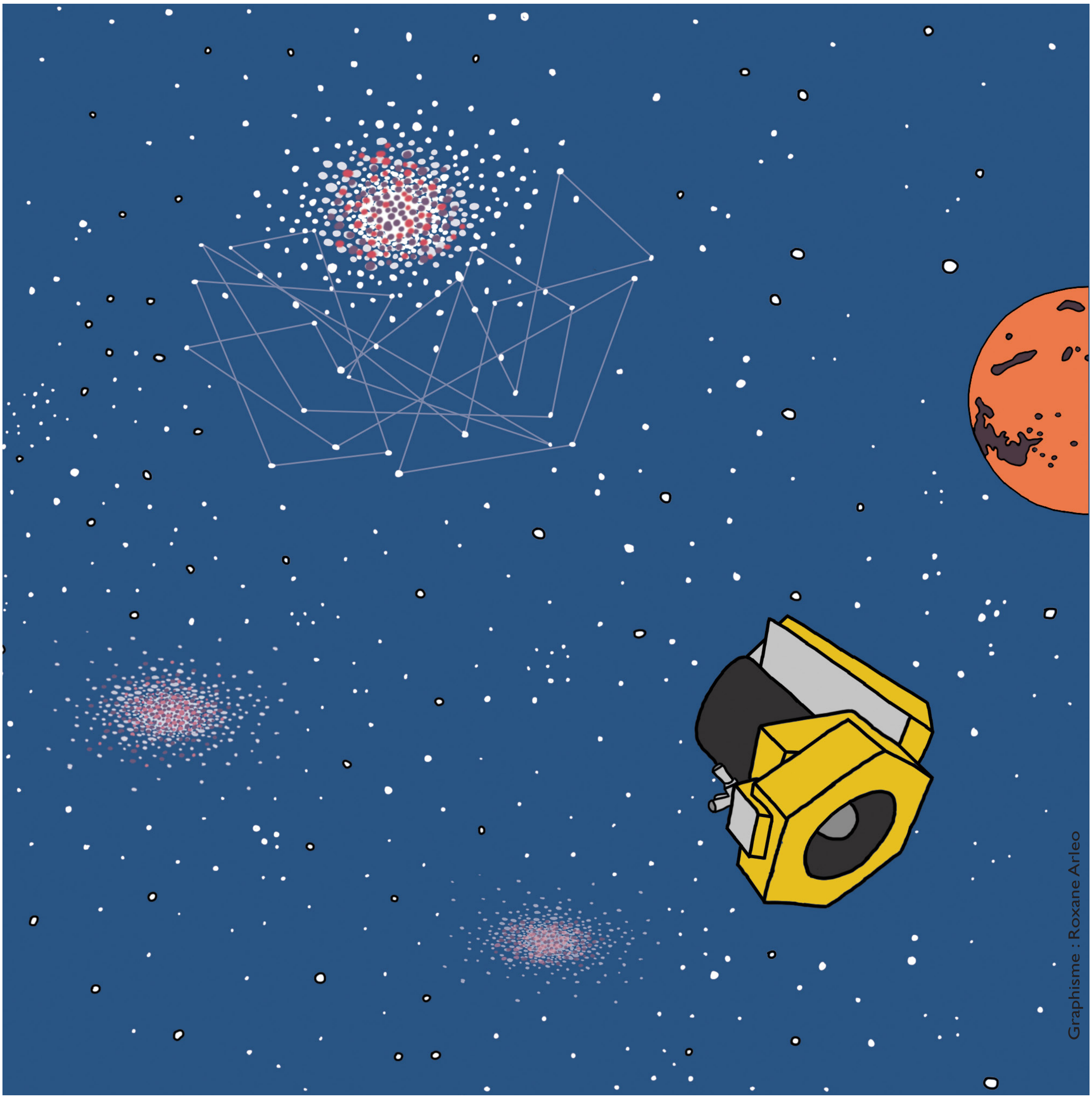
THEIA

Microarcsecond Astrometric Observatory



Faint objects in motion : the new astrometry frontier

Proposal for a medium size mission opportunity in ESA's science programme (M5) mission

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Theia: Faint objects in motion. The new astrometry frontier.

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For a better view of the organization of the proposing team, please read Sect. 7.

1 Executive summary

1.1 *Theia*'s aims

What is the nature of dark matter? Are there habitable exo-Earths nearby? What is the equation of state of matter in extreme environments? These are the fundamental questions the *Theia* astrometric space observatory is designed to answer. Through its ultra-precise micro-arcsecond relative astrometry, *Theia* will address a large number of prime open questions in three themes of ESA's cosmic vision:

• Dark matter (the main focus of the mission)

Theia will dramatically advance cosmology by determining the small-scale properties of the dark matter (DM) component in the local Universe. It is the first space observatory designed to test for signatures of models beyond the Standard Model of particle physics, and it will either confirm or invalidate Cold Dark Matter (CDM) and various theories of primordial inflation. *Theia* will:

- examine whether DM in the inner part of faint dwarf spheroidal galaxies is cuspy or more homogeneously distributed;
- determine whether the outer halo of the Milky Way is prolate;
- detect small DM halos by finding the gravitational perturbations they have left on the Milky Way disc; and
- test inflationary models by detecting ultra-compact mini-halos of DM.

This will help us understand the origin and composition of the Universe (theme 4 of ESA's Cosmic Vision).

• Exoplanets

Theia will provide the first direct measurements of the masses and inclinations of a significant sample of Earth and super-Earth planets orbiting our nearest star neighbours. This census of habitable exoplanets will be crucial for future exobiology missions. Spectroscopic follow-ups to *Theia* will enable the detection of possible signatures of complex life and the chemical pathways to it. This will help us understand the conditions for planet formation and the emergence of life, and how the Solar System works (themes 1-2 of ESA's Cosmic Vision).

• Neutron stars and black holes

Theia will determine the masses of more than 15 neutron stars by measuring binary orbital motion. In conjunction with X-ray measurements from other missions (e.g., Athena), *Theia* will improve neutron star radius measurements for a dozen systems, which will constrain their composition and equation of state. For black hole binaries, *Theia* will also make proper motion measurements to understand their formation, and orbital measurements to determine if their accretion discs are warped. This will help us understand the fundamental physical laws of the Universe (theme 3 of ESA's Cosmic Vision).

1.2 Scientific instruments

The payload is deliberately simple: it includes a single three-mirror anastigmat telescope, with metrology subsystems and a camera. The telescope is an Korsch on-axis three-mirror anastigmat telescope (TMA) with an 80 cm primary mirror. The camera focal plane consists of 24 detectors, leading to a Nyquist sampled field of view $\simeq 0.5°$, and four wavefront sensors. Its metrology subsystems ensure that *Theia* can achieve the sub-microarcsecond astrometric precision that is required to detect habitable exoplanets near us.

1.3 Significant additional benefits

Theia's main purpose is to observe the targets set by our science cases, but it will use its repointing and stabilization phases to perform photometric observations to infer the age of the Universe to a unique precision. In addition, *Theia* will benefit the community by reserving 15% of the observing time for open call proposals, and allowing the public to "crowd-select" four astronomic objects to be scrutinised. *Theia*'s measurements will significantly improve the knowledge we gain from other key ground and space research programs. *Theia*'s ultra-precise astrometry will serve as a new reference standard, and benefit the broader astronomical community, as the natural astrometric successor to ESA/*Hipparcos* and *Gaia*. It will open promising new avenues for scientific breakthroughs in astronomy, astrophysics and cosmology.

Science case	Dark Matter (∼ 70% observational time); Exoplanets (including binaries), Neutron stars and Binary Black Holes.
Science objectives	• To discover the nature of dark matter; • To find nearby habitable Earths; • To probe Nature's densest environments.
Overview	• Spacecraft at L2 for 4.5 years; • Optical telescope (350nm-1000nm); • Micro-arcsecond astrometry, sub-percent photometry; • Point and stare strategy, to enable relative (differential) astrometry; • Built on *Gaia*'s "absolute" reference frame.
What makes *Theia* unique?	• Ultra-high-precision astrometry, only reachable from space: from 10 μas (dark matter) down to 0.15 μas (exoplanets); • Dedicated payload design to achieve the required astrometric precision; • Unprecedented sensitivity to DM targets, enabling particle physics tests; • True masses and orbital architecture of habitable-zone terrestrial planets, and complete orbital characterization of planetary systems; • Measurements of orbits and distances to probe the interiors of neutron stars and the structure of black hole accretion discs.
Main observational targets	• dwarf spheroidals & ultra-faint dwarf galaxies, hyper-velocity stars; • nearby A, F, G, K, M stellar systems; • neutron stars in X-ray binaries; • Milky Way disc + open observatory targets.
Payload	• Korsch on-axis TMA telescope with controlled optical aberrations; • Primary mirror: $D = 0.8$ m diameter; • Long focal length, $f = 32$ m; • FoV ∼0.5 deg, with 4 to 6 reference stars with magnitude $R \leq 10.8$ mag; • Focal plane with 24 CCD detectors (∼402 Mpixels, 350nm-1000nm); • Nyquist sampling of the point-spread-function; • Metrology calibration of the focal plane array: relative positions of pixels at the micropixel level using Young's interferometric fringes; • Interferometric monitoring of the telescope: picometer level determination; of the telescope geometry using laser interferometric hexapods.
Spacecraft	• Spacecraft dry mass with margin: 1063 kg. Total launch Mass: 1325 kg; • Attitude Control System: synergistic system with hydrazine, reaction wheels and cold-gas thrusters. RPE: 20 mas rms in a few minutes (1σ); • Thermal Control System: active thermal control of telescope; dedicated radiator for the payload; • Telecommand, Telemetry and Communication: Ka-band, ∼95 GBytes of science data per day. High Gain Antenna and 35m stations.
Launcher and operations	• Ariane 6.02. Lissajous orbit at L2. Launch in 2029; • Nominal mission: 4 yrs + 6 months transit, outgassing & commissioning; • MOC at ESOC, SOC at ESAC.
Data policy	• Instrument Science Data Centers at consortium member states; • Short proprietary period and 2 data releases.
Consortium	• > 180 participants from 22 countries; UK, France, Germany, Italy, Spain, Switzerland, Poland, Portugal, Sweden, The Netherlands, Hungary, Greece, Denmark, Austria, Finland, USA, Brazil, China, Canada, India, Israel, Japan.
Estimated cost	• 536 M€ for the spacecraft and telescope, including launcher (70), ground segment (85), project (53) and payload contribution (56). • 51.3 M€ for the payload (consortium member states only)

Annexes

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