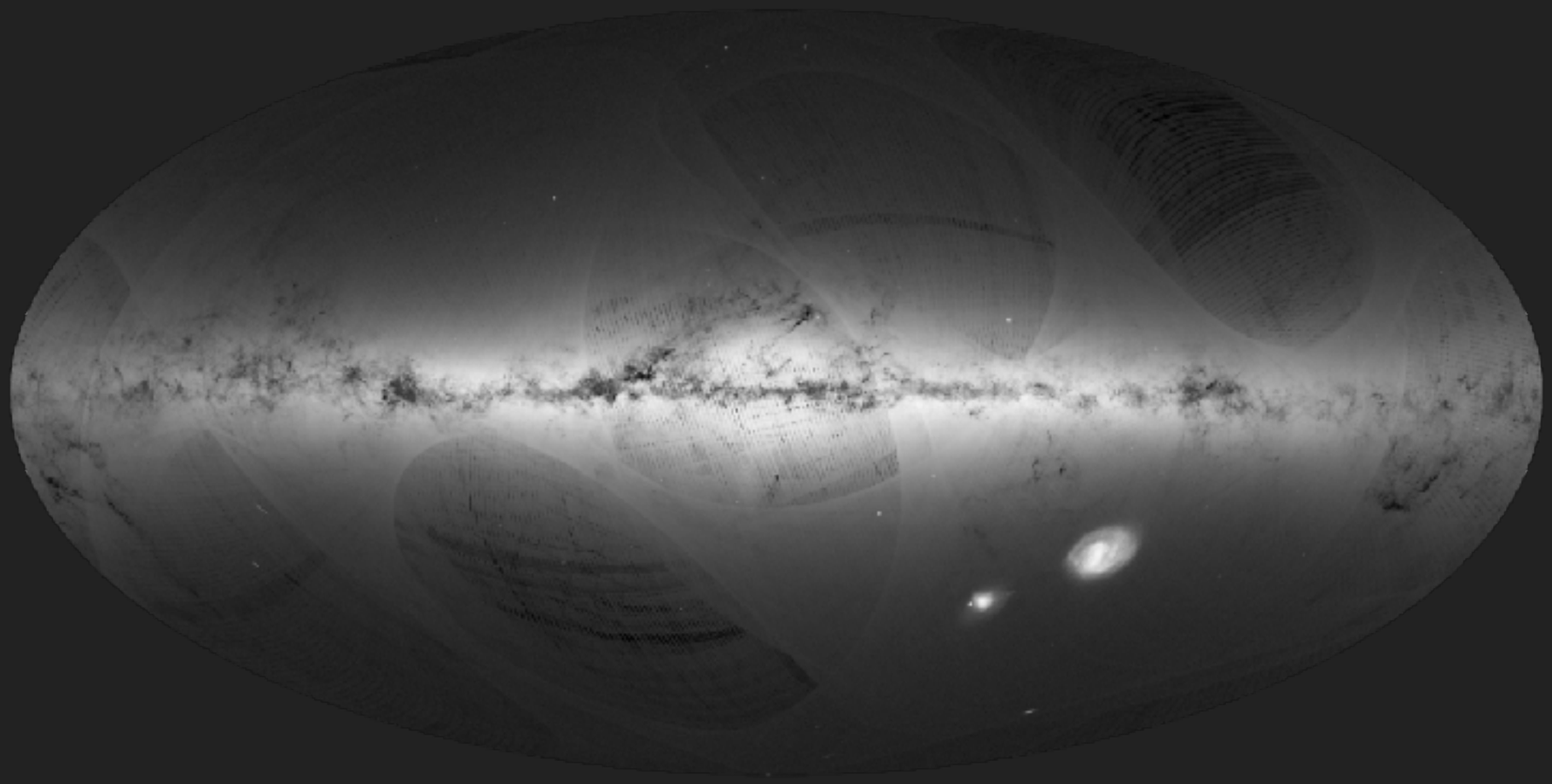
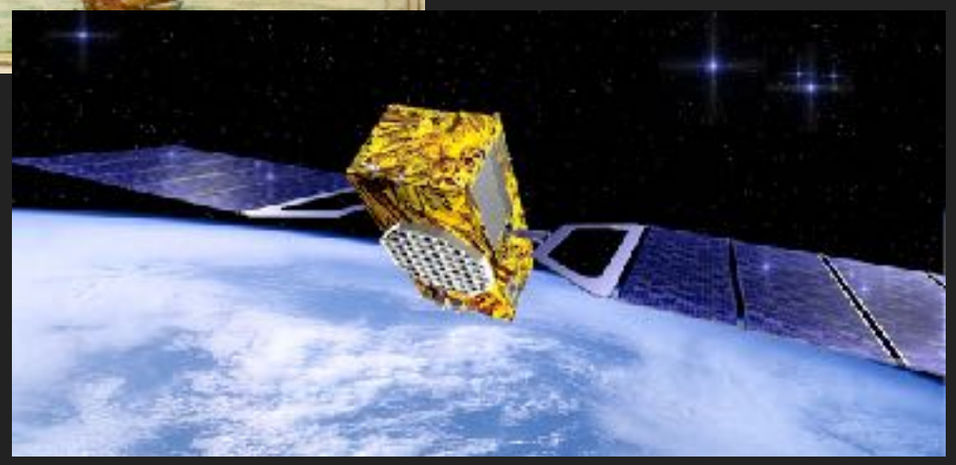


Alberto Krone-Martins (U. Lisboa/CENTRA)

A glimpse of current space astrometry concepts

ESA/DPAC/U.Lisboa/CENTRA

Why should I care?



"Mais ce serait prendre la question par son petit côté."

"But this would be to take the question by its least important side."

Henri Poincaré

in *La valeur de la science*

"(...) c'est elle qui nous a fait une âme capable de comprendre la nature."

"(...) it is she who made us a soul capable of understanding nature."

"Et d'abord, c'est l'astronomie qui nous a appris qu'il y a des lois."

"And first of all, astronomy it is which taught that there are laws."

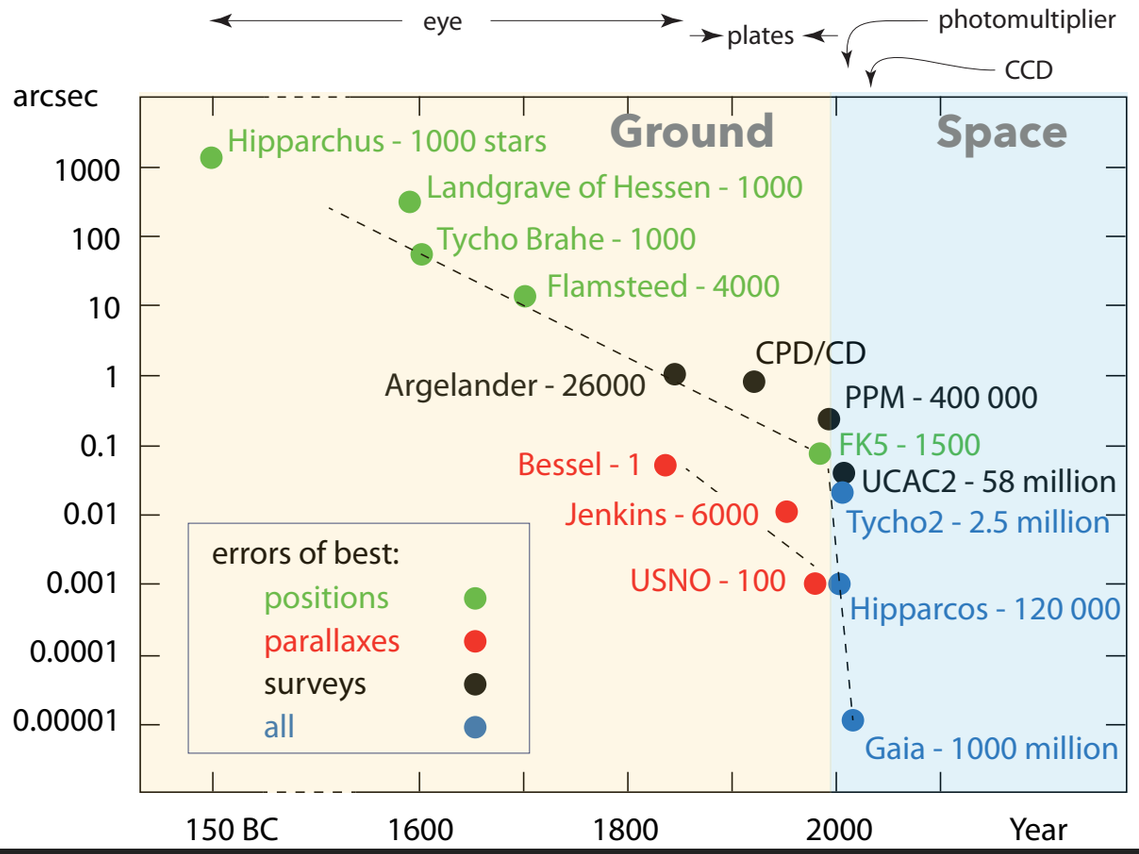
Henri Poincaré

in *La valeur de la science*

ESA/HIPPARCOS

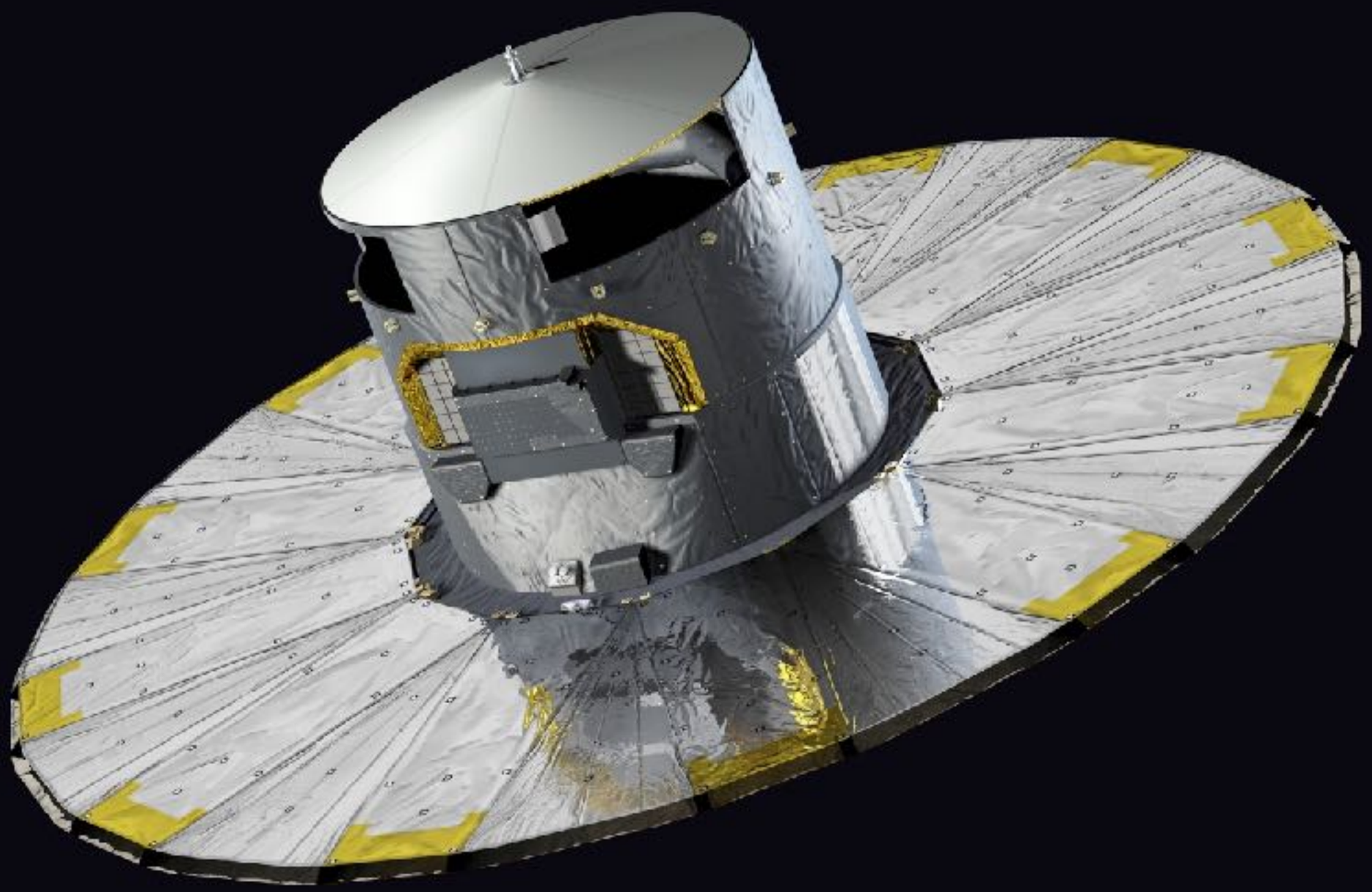
NASA/ESA/HST FGS

Astrometric accuracy over time



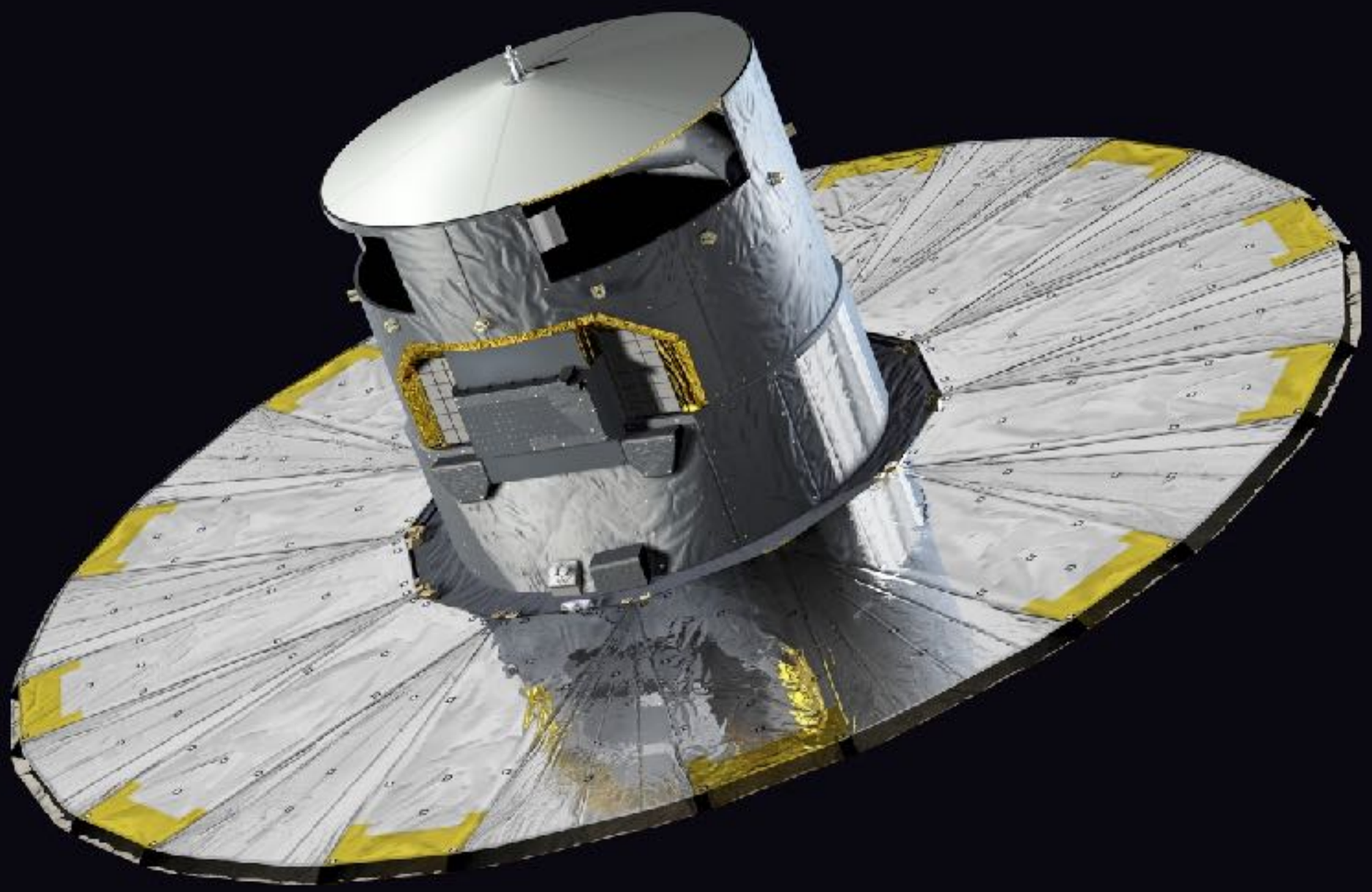
Perryman 2017, adapted

The present: ESA/Gaia



ESA/Airbus

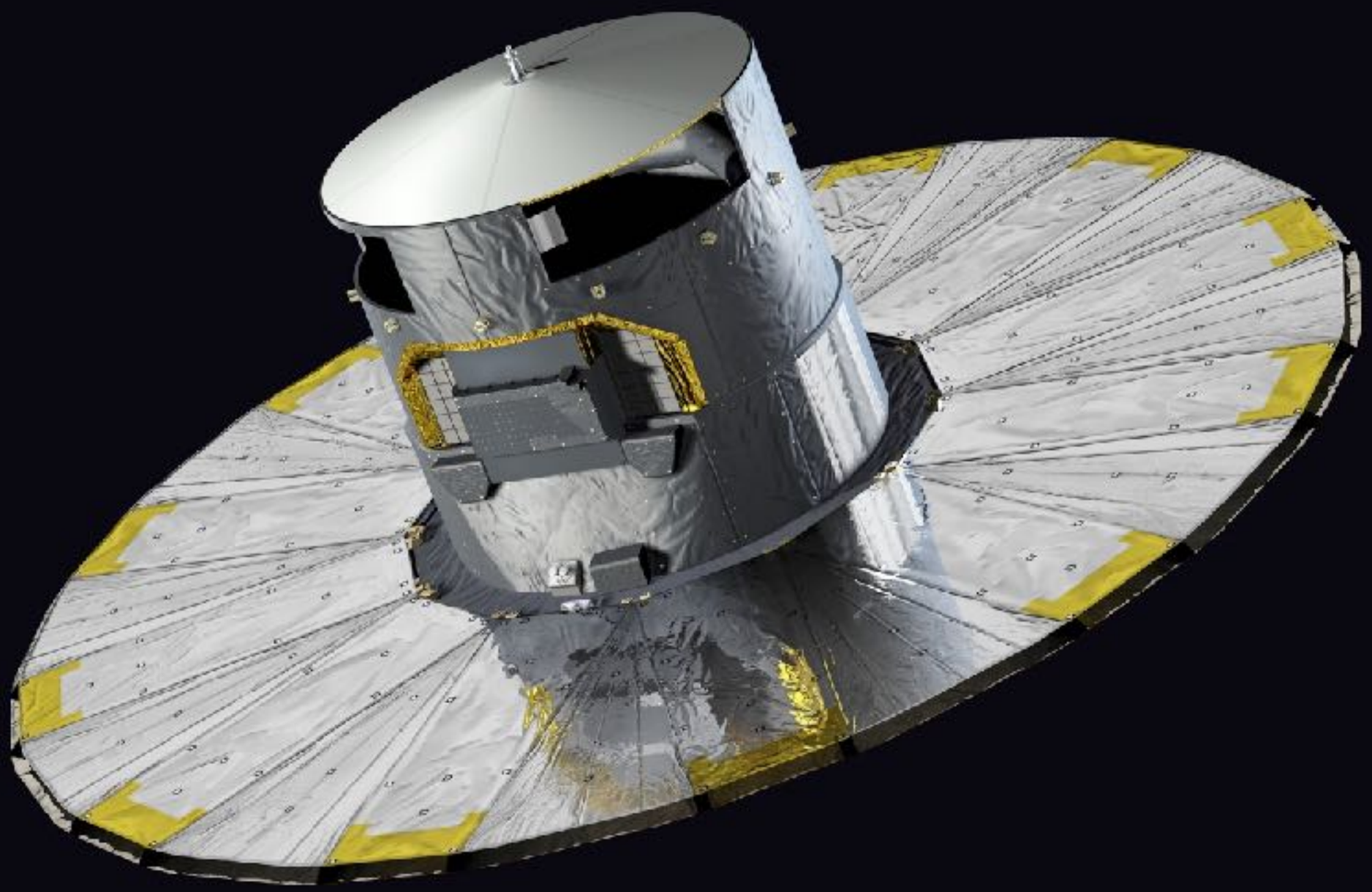
LAUNCHED ON DEC. 2013 TO L2



ESA/Airbus

LAUNCHED ON 19 DEC. 2013
IN NOMINAL OPERATIONS

gaia

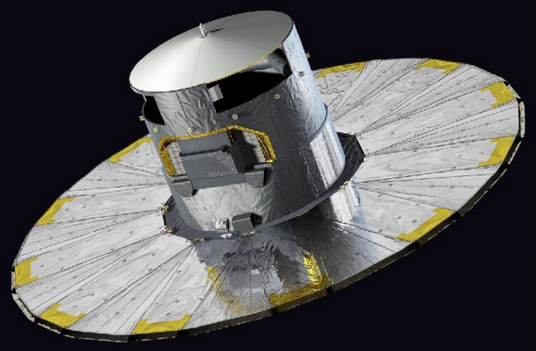


ESA/Airbus

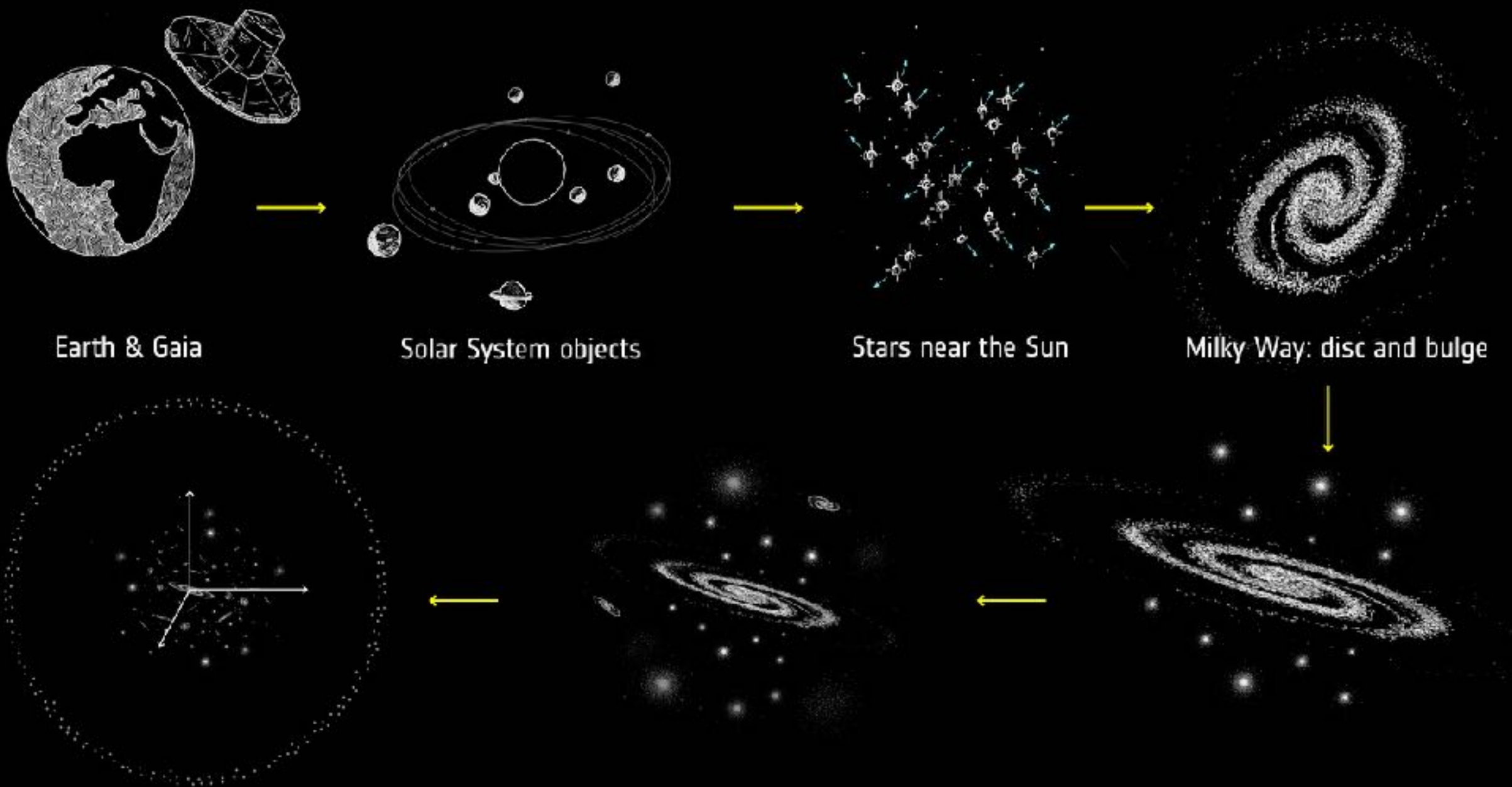
ESA/Gaia

THE SKY AT μas : MW in 3D

- Main scientific driver:
  - Unravel the structure, dynamics and history of the Milky Way



gaia


Earth & Gaia
Solar System objects
Stars near the Sun
Milky Way: disc and bulge
Celestial reference frame: distant quasars
Nearby galaxies
Milky Way: halo and globular clusters

ESA/Gaia

- Accurate spatial and dynamic structure of the disk and halo
- Accurate and detailed mapping of the Galactic dark-matter distribution
- Large-scale survey of extra-solar planets (~7,000) : *architecture*
- Large-scale survey of Solar-system bodies (~250,000)
- Accurate and definitive distance standards out to the LMC/SMC
- Quasar and lenses detection, redshifts, microlensing structure (~500,000)
- Fundamental quantities like PPN γ to 10^{-6}

ESA/Gaia

THE SKY AT µas : MW in 3D

- Provide global and absolute astrometry > 10^9 sources, ~10-100 µas
- Magnitude limited at G < 20.7 (completeness to 20)
- Objects: Stars, asteroids, galaxies, QSOs
- Derived catalogue data: Parallaxes, proper-motions, time-resolved & multi-band photometry (G < 20.7) and radial velocities (G ~< 16.5)

ESA/Gaia

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> ONE TRILLION Gaia measurements as of this morning (18th Nov)

Astrometry + G-Photometry	> 1.1 x 10^{12}
Spectrophotometry (300-1000 nm SEDs)	> 2.2 x 10^{11}
Spectroscopy (R~11500, 847-874 nm)	> 2.1 x 10^{10}

ESA/Gaia

THE SKY AT μas : MW in 3D

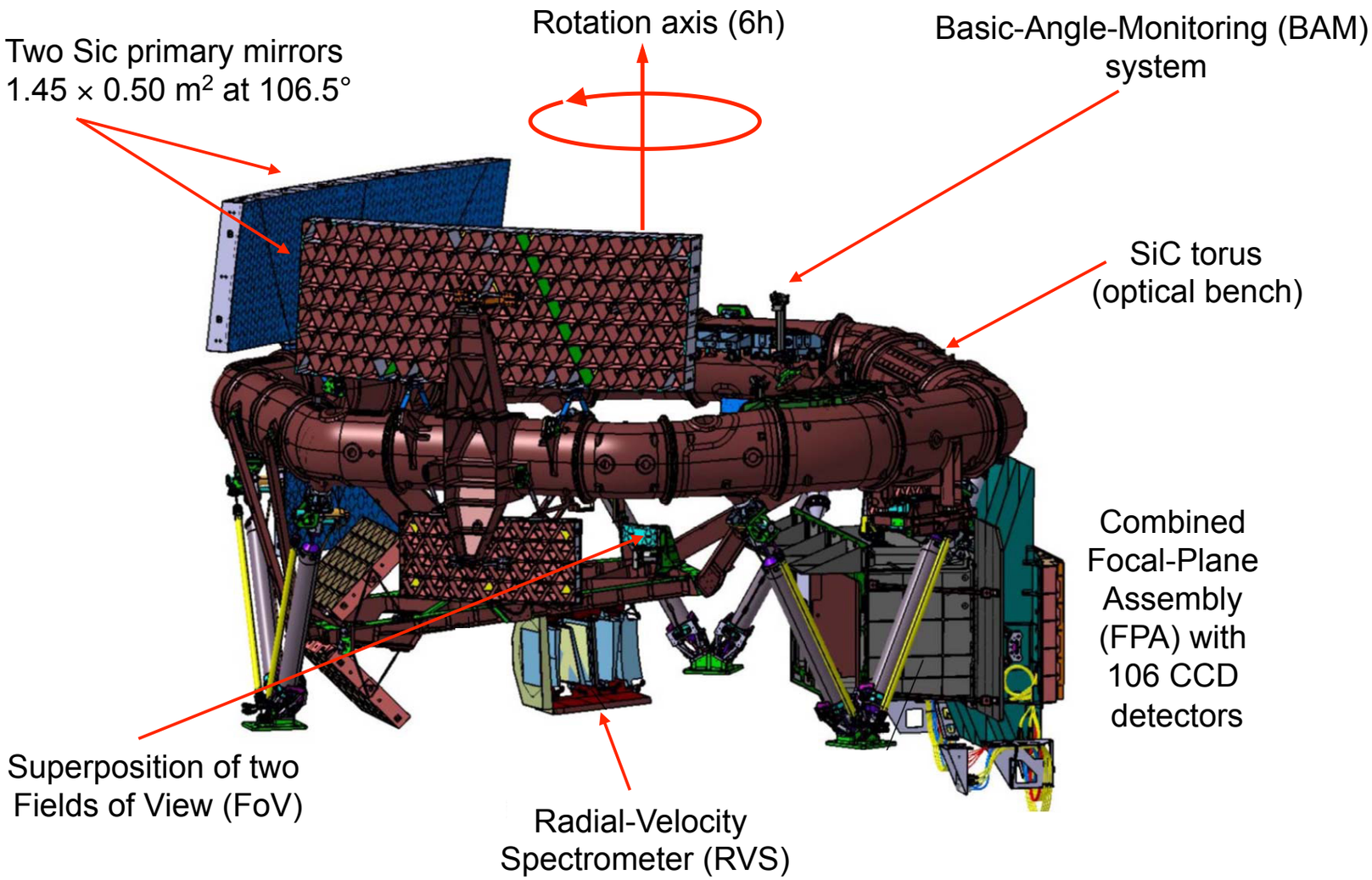
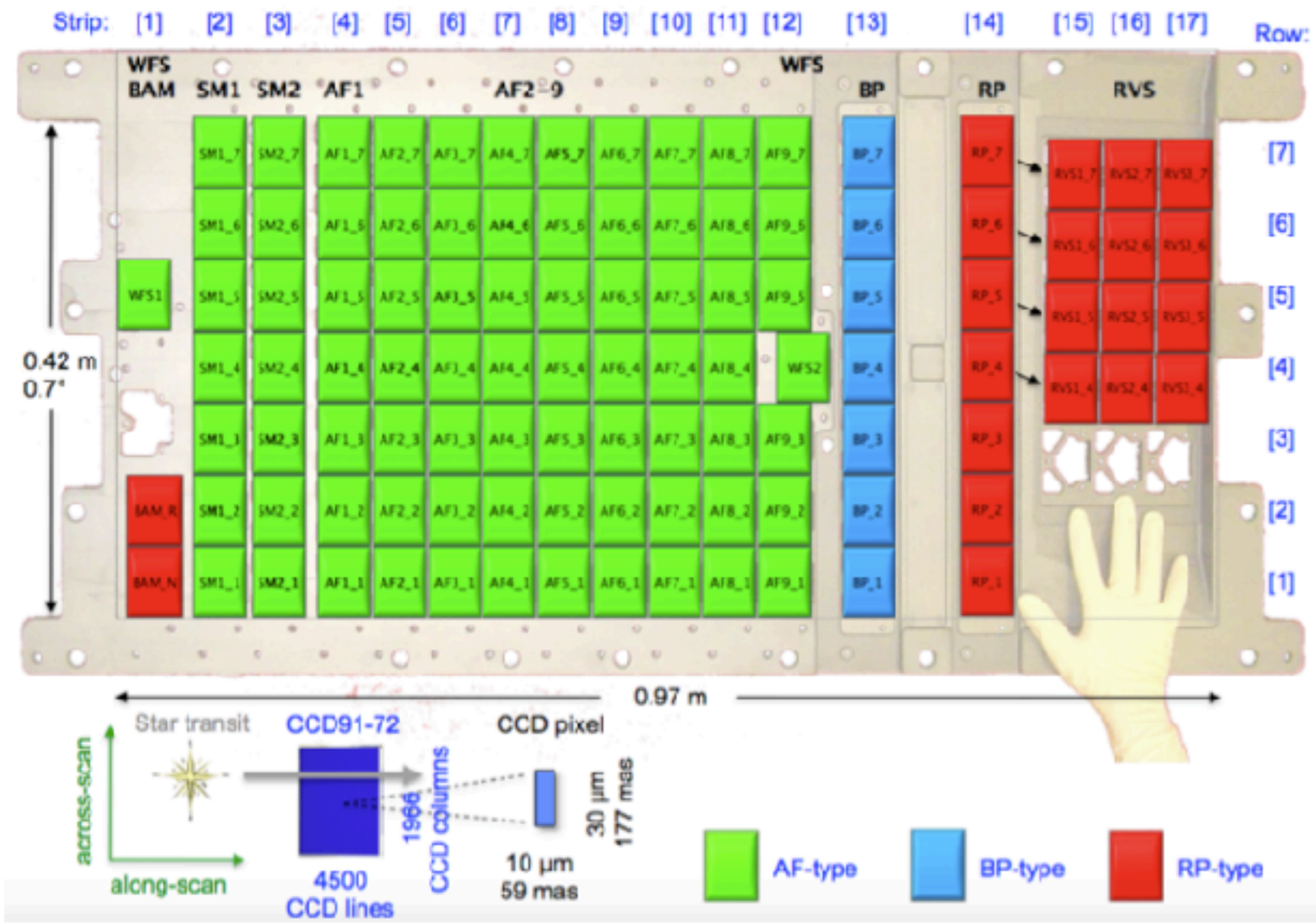


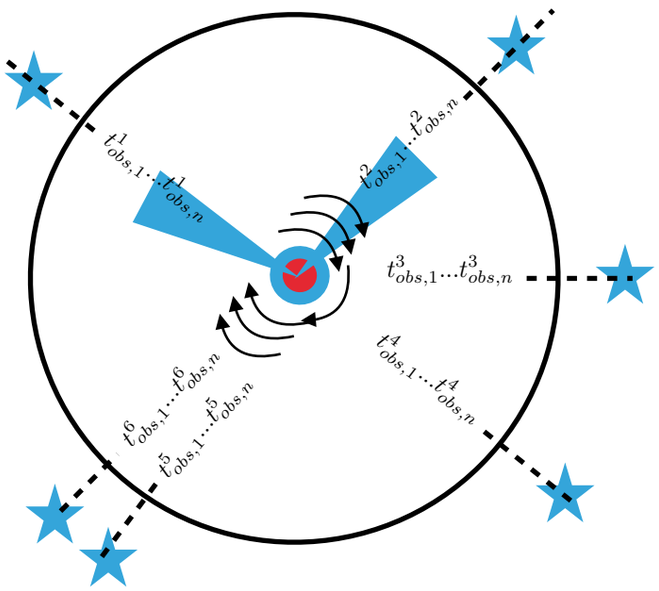
Figure courtesy EADS-Astrium

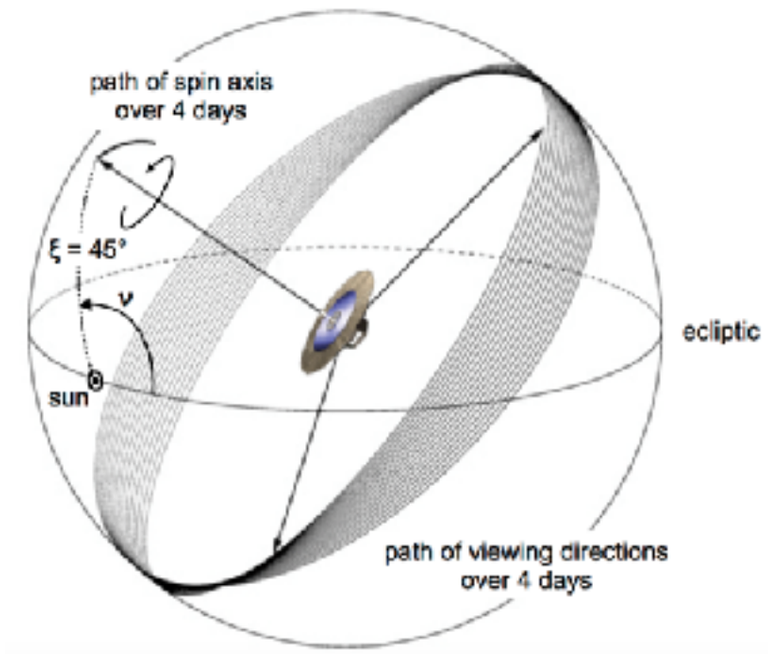
ESA/Gaia

THE SKY AT µas : MW in 3D



PRINCIPLE





Adapted from Gaia Collaboration 2016

Astrometric Global Iterative Solution

(see Lindegren et al. 2012)

$$\frac{\partial t}{\partial s_i}\Delta s_i + \frac{\partial t}{\partial a_j}\Delta a_j + \frac{\partial t}{\partial c_k}\Delta s_k + \frac{\partial t}{\partial g}\Delta g \approx t_{obs} - t_{calc}(s_i, a_j, c_k, g)$$

s_i : object astrometric parameters of the i-th star

a_j : satellite attitude parameters at the j-th time interval

c_k : instrument calibration parameters for the k-th CCD/FOV, etc

g : global parameters (e.g. light deflection in Solar System)

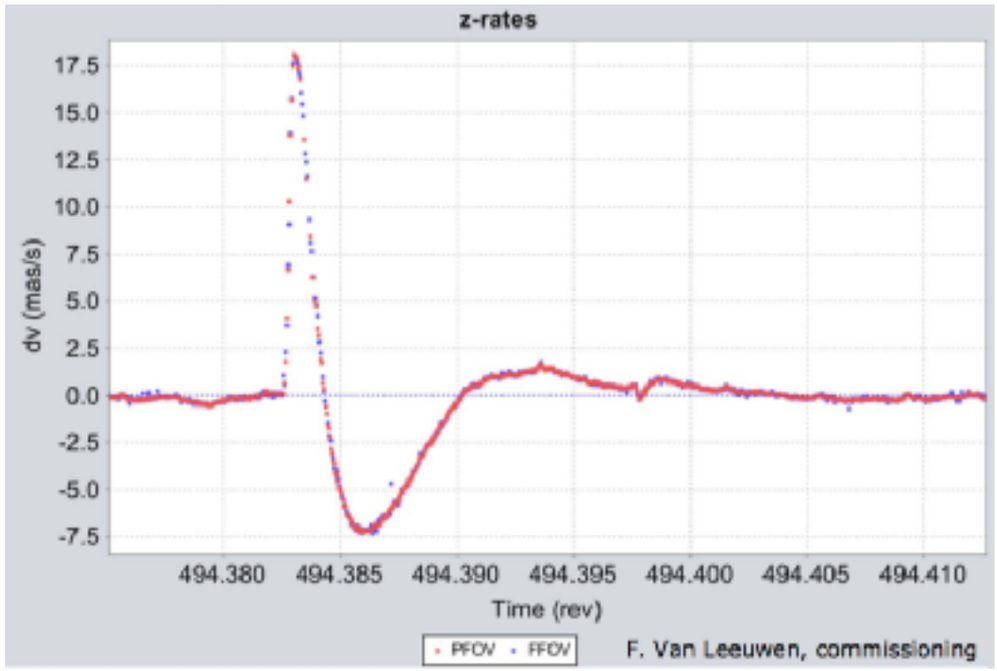
$$\min \quad \sum_{obs}[t_{obs} - t_{calc}]^2 W_{obs}$$

VERY CHALLENGING!

Primary solution:
- at least 10^{11} equations with $6x10^8$ unknowns
- no direct solution possible…

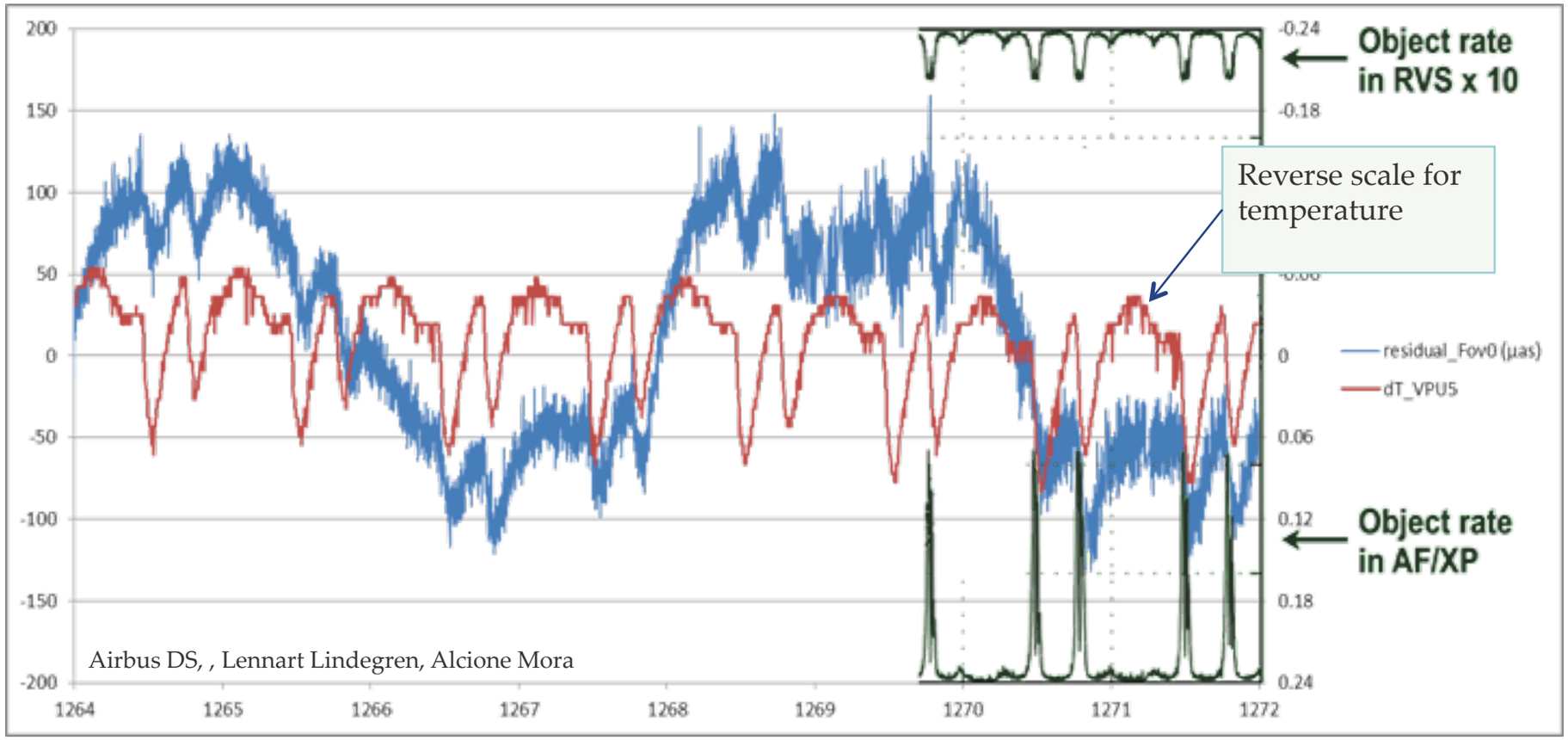
Some lessons

- Certain things are not stable as initially thought (or planned)
  - So: no moving parts (gyros, reaction wheels, antenna steering, …)
  - Passive thermal stability if possible
  - Focus evolves significantly (hysteresis)
- Micrometeoroids (+/- expected)
- Micro-clanks in the SiC structure
  - SiC layers: 1-2 mas, 7.5nm, ~20 Si at.
  - Ground calibration.
- Contamination and outgassing: decontamination campaigns: required to modify SAA
- Unexpected stray-light levels : on-board VPU software mitigation



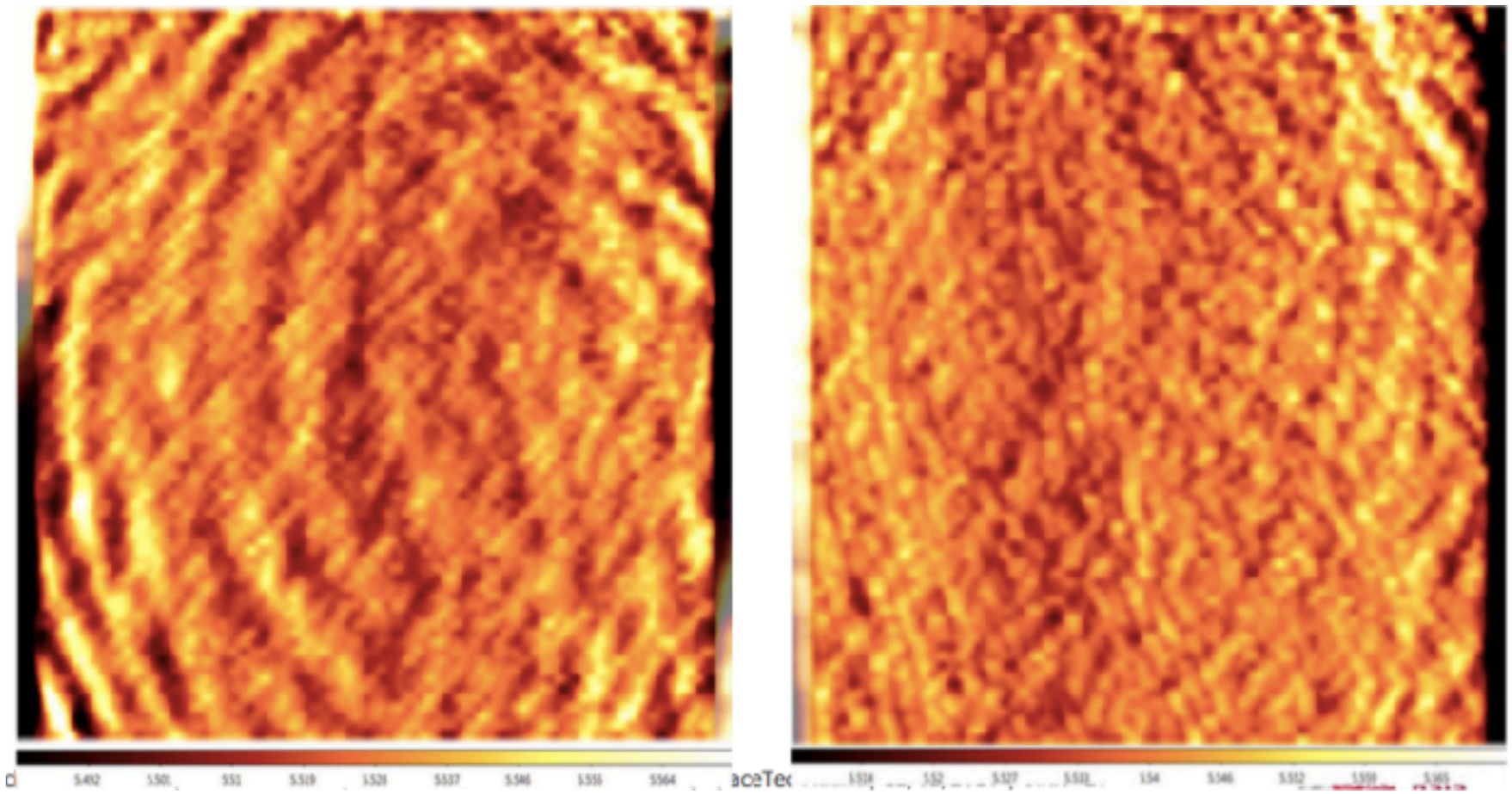
Some lessons

- Certain things are not stable as initially thought (or planned)
  - 24 h slow component: related to downlink (transponder + PDHU)
  - Peaks: follow sky density (galactic plane) SVM computers thermoelastic efffect
  - SVM perturbations propagates to the basic angle. Rule of thumb: 100 μas/K



Some lessons

- Constant frindge period does not exist… wavelet analysis
- Data from the Gaia BAM



Approved : ESA/Gaia Extension of 1.5 years

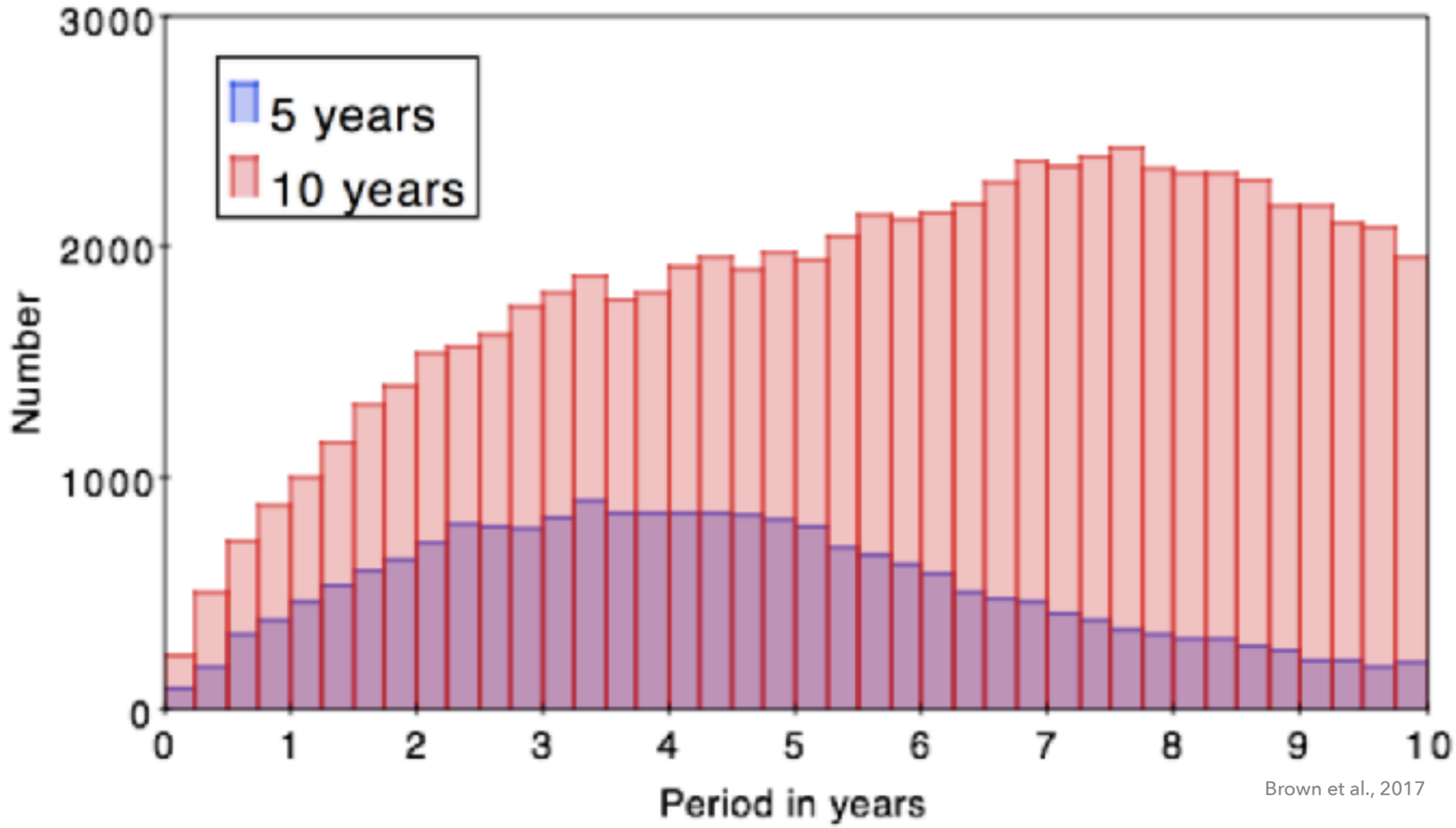
- Most mission results:

$$\sigma(\alpha, \delta, \varpi, \mathrm{mags}, v_{\mathrm{rad}}) \propto t^{-0.5}$$

- Kinematics and dynamics:
  - Proper motions: $\sigma(\mu_\alpha, \mu_\delta) \propto t^{-1.5}$
  - Orbital periods, masses, distances of perturbing bodies: $\propto t^{-4.5}$
- Additional extensions will be requested [final catalogue then TBD], but indicative extension until 2022.

ESA/Gaia Extension

- Exoplanets (Neptune-Jupiter mass)



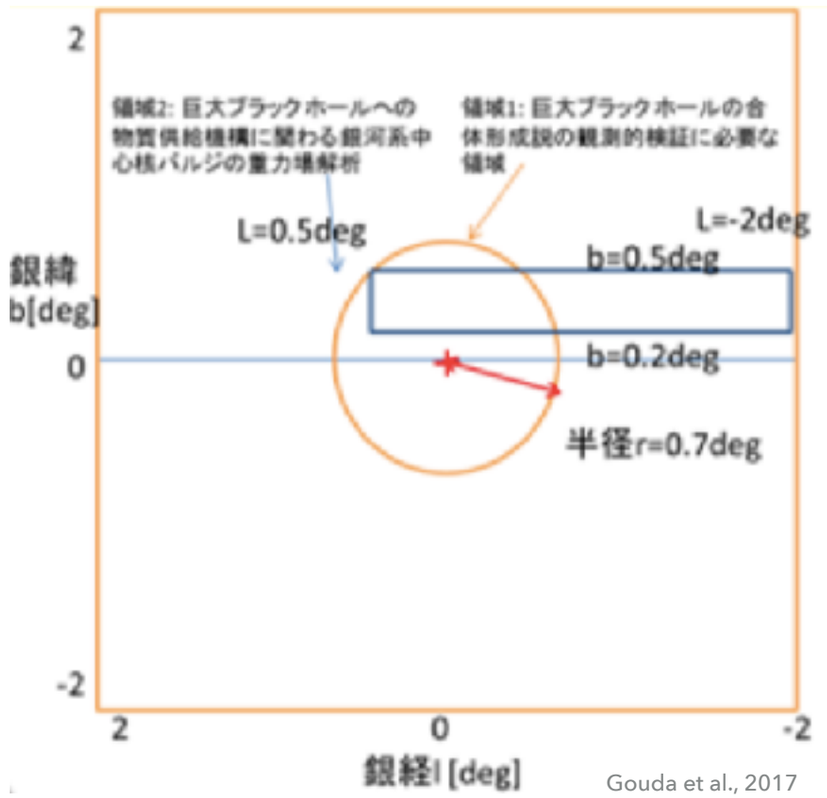
Brown et al., 2017

A glimpse of some of the current proposed concepts

Concept :: Small-JASMINE

THE MISSING LINK BETWEEN THE OUTER BULGE (GAIA) AND THE CENTRAL REGION (GRAVITY, MICADO, ETC)

- Main science drivers:
  - *Study if small supermassive black holes merge to form the supermassive black holes in the centers of galaxies*
    - Galactic Bulge: ~4900 stars (Hw<12.5)
    - +3500 at LOS
  - *Does the MW has an inner bar?*
    - Near-plane: ~5000 stars (Hw<12.5)
    - +1600 at LOS

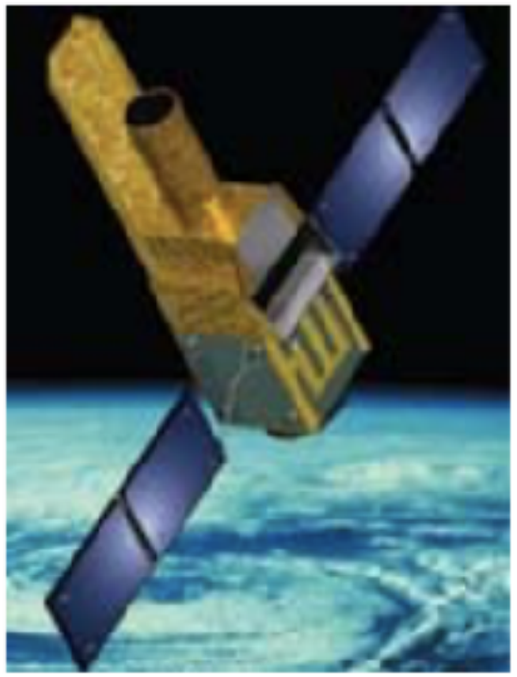


Gouda et al., 2017

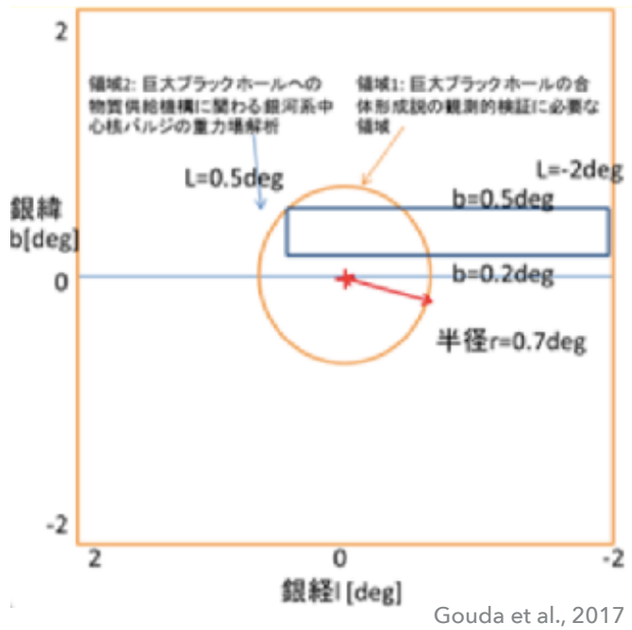
PI: N. Gouda (NAOJ)

Concept :: Small-JASMINE

- Pointed, step and stare mission
- 3 years mission at Sun Sync. Orbit (550km)
- JAXA proposal with launch: 2023-2024 (advanced Epsilon)
- Parallax, positions <20 μas (at Hw<12.5)
  - ~16% at 8kpc
- Proper motions <20 μas/yr
  - ~0.8 km/s at 8kpc
- Photometry at J and H < 0.01 mag



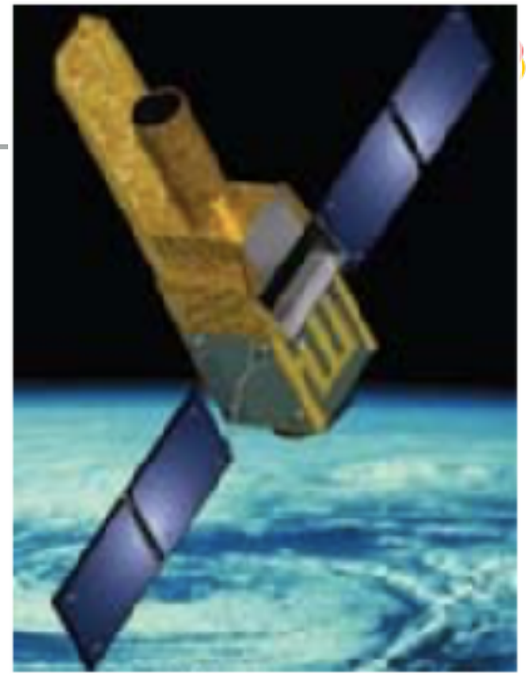
Gouda et al., 2017



Gouda et al., 2017

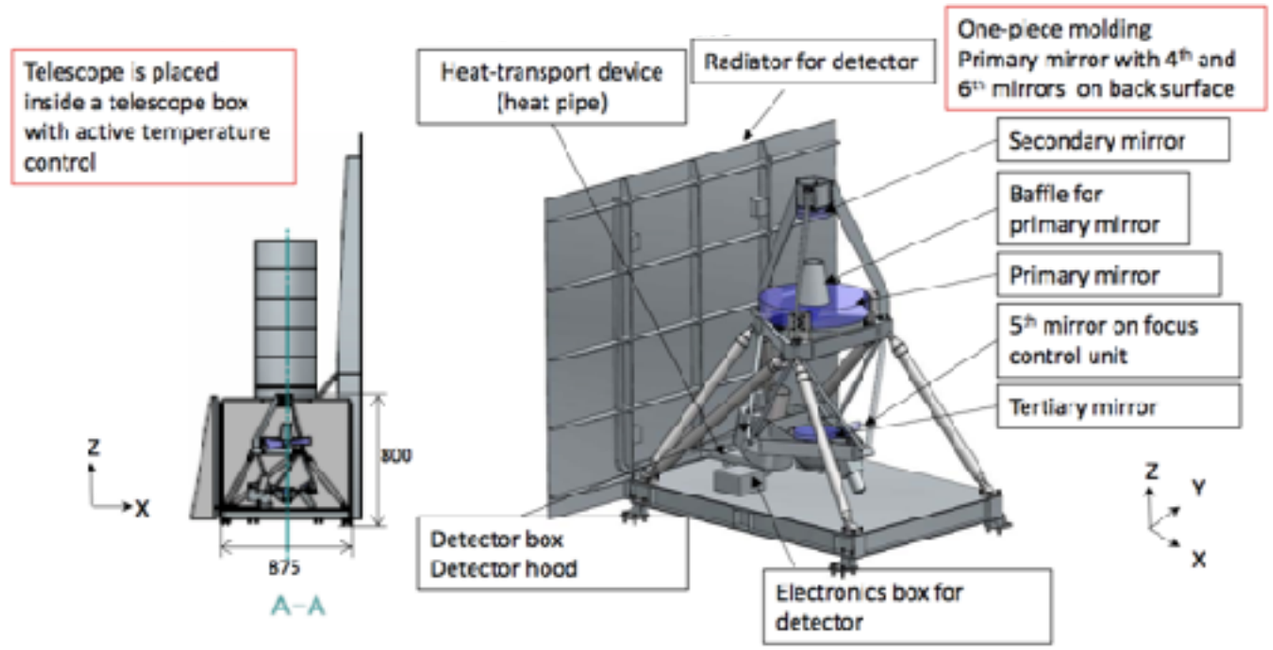
PI: N. Gouda (NAOJ)

Concept :: Small-JASMINE



Gouda et al.. 2017

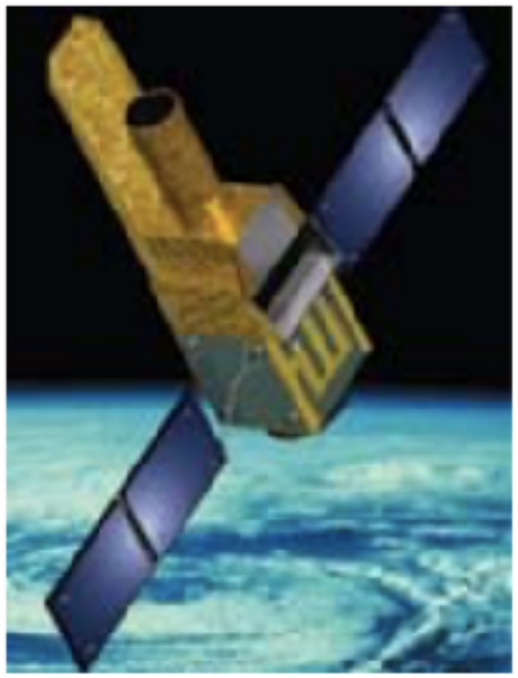
- Modified Korsch System, 0.3m Aperture
- FoV : 0.6° x 0.6°
- FPA Detectors:
  - 1x H4RG10 (1.1 - 1.7μm)
  - 2x H1RG (J, H)
- Optics: CLEARCERAM-Z EX (CTE ~ 0 +/- 1 10^{-8}/K)
- Structure: New **super-super-invar** space alloy created for Small-JASMINE with CTE ~ 0 +/- 5 10^{-8}/K



PI: N. Gouda (NAOJ)

Concept :: Small-JASMINE

- Status:
  - Successfully passed the MDR (Mission Design Review)
  - Successfully passed the ISAS/JAXA International Review (12/2017)
  - Currently in phase Phase A2 with *only one competitor*



Gouda et al., 2017

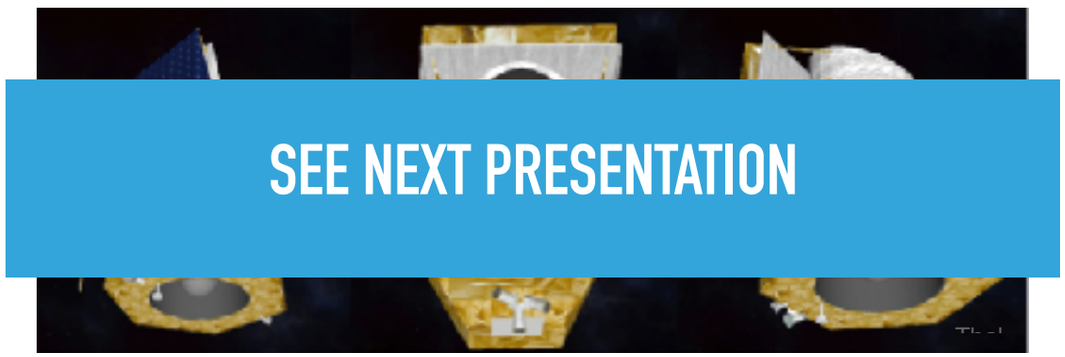
PI: N. Gouda (NAOJ)

PROPOSAL UNDER EVALUATION

Concept :: Theia

PUSHING RELATIVE ASTROMETRY TO Sub-μas

- Main science drivers:
  - The nature of Dark Matter
  - Habitable exoplanet system architectures
  - Matter in&around compact objects
- Minimum “dead-time”: All astrometric stabilization time is used for quasar lenses time delay measurements -> H_0



SEE NEXT PRESENTATION

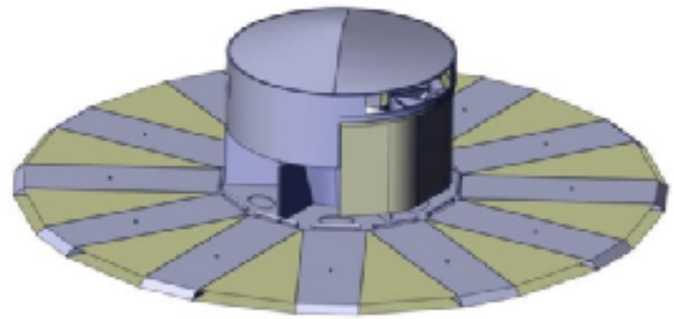
PI: C. Boehm (Durham Univ. & Sydney Univ.)

arXiv:1707.01348

Concept :: GaiaNIR

GAIA IN NIR

- Main science drivers:
  - Spiral arms and GC **obscured by interstellar extinction**
  - Central MW black hole region
  - Brown dwarfs, free floating planets
  - Global (accurate) astrometry inside dusty SFR and young clusters: internal dynamics
  - DM distribution inside the thin disk and spiral arms
  - **Exoplanets & binary systems with periods of 30-40 yr**



PI: D. Hobbs (Lund Univ.)

Concept :: GaiaNIR

ENABLES A JOINT GAIA + GAIANIR GLOBAL SOLUTION

- Proposed separation from Gaia: ~20 years (~2040)
- **Similar precision&accuracy as Gaia for objects seen only in NIR**
- **For objects seen in Optical (Gaia) & IR (GaiaNIR):**
  - Improved parallaxes:
    - **sqrt(2) improvement**
  - Improved overall proper motions:
    - **14x better proper motions. At G~15, ~1.8 uas/yr.**

PI: D. Hobbs (Lund Univ.)

Concept :: GaiaNIR

- Challenges identified at ESA/CDF:
  - Critical detector technology NIR+TDI is not available
  - The large FPA is challenging
  - Payload Data Handling and Telemetry are very challenging (TRL-2)
  - A large (L4?) mission is necessary
    - M with very significant international contributions

CONCEPT STAGE
WAITING FOR ESA DEFINITION OF LARGE MISSION PLANS

PI: D. Hobbs (Lund Univ.)

The shopping cart

Early-Mid 21st Century Space-Astrometry needs

- Infra-red capable detectors operating in TDI mode [Global missions]
- Structural materials with very low CTE (<10^{-8})
- Stricter stray-light control (materials better than Vantablack)
- Detectors capable of high-dynamical ranges (mag. 10-24)
- Higher downlink telemetry: >100 Mbps
- “Intelligent” satellite operations
  - Routine is good: maximize routine + minimize dSAA and thermal

Early-Mid 21st Century Space-Astrometry needs

- **Long-term instrument stability**
  - Aberrations are less important than long-term stability of the aberrations
- **Build for stability, plan for instability**
  - Gaia lesson: **continuous monitoring** is essential
  - Interferometers + detailed calibration plan (with generous margins) for optics, instrument geometry and detectors
- **External constraints:**
  - **Environment**, e.g. micrometeorites, detector evolution + CR (CTI), GWs for Global
  - Light deflection parametrization in the solar system is good to nas for narrow FoVs
  - **Stellar activity** start to play a serious role for nearby objects: effects at uas scales

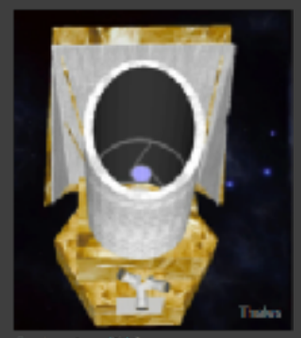
2020 2030 2040

Relative
"large" FoV

Small-JASMINE

Explore
STEP
(+WFIRST, Euclid, etc.)

Theia



Relative
Fizeau

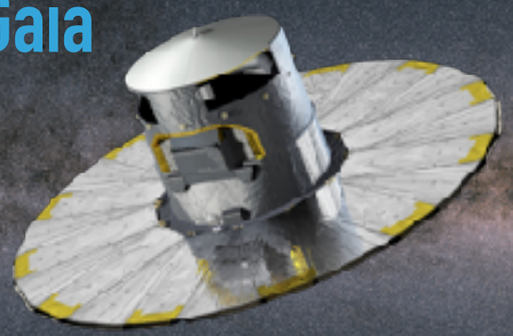
TOLIMAN

STARE

AGP

Global
All-Sky

Gaia



GaiaNIR