

Unlocking the Local Volume

Gaia DR4 as an Astrometric Anchor

Combining Decades of Archival Imaging

PIAZZI 200: New Frontiers in Astrometry, Small Bodies and Technologies

Palermo, Italy — September 30 – October 2, 2026

Giuseppe Piazzì's Foundation

- **Palermo Catalogs (1803, 1814):** Piazzì's precise position catalog of 7,646 stars laid the bedrock for 19th-century celestial mechanics.
- **Ceres Discovery (1801):** Combined high-precision positions with Gauss's orbital calculations to track small bodies.
- **Bicentennial Synergy:** The core principle remains unchanged — precise reference frames unlock hidden motions.

Gaia Data Release 4 (DR4) Capabilities

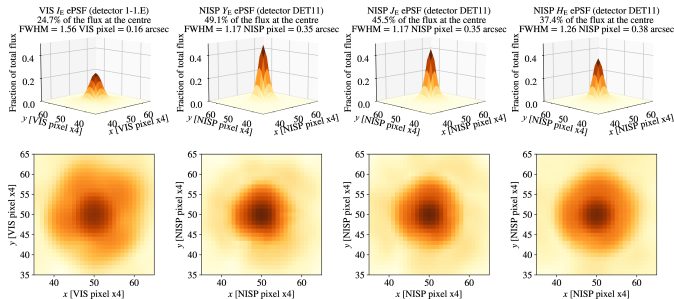
- **Extended Baseline:** 66 months of operations providing full epoch time-series astrometry.
- **Precision Anchor:** Serves as an absolute astrometric anchor across the sky.
- **Archival Re-calibration:** Allows retroactive correction of plate scale, atmospheric refraction, and distortion in legacy datasets.

Overcoming Space Detector Under-Sampling

- **Pixel Scale:** VIS (100 mas/pix) moderately & NISP (300 mas/pix) under-sampled.
- **Drizzling degradation:** Resampling – correlation – degrade centroiding precision.

Empirical ePSF & Distortion Modeling

- **Empirical Fitting:** Spatially-variable effective PSF and Geometric Distortion.
- **Gaia Anchor:** Gaia proper motions provides anchor.



3D effective PSF models for VIS and NISP detectors, from Libralato et al. (2024).

Superb Astrometric Precision & Gaia Synergy

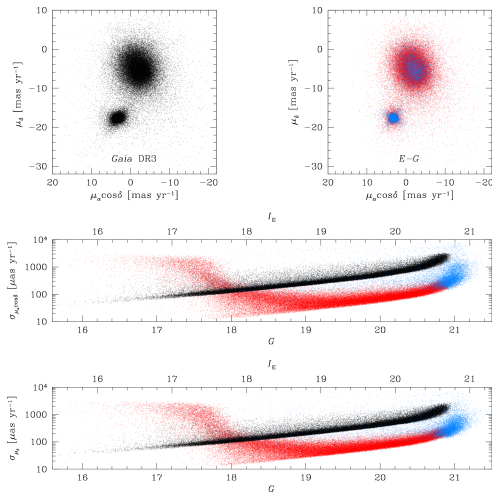
Precision Benchmarks on NGC 6397

- **VIS (Optical):** Achieves **0.7 mas** 1D RMS precision for point sources.
- **NISP (NIR):** Achieves **3.0 mas** despite detector under-sampling.

Euclid-Gaia (E-G) Synergy

- **Baseline:** Euclid 2023.7 to Gaia DR3 2016.0 = 7.7-year baseline.
- **PM Precision:** PM errors reduced to **few hundred $\mu\text{as}/\text{yr}$** at $19 \leq G \leq 21$... $10\times$ better ...

Member separation and PM error comparison Gaia DR3 vs E-G synergy - Libralato et al. (2024)

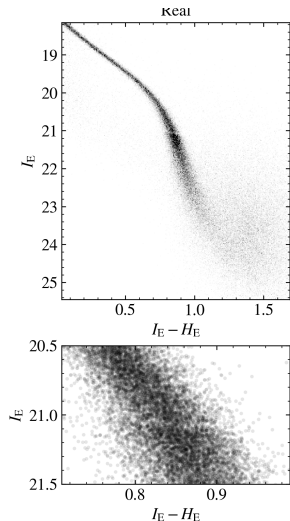


Second-Pass Reductions (KS2)

- **Limitation:** Single-pass struggles in crowded clusters.
- **Deblending:** Griggio et al. adapted HST KS2 software for Euclid to model and subtract neighboring stars.
- **Positional Constraints:** Solves positions in high-res VIS, then holds them fixed for NISP photometry.

Discovery of the Convective Gap

- **Stellar Gap:** In NGC 6397 Revealed a narrow gap ($\Delta I_E \approx 0.05$ mag) at $I_E \approx 21.06$ mag ($\sim 0.35 M_\odot$) with $> 5\sigma$ **confidence**.
- **Significance:** First detection of the Jao Gap in a Globular Cluster, constraining distance and metallicity.



The Challenge of Optical Faintness

- **Substellar Boundary:** Late-M, L, T, and Y dwarfs peak in the NIR and drop sharply in optical bands.
- **Gaia Detection Limit:** Objects redder than mid-L drop past Gaia's magnitude threshold ($G > 20.5$).
- **Incomplete Solutions:** Many cold dwarfs have marginal or missing Gaia proper motions and parallaxes.

Gaia DR4 Background Field Anchoring

- **Reference Star Precision:** Even when a UCD is faint or undetected in Gaia, DR4 measures dozens of surrounding field stars with micro-arcsecond accuracy.
- **Distortion Removal:** Gaia DR4 background star coordinates tie down historical ground-based CCD/NIR frames.
- **Precision Conversion:** Transforms legacy positions into absolute ICRS coordinates.

Torino Observatory Parallax Program

- **Setup:** 1.2m telescope + Astromed CCD at Torino Observatory.
- **Sample:** ~ 100 low-mass targets observed between **1994 and 2000**.
- **Coverage:** 50 to 200 individual observations per object.
- **Value:** Establishes a **30-year baseline** when tied to DR4, highly sensitive to long-period binarity.

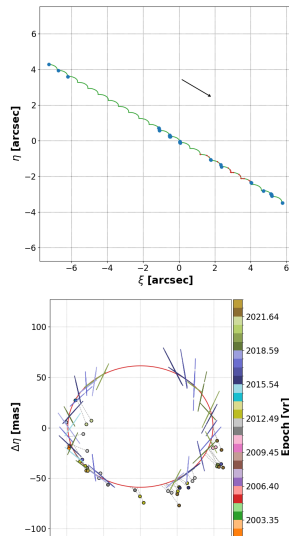
PARSEC (ESO 2.2m + WFI Parallaxes)

- **Setup:** ESO 2.2m telescope + Wide Field Imager (WFI) at La Silla (**2005–2012**).
- **Sample:** 120 southern L and T dwarfs.
- **DR4 Improvement:** Most targets are in Gaia but near the faint limit.
- **Synergy:** Combining Gaia + PARSEC and will refine parallaxes, proper motions and orbital accelerations.

Not just bright objects

NTT Parallaxes of Southern Extremely Cool Objects

- **Program:** NTT + SOFI on 100 T dwarfs, ~ 50 epochs from 2000 to 2023).
- **NIR Precision:** High-quality near-infrared observations of faint, methane-dominated Ts.
- **Gaia Detection:** Only ~ 10 of the 100 NPARSEC T dwarfs are in Gaia.
- **Background Field Solution:** Gaia DR4 provides ultra-precise positions and PMs for reference stars in the SOFI frames.
- **Rescued Solutions:** Enables sub-mas parallax and PM solutions for the 90 non-Gaia T dwarfs, opening a 23-year baseline.



Unveiling Hidden Binaries & Next-Gen Synergies

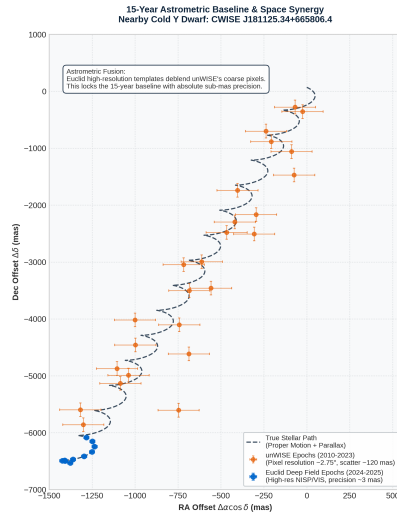
Astrometric accelerations and future space surveys

Multi-Decade Astrometric Baseline (15–30 Years)

Decoupling Proper Motion & Parallax

- **Long Baseline:** Combining 1990s–2010s archival epochs (TOPP, UKIRT, WISE) with Gaia DR4 and Euclid creates a 15–30 year baseline.
- **Unambiguous Motion:** A 30-year span separates subtle orbital acceleration ($\ddot{\mu}$) from annual parallax loops (π).
- **Cold Target Fusion:** Resolves optical pixel blending and establishes sub-mas kinematic solutions.

15-year trajectory of CWISE J1811+6658 (14.3 pc),
25 unWISE with 10 high-precision EULCID epochs.



Astrometric Acceleration ($\ddot{\mu}$)

- **Curvature Detection:** Comparing Gaia DR4 epoch time-series against 20-year TOPP/PARSEC/NPARSEC baselines flags long-period companions (10 – 100 AU).
- **Non-Linear Motion:** Curvature ($\ddot{x}, \ddot{y}$) and proper motion anomalies ($\Delta\mu = \mu_{\text{long}} - \mu_{\text{short}}$) reveal unseen orbiters.
- **Dynamical Masses:** Delivers model-independent mass constraints for substellar companions.

Sensitivity to Extreme Mass Ratios

- **Low Mass-Ratio Binaries ($q \ll 1$):** Highly sensitive to White Dwarf + UCD or M-dwarf + Brown Dwarf pairs.
- **Unresolved Systems:** Captures wide and intermediate orbits that escape radial velocity or transit detection.
- **Demographic Impact:** Resolves the true substellar binary fraction across L, T, and Y spectral types.

Vera C. Rubin Telescope (LSST)

- **Rubin Observatory Capabilities:** 10-year 6-filter (*ugrizy*) cadence delivers $S/N \geq 10$ parallaxes for thousands of L/T dwarfs [Gizis 2022].
- **Census Boost:** Provides 50–100 objects per spectral type bin for late-L to mid-T dwarfs, creating unbiased censuses.
- **DECam Baseline:** 12-year DECam reprocessing provides an instant baseline for Rubin Y1.

China Space Station Telescope (CSST)

- **Space Capabilities:** 2 m space telescope ($0.073''/\text{pixel}$, 1.1 deg^2 FoV) operating in 400 km orbit [Fu et al. 2023].
- **Sky Survey:** $17,500 \text{ deg}^2$ survey covering $0.25 - 1.7 \mu\text{m}$ over 7+ years.
- **Precision:** Reaches $< 1 \text{ mas/yr}$ accuracy for 18–22 mag and 1–10 mas/yr for 22–26 mag, extending Gaia to faint solar system small bodies and stars.

Summary & Conclusions

- **Legacy Integration:** Re-analyzing legacy observations (TOPP, PARSEC all the way to Carte du Ciel etc) with DR4 opens up large proper motion baselines.
- **Rescuing Non-Gaia T/Y Dwarfs:** Even for faint T/Y dwarfs undetected by Gaia, DR4 reference star anchors dramatically improve parallax and PM solutions (NTT, VISTA, UKIRT, VLT).
- **Hidden Binary Discovery:** Combining 20–30 year baselines with Gaia DR4 epoch time-series accelerates the discovery of long-period substellar companions via astrometric accelerations ($\dot{\mu}$).
- **Local Volume Framework:** Fusing legacy archives with upcoming surveys (LSST, Euclid, Rubin, CSST) allows a multi-epoch 3D census of our Solar neighborhood.

Not possible without Gaia DR4 as the Ultimate Anchor

66-month epoch astrometry anchors historical ground-based surveys, correcting optical distortions across decades of legacy data. **Thank you! Questions are welcome.**

The Proposed Euclid Astrometric Extension (Bedin 2025)

Propellant-Driven Opportunity

- **Nominal Mission:** 6 years (cosmology focus).
- **Propellant Reserve:** Cold gas propellant can sustain operations for up to **14 years total**.
- **Proposal:** Repeat the Euclid Wide Survey (EWS) over $\sim 15,000 \text{ deg}^2$ (1/3 of the sky) over 6 extended years.
- **Identical Cadence:** Keep identical observing sequence, cadence, and dither patterns.

Scientific Dividends

- **Proper Motions to $V \approx 27$:** Captures kinematics for 7–9 billion stars, extending Gaia by **six magnitudes**.
- **Small Bodies & Streams:** Tracing faint asteroids, Kuiper Belt Objects, stellar streams, and cluster outskirts.
- **Time-Domain Legacy:** Opens a vast transient, variable, and microlensing search space.