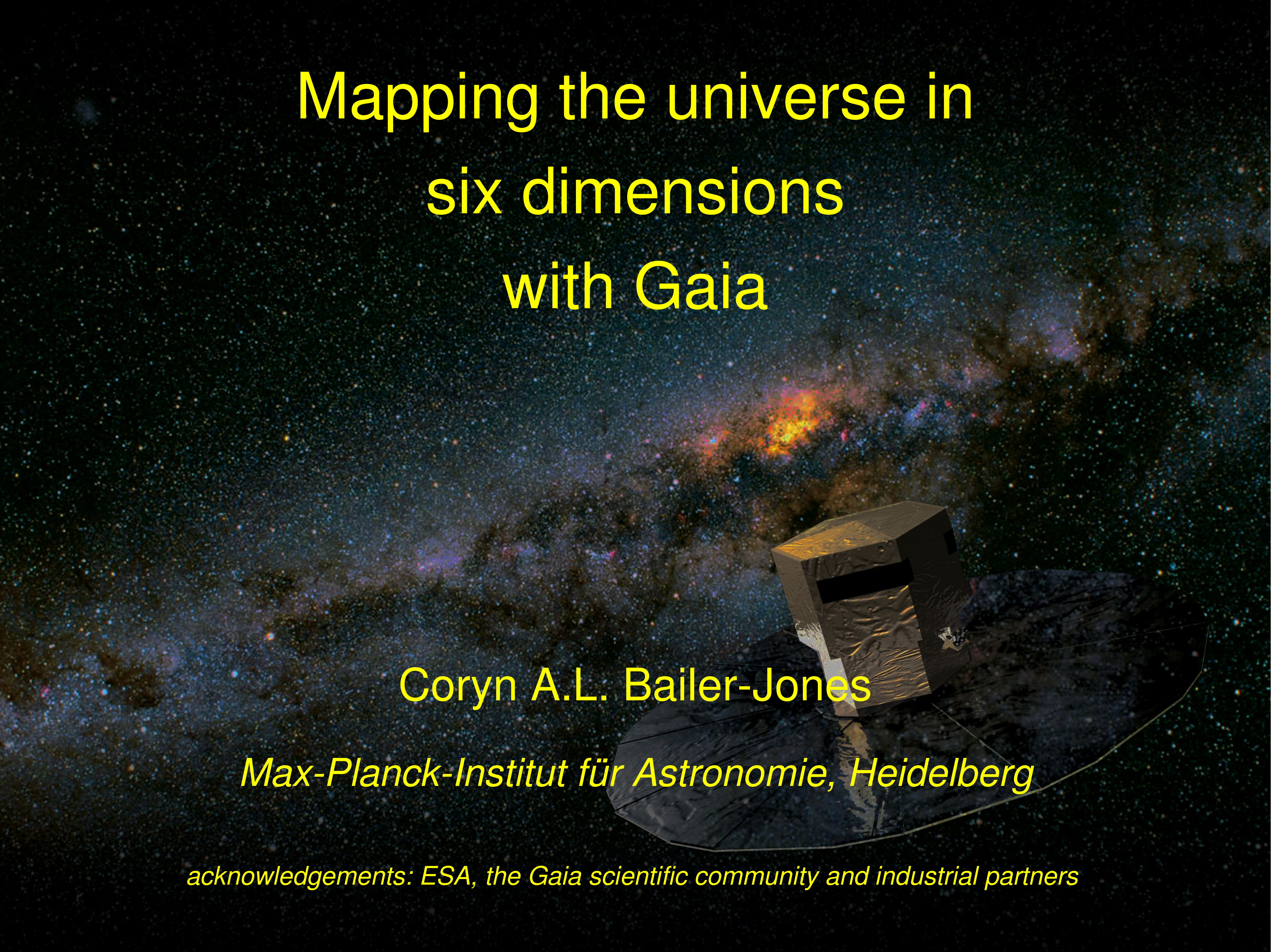

Mapping the universe in six dimensions with Gaia

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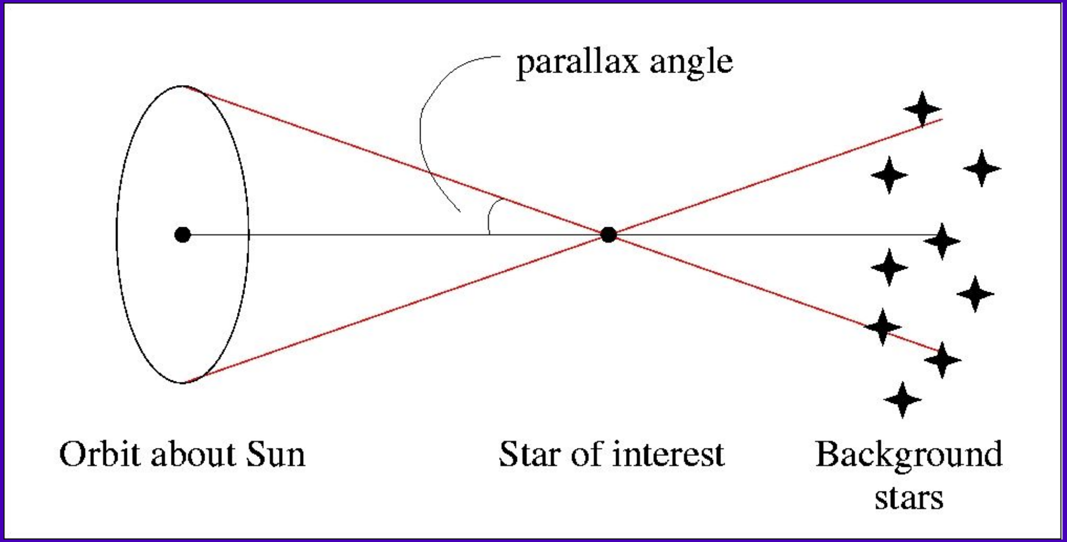
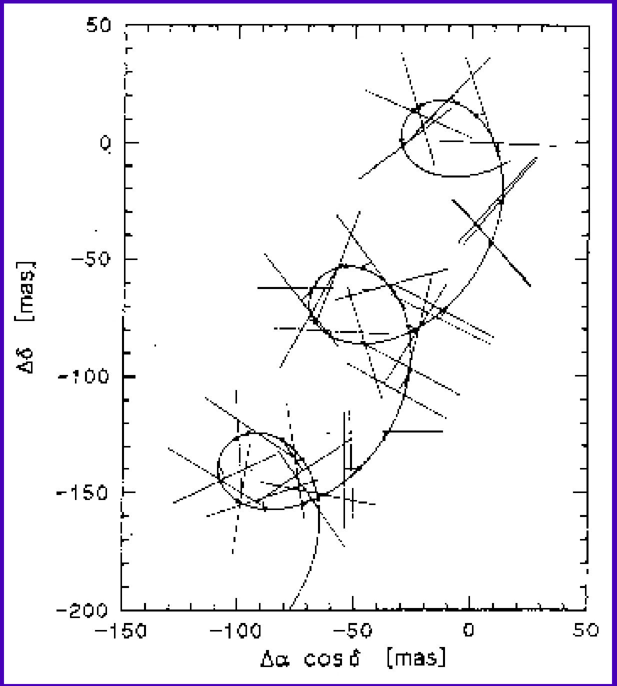
acknowledgements: ESA, the Gaia scientific community and industrial partners

What is astrometry?

- Positions
  - Right Ascension, Declination
- Distances
  - parallaxes
- Kinematics
  - 2D (angular) proper motions
  - combined with parallaxes
    => 2D transverse velocities





Astrometry gives five components of **r**,**v** phase space

What do we learn from astrometry?

- Distances
  - fundamental problem in astronomy (sky is 2D)
  - puts angular measurements on a spatial scale $\rightarrow$ 3D structure
  - converts *apparent* luminosities to *absolute* luminosities
  - all other distance measures depend on astrometric parallaxes
- Kinematics (3D motions)
  - identify common motions of widely separated stars (e.g. streams)
  - determine orbits (star, planets, asteroids etc.)
  - measure gravitational potential (mass distribution)

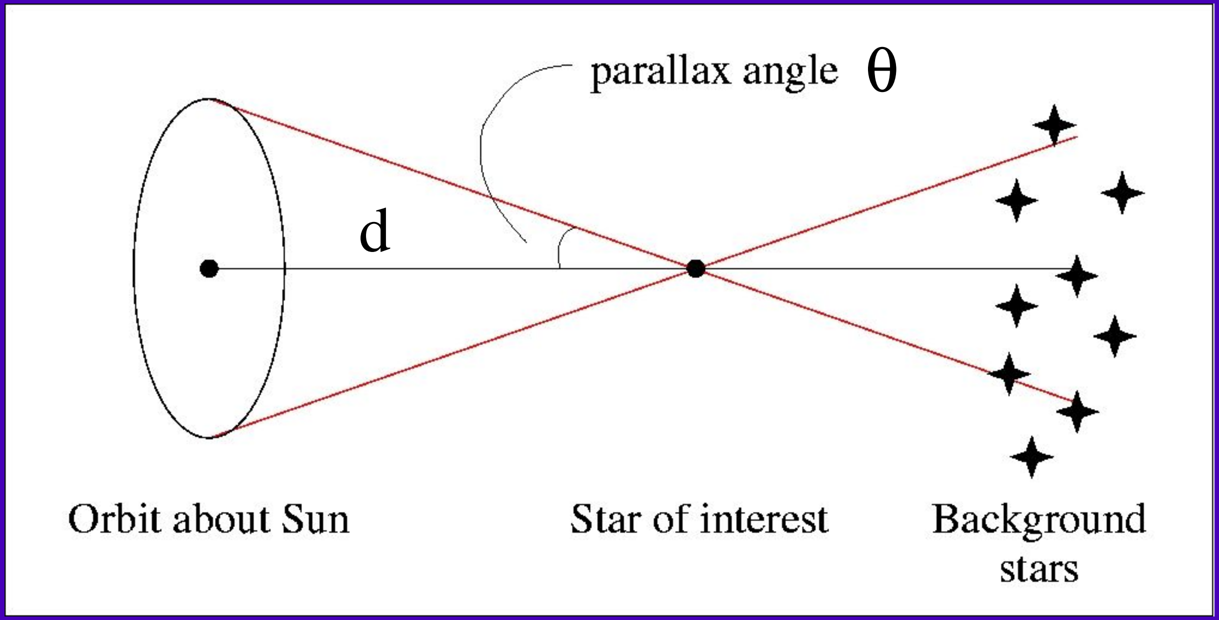
A brief history of astrometry

125 B.C.	Precession of the equinoxes (Hipparchus)
1717	First proper motions measured (Halley)
1725	Stellar aberration (Bradley), confirming
	➔ Earth's motion through space
	➔ finite velocity of light
1761/1769	Transits of Venus across the Sun (various)
	➔ solar parallax
1838/9	First stellar parallaxes (Bessel, Henderson, Struve)
1989-1993	Hipparcos satellite (ESA)

arcseconds and parsecs

$$d/\text{parsec} = \frac{1}{\theta/\text{arcseconds}}$$

1 pc = 31 x 10^{12} km = 3.26 light years

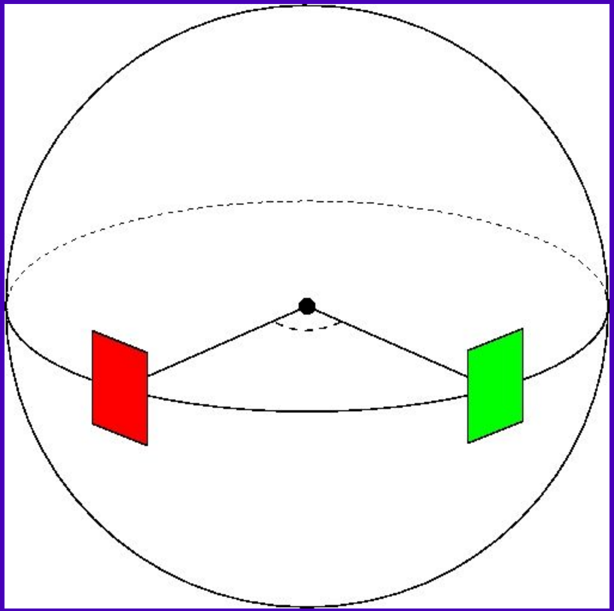


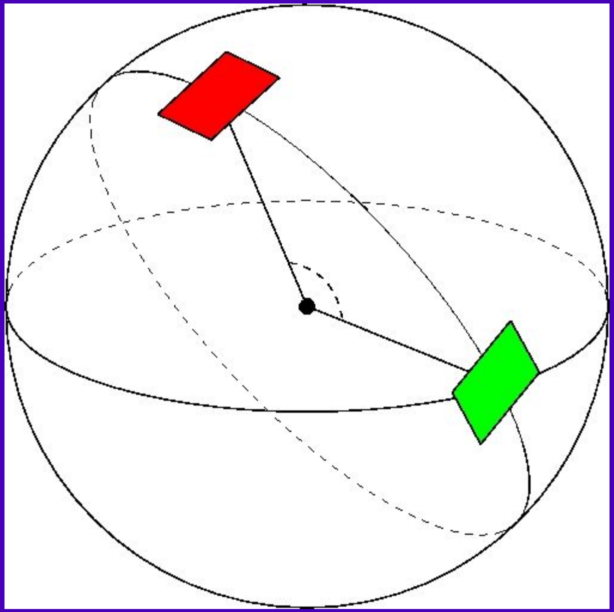
1 *micro* arcsecond is the angular size of

- a grain of rice seen on the Moon
- a human hair seen in Kabul

Global astrometry from space

- Ground-based astrometry
  - narrow field
  - reference stars share common parallax effect
  - therefore only *relative* astrometry
  - limited to a few milliarcseconds precision
- Space-based astrometry
  - observe simultaneously in two widely separated fields separated by a fixed *basic angle*
  - measure relative positions along great circle
  - repeat for many orientations over whole sky





Gaia in a nutshell

spatial distributions,
motions, physical properties

Entire sky to V=20

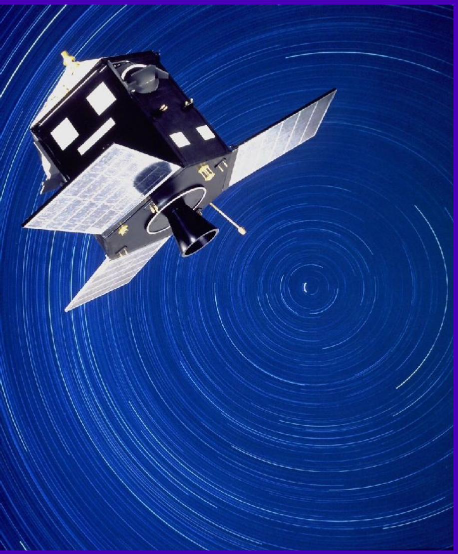
high accuracy astrometry: 10 μas @ V=15

radial velocities and photometry

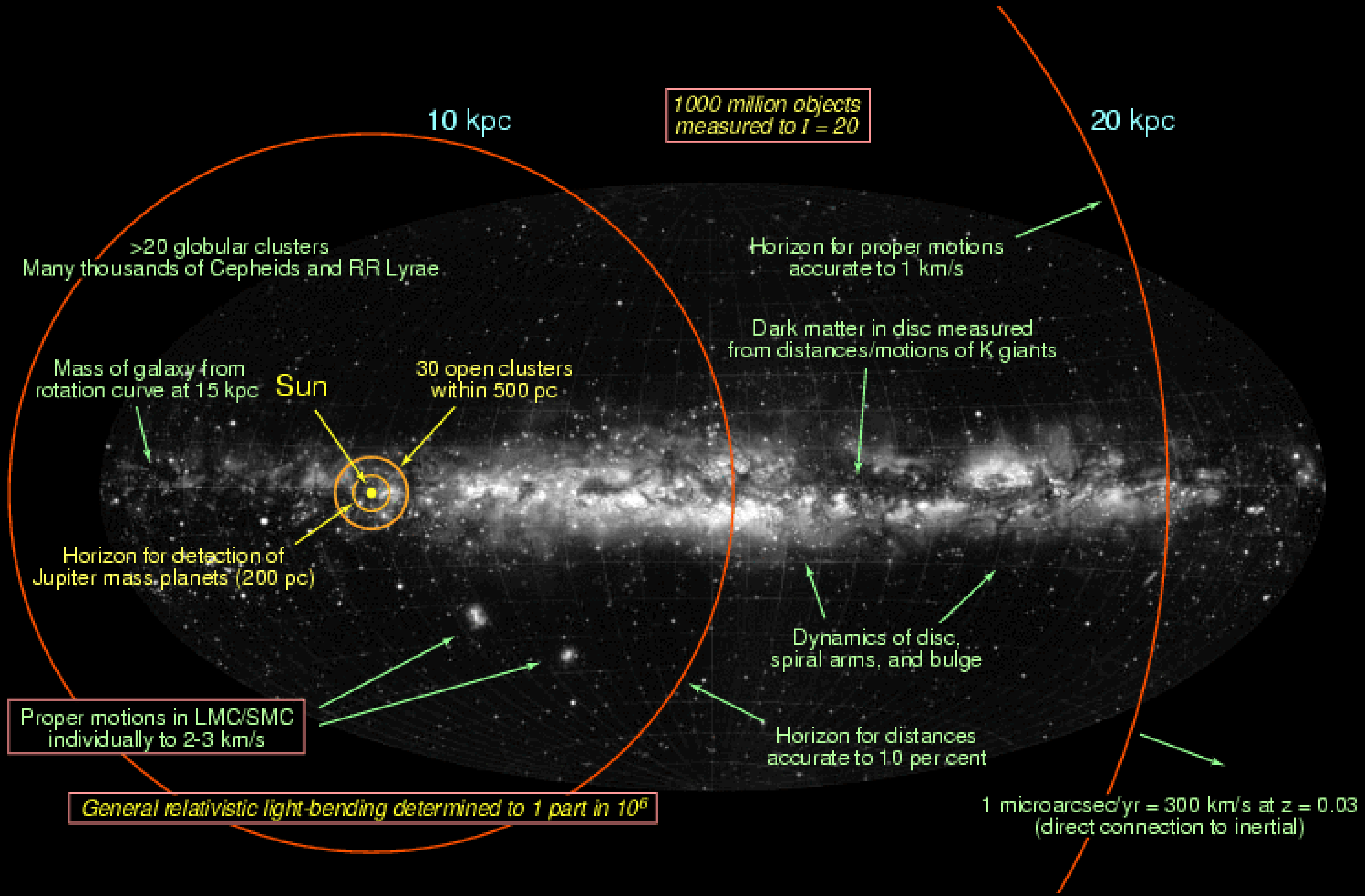
ESA mission launch 2011

Key objective: composition, formation and evolution of the Galaxy

Hipparcos vs. Gaia



	Hipparcos	Gaia
Magnitude Limit	12.4	20
No. sources	120 000	1000 000 000
No. quasars	none	0.5-1 million
No. galaxies	none	1-10 million
Astrometric accuracy	~1000 μas	2-3 μas at V<10
		5-15 μas at V=15
		40-200 μas at V=20
Photmetry	2 bands	19 bands
Radial velocities	none	1-10 km/s to V=17-18



10 μas = 10% distances at 10 kpc

10 μas/yr = 1 km/s at 20 kpc

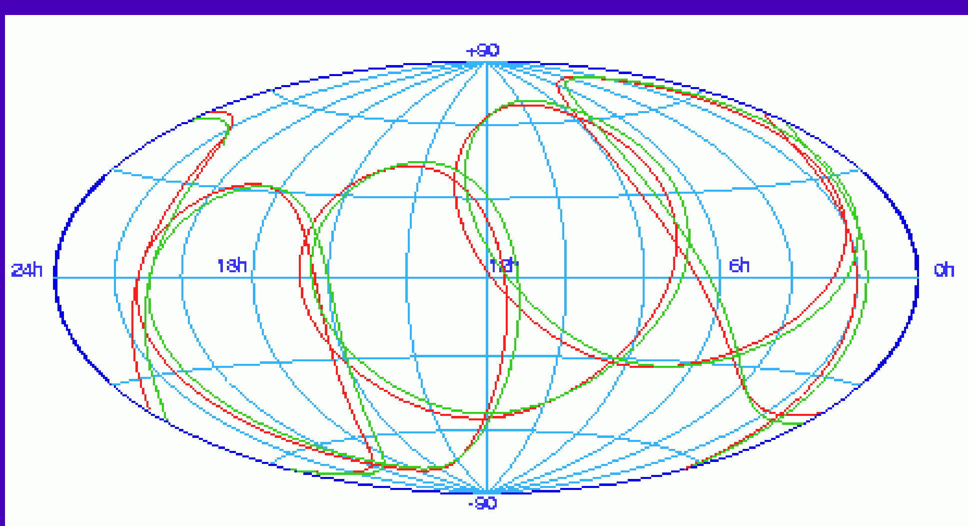
Sky scanning principle

Continuous three-axis motion:

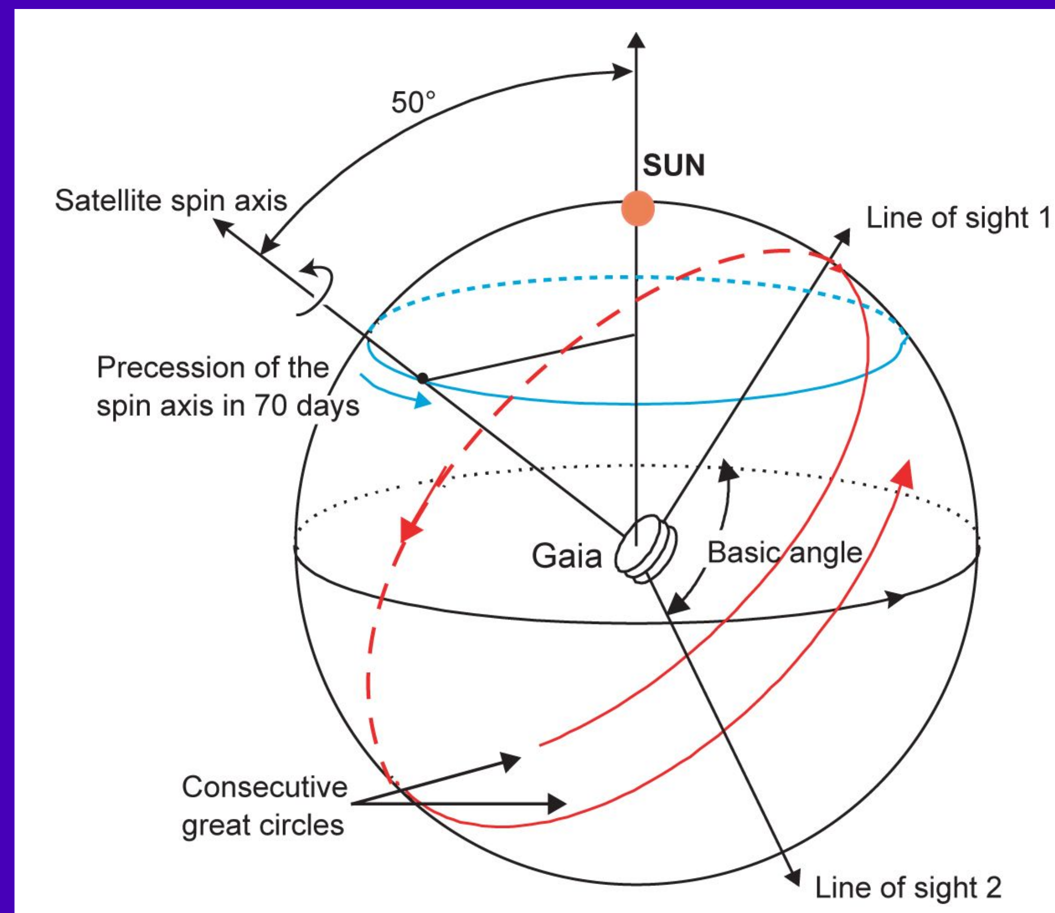
- axis rotation (P = 6 days)
- fixed sun angle precesion (P = 70 days)
- orbit around sun (P = 1 year)

Traces quasi great circles on sky

5 year mission



Ecliptic co-ordinates

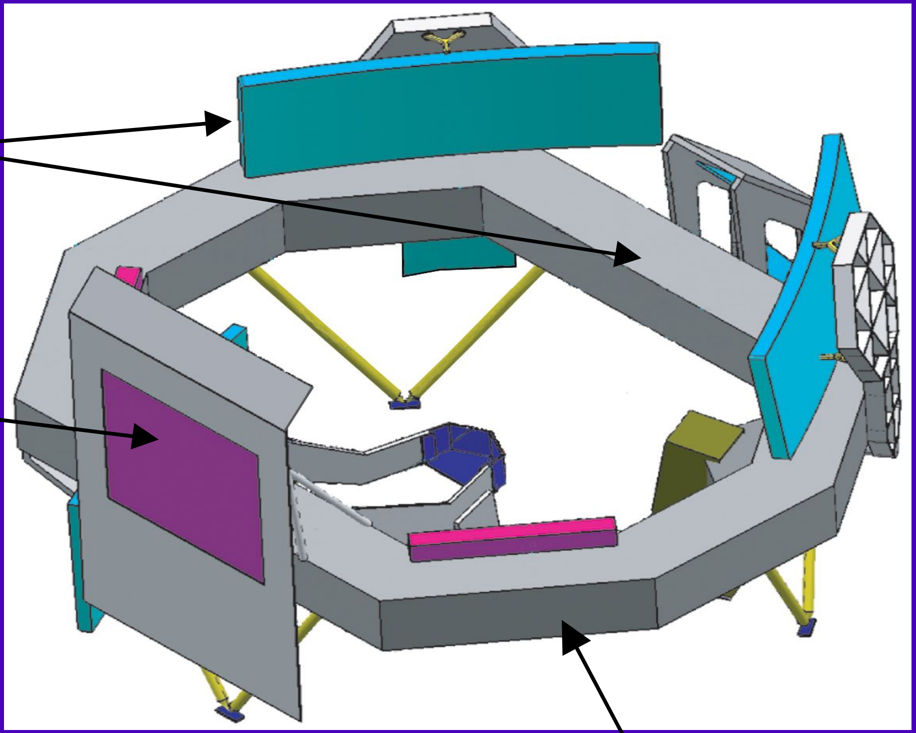


The satellite

Sunshield diameter = 11m Total mass = 1700kg (800kg telescope/instruments)

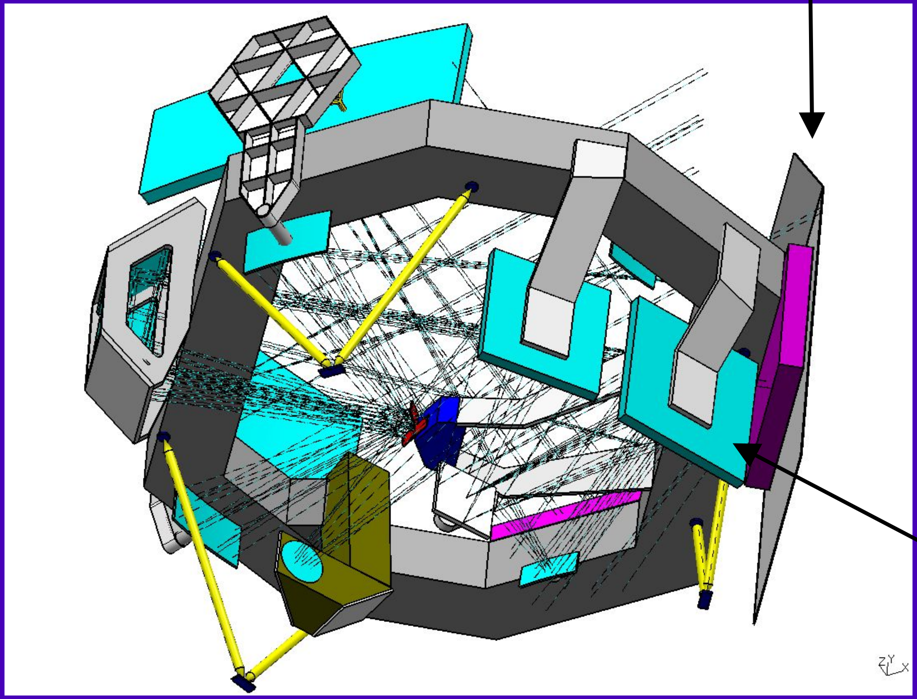
Payload overview

Astrometric instrument:
1.4m x 0.5m primary mirrors



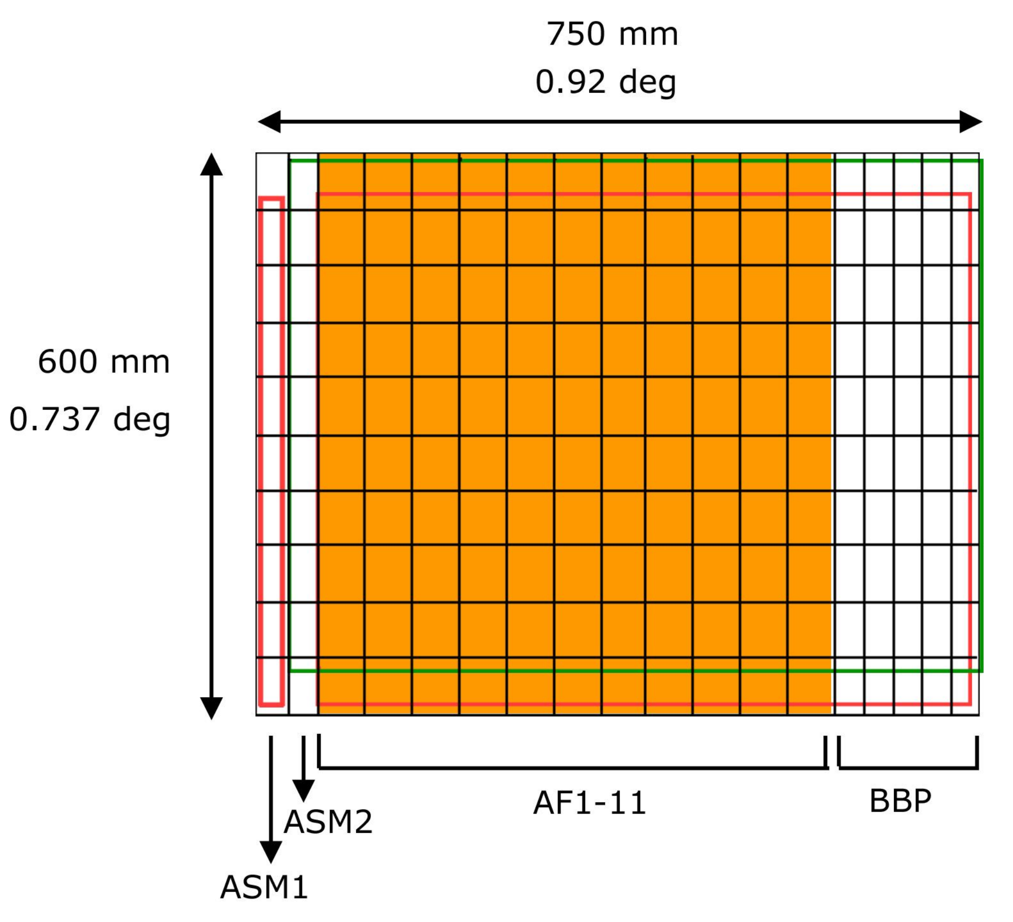
Astrometric focal plane

SiC optical bench



Spectroscopic instrument:
0.56m x 0.45m primary mirror

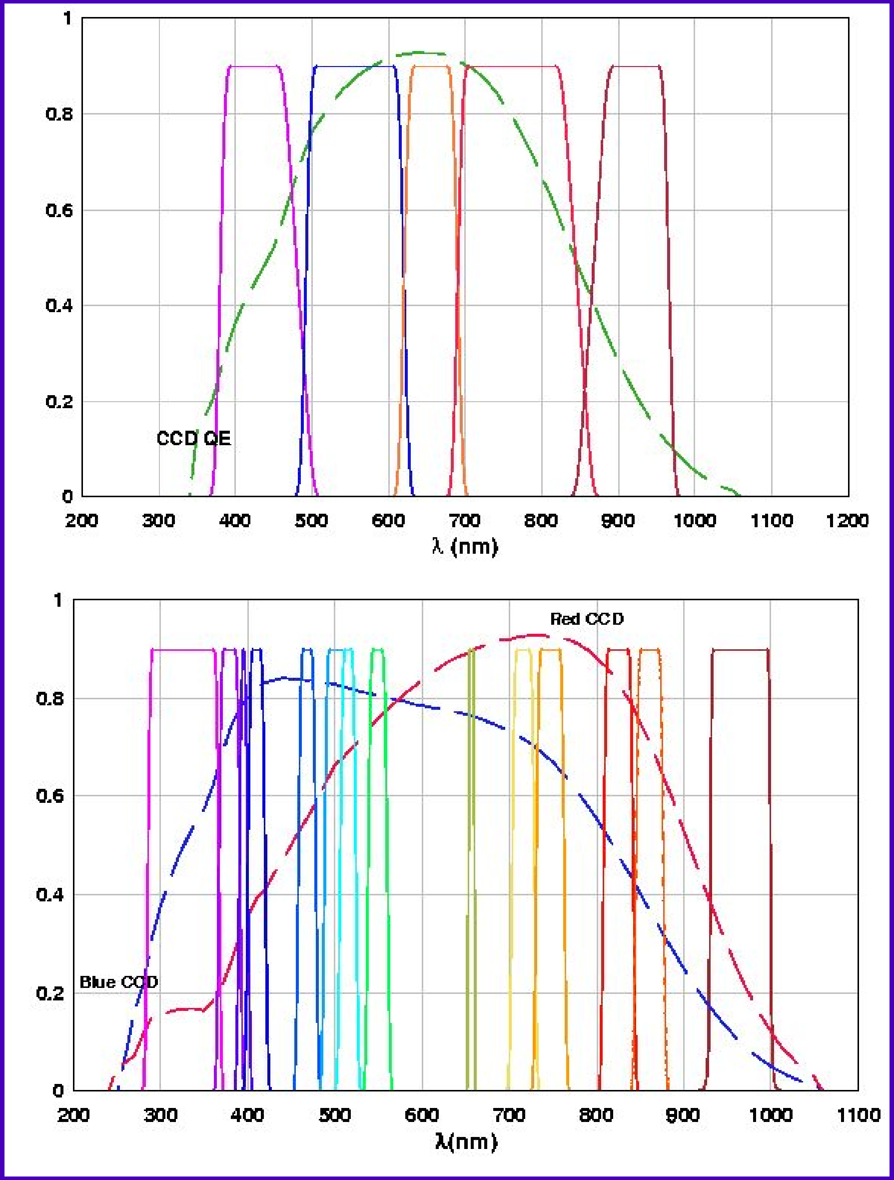
Astrometric focal plane



direction of motion across focal plane

- the two fields-of-view are superimposed on a single CCD focal plane
- 180 CCDs (2000 x 5600 pixels)
- CCDs clocked in “TDI mode”
- real-time detection of objects
- transmission only of “windows” around objects

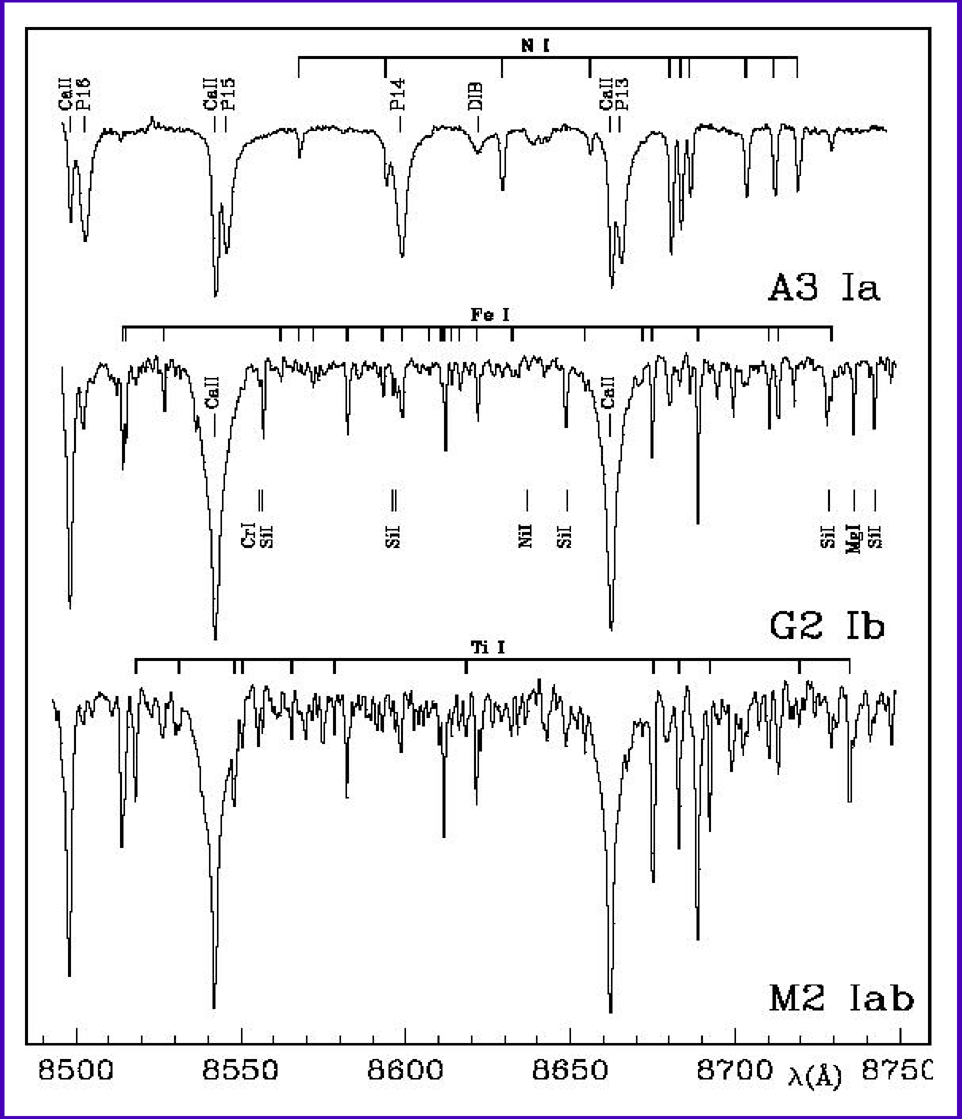
Gaia photometry



- Broad Band Photometric system (BBP)
  - 5 broad bands
  - primarily for chromatic correction
- Medium Band Photometric system (MBP)
  - 14 medium bands
  - object classification
  - determinaton of stellar parameters and interstellar extinction
- systems optimized specifically for Gaia
- vital for exploiting astrometric data!

Gaia spectroscopy

- Slitless spectrograph
- R = 11 500
- around CaII triplet (848–874 nm)
- radial velocities (Doppler effect)
- V_{rad} to 1–10 km/s for V < 17.5
- high SNR spectra for millions of stars with V < 14
  - physical stellar parameters, e.g. [α/Fe]



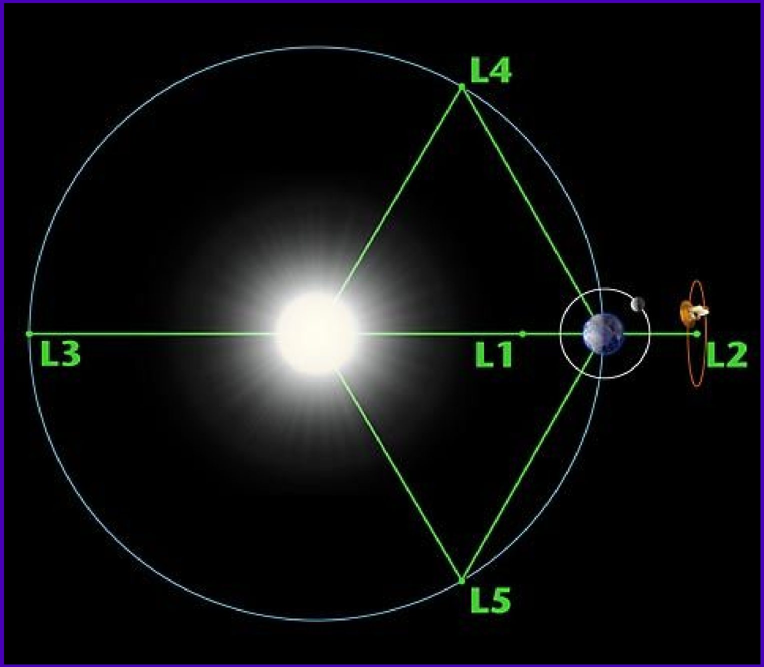
Launch and orbit

basic angle must be stable to ~1 μas over 6 hours

⇒ 25 μK thermal stability
⇒ high mechanical stability (no moving parts!)

Lissajous' orbit about Earth-Sun L2 point
5 year mission

Phased antenna array:
- 3 Mb/s for 8 hours per day
- single ground station (Perth or Madrid)



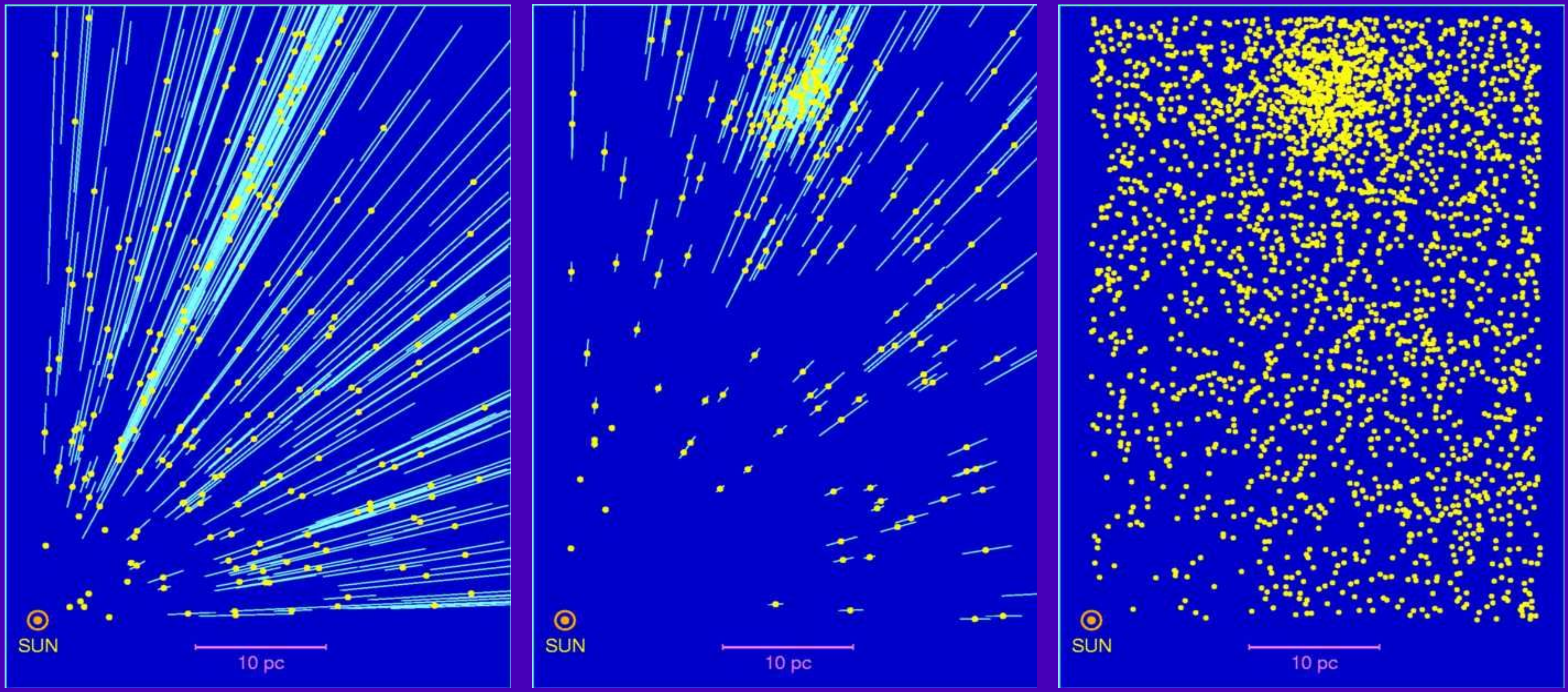
Distance and velocity accuracy

Astrometric accuracy = 10 μas @ V=15

astrometric error: $$\delta\pi \propto \frac{1}{\sqrt{N_{photons}}}$$

Distances			**Transverse motions**		
1% accuracy at 1 kpc at V=15			1 km/s accuracy at 20 kpc at V=15		
20% accuracy at 1 kpc at V=20			1 km/s accuracy at 1kpc at V=20		
<0.1%	for	700 000 stars	<0.5 km/s	for	44 million stars
<1%	for	21 million stars	<1 km/s	for	85 million stars
<10%	for	220 million stars	<5 km/s	for	300 million stars

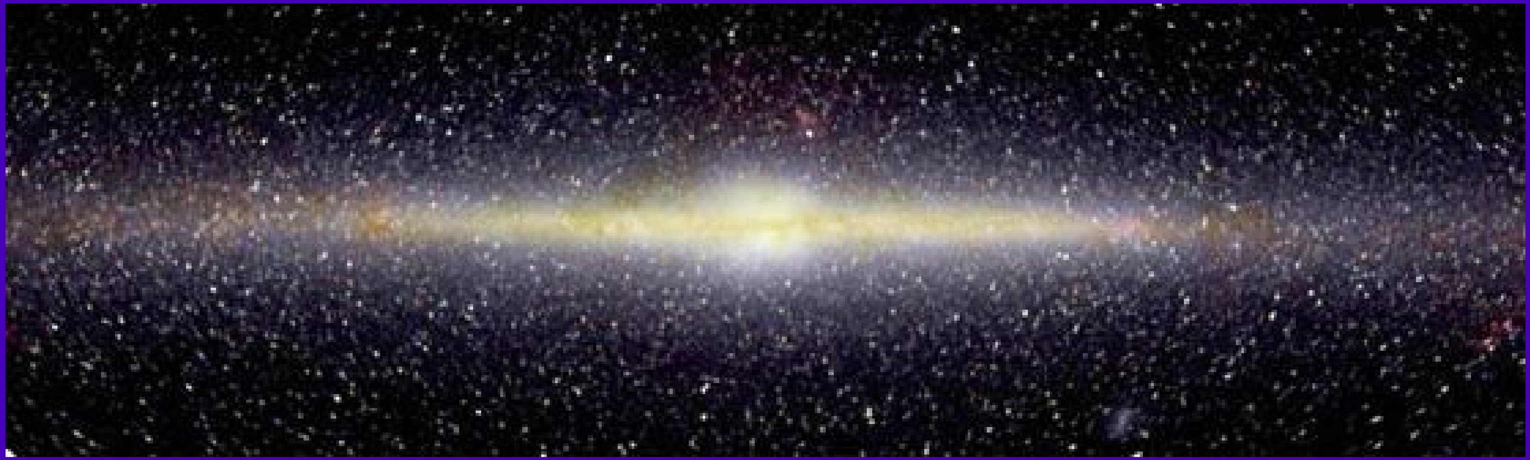
Distance accuracy to nearby stars



Ground Hipparcos Gaia

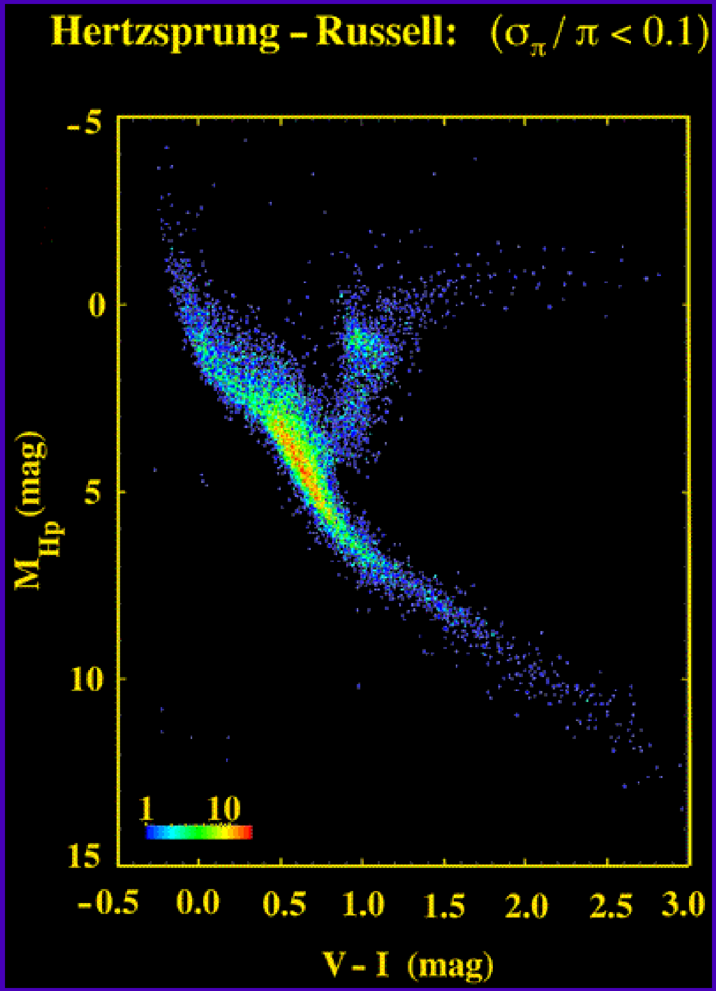
Galactic structure

- galaxy formation
  - how and when did the galaxy form?
  - structure/origin of bulge, halo, disk, spiral arms
  - substructure in the halo (merger history)
- evolution of stellar populations
  - star formation history and chemical evolution
  - abundance distributions in 6D phase space
- mass and dark matter
  - gravitational potential from 3D stellar motions



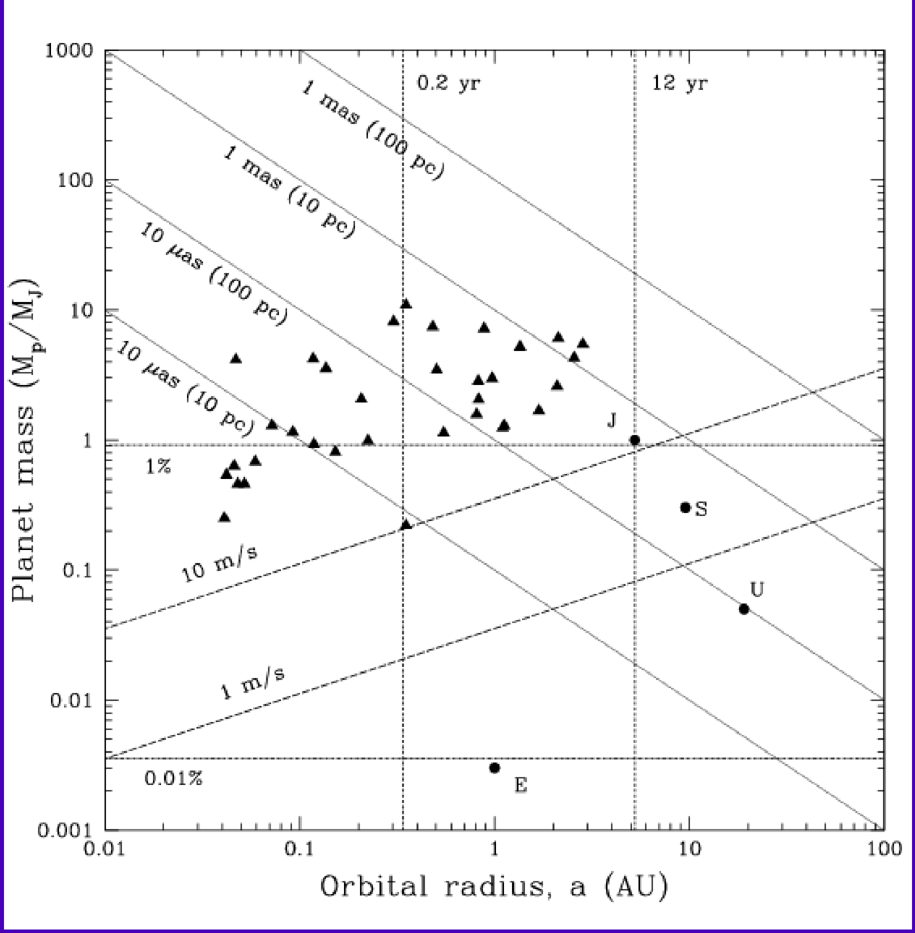
Stellar clusters

- ~70 clusters within 500 pc
  - *individual* distances to 0.5%, <2.5pc at V=15
  - transverse velocities to <1 km/s for all stars down to M dwarfs out to 200pc
- stellar structure and evolution
  - calibration of luminosity–mass relation
  - ages from Main-Sequence turn off
- kinematics
  - mass segregation (dynamic vs. primordial)
  - evaporation of low mass members, dispersion into interstellar medium
- Gaia will discover thousands more open clusters



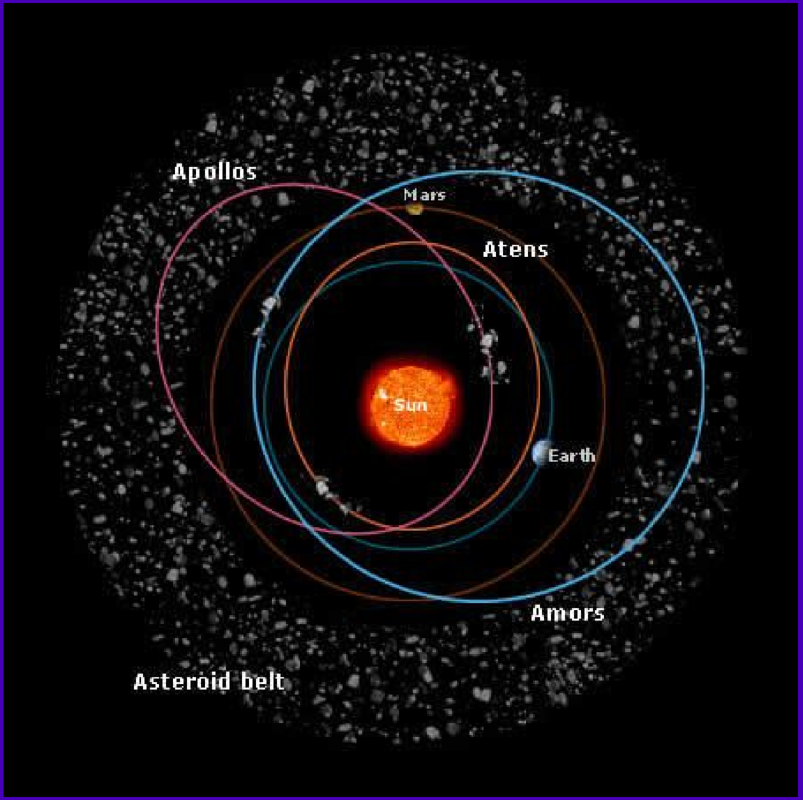
Exosolar planets

- astrometric companion search
  - $\alpha = (M_p/M_s)(a_p/d)$
  - 47 UMa: astrom. displacement 360 μas
  - no *sin i* ambiguity in mass
- extensive, unbiased survey
  - monitor 10^5 stars to 200 pc (V<13)
  - all stellar types to P ~ 10 years
  - ~ 5000 new planets expected
  - orbital solutions for 1000-2000 systems
  - masses to 10 M_E to 10pc
- transits
  - Jupiter across Sun ⇒ 0.01 mag photometric ampltiude
  - expect 6000 detections for 0-2 AU orbit around F-K stars

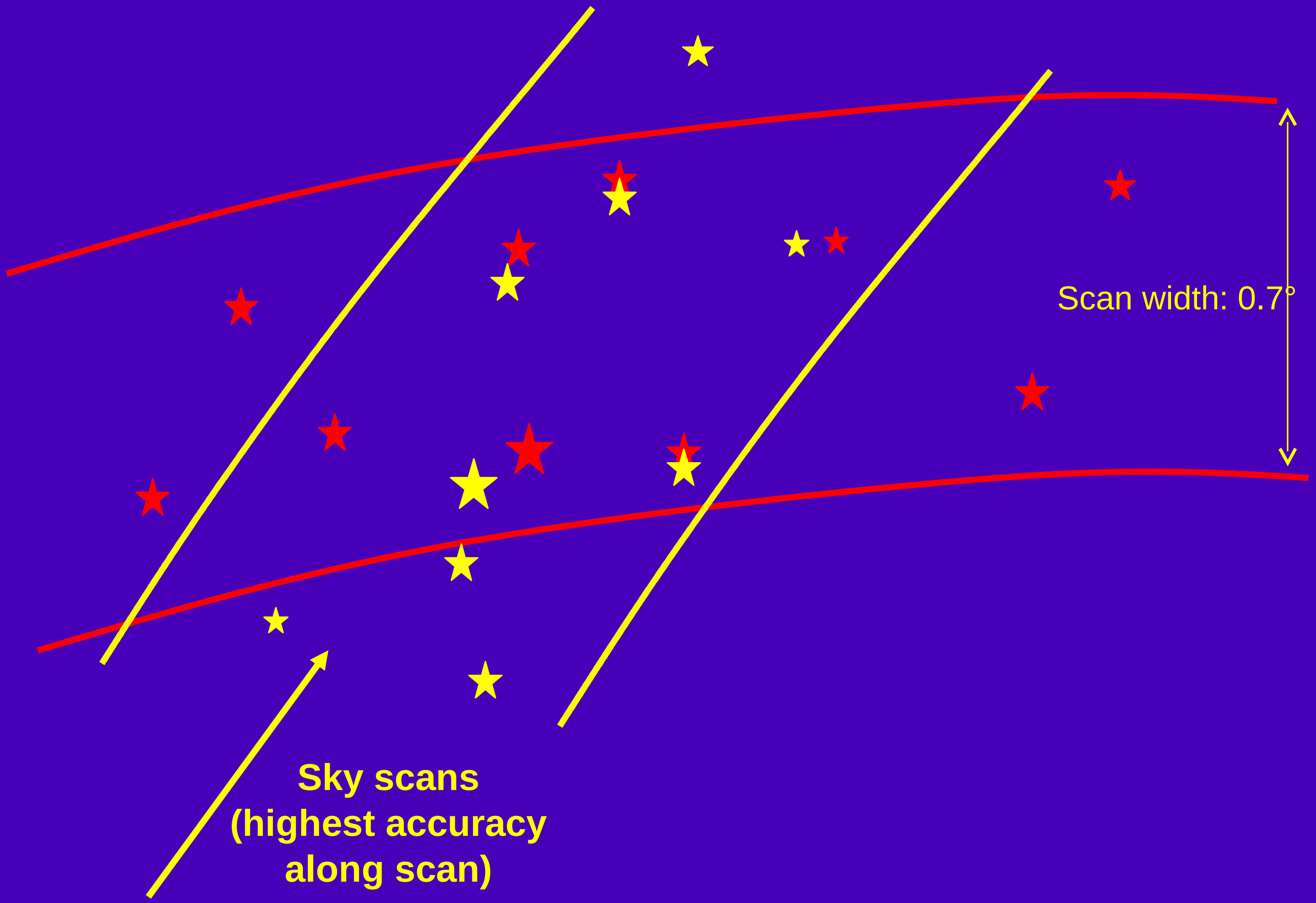


Solar system

- Gaia capabilities
  - all sky complete survey to G=20, to within 35° of Sun ("daytime")
  - discovery of 10^5-10^6 new objects (cf. 65000 now)
  - very accurate orbital elements (~30 times better)
  - multi-band photometry (taxonomy, chemistry)
- main belt asteroids
  - solar system formation
  - sizes, albedos, masses (~ 100, cf. 10 now)
- Near-Earth Objects
  - expect 1600 Earth-crossing (vs. 100 now)
- General Relativity
  - light bending (Sun: 4 mas at 90°), γ to 5×10^{-7}
  - perihelion precession (and solar J_2)



Data reduction principle



Data processing

- 1 Mb/s for 5 years (~ 100 TB raw)
- complex data treatment
  - objects mixed up in time and space
  - astrometry, photometry and spectroscopy
  - iterative adjustment of parameters for ~100 million stars
- *many* tasks, e.g.
  - object matching, attitude modelling, global astrometric processing, binary star analysis, radial velocity determination, photometry, variablity analysis, CCD calibration, object classification, determination of stellar physical parameters
- ~10^{21} FLOPS (10^{17} FLOPS from 1 PC in 1 year)
  - 1s per star for *all* operations would require 30 years
- basic data processing prototype (GDAAS)

Timeline and the scientific community

- Fully approved and funded ESA mission
  - phase A study 2001-2005
  - implementation phase starts early 2006
  - launch 2011
  - end of nominal mission in 2016 – 2017
  - data processing complete ca. 2019
- Scientific community is responsible for the data processing
  - funding by national agencies
  - DACC currently responding to “Letters of Intent” to set up an trans-European data processing consortium
  - significant commitment, investment and expertise required
  - but rewards will be extensive

Summary

Formation and evolution of the Galaxy
Stellar structure and formation
Exoplanets
Solar system
Fundamental physics

All sky survey to V=20 (10^9 stars)
5D phase space (6D to V~17)

Physical stellar properties
(multiband photometry)

Accuracy = 10 μas @ V=15:
⇒ distances to <1% for 20 million stars
⇒ transverse velocities to 1km/s at 20 kpc

Launch 2011; 5 year mission
http://www.rssd.esa.int/Gaia