Introduction to Space Astrometry
The Gaia Mission

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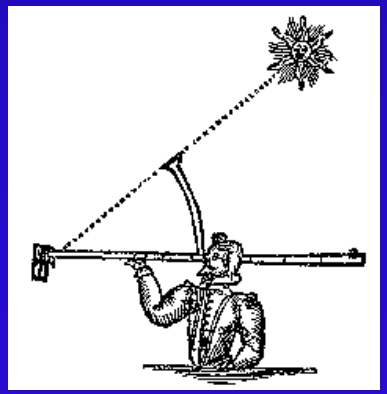
Summary

- Astrometry
- Reference frames & Parallaxes
- Hipparcos
- Gaia

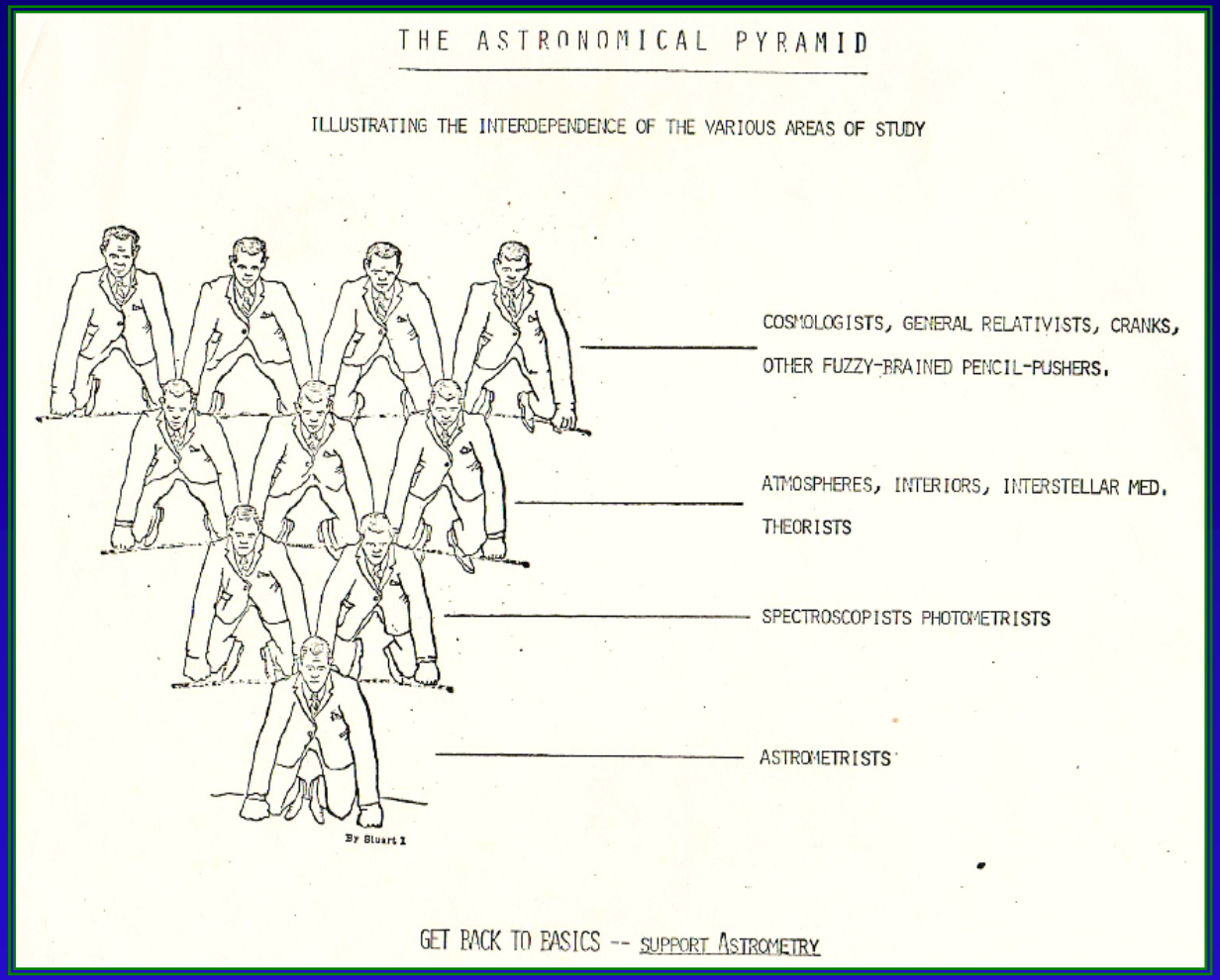
Astrometry in a nutshell

What is Astrometry ?

- Astrometry deals with the measurement of the positions and motions of astronomical objects on the celestial sphere.
  - Global or wide field astrometry
  - Local or small field astrometry
- Astrometry relies on specialized instrumentation and observational and analysis techniques.
- It is fundamental to all other fields of astronomy.



Astrometry: a pre-Hipparcos diagram



Circulated ca. 1974, by R. Probst, UVa

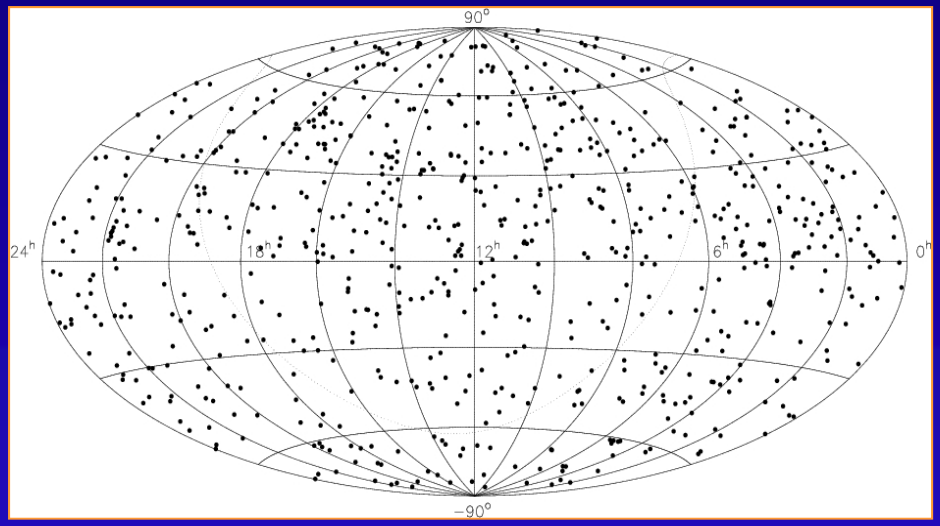
Daher sind die Oerter der Fixsterne die Grundlagen der Astronomie.

Bessel, Pop. Vorlesungen p. 22

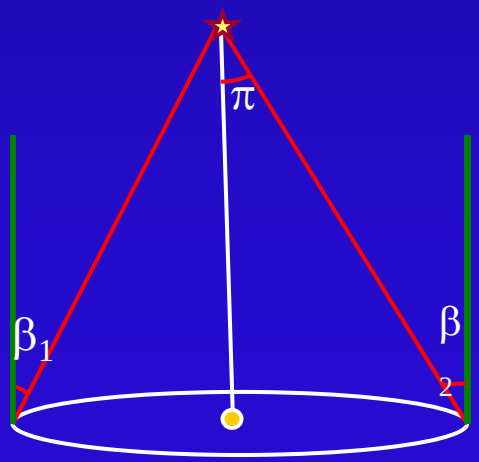
' the places of the stars are the foundation of astronomy '

- The two pillars of space astrometry

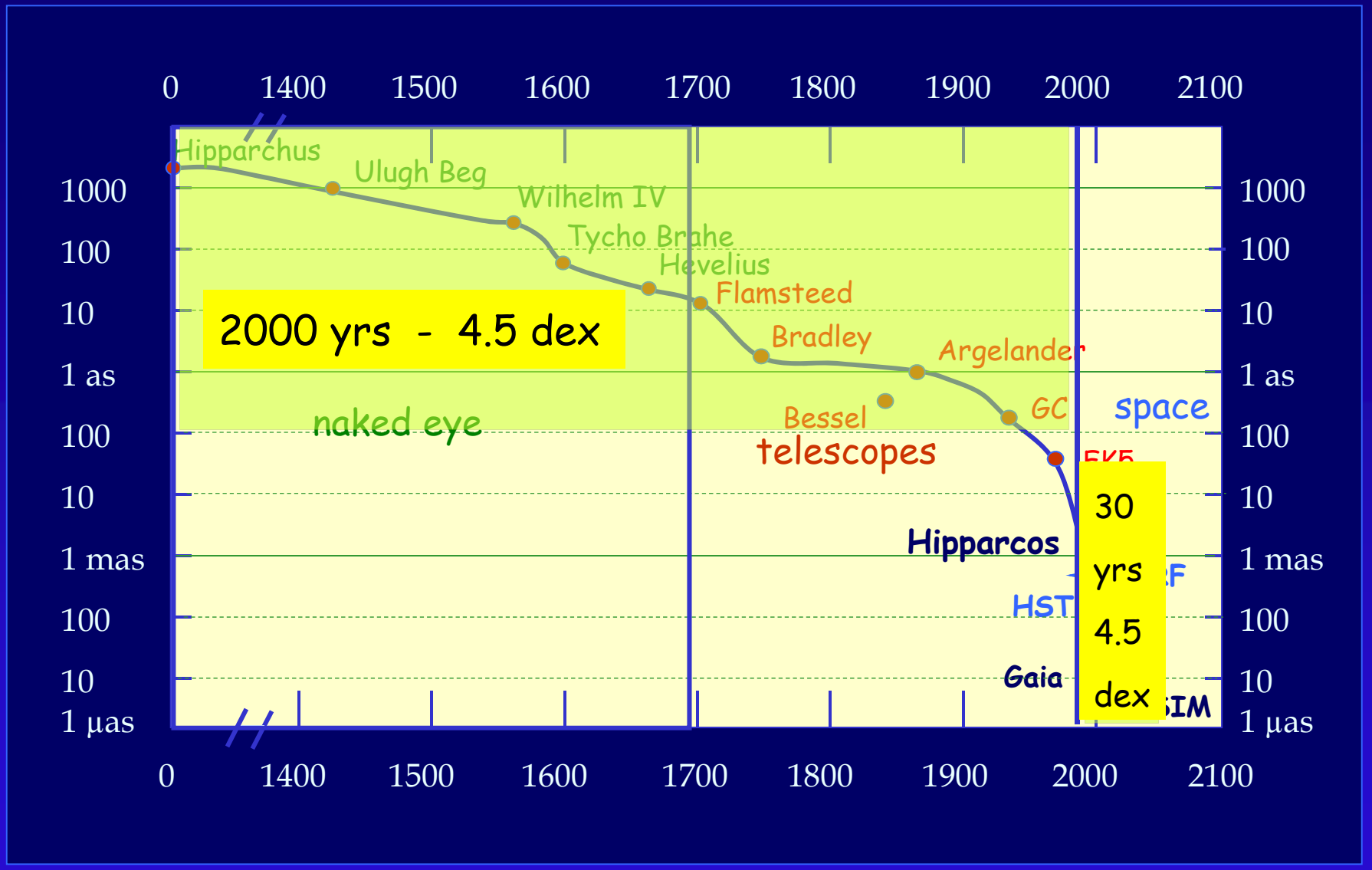
Reference frame

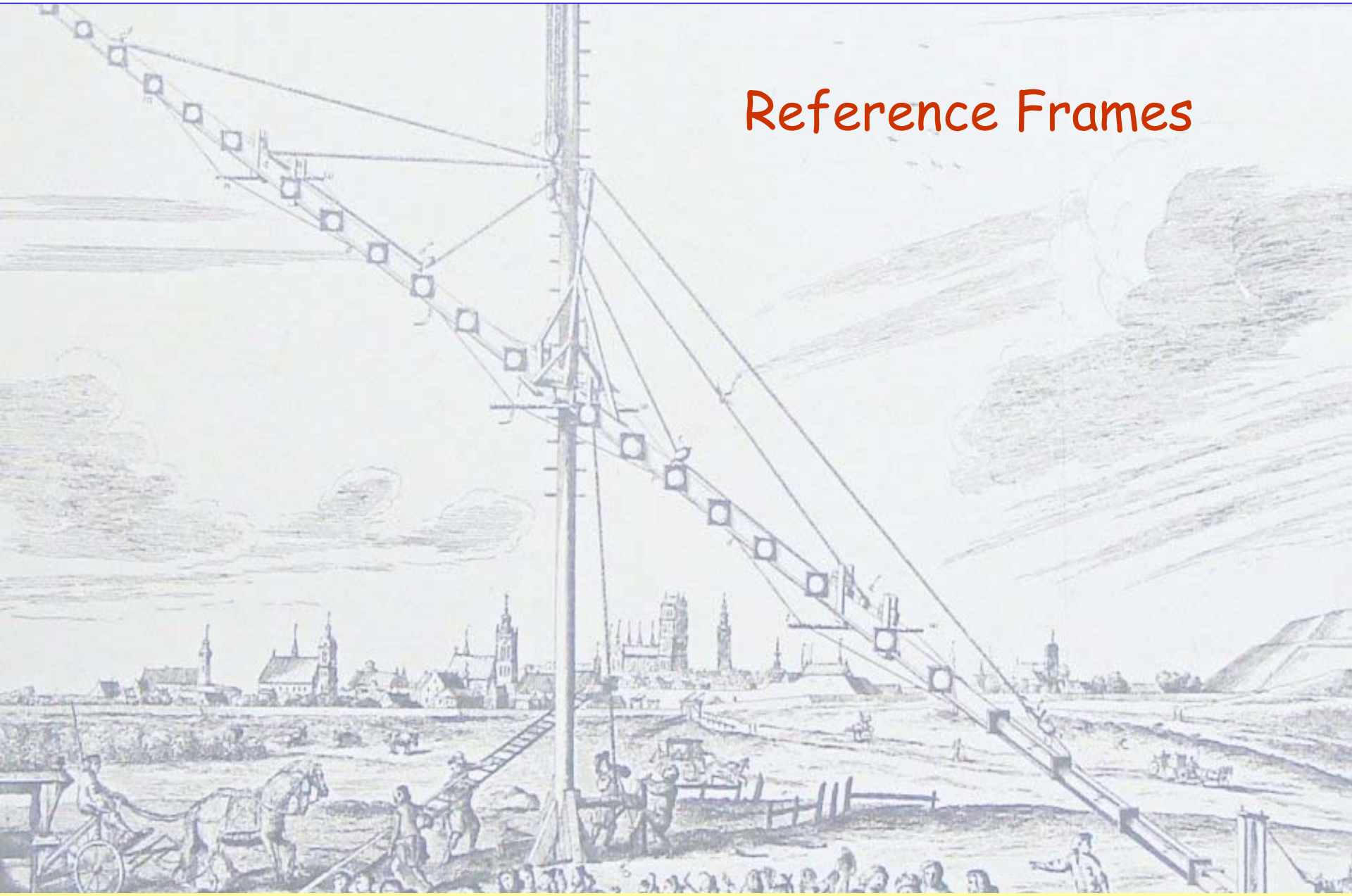


Absolute parallaxes



Astrometry Golden Age

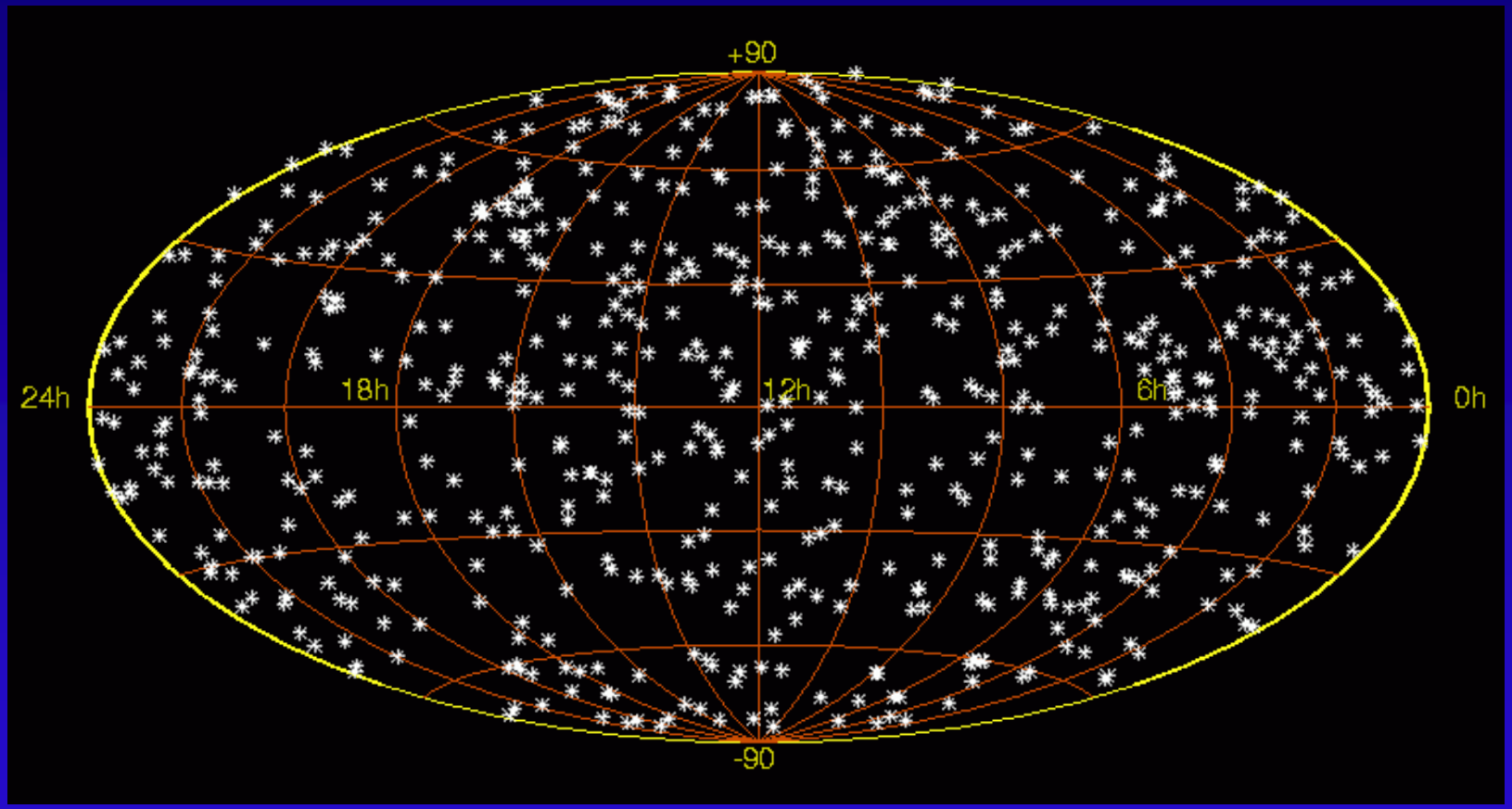




Reference Frames

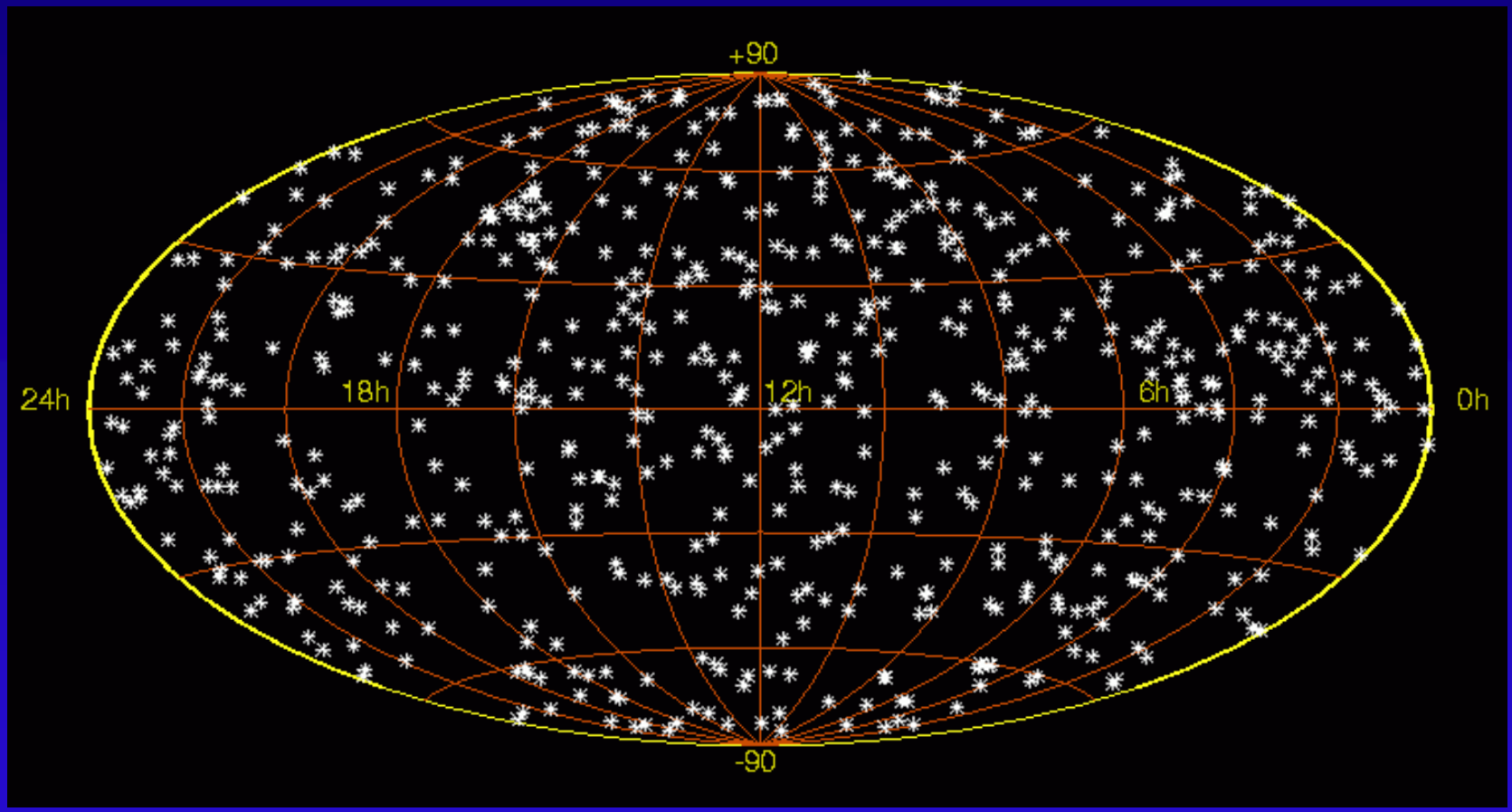
Reference frame : standard view

- Pre-existing reference graticule



Reference frame : fundamental view

- Stellar sources as fiducial points



Classical Astronomical Reference Frames

- Astronomical catalogues
  - Large full sky astronomical catalogues widely available in 1970
    - BD (1860) & Cordoba (1890) with 700,000 stars
    - HD (Henry Draper) since 1920, 230, 000 entries with spectral type
    - SAO (1966) with 270,000 stars with positions and PM
  - Positions and PM based on an existing reference frame
- Fundamental catalogues
  - Absolute observations with no reference to previous determinations
  - Historically tied to the equator and equinox at a particular epoch
    - assumed to provide absolute and inertial orientation
  - observations of the Sun or planets mandatory

Fundamental Catalogues

- Small catalogues, many years of tedious labour to get absolute positions

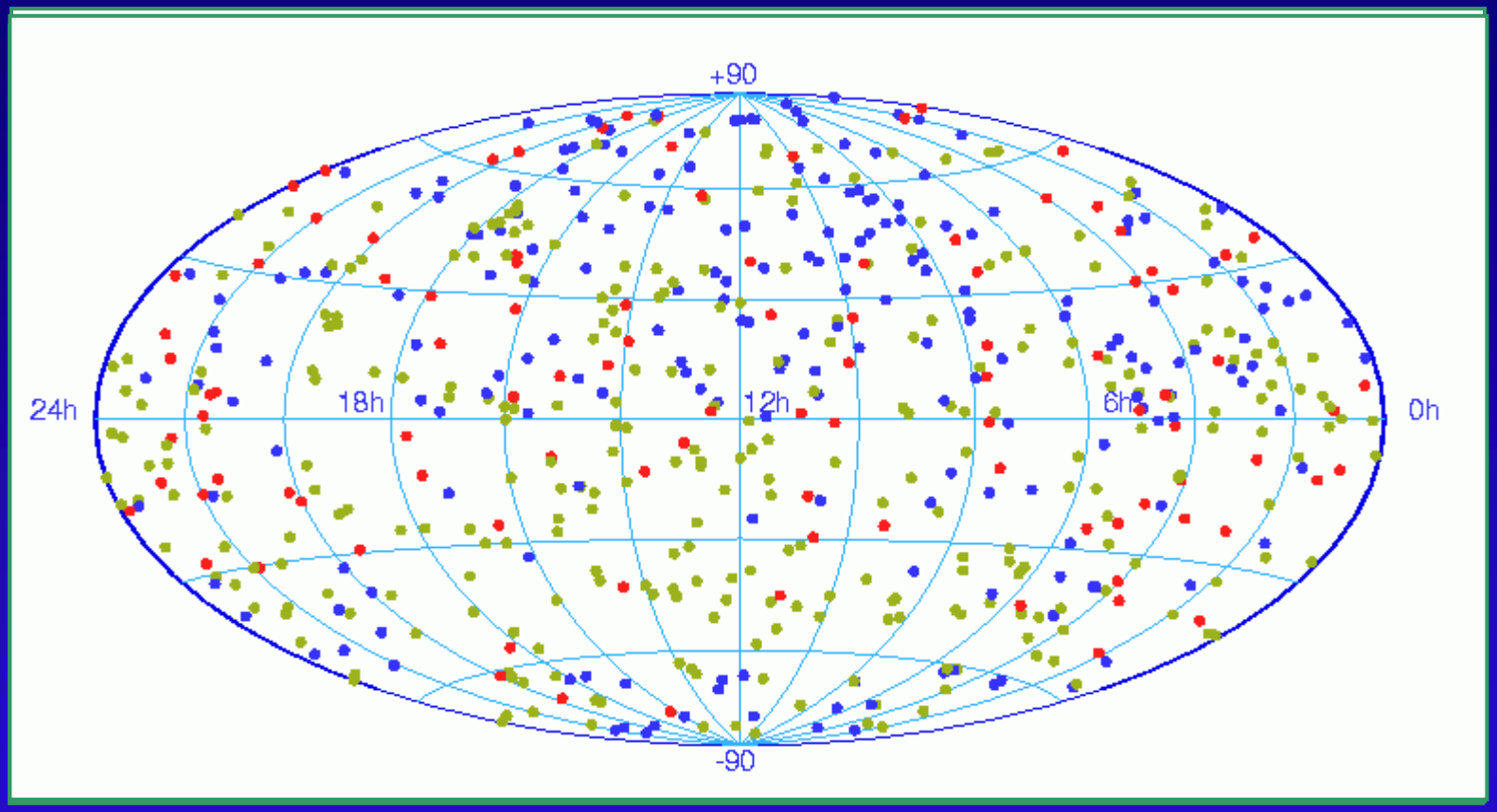
- 1790	Maskelyne	36	zodiacal stars, one epoch
- 1818	Bradley/Bessel	3000	no PM, nearly fundamental
- 1830	Bessel	36	with PM, + precession
- 1878	FK1	539	
- 1898	Newcomb	1297	Start of the GC series
- 1907	FK2	925	
- 1937	FK3	873	1st IAU supported international RF
- 1963	FK4	1535	σ_{1950} ~ 0"07- 0"15, σ_{2000} ~ 0".15-0"30
- 1988	FK5	1535	σ_{2000} ~ 0".05 - 0"10
- 1997	Hipparcos	100,000	(quasi fundamental)
- 1998	ICRF	212	

Limitations of the classical approach

- System defined with equator and equinox
  - precession and nutation modelling
    - solution: fixed frame not linked to solar system ➔ ICRS
- Observations from the ground
  - many stations needed to cover the sky
  - disturbances from the atmosphere
    - solution: go to space for global astrometry ➔ Hipparcos
- System based on stars
  - problems with proper motions, multiplicity
    - solution: distant sources ➔ already considered by W. Herschel & Laplace
    - Adopted in ~ 1990 with ICRS and ICRF in 1998

ICRF-1 (1998)

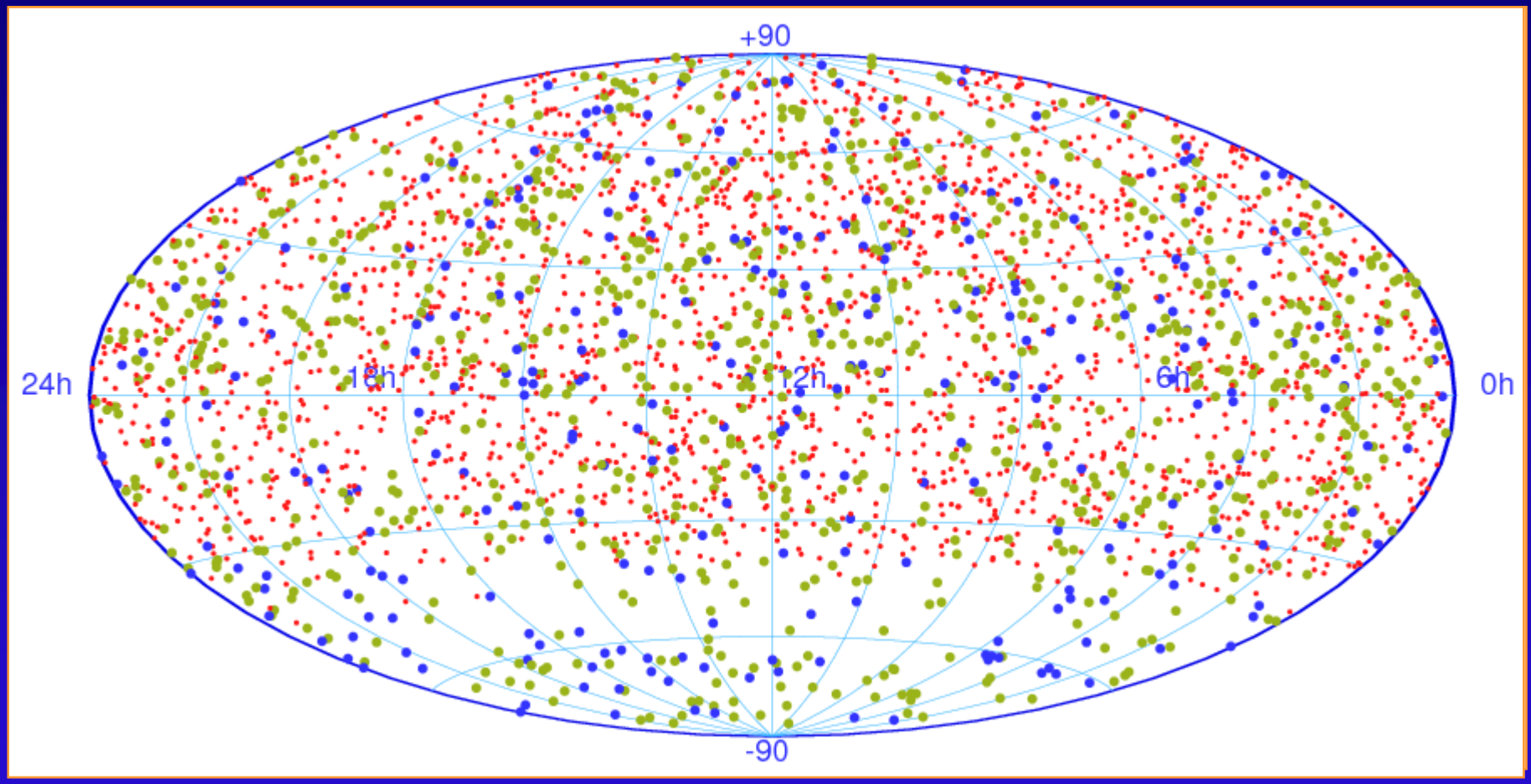
Accuracy ~ 1 mas



- Definition sources (212)
- Candidate sources (294)
- Other sources (102)

ICRF-2 (2009)

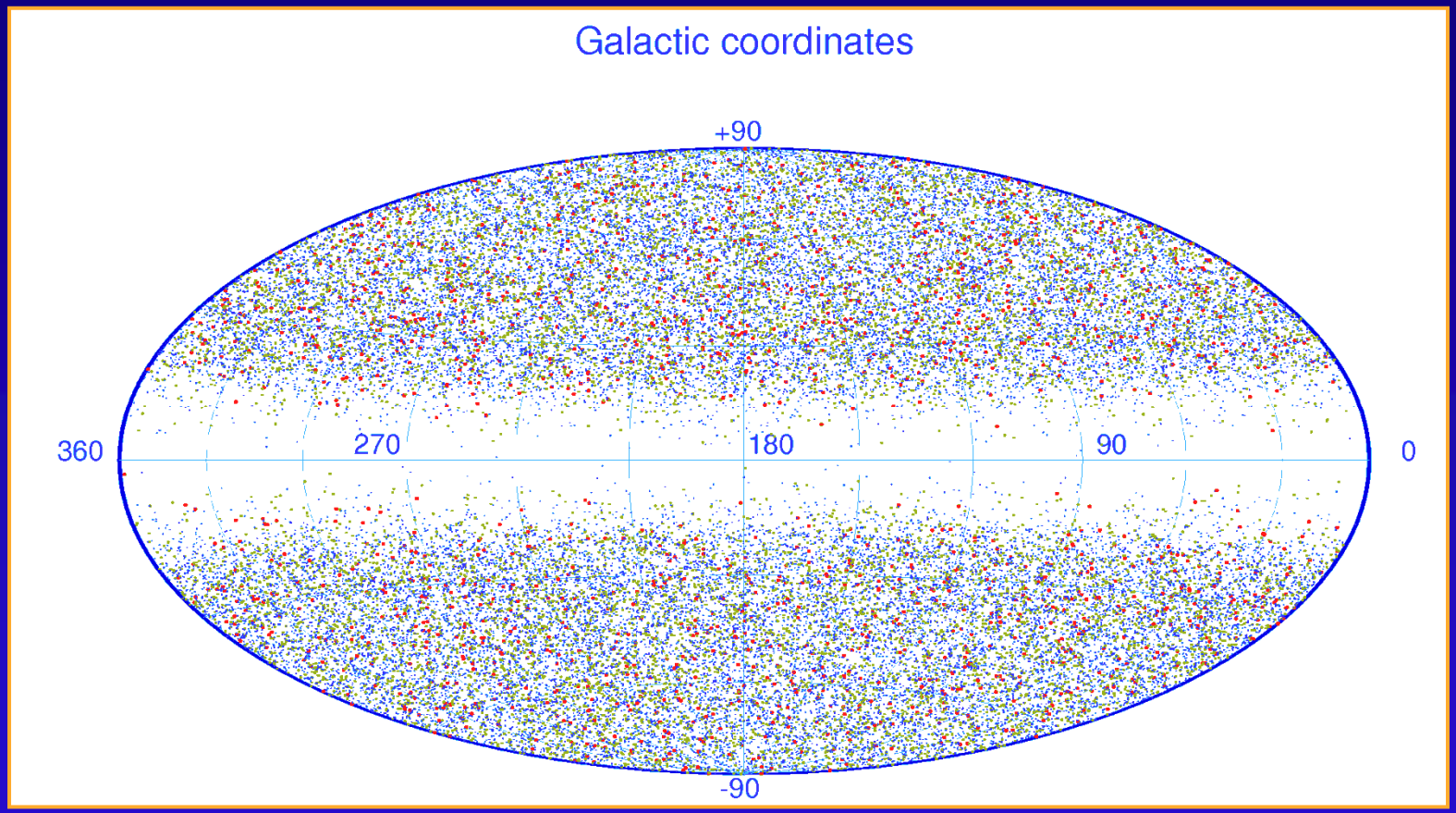
- Accuracy ~ 0.2 to 2 mas



defining (294) VLBI (923) VLBA Calib. (2197)

QSOs distribution with Gaia

- Based on the simulation used in the DPAC Universe model

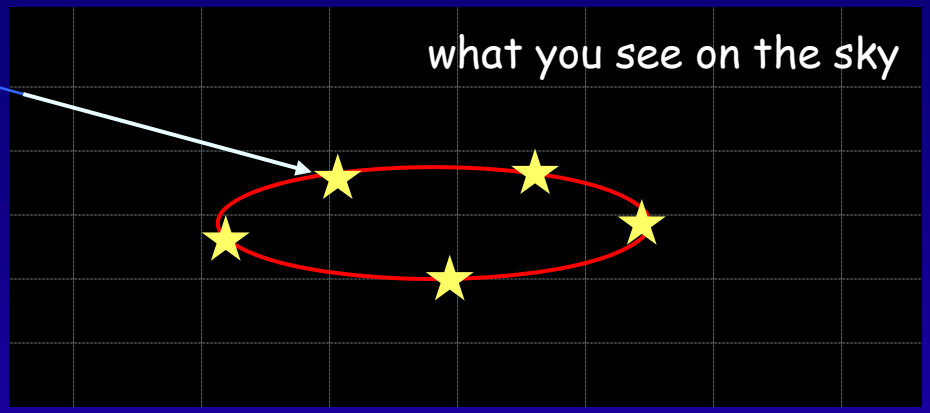


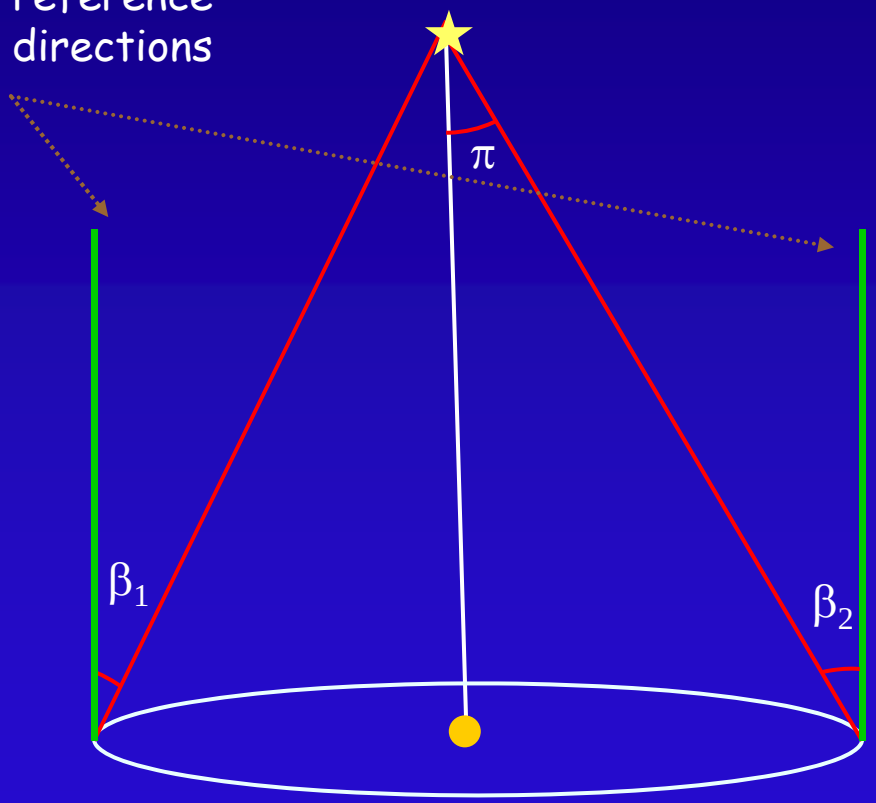
Slezak & Mignard, 2007

Stellar Parallaxes

Parallactic effect

smaller than 1 "

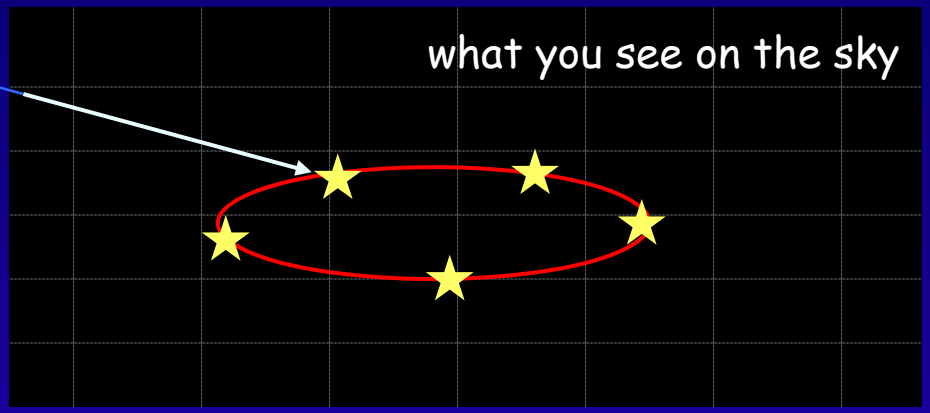




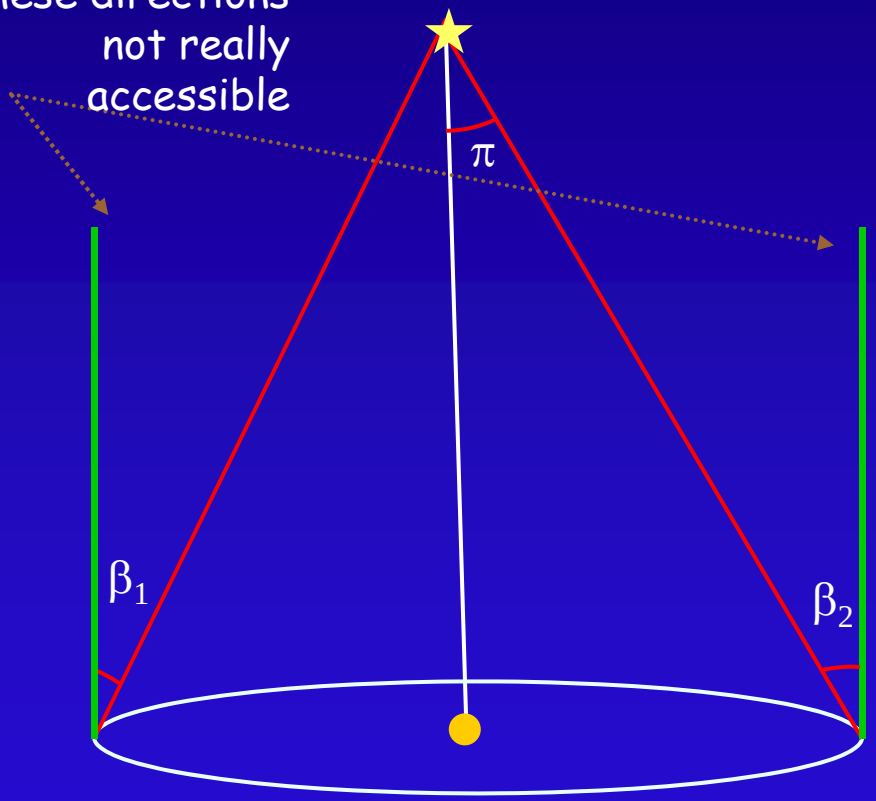
$$\pi = \frac{\beta_1 + \beta_2}{2}$$

Absolute parallaxes

Absolute positions
No reference to distant stars



these directions
not really
accessible



$$\pi = \frac{\beta_1 + \beta_2}{2}$$

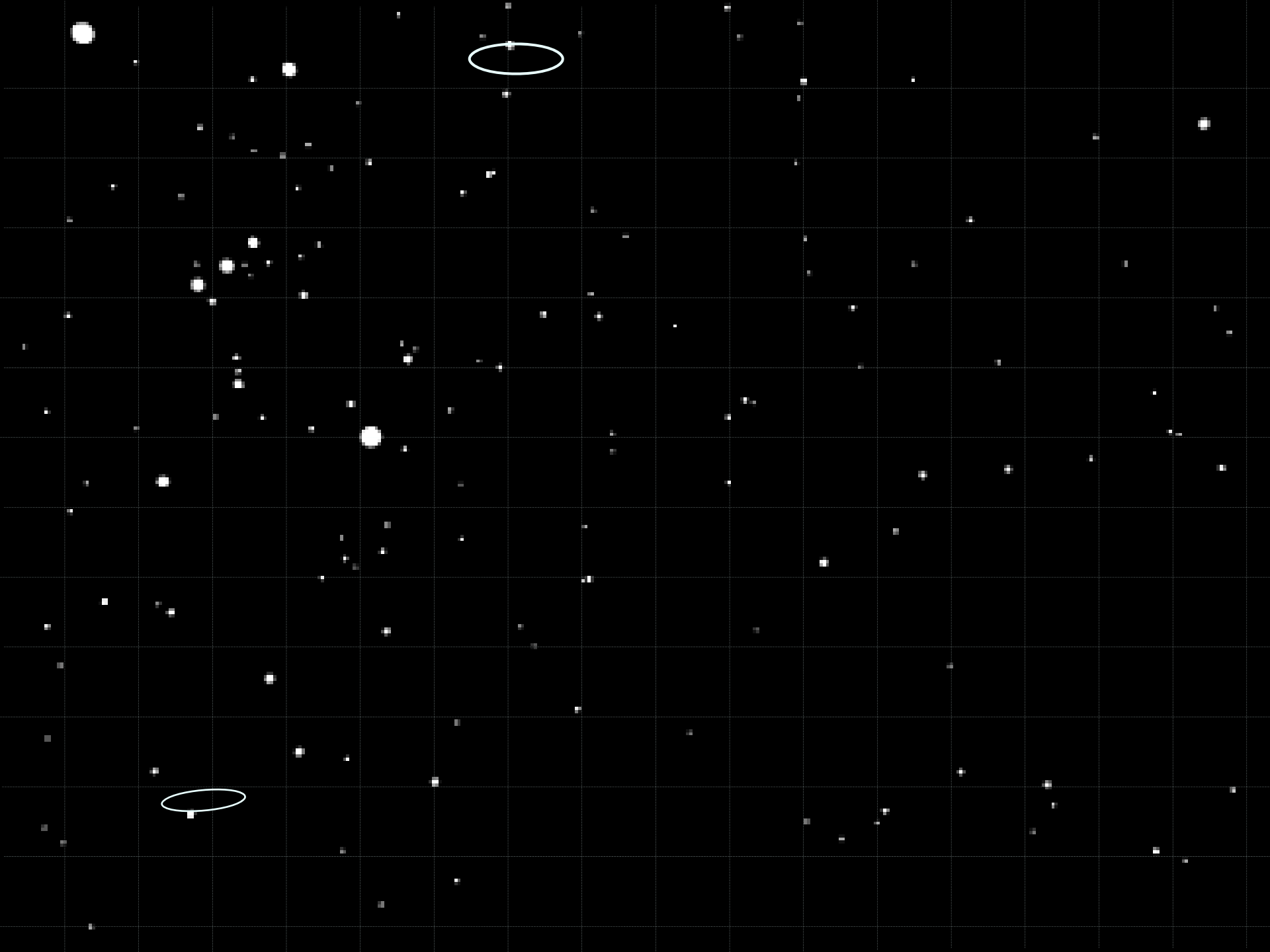
Methods applied :

measurements of declinations

zenith distances

wide angle or global astrometry

virtually impossible from the Earth to 0"001



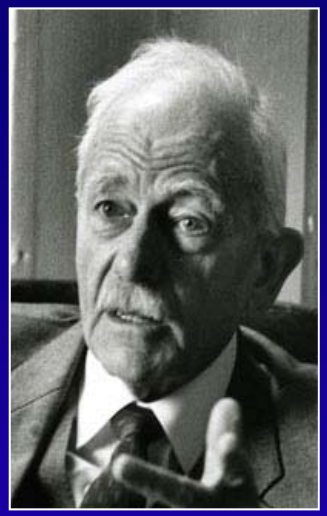
Parallaxes: Evolution 1840 - 1980

• 1840	3	published parallaxes
• 1850	20	Catalogue of Peters
• 1888	40	Catalogue of Oudemans
• 1910	100	of which 52 photog. parall. from Kapteyn
• 1912	250	Catalogue of Bigourdan
• 1917	500	Catalogue of Walkey
• 1924	1870	Catalogue Schlesinger
• 1930	2000	From here it may include spectroscopic parallaxes
• 1950	5800	"
• 1965	7000	"
• 1980	10000	"

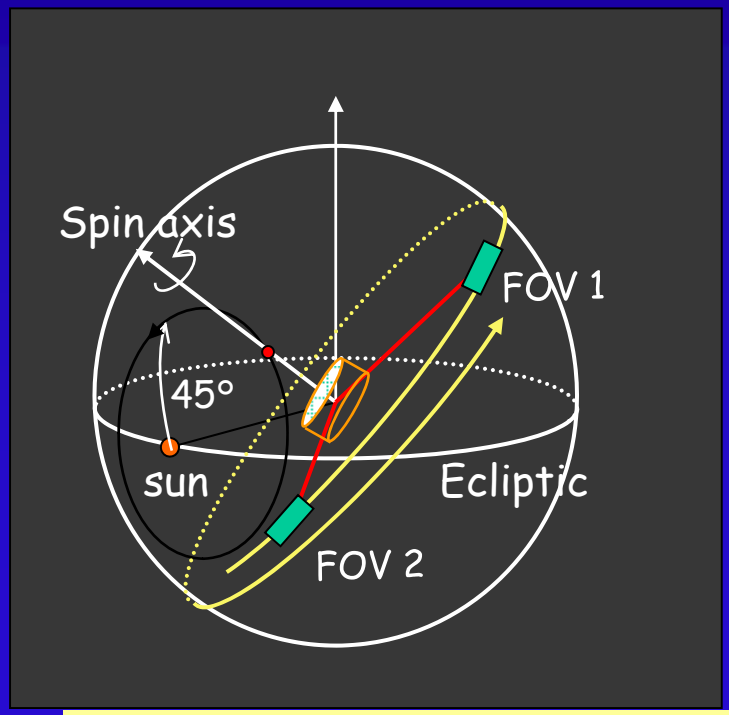
- Estimated error : 0".016
  - ➔ $\sigma(\pi)/\pi$ = 50% at 30 pc !
- Mean value of the parallaxes : 0".018

Many of these parallaxes have no individual significance

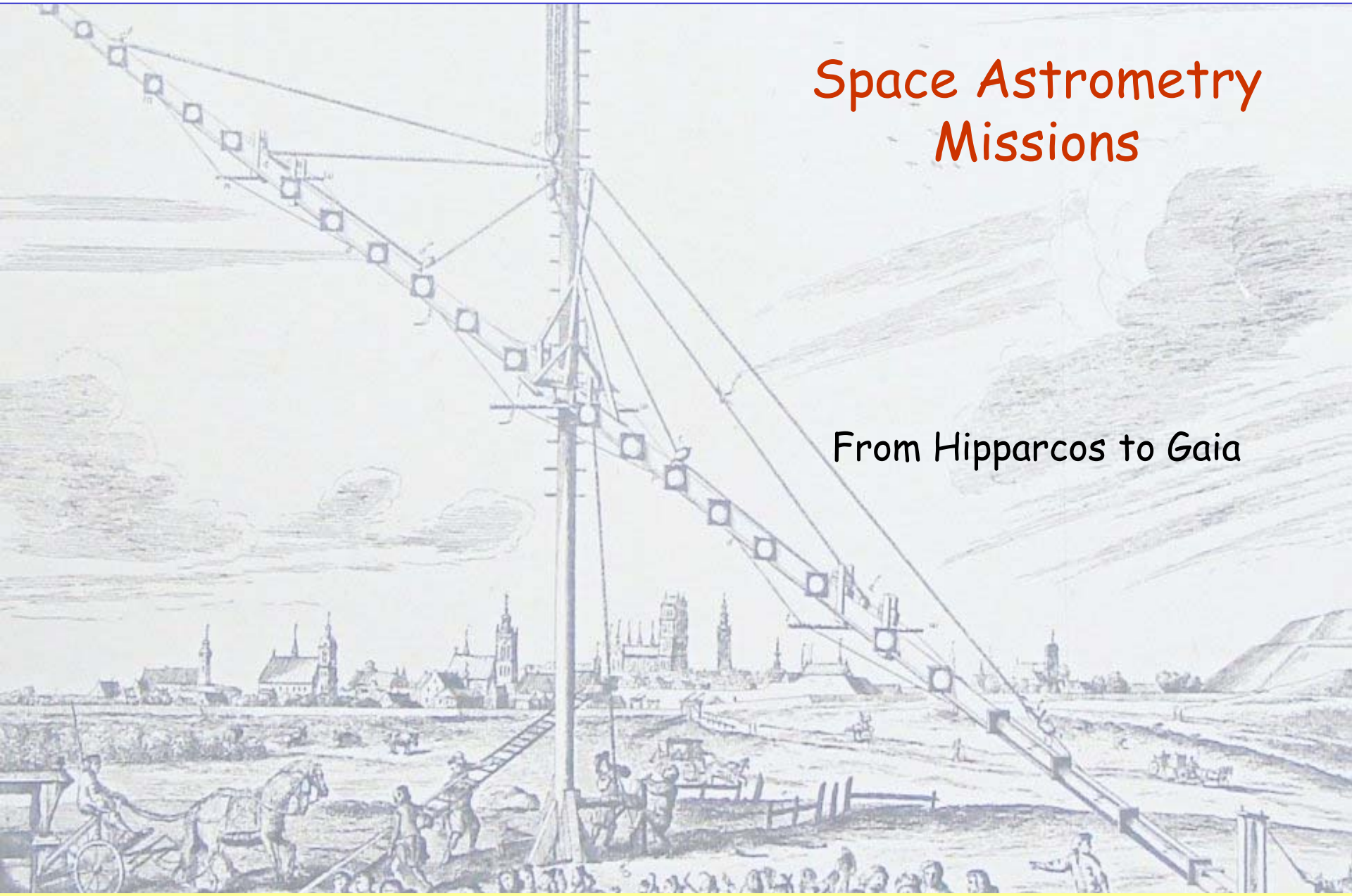
A route to absolute parallaxes : Two fields of view



P.Lacroute
1906-1993



- Overall principles set forth by P. Lacroute in 1967.
- Optical combination of two viewing directions
- The two FOVs are mapped onto a common focal plane
- Stars are combined by pairs
- Wide angle measurements are carried out



Space Astrometry Missions

From Hipparcos to Gaia

Space astrometry

- Astrometry is the main reason to go to space …
  - global, accurate, absolute
  - not achievable from the ground
- but astrophysics is the main reason to pay for it
  - benefits almost everywhere
  - secures its foundations

Goals of Space Astrometry

- Primary Objectives not achievable from Earth
  - Ascertain the distances of the stars
    - stellar parallaxes for astronomers
  - Define and materialise the inertial frame
    - now based on extragalactic sources

- Secondary objectives
  - Astrophysics with astrometry, photometry, spectroscopy
    - stellar and galactic physics
    - detection of extrasolar planets
    - solar system dynamics
  - Tests of fundamental physics in space
    - based on light path geometry

Space astrometry : two complementary concepts

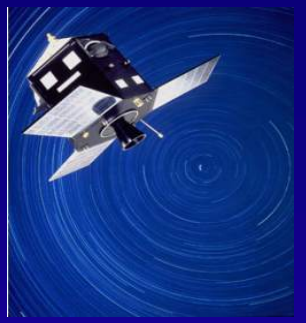
- Survey of a large number of stars
  - Continuous scanning of the sky
  - Input catalogue or on-board detection
  - Complete up to a limiting magnitude or selection of stars
  - The scanning law determines the integration time
  - Frozen observing program

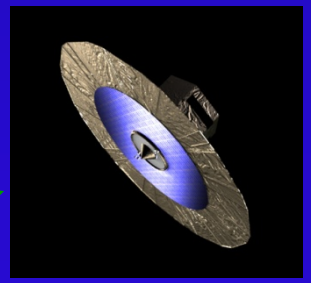
- Pointing at individual sources
  - Pre-selected sources
  - Variable and adapted integration time
  - Longer operation dead time
  - Flexible program, can react to external demand

Space Astrometry: Past & Present

- A successful forerunner: HIPPARCOS (ESA)
  - accuracy of 1 mas ~ a coin @ 1000 km
- The unfortunate followers
  - accuracy of 0.1 mas ~ a nail @ 1000 km
  - Roemer, FAME-1, FAME-2, DIVA, Lomonossov, AMEX

    ESA US US DE RU US
- Study phase
  - JASMINE (Japan) in the IR
- Cancelled (Dec 2010)
  - SIM (US) with 1 μas accuracy
- Funded – launch 2011 - 2014
  - NanoJasmine [4 mas], J-MAPS (US) [1mas]
  - Gaia (ESA) : 25 μas (a hairwidth @ 1000 km)

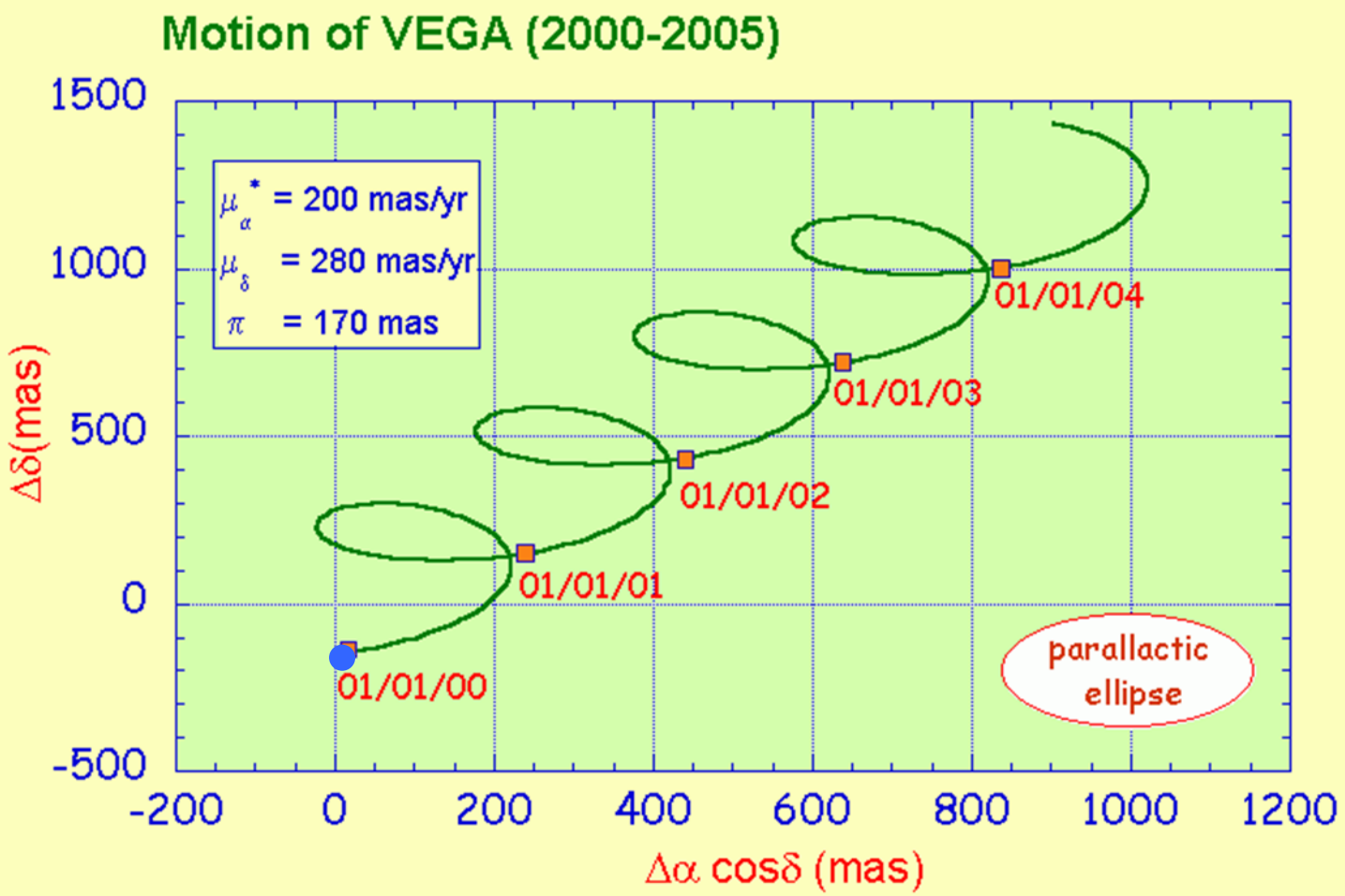




Main Features of Hipparcos

- ESA mission launched in August 1989
- Continuous sky scanning over 3.5 years
- Results published in 1996-7
- One single telescope of 29 cm in diameter
- Two fields of view separated by 58°
- Detection with a photoelectric tube (r = 0.003)
- One source observed at a time

- Absolute motion of Vega
  - non rotating reference frame



Main features

- Simultaneous observations in two widely separated directions
  - angular distance between pair of stars
  - angular scale determined by the angle of a complex mirror
  - self calibrating instrument
- Regular scanning of the sky over 3 years
  - scanning instrument with no pointing
  - every direction sampled about 110 times during the mission
- Observation of selected sources : no on-board detection
  - fixed observing program

Main Results of Hipparcos

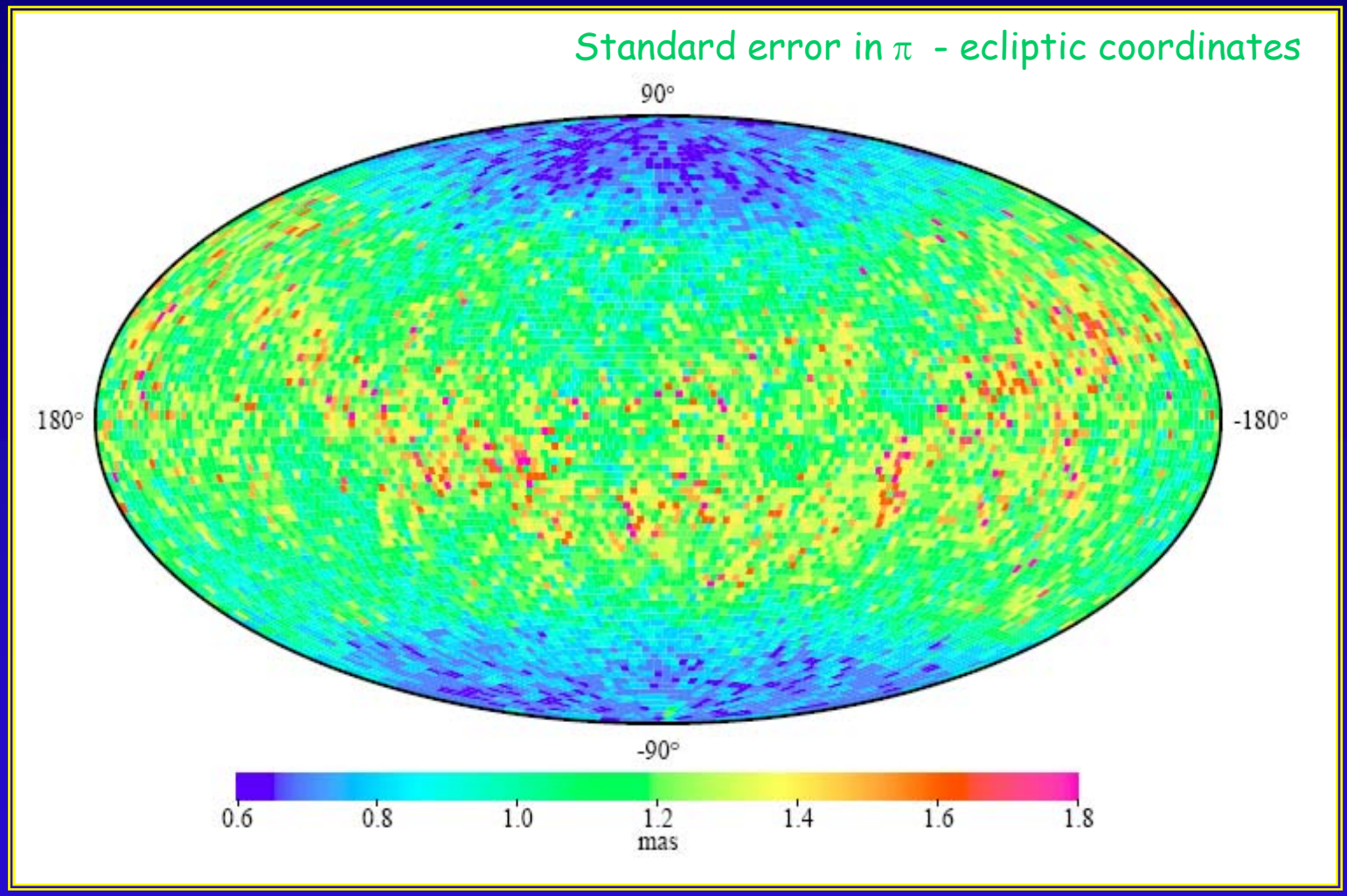
- An astrometric catalogue of 118 000 stars
  - Hipparcos is a quasi-fundamental catalogue
  - $\sigma(\alpha) \sim \sigma(\delta) \sim \sigma(\pi)$ ~ 1 mas at V = 9 at 1991.25
  - $\sigma(\mu_\alpha) \sim \sigma(\mu_\delta) \sim 1$ mas/yr at V = 9
- Complete to V = 7.3 - 9.2 (depending on galactic latitude)
- Limiting magnitude 12.4
- Distances better than 10% for 21 000 stars , D < 200 pc
- Density : 3.0 */ deg^2
- Linked to the ICRF with radio stars to within 0.6 mas and 0.25 mas/yr
- Supplemented by Tycho and later Tycho-2

Additional products

- A survey of binary stars
  - solution for 13000 systems
  - discovery of about 3000 new systems
  - astrometric detection of nearly 2000 pairs
  - masses for about 50 systems

- A photometric data base with 130 observations per star
  - $\sigma(H) \sim 0.001$ mag
  - 13×10^6 epoch observations
  - survey of variability for many types of stars to the 10^{-3} mag level
    - remains the best source of homogenous data today
  - 2500 periodic variables with periods and folded light-curves

Gaia DPAC


Standard error in π - ecliptic coordinates
90°
180°
-180°
-90°
0.6
0.8
1.0
1.2
1.4
1.6
1.8
mas

PPN parameter γ with Hipparcos

- Relativistic effect of light bending introduced in the model
- Solution with Hipparcos data
  - general parameter in the astrometric model
  - measurements a large angles from the Sun
    - from 47° ($\delta\theta$ ~ 10 mas) to 133°
  - serious problem with the correlation with parallaxes
- Solution in absolute astrometry
  - no comparison of position with or without the Sun
  - no use of small field astrometry
- Numerous experiments designed to assess the accuracy
- Result : $\gamma = 0.997 + 0.003$ (Froeschlé, Mignard & Arenou, 1997)
- First determination of light deflection at large angle

After Hipparcos ?

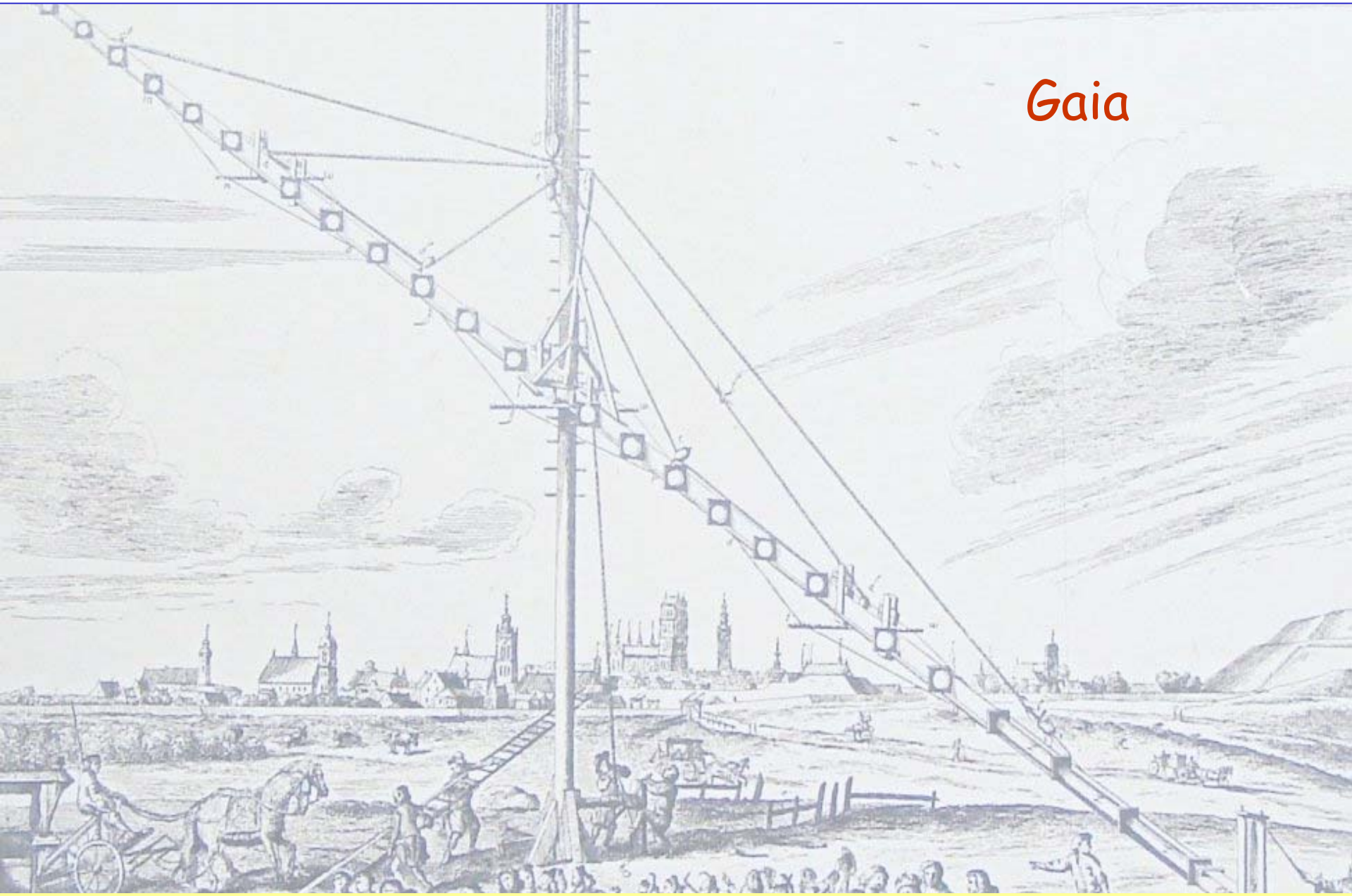
- W. Fricke (Fundamental Catalogues: Past, Present & Future, 1985)
  - "***one would wish that the Hipparcos mission should not be unique but be repeated after a period of 10 to 20 years***".
- Hipparcos positions degrade quickly (1 mas/yr)➔ σ ~ 15 mas today
- With no technological improvement, two absolute catalogues

  ↑ σ ~ 1 mas :

  - Δt ~ 20 yrs

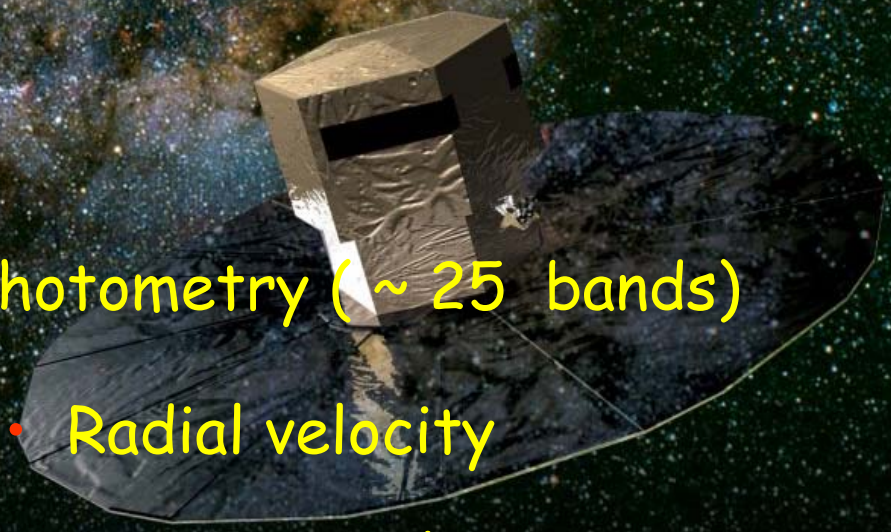
    ➔ PM to 50 muas/yr ➔ just one order of magnitude improvement.
- ESA Survey Committee in 1994:

  " Initiate a Cornerstone-level program in interferometry to perform astrometric observations at the 10 μas level"


Gaia

GAIA

- 10^9 stars
- 10 μas @ V < 13 mag
- 25 μas @ V = 15 mag



- Photometry (~ 25 bands)
- Radial velocity
- Low resolution spectroscopy

ESA mission

Launch : mid 2013

Mission : 5 years

Mission requirements summary

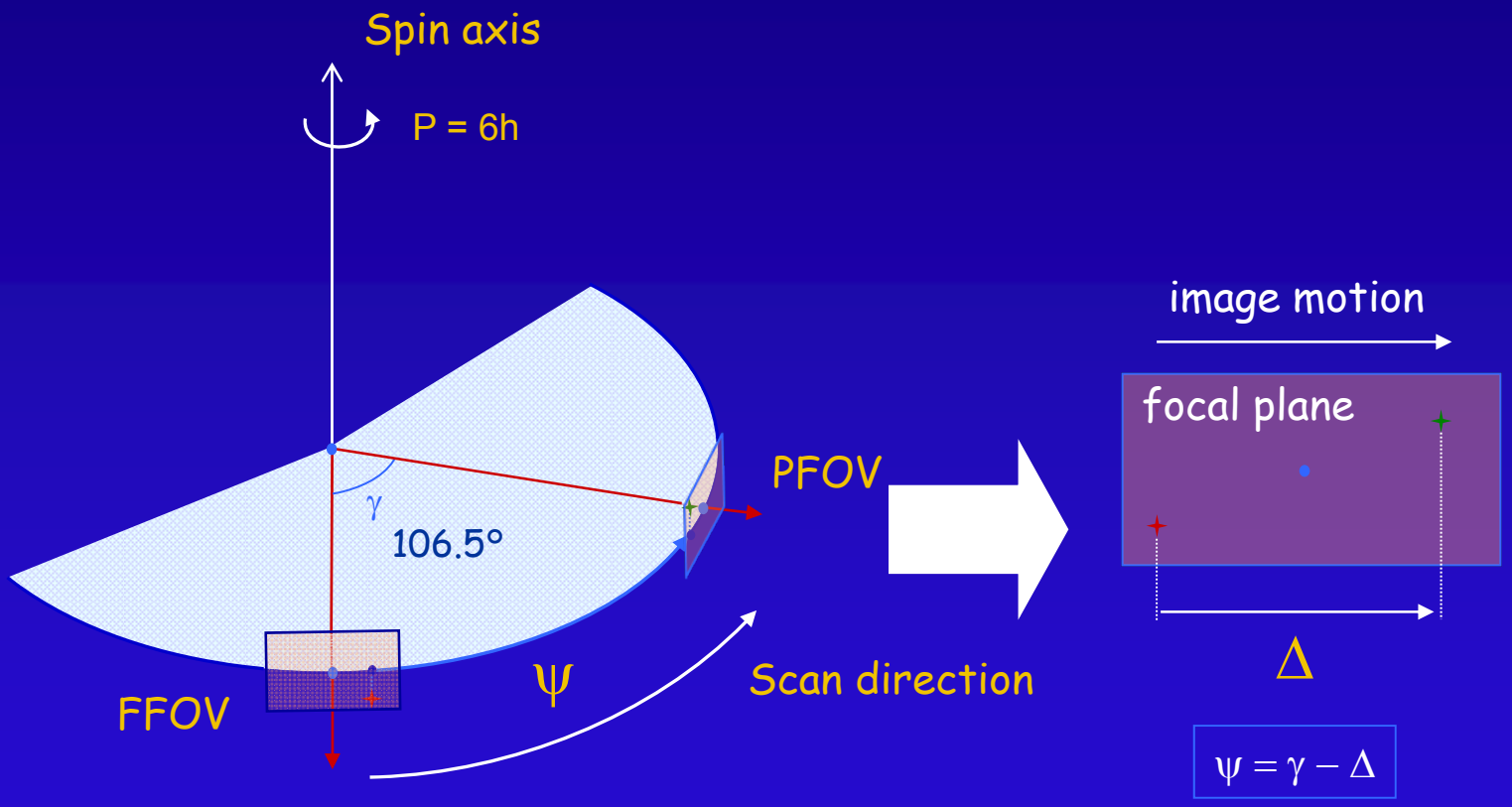
- A Stereoscopic Census of Our Galaxy
- Astrometry (V < 20):
  - completeness to 20 mag (on-board detection) 10^9 stars
  - parallax accuracy: 7 μas at <10 mag; 12–25 μas at 15 mag 100–300 μas at 20 mag
- Photometry (V < 20):
  - astrophysical diagnostics (low-dispersion photometry) + chromaticity
  - 8–20 mmag at 15 mag: Teff ~ 200 K, log g, [Fe/H] to 0.2 dex, extinction
- Radial velocity (V < 16.5–17):
  - Third component of space motion, perspective acceleration
  - <1 km/s at 13-13.5 mag and <15 km/s at 16.5-17 mag

Assets of Gaia

- A single mission with three nearly synchronous data taking
  - Astrometric, photometric and spectroscopic data
- GAIA is a scanning mission
  - no pointing, no change in the schedule Uniform coverage of the sky
- Quasi regular time sampling over 5 years
  - ~ 80 observations ➔ photometry, orbits of binaries, asteroids
- Survey mission sensitivity limited
- Internal and autonomous detection system to G = 20
- Global astrometry of staggering precision
  - Internal metrology, thermal and mechanical stability
- Experienced and motivated community in Europe after Hipparcos
  - scientific and in industry

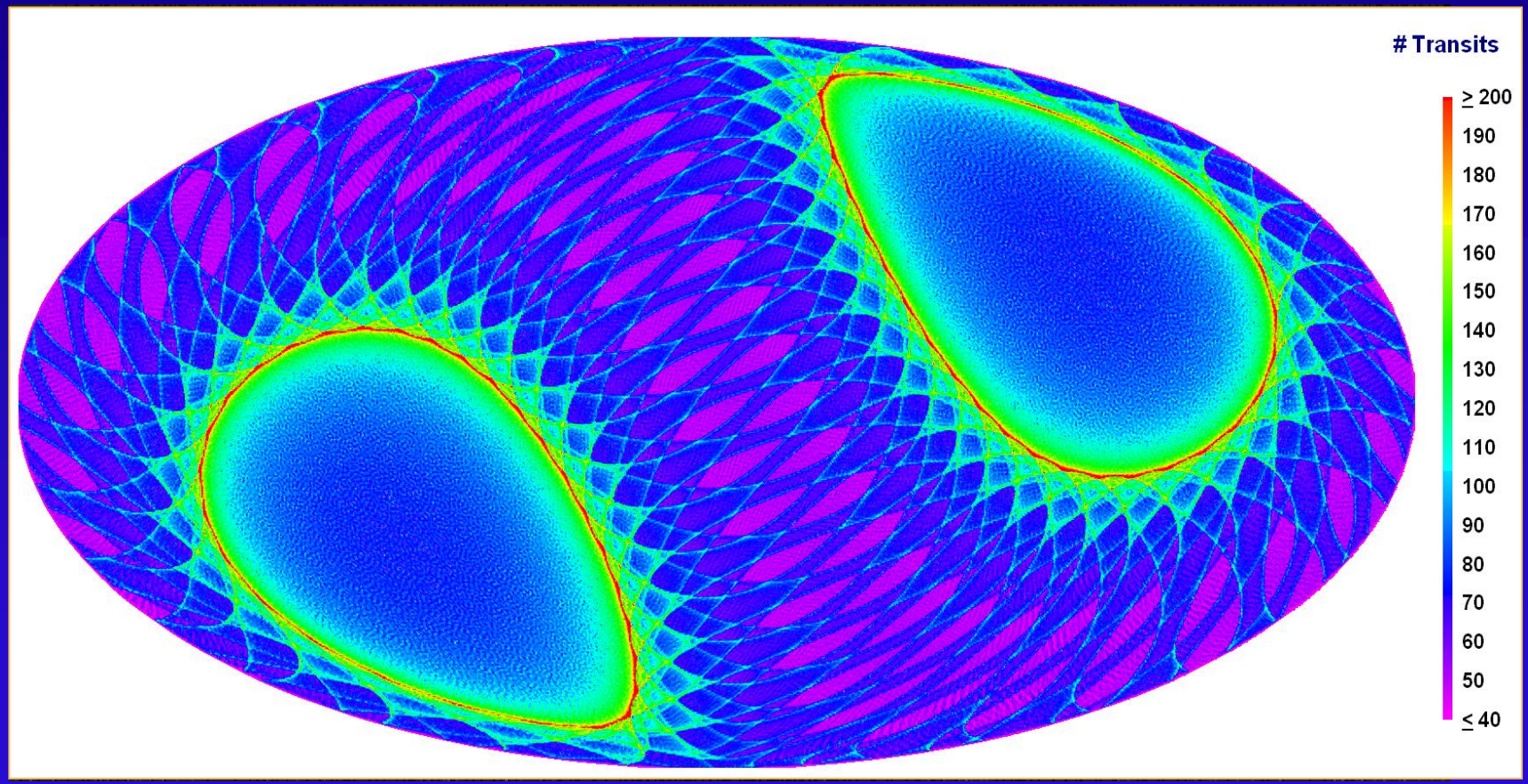
Global astrometry in space

- Wide angle measurements
- Two fields of view
- One common focal plane



Scanning & Sky coverage

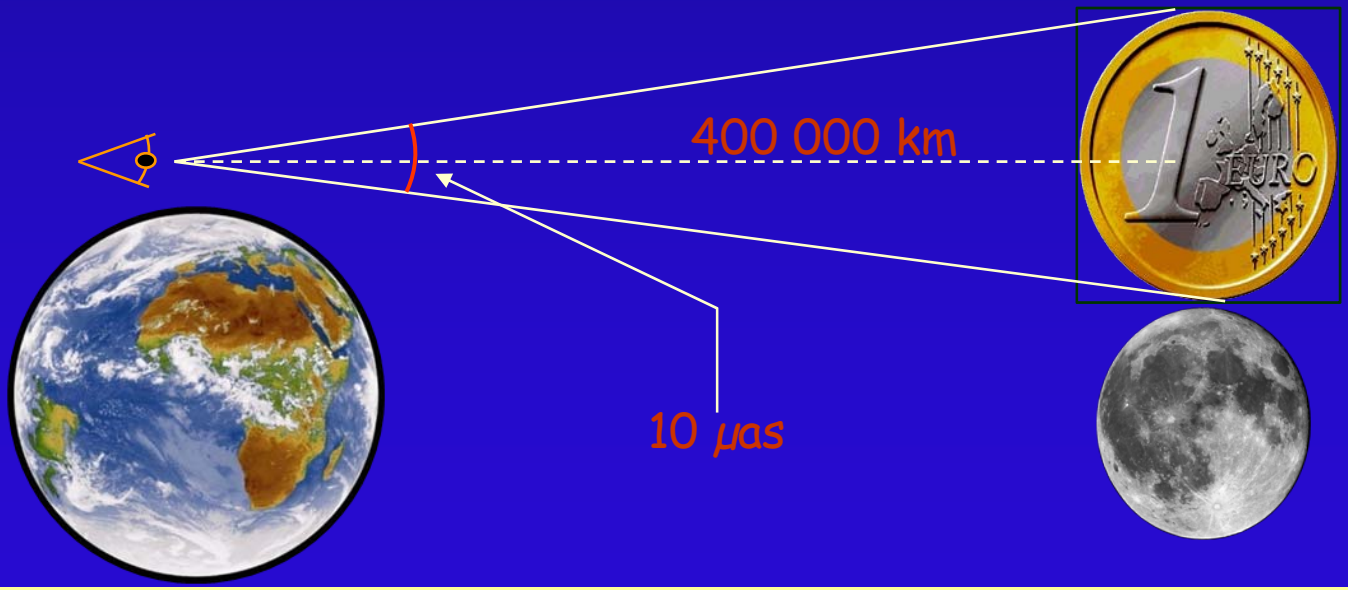
- Time average is a combination of the sky distribution and the scanning law
  - two different symmetries: galactic plane and eclitpic plane



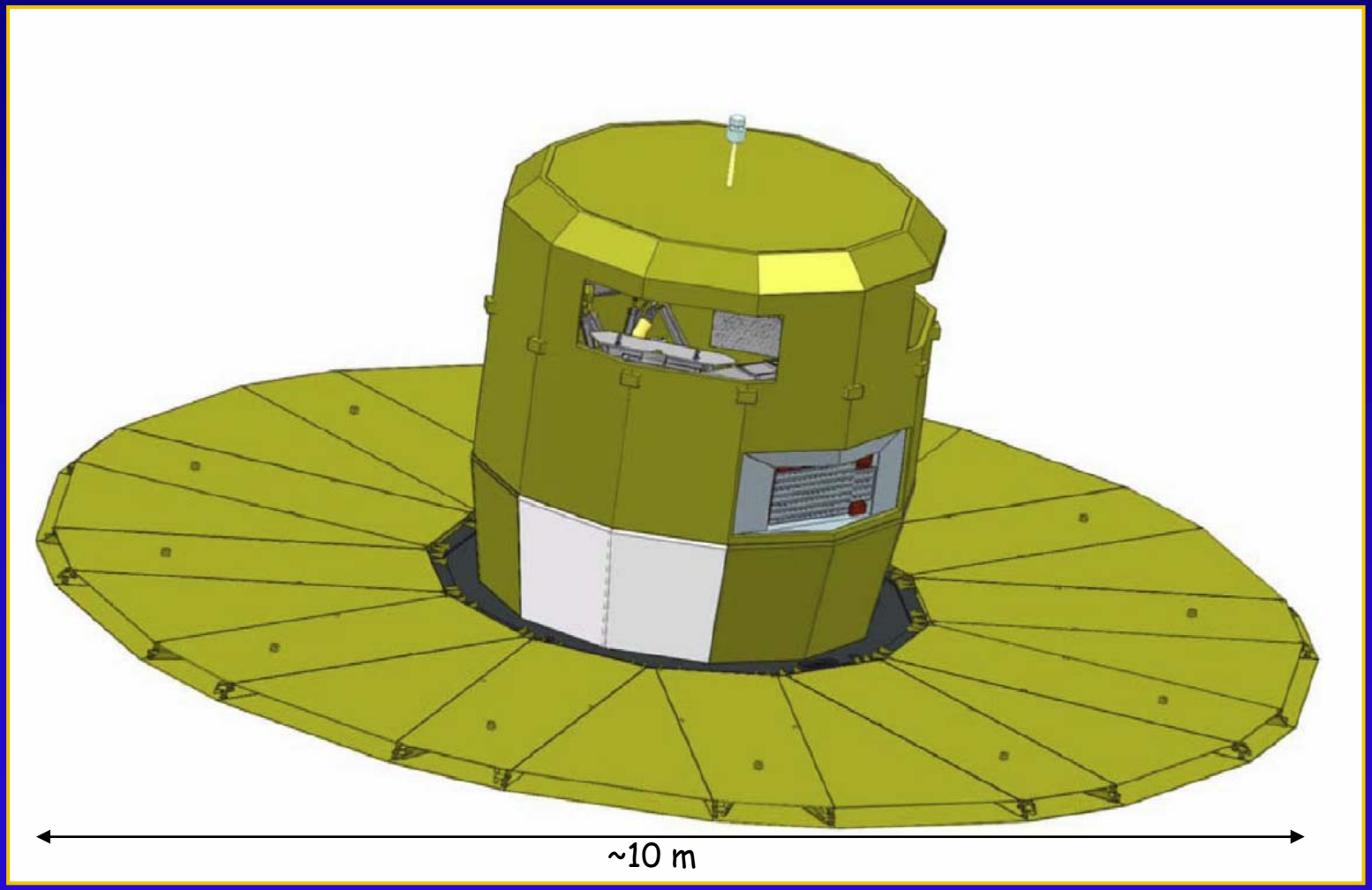
10 μas: Incredibly small !

10 μas = 50 prad

- 0.3 mm displacement on the Earth
- edge-on sheet of paper @ 2000 km
- 1 hair @ 1000 km
- displacement of a 100 mas/yr star in one hour
- motion of a fast minor planet in 100 μs.

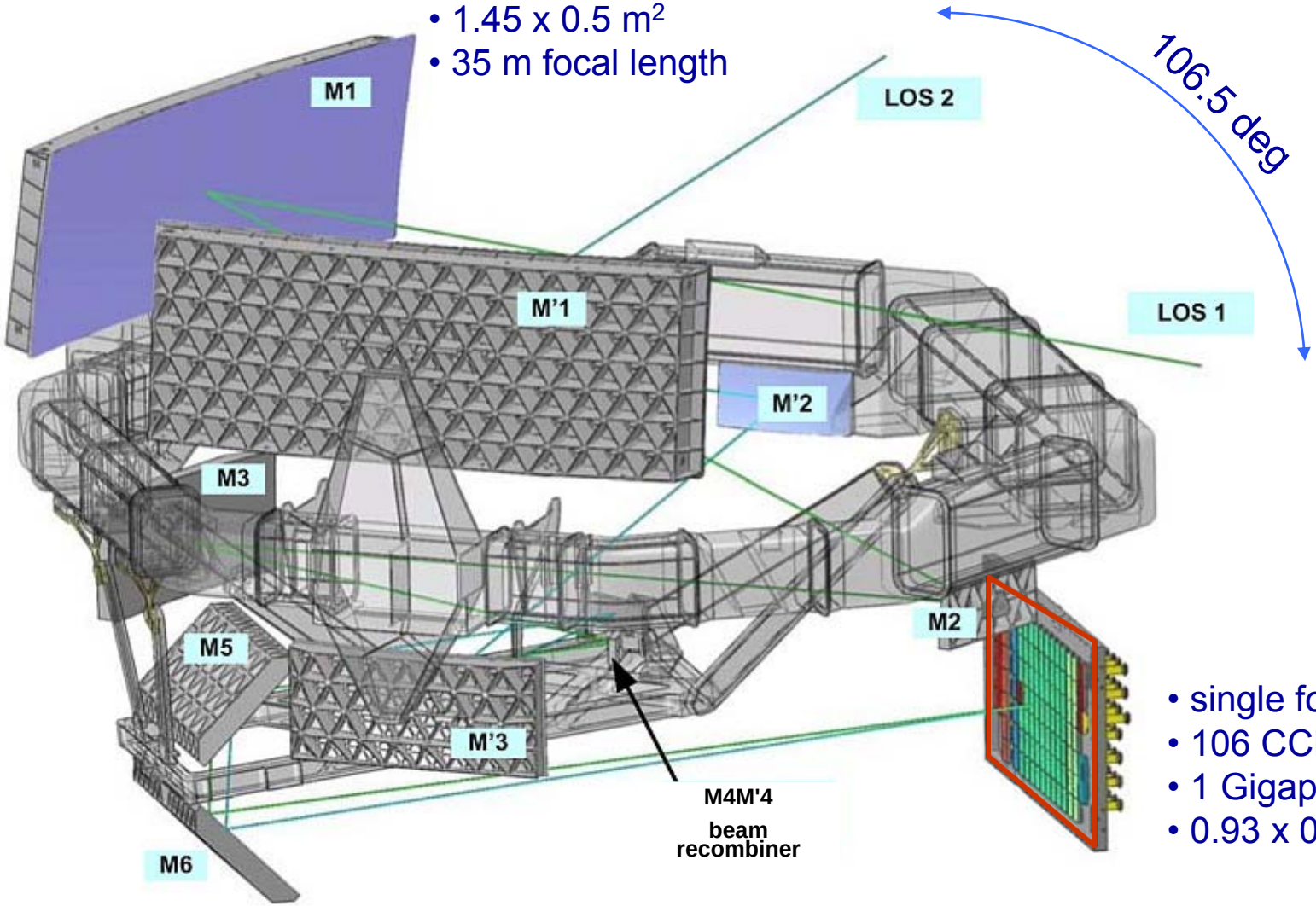


The Spacecraft in orbit



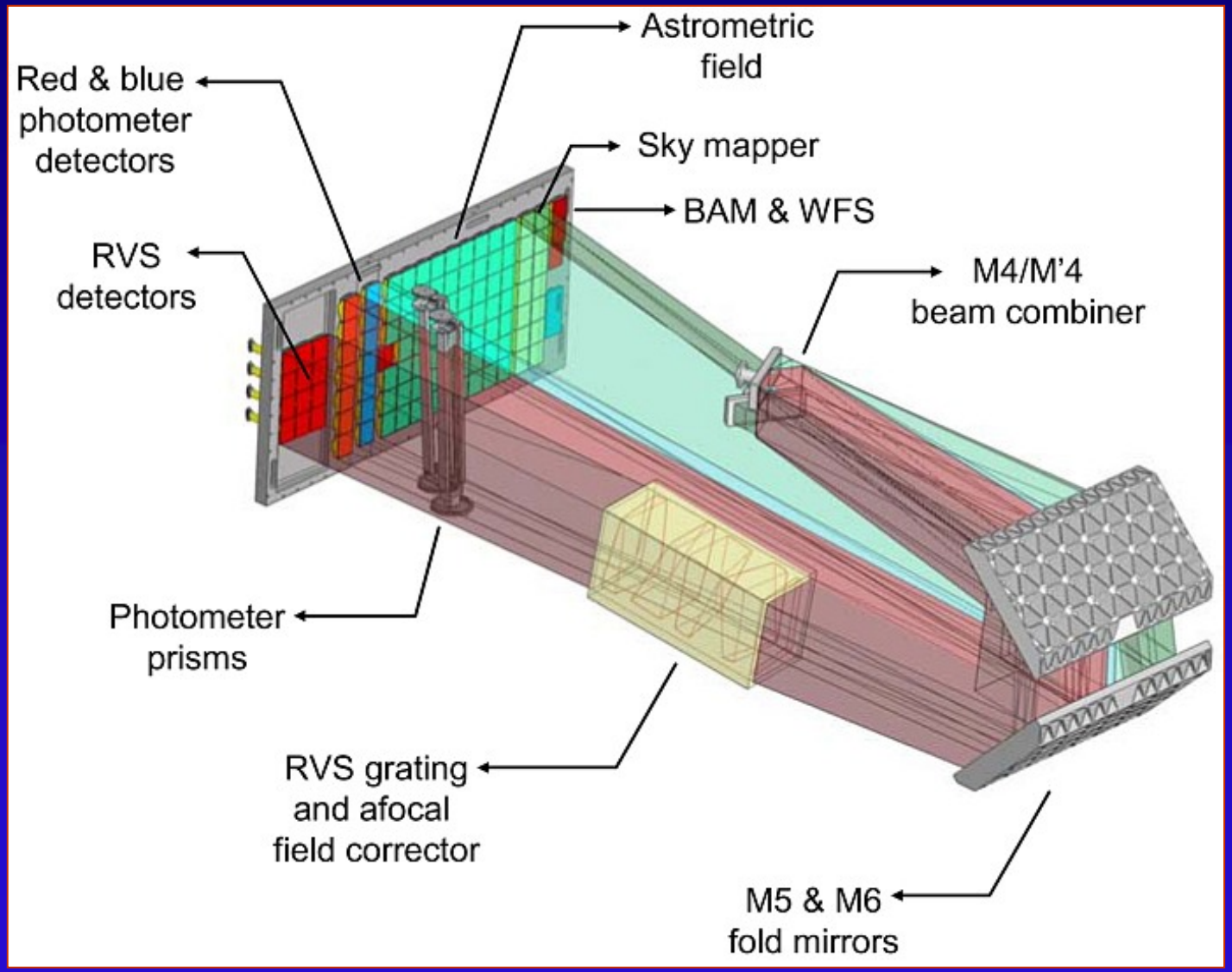
Gaia : telescopes and detector

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



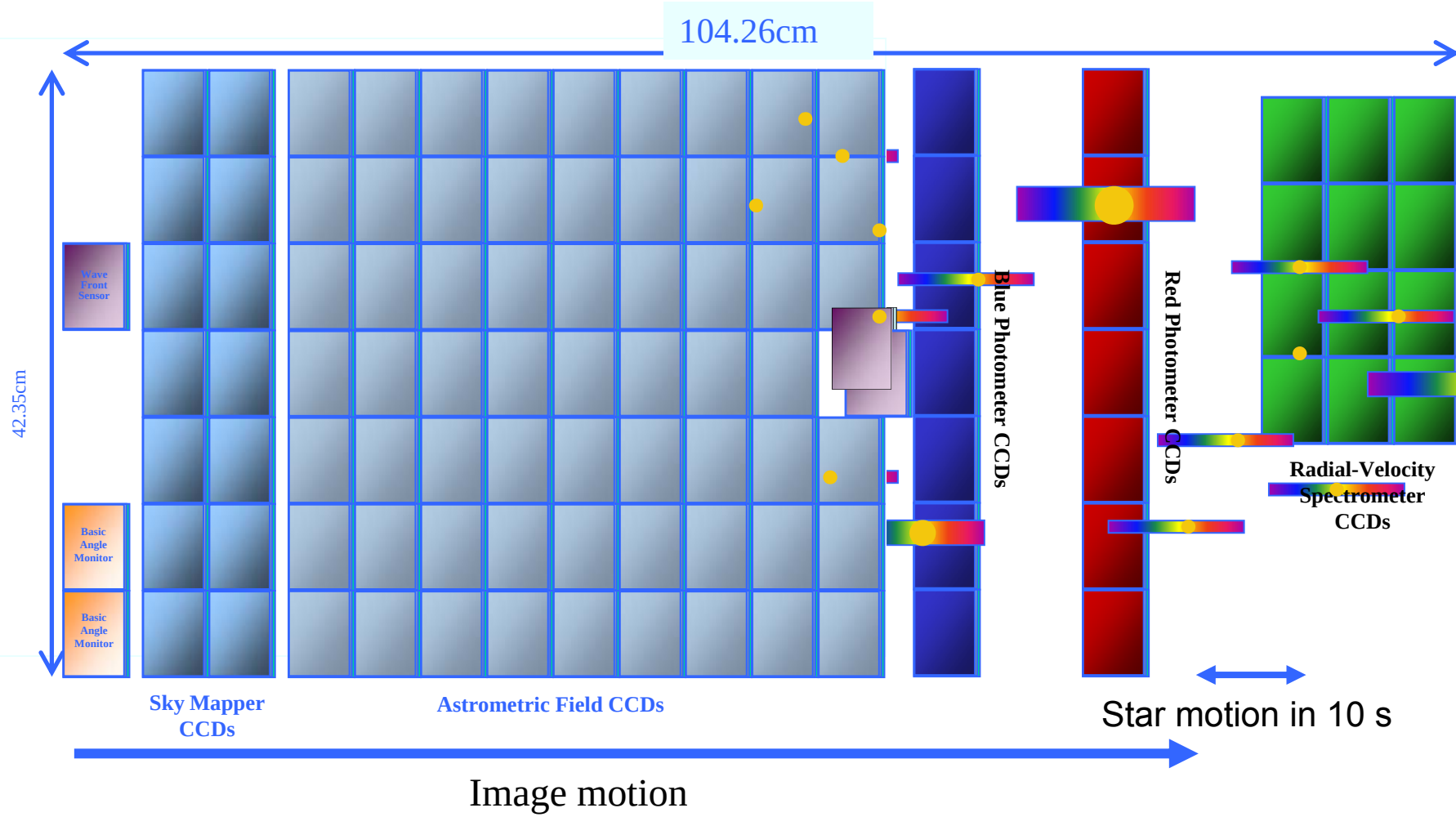
- single focal plane
- 106 CCDs
- 1 Gigapixel
- 0.93 x 0.42 m^2

Detection and measurement systems



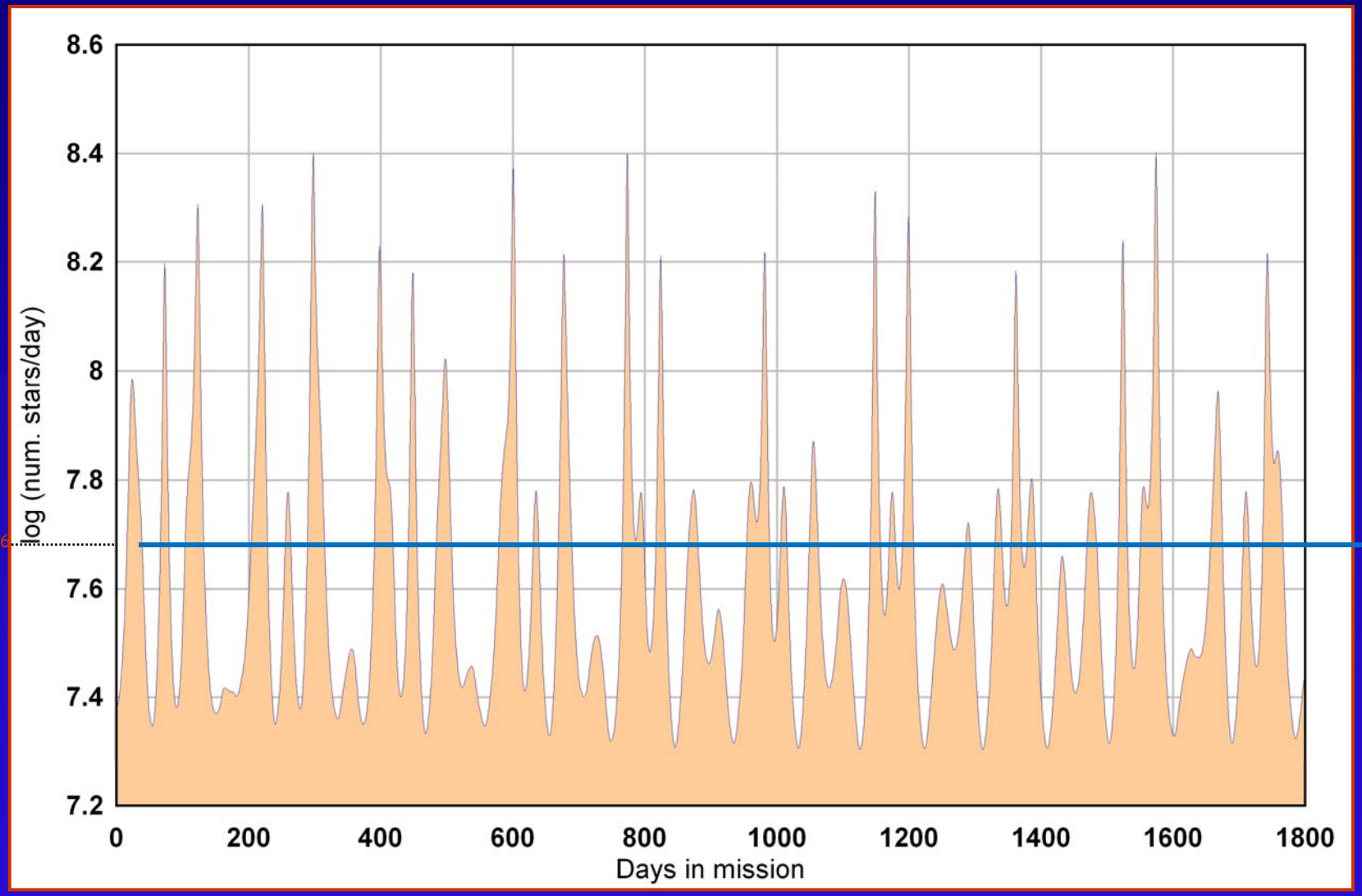
Multiplexing observations

106 CCDs , 938 million pixels, 2800 cm^2



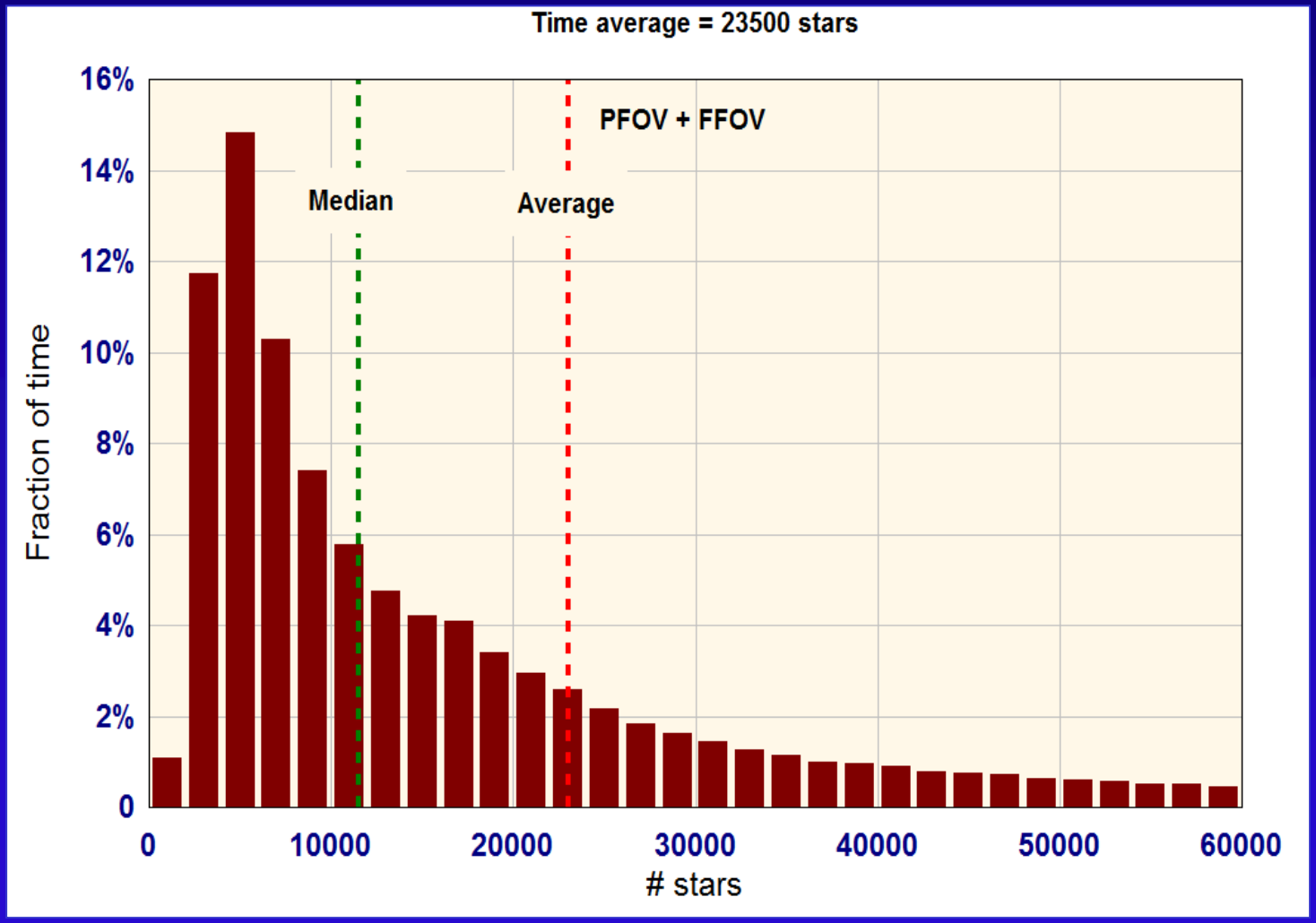
Number of sources per day

- Number of sources detected per day (log scale) during the mission



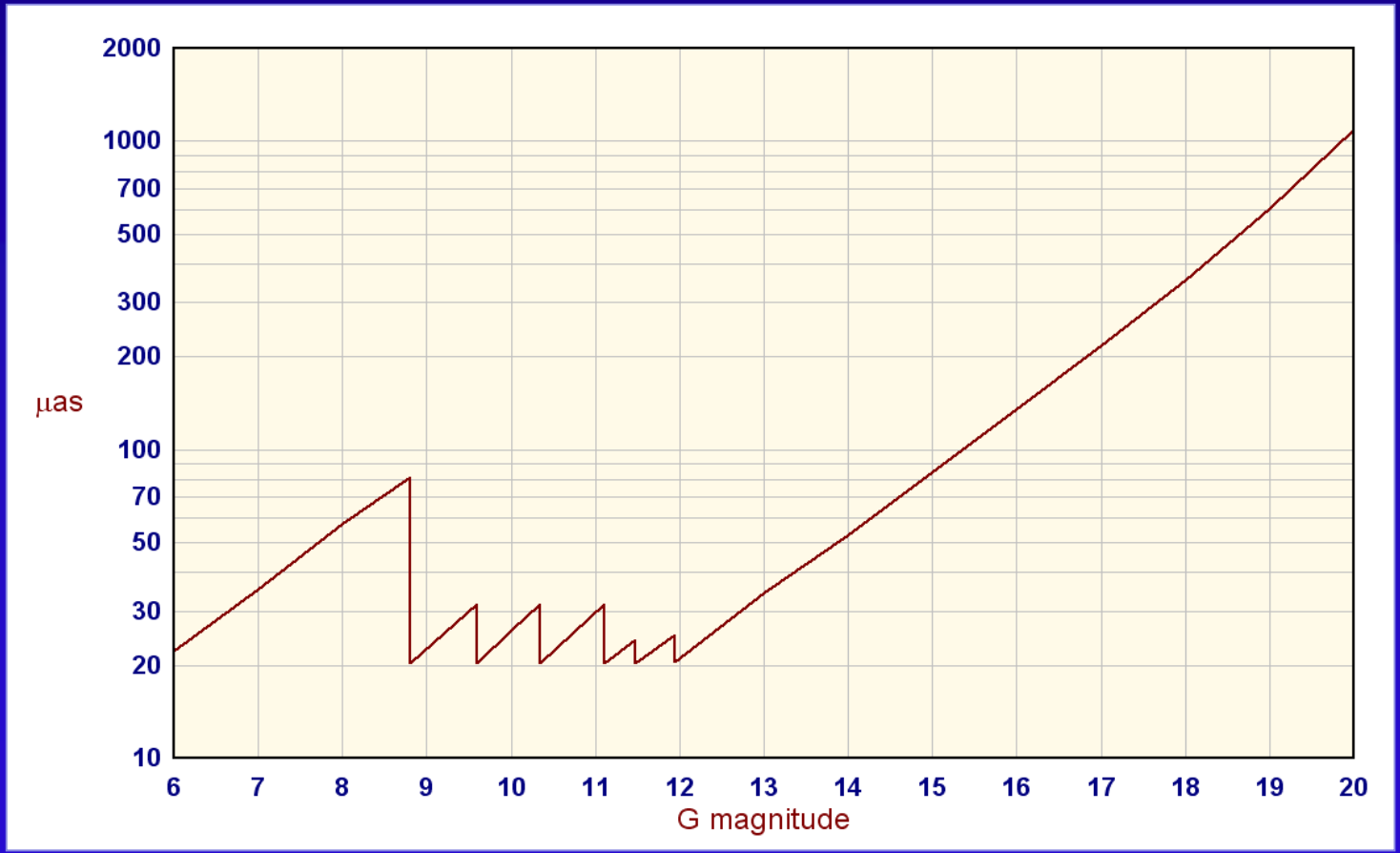
Number of stars in the FOVs

- # stars measured at any time in the combined FOVs

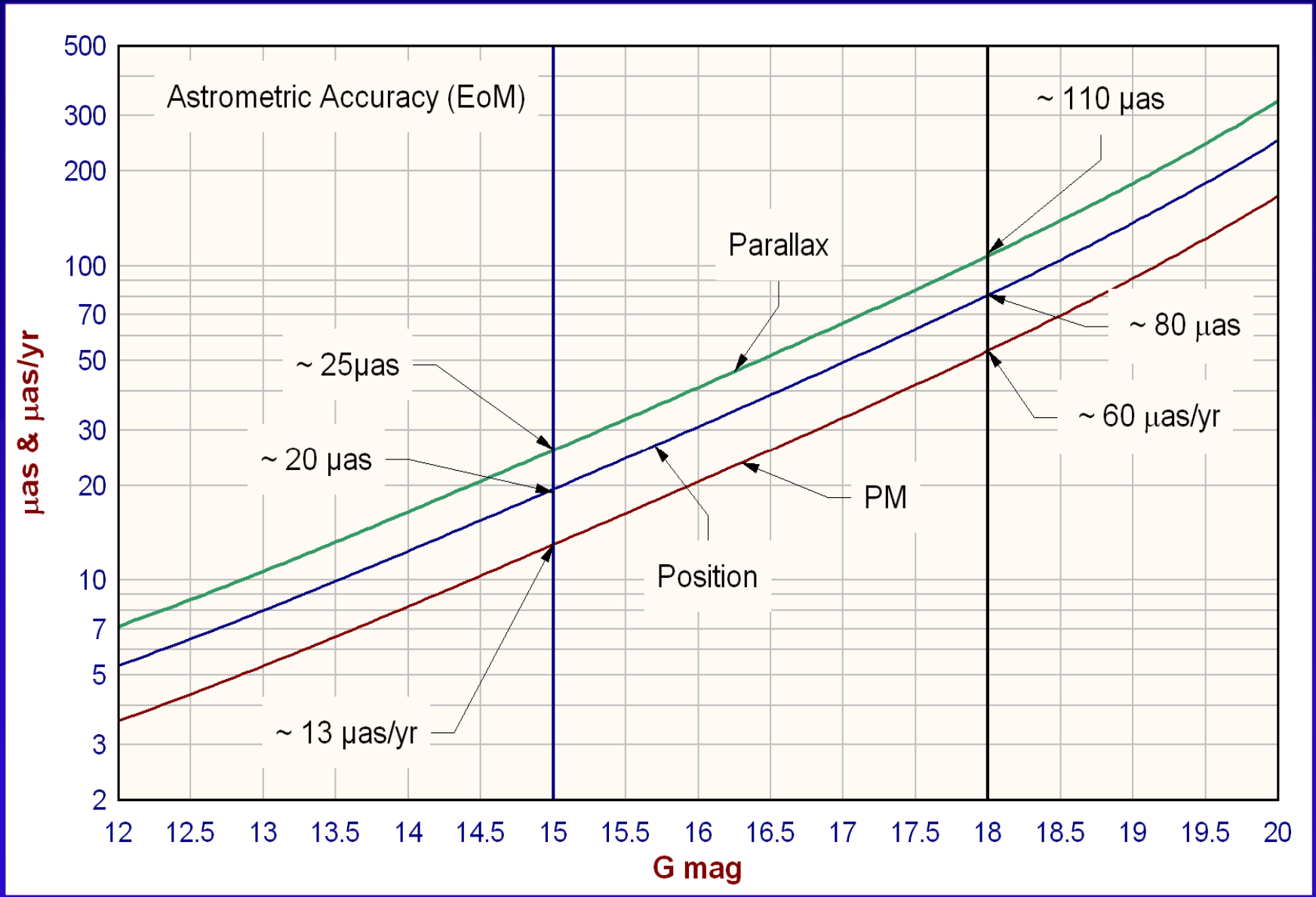


Astrometric accuracy: single transit

- Single observation accuracy ➔ orbit, solar system
  - one field transit: integration over 9 AF CCDs
  - point source, 1D astrometry

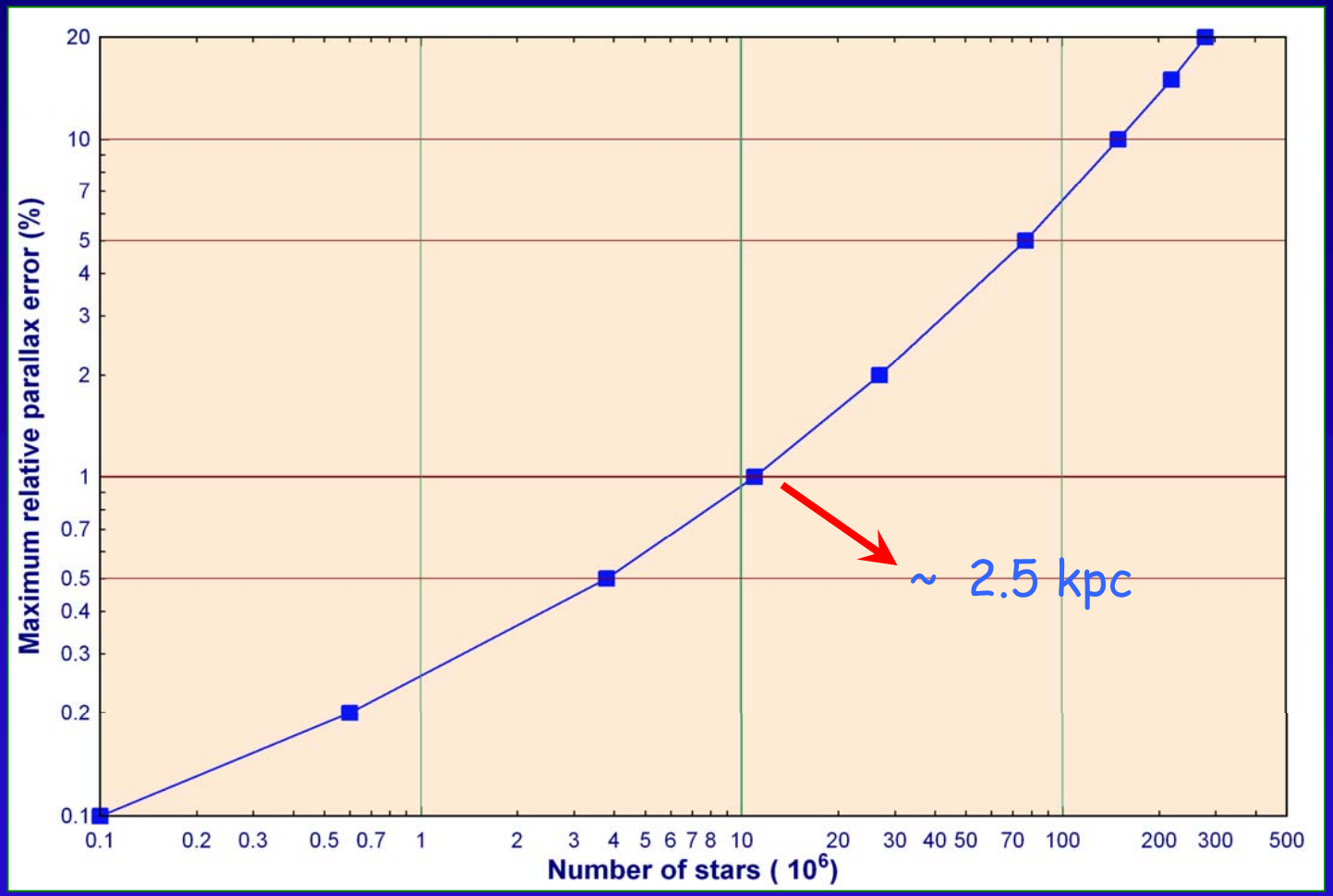


Astrometric Accuracy : EOM



Distances for stellar physics

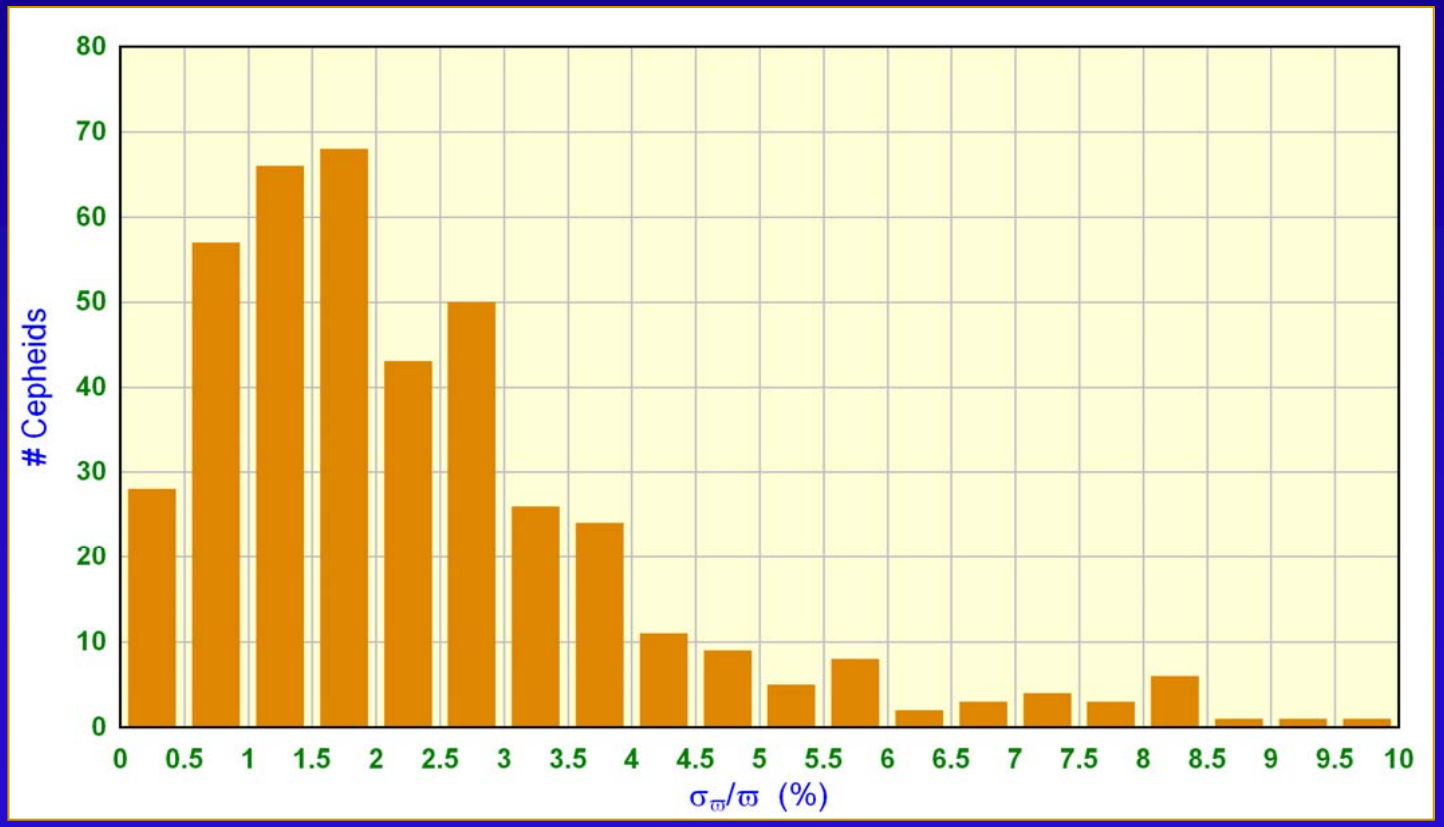
- Accurate distances through the Galaxy



Recall: Hipparcos : 20,000 stars with $\sigma_\pi/\pi < 10\%$

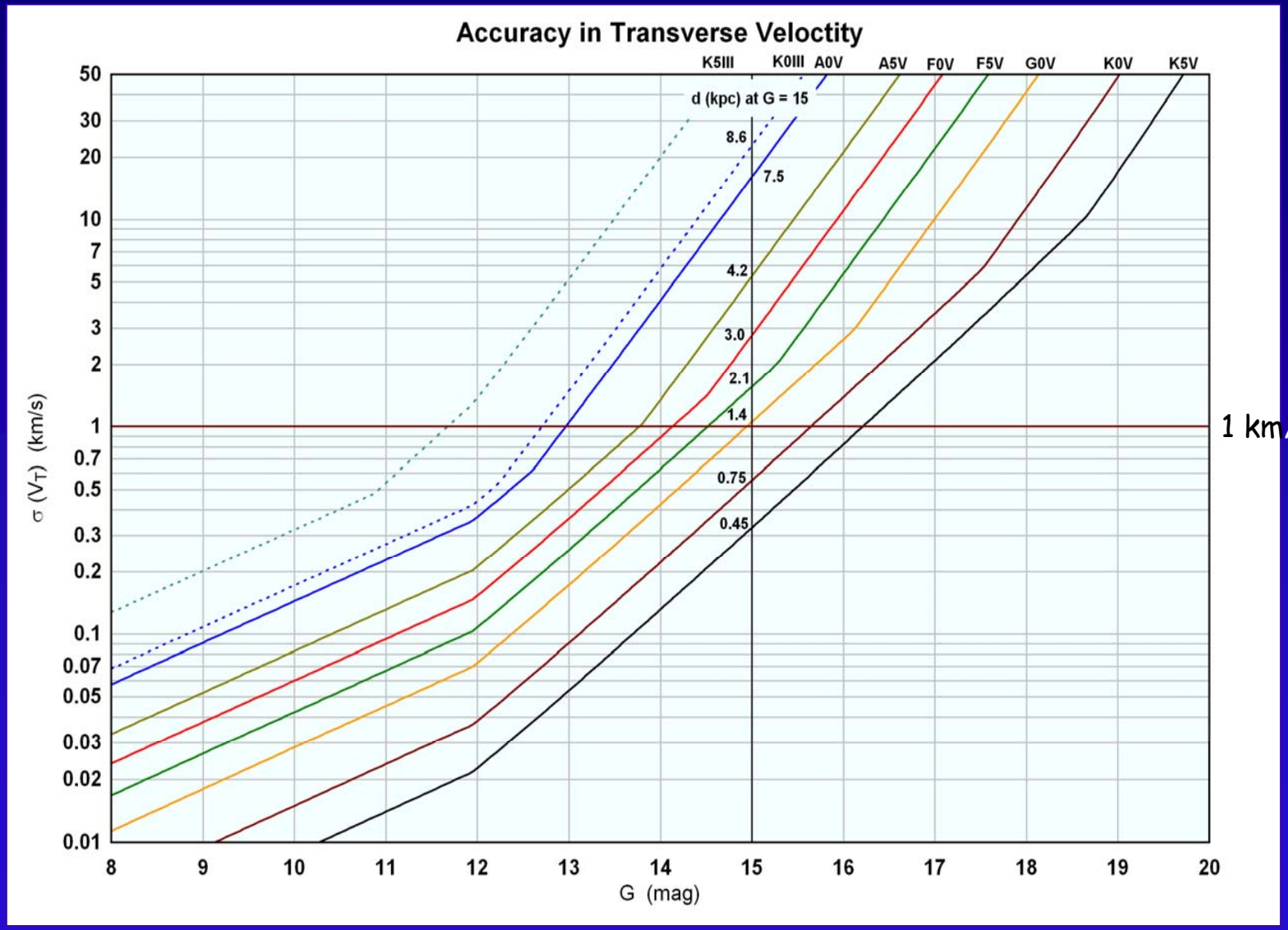
Cepheids with Gaia

- 15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc
  - bright enough (V < 14)
- In the plot : 400 galactic cepheids from David Dunlap DB
  - distance and magnitude ➔ Gaia predicted accuracy for parallax



F. Mignard 2002, 2009

Transverse velocity estimate with Gaia



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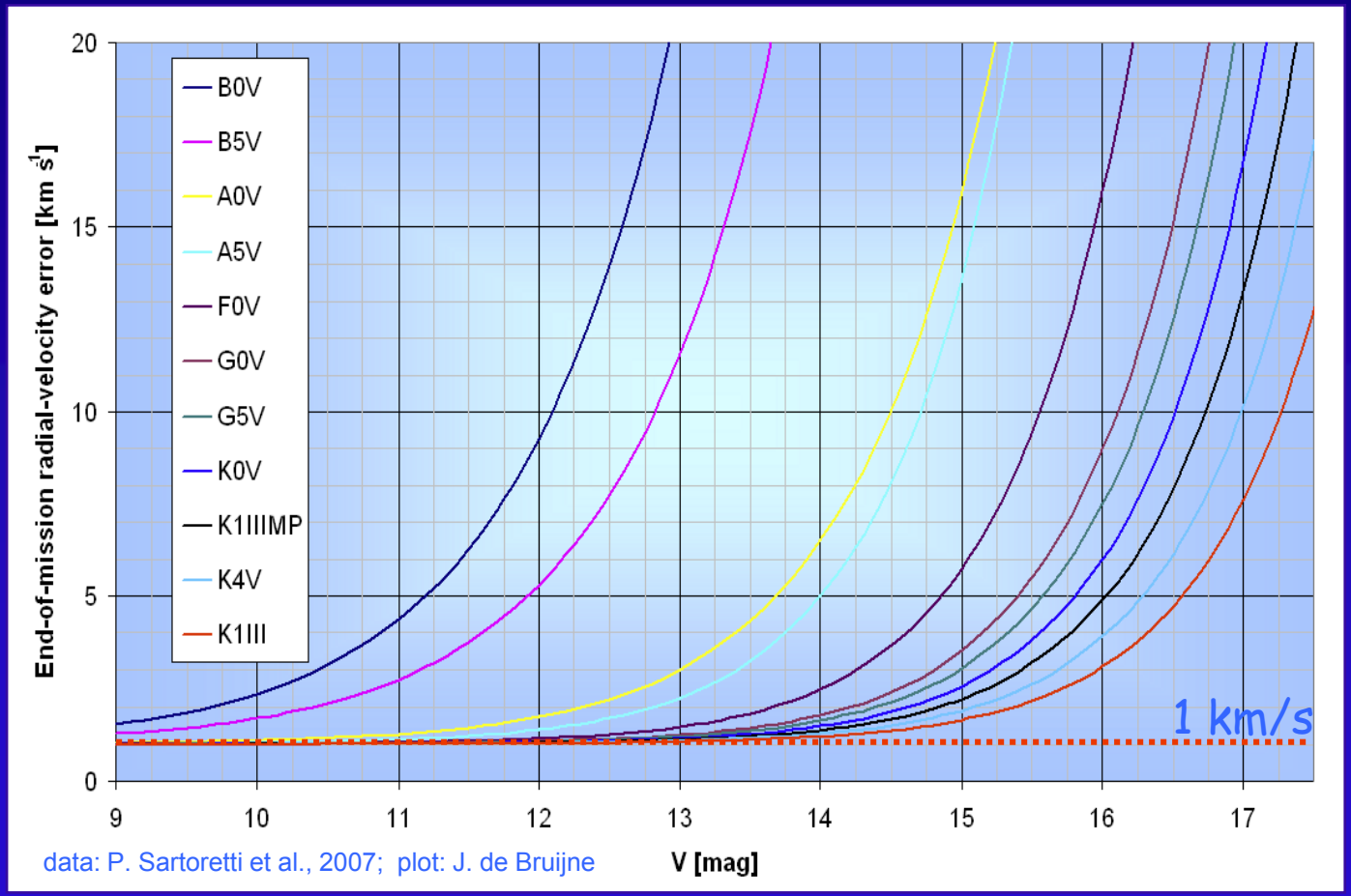
Radial velocity accuracy (EOM, km/s)

- Performances strongly dependent on stellar type
- Average of 40 transits (*i.e* 120 CCD crossings)

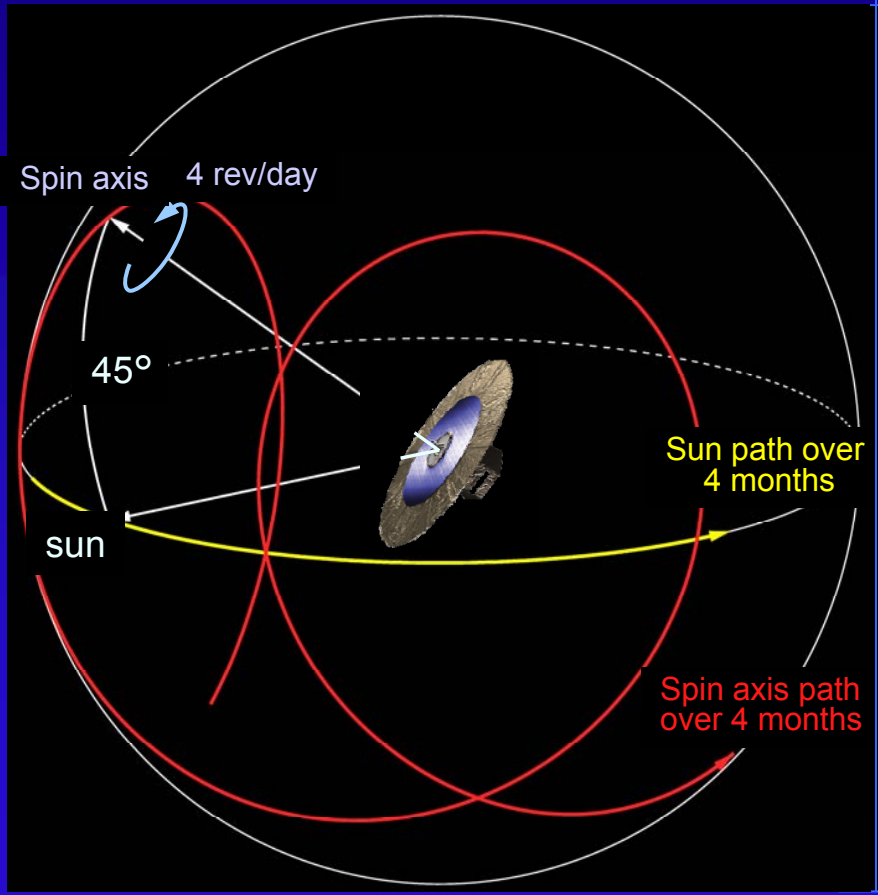


RAVE : $\langle V_r \rangle$ ~ 2 km/s, 9<I<12

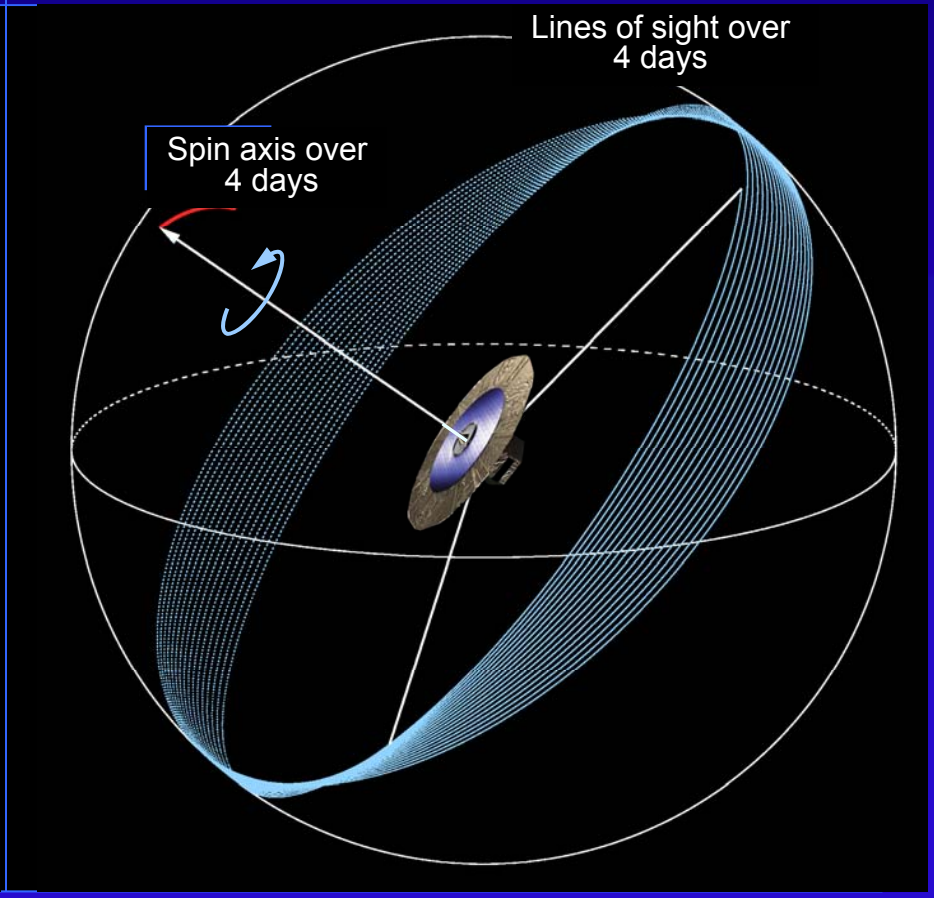
Sky coverage

- The Scanning law is optimized to explore the same area at more or less regular intervals ➔ parallax, proper motions, variability, orbits
- The scan direction must allow alpha and dec measurements
- The along-scan speed must be constant
- Mathematically: a set of two differential equations

Motion of the spin axis



Sky covered over 4 days



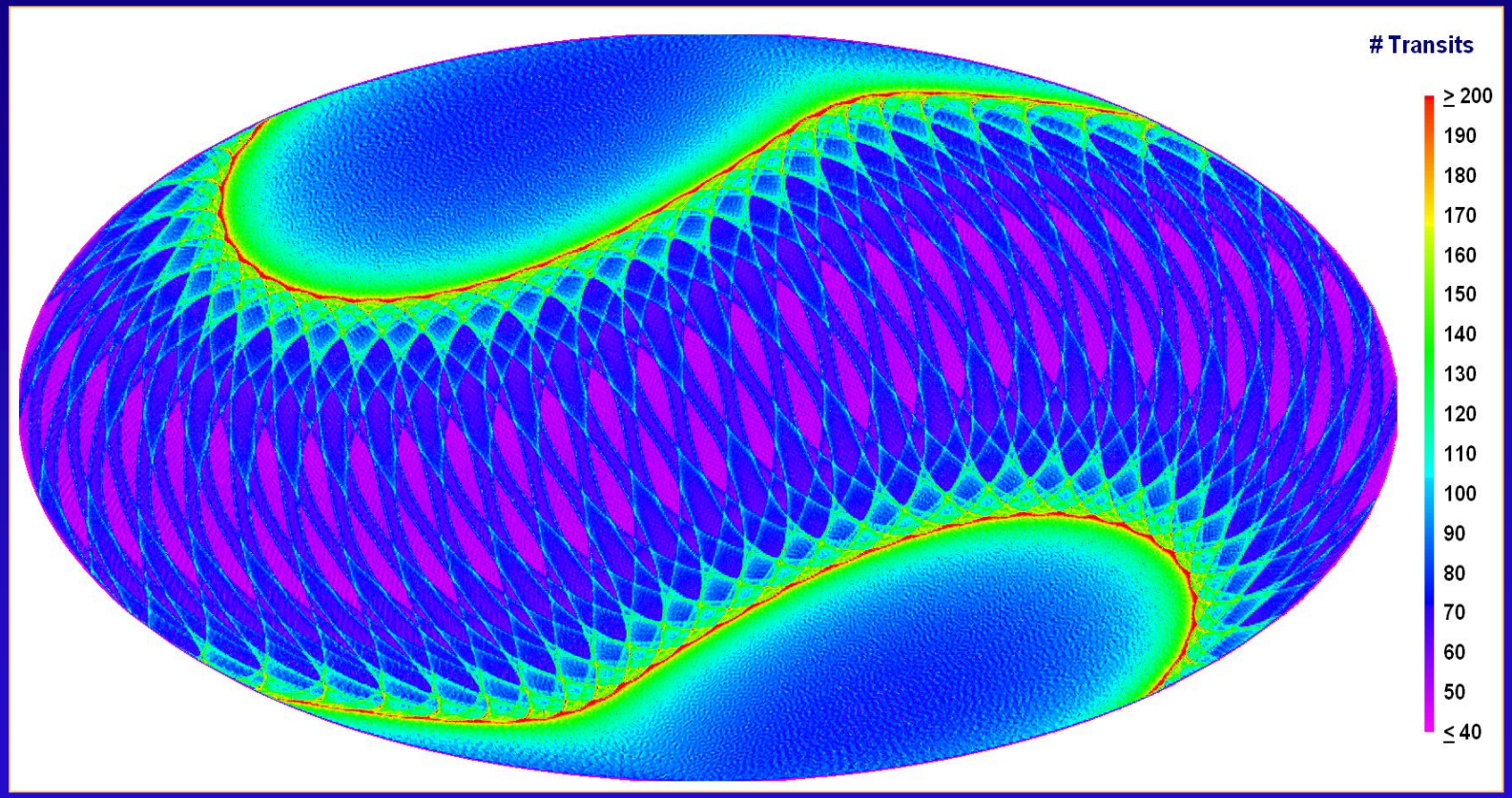
Crédit : L. Lindegren

Sky coverage

- The Scanning law is optimized to explore the same area at more or less regular intervals ➔ parallax, proper motions, variability, orbits
- The scan direction must allow α and δ measurements
- The along-scan speed must be constant
- Mathematically: a set of two differential equations
  - **Three independent rotational motions**

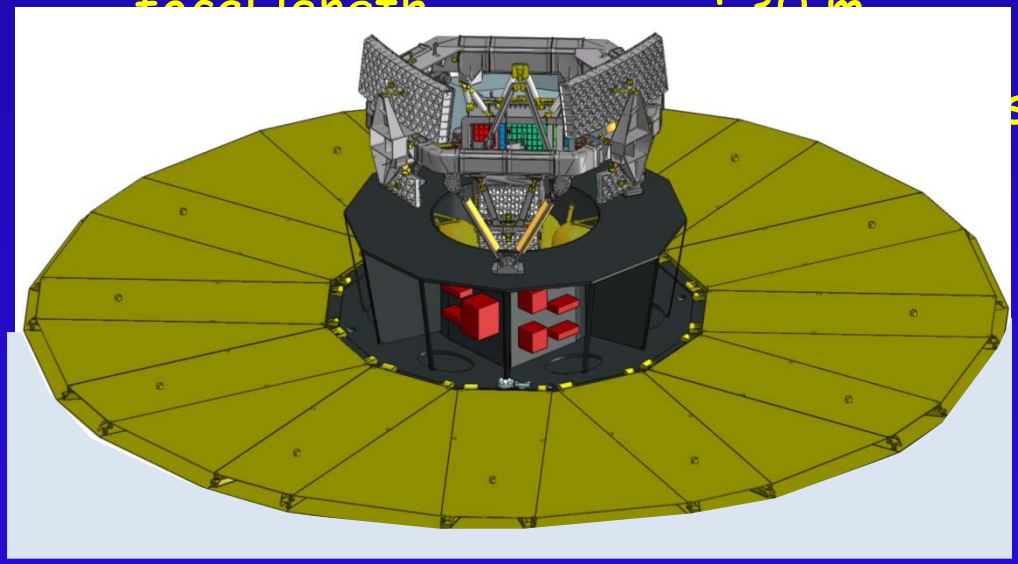
Sky coverage: Equatorial coordinates

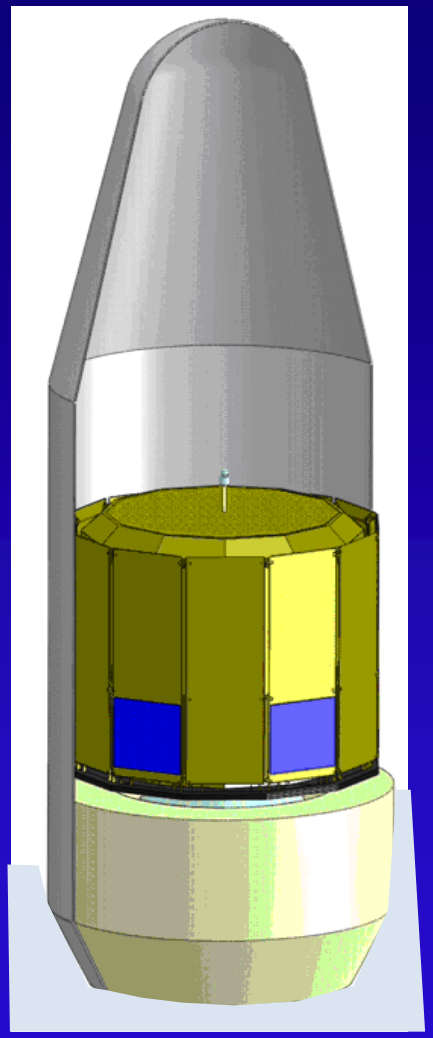
Transits during the mission



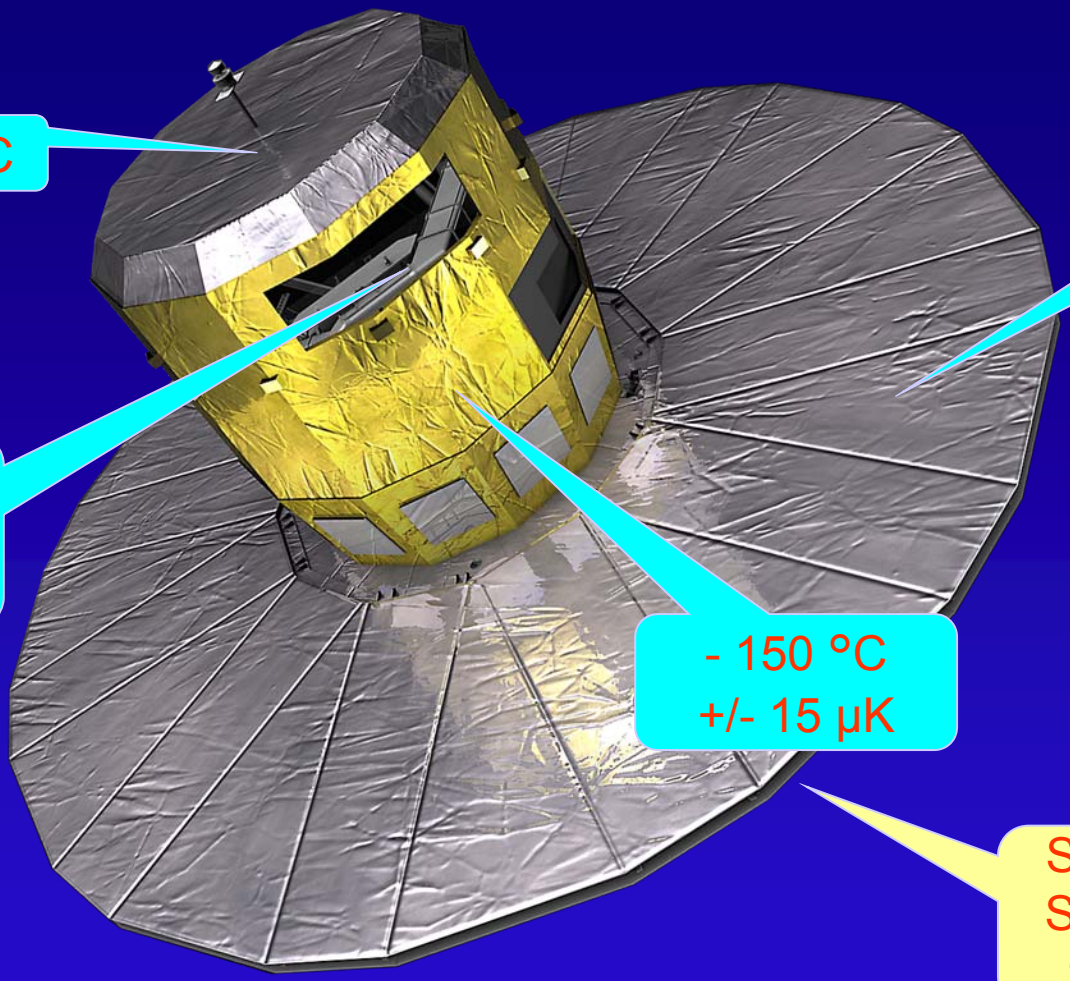
S/C main characteristics

- S/C launch mass : 2 t
- Power available : 2 kW
- S/C height : 3 m
- Sunshield diameter : ø = 10 m
- Payload
- - entrance pupil : 1.45 x 0.5 m²
- - focal length : 20 m
- - [illegible]s



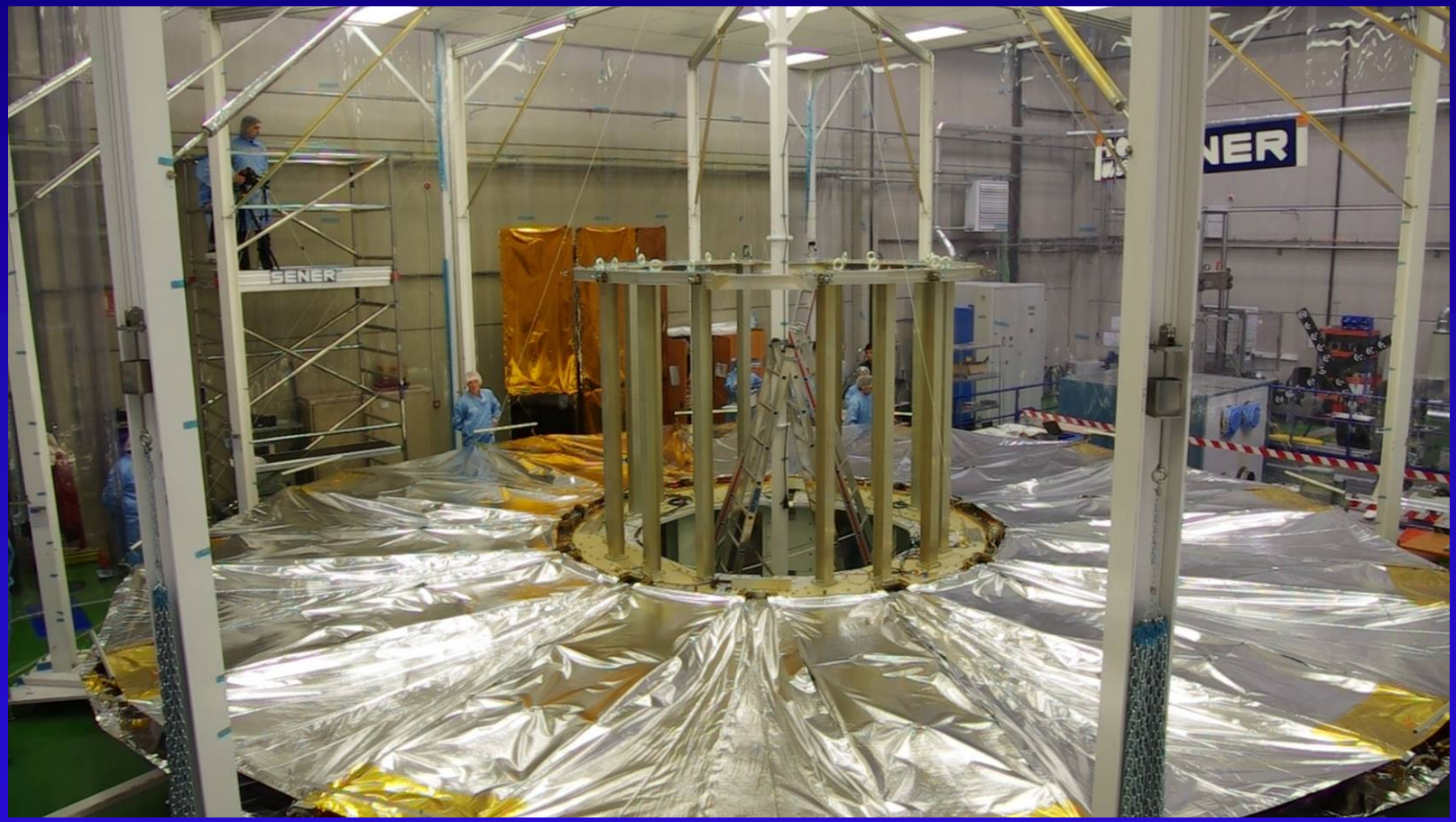


Thermal Insulation



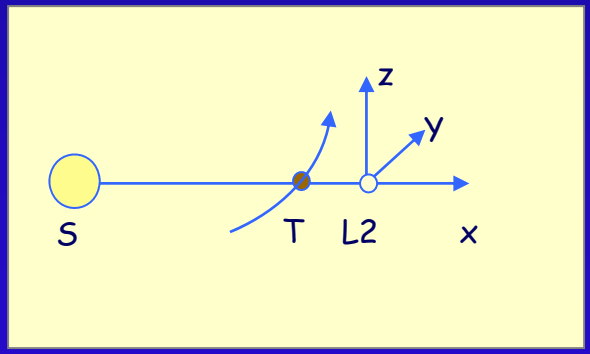
Credit: F. Chassat, Astrium

First full deployement test with new motor



Timeline of the mission

- Selection by ESA in 2000 (and confirmed in 2002)
- Prime contractor selected in February 2006
- Data analysis consortium formed in June 2006
  - selected by ESA SPC in March 2007
- Launch : summer 2013
  - from Kourou with a Soyouz rocket
- Orbit around L2
- Continuous observation to 2018
- End of data processing to 2020
  - data base of 1pB of volume
  - volume of computation ~ 10^{21} FLOPS
- Results and data available in 2020
  - one or two intermediate releases foreseen




Thanks for your attention
esa