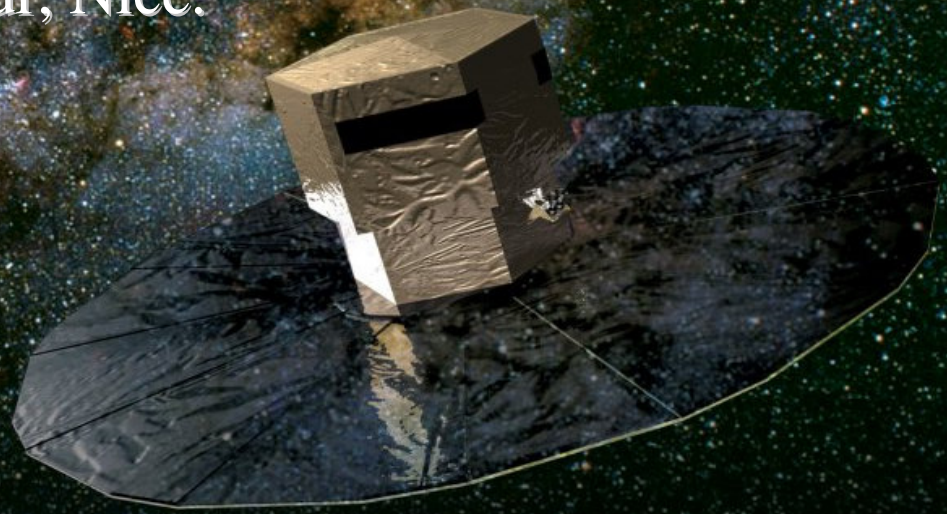
Astrometry : 1980-2020

From Hipparcos to Gaia

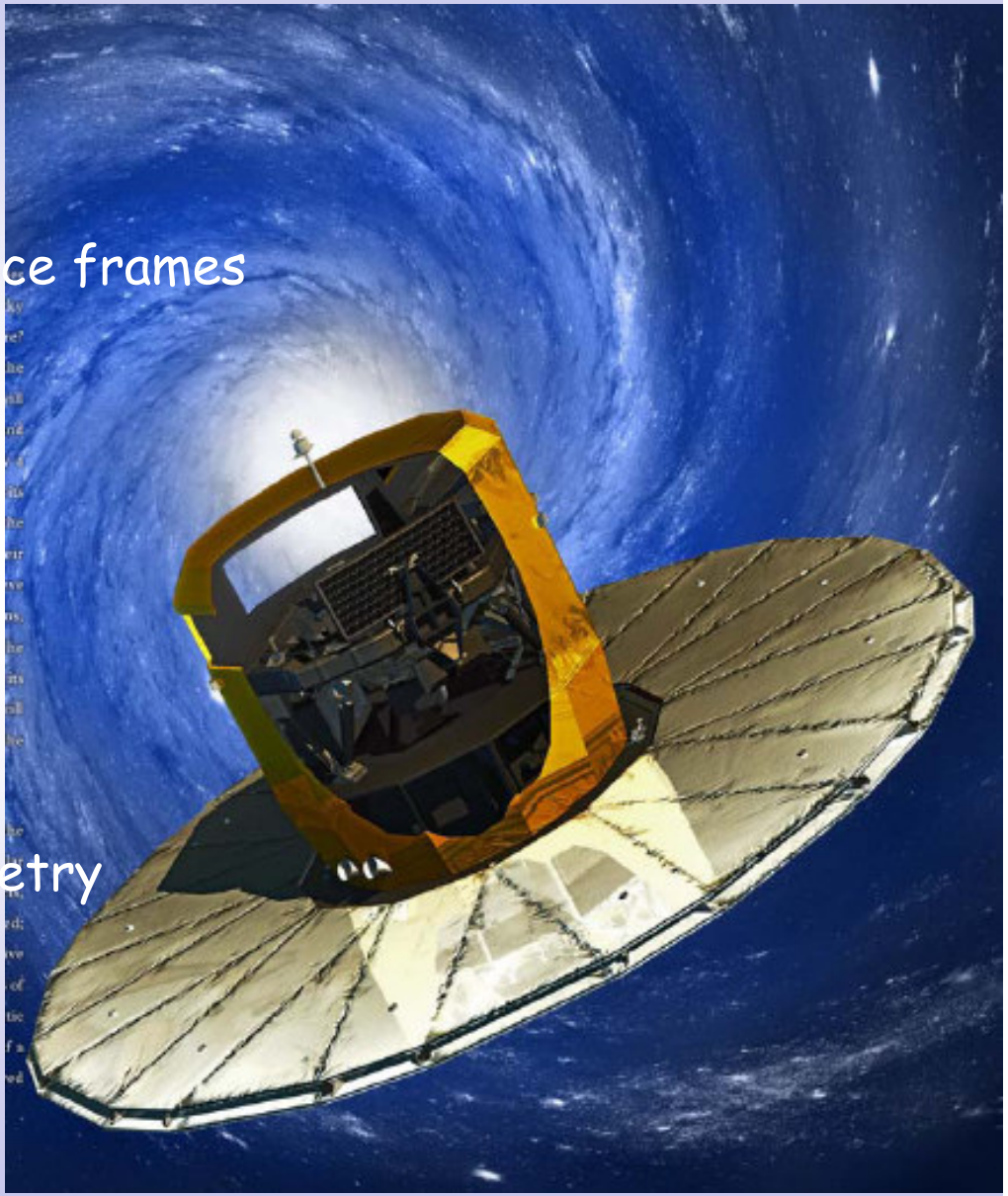
F. Mignard

Observatory of the Côte d'Azur, Nice.



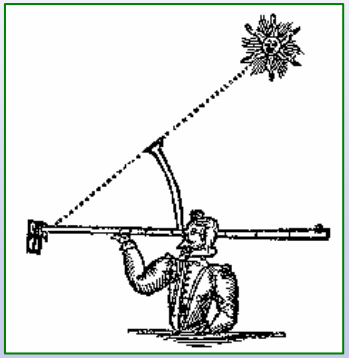
Outline

- Astrometry
- Fundamental catalogues and reference frames
- Absolute parallaxes
- Hipparcos and its legacy
- Gaia in brief
- Summary : the golden age of astrometry



What is astrometry?

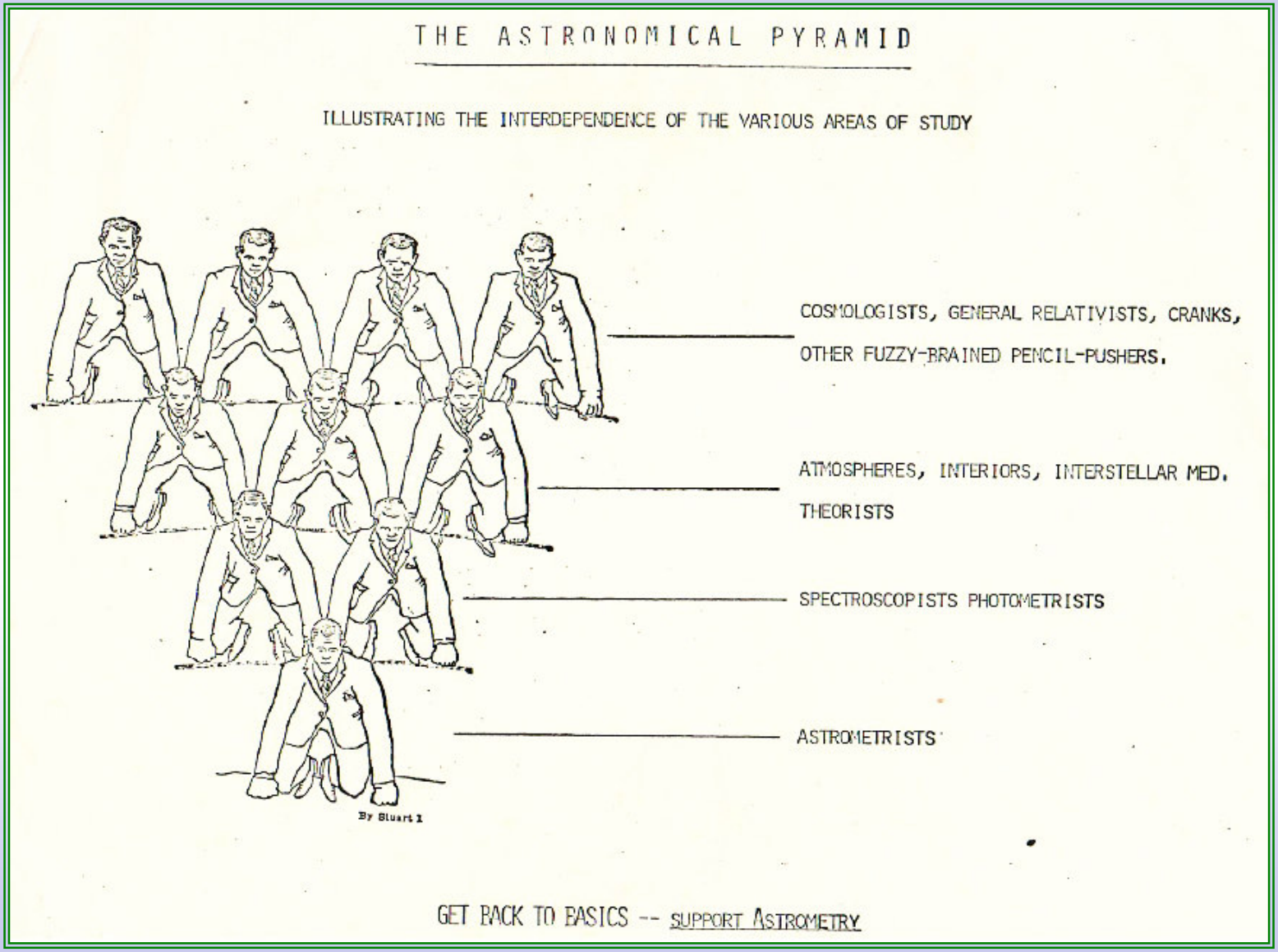
- Astrometry deals with the measurement of the positions, distances and motions of astronomical objects on the celestial sphere.
  - Global or wide field astrometry ➔ reference frame
  - Local or small field astrometry ➔ parallaxes, binaries
- Astrometry relies on specialized instrumentation and observational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



Astrometry 1975

- Reference system based on the FK4
  - dynamical system
  - 1500 stars, accuracy of 0."1
  - based on principles more than 200 years old
- Parallaxes with small field astrometry
  - ~ 10000 stars with accuracy 0"01
  - extensive photographic program
- The Carte du Ciel officially terminated in 1970 (started in 1887)
- Start of CCD observations
- Solar system distances with radar
- Satellite and lunar laser ranging still in infancy

Astrometry: a pre-Hipparcos diagram

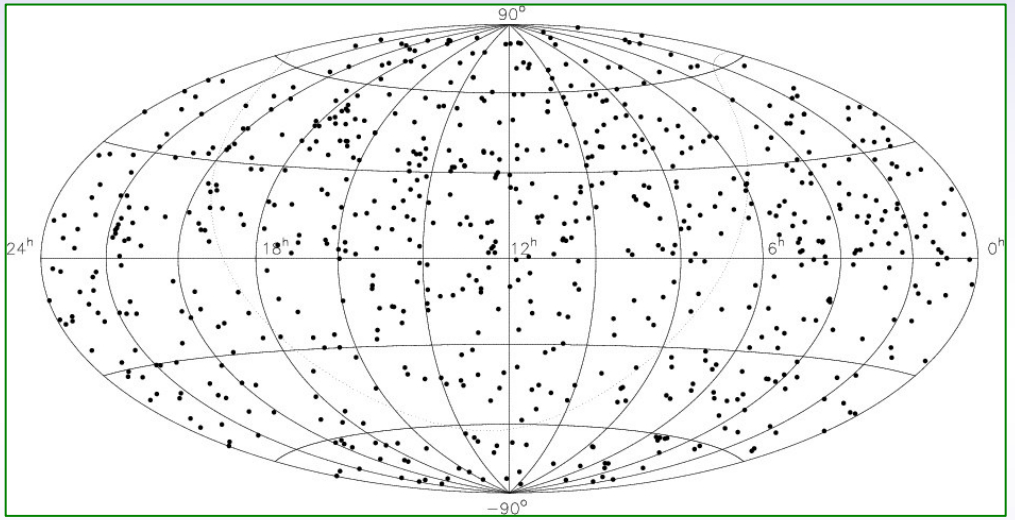


Circulated ca. 1974 by R. Probst, UVa

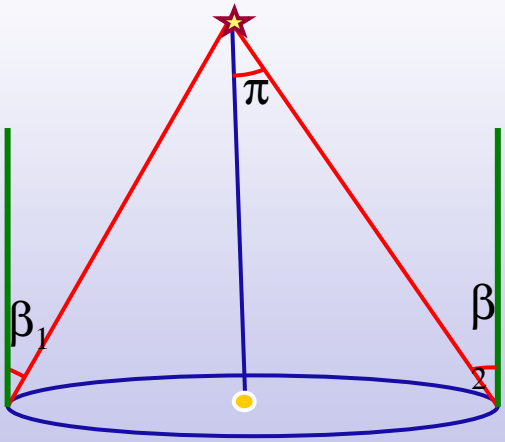
The astrometric revolution

- Two good reasons to do astrometry in space

Reference frame



Absolute parallaxes



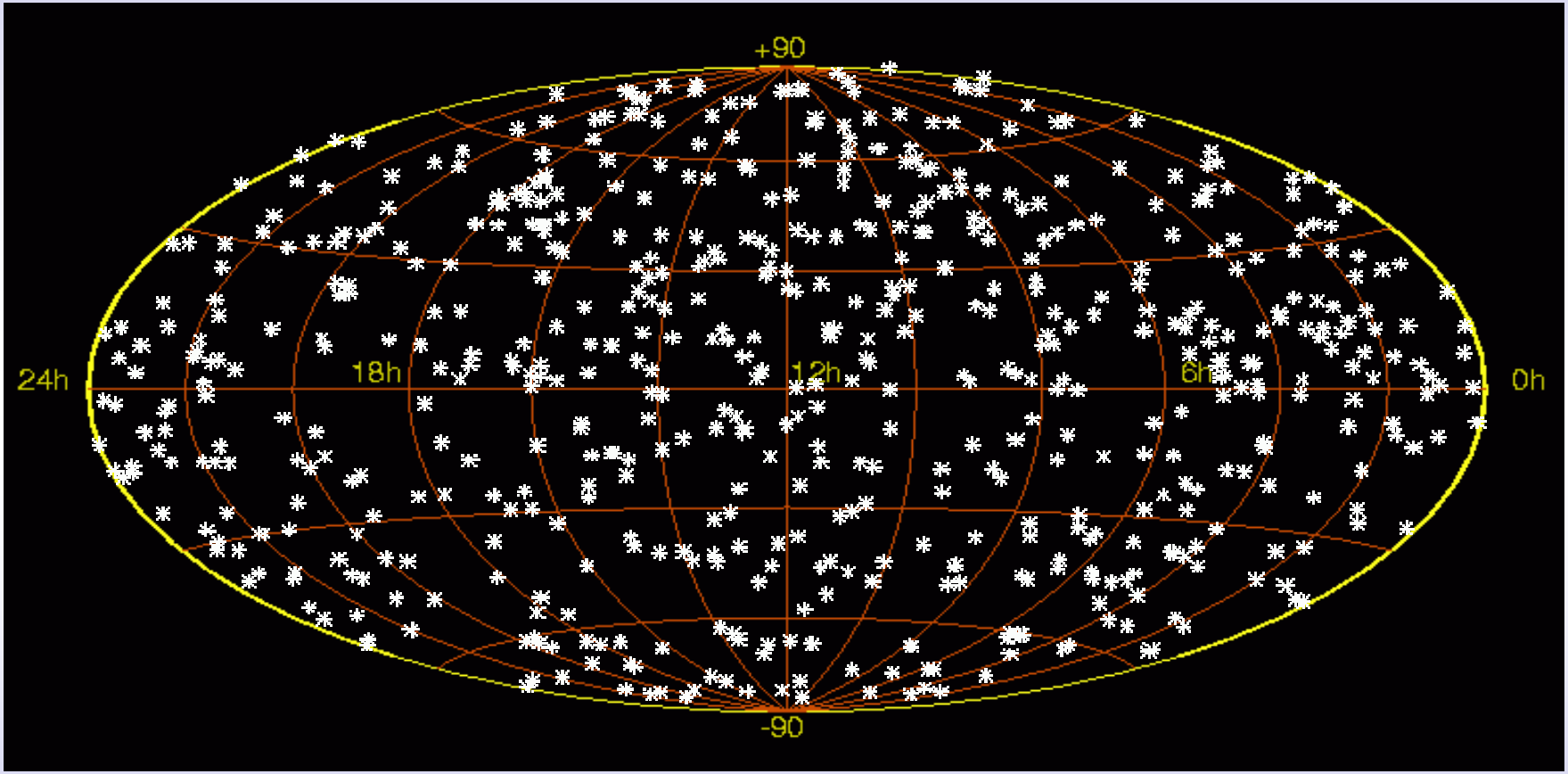
Reference frames

Reference Frames

- Astronomical catalogues vs. Fundamental catalogues
  - Large full sky astronomical catalogues widely available in 1970
    - BD (1860) & Cordoba (1890) with 700,000 stars
    - HD (Henry Draper) since 1920 with 230, 000 entries
    - SAO (1966) with 270,000 stars with positions and PM
  - Positions and PM based on an existing reference frame

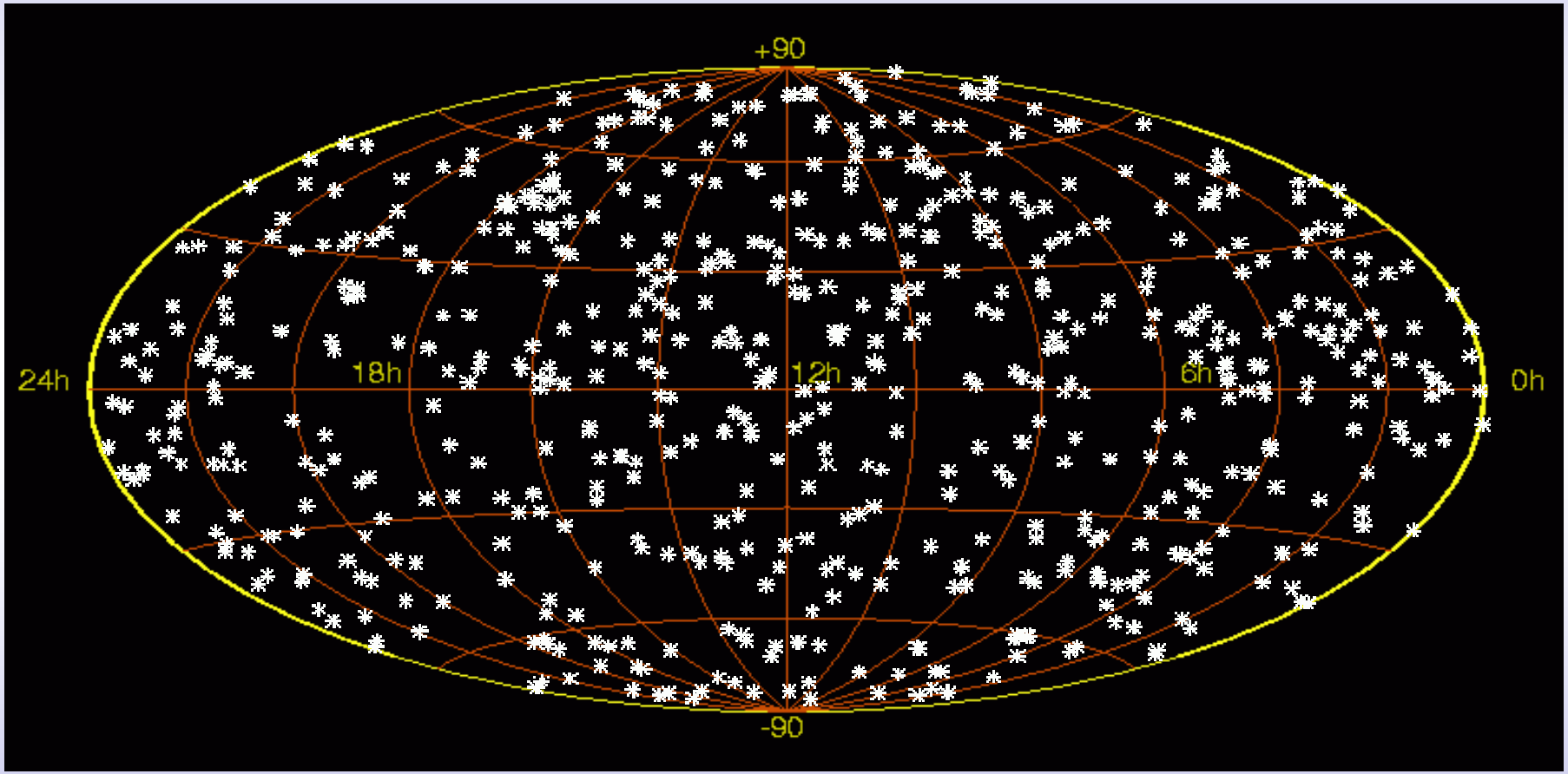
Reference frame : standard view

- Pre-existing reference graticule



Reference frame : fundamental view

- Stellar sources as fiducial points



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
- 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 for one epoch
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	

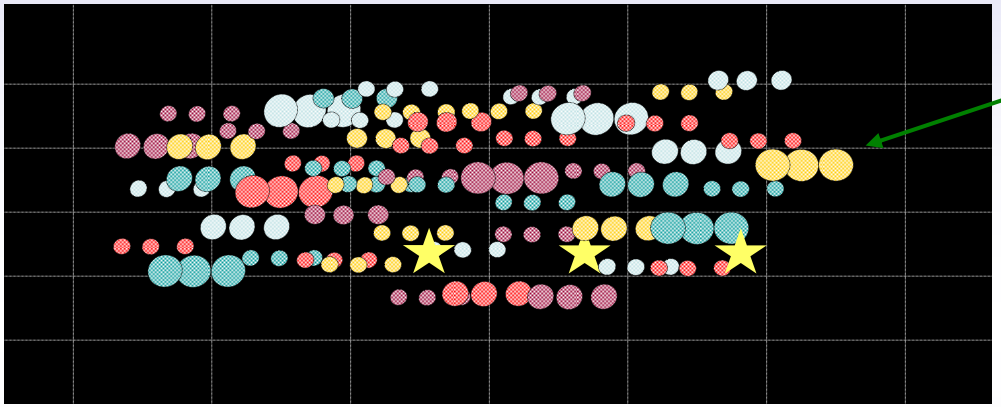
Limitation of the classical approach

1. 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
2. System defined with equator and equinox
   - precession and nutation modelling
     - solution: fixed frame not linked to solar system ➔ ICRS
3. Observations from the ground
   - many stations needed to cover the sky
   - disturbances from the atmosphere
     - solution: go to space ➔ Hipparcos

Parallaxes

Relative parallaxes

Insight of the technique in the Dialogo of Galileo (Galileo, Dialogue 3rd day)



Background stars

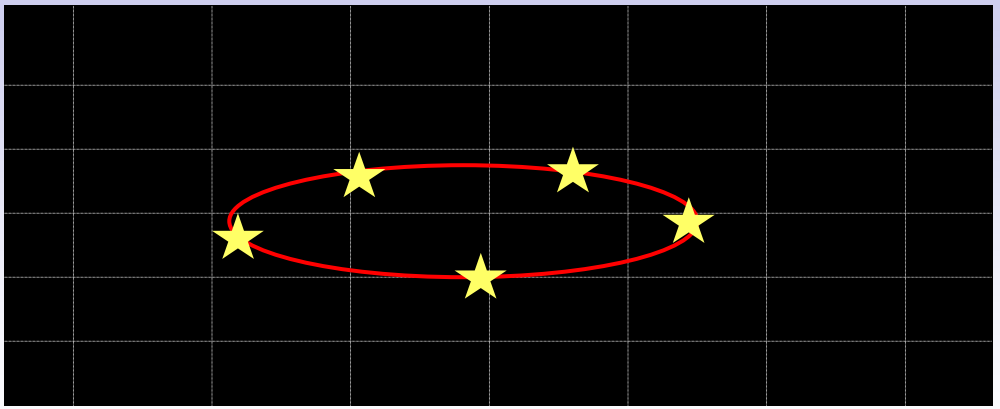
$$\pi_* = \pi_{rel} + \langle\pi\rangle$$

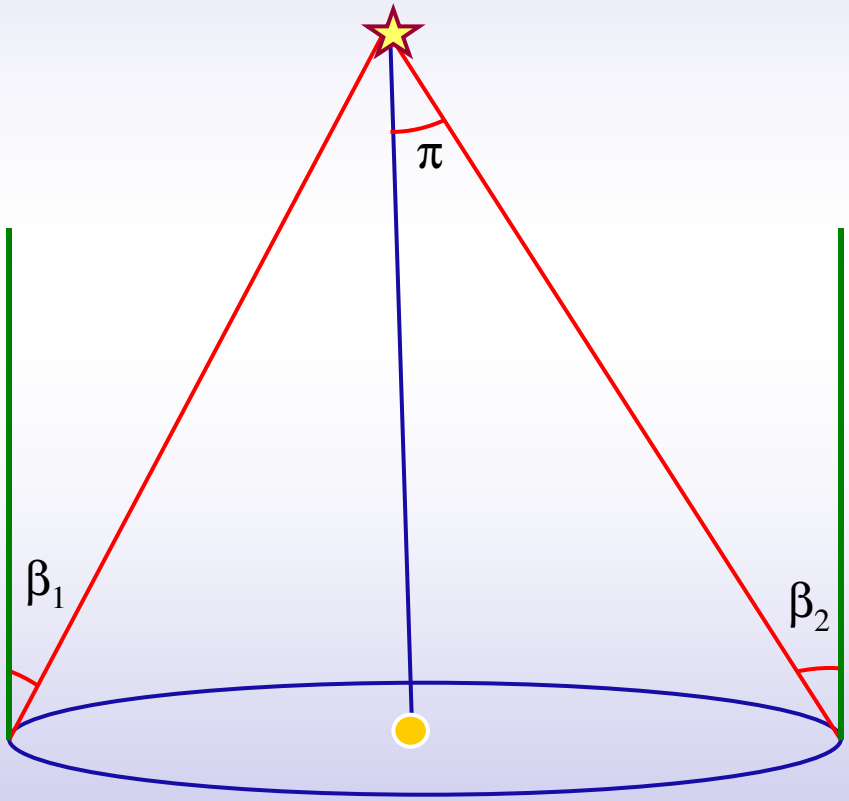
Relative measurements on a small field

assumption for the faint stars

- systematic errors as a result of a wrong $\langle\pi\rangle$
- not usable for distances > 100 pc

Absolute parallaxes



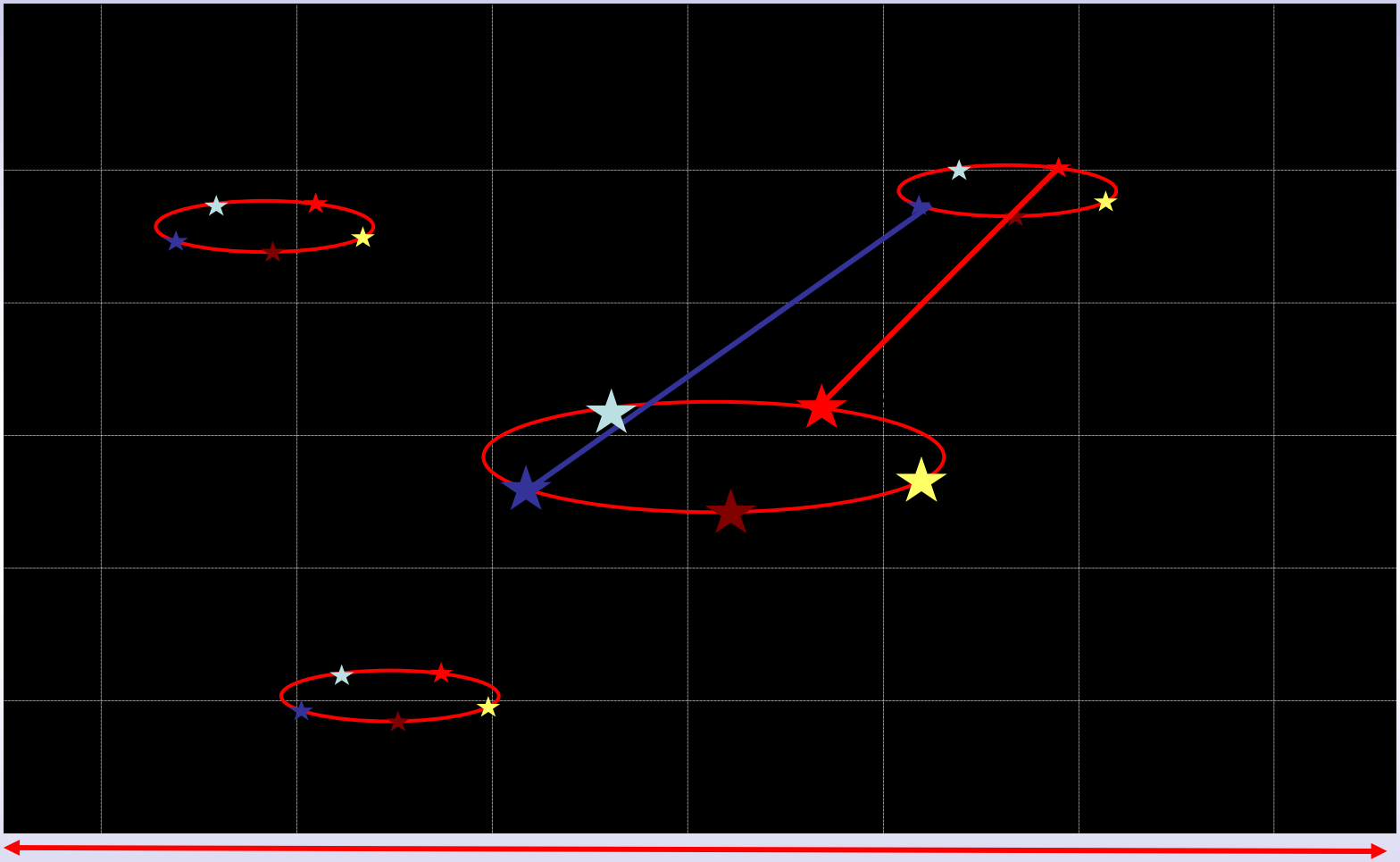


$$\pi = \frac{\beta_1 + \beta_2}{2}$$

Methods applied :

- measurements of declinations
- zenith distances
- virtually impossible from the Earth

Small field astrometry



~ 1 degree

Measurable quantity : $f(t)*(\pi_2-\pi_1)$ → $\pi_2-\pi_1$

Evolution 1850 - 1980

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

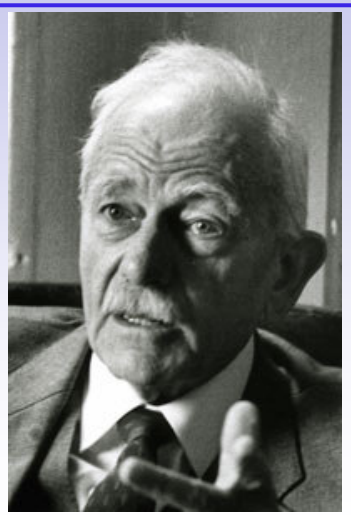
- Estimated error : 0".016

  ==> $\sigma(\pi)/\pi$ = 50% at 30 pc !

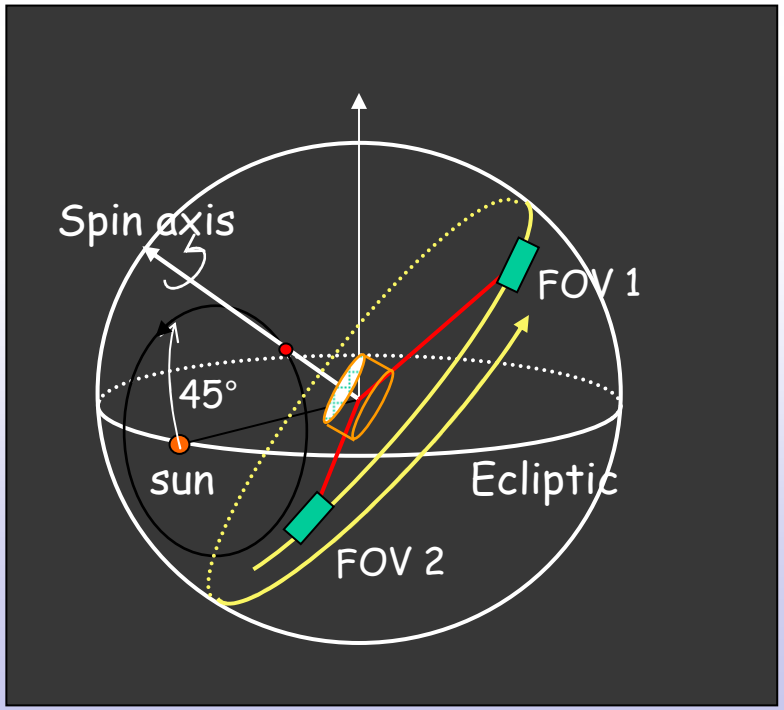
- Mean value of the parallaxes : 0".018

Most of these parallaxes have no individual meaning

A route to absolute parallaxes : Two fields of view

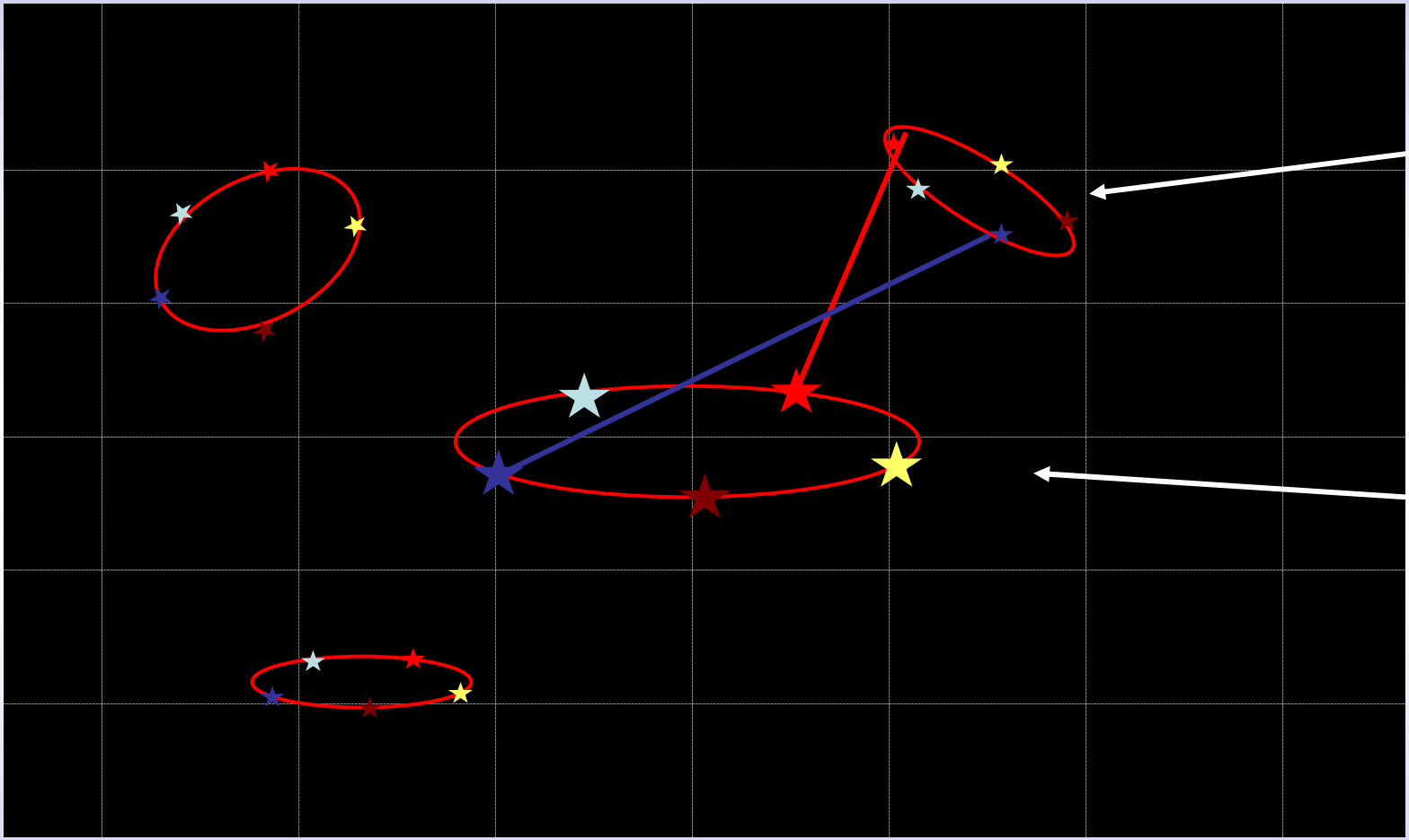


P.Lacroute
1906-1993



- 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

How parallaxes get absolute

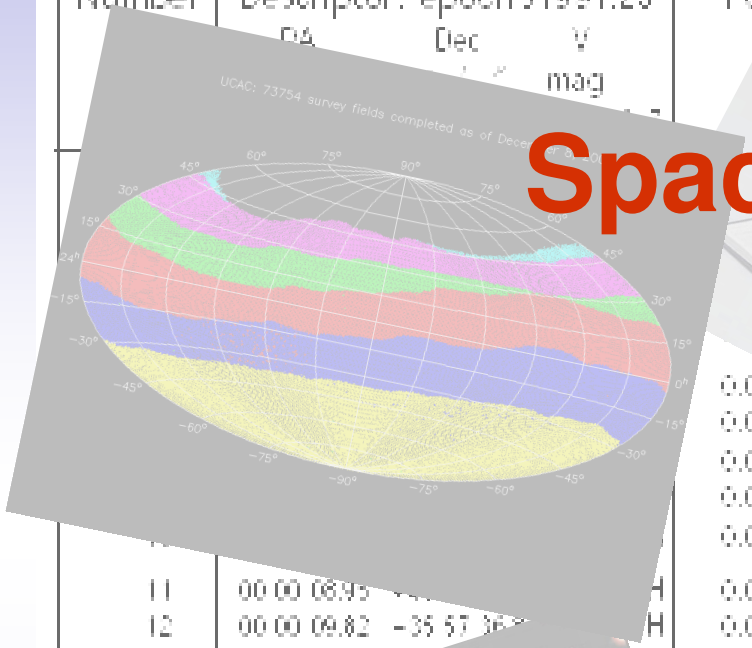


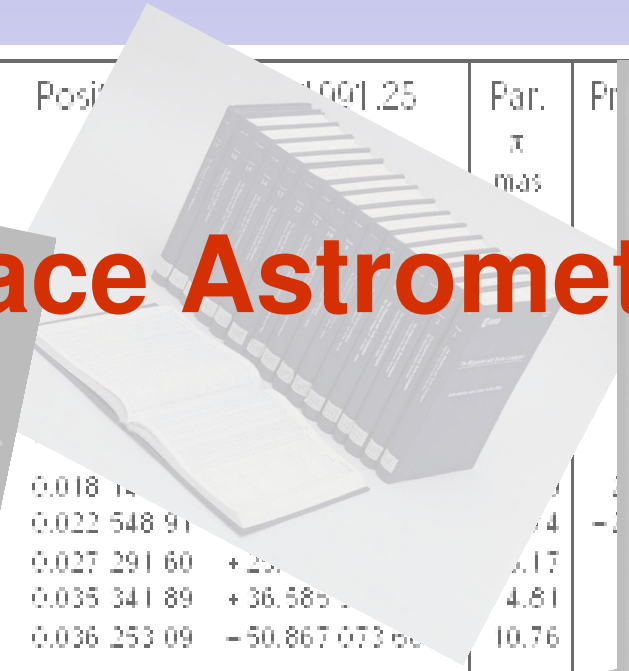
Measurable quantity : $f_2(t)*\pi_2 - f_1(t)*\pi_1$ → π_2 and π_1

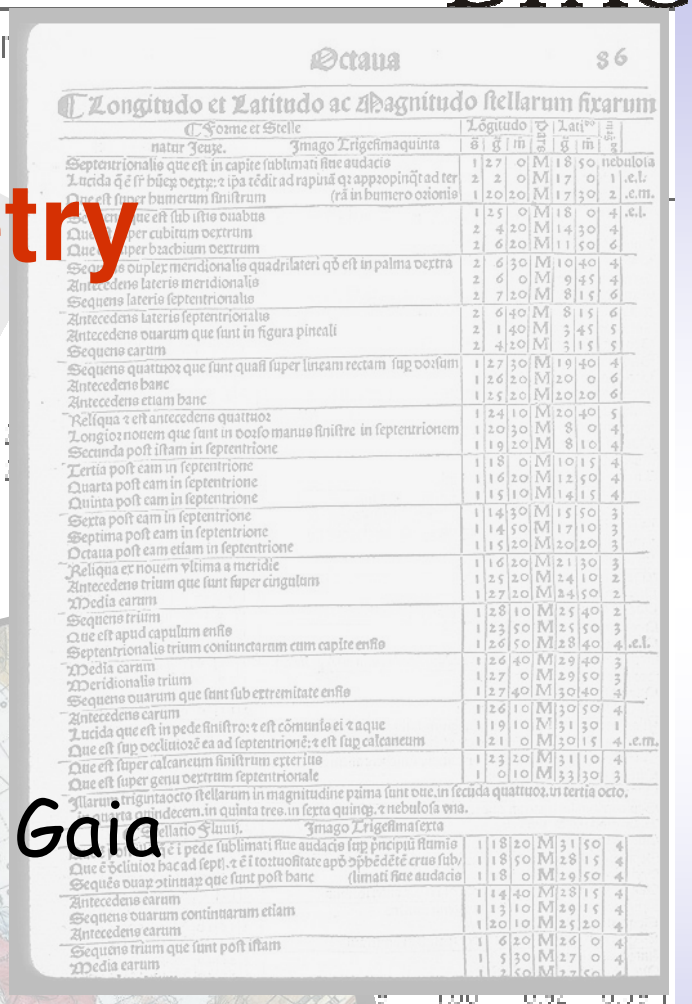
Observatoire de la Côte d'Azur

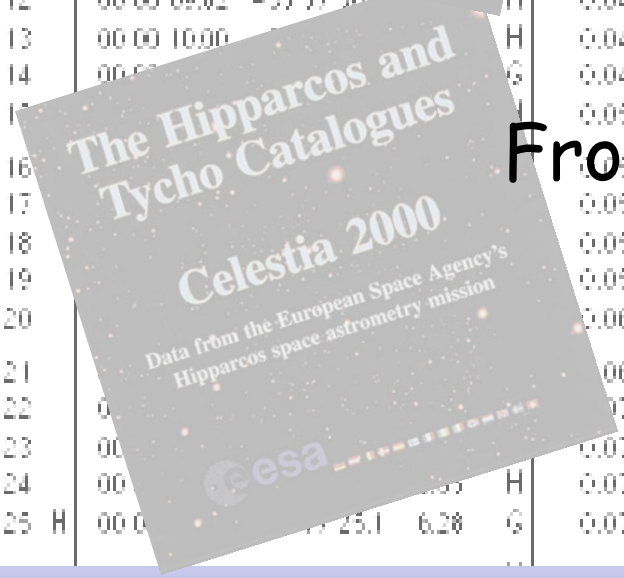
Gaia DPAC

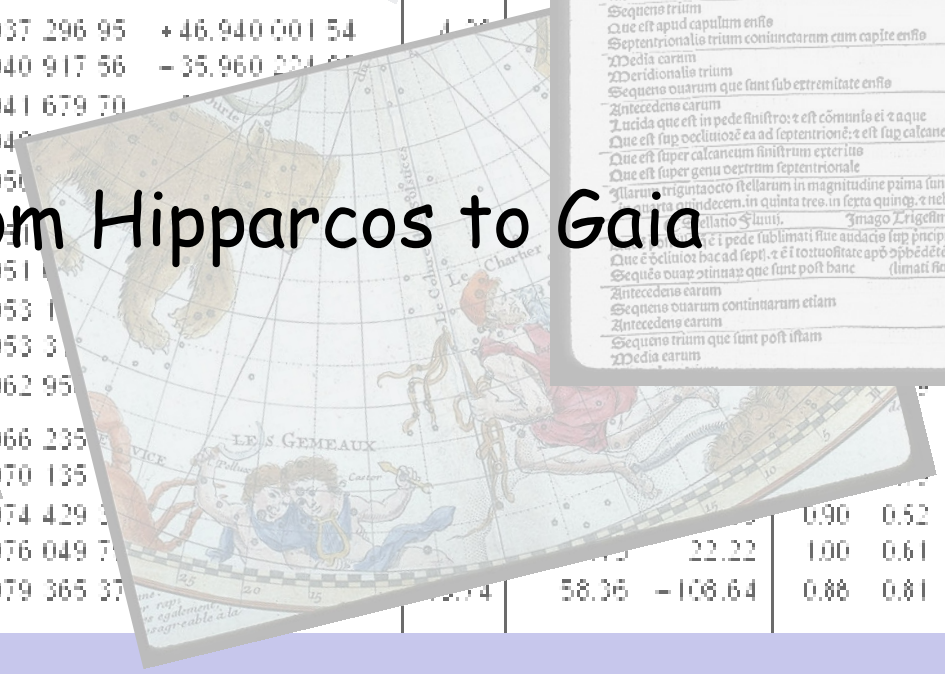
Space Astrometry











From Hipparcos to Gaia

Space astrometry

- Astrometry is the main reason to go to space …
  - global, accurate, absolute
  - not achievable from the ground

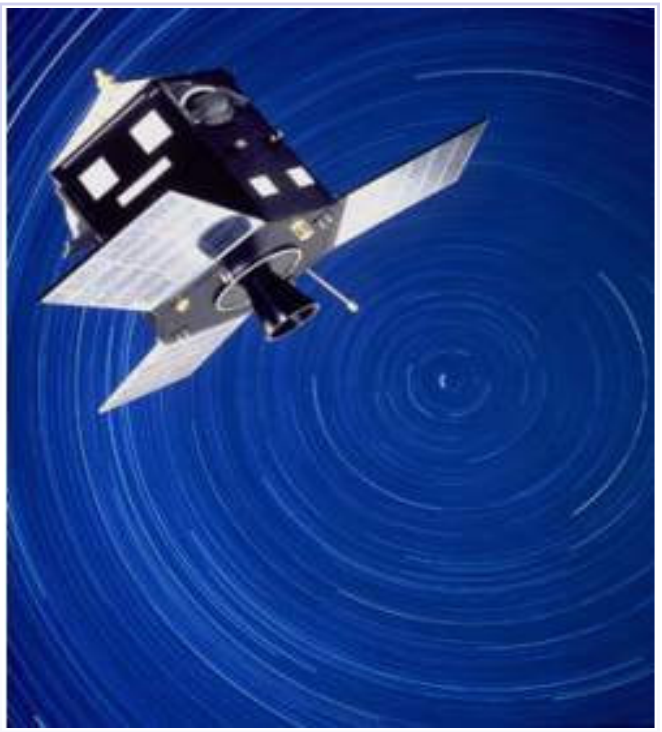
- but astrophysics is the main reason to pay for it
  - benefits almost everywhere
  - secure its foundations

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

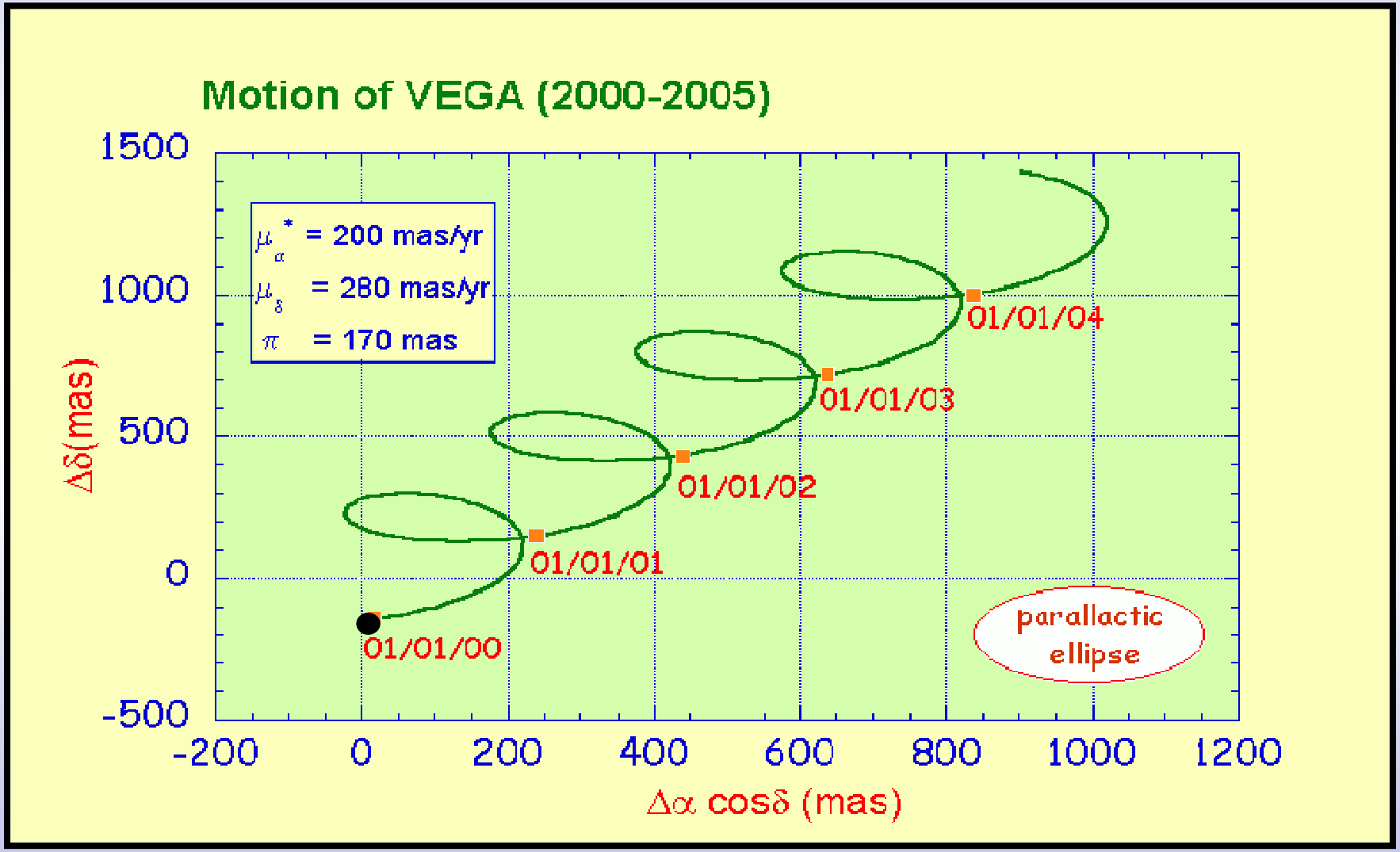
Main Features of Hipparcos



- ESA mission launched in August 1989
- Continuous sky scanning over 3.5 years
- Results published in 1996-7
- One single telescope àf 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

Basic astrometric model

- 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

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 catalogue 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
  - 2500 periodic variables with periods and folded light-curves

Impact of Hipparcos : Publications

- Number of published papers using Hipparcos data

year	all	refereed
1996	57	24
1997	422	92
1998	411	220
1999	429	208
2000	427	195
2001	282	143
2002	260	143
2003	254	127
2004	190	96
2005	193	101
2006	205	110
2007	162	86

Impact of Hipparcos : Access

Access to the Catalogues at the CDS

% of retrieval

1997 to	➔ 2000	➔ 2005	
• Hipparcos	10%	2MASS	10%
• Tycho-2	5%	UNSO-B1	4.5%
• USNO A2	3%	Hipparcos	3.5%
• IRAS	1.5%	Tycho-2	3%
		GCS2	2.3%

After Hipparcos ?

- W. Fricke (Fundamental Catalogues: Past, Present & Future, 1985)
  - "***one would wish that the Hipparcos mission should not be unique one but be repeated after a period of 10 to 20 years***".

- Hipparcos positions degrade quickly (1 mas/yr)
- With no technological improvement, two absolute catalogues
  - $\sigma \sim$ 1 mas :
  - $\Delta t \sim$ 20 yrs

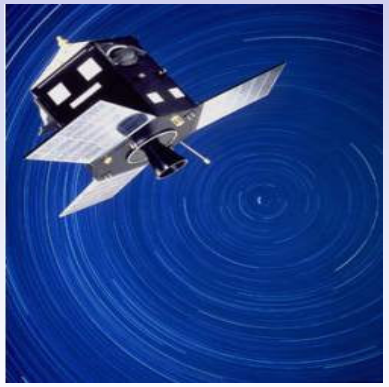
    ➔ PM to 50 muas/yr

Astrometry for Astrophysics

- Direct Products
  - **Accurate positions, absolute parallaxes, proper motions for many stars**
    - 1 mas (Hipparcos) to 1 μas (SIM)
  - **Millimag and multi-epochs photometry in several bands**
    - 50 to 400 observations
  - **Radial velocity to few km/s (GAIA)**
  - **Spectrophotometry in the near IR or UV**
  - **Solar system objects (Hipparcos, DIVA, GAIA)**
  - **Detection and measurement of visual and astrometric binaries**

- **Final goals:**
  - **Stellar and Galactic physics ➔ support of a wide community**

Gaia : The context



- A forerunner : HIPPARCOS (ESA)

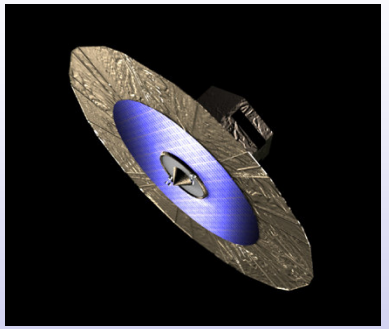
  accuracy 1 mas ~ 5 c at 1000 km

- The unfortunate followers :

  ROEMER, FAME_1, FAME_2, DIVA, LOMONOSSOV, AMEX

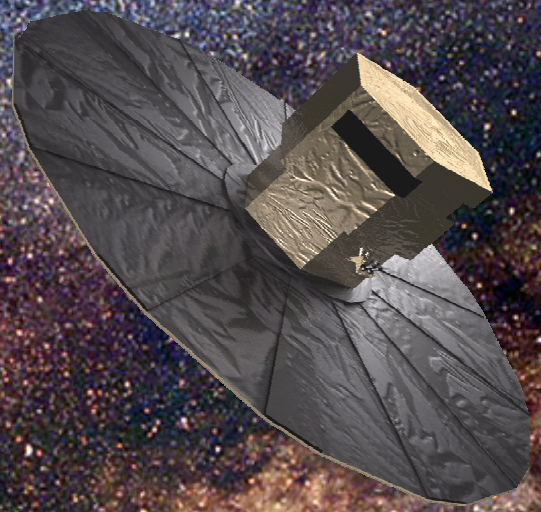
  ESA US US DE RU US

  Accuracy 0.1 mas ~ 1 nail at 1000 km



- Still under study : JASMINE (JAP), J-MAPS
- Delayed but still alive : SIM (US)
- Fully funded mission: GAIA (ESA)
  - *Accuracy 25 µas ~ 1 hairwidth at 1000 km*

GAIA



- 10^9 stars
- 25 μas @ V = 15 mag

ESA mission

Launch: end 2011

Mission : 5 yrs

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

Observation principles

- GAIA is a scanning mission
  - no pointing, no change in the schedule
- GAIA gathers astrometric, photometric and spectroscopic data
  - each source is observed ~ 80 times in astrometry, 50 in spectroscopy
- GAIA has an internal system of detection
  - sensitivity limited detection at G ~ R = 20
- Objects are more or less regularly measured during the mission
  - orbit reconstruction
  - light curves

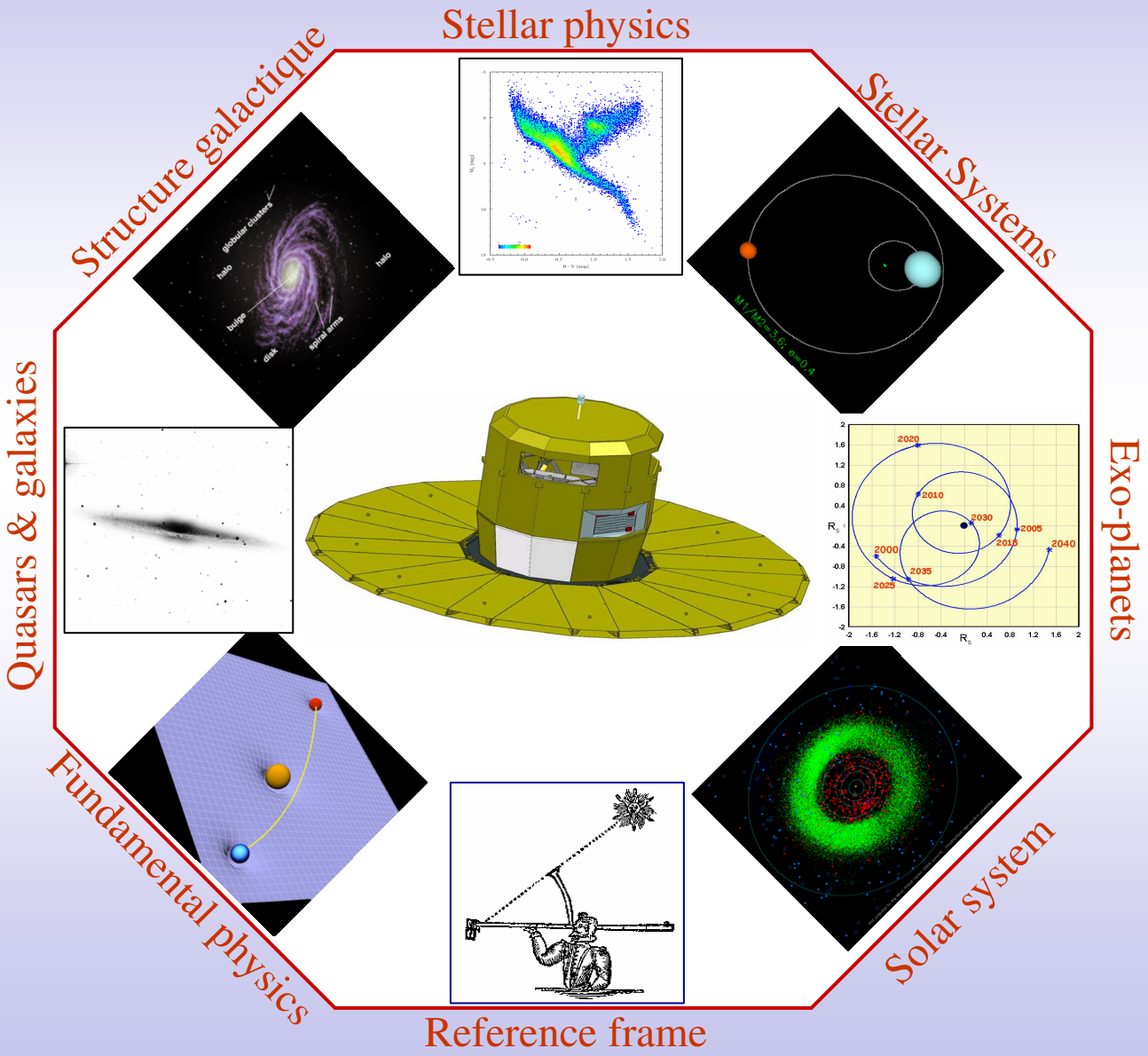
Assets of Gaia

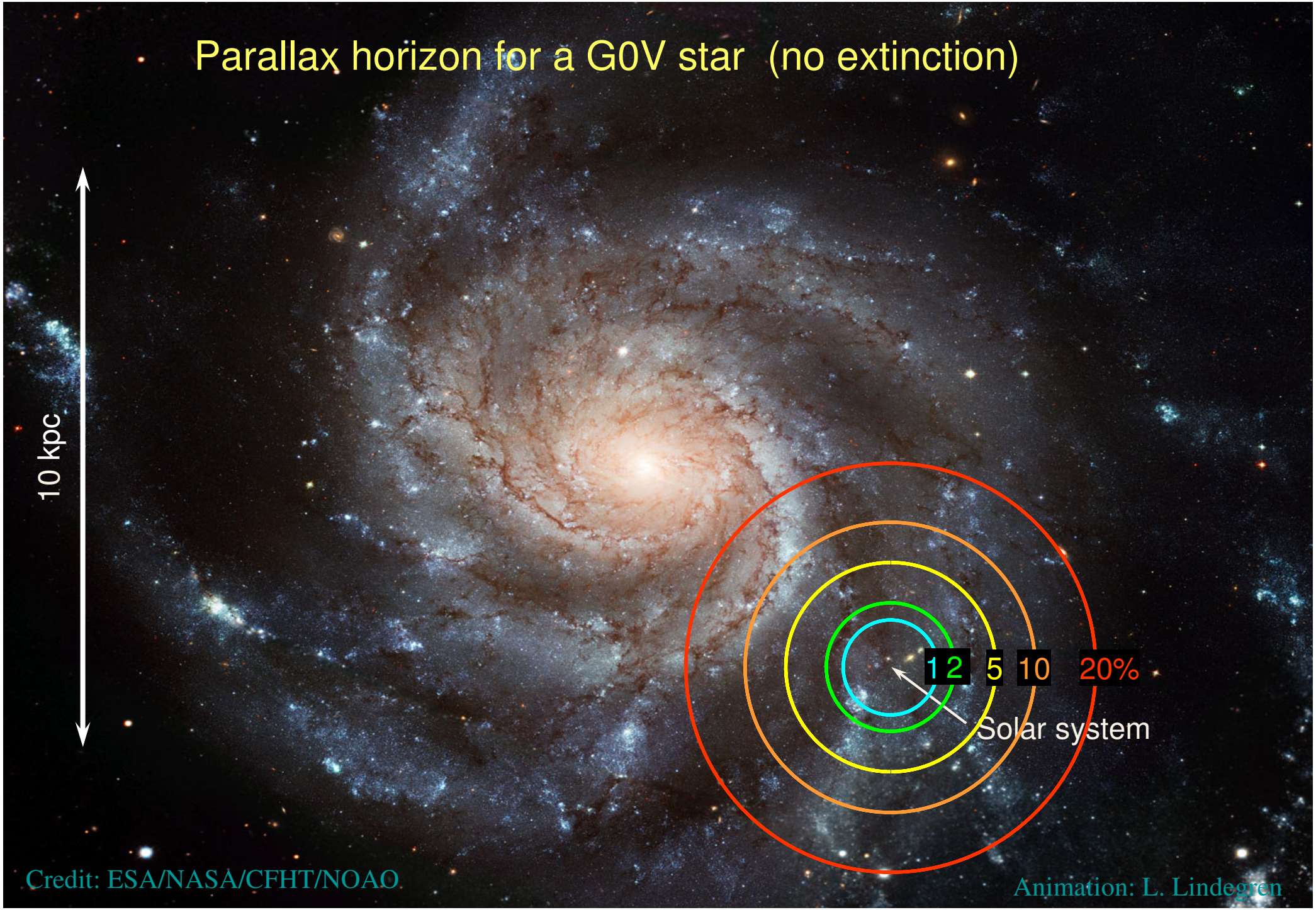
- A single mission with three instruments
  - Astrometric, photometric and spectroscopic data
- Uniform coverage of the sky
- Quasi regular time sampling over 5 years
  - ~ 100 observations ➔ photometry, orbits of binaries, asteroids
- Survey mission sensitivity limited
- Internal and autonomous detection system
- Global astrometry of staggering precision
  - Internal metrology, thermal and mechanical stability
- Experienced and motivated community in Europe after Hipparcos
  - scientific and industrial

Few major past steps

- 1994 — ESA is advised for its future programs to have an astrometry mission to 10μas
- 1996/2000 — Pre-studies and science case
- 07/2000 — Concept and Technology Study Report
- 10/2000 — ESA selected Gaia as Corner Stone # 6,
  - Ariane V, → σ = 10 μas
- 01-05/02 — Descoped and lighter version reselected (SPC)
  - Soyuz, → σ = 15 μas (then 24 μas in 2004)
- 07/2005 — Publication of the MRD (Mission Requirement Document)
- 07/2005 — ITT (Invitation to tender) to industry released
- 02/2006 — Astrium selected as prime contactor to build Gaia → Phase B
- 06/2006 — Formation of the DPAC (Data Processing and Analysis Consortium)
- 11/2006 — AO (Announcement of opportunity) to scientific community released
- 05/2007 — Selection of the DPAC by ESA

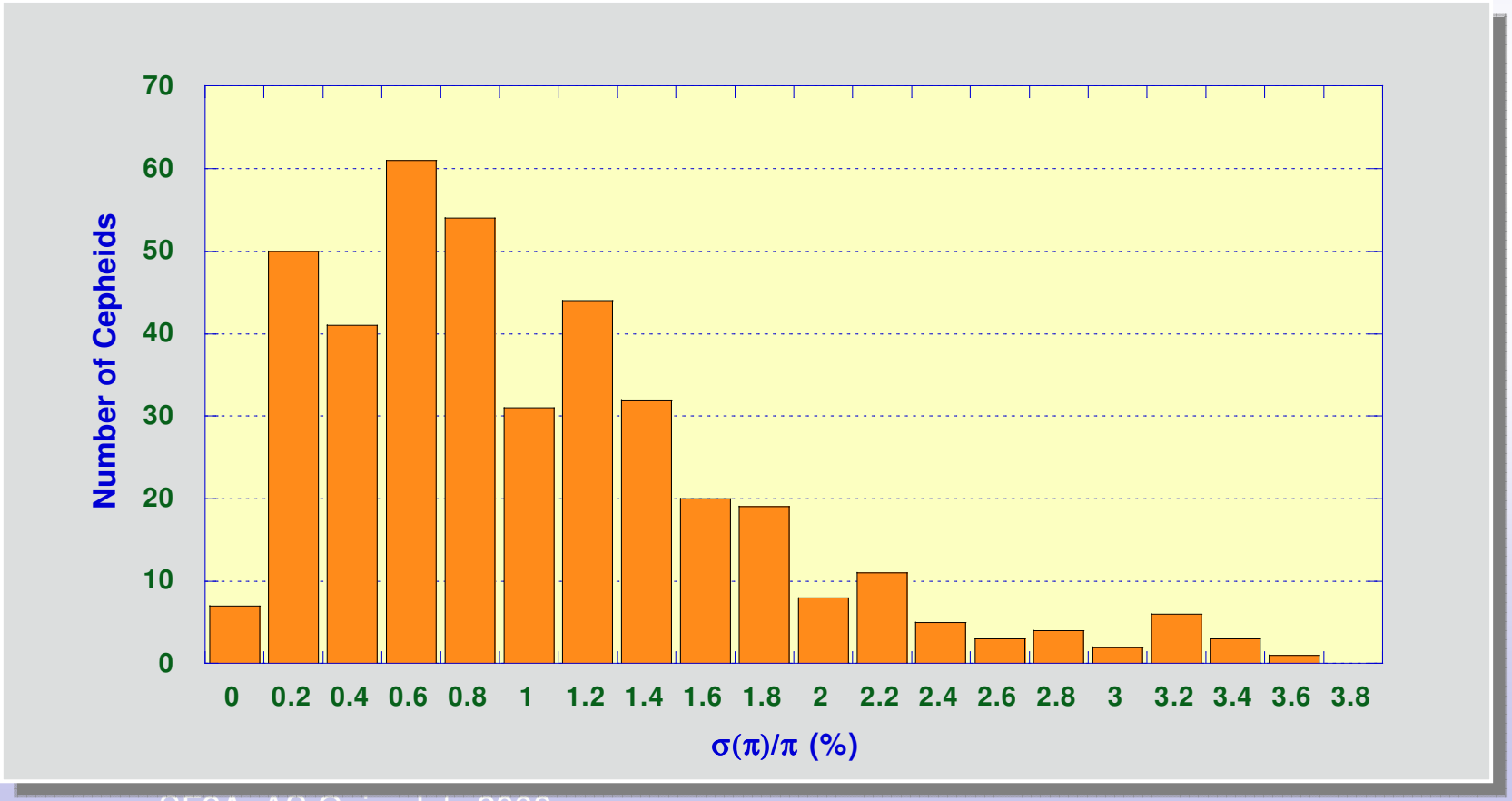
What science with Gaia?




Parallax horizon for a G0V star (no extinction)
10 kpc
12
5
10
20%
Solar system
Credit: ESA/NASA/CFHT/NOAO
Animation: L. Lindegren

Cepheids with Gaia

- 15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc
  - bright enough (V < 13) and red
- In the plot : 400 galactic cepheids from David Dunlap DB
  - distance and magnitude ➔ one can use the Gaia predicted accuracy



Expected astrometric accuracies

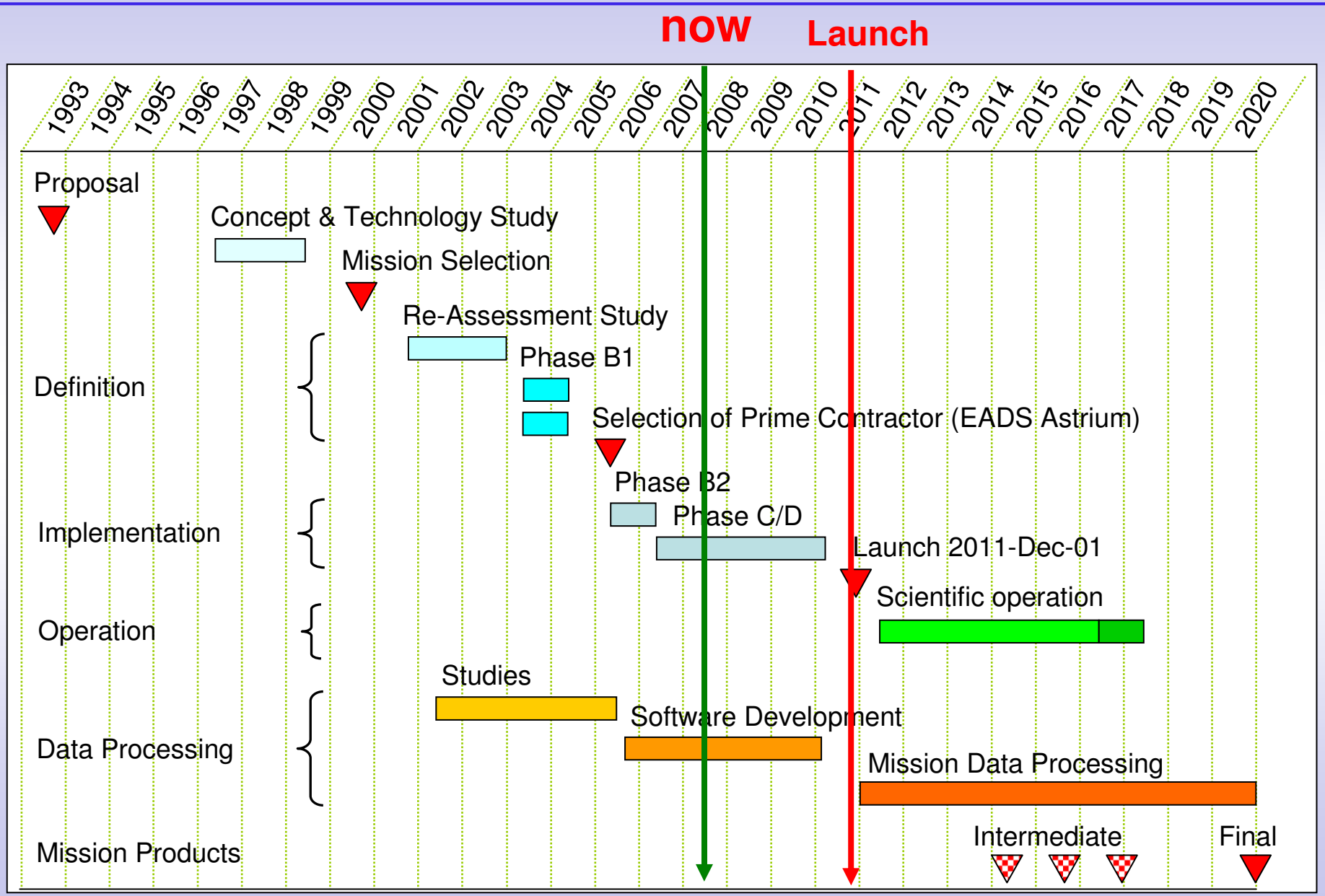
Sky-averaged standard errors for G0V stars (single stars, no extinction)

V magnitude	6 - 13	14	15	16	17	18	19	20	mag
Parallax	8	13	21	34	55	90	155	275	μas
Proper motion	5	7	11	18	30	50	80	145	μas / an
Position @2015	6	10	16	25	40	70	115	205	μas

Notes:

- Estimates calculated with the Gaia Accuracy Tool (courtesy J. de Bruijne, ESA)
- Radiation-damage effects on CCDs not fully taken into account
- Estimates include a 20% margin (factor 1.2) for unmodelled errors

Gaia – Project status and schedule

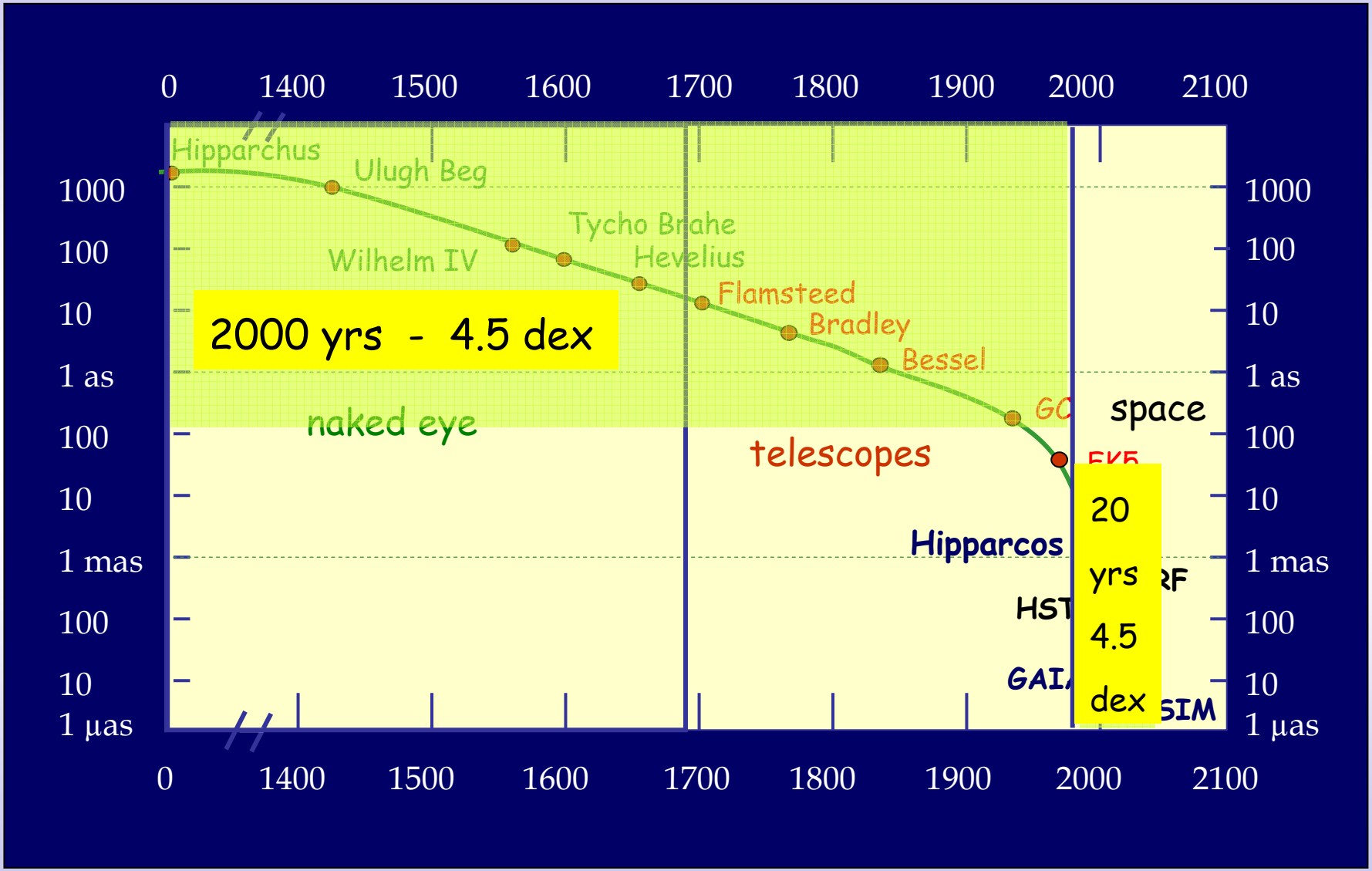


Therefore, if everything goes as planned...

in 2018…

- 10^9 stars
  - 10^6 V = 12, 30×10^6 V = 15 , 250×10^6 v = 18
  - $\sigma \sim 4$ μas V < 12, 10 μas V = 15, 150 μas V =20
- 25000 ✯/ deg^2 ; max : 3×10^6 /deg^2 .
- 200×10^6 radial velocities
- Stellar classification for all classes and types
- Variability analysis over ~ 10^8 stars
- 10 000 stellar masses σ < 1 %
- Extra solar planets to 200 pc
- 3×10^5 minor bodies of the solar system, 100 masses
- ~ 5×10^5 QSOs + z + photometry, ICRF in the visible
- γ to ~ 10^{-7}

My main point: The Golden Age of astrometry



GAIA or Gaia ?

Gaia is the Greek Goddess of the Earth!!

Originally in ESA this was :

GAIA: **G**lobal **A**strometric **I**nteferometer for **A**strophysics

Now this is simply Gaia : a proper name, not an acronym

Gaia DPAC

Merci de votre attention

Mirage de la Corse vue de Nice

Precession Nutation