# 21st Century Astrometry and its Science Applications

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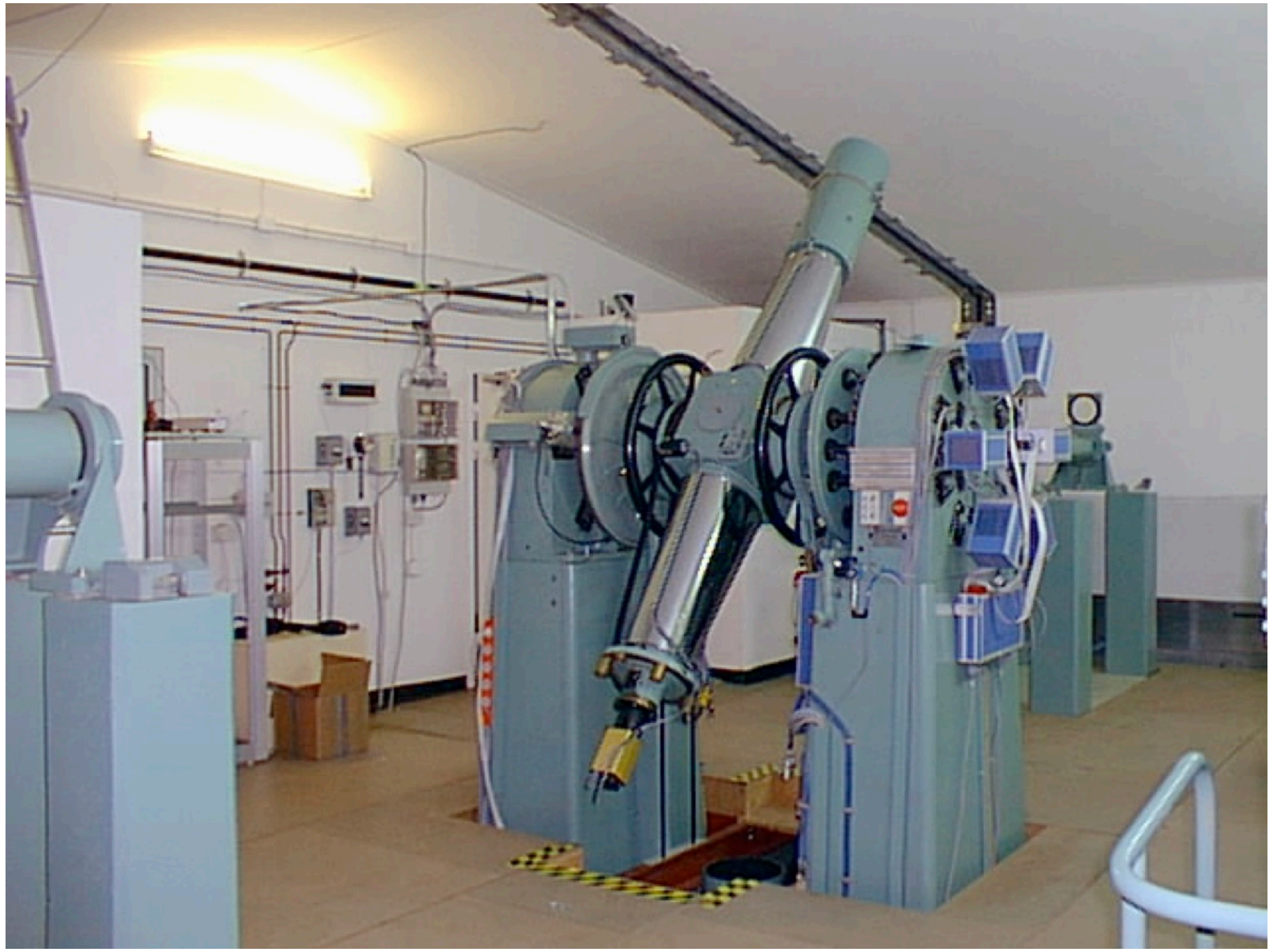
Astrometry for 21st Century Astronomy, IAUGA 2022 FM7, Busan

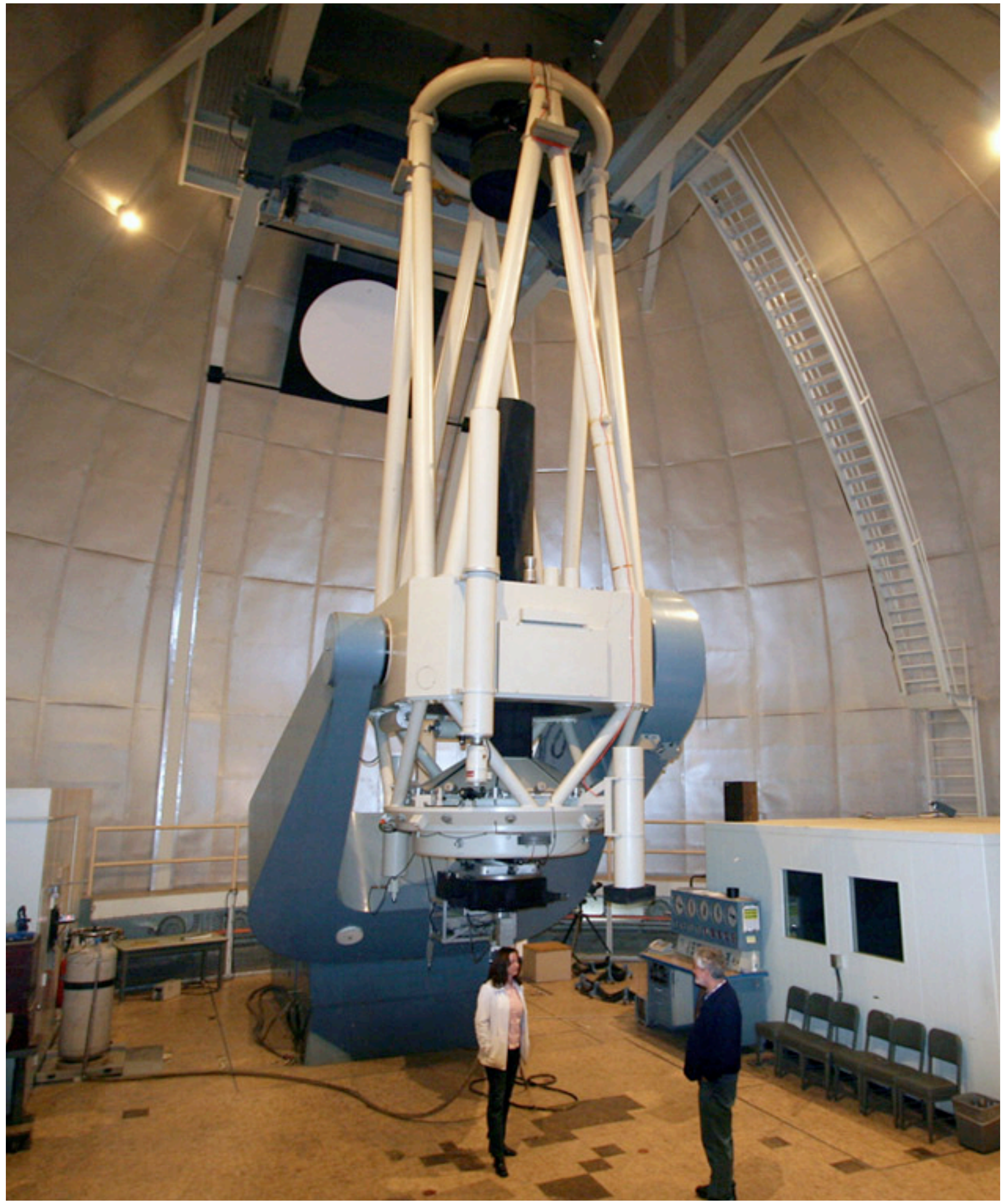
# Optical astrometry (c. 1990)

## Global astrometry to ~0.1 arcsec



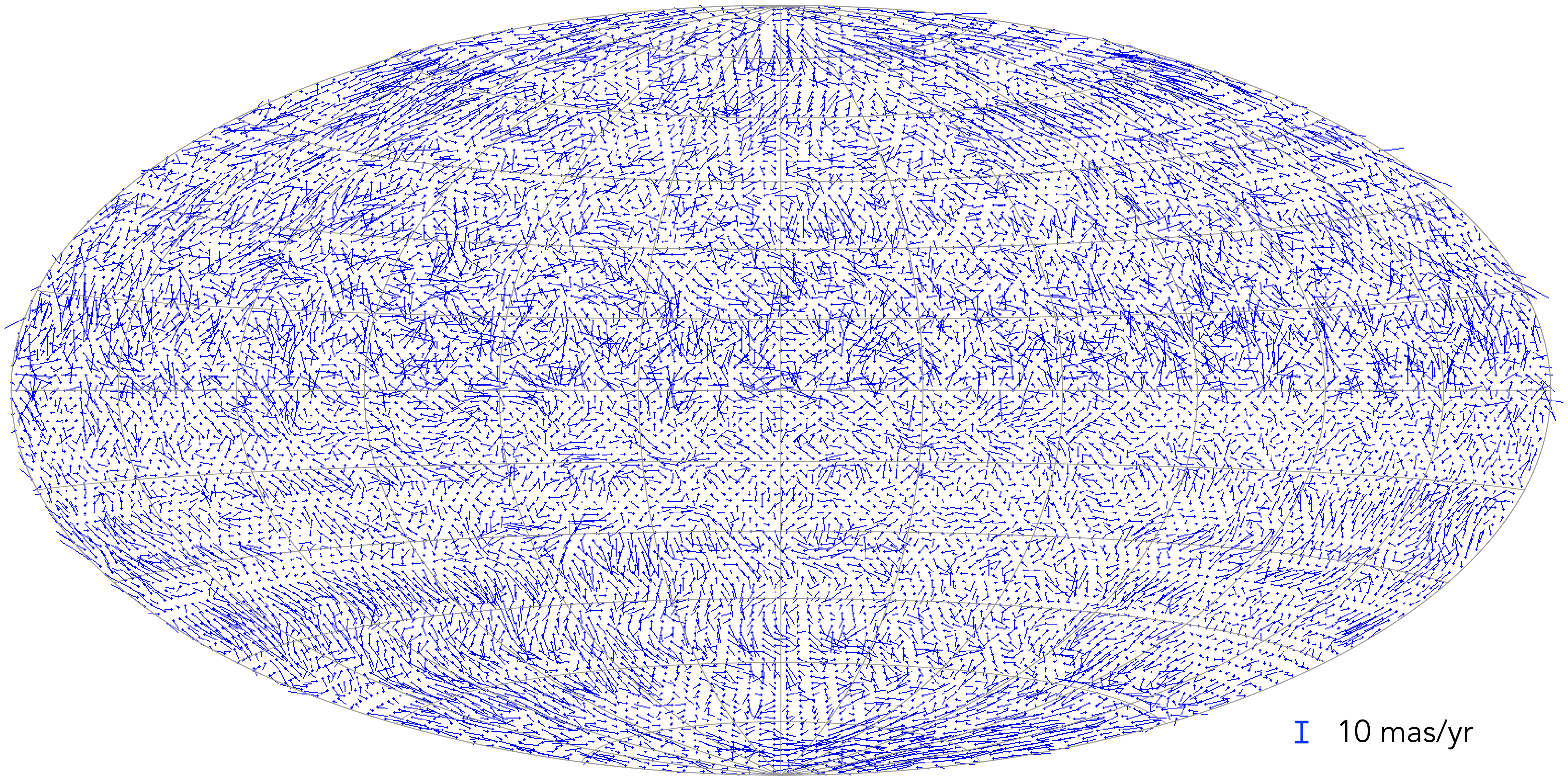
Carlsberg Automatic Meridian Circle on La Palma (Credit: ROA)

## Differential to ~0.001 arcsec



1.55 m Strand Astrometric Reflector (USNO, Flagstaff)
(Credit: Debra & Peter Ceravolo)

# Systematic errors in ground-based proper motions (pre-HIP)



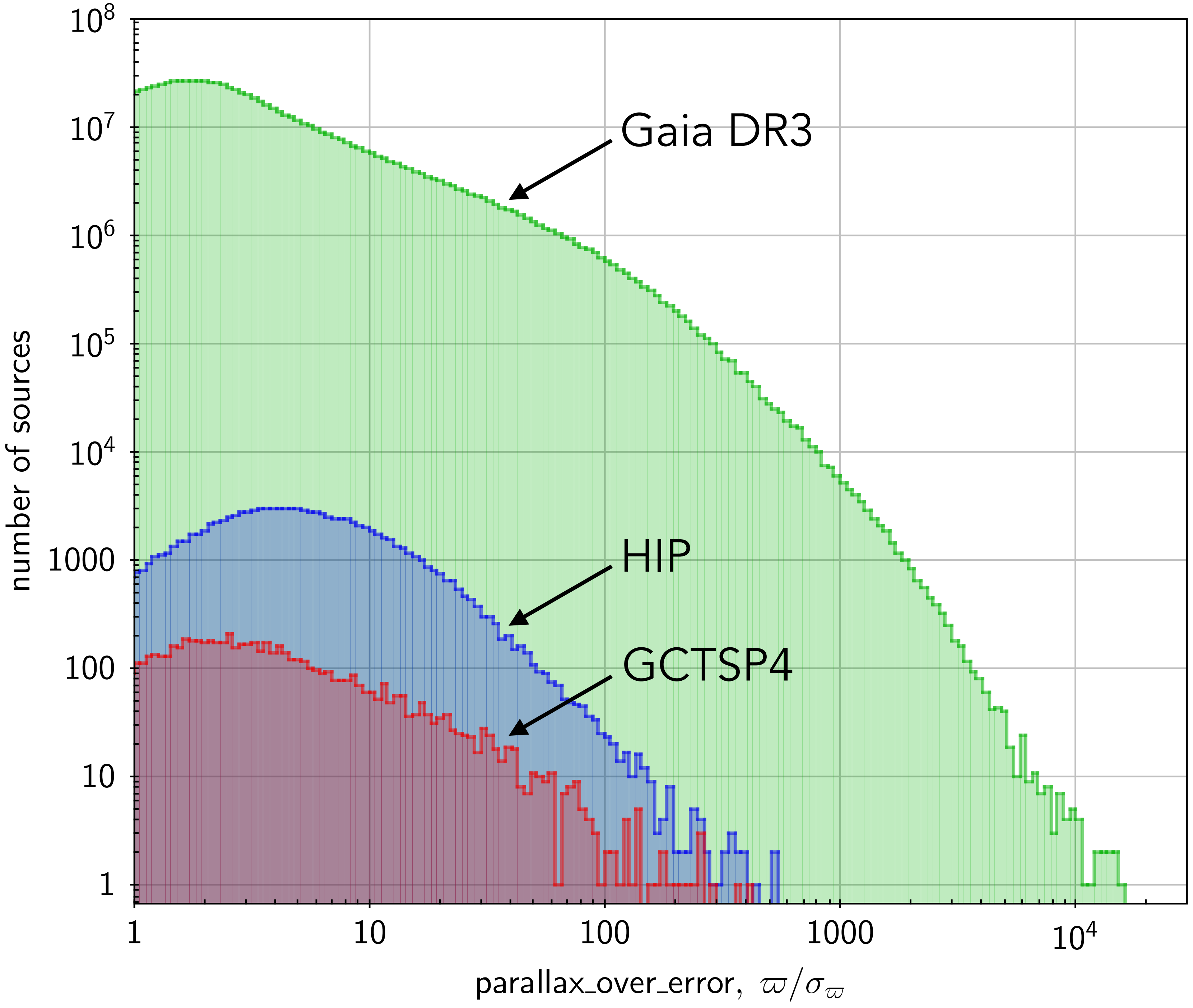

Median difference in proper motion between PPM and Gaia DR3 for 364,000 stars (3.4 deg$^2$ resolution)
(PPM = The PPM Star Catalogue of Positions and Proper Motions; Röser & Bastian 1988; Bastian & Röser 1995)

# Growth in the knowledge of (accurate) stellar distances

Number of stars with $\varpi/\sigma_\varpi > 20$
(5% distance uncertainty, 0.1 mag in DM) :

- GCTSP4 (1995): 414
- HIP (1997): 6107
- Gaia DR3 (2022): 48.8 million

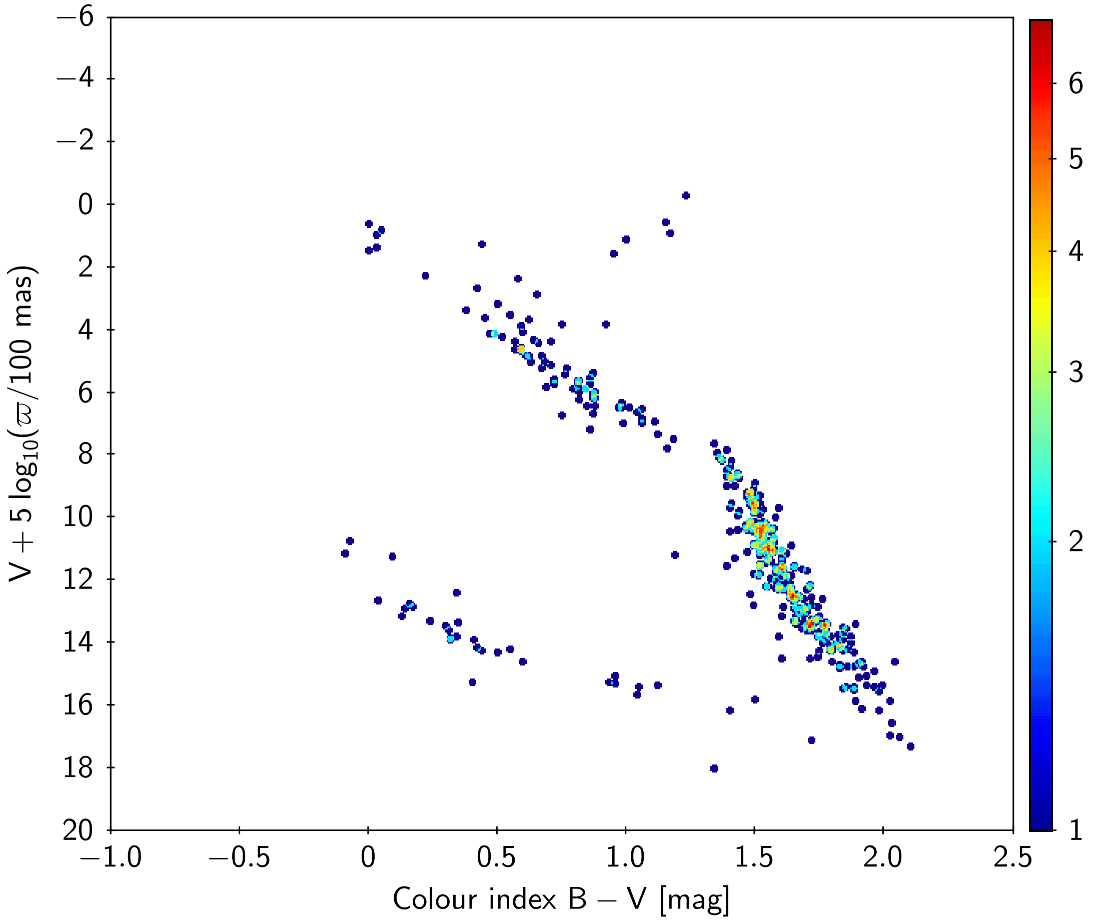
GCTSP4 = 4th General Catalogue of Trigonometric Stellar Parallaxes (van Altena et al., 1995)



# The HR diagram for stars with $\varpi/\sigma_\varpi > 20$

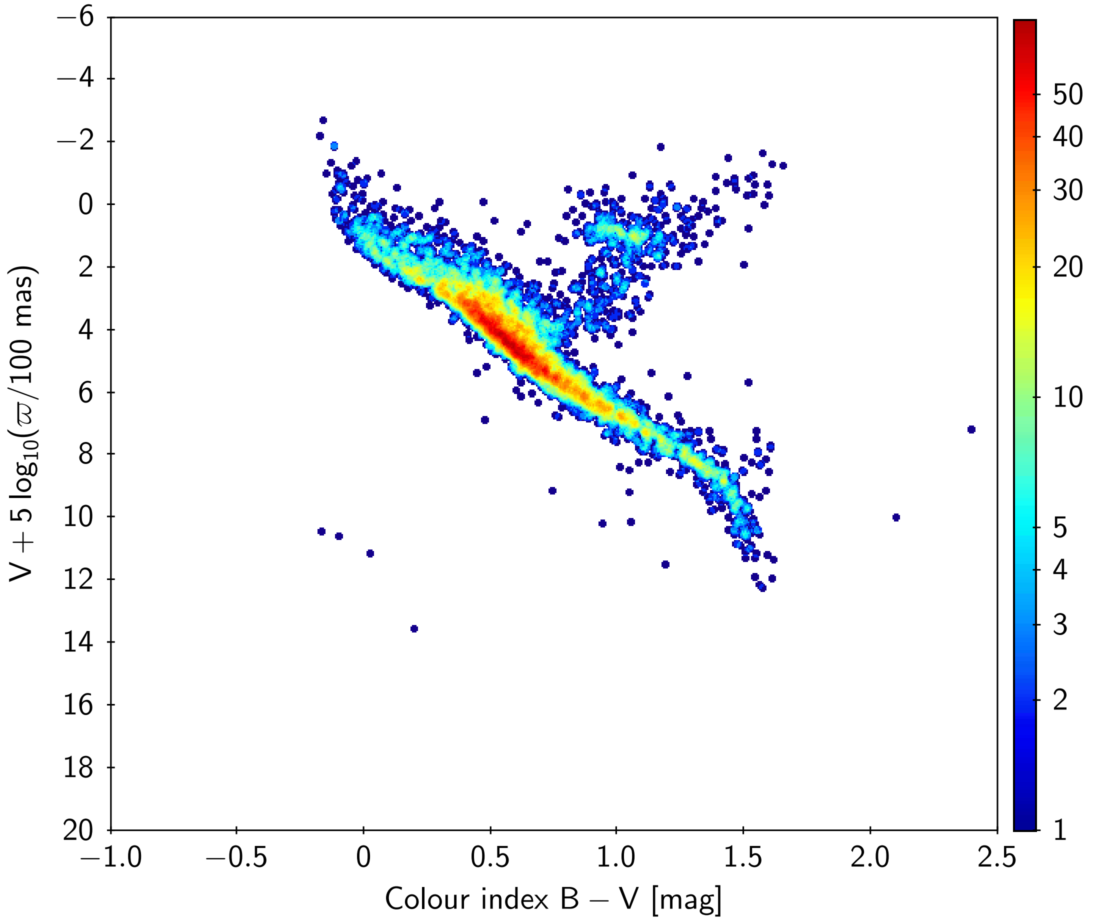
**1995**

GCTSP4 (414 stars)



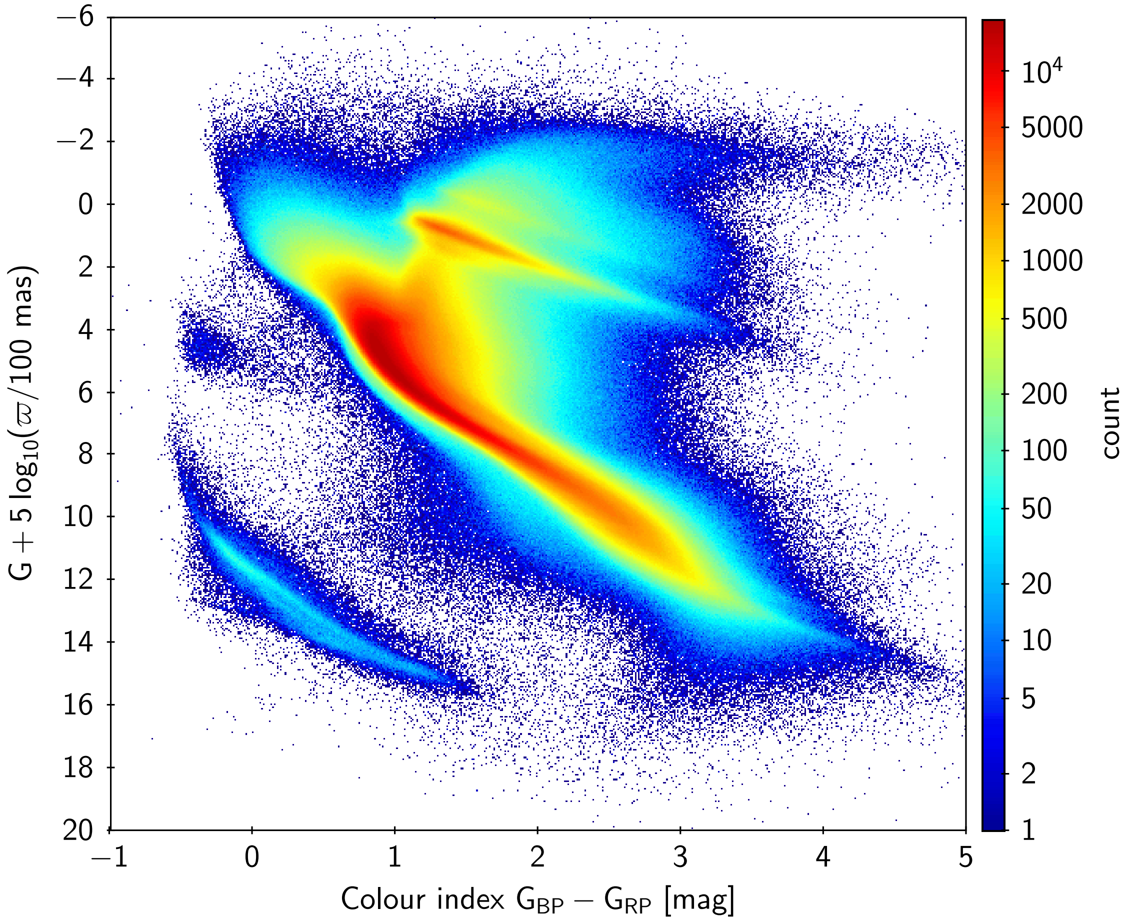

**1997**

Hipparcos (6107 stars)




**2022**

Gaia DR3 (48.8 million stars)



# Examples of modern uses of astrometry

Positions (celestial reference frame):
- object identification across all wavelengths (gamma to radio)
- telescope pointing and space navigation
- occultation prediction

Stellar parallaxes:
- geometric stellar distances
- stellar astrophysics
- calibration of standard candles, comological distance scale
- Galactic structure and kinematics, 3D extinction

Stellar proper motions (including non-linear/orbital):
- Galactic structure and kinematics
- phase space structures, including cluster dynamics and membership
- perturbations (companions, masses, microlensing)

Solar system:
- orbits, masses, predictions
- sizes, shapes

Fundamental physics:
- tests of General Relativity
- gravitational waves

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Different applications have very different requirements in terms of

- accuracy
- number of objects
- size of field
- range of magnitudes
- wavelength bands
- completeness
- …

➜ a variety of complementary techniques are needed

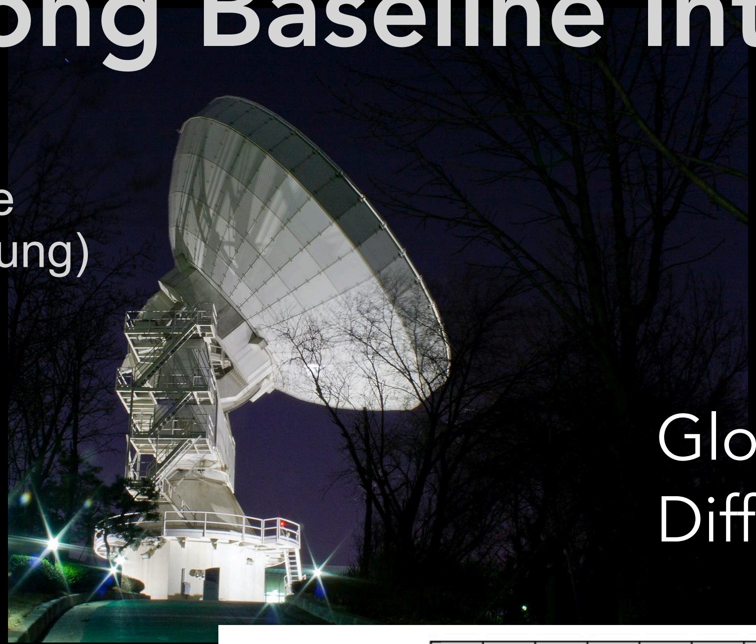
# Classification of astrometric techniques

| | | |
|---|---|---|
| optical (visual/NIR) | ⟷ | radio |
| small-field | ⟷ | global |
| targeted | ⟷ | survey |
| ground-based | ⟷ | space |
| imaging | ⟷ | interferometric |
| pointed | ⟷ | scanning |

⋮

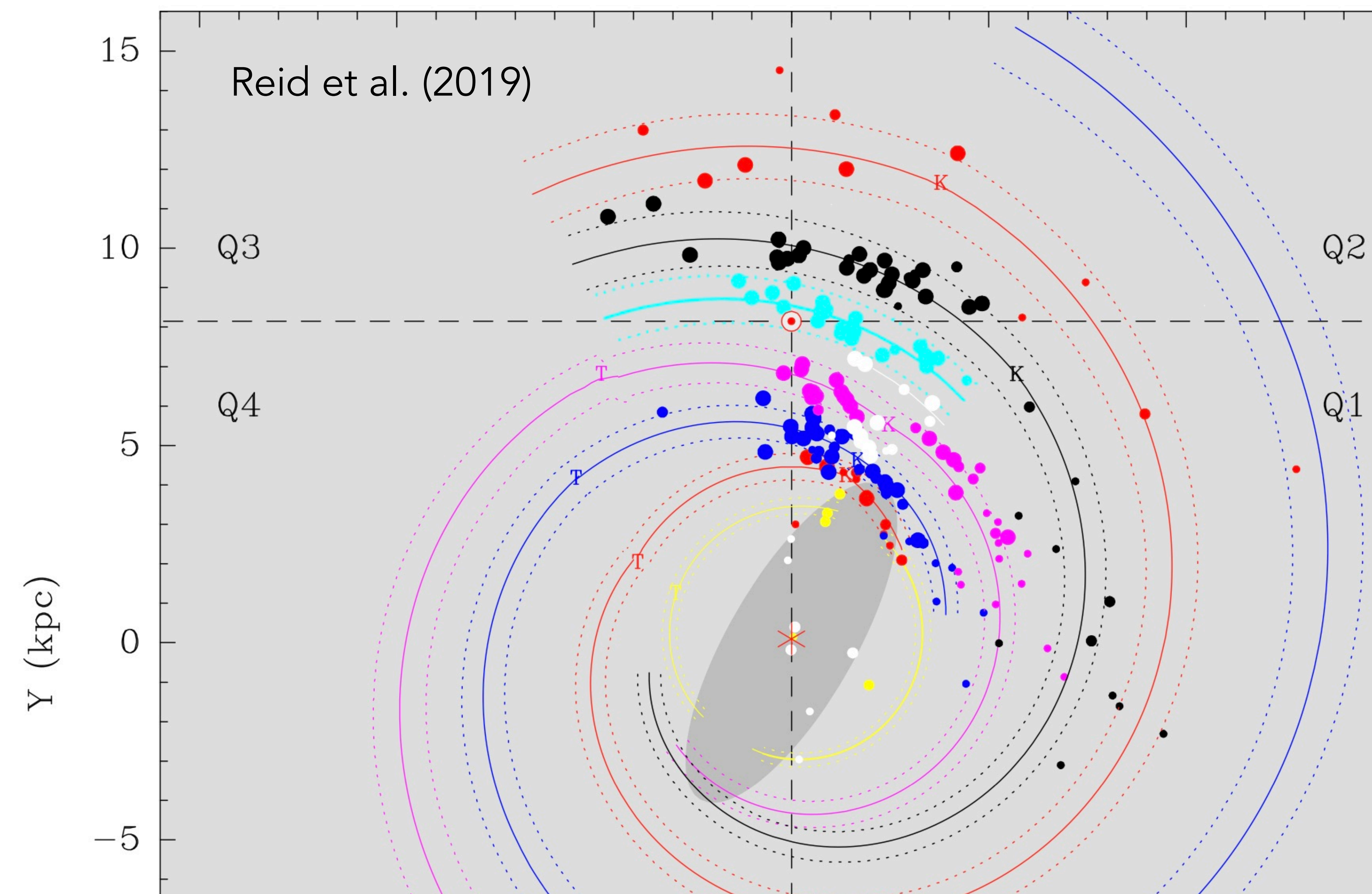
# Radio astrometry: Very Long Baseline Interferometry (VLBI)

The 21 m radio telescope
in Yonsei (Credit: HyeRyung)



Global positions (ICRF3) to ~100 μas
Differential (phase referencing) to ~10 μas


The European VLBI Network

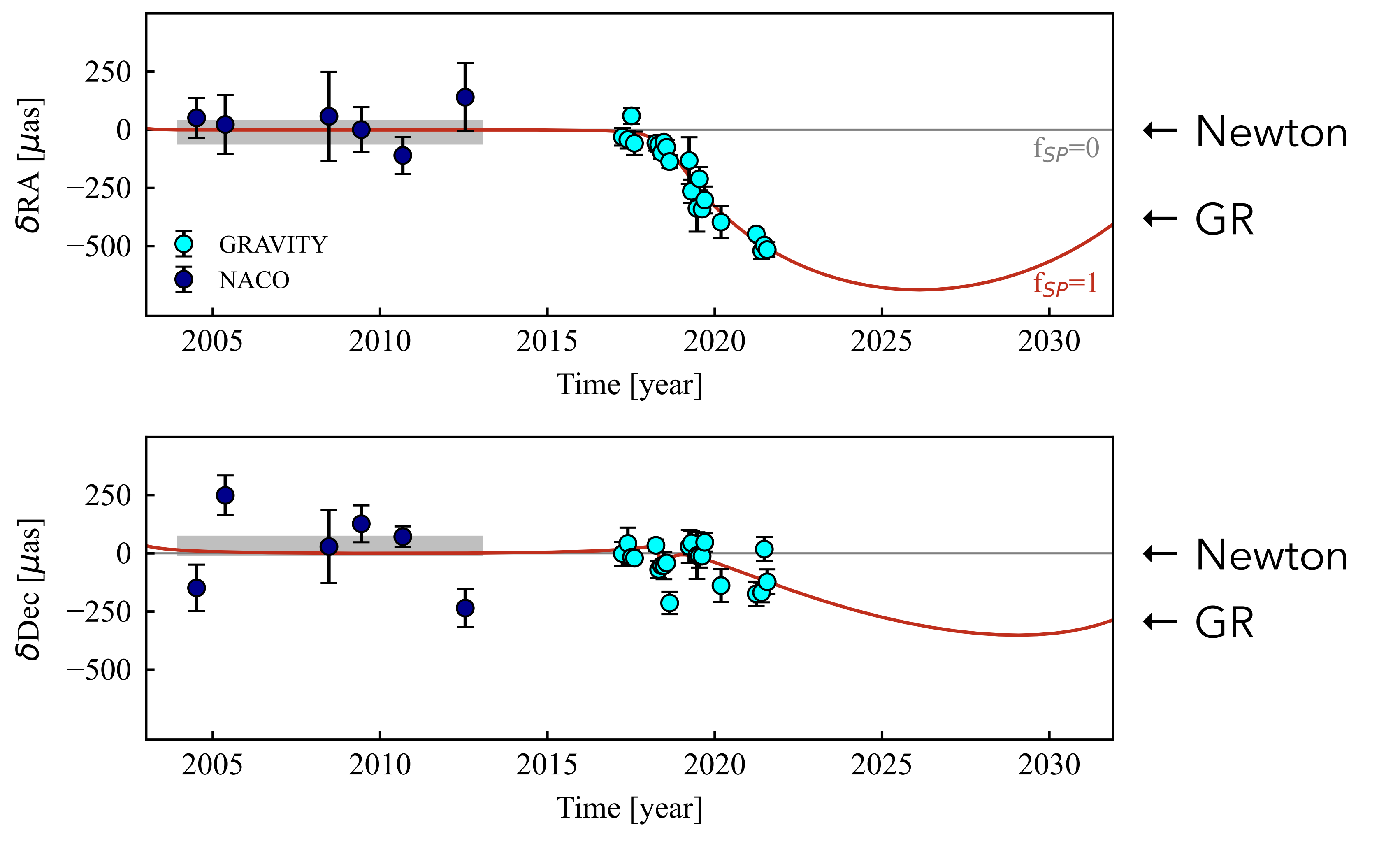



FM7

# Optical interferometry: GRAVITY at VLTI

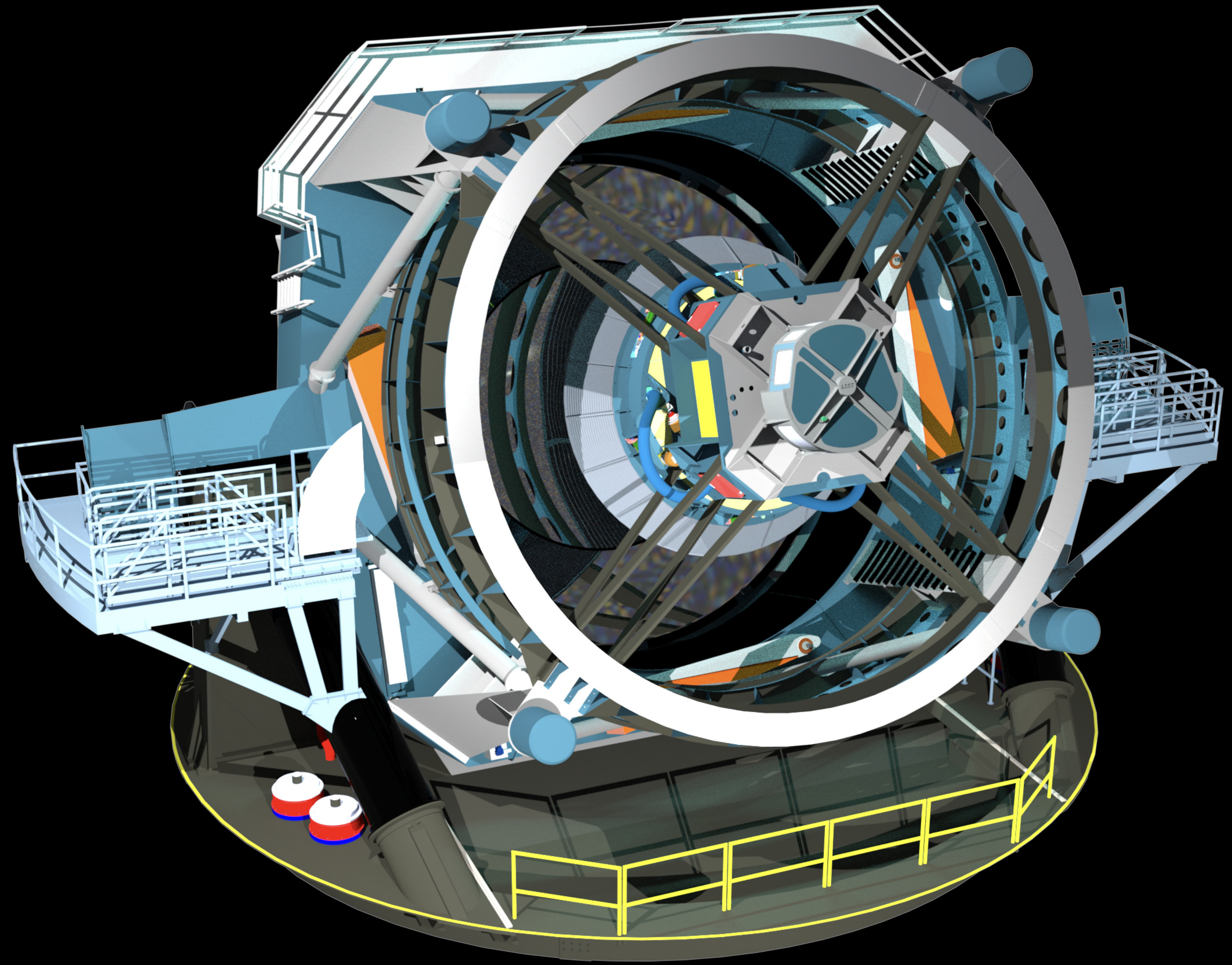

Narrow-field (0.2 arcsec) IR astrometry to ~30 μas

$R_0$ = 8.178 ± 0.026 kpc (GRAVITY Coll. et al. 2019)

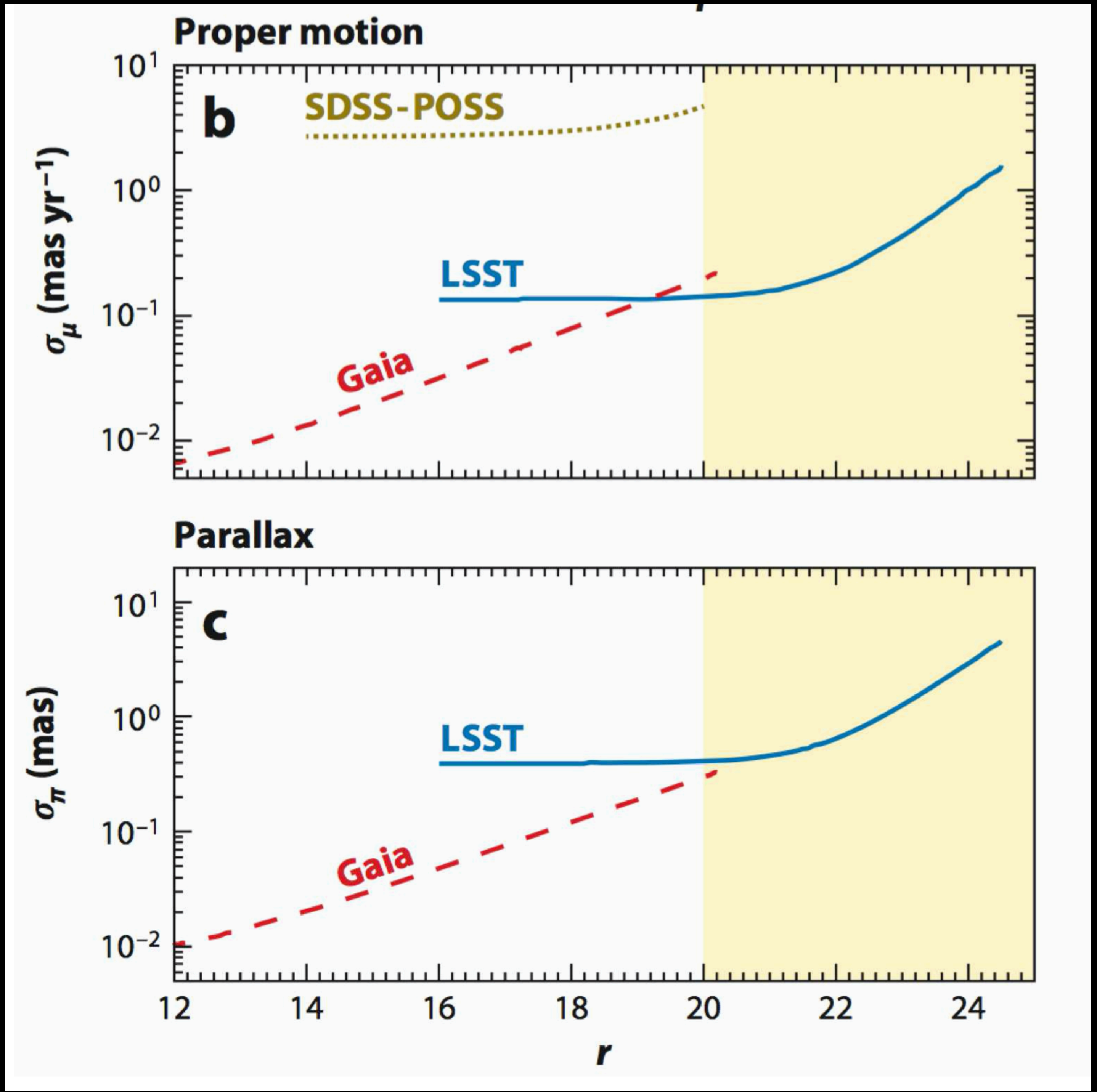



Precession of the orbit of S2 around Sgr A* (GRAVITY Coll. et al. 2022)

# Vera C. Rubin Observatory (LSST)



Rendering of the Large Synoptic Survey Telescope (LSST Project Office, 2013)



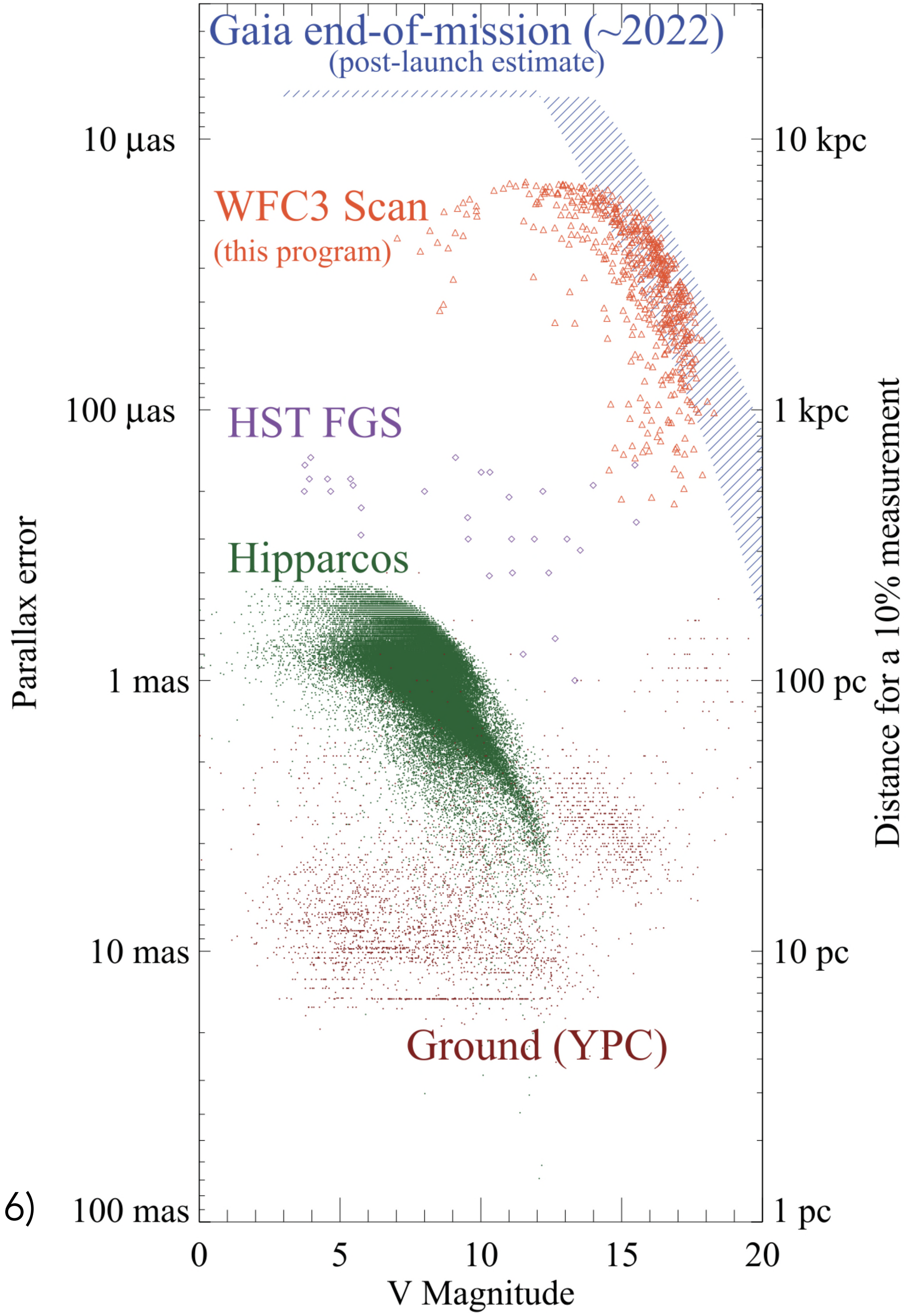

Ivezic et al. (2015)

# Hubble Space Telecope

HST FGS (Fine Guidance Sensors) astrometry:
parallaxes to ~150 µas (Benedict et al. 2011)

HST WFC3 image centroiding:
~0.008 pix = 300 µas (Bellini et al. 2011)

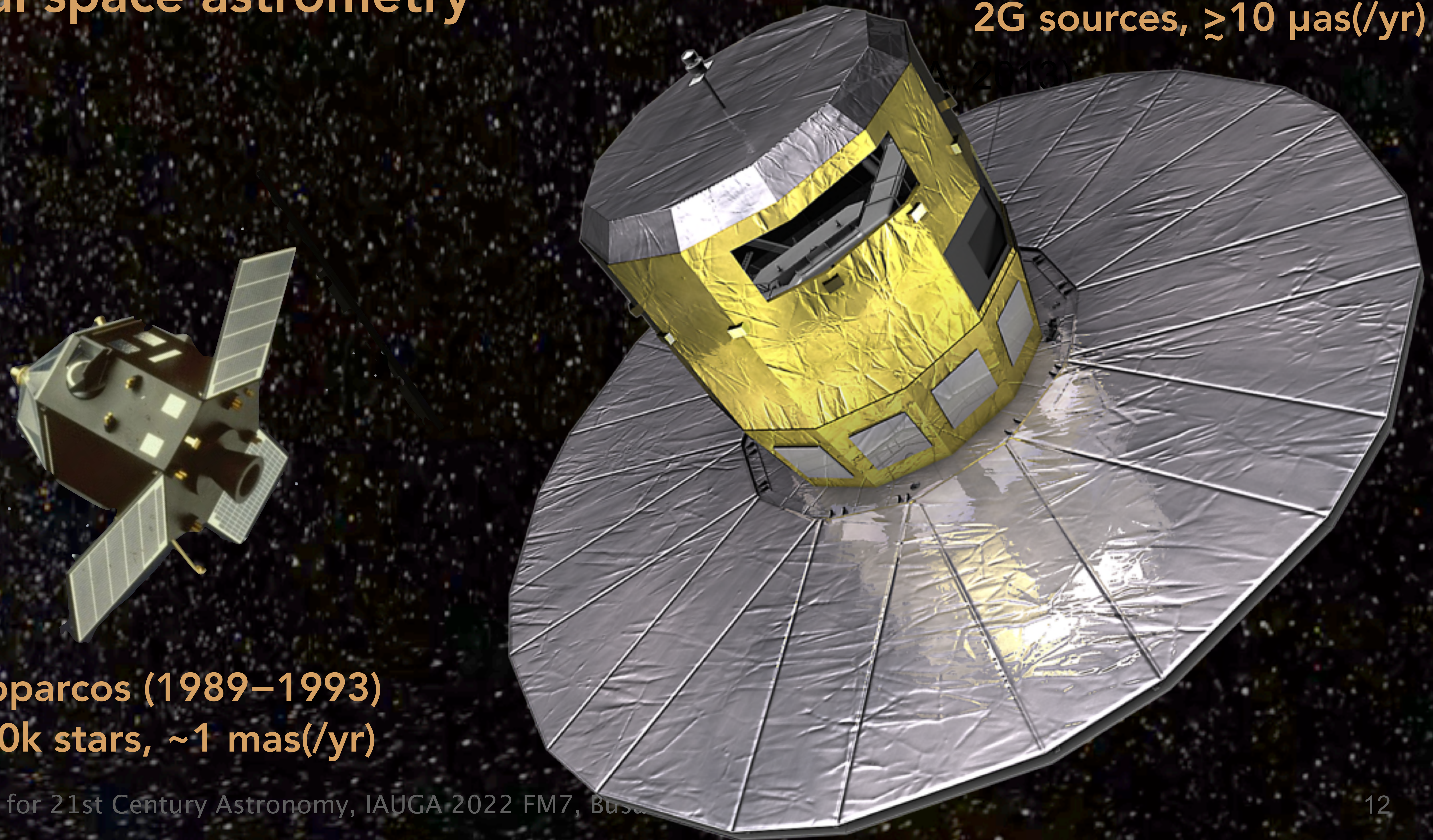
HST WFC3 spatial scanning:
parallax to ~30 µas (Riess et al. 2018)




Casertano et al. (2016)

# Global space astrometry

Gaia (2013–2025?)
2G sources, $\gtrsim$10 μas(/yr)



Hipparcos (1989–1993)
100k stars, ~1 mas(/yr)

# Advantages of space for astrometry

- ✓ Absence of atmosphere
- ✓ Weightlessness
- ✓ Thermo-mechanical stability
- ✓ Whole sky accessible from a single observatory
- ✓ Continuous observation over several years
- ✓ Enhanced science from (required) photometric data and (optional) spectra

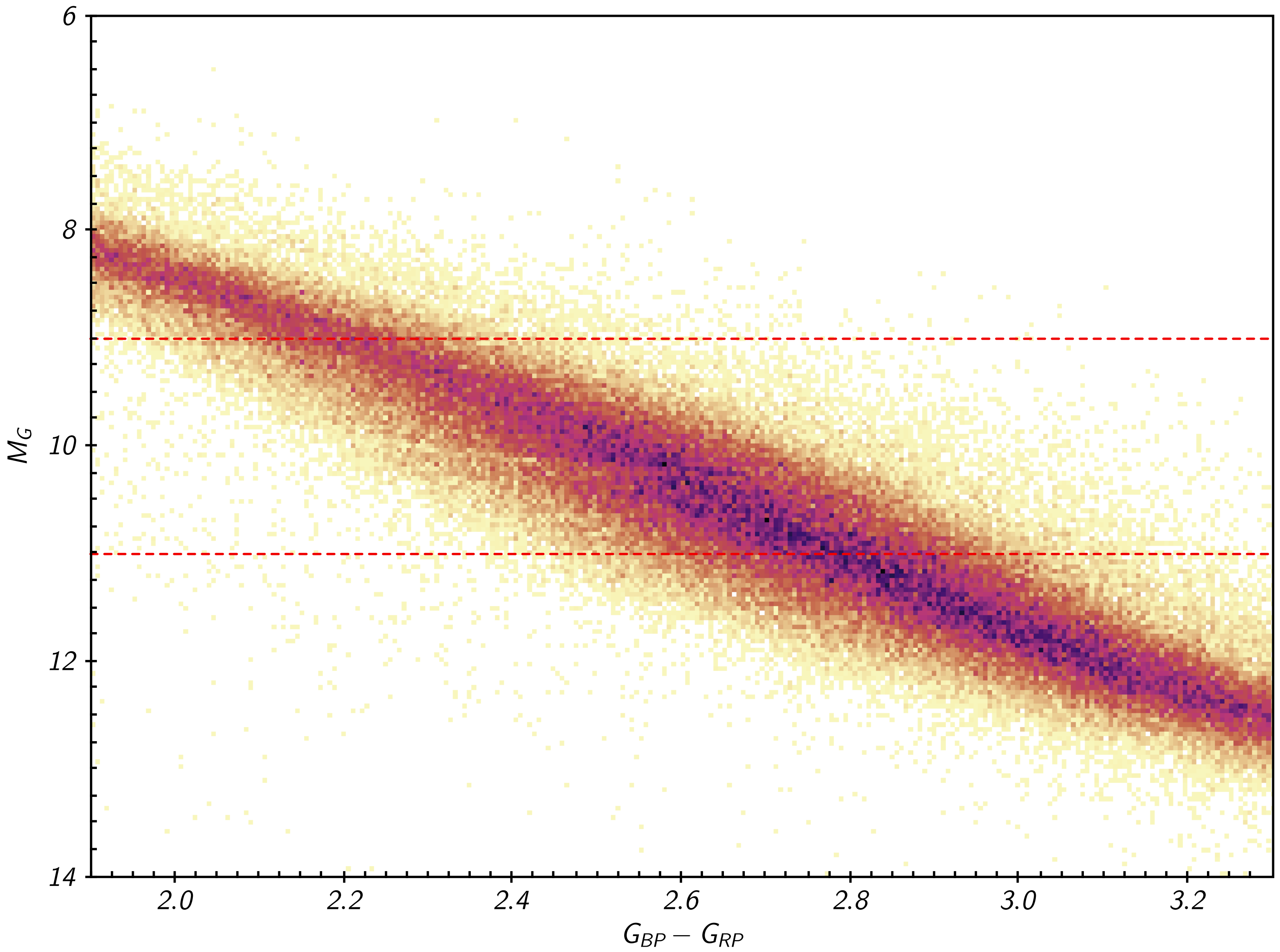
⇒ ***accurate global astrometry***
(celestial reference frame, absolute parallaxes, consistent proper motions over whole sky)

⇒ ***survey, completeness, good time sampling, astrophysical data***

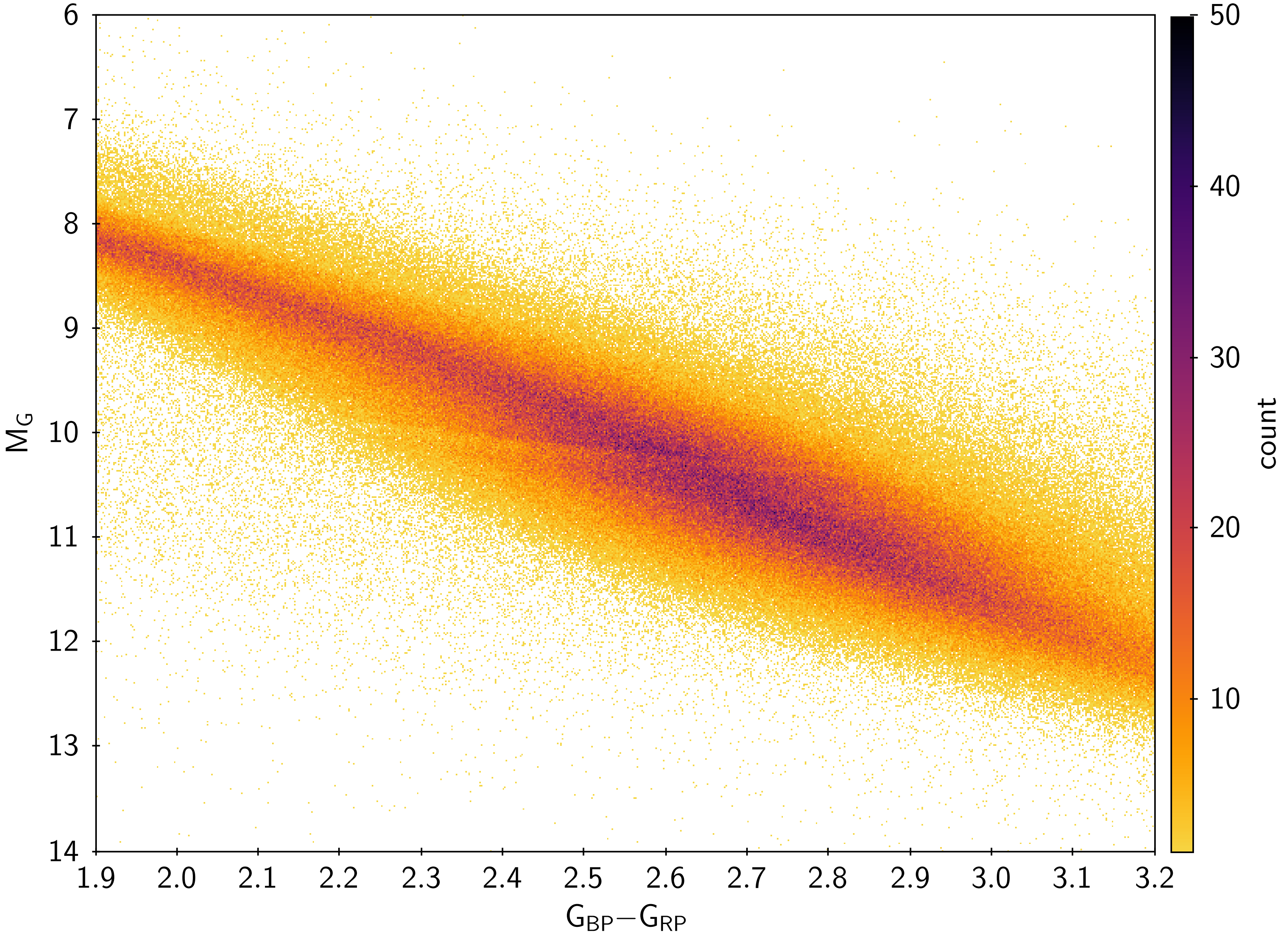
⇒ ***Gaia***

# A gap in the lower main sequence (Jao et al. 2018)

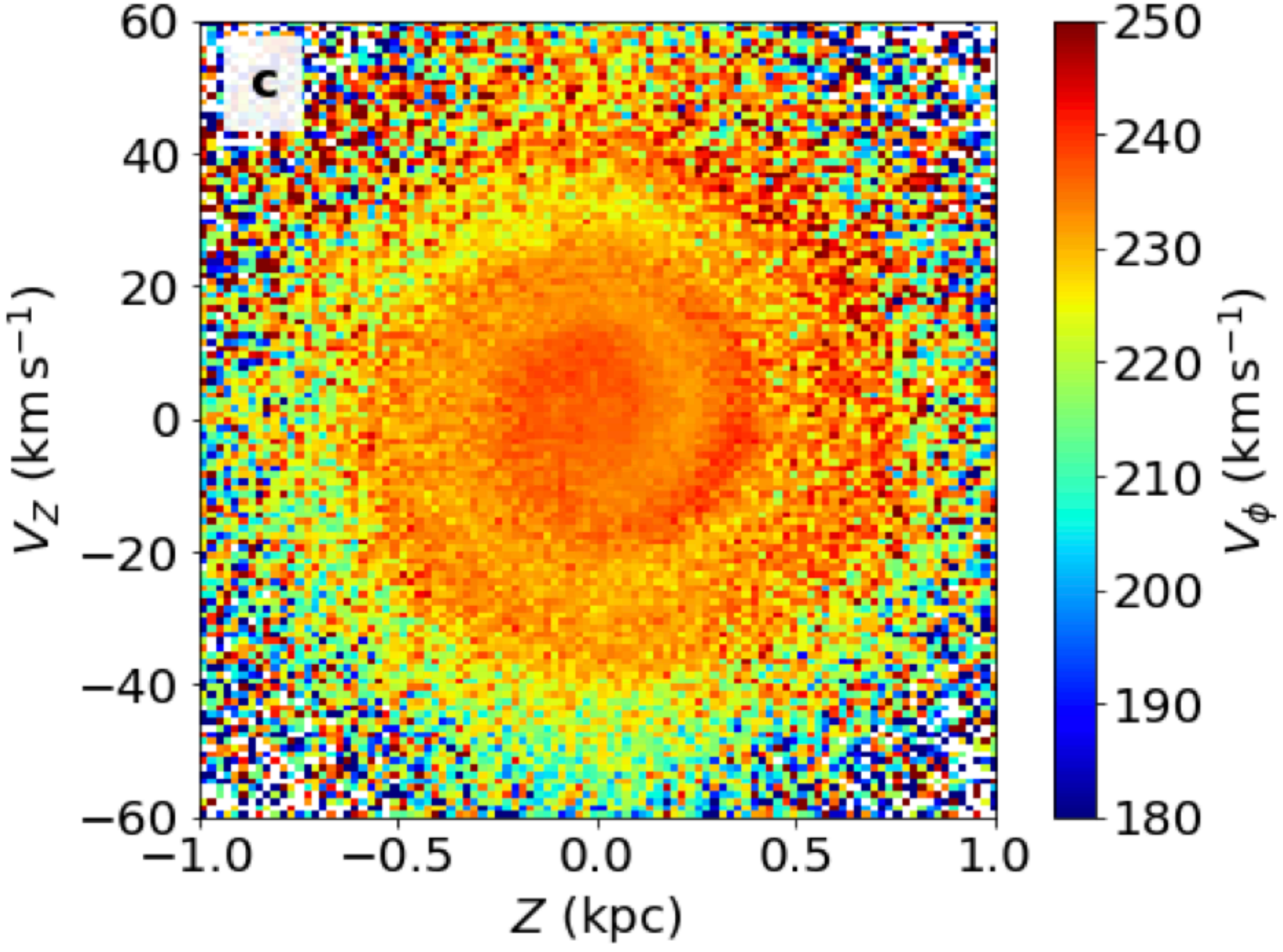
HRD for Gaia DR2 stars within 100 pc (Jao et al. 2018)



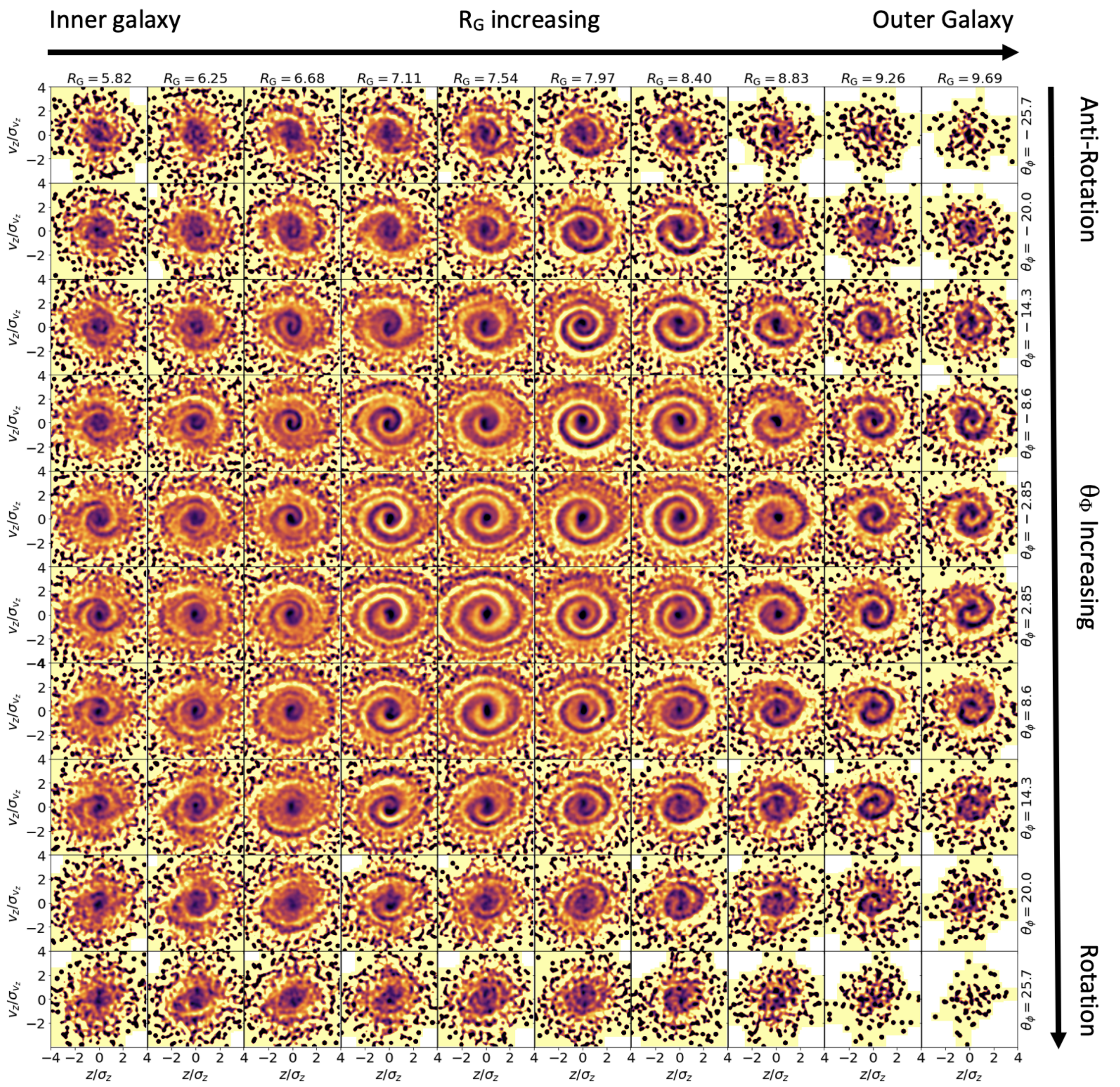

HRD for Gaia DR3 stars within 200 pc and $\varpi/\sigma_{\varpi} > 50$



# Phase-space spirals

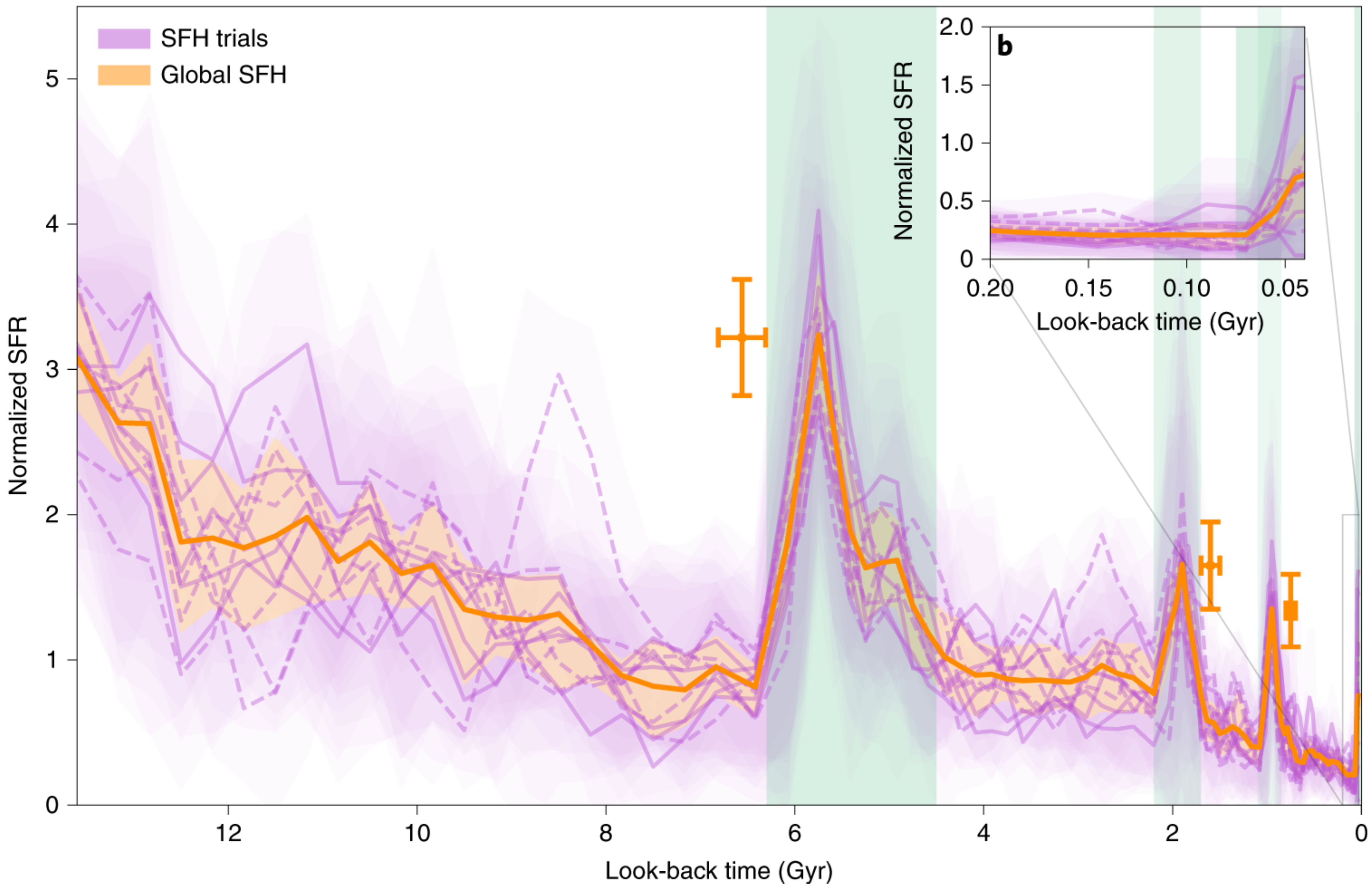



Using Gaia DR2 (Antoja et al. 2018)




Using Gaia DR3 (Hunt et al. 2022)

# Star formation rate in the solar neighbourhood inferred from Gaia data



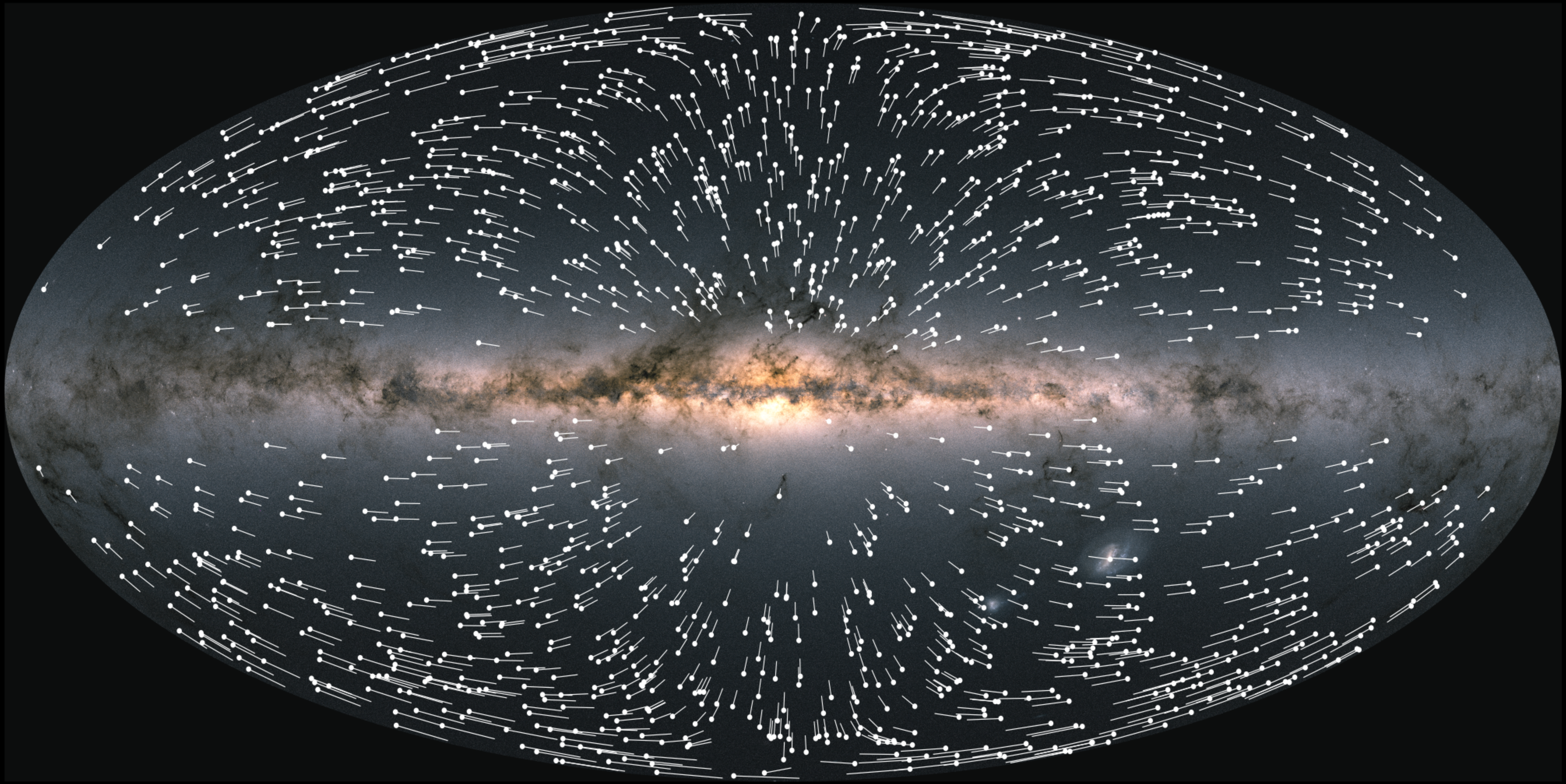

Star formation rate (SFR) derived from fitting synthetic CMD to Gaia DR2 data for stars within 250 pc of the Sun.

Narrow episodes of enhanced star formation coinciding with proposed Sgr pericentre passages.

(Ruiz-Lara et al. 2020)

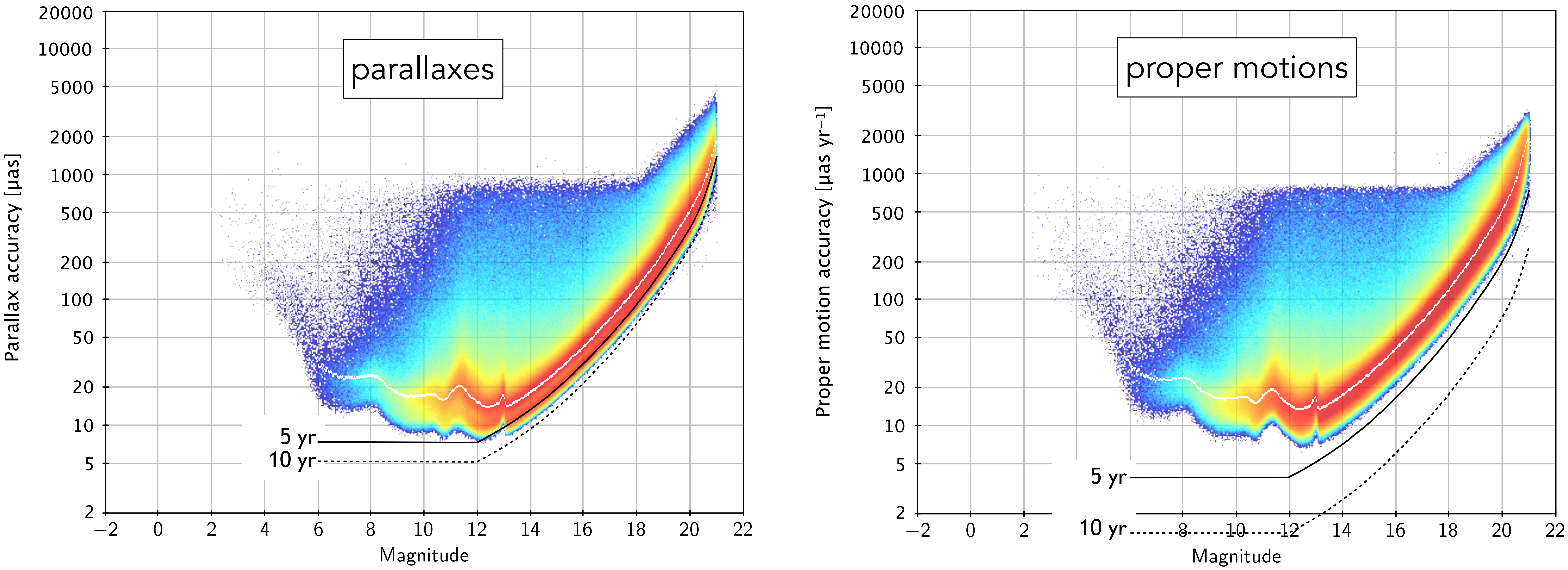
# Acceleration of the Solar System Barycentre (Gaia Collaboreation et al. 2021)

Plot shows the fitted proper motion model (amplitude $a/c$ = 5.05 ± 0.35 µas/yr) for a random 0.1% subset of the Gaia EDR3 quasars



Background image credit: ESA/Gaia/DPAC (A. Moitinho and M. Barros)

# Astrometric precision of Gaia DR3/DR4/DR5



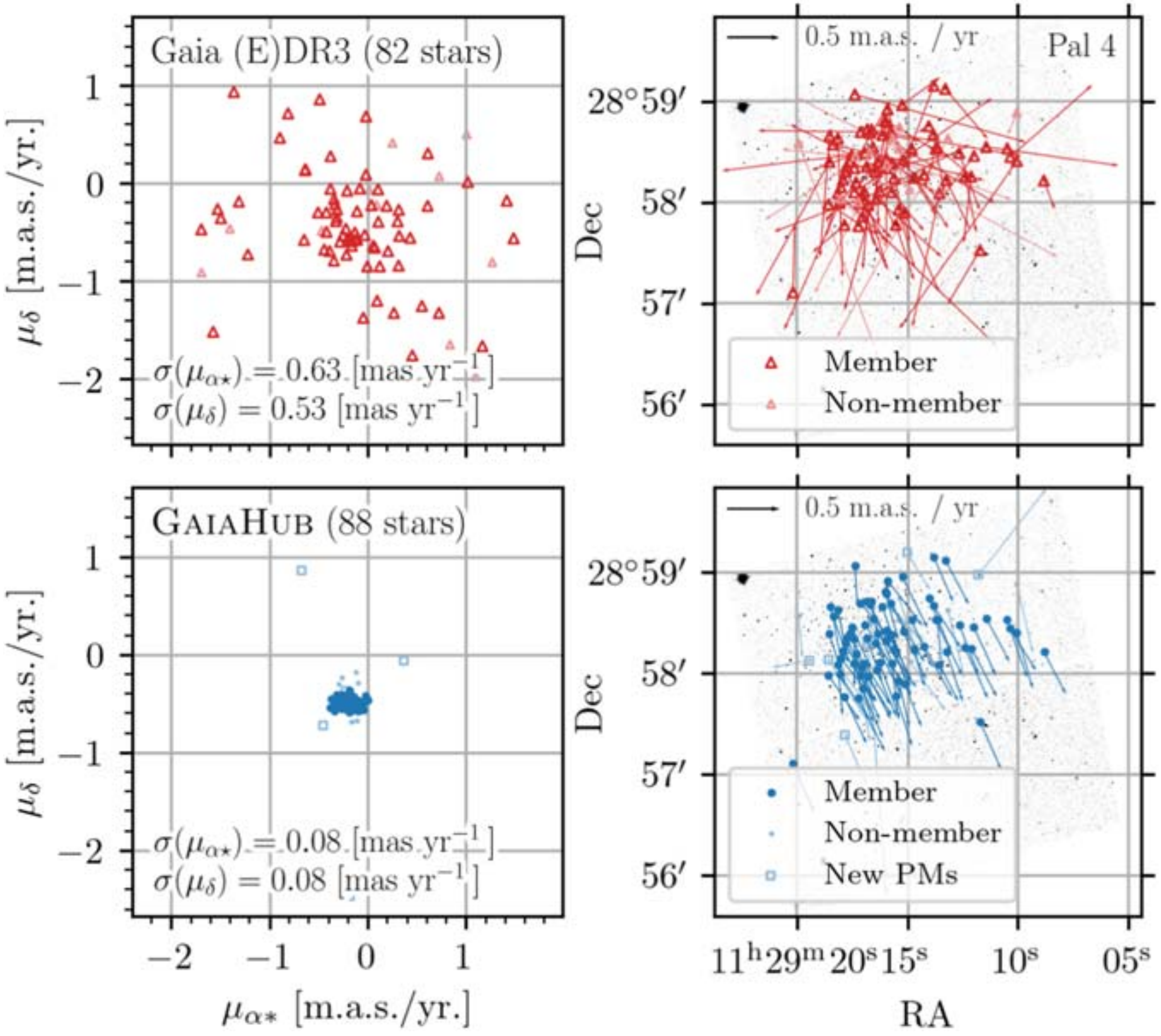

Coloured distribution: actual uncertainties in EDR3 and DR3 (white line = median)

Black curves: extrapolated median uncertainties for DR4 and DR5

# Gaia cannot do everything (alone)

| | *Gaia* | *extension/synergy* |
|---|---|---|
| ***sensitivity*** | G < 21 | large ground-based telescopes<br>space telescopes (HST, JWST, ...) |
| ***precision*** | 10–1000 μas | optical/IR interferometers<br>space telescopes |
| ***resolution*** | 0.1 arcsec | adaptive optics, optical/IR interferometers<br>space telescopes |
| ***time baseline*** | ≤10 years | archival data, HST, Hipparcos<br>GaiaNIR |
| ***wavelength*** | 0.4–1.0 μm | IR interferometers, radio arrays (VLB, SKA), VLBI<br>GaiaNIR, JWST |

# An example of synergies: Gaia + archival HST data




Improved proper motions for faint stars in globular cluster Palomar 4 (at 109 kpc), obtained by combining Gaia DR3 data with archival HST data:

Gaia only: $\sigma_\mu \simeq 0.6$ mas yr$^{-1}$

Gaia + HST: $\sigma_\mu \simeq 0.08$ mas yr$^{-1}$

(del Pino et al. 2022)

# Summary

- ✓ Global astrometry (large-angle measurements) is essential for providing a celestial reference frame, undistorted proper motions over the whole sky, and absolute parallaxes
- ✓ In the radio domain, ground-based VLBI achieves sub-mas global astrometry and differential measurements at the 10 μas level
- ✓ In the optical domain, the Earth's atmosphere and gravity impose insurmountable problems for global astrometry, and high-precision differential measurements are only possible under special circumstances
- ✓ Gaia uniquely combines the advantages of space in a global optical scanning survey mission
- ✓ Gaia provides a framework for combining and unifying the astrometric capabilities of various ground-based and space facilities
- ✓ To maintain and extend this framework, another global mission will be needed in the future