Und? Wie war die Uni heute?

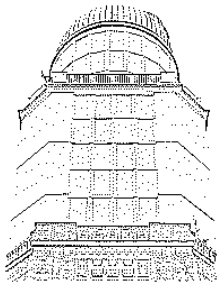

Schöner Vortrag über
“Die Entfernung der Sterne”
Und? Wie war die Uni
heute?

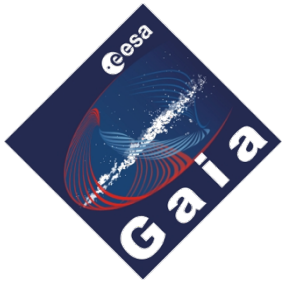

Schöner Vortrag über
“Die Entfernung der Sterne”
Und? Wie war die Uni heute?
Das ist ja interessant! Und wie entfernt man sie?

# Weltraumastrometrie mit Gaia:
## Der beste Sternkatalog der Geschichte

S.A.Klioner

Lohrmann-Observatorium, Technische Universität Dresden





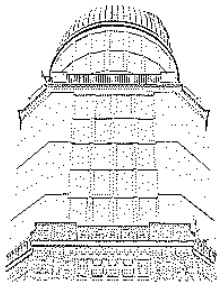


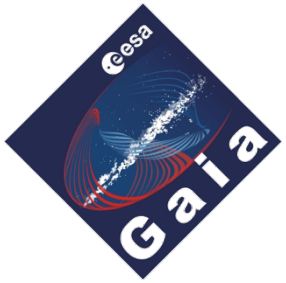
Dresden, 15 September 2016

# Weltraumastrometrie mit Gaia:
## 1001 Nacht mit den Beobachtungen

S.A.Klioner

Lohrmann-Observatorium, Technische Universität Dresden







Dresden, 15 September 2016

# A science fiction movie: Star Wars

# Where are the stars?

# Astrometry: the art of measuring stellar positions

Astronomy cannot touch
Its objects!

Astronomy cannot make
experiments!

Astronomy analyses stellar light:

| | |
|---|---|
| Astrometry | – direction |
| Photometry | – quantity |
| Spectroscopy | – wave length |
| Polarimetry | – polarization |

+ cosmic particles

++ gravitational waves

# One of the main problems of astronomy: distance

Without knowing how far the object is,
physical understanding of that object is impossible…

A comet: far away and very big or
inside the Earth atmosphere and rather small?

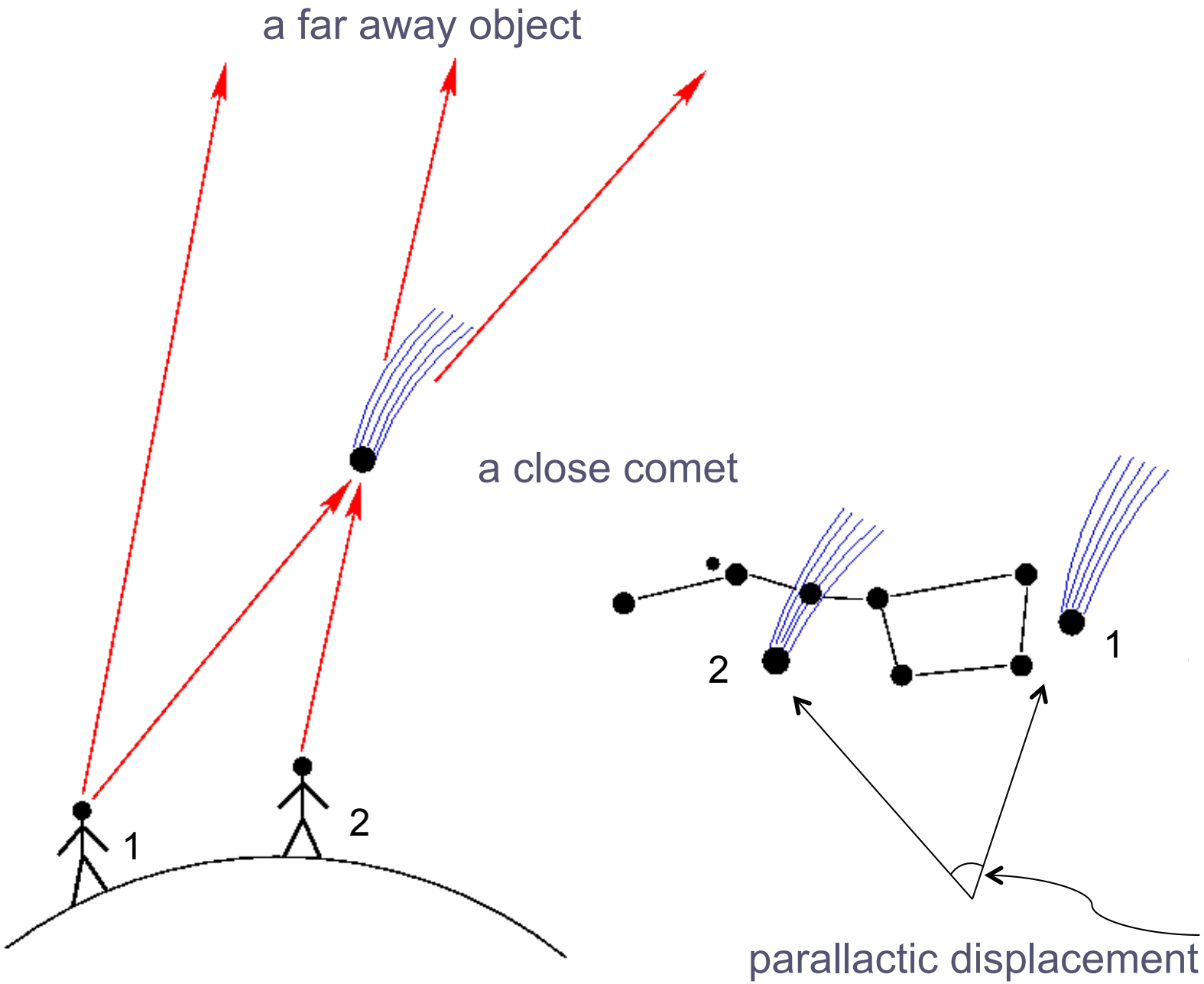
# One of the main problems of astronomy: distance

Without knowing how far the object is,
physical understanding of that object is impossible…

A comet: far away and very big or
inside the Earth atmosphere and rather small?

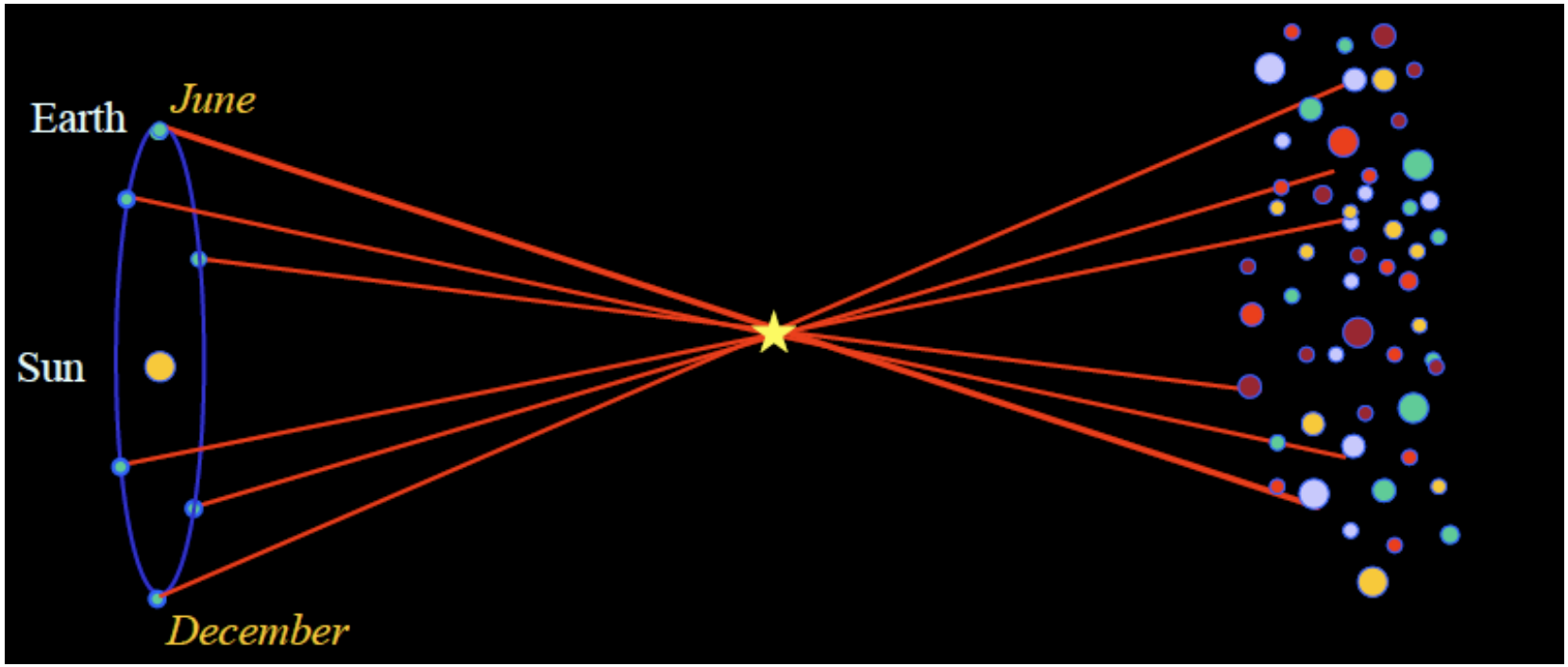
Tycho Brahe
1577

# One of the main problems of astronomy: distance



# Stellar parallaxes

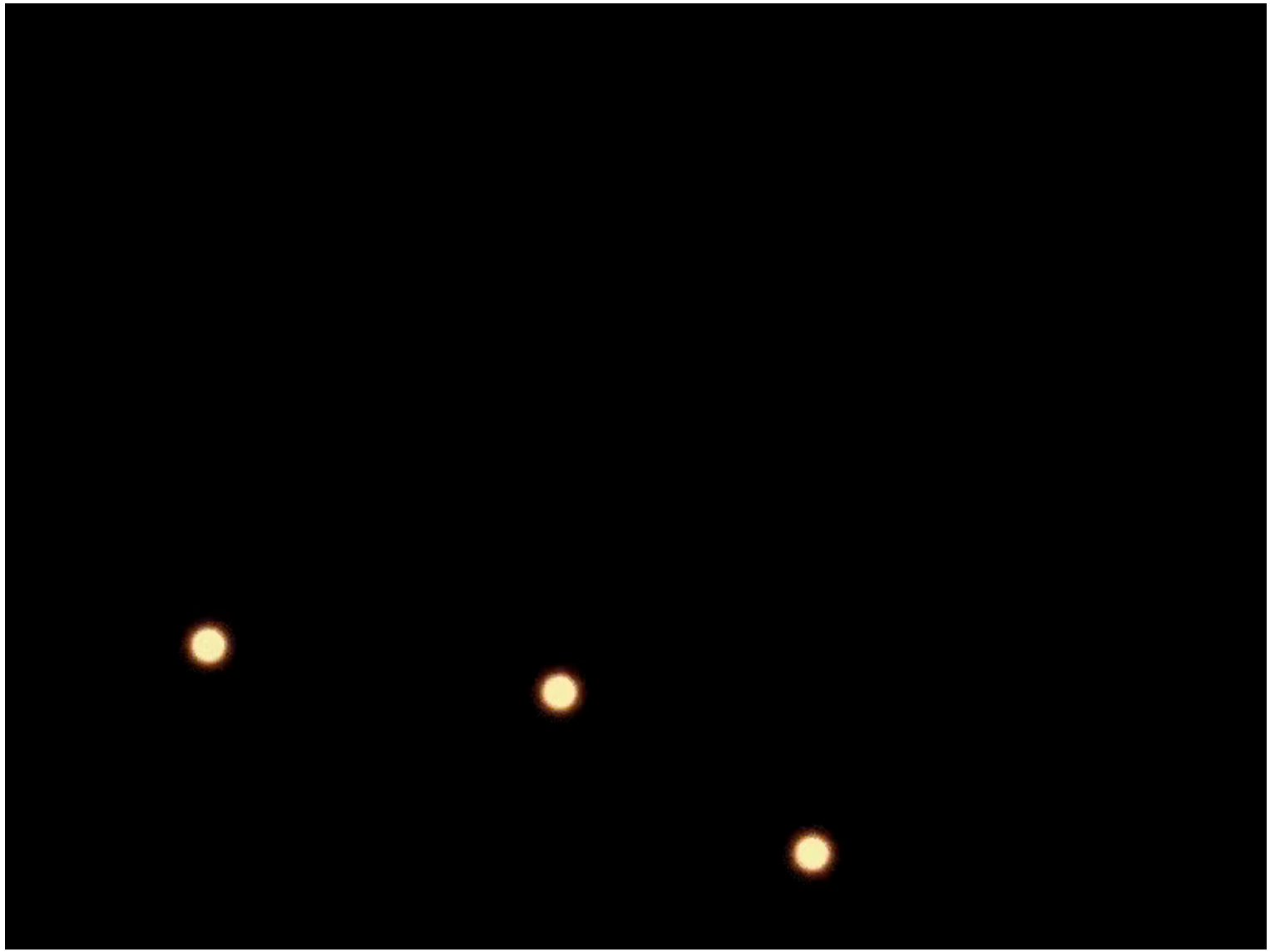
Earth's orbit a closer star very distant stars



# Stellar parallaxes

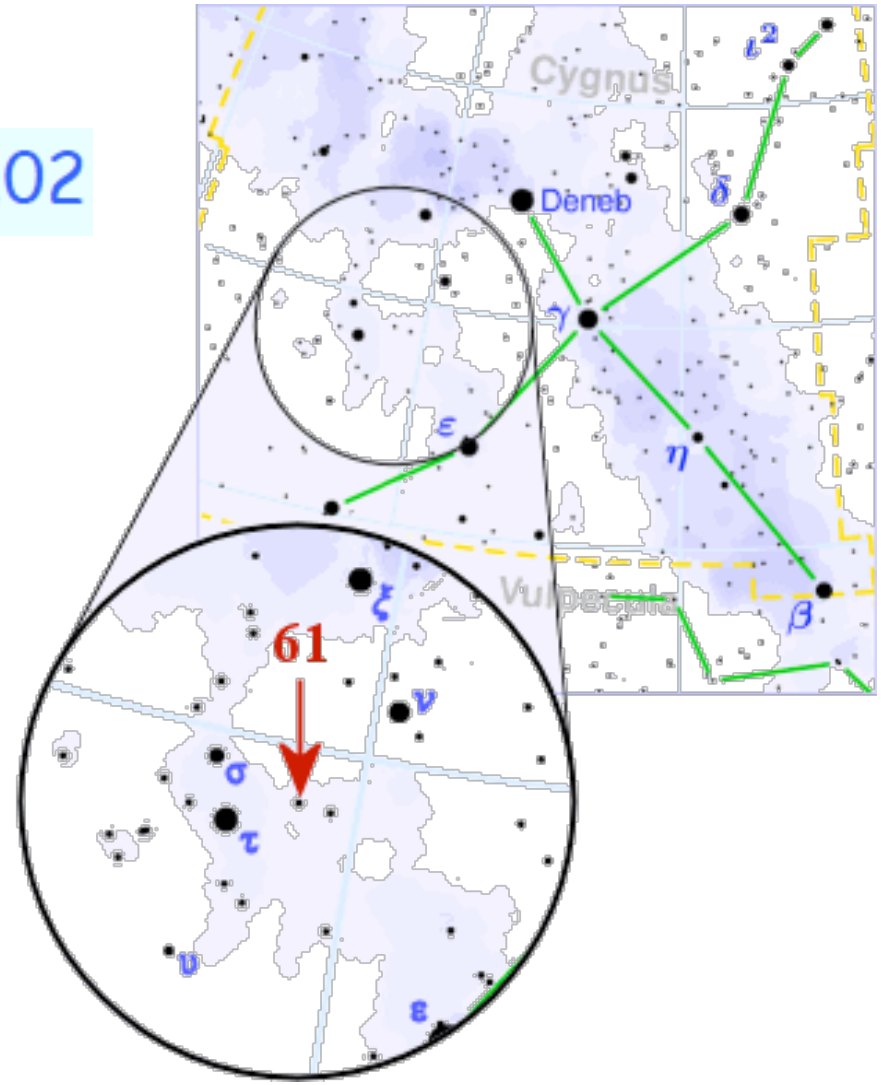
S.Jordan, T. Sagrista, ZAH, Heidelberg

# Stellar parallaxes and proper motions



# The first parallaxes: Friedrich Bessel, 1838: Cyg 61

$\pi = 0''.314 \pm 0.02$




| | |
|---|---|
| 1840 | 3 published parallaxes |
| 1880 | 17 |
| 1900 | 50 |
| 1910 | 100 |
| 1930 | 2000 |
| 1965 | 7000 |
| 1980 | 10000 |


# Why to bother?

- We need to understand stars

  (our Sun is a star!)

  Without knowing the distance it is not possible to judge if a star is big or small, etc.

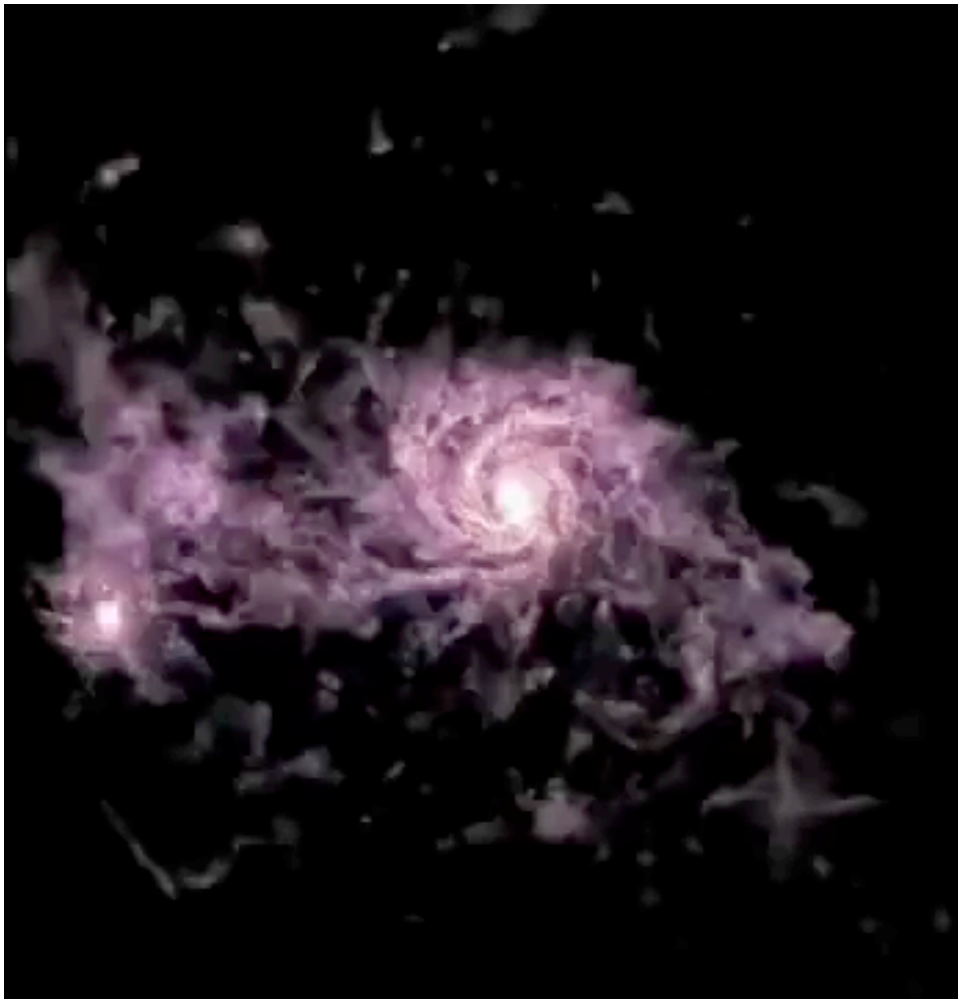
- We live in a galaxy.

  We need to understand how our Galaxy was formed.

# Galaxies have involved history

HST, STSci, NASA, ESA

# Galaxies: stars, gas, dust and gravitation



Mayer, Guedes, University of Zurich/Swiss Computing Centre

… and how was it with our Milky Way?

# What do we know about our Galaxy?

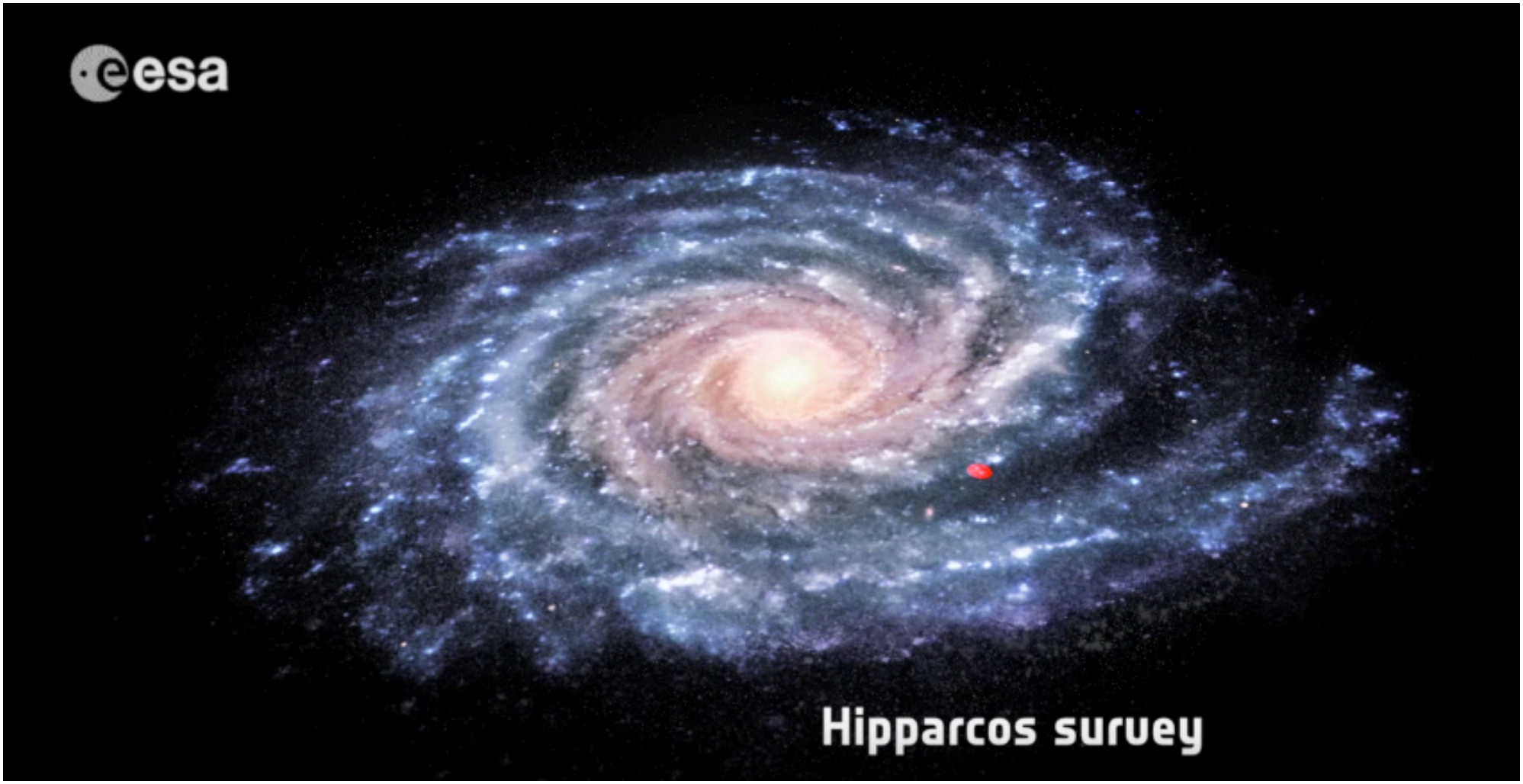
It should look like this (artistic view):

# What do we know about our Galaxy?

The Sun should be here:

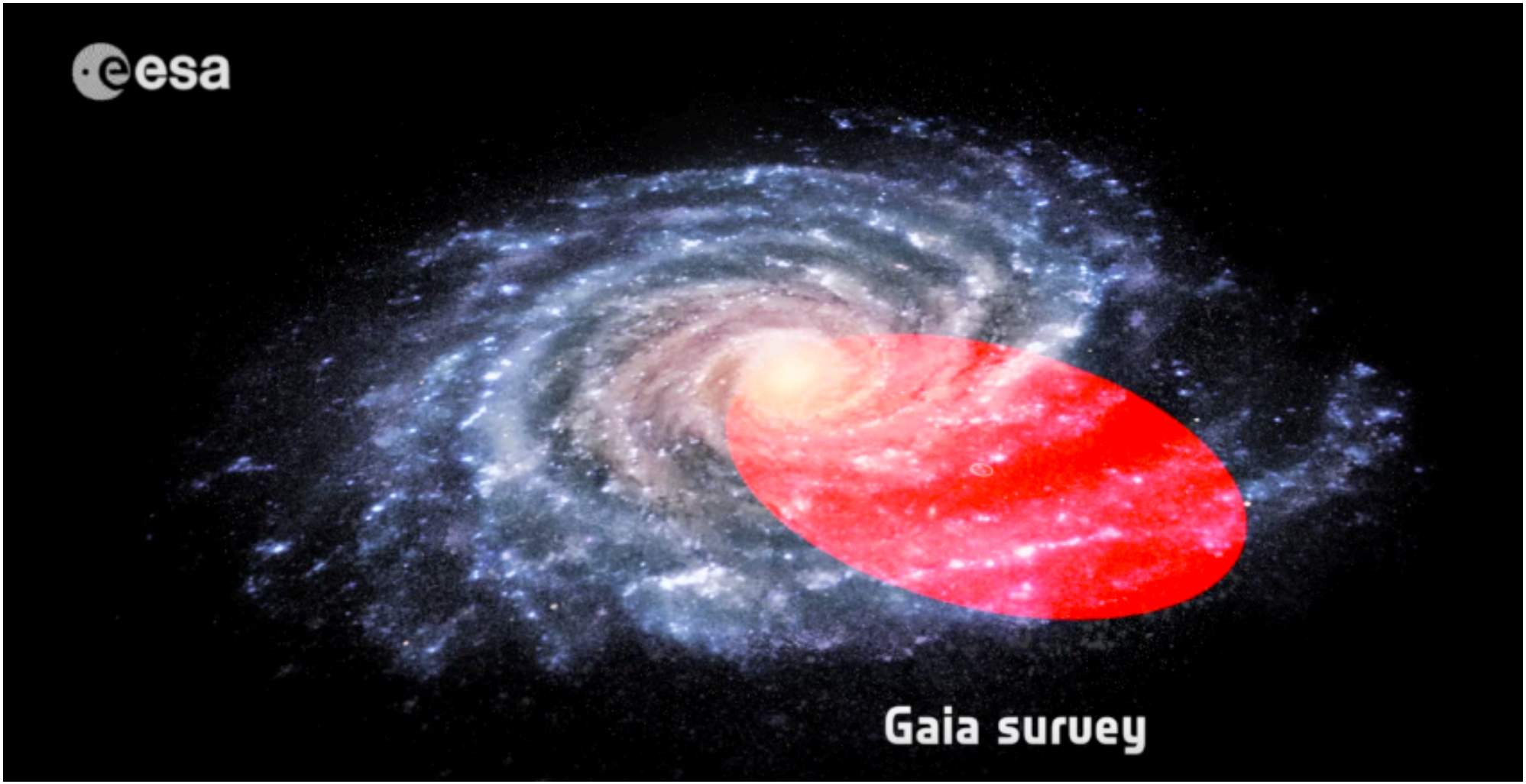
# What do we know about our Galaxy?

The stars with distances known till 2016 are all in the small red spot:



# What do we know about our Galaxy?

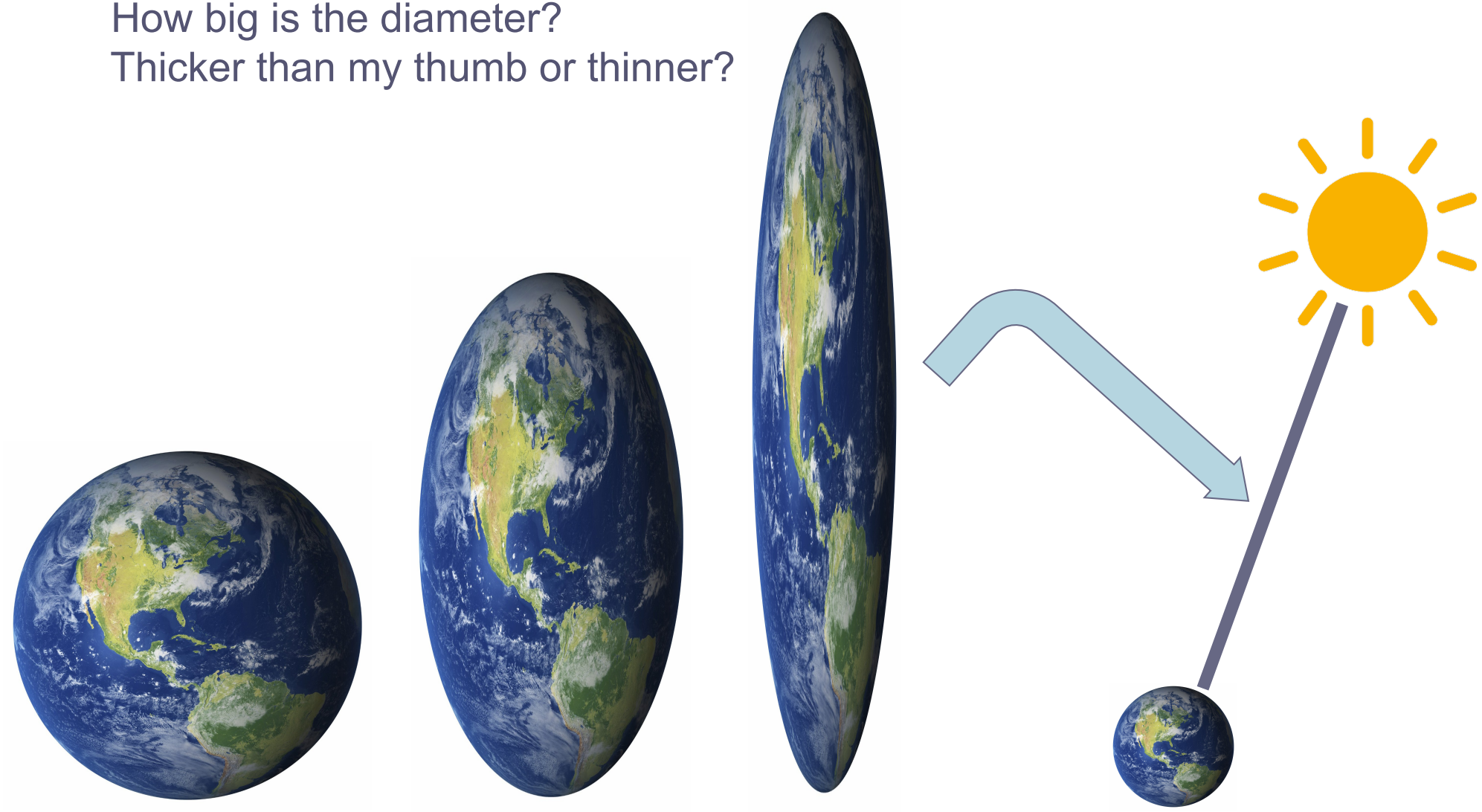
With Gaia we will explore a significant part of our Galaxy:



# Is the Universe large or small?

We take the material of the whole Earth and make a cylinder out of it.

1. The cylinder goes from the Earth to the Sun (1 AU = 150 million km).
   How big is the diameter?
   Thicker than my thumb or thinner?



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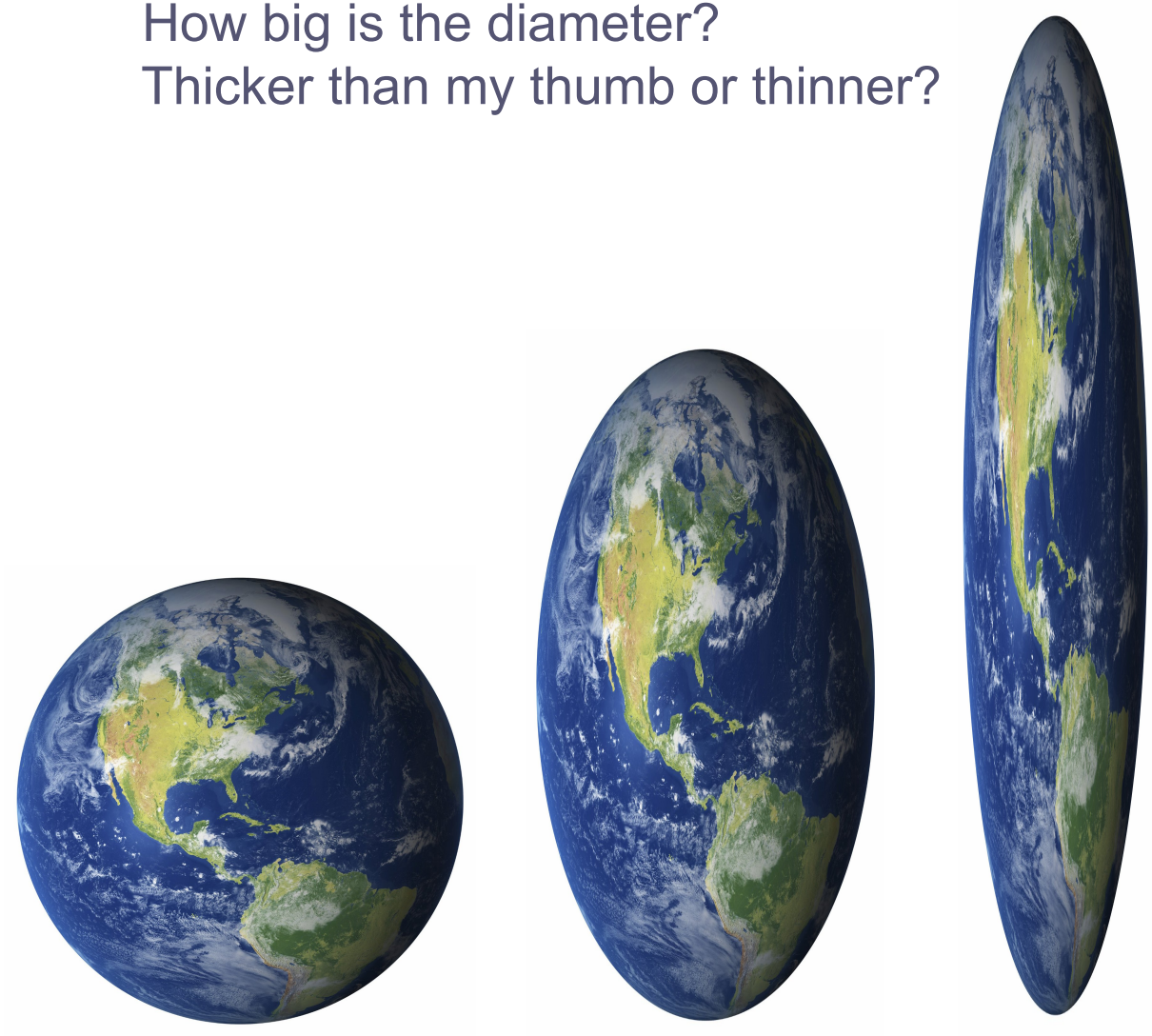
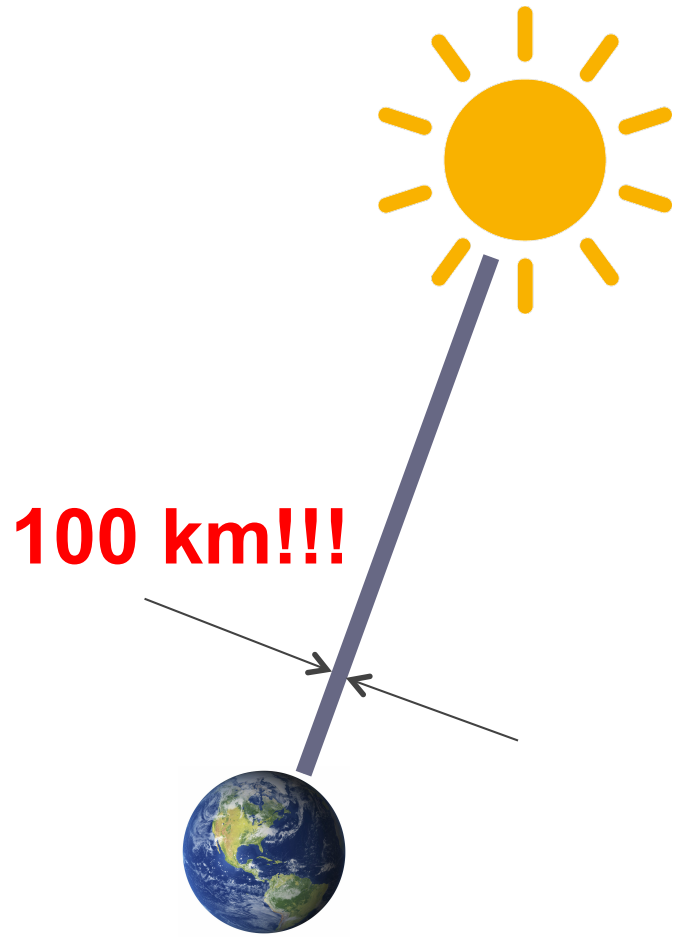




# Is the Universe large or small?

We take the material of the whole Earth and make a cylinder out of it.

1. The cylinder goes from the Earth to the Sun (1 AU = 150 million km). How big is the diameter?

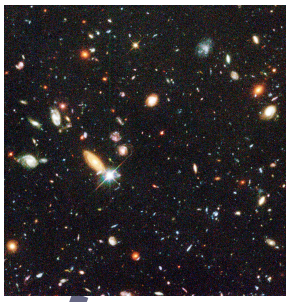
   Thicker than my thumb or thinner? **100 km**

2. To the nearest star (200000 AU = 1 parsec) ? **200 m**

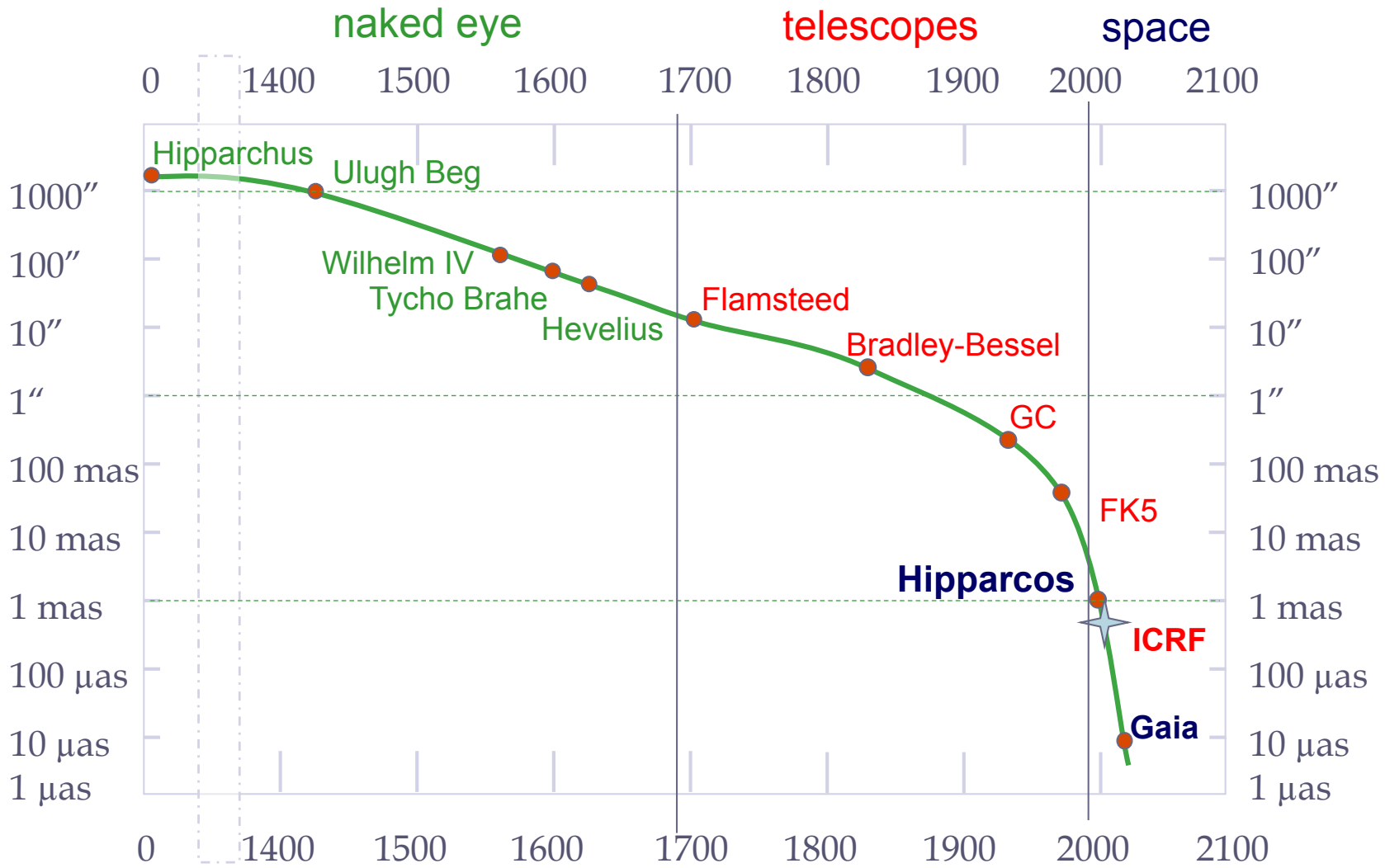
3. Across the whole Galaxy (40000 parsec)? **1 m**

4. To the nearest galaxy (1 million parsec)? **20 cm**

5. To the edge of observable Universe (4000 million parsec)? **4 mm**

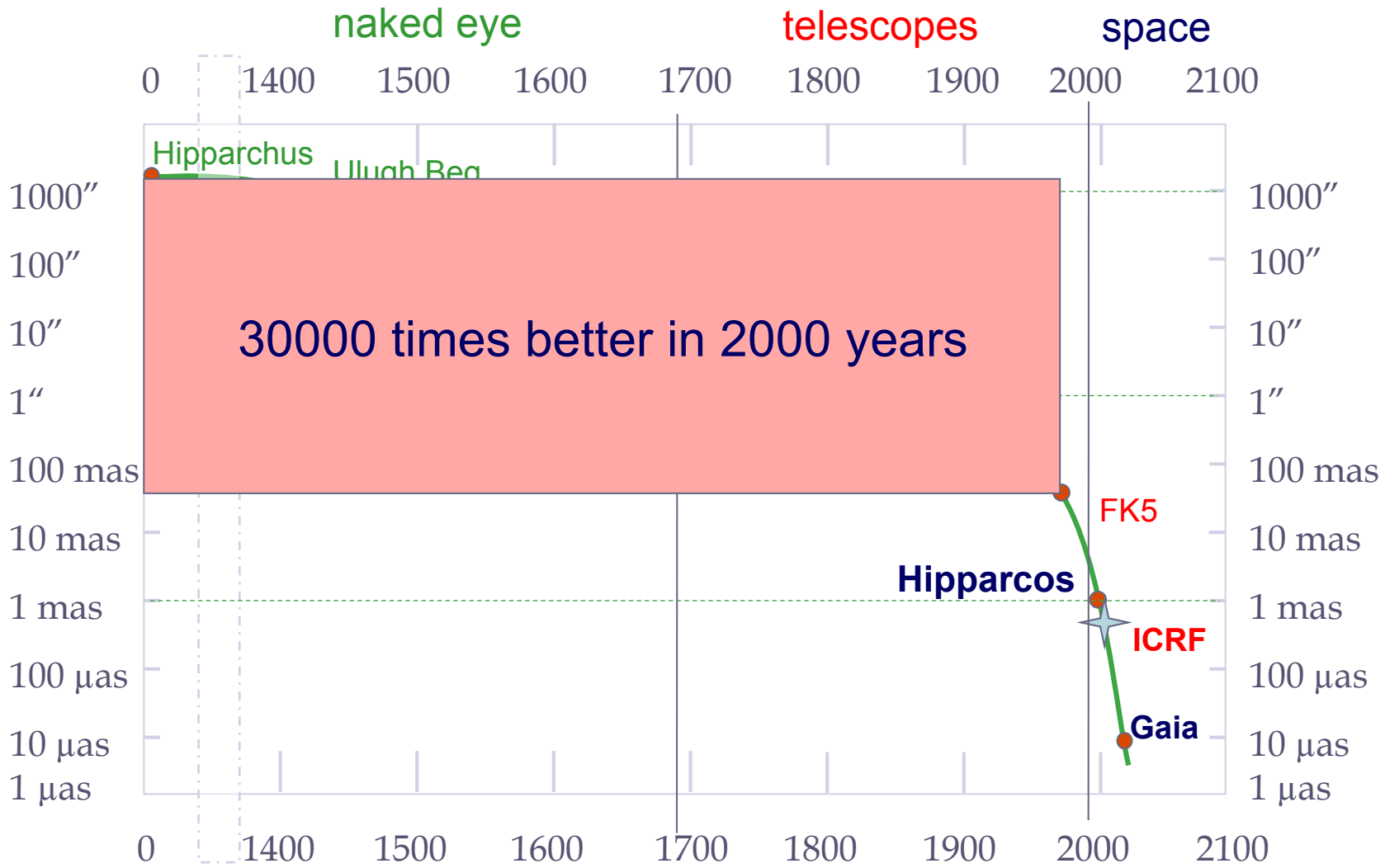


# Accuracy of astrometric observations




1 µas is the thickness of a sheet of paper seen from the other side of the Earth

# Accuracy of astrometric observations

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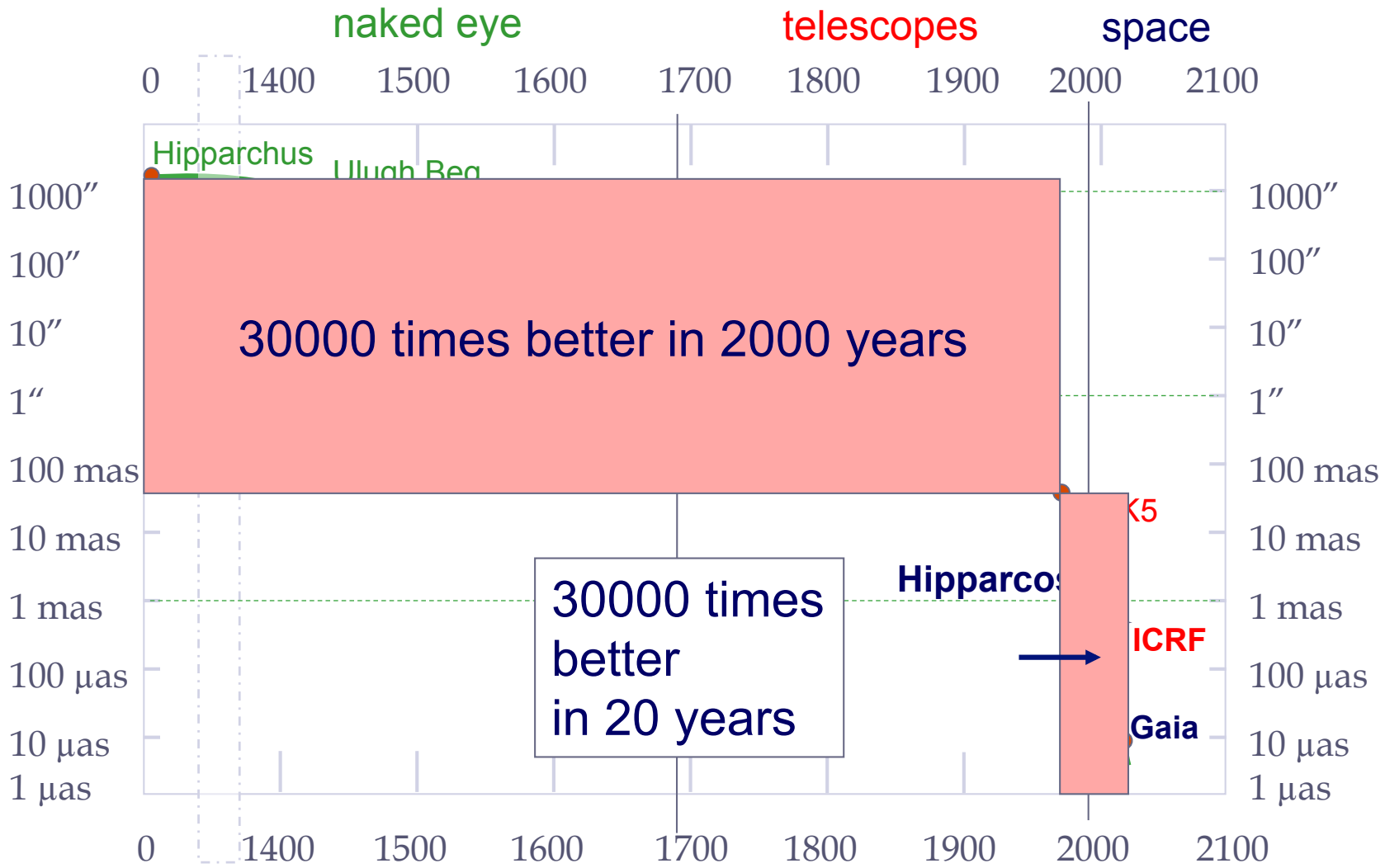


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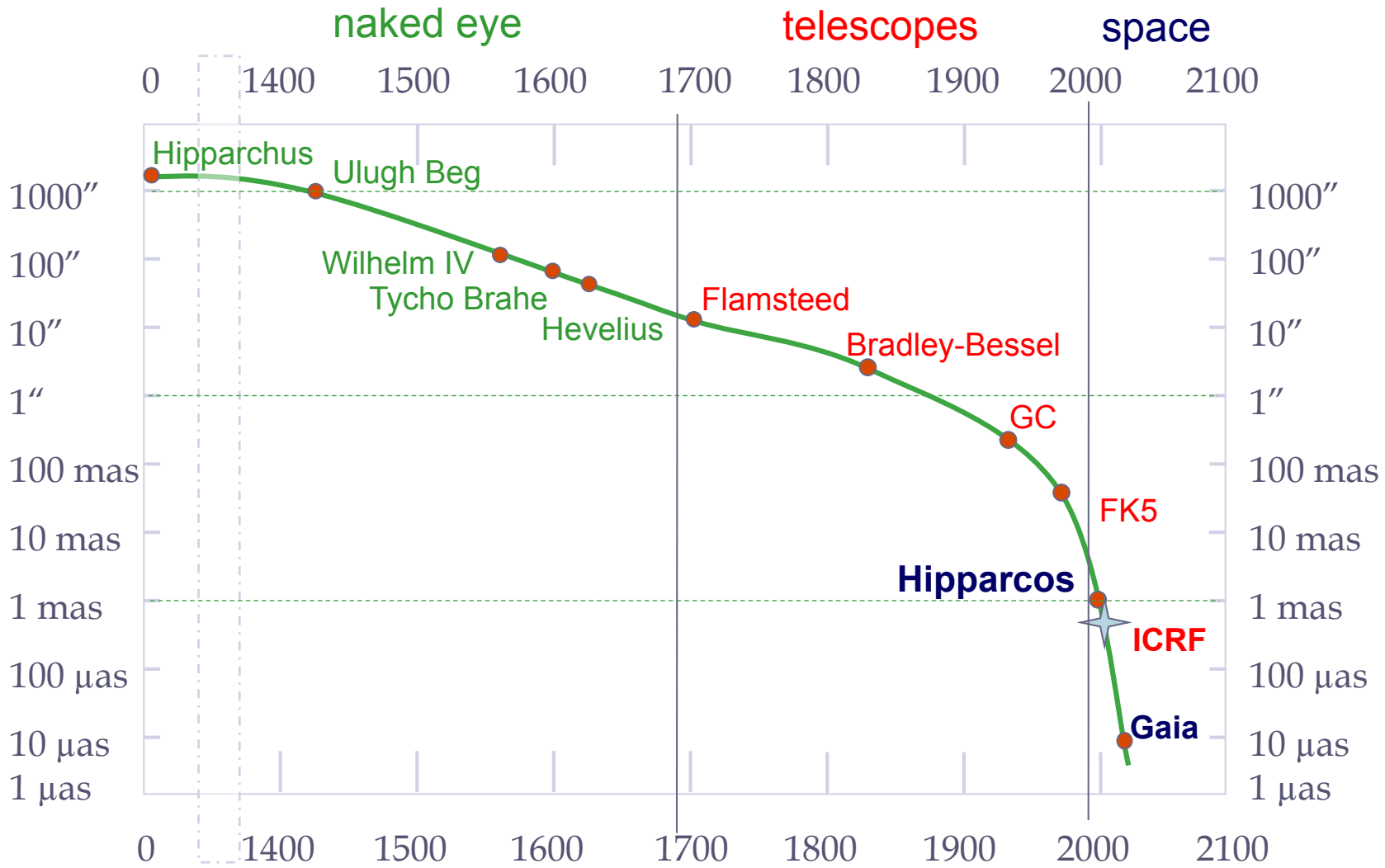
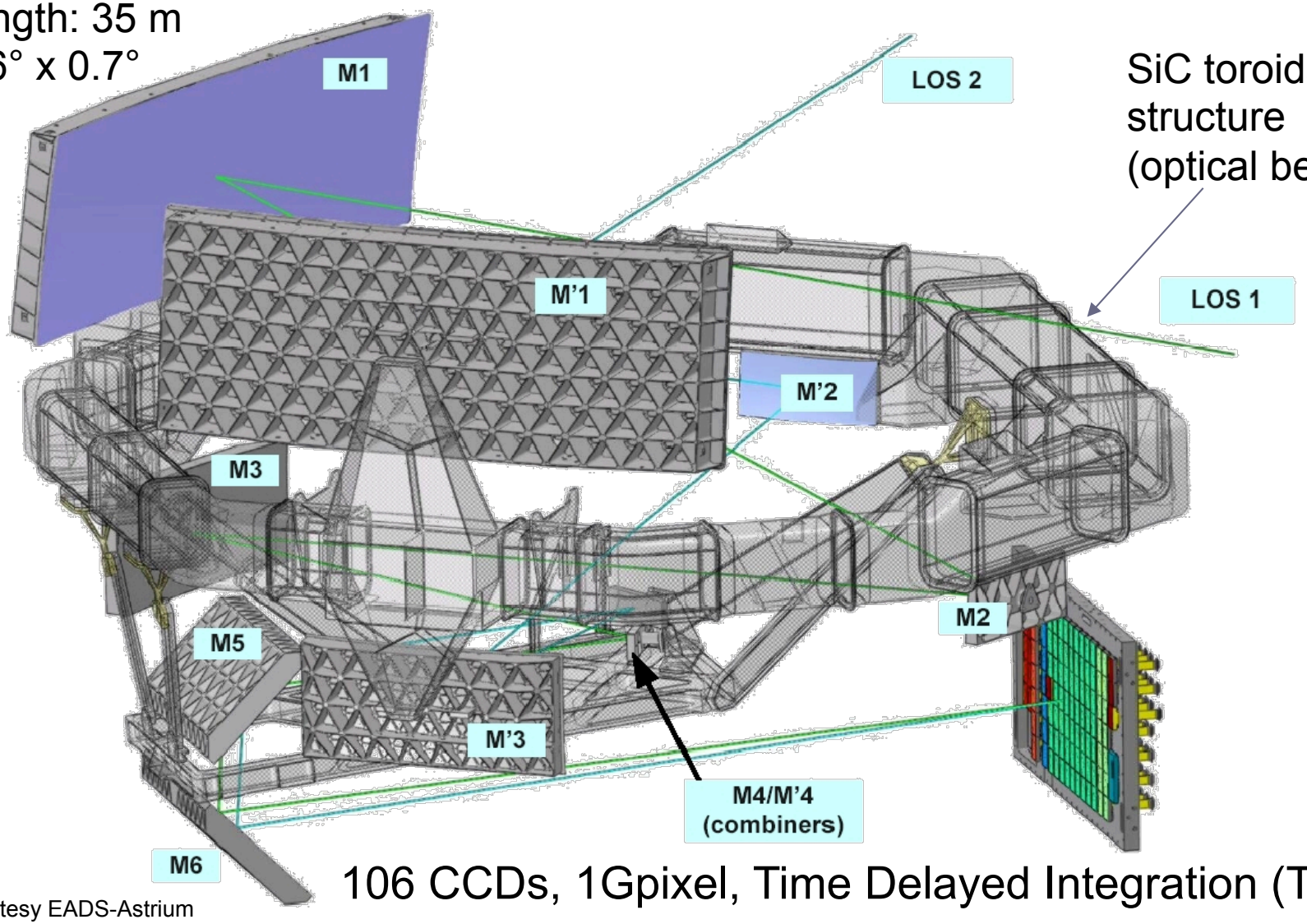



1 µas is the thickness of a sheet of paper seen from the other side of the Earth

# Gaia: a space telescope

## Astrometry+photometry of $10^9$ sources up to 20 mag (+radial velocities)

2 SiC primary mirrors at 106.5°
Aperture:1.45 m x 0.5 m
Focal length: 35 m
FOV: 1.6° x 0.7°



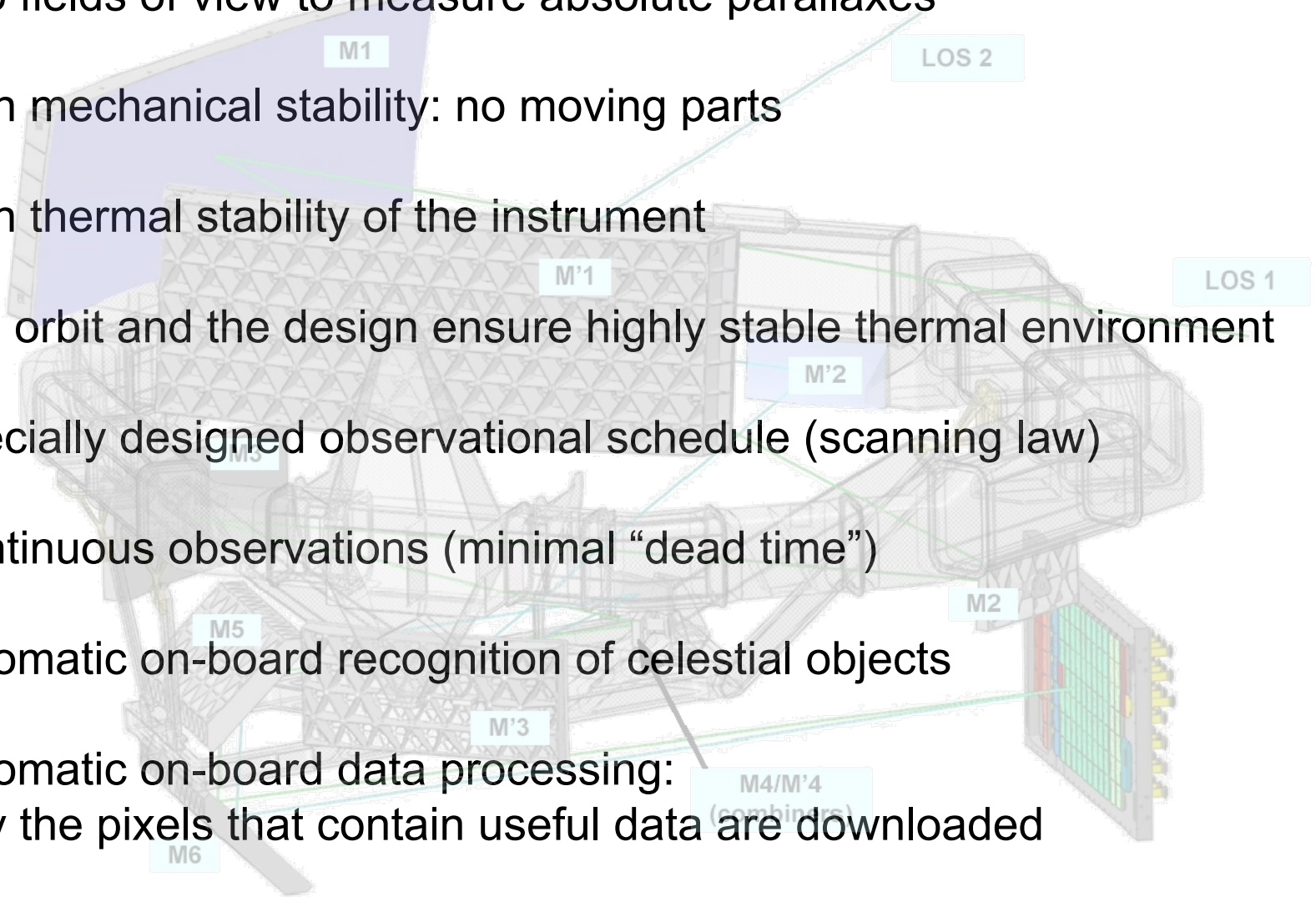

106 CCDs, 1Gpixel, Time Delayed Integration (TDI)



Figure courtesy EADS-Astrium

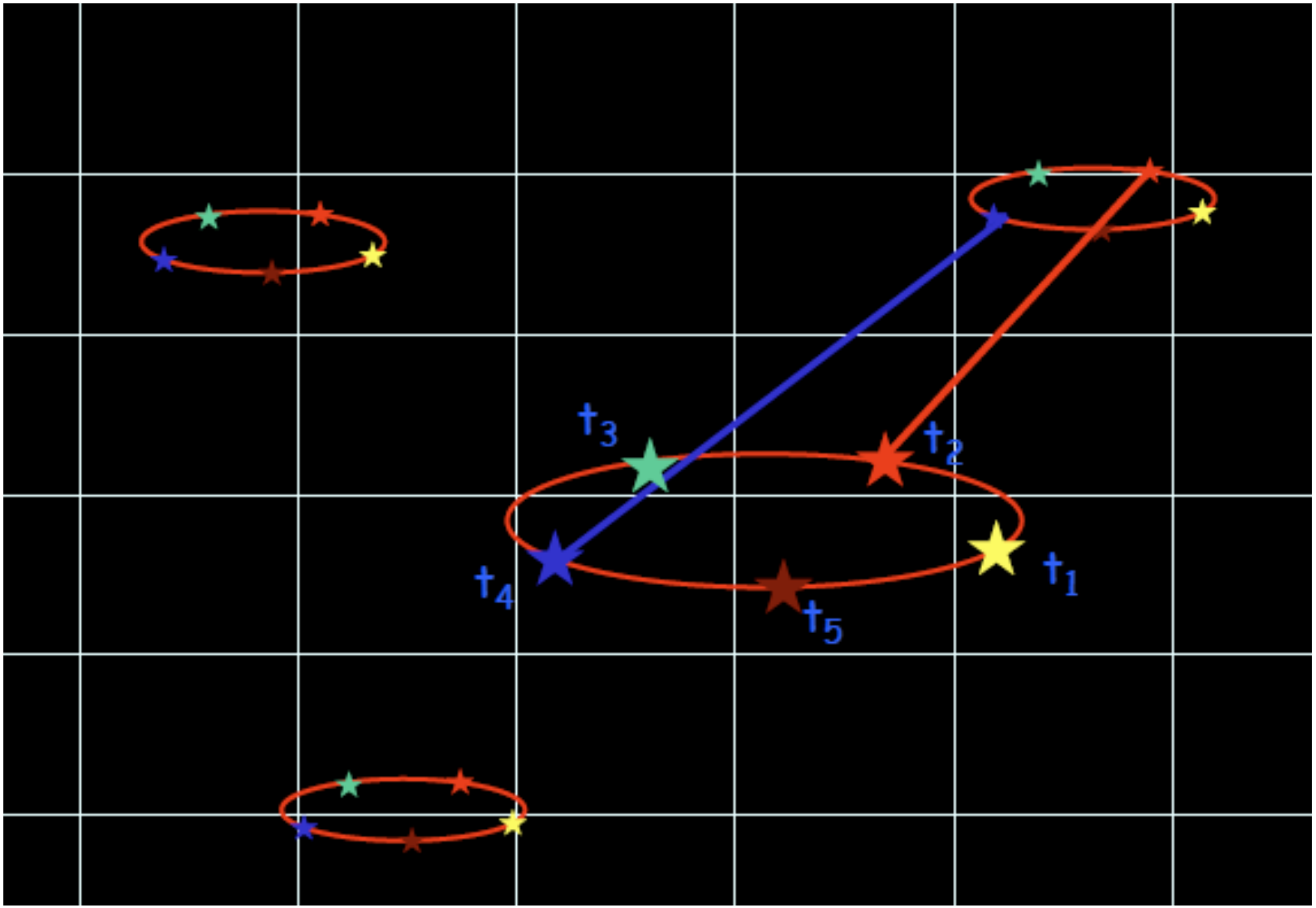
# Gaia: tuned for high-accuracy astrometry

1. Two fields of view to measure absolute parallaxes
2. High mechanical stability: no moving parts
3. High thermal stability of the instrument
4. The orbit and the design ensure highly stable thermal environment
5. Specially designed observational schedule (scanning law)
6. Continuous observations (minimal “dead time”)
7. Automatic on-board recognition of celestial objects
8. Automatic on-board data processing:
   only the pixels that contain useful data are downloaded




1 PB of raw data; 800 observations for each of $10^9$ objects; $10^{10}$ unknowns

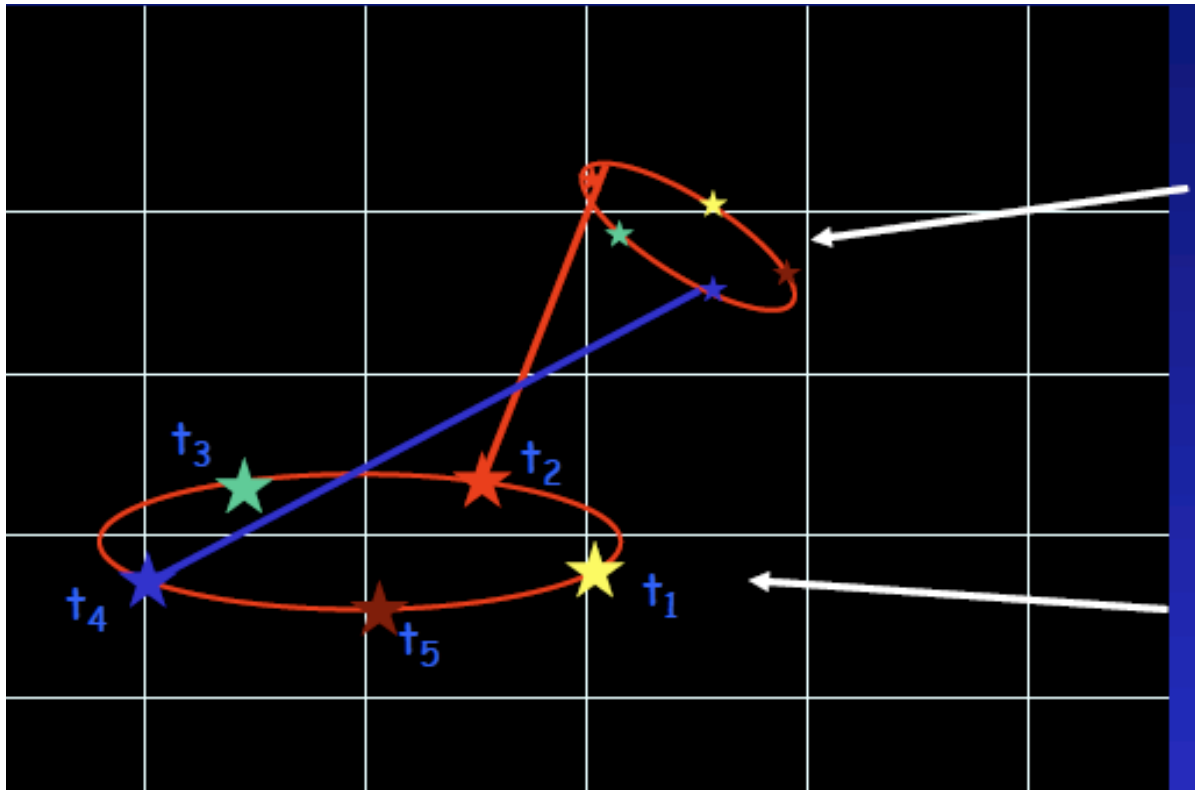
# One field of view: relative parallaxes




Measurable quantity: $f(t) \times (\pi_2 - \pi_1) \quad \Rightarrow \quad \pi_2 - \pi_1$

# Two fields of view: absolute parallaxes

Pierre Lacrout, 1968:



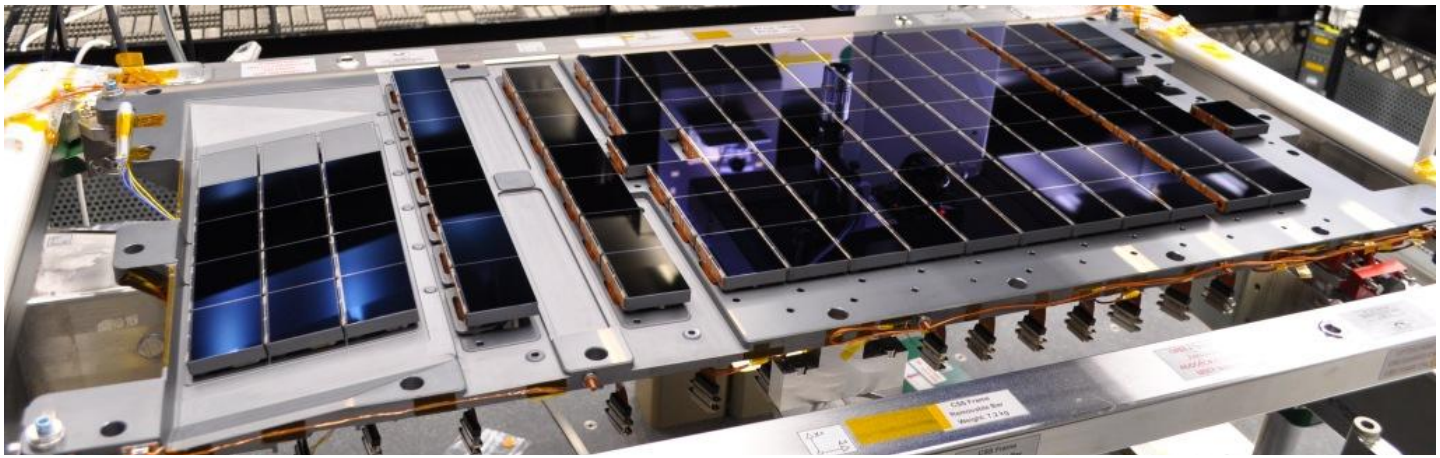

Telescope 1

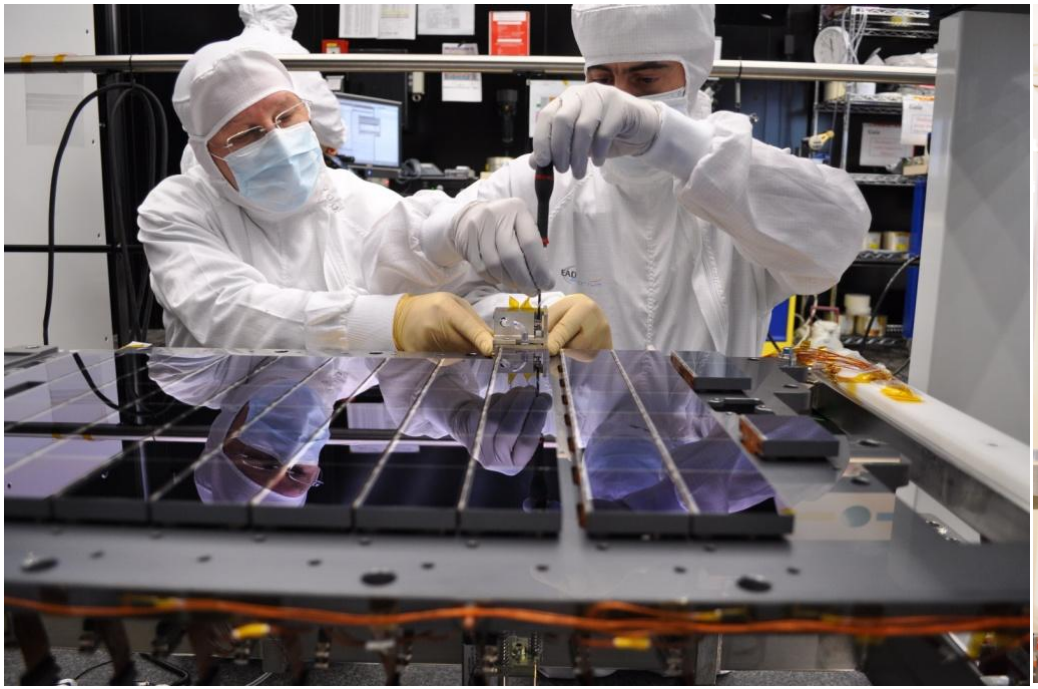
Telescope 2

Measurable quantity: $f_2(t)\pi_2 - f_1(t)\pi_1 \quad \Rightarrow \quad \pi_2$ and $\pi_1$

Implemented by ESA twice: Hipparcos (1989-1993), Gaia (2013-)

# Gaia focal plane: 106 CCDs, 1000 Megapixel



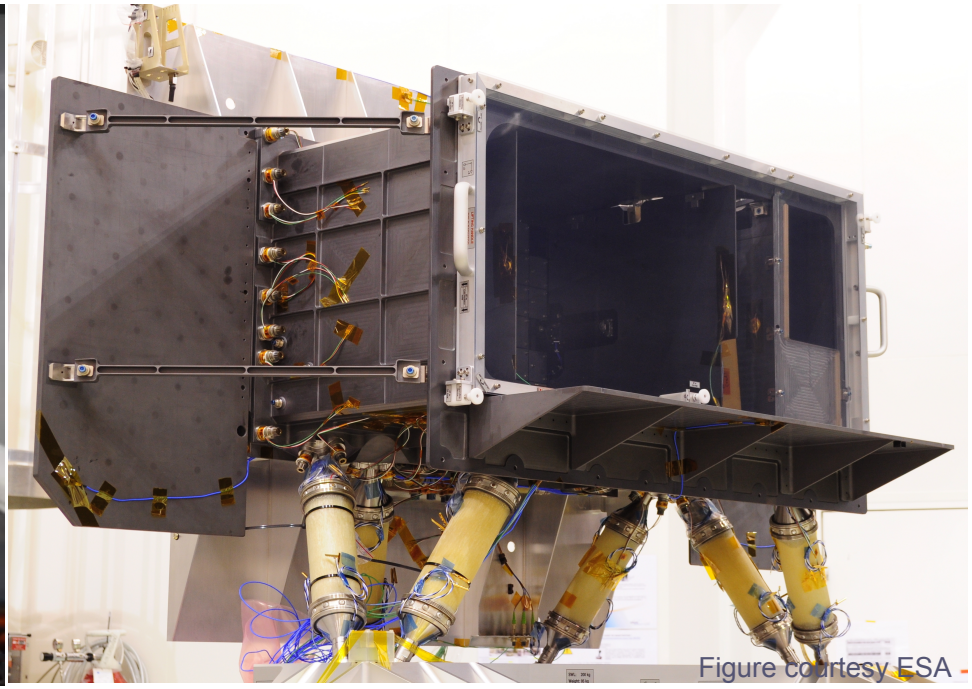
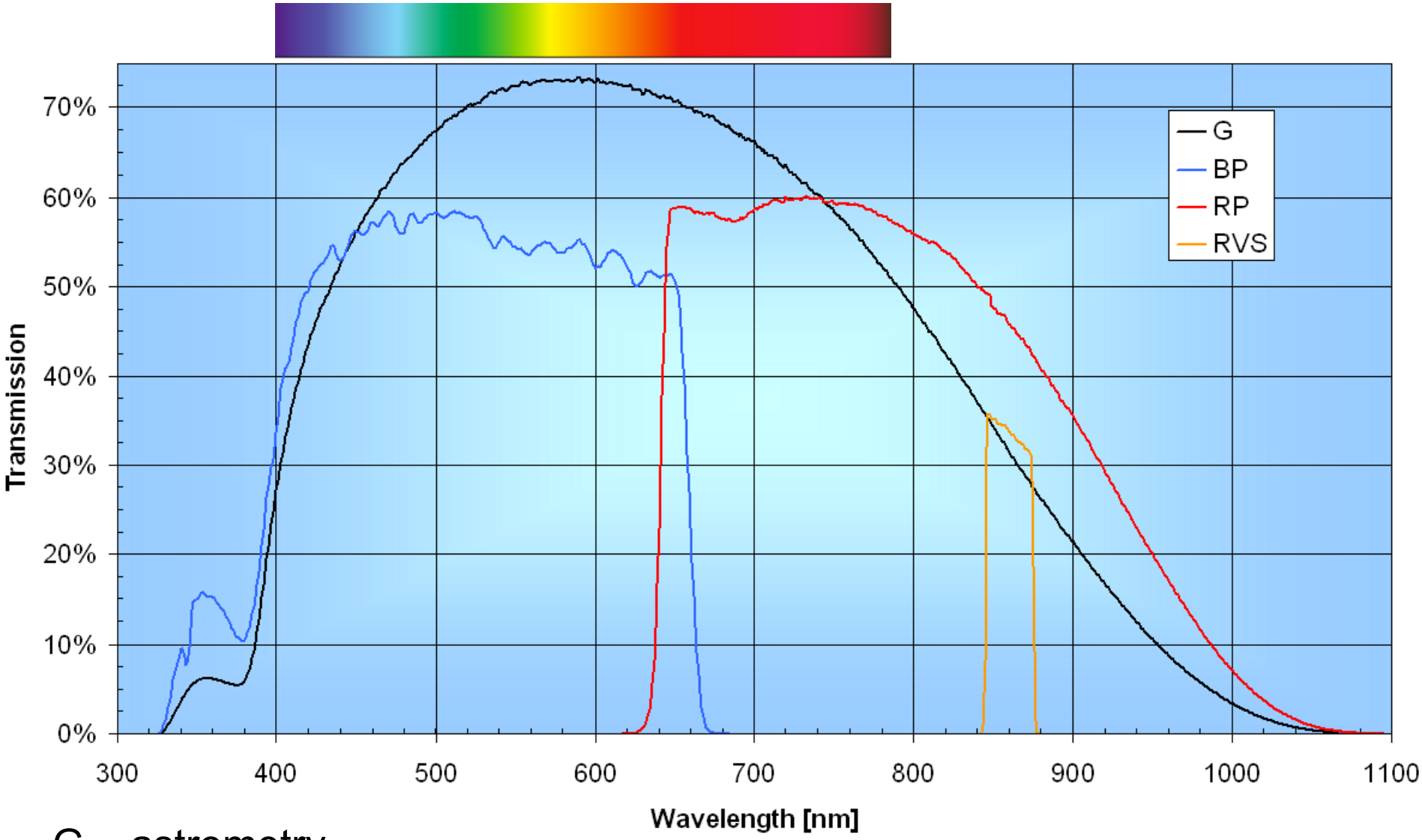


Figure courtesy ESA

# Gaia: wavelength coverage



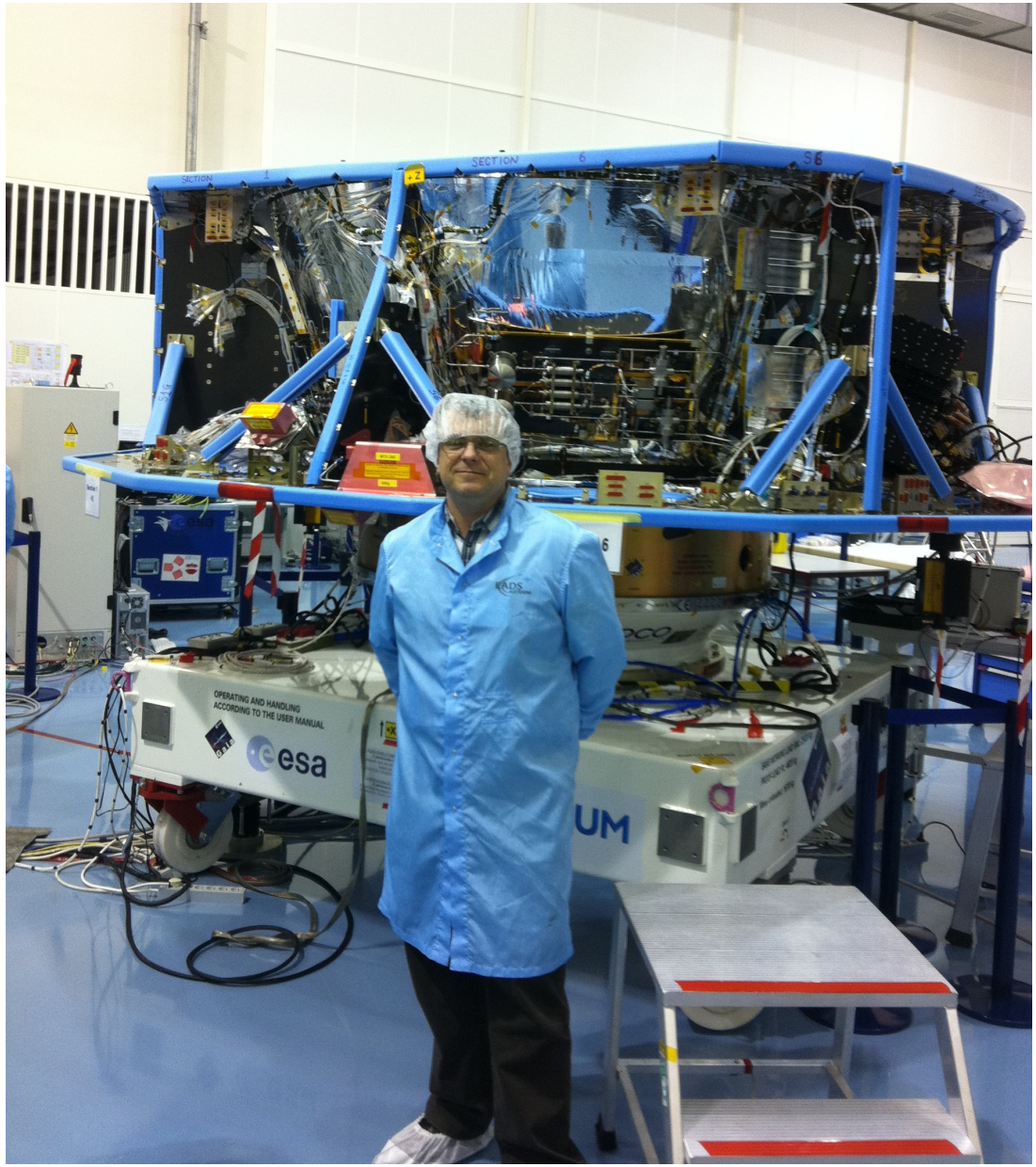

G – astrometry

BP/RP – blue/red low dispersion spectro-photometers: 7-27 nm/pixel

RVS – radial velocity spectrometer: resolving power 11500 @ 860 nm

# Gaia Service Module

CCD clocking,
CCD data processing,
antennas,
propulsion system, etc…



# Gaia CCD clocking

Rubidium atomic clock module:

4e-14 @ 6 hours

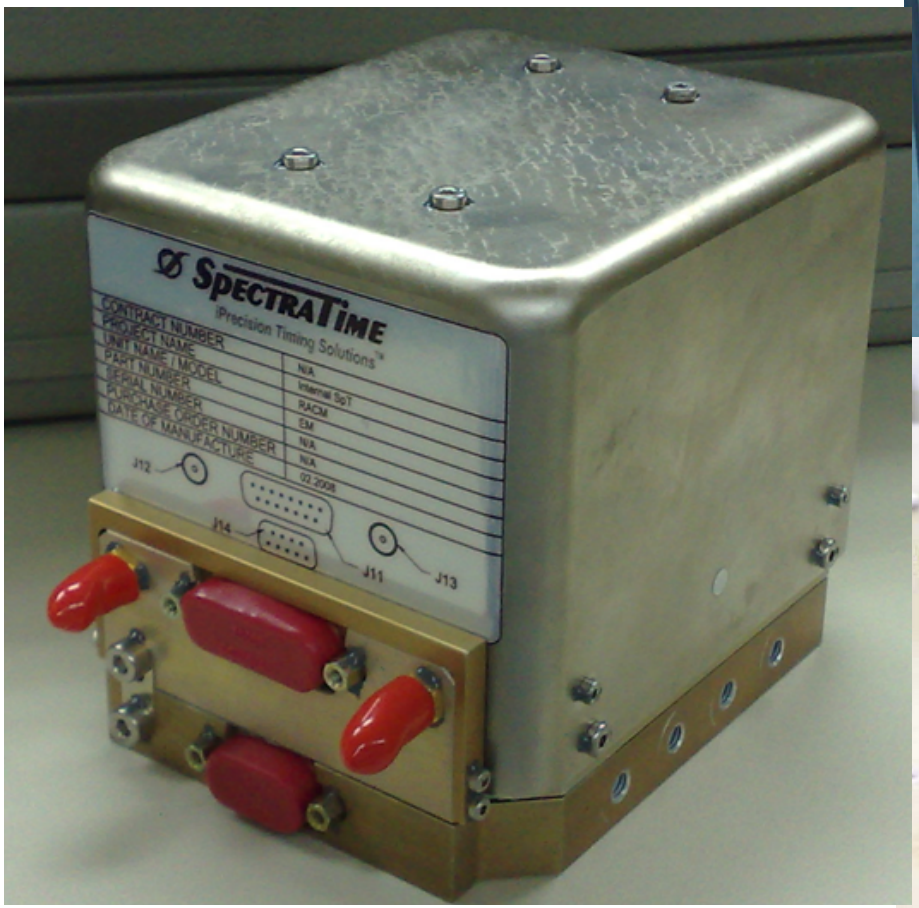
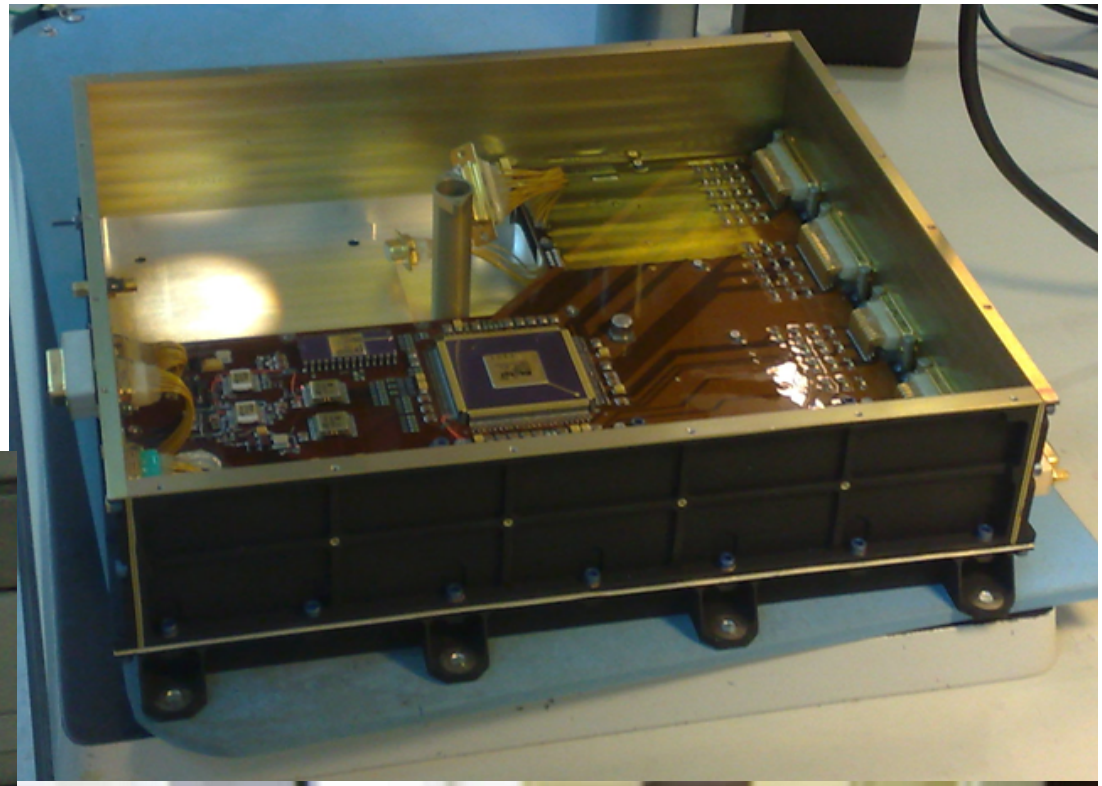



Figure courtesy ESA



# Gaia on-board computers

3 redundant IBM PowerPC processors @800 MHz in each of 7 computers:

Highest **space-qualified** performance @1800 MIPS

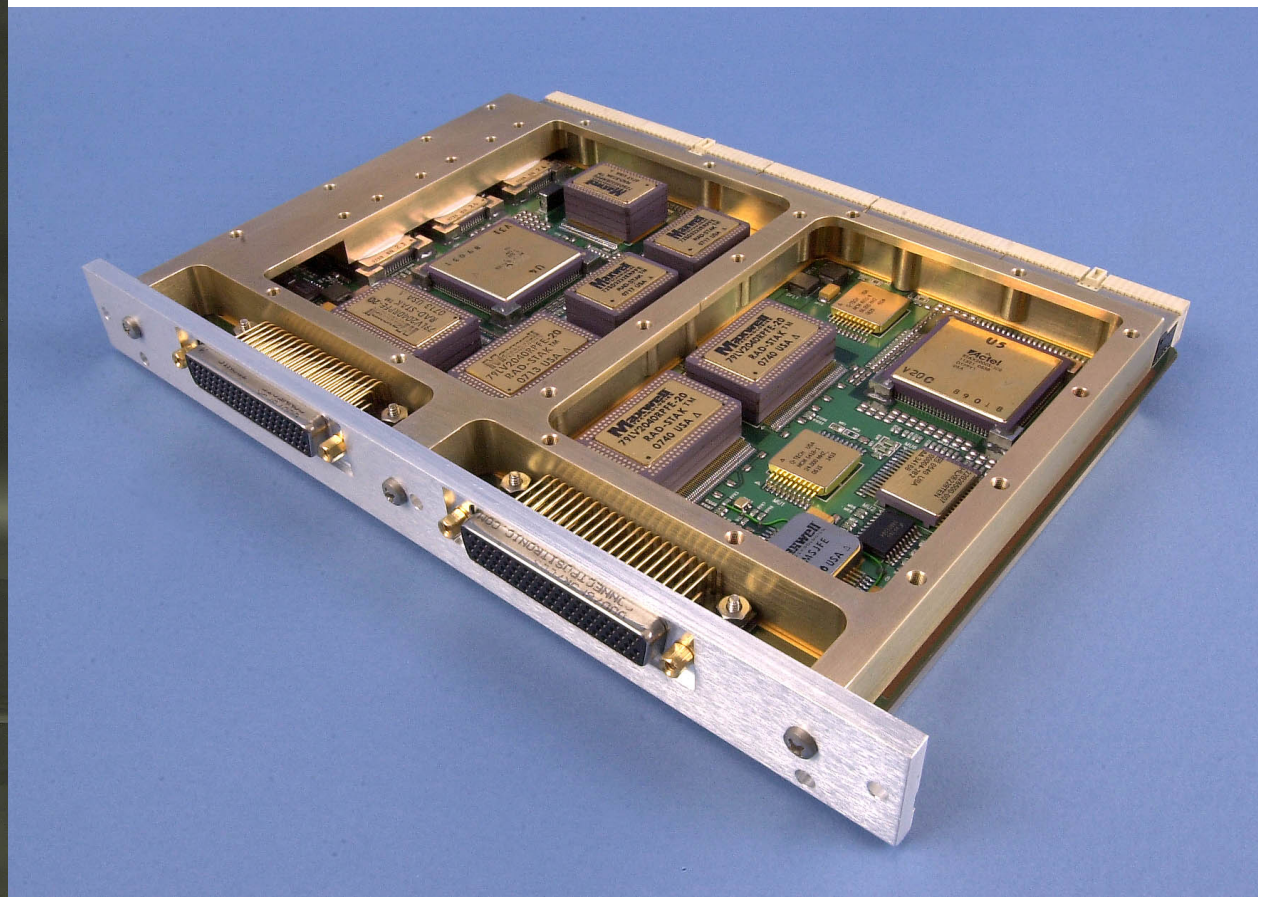


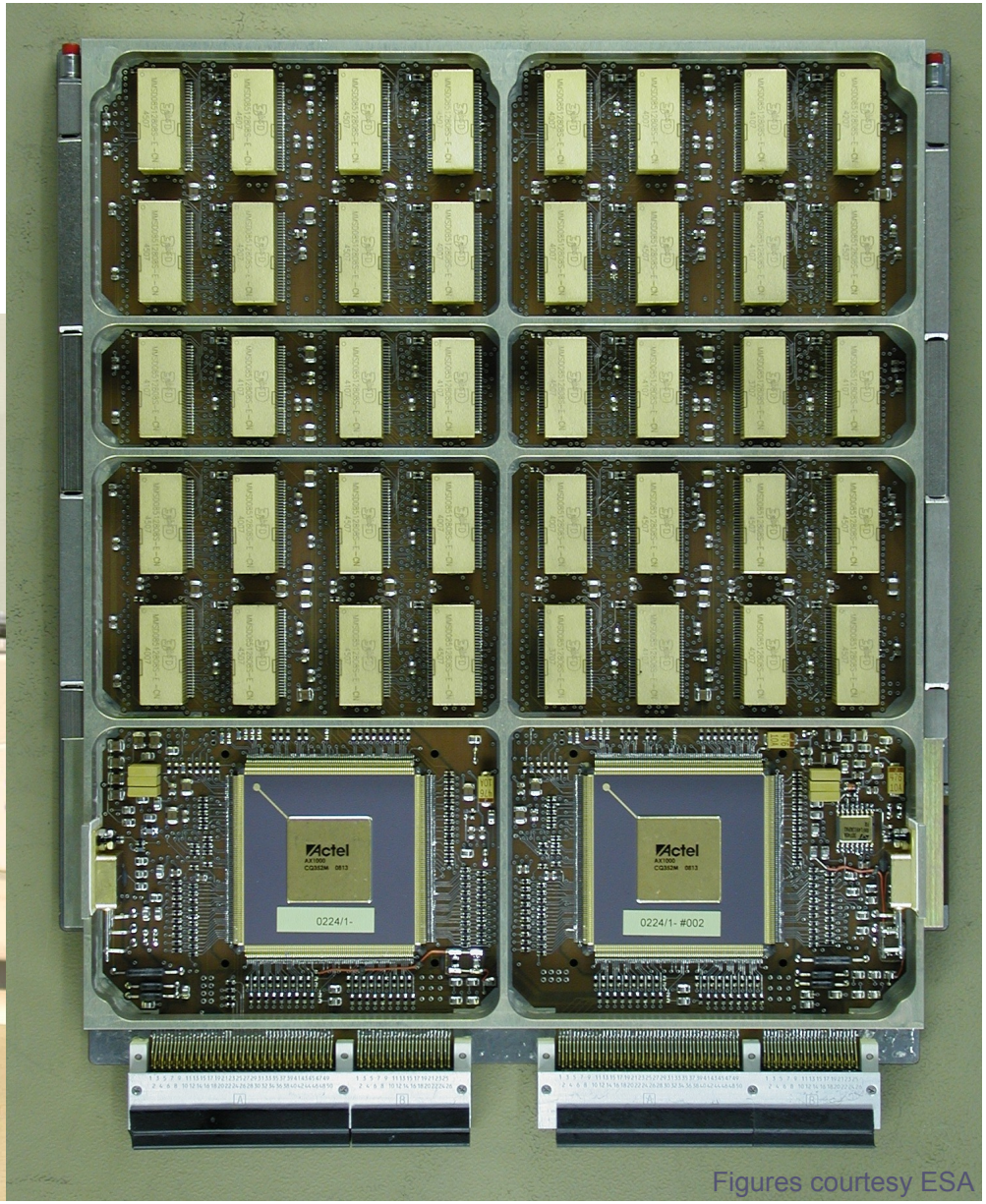
Figure courtesy ESA

# Gaia on-board computers

Solid-state memory: 240 SDRAM modules, 4GB each => 940 GB “HDD”

On-board software in C

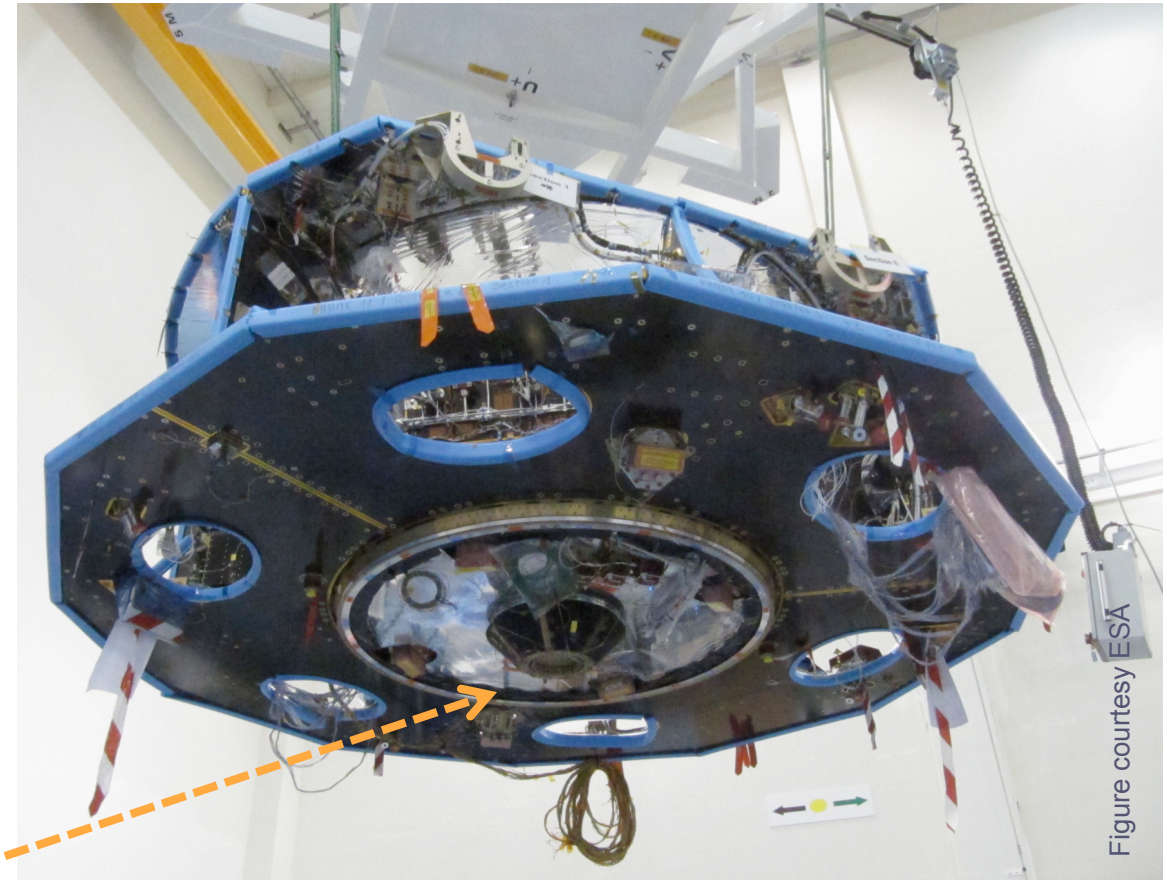
No operating system; low-level code


Figures courtesy ESA

# Gaia service module with phase array antenna

July 2012



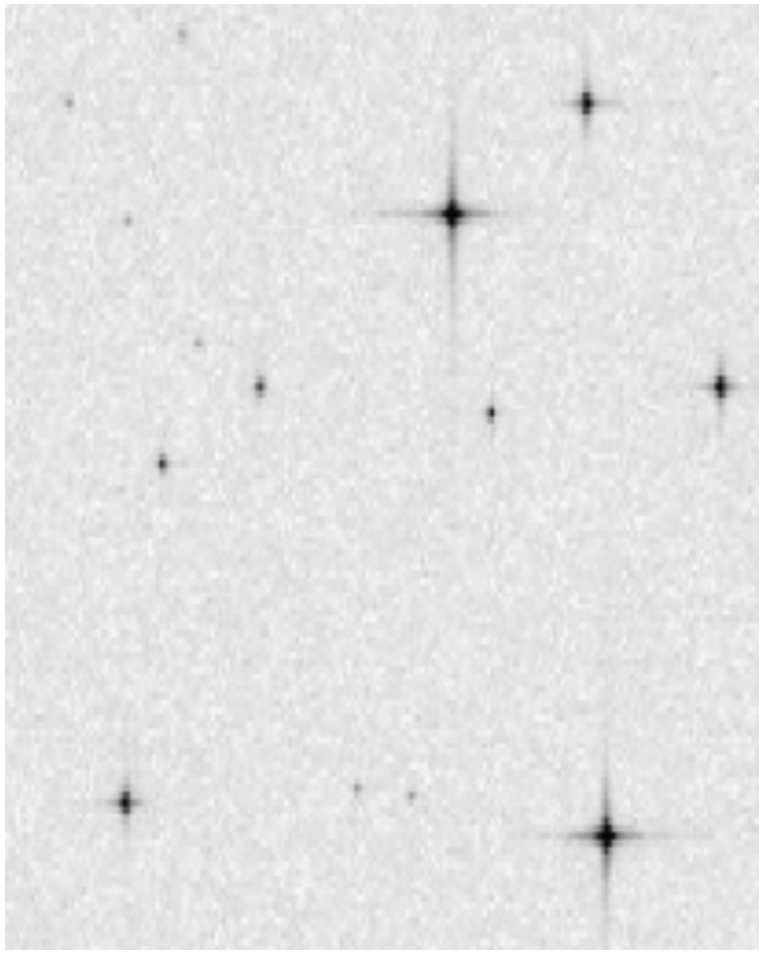


up to 10 Mbit per second

( 1500000 km from the Earth )

# Gaia raw observations: $10^{12}$ stellar “images”

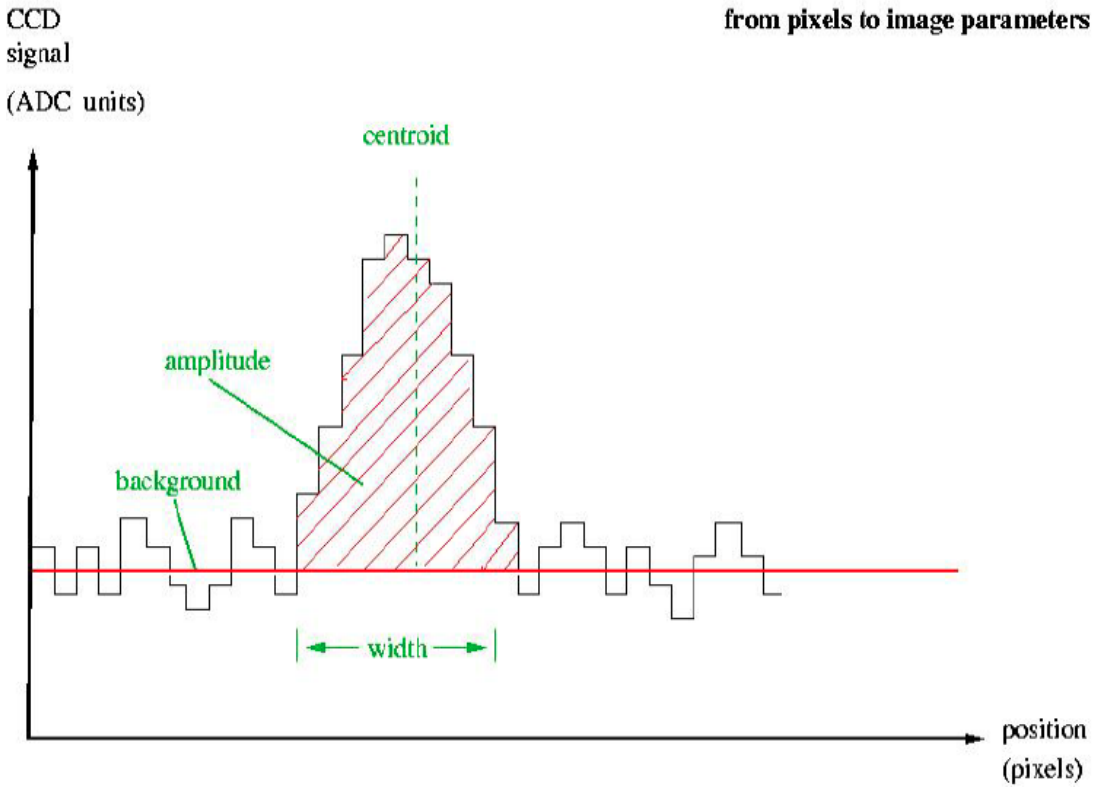
CCD pixel count read off a certain CCD at a certain moment of time



(binned) CCD pixels with time-tags for each pixel

Windows for each observed object

Centroiding accuracy: millipixels



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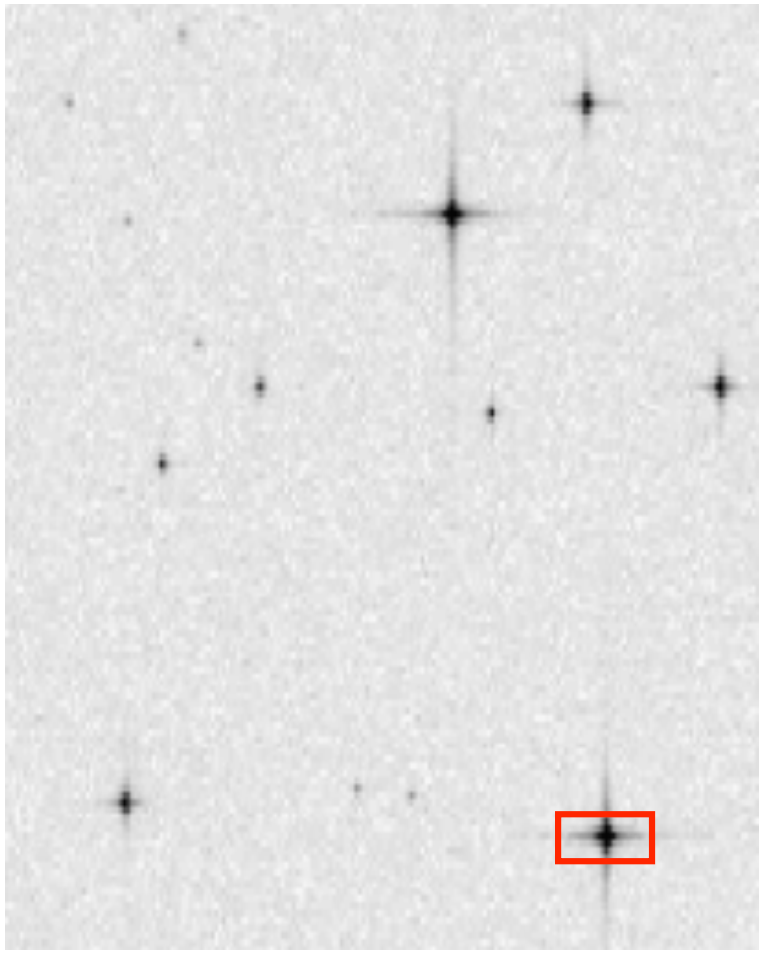

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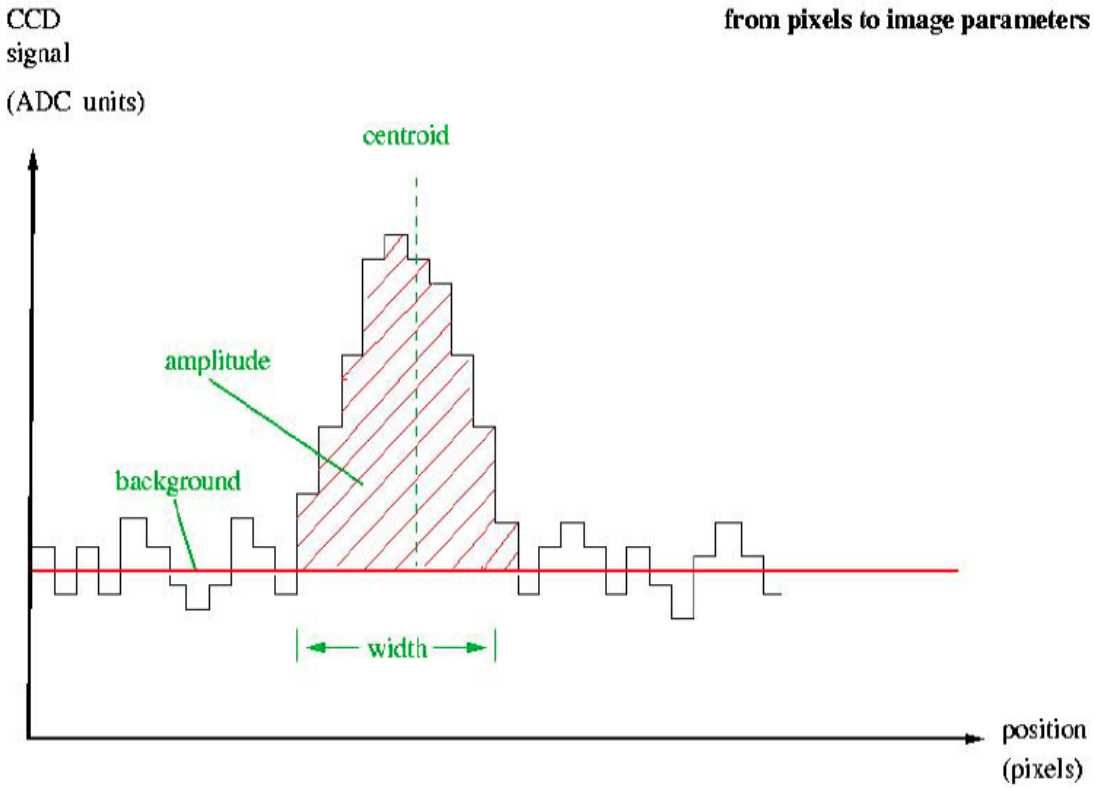

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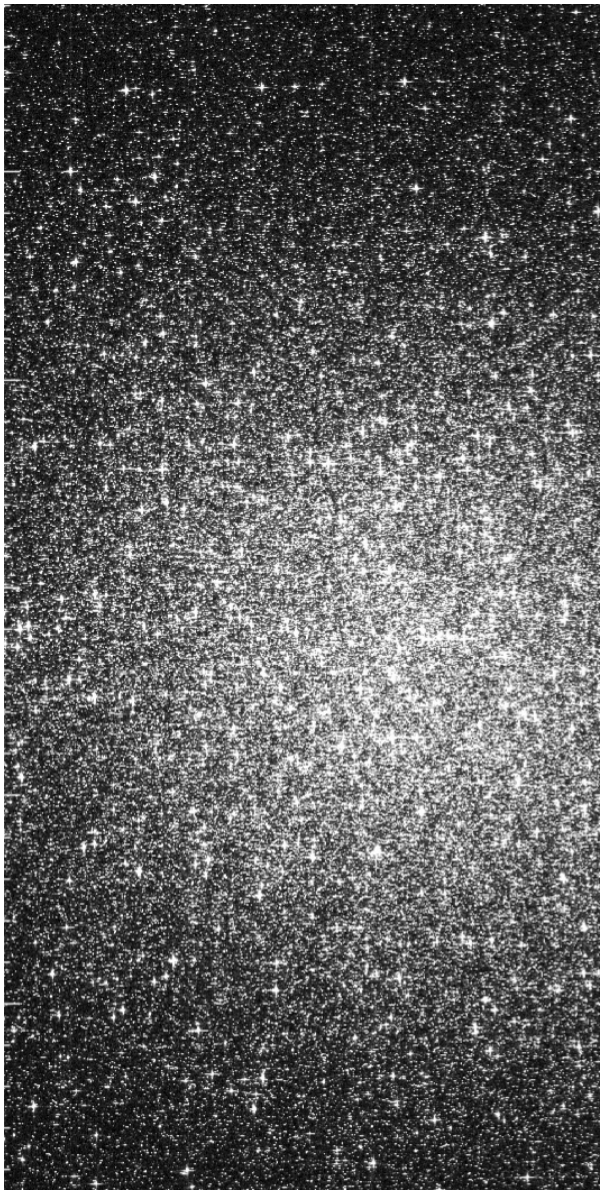

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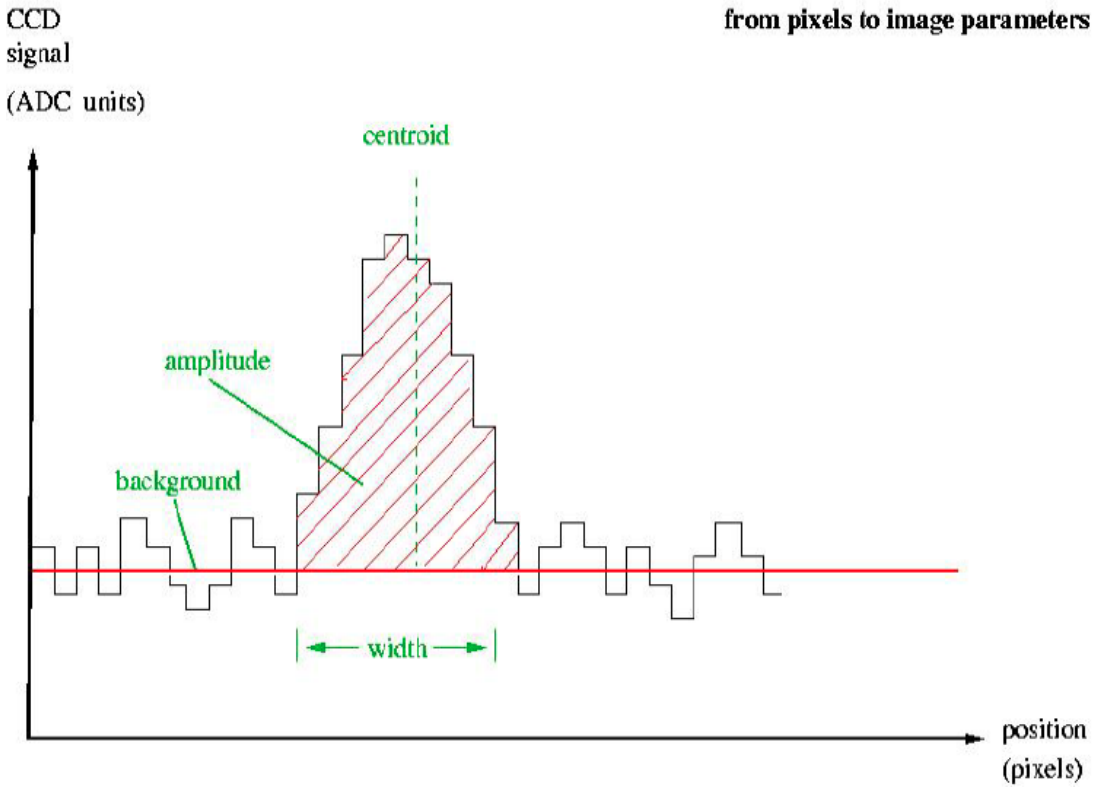
Windows for each observed object

Centroiding accuracy: millipixels



# The challenge of data processing

- Parameters
  - At least 5 parameters for each star: $5\ 10^9$
  - 4 parameters of orientation each 15 seconds: $10^8$
  - 2000 calibration parameters per day: $4\ 10^6$
  - global parameters: $<10^4$

- Observations

  about 1000 raw images for each star: $10^{12}$

- Data volume: 1 PB (iteratively!)
- Computational efforts: $\sim 10^{22}$ flops
- Direct least squares solution is impossible

# Gaia payload ready for launch (2013)

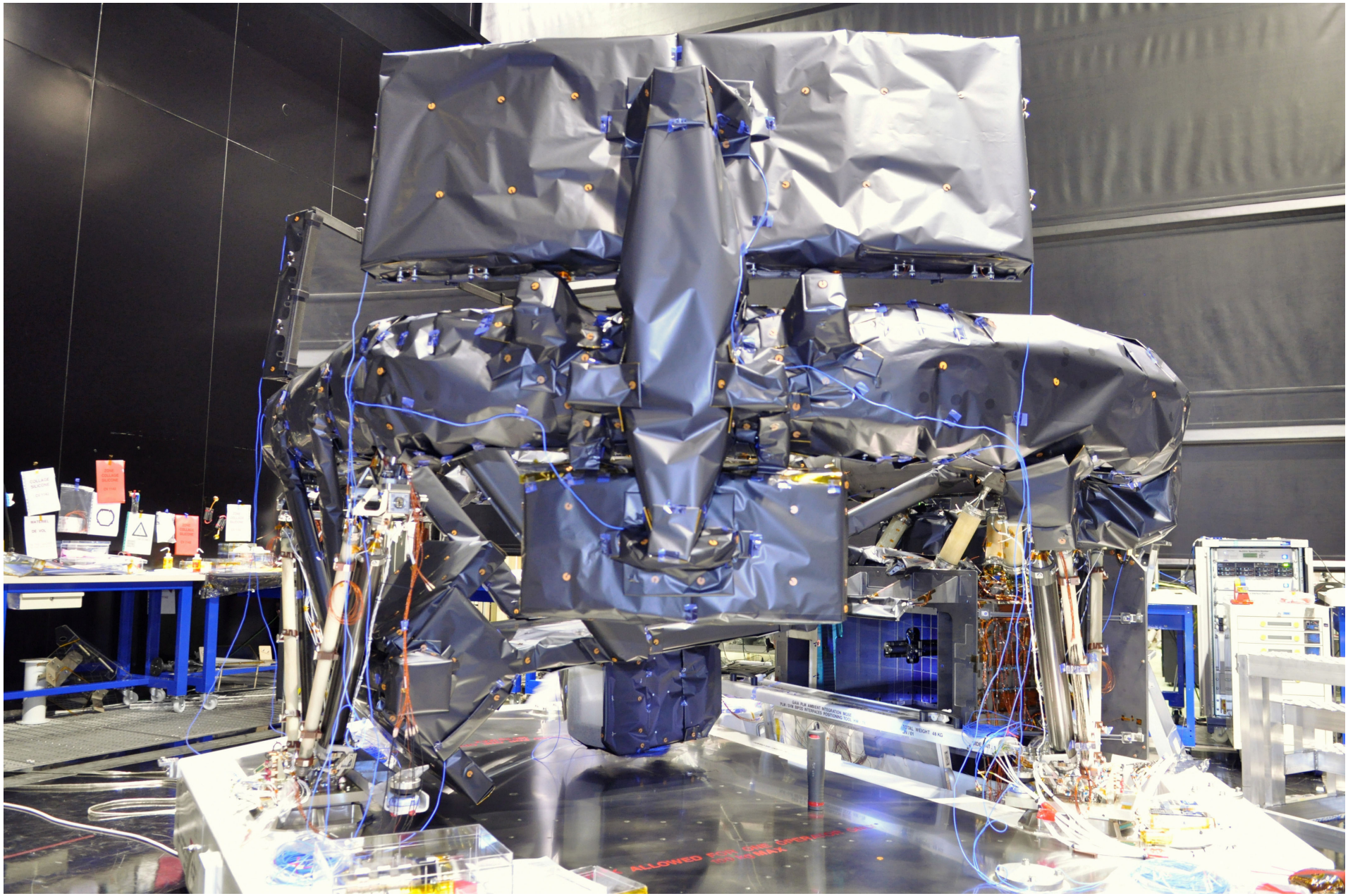


Figure courtesy EADS-Astrium

# Gaia: almost ready to fly…

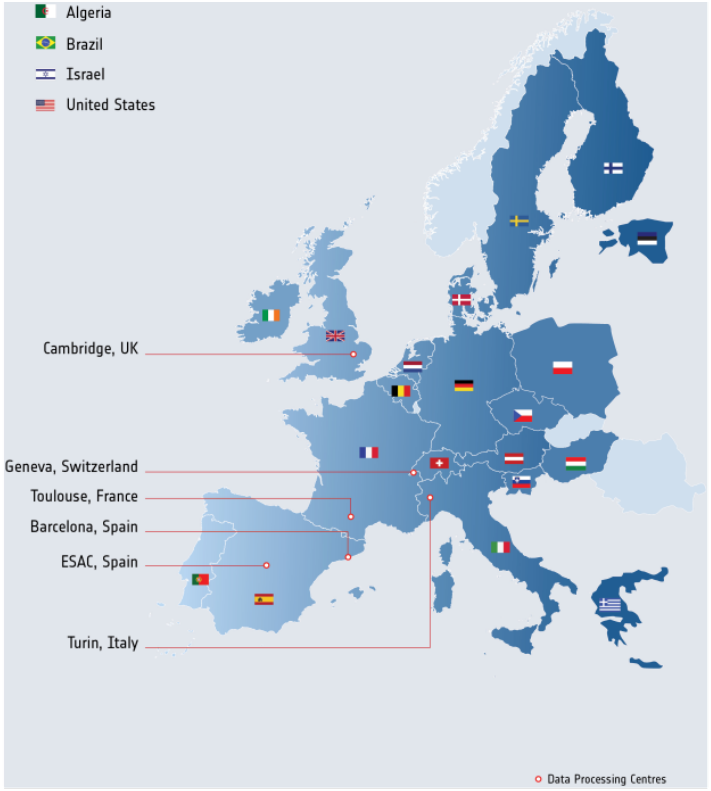
Figure courtesy ESA

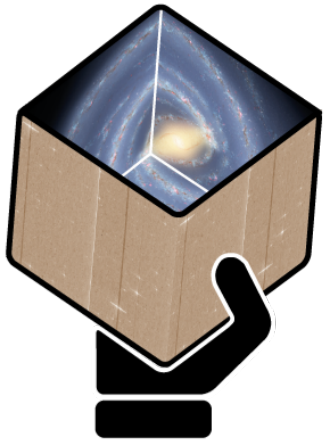
# The new era begins: Gaia launch 19.12.2013

Figures courtesy Arianespace

# Teamwork to deliver the promise of Gaia

- 450 scientists and engineers
- from 160 institutes
- in 24 countries
- working more than 15 years



gaia

0 1 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

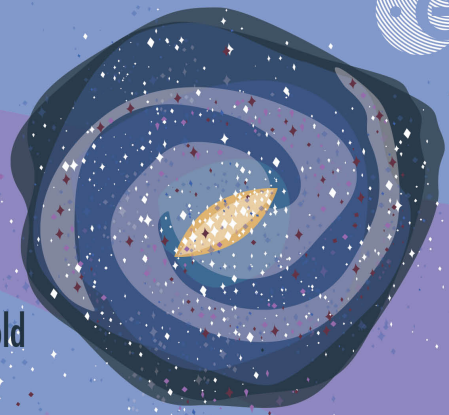
α δ ϖ $\mu_{\alpha*}$ $\mu_\delta$ G . . .

# → GAIA DATA RELEASE 1

**14**
September 2016

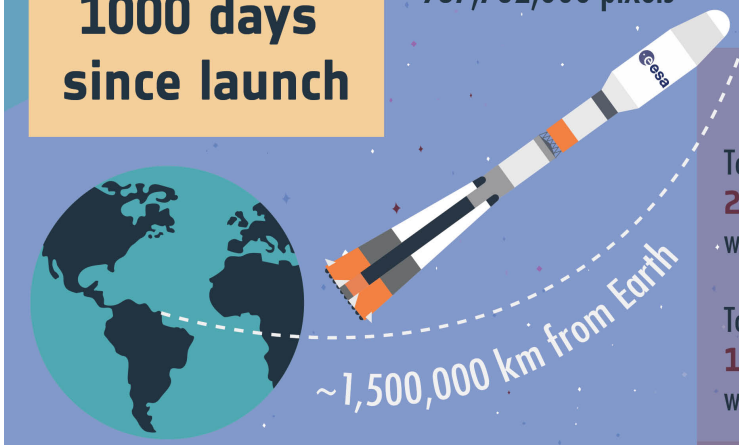
**1000 days since launch**

1 spacecraft
2 telescopes
10 mirrors
1 camera
106 CCDs
937,782,000 pixels



## 1 Milky Way

>100,000,000,000 stars
~13,000,000,000 years old




## Content of the release

Total number of sources in primary astrometric data set:
**2,057,050**
with position, magnitude, parallax & proper motion

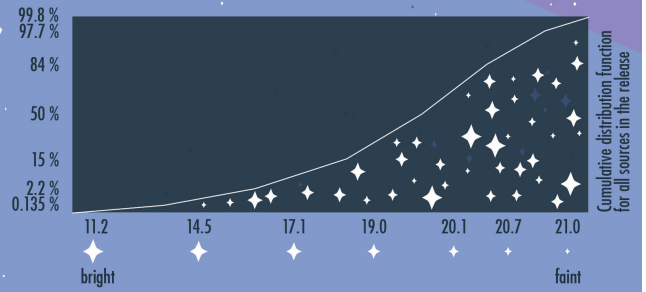
Total number of sources in secondary astrometric data set:
**1,140,622,719**
with position & magnitude

**3194 Variable stars**
- 599 Cepheids (43 new discoveries)
- 2595 RR Lyrae (343 new discoveries)

**2152 Quasars**
with position & magnitude

Data collected over 14 months

## Magnitude distribution



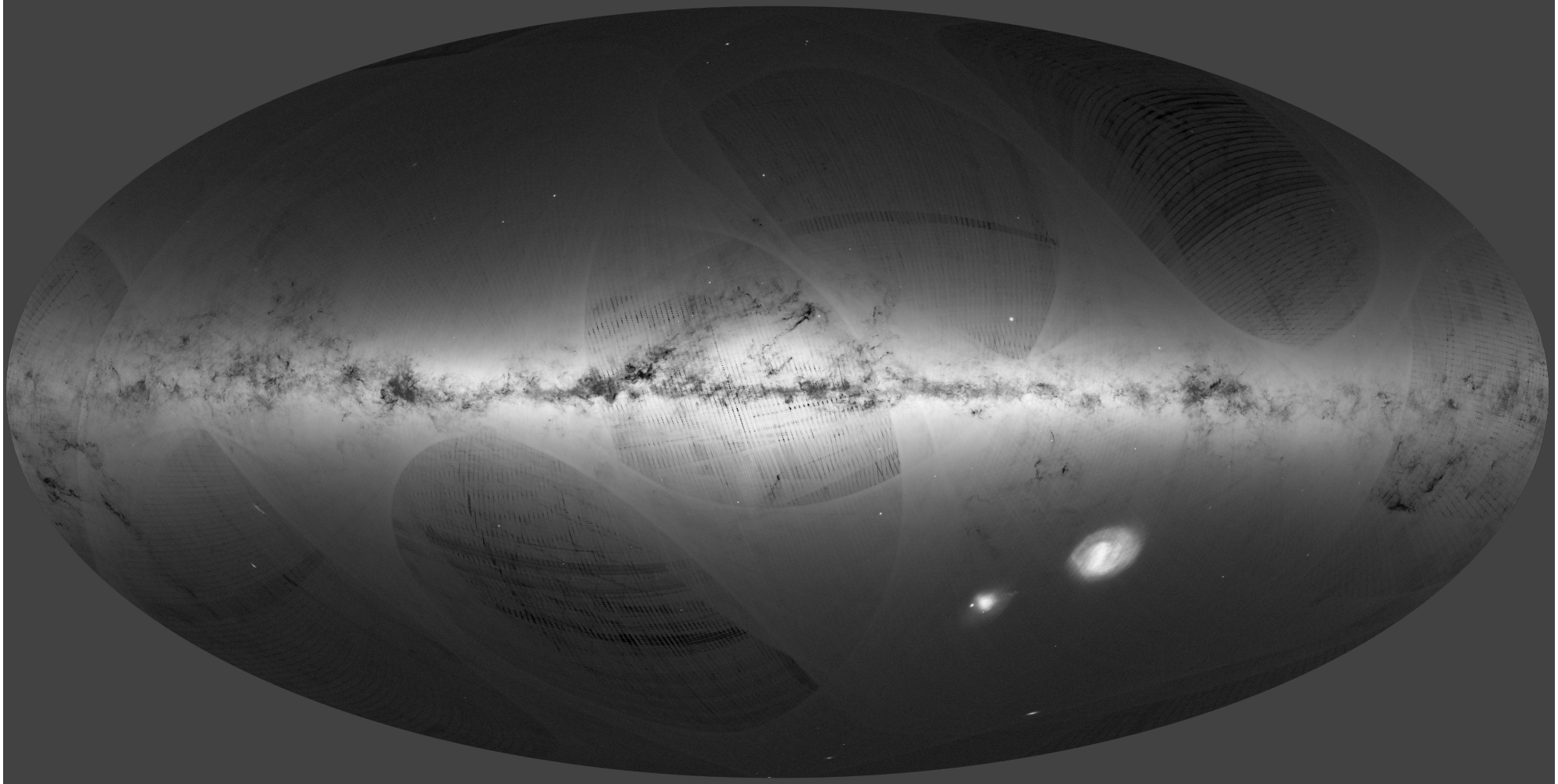

## Data challenge so far

>50 billion focal plane transits
>110 billion photometric observations
>9.4 billion spectroscopic observations
~120,000 hours of computing time to identify stars
6 data processing centres

## 1 day on Gaia

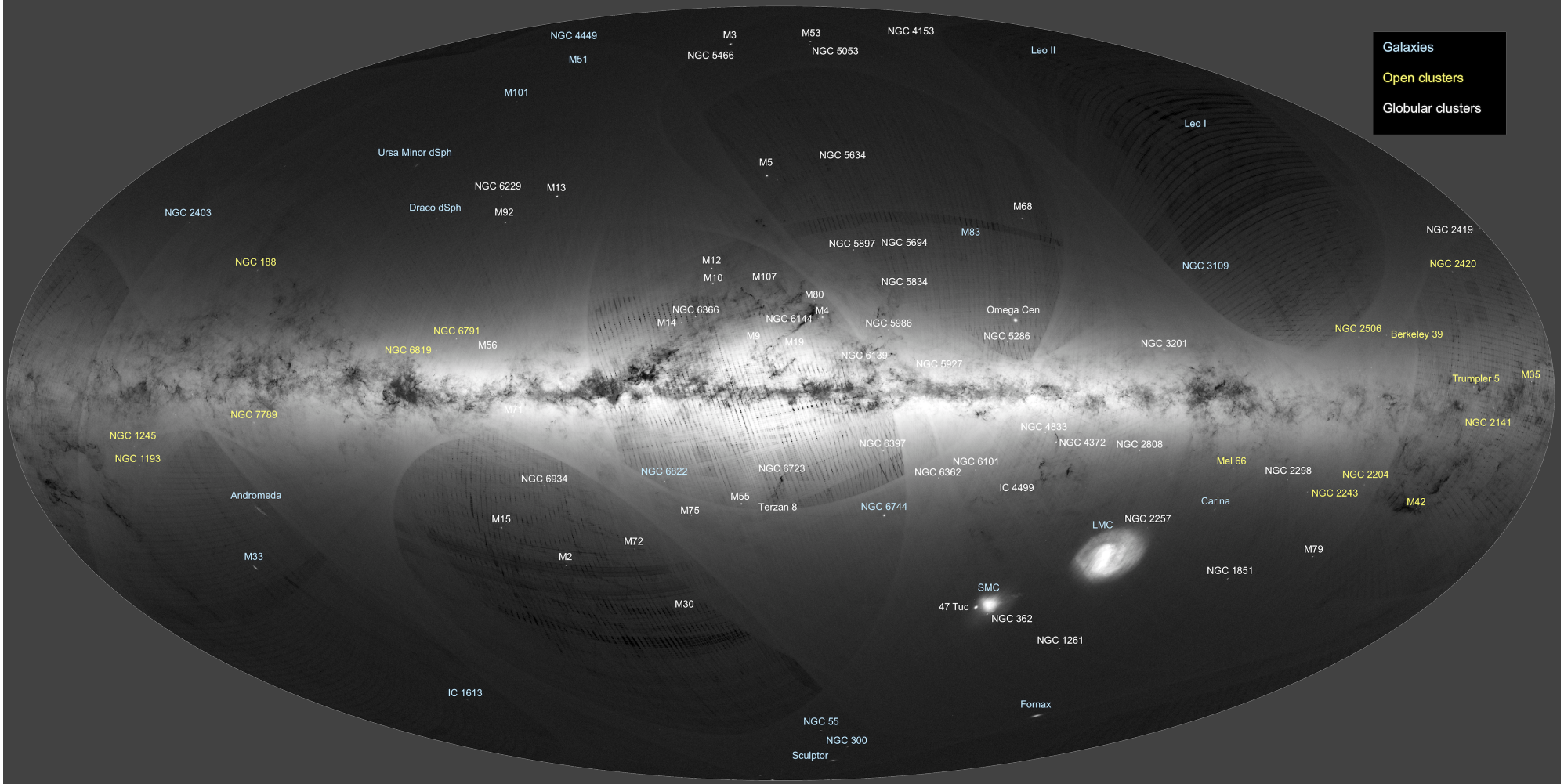
637,000,000 astrometric measurements
155,000,000 photometric measurements
13,000,000 spectrometric measurements
70,000,000 celestial objects
40 GB of data downlinked to Earth

# Gaia Data Release 1 as density plot



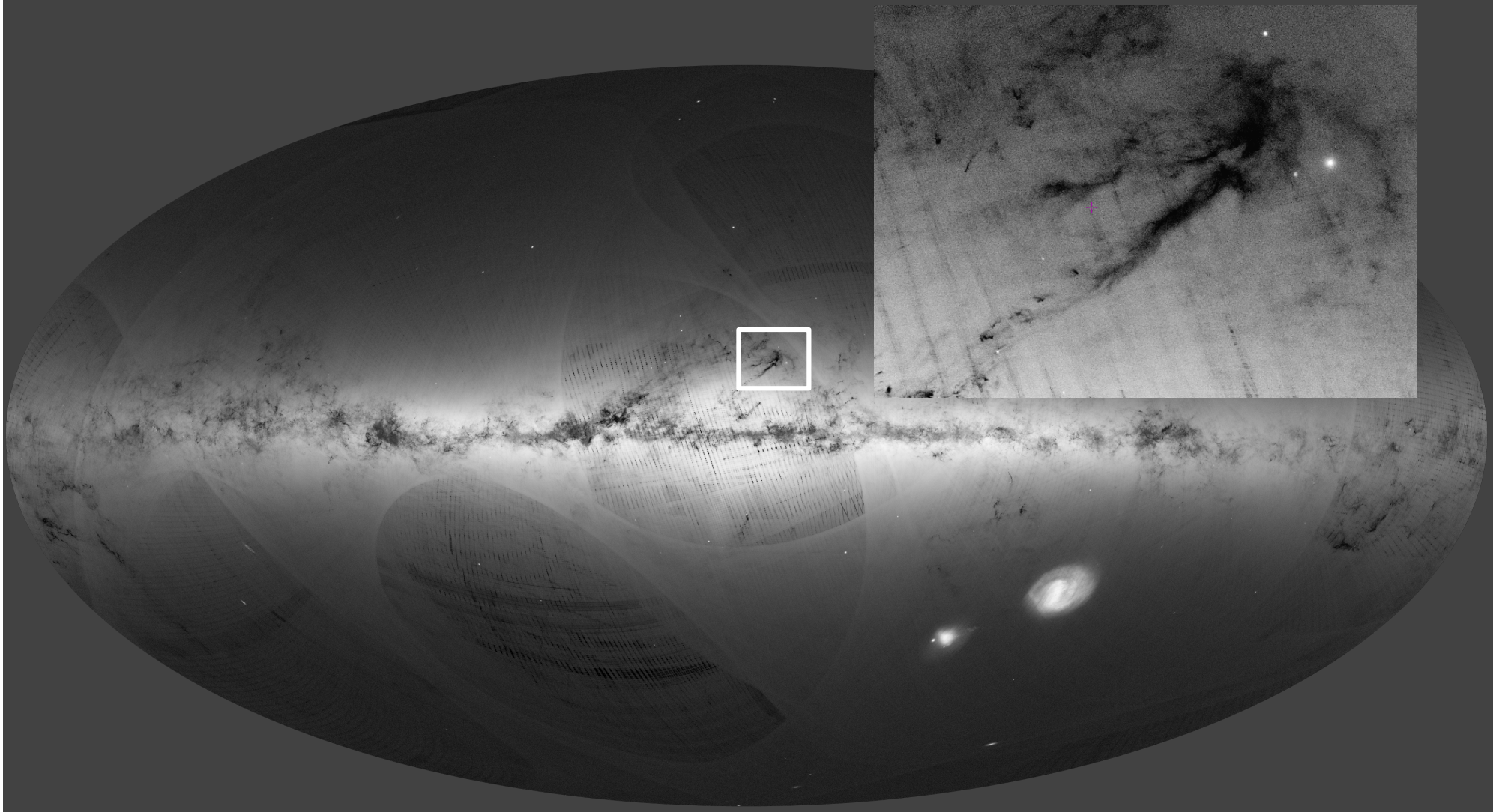
Credit: ESA/Gaia/DPAC
Image generated by A.Moitinho, M.Barros (CENTRA - University of Lisbon) on behalf of DPAC

# Gaia Data Release 1 as density plot



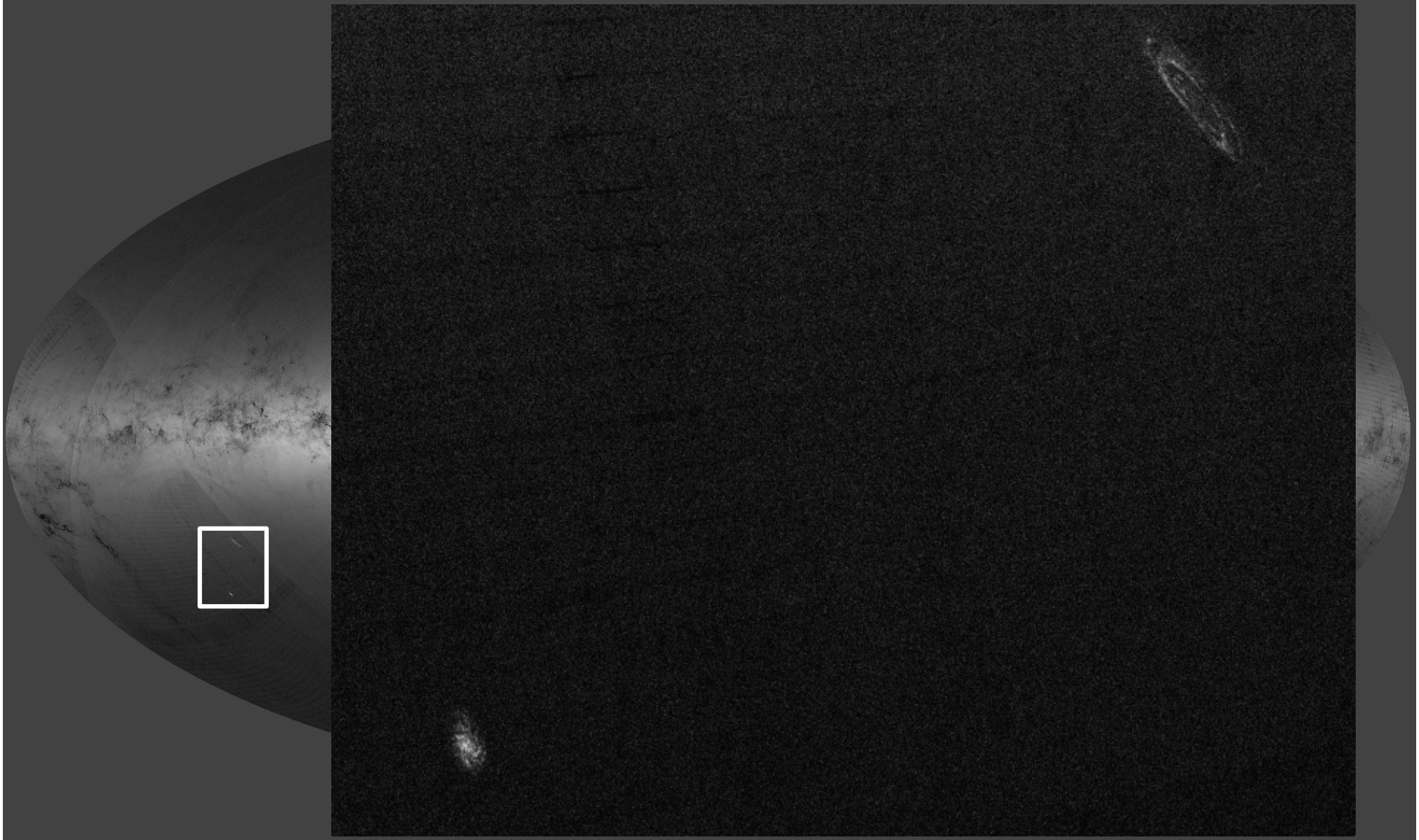

Credit: ESA/Gaia/DPAC
Image generated by A.Moitinho, M.Barros (CENTRA - University of Lisbon), F.Mignard (OCA-CNRS) on behalf of DPAC

# Gaia Data Release 1 as density plot



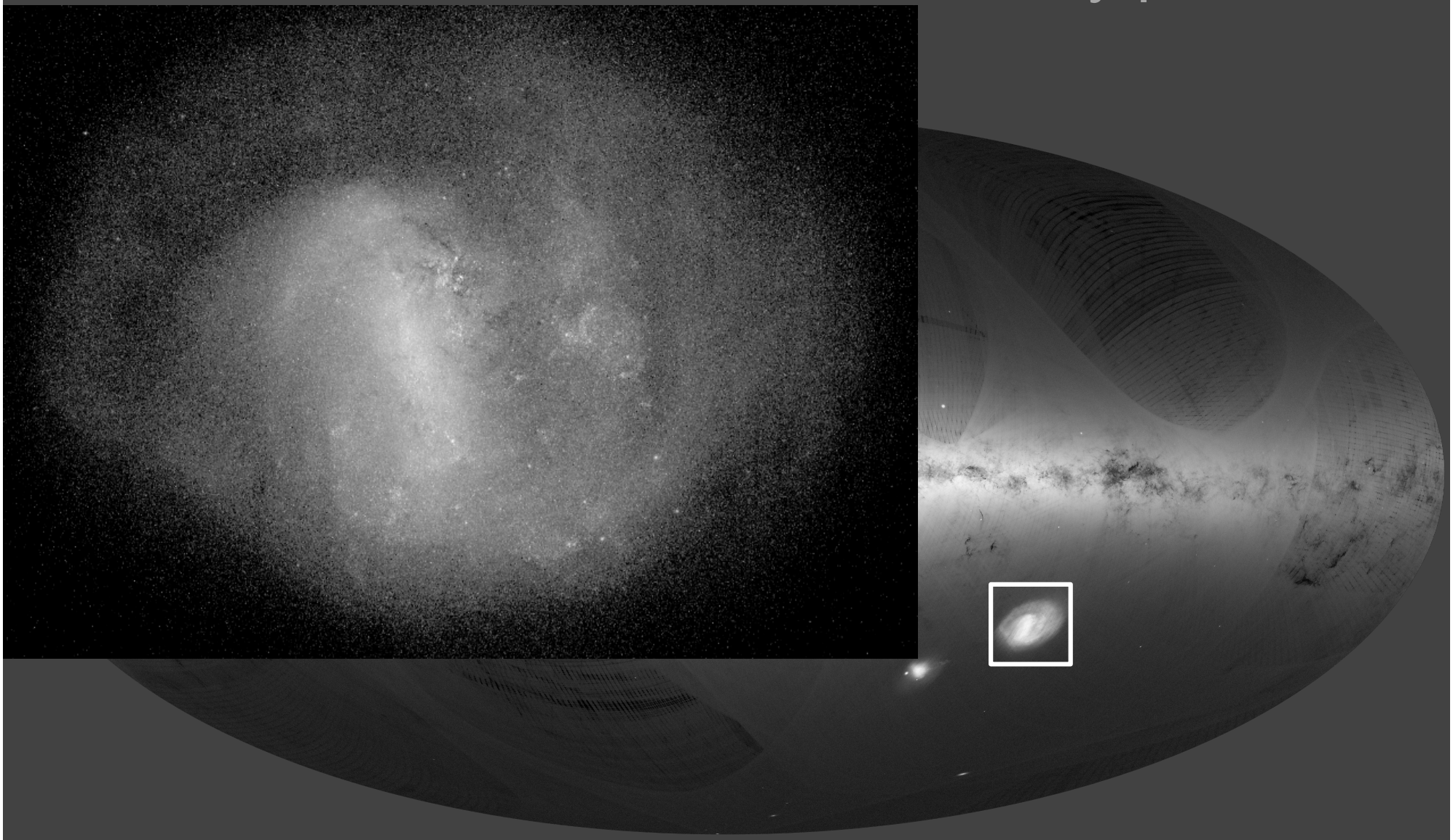
Credit: ESA/Gaia/DPAC
Image generated by A.Moitinho, M.Barros (CENTRA - University of Lisbon) on behalf of DPAC

# Gaia Data Release 1 as density plot



Credit: ESA/Gaia/DPAC
Image generated by A.Moitinho, M.Barros (CENTRA - University of Lisbon) on behalf of DPAC

# Gaia Data Release 1 as density plot

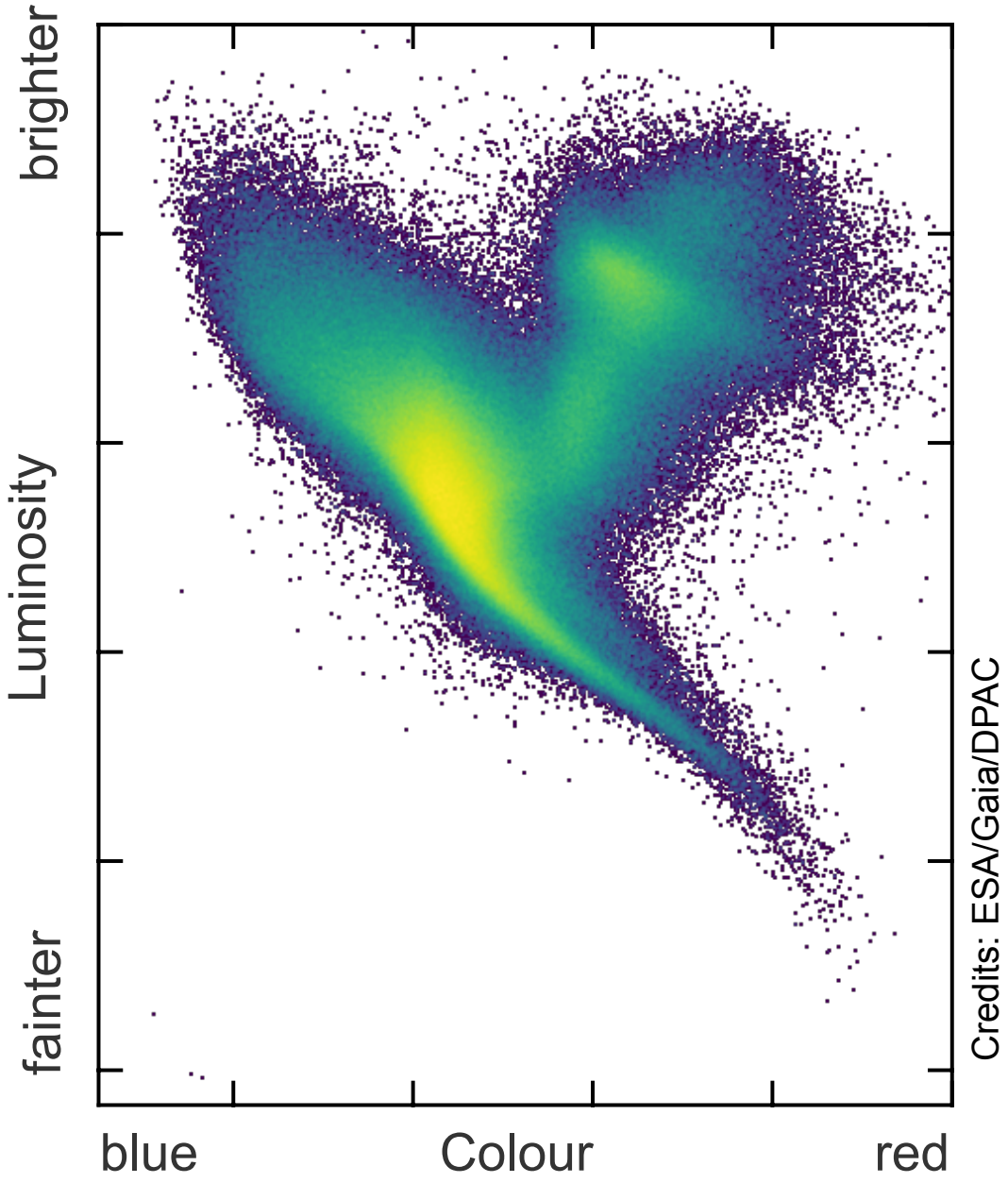


Credit: ESA/Gaia/DPAC
Image generated by A.Moitinho, M.Barros (CENTRA - University of Lisbon) on behalf of DPAC

# Where are the stars?

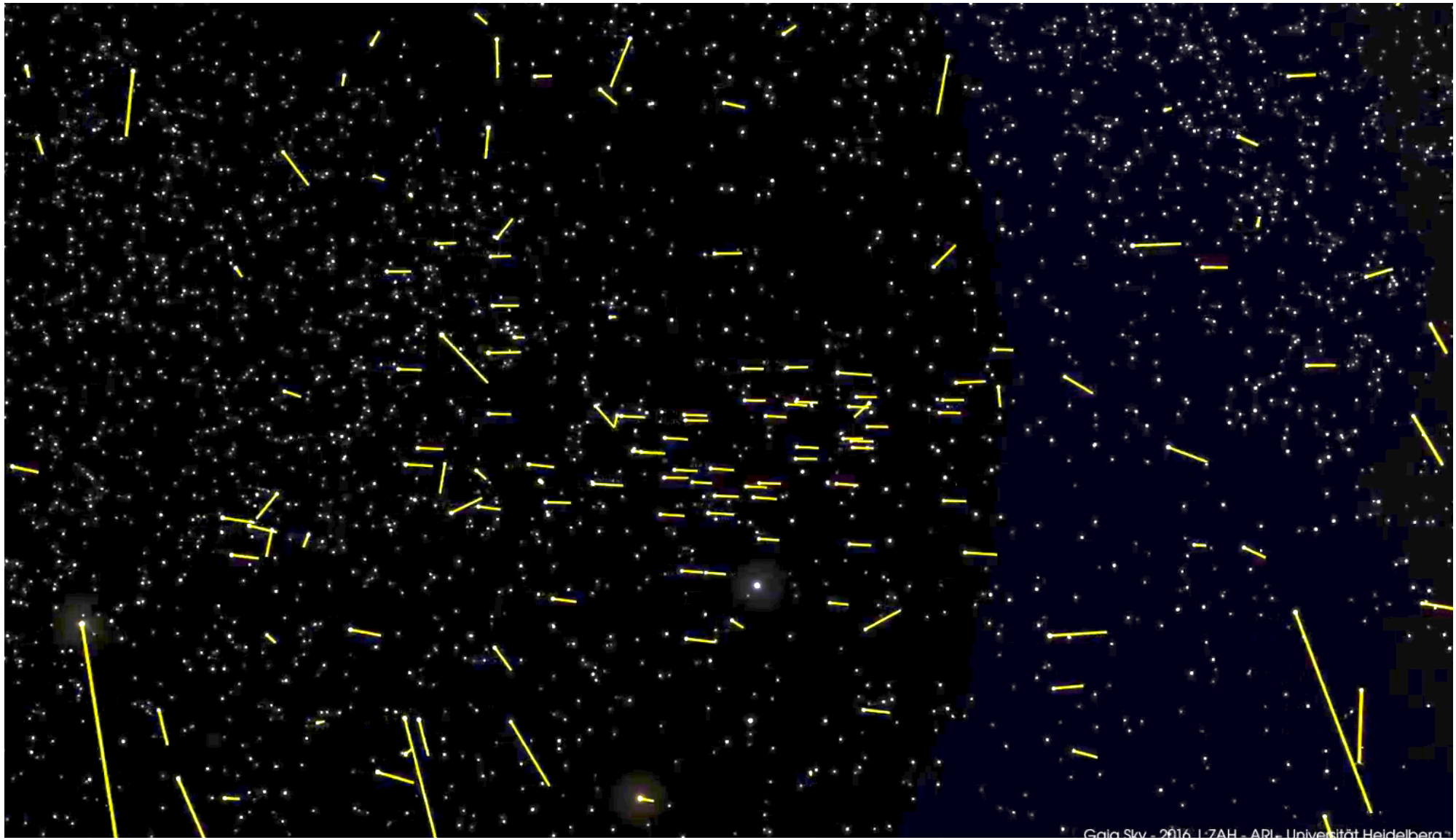
# Gaia Data Release 1 as a cloud of stars

# The “Hertzsprung-Russel diagram” from Gaia




> 1000000 Gaia stars
with distances measured to 20%

# Stellar clusters from Gaia




S.Jordan, T. Sagrista, ZAH, Heidelberg

# Gaia in Dresden

1. The model of observations in Einstein's General Relativity

2. Tests of fundamental physical laws with Gaia data

3. Synchronization and monitoring of Gaia's atomic clock

4. Special aspects of the core astrometric solution:

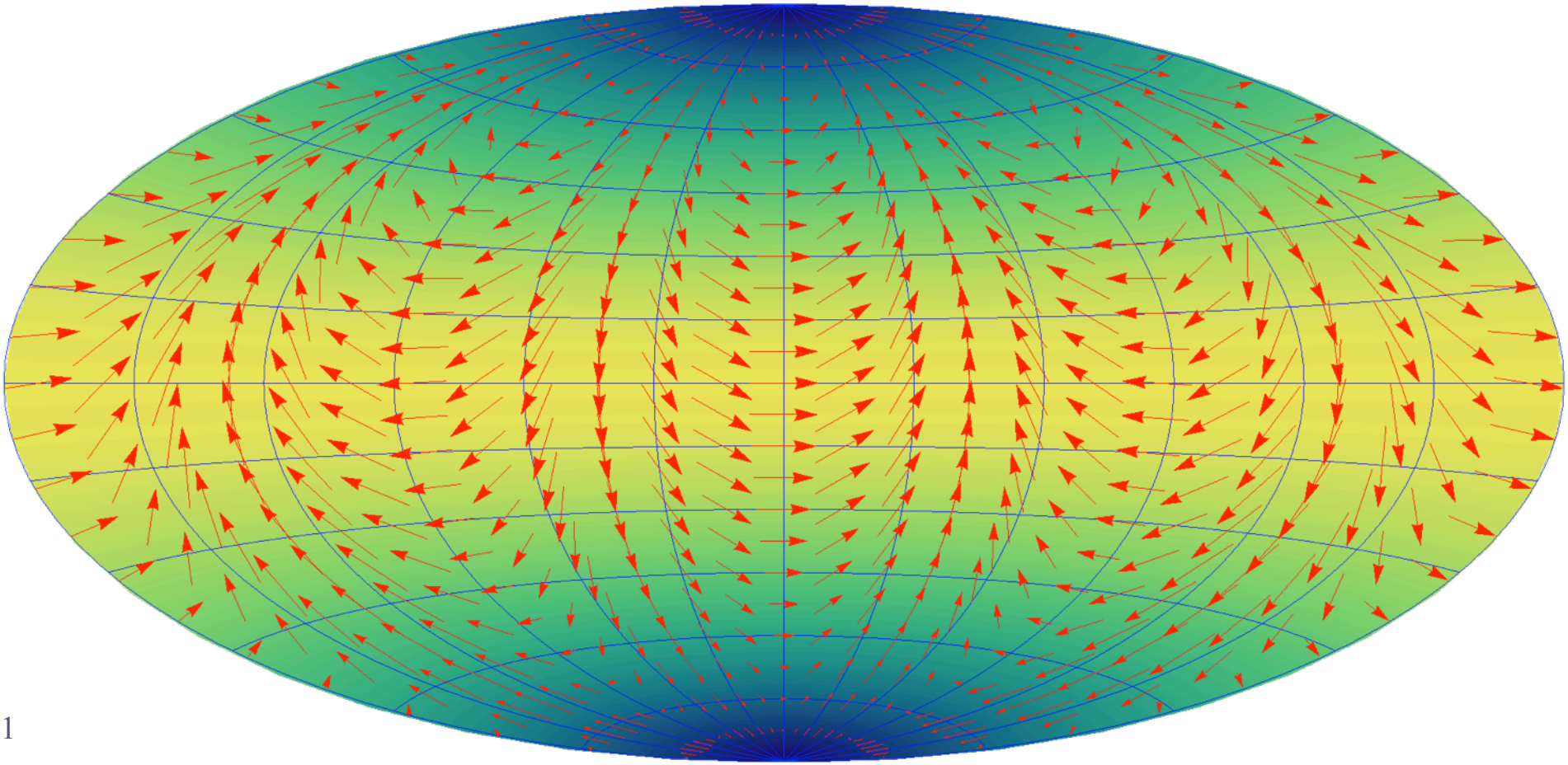
   stability and quality tests,
   special calibration of the instrument,
   relativistic tests

Special thanks to the Center for Information Services and High Performance Computing (ZIH), TU Dresden!

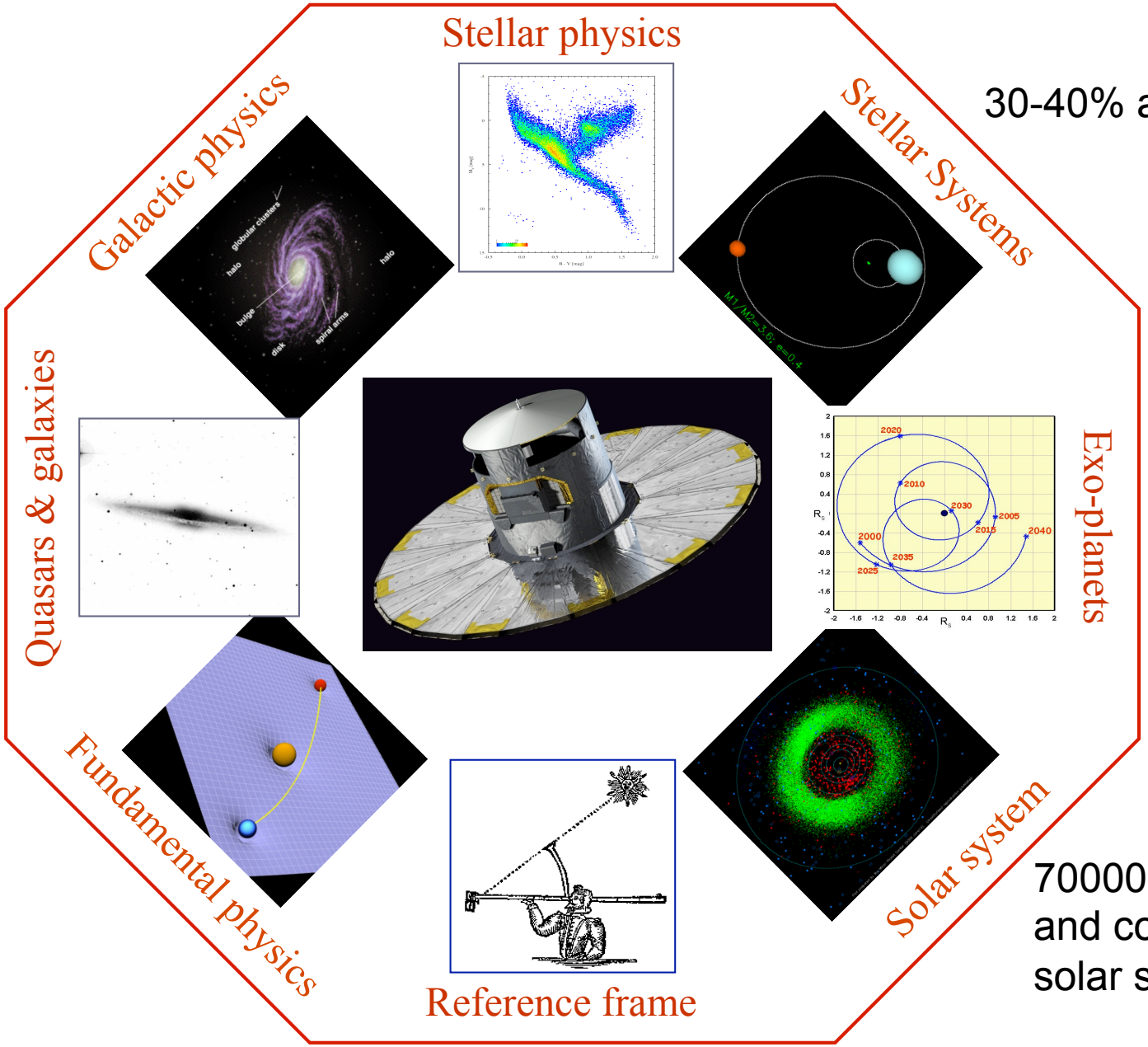
# Just one example: Gravitational waves

- At each moment of time a GW produces a deflection pattern on the sky: it is not a pure quadrupole, but rather close to it (Pyne et al, 2006; Gwinn et al, 2006; Book, Flanagan, 2011; Klioner, 2014)

  This is for a GW propagating in the direction δ=90°:



# Gaia: goals



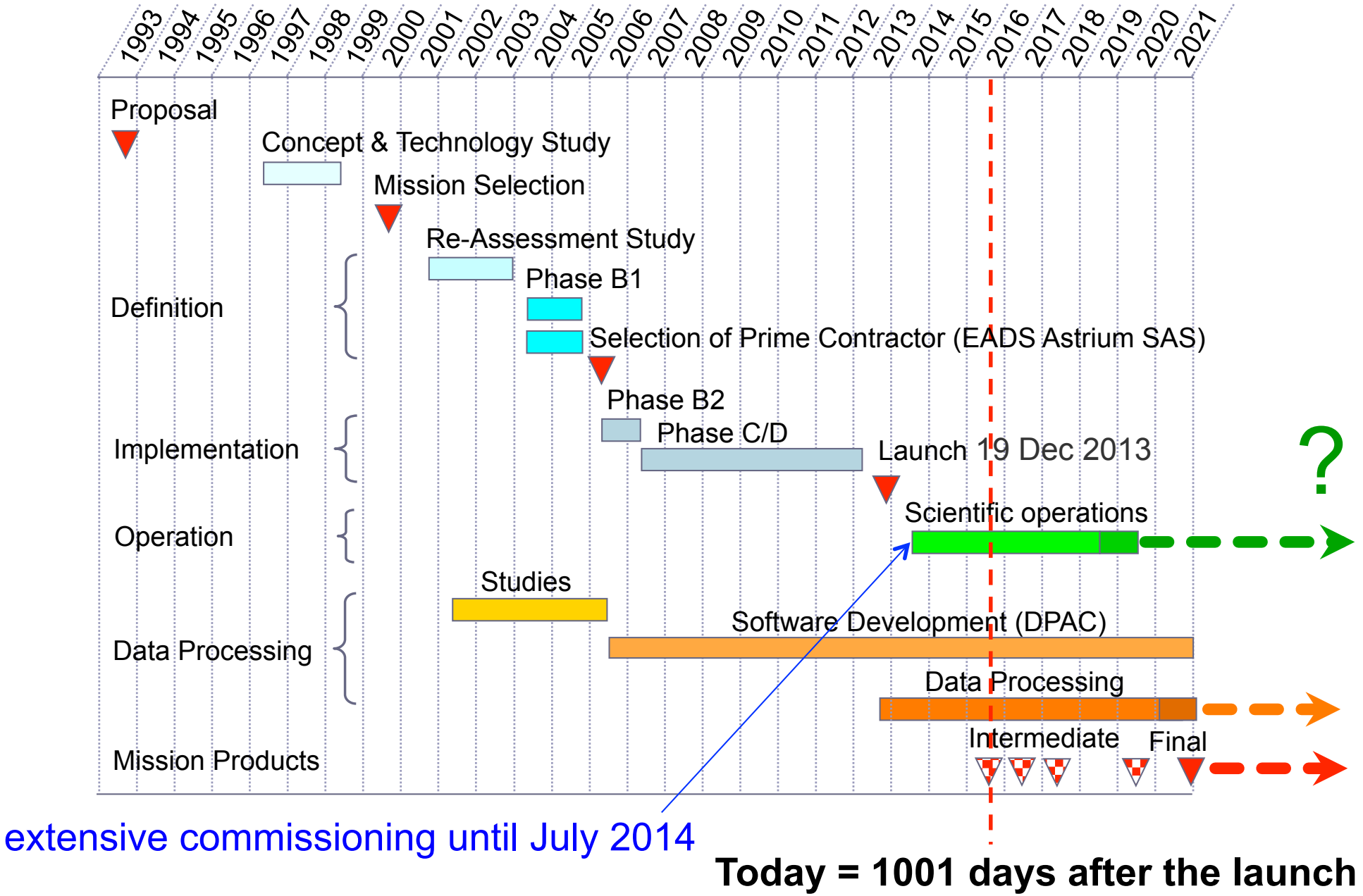

30-40% are binaries

20000 new exoplanets

700000 asteroids and comets in solar system

1 million quasars

# Schedule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2018
2019
2020
2021
Proposal
Concept & Technology Study
Mission Selection
Re-Assessment Study
Definition
Phase B1
Selection of Prime Contractor (EADS Astrium SAS)
Phase B2
Implementation
Phase C/D
Launch 19 Dec 2013
?
Operation
Scientific operations
Studies
Software Development (DPAC)
Data Processing
Data Processing
Intermediate
Final
Mission Products
extensive commissioning until July 2014
Today = 1001 days after the launch

# Is nanoarcsecond astrometry possible?