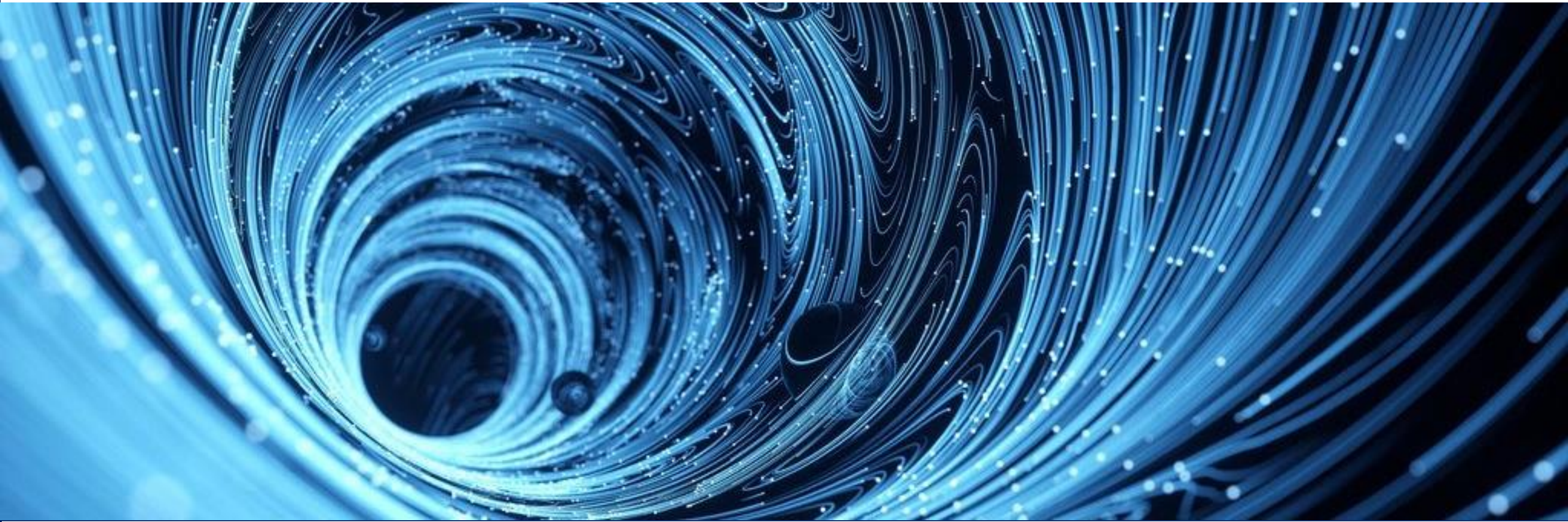




TETRA-GGT: A Tetrahedral Heliocentric Field-Equations Observatory

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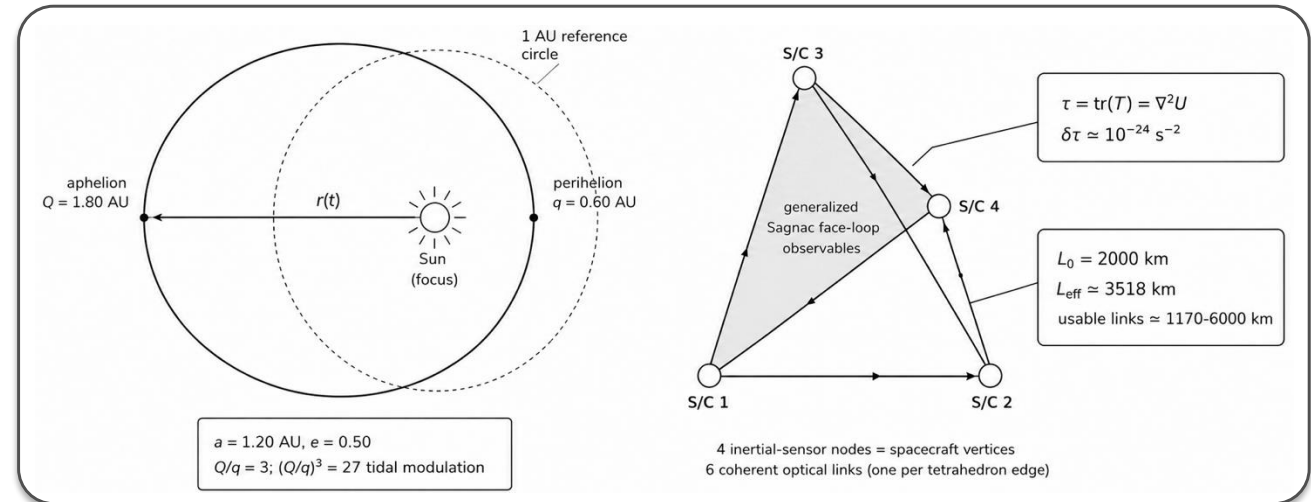
TETRA-GGT

A four-spacecraft heliocentric gravitational observatory for ASTRA

Precision gravity | Dark-sector time-domain physics | Bridge-band gravitational waves

Selection thesis:

- One decisive primary test: vacuum field-equation residual $\tau = \text{tr}(GGT) = \Delta U$.
- Two secondary objectives: dark-sector signatures and 0.1-5 Hz gravitational waves.
- Non-traditional distributed architecture with a clear ASTRA maturation path.



- S. G. Turyshev, S.-w. Chiow, and N. Yu, "Searching for new physics in the solar system with tetrahedral spacecraft formations", Phys. Rev. D 109(8), 084059 (2024), arXiv:2404.02096 [gr-qc]
- S. G. Turyshev, "Solar System Experiments in the Search for Dark Energy and Dark Matter", Phys. Rev. D 112, 123003 (2025), arXiv:2509.05910 [astro-ph.CO]
- S. G. Turyshev, "Dark Energy After DESI DR2: Observational Status, Reconstructions, and Physical Models", Phys. Rev. D (accepted, May 4, 2026), arXiv:2602.05368 [astro-ph.CO]

For ASTRA, we propose: to study TETRA-GGT as a portfolio-diversifying distributed observatory with a strong primary science case and several credible secondary objectives.

Primary Observable: Access to Additional Long-range Fields

1 Observable and null test

$$\tau(r, t) = tr(T) = \nabla^2 U_{\text{eff}}$$

GR / Newtonian vacuum: $\tau \rightarrow 0$

Additional long-range field or effective source: $\tau(r, t) \neq 0$

Mission-level trace sensitivity:
 $\delta\tau \approx 10^{-24} \text{ s}^{-2}$

Measurement basis



6 optical links: $r_{ij}(t), \dot{r}_{ij}(t)$



3 Sagnac observables: $S_{ijk}(t) \rightarrow \Omega(t)$



4 inertial-sensor streams: $a_{ng}(t)$



Null channels: geometry-aware closure and common-mode rejection

2 Primary science objectives

Mission-scale trace sensitivity: $\delta\tau \sim 10^{-24} \text{ s}^{-2}$ ($\sim 10^{-10}$ of the solar tidal scale near 1 AU)

A

Yukawa-like fifth forces

$$\tau_Y(r) = \alpha_Y GM_{\odot} \frac{e^{-r/\lambda}}{r\lambda^2}$$

Best quantified reach:

$|\alpha_Y| \sim 10^{-11}$ for AU-scale λ (roughly $\lambda \sim 0.3\text{--}3 \text{ AU}$)

Direct AU-scale test of weak long-range couplings

B

Galileon / Vainshtein screened scalars

Non-harmonic residual radial law in the screened Solar-System regime

Primary dark-energy-motivated target class
Tests local residuals from screening that standard orbital fits can miss

C

Chameleon / symmetron / screened $f(R)$

Partially unscreened local residuals, environment dependence, or screening-consistency limits

Sensitivity to partial unscreening at the $\sim 10^{-10}$ solar-tidal level; secondary screening-consistency science

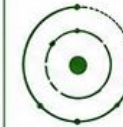
D

Pure cosmological constant

$$\tau_{\Lambda} \approx -5.6 \times 10^{-36} \text{ s}^{-2}$$

Not directly accessible; TETRA instead tests dark-energy alternatives that leave AU-scale residual fields

3 Secondary science objectives



1) Radial-dependence tests

- Sample $r = 0.60 \rightarrow 1.80 \text{ AU}$
- Solar tidal leverage: $(Q/q)^3 = 27$
- Discriminates Yukawa templates from screened residual laws



2) Dark-sector fields

- Coherent narrow-band modulation in $\tau(t)$, link phases, or inertial residuals
- Ultralight scalar/vector backgrounds
- Transient defects and common-mode signals



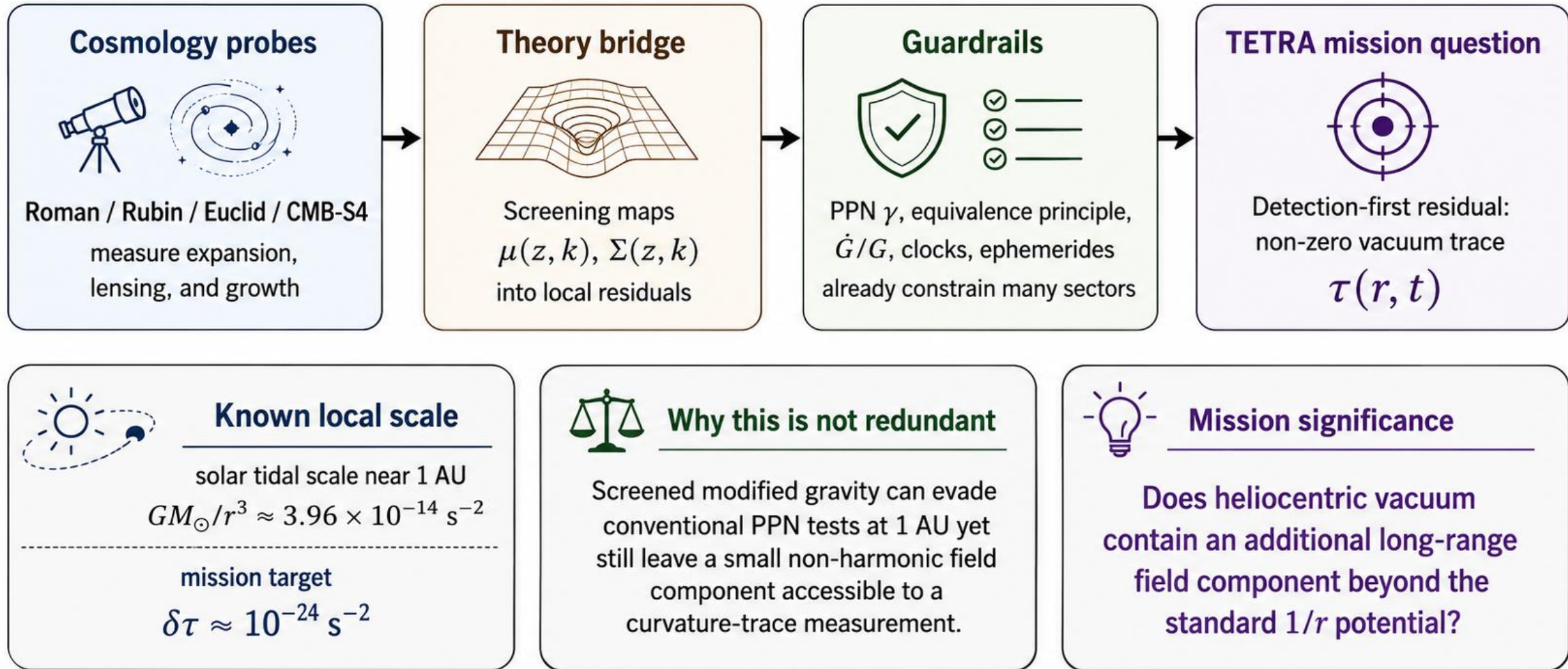
3) Time-domain observables

- Cross-node coherence and geometry-aware vetoes
- Transient / defect-crossing timing structure
- Bridge-band phase archive: $0.1\text{--}5 \text{ Hz}$ secondary GW-sensitive product



Selection logic: the gravity-gradient trace is a direct field-equation measurement. A nonzero vacuum trace maps to an additional long-range field or screened effective source; radial dependence and null channels then separate fifth-force, screened-gravity, dark-sector, and time-domain interpretations.

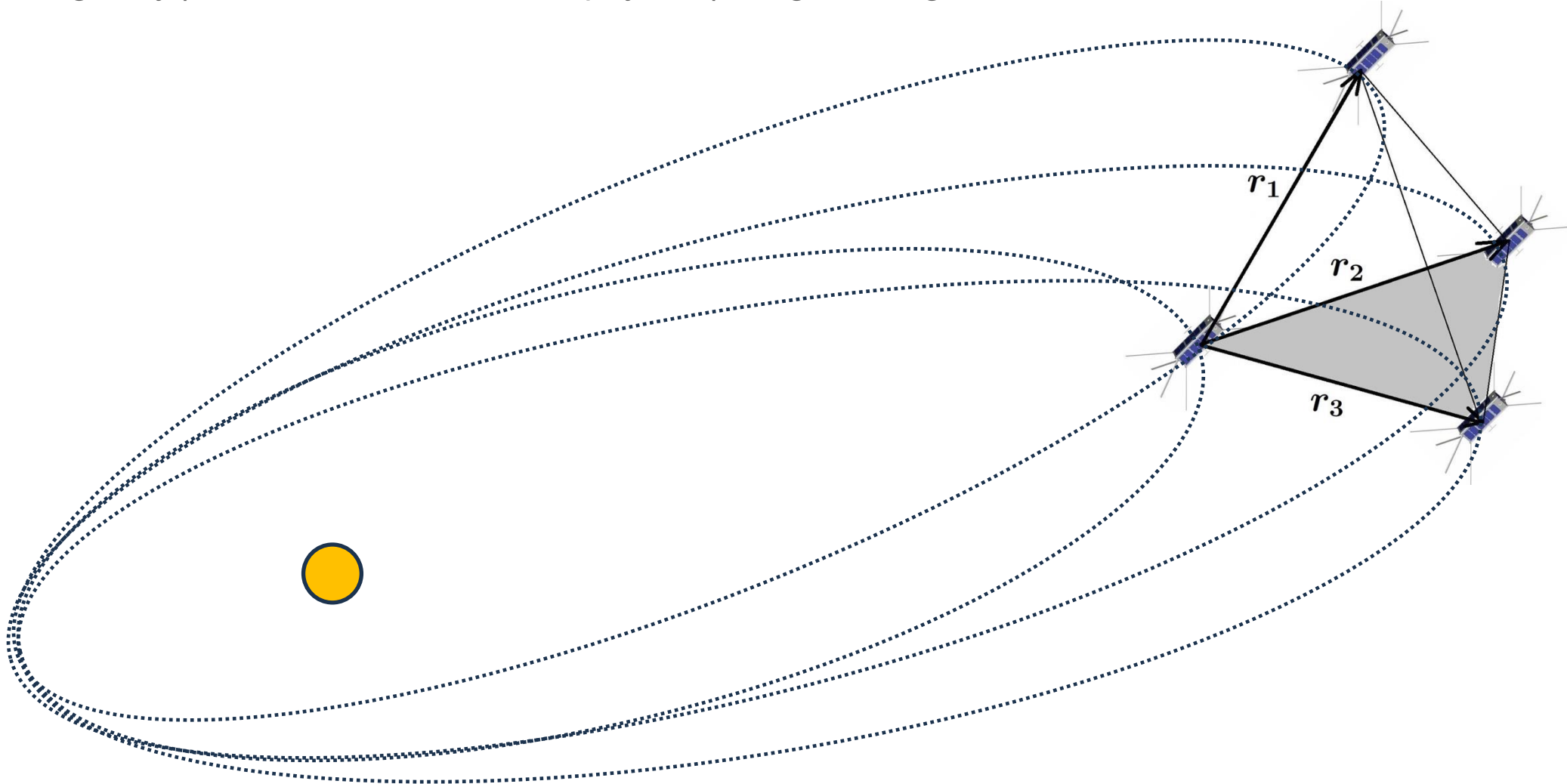
Science Context: Why a Local Field-Equation Test Matters?



TETRA provides a local boundary condition for interpreting next-decade cosmology.

Relative Dynamics in Nearby Orbits

Precision gravity | Dark-sector time-domain physics | Bridge-band gravitational waves



Tetrahedral constellation simulation

Load Save

Version 0.9.4

Simulation Controls

Zoom Control

Play/Pause



Initial state vector: High ecc.

To reset, reload the page.

Camera location: Z-axis

For viewing, the z-axis points from the constellation towards the Sun; the x-axis lies in the ecliptic plane.
 $\varphi = 0.00^\circ$, $\theta = 0.00^\circ$

Orbit characteristics

Volume: $-0.33 \times 10^9 \text{ km}^3$

tr **M**: 0.0000 s^{-2}

tr **T**: 0.0000 s^{-2}

tr **E**: 0.0000 s^{-2}

tr **W**: 0.0000 s^{-2}

Elapsed time: 0.00 days

Eccentricity: 0.5909

Orb. period: 648.80 days

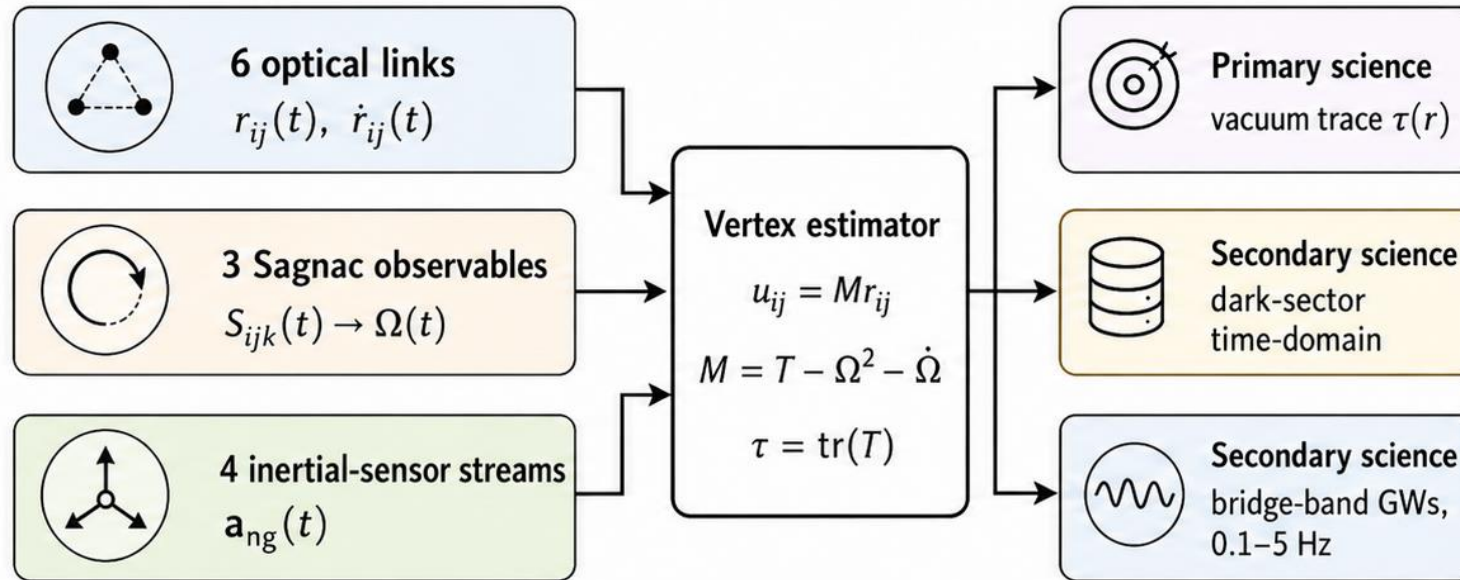
Description/comments

This simulation shows 4 spacecraft in a heliocentric orbit, in a tetrahedral configuration. As they orbit, the tetrahedron will be distorted. The trace **tr M** is calculated using the six intersatellite lengths only, with no inertial reference.
The trace **tr T** is calculated in an inertial reference frame; as expected, it is zero within the limits of double-precision rounding.



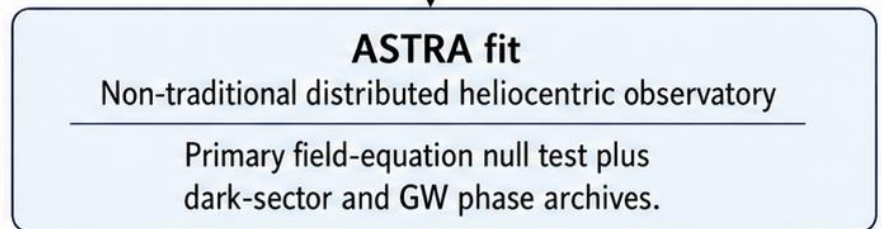
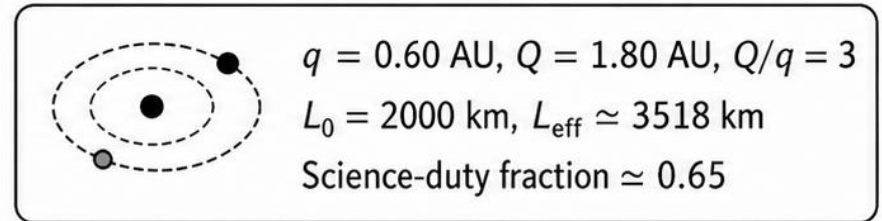
What ASTRA Would be Studying: One Observatory, Three Science Data Products

(a) Science-to-measurement chain



Flowdown targets			
Range precision	Angular-rate precision	Inertial-acceleration precision	Mission-level vacuum trace
$\sigma_r \sim 10^{-11} \text{ m}$	$\sigma_\omega \sim 2 \times 10^{-15} \text{ s}^{-1}$	$\sigma_{a,ng} \sim 10^{-15} \text{ m s}^{-2}$	$\delta\tau \sim 10^{-24} \text{ s}^{-2}$

(b) Reference architecture and ASTRA relevance

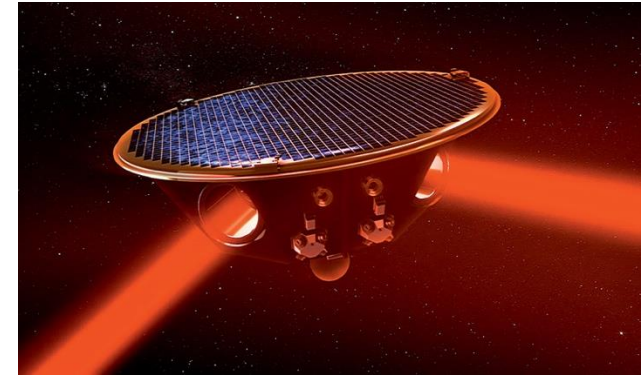


The architecture is compelling only if the six-link dataset closes the primary τ measurement while preserving scientifically useful dark-sector and GW time-domain products.

Key technical aspects guiding TETRA mission design

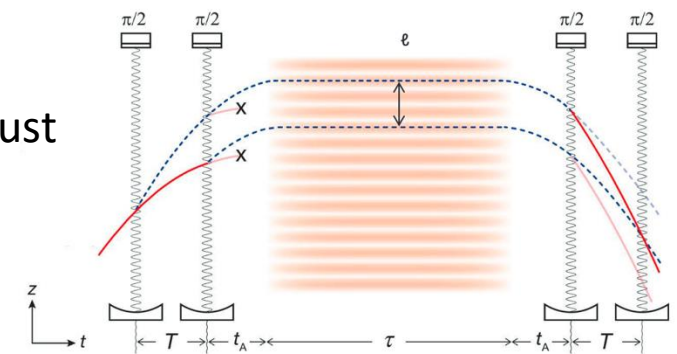
- **Precision Laser Ranging Systems:**

- Their role: i) To measure range changes between s/c pairs. ii) By measuring in multiple directions, they can isolate the [trace\[Grav. Gradient Tensor\]](#).
- Specifically, we rely on laser ranging to measure the [range](#) and to [compute range-rate](#) between any pair of s/c at nominal separation of 1,000 km.
- We assume each s/c is equipped with i) 3 small telescopes (~5cm aperture), ii) 3 precision gimbals capable of a wide angular articulations in 2D.
- We assume a LISA-class laser ranging system with sensitivity of [10 pm/ \$\sqrt{\text{Hz}}\$](#) .
- [We identified the range of angular articulation, pointing knowledge and stability needed to support the science operations.](#)



- **Atom-wave Interferometers (AI):**

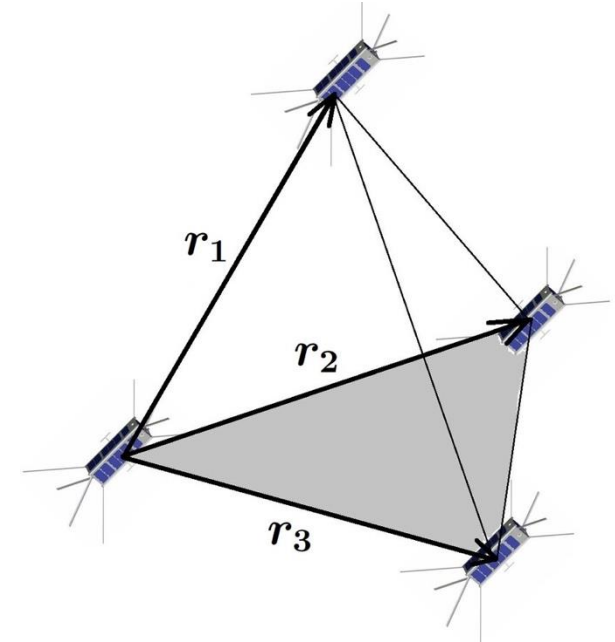
- We use AI to maintain stable, drag-free conditions for each s/c. AI is to adjust for non-grav forces: solar rad pressure, outgassing, attitude control, etc.
- We assume AI can correct any local non-grav disturbances, maintaining stability to within [~1e-15 m/s²/ \$\sqrt{\text{Hz}}\$](#) of differential acceleration.
- [LISA DRS may be used to reach similar performance.](#)



Key technical aspects guiding TETRA mission design (2)

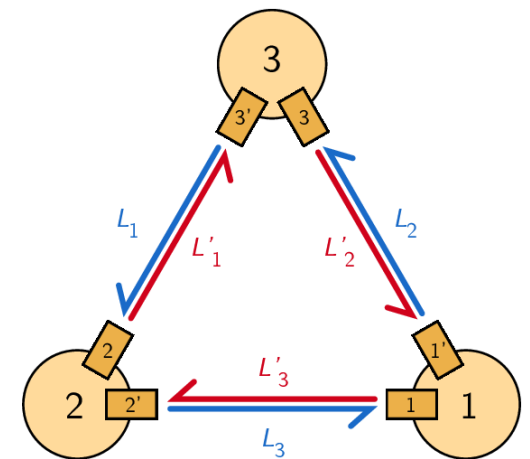
• Tetrahedral Configuration:

- To ensure that gravitational effects are sampled in 4 non-coplanar directions.
- Tetrahedral formation established by 4-spacecraft on nearby elliptic orbits.
- We studied dynamical behavior of such a configuration, its evolution, rotation, and elastic properties.
- We have: i) expressed trace of gravity gradient tensor via inter-satellite range measurements, and computed quantities, such as range-rates and range-accelerations; ii) shown that TETRA is enabled by a set of local differential measurements done at the local tetrahedral coordinate frame.



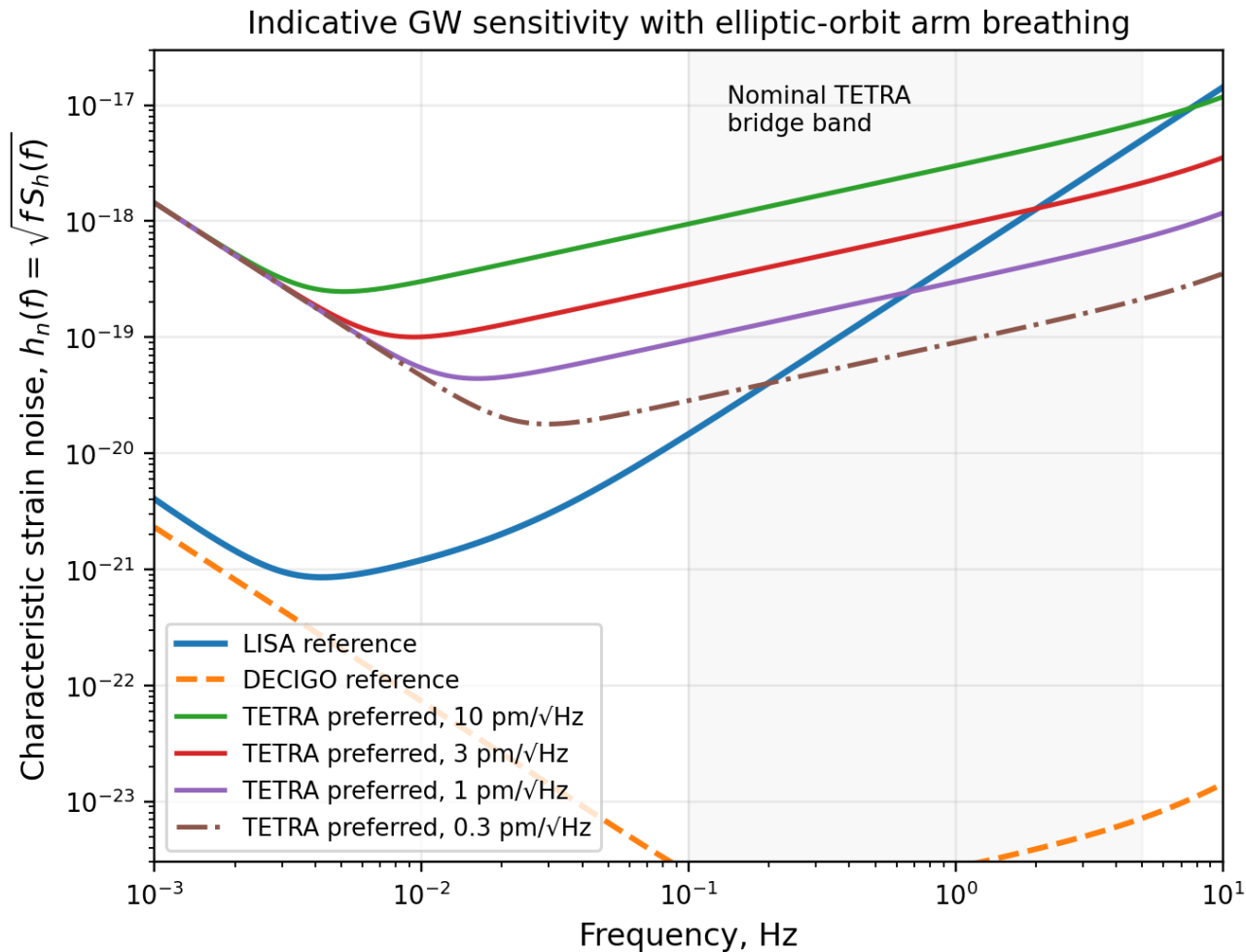
• Sagnac Interferometers (SI):

- SI on any 3 non-coplanar triangles at any vertex can determine 3 components of the angular velocity, Ω , to measure elastic rotation to high-precision.
- We assume that SI can measure optical path differences (OPD) between co- and contra-propagating beams at $30 \text{ pm}/\sqrt{\text{Hz}}$, which is compatible with LISA.
- SI allows determining the angular velocity of the tetrahedron with respect to the solar system barycentric (SSB) coordinate reference frame.



TETRA targets a detection sensitivity of $\sim 10^{-24}/s^2$ for gravity gradients.

Bridge-band GW Study: Complementing, not Competing with, LISA



Interpretation for ASTRA

- TETRA becomes useful in the 0.1–5 Hz bridge band only if displacement ASD reaches the 1–3 pm/ $\sqrt{\text{Hz}}$ class.
- 10 pm/ $\sqrt{\text{Hz}}$ is not enough for compelling bridge-band astrophysics.
- DECIGO-like sensitivity is not achievable without changing to a resonant Fabry–Pérot architecture.
- The attractive role is early inspiral phase tracking, multiband priors, source-direction improvement, and propagation/polarization tests.

$$f = c/(2\pi L) \approx 5\text{--}50 \text{ Hz} \\ \text{for } L \approx 10^3\text{--}10^4 \text{ km}$$

ASTRA task: close moving-arm response, laser/clock-noise suppression, and source reach.

Recommendation: study TETRA-GGT as an ASTRA entrant

Why this is worth an ASTRA slot

- It opens a missing local field-equation measurement in heliocentric vacuum.
- It is a genuinely non-traditional distributed observatory, not a conventional telescope recast as a constellation.
- It has a quantitative primary requirement chain and a bounded path to CML3.
- The same flight system can produce dark-sector and GW time-domain datasets without adding a separate mission.
- It matures technologies needed for future distributed astrophysics observatories.

ASTRA decision questions

Can the τ estimator close at approximately 10^{-24} s^{-2} ?

end-to-end systematics model

Which inertial sensor is baseline?

classical GRS vs hybrid GRS + AI

Is the GW dataset scientifically useful?

1–3 pm/ $\sqrt{\text{Hz}}$ displacement regime

What orbit best balances science and operations?

radial leverage, duty fraction, thermal/power

Can replicated nodes reduce cost and risk?

common spacecraft, optical terminals, launch

One decisive primary gravity test, two credible secondary datasets, and a clear CML3 maturation plan.