第四章 天体物理
研究所需要的主要观测数据

§1 天体的位置：

- 在天球上投影的位置，即它的球面坐标（赤道、黄道、银道坐标系），属于天体测量学：比较容易。
- 距离：很困难。

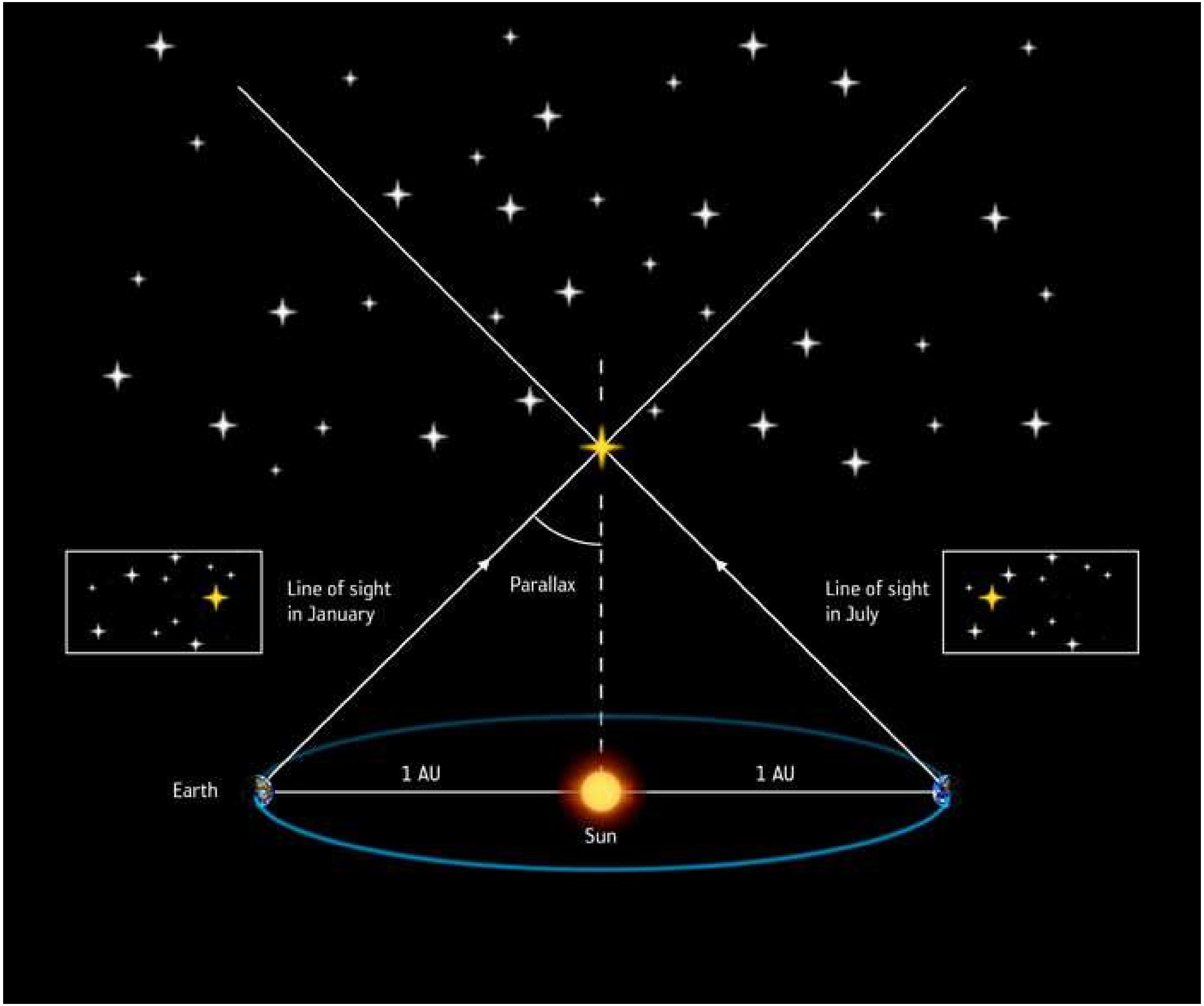
测量距离的方法：

- 直接方法：

三角视差法：利用地球的公转，半年间隔中天体在天球上视位置移动2θ角，则天体的距离

$$\rho(PC) = \frac{1}{tg\theta} \approx \frac{1}{\theta} = \frac{206265}{\theta(\text{角秒})}$$

由于观测精度的限制，三角视差方法只能用于100PC以内的天体，而当天体距离大于50PC时，误差已经很大。



Line of sight
in January
Parallax
Line of sight
in July
Earth
1 AU
1 AU
Sun

- 间接方法：

利用天体的绝对星等M和它的某些物理特征之间的关系求出天体的绝对星等M，再根据测量得到视星等m，从而求出距离ρ（以PC为单位）：

$$\lg \rho = \frac{1}{5}(m - M + 5)$$

这类物理特征常用的有:

- 天体光谱中的一些特征，如H的Balmer 线的宽度，CaII H,K线中发射核的强度，它们都可以用做绝对星等的“指示器”。
- 造父变星的周光关系。
- 新星和超新星绝对星等的极大值。

- 河外天体距离可用哈勃定律来测定：

$$u = H_0 \rho$$

$$\rho = \frac{1}{H_0} u = \frac{c}{H_0} \frac{\Delta\lambda}{\lambda}$$

$\frac{\Delta\lambda}{\lambda}$为星系的红移值，$c$为光速，$H_0$为哈勃常数

- 天体位置的确定对于天体物理研究至为重要，例如：
  - 从观测得到的天体辐射流量密度，推算天体绝对光度，必须知道天体距离。
  - 从天体视直径去推知它的线尺度，也要知道距离值。
  - 银河系结构的确定或河外天体空间分布的研究也完全依赖于天体位置的确定。

§2 天体的空间运动：

天体的空间运动可以分解为两个分量：

- 在天球上的投影：自行μ（角秒/年）
  实际上是一个角速度值，与切向速度相对应：
  $$\mu = (v_{\perp} / \rho) \times 3.33 \times 10^{-5}$$
- 在视线方向的投影：视向速度v_r (km/s)
  可采用多普勒定律，从光谱中谱线的位移来确定：
  $$v_r = \frac{c}{\lambda} \Delta\lambda$$

常用天体测量星表

- USNO-B1.0
- GSC2.3
- PPMXL
- UCAC4

USNO-B1.0

- Monet et al., 2003, AJ, 125, 984
- http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/usno-b1.0
    - all-sky catalog that presents positions, proper motions, magnitudes in various optical passbands, and star/galaxy estimators for 1,042,618,261 objects derived from 3,643,201,733 separate observations.
    - The data were obtained from scans of 7435 Schmidt plates taken for the various sky surveys during the last 50 years.
    - USNO-B1.0 is believed to provide all-sky coverage, completeness down to V=21, 0.2" astrometric accuracy, 0.3 mag photometric accuracy in up to five colors.

GSC2.3

- Lasker et al., 2008, AJ, 136, 735
- http://archive.stsci.edu/gsc/
  - The Guide Star Catalog II (GSC-II) is an astronomical database constructed from the scanned images of 9541 Palomar and UK Schmidt photographic sky survey plates digitized at Space Telescope Science Institute (STScI).
  - contains astrometry, photometry, and classification for 945,592,683 stars.
  - absolute error per coordinate ranges from 0.2" to 0.28" depending on magnitude.
  - Stellar photometry is determined to 0.13-0.22 mag as a function of magnitude and photographic passbands (B,R,I).

PPMXL

- Roeser, S. et al., 2010, AJ, 139, 2440
- http://vo.uni-hd.de/ppmxl

  - performed a new determination of mean positions and proper motions on the ICRS system by combining USNO-B1.0 and 2MASS astrometry.
  - it aims to be completed from the brightest stars down to about $V \approx 20$ all sky. PPMXL contains about 900 million objects, some 410 million with 2MASS photometry, and is the largest collection of ICRS proper motions at present.
  - The resulting typical individual mean errors of the proper motions range from 4 mas yr^{-1} to more than 10 mas yr^{-1} depending on observational history.
  - The mean errors of positions are 80-120 mas, if 2MASS astrometry could be used, 150-300 mas else.

UCAC4

- Zacharias et al., 2013, AJ, 145, 44
- http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/ucac
  - UCAC4: The fourth United States Naval Observatory (USNO) CCD Astrograph Catalog
  - contains over 113 million objects; over 105 million of them with proper motions.
  - The positional accuracy of stars in UCAC4 is about 15-100 mas per coordinate,
  - formal errors in PMs range from about 1 to 10 mas yr^{-1}
  - Systematic errors in PMs are estimated to be about 1-4 mas yr^{-1}.

空间天体测量观测

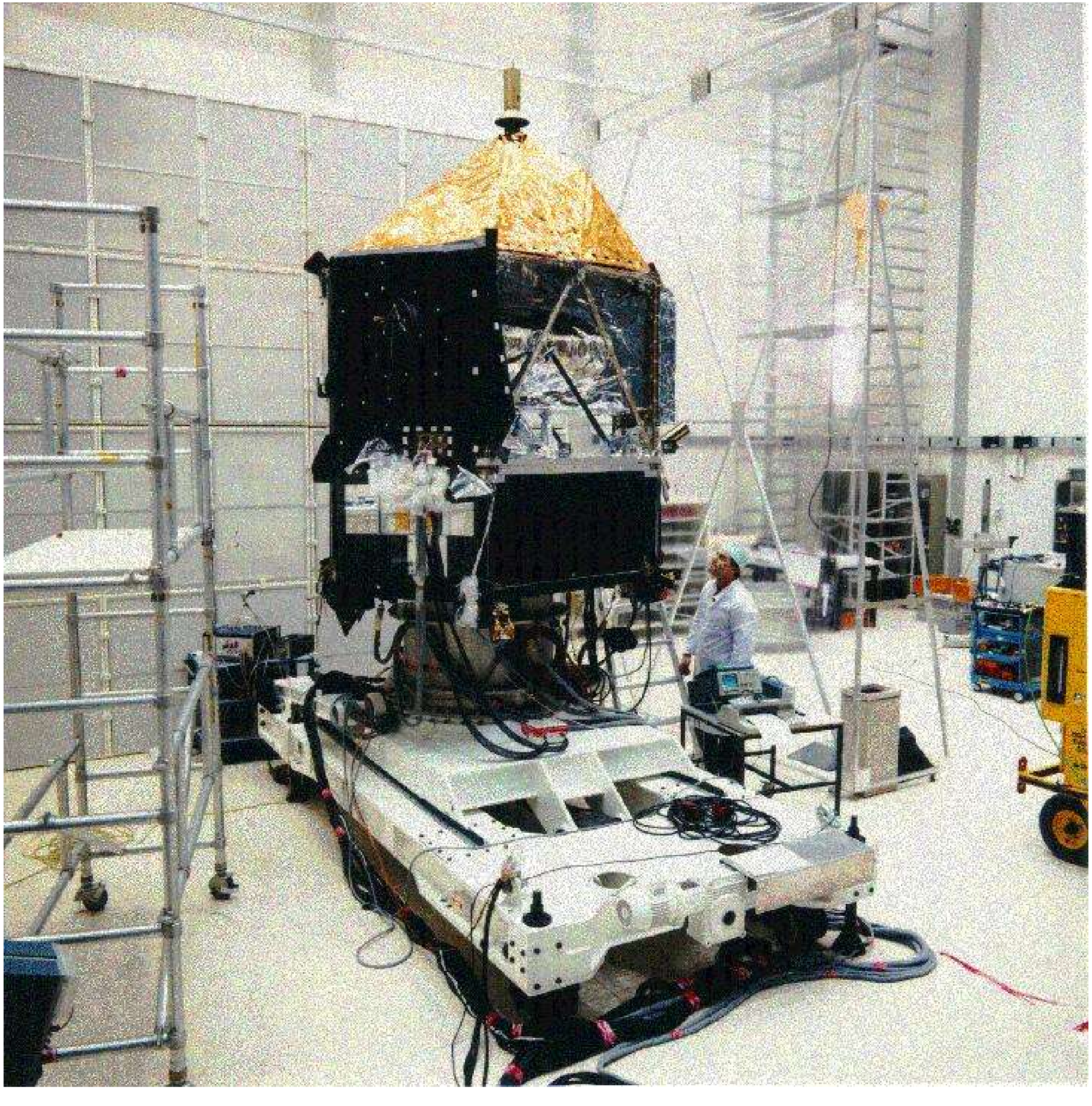
依巴谷卫星

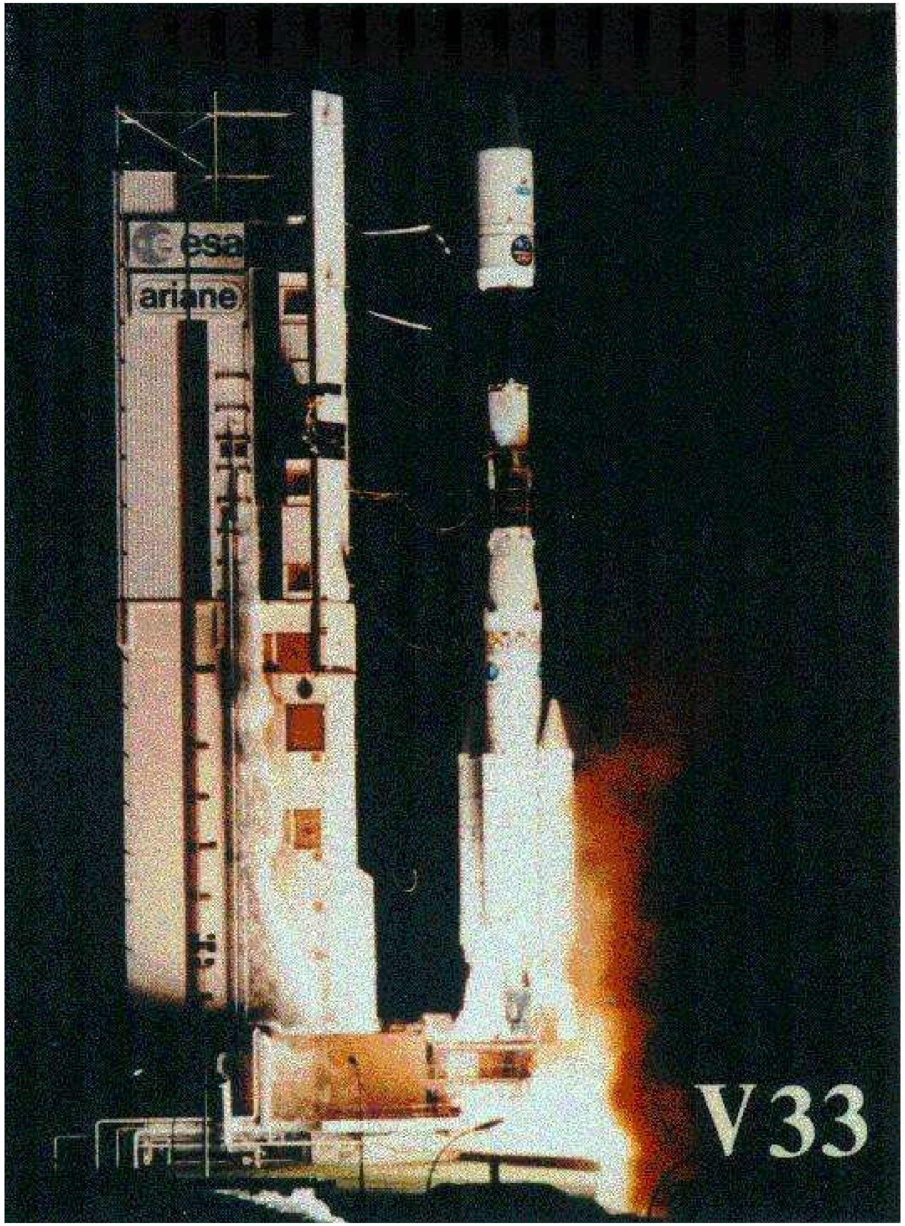
http://astro.estec.esa.nl/SA-general/Projects/Hipparcos/hipparcos.html

- Hipparcos is a pioneering space experiment dedicated to the precise measurement of the positions, parallaxes and proper motions of the stars.

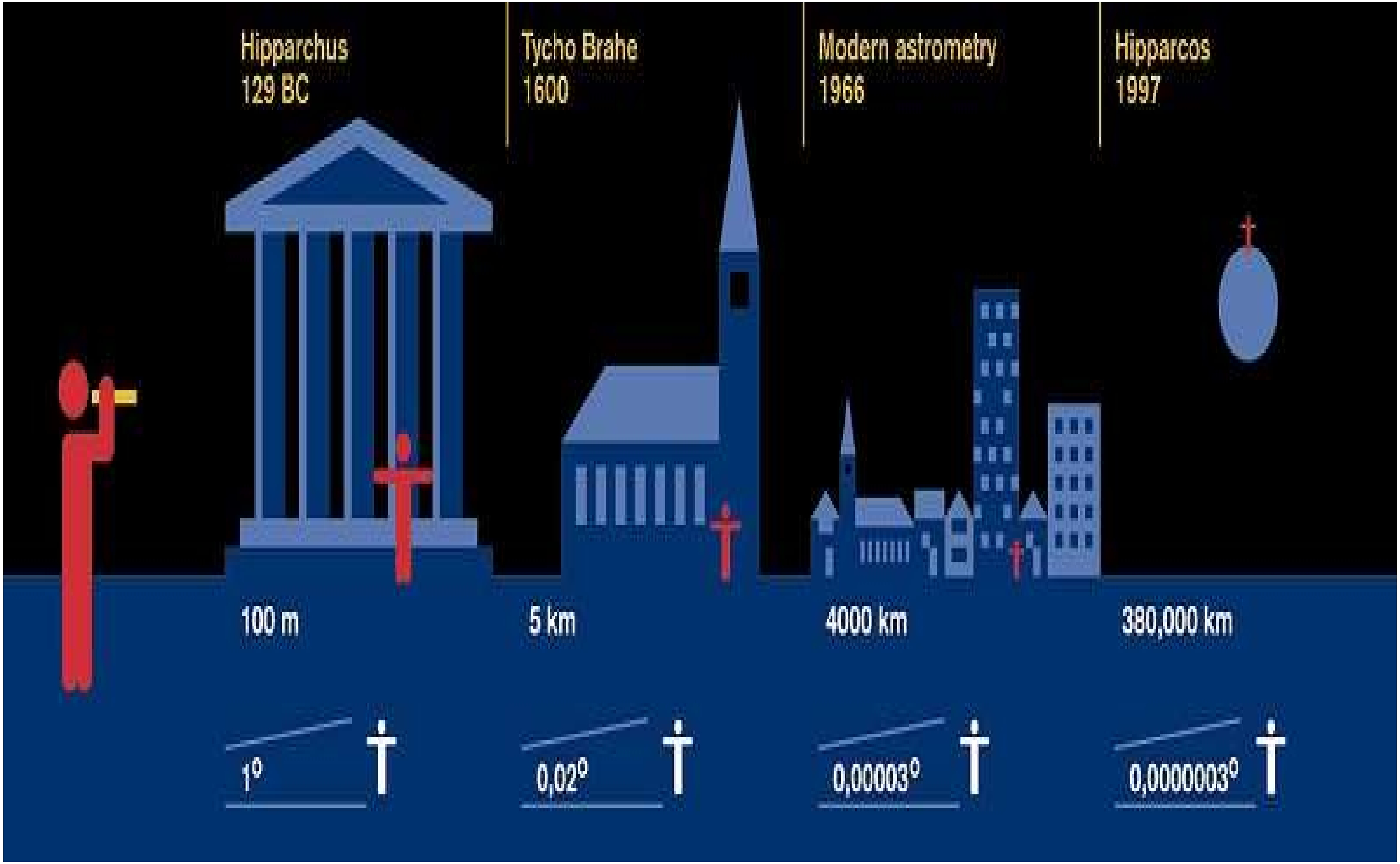
- The project was accepted within the ESA scientific programme in 1980.

- The satellite was launched by Ariane, in August 1989.
- After collecting more than three years of extremely high-quality scientific data, communications were terminated with the satellite in August 1993.
- All of the mission goals have been significantly exceeded.





Launch of the Hipparcos Satellite by Ariane 4 Flight V33, 8 August 1989, from Kourou, French Guiana.



1arcmin 100mas 1mas

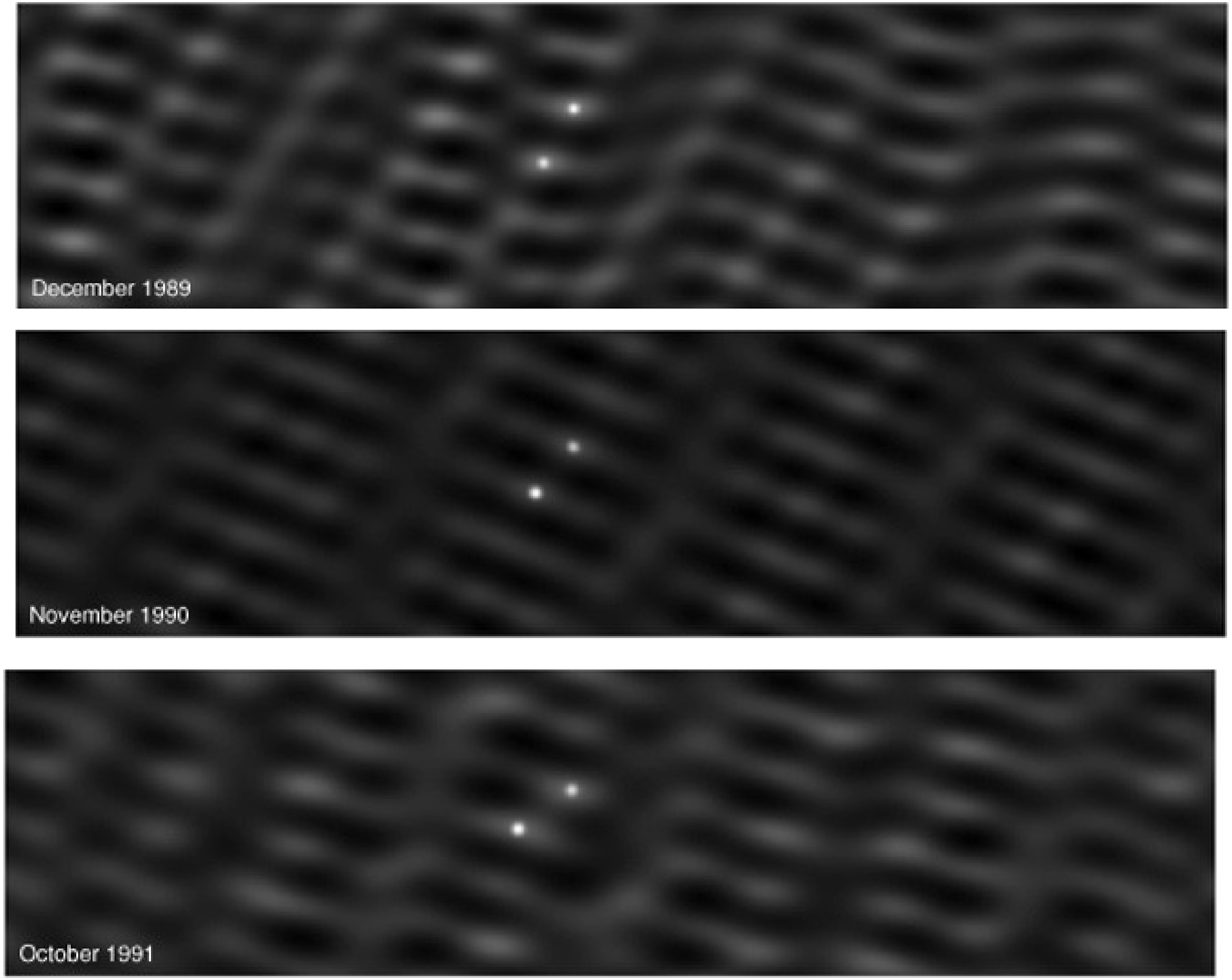
- Main Experiment:
  - Number of stars: 100 000
  - Limiting magnitude: V = 12.4 mag
  - Complete to: V = 7.3 - 9.0 mag
  - Positional accuracy: 0.002 arcsec (B=9 mag)
  - Parallax accuracy: 0.002 arcsec (B=9 mag)
  - Proper motion accuracy: 0.002 arcsec per year (B=9 mag)
  - Systematic errors: <0.001 arcsec

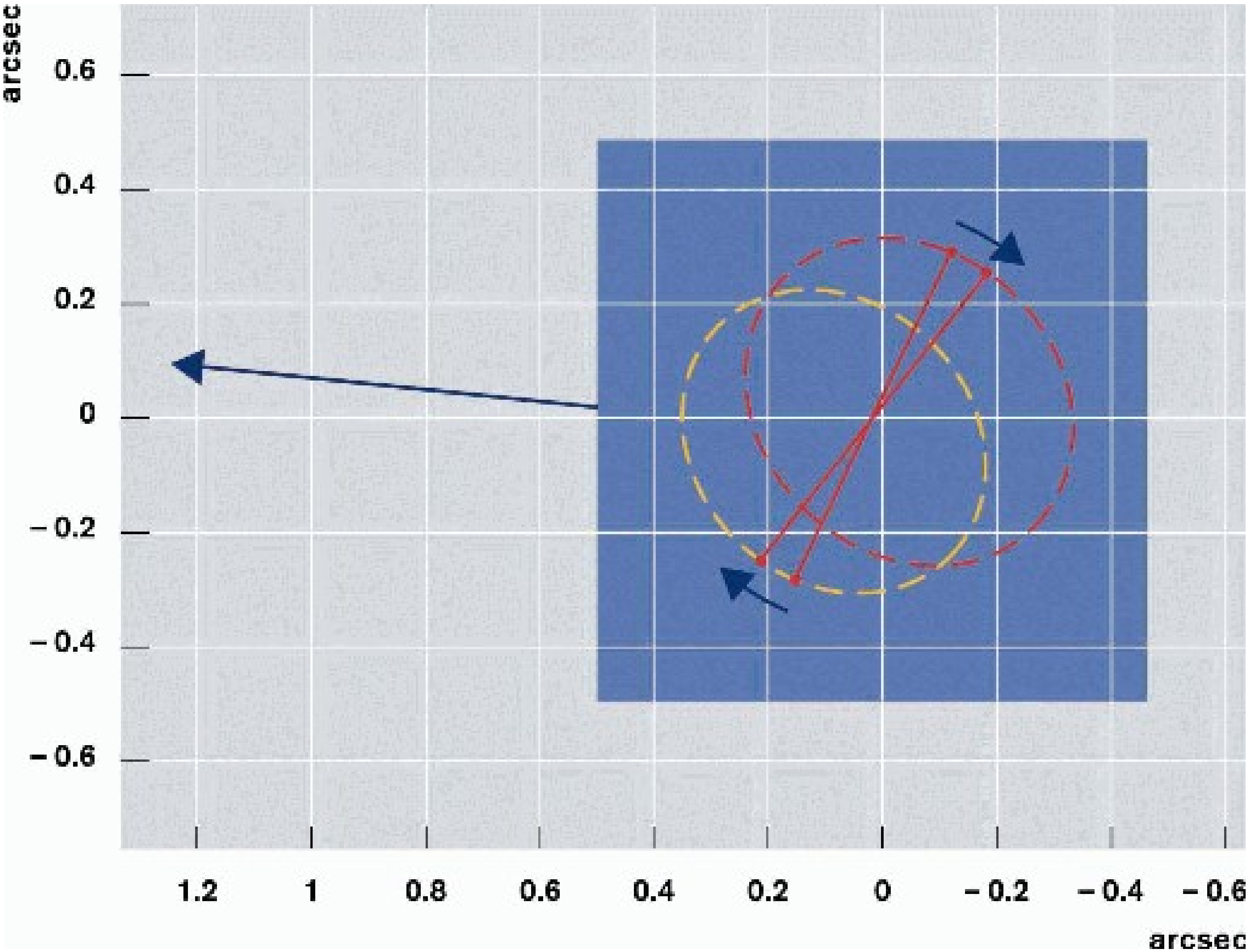
- Tycho Experiment:
  - Number of stars: >400 000
  - Limiting magnitude: B = 10 - 11 mag
  - Positional accuracy: 0.03 arcsec (B=10 mag)
  - Photometric accuracy: 0.05 mag in B and V (per observation)

- The final Hipparcos Catalogue (120 000 stars with 1 milliarcsec level astrometry) .

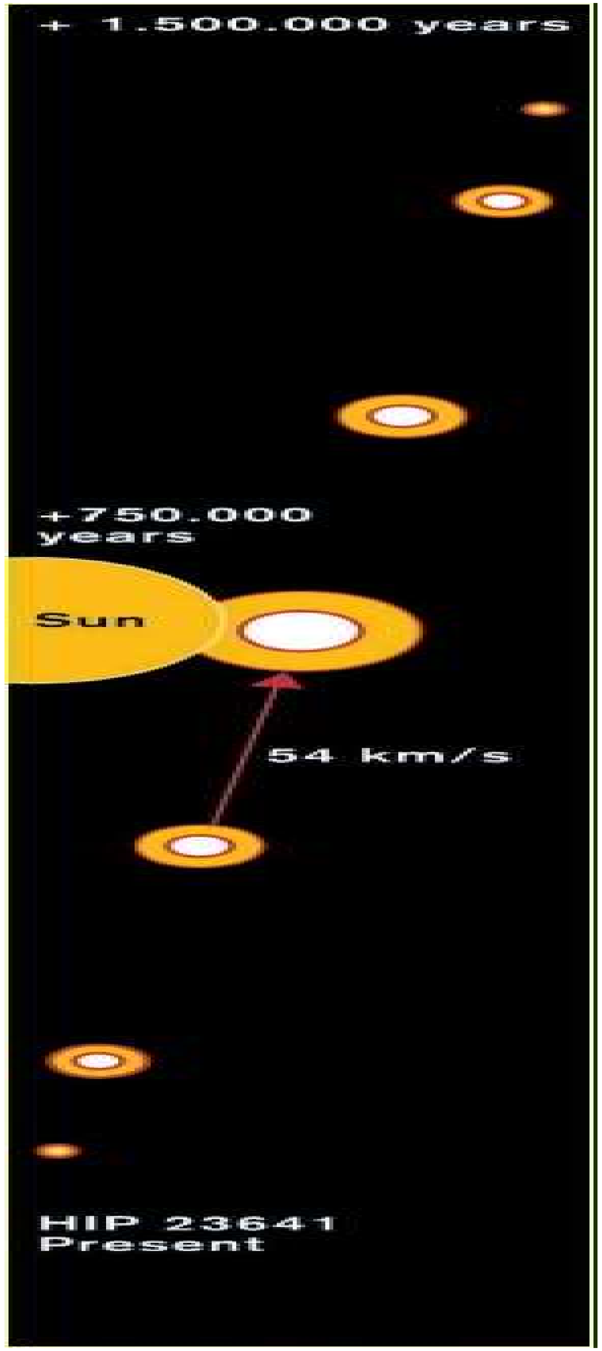
- The final Tycho Catalogue (more than one million stars with 20-30 milliarcsec astrometry and two-colour photometry) .

Double star HIP 46706





arcsec
0.6
0.4
0.2
0
– 0.2
– 0.4
– 0.6
1.2
1
0.8
0.6
0.4
0.2
0
– 0.2
– 0.4
– 0.6
arcsec



HIP 23641 = HD33487

- D=136 Ly
- V=9.26
  - too faint for the unaided eye to see

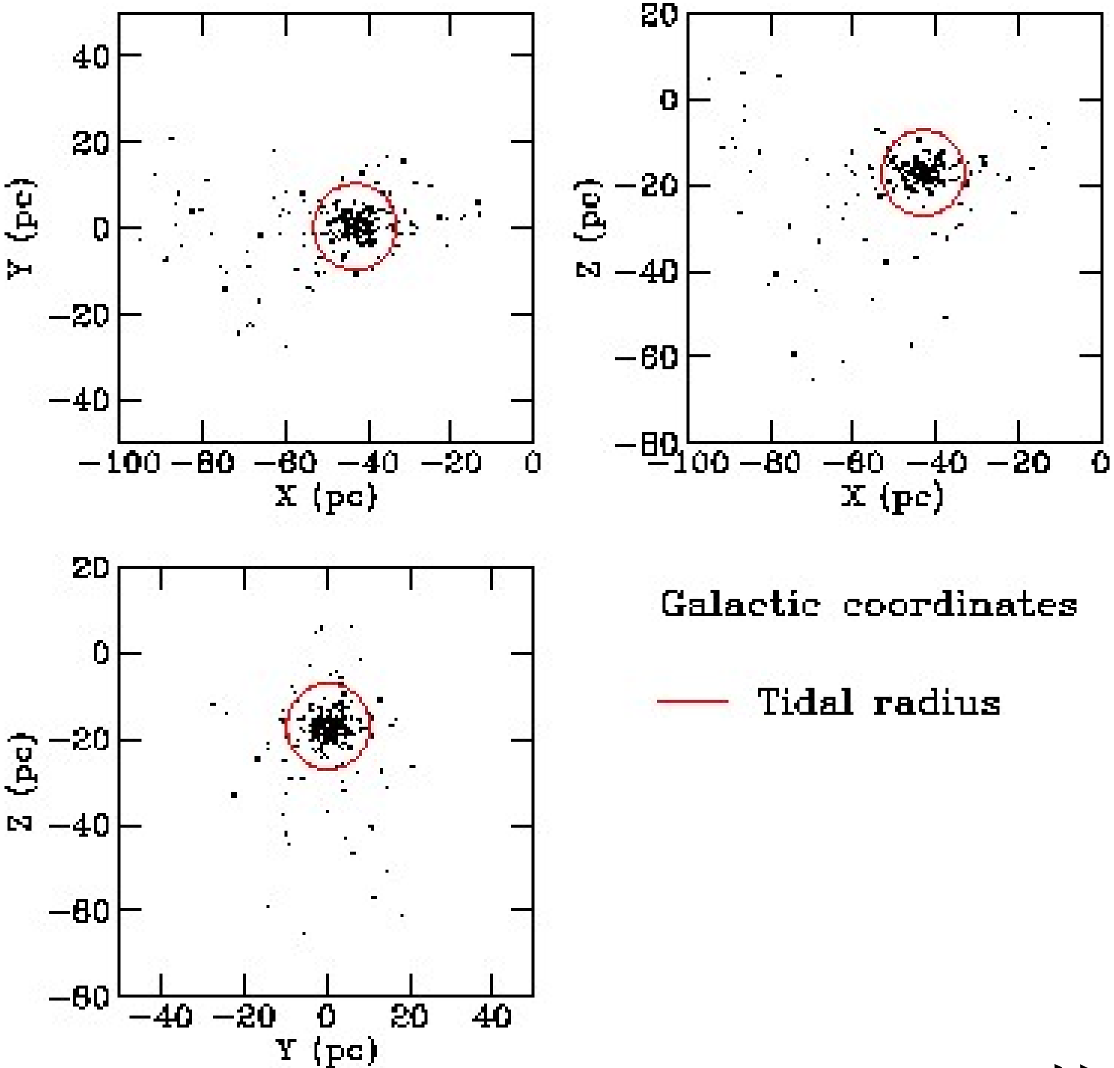
- V=54km/s

- 750,000 years' time it will pass at 4 or 5 Ly, which is similar to the distance of the present nearest star system, Alpha Centauri.

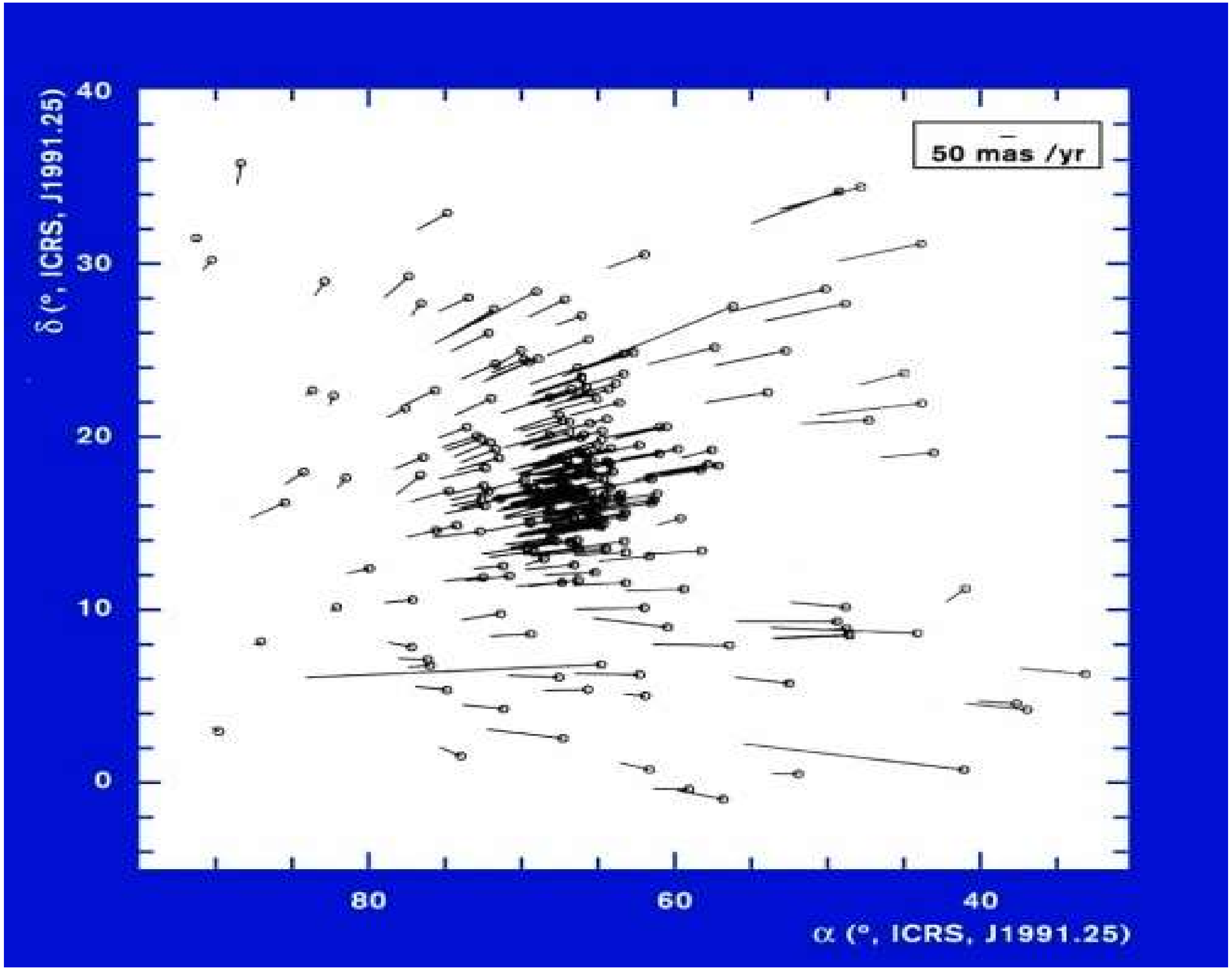
  - will then rank among the 40 brightest stars.

Pleiades (or the Seven Sisters) 昴星团

- D=125pc
  - about 10 per cent closer than previously thought



Hyades： 毕星团



Hyades： 毕星团

Gaia

A Stereoscopic Census of our Galaxy

http://www.cosmos.esa.int/web/gaia

August 2014

Gaia: Design Considerations

- Astrometry (G < 20 mag):
  - completeness to 20 mag (on-board detection) $\Rightarrow 10^9$ stars
  - accuracy: 26 μarcsec at G=15 mag (Hipparcos: 1 milliarcsec at 9 mag)
  - scanning satellite, two viewing directions
    $\Rightarrow$ global accuracy, with optimal use of observing time
  - principle: global astrometric reduction (as for Hipparcos)

- Photometry (G < 20 mag):
  - astrophysical diagnostics (low-dispersion photometry) + chromaticity
    $\Rightarrow \Delta T_{eff}$ ~ 100 K, log g, [Fe/H] to 0.2 dex, extinction (at G=15 mag)

- Radial velocity (G_{RVS} < 16 mag):
  - accuracy: 15 km s^{-1} at G_{RVS}=16 mag
  - application:
    - third component of space motion, perspective acceleration
    - dynamics, population studies, binaries
    - spectra for G_{RVS} < 12 mag: chemistry, rotation
  - principle: slitless spectroscopy in Ca triplet (845-872 nm) at R = ~10,800SV1

SV1 GAIA-CO-TN-LEI-AB-052
Sandra Vogt, 2014/8/29

Gaia: Complete, Faint, Accurate

	Hipparcos	Gaia
Magnitude limit	12 mag	20 mag
Completeness	7.3 – 9.0 mag	20 mag
Bright limit	0 mag	3 mag (assessment for brighter stars ongoing)
Number of objects	120,000	47 million to G = 15 mag 360 million to G = 18 mag 1192 million to G = 20 mag
Effective distance limit	1 kpc	50 kpc
Quasars	1 (3C 273)	500,000
Galaxies	None	1,000,000
Accuracy	1 milliarcsec	7 μarcsec at G = 10 mag 26 μarcsec at G = 15 mag 600 μarcsec at G = 20 mag
Photometry	2-colour (B and V)	Low-res. spectra to G = 20 mag
Radial velocity	None	15 km s^{-1} to G_{RVS} = 16 mag
Observing	Pre-selected	Complete and unbiased

Stellar Astrophysics

- Comprehensive luminosity calibration, for example:
  - distances to 1% for ~11 million stars to 2.5 kpc
  - distances to 10% for ~150 million stars to 25 kpc
  - rare stellar types and rapid evolutionary phases in large numbers
  - parallax calibration of all distance indicators
    e.g., Cepheids and RR Lyrae to LMC/SMC
- Physical properties, for example:
  - clean Hertzsprung–Russell diagrams throughout the Galaxy
  - Solar-neighbourhood mass and luminosity function
    e.g., white dwarfs (~400,000) and brown dwarfs (~500)
  - initial mass and luminosity functions in star-forming regions
  - luminosity function for pre-main-sequence stars
  - detection and dating of all spectral types and Galactic populations
  - detection and characterisation of variability for all spectral types

One Billion Stars in 3D will provide …

- in our Galaxy …
  - the distance and velocity distributions of all stellar populations
  - the spatial and dynamic structure of the disk and halo
  - its formation history
  - a detailed mapping of the Galactic dark-matter distribution
  - a rigorous framework for stellar-structure and evolution theories
  - a large-scale survey of extra-solar planets (~7,000)
  - a large-scale survey of Solar-system bodies (~250,000)

- … and beyond
  - definitive distance standards out to the LMC/SMC
  - rapid reaction alerts for supernovae and burst sources (~6,000)
  - quasar detection, redshifts, microlensing structure (~500,000)
  - fundamental quantities to unprecedented accuracy: γ to 2×10^{-6} (2×10^{-5} present)

Exo-Planets: Expected Discoveries

- Astrometric survey:
  - monitoring of ~150,000 FGK stars to ~200 pc
  - detection limits: ~1M_J and P < 10 years
  - complete census of all stellar types, P ~ 2-9 years
  - masses, rather than lower limits (m sin i)
  - multiple systems measurable, giving relative inclinations
- Results expected:
  - ~2000 exo-planets (single systems)
  - ~300 multi-planet systems
  - displacement for 47 UMa = 360 μas
  - orbits for ~1000 systems
  - masses down to 10 M_{Earth} to 10 pc
- Photometric transits: ~5000

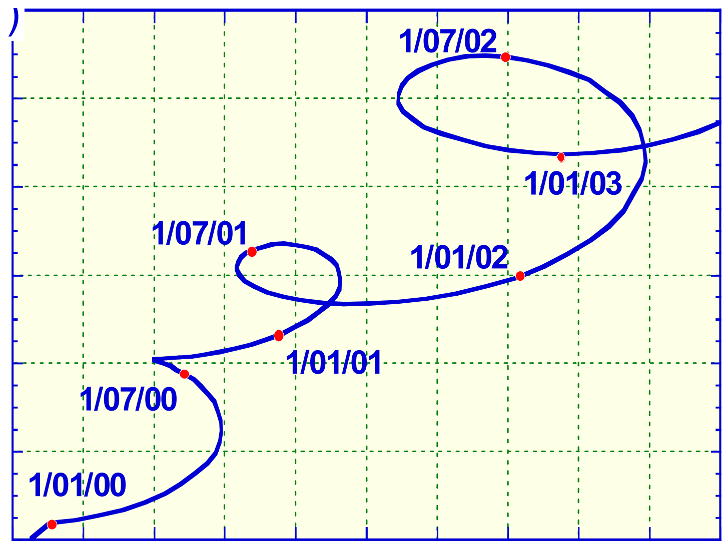
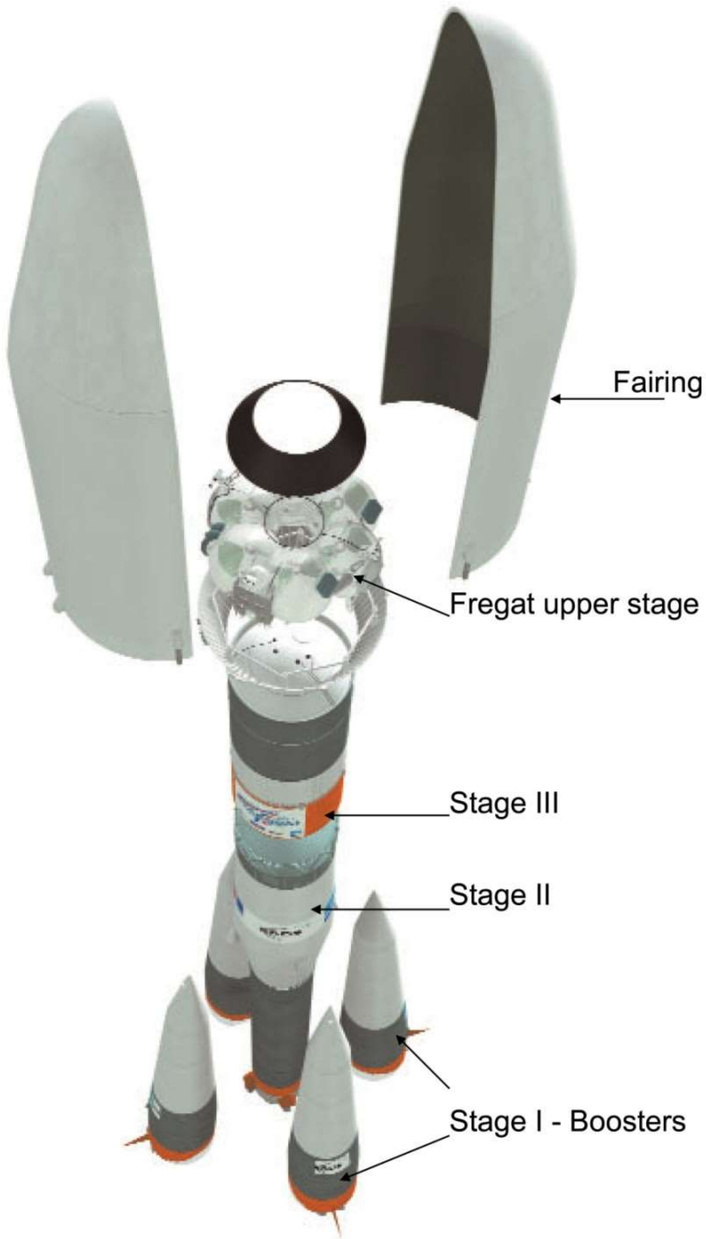


Figure courtesy François Mignard

Studies of the Solar System

- Asteroids etc.:
  - deep and uniform (G=20 mag) detection of all moving objects
  - ~250,000 objects observed, mainly main-belt asteroids
  - orbits: 30 times better than present, even after 100 years
  - spin-axis direction, rotation period, shape parameters for majority
  - taxonomy/mineralogical composition versus heliocentric distance
  - diameters for ~1000 to 20%, masses for ~150 to 10%
  - Trojan companions of Mars, Earth, and Venus
  - Kuiper-Belt objects: ~50 objects to G=20 mag (binarity, Plutinos)
  - Centaurs: ~50 objects

- Near-Earth Objects:
  - Amors, Apollos and Atens (4389, 5156, 811 known today)
  - ~1600 Potentially Hazardous Asteroids (PHA) >1 km predicted (1435 currently known)
  - detection limit: 260-590 m at 1 AU, depending on albedo



Satellite and System

- ESA-only mission
- Launch: 19 December 2013
- Launcher: Soyuz–Fregat from French Guiana
- Orbit: L2 Lissajous orbit
- Ground stations: Cebreros, New Norcia + Malargüe
- Lifetime: 5 years (1 year potential extension)
- Downlink rate: 4 - 8 Mbps

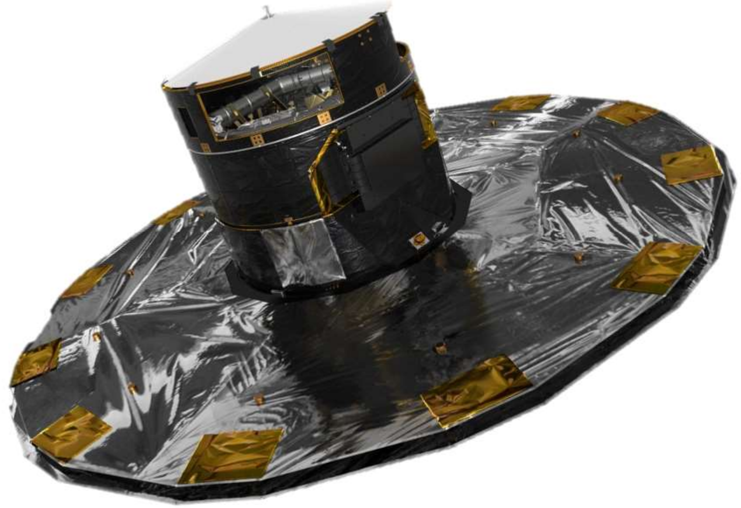


Figure Soyuz: Arianespace; figure Gaia: ESA - C. Carreau

Payload and Telescope

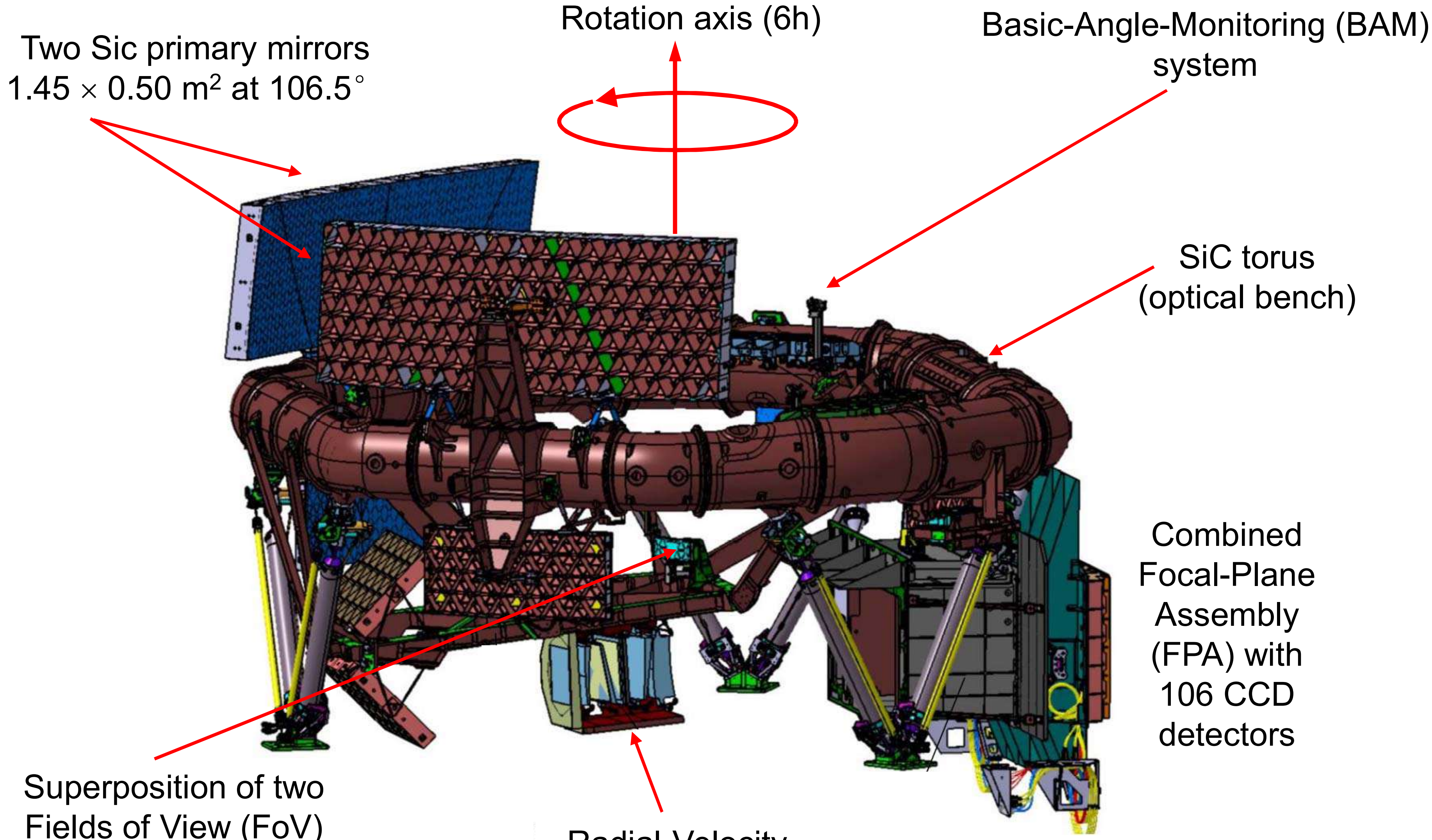
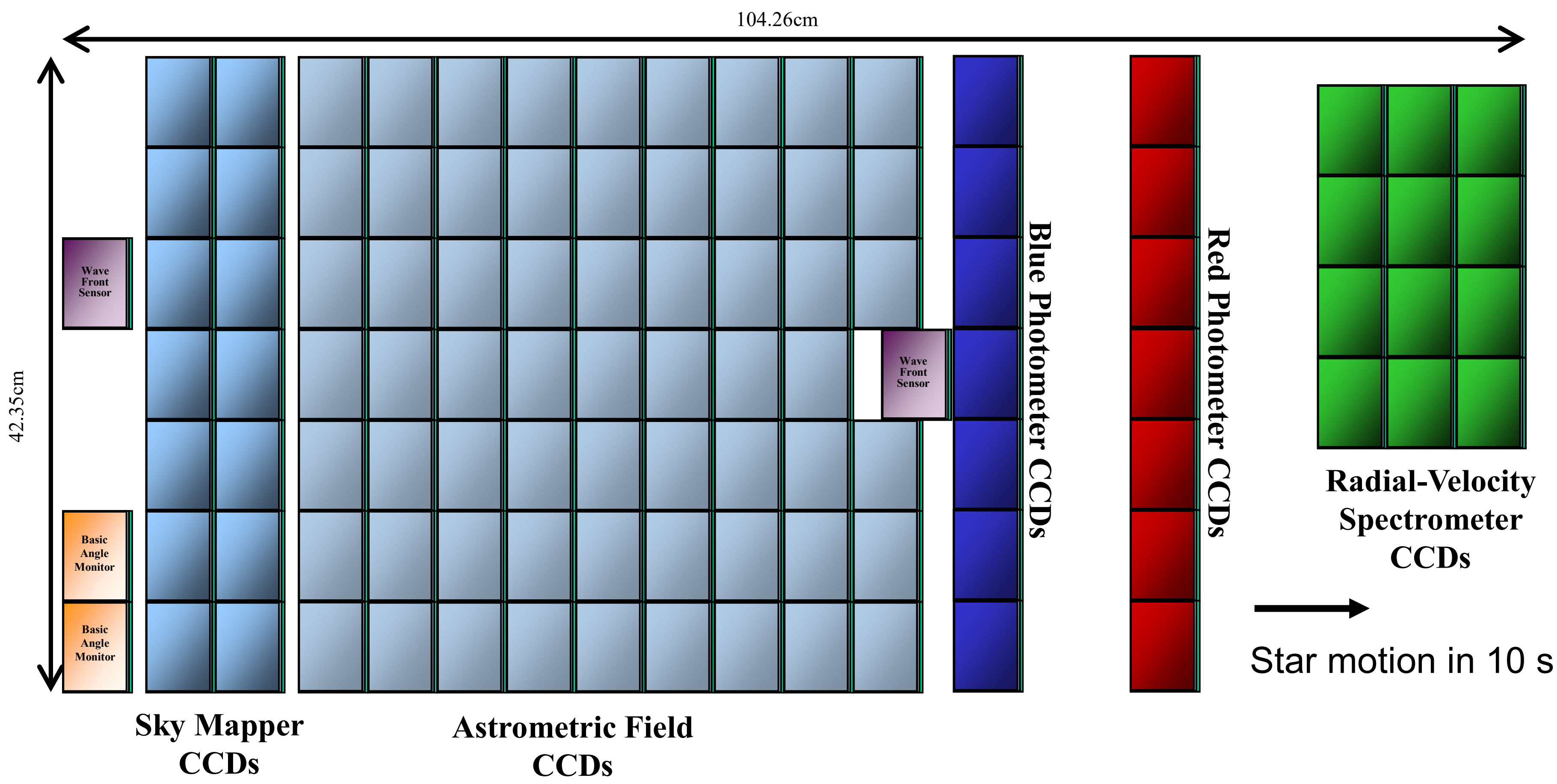


Figure courtesy EADS-Astrium

Figure courtesy Alex Short

Focal Plane



Total field:

- active area: 0.75 deg^2
- CCDs: 14 + 62 + 14 + 12 (+ 4)
- 4500 x 1966 pixels (TDI)
- pixel size = 10 µm x 30 µm
  = 59 mas x 177 mas

Sky mapper:

- detects all objects to G=20 mag
- rejects cosmic-ray events
- field-of-view discrimination

Astrometry:

- total detection noise ~ 4 e^-

Photometry:

- spectro-photometer
- blue and red CCDs

Spectroscopy:

- high-resolution spectra
- red CCDs

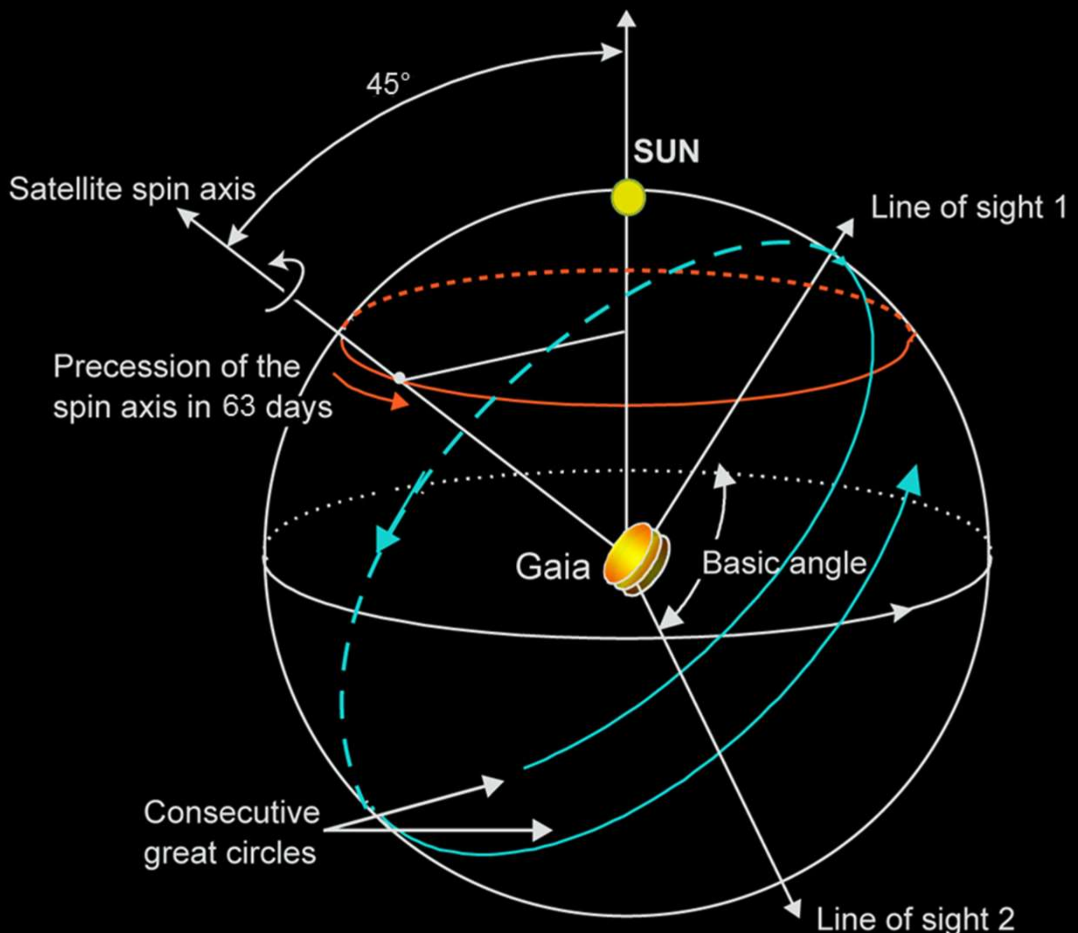
On-Board Object Detection

- Requirements:
  - unbiased sky sampling (magnitude, colour, resolution)
  - all-sky catalogue at Gaia resolution (0.1 arcsec) to G~20 mag does not exist

- Solution is on-board detection:
  - no input catalogue or observing programme
  - good detection efficiency to G~21 mag
  - low false-detection rate, even at high star densities

- Gaia will therefore detect:
  - variable stars (eclipsing binaries, Cepheids, etc.)
  - supernovae: ~6,000
  - gravitational-lensing events: ~1000 photometric and ~100 astrometric
  - Solar-system objects, including near-Earth asteroids and Kuiper-Belt objects

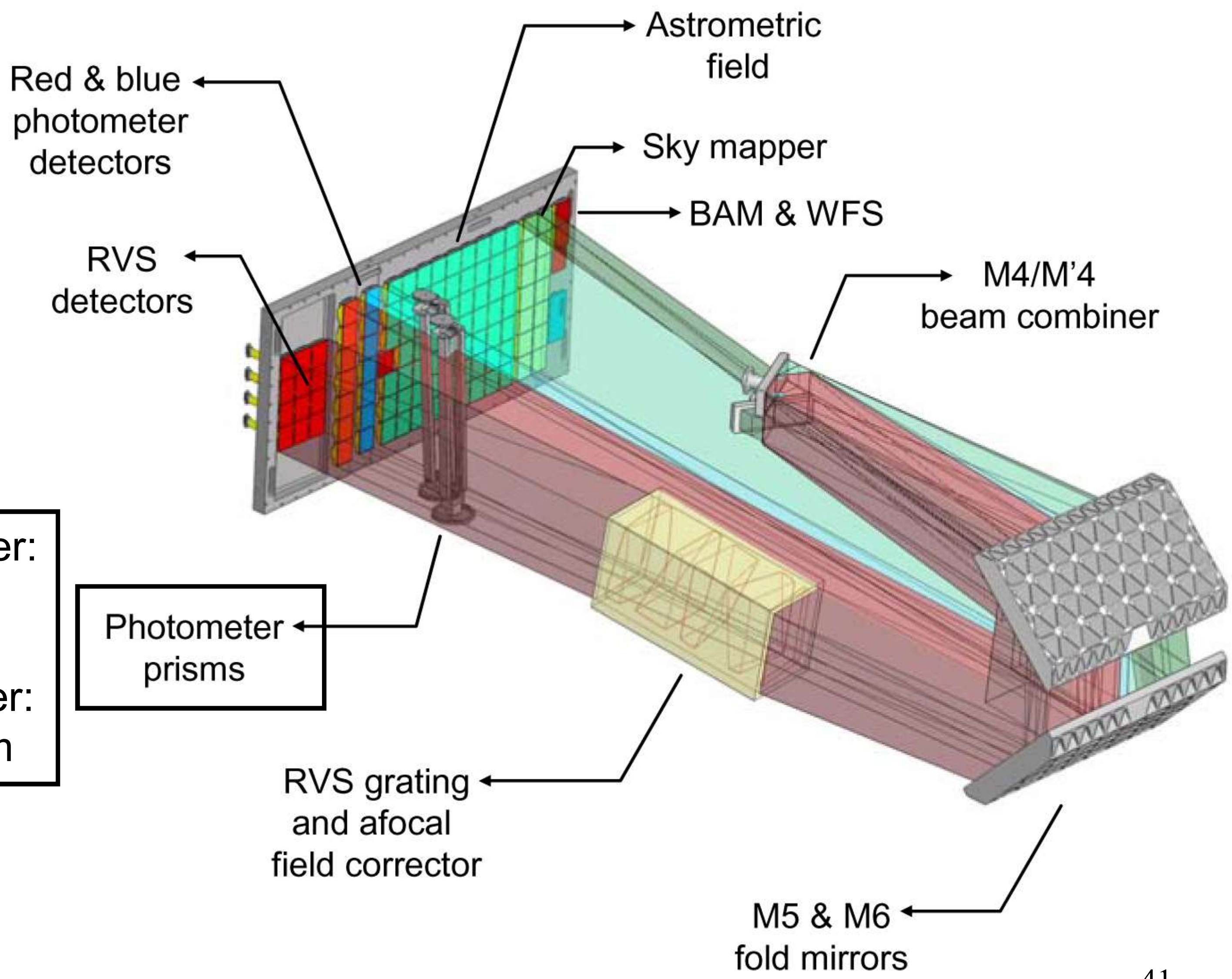
Sky-Scanning Principle



Spin axis	45^{o} to Sun
Scan rate:	60 arcsec s^{-1}
Spin period:	6 hours

Figure ESA

Photometry Measurement Concept (1/2)

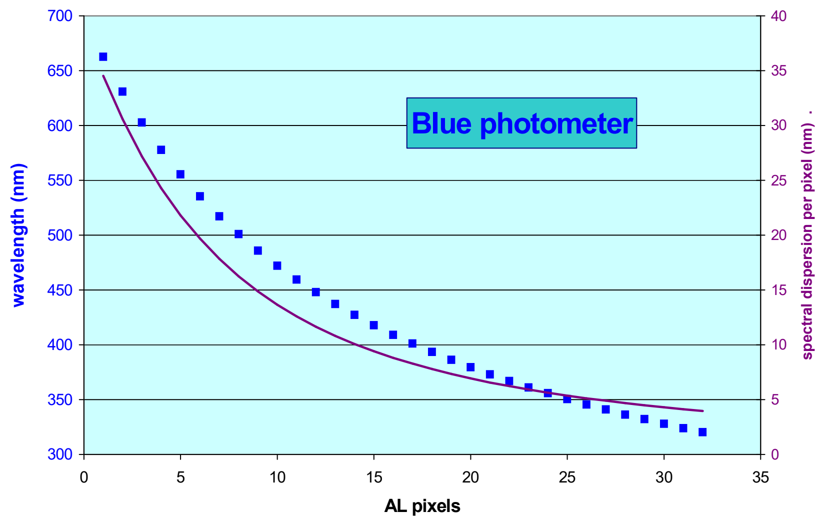


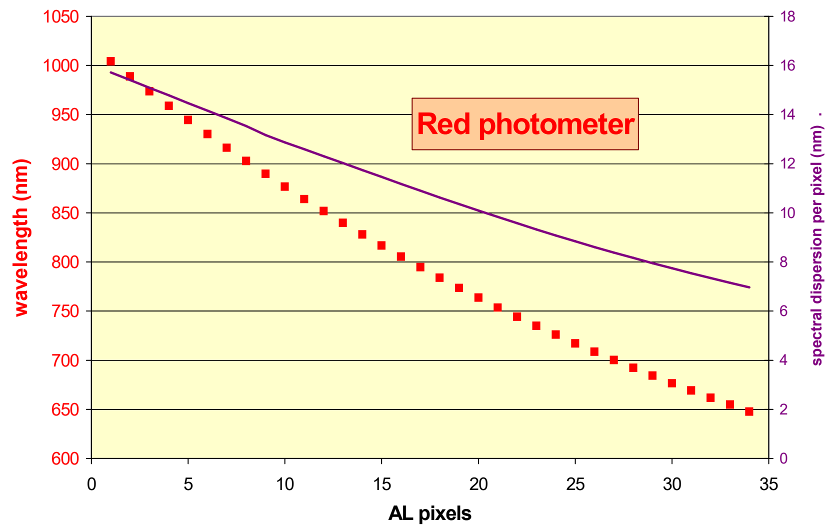
Blue photometer:
330 - 680 nm

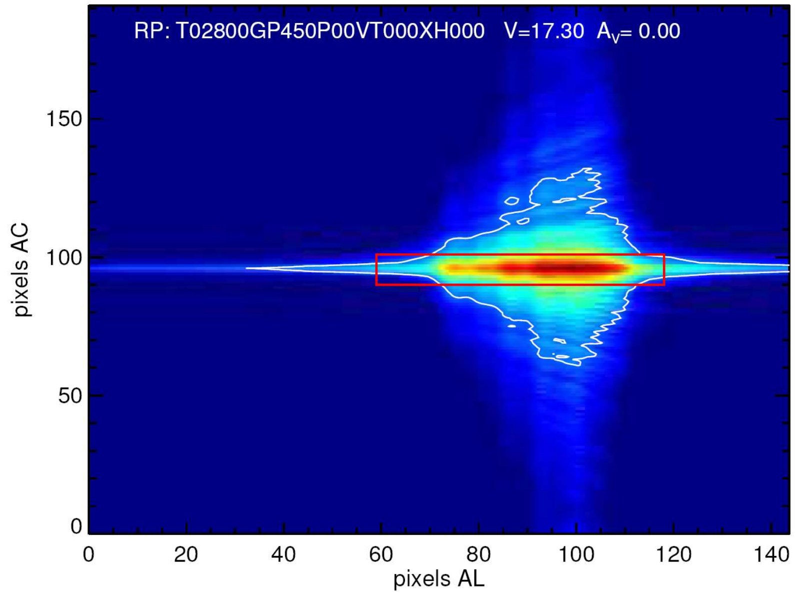
Red photometer:
640 - 1050 nm

Figure courtesy EADS-Astrium

Photometry Measurement Concept (2/2)



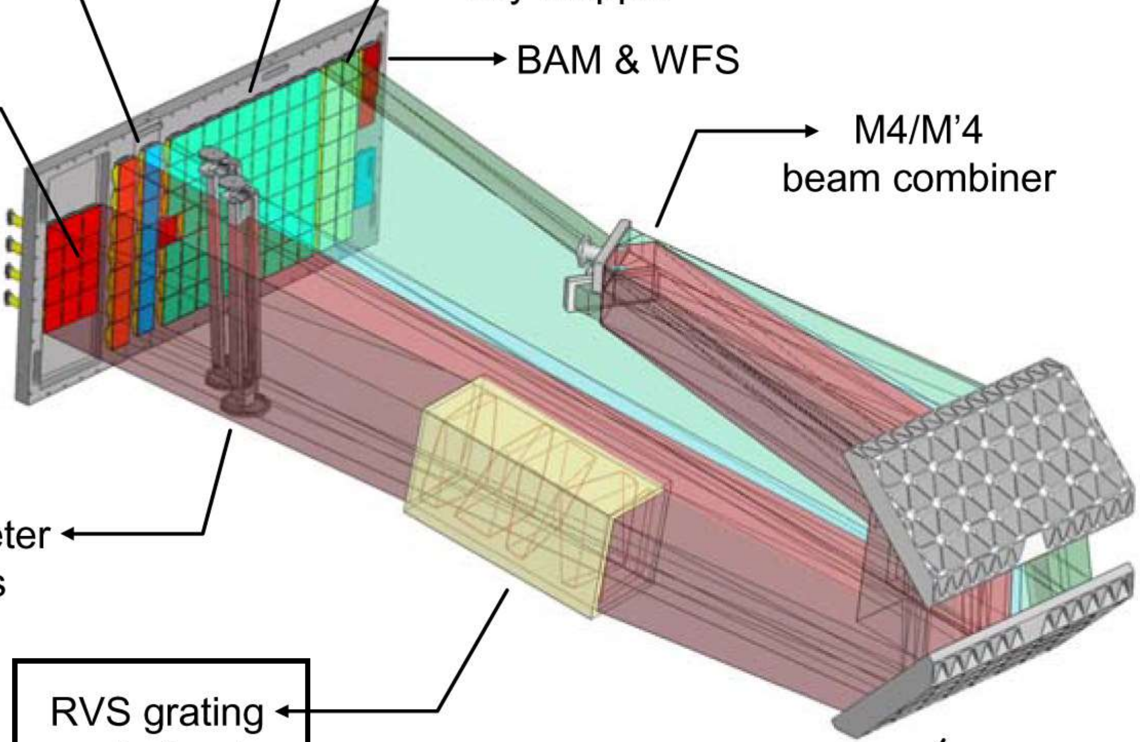




RP spectrum of M dwarf (V = 17.3 mag)
Red box: data sent to ground
White contour: sky-background level
Colour coding: signal intensity

Figures courtesy Anthony Brown

Radial-Velocity Measurement Concept (1/2)

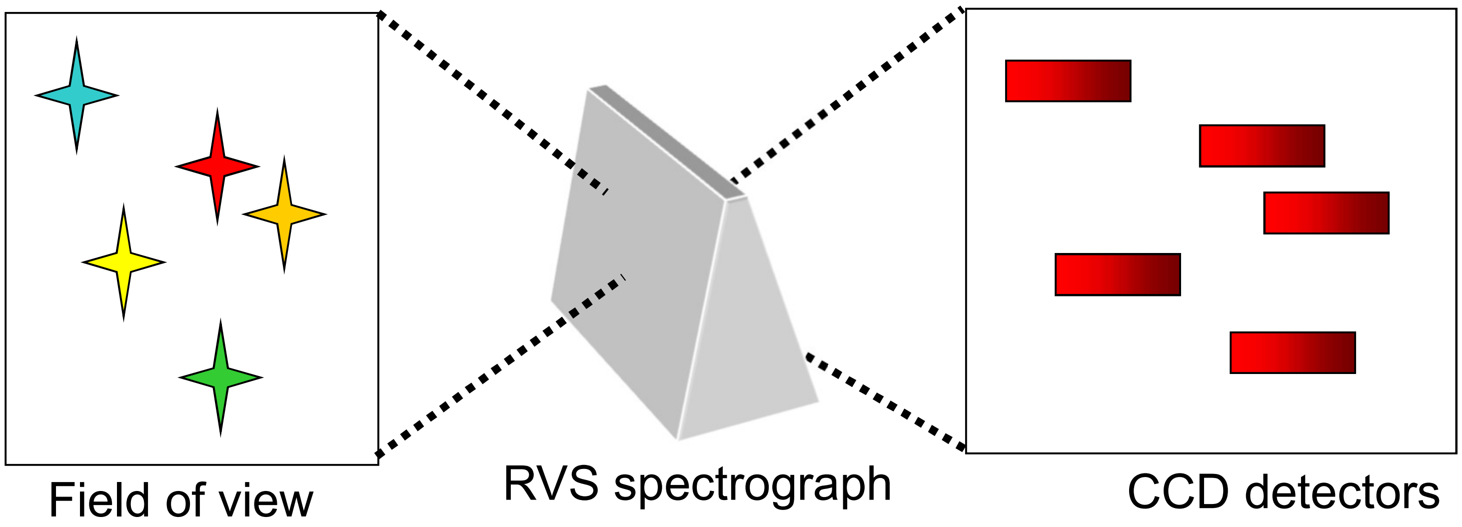


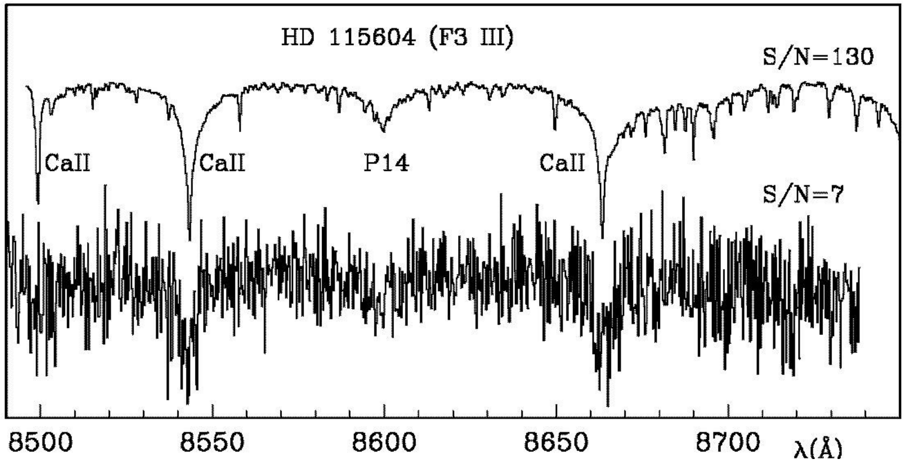
Spectroscopy:
845 - 872 nm
(resolution
~10,800)

Figure courtesy EADS-Astrium

SV2 GAIA-CO-TN-LEI-AB-052
Sandra Vogt, 2014/8/29

Radial-Velocity Measurement Concept (2/2)

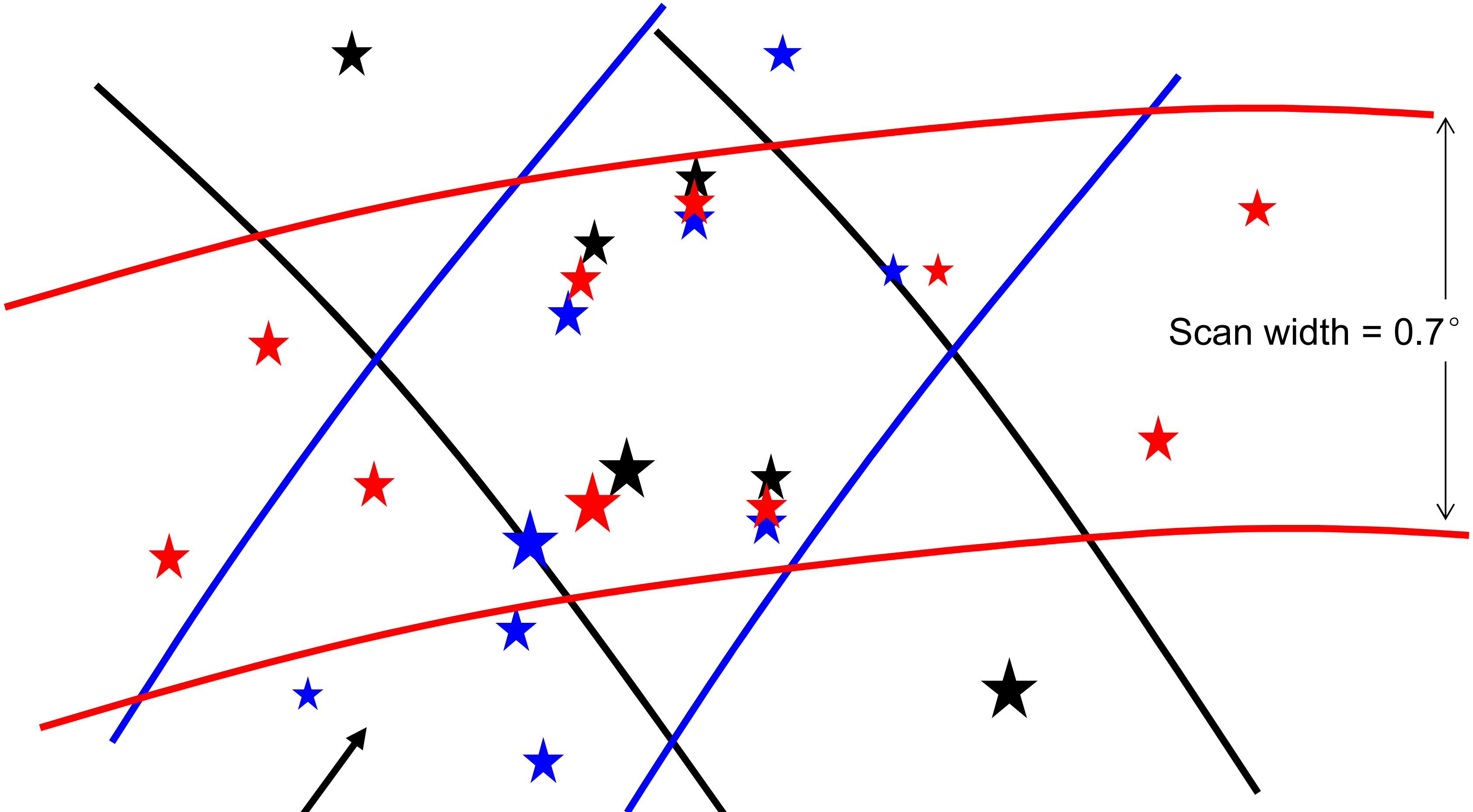




RVS spectra of F3 giant (V = 16 mag)
S/N = 7 (single measurement)
S/N = 130 (summed over mission)

Figures courtesy David Katz

Data-Reduction Principles



Sky scans
(highest accuracy
along scan)

1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc. are solved
4. Higher-order terms are solved
5. More scans are added
6. System is iterated

Figure courtesy Michael Perryman

Scientific Organisation

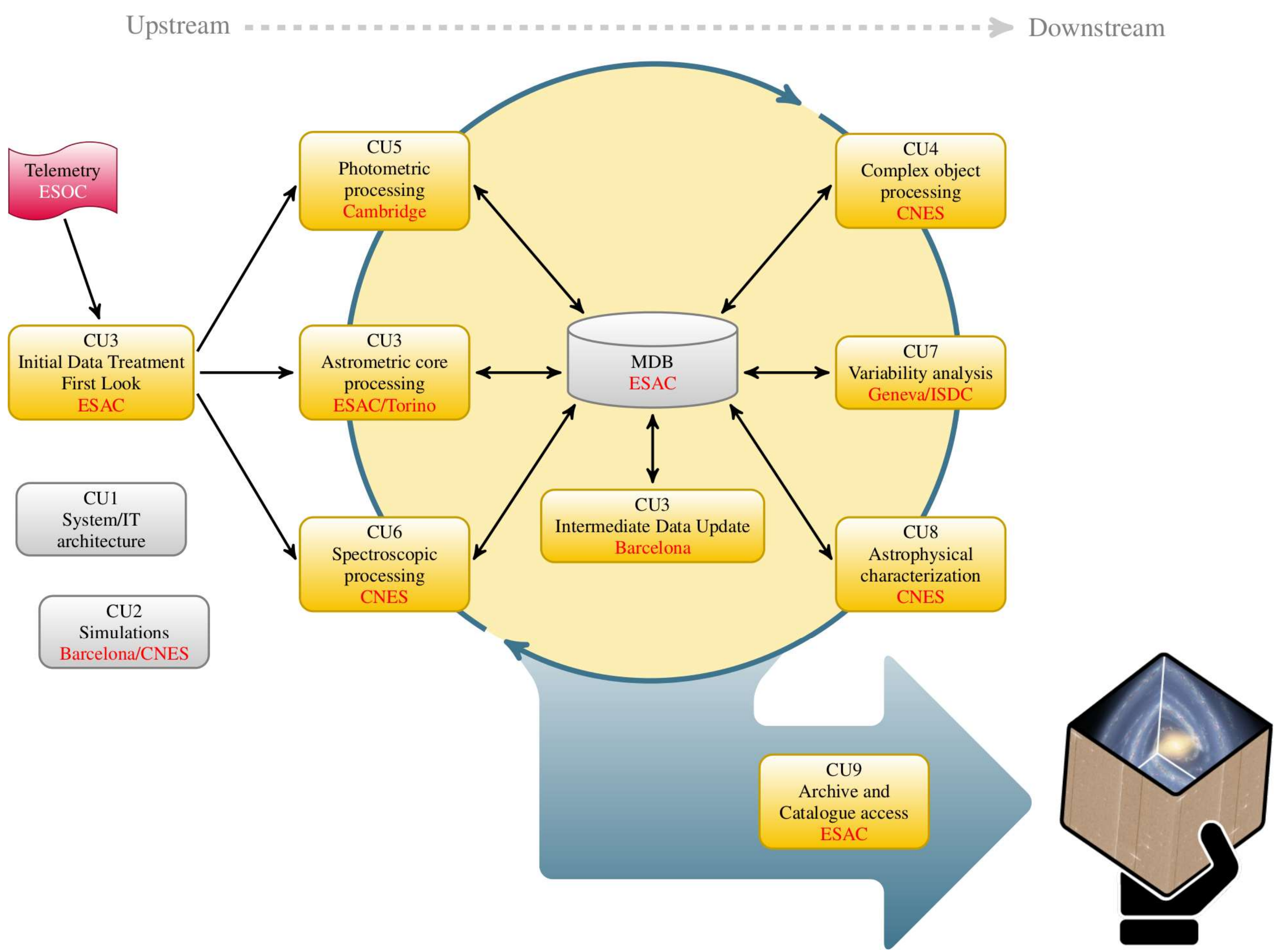
- Gaia Science Team (GST):
  7 members + ESA Project Scientist + DPAC Executive Chair

- Scientific community:
  - organised in Data Processing and Analysis Consortium (DPAC)
  - 450+ scientists in 20+ countries active at some level
  - GREAT network for post-mission science exploitation

- Community is active and productive:
  - regular Science Team / DPAC meetings
  - growing archive of scientific and processing-software reports
  - advance of algorithms, calibration models, accuracy models, etc.

- Data-distribution policy:
  - final catalogue ~2022
  - intermediate catalogues defined
    - intermediate releases starting 2016 with positions; parallaxes and proper motions will be added in 2017
  - science-alerts data released immediately
  - no proprietary data rights

Data Processing Concept



Schedule

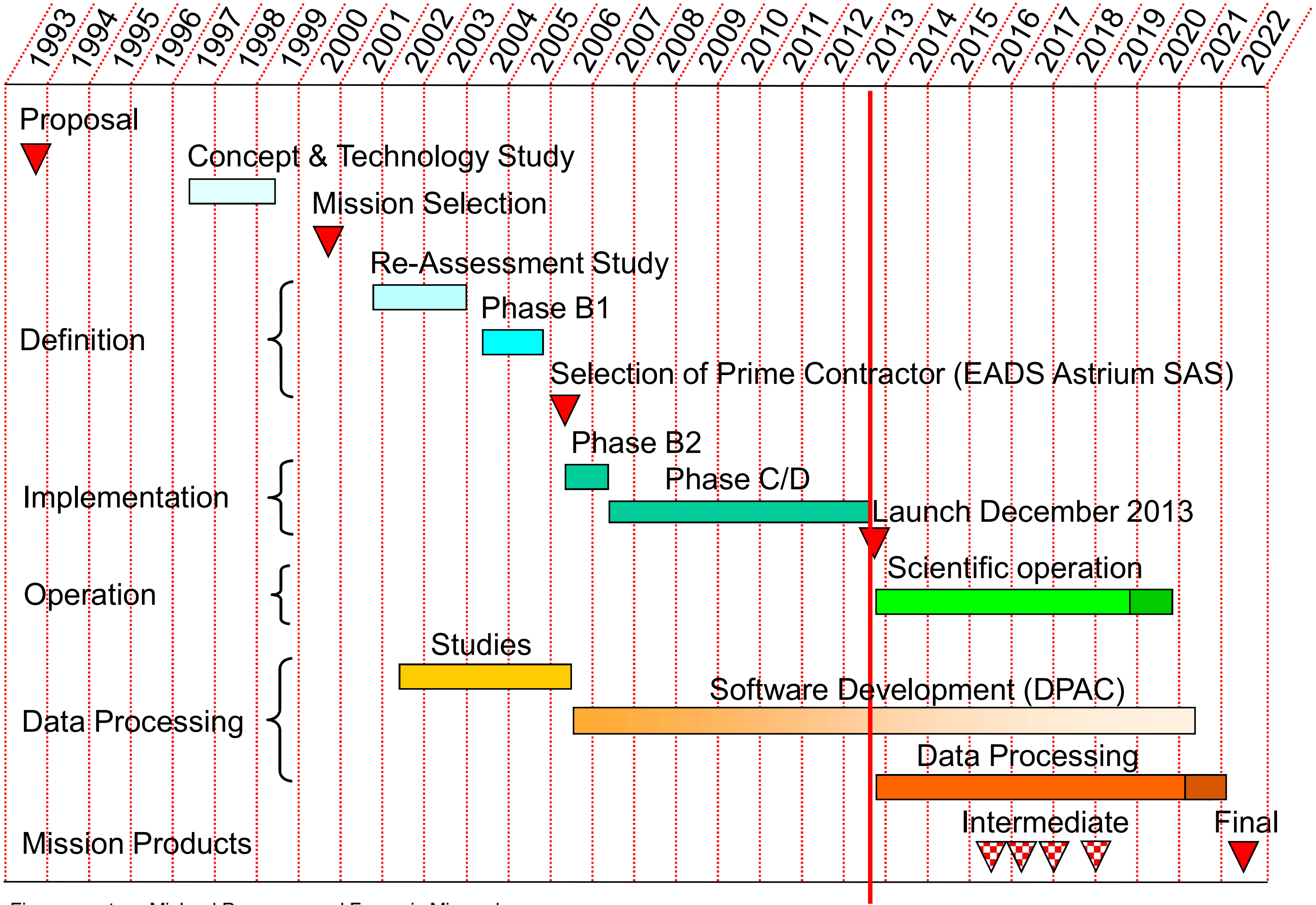
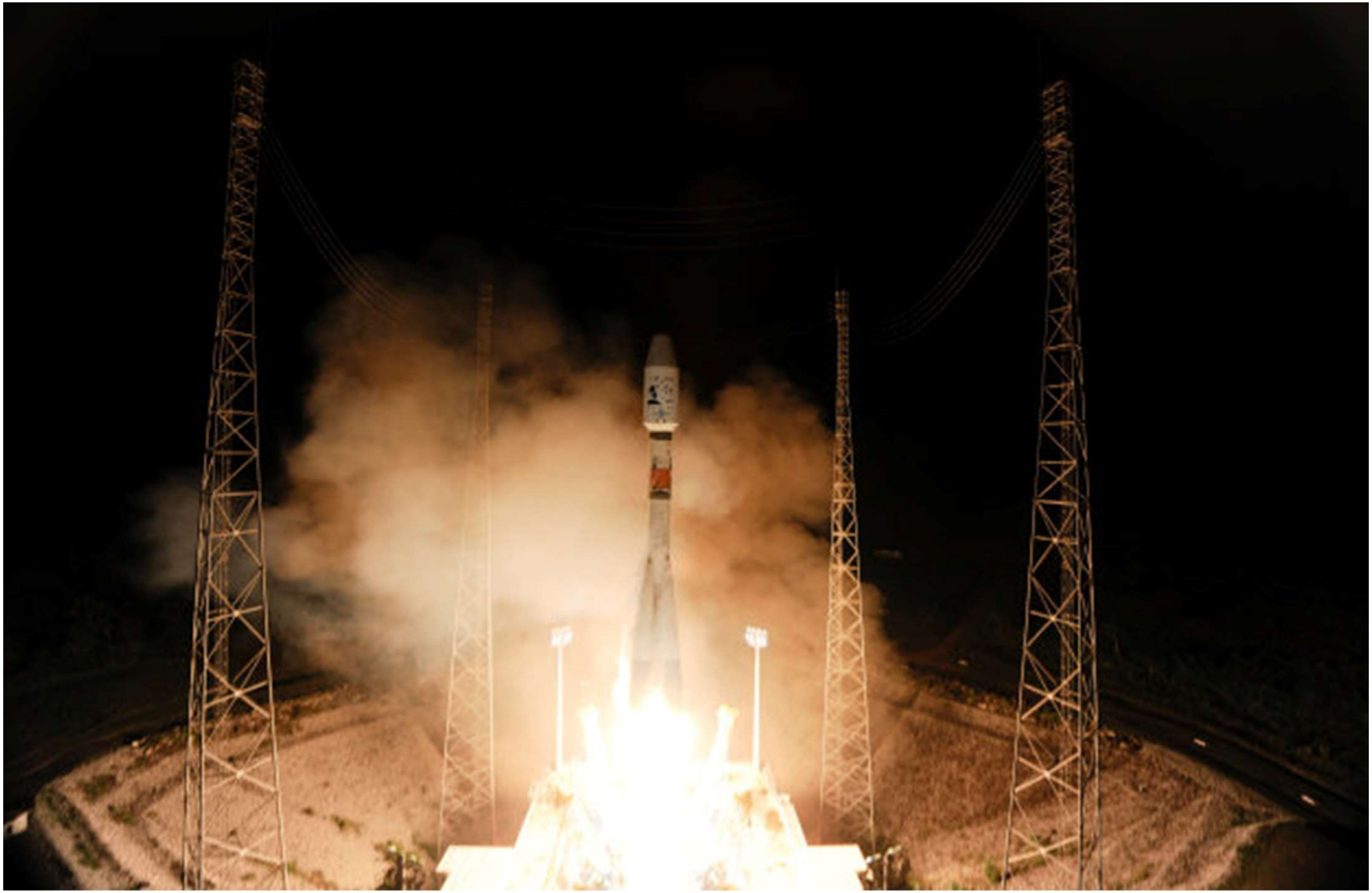


Figure courtesy Michael Perryman and François Mignard

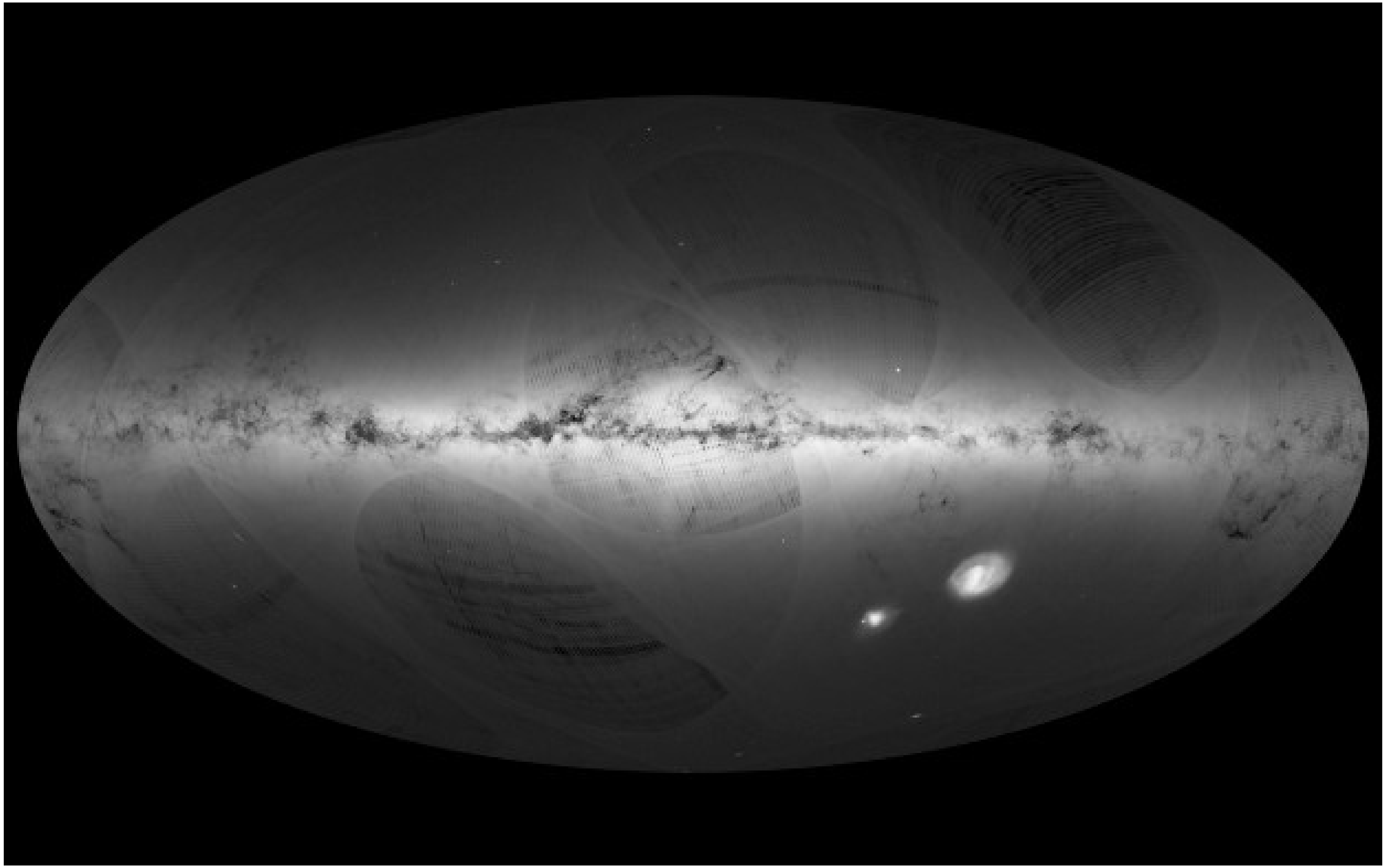


Date: 19 December 2013

Location: Kourou, French Guiana

GAIA data release 1

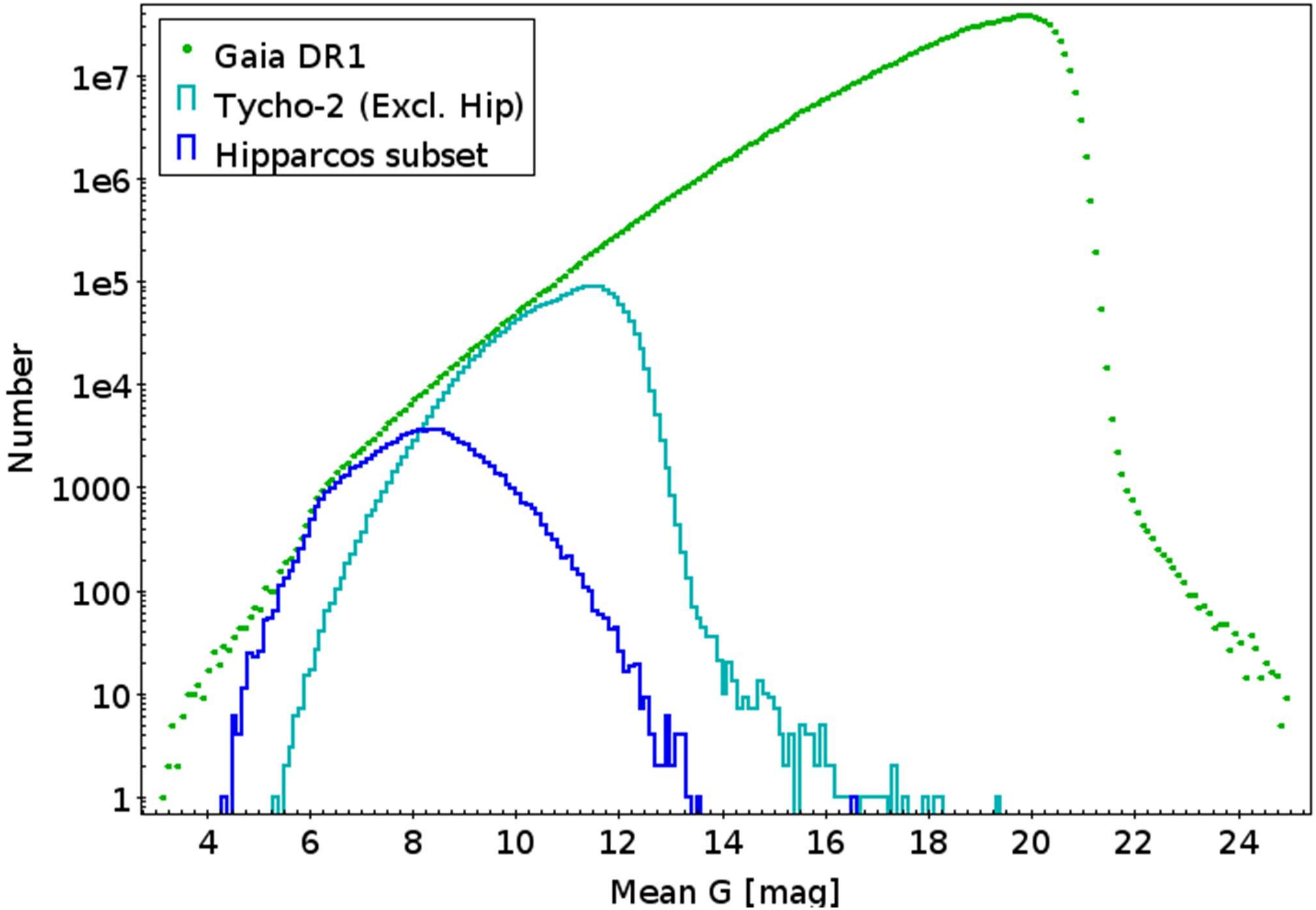
14 September 2016



GAIA DR 1

- **Contents**
  - Positions and Gaia 'G' magnitudes for 1.1 billion stars using only Gaia data;
  - Positions, parallaxes (distances) and proper motions for more than 2 million stars using the Tycho-Gaia Astrometric Solution (TGAS);
  - Light curves and characteristics for about 3000 variable stars;
  - Positions and G magnitudes for more than 2000 quasars - extragalactic sources used to define the celestial reference frame.

- **Access**
  - All the data are available from the ESA Gaia Archive:
    http://archives.esac.esa.int/gaia

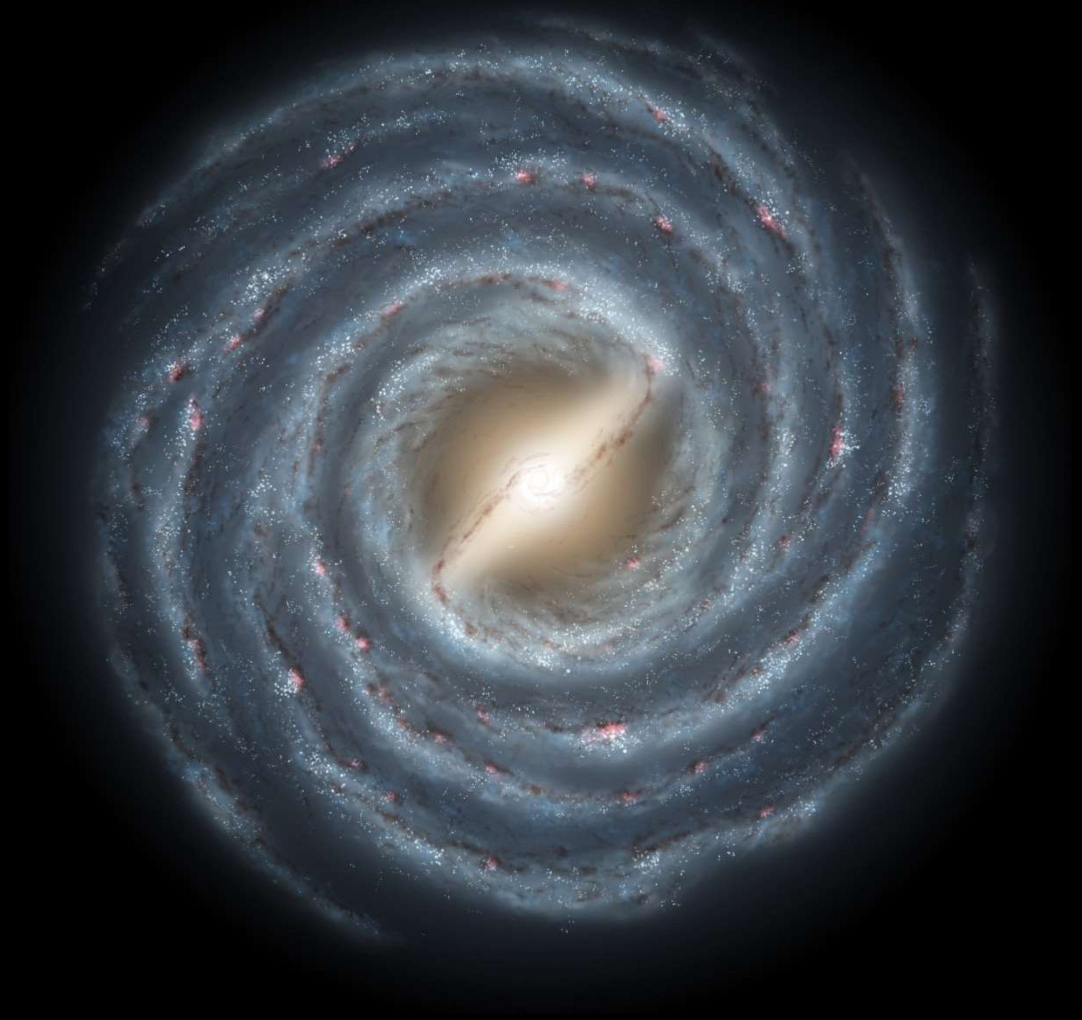

Gaia DR1
Tycho-2 (Excl. Hip)
Hipparcos subset
1e7
1e6
1e5
1e4
1000
100
10
1
Number
4
6
8
10
12
14
16
18
20
22
24
Mean G [mag]

- **The Gaia mission**
  - Gaia Collaboration
  - arXiv: 1609.04153.pdf

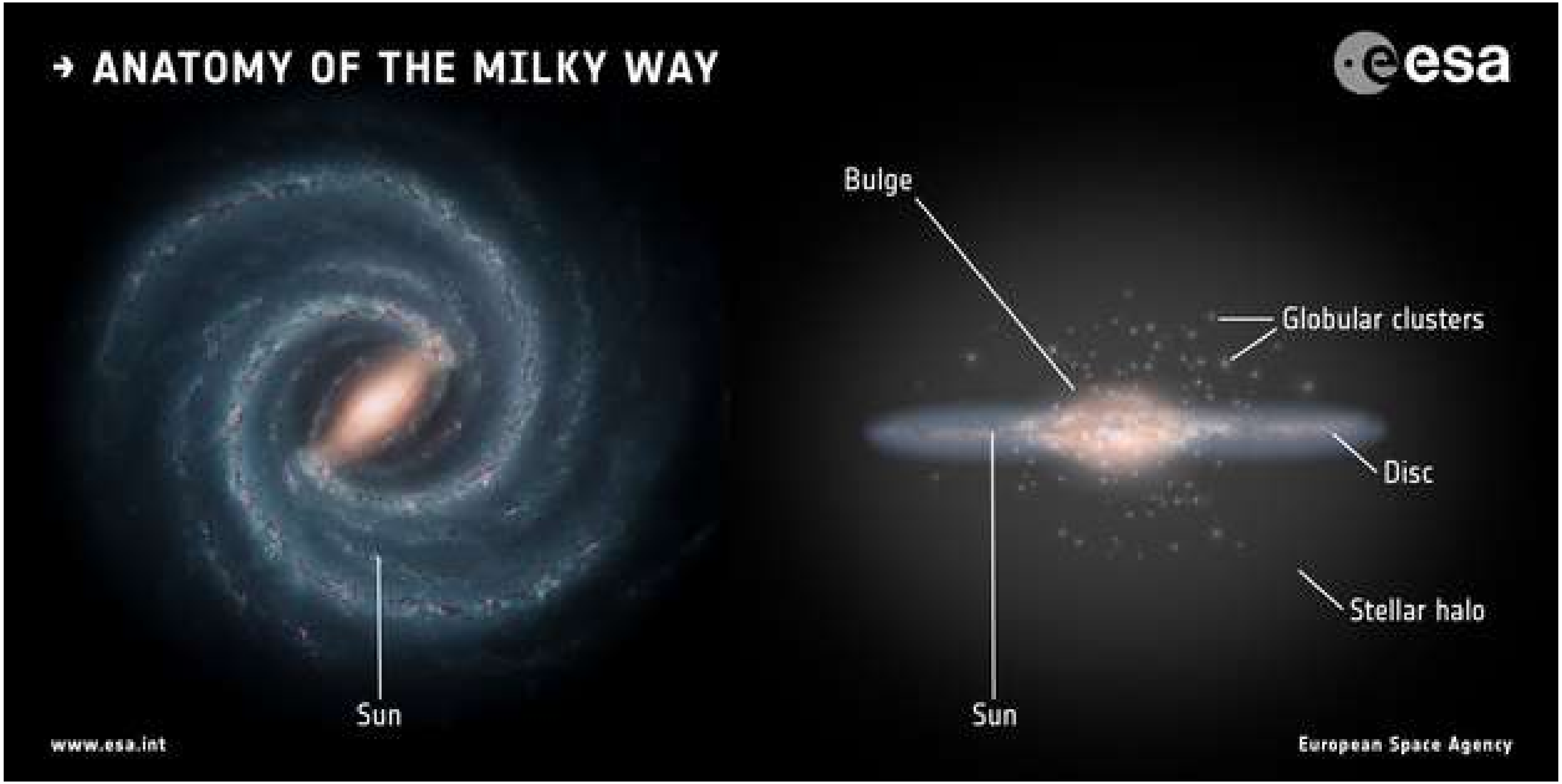
- **Gaia Data Release 1. Summary of the astrometric, photometric, and survey properties**
  - Gaia Collaboration
  - arXiv: 1609.04172.pdf

- **Gaia Data Release 1: Astrometry: one billion positions, two million proper motions and parallaxes**
  - Lindegren et al.
  - arXiv: 1609.04303.pdf

Gaia



Unraveling the chemical and dynamical history of our Galaxy

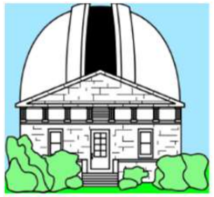


ANATOMY OF THE MILKY WAY
esa
Bulge
Globular clusters
Disc
Stellar halo
Sun
Sun
www.esa.int
European Space Agency

Astrometric surveys in the Gaia era

Norbert Zacharias

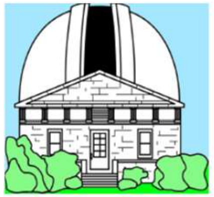
U.S. Naval Observatory



GAIA

DR2 = big step for astrometry

- accurate proper motions and parallaxes for over 1 billion objects (sub-mas level)
- superior astrometry to ground-based surveys, most between about G = 4 to 20.7 “done” for mean position + simple motion
- era of traditional astrometric sky surveys will be over very soon (position and proper motion catalogs like GSC, PPM, PPMXL, NPM, SPM, UCAC, URAT, USNO-B ...)



summary

(1) Gaia DR1: TGAS (2 million stars) = new optical reference frame

(2) short-term ground-based astrometric surveys use Gaia DR1:

  (a) reduce earlier epoch data

  (b) combine with 1.14 billion Gaia positions only → new proper motions

  (c) use several years of ground-based observ.: new trigon. parallaxes

(3) Gaia DR2 will "put an end to this" : positions, proper motions and parallaxes for stars in about 4 to 20.7 mag: all done

(4) current and future ground-based surveys for astrometry:

  (a) very bright star observations (URAT-south).

  (b) go deeper than Gaia limit (LSST, ...)

  (c) many epochs, long-term programs for complex motions

  (d) other than optical bandpass (VISTA), positions depending on color

astrometric research not fully covered by Gaia

(1) very bright stars (G <= 3.x), until near final Gaia DR, likely after 2020

(2) faint objects (G >= 20.7) = main open area

(3) other than optical bandpass (like near-IR)

(4) complex motion or variable centroid objects, i.e. "time domain astronomy" require observations at multiple, specific epochs or long time-line observations:

  (a) orbital motions of natural satellites (USNO + Paris Observatory)

  (b) asteroid mass determination (close encounters)

  (c) many double and multiple star systems, companions, exo-planets

  (d) some AGN, extragalactic reference frame objects (variability induced center motion)

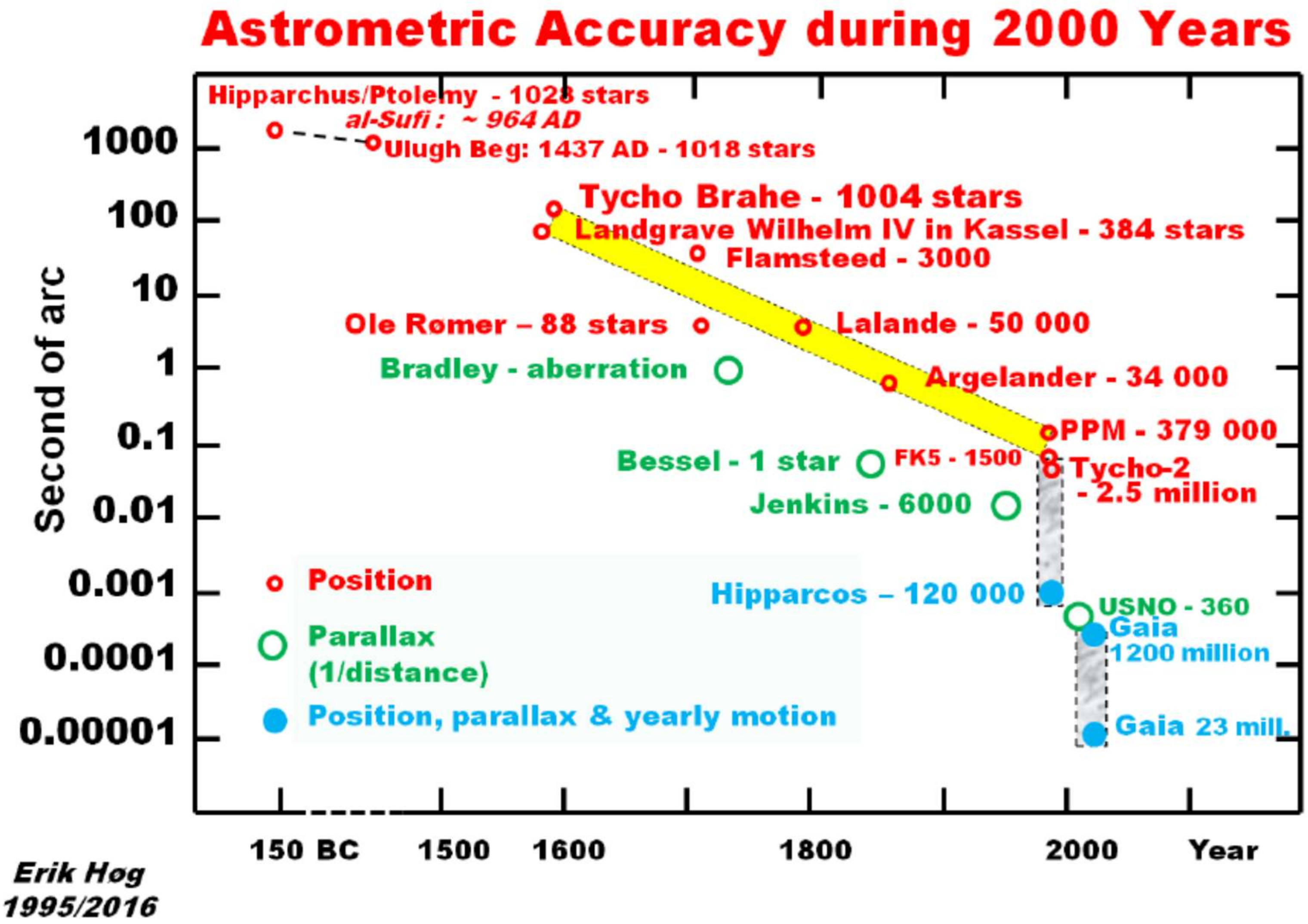


Fig. 1a. Astrometric accuracy during 2000 years: Høg-2016. The accuracy was greatly improved shortly before 1600 AD by the Landgrave in Kassel and by Tycho Brahe in Denmark. The following 400 years brought even larger but much more gradual improvement before space techniques with the Hipparcos satellite started a new era of astrometry.

§3 天体的物质分布、其所处的物理状态和内部运动

- 恒星：除太阳外，不能分辨它们的视面
- 有些天体，如星云、星系等，它们具有一定的可分辨视面，利用不同的方法和手段，我们可以了解其物质分布、不同部分物质的物理状态以及它们的内部运动。

§4 天体的物理参数

- 天体的温度
- 天体的密度
- 天体的化学丰度
- 天体的总质量
- 天体的线尺度
- 天体的辐射机制
- 天体的磁场

光学天文测量：

- 天体光度测量
- 天体分光测量
- 天体偏振测量