The first release of astrometric and photometric data from ESA's Gaia mission

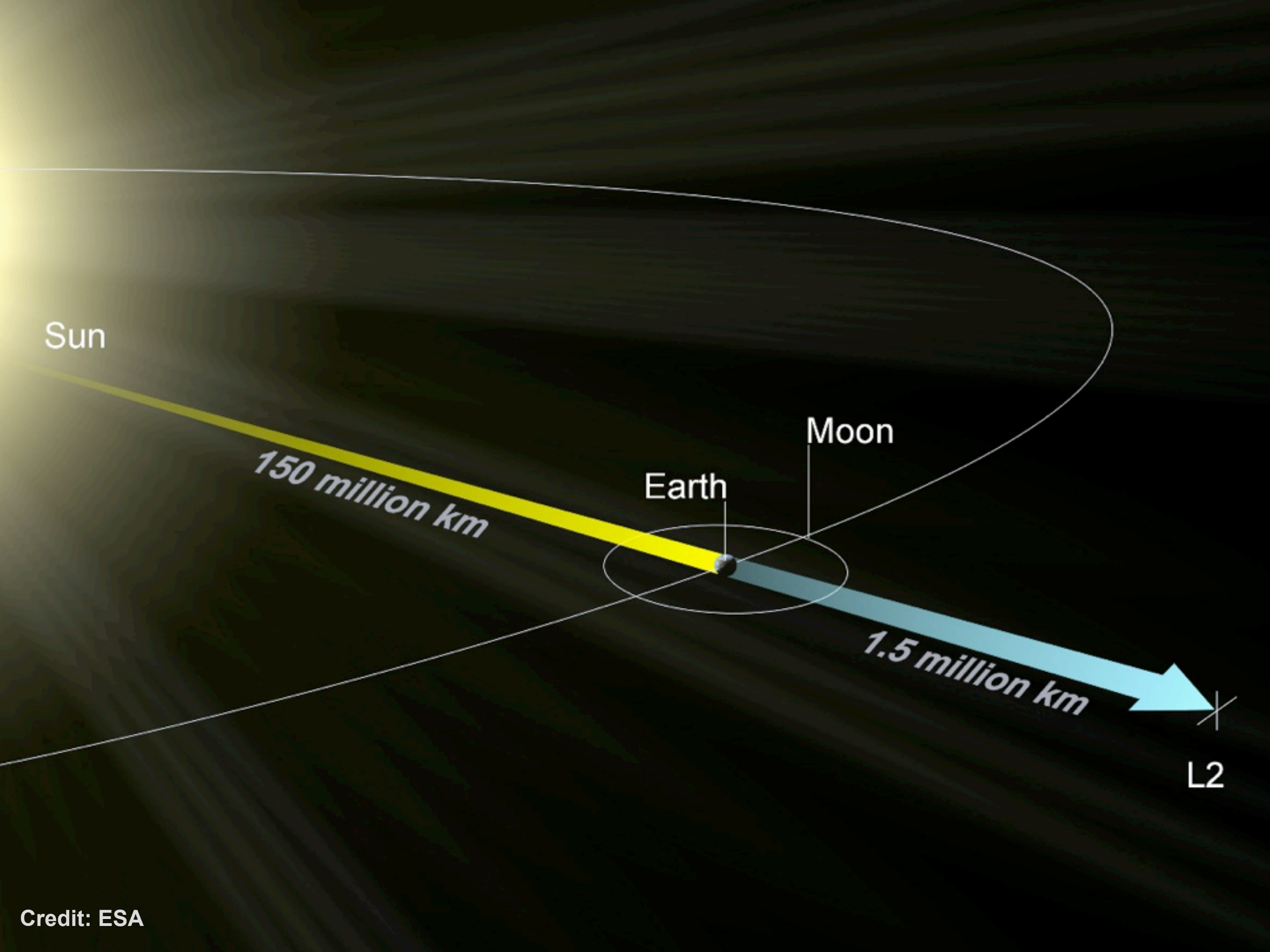
Lennart Lindegren

Department of Astronomy and Theoretical Physics
Lund University

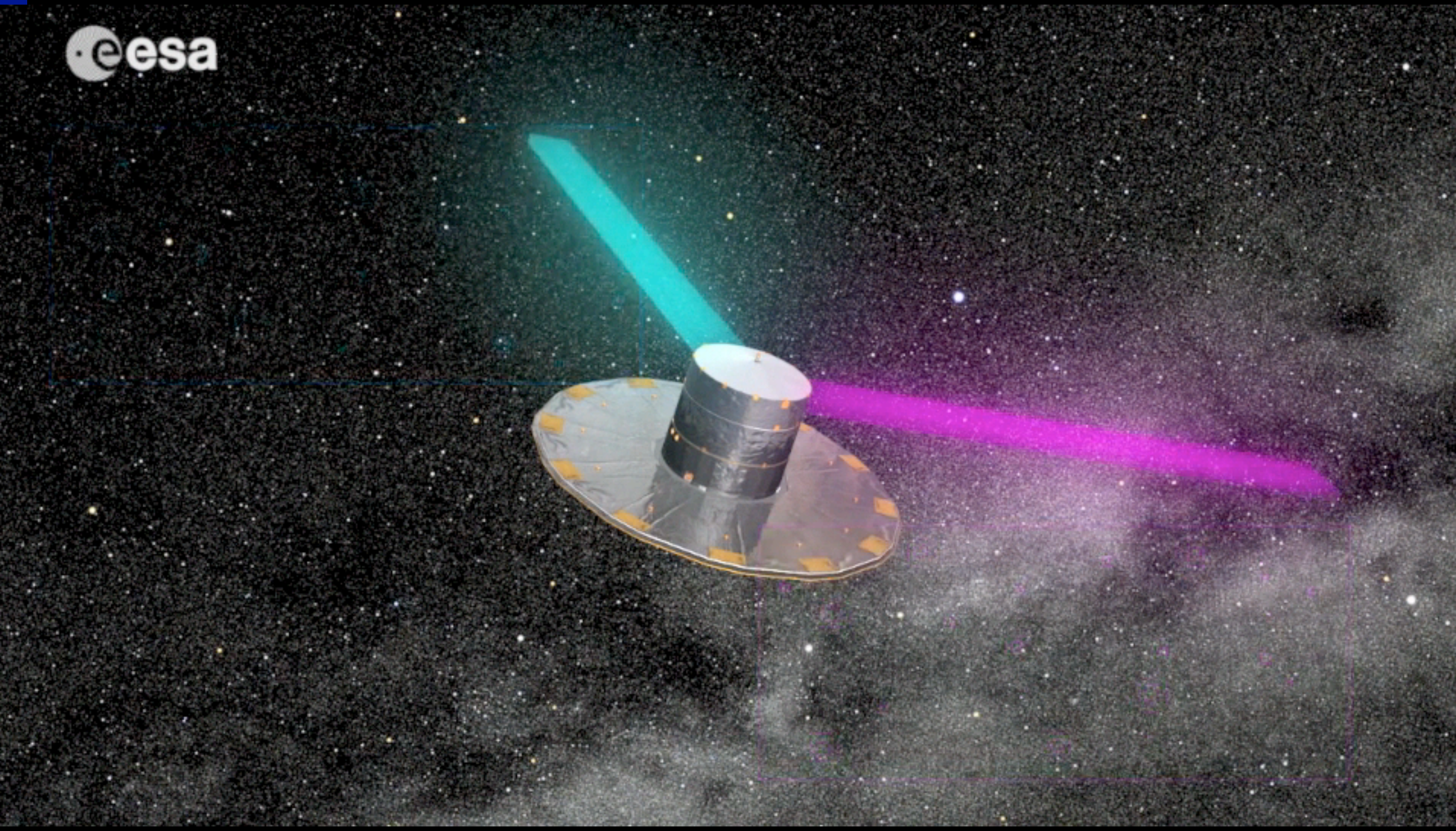
2016 September 14

19 December 2013 (09:12 UTC)

19 December 2013 (09:12 UTC)



Credit: ESA



Understanding the Milky Way Galaxy

Credit: NASA/JPL

Understanding the Milky Way Galaxy

Gaia combines three complementary approaches:

Credit: NASA/JPL

Understanding the Milky Way Galaxy

Gaia combines three complementary approaches:

- Census of large, representative parts of the Galaxy

Credit: NASA/JPL

Understanding the Milky Way Galaxy

Gaia combines three complementary approaches:

- Census of large, representative parts of the Galaxy

- Spatial structure from stellar distances

Credit: NASA/JPL

Understanding the Milky Way Galaxy

Gaia combines three complementary approaches:

- Census of large, representative parts of the Galaxy
- Spatial structure from stellar distances
- Gravitational field from the stellar motions

Credit: NASA/JPL

Understanding the Milky Way Galaxy

Gaia combines three complementary approaches:

- Census of large, representative parts of the Galaxy

- Spatial structure from stellar distances

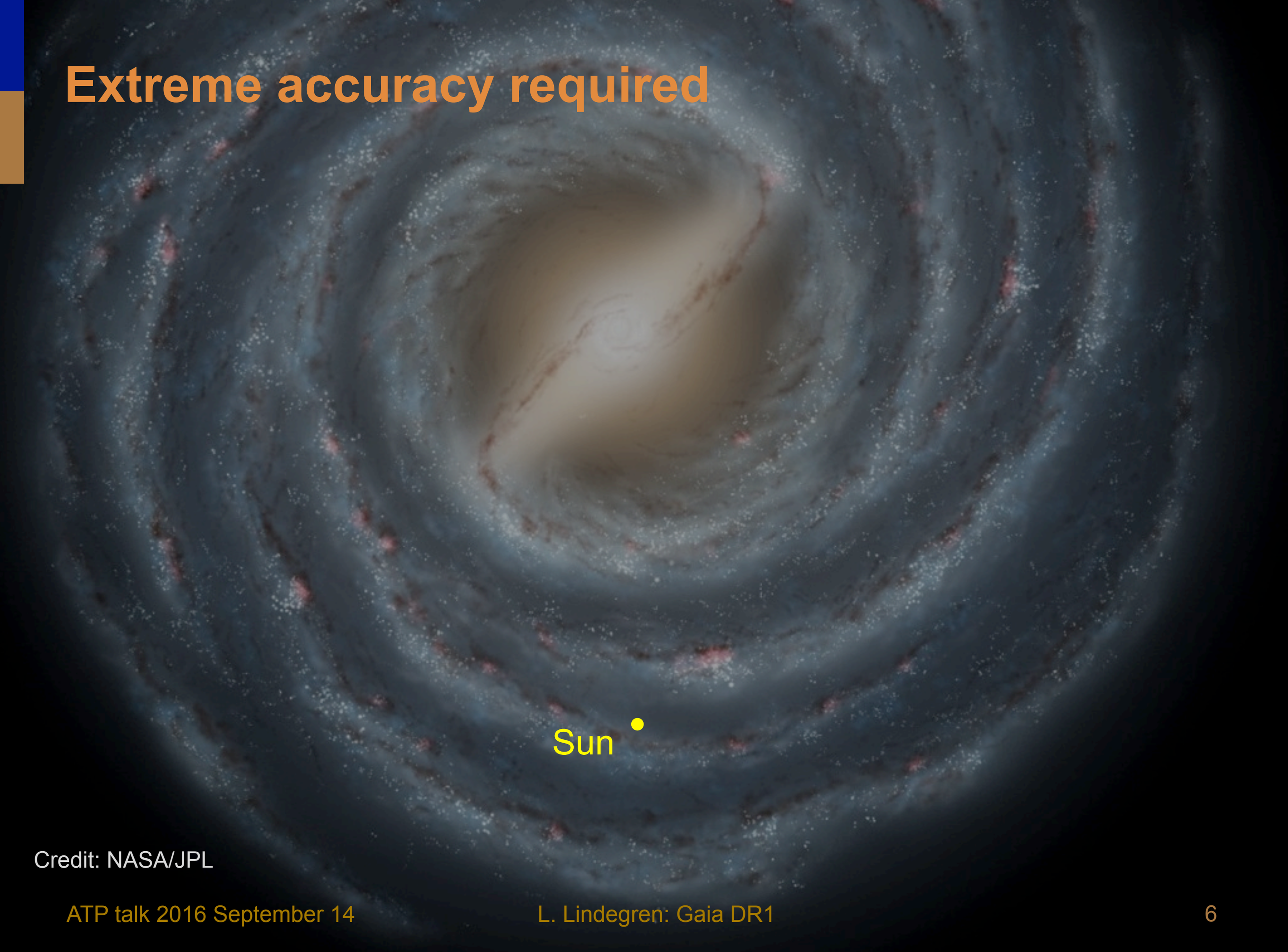
- Gravitational field from the stellar motions

"Side benefits":

Stellar astrophysics, binaries, exoplanets
Solar system objects (asteroids)
Reference frame
Cosmology

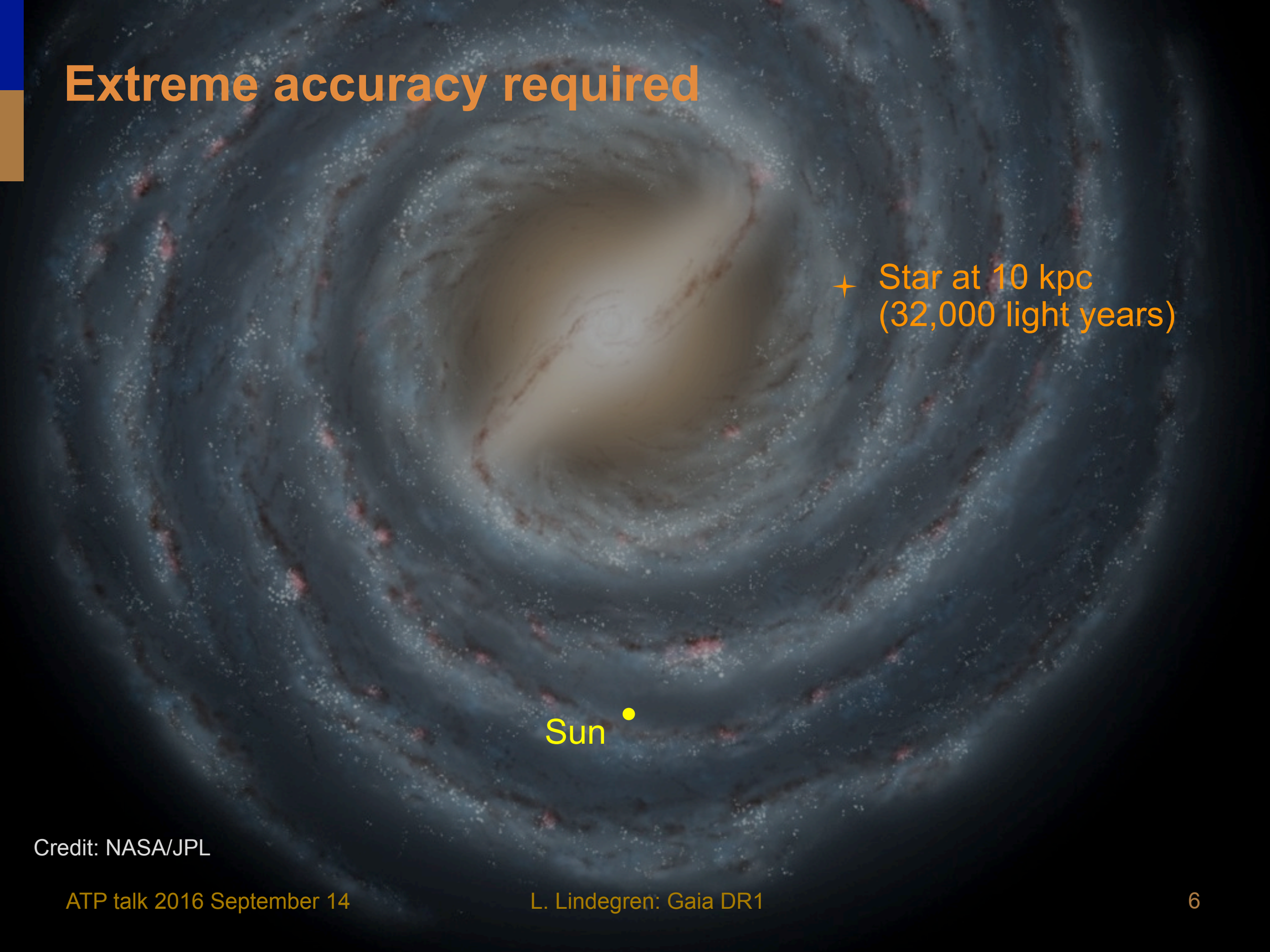
Credit: NASA/JPL

Extreme accuracy required



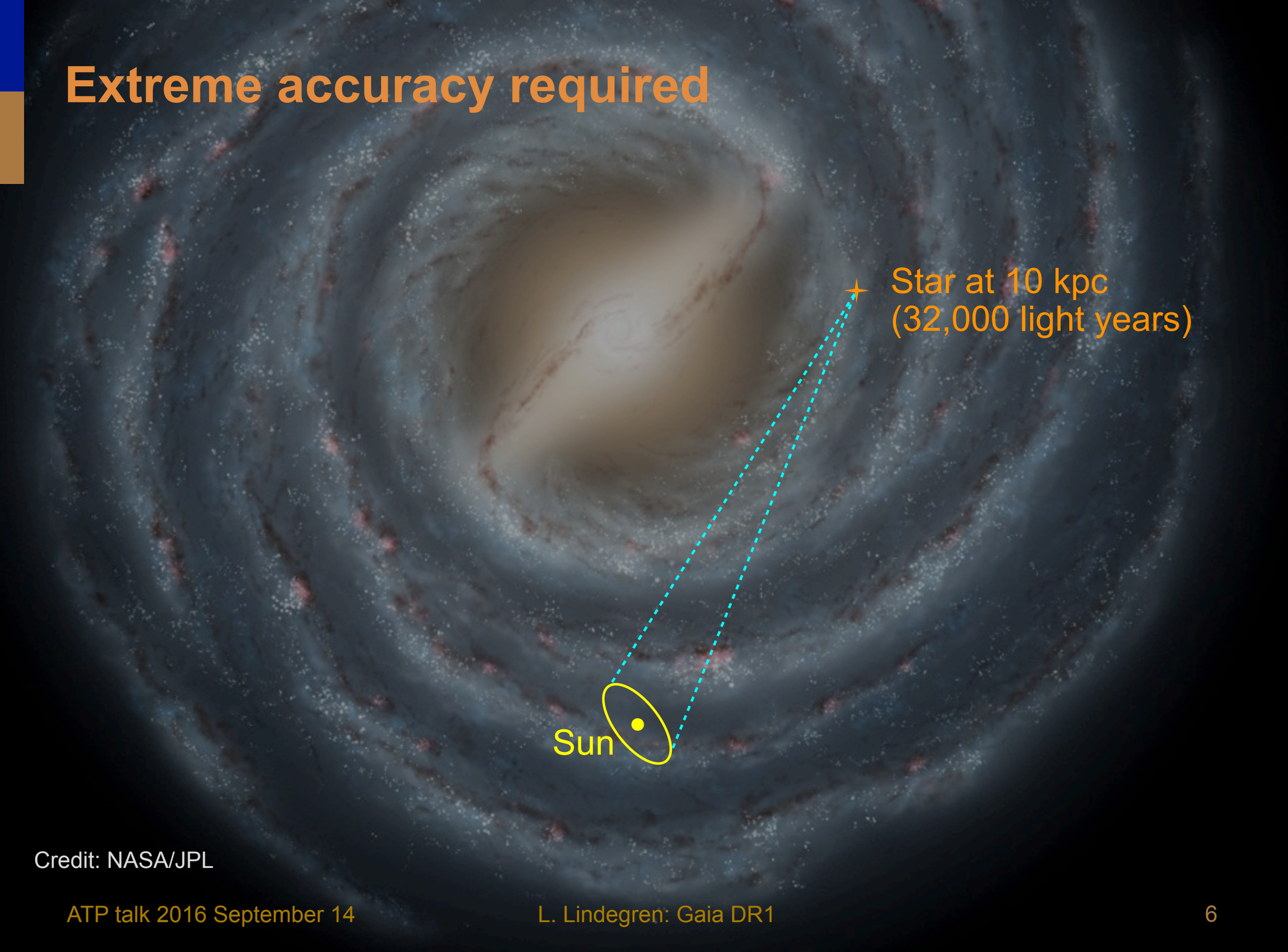
Credit: NASA/JPL

Extreme accuracy required



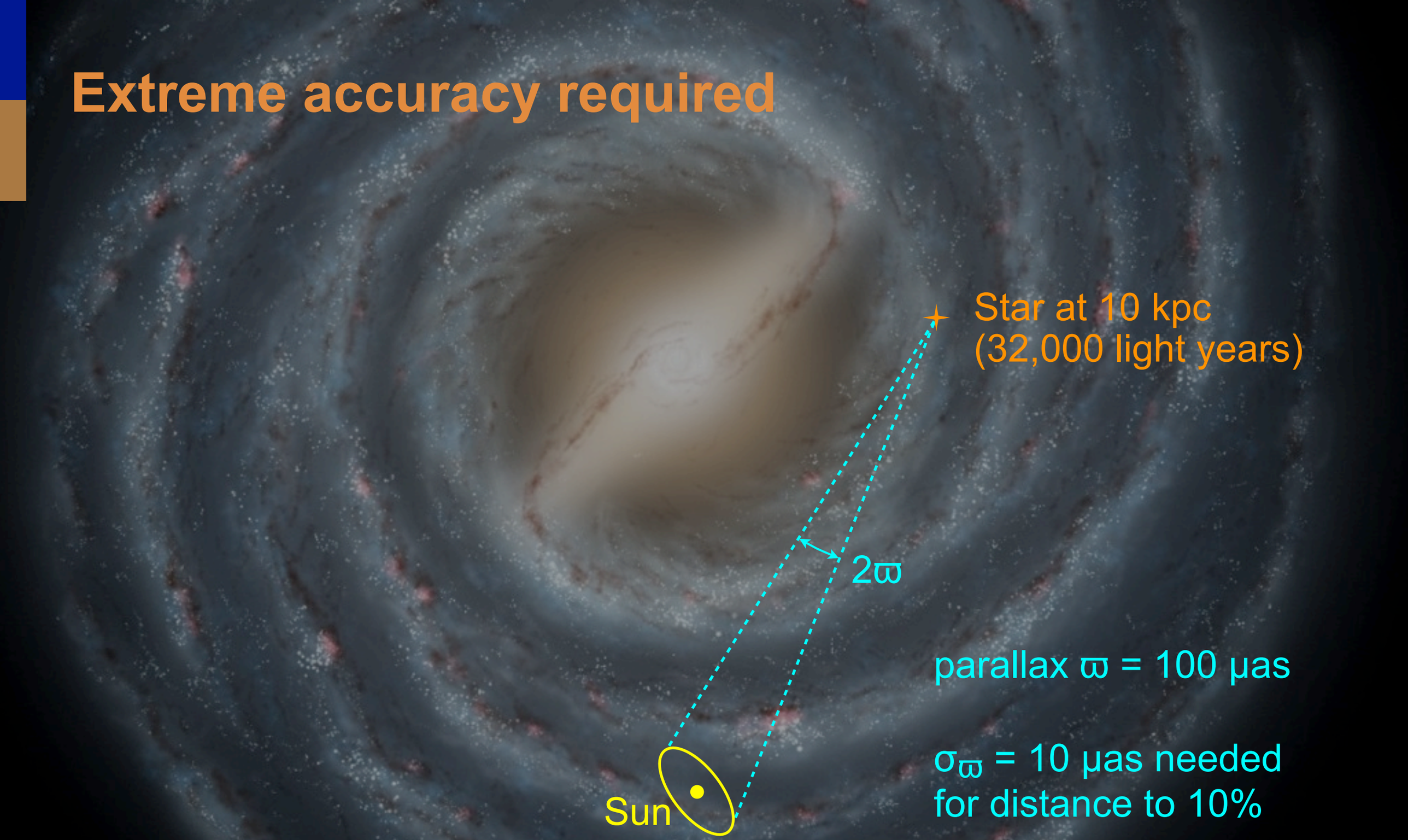
Credit: NASA/JPL

Extreme accuracy required



Credit: NASA/JPL

Extreme accuracy required

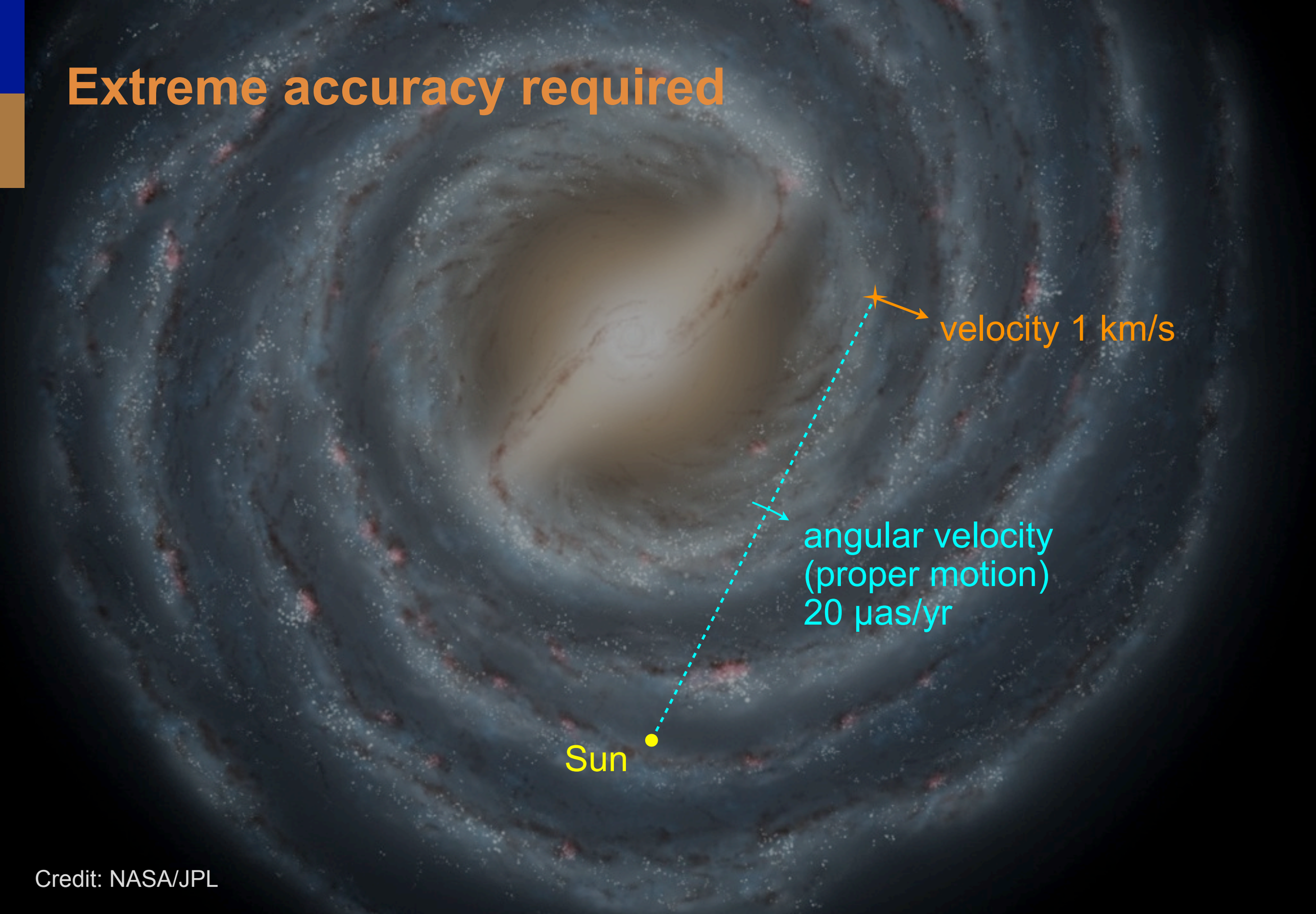


parallax ϖ = 100 μas

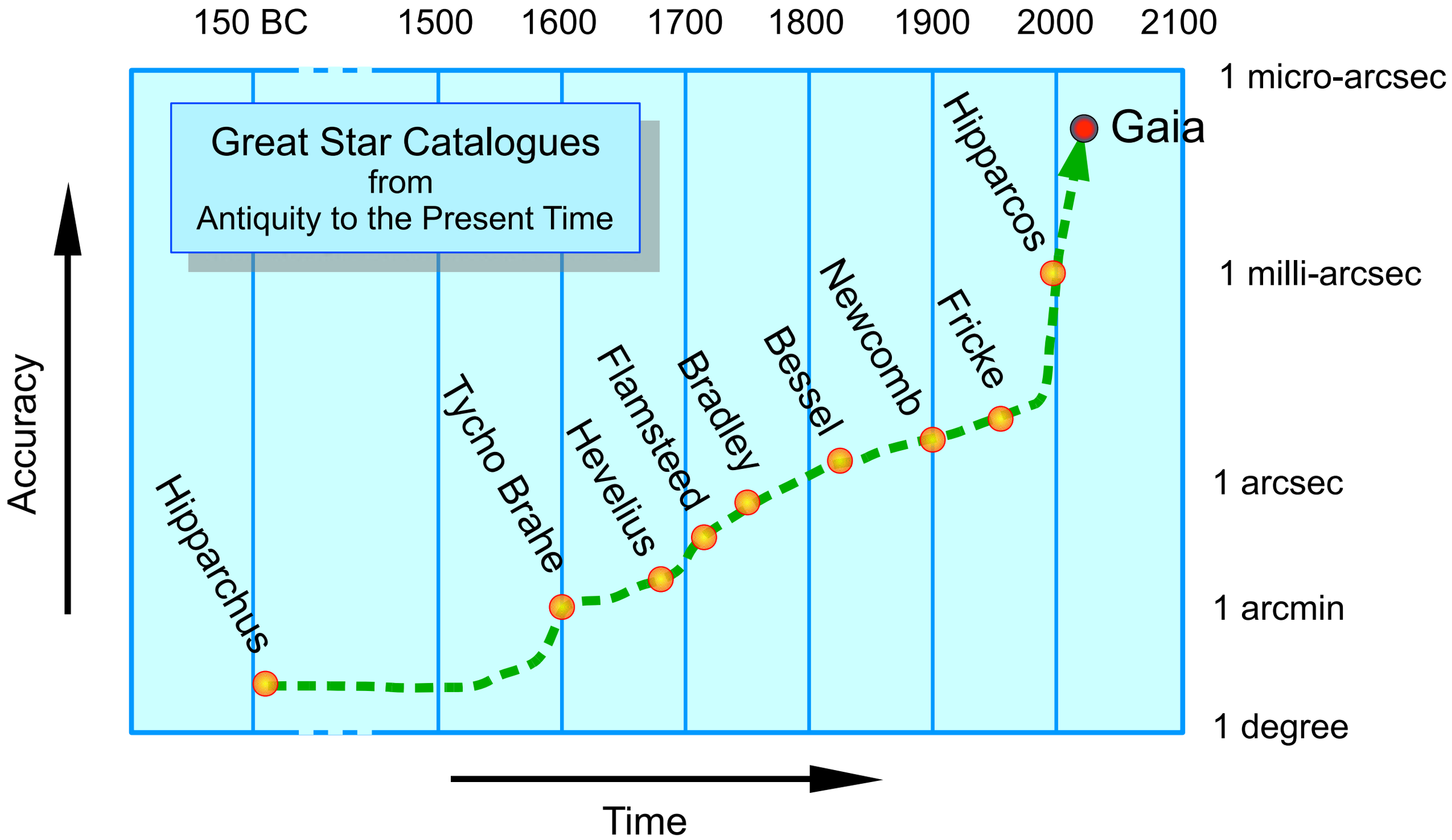
σ_{ϖ} = 10 μas needed
for distance to 10%

Credit: NASA/JPL

Extreme accuracy required



Credit: NASA/JPL


150 BC
1500
1600
1700
1800
1900
2000
2100
Great Star Catalogues
from
Antiquity to the Present Time
Accuracy
Time
Hipparchus
Tycho Brahe
Hevelius
Flamsteed
Bradley
Bessel
Newcomb
Fricke
Hipparcos
Gaia
1 micro-arcsec
1 milli-arcsec
1 arcsec
1 arcmin
1 degree

Gaia:
Predicted astrometric performance after 5 years

Sky-averaged standard errors for G0V stars

V magnitude	6-13	14	15	16	17	18	19	20	mag
Parallax	8	13	21	34	54	89	152	385	μas
Proper motion	5	7	11	18	29	47	80	203	μas/yr
Position @2016	6	10	16	25	40	66	113	286	μas

Note:
20 μas = 10^{-10} rad (the size of a pin-head at 10,000 km)

Lund Observatory was involved in Gaia from the very beginning (1993)

Response to Call for Mission Concepts for Horizon 2000 Follow Up
Proposal for an astrometric interferometer as an ESA Cornerstone Mission

GAIA

Global Astrometric Interferometer for Astrophysics

L. Lindegren, M.A.C. Perryman, U. Bastian, J.C. Dainty,
E. Høg, F. van Leeuwen, J. Kovalevsky, A. Labeyrie,
F. Mignard, J.E. Noordam, R.S. Le Poole, P. Thejll and F. Vakili

Summary

We propose that a small interferometer of the Fizeau type (baseline ~ 3 m), dedicated to global astrometry, should be studied as a possible concept for an ESA Cornerstone Mission. Positions, absolute parallaxes and annual proper motions could be determined with accuracies on the 20 micro-arcsec level. The observing programme could consist of all objects to a limiting magnitude around $V = 15$–16, or some 50 million stars, extragalactic and solar-system objects.

... and continues to be a major participant (2016)

Gaia Data Release 1

Astrometry – one billion positions, two million proper motions and parallaxes

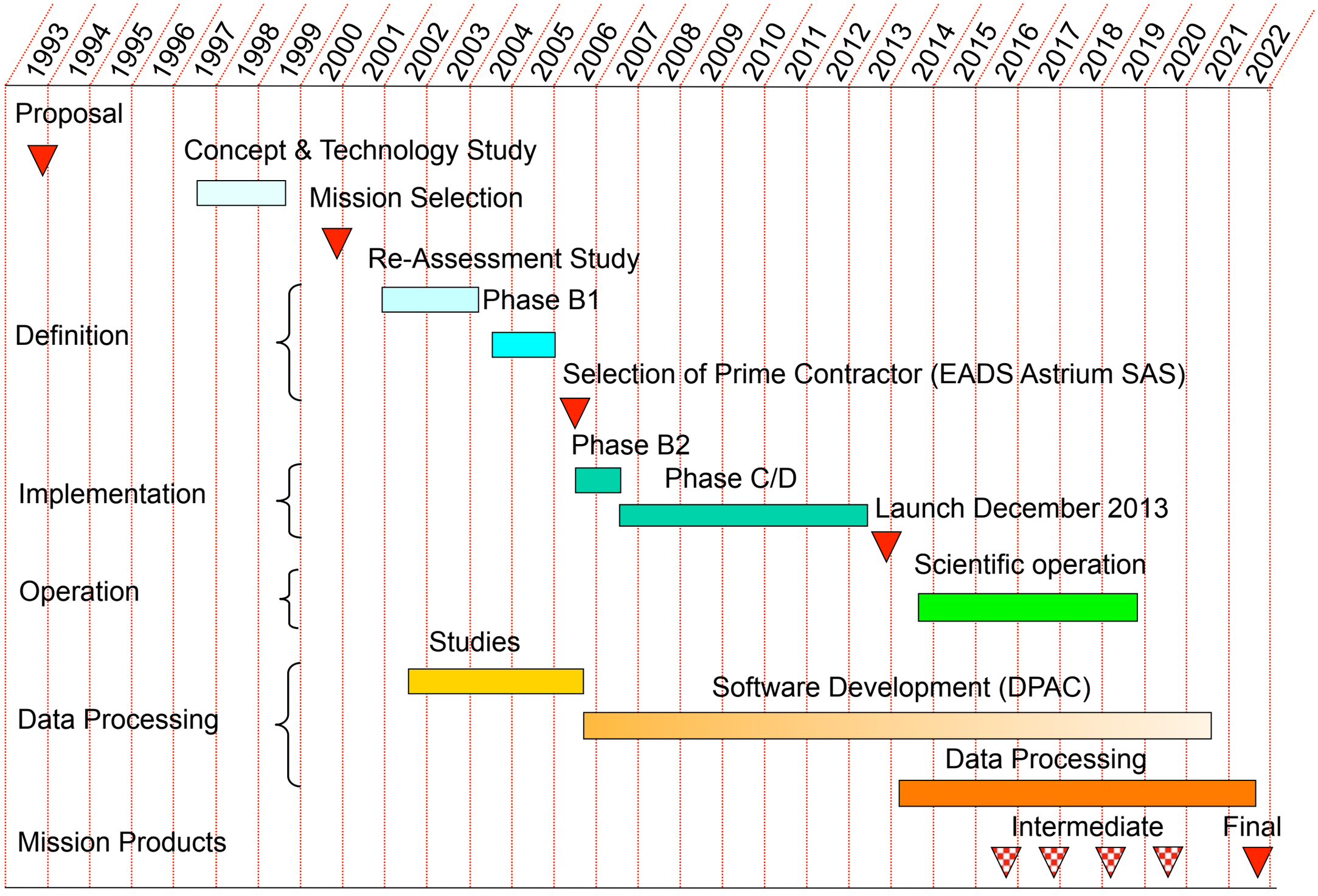
L. Lindegren[1], U. Lammers[2], U. Bastian[3], J. Hernández[2], S. Klioner[4], D. Hobbs[1], A. Bombrun[5], D. Michalik[1], M. Ramos-Lerate[6], A. Butkevich[4], G. Comoretto[7], E. Joliet[8,5], B. Holl[9], A. Hutton[10], P. Parsons[11], H. Steidelmüller[4], U. Abbas[12], M. Altmann[3,13], A. Andrei[14], S. Anton[15,16], N. Bach[10], C. Barache[13], U. Becciani[17], J. Berthier[18], L. Bianchi[19], M. Biermann[3], S. Bouquillon[13], G. Bourda[20,21], T. Brüsemeister[3], B. Bucciarelli[12], D. Busonero[12], T. Carlucci[13], J. Castañeda[22], P. Charlot[20,21], M. Clotet[22], M. Crosta[12], M. Davidson[23], F. de Felice[24], R. Drimmel[12], C. Fabricius[22], A. Fienga[25], F. Figueras[22], E. Fraile[26], M. Gai[12], N. Garralda[22], R. Geyer[4], J.J. González-Vidal[22], R. Guerra[2], N.C. Hambly[23], M. Hauser[3], S. Jordan[3], M.G. Lattanzi[12], H. Lenhardt[3], S. Liao[12,27], W. Löffler[3], P.J. McMillan[1], F. Mignard[25], A. Mora[10], R. Morbidelli[12], J. Portell[22], A. Riva[12], M. Sarasso[12], I. Serraller[28,22], H. Siddiqui[7], R. Smart[12], A. Spagna[12], U. Stampa[3], I. Steele[29], F. Taris[13], J. Torra[22], W. van Reeven[10], A. Vecchiato[12], S. Zschocke[4], J. de Bruijne[30], G. Gracia[31], F. Raison[32,33], T. Lister[34], J. Marchant[29], R. Messineo[35], M. Soffel[4], J. Osorio[15], A. de Torres[5], and W. O'Mullane[2]

(Affiliations can be found after the references)

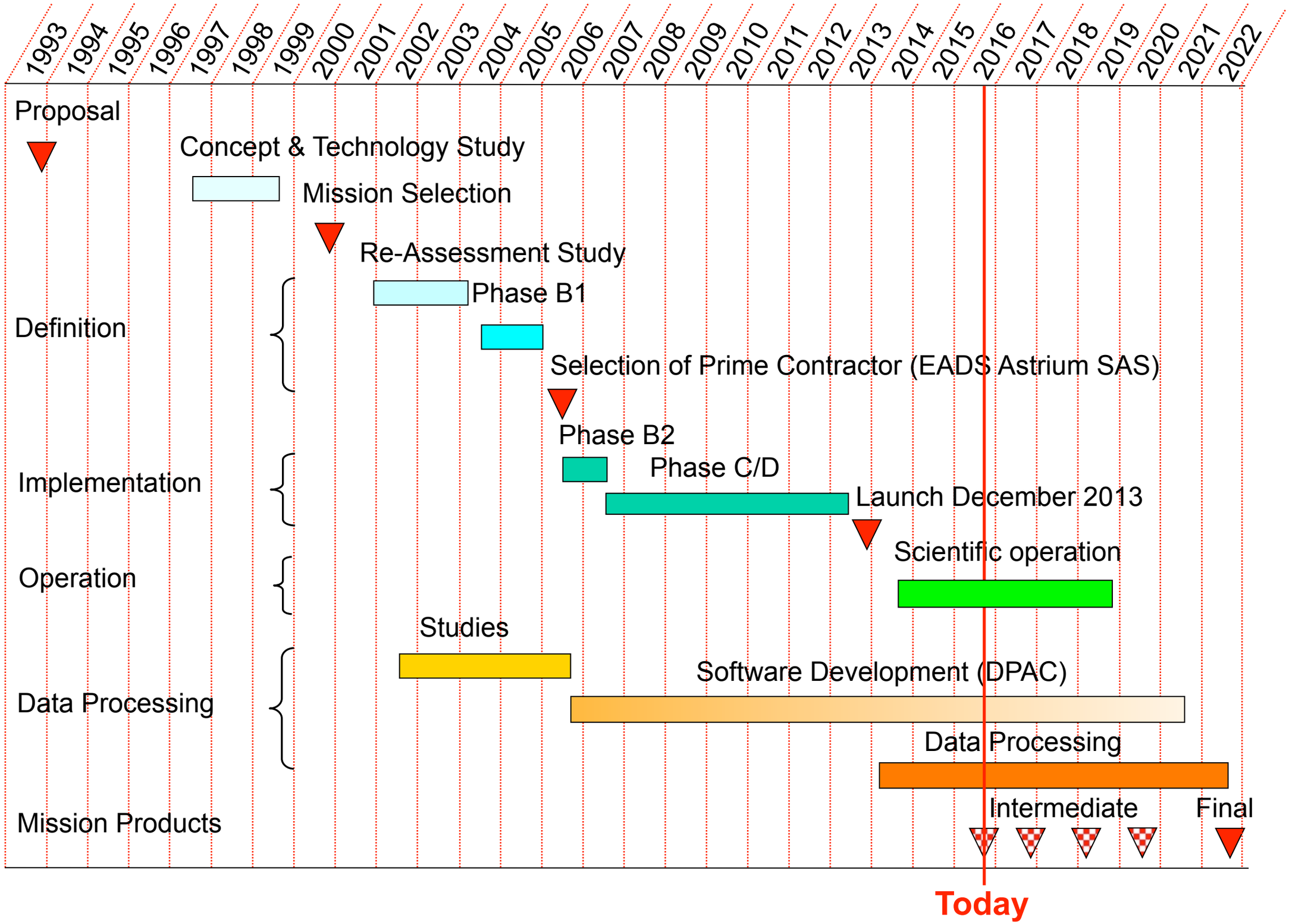
ABSTRACT

Context. Gaia Data Release 1 (Gaia DR1) contains astrometric results for more than 1 billion stars brighter than magnitude 20.7 based on observations collected by the Gaia satellite during the first 14 months of its operational phase.

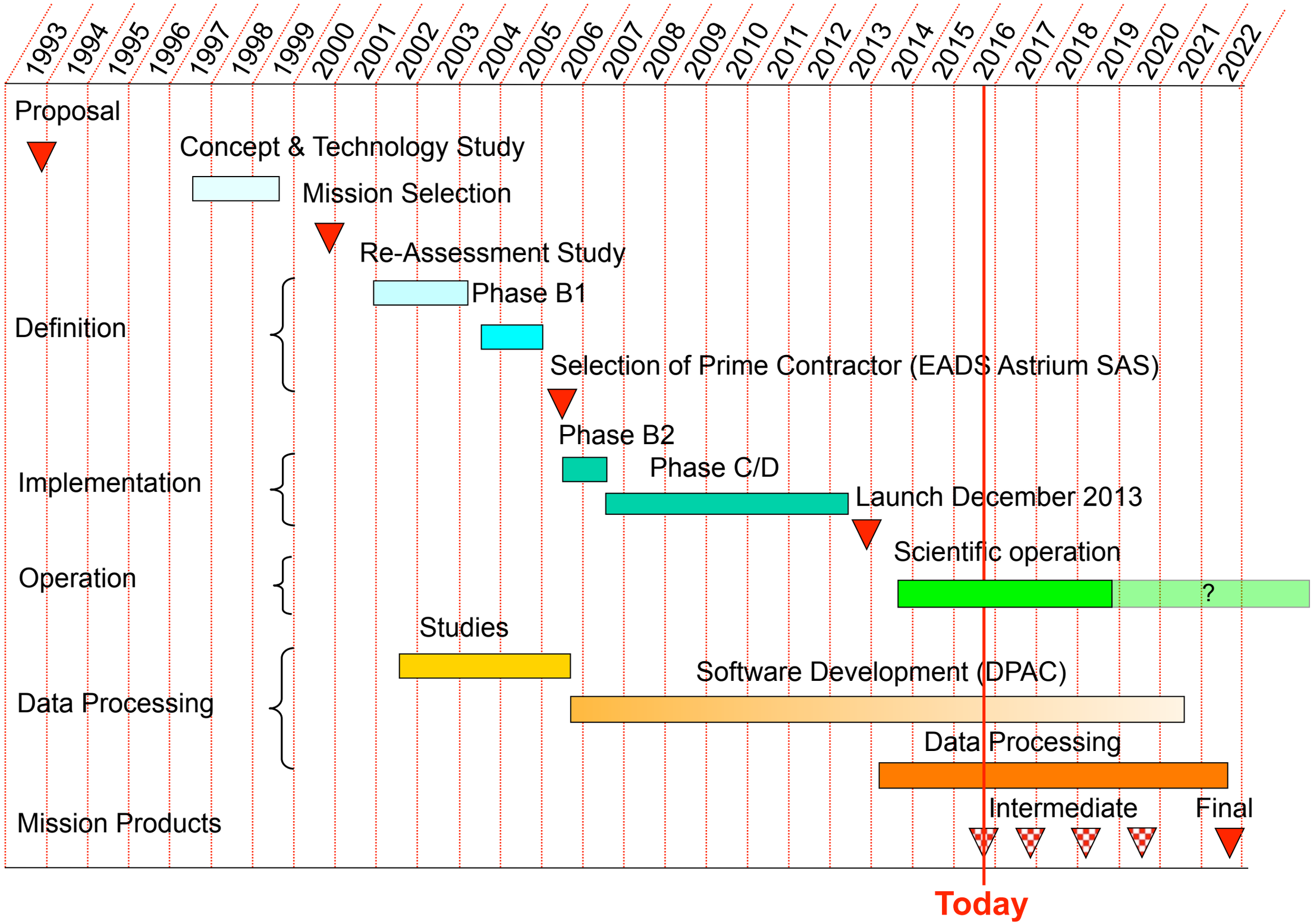
Schedule


1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Proposal
Concept & Technology Study
Mission Selection
Re-Assessment Study
Definition
Phase B1
Selection of Prime Contractor (EADS Astrium SAS)
Phase B2
Phase C/D
Launch December 2013
Implementation
Scientific operation
Operation
Studies
Software Development (DPAC)
Data Processing
Data Processing
Intermediate
Final
Mission Products

Schedule


1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Proposal
Concept & Technology Study
Mission Selection
Re-Assessment Study
Definition
Phase B1
Selection of Prime Contractor (EADS Astrium SAS)
Phase B2
Phase C/D
Implementation
Launch December 2013
Operation
Scientific operation
Studies
Software Development (DPAC)
Data Processing
Data Processing
Mission Products
Intermediate
Final
Today

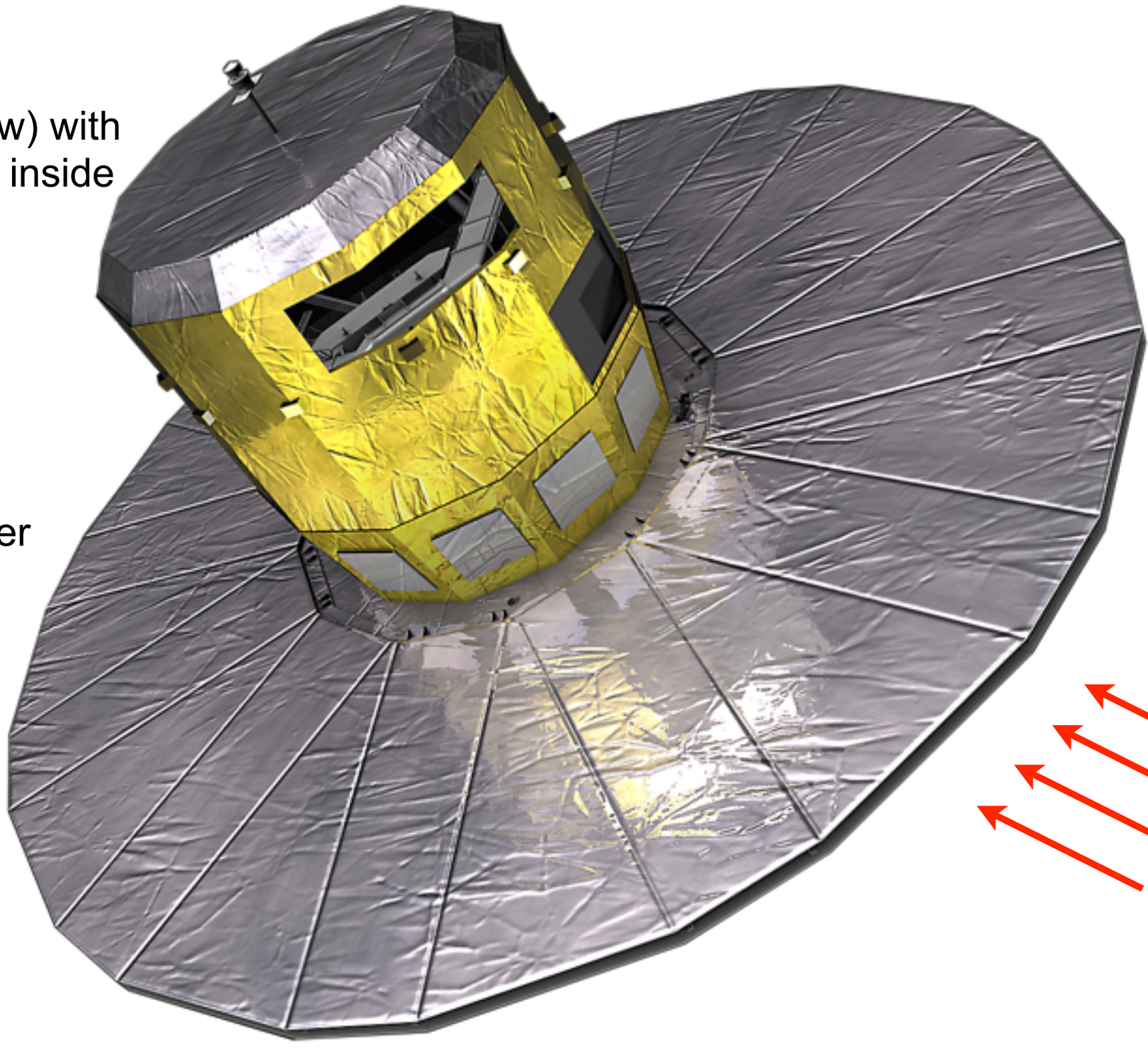
Schedule


1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Proposal
Concept & Technology Study
Mission Selection
Re-Assessment Study
Phase B1
Definition
Selection of Prime Contractor (EADS Astrium SAS)
Phase B2
Phase C/D
Launch December 2013
Implementation
Operation
Scientific operation
?
Studies
Software Development (DPAC)
Data Processing
Data Processing
Intermediate
Final
Mission Products
Today

The Gaia satellite

thermal cover (in permanent shadow) with optical instrument inside

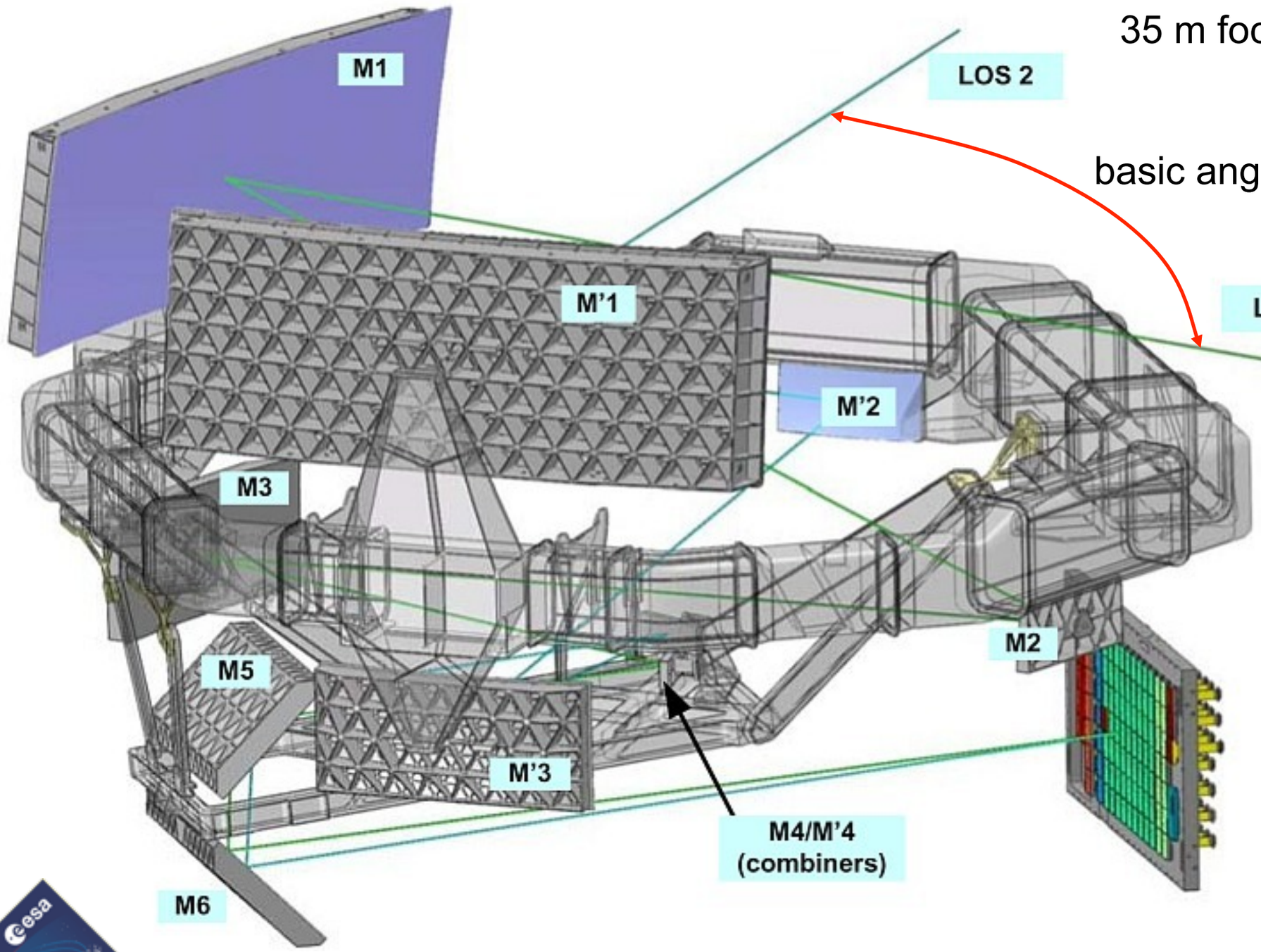
10 m diameter deployable sunshield



sunlight

EADS ASTRIUM

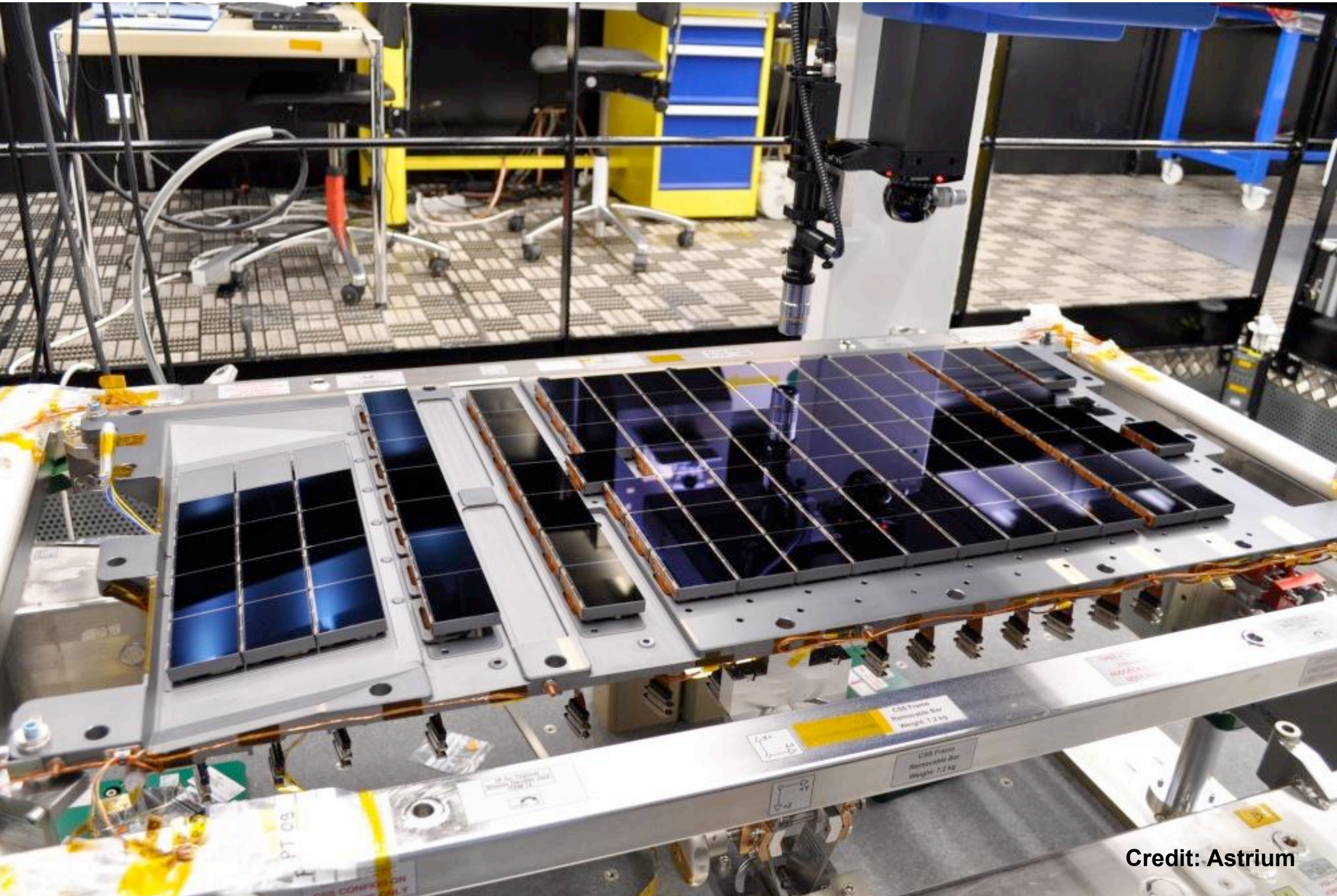
2 off-axis telescopes
1.45 x 0.5 m^2 aperture
35 m focal length



common focal plane, 106 CCDs (1 Gigapixel)
0.93 x 0.42 m^2

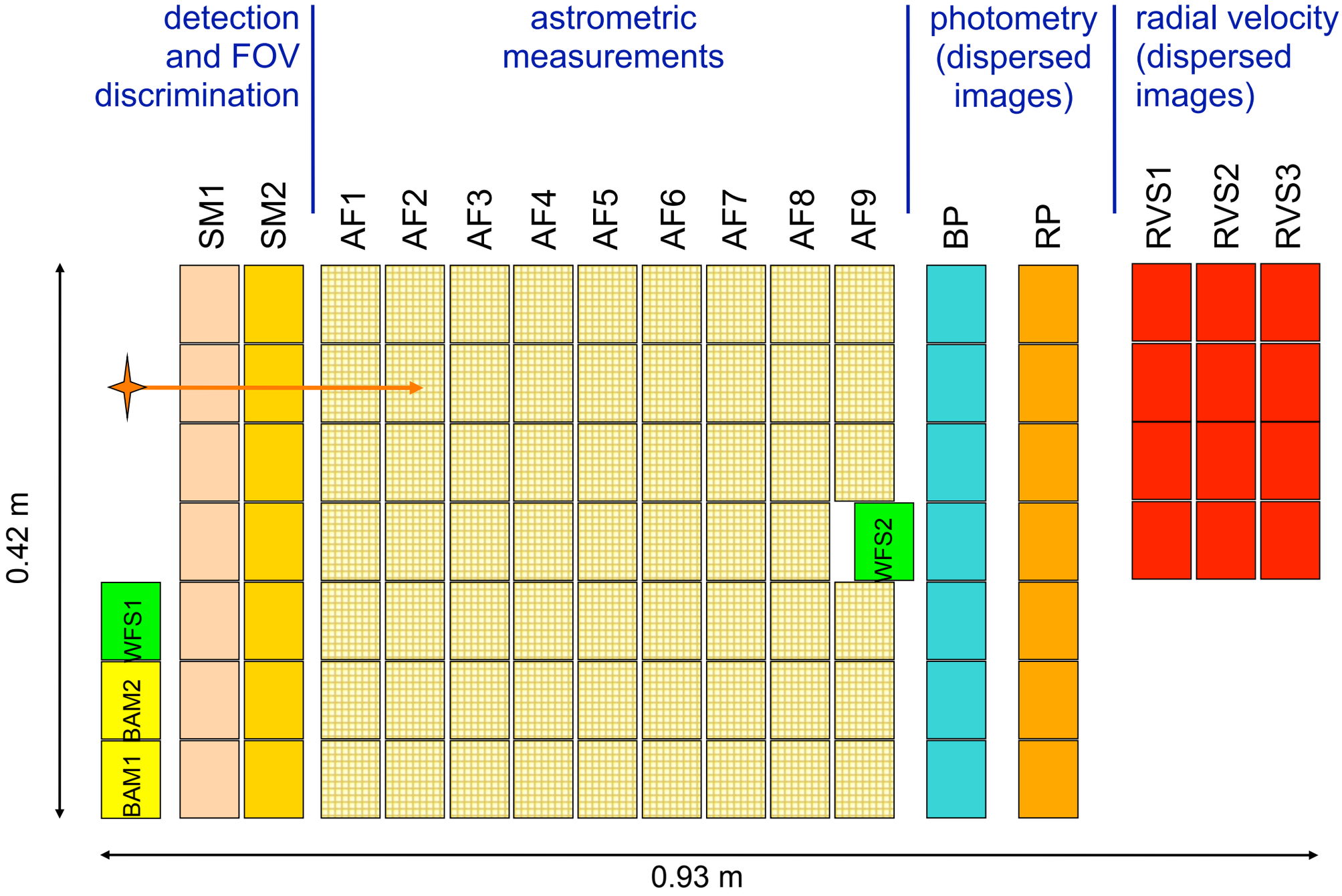
esa Gaia

Gaia’s focal plane



Credit: Astrium

Gaia's focal plane (106 CCDs)



BAM = basic angle monitor, WFS = wavefront sensor

Gaia detects ALL point objects brighter than 20.7

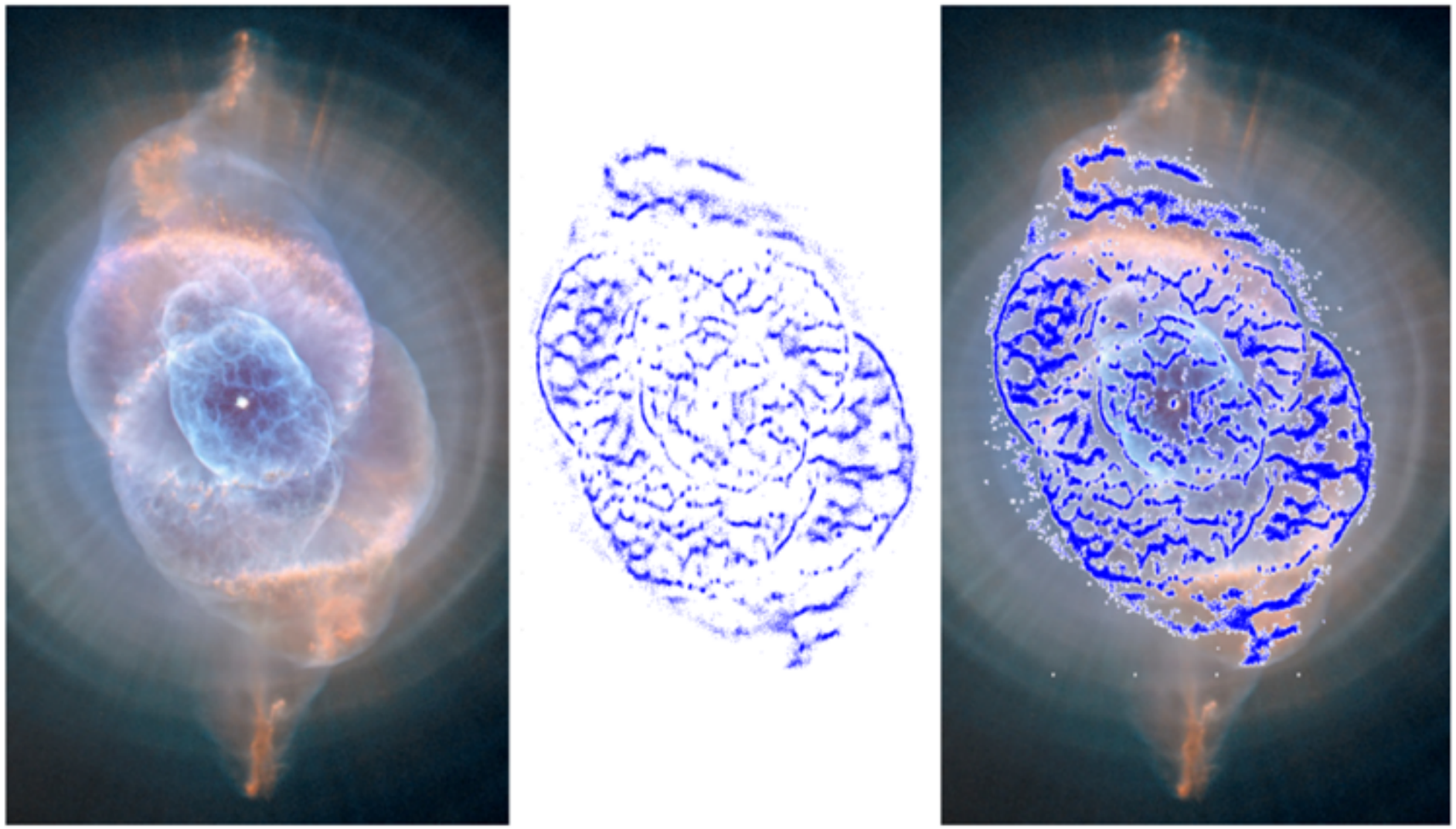


Fig. 14. Cat's Eye Planetary Nebula (NGC 6543) observed with the Hubble Space Telescope (left image) and as Gaia detections (the 84 000 blue points in middle and right images) (Credit: Photo: NASA/ESA/HEIC/The Hubble Heritage Team/STScI/AURA).

Fabricius et al. (2016)

Unfortunately also optical artefacts (speckles)

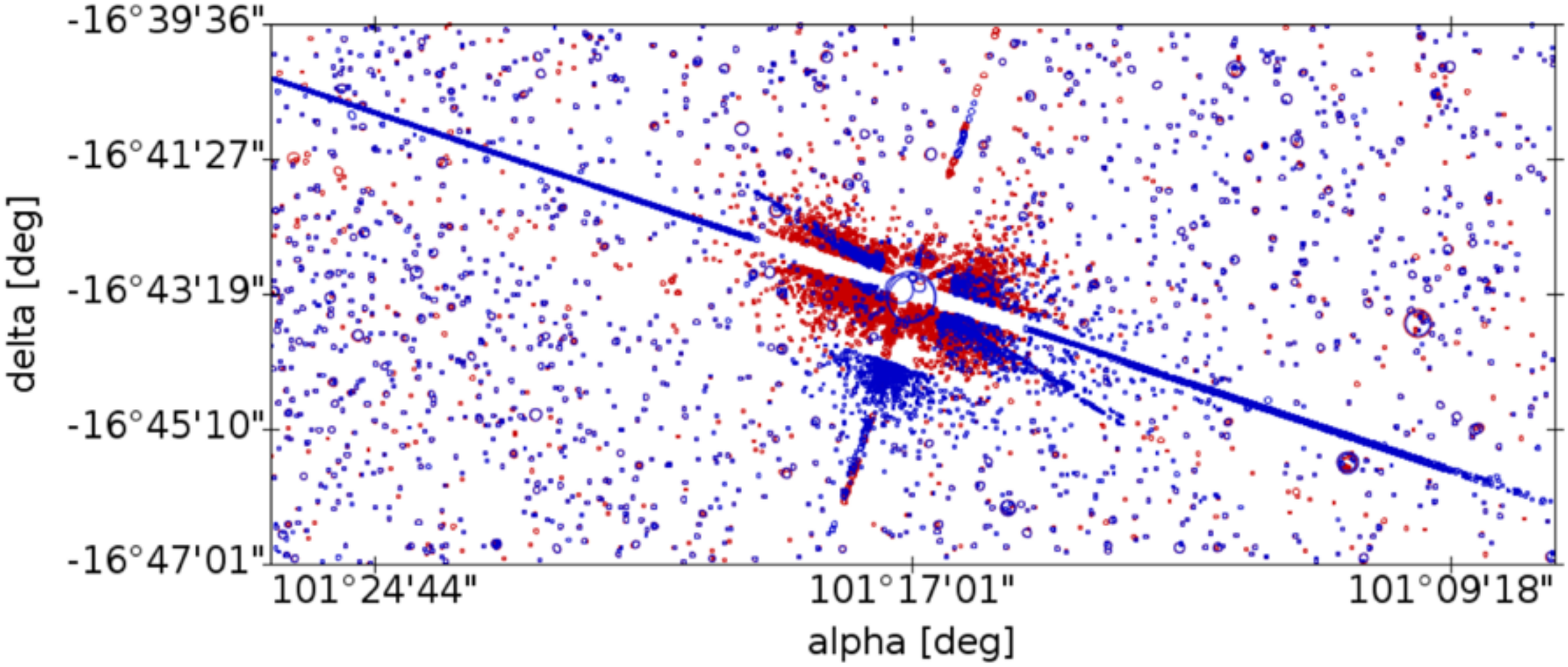
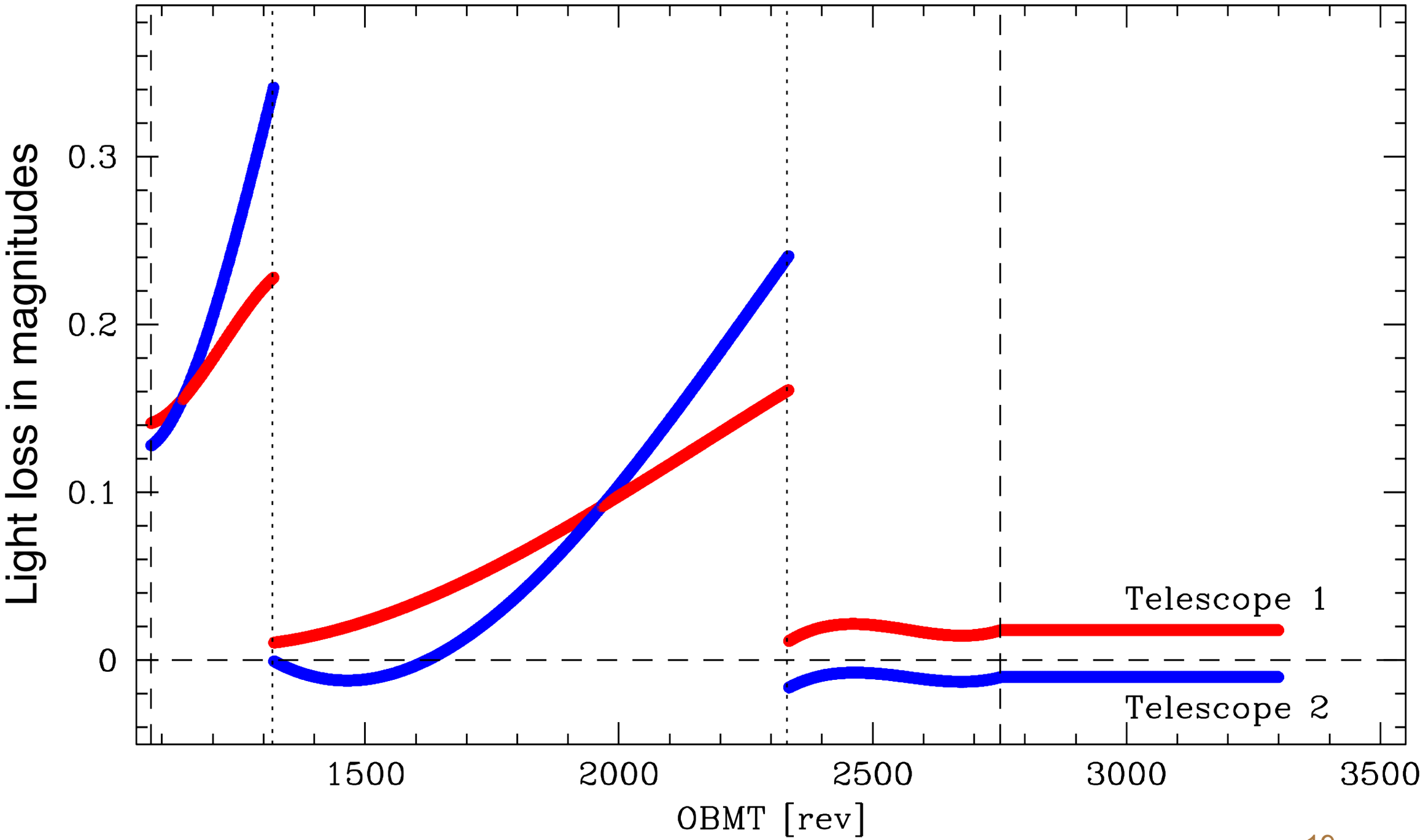


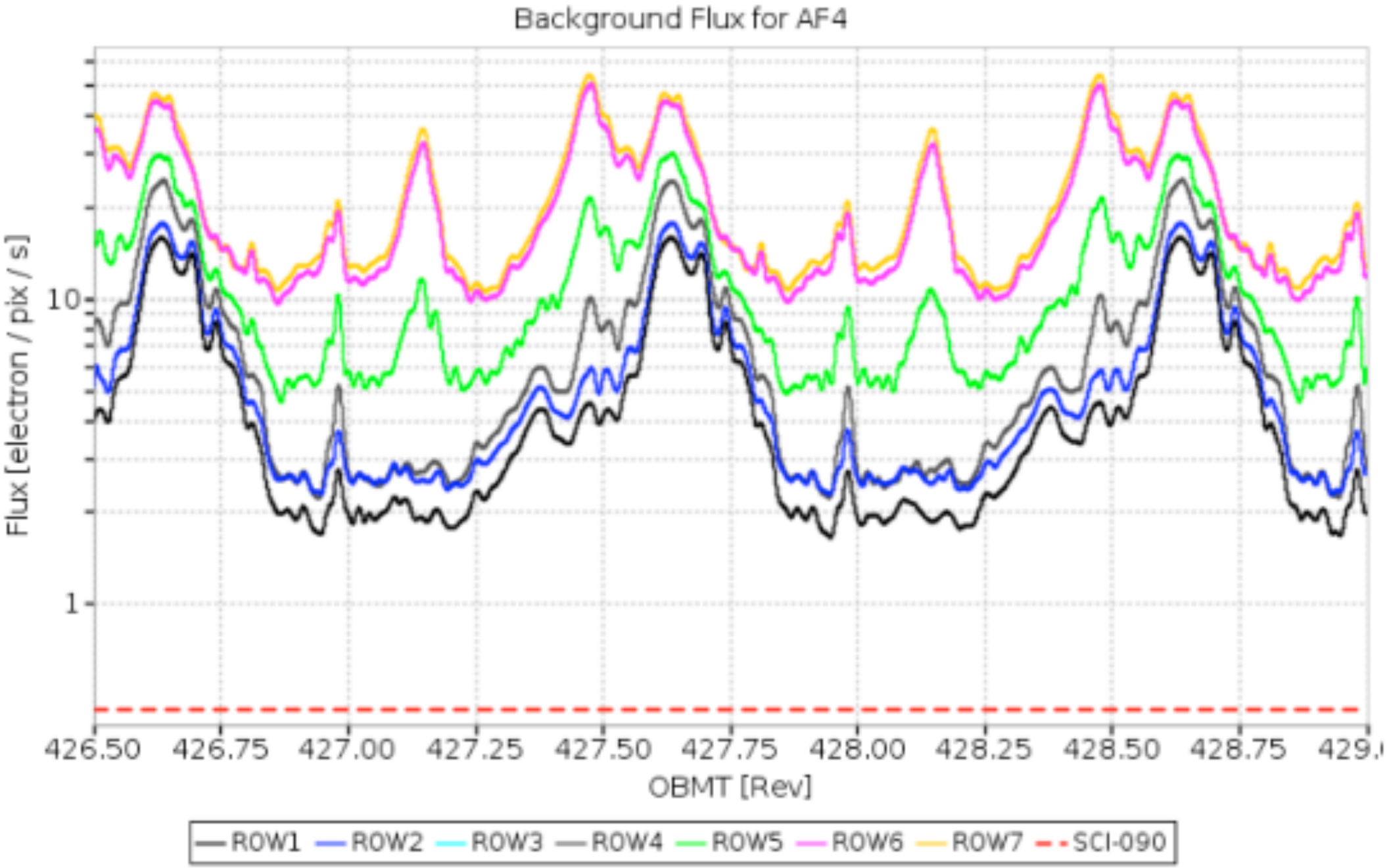
Fig. 12. 13 172, mostly spurious, detections from two scans of Sirius, one shown in blue and one in red. The majority of the spurious detections are fainter than 19 mag. In the red scan Sirius fell in between two CCD rows.

Fabricius et al. (2016)

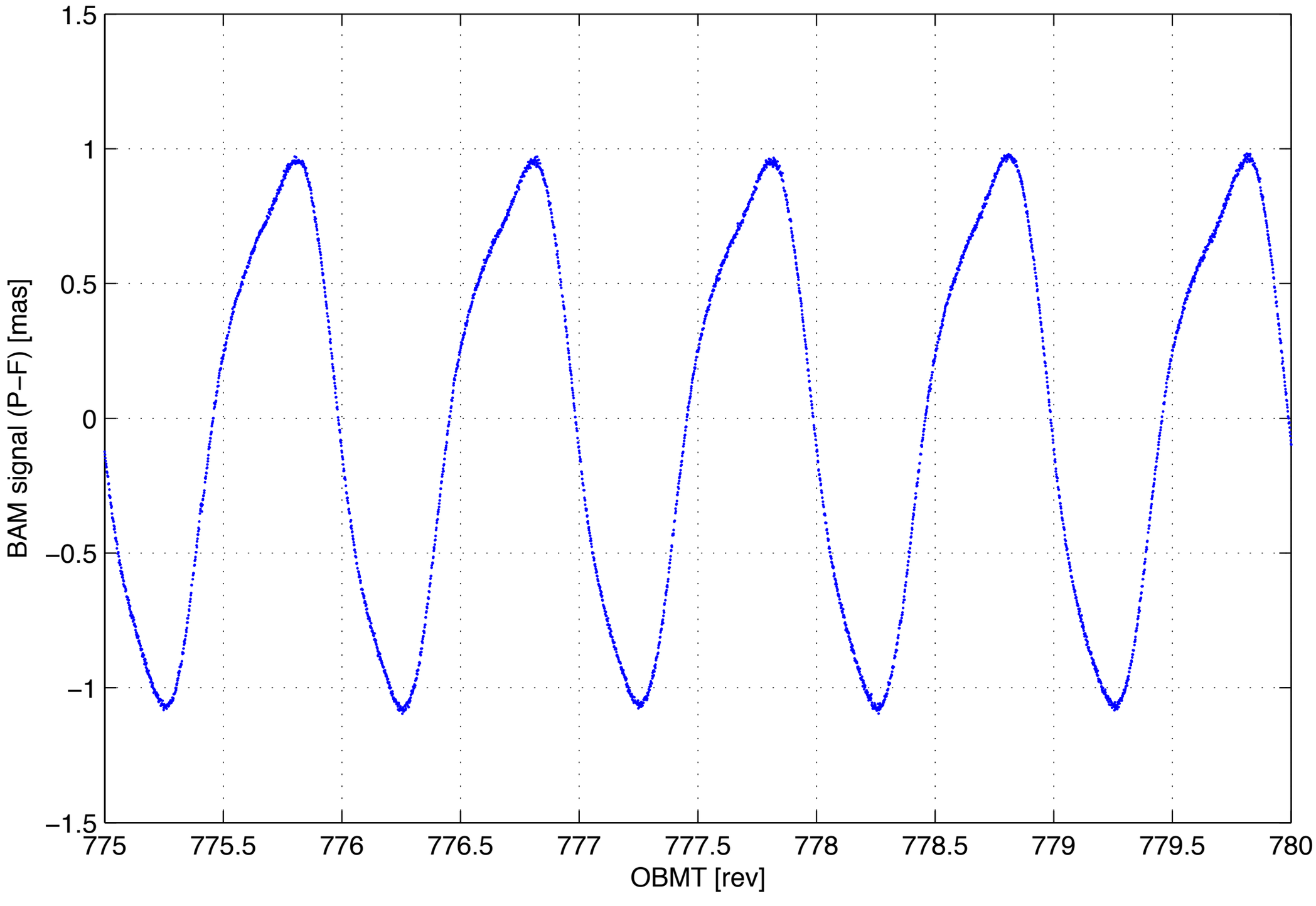
Unexpected problems with Gaia (1/3): Ice condensation on mirrors



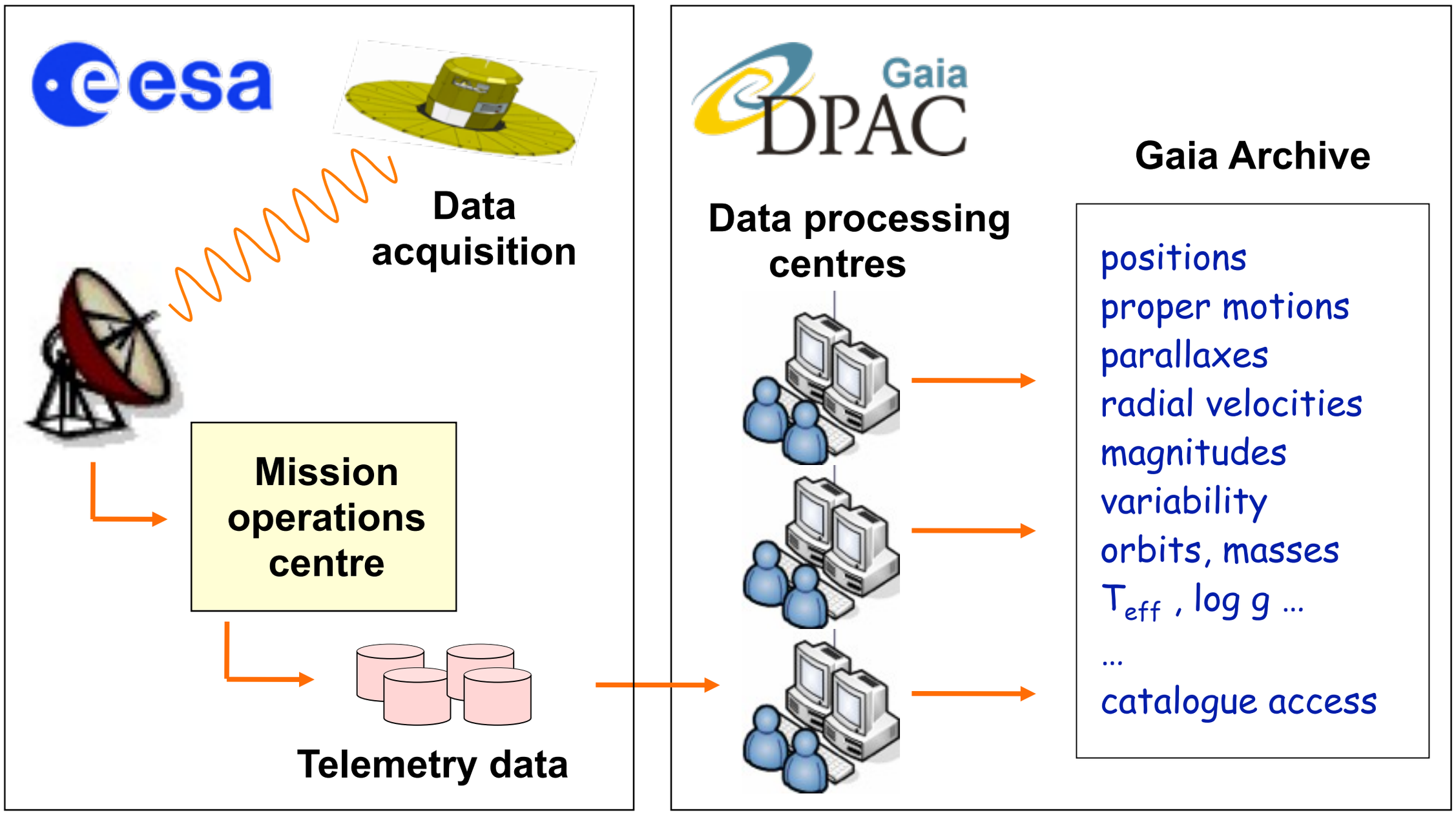
Unexpected problems with Gaia (2/3): Scattered light



Unexpected problems with Gaia (3/3): “Large” (±1 mas) basic angle variations



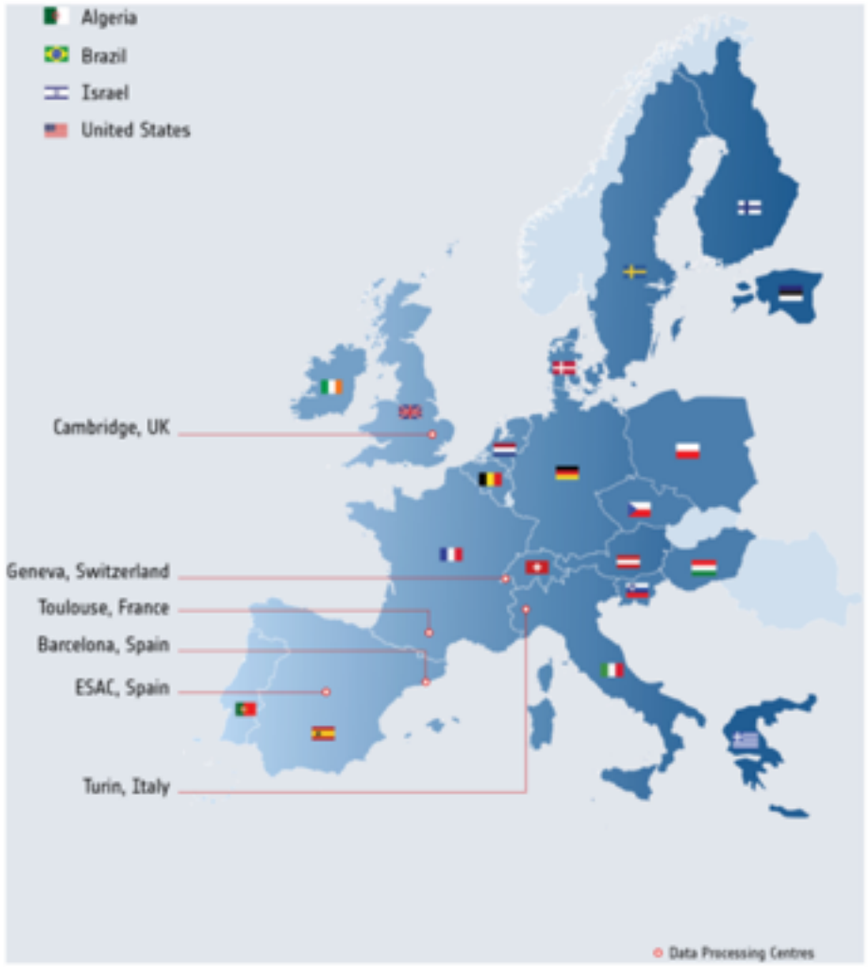
Gaia: ESA and DPAC responsibilities

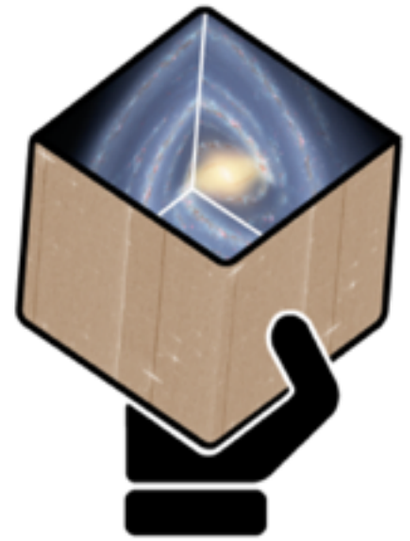


Lund Observatory is a major contributor to the development of the core astrometric solution (concepts, software, tests), but the data processing is done elsewhere

Teamwork to deliver the promise of Gaia

- 10+ years of effort
- 450 scientists and engineers
- 160 institutes
- 24 countries and ESA
- Six data processing centres





0 1 0 0 0 0 0 0 1 1 0 0 1 0 0 1 1 0 0 1 1 0 1 1 0 0 1 0 1 0

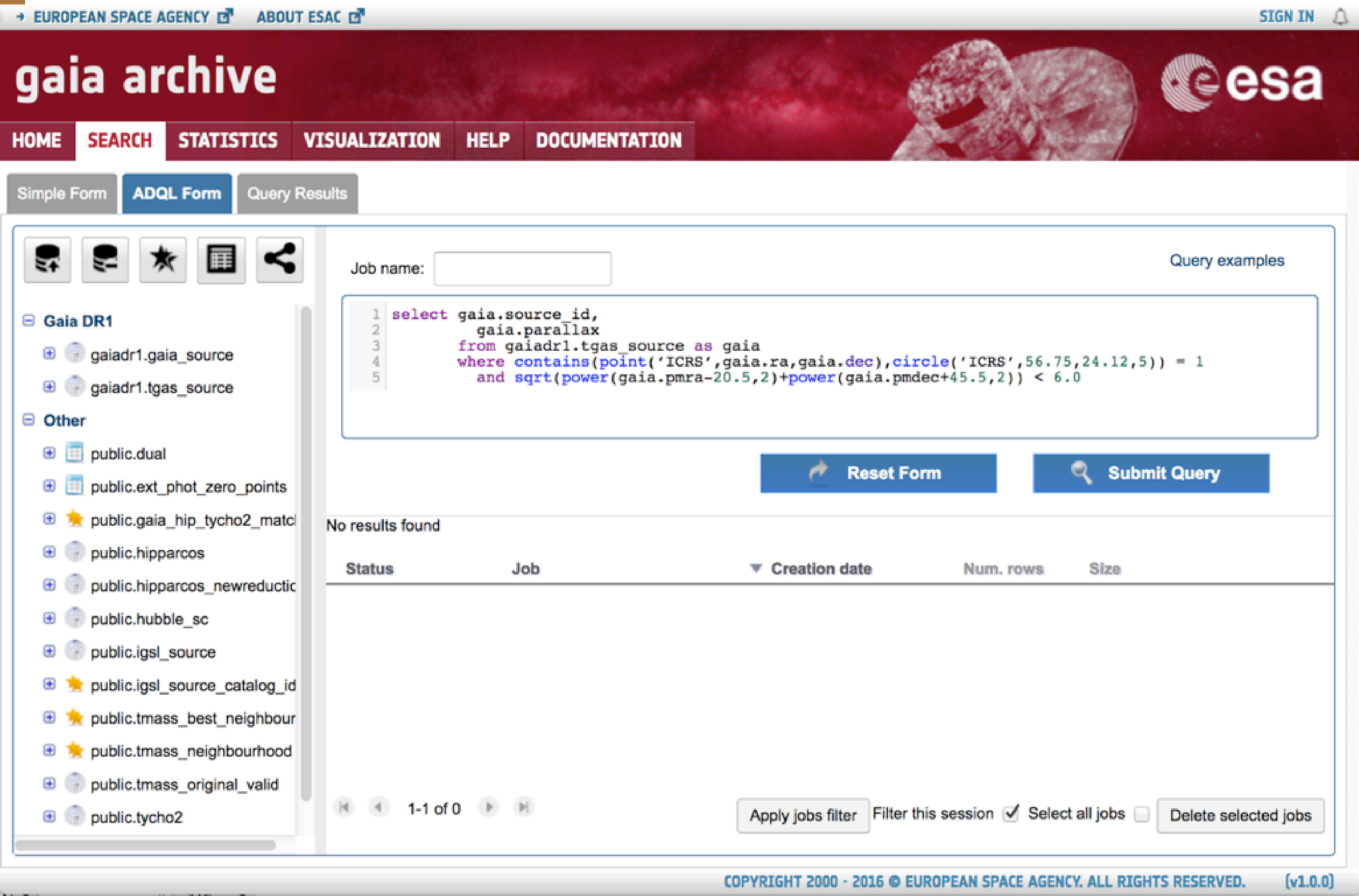
Gaia DPAC Data Processing & Analysis Consortium

α δ B $\mu_{\alpha*}$ μ_δ G ...

Leiden - 2016.09.16

Slide: A. Brown

http://archives.esac.esa.int/gaia/



This and future data releases

	DR1	DR2	DR3	DR4	Final
Positions	✓	✓	✓	✓	✓
White-light (G) magnitudes	✓	✓	✓	✓	✓
Parallaxes	(✓)*	✓	✓	✓	✓
Proper motions	(✓)*	✓	✓	✓	✓
Broad-band (BP, RP) magnitudes		✓	✓	✓	✓
Radial velocities		✓	✓	✓	✓
Object classification, astrophysical parameters			✓	✓	✓
BP, RP, RVS spectra			✓	✓	✓
Variable stars				✓	✓
Non-single star solutions				✓	✓
Solar-system objects				✓	✓
Exoplanets					✓

* Only 2 million objects

This and future data releases

	DR1	DR2	DR3	DR4	Final
Positions	✓	✓	✓	✓	✓
White-light (G) magnitudes	✓	✓	✓	✓	✓
Parallaxes	(✓)*	✓	✓	✓	✓
Proper motions	(✓)*	✓	✓	✓	✓
Broad-band (BP, RP) magnitudes		✓	✓	✓	✓
Radial velocities		✓	✓	✓	✓
Object classification, astrophysical parameters			✓	✓	✓
BP, RP, RVS spectra			✓	✓	✓
Variable stars				✓	✓
Non-single star solutions				✓	✓
Solar-system objects				✓	✓
Exoplanets					✓

* Only 2 million objects

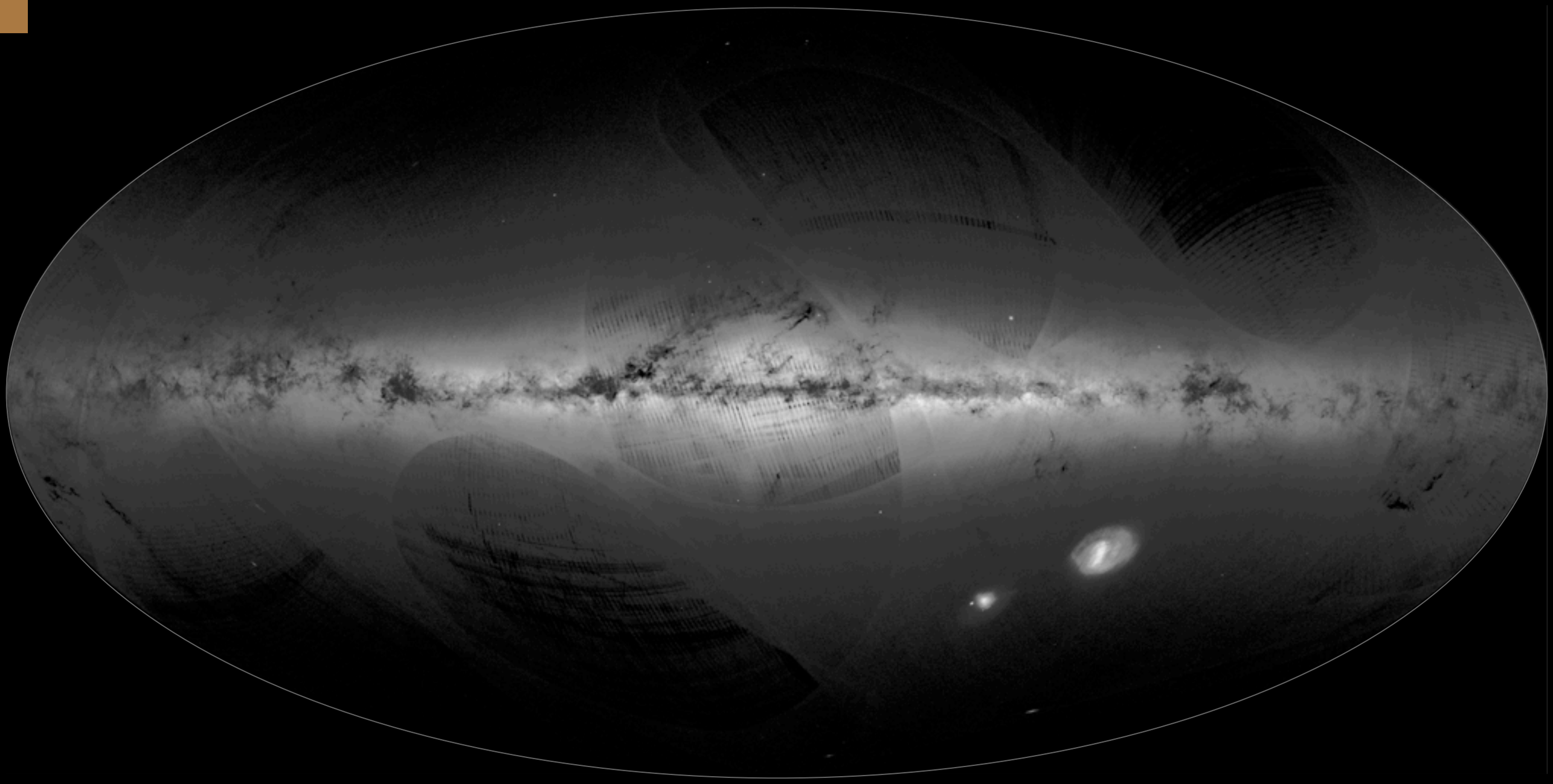
Gaia DR1: Number of objects ("sources")

Source numbers	
Total number of sources	1 142 679 769
No. of primary (TGAS) sources	2 057 050
HIPPARCOS	93 635
Tycho-2 (excluding Hipparcos stars)	1 963 415
No. of secondary sources	1 140 622 719
No. of sources with light curves	3194
Cepheids	599
RR Lyrae	2595

Gaia DR1: Number of objects ("sources")

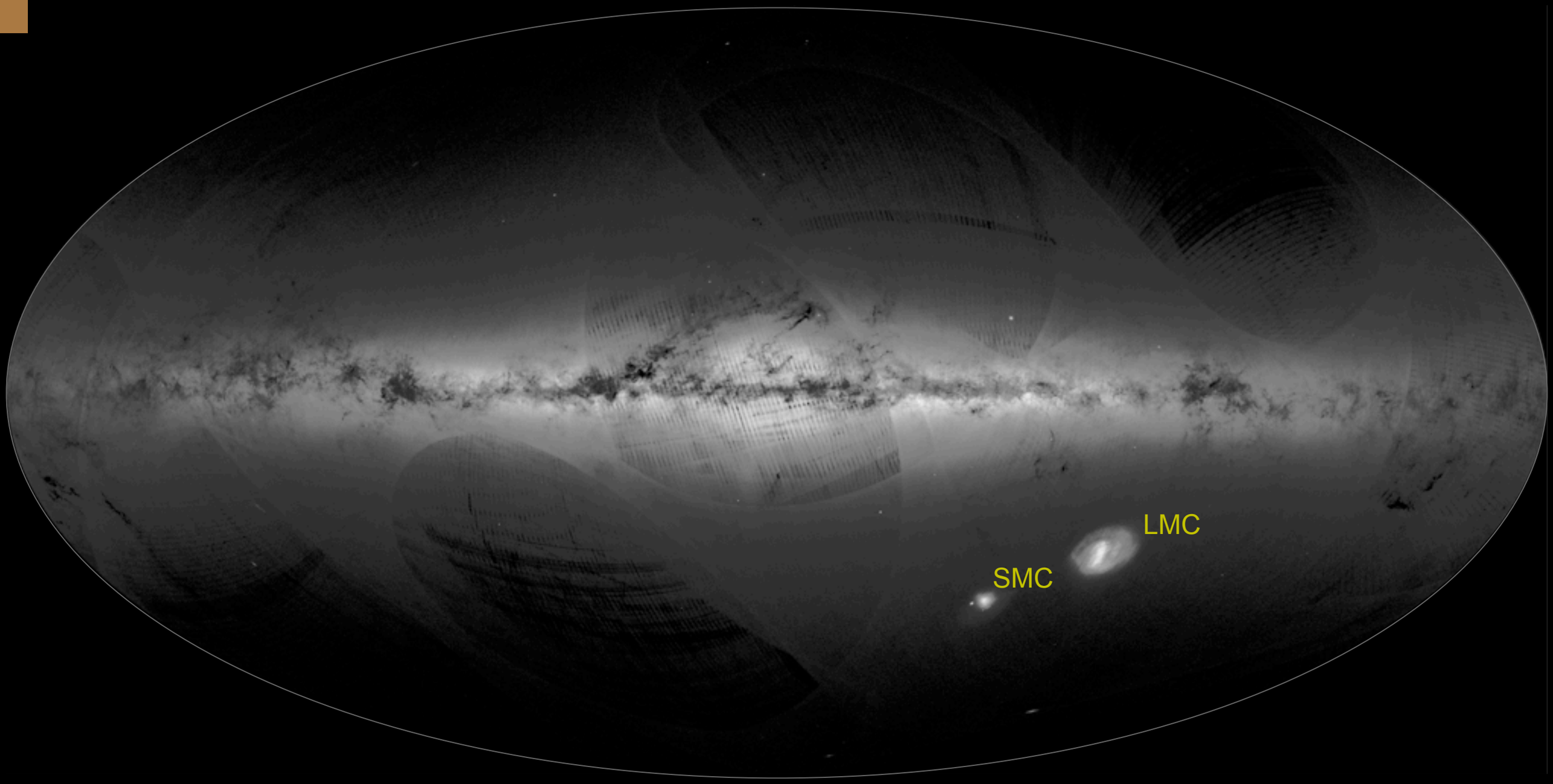
Source numbers	
Total number of sources	1 142 679 769
No. of primary (TGAS) sources	2 057 050
HIPPARCOS	93 635
Tycho-2 (excluding Hipparcos stars)	1 963 415
No. of secondary sources	1 140 622 719
No. of sources with light curves	3194
Cepheids	599
RR Lyrae	2595

Source density map (3 arcmin resolution)



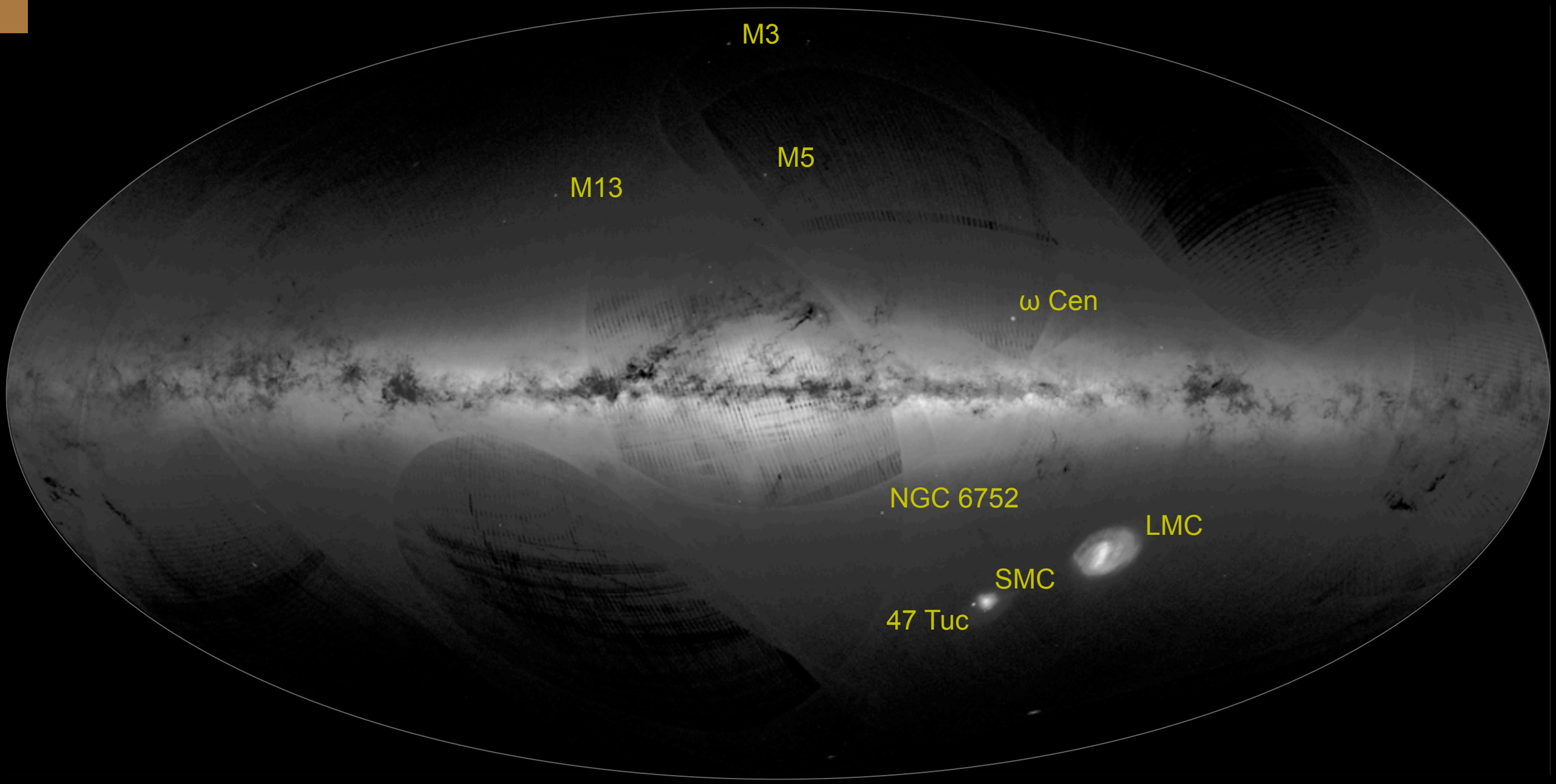
ESA/Gaia/DPAC/André Moitinho & Márcia Barros (CENTRA - University of Lisbon)

Source density map (3 arcmin resolution)



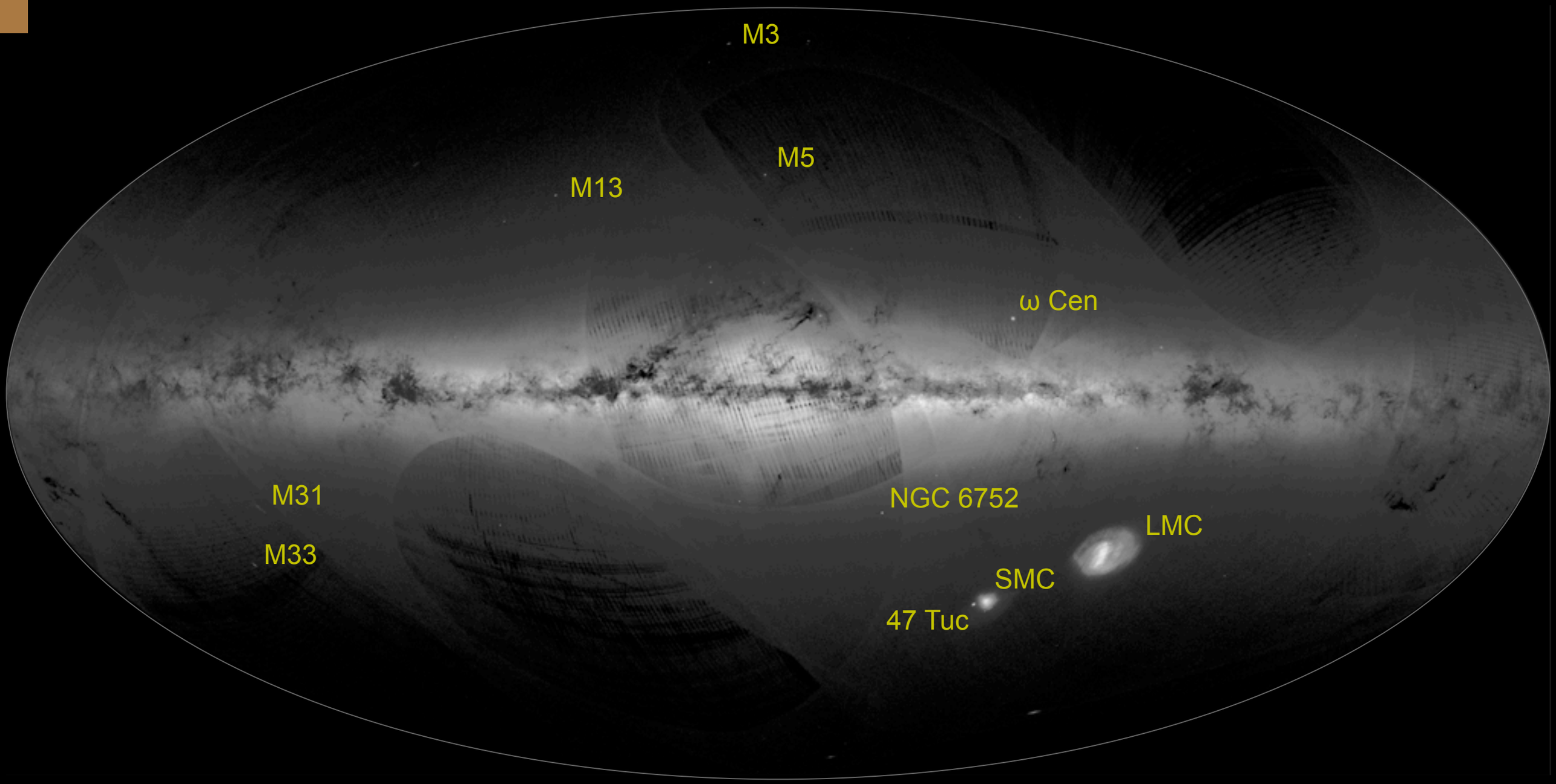
ESA/Gaia/DPAC/André Moitinho & Márcia Barros (CENTRA - University of Lisbon)

Source density map (3 arcmin resolution)

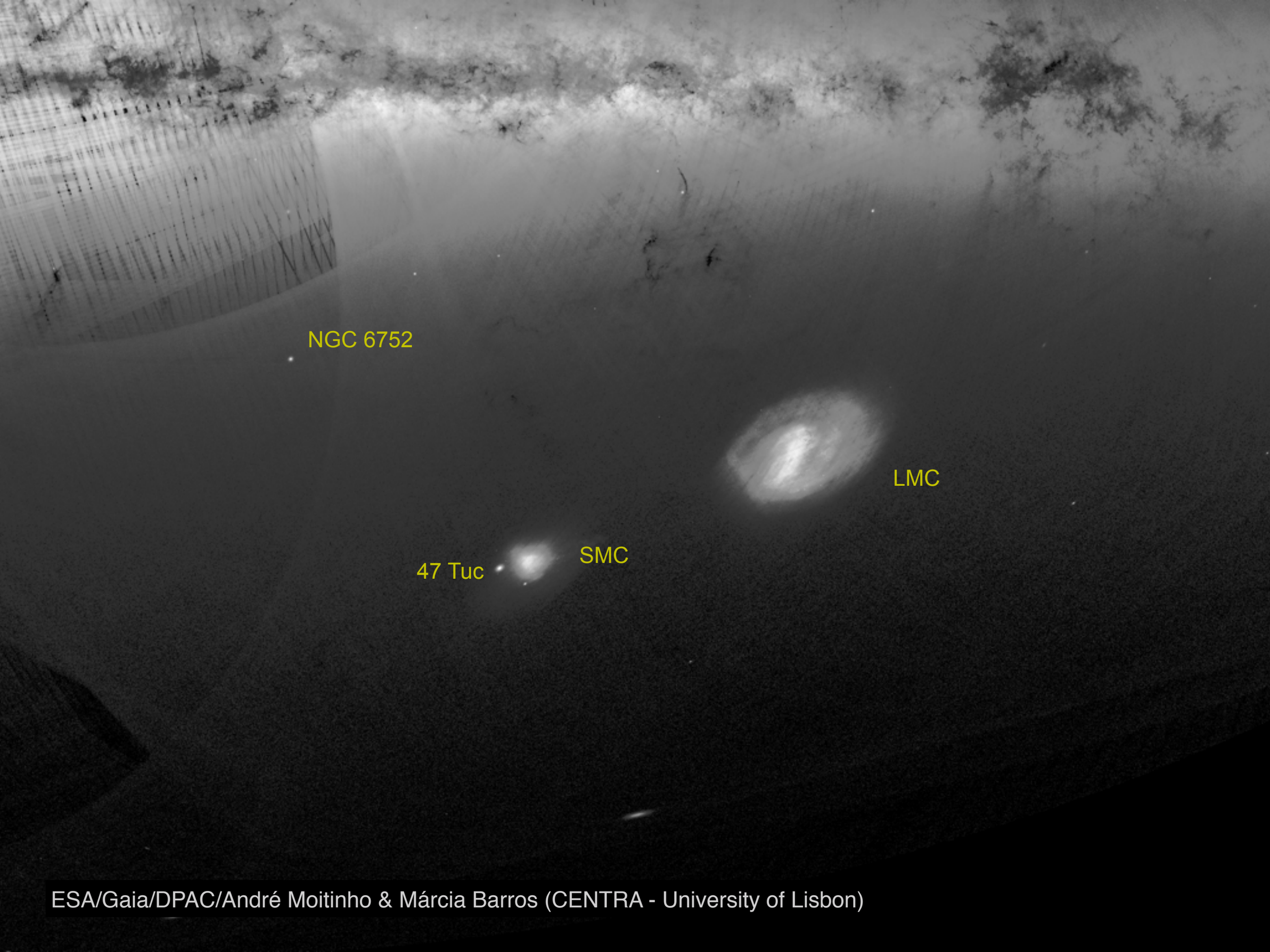


ESA/Gaia/DPAC/André Moitinho & Márcia Barros (CENTRA - University of Lisbon)

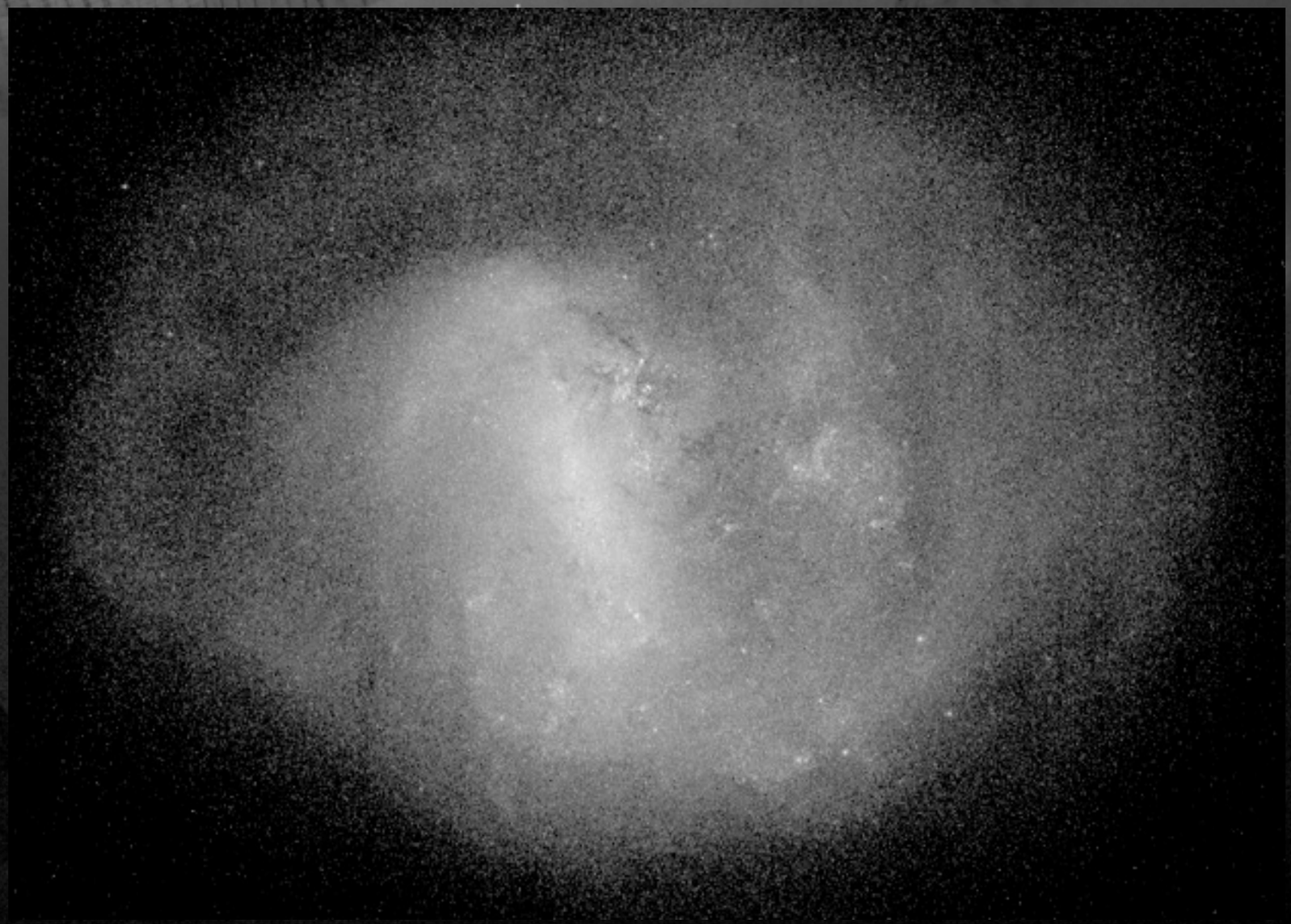
Source density map (3 arcmin resolution)



ESA/Gaia/DPAC/André Moitinho & Márcia Barros (CENTRA - University of Lisbon)

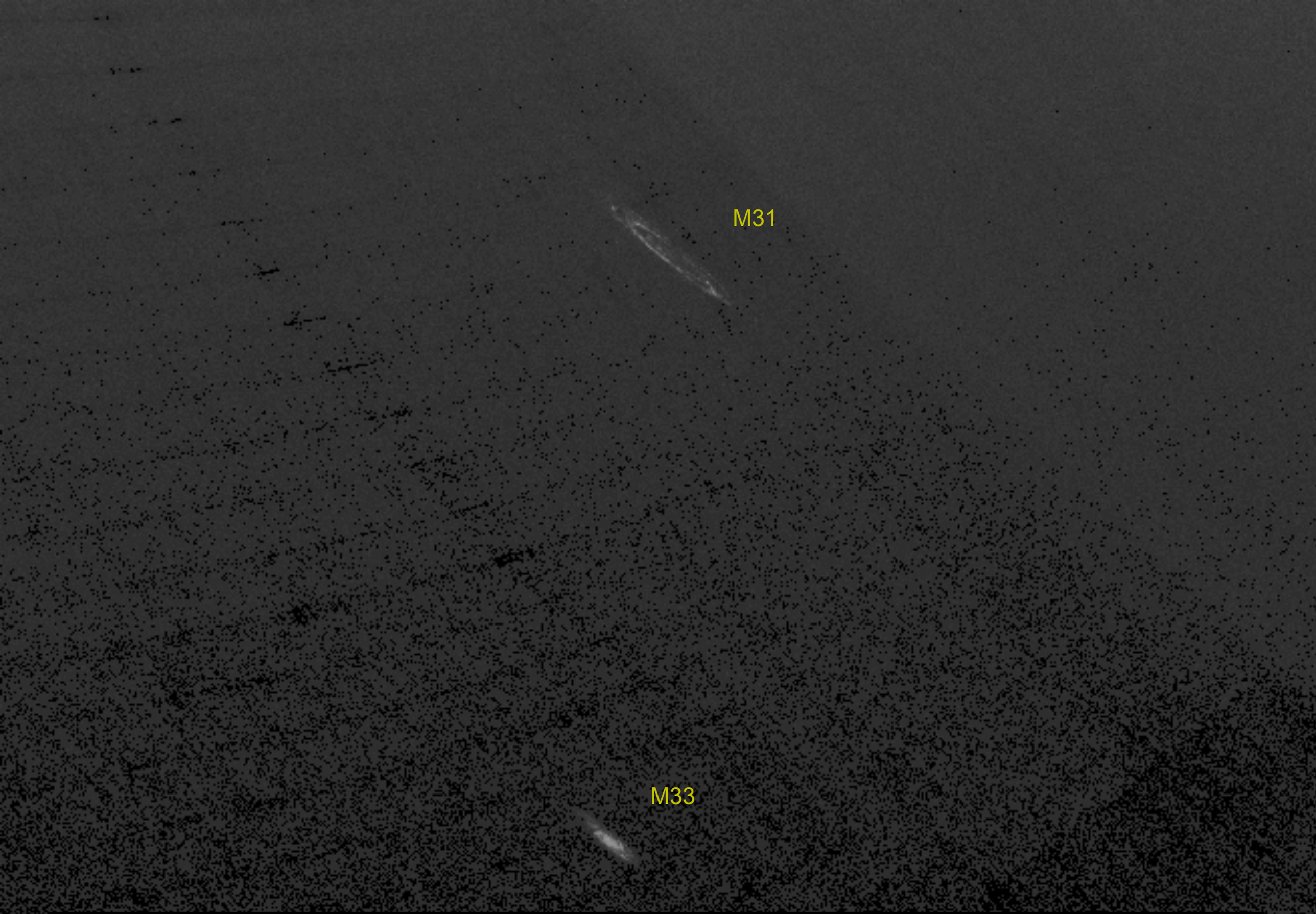


ESA/Gaia/DPAC/André Moitinho & Márcia Barros (CENTRA - University of Lisbon)



LMC

ESA/Gaia/DPAC/André Moitinho & Márcia Barros (CENTRA - University of Lisbon)

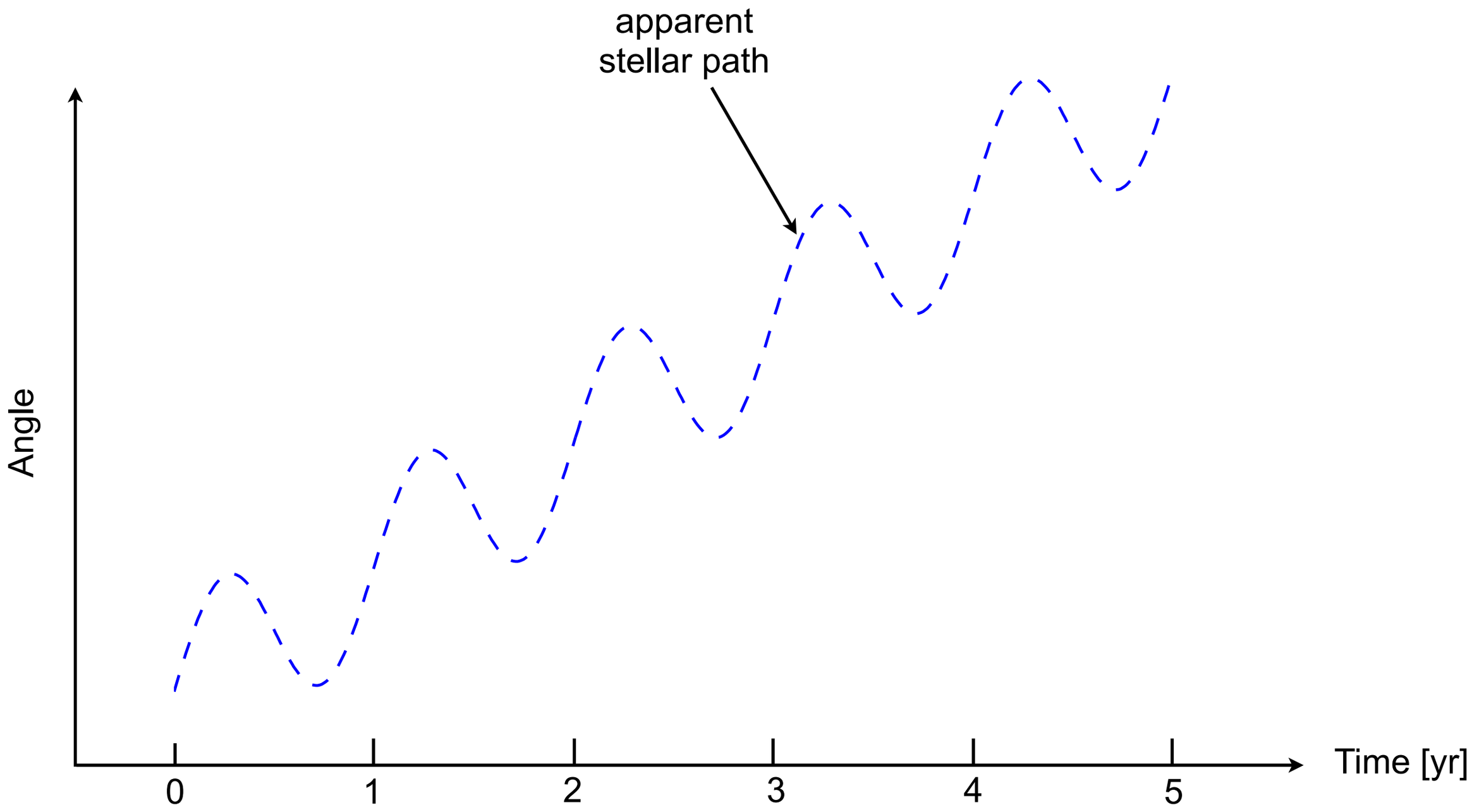


ESA/Gaia/DPAC/André Moitinho & Márcia Barros (CENTRA - University of Lisbon)

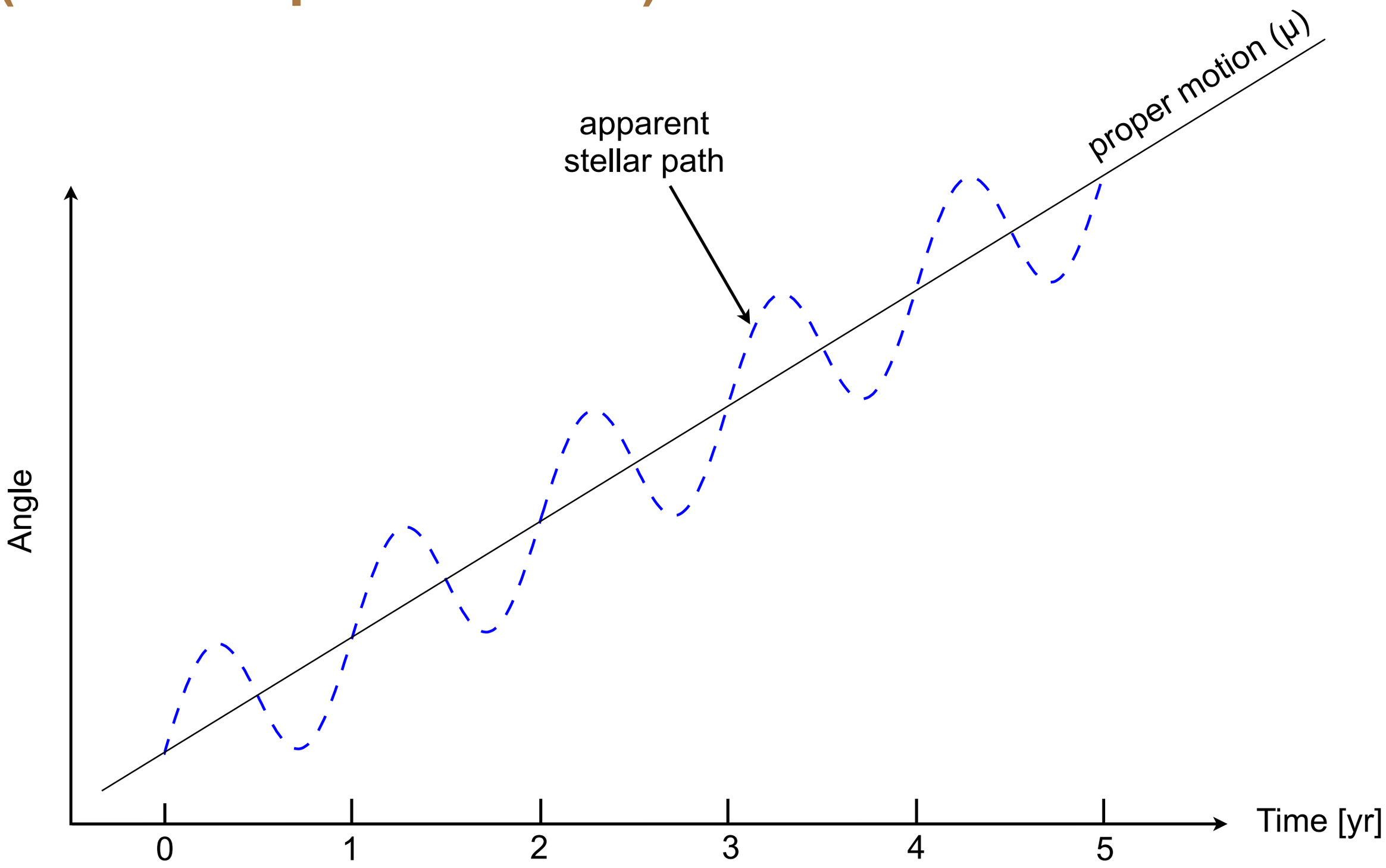
Gaia DR1: Number of objects ("sources")

Source numbers	
Total number of sources	1 142 679 769
No. of primary (TGAS) sources	2 057 050
HIPPARCOS	93 635
Tycho-2 (excluding Hipparcos stars)	1 963 415
No. of secondary sources	1 140 622 719
No. of sources with light curves	3194
Cepheids	599
RR Lyrae	2595

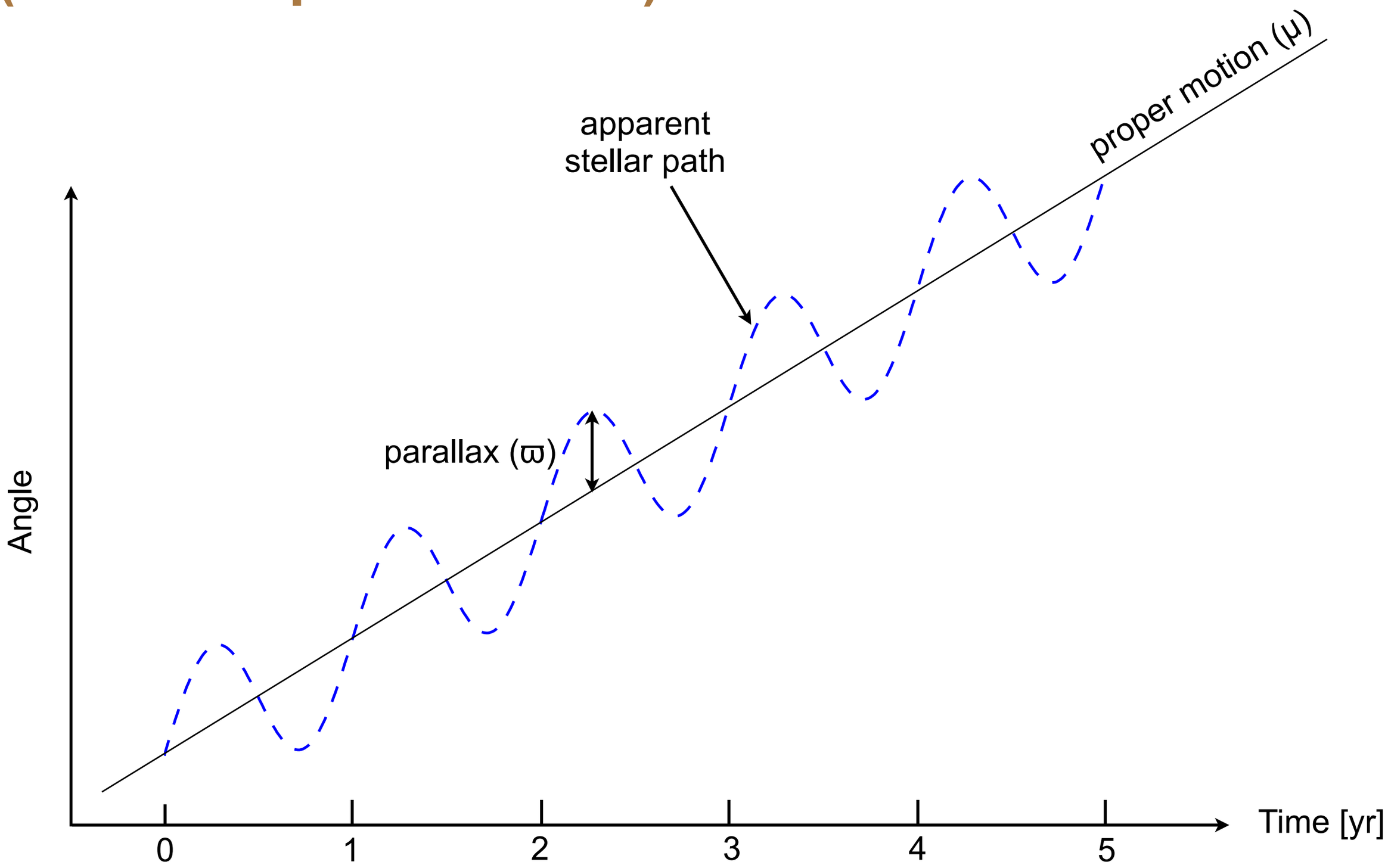
Astrometric parameters for a single star (uniform space motion)



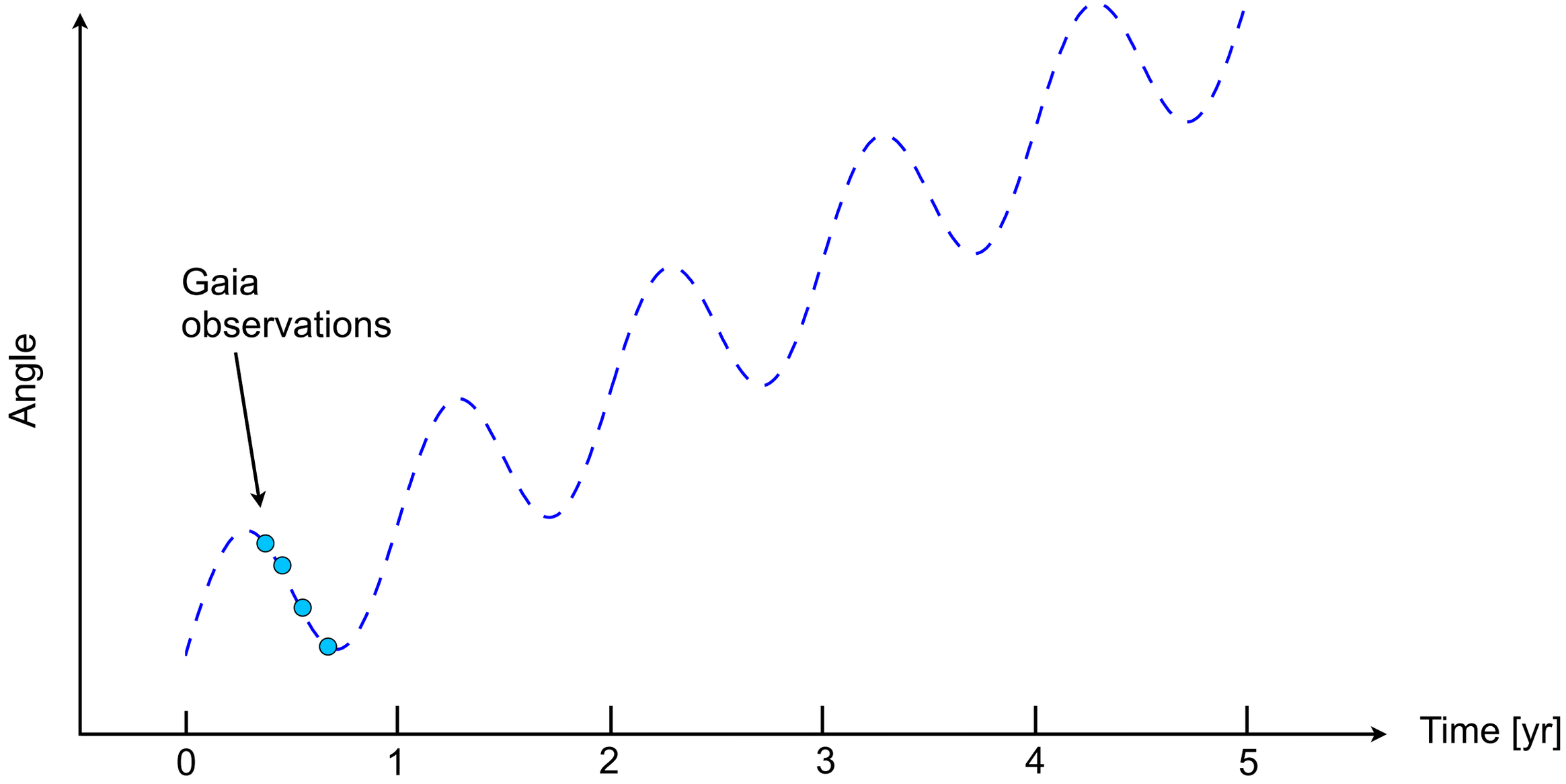
Astrometric parameters for a single star (uniform space motion)



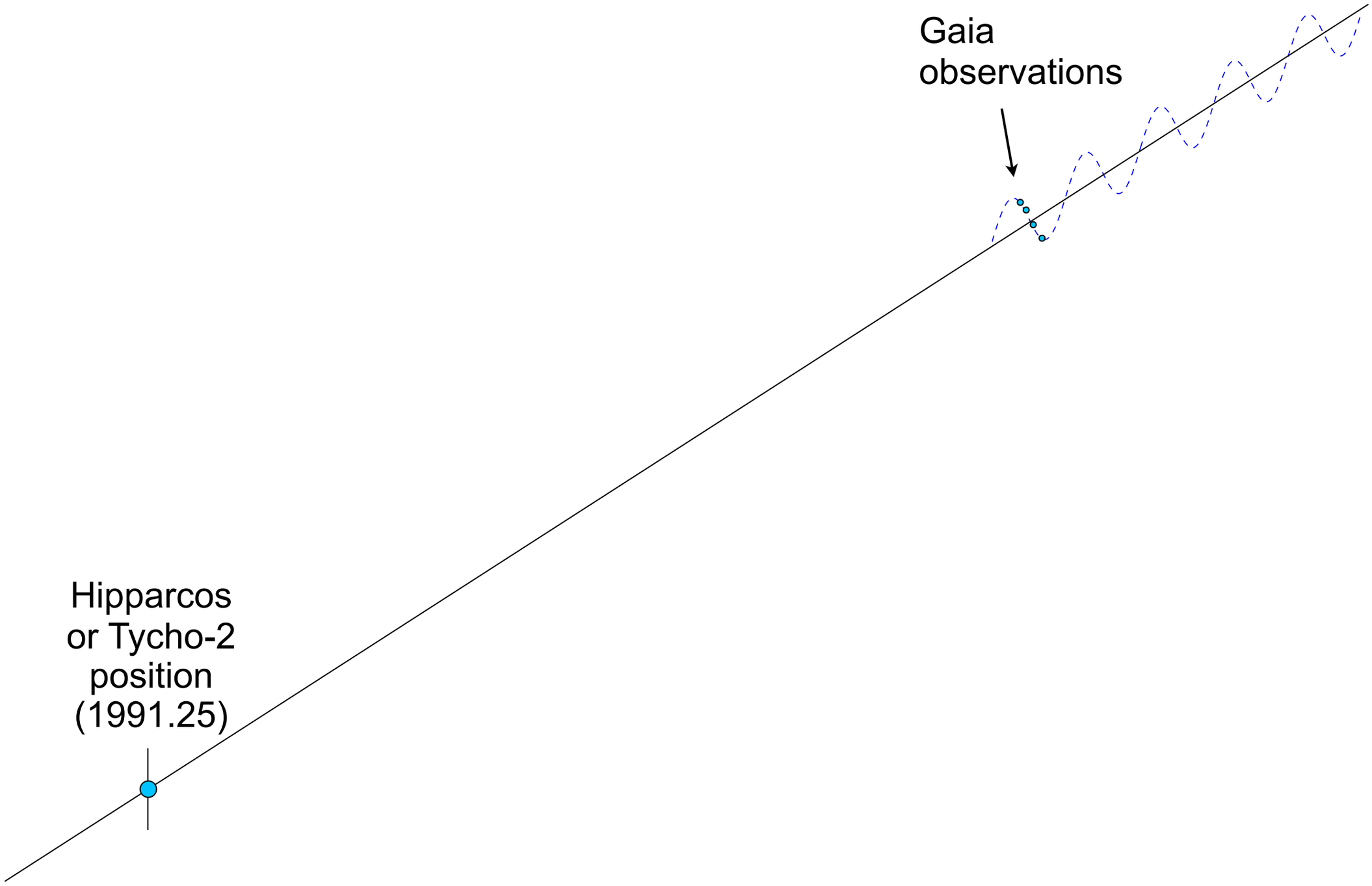
Astrometric parameters for a single star (uniform space motion)



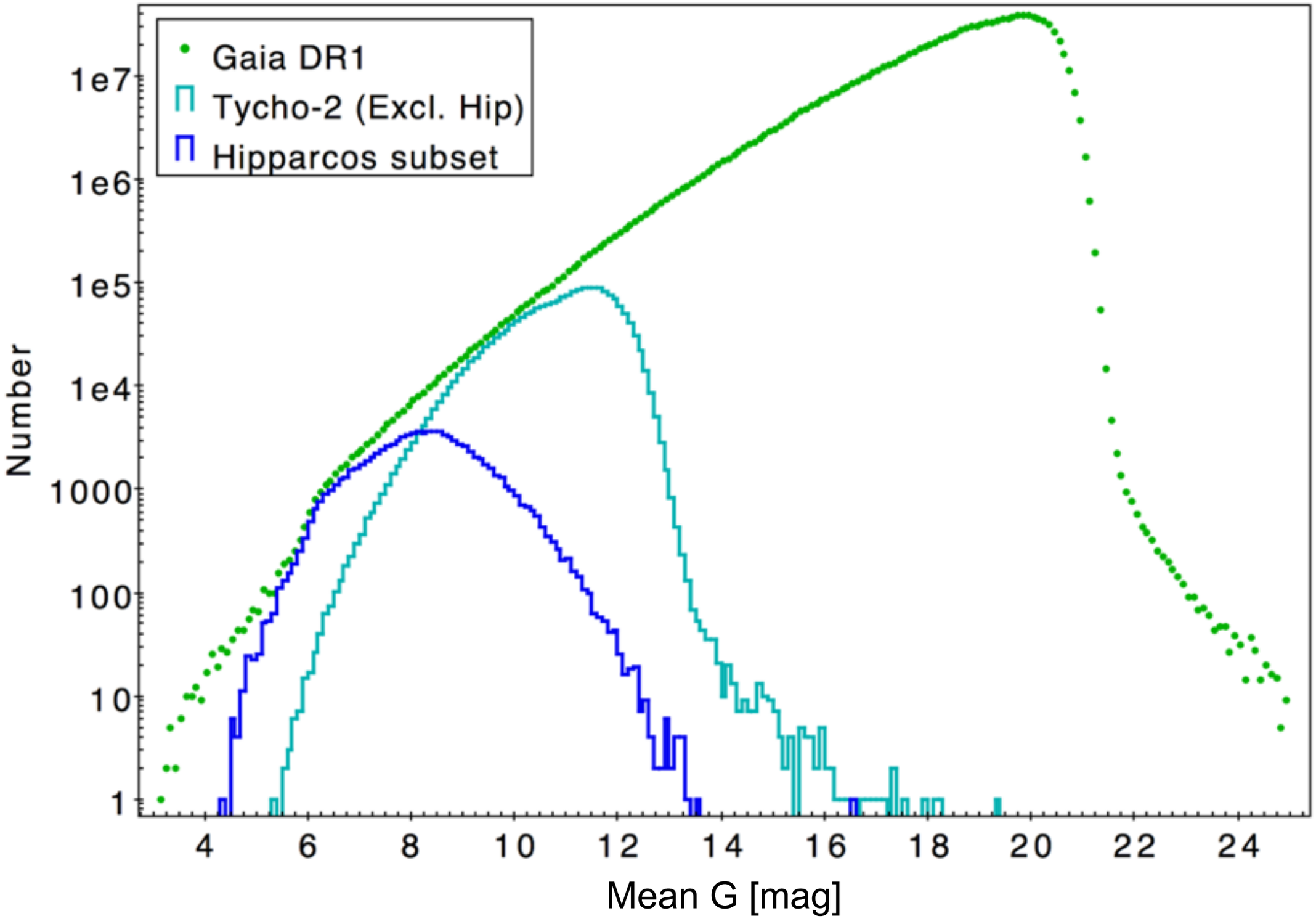
μ–ϖ degeneracy for < 1 yr of observations



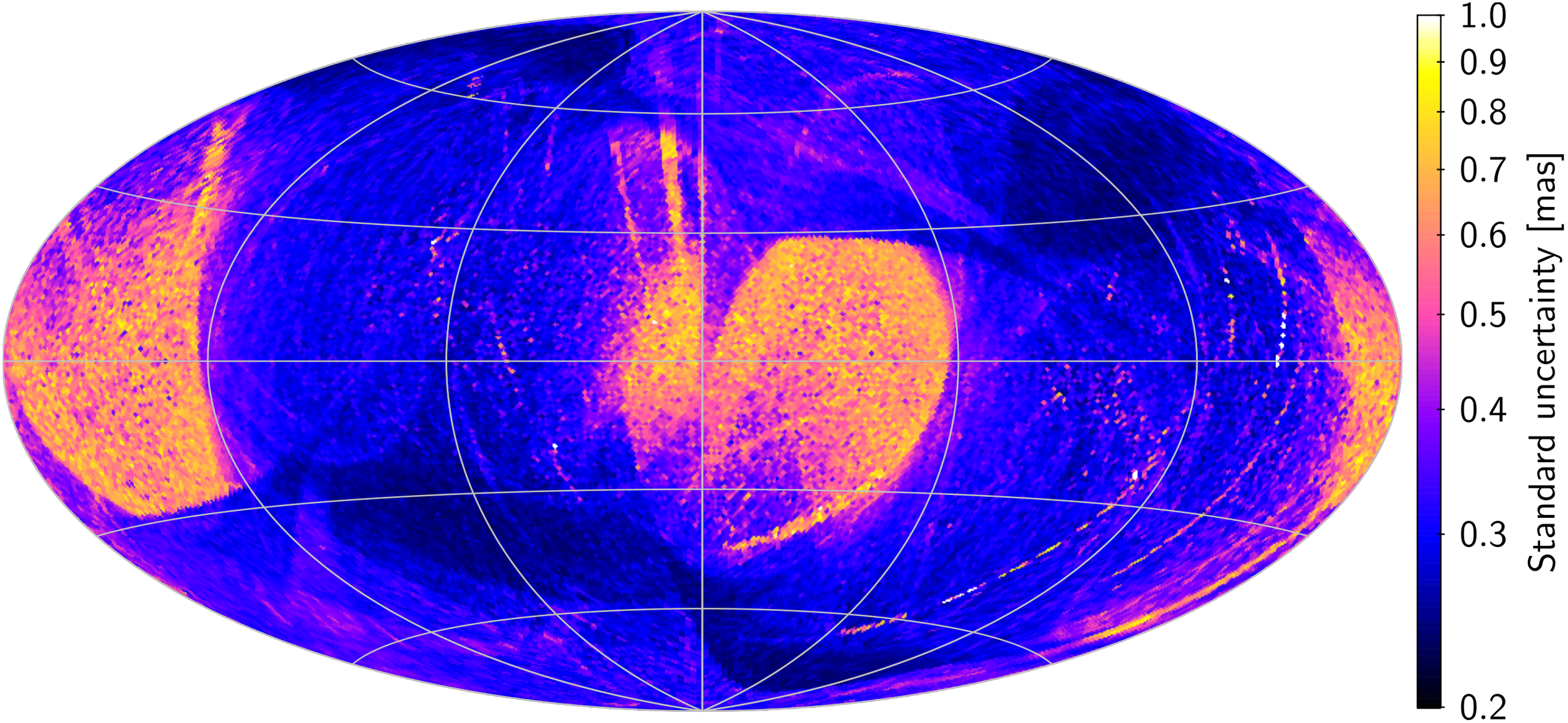
Lifting the degeneracy:
TGAS - Tycho-Gaia Astrometric Solution (Michalik et al. 2015)



Gaia DR1: Magnitude distribution of sources



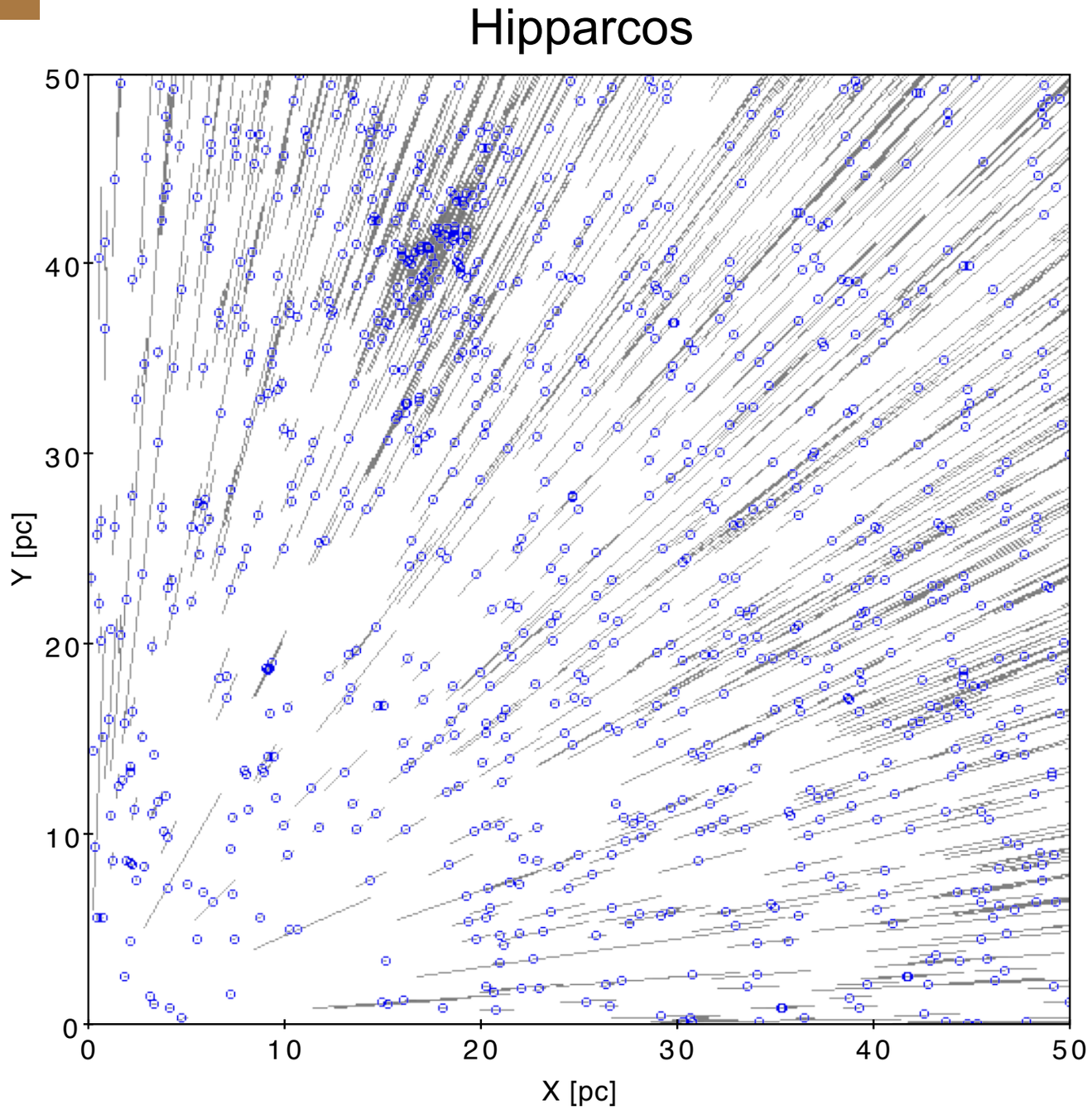
TGAS: Standard uncertainty in parallax



Median uncertainty per pixel (~1 deg^2)

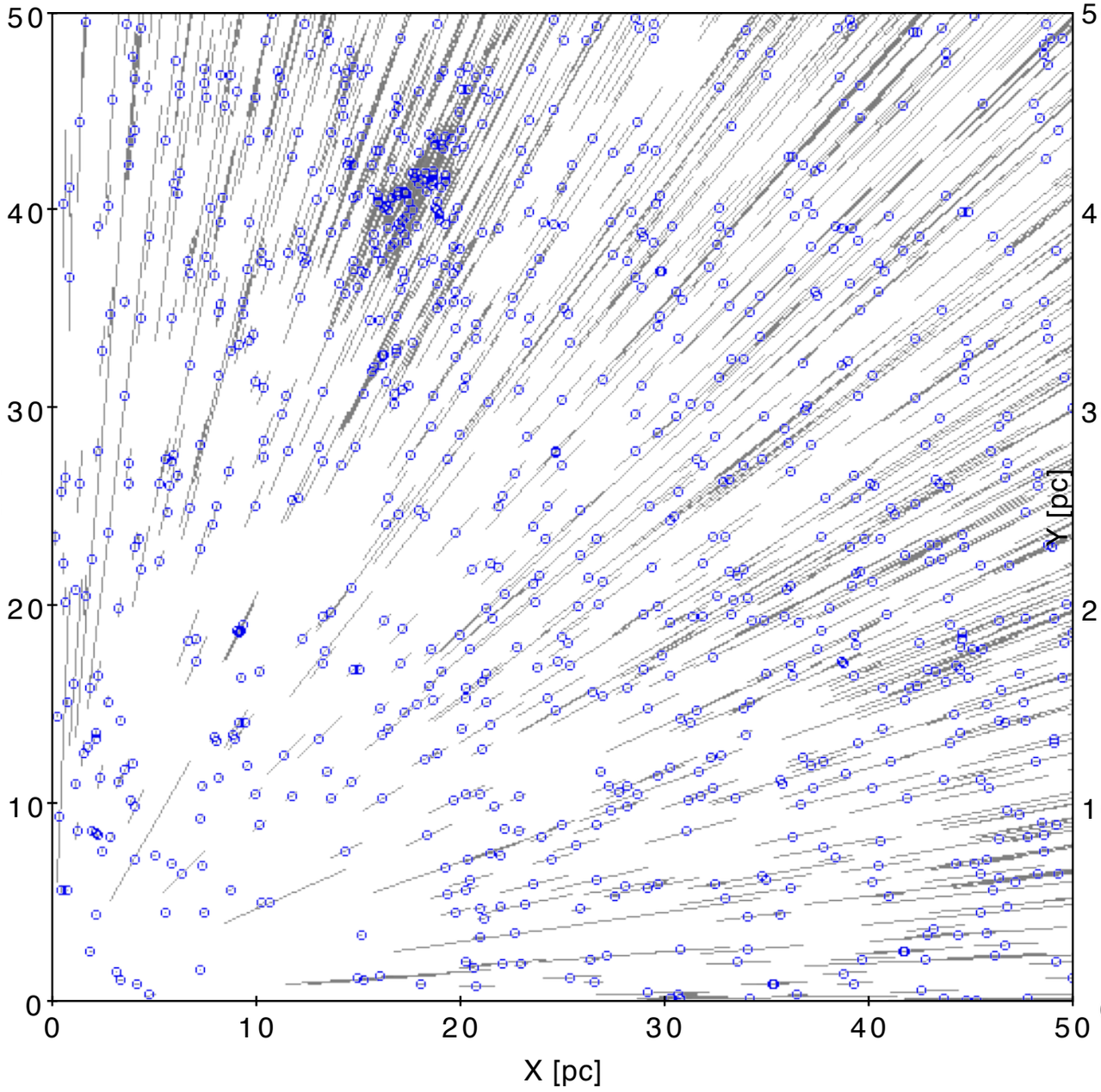
Overall median = 0.32 mas

Improved distances to nearby stars

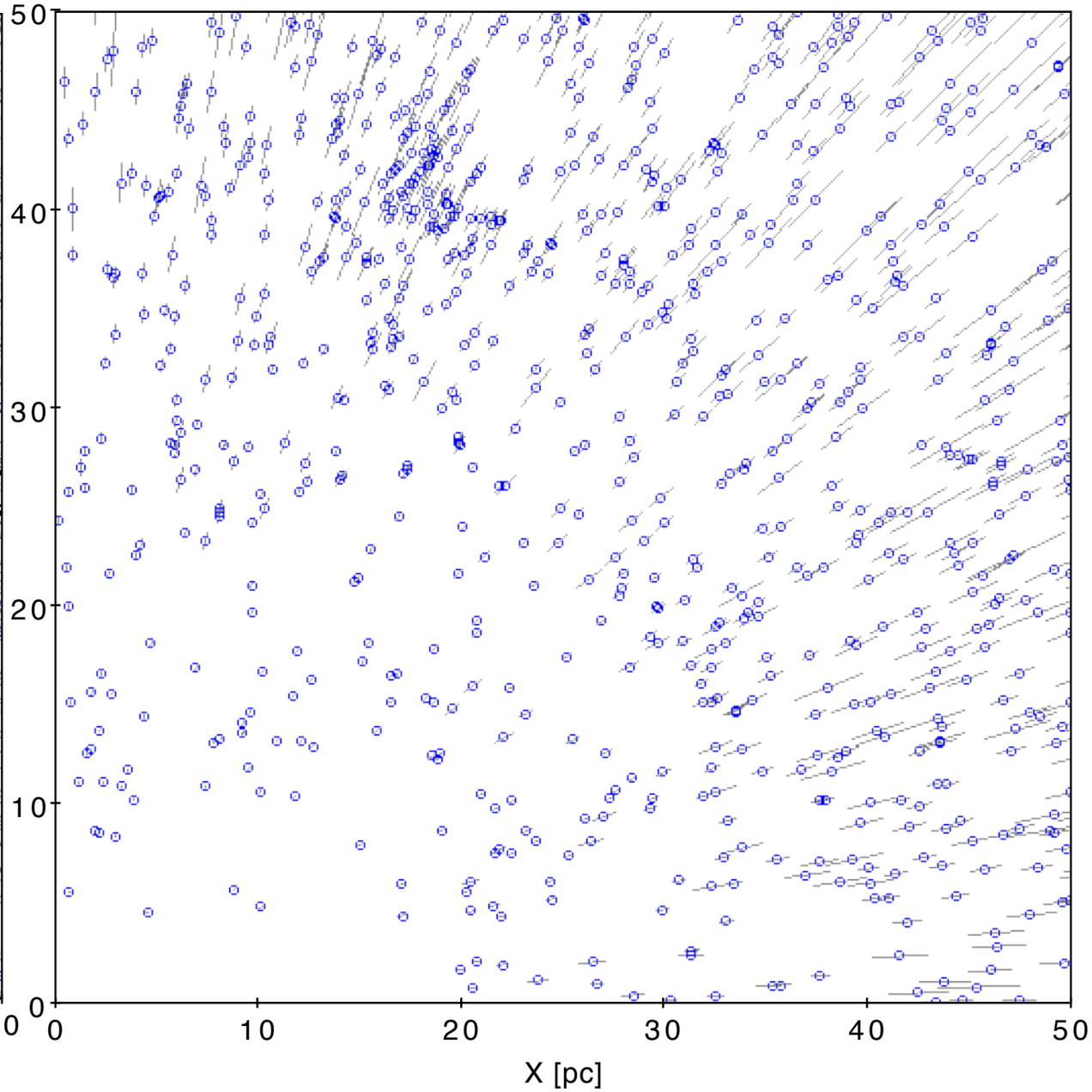


Improved distances to nearby stars

Hipparcos

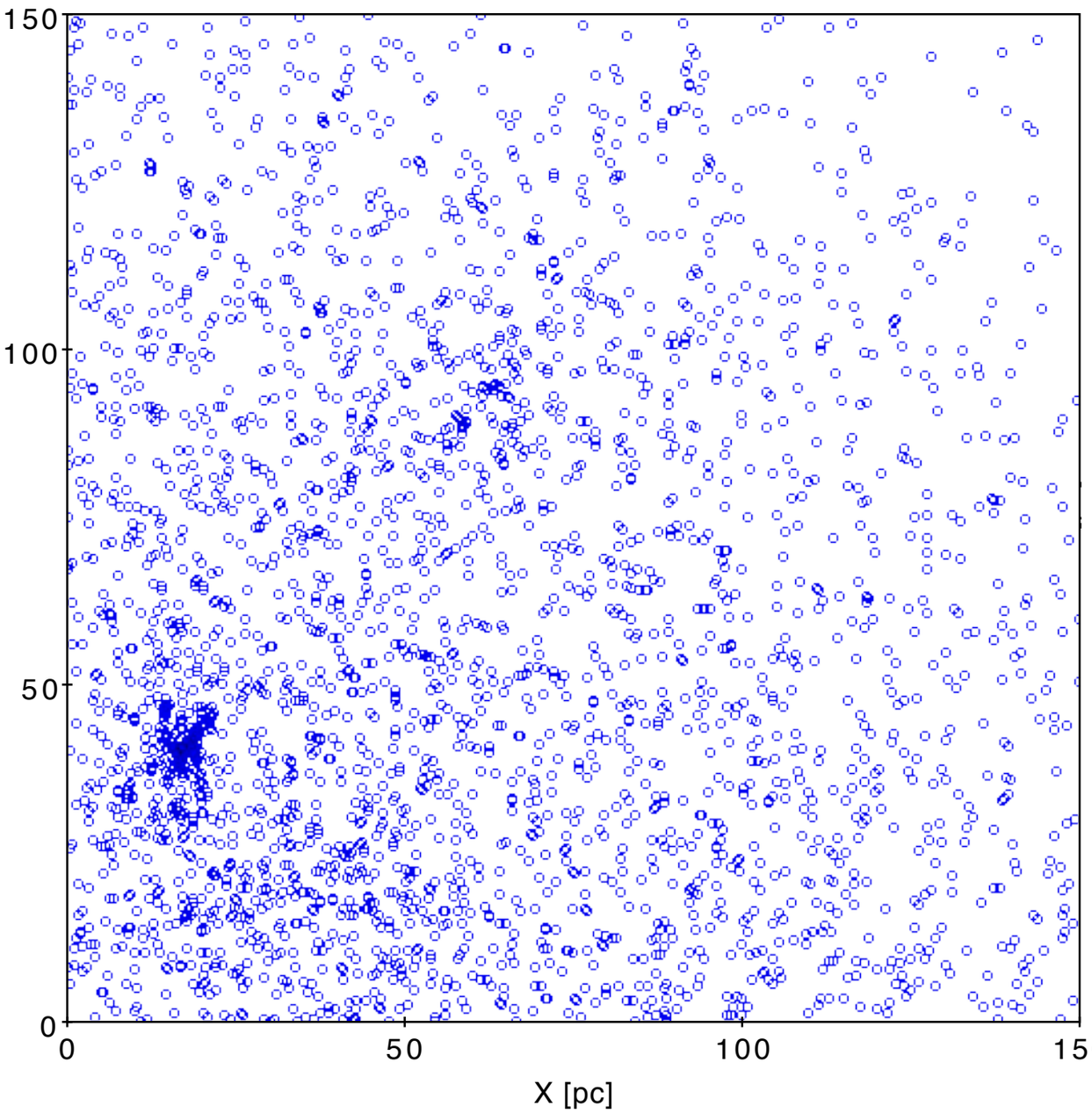


Gaia DR1 (TGAS)

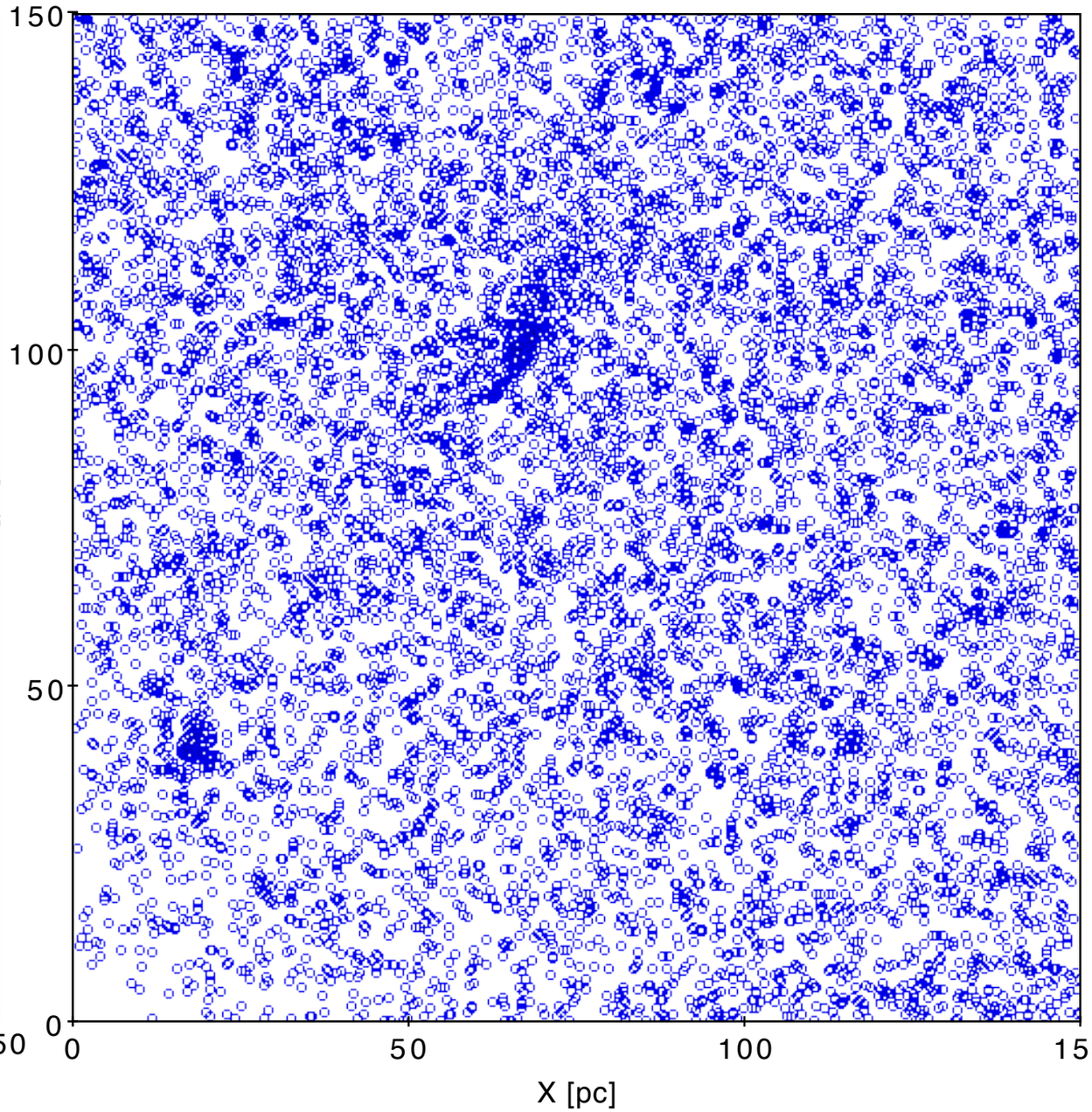


More stars within parallax horizon ($\varpi/\sigma_\varpi > 5$)

Hipparcos



Gaia DR1 (TGAS)



Known problems (1): Where is Proxima?

A number of (bright) sources are missing in Gaia DR1:

- Stars brighter than magnitude 6 are generally missing because of CCD saturation
  - This problem will remain in future releases
- Stars with proper motion > 3.5 arcsec/yr are missing because of a problem with the cross-matching
  - E.g. Proxima Cen and Barnard's Star are missing
  - This problem will be remedied in Gaia DR2

Known problems (2): Systematic errors

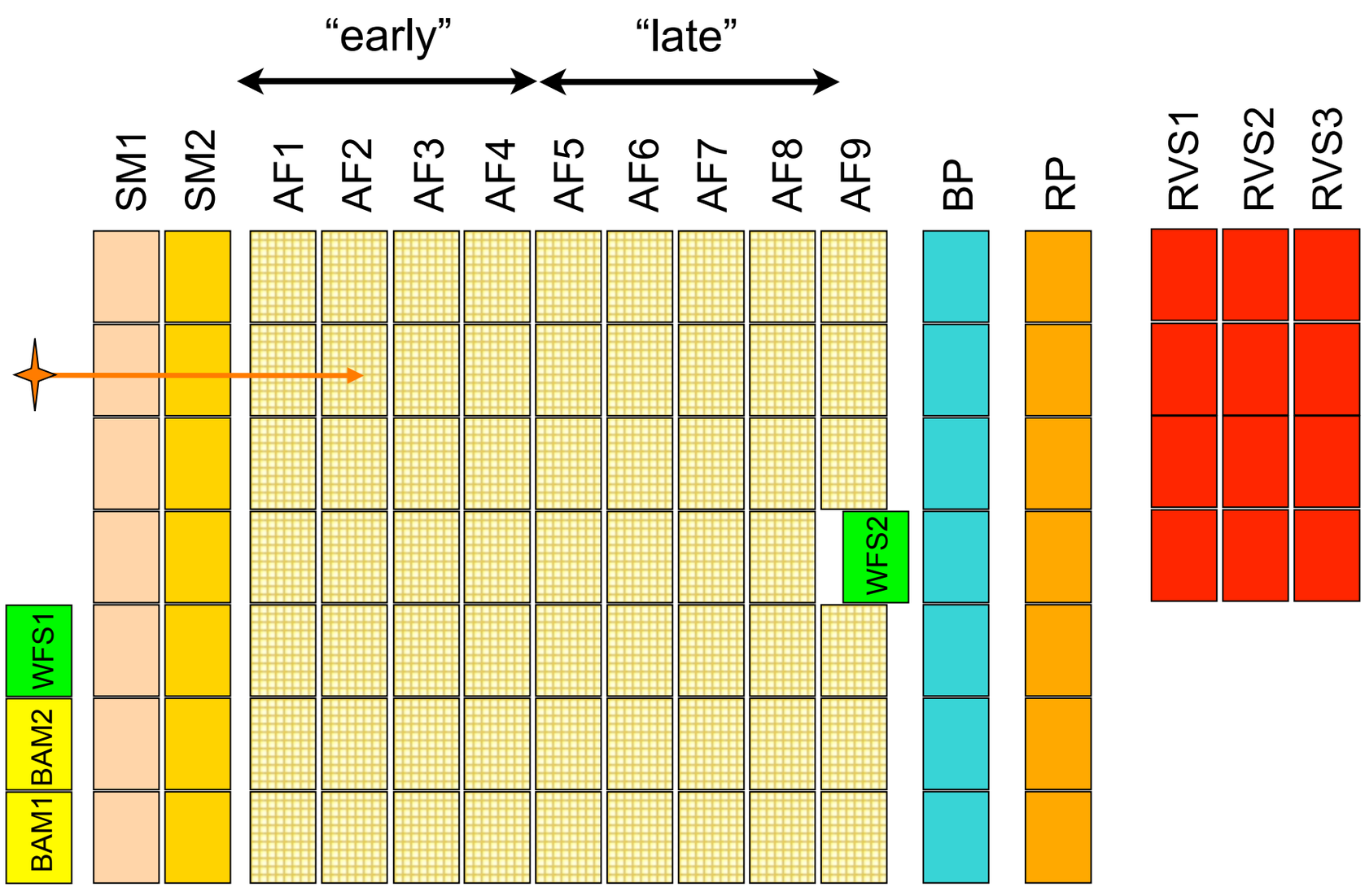
The instrument and attitude models used in Gaia DR1 are very primitive. For example, colour-dependent image displacements are not calibrated.

Cross-validation solutions indicate systematic errors of ±0.3 mas.

Known problems (2): Systematic errors

The instrument and attitude models used in Gaia DR1 are very primitive. For example, colour-dependent image displacements are not calibrated.

Cross-validation solutions indicate systematic errors of ±0.3 mas.

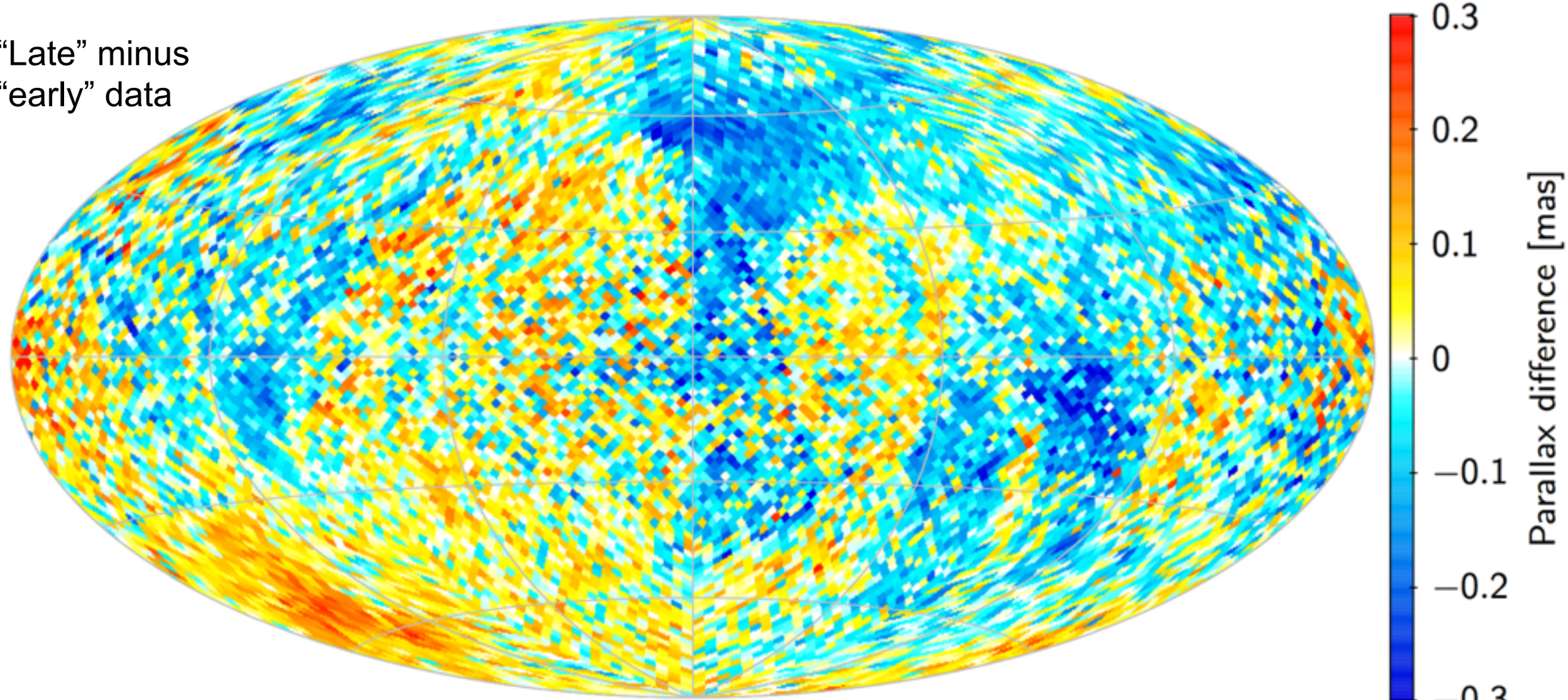


Known problems (2): Systematic errors

The instrument and attitude models used in Gaia DR1 are very primitive. For example, colour-dependent image displacements are not calibrated.

Cross-validation solutions indicate systematic errors of ±0.3 mas.

“Late” minus
“early” data



Systematics in Gaia DR1 parallaxes

Due to known limitations in the astrometric processing

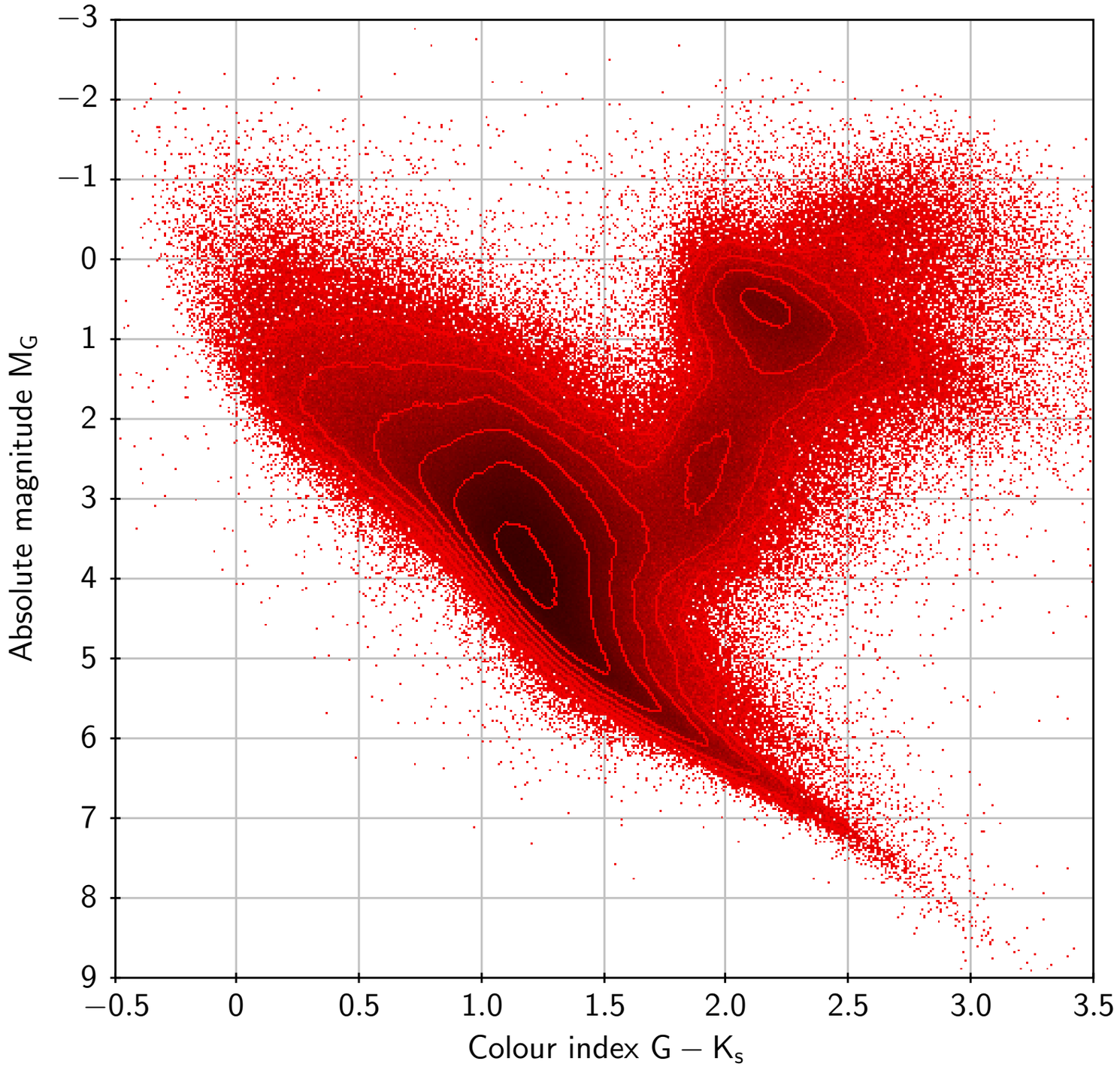
- a global offset of ±0.1 mas may be present
- there are colour dependent, spatially correlated errors of ±0.2 mas
- over large spatial scales, parallax zero point errors reach ±0.3 mas
- in a few small areas even ±1 mas

Parallax uncertainties should be quoted as

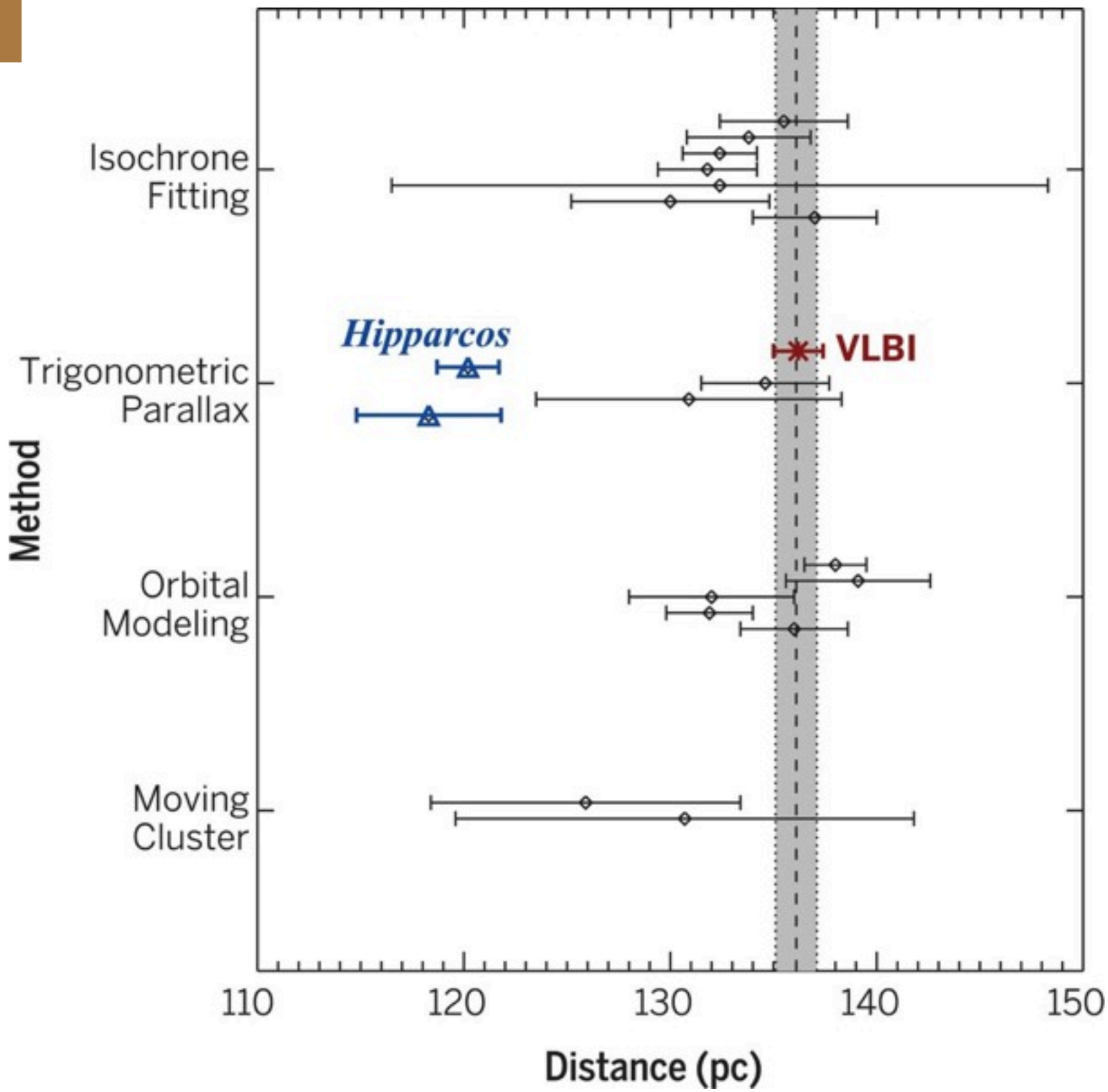
$$\varpi \pm \sigma_{\varpi} \text{ (random)} \pm 0.3 \text{ mas (syst.)}$$

Averaging parallaxes e.g. in a cluster does not reduce the systematics!

HR diagram for 1 million stars with $\varpi/\sigma_\varpi > 5$



Distance to the Pleiades

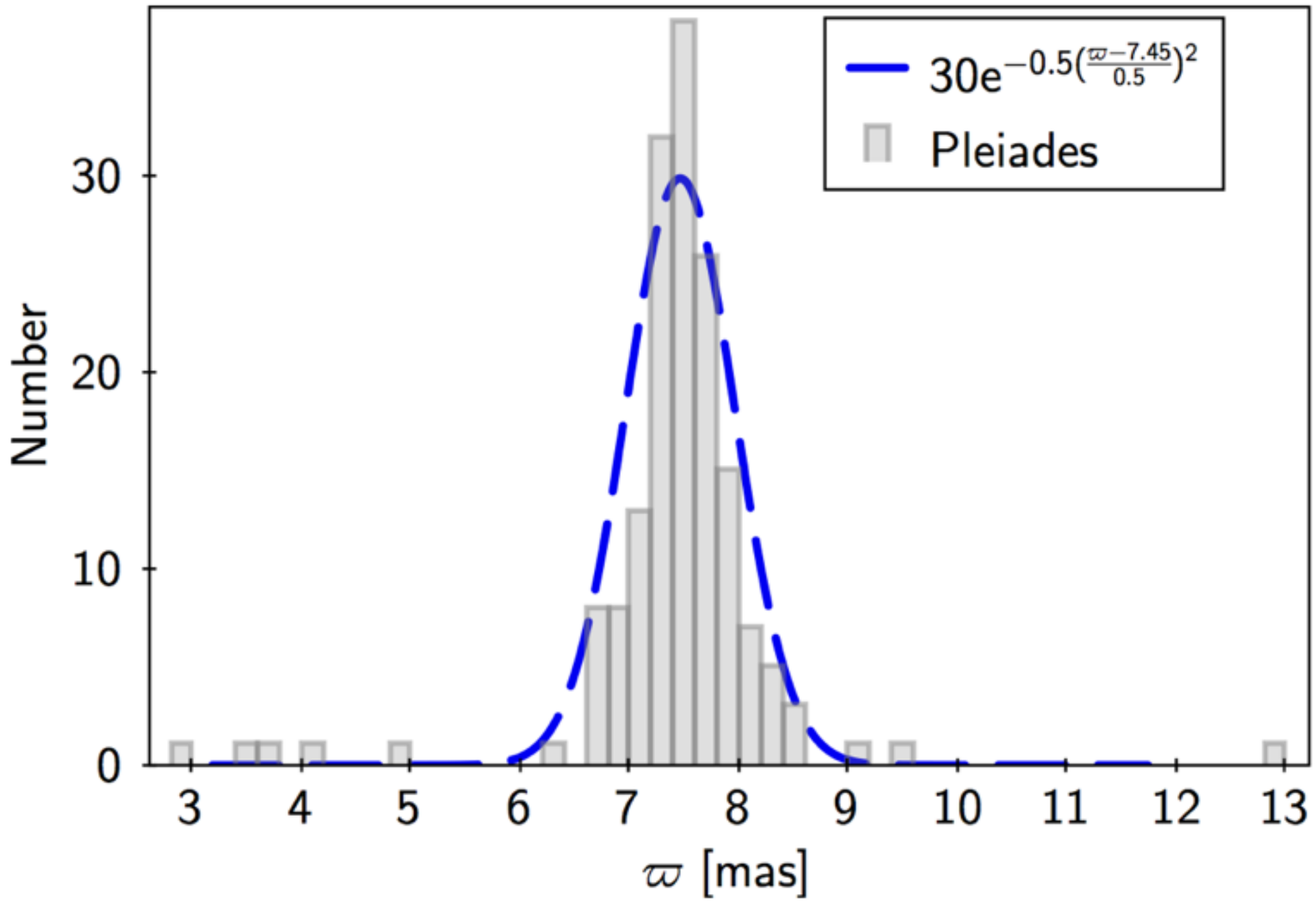


Melis et al.
Science 345, 1029 (2014)

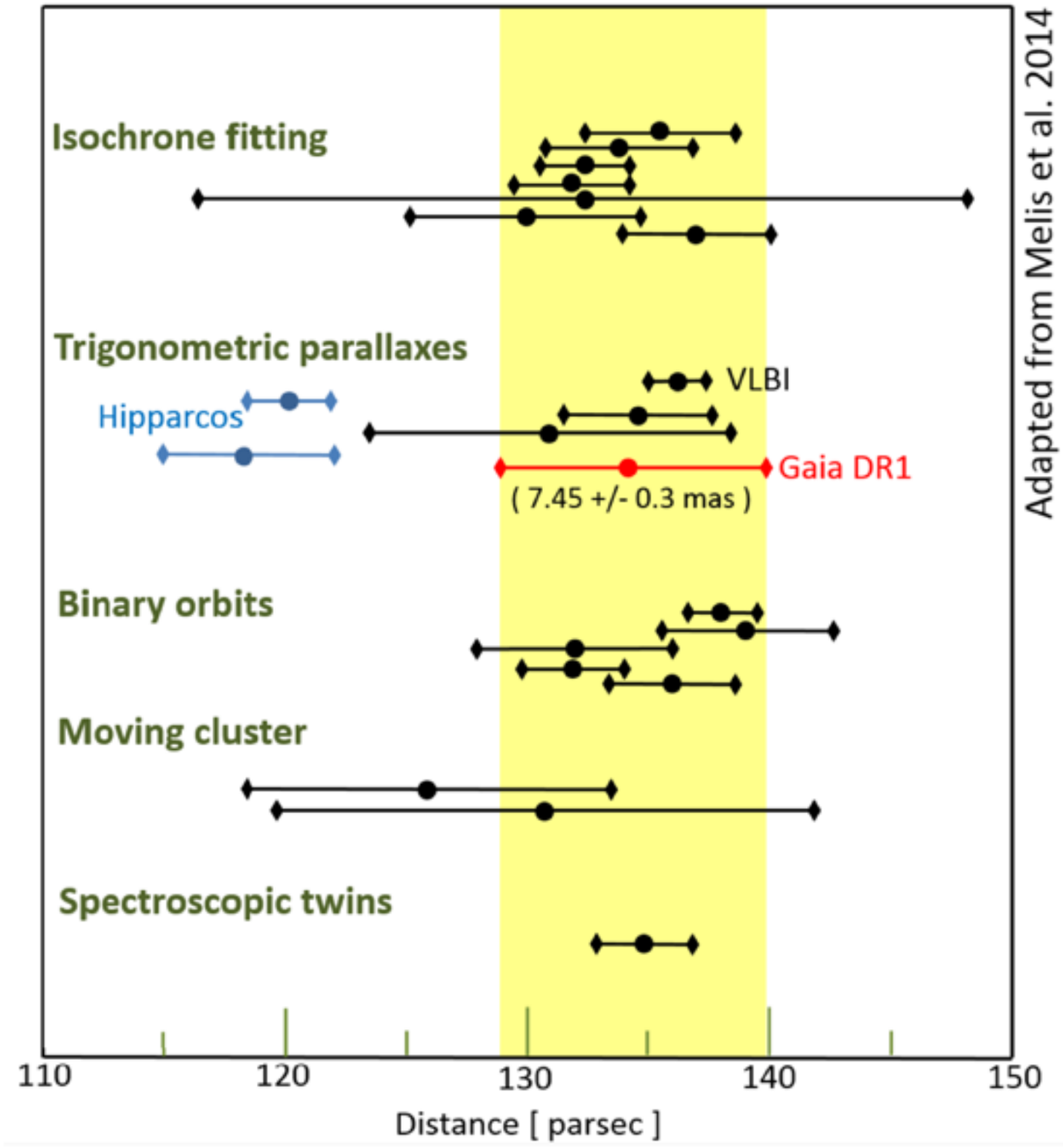
A VLBI resolution of the Pleiades distance controversy

Carl Melis,[1*] Mark J. Reid,[2] Amy J. Mioduszewski,[3] John R. Stauffer,[4] Geoffrey C

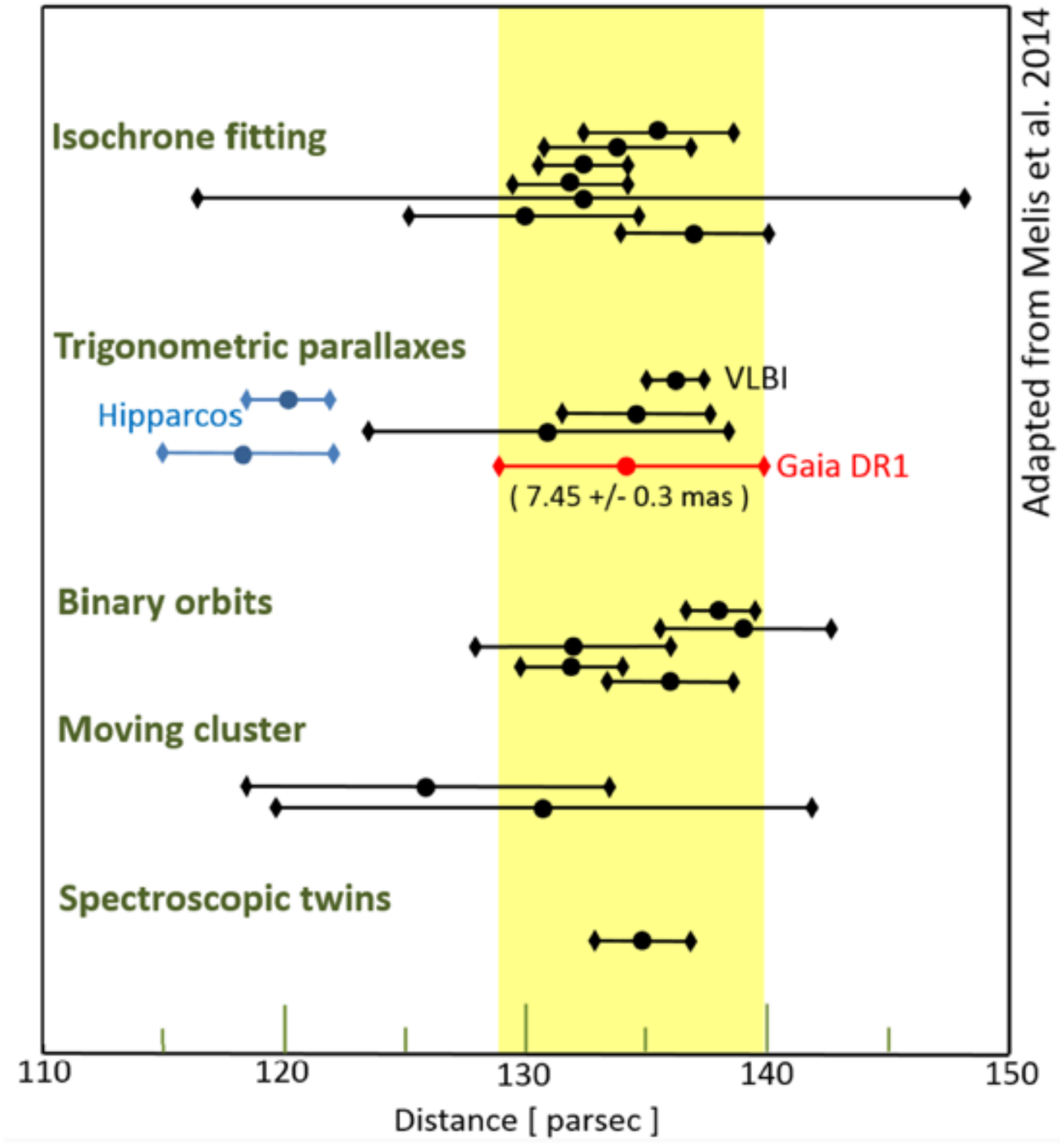
Distance to the Pleiades in Gaia DR1



Distance to the Pleiades in Gaia DR1



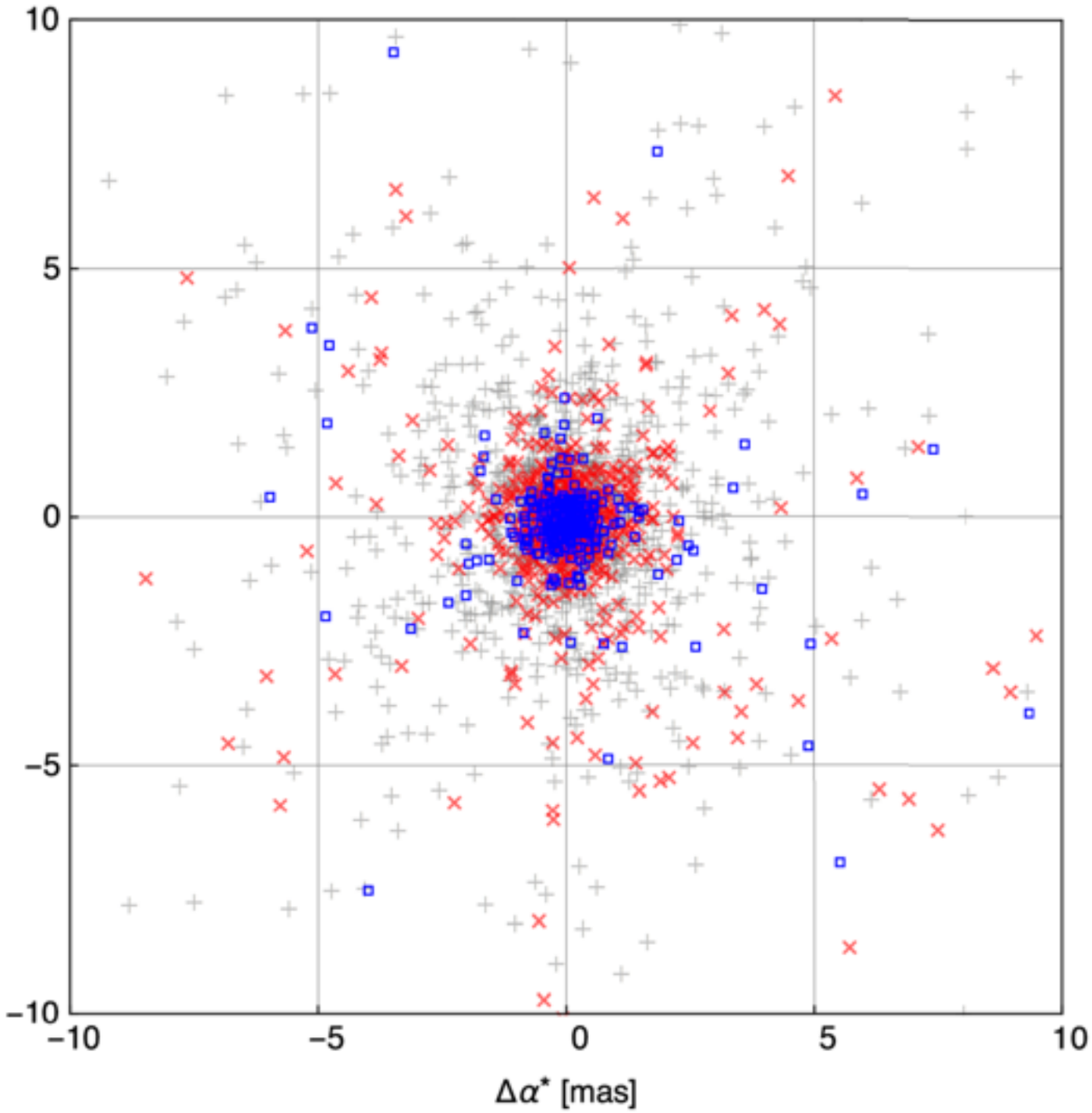
Distance to the Pleiades in Gaia DR1



HII 174 (TYC 1803-0008-1):

Gaia DR1 $\varpi = 7.394 \pm 0.301$ mas
VLBI $\varpi = 7.418 \pm 0.025$ mas
---
difference -0.024 ± 0.302 mas

Reference frame from observations of quasars



Gaia DR1 is aligned with the International Celestial Reference Frame through Gaia's observations of ~2000 faint (17-20 mag) quasars with accurate VLBI positions.

Gaia's observations show:

(1) excellent agreement between radio and optical positions (RMS < 1 mas)

(2) that the Hipparcos reference frame rotates wrt QSOs by 0.24 mas/yr

Data access

Main portal at ESDC: `http://archives.esac.esa.int/gaia`

- online documentation
- VO compatible, TAP interface, visualization apps

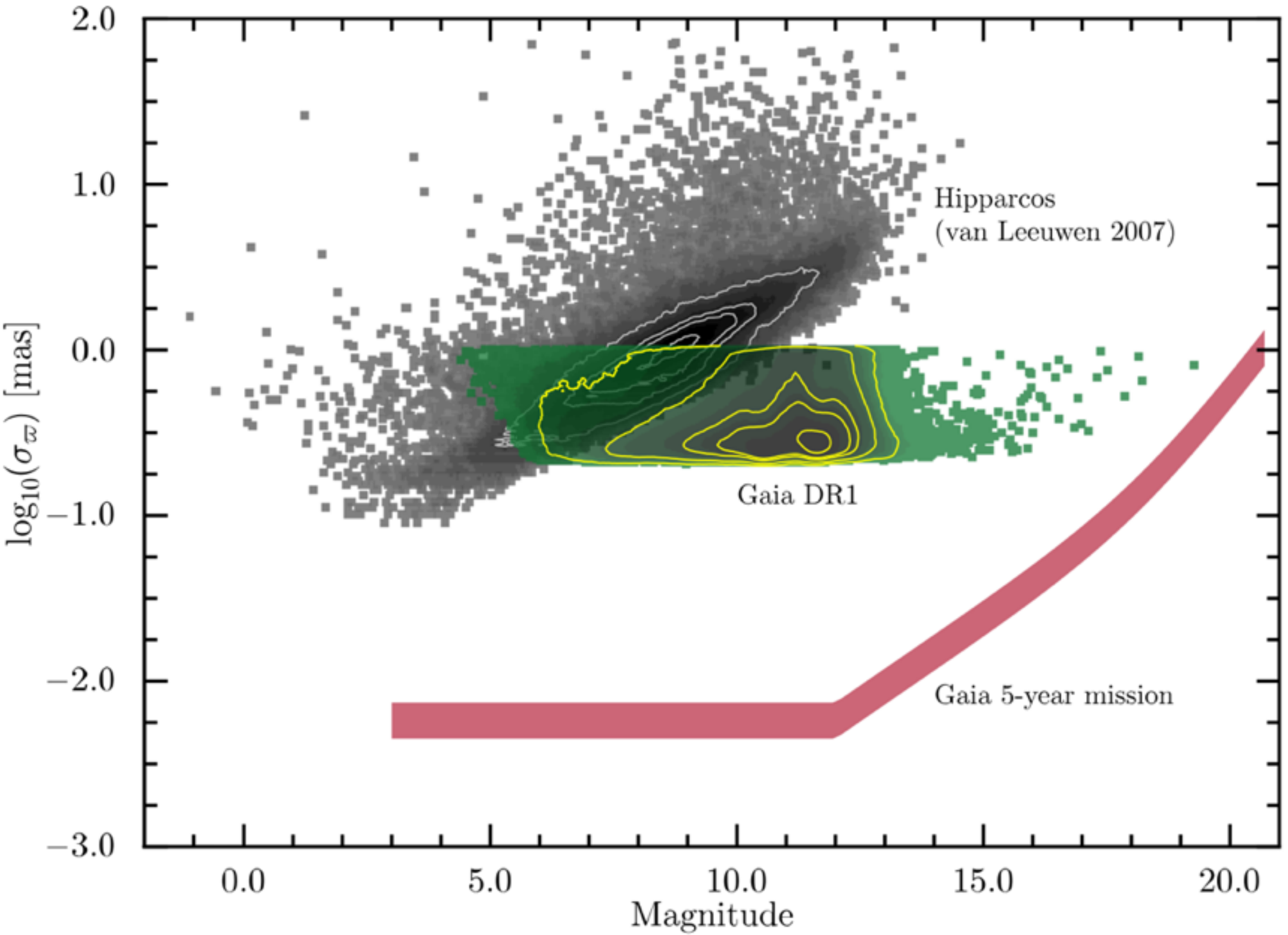
Partner data centres (data available today)

- Centre de Données astronomiques de Strasbourg (CDS): `http://cds.unistra.fr/gaia`
- ASI Science Data Center (ASDC): `http://gaiaportal.asdc.asi.it`
- Astronomisches Rechen-Institut (ARI): `http://gaia.ari.uni-heidelberg.de`
- Leibniz-Institut fr Astrophysik Potsdam (AIP): `http://gaia.aip.de`

Affiliate data centres

- US Naval Observatory (USNO)
- National Astronomical Observatory of Japana (NAOJ)
- Space Telescope Science Institute (STScI)
- South African Astronomical Observatory (SAAO)
- Observatoire the Paris-Meudon (ObsPM)
- Infrared Science Archive (IRSA)

Slide: A. Brown


2.0
1.0
0.0
−1.0
−2.0
−3.0
$\log_{10}(\sigma_\varpi)$ [mas]
0.0
5.0
10.0
15.0
20.0
Magnitude
Hipparcos
(van Leeuwen 2007)
Gaia DR1
Gaia 5-year mission