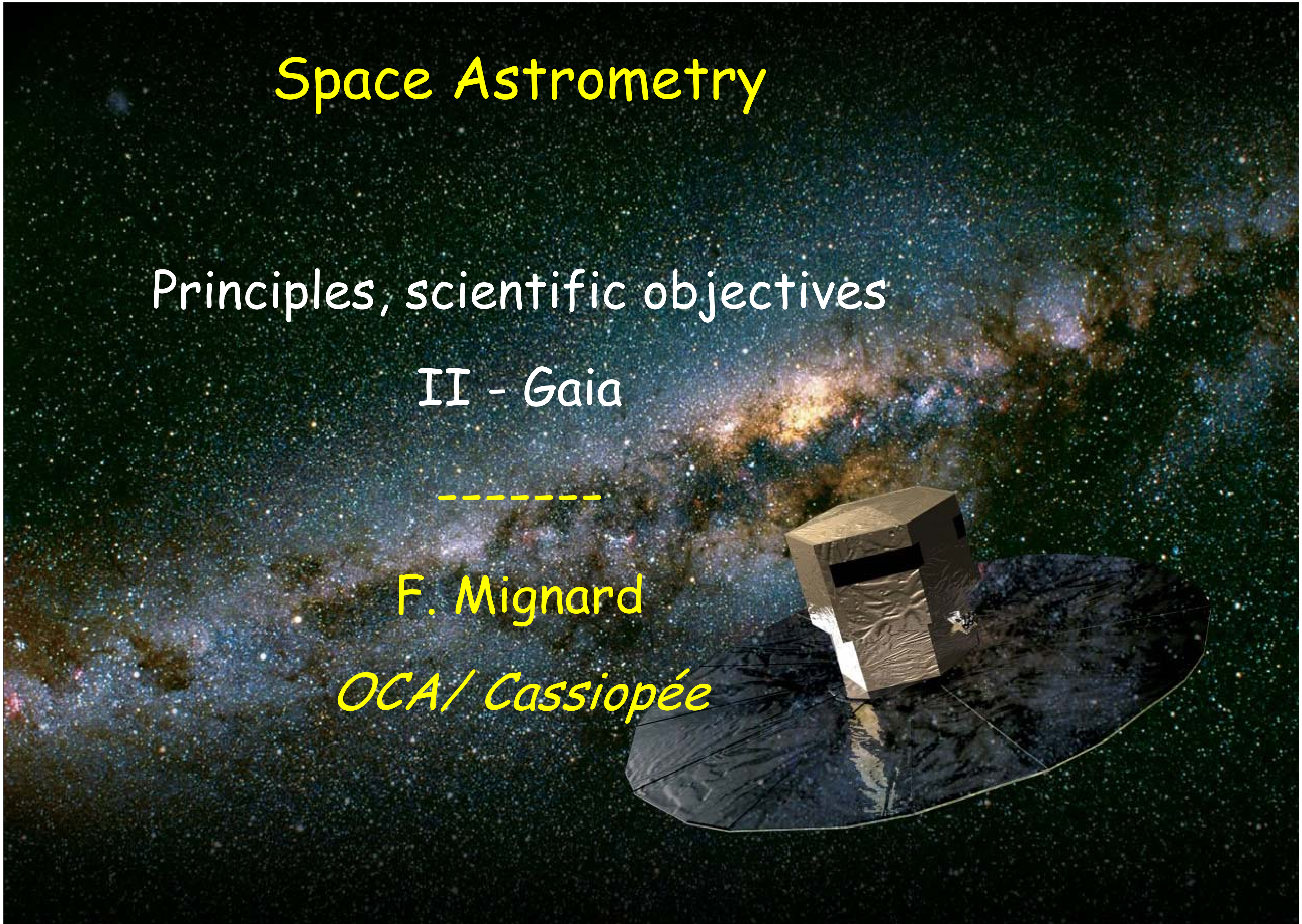


Space Astrometry

Principles, scientific objectives

II - Gaia

F. Mignard

OCA/ Cassiopée

Summary : Lecture 2

- Gaia : a quick tour
- Spacecraft and payload
- Orbit and scanning law
- Astrometry and reference frame
- Astrophysical exploitation
- Conclusion

GAIA

- 10^9 stars
  - 20 μas @ V = 15 mag

Launch : 2011

Mission : 5 years

- Photometry (4 + 11 bands)
  - Radial velocity
    - Low resolution spectroscopy

Milestones of the mission

- 1994 Recommendation for an astrometric interferometric mission with an accuracy of 10μas
- 1996/2000 Design study and science case
- 07/2000 Concept and Technology Study Report
- 10/2000 ESA selection as Cornerstone 6
- 01-05/02 Selection confirmed with slight descoping
- 2001-05 Definition studies (Alenia- Alcatel, Astrium) + ~ 10 industrial technology developments (CCDs, Inch-worm, antenna, FEEP, Sunshield, PDHE ..)
- 01/2005 Letter of Intent to the scientific community
- 04/2005 Setting up of the DACC (Data Analysis Coordination Committee)
- 07/2005 ITT to industry (Invitation to tender)

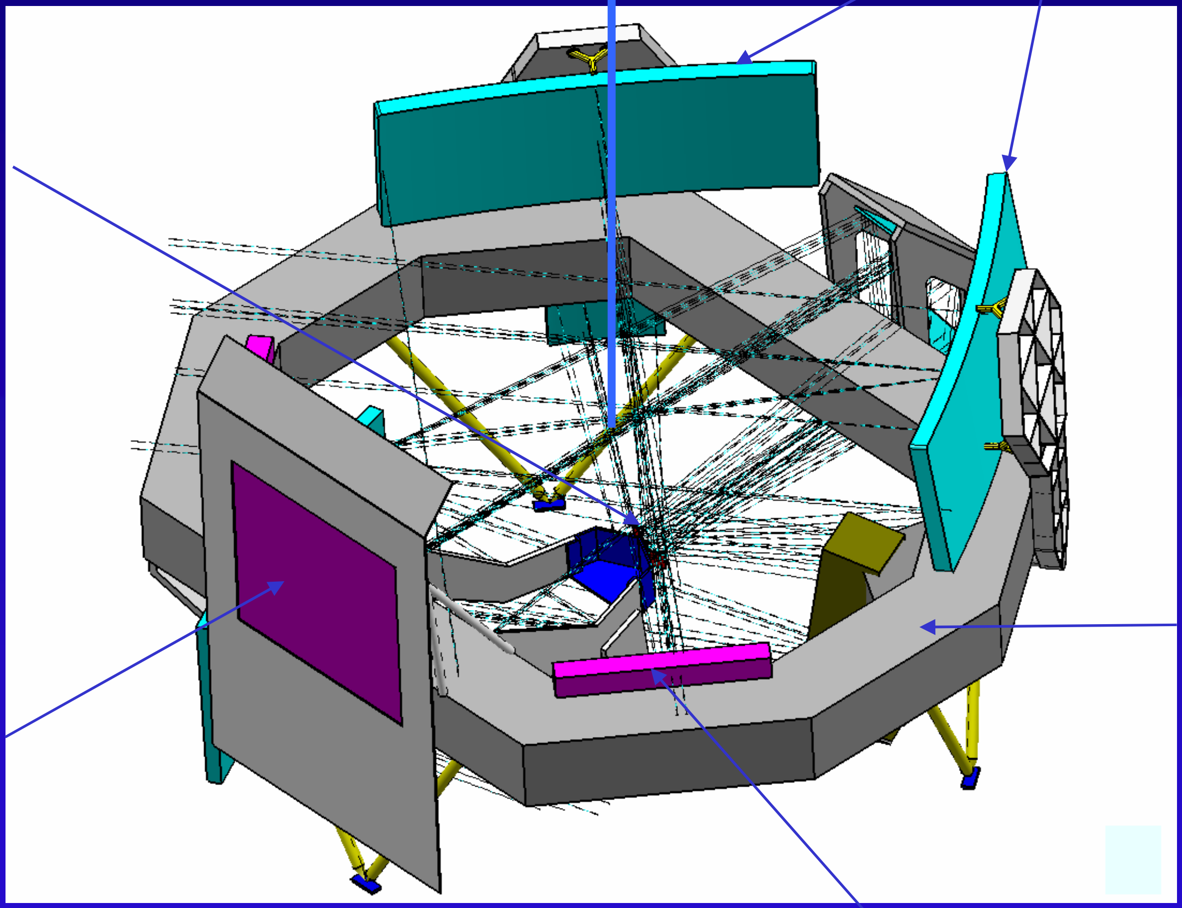
GAIA Compared to Hipparcos

	Hipparcos	GAIA
Magnitude limit	12	20-21 mag
Completeness	7.3 – 9.0	~20 mag
Bright limit	~0	~7 mag
Number of objects	120 000	35 million to V = 15 350 million to V = 18 1000 million to V = 20
Effective distance limit	1 kpc	1 Mpc
Quasars	None	$\sim 5 \times 10^6$
Galaxies	None	$> 10^7$
Accuracy	~1 milliarcsec	8 μarcsec at V = 10 20 μarcsec at V = 15 200 μarcsec at V = 20
Broad band	2-colour (B and V)	4-colour to V = 20
Medium band	None	11-colour to V = 20
Radial velocity	None	1-10 km/s to V = 16-17
Observing program	Pre-selected	On-board and unbiased

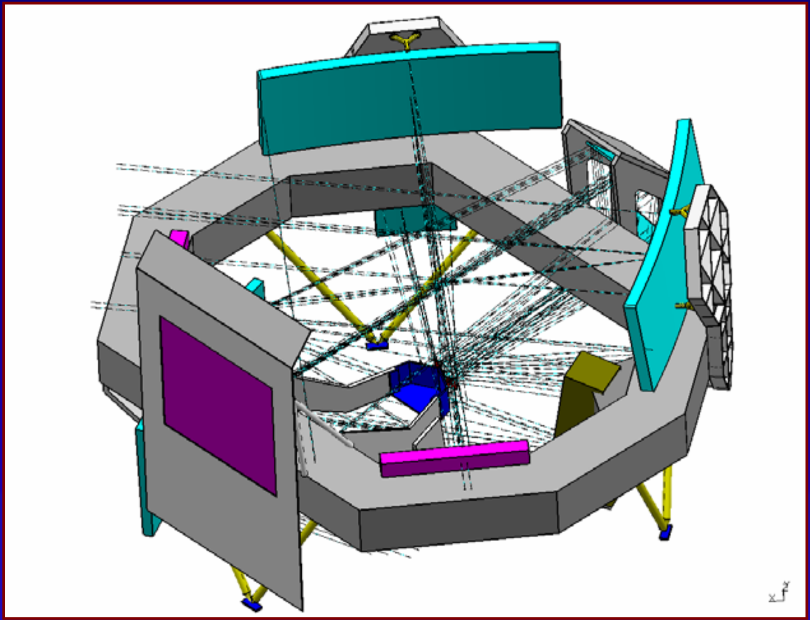
Assets of Gaia

- 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

GAIA : Optical Systems

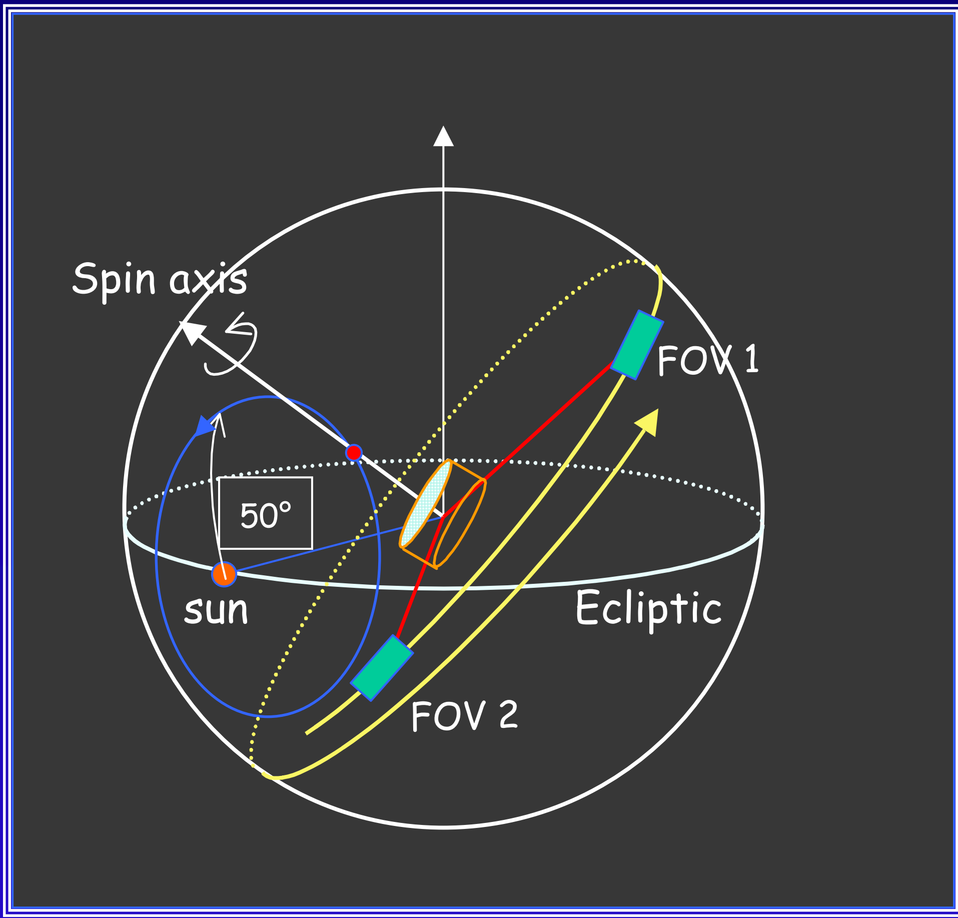


Main instrumental parameters



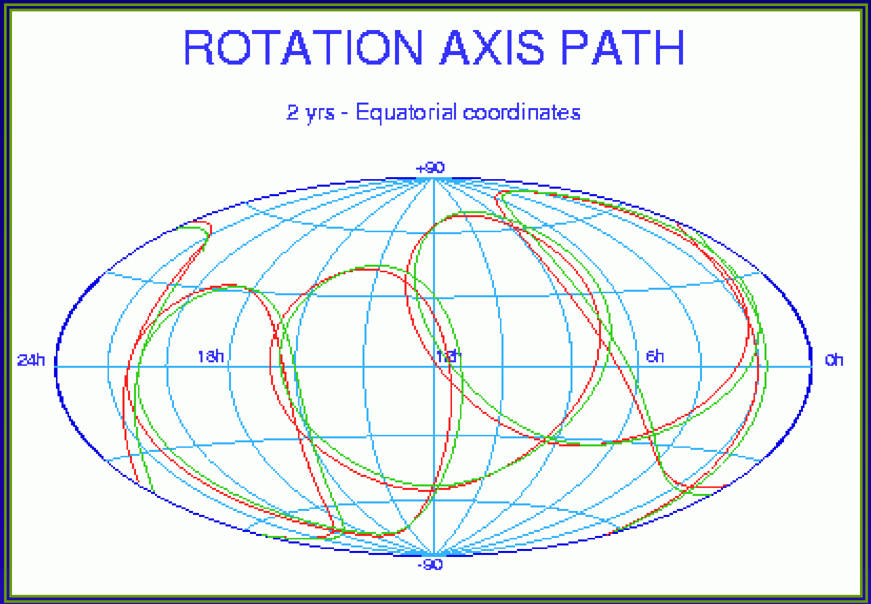
•	Aperture	1.4 x 0.5 m^2
•	Focal length	47 m
•	Scale	1 mas = 0.2 μm
•	Basic angle	99.4°
•	Spin period	6 h
•	Astro Field of view	
		0.66 x 0.66 deg^2
•	Extended	0.92 x 0.66 deg^2

Scanning law I



	HIP	GAIA
Spin/Sun	43	50°
Scan rate "/s	167	60
Period (h)	2.2	6.0
Precession (d)	58	72
Basic angle (°)	58	99

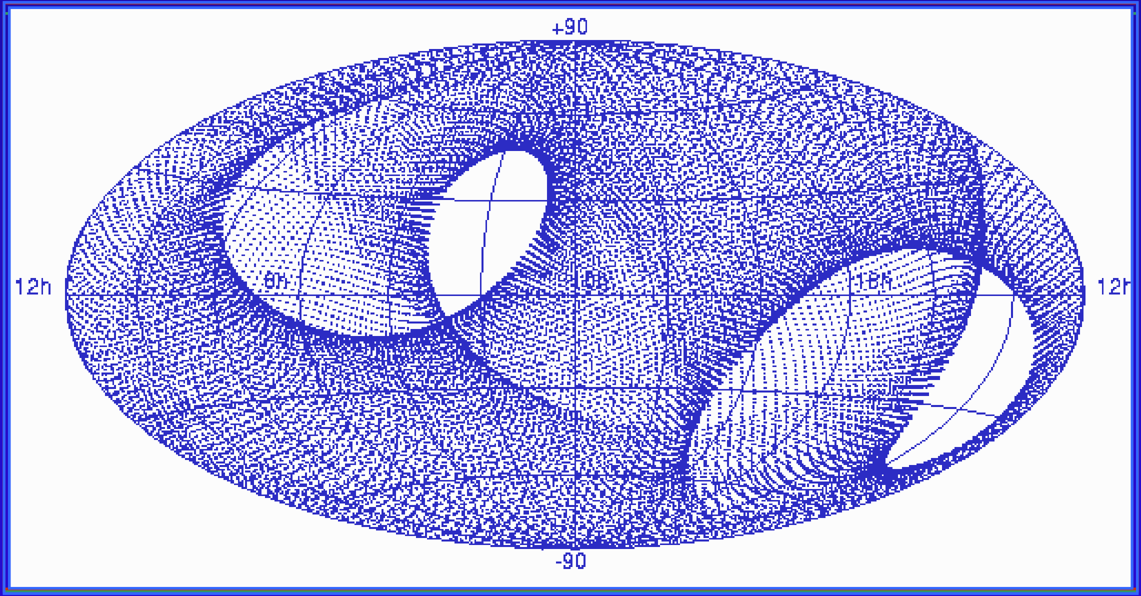
Scanning law II



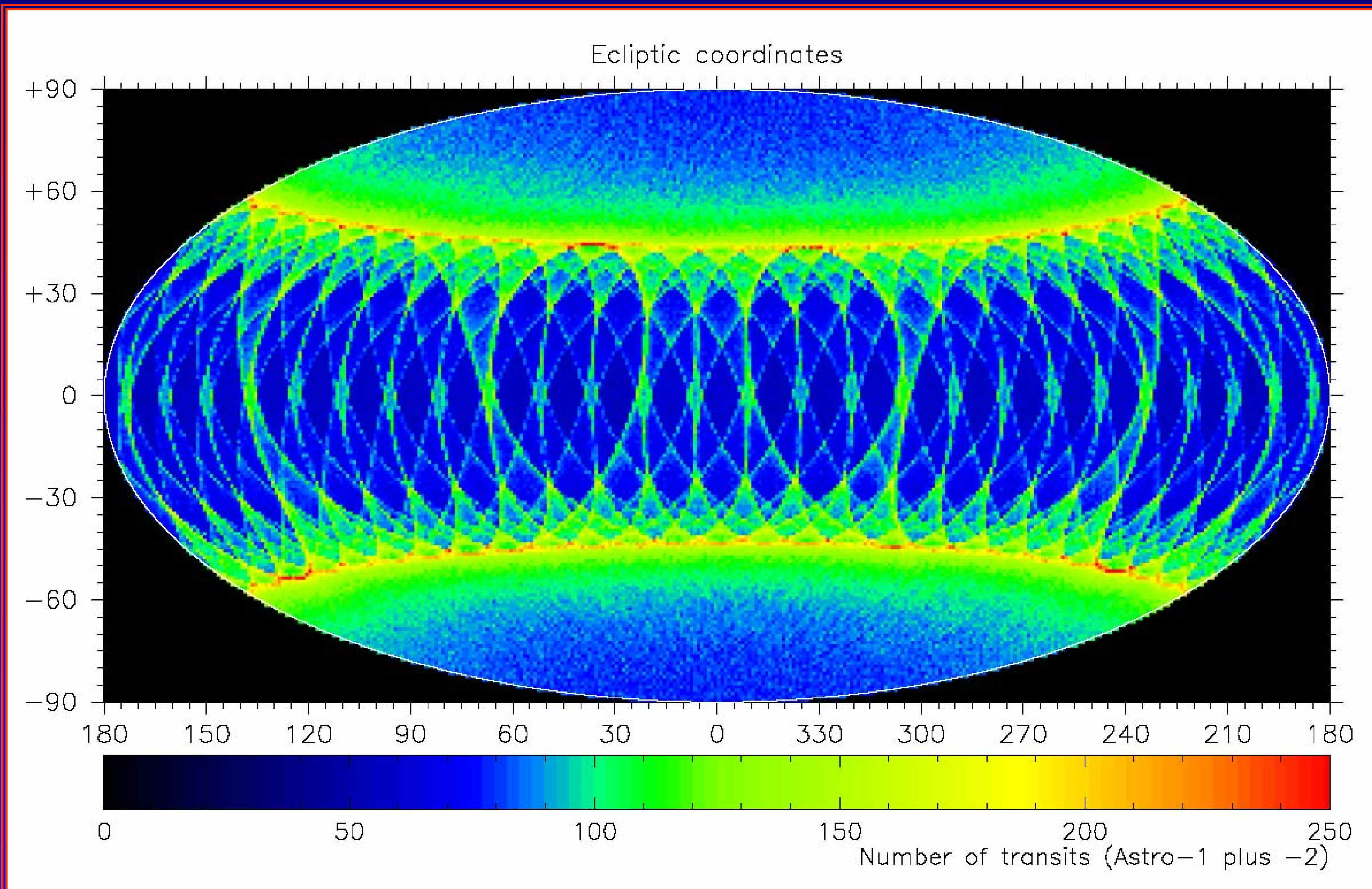
30 days

60 days

100 days

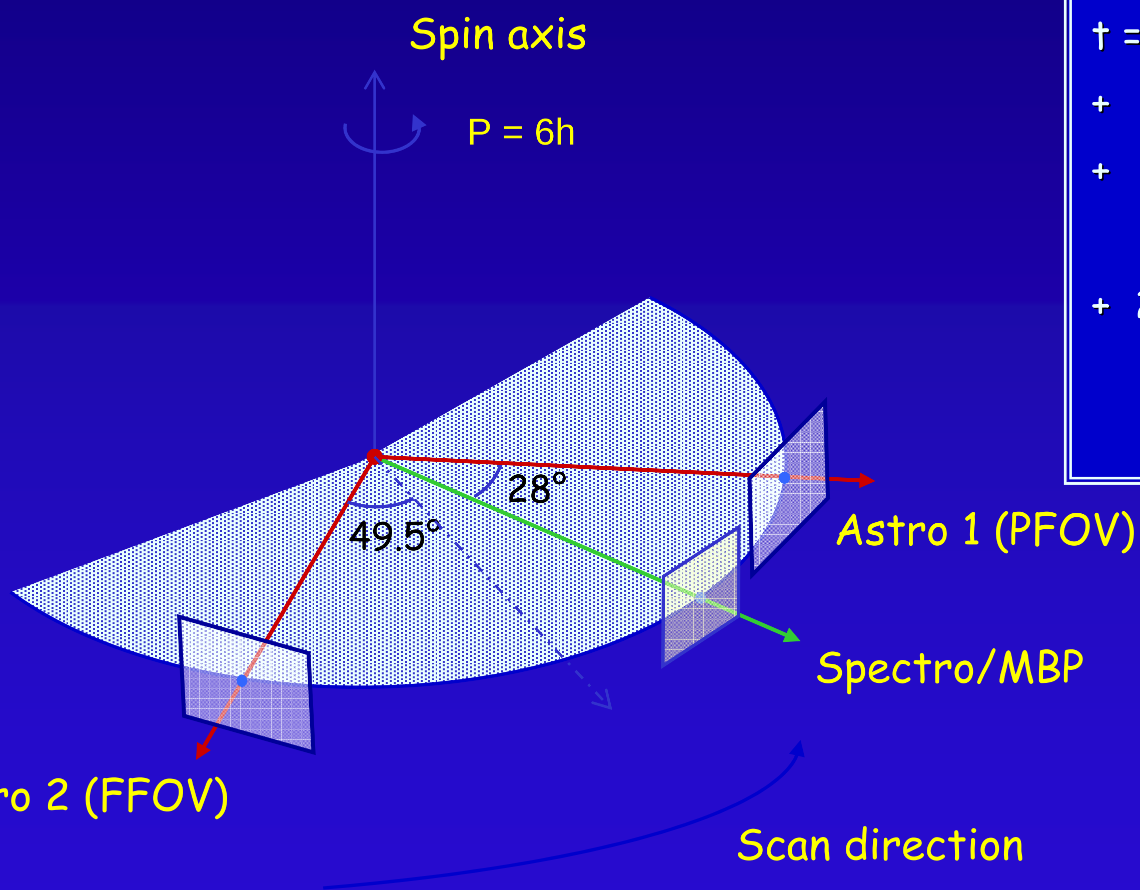


Observation distribution



J. de Bruijne, 2003

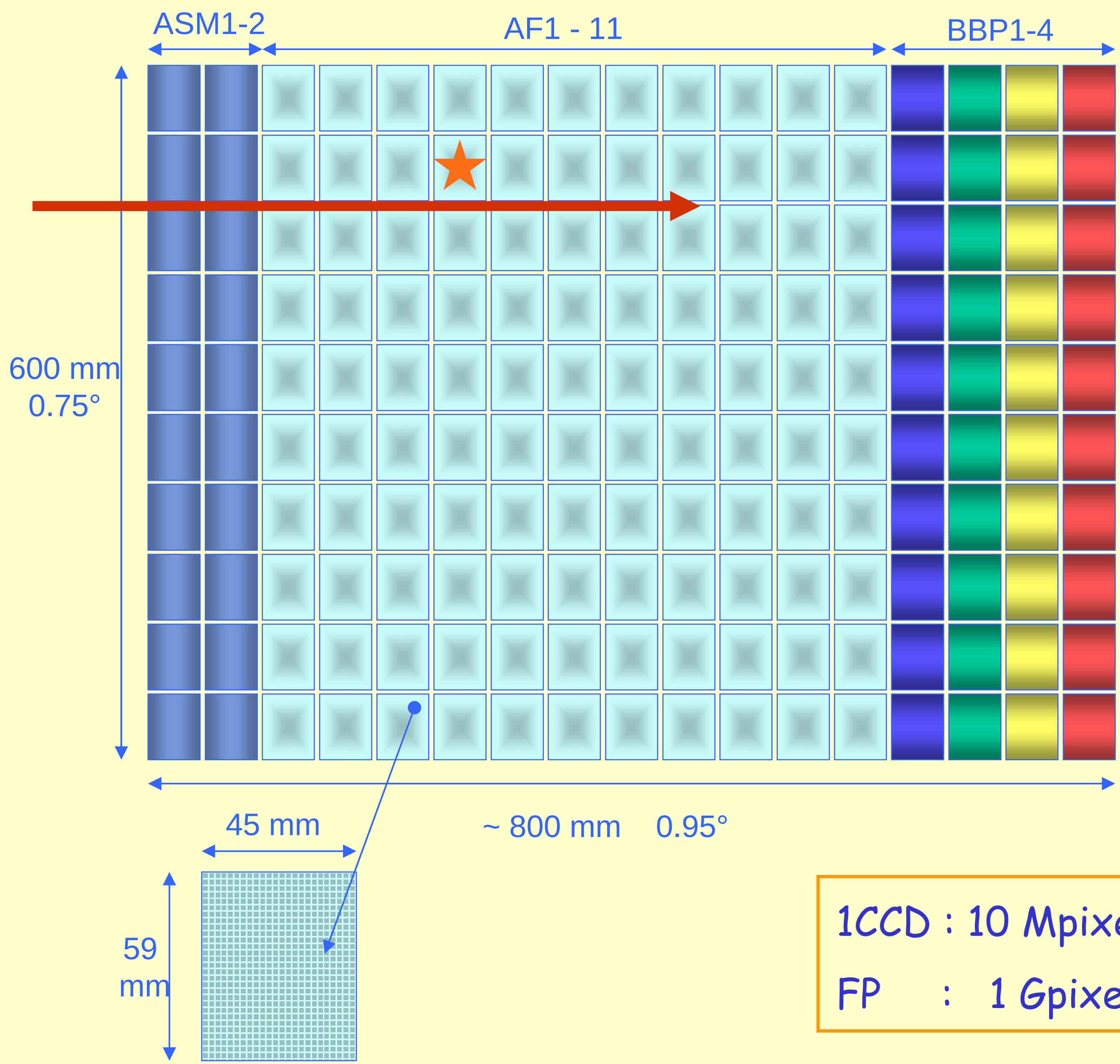
Relative position of the FOV's



Sequence

	Observation
t = 0	AF1
+ 28 mn	Spectro
+ 78 mn	AF2
+ 254 mn	AF1
etc…	

Astro Field



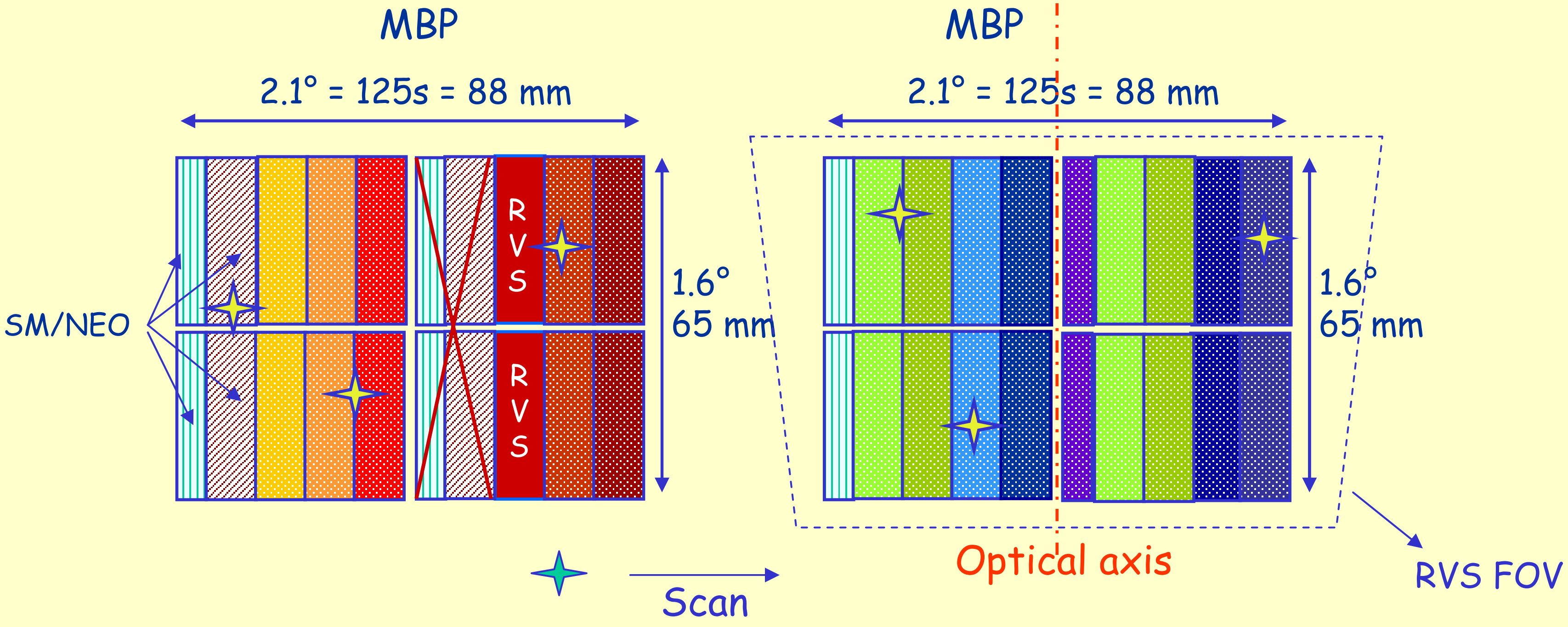
<u>Astro Field</u>

- Cell size : 49 x 60 mm^2
- CCD size : 45 x 59 mm^2
- 4.5 k x 2 k
- Pixel size 10 x 30 μm^2
- = 44 x 133 mas^2
- TDI : 0.735 ms
- Airy (along) 103 mas
- Integration time : 3.3 s

1CCD : 10 Mpixels

FP : 1 Gpixels

MBP Fields + RVS



<u>CCDs</u>

MBP : 800 x 1960 pxs

<u>Pixel size</u>

10 x 15 μm^2

0.9 x 1.35 $arcsec^2$

Full read-out or windowing mode

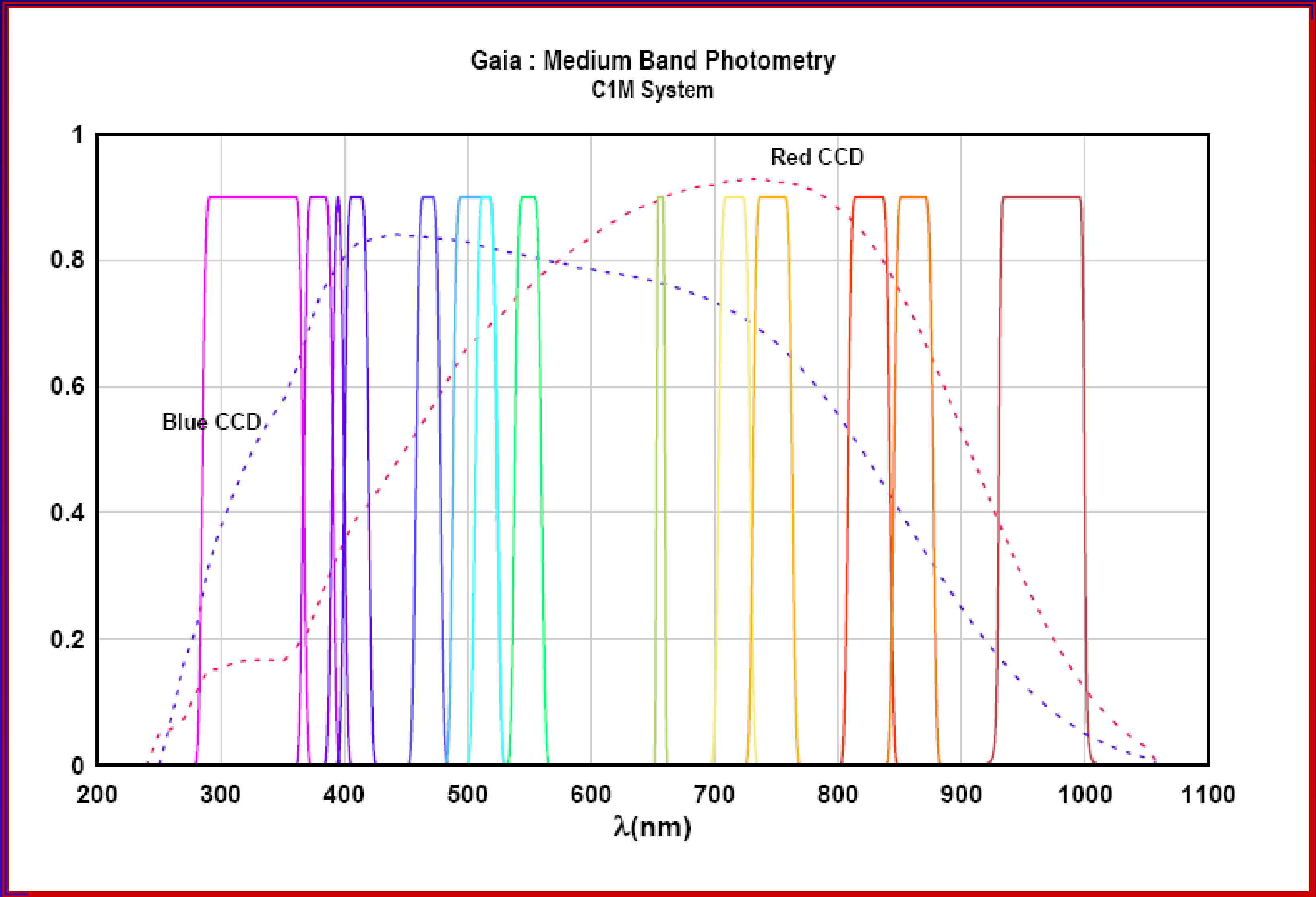
<u>Integration time</u>

MBPSM ~ 6.7s

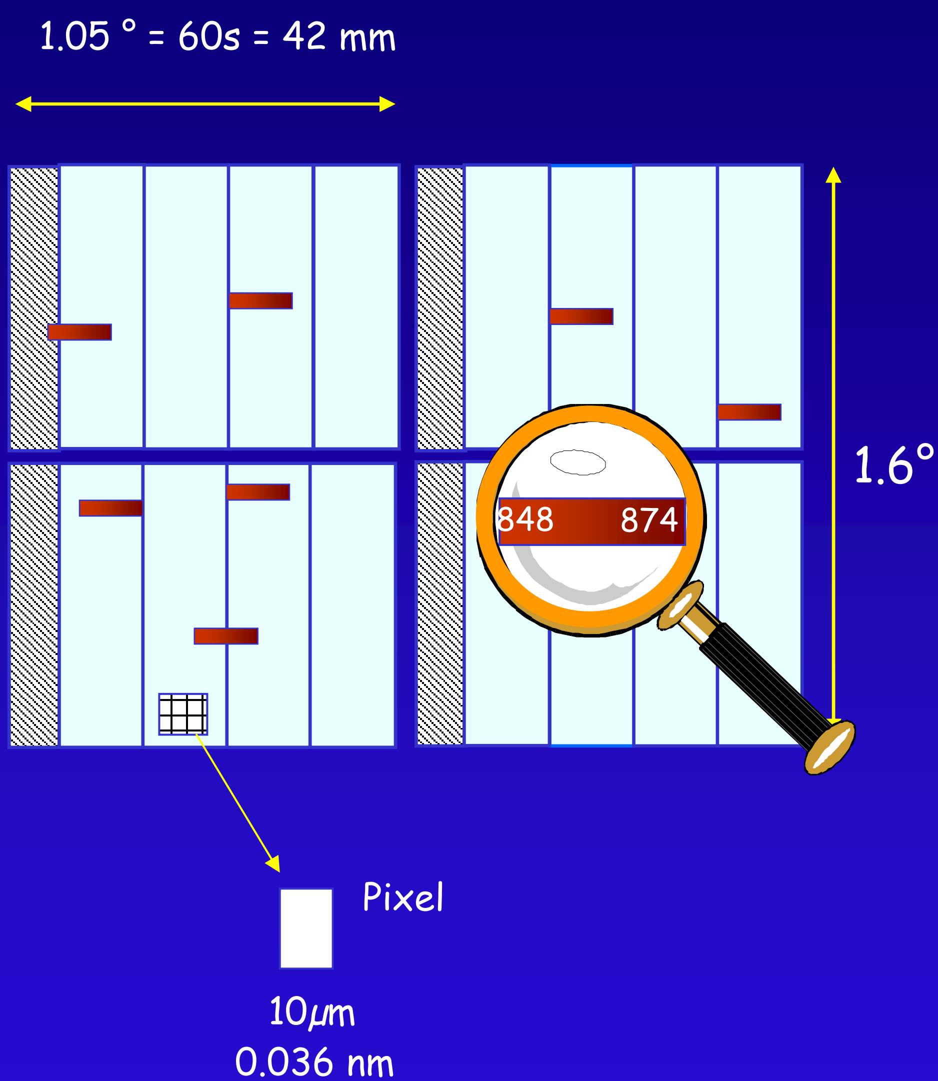
MBP ~ 12.5 s

Photometric System

- Optimized for astrophysical purposes



RVS Field of View



Field : 2.0° x 1.6°

Spectro type : Integral field

Pixel size

10 x 15 μm^2

1 x 1.5 $arcsec^2$

Integration time

RVS ~ 8 x 15s

Resolution

R ~ 11500 = 0.036 nm/pixel

λ = 848 - 874 nm

GAIA accuracy scaled to Hipparcos

Parameter	Hipparcos	GAIA	Ratio	Accuracy x
Baseline	28cm	140cm	5	5
Sensitivity	0.008	0.6	80	9
Collecting area	0.035 m^2	0.7m^2	20	4.5
Duration	37*0.65 mths	60 mths	2.5	1.6
FOV size	0.9 deg^2	0.4 deg^2	0.45	0.65
Parallel/Sequential	20% time per star	100%	5	2.3
Grid/image	1	3	3	3
Overall improvement				**~ 1400**

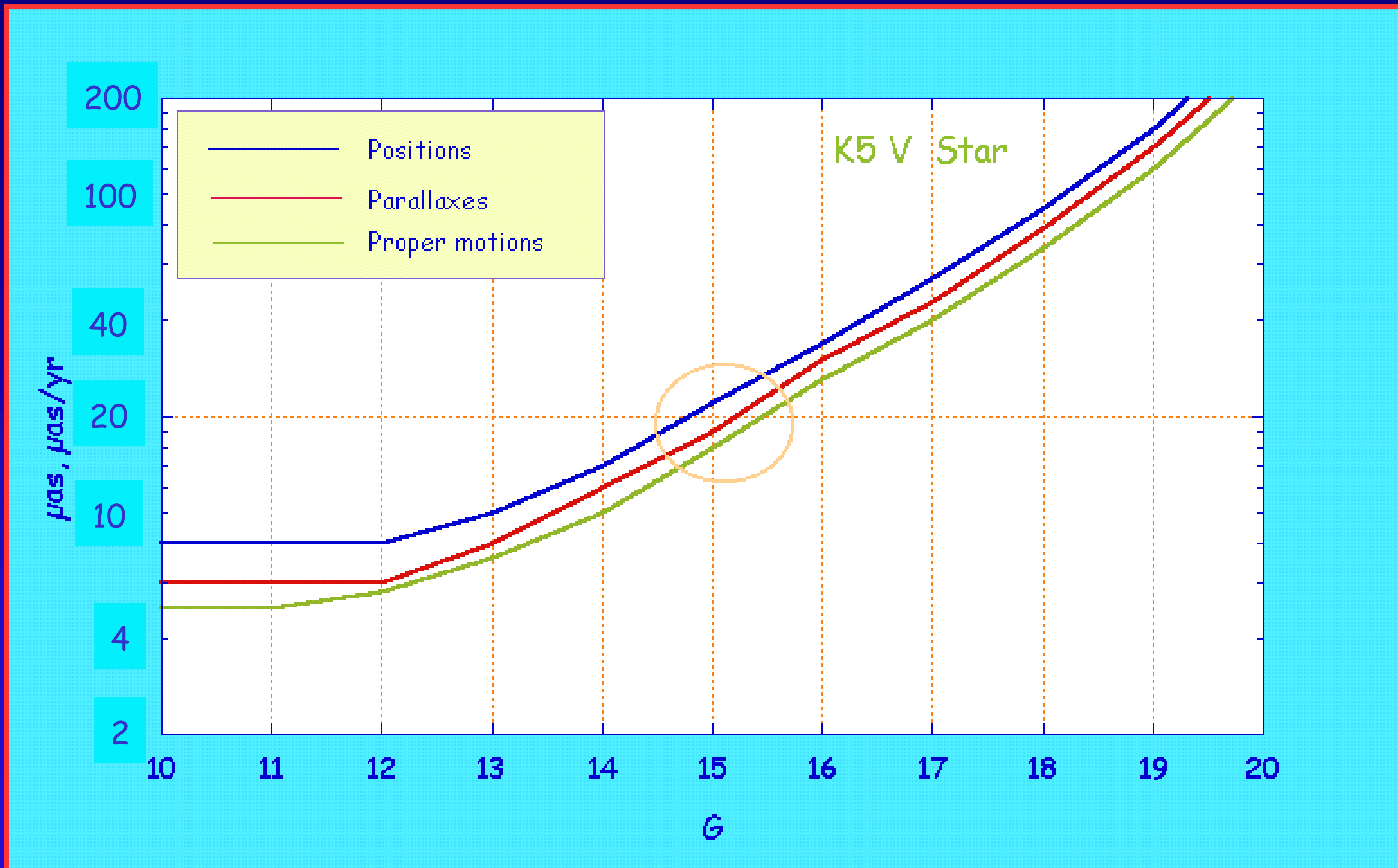
Hipparcos V = 9 ➡ σ = 1 mas

GAIA(*) V = 9 ➡ σ = 0.7 µas

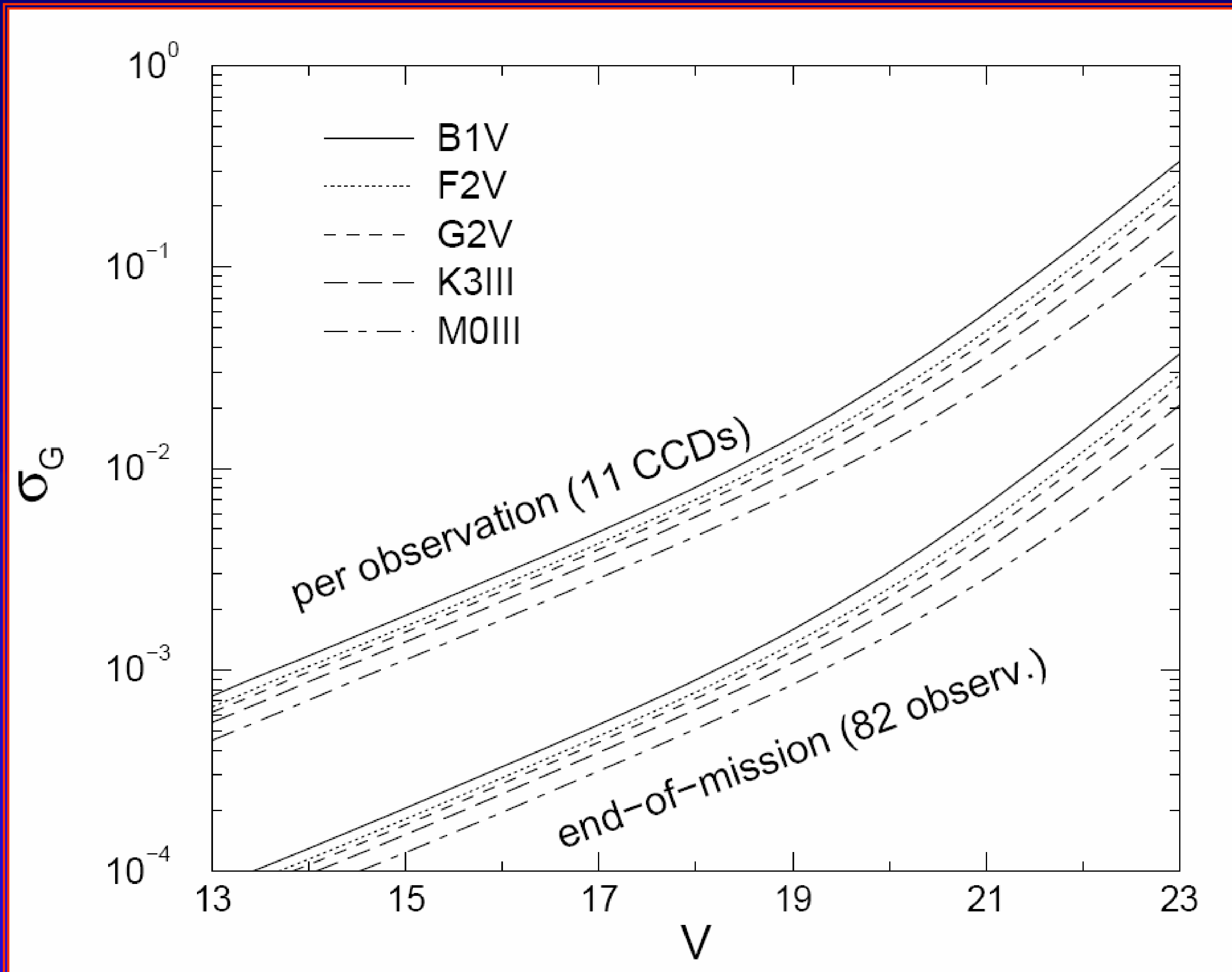
➡ **V=15 : σ = 11 µas**

(*) : photon noise limited

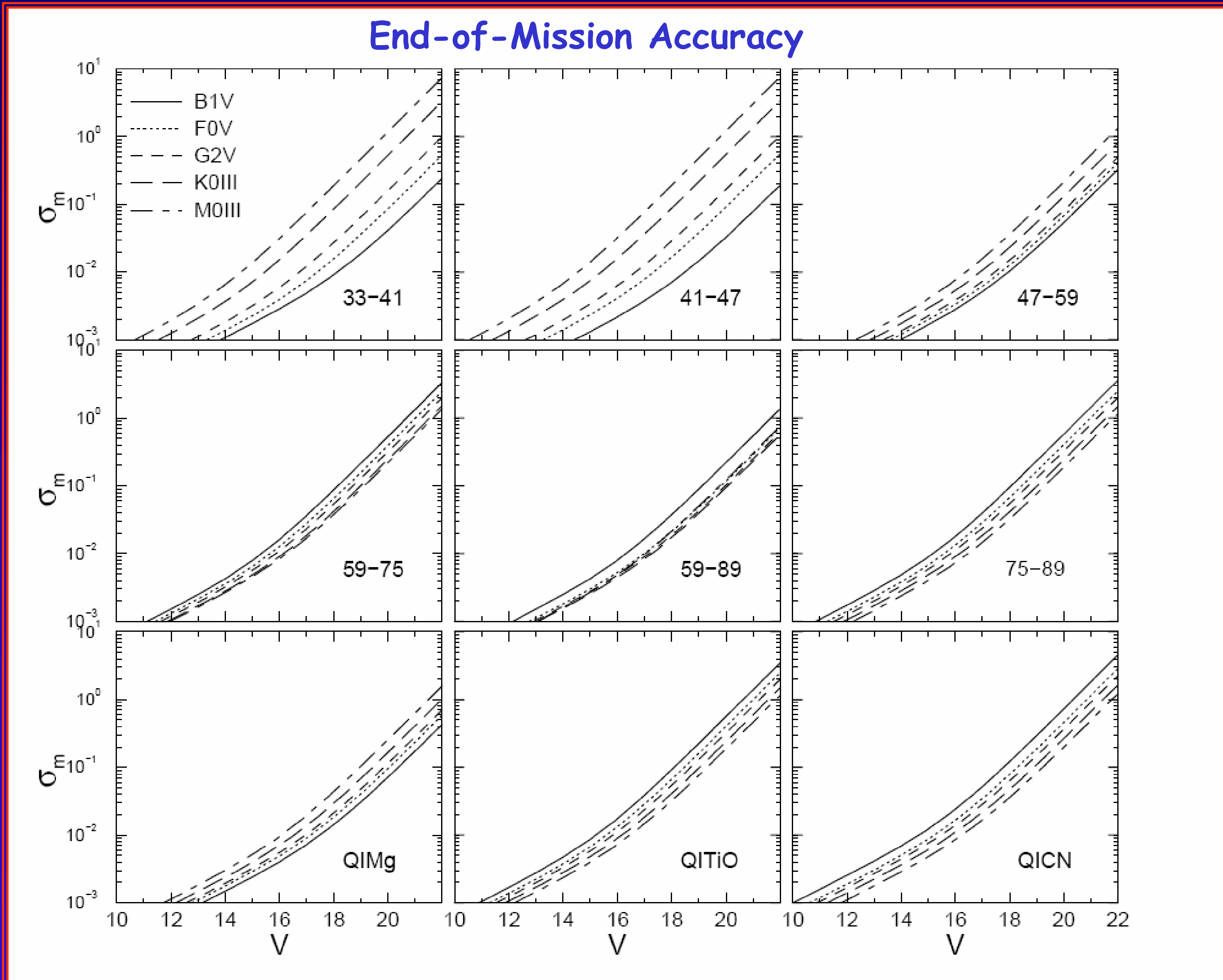
Astrometric accuracy



Photometric accuracy- G Band



Photometric accuracy- MBP Bands



Radial Velocity measurements

- Doppler measurements on 848-875 nm
- R ~ 12000

Expected accuracy for a star : (K1 III, [Fe/H] =0.0)

Single Observation

V	km/s
11.0	< 1
12.0	1.1
13.0	2.3
14.0	4.7
15.0	11.5
15.5	34.9

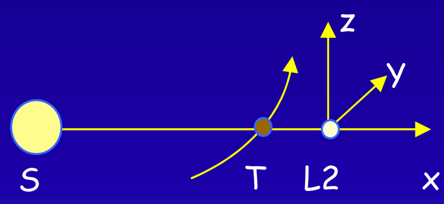
End of mission

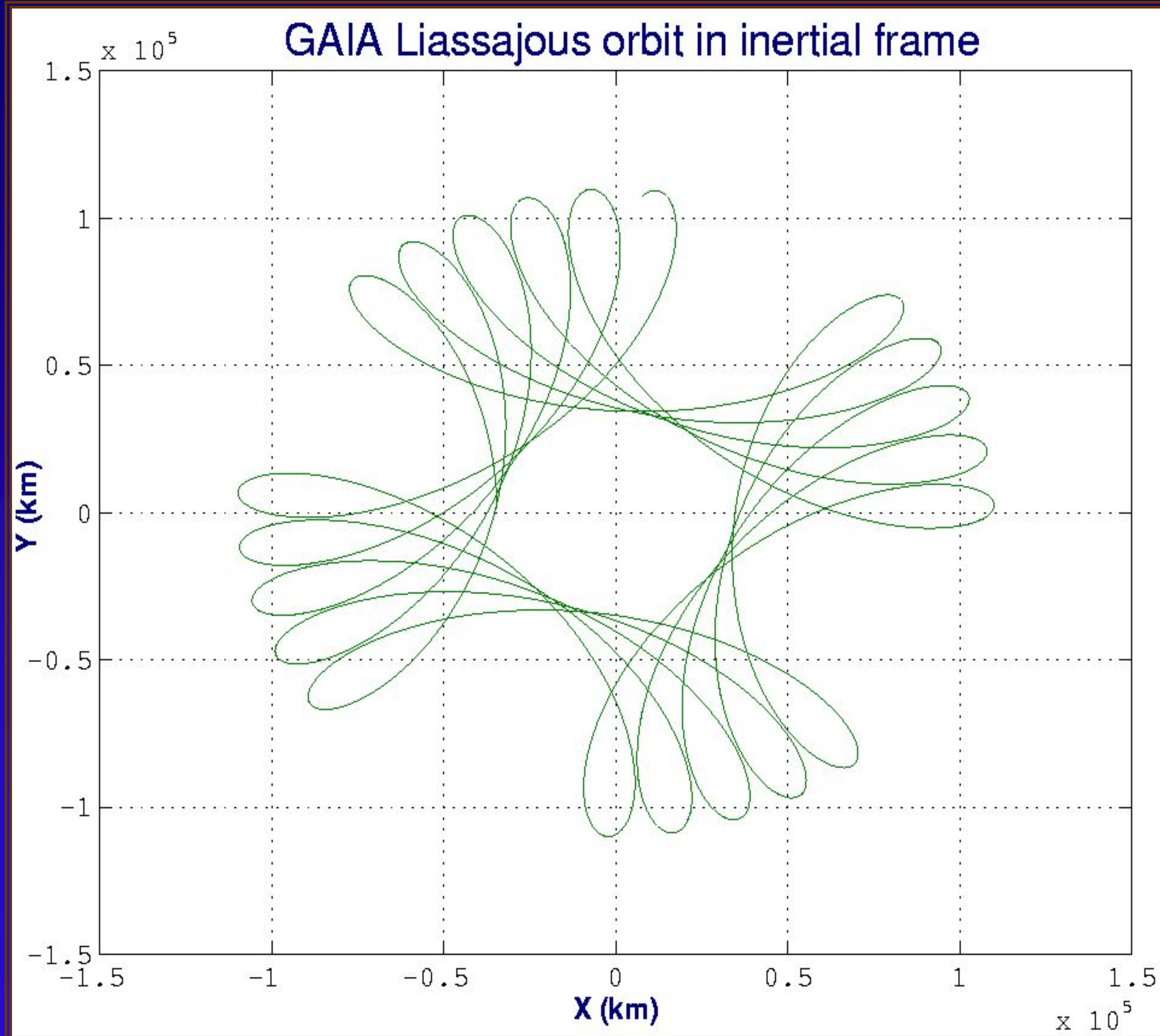
V	km/s
14.0	< 1
15.0	1.1
16.0	2.6
17.0	6.2
17.5	7.9
18.0	16.3

- The accuracy degrades with :
  - higher T_{eff},
  - lower metallicity

Katz et al., 2004

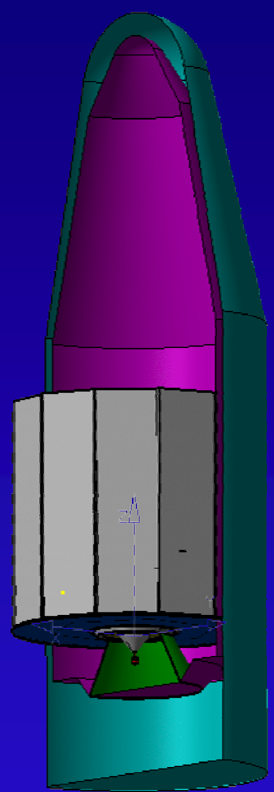
The Gaia orbit



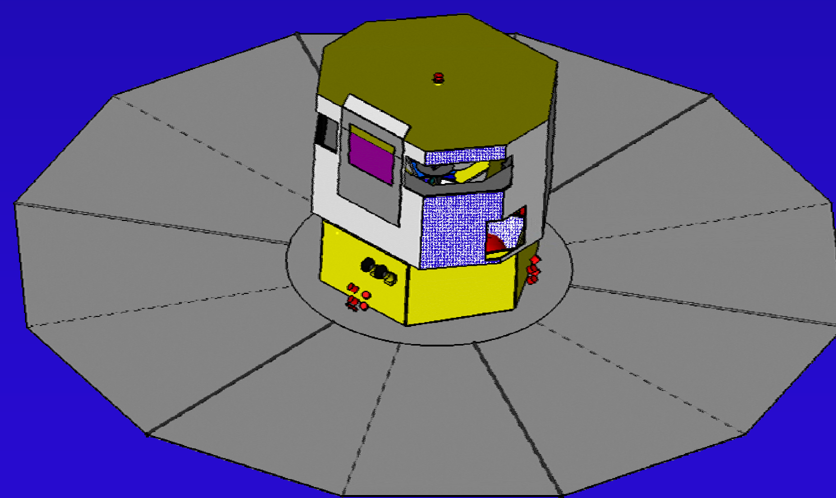


F. Mignard, 2003

Spacecraft

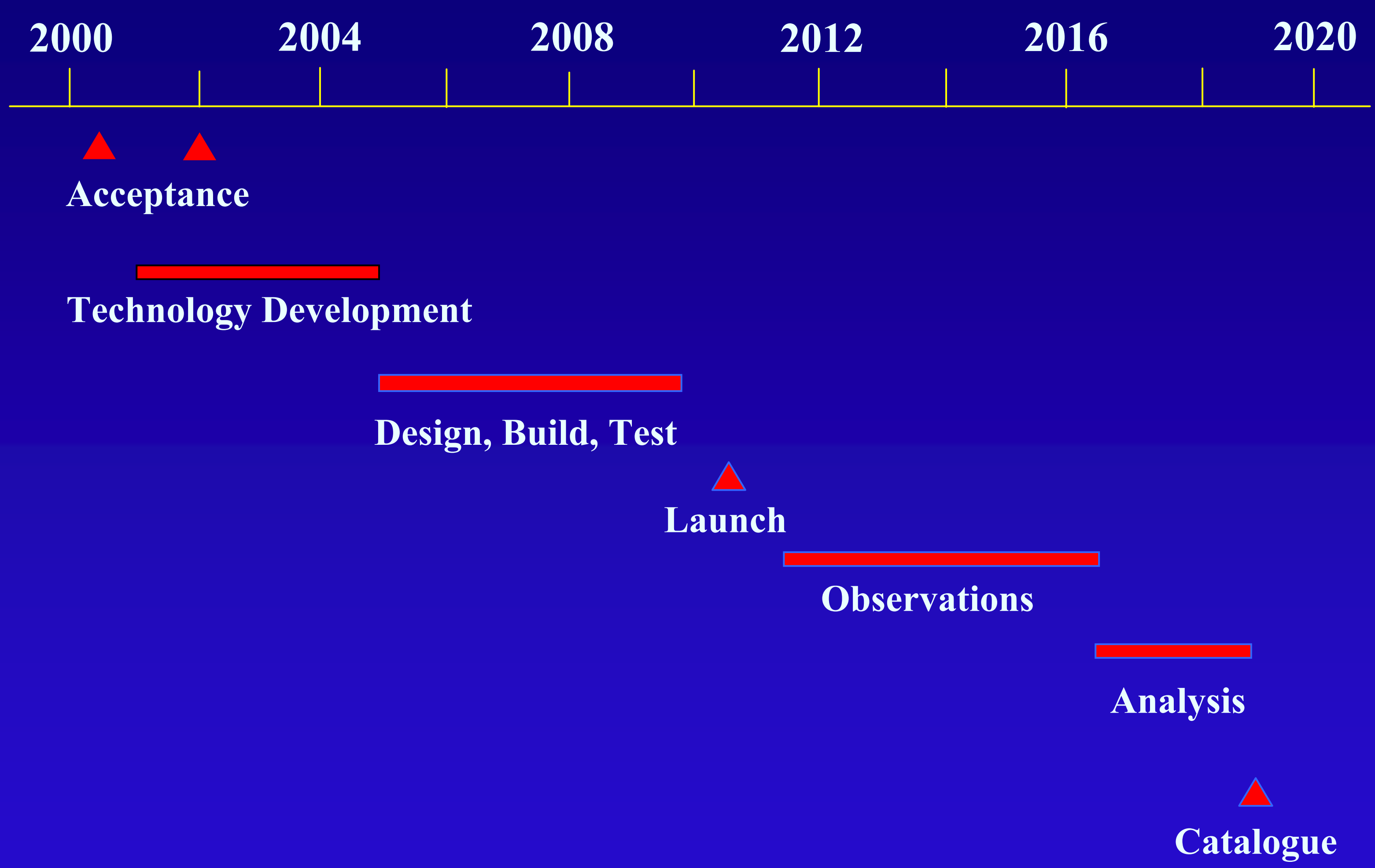


- Mission 100% ESA
- Lunch : 2011
- Operations : 5 years
- Launcher : Soyuz
- Orbit : L2
- Ground station : Madrid and/or Perth
- Data rates: 1.5 Mbps



- Mass : 1700 kg (P/L 800 kg)
- Power : 2000 W (P/L 1200 W)

GAIA Schedule



Mission operations

- Launch at t
- Transfer to L2 t + 5 months
- Observation with a continous scanning law over 5 years

  Average : 80 observations in astro field per object
  120 " in the spectro field per object
  120 " in the photometric field per object

- On board detection with the astro and spectro sky mappers
- Selection of targets at about V_{lim} ~ 20
- Astrometry and photometry for ~ 1 billion sources
- Storage of data over one day and downlink for ~ 10 hours every day
- Quick look processing for ground based follow up (SN, NEOs)

Data Flow

- Astrometric fields
  - Astrometric data ::
    - Sky mapper counts :: 20 CCds
    - Astrometric counts on a field transit :: 110 CCDs
  - BBP photometric data
    - Photon counts on five bands :: 40 CCDs
- Spectro field
  - MBP photometric data :: 32 CCDs
  - Spectra data from the RVS
- Housekeeping data, timing …
  - on-board processing results

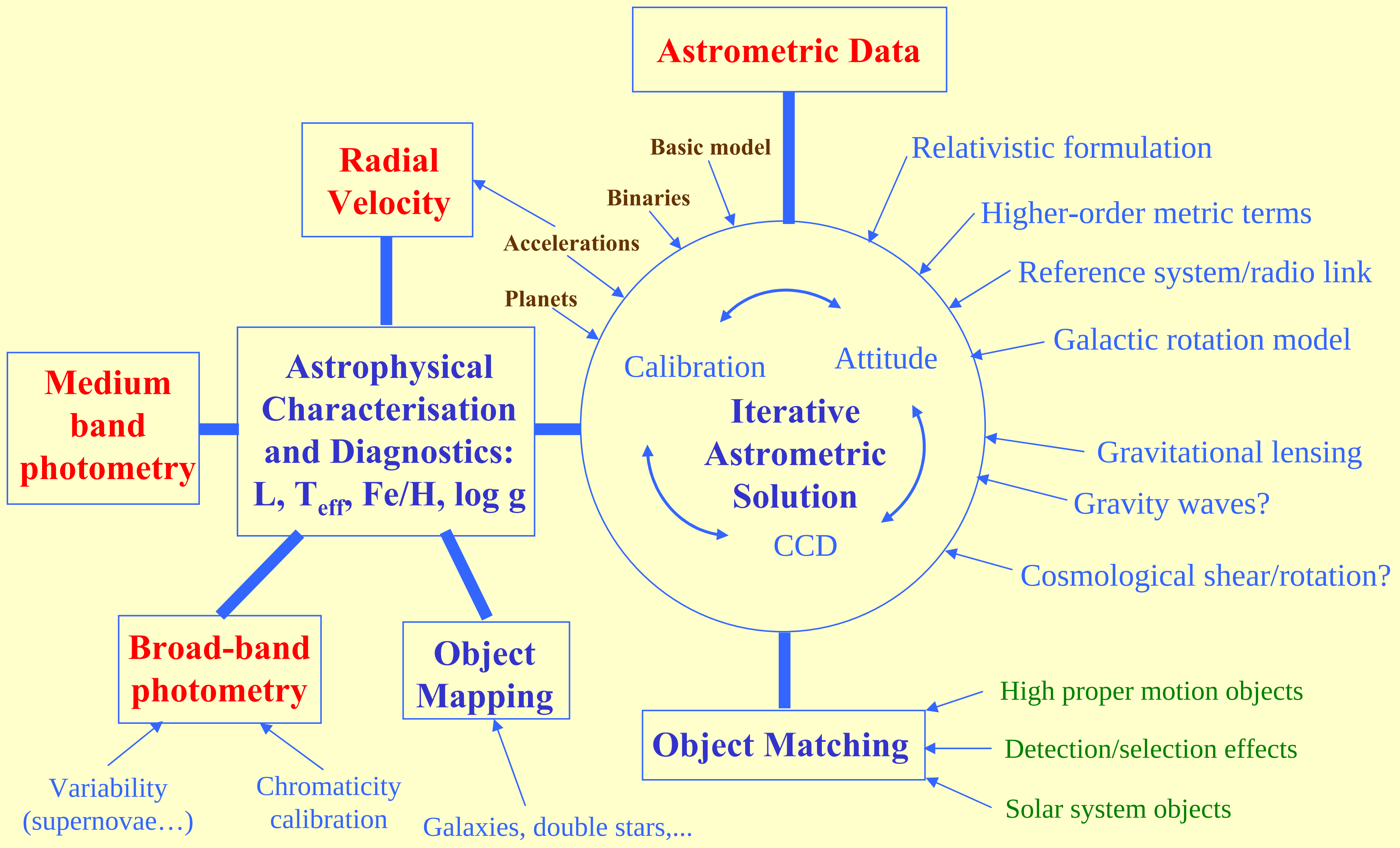
Number of images per second

Moyenne	Typique	Max
19,000	110,000	2.3×10^6

Data volume

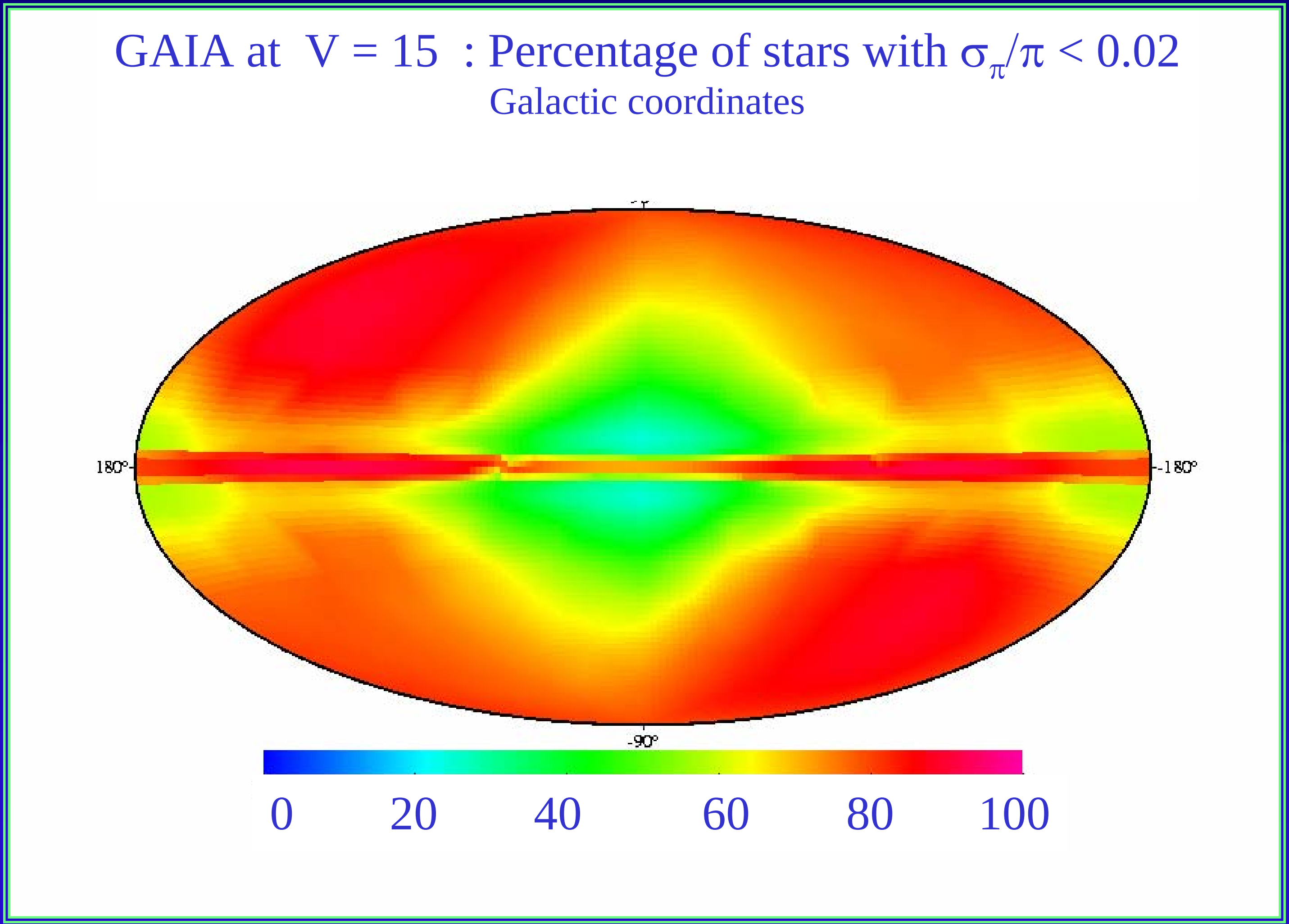
- Compressed telemetry
  - 5 yrs, 1.5 Mb/s = 250 Tb = 30 TB
- Usable data on-ground
  - x ~ 5 = 150 TB
- Science data
  - x ~ 5 – 10 = ~ 1 PB

Data processing : Overall chart



Science Highlights

Stellar distances



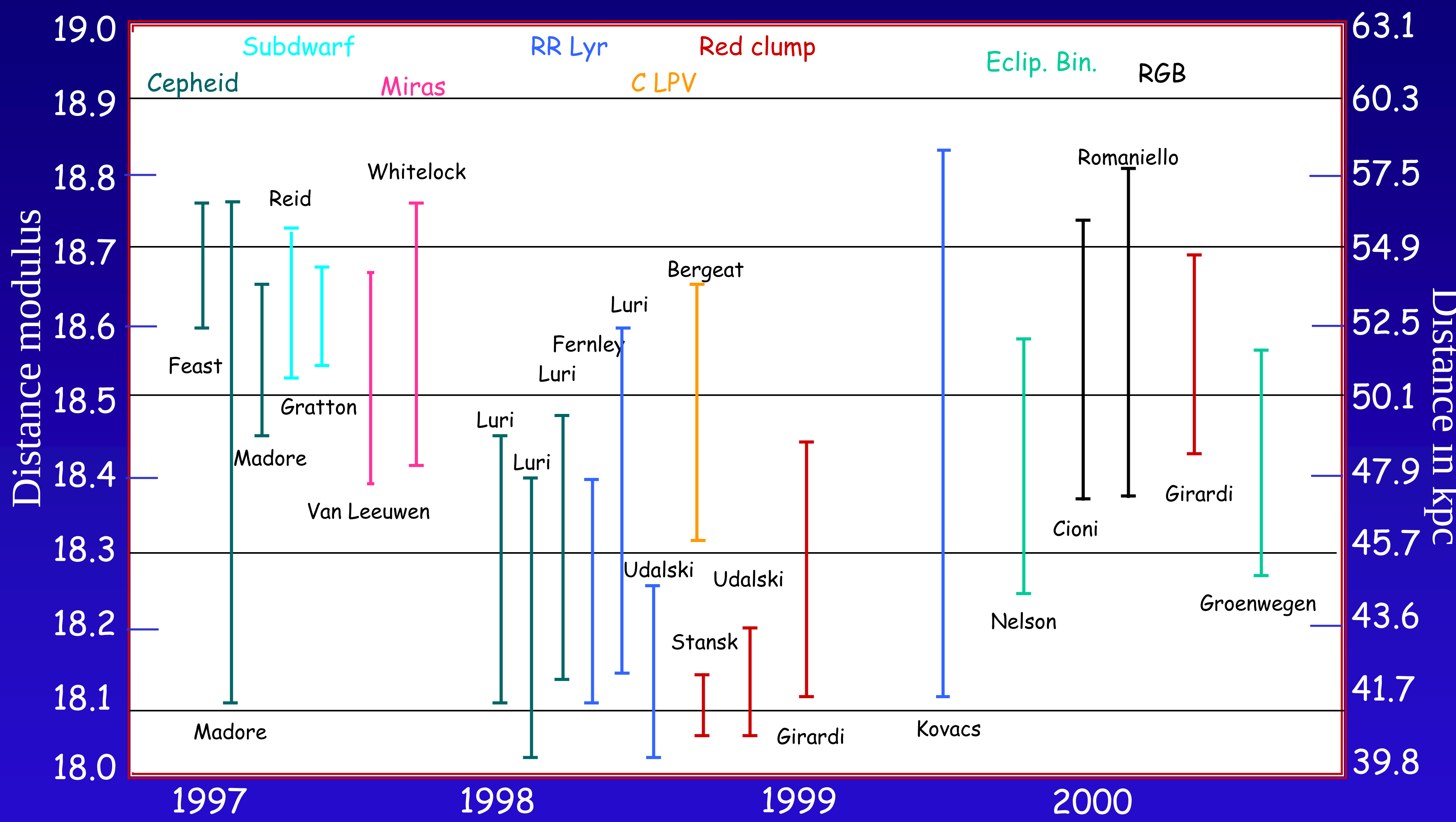
…And more

Cepheids	$\sigma_\pi / \pi < 1\%$	d < 3 kpc	(55 d < 1 kpc)
	$\sigma_\pi / \pi < 4\%$	all galactic cepheids	
RR Lyr	$\sigma_\pi / \pi < 1\%$	d < 3 kpc	(26 d < 1 kpc)
	$\sigma_\pi / \pi < 10\%$	most galactic RR Lyr	
Mirae	$\sigma_\pi / \pi < 6\%$	all galactic Mirae	
Glob. Clust.	20 with $\sigma_\pi / \pi < 10\%$ per star		➔ ages of oldest stars
	mean distance < 1% for 110 clusters		
LMC-SMC	~ 10^6 stars observable <d> ~ 1 to 2 %		
	Cepheids with $\sigma_\pi / \pi < 30\%$		
Local group	Geometric distances to ~ 8 galaxies		
	Rotational parallaxes for few others		
SNe Ia	Gaia could detect ~ 20 per month (➔ GB follow up)		

Key questions for the distance scale

- Two major indicators
  - Cepheids with PL, SNe Ia
  - LMC is the keystone for calibration
- Standard PL :
  - M_v = -2.76 log P –1.46 M_I = -3.06 log P –1.87 (Madore & Freeman, 1991)
  - M_v = -2.49 log P –1.79 M_I = -2.82 log P –2.12 (Udalski, from OGLE 1999)
    - Slope and zero point from LMC with μ = 18.56
- But there are indications that :
  - Galactic Cepheids behave differently
  - the PL relation depends on the metallicity
  - Not a single relation applies to all periods
- Gaia will bring much light there with ….

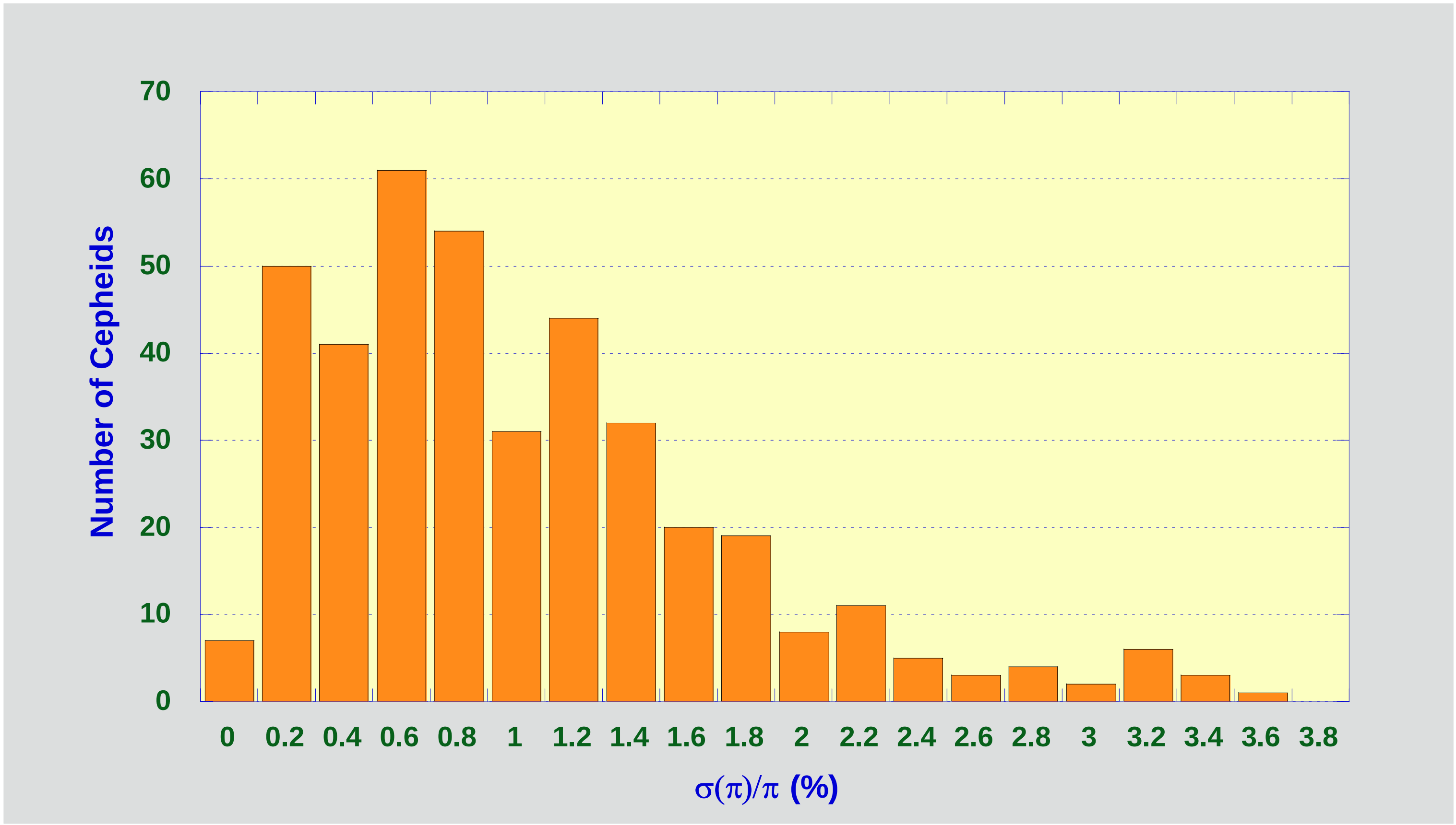
Distance to the LMC



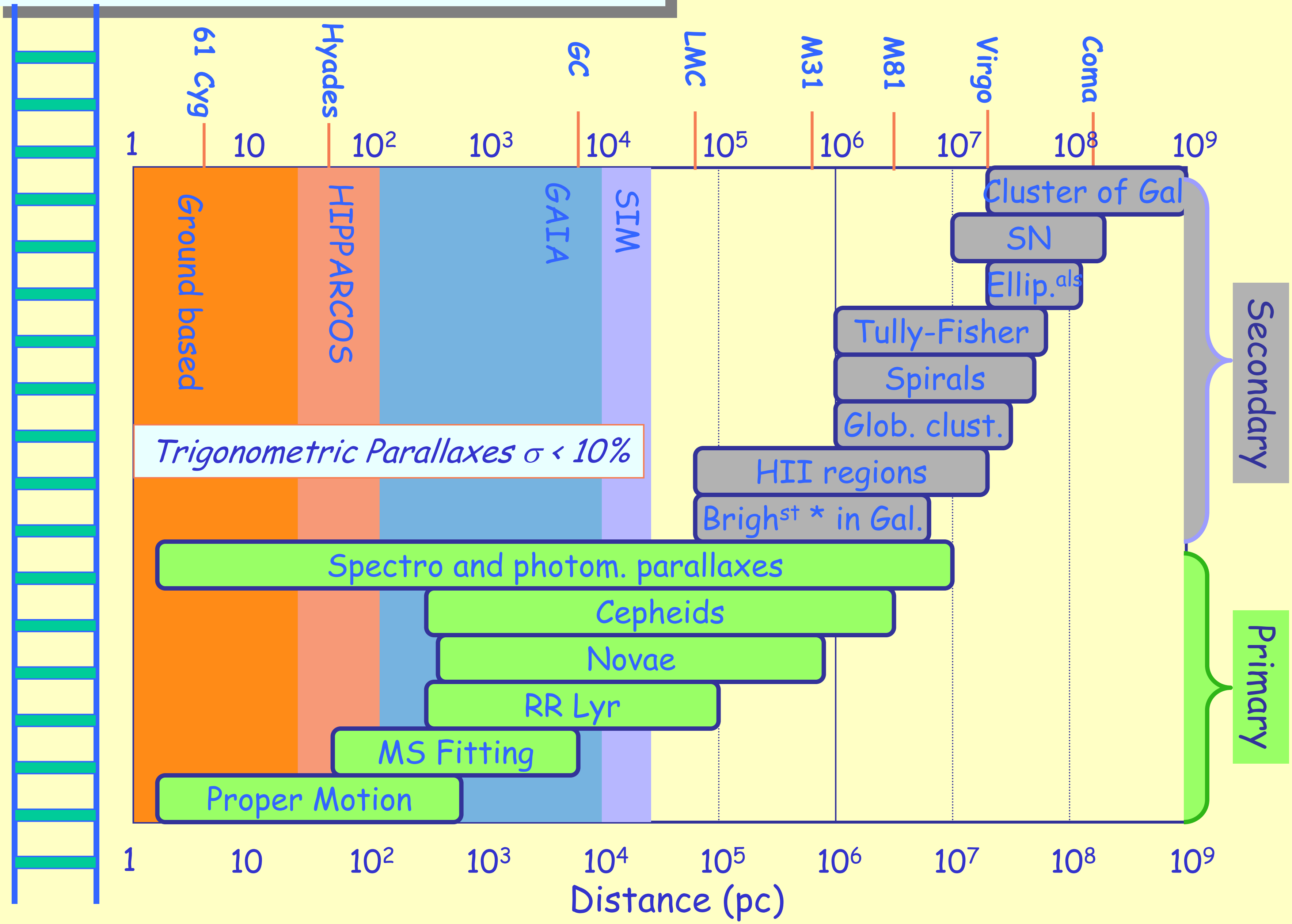
with Gaia : π = 20 μas N* ~ 10^6 σ_π/π ~ 2 %

Cepheid Distance

- 15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc
  - rather bright (V < 13) and red
- In the plot : 400 galactic cepheids from David Dunlap DB
  - distance and brightness → estimate of the Gaia accuracy



The Cosmic Distance Ladder



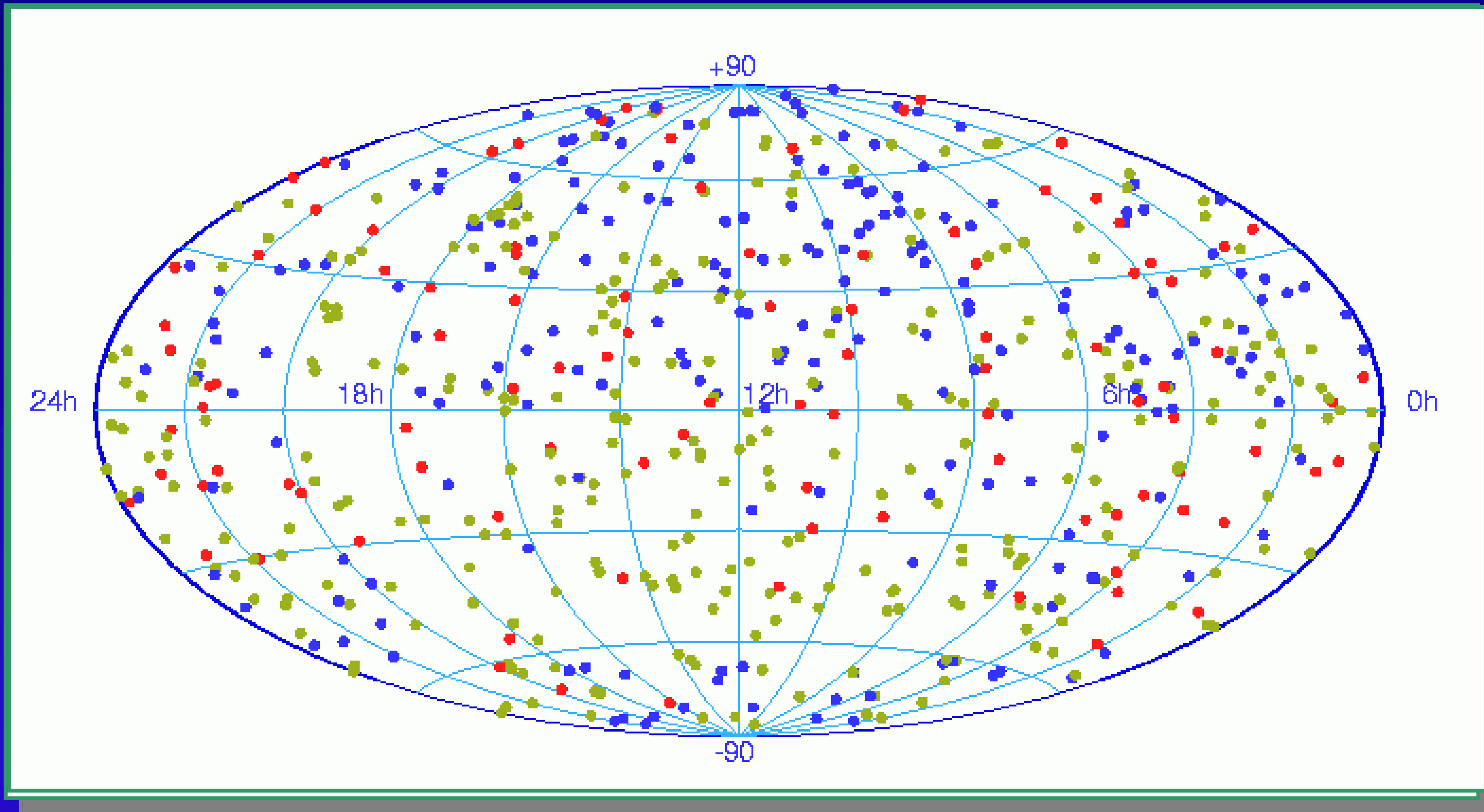
Data from : Rowan-Robinson

Reference Frame

Current status

- Overall principle : Extra-galactic source have no global rotation
- Realisation of the ICRF with radio observations of QSOs
- ~ 15 years of observation , 3 million measurements
- Global solution with international coordination

ICRF 1998



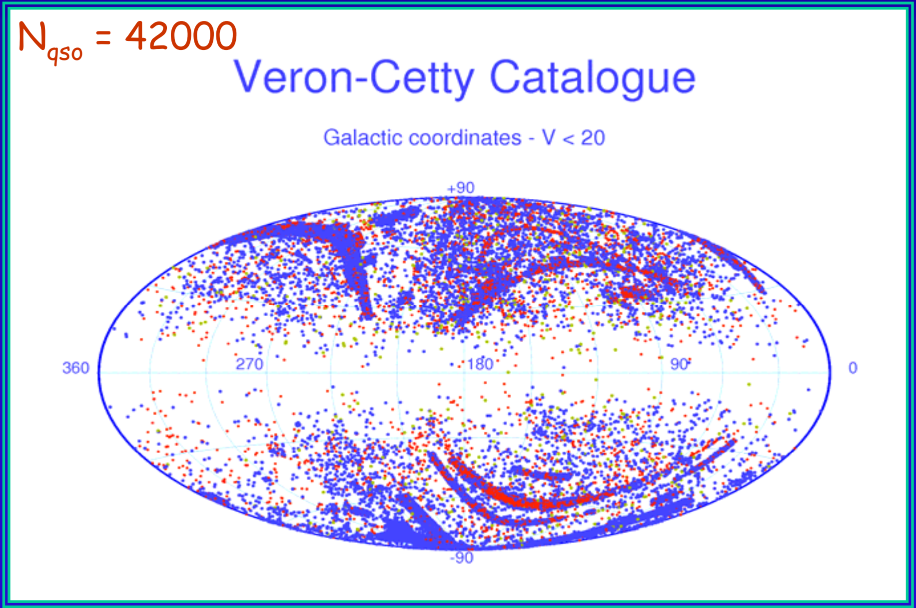
Definition sources (212) Candidate sources (294) Other sources (102)

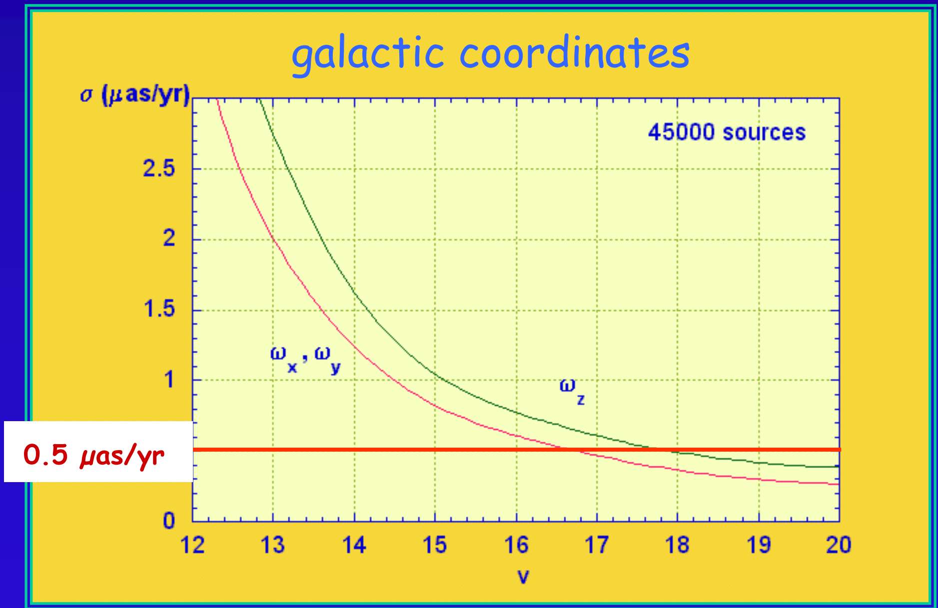
Basic procedure with GAIA

- Observe extragalactic sources in the visible
- There are plenty brighter than V =20
- Look for the anomalous proper motions to clean the sample
- The remaining set will display an overall spin
- Find ω and apply $-\omega$ everywhere
- The results will be referred to the best inertial frame
  - paradigm of the ICRS

Quasars and reference frame

- The inertial frame
  - Gaia will detect and measure the position of ~ 400,000 QSOs
    - They will be identified with photometric filtering + astrometry
  - This will improve the current survey by a factor ~ 10
  - A clean subset (free of stars) can be constructed
    - The Gaia sphere will be rigidly attached to the EG sources





Transverse motion

- So far no systematic transverse motion detected
  - QSOs have fixed comoving coordinates
- If $V_t \sim H_0 D$ ===> $\mu \sim 10\ \mu as/yr$
  - VLBI in 20 yrs with $s_{pos} \sim 1$ mas ===> $\mu < 50\ \mu as$
  - but sub-mas structure instabilities (P. Charlot in JD16)
- Other sources :
  - microlensing $P = 10^{-6}$ (Belokurov) ==> only a handful
  - matter ejection, superluminous motion
  - Variable galactic aberration (Kovalevsky, 2003)
  - Macrolensing $P = 10^{-2}$ (Mignard, 2003)
  - Accelerated motion in the local group ?

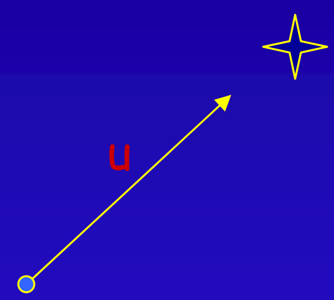
- GAIA has the opportunity to test the ICRS paradigm
- Small proper motion is not a good test to keep or reject
- Large PM and/or distance is a good one to reject stars

More on QSOs and reference frame

- Detection of tangential velocity
  - Random and systematic motion of QSO optical photo-centers
  - Correlation with optical variability
- Observation of multi-imaged lensed Quasars

- Any acceleration Γ wrt to QSOs ➔ systematic proper motion

$$\frac{d\mathbf{u}}{dt} = \frac{\mathbf{\Gamma}}{c} - \left(\frac{\mathbf{\Gamma}}{c} \cdot \mathbf{u}\right)\mathbf{u}$$



- Precision of ~ 0.4 μas/an (2 prad/an) on Γ/c

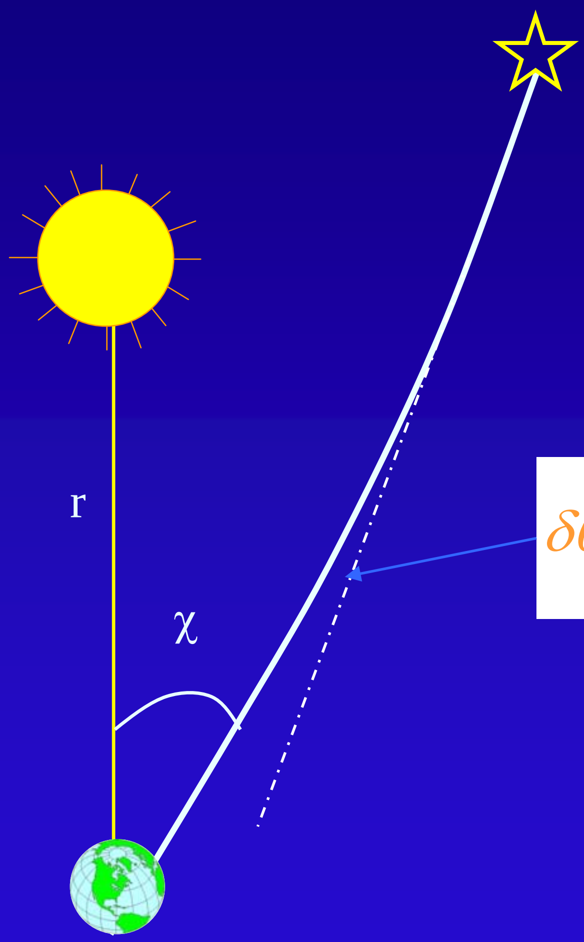
  = 0.2x 10^{-10} m s^{-2} (Γ_0 Pionner/40)

  - 0.1x Γ from galactic rotation
  - Galactic rotation (μ ~ 4 μas/yr)
  - Acceleration of the local group ➔ CDM ?

Relativity testing

Relativity Experiments

- Light Deflection : determination of γ



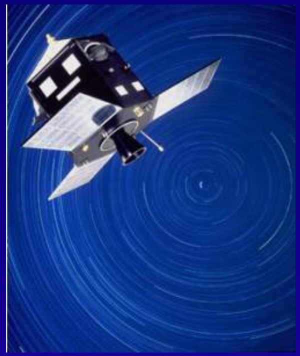
Light deflection in mas

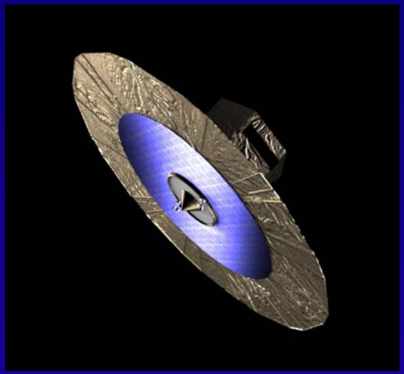
	min χ	χ = 45 deg
Sun	13 mas	10 mas
Jupiter	16 mas	2 μas
Saturn	6 mas	0.8 μas

$$\delta\theta = \frac{2GM}{rc^2}\frac{1+\gamma}{2}\frac{\sin\chi}{1-\cos\chi}$$

- 2×10^7 stars V < 14
- 80 observations per star
- measurable effect even at 90° from the Sun
- but large correlation with parallax (~ -0.85)

Light deflection





Hipparcos

- 10^5 stars V < 10
- 2.5×10^6 abscissas
- $\sigma \sim 3$ to 8 mas
- $\chi > 47$ degrees

↓

$$\gamma = 1 \pm 3 \times 10^{-3}$$

GAIA

- 8×10^6 stars V < 13
- 2.5×10^8 abscissas
- $\sigma \sim 10$ μas
- $\chi > 40$ degrees
- \+ fainter stars

↓

$$\sigma_\gamma \approx 1 \times 10^{-6} \text{ to } 3 \times 10^{-7}$$

σ_H / σ_G

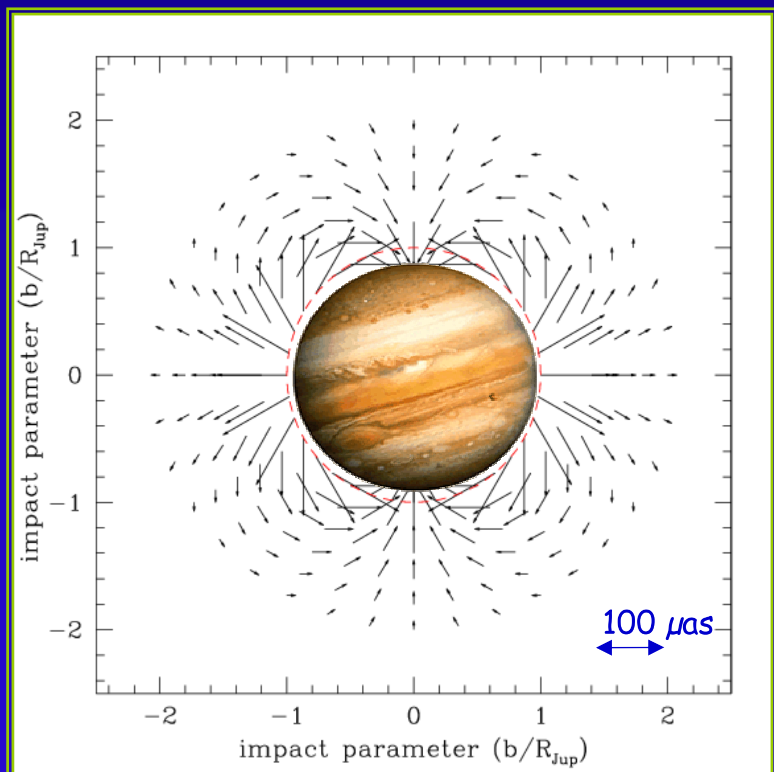
→ 10

→ 400

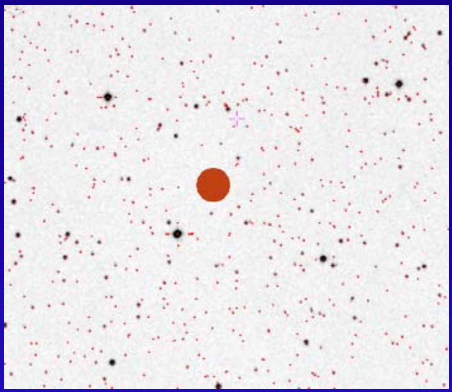
→ 2

Gaia Relativity Experiments

- Jupiter light deflection
  - Small field astrometry with Gaia
  - Remative measurements of star position around Jupiter
  - Same field observed earlier or later



Deflection from Jupiter quadrupole



Jupiter en 2013

- On-going simulation
  - ~ 60 observations of Jupiter
  - galactic plane crossing in 2013
  - detection with S/N = 3

Détermination of β : Orbits of minor planets

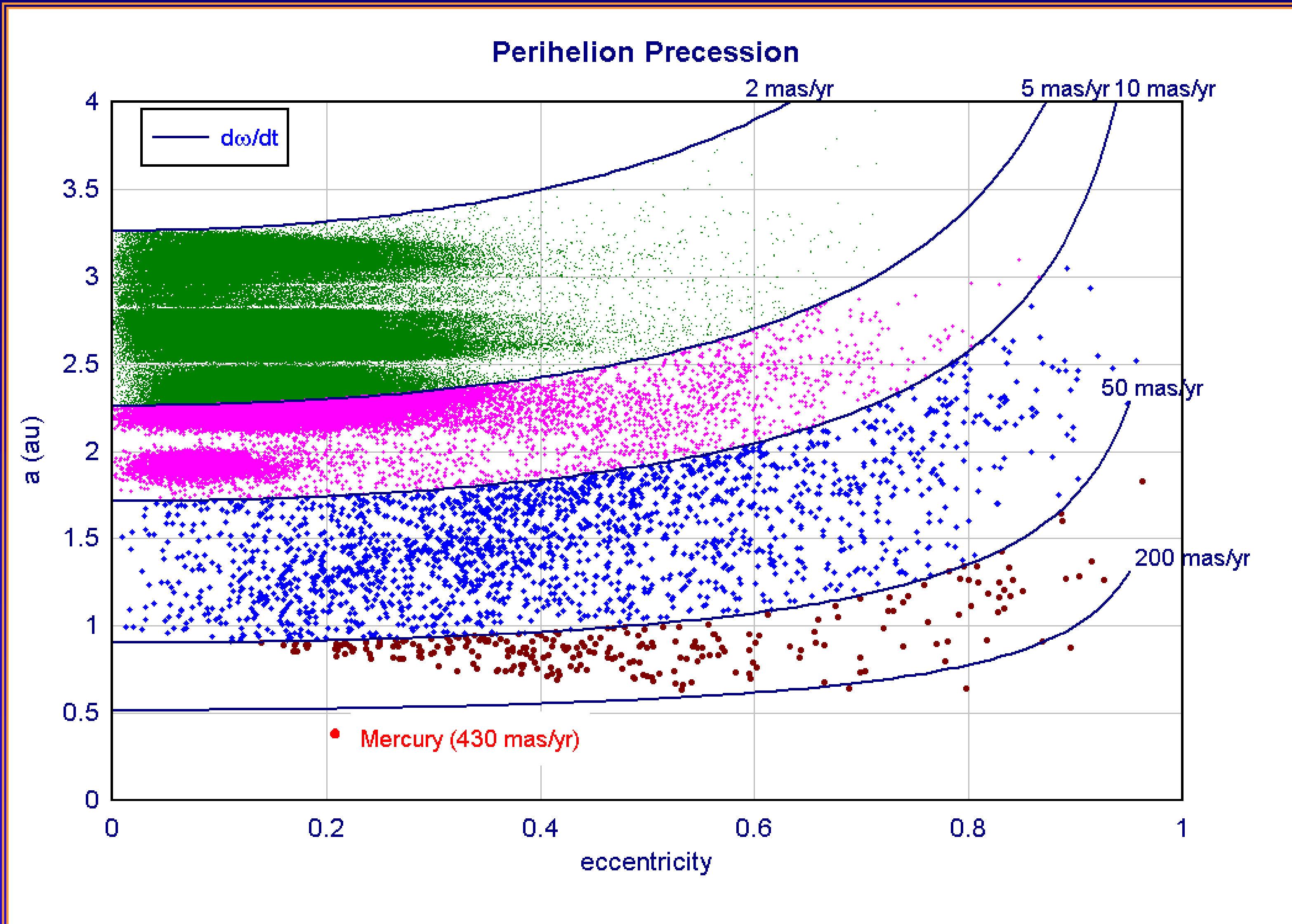
- Between 10^5 and 10^6 asteroids
- Accurate astrometry corrected for phase effect
- ~ 60 observations over 5 years
- Accurate orbits determined with Gaia data
- Perihelion precession included in the dynamical model

$$\Delta\varpi = \frac{6\pi\lambda GM}{a(1-e^2)c^2} + \frac{3\pi J_2 R^2}{a^2(1-e^2)^2}$$

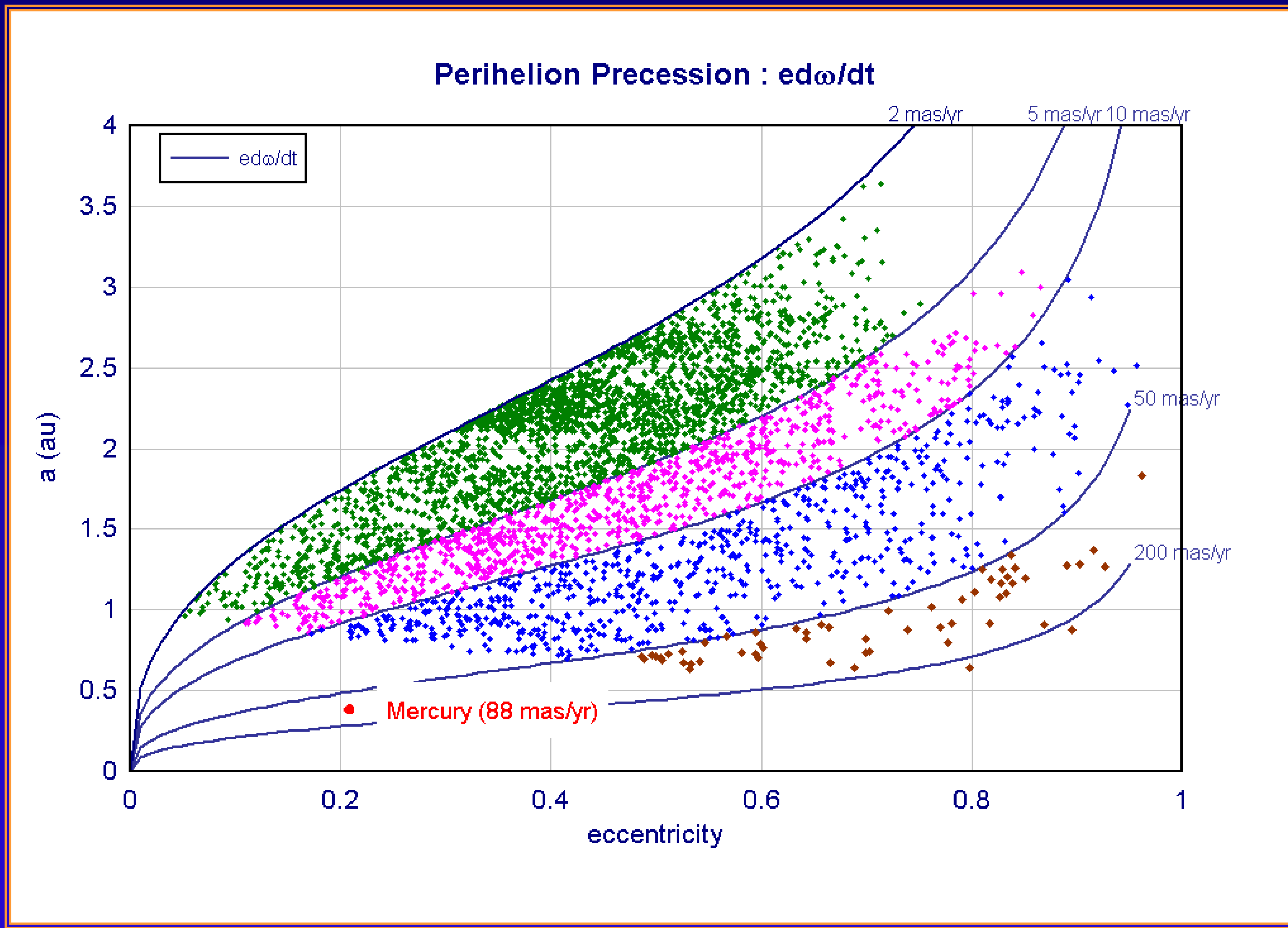
$$\lambda = (2\gamma - \beta + 2)/3$$

$$\dot{\omega} = \frac{38\lambda}{a^{5/2}(1-e^2)} + \frac{0.04(J_2/10^{-6})}{a^{7/2}(1-e^2)^2} \quad \text{mas/yr} \ (a \text{ in AU})$$

Perihelion Precession : dω/dt



Perihelion Precession : edω/dt

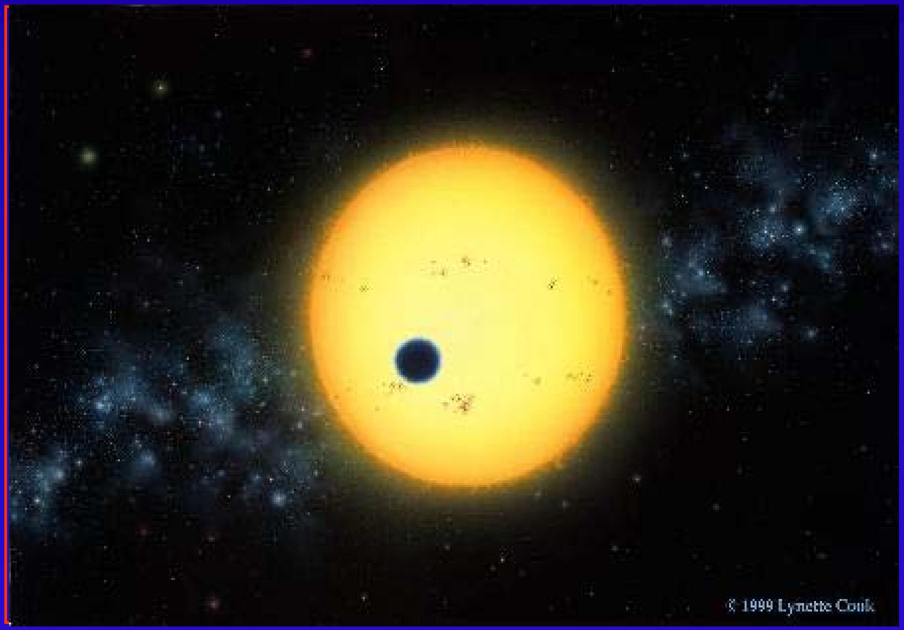


Astophysical Pieces of Science in brief

Extra-solar Planets: Expected Discoveries

- Astrometric survey:
  - monitoring of hundreds of thousands of 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

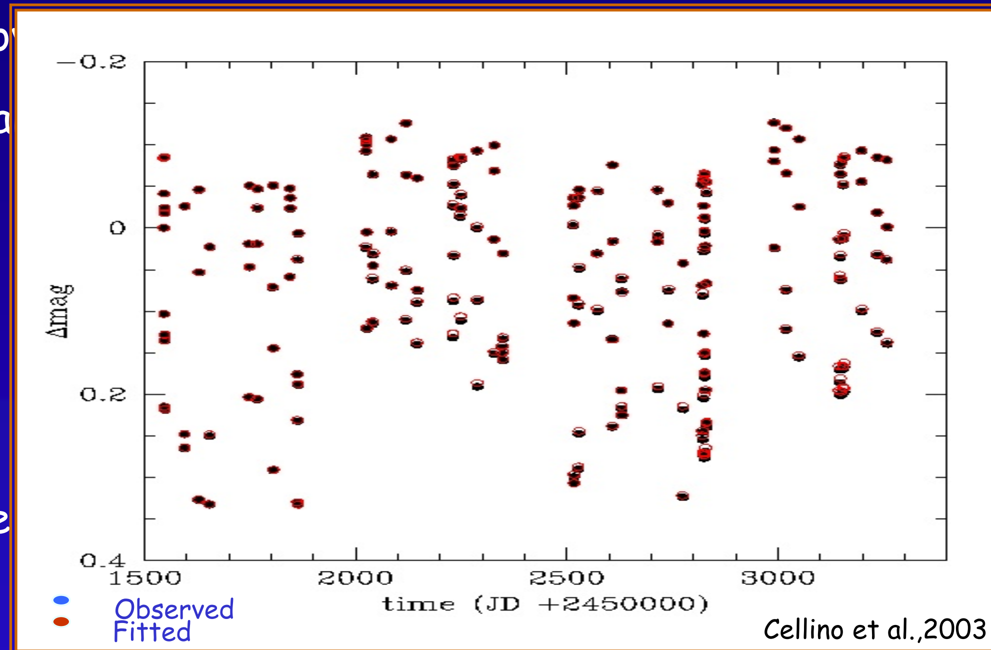
- Results expected:
  - 10–20,000 planets (~10 per day)
  - displacement for 47 UMa = 360 μas
  - orbits for ~5000 systems
  - masses down to 10 M_{Earth} to 10 pc



- Photometric transits: ~5000?

Solar system science

- Observational material from Gaia
  - GAIA will survey solar system objects to V = 20
  - Objects will be repeatedly observed o
  - Single measurement astrometry (1 tra
    - 100 muas @ V = 15
    - 2 mas @ V= 20
  - Photometric data in ~ 10 bands

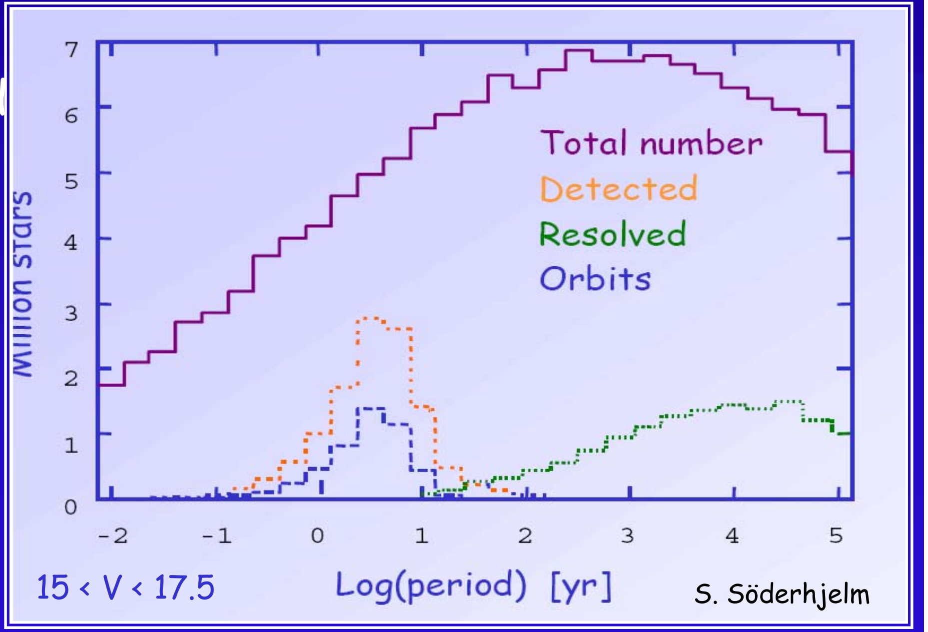


- Results expected
  - Detection of NEOs, specifically inside
  - taxonomic classification
  - relation with orbital properties
  - Light curves and rotation parameters
  - Orbits drastically improved with 5 years of observation
  - then use of the astrometric archives with the new catalogue
  - ~ 100 masses expected from close approaches

Small stellar systems

- Power of Gaia
  - Survey mode, sensitivity to non linear motion
  - ~ regular time sampling over 5 yrs
  - Large range of separations and dm
  - Spectroscopic measurements

- Expected results
  - Detection of Detection of various kind binaries : ~ $6x10^7$ binaries
    - 10^7 resolved within 250 pc
    - 10^7 astrometric binaries
    - 10^{6-7} eclipsing, 10^6 spectro
  - 50% Complete census to 250 pc
  - Masses to 1% for 10^4 stars
  - Severe constraints on evolutionary models

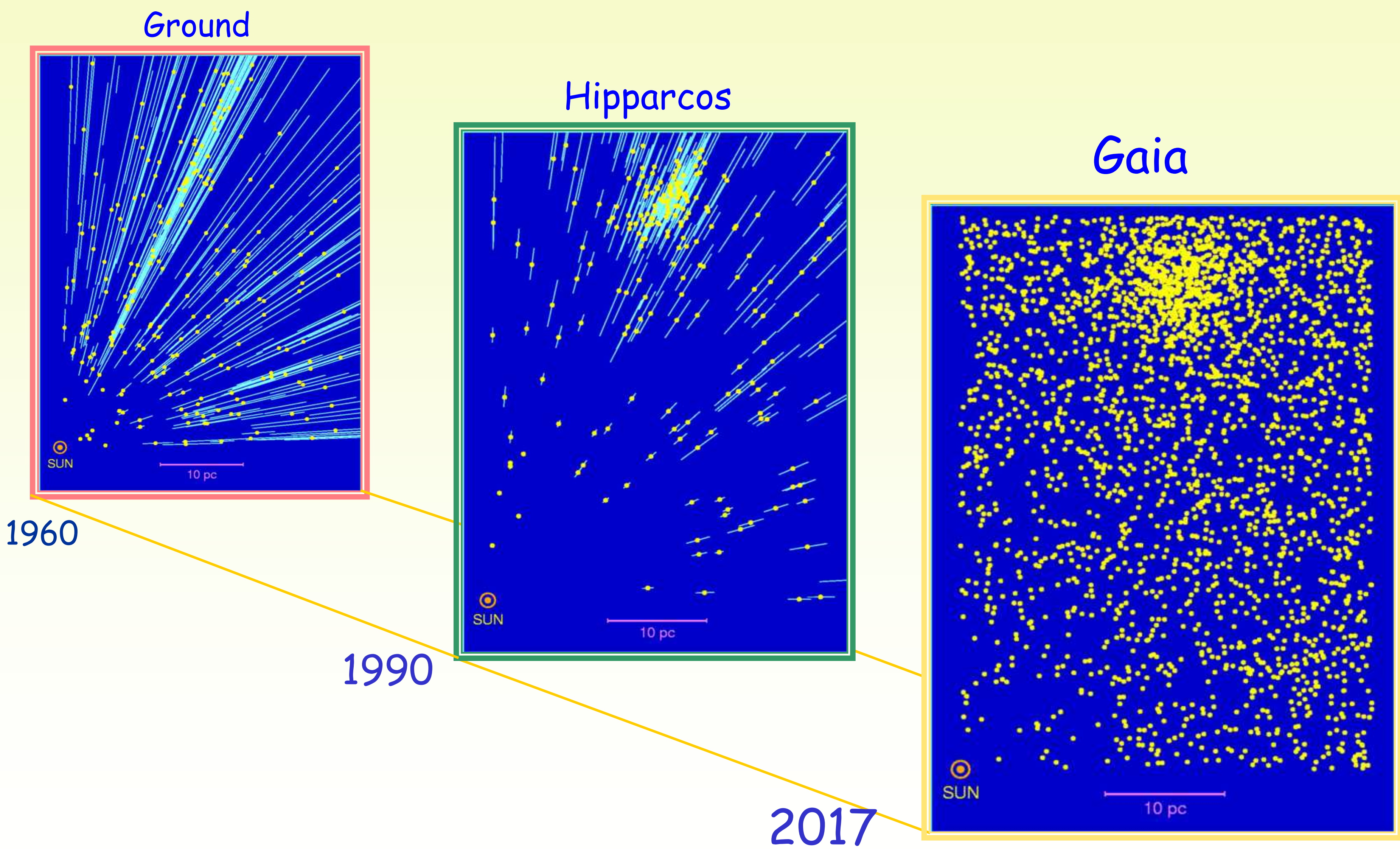


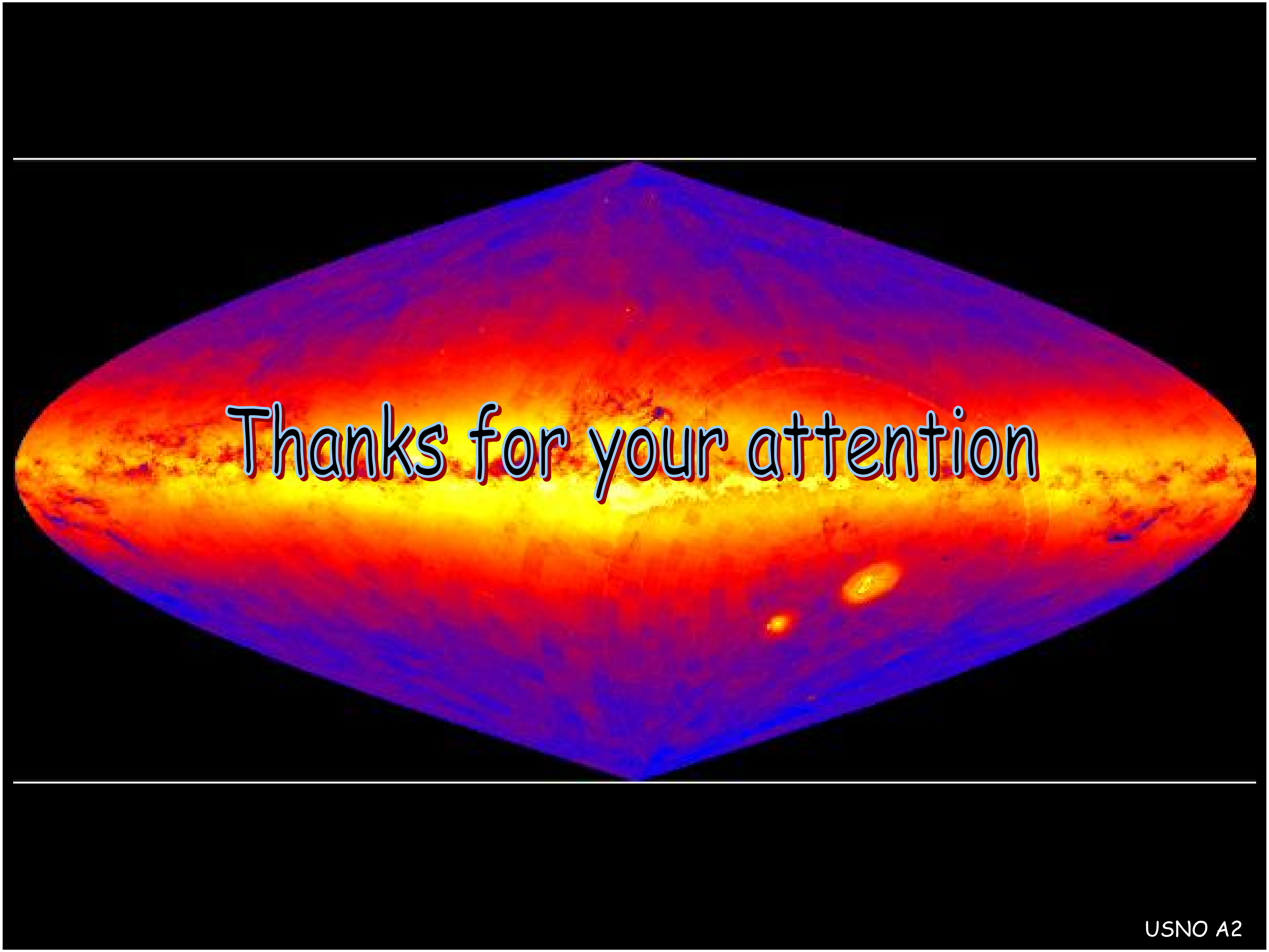
Therefore if everything goes well ….

In 2017…

- 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 $\sigma < 1$ %
- Extra solar planets to 200 pc
- 5×10^5 minor bodies of the solar system, 100 masses
- ~ 5×10^5 QSOs + z + photometry, ICRF in the visible
- γ to ~ 10^{-7}

Just, be patient....




Thanks for your attention
USNO A2

Stellar and galactic Physics :: too much to say …

- New astrophysical text books for the 2020s :
  - What is the mass of the heaviest stars ?
  - What is the rate of formation of stars in the milky way ?
  - What are the cooling sequence and the LF of the white dwarfs ?
  - Are brown-dwarfs common in binary systems ?
  - Are all stars ultimately variable ?
  - Are M, T_{eff}, $\log g$, [Fe/H] enough to make a star ?
  - How often a planetary system is found in binary systems ?
  - Are massive stars still forming in the galactic halo ?
  - Where does the halo come from ?
  - Is there dark matter out there ?
  - …

Close approaches and masses

Number of approaches < 0.05 AU between :

- a large planet (ID < 100)

- one of the first 10,000