Astrometry : 1975-2025

From Ground to Space: astrometry in perspective

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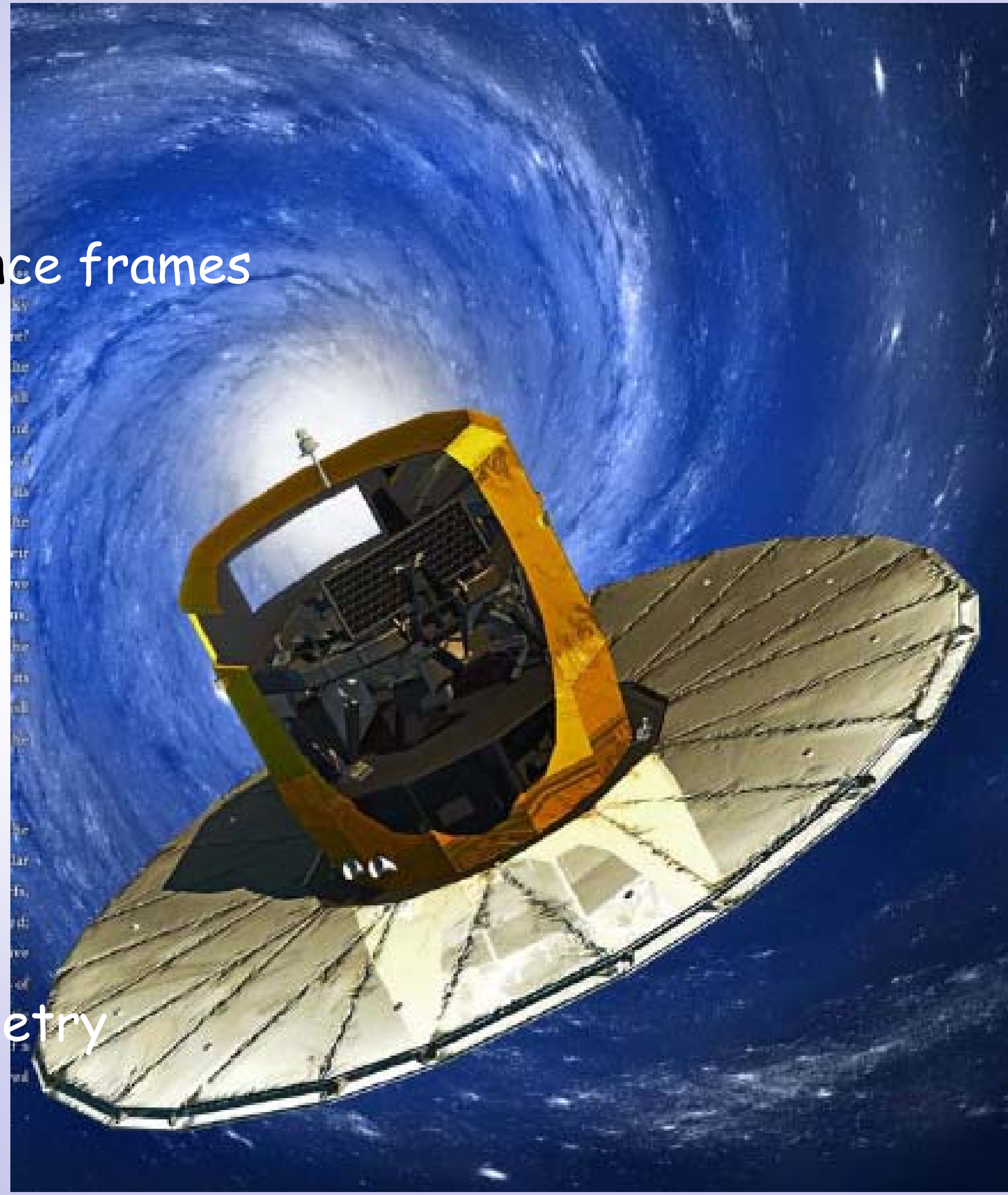
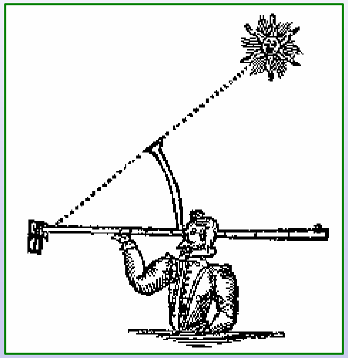
Outline

- Astrometry
- Fundamental catalogues and reference frames
- Absolute parallaxes
- Hipparcos and its legacy
- Gaia & SIM in brief
- What could come next ?
- 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.

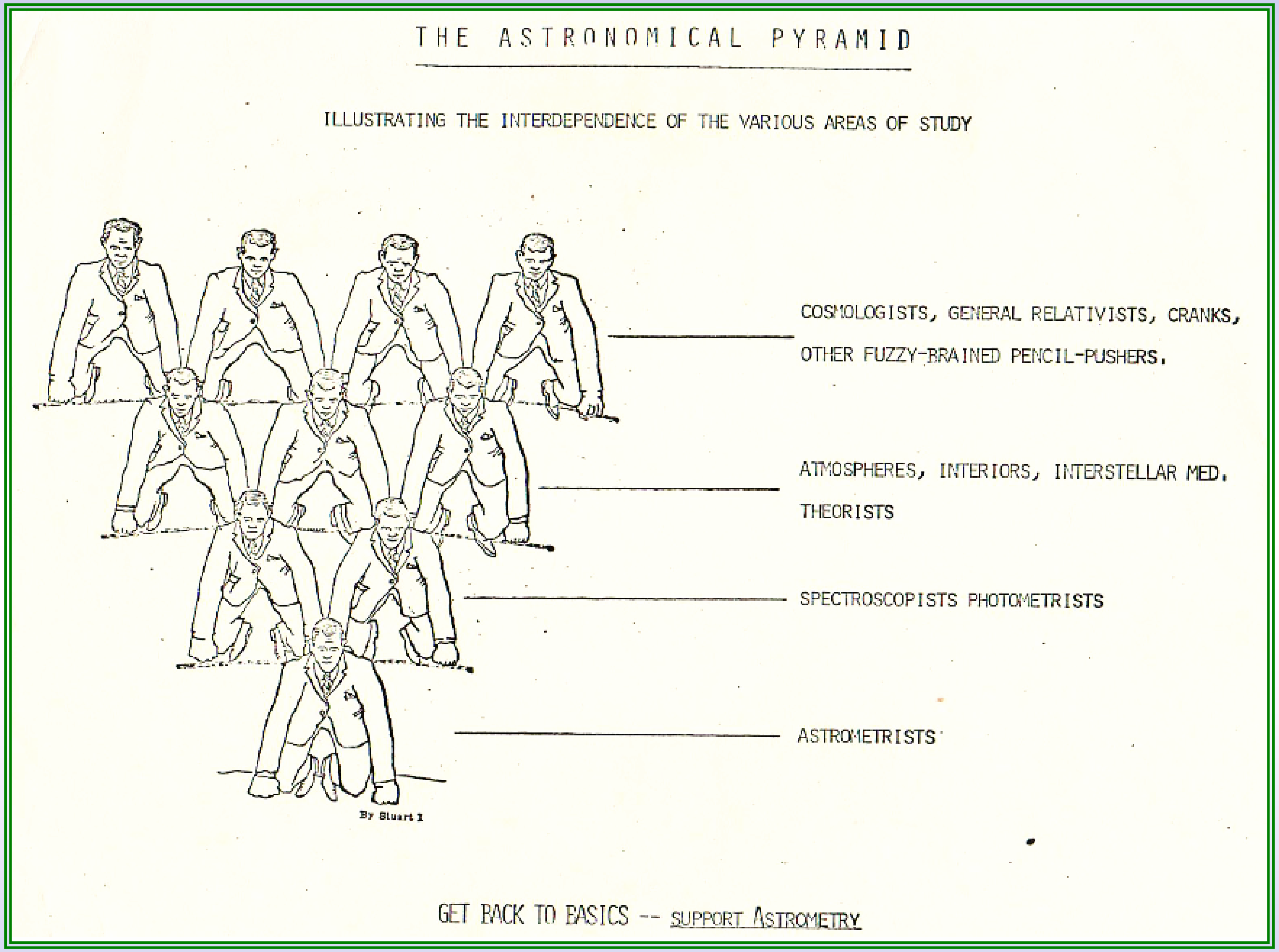




Astrometry 1975

- 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"01-0"005
  - extensive photographic program under way
- The Carte du Ciel officially terminated in 1970 (started in 1887)
  - But publication of AC 2000.2 in 2001: main source of first epoch for PM inTycho-2.
- Start of CCD observations
- Solar system distances with radar
- Satellite and lunar laser ranging still in infancy

Astrometry: a pre-Hipparcos diagram



Daher sind die Oerter der Fixsterne die Grundlagen der Astronomie

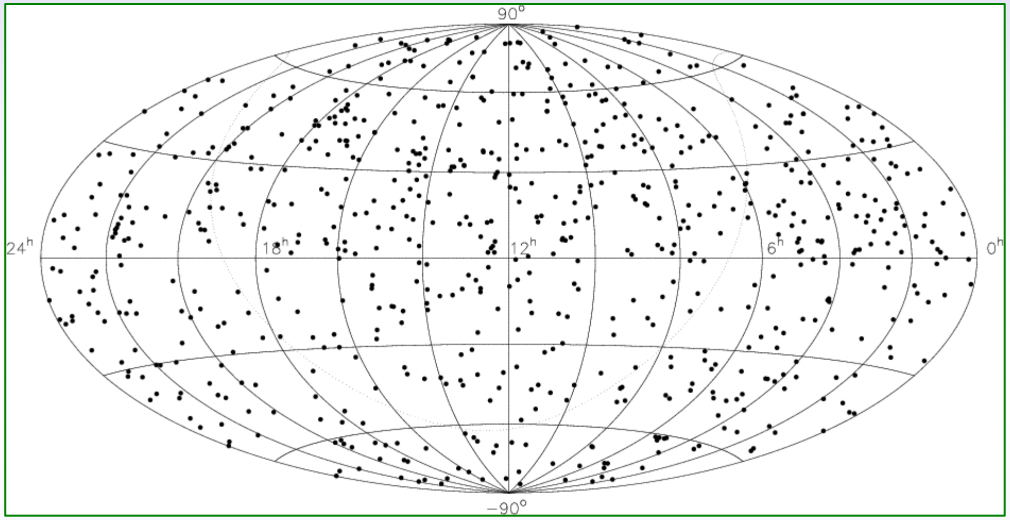
Bessel, Pop. Vorlesungen p. 22

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

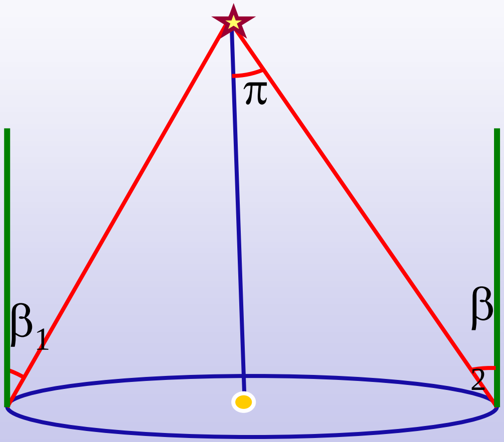
Circulated ca. 1974 by R. Probst, UVa

- Two good reasons to do astrometry in space

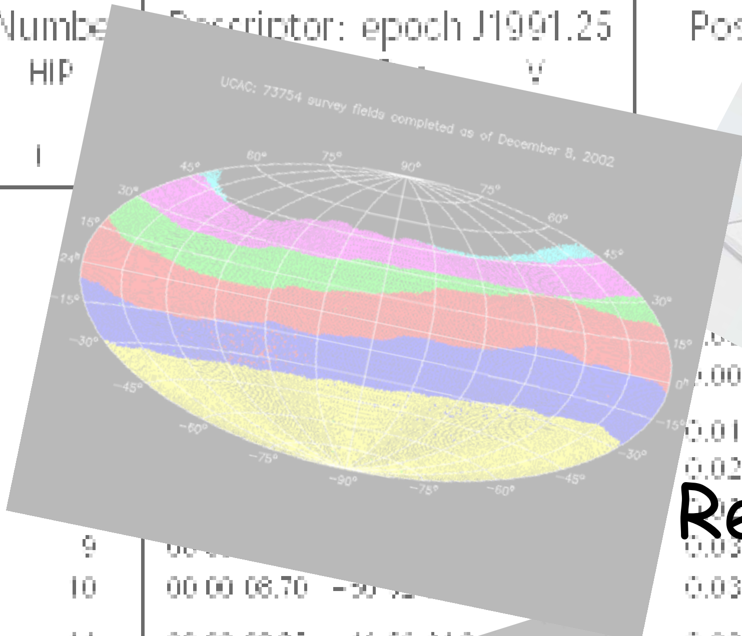
Reference frame

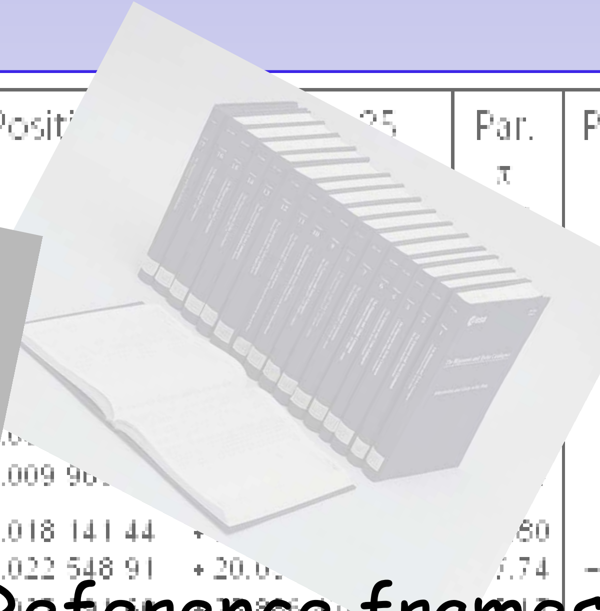


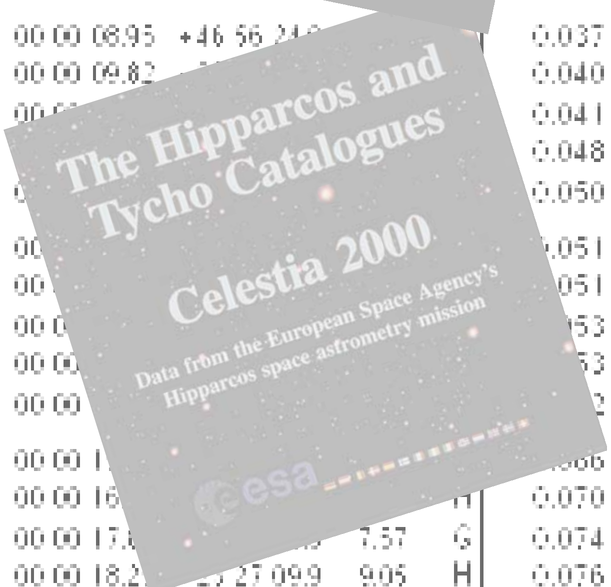
Absolute parallaxes

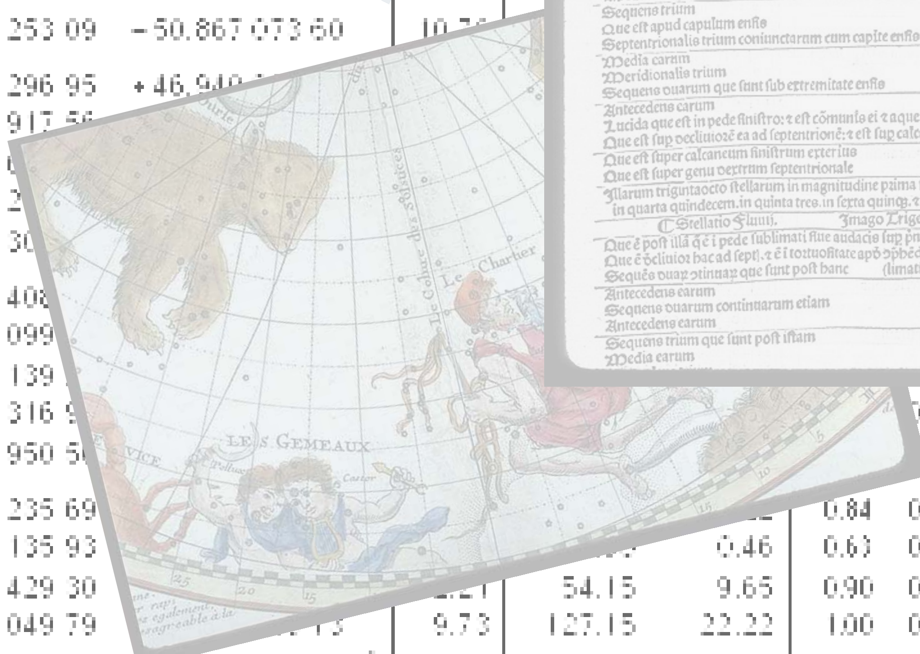


Reference frames









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

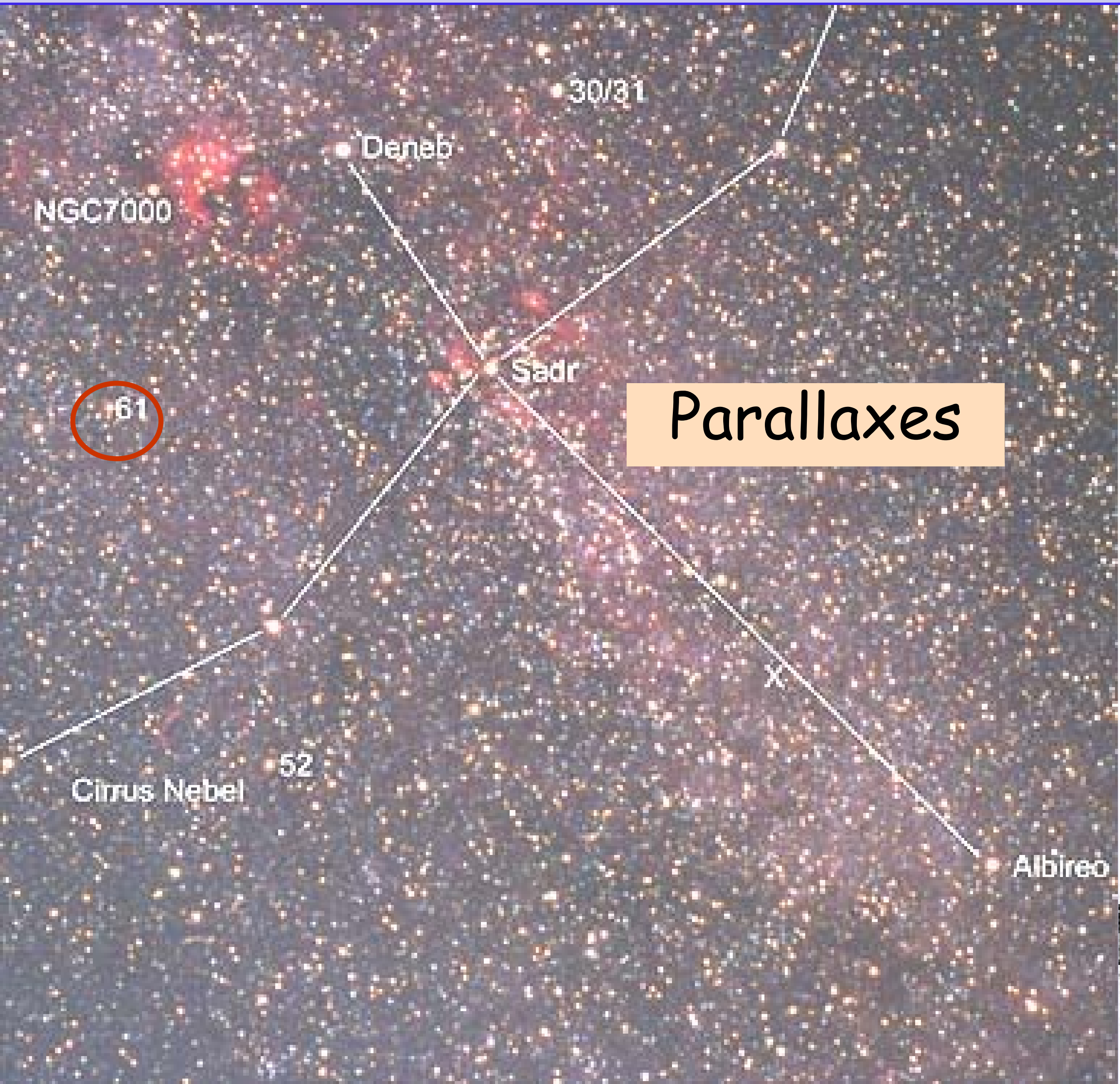
1790	Maskelyne	36	zodiacal stars, one epoch
1818	Bradley/Bessel	3000	no PM, nearly fundamental for one epoch
1830	Bessel	36	with PM, + precession
1878	FK1	539	
1898	Newcomb	1297	Start of the GC series
1907	FK2	925	
1937	FK3	873	1st IAU supported international RF
1963	FK4	1535	σ_{1950} ~ 0"07- 0"15, σ_{2000}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

Limitations of the classical approach

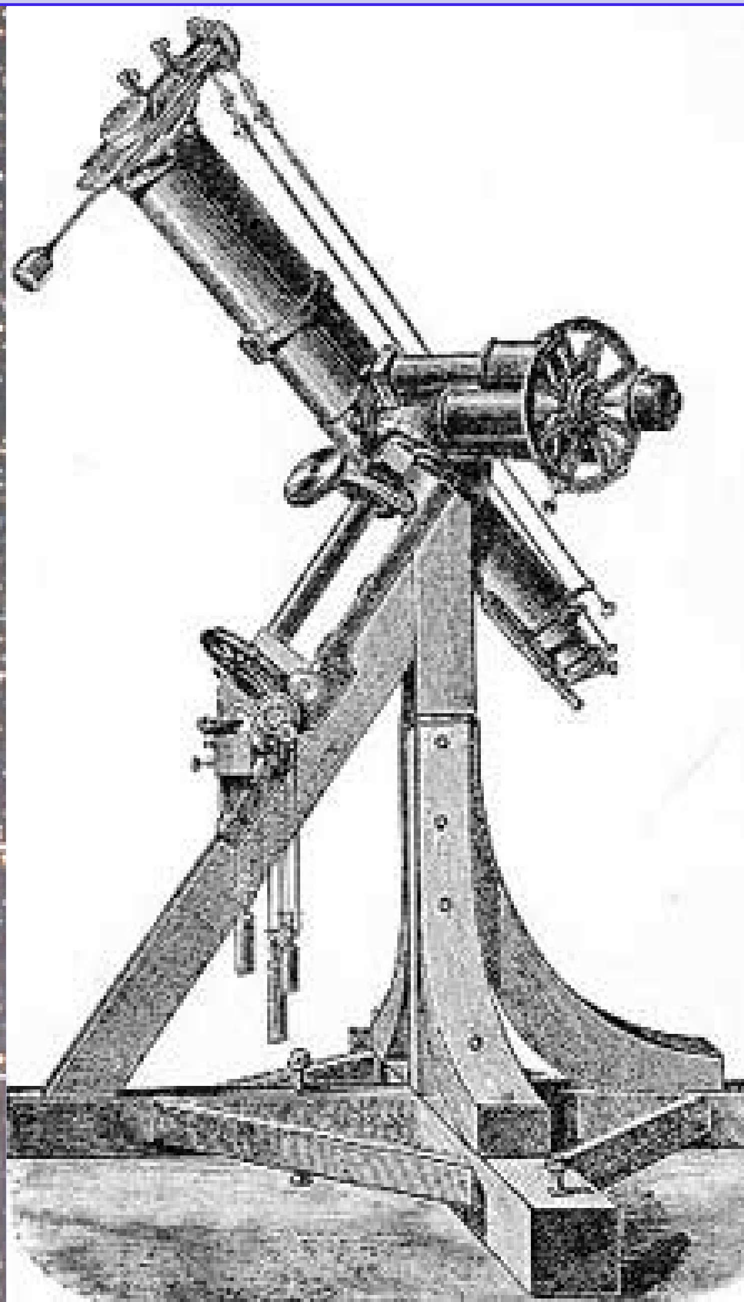
1. System based on stars
   - problems with proper motions, multiplicity
     - Solution: distant sources ➔ already considered by W. Herschel & Laplace
     - Adopted in ~ 1990 with ICRS and ICRF in 1998
2. System defined with equator and equinox
   - precession and nutation modelling
     - solution: fixed frame not linked to solar system ➔ ICRS

more on nutation

3. Observations from the ground
   - many stations needed to cover the sky
   - disturbances from the atmosphere
     - solution: go to space for global astrometry ➔ Hipparcos

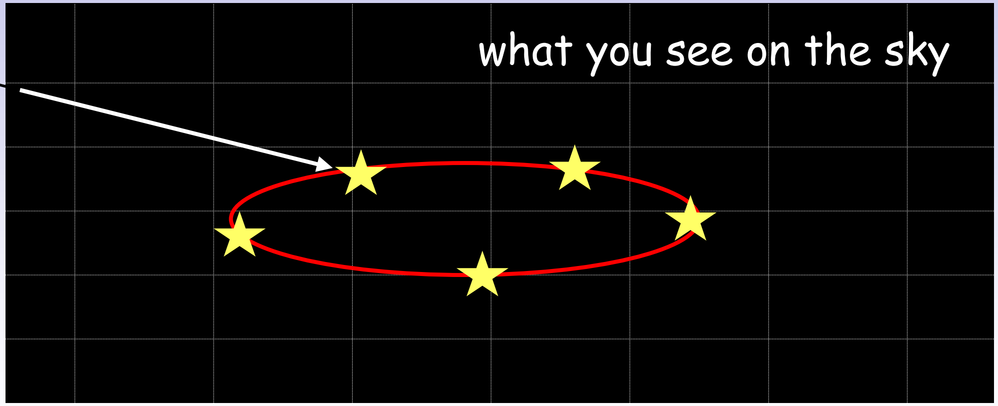


Parallaxes

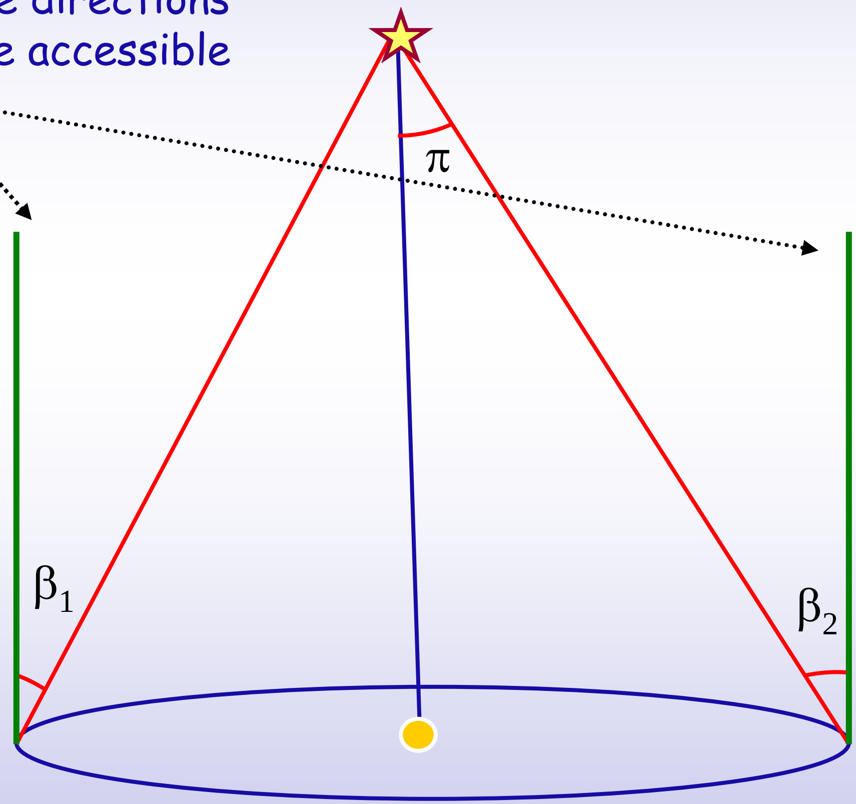


Absolute parallaxes

absolute positions
no reference to distant stars



these directions
must be accessible

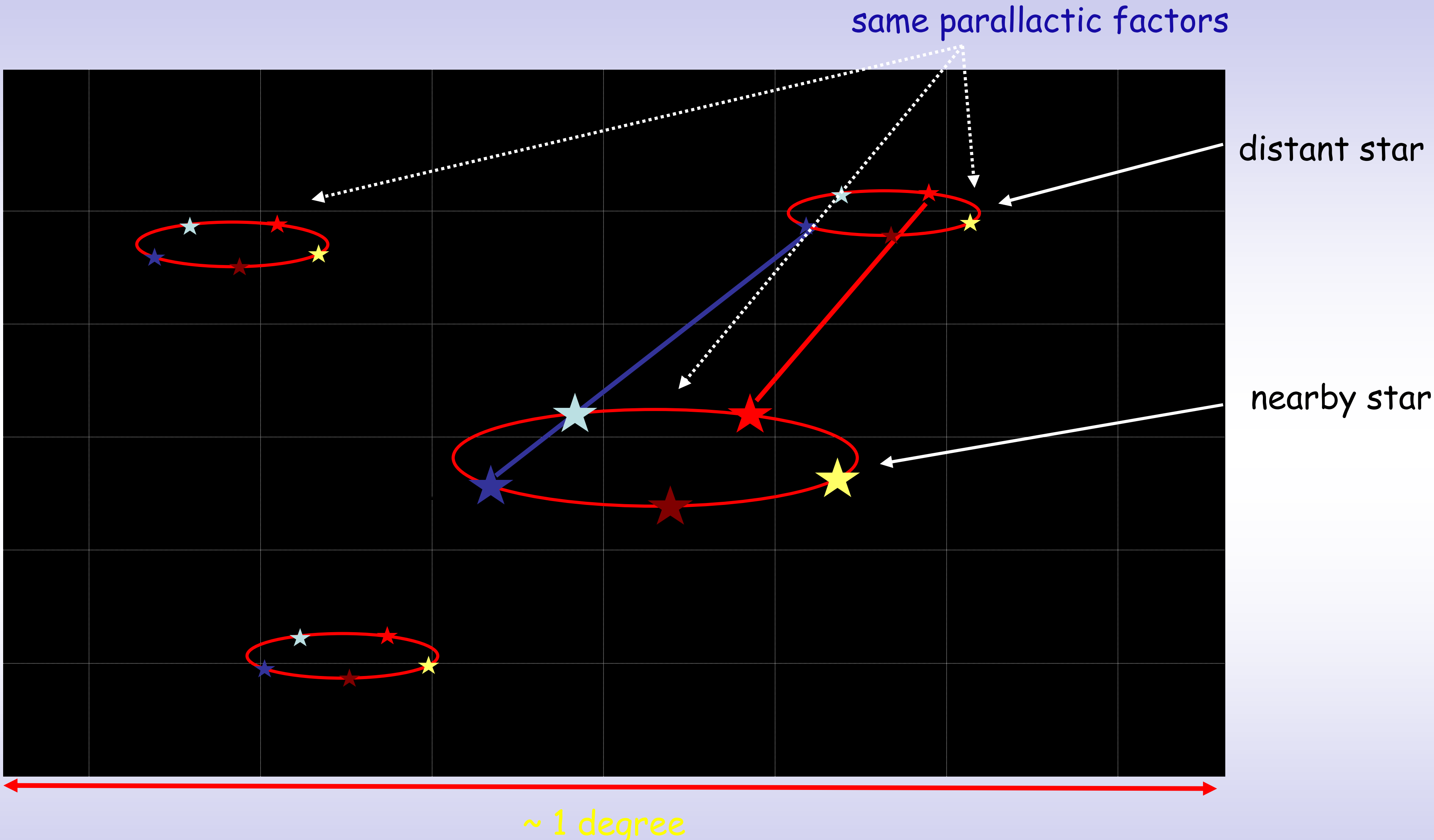


$$\pi = \frac{\beta_1 + \beta_2}{2}$$

Methods applied :

- measurements of declinations
- zenith distances
- wide angle or global astrometry
- virtually impossible from the Earth to 0"001

Small field astrometry



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

Parallaxes: Evolution 1840 - 1980

Gaia DPAC

1840	3	published parallaxes
1850	20	Catalogue of Peters
1888	40	Catalogue of Oudemans
1910	100	of which 52 photog. parall. from Kateyn
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	"

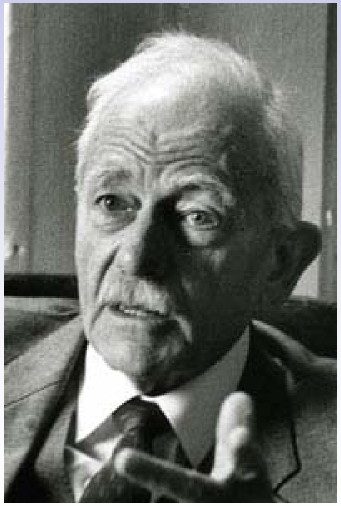
Parsec

- Estimated error : 0".016

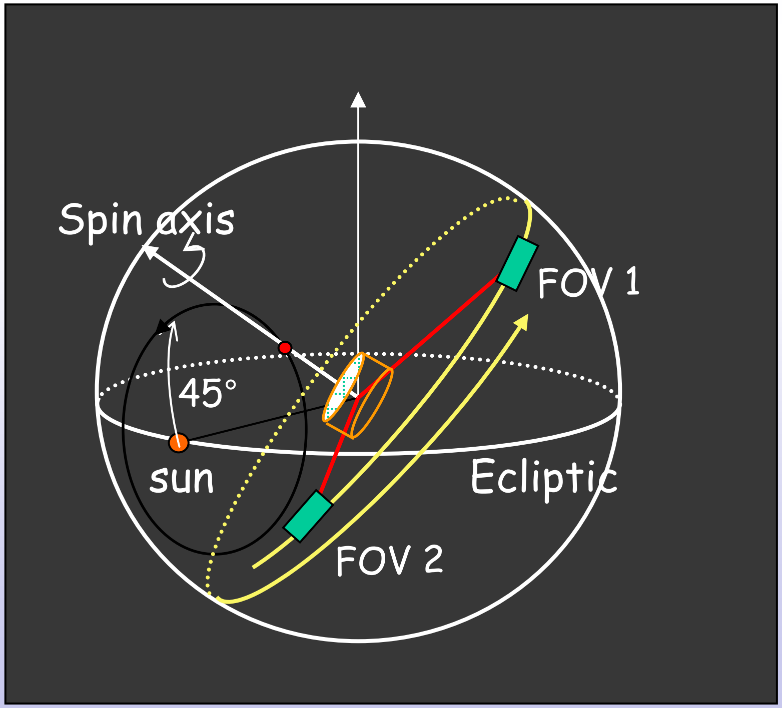
  ➔ $\sigma(\pi)/\pi$ = 50% at 30 pc !
- Mean value of the parallaxes : 0".018

Many of these parallaxes have no individual significance

A route to absolute parallaxes : Two fields of view

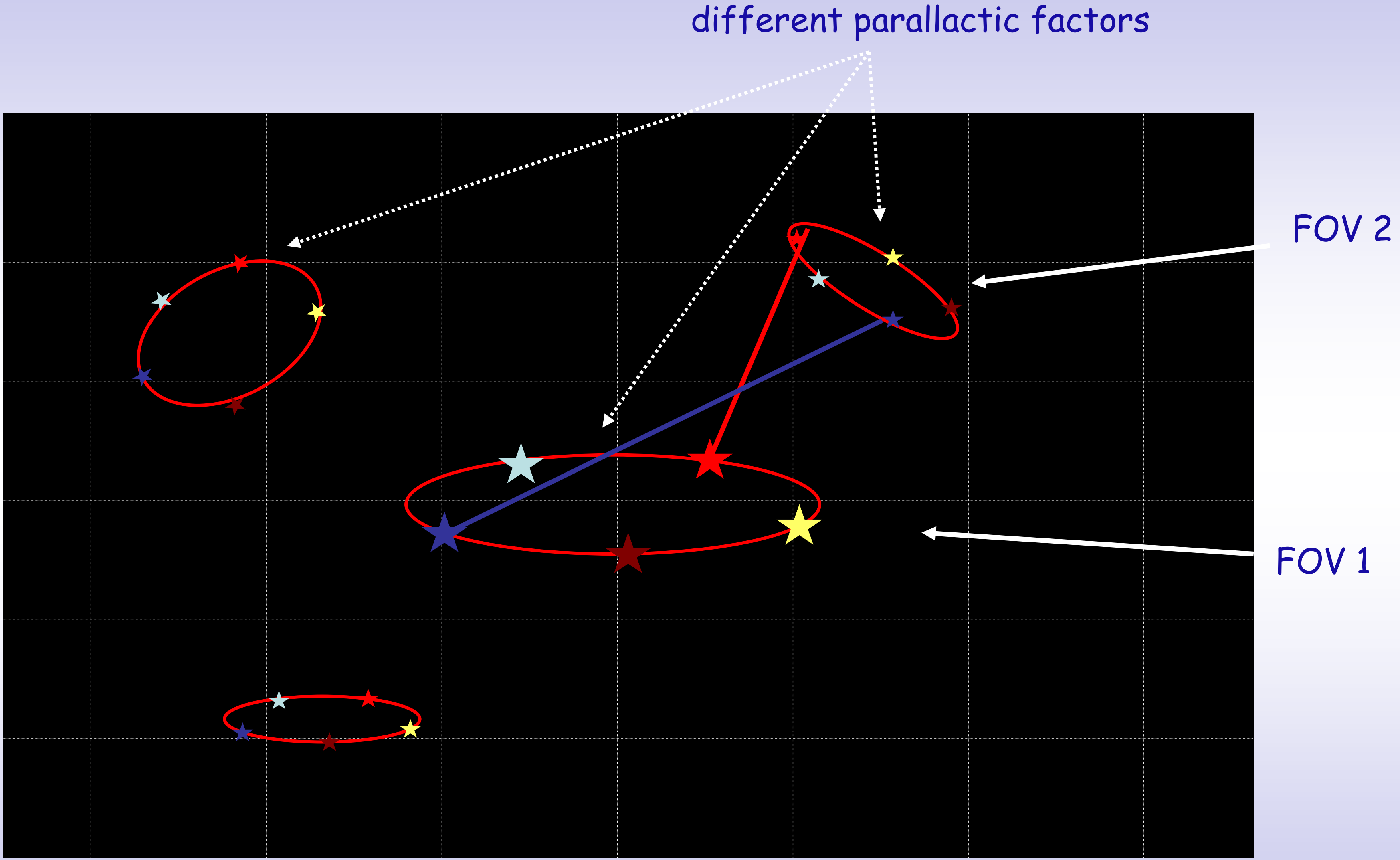


P.Lacroute
1906-1993

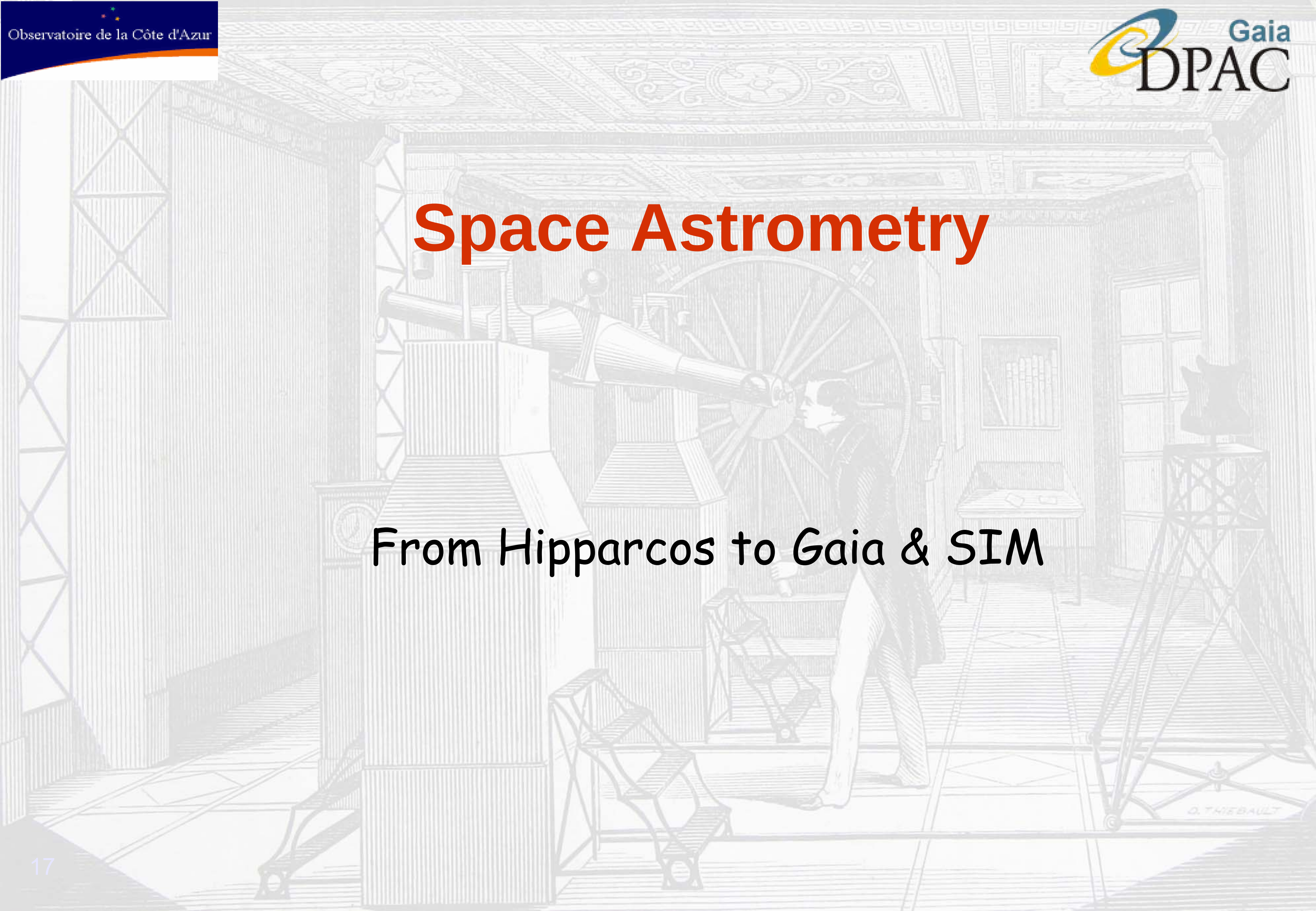


- Overall principles set forth by P. Lacroute in 1967.
- Optical combination of two viewing directions
- The two FOVs are mapped onto a common focal plane
- Stars are combined by pairs
- Wide angle measurements are carried out

How parallaxes get absolute



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



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Gaia DPAC

Space Astrometry

From Hipparcos to Gaia & SIM

Space astrometry

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

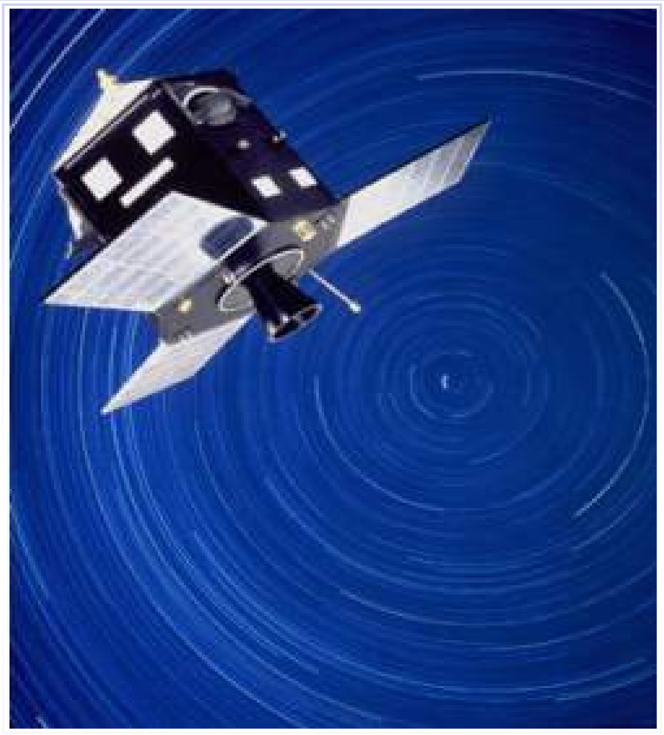
- but astrophysics is the main reason to pay for it
  - benefits almost everywhere
  - secures its foundations

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

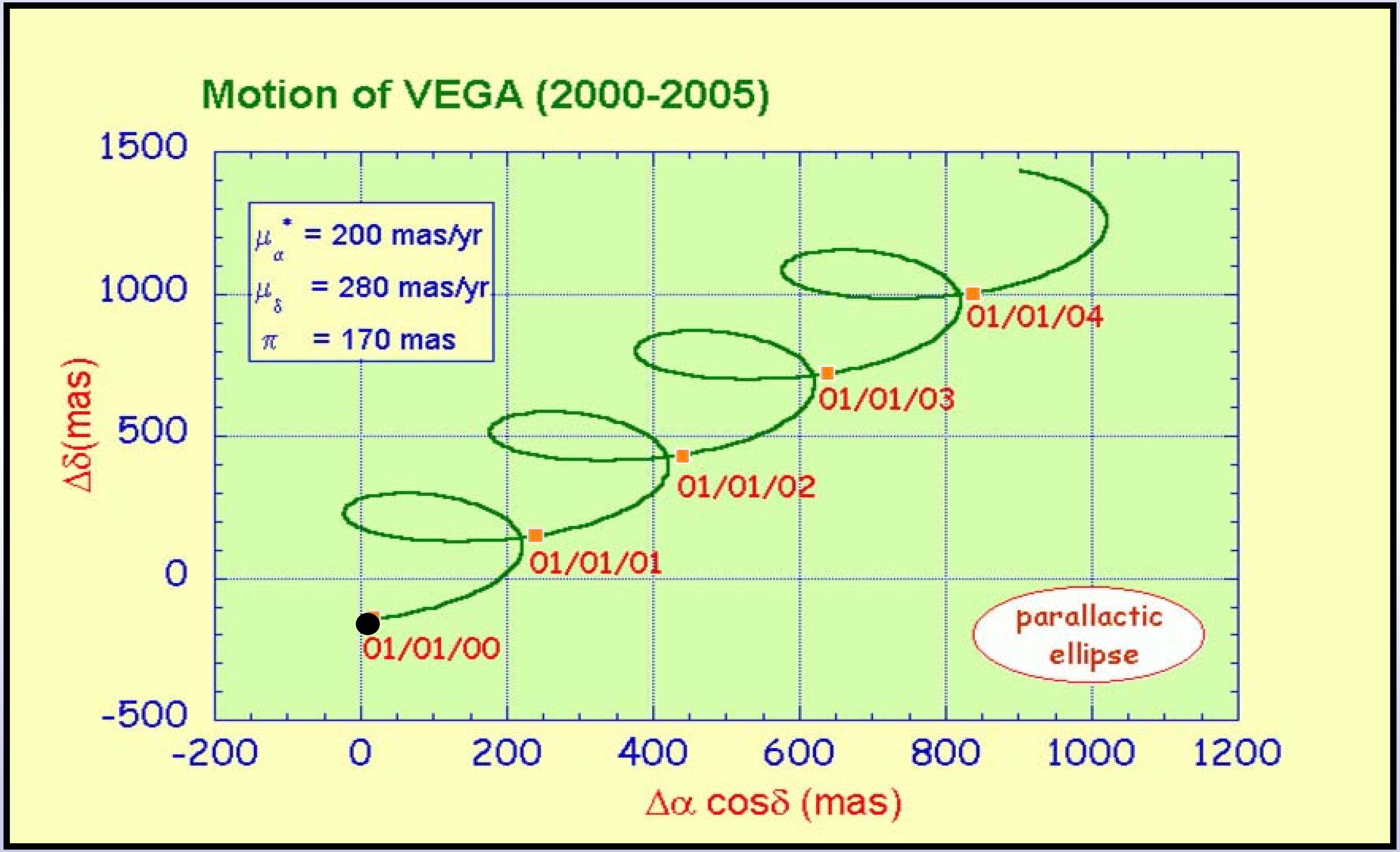
Main Features of Hipparcos



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

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

Gaia DPAC

- 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

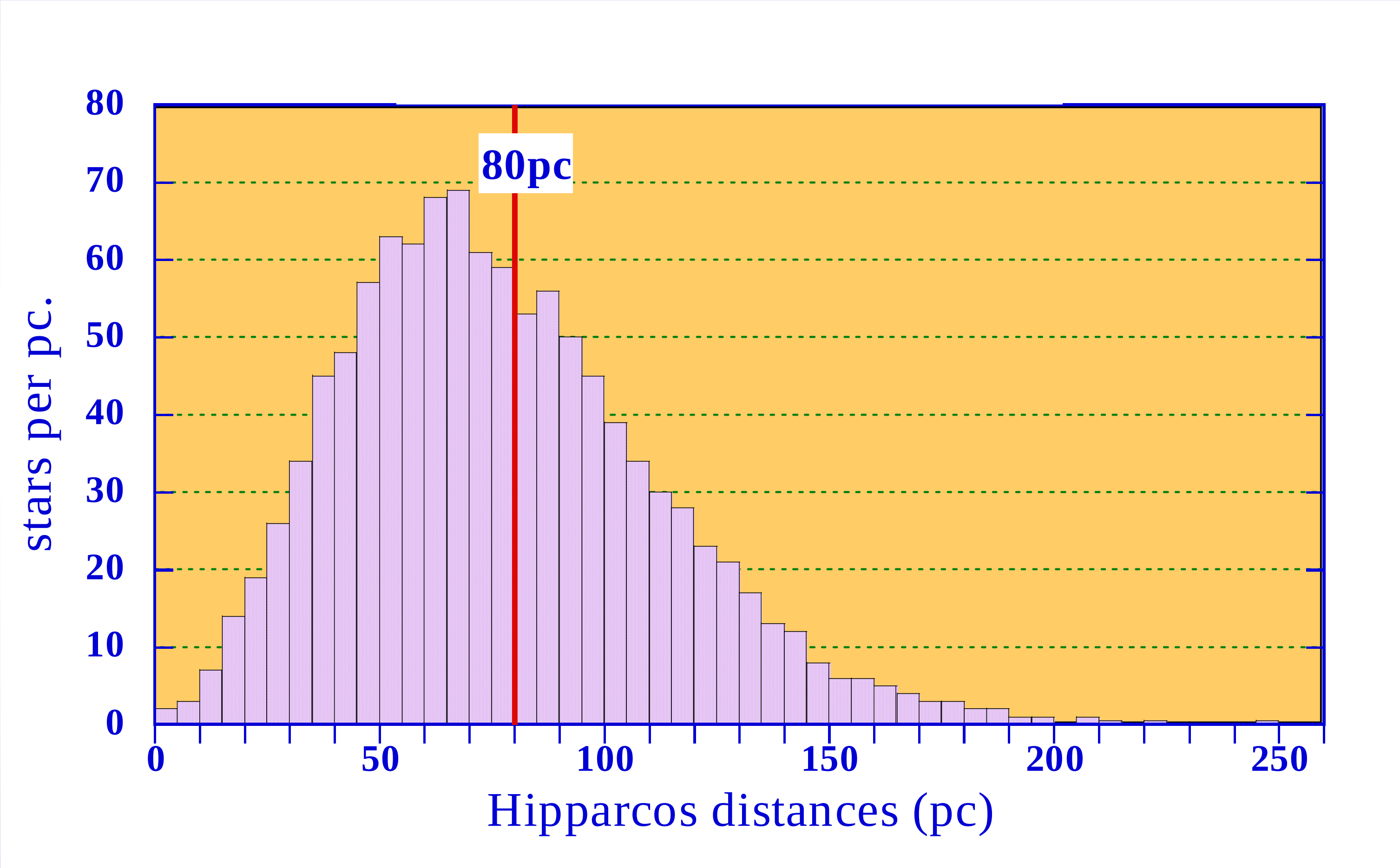
Additional products

- 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

Ground-based and Hipparcos parallaxes

- Ground based ➔ 5610 * with distances d < 80 pc



Hipparcos ➔ 2384 * > 80 pc

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

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:

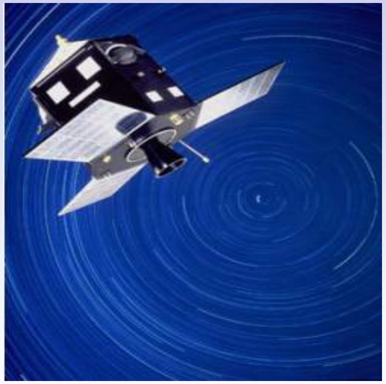
" Initiate a Cornerstone-level program in interferometry to perform astrometric observations at the 10 μas level"

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*, *FAME*, Gaia)**
  - **Detection and measurement of visual and astrometric binaries**

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

Gaia : The context



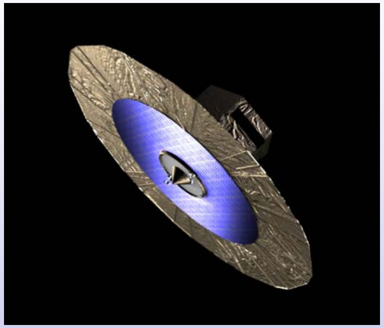
- A forerunner : HIPPARCOS (ESA)

  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(US)
- Delayed but still "breathing" : 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

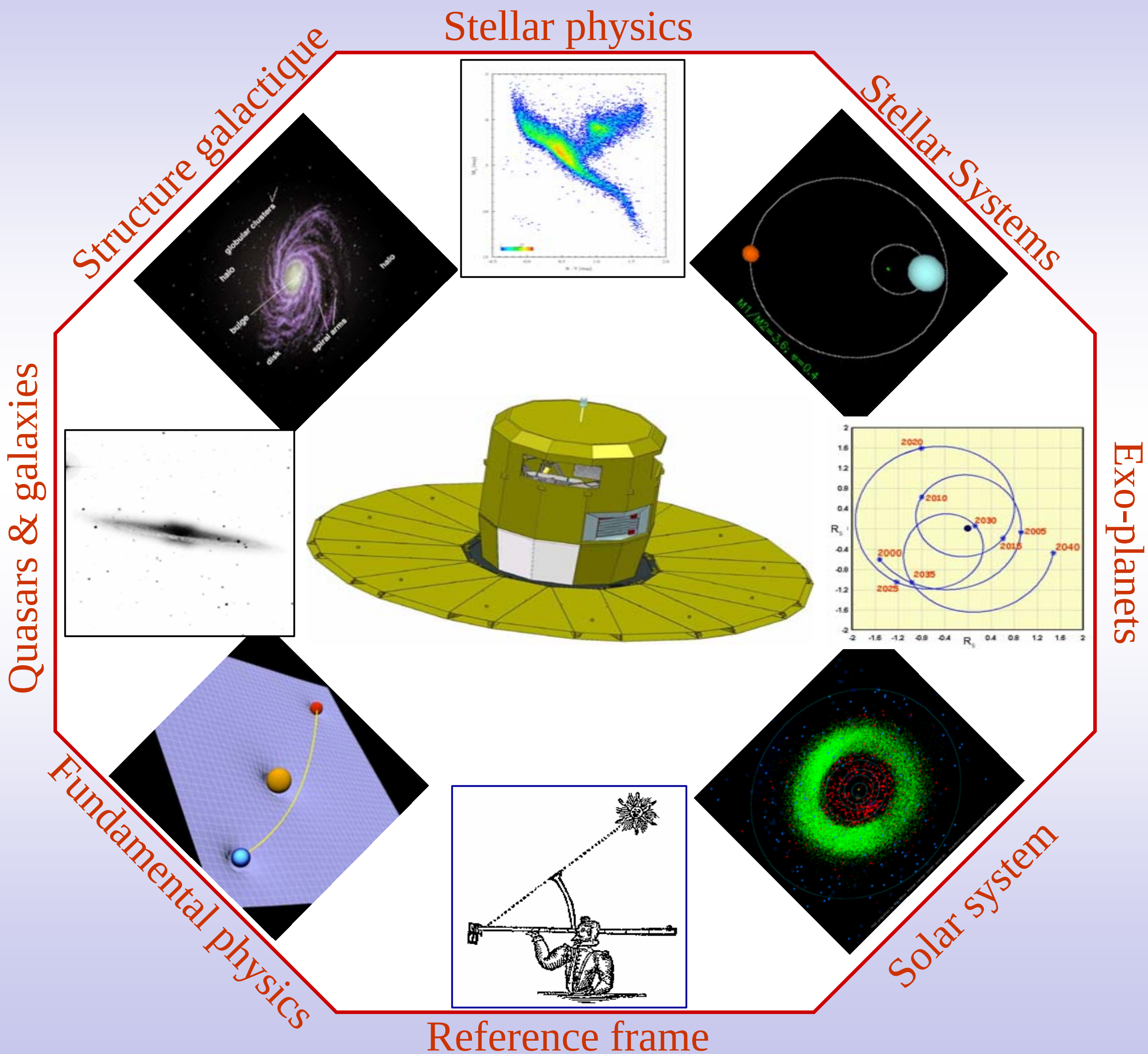
- A single mission with three instruments
  - Astrometric, photometric and spectroscopic data
- Uniform coverage of the sky
- Quasi regular time sampling over 5 years
  - ~ 100 observations ➔ photometry, orbits of binaries, asteroids
- Survey mission sensitivity limited
- Internal and autonomous detection 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

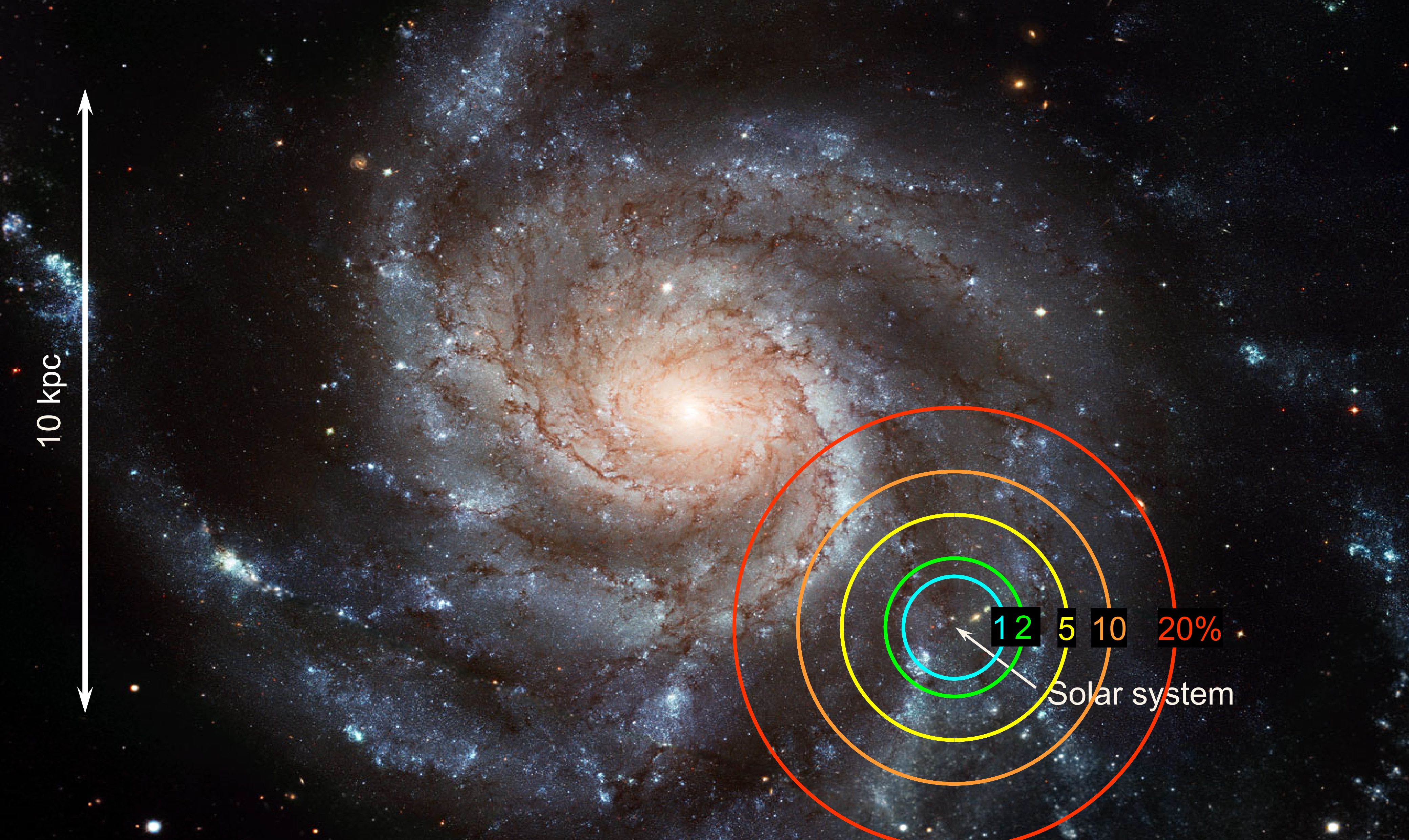
Gaia DPAC

- 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 — Final selection of the DPAC by ESA ➔ data processing system in progress
- 07/2007 — Phase C/D started ➔ manufacturing in progress

What science with Gaia?



Parallax horizon for a G0V star (no extinction)

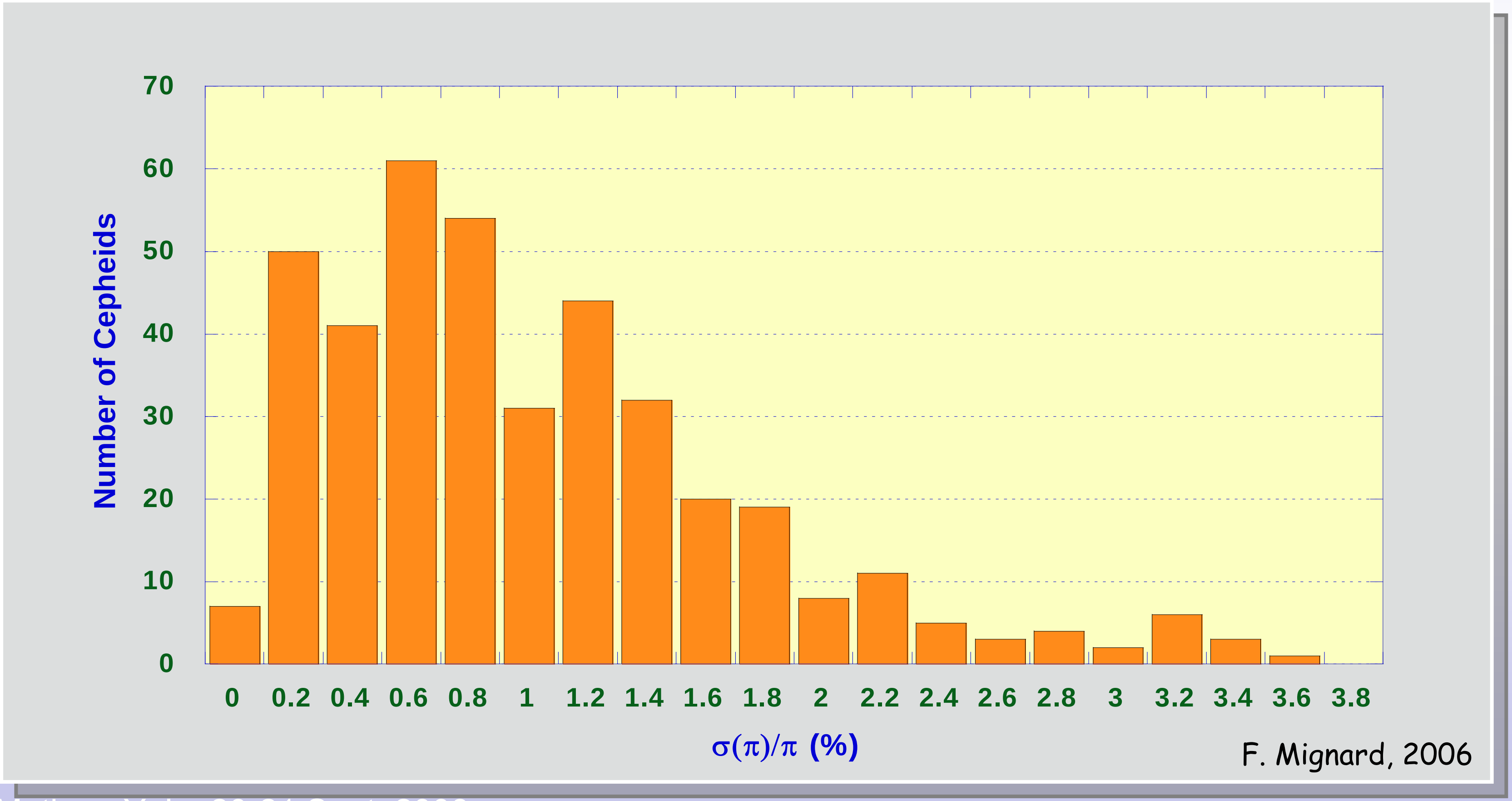


Credit: ESA/NASA/CFHT/NOAO

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

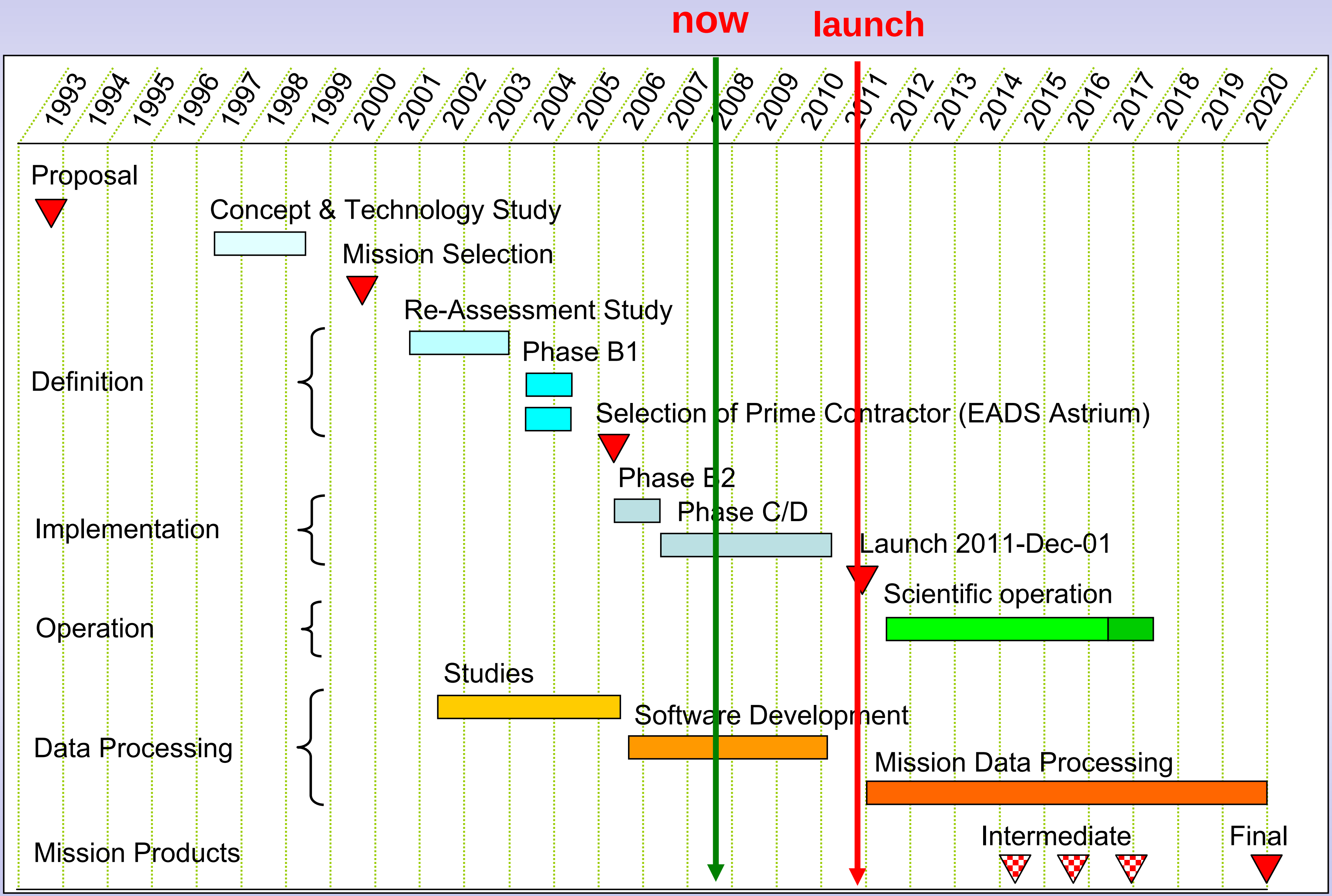
Sky-averaged standard errors for G0V stars (single stars, no extinction)

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

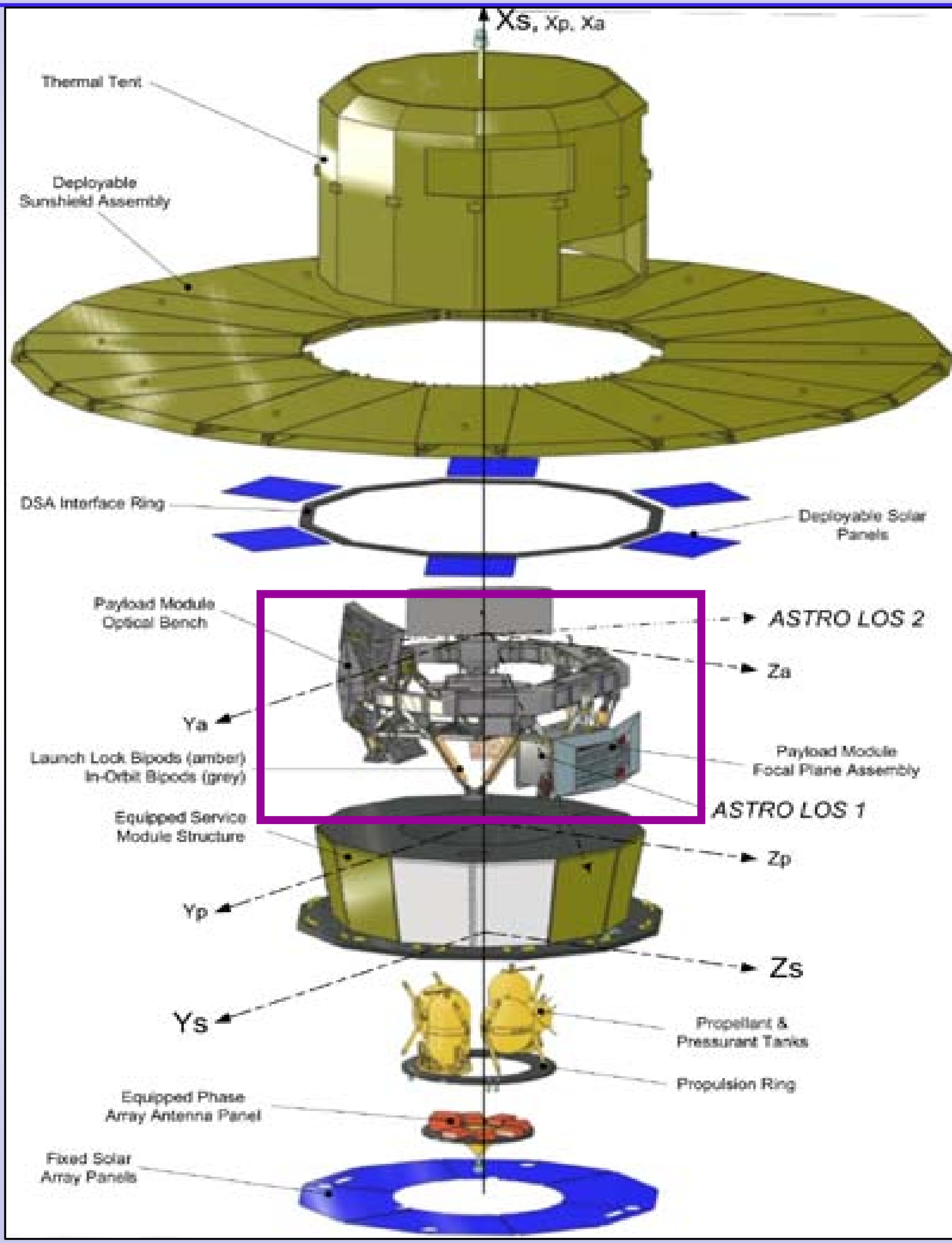
Notes:

- Estimates calculated with the Gaia Accuracy Tool (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



Gaia: The Spacecraft



Thermal shielding

Ø ~ 10 m

Solar panels

Telescopes

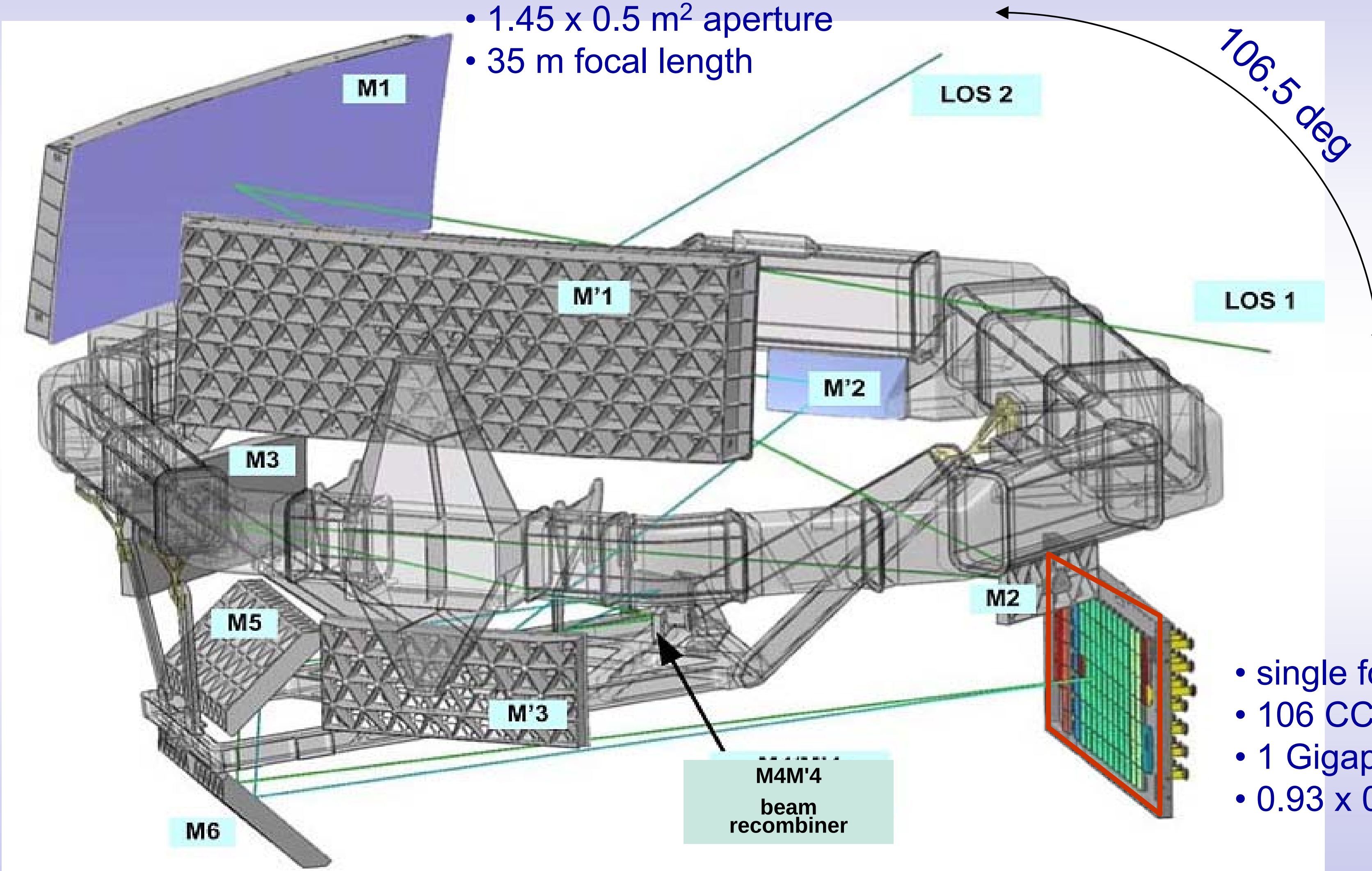
focal plane

Propulsion module

Antenna (1 Mbit/s)

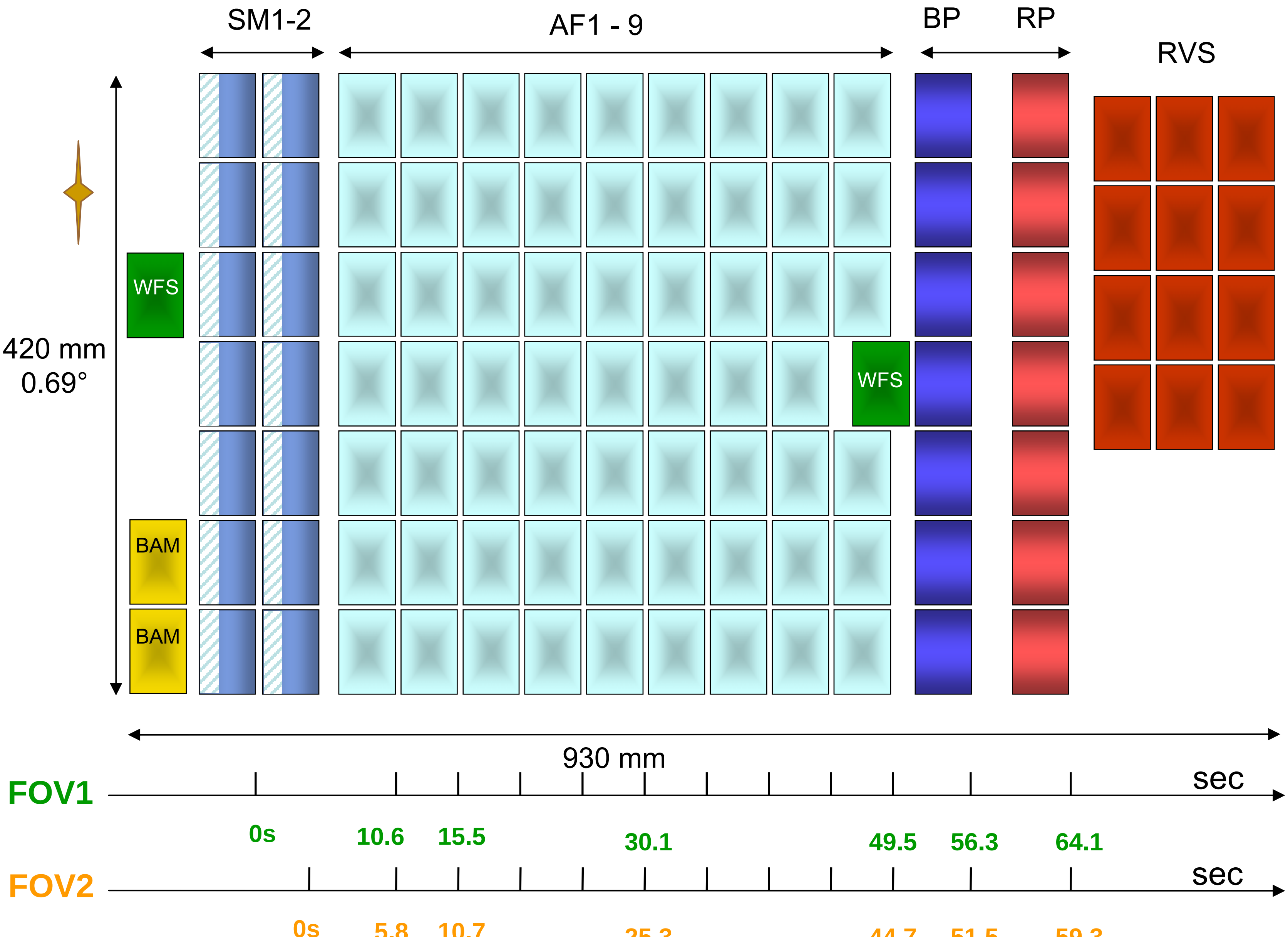
Gaia : telescopes and detector

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

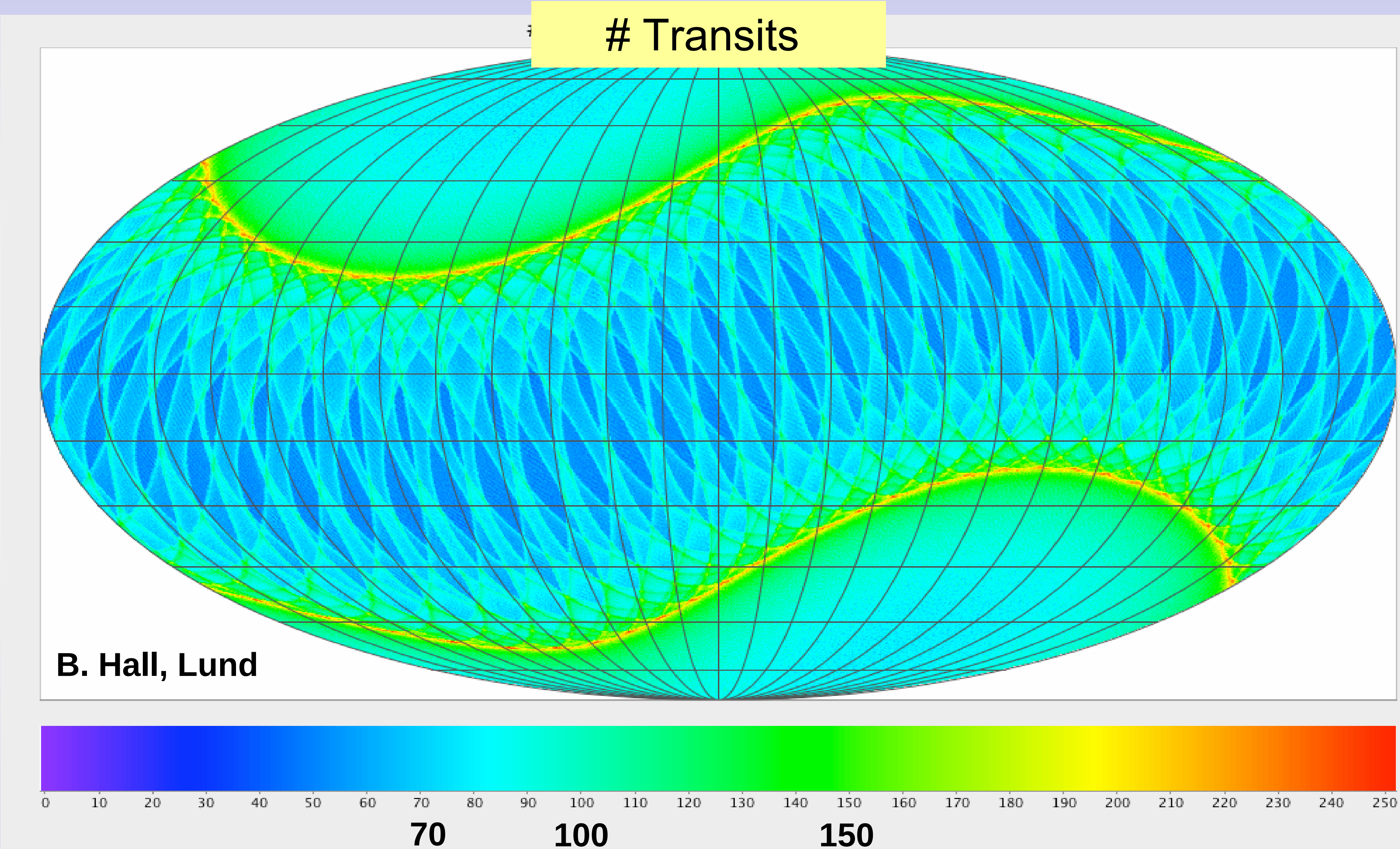


- single focal plane
- 106 CCDs
- 1 Gigapixel
- 0.93 x 0.42 m^2

Focal Plane Assembly

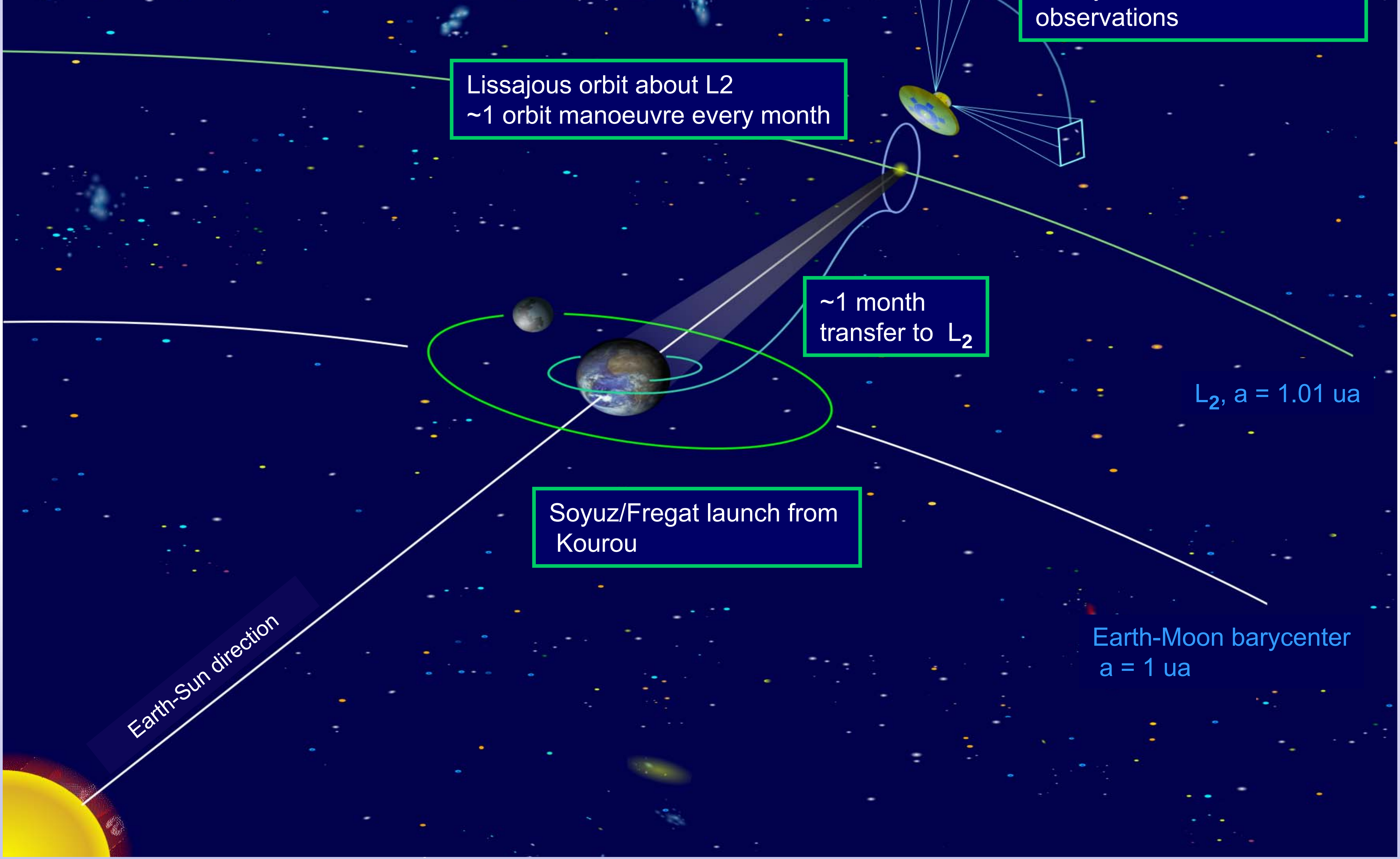


Sky coverage



Gaia launch and orbit

(credit: EADS Astrium)



Observatoire de la Côte d'Azur

Gaia DPAC

Data Processing

The data

Sources of data

- Gaia has three instruments with three data flow
  - Astrometric CCDs
  - Photometric CCDs in the BP/RP bands
  - Spectroscopic data
- Data is organized in form of telemetry packets
  - one must also add house-keeping data and orbit data

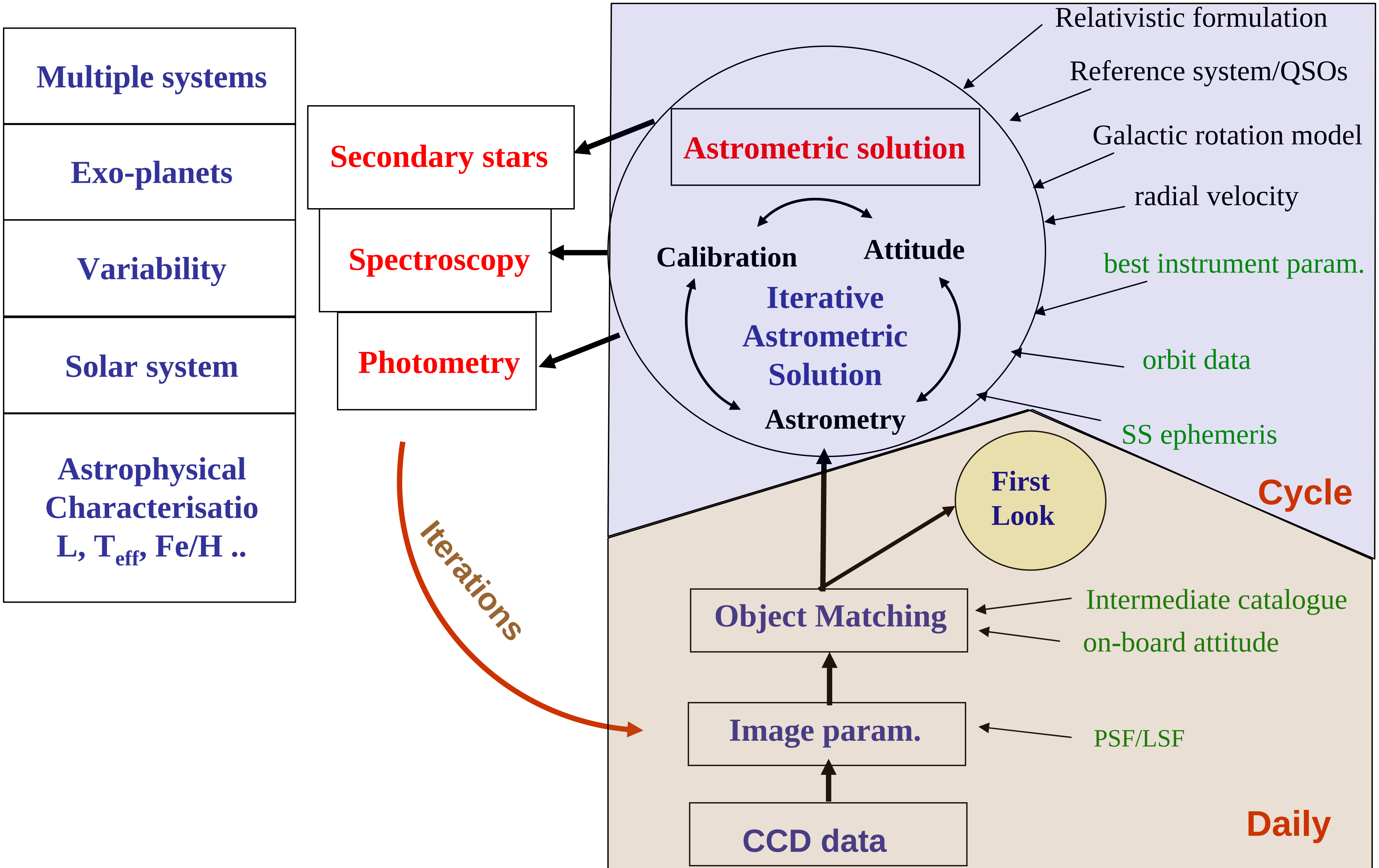
Hints

- Allocating 1s per star for astrom, phot., spec.
  - 30 years for the data processing
- One day of observation in the densest regions:
  - 600 days to ingest in the data base
    - with one processor and today power
- Straight Fourier transform of all the detected variables
  - 30 years of CPU with one standard PC

Few relevant numbers

- Data volume
  - compressed telemetry 250 Tb
  - raw data 100 TB
  - processed data and archives ~1 PB
- Computational size
  - 1.5×10^{21} FLOPs
- Computational power in the DPAC
  - > 20 TFLOP/s ➔ 2 yr CPU for 10^{21} FLOPs
- Data transfer
  - Downlink 50 GB/day
  - Data exchange between ESAC and DPCs : challenging

Overall chart of the data processing



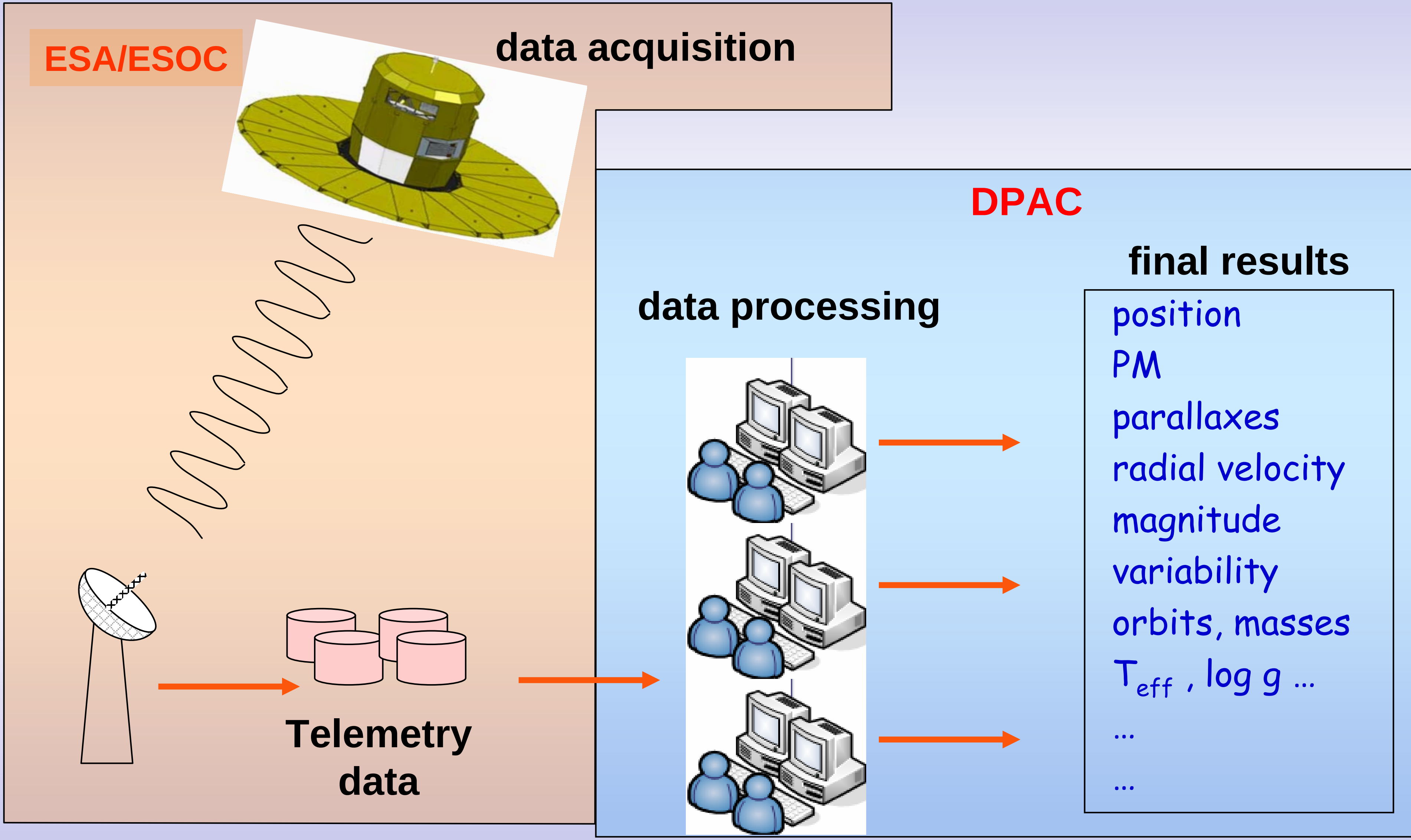
Organization

The DPAC

Formation of the DPAC: Context

- ESA has issued an Announcement of Opportunity
  - released in Nov 2006
  - it deals with the Gaia Data Processing
- A Consortium has been formed to answer this AO
  - DPAC = Data Processing & Analysis Consortium
  - Forms the "Science Ground Segment" for Gaia
  - must transform the telemetry data into science products
    - a large catalogue of astrometry, photometry, spectroscopy
    - stellar sources, QSOs, Solar system objects
  - Formally selected by ESA Science Program Committee in May 2007
    - response compiled in a 700-page proposal

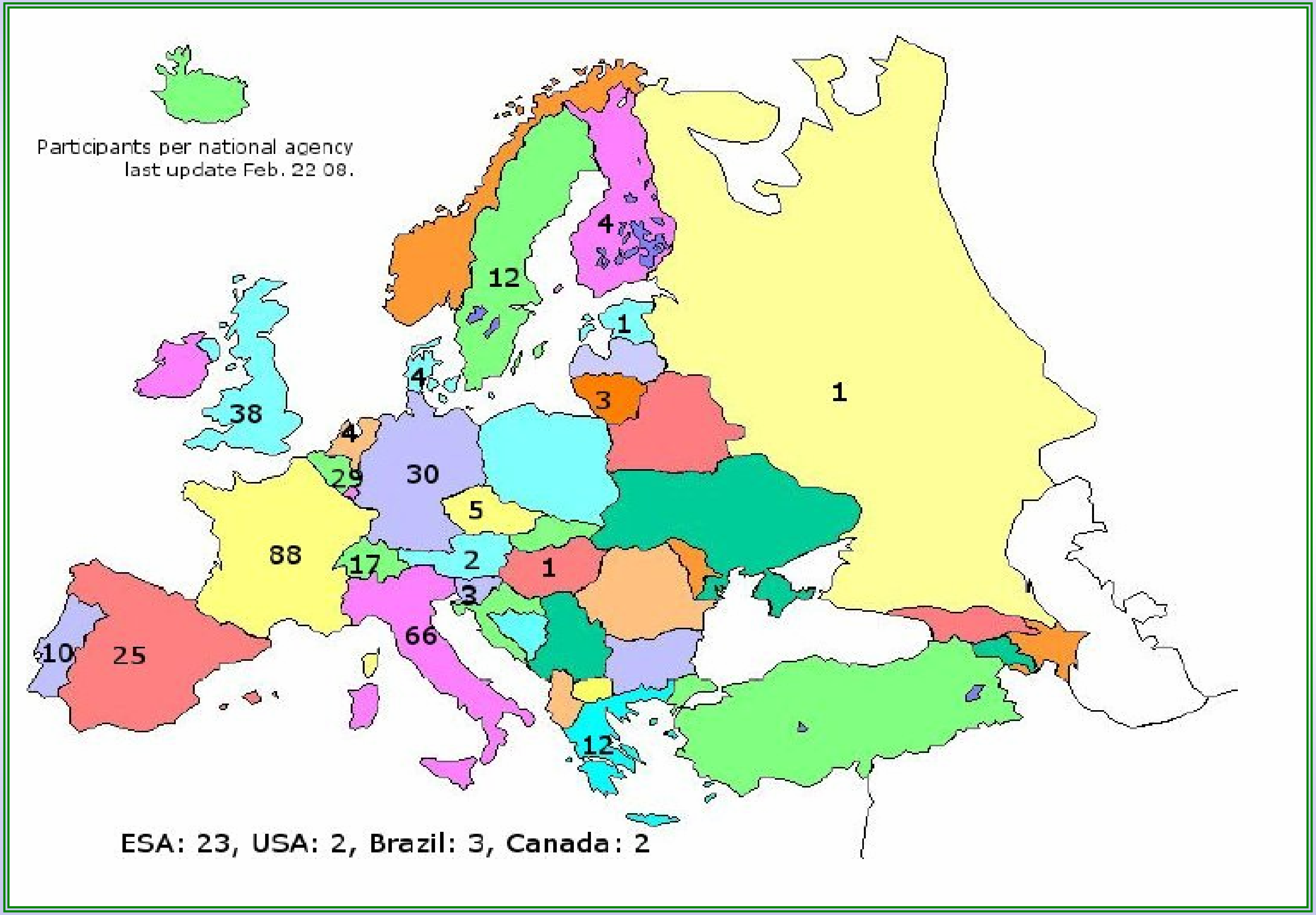
Where do the DPAC activities lie?



DPAC membership & management

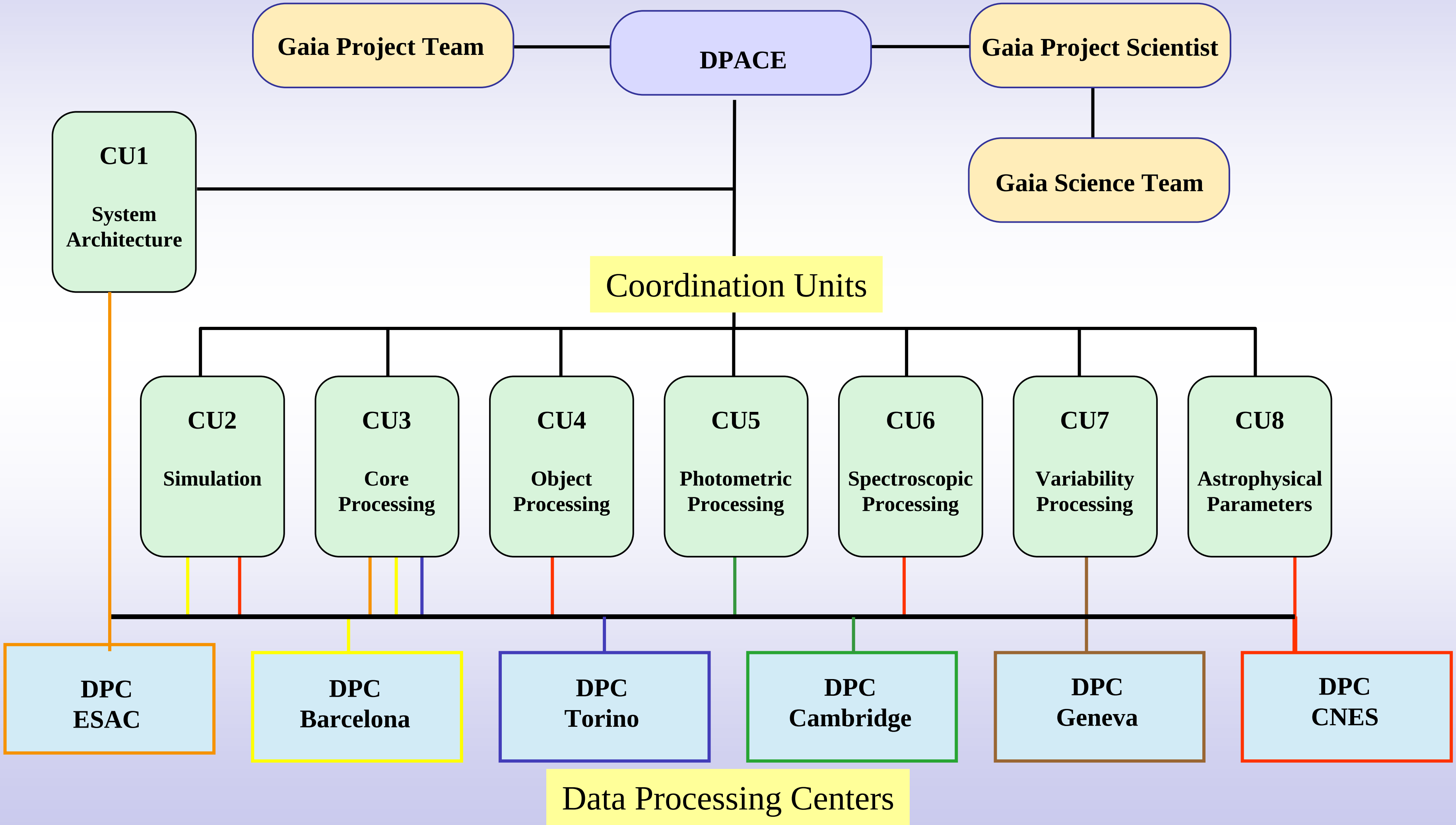
- As of 01 Sept 2008 : 395 members ➔ ~ 170 FTE
- 16 countries represented + ESAC
- Primarily stable positions in the academic world
  - Full time must be interpreted with care
    - teaching duties, University committees, student training, …
- Divided into 8 topical Coordination Units (CU)
  - CU1: System architecture
- Top coordination by the Executive Committee (DPACE)
  - Chair : F. Mignard
  - Deputy: R. Drimmel

Geographical distribution



Top level structure of the DPAC

- Separation between development and processing



F. Mignard
France

X. Passot
CNES

C. Bailer-Jones
Germany

X. Luri
Spain

W. O'Mullane
ESAC

F. van Leeuwen
UK

R. Drimmel
Italy

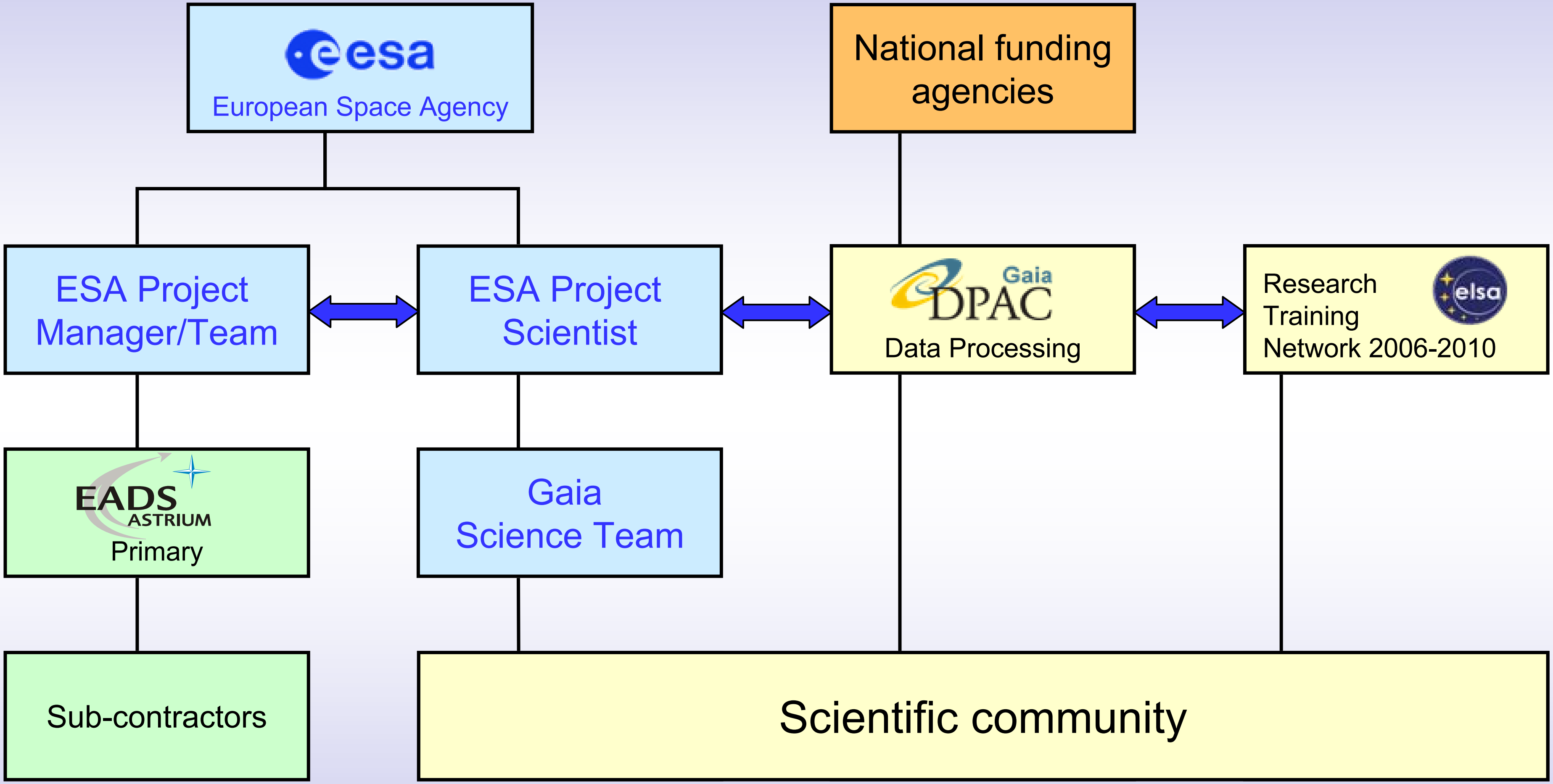
D. Pourbaix
Belgium

L. Eyer
Switzerland

U. Bastian
Germany

D. Katz
France

The DPAC in the mission overall chart



Therefore, if everything goes as planned...

in 2018…

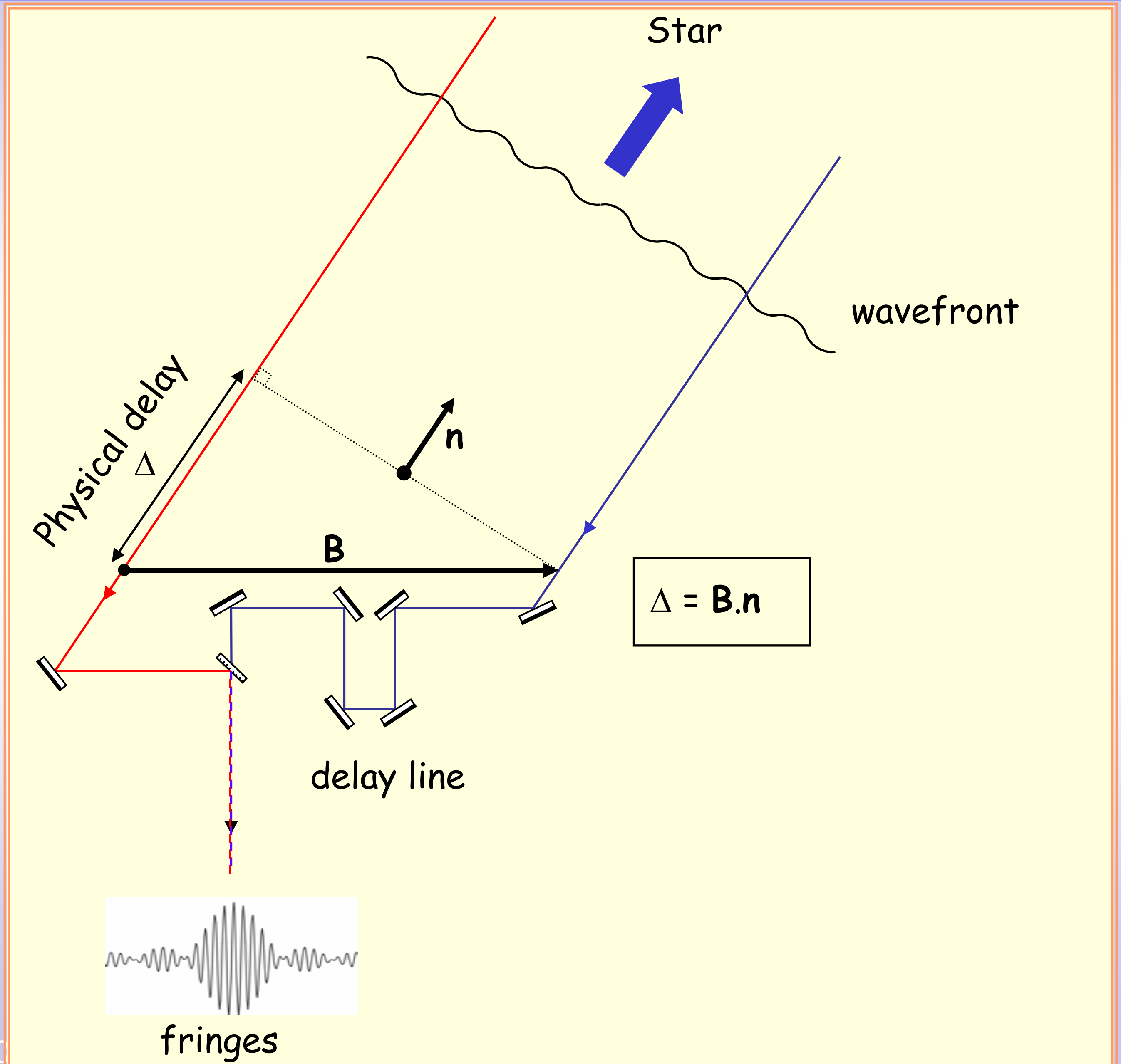
- 10^9 stars
  - 10^6 V = 12, 30×10^6 V = 15 , 250×10^6 v = 18
  - $\sigma \sim$ 4 μas V < 12, 10 μas V = 15, 150 μas V =20
- 25000 ✯/ deg^2 ; max : 3×10^6 /deg^2 .
- 200×10^6 radial velocities
- Stellar classification for all classes and types
- Variability analysis over $\sim 10^8$ stars
- 10 000 stellar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

Astrometric Interferometry

SIM & SIM-Lite

Michelson Interferometry for Astrometry

- Peak fringes tuned with internal delay
- It matches the external delay
- Relative orientation between source and baseline direction
  - equivalent in imaging astrometry to stellar direction w.r.t telescope axis.
- Needs a second measurement at ~ 90°



SIM & SIM PQ

- Long history starting in 1991
  - Astrometric Interferometry Mission for astrophysics recommended by NRC
- First selection in 1996
- Strand of fathers and sons over the years
  - became SIM Planet Quest in 2005 ➔ primary objective highlighted
- Successful 10-year technology program and numerous test-beds
- Underwent several cost-reduction reviews
  - one of the best reviewed mission ever
- Redirection of NASA priorities in 2007 ➔ program postponed

SIM & SIM-Lite Science

- Planet searching:
  - Search for astrometric signature of terrestrial planets around nearby stars
  - Statistics and properties of planetary systems
- Distances and Luminosities:
  - Calibration of the cosmic distance 'ladder'
  - Ages of globular clusters
- Galaxy and star cluster dynamics and structure
  - Mass distribution in the halo of our Galaxy
  - Spiral structure of our Galaxy
  - Internal dynamics of globular clusters
  - Masses and distances to gravitational lenses
  - Dynamics of our Local Group of galaxies
- Quasars
  - Origin of light in QSOs
  - Binary black holes

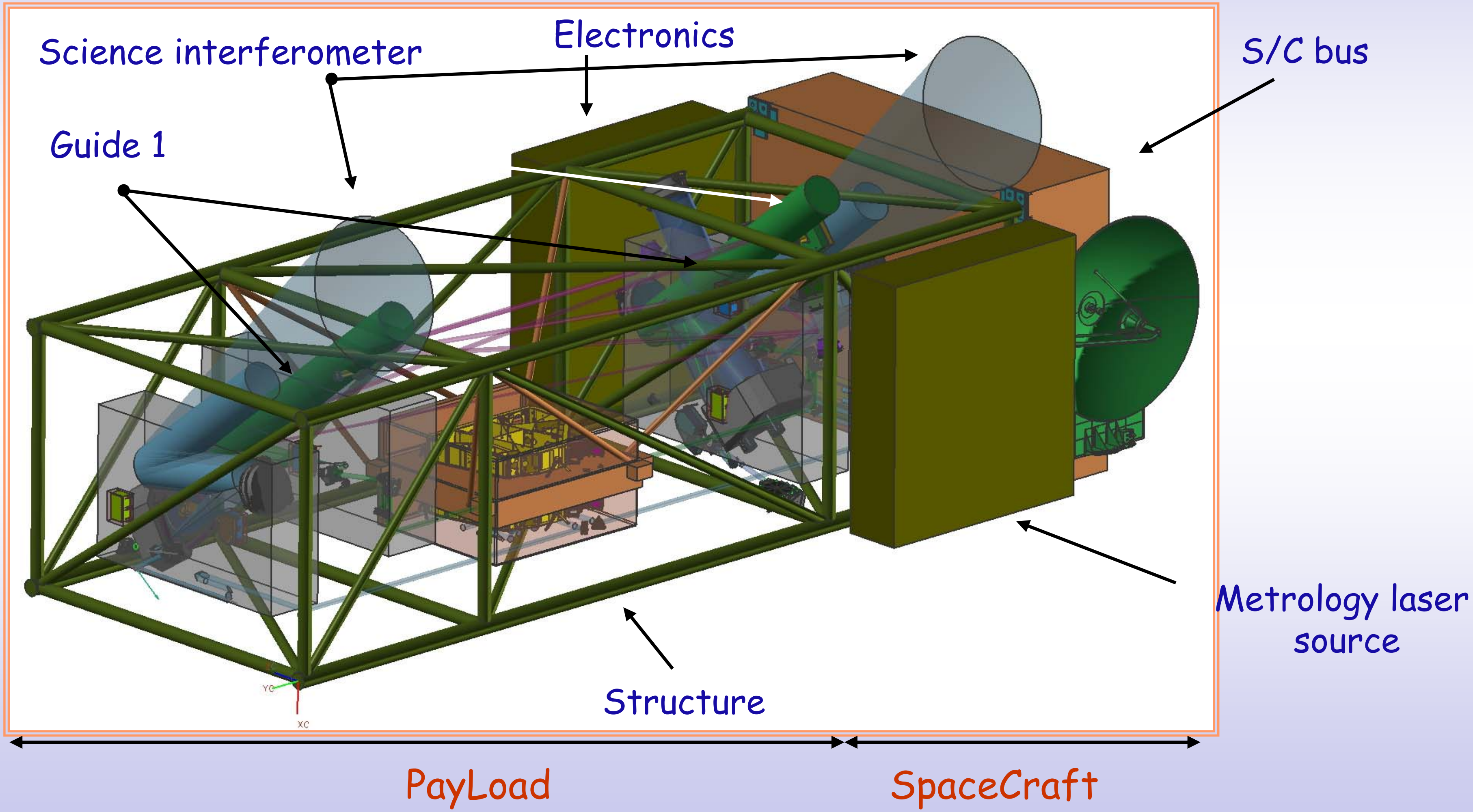
SIM Status

- SIM PlanetQuest Status (as of May 2008):
  - The Project is currently in Phase B (Preliminary Design). Launch deferred indefinitely by NASA HQ
- SIM Technology is Complete:
  - Ten-year technology program, including eight NASA HQ specified technology gates, are all complete,
  - Technology completion/readiness confirmed by multiple external reviews.
- Recently Completed Milestone(s) and Events:
  - SIM Science Team Meeting, Caltech, June 9-11, 2008
  - SIM Special Session, Winter AAS Meeting, January 9, 2008
  - SIM Technical Advisory Committee March 13, 2007
- Upcoming Meetings and Reviews:
  - SIM Science Team Meeting, November 2008
  - SIM/Gaia Science Meeting, London, 6 November, 2008

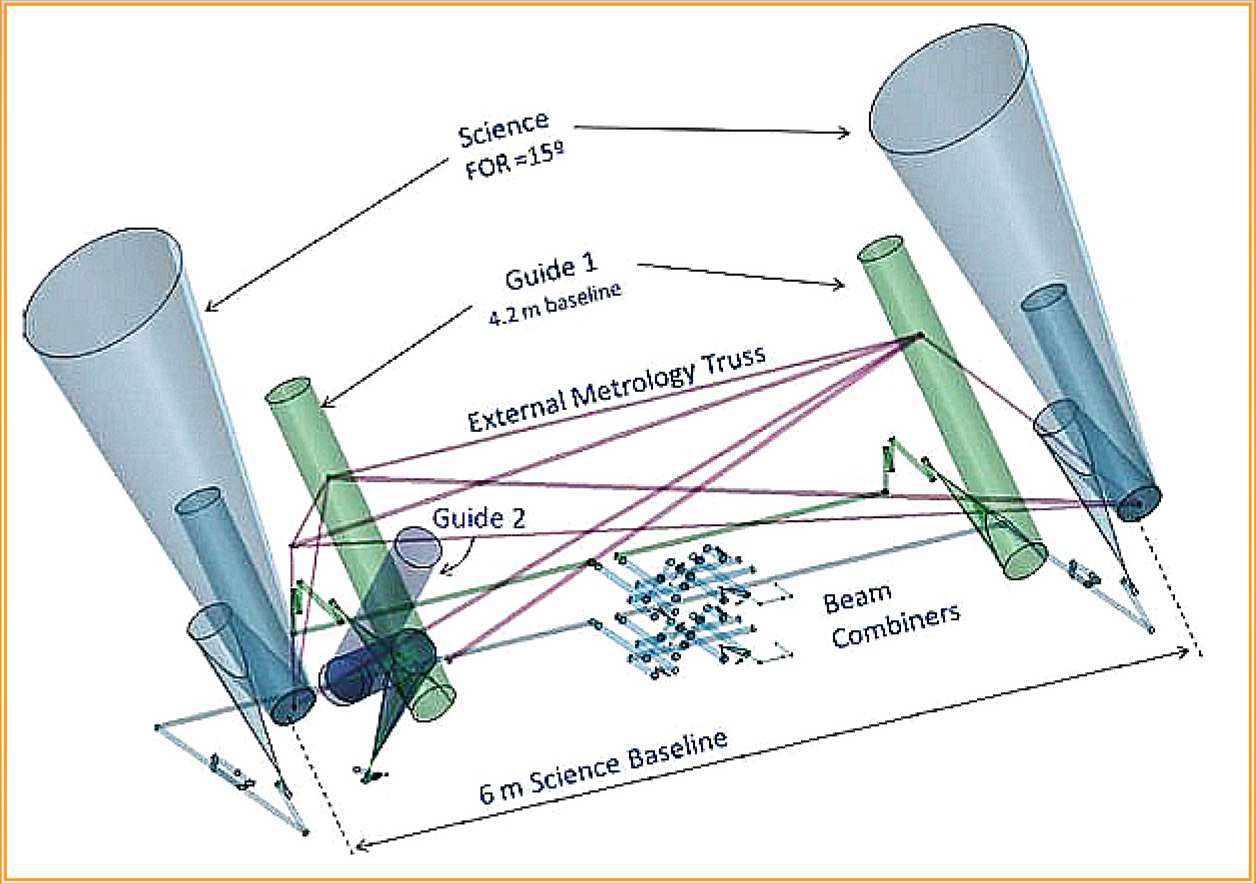
SIM-Lite

- Alternative to SIM-PQ using the completed technology
  - SIM PQ technology matured, but postponed indefinitely
- Smaller and cheaper version of SIM Planet Quest
  - Minimum science descoping
  - lower precision and less throughput
- Grid of absolute astrometry $V < 10.5$ $\sigma \sim 4$ μas
  - 8 μas @ $V = 19$
- Small angle astrometry (2 deg.) $V < 6$
  - 65 stars for planet detection in the HZ
- 5-year mission , Earth trailing orbit

Sim-Lite overall configuration



SIM-Lite optical configuration



Compared to SIM-PQ

- Baseline = 6 m (9m)
- Guide-1 : 4m baseline
- Guide-2 : single telescope

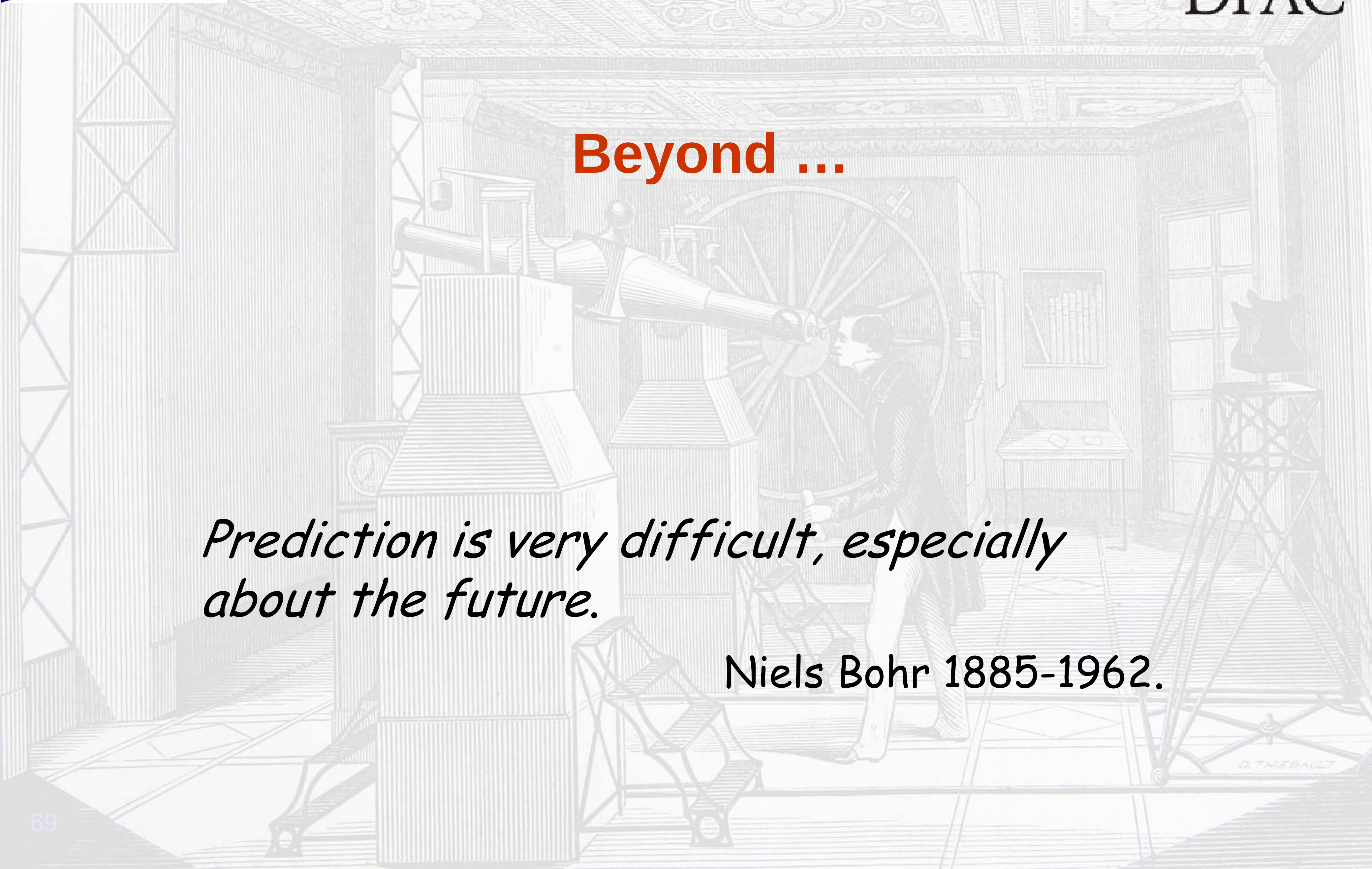
SIM-Lite : Mission Time Allocation

Task	Target	Allocation
		%
Earth planets	65 *	46
Larger planets	1050 *	5
Young stars	67 *	2
Grid	44,000 tiles	9
Reference frame	50 QSOs	1.5
Wide angle	8300 h	19
S/C maneuvers		14.5
Servicing/calib	45mn/day	3

total : 100 %

JASMINE

- Japanese Astrometry Mission
  - observes in the IR z-band (0.9 μm)
  - 10 μas astrometric accuracy in global astrometry
  - 10 million stars , z < 14
- A single field of view
  - overlapping tiles of 0.6x0.6 deg^2
  - will cover a field of 20x10 deg^2
  - one telescope of 70 cm diameter
- Main goal : study of the galactic bulge components
- Launch > 2017
  - 5-year mission
- Current status :



Beyond …

Prediction is very difficult, especially about the future.

Niels Bohr 1885-1962.

Scientific key questions relevant to astrometry I

- Small field astrometry
  - routine astrometry of earth-like planets ➔ main goal
  - extended velocity fields in clusters and galaxies
  - astrometric micro-lensing for galactic structure, planet detection
  - high-precision light deflection by planets
  - star-spots and stellar activity

more

Scientific key questions relevant to astrometry II

- Global astrometry
  - absolute astrometry in the Local Group ➔ mapping Dark Matter
  - distances to globular clusters to 0.001 ➔ age of oldest stars
  - detection and mapping of the stochastic gravitational waves field
  - curvature (acceleration) of 3D stellar motions ➔ galactic potential
  - transverse motions of quasars ➔ dynamic properties ➔ cosmology
  - primary reference frame with CMB ?➔ great appeal ➔ but how to do it
  - fundamental physics: cosmic acceleration, relativity testing

General ideas about concepts

- Instrument in space is mandatory
- We need small field astrometry with the highest accuracy
  - but the reference frame must be constructed in parallel
- I like the SIM concept for this purpose:
  - high performance in small field
  - grid of reference sources with the same instrument
- The survey mode (many sources) is (at least for astronomers) more important than few bright discoveries (more appealing to agencies)
- simultaneous observations of many objects in the FOV required
  - seems to rule-out interferometry
- Interferometers heavier, less cost-effective than imaging telescopes
  - technology in space still to be demonstrated

General ideas about concepts

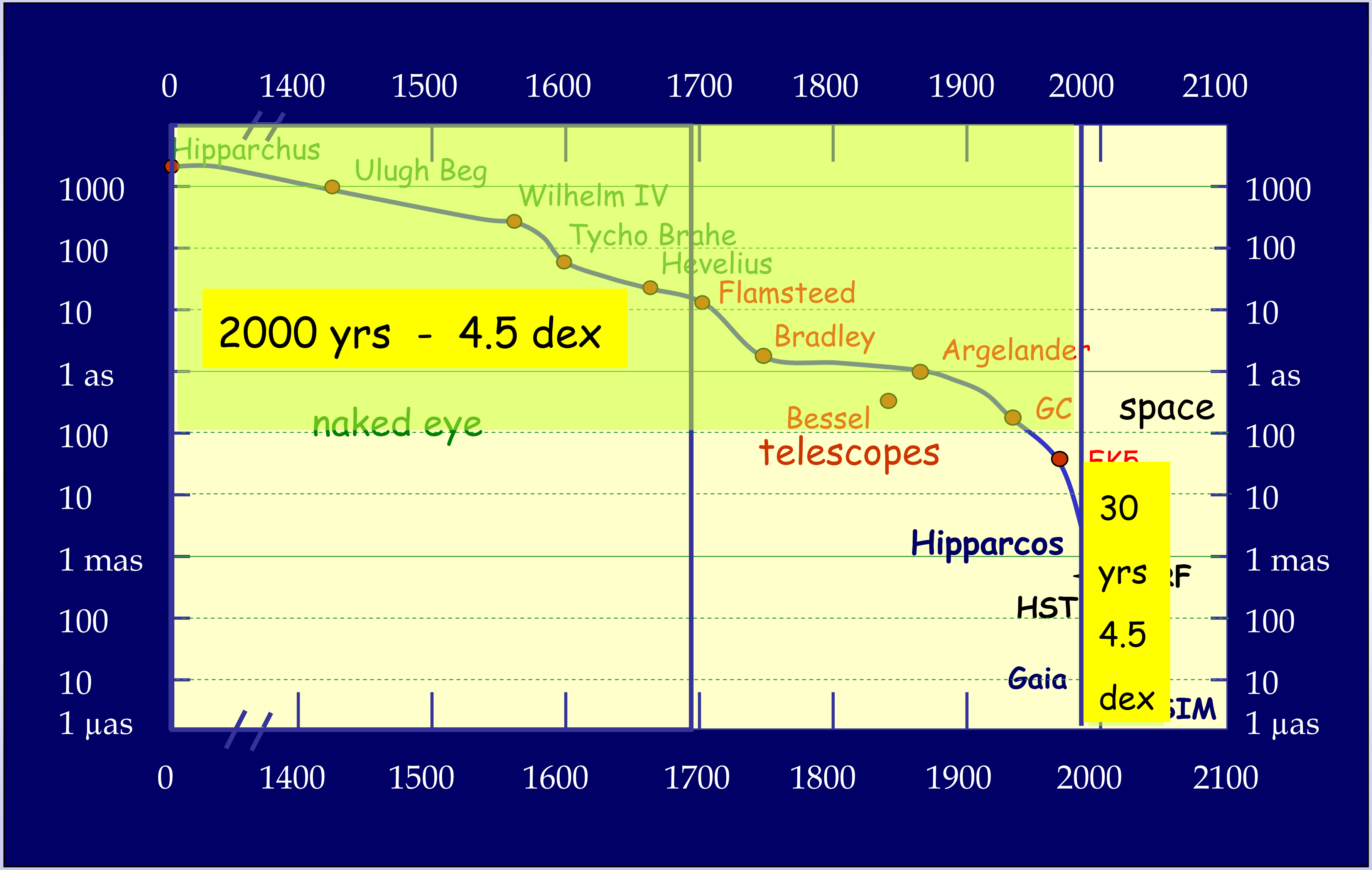
- Complementary instruments on board :
  - spectroscopy, primarily for RV
  - multi-band photometry
  - polarization measurements
    - can be done in principle from the ground, but very hard to organise to get a large throughput
- Visible of near IR ?
  - good question: pros and cons for both.
    - with similar performance, IR better for stellar physics
  - detector performances may provide the answer

Performances

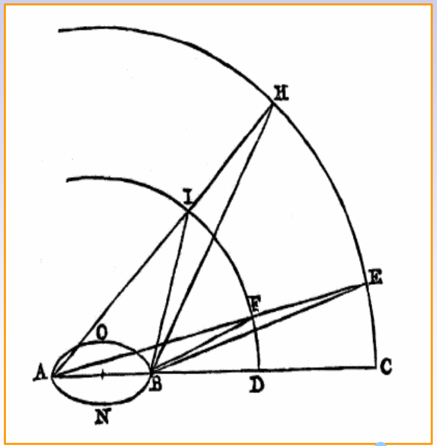
- Many factors to be considered
  - single measurement error
  - sensitivity
  - accuracy vs. magnitude
  - time sampling
  - overall duration
  - needs for global vs. local astrometry
- Duration is an important issue
  - PM accuracy improves as $t^{3/2}$
  - orbit and other periodic phenomena gain dramatically from time coverage
- Always a trade-off between science and technological capabilities
  - not a single mission can be optimised for all the goals

Conclusions

My main point: The Golden Age of astrometry

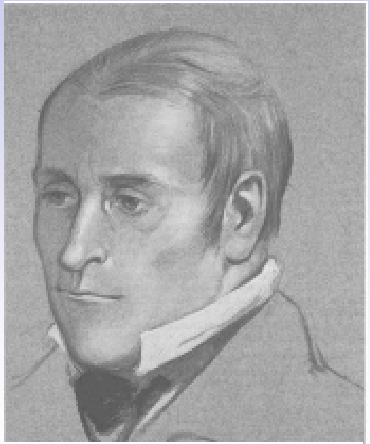


The dedicated fellows … (a sample)



Galileo, Dialogo


F.W. Bessel

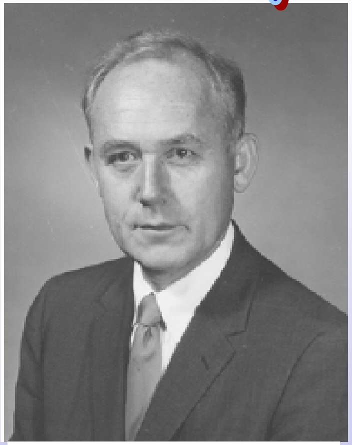

Th. Henderson

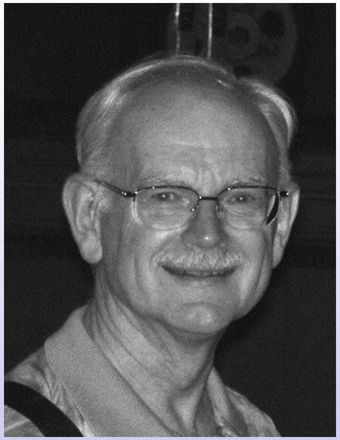

F. W. Struve

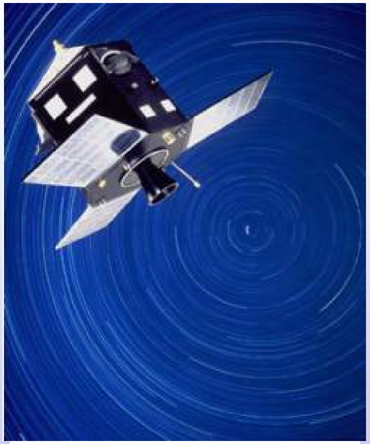
Thanks for you attention


J. Kapteyn


F. Schlesinger

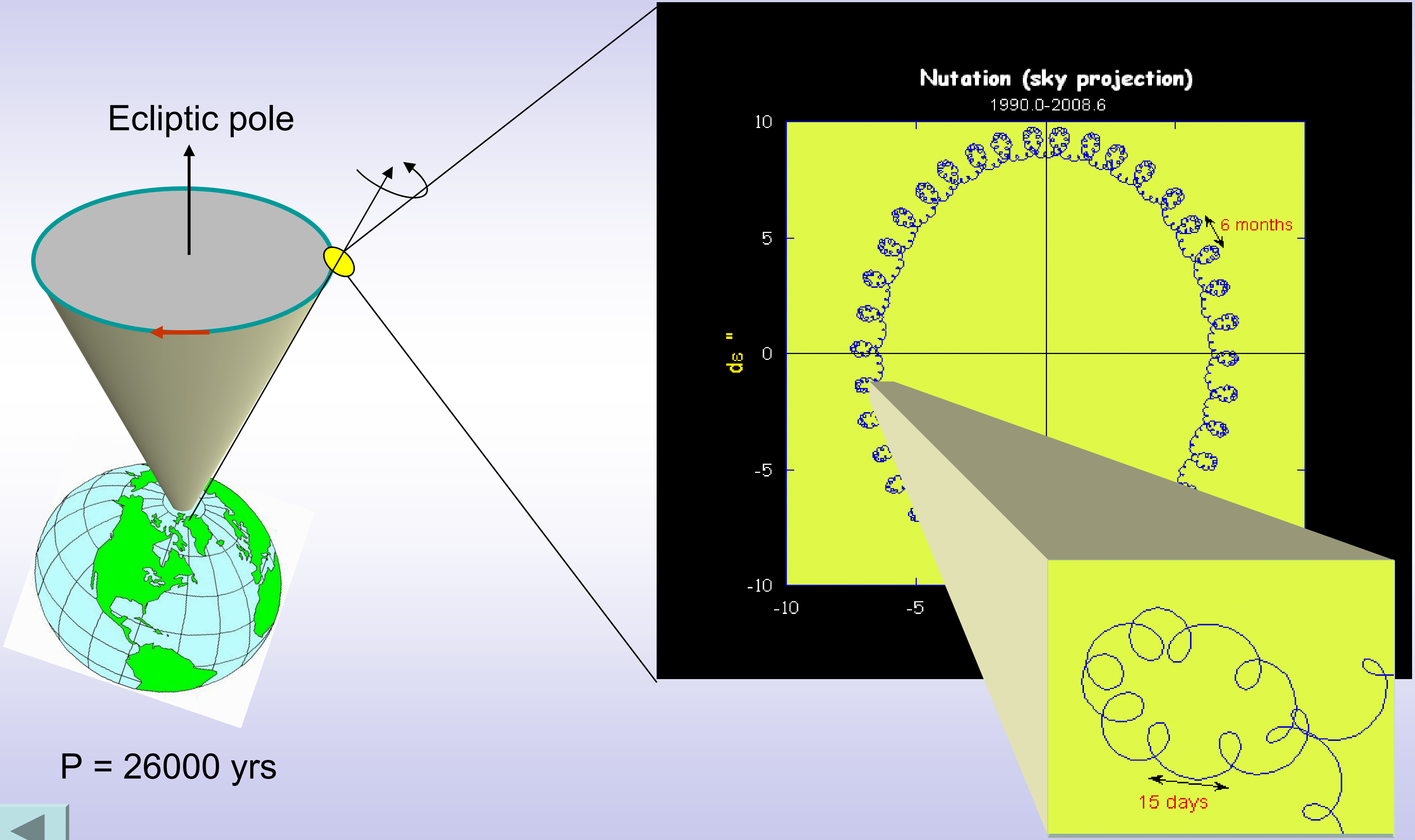

K. Strand


W. Van Altena


Hipparcos

Linked slides

Precession Nutation



P = 26000 yrs

Who coined *parsec* ?

Gaia DPAC

back to parallax

MONTHLY NOTICES

OF THE

ROYAL ASTRONOMICAL SOCIETY.

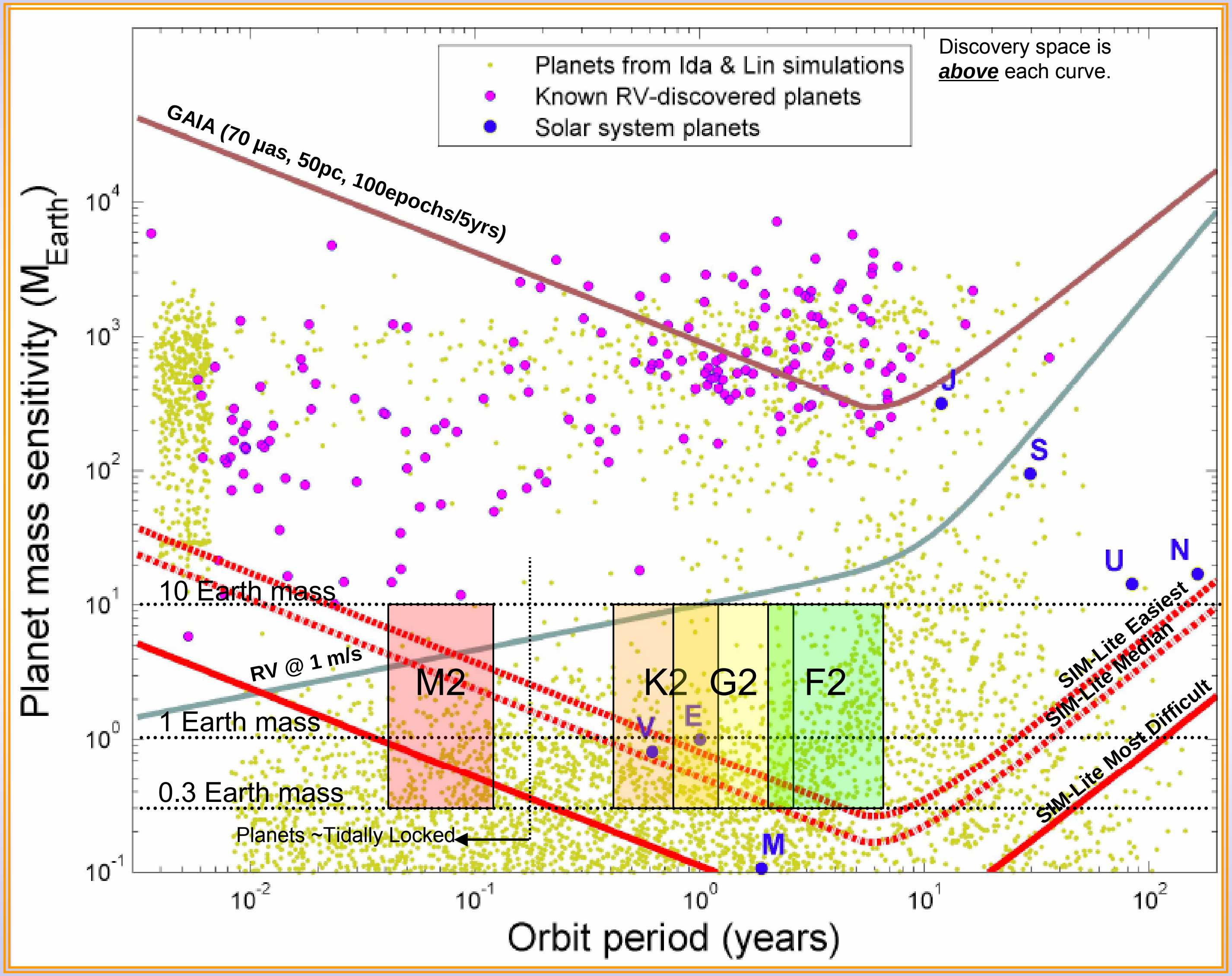
VOL. LXXIII. MARCH 14, 1913. No. 5

The Distribution in Space of the Stars in Carrington's Circum-polar Catalogue. By F. W. Dyson, LL.D., Astronomer Royal.

of the results given by the index 1·5 or 1·4 in the above formulæ. Taking the unit of distance R* to be that corresponding to a parallax of 1″·0, and adopting Campbell's value 19·5 km/sec

* There is need for a name for this unit of distance. Mr. Charlier has suggested Siriometer, but if the violence to the Greek language can be overlooked, the word *Astron* might be adopted. Professor Turner suggests *Parsec*, which may be taken as an abbreviated form of "a distance corresponding to a parallax of one second."

Planet Search: discovery space

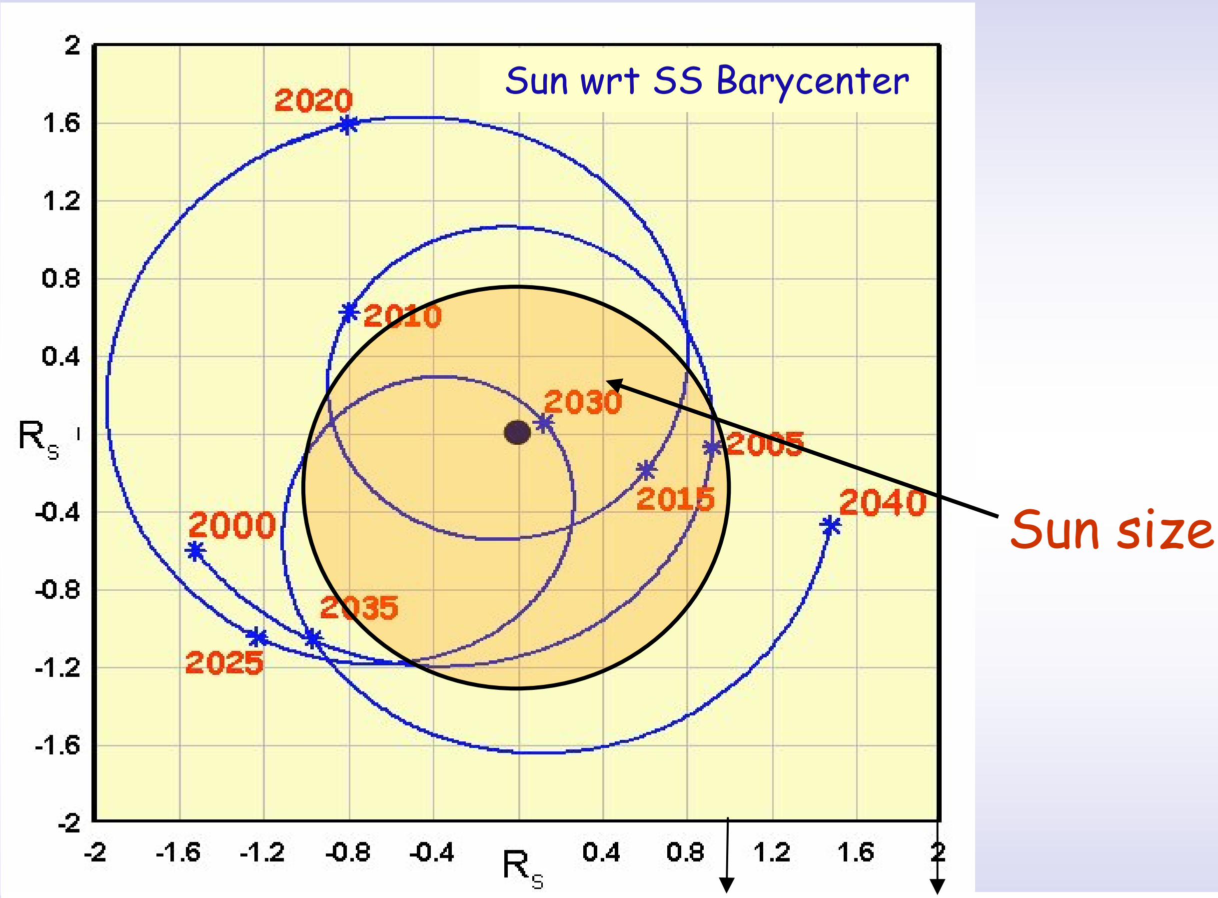


Crédit: J. Catanzarite

Identify habitable planets: a roadmap (from A. Leger)

- Statistical determination of the frequency of habitable planets;
- Identification of potentially habitable, terrestrial planets around nearby stars
- Spectroscopic studies of these planets with the aim of identifying key atmospheric gases for comparative planetology and search for life.

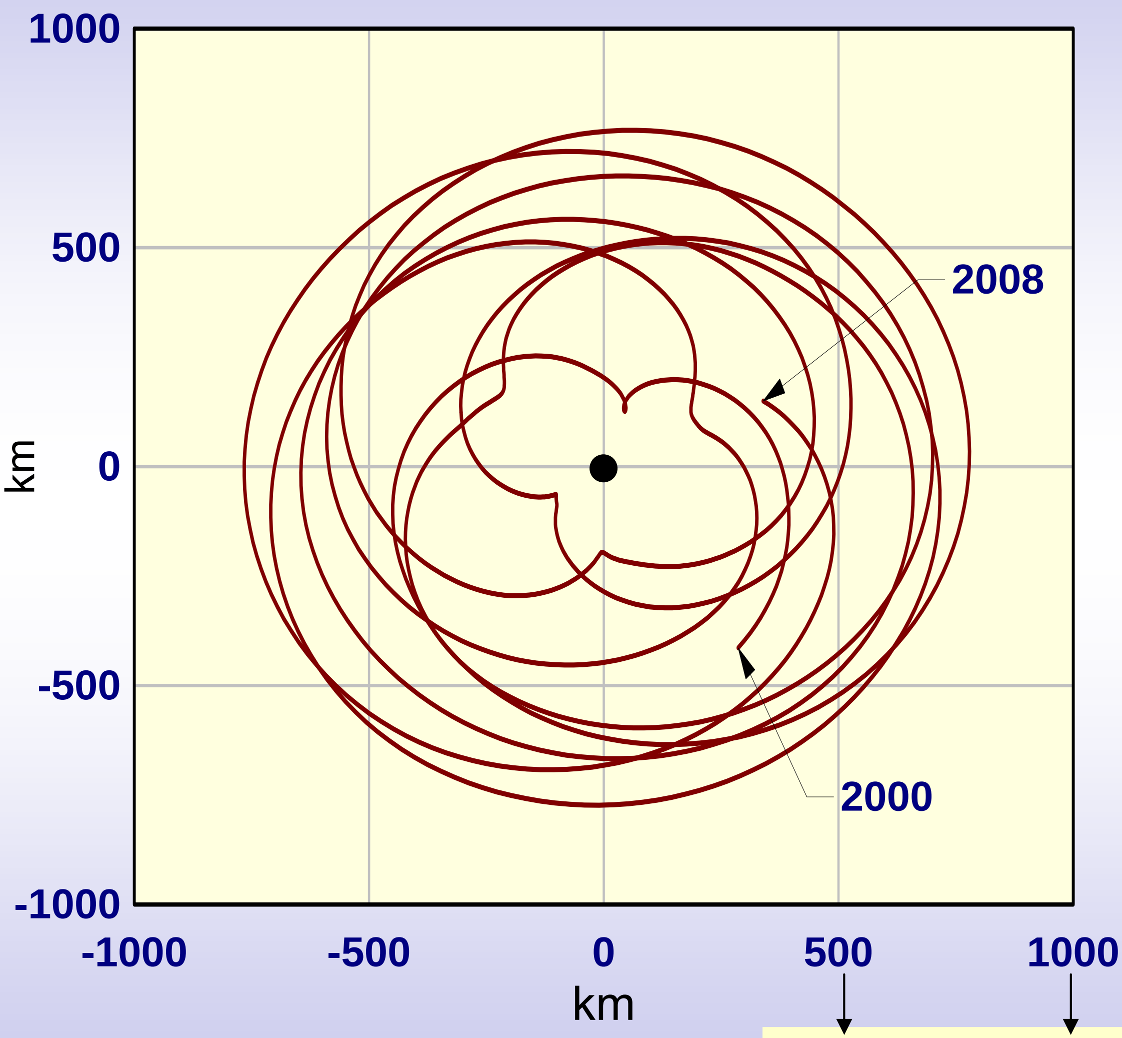
Sun motion in solar system



0	0.5	1	mas	@	10 pc
0	5	10	µas	@	1 kpc

- Full solar system
- Reflex motion of the Sun
- Period 10- 30 yrs
- Wobble dominated by Jupiter and Saturn

Barycenter with inner planets



- Solar system with the four inner planets
- Reflex motion of the sun
- Challenge for detection of planets in the HZ

0.3	0.6	μas	@ 10 pc
30	60	nas	@ 100 pc

to key questions