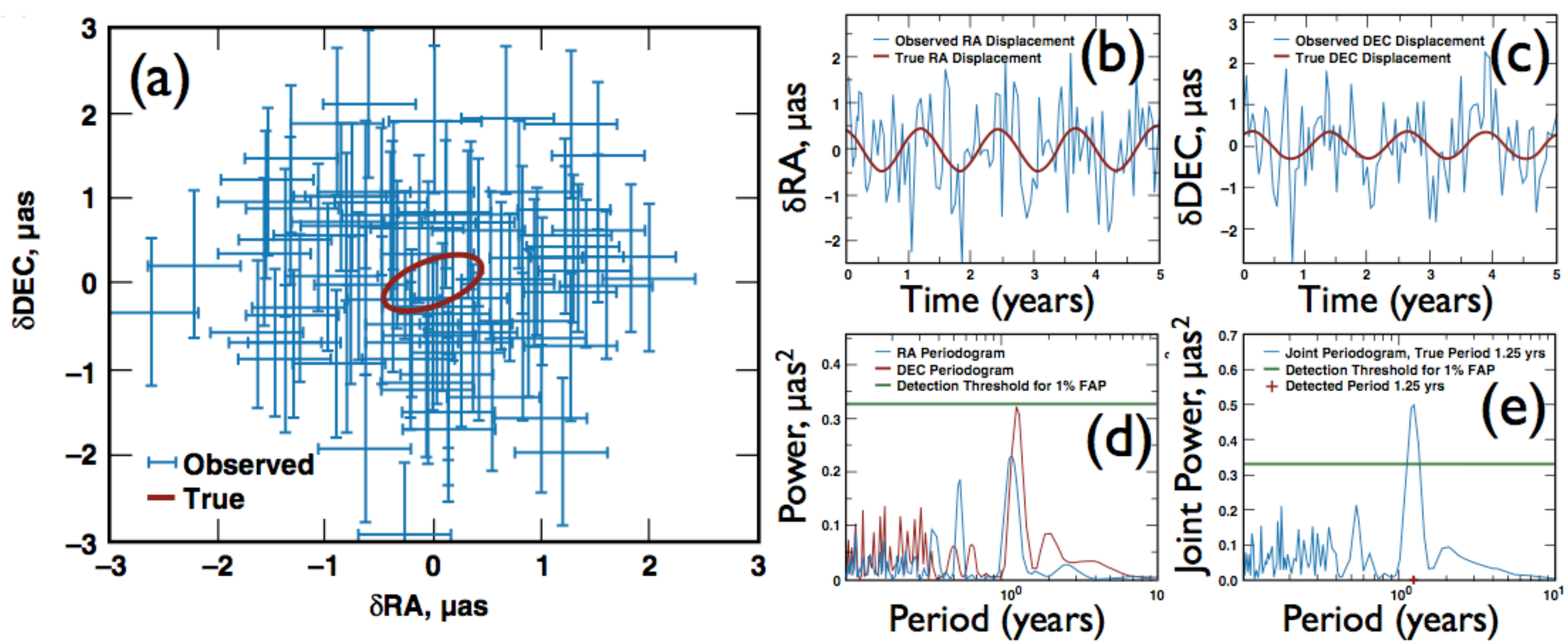
Very simplistic way to perform a detection of a 1.5 MEarth planet at the HZ of a Sun at 10pc



Malbet et al. 2012 (NEAT proposal)

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DIFFERENTIAL ASTROMETRY?

- **Astrometry determines the coordinates of celestial bodies and their derivatives.**

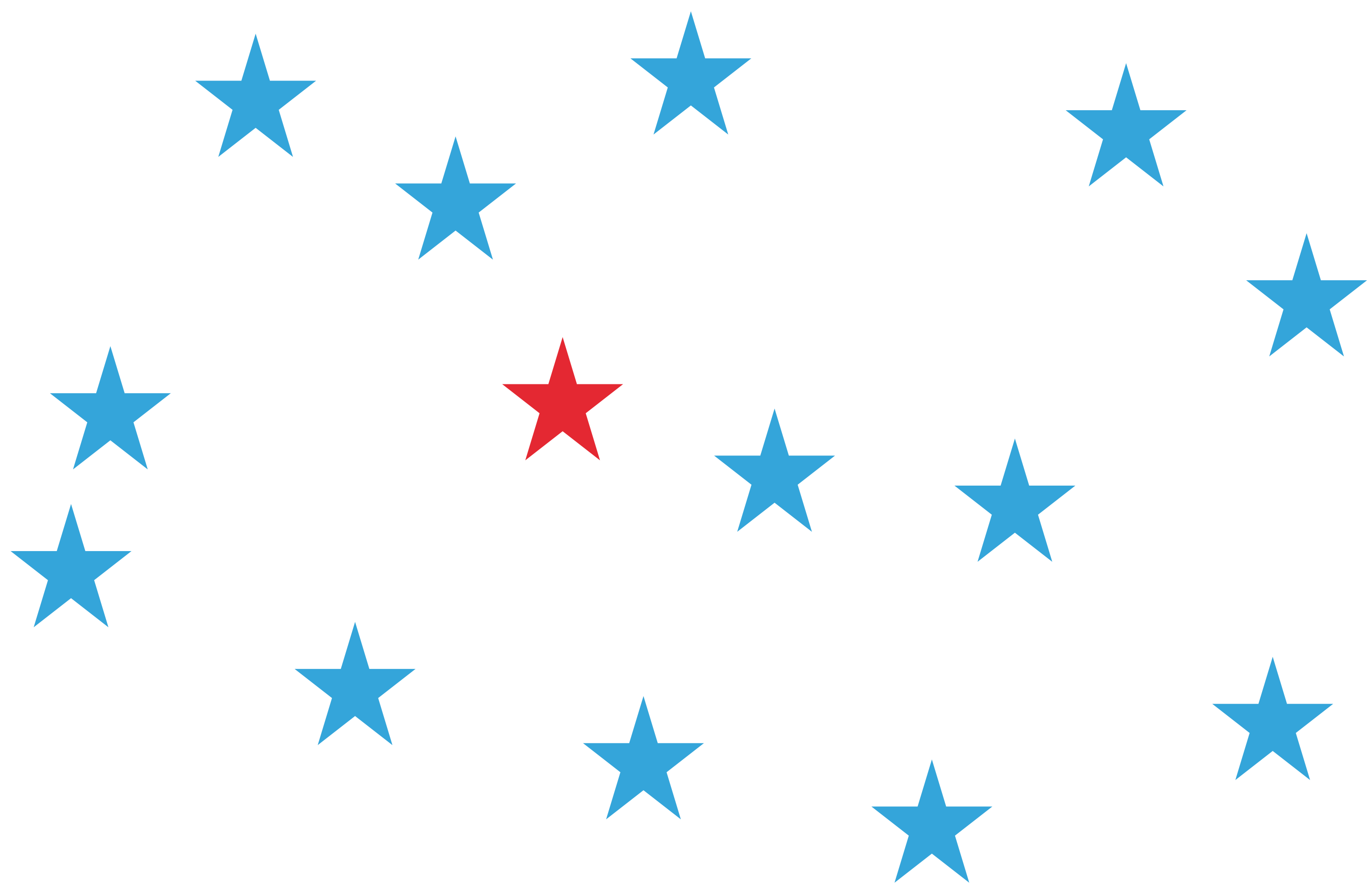
↓

WITH RESPECT TO EACH OTHER

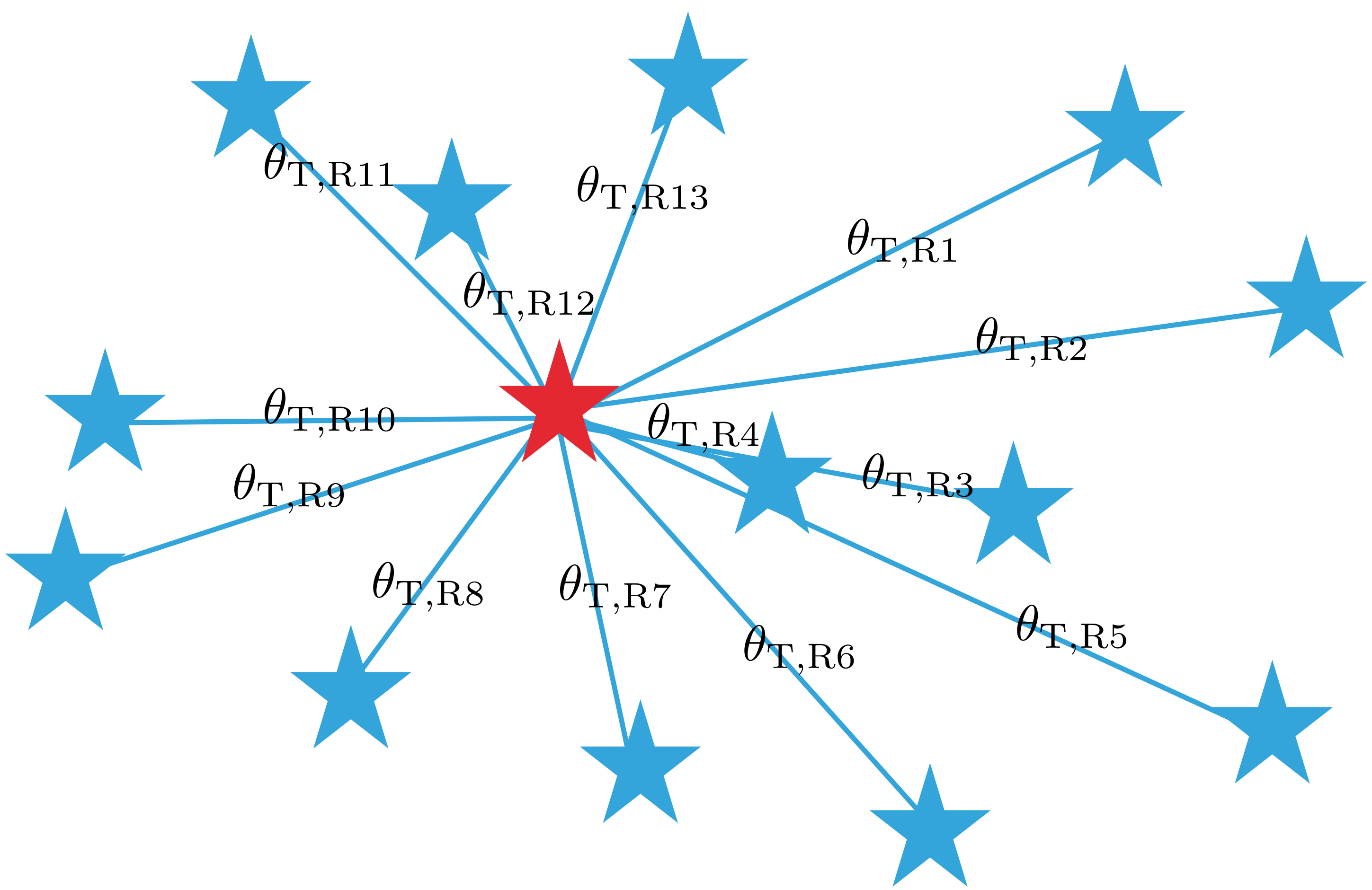
↓

DIFFERENTIAL OR RELATIVE ASTROMETRY

CONCEPTS OF DIFFERENTIAL ASTROMETRY

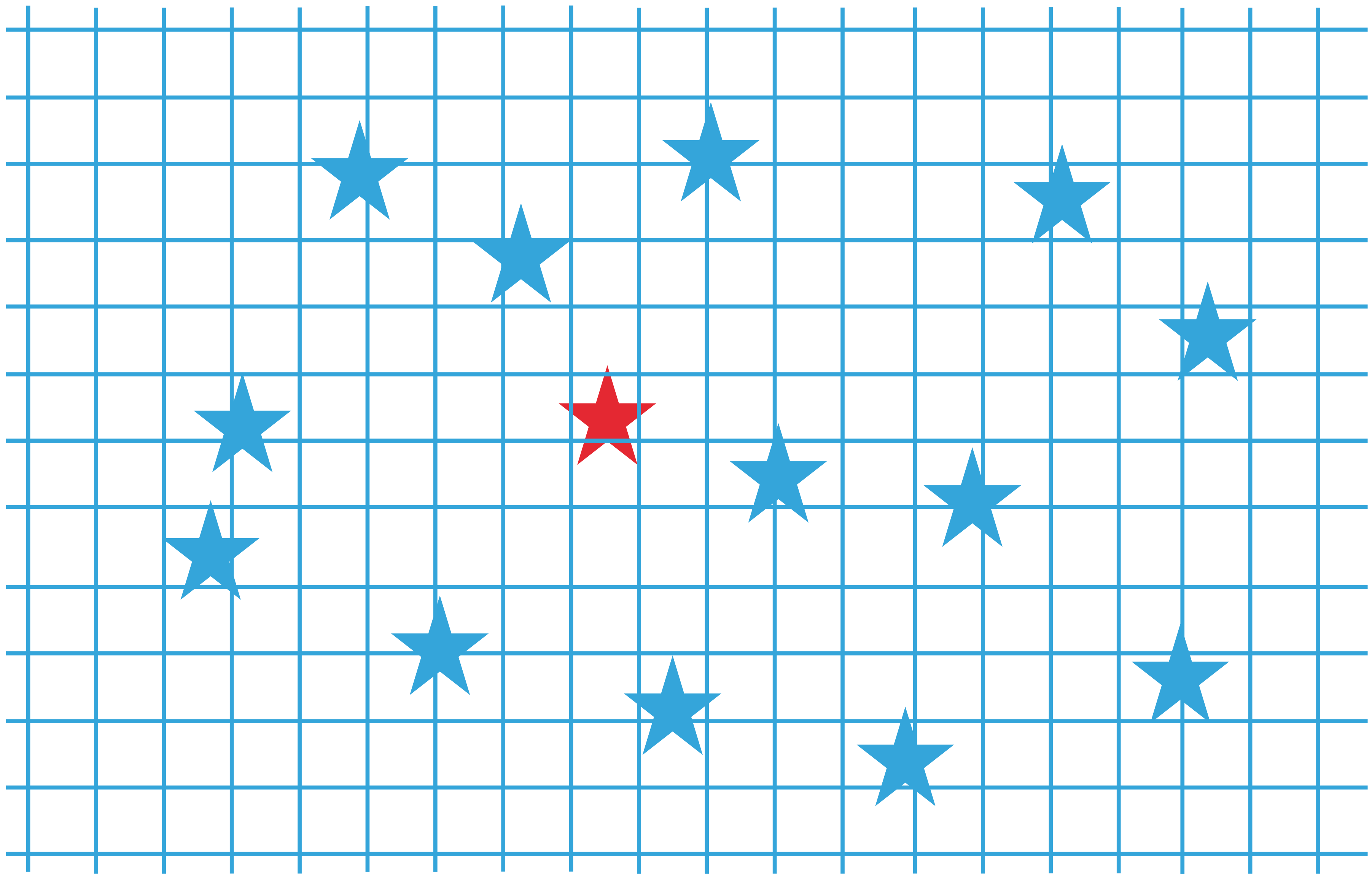


CONCEPTS OF DIFFERENTIAL ASTROMETRY



Alberto Krone-Martins

CONCEPTS OF DIFFERENTIAL ASTROMETRY



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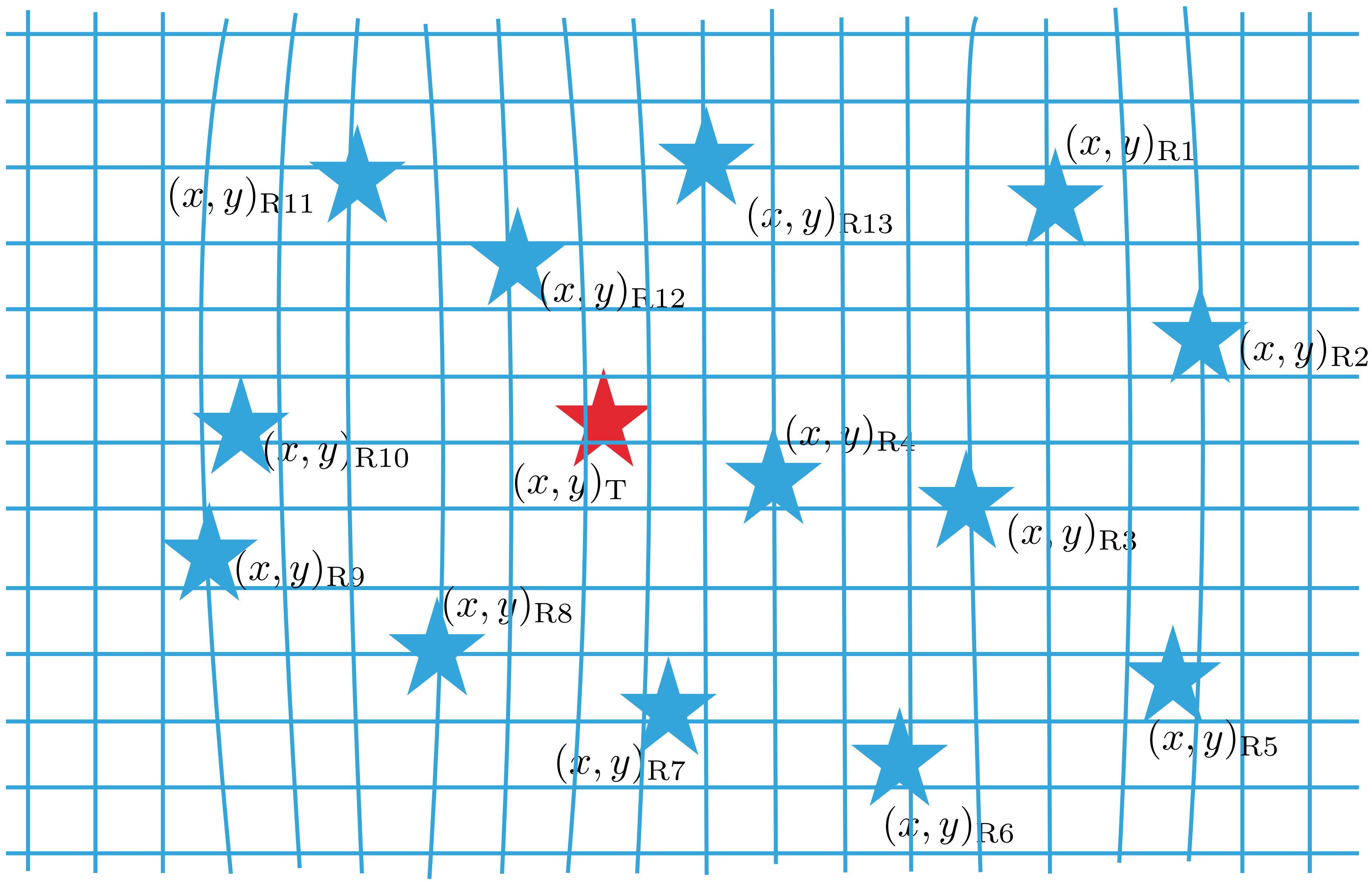
CONCEPTS OF DIFFERENTIAL ASTROMETRY



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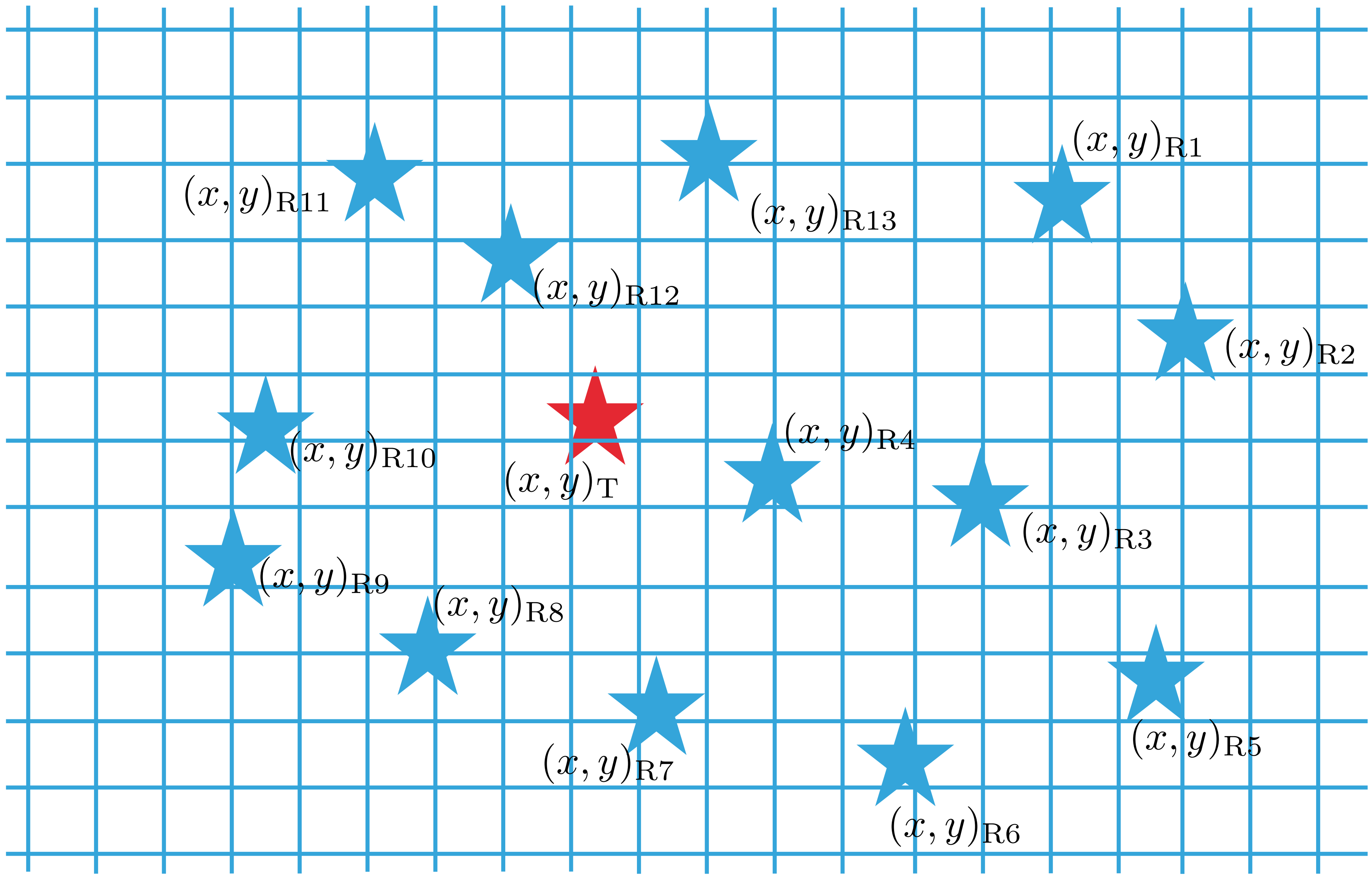

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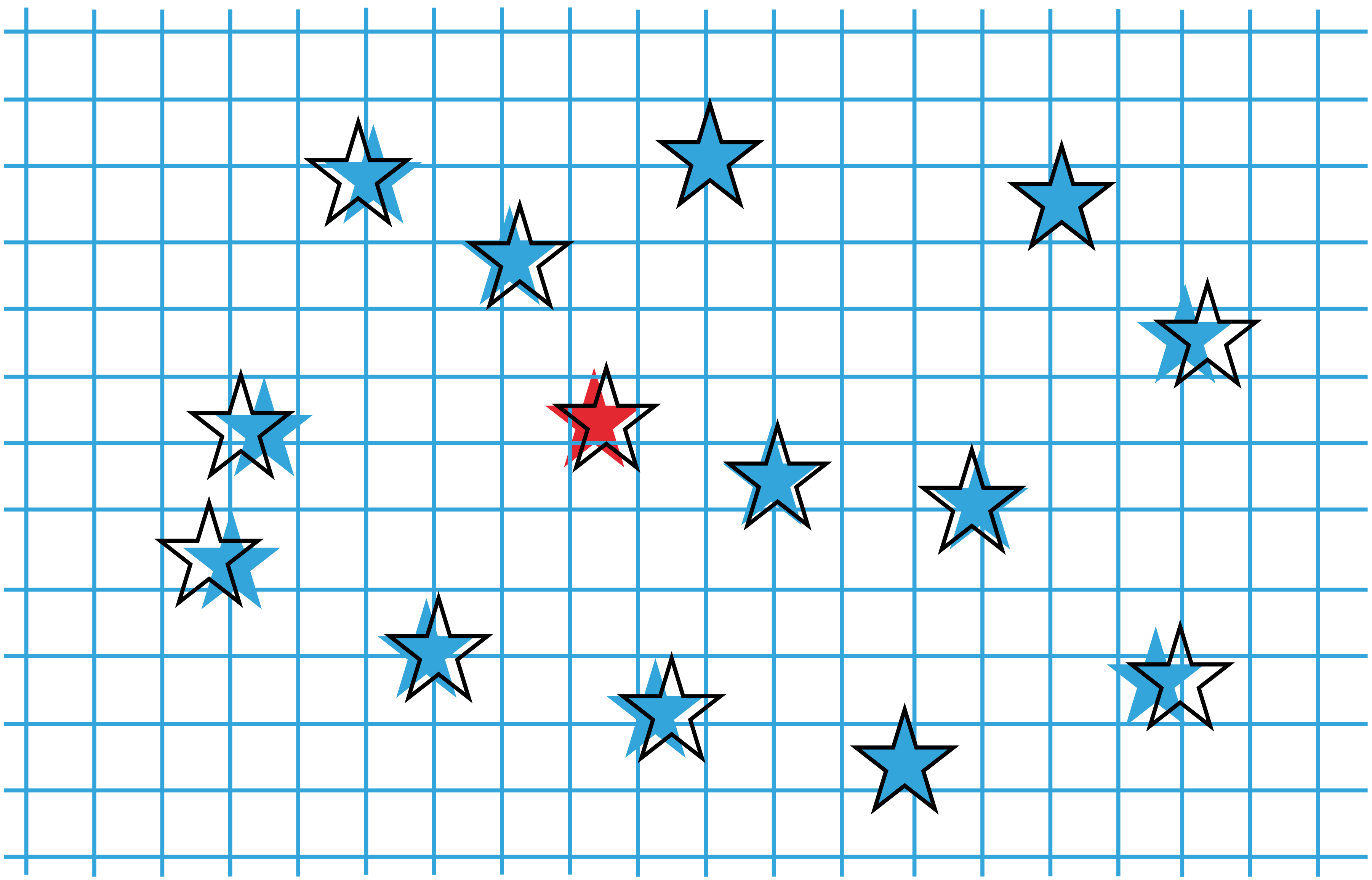
CONCEPTS OF DIFFERENTIAL ASTROMETRY



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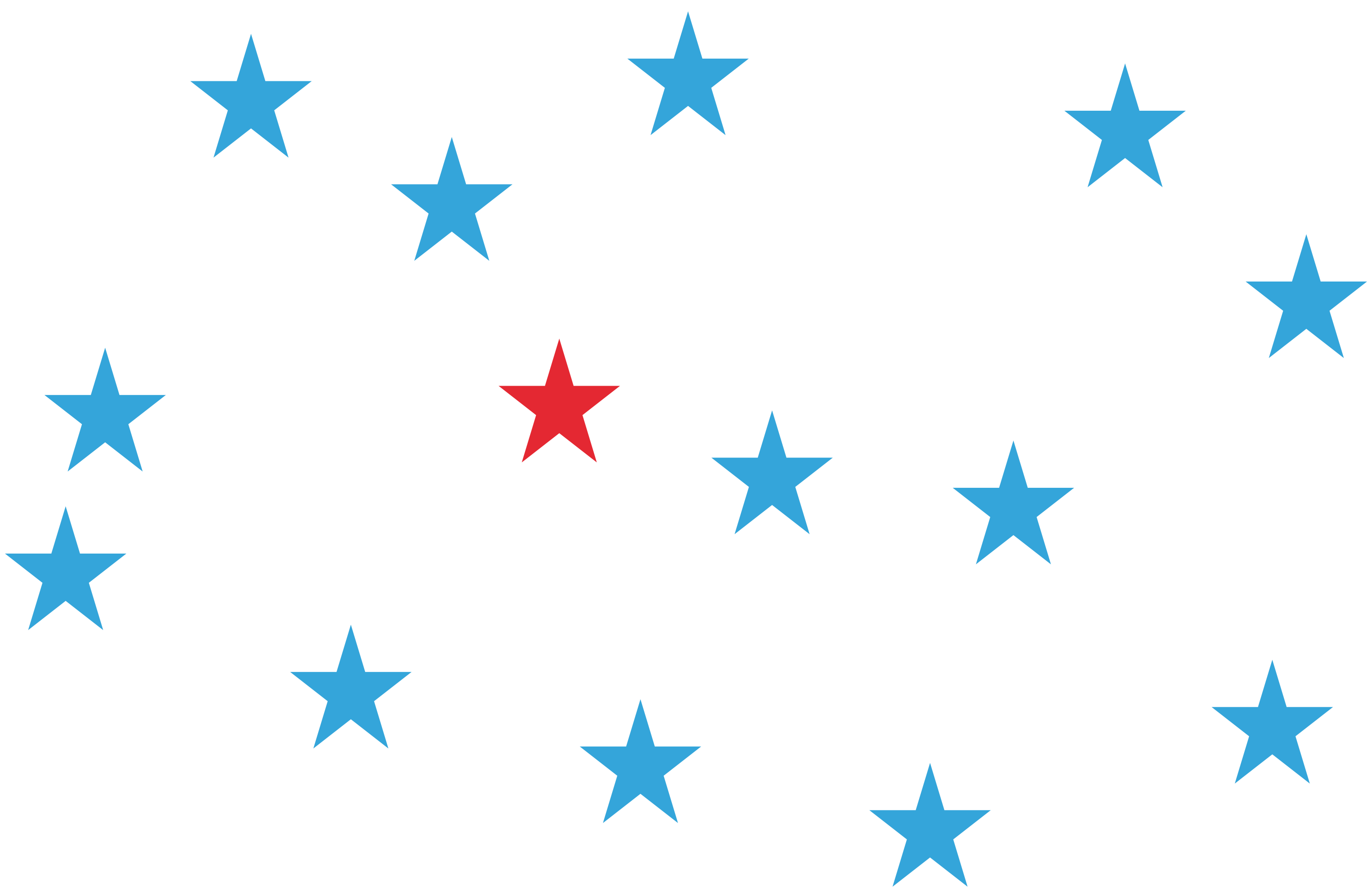

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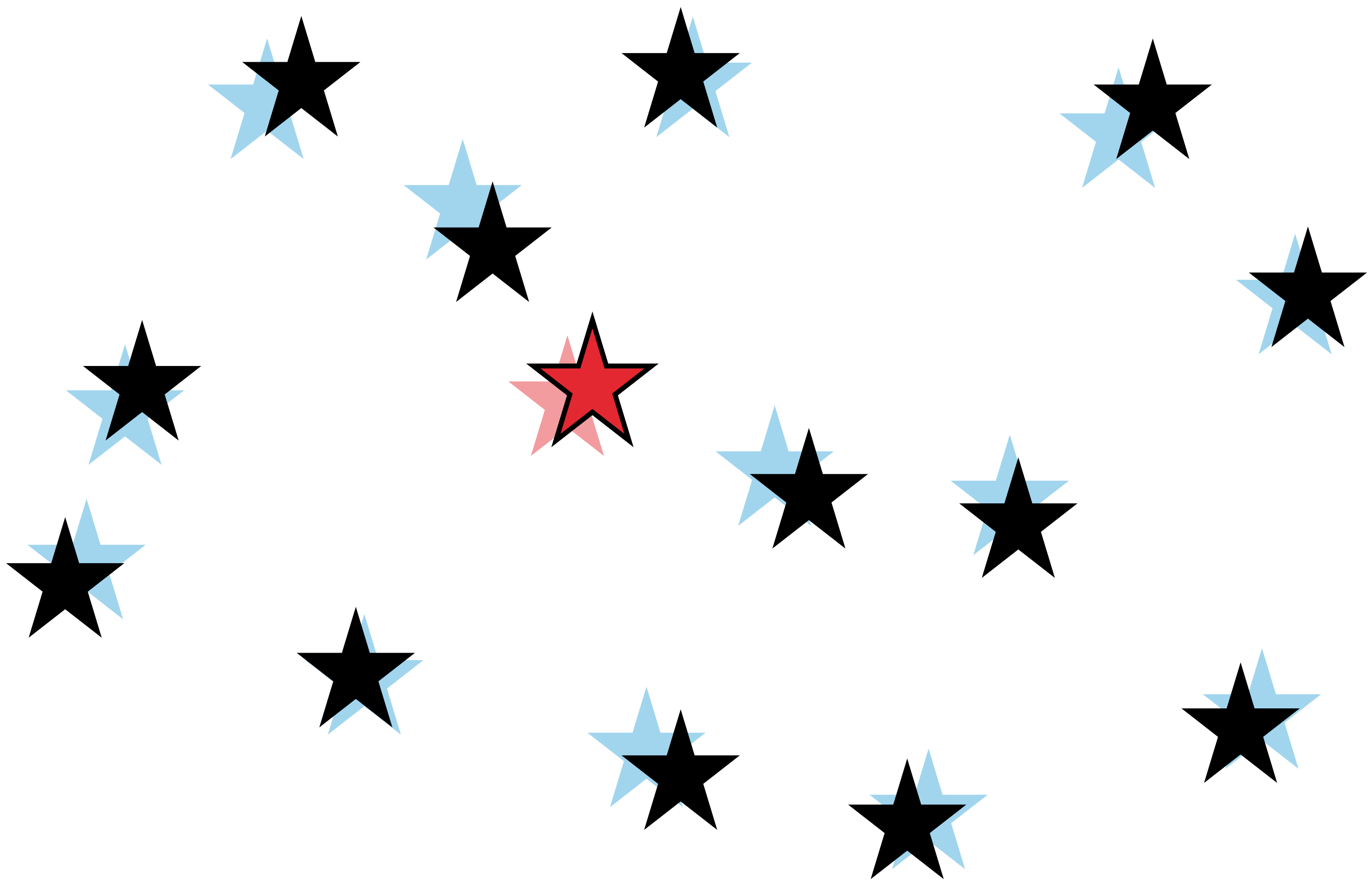
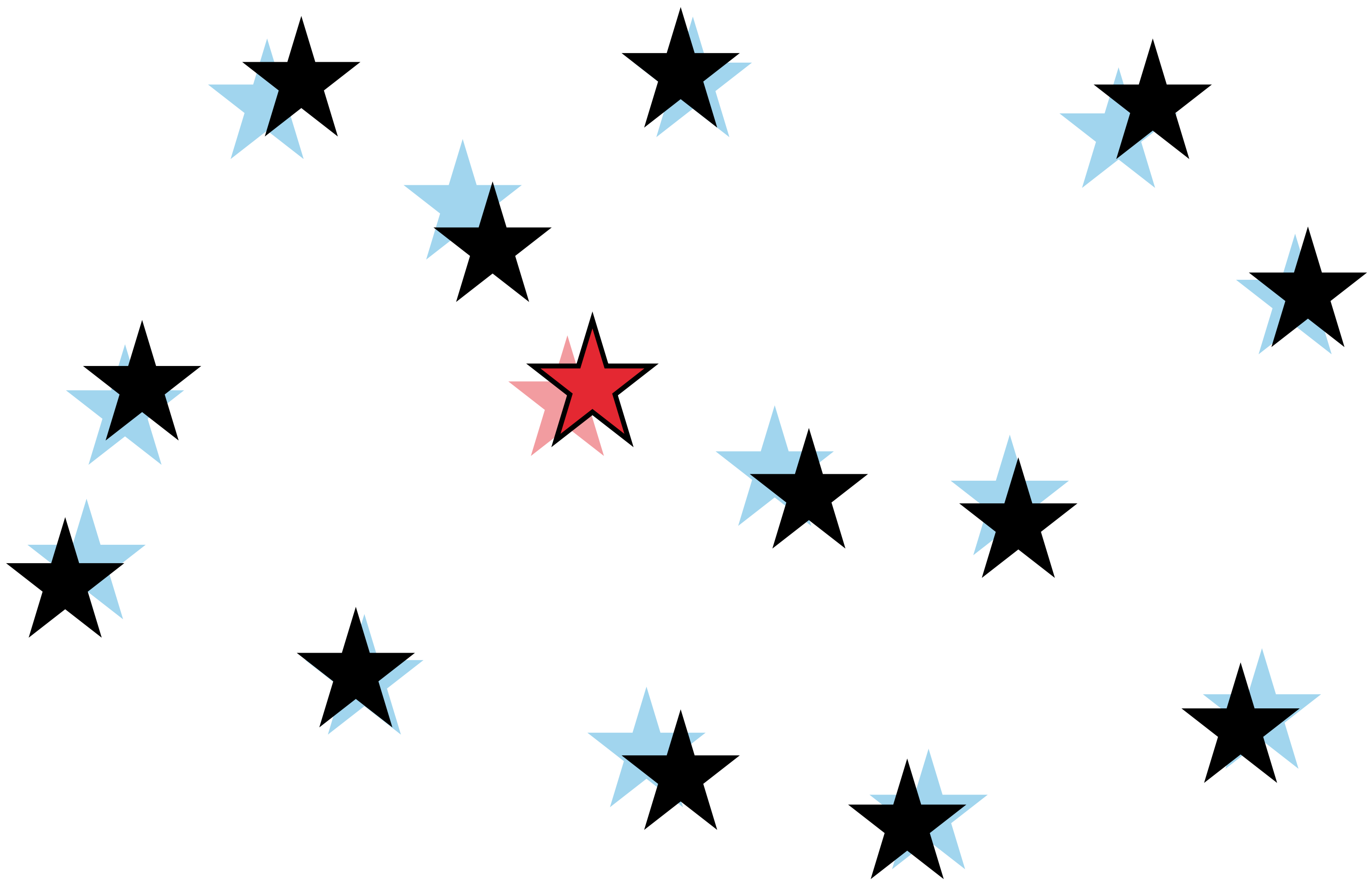
CONCEPTS OF DIFFERENTIAL ASTROMETRY



$$\alpha_i = \alpha_{i0} + \mu_{\alpha i} t_j$$
$$\delta_i = \delta_{i0} + \mu_{\delta i} t_j$$

CONCEPTS OF DIFFERENTIAL ASTROMETRY



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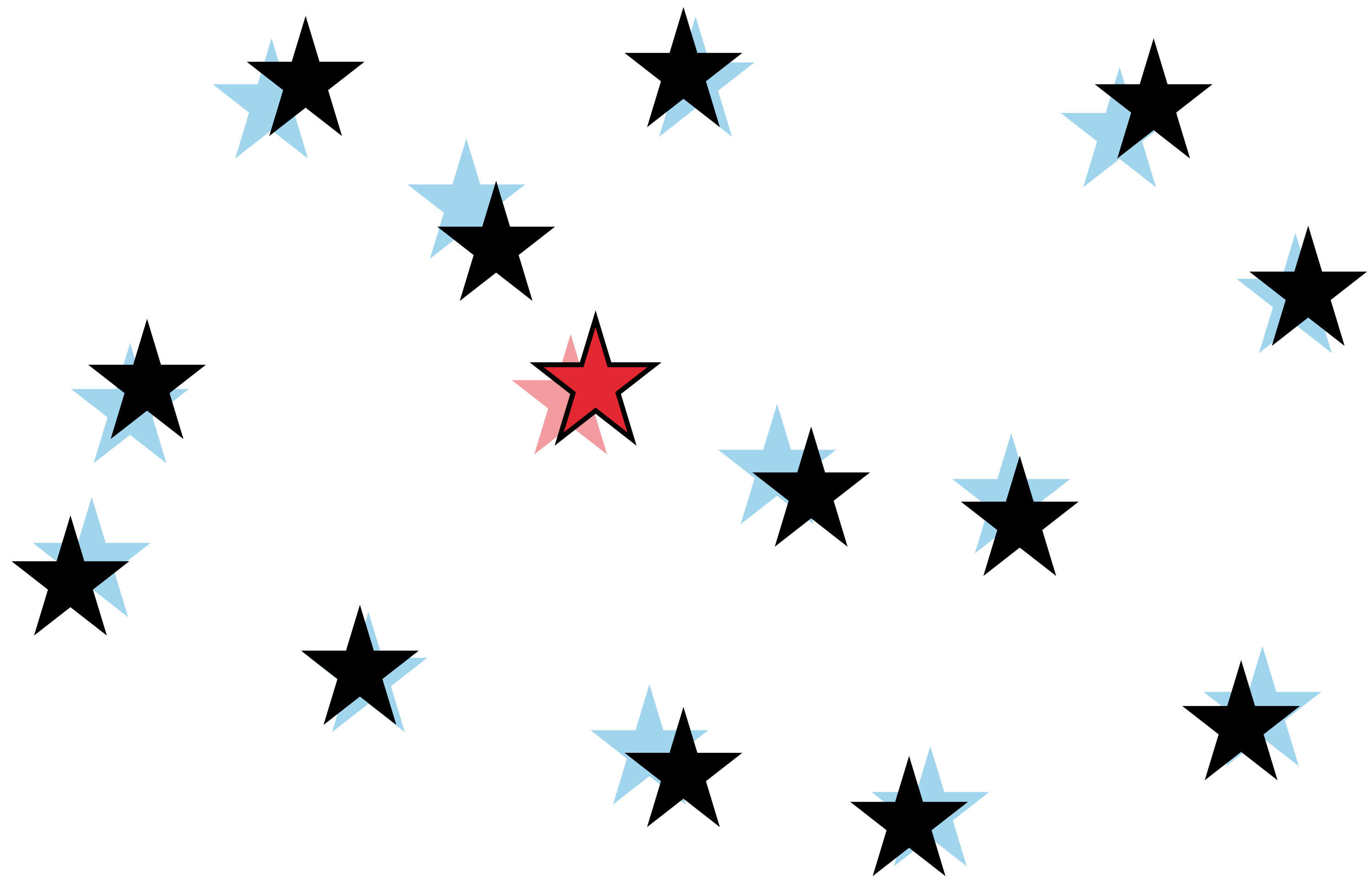
CONCEPTS OF DIFFERENTIAL ASTROMETRY



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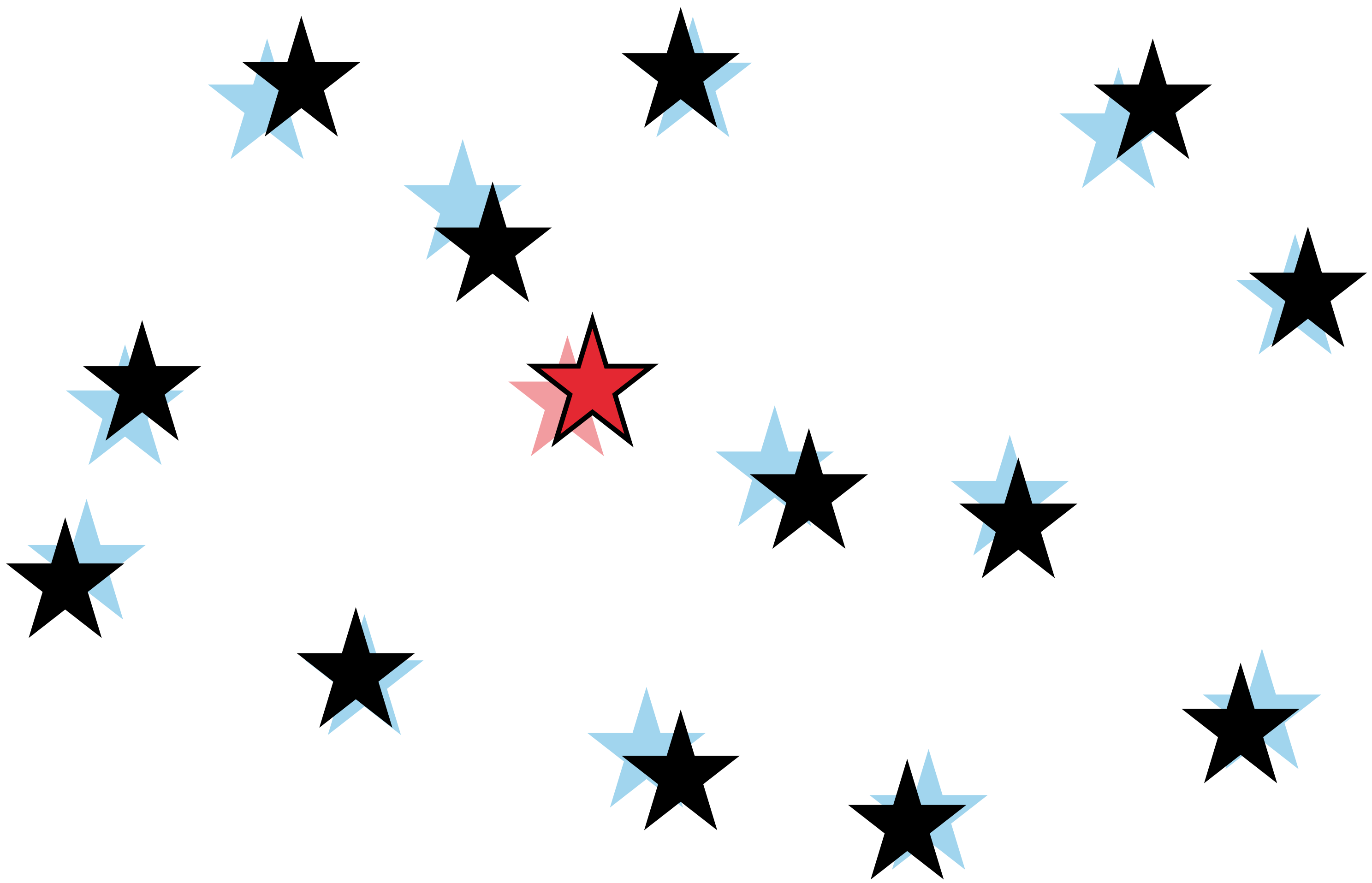
CONCEPTS OF DIFFERENTIAL ASTROMETRY



$$\alpha_i = \alpha_{i0} + \mu_{\alpha i} t_j + \varpi_i P_j + L_{ij} + \epsilon_\alpha(t_j)$$
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In this short talk…

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SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

- REFERENCE FRAME
- INSTRUMENT STABILITY
- PHYSICAL MODELLING
- METHODOLOGY

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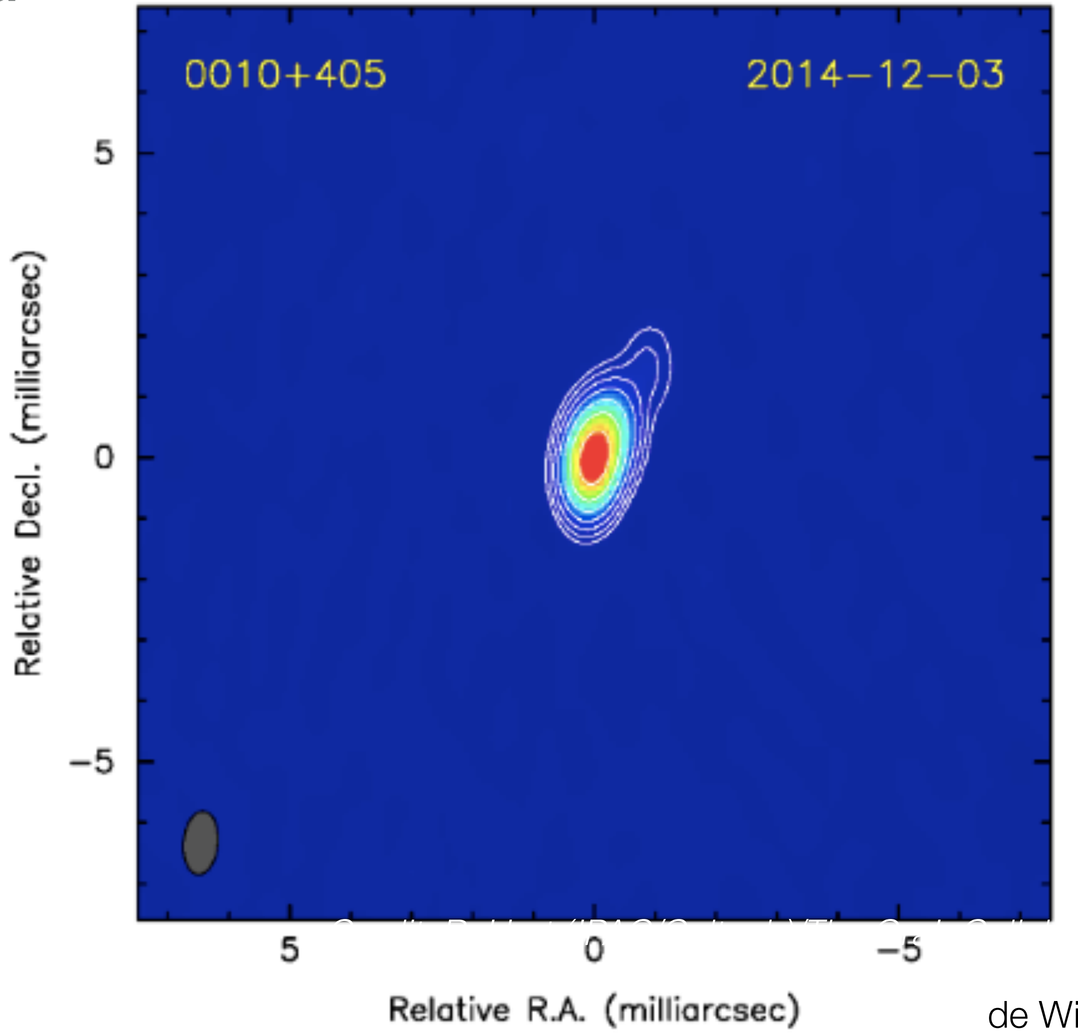
SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

REFERENCE FRAME	THE FRAME AGES AND DEGRADES
INSTRUMENT STABILITY	
PHYSICAL MODELLING	
METHODOLOGY	

REFERENCE FRAME DEGRADATION

- Primary system materialization: QSOs
    - QSOs are not really point sources; they do have structure after enough resolution is reached



de Witt, Charlot, et al., 2022

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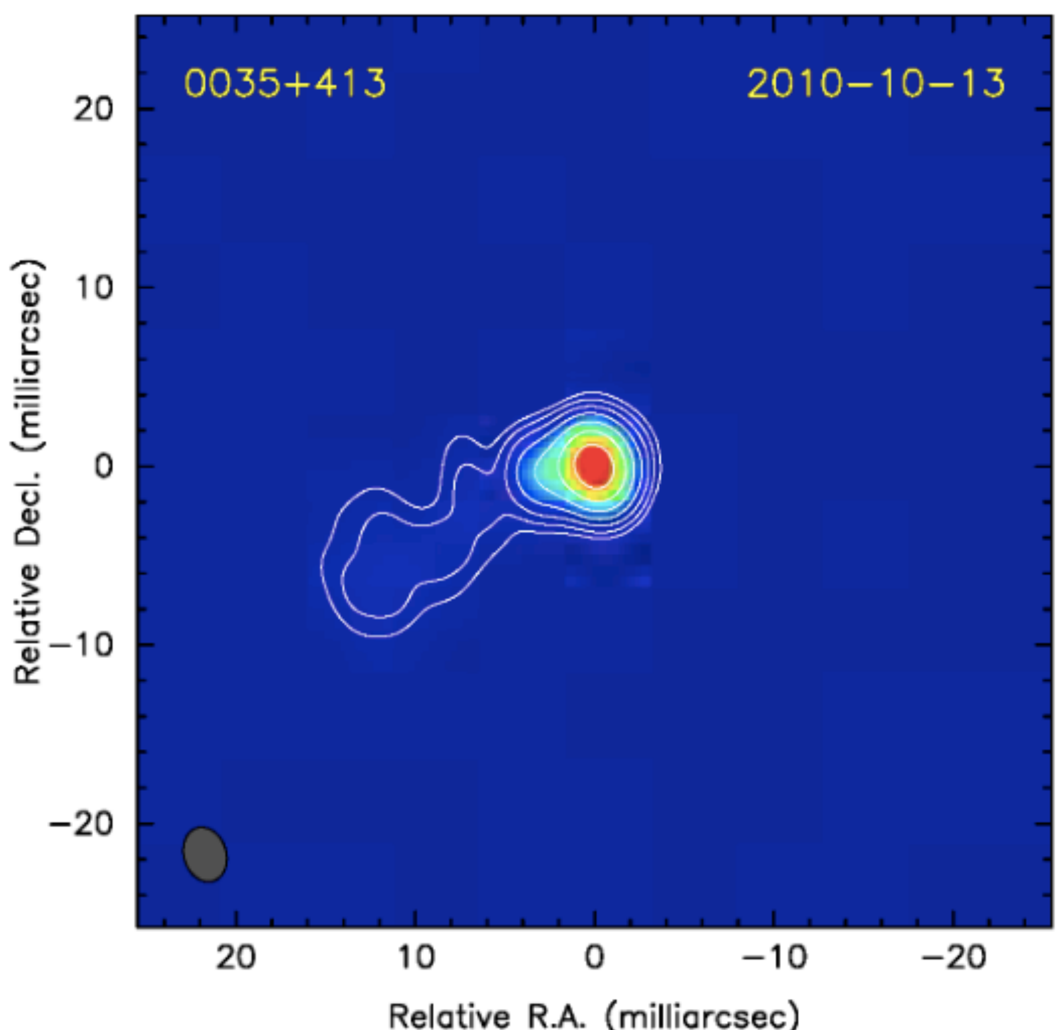

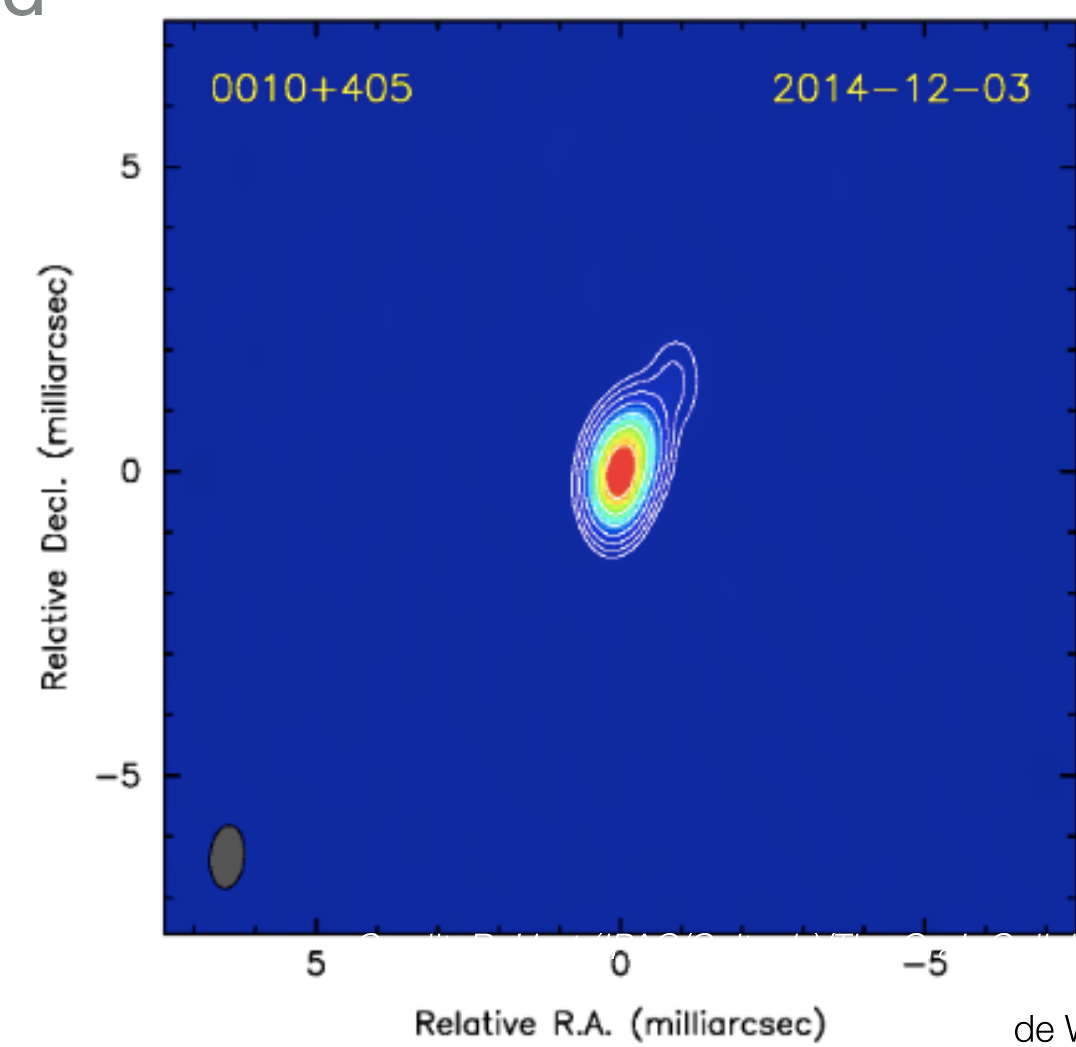

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  - Small uncertainty in the overall frame motion due to galactic acceleration ($\sigma \sim 0.5$ uas yr^{-1})
- **The most accessible system materialization: stars**
  - Need to propagate the stars to the epoch of observations
  - But proper motions are uncertain! So for large t,

$$\sigma_{\alpha*}(t) \sim \sigma_{\mu_{\alpha*}}(t - t_0)$$
$$\sigma_{\delta}(t) \sim \sigma_{\mu_{\delta}}(t - t_0)$$

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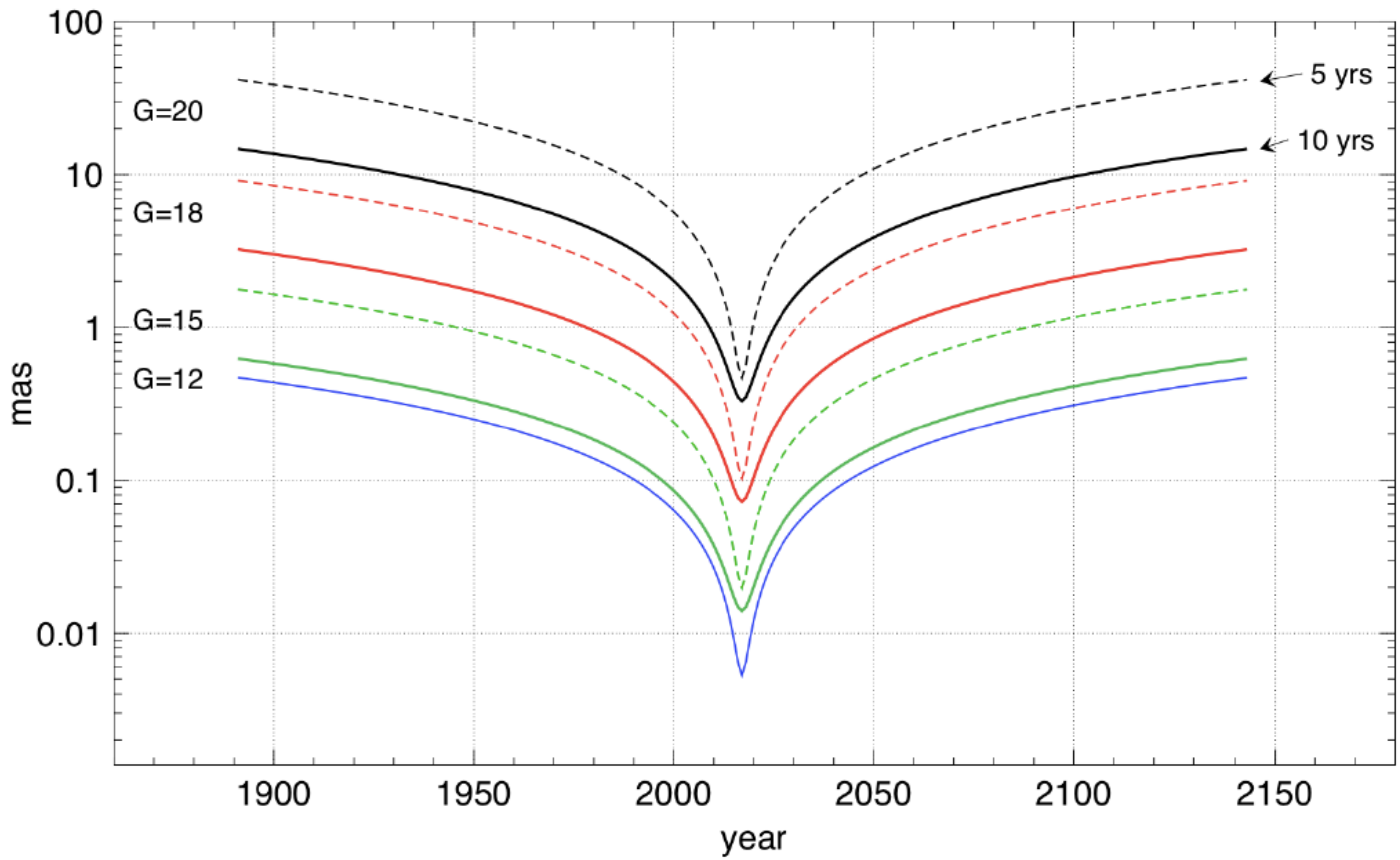
REFERENCE FRAME DEGRADATION



Brown et al., 2017 (Gaia Mission Extension)

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SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

REFERENCE FRAME

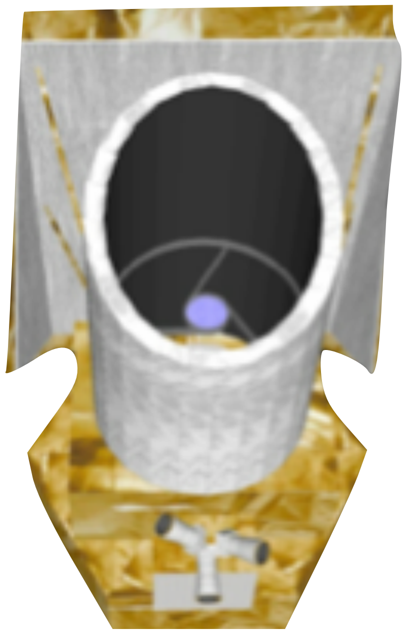
INSTRUMENT STABILITY

IMPERFECT, UNSTABLE INSTRUMENTS

PHYSICAL MODELLING

METHODOLOGY

SOME INSTRUMENT STABILITY ISSUES



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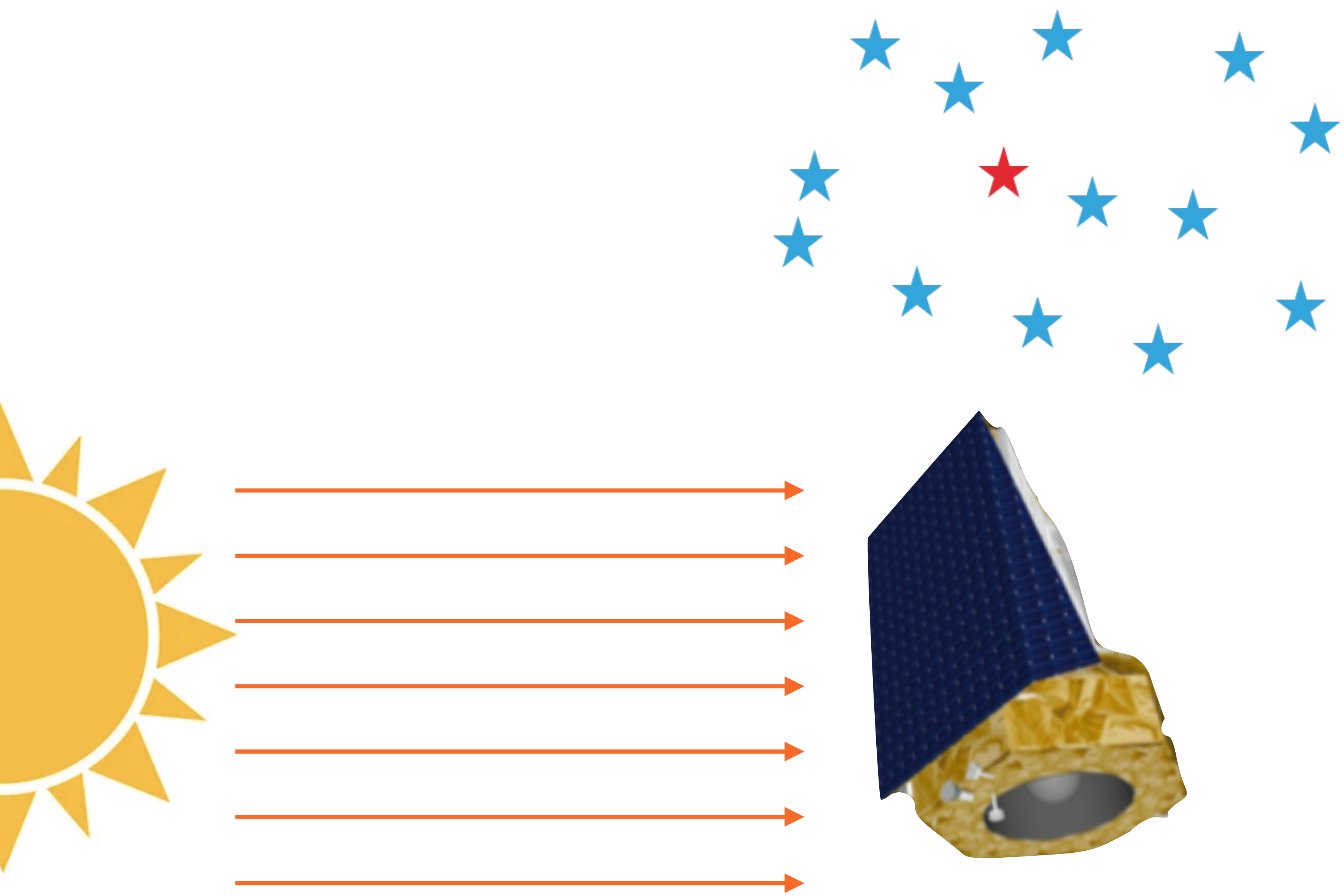

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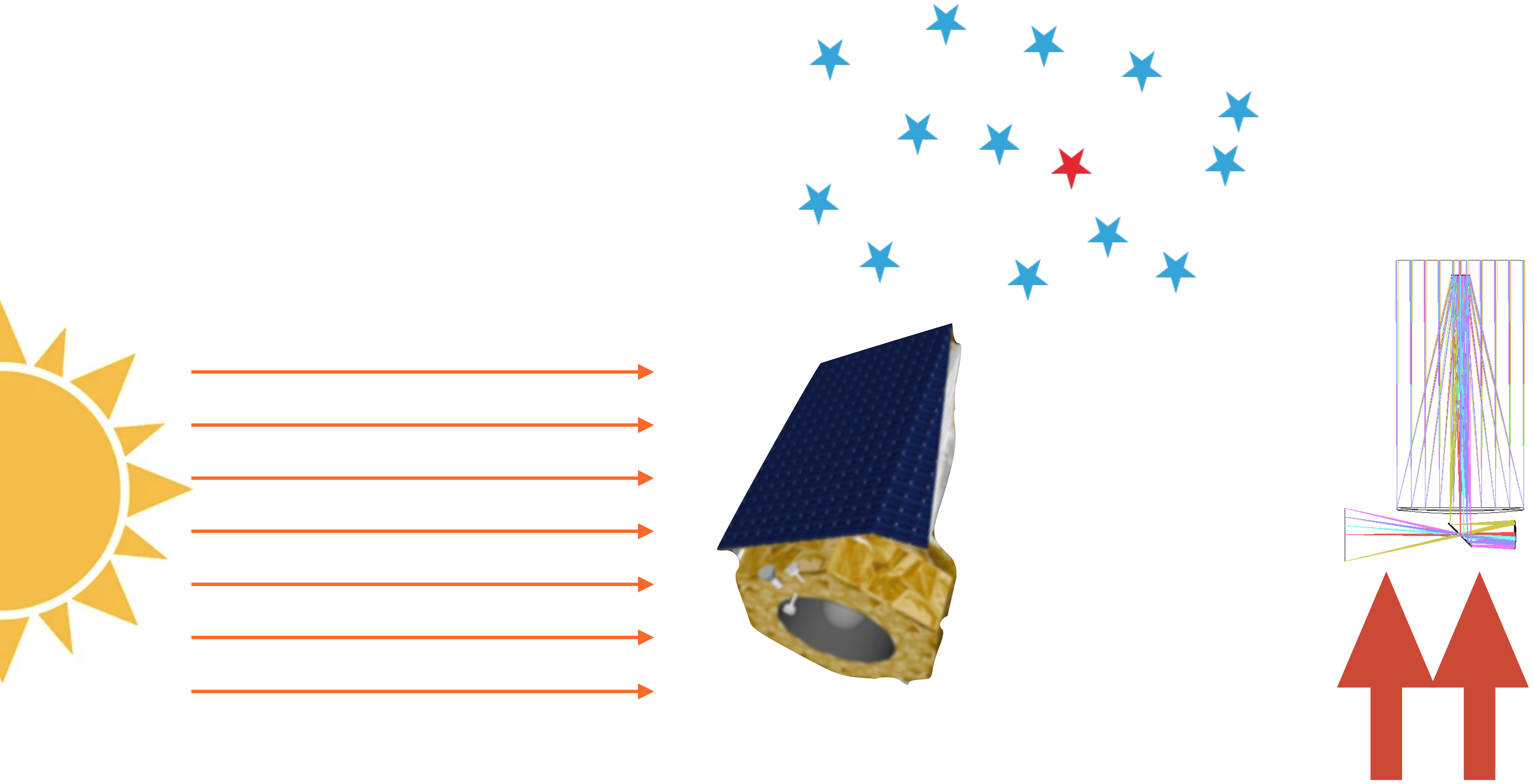

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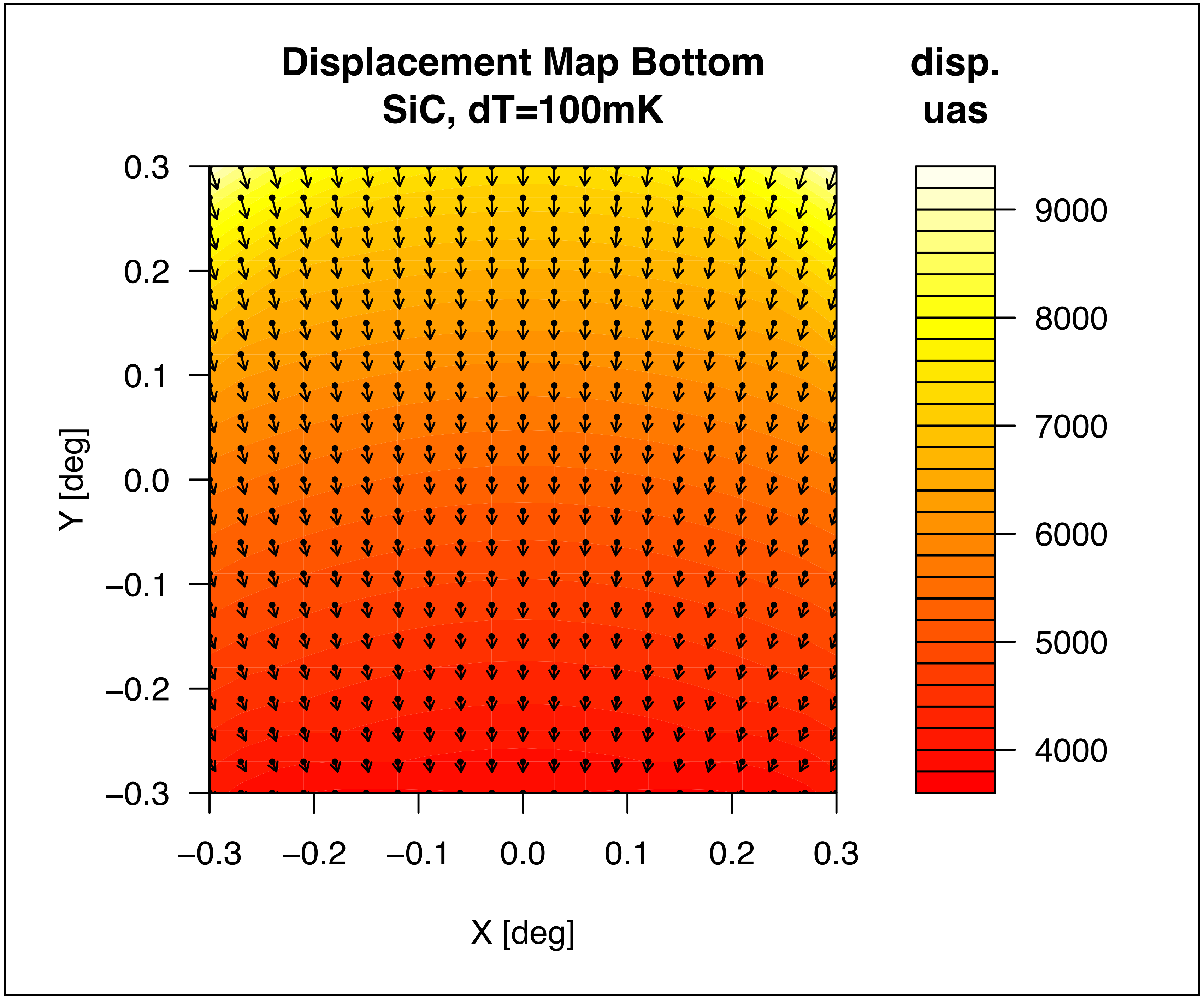

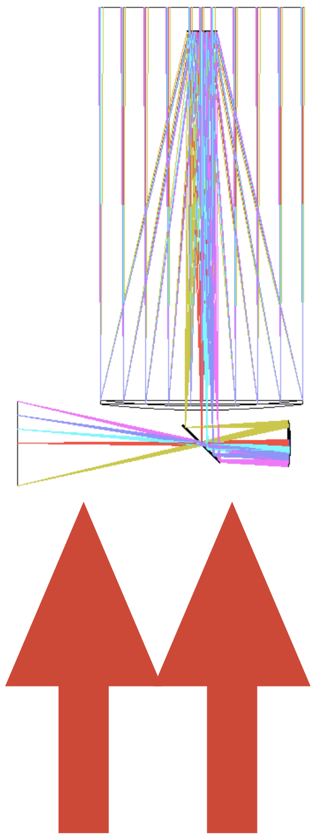

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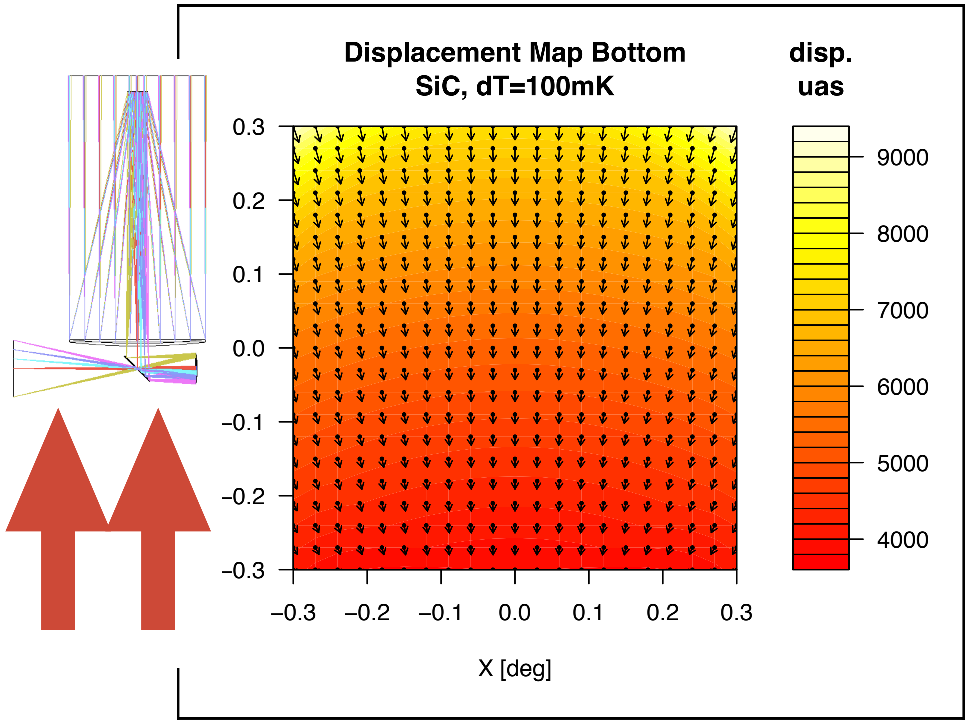

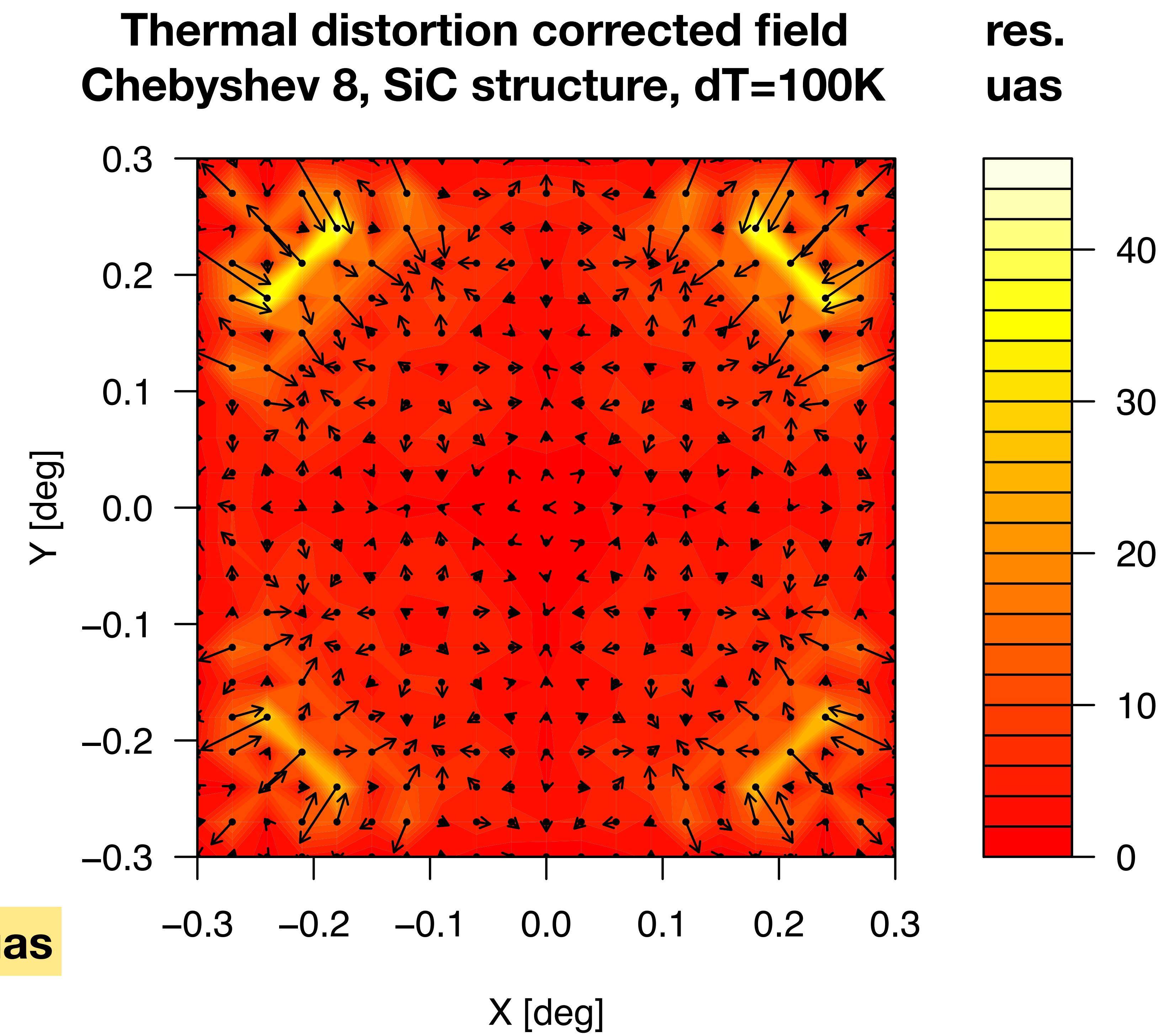

Median residuals 3.31 uas

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SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

REFERENCE FRAME

INSTRUMENT STABILITY

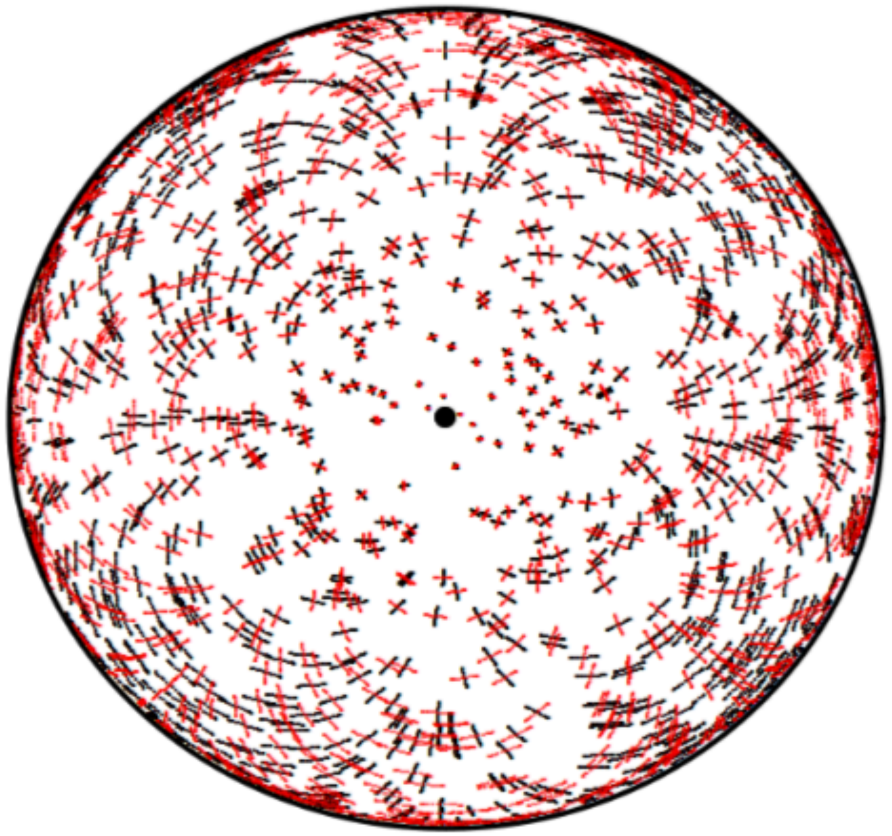
PHYSICAL MODELLING

WE CONSIDER MOST, BUT NOT ALL, PHYSICAL PHENOMENA

METHODOLOGY

PHYSICAL MODELLING

- Stochastic time-variable GW effects: **fundamental limitation**?
  - Apparent astrometric oscillations



Moore et al., 2017 (Phys. Rev. Lett. 119)
see also Klioner, 2018 (Classical and Quantum Gravity, 35)

PHYSICAL MODELLING

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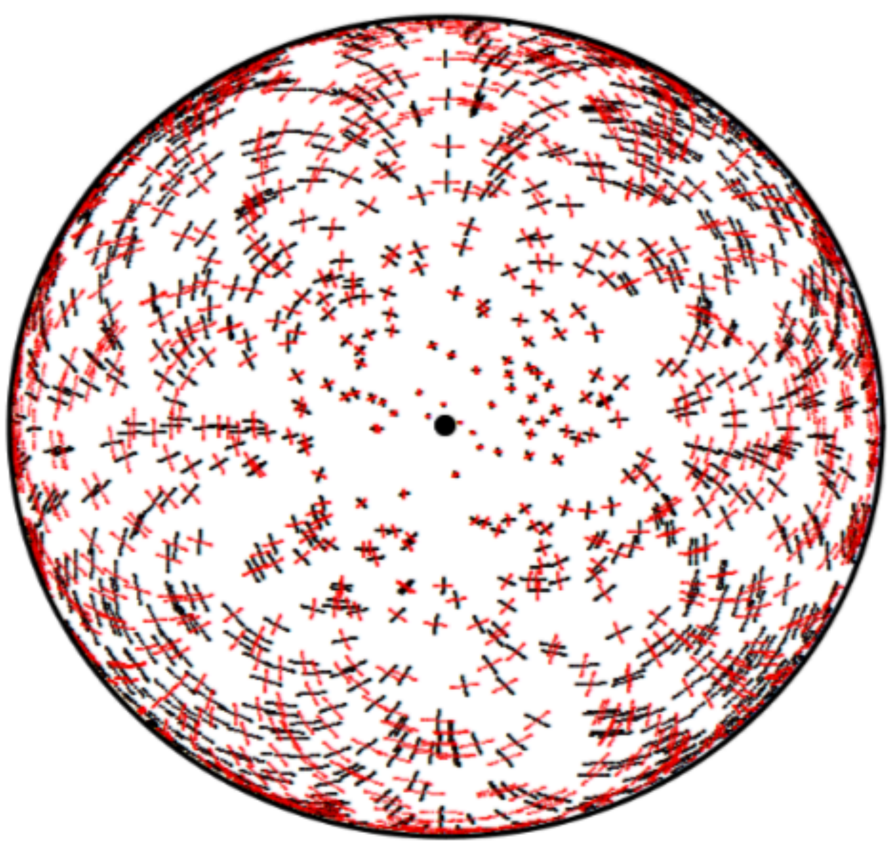

Moore et al., 2017 (Phys. Rev. Lett. 119)
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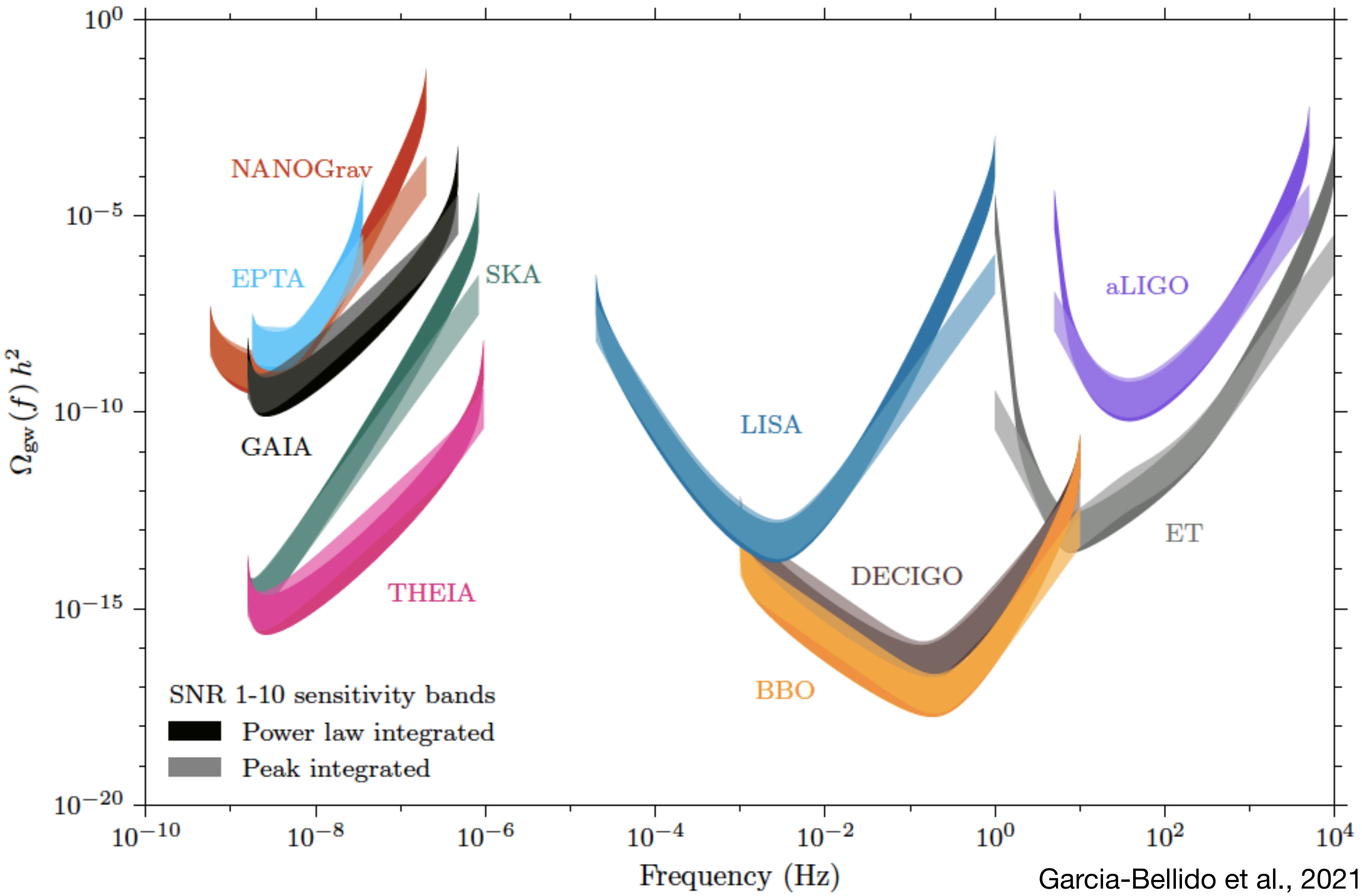

Garcia-Bellido et al., 2021

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SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

REFERENCE FRAME

INSTRUMENT STABILITY

PHYSICAL MODELLING

METHODOLOGY

BREAKING MODEL DEGENERACIES, GOING DEEPER IN THE NOISE

In this short talk…

What and why?

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The future?

SOME DIFFERENTIAL ASTROMETRY CHALLENGES FOR PLANETS

REFERENCE FRAME	FRAME AGES AND DEGRADES : FUTURE GLOBAL SPACE ASTROMETRY MISSIONS AS GAIANIR ARE VITAL TO ASTRONOMY
INSTRUMENT STABILITY	BETTER DESIGN (MATERIALS, OPERATIONS) BETTER MONITORING (ON BOARD METROLOGY SYSTEMS PM)
PHYSICAL MODELLING	AT THE SUB-MAS REGIME: GRAVITATIONAL EFFECTS DEPENDING ON FOV AND MISSION PROFILE
METHODOLOGY	BREAKING MODEL DEGENERACIES, GOING DEEP IN THE NOISE INTEGRATING SIGNAL PROCESSING + STATISTICAL + MATHEMATICAL + COMPUTER SCIENCE KNOWLEDGE

2020 | 2030 | 2040

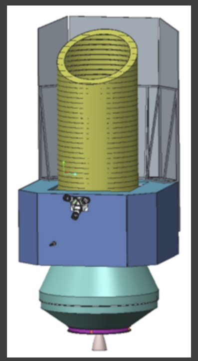
Relative
"large" FoV

JASMINE


Gouda et al., 2017

+ Non dedicated missions
that can (and hopefully will)
do relative astrometry
as Roman, Euclid, etc.

CHES



Theia

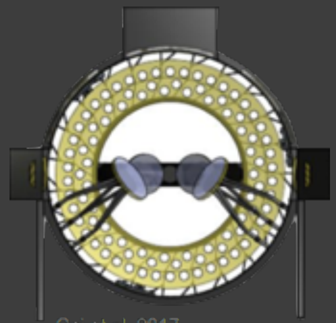
Boehm et al., 2017

Relative
Diffraction-based
or interferometric

TOLIMAN

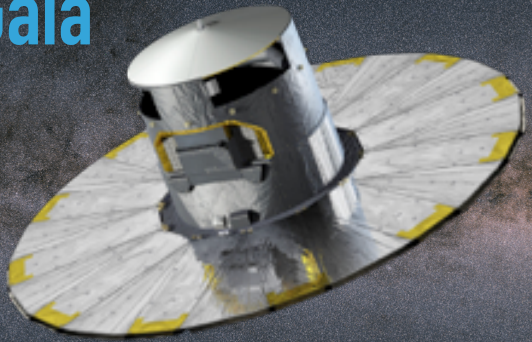

Bendek et al 2018

AGP

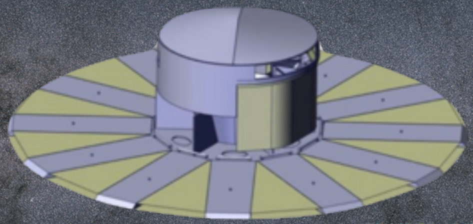

Gai et al. 2017

Absolute
Global
All-Sky

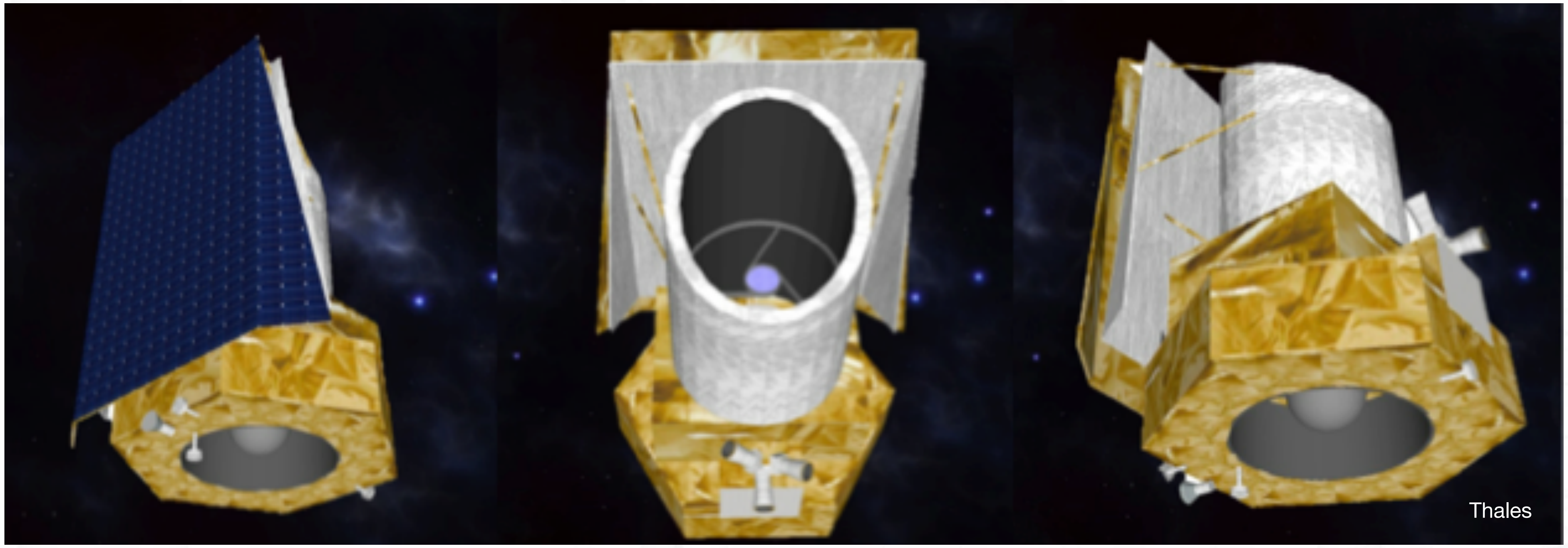
Gaia


ESA/Airbus

GaiaNIR



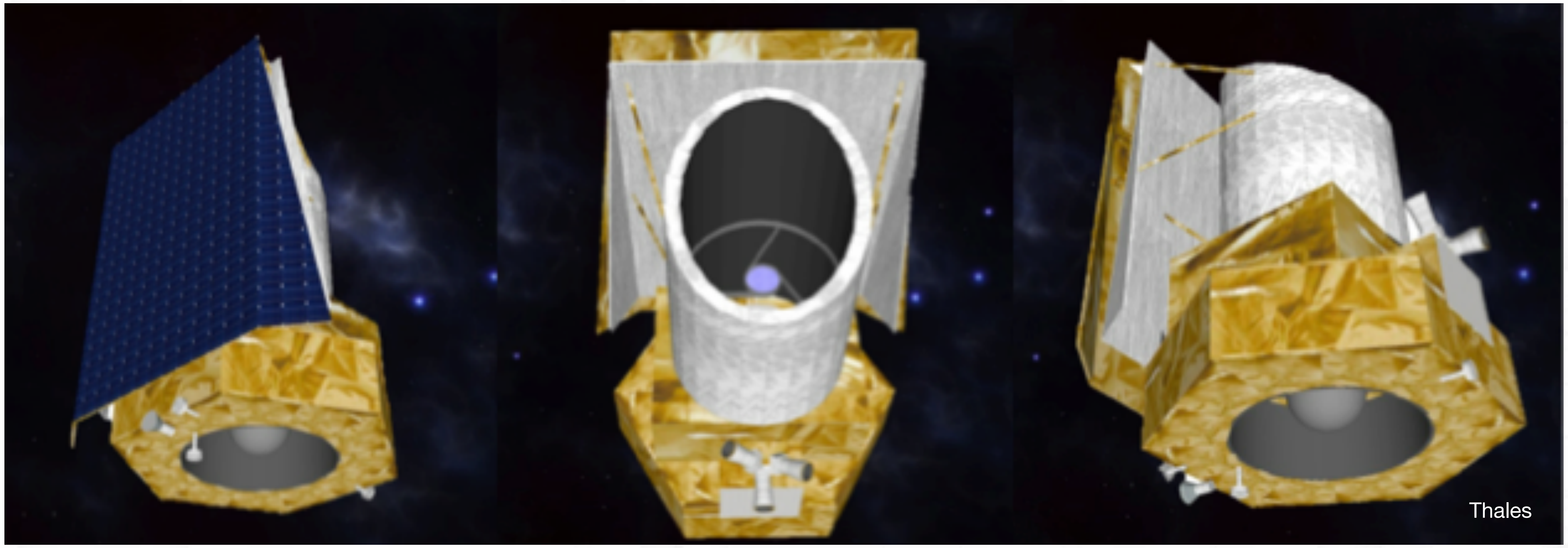
THEIA MAJOR SCIENCE CASES



- To probe small-scale properties of Dark Matter
- To reliably probe the shape of MW DM halo
- **To detect and study habitable exo-Earths around nearby FGK stars unambigously and to probe their planetary system architectures**
- Significantly improve the knowledge of Neutron Star EOS and of matter around Black Holes
- Micro-arcsecond astromery dead-time due to stabilization dedicated to photometry

arXiv:1707.01348

THEIA MAJOR SCIENCE CASES



- Measure true mass function of **temperate 1–5 M⊕ rocky planets** around solar-type stars
- **Study the three-dimensional architecture** of FGK systems harboring telluric planets
- Provide input target lists of stars with **telluric planets for direct-imaging / spectroscopic** missions aimed at searching for atmospheric biomarkers.

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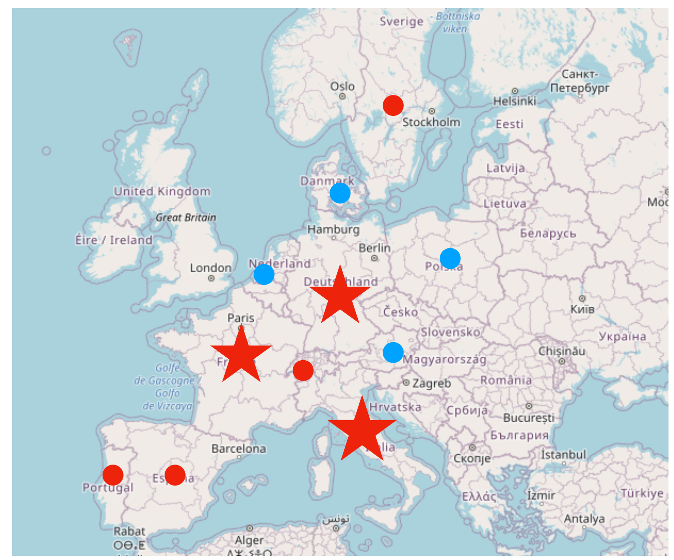
THEIA PROPOSAL

Theia core team

Alessandro Sozzetti
INAF - Osservatorio Astrofisico di Torino, Italy
Fabien Malbet
Université de Grenoble Alpes/CNRS/IPAG, France
Lucas Labadie
Universität zu Köln, Germany



- The core team includes members from **Italy, France, Germany**, Sweden, Spain, Switzerland and Portugal (and USA)
- Additional contributions from Austria, Denmark, The Netherlands and Poland.
- Participants from several countries outside Europe: Australia, Israel and USA ("non-enabling" contribution). Several countries have expressed their interests
- In M5 proposal : 22 countries, 209 researchers

Europe

Antonio Amorim (*Universidade de Lisboa, CENTRA, Portugal*)
Guillem Anglada-Escudé (*ICE CSIC, Spain*)
Alexis Brandeker (*Stockholm University, Sweden*)
Enzo Brocato (*INAF - Osservatorio Astronomico d'Abruzzo, Italy*)
Lars Buchhave (*National Space Institute & Niels Bohr Insitute, Denmark*)
Deborah Busonero (*INAF - Osservatorio Astrofisico di Torino, Italy*)
Silvano Desidera (*INAF - Osservatorio Astronomico di Padova, Italy*)
Antonaldo Diaferio (*Universitá degli Studi di Torino, Italy*)
Luca Fossati (*OEAW, Austria*)
Mario Gai (*INAF - Osservatorio Astrofisico di Torino, Italy*)
Juan Garcia-Bellido (*Universidad Autónoma de Madrid, Spain*)
Manuel Güdel (*University of Vienna, Austria*)
Berry Holl (*Geneva Observatory, Switzerland*)
Markus Janson (*Stockholm University, Sweden*)
Anne-Marie Lagrange (*Université de Grenoble Alpes/CNRS/IPAG, France*)
Mario Gilberto Lattanzi (*INAF - Osservatorio Astrofisico di Torino, Italy*)
Alain Leger (*IAS-CNRS, France*)
Gary Mamon (*IAP [Sorbonne U. & CNRS], Paris, France*)
Nadege Meunier (*Université de Grenoble Alpes/CNRS/IPAG, France*)
André Moitinho (*CENTRA, Universidade de Lisboa, Portugal*)
Sascha Quanz (*ETH-Zurich, Switzerland*)
Rafael Rebolo (*Instituto de Astrofisica de Canarias, Spain*)
Alberto Riva (*INAF - Osservatorio Astrofisico di Torino, Italy*)
Ignas Snellen (*Leiden, Netherlands*)
Andrzej Udalski (*Warsaw University, Poland*)
Eva Villaver (*Universidad Autónoma de Madrid, Spain*)

Outside Europe

Céline Boehm (*University of Sydney, Australia*)
Renaud Goullioud (*JPL/NASA, USA*)
Alberto Krone-Martins (*University of California, Irvine, USA*)
Tom Maccarone (*Texas Tech University, USA*)
Barbara McArthur (*University of Texas at Austin, USA*)
Adi Nusser (*Technion - Israel Institute of Technology,Israel*)
Michael Shao (*JPL/NASA, USA*)

THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

INSTRUMENT STABILITY	SIMPLE OPTICAL SYSTEM, LOW CTE AND WELL UNDERSTOOD MATERIALS, ALMOST NO MOVING PARTS
	METROLOGICAL SYSTEMS (SUB-UAS)
	CALLIBRATION (UAS)
	MULTIPLE THERMAL MONITORING POINTS

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THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

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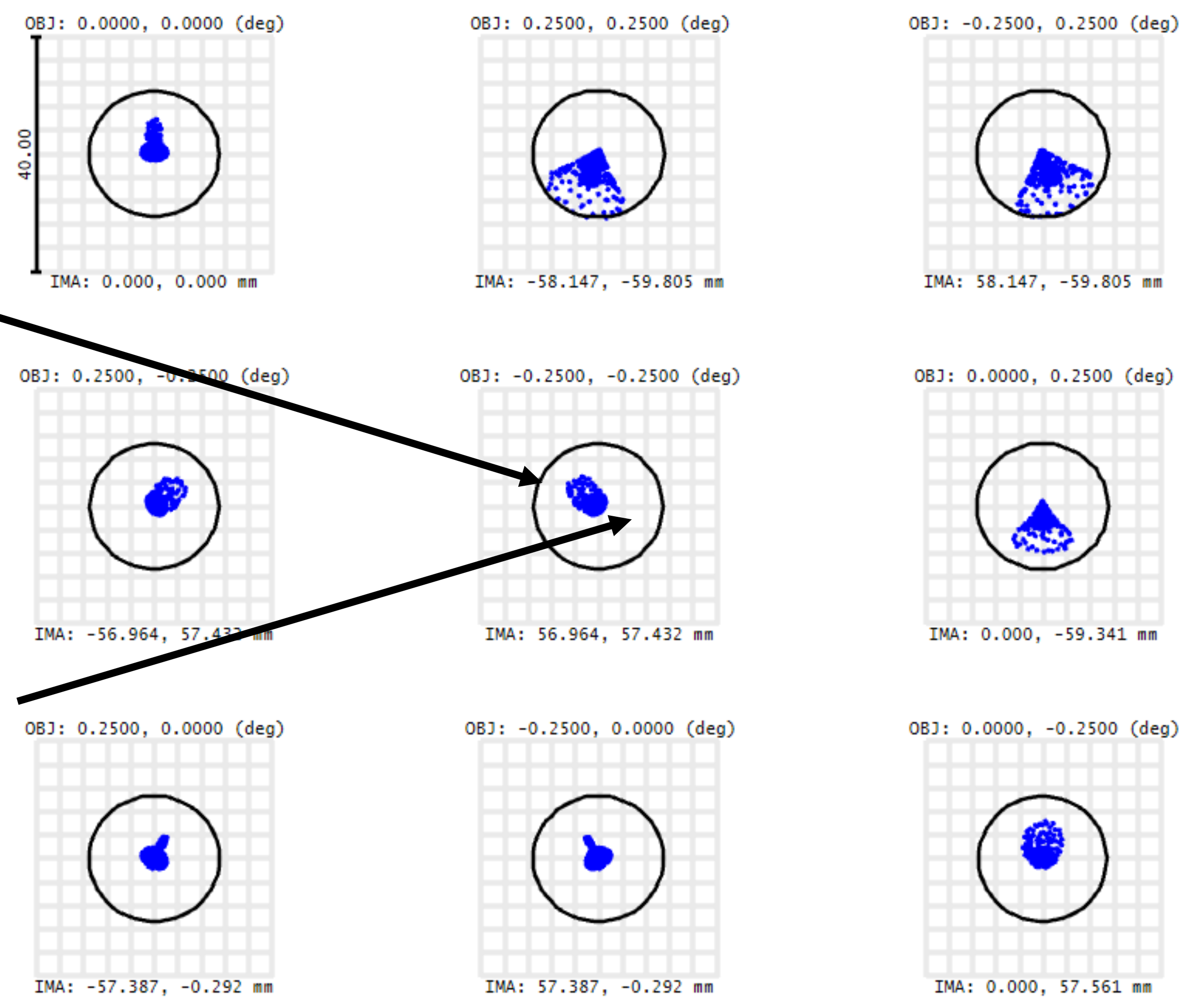
THEIA: SIMPLE OPTICAL SYSTEM

Airy disk

Spot diagram



Surface: IMA

Spot Diagram

19/07/2022
Units are µm. Airy Radius: 10.84 µm. Legend items refer to Wavelengths

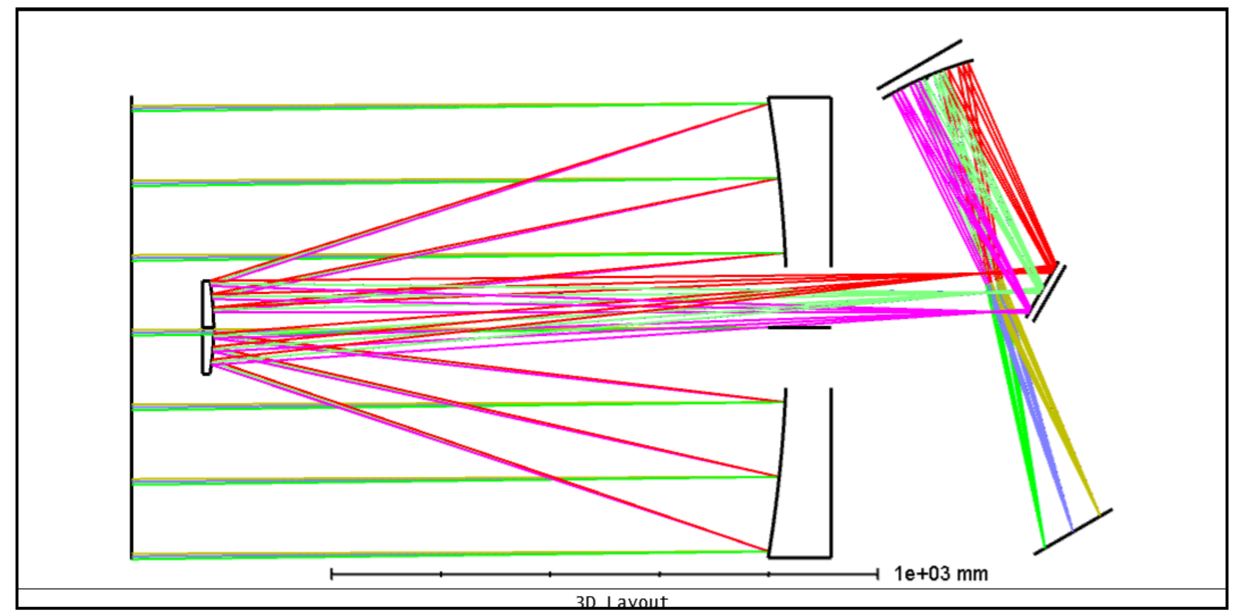
Field	1	2	3	4	5	6	7	8	9
RMS radius	1.880	4.831	4.903	2.074	2.144	3.484	1.608	1.637	2.102
GEO radius	5.820	10.979	10.786	6.156	6.347	8.111	4.187	4.193	6.354

Scale bar : 40 Reference : Chief Ray

Zemax
Zemax OpticStudio 22.2

Theia.zmx
Configuration 1 of 1

Korsch Three Mirror Anastigmat (TMA): no aberrations up to third order



Korsch TMA
0.8m primary mirror
Effective Focal Length (EFL) : *f* = 13 m
FoV : 0.5 x 0.5 deg

- all optics are coaxial
- M1: 800mm CA diameter, 220mm hole diameter, R=-2547mm (same as previous THEIA proposal), C=-0.98615
- M1 to M2: d=1050mm
- M2: 180mm CA diameter, R=530mm, C=-1.7567
- M2 to Fold: d=1477mm
- Fold to M3: d=488mm
- M3: 180x180mm square CA, R=661.7mm, C=-0.6391
- Field of View: 0.5x0.5deg square
- Field of View bias: 0.45deg (in order for the light beam to avoid the plane mirror after reflection on M3).

Labadie et al., to appear in SPIE 2022

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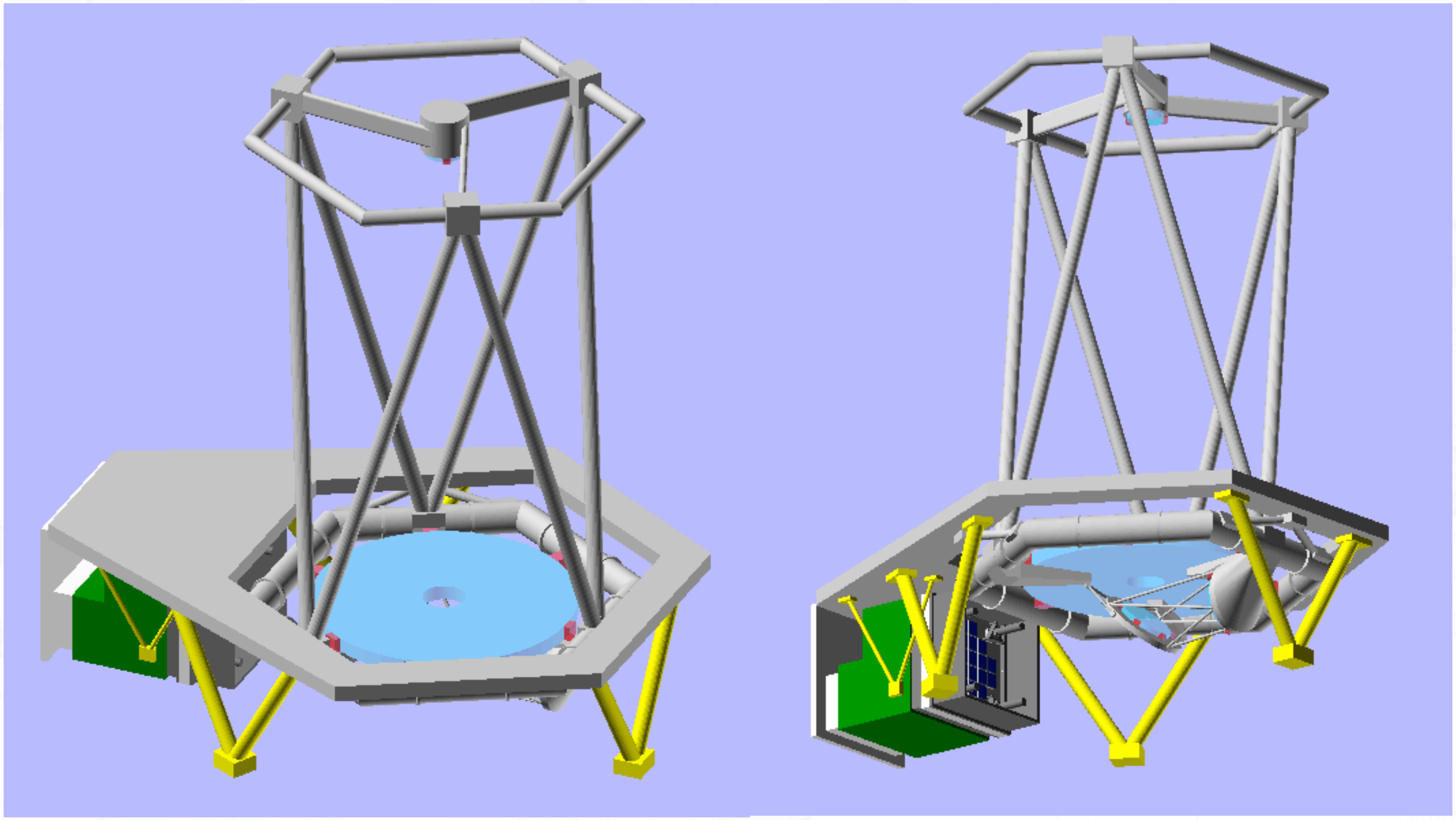
THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT



Korsch on-axis TMA
0.8m primary mirror
EFL 32m

Optics: Zerodur, ULE or Sitall
Structures: SiC or Si3N4
Rigid Hexapod configuration

Lifetime : 4yr (built considering 8 yrs)

arXiv:1707.01348

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THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

- INSTRUMENT STABILITY
  - SIMPLE OPTICAL SYSTEM, LOW CTE AND WELL UNDERSTOOD MATERIALS, ALMOST NO MOVING PARTS
  - METROLOGICAL SYSTEMS (FOR SUB-UAS)
    - TELESCOPE STRUCTURE METROLOGY
    - FOCAL PLANE METROLOGY

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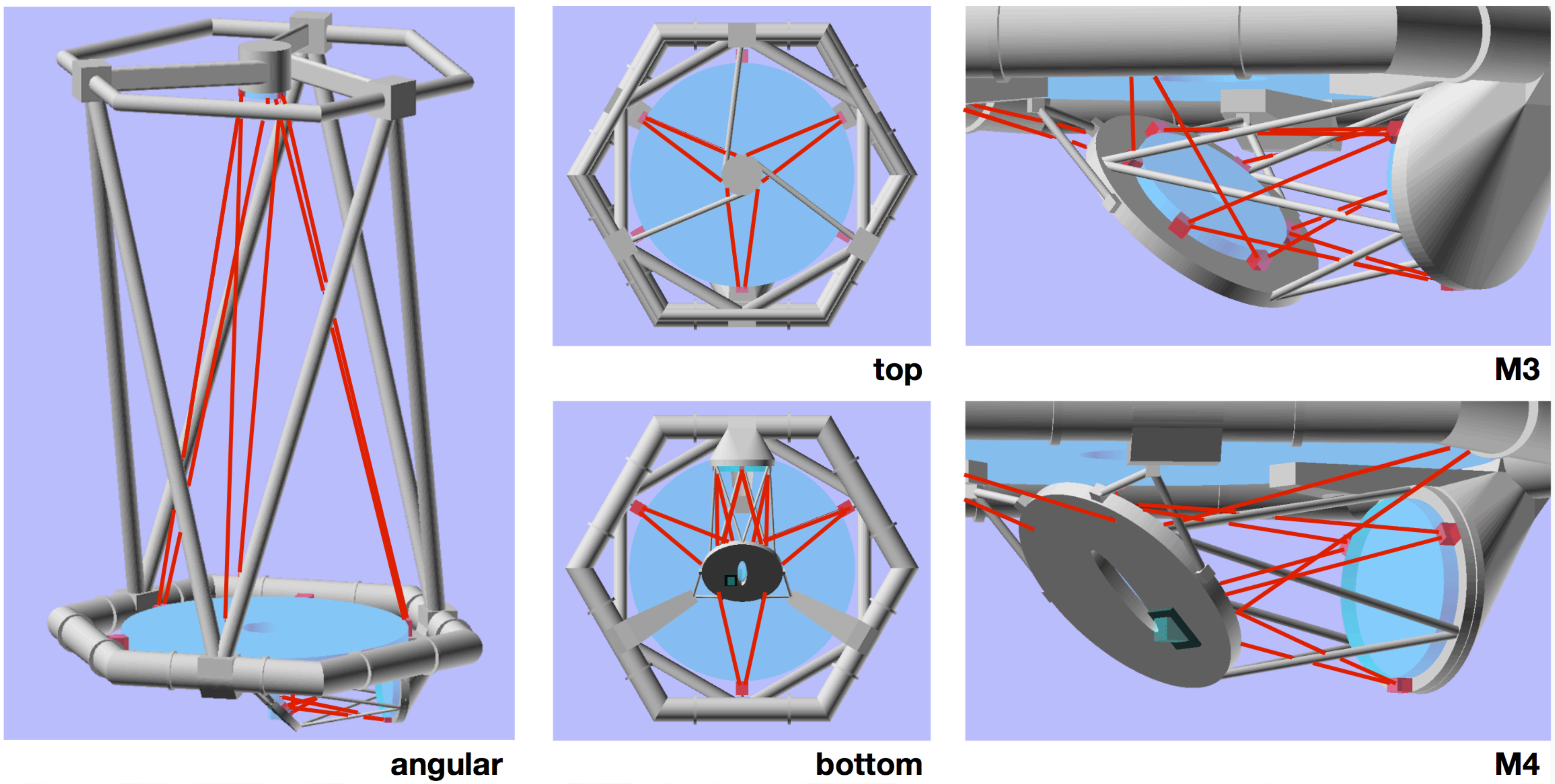
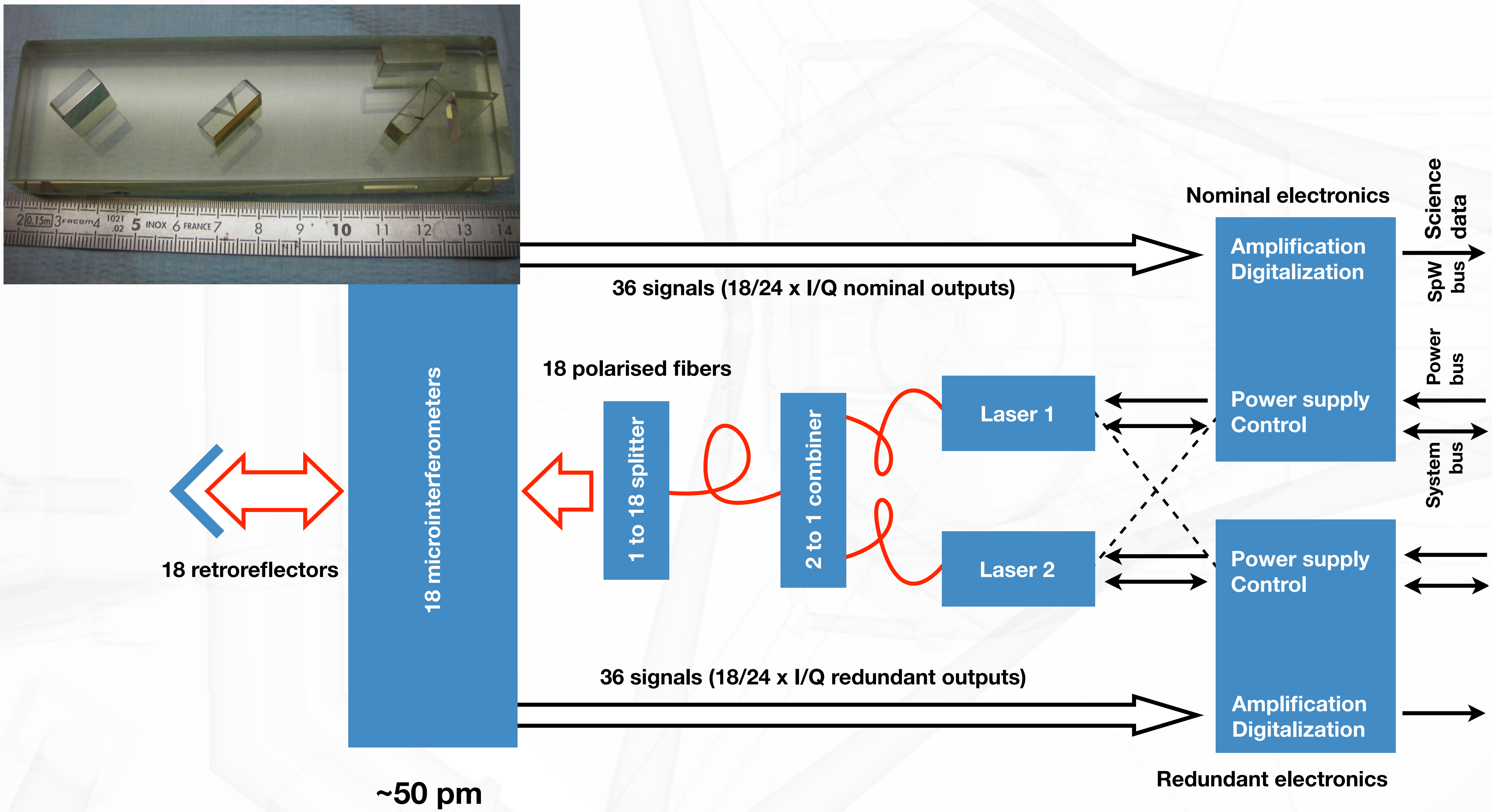
THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT



Independent linear interferometers : continously monitoring instrument changes during the lifetime of the mission for corrections on ground.

arXiv:1707.01348

THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT



Independent linear interferometers : monitoring for corrections on ground.

arXiv:1707.01348

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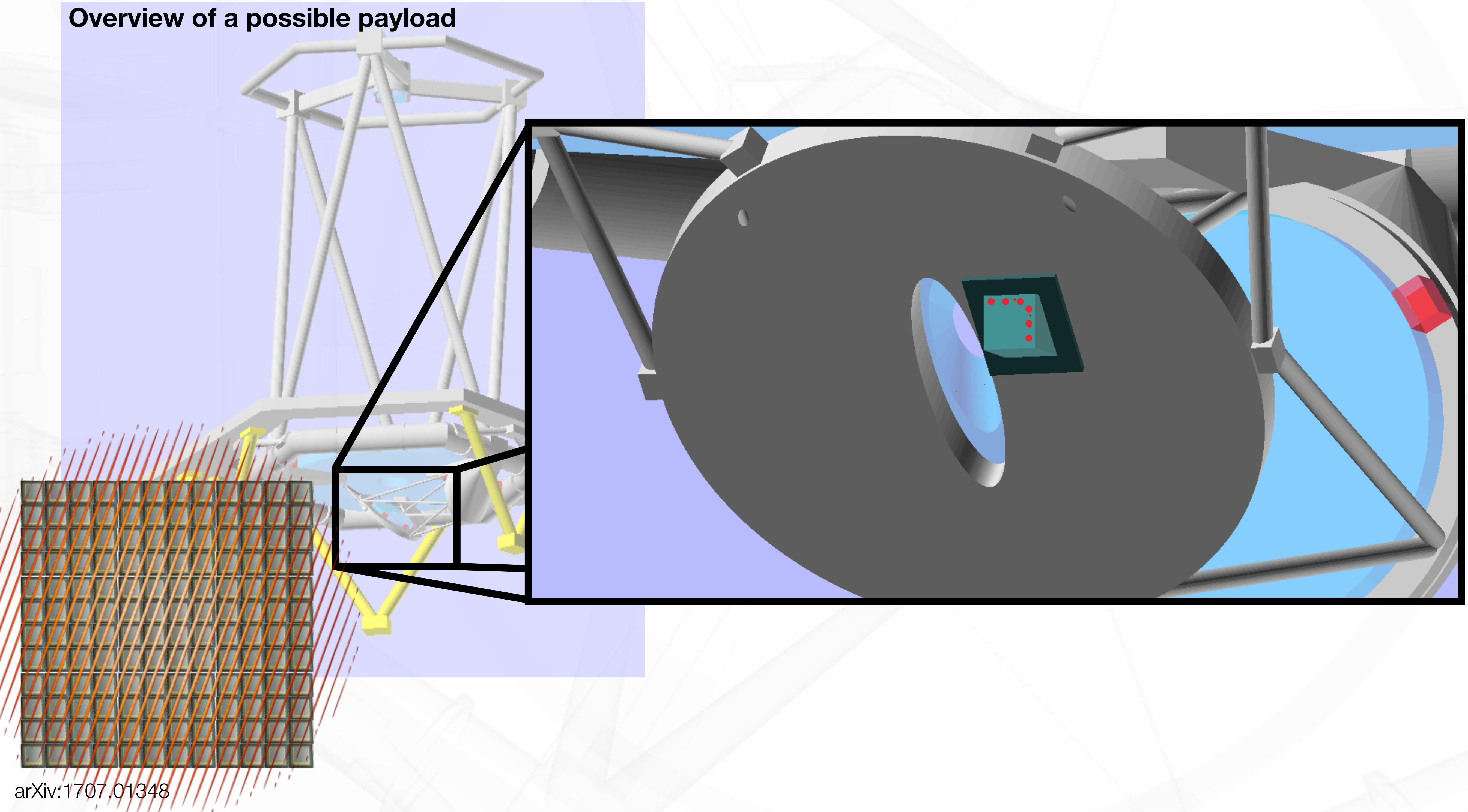
THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

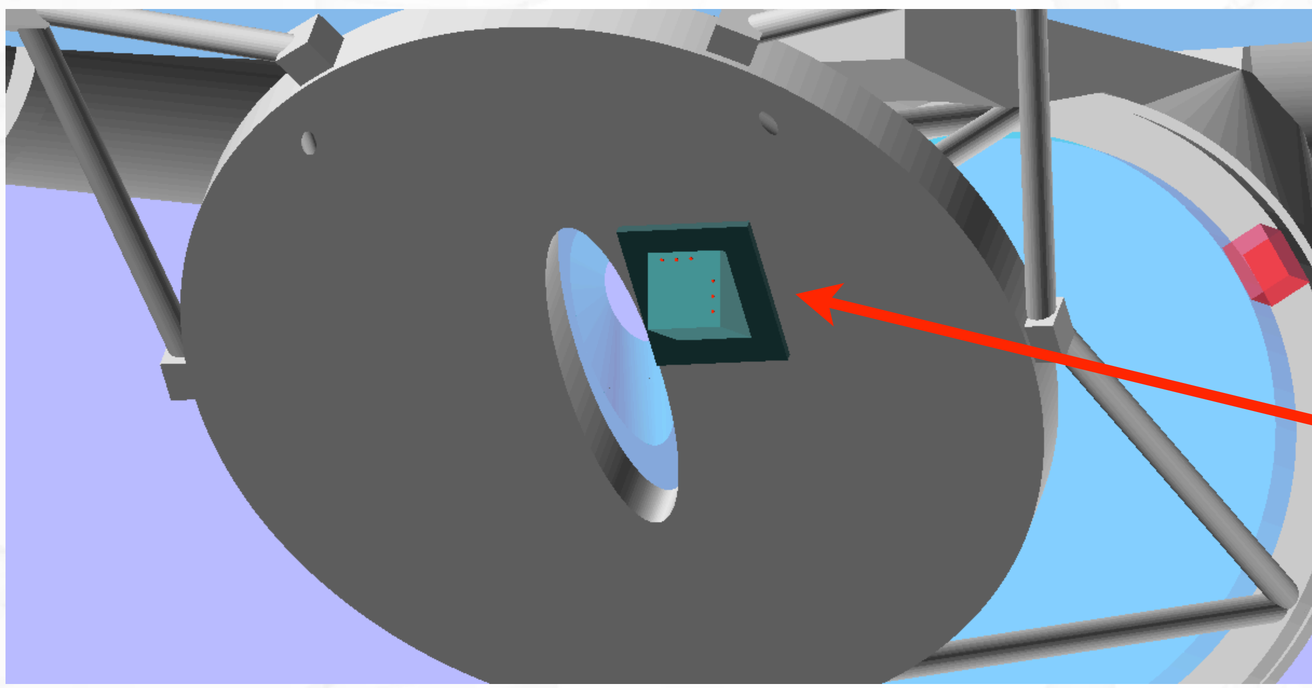
Overview of a possible payload

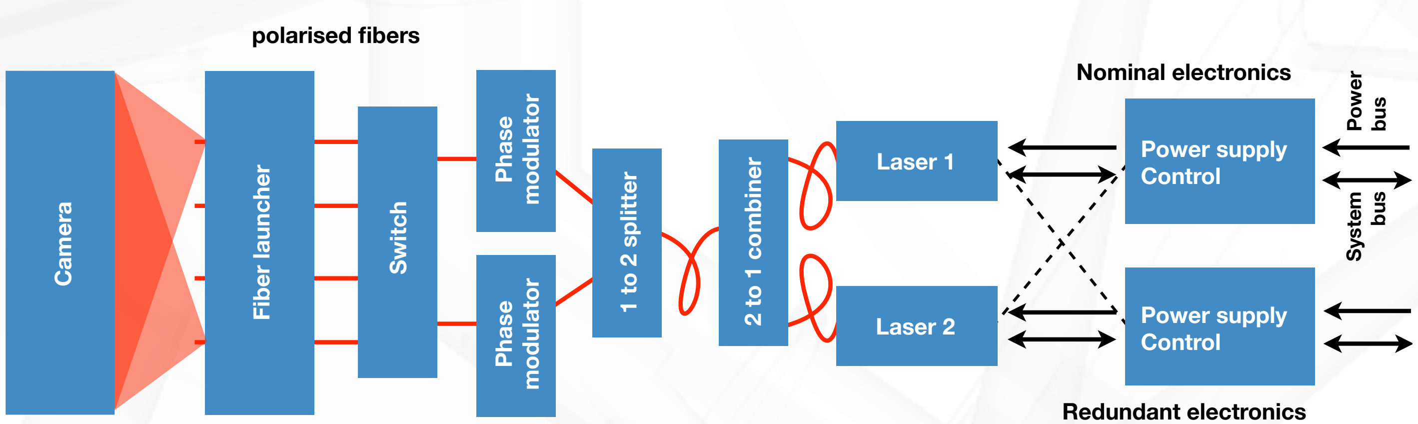


arXiv:1707.01348

THEIA: INSTRUMENT STABILITY AND MONITORING CONCEPT

Interferometric FPA callibration
Prototype @ IPAG
reaches ~5x10^{-5} pixel size





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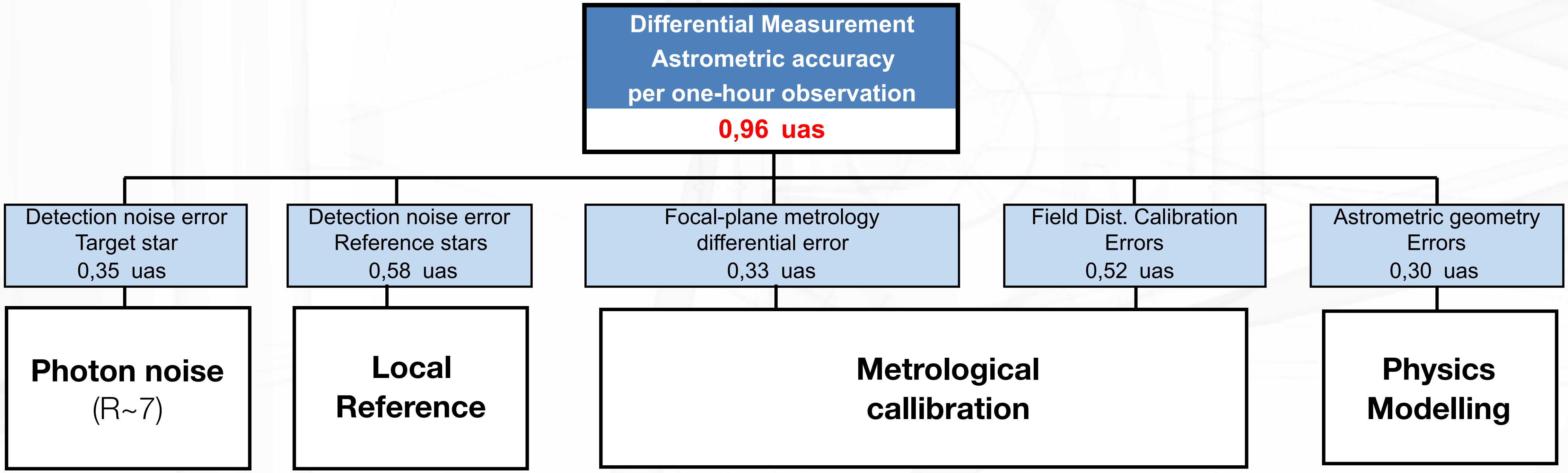

arXiv:1707.01348

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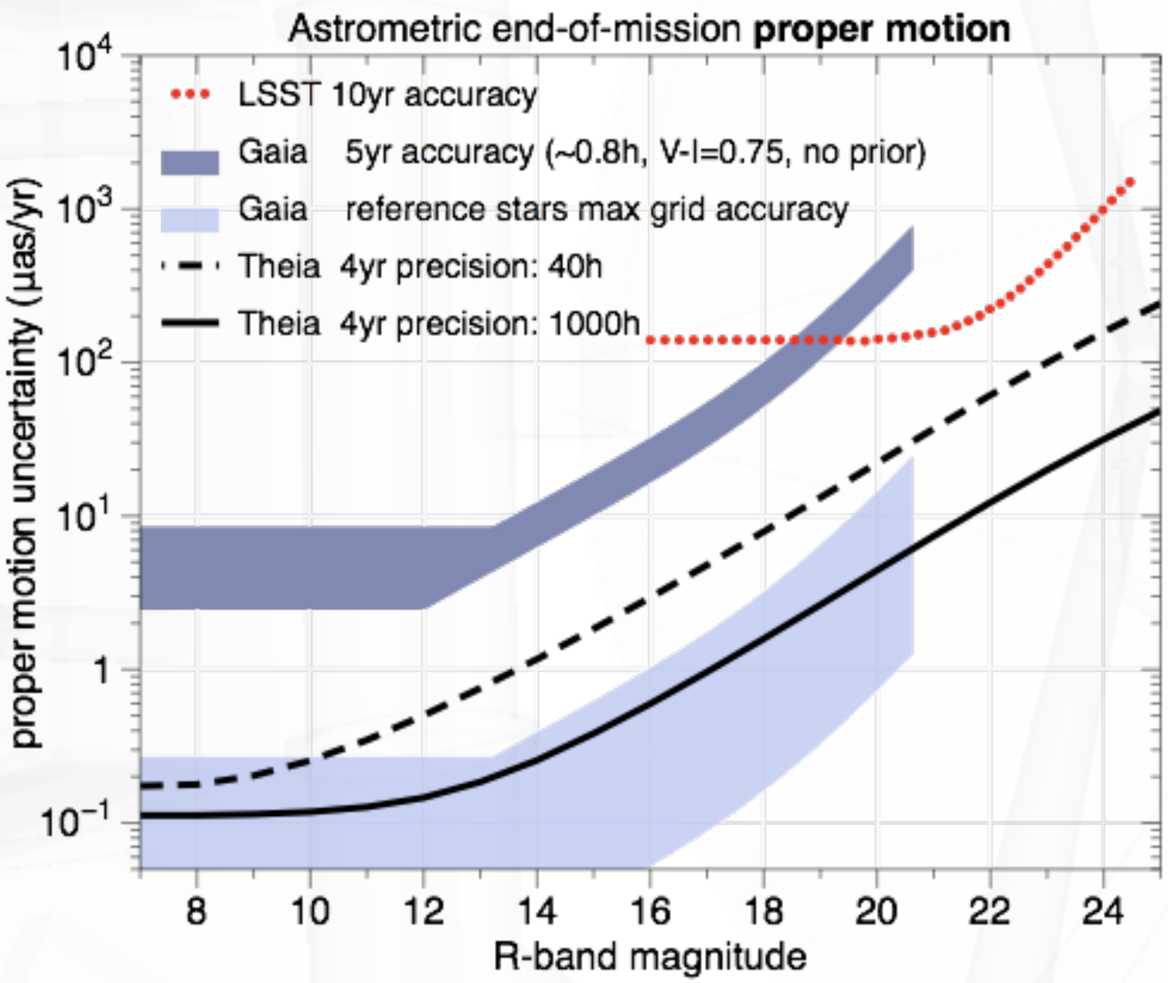

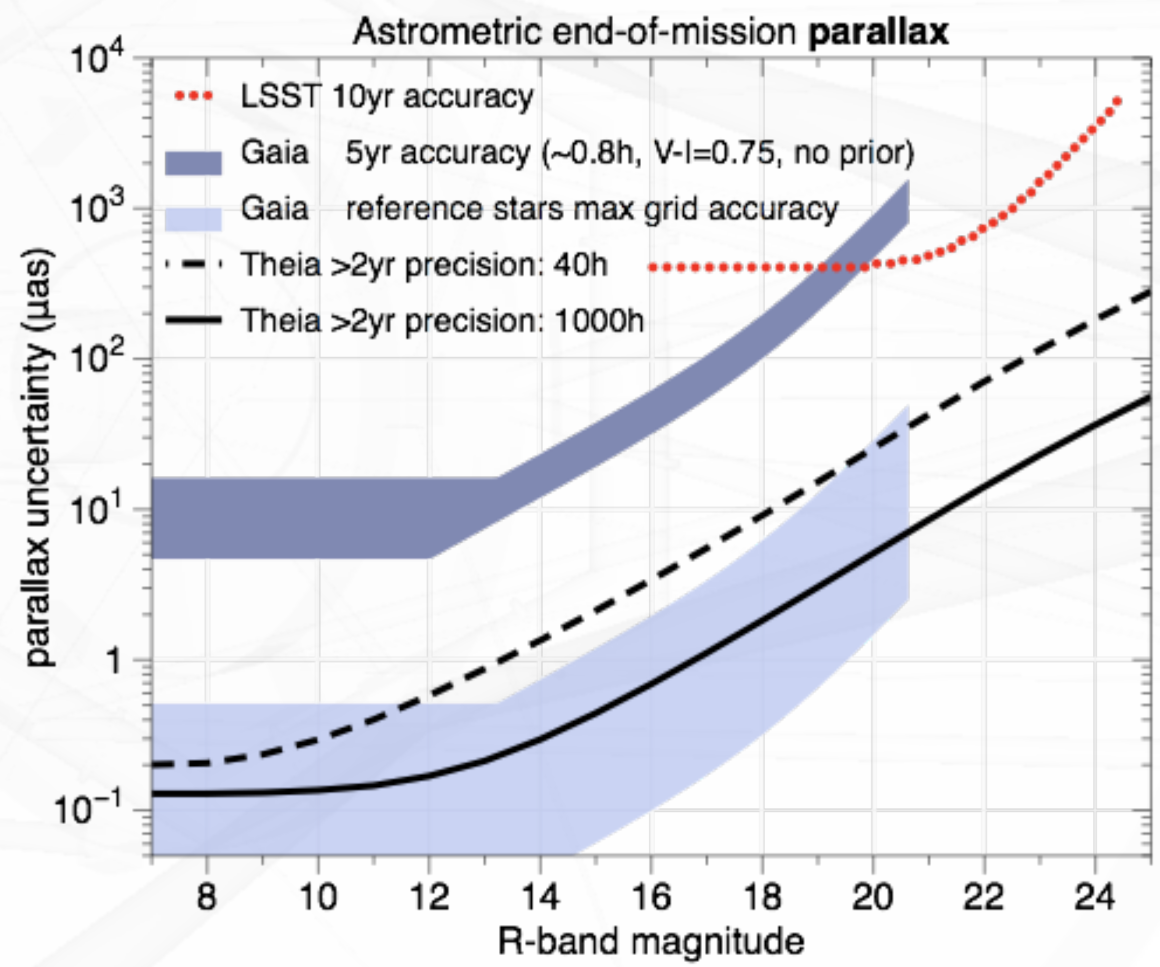

arXiv:1707.01348

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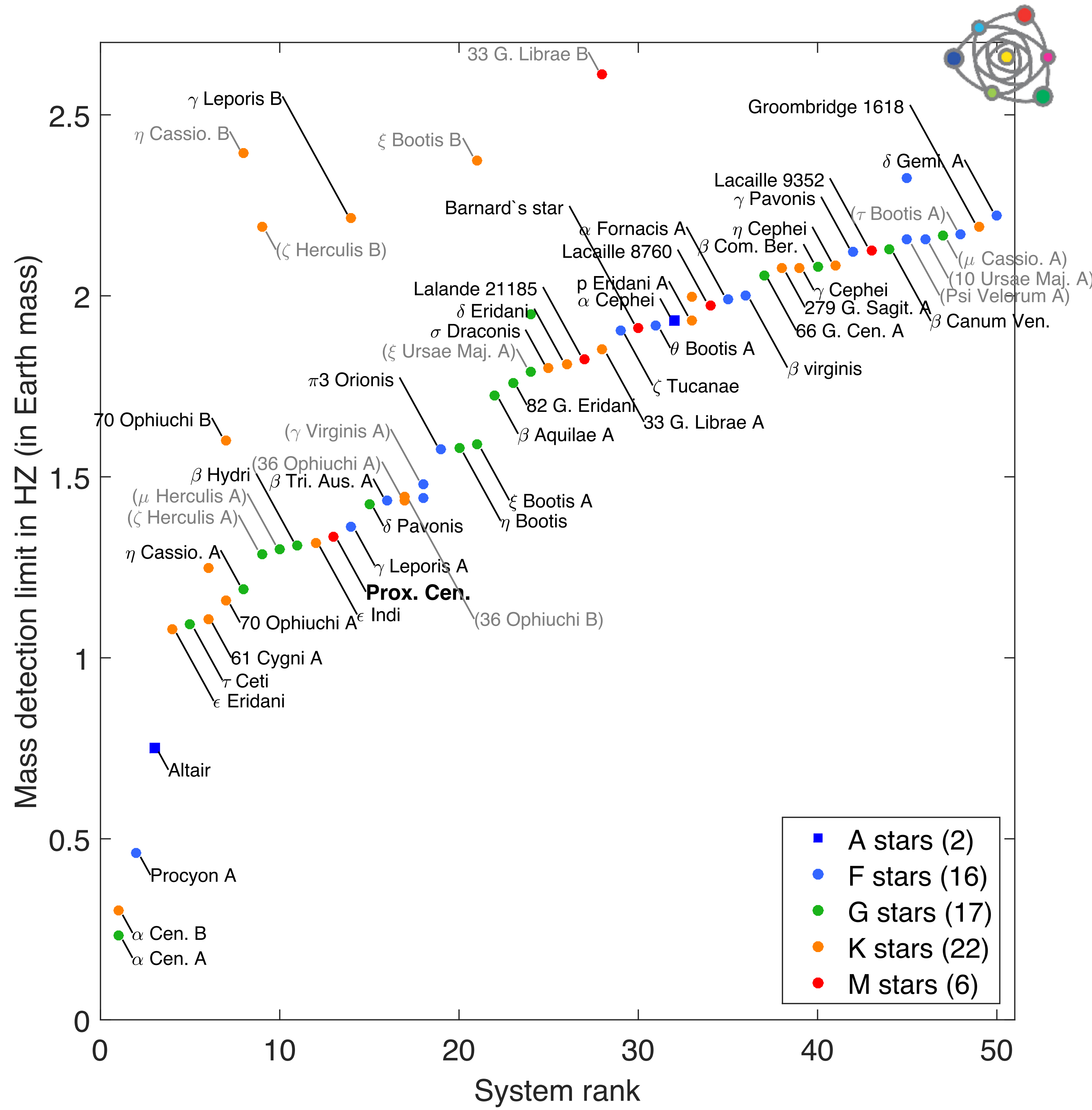
THEIA EXOPLANET CASE

- Nearby telluric planets in the HZ of AFGKM stars



arXiv:1707.01348

Differential astrometry: relative measurements

Differential astrometry: relative measurements

Measurement precision depends on:
instrument stability and/or monitoring and callibration

Differential astrometry: relative measurements

**Measurement precision depends on:
instrument stability and/or monitoring and callibration**

Relative to absolute transformation depends on some external Reference Frame that degrades with age

Sagan Summer Workshop

Differential astrometry: relative measurements

Measurement precision depends on:
instrument stability and/or monitoring and callibration

Relative to absolute transformation depends on some external Reference Frame that degrades with age

Exciting concepts are being proposed for dedicated micro-arcsecond relative astrometry missions to study faint objects and telluric planets in Habitable Zones of nearby stars


Sagan Summer Workshop
NExScI
THANK YOU!

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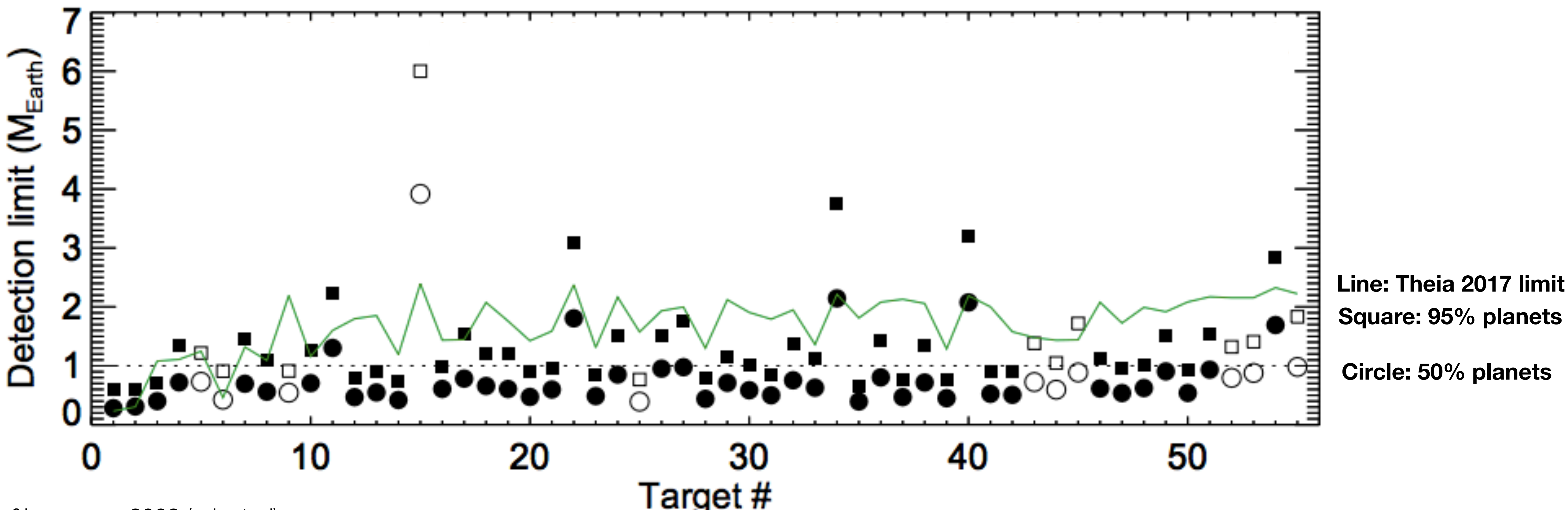
THEIA EXOPLANET CASE



Meunier&Lagrange, 2022 (adapted)

Results of a recent blind test on Theia targets, including the expected stellar activity in the simulation but not accounting for them in the modelling

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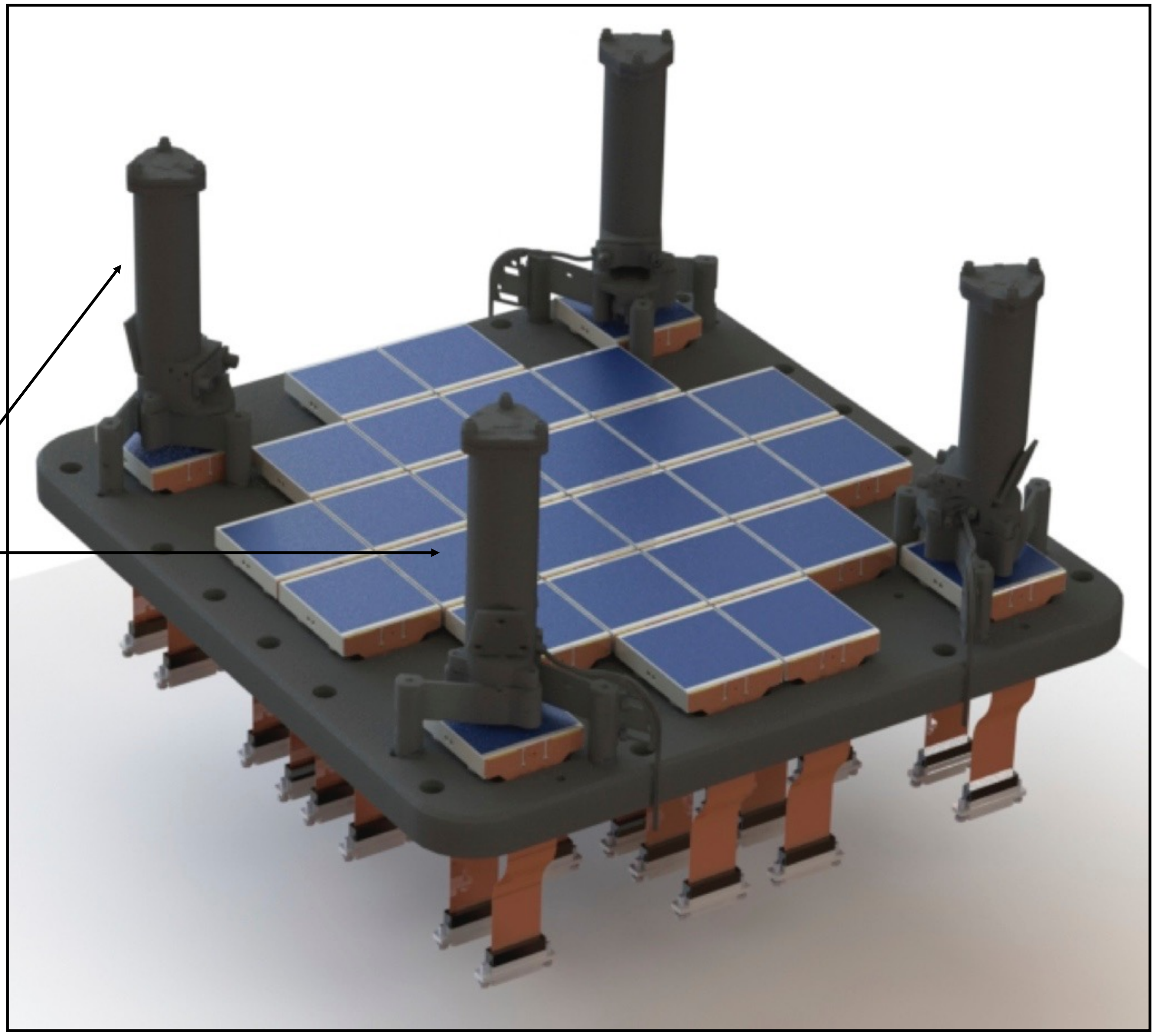
M5 Focal plane array

Specifications:

Diffraction-limited 0.5° FOV
~ 30,000 x 30,000 pixels
≤ 1 billion pixels

Wavefront sensors



Detectors:
-FPA: 24 e2V 4k^2 CCD
-WFS: 4 e2V 4k^2 CCD

6x6 Elliptical FoV Science Array of 4k vs. 4k Detectors

New large detectors with small pixels !

EL*ectronics* EX*press*

Zoom arrière

LETTER IEICE Electronics Express, Vol.13, No.15, 1–11

Systematic experimental study on stitching techniques of CMOS image sensors

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[2] *Shanghai Huali Microelectronics Corporation, Shanghai 201203, China*
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a) *qwangever@126.com*

Abstract: On the basis of the systematic study of stitching techniques, a large area, 28.3 mm × 38.8 mm, 42 Mega pixels CMOS Imaging Sensor (CIS) had been demonstrated on 12 inch silicon wafer in a 0.055 µm CMOS process. By scanning a reticle across a wafer of silicon, smaller arrays can be stitched together to construct larger area sensors. Meanwhile, in order to verify the feasibility and capability of stitching, a 203 mm × 179 mm, 1.8 Billion pixels CIS was also created without any performance deficiency.

Keywords: CMOS Imaging Sensor (CIS), stitching technique, 12 inch, 0.055 µm CMOS process
Classification: Integrated circuits

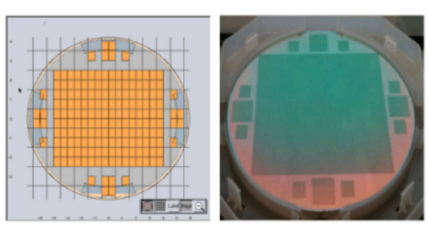
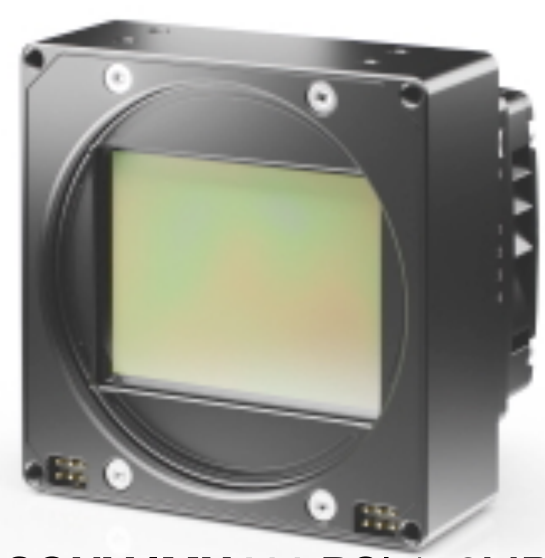


Fig. 14. A huge area, 203 mm × 179 mm, 1.8 Billion pixels CIS (Left: A photograph of the exposure shot map placement and the sensor fabricated on 12 inch; Right: the corresponding wafer image.)

Large detector arrays starting in 2016 thanks to the stitching technology

Pixels of ~4µm
=> array of 12 cm x 12 cm
can be manufactured on a wafer of 12'' (300mm)

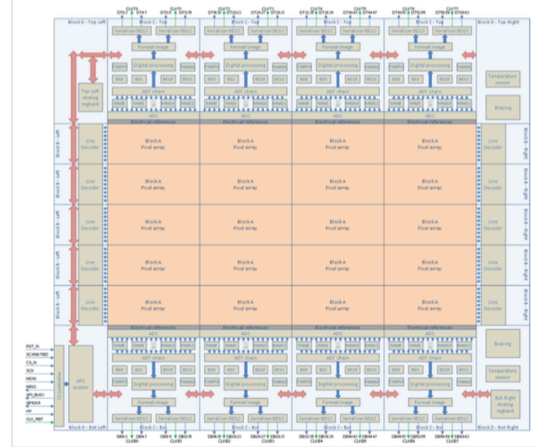


SONY IMX411 BSI 150MP
11648 x 8542
[43.8 x 32.87 mm]

GIGAPYX 4600
46 Megapixel, BSI Rolling Shutter
High Speed HDR CMOS image sensor

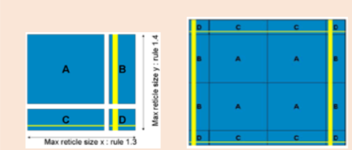
Ultimate video image quality
pyxalis Your Image Sensor Solution

GIGAPYX is a family of large image sensors designed for those applications that demands the best of image quality CMOS sensor has to offer. Manufactured using the most advanced CIS technologies available, it offers low noise, sensitivity, intra-scene dynamic range, resolution and frame rate with no compromises. Ranging from the optical 1.5" format (14 x 18 mm^2) up to 6x6 and 6x7 Medium-formats (73 x 58 mm^2), this family of sensor is compliant with the major large scale optical formats of high quality applications. GIGAPYX 4600 is the first release of this family of sensors: it is a Full-Frame (35 mm) sensor, with 46 Megapixels. The device operates in Rolling-Shutter, up to 150 frames per second with 12 bits per pixel acquisition mode at full resolution, and up to 200 FPS with 8K format (8320 x 4320). The sensor provides up to 92 dB intra-scene dynamic-range thanks to in-pixel true HDR (linear output, single shot acquisition).



Make your own GigaPYX sensor

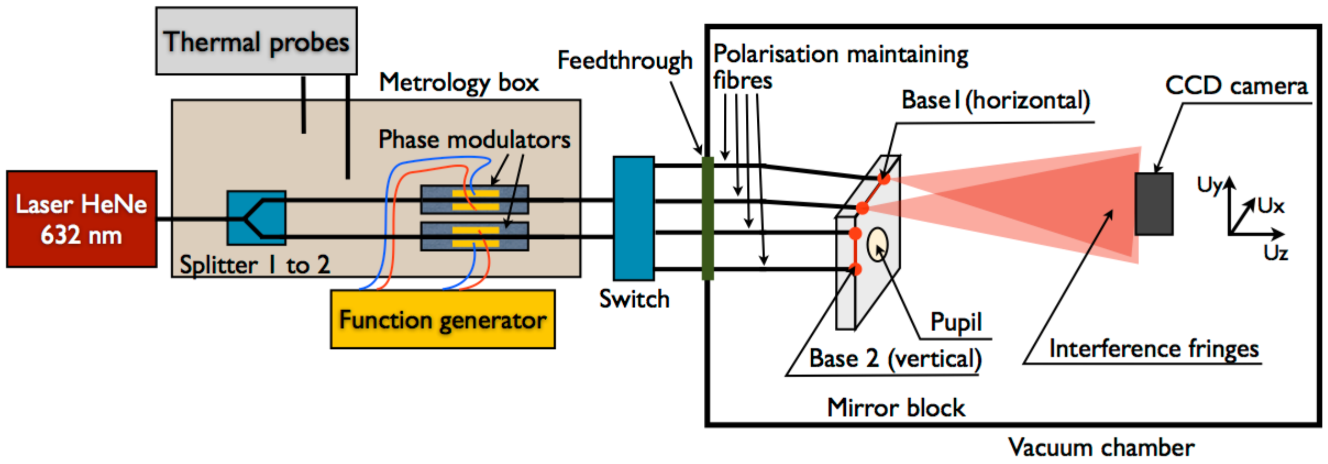
- GigaPYX is manufactured using stitching technology
- By combining multiple blocks of pixels and readout, Pyxalis can manufacture the right dimension you need for your application.
- All GigaPYX family members will share the same electro-optical performances, and the same readout and addressing method
- this allows you to offer a range of cameras with consistent performance and image signature while leveraging electronic design efforts across multiple products.

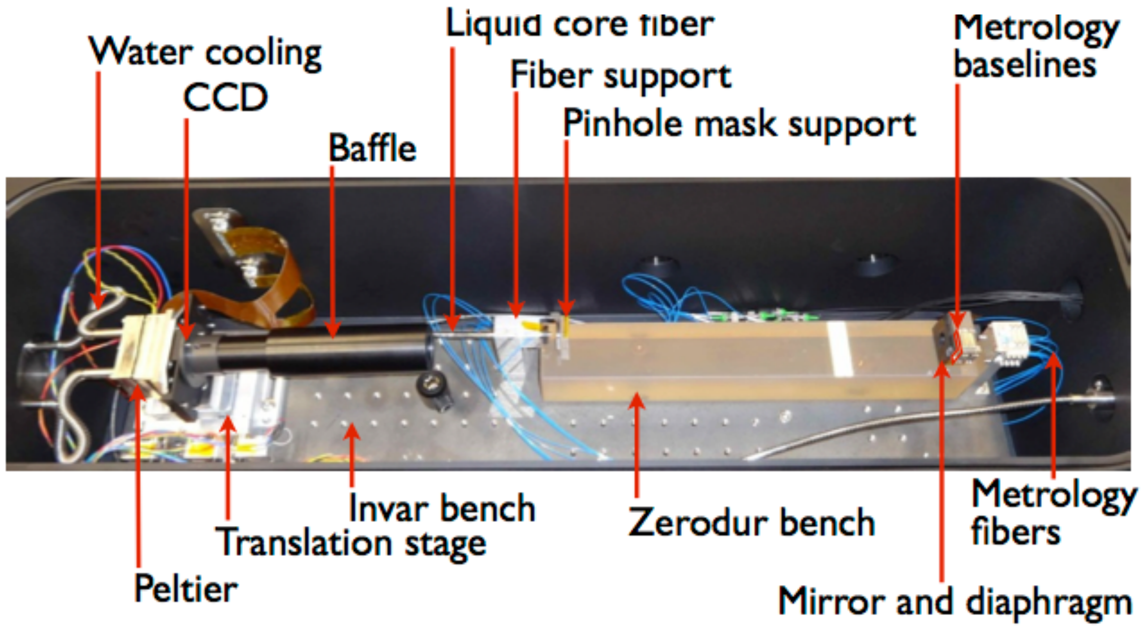


GIGAPYX Family	Format	# of block A Along X axis	# of block A Along Y axis	Matrix sizes in mm Width x Height	Die sizes in mm Width x Height	# of data Lane + clock
GIGA46M	**35 mm Full-frame**	**4**	**5**	**36.6 x 24.2**	**39 x 38.2**	**128 + 16**
GIGA37M		4	4	36.6 x 19.4	39 x 33.4	128 + 16
GIGA110M		6	8	54.9 x 38.7	57.3 x 52.7	192 + 24
GIGA82M	65 mm	6	6	54.9 x 29	57.3 x 43	192 + 24
GIGA80M		5	7	45.8 x 33.9	48.2 x 47.9	160 + 20
GIGA27M	Super 35 mm	3	4	27.5 x 19.4	29.9 x 33.4	96 + 12
GIGA14M		2	3	18.3 x 14.5	20.7 x 28.5	64 + 8
GIGA151M	65 mm square	6	11	54.9 x 53.2	57.3 x 67.2	192 + 24
GIGA220M	Max size	8	12	73.2 x 58.1	75.6 x 72.1	256 + 32

Detector Interferometric Calibration Experiment (DICE)

Crouzier et al. 2016, A&A 595, A108





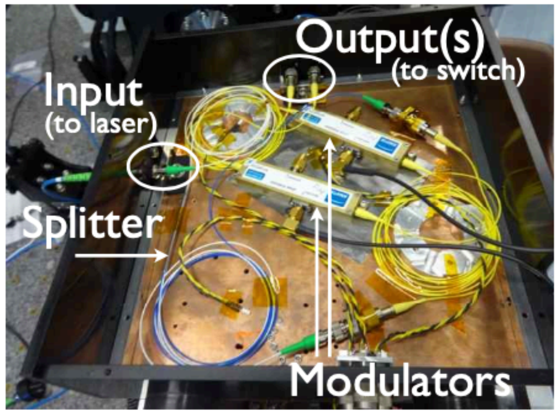
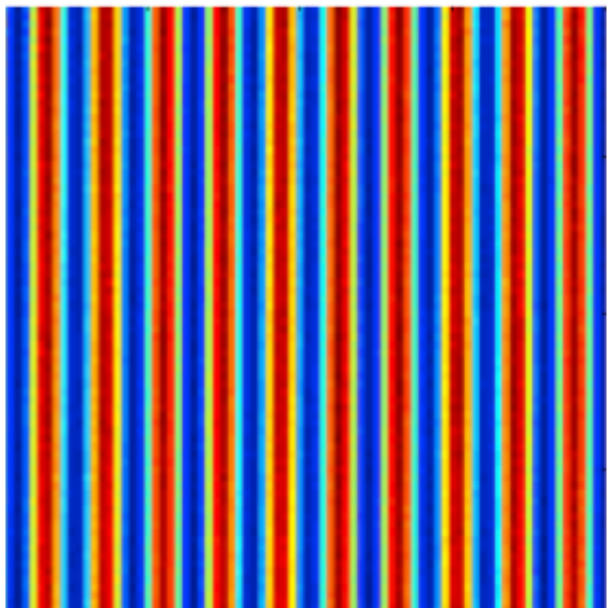
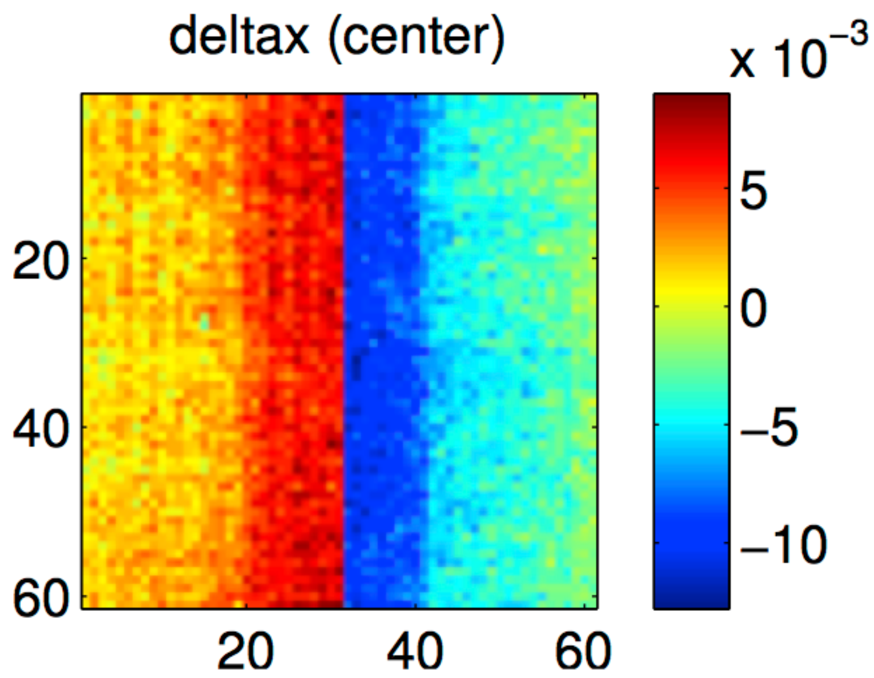
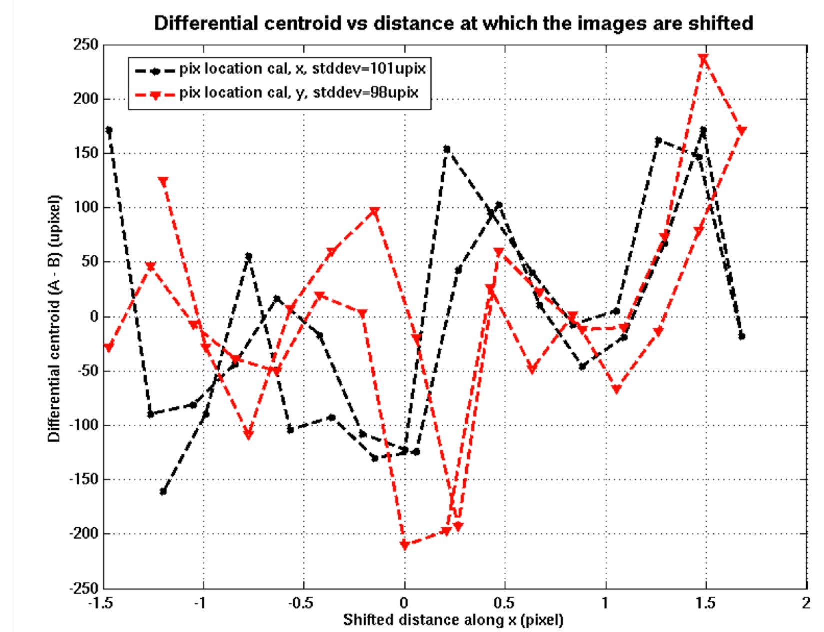


Figure III.7: **Picture of the metrology box.**

Laboratory results







Best results so far:

- JPL/VESTA: 10^{-4} pixels
- IPAG/CNES: 6 10^{-5} pixels (Crouzier et al. 2016)

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

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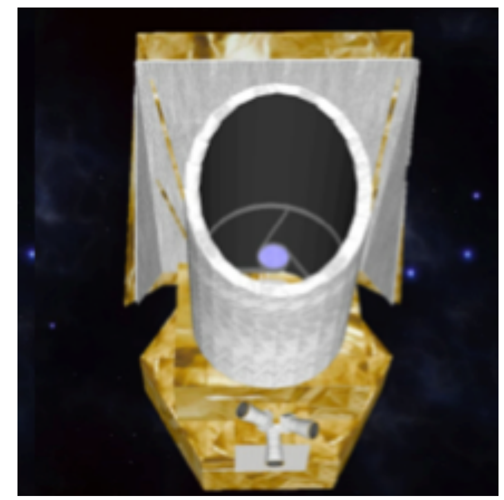
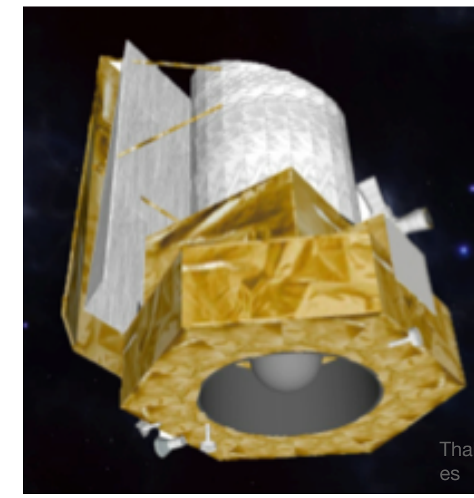
Mission profile

- **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

Launch and Early Operations (~days)	L2 Transfer and commissioning (6 months)	**Nominal Theia Science Operations** (4 years)	Decommissioning (1 month)

Launch date	No constraints, allowing launch date in **2037**
Orbit	Large Lissajous in L2
Lifetime	● 4 years of nominal science operations ● Tecnical operations: 6 months orbit transfer plus instrument commisioning and 1 month decomissioning
Concept	Single spacecraft, single telescope in the PLM, single camera in the focal plane, metrological monitoring of PLM
Communication architecture	75 Mbps, 4h/day





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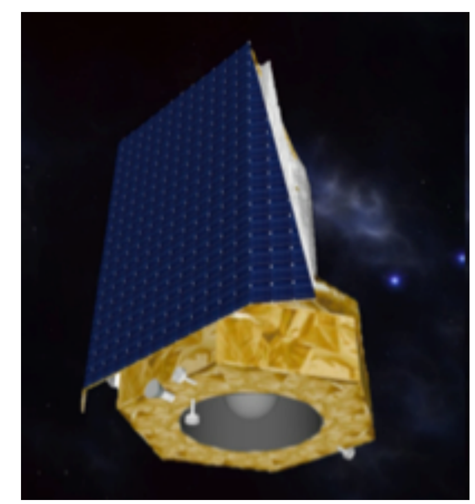

TRL evaluation and foreseen development plans for the Theia payload

Technology Item	Heritage or Comments	Current TRL	Foreseen TRL by end of Phase A (2026)	Development plans for the baseline design
Camera detectors	**Option 1**) several 50-150 Mpixels CMOS (Sony IMX411, Pyxalis GP4600). Current baseline.	4-5	6	**Option 1)** Performance demonstrated for the operational environment. Flight model qualified for nanosat with a smaller format (50Mpixels). Option 1 will require a 2x2 GP4600 mosaic for the FPA or small reduction of science.
	Option 2) A single new gigapixel visible CMOS (30k x 30k). Desired option.	3	5	
Camera electronics	CMOS TDI platform product families for line scanning in Earth observation	6	8	
Camera system	**Options 1)** 2x2 detector array or single detector if FOV reduction is scientifically acceptable.	7	8-9	**Option 2)** Simpler system solution as only one detector is implemented, but further test of the detector chip must be performed
	Option 2) a single sensor and electronics. Implemented in Earth observation	7	8-9	
Camera WFS	Gaia. But modifications to fit Theia optics are necessary.	6-9	6-9	Use of the corner of the gigapixel detector
FPA metrology laser source	Meteosat Third Generation (MTG)	9	9	
FPA metrology optical components	High NA single/multimode fibers required and commercially available on ground. Space qualification is being addressed by fiber manufacturers.	5	6-7	Work on radiation hardening data with companies like Nufern. Data on Gamma and Proton irradiation exist (Alam 2006, SPIE 6308, 630808)
FPA metrology electronics	Laboratory benches.	4		Laboratory work foreseen for FPA calibration
FPA metrology system	Laboratory benches, but not yet for Theia FPA scale.	4		
Telescope metrology laser source	Tesat LISA, MTG.	9	9	
Telescope metrology picometer interferometers	Interferometers performing at the level required by Theia already flying (Gaia-BAM).	5	5-6	Independent active actuators (piezo) coupled to standard nm laser metrology to maintain position. However, TMA design with gigapixel array (Option 1 & 2) will relax the needs for metrology of the telescope structure considering few tens of mK environmental stability. Telescope metrology is also relaxed with alternative design with only one mirror (Formation Flying, deployable boom).
Telescope metrology electronics and optoelectronics components	Based on Actel RTG4 and Gooch & Housego.	5		
Telescope metrology system	Each actuator with its own metrology at TRL >5.	4		
Telescope structure	Ceramics telescopes have been used in Herschel, Gaia, Euclid.	9	9	
Telescope optics	Several flying TMA. Design similar to Euclid. Straylight needs assessment.	5	8	Laboratory tests and optical design analysis
Thermal control system	Euclid, Ariel	6-7	8	Optimize V-groove passive cooling configuration coupled to e.g. active JT coolers
Fine Guidance Sensor	Euclid, Ariel	6-7	8	Similar to existing FGS designs