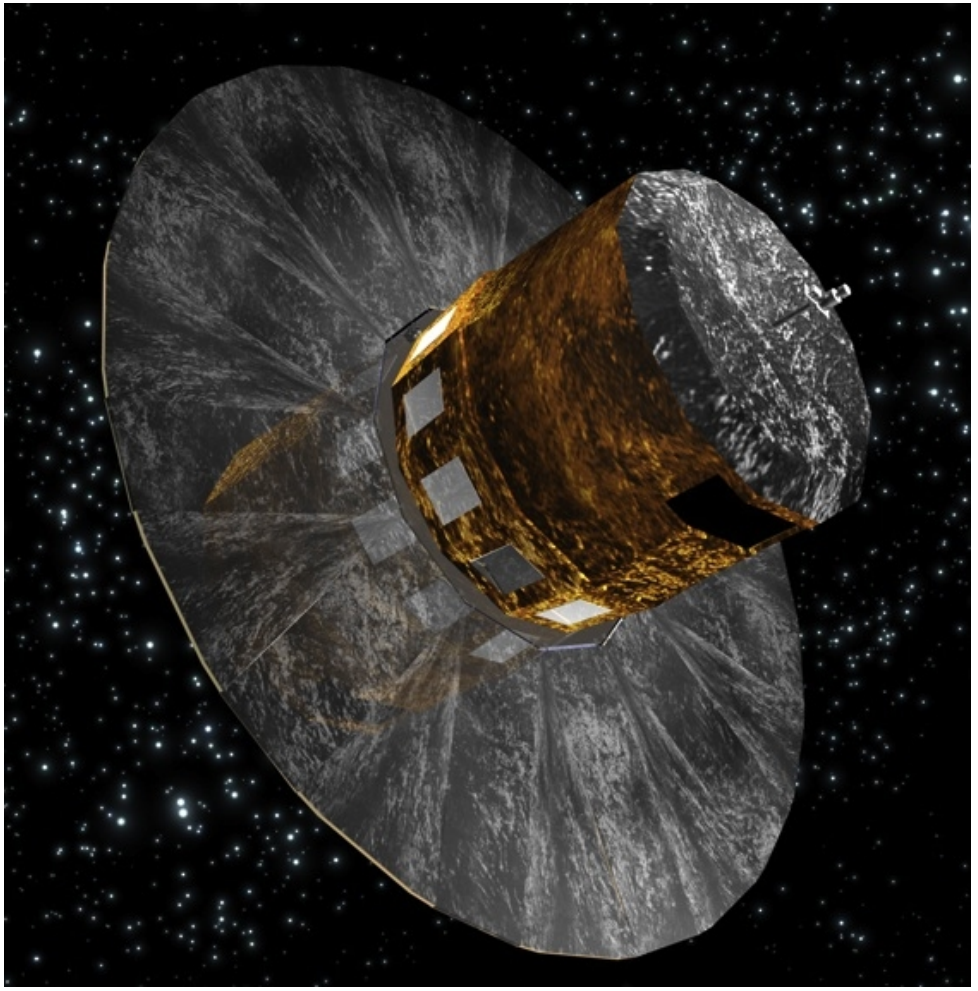
EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

GREAT-ITN MARIECURIE ACTIONS



# Gaia: Mapping The Cosmos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(Institute of Astronomy)

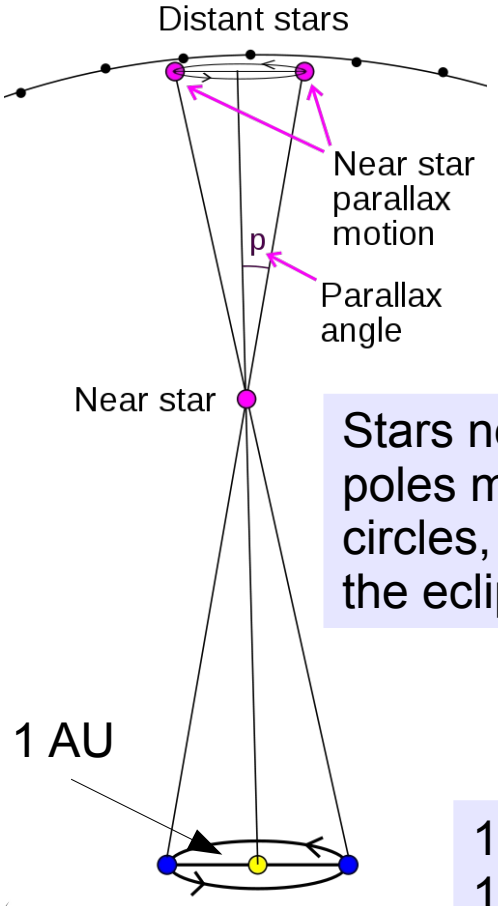
UNIVERSITY OF CAMBRIDGE


ioa

GREAT

# Measuring Distances

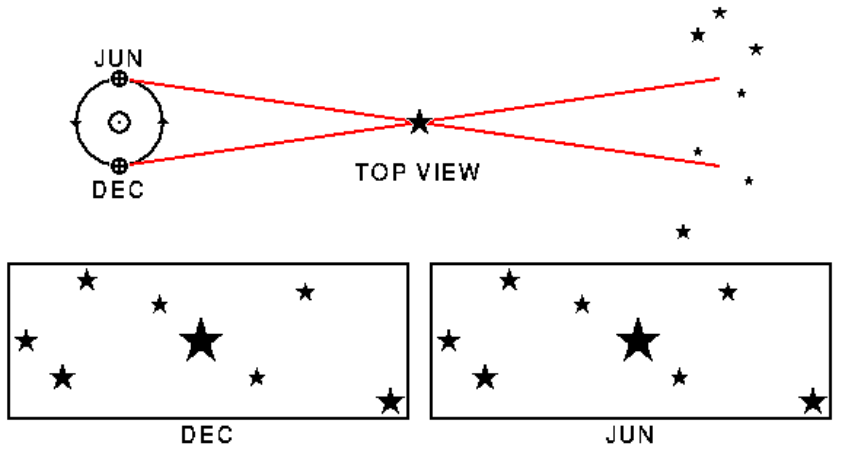
- Many techniques to determine the distance to objects in the sky … but 'Astrometrical parallax' is direct




Stars near the poles map out circles, those at the ecliptic, lines

$d = 1/p$

d (parsec), p in arcsecs
(as small angle approximation = $\tan\theta \approx \theta$)




1 Parsec = 206,000 AU = ~ $3.09 \times 10^{13}$ km = ~ 3.26 light years
1 AU = $1.5 \times 10^{8}$ km

# Motion of a star on the sky is complex

- Observed motions of stars on the sky can be complex
- This example of HR6046 shows the path of its centre of light on the plane of the sky, a combination of motion due to proper motion, parallax and orbital motion (it's a 6yr period spectroscopic binary)
- These measurements are from Hipparcos, so the units are mas (for Gaia it will be in μas)

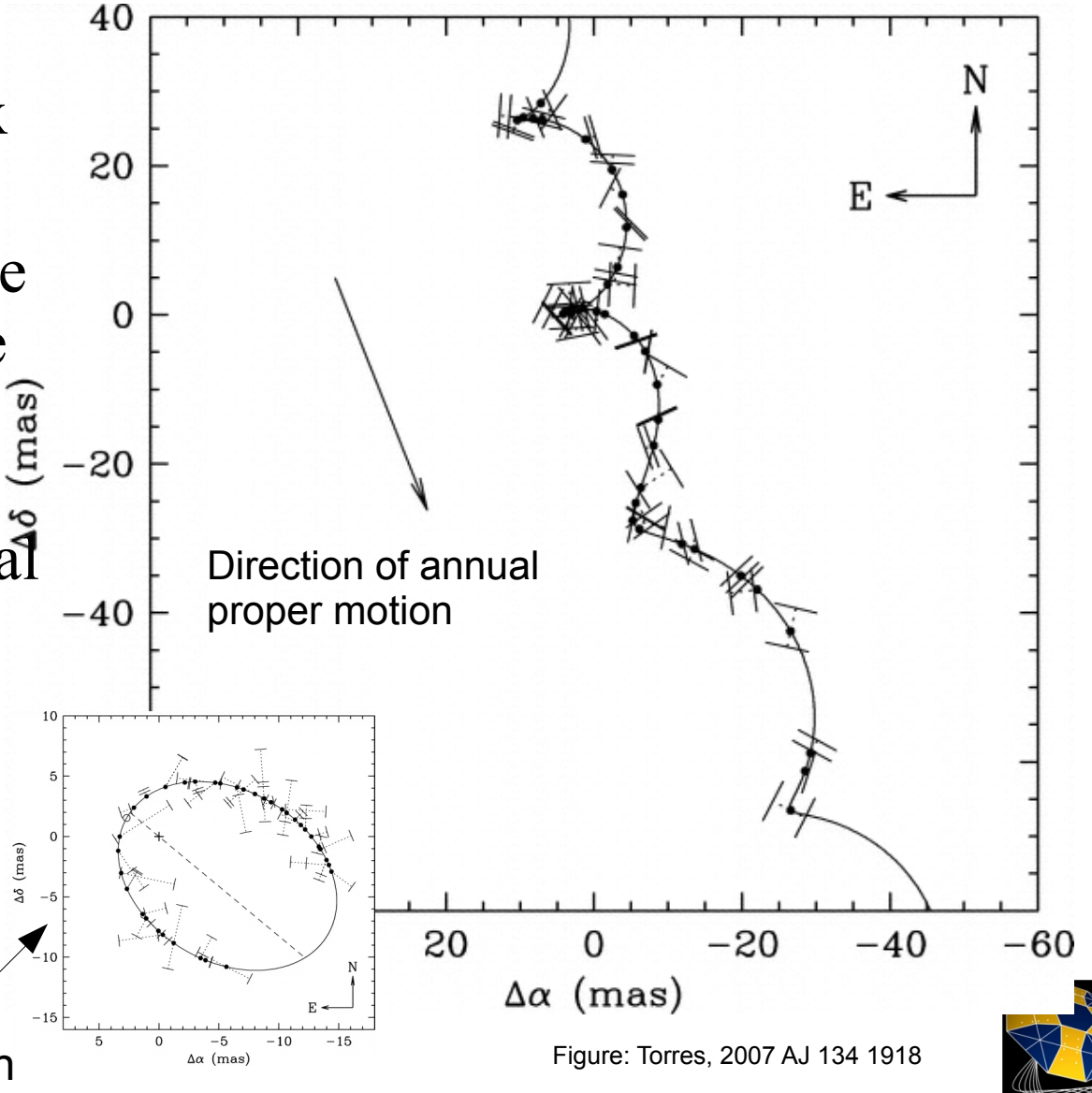


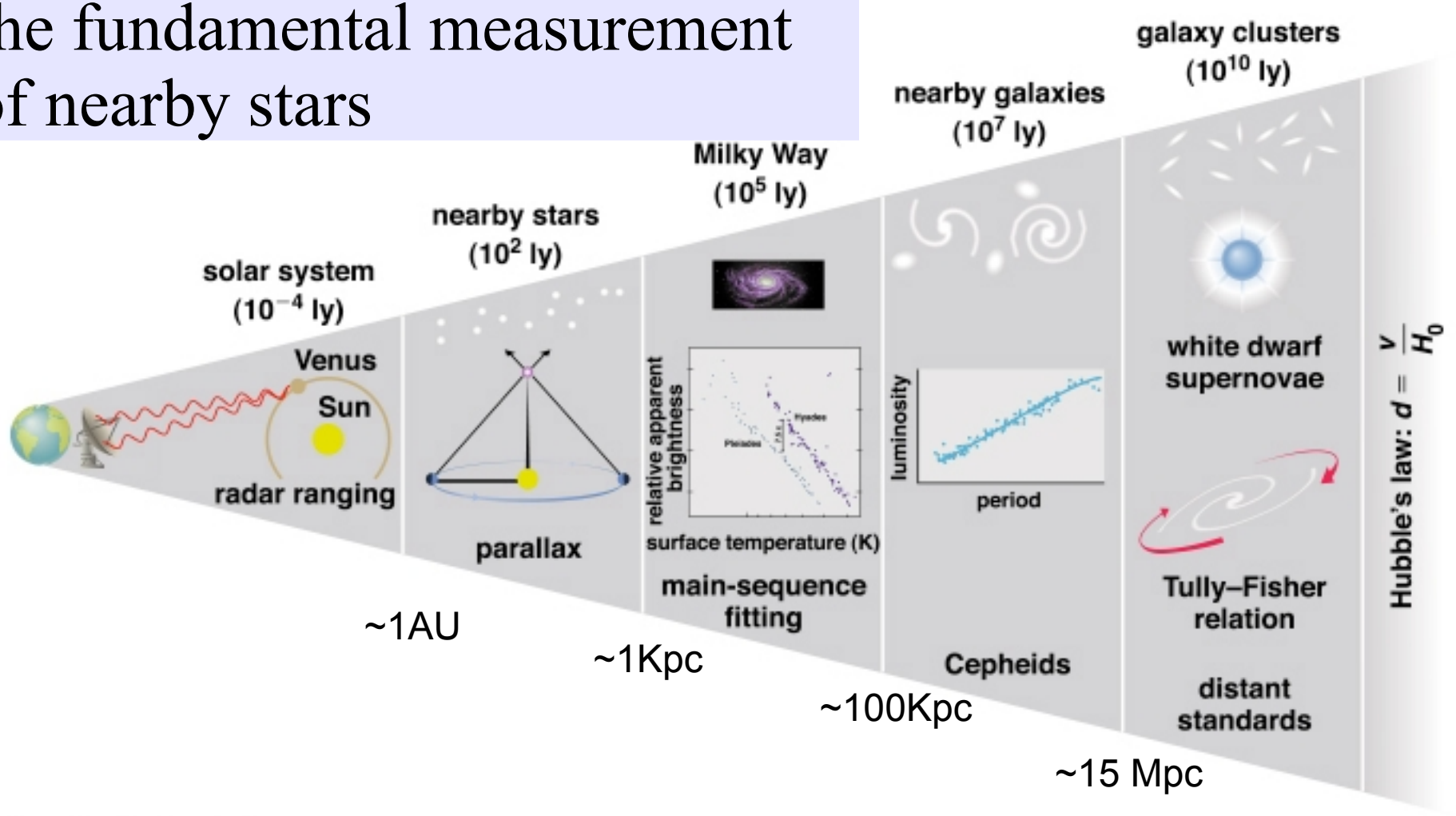

Figure: Torres, 2007 AJ 134 1918

# Parallaxes of stars

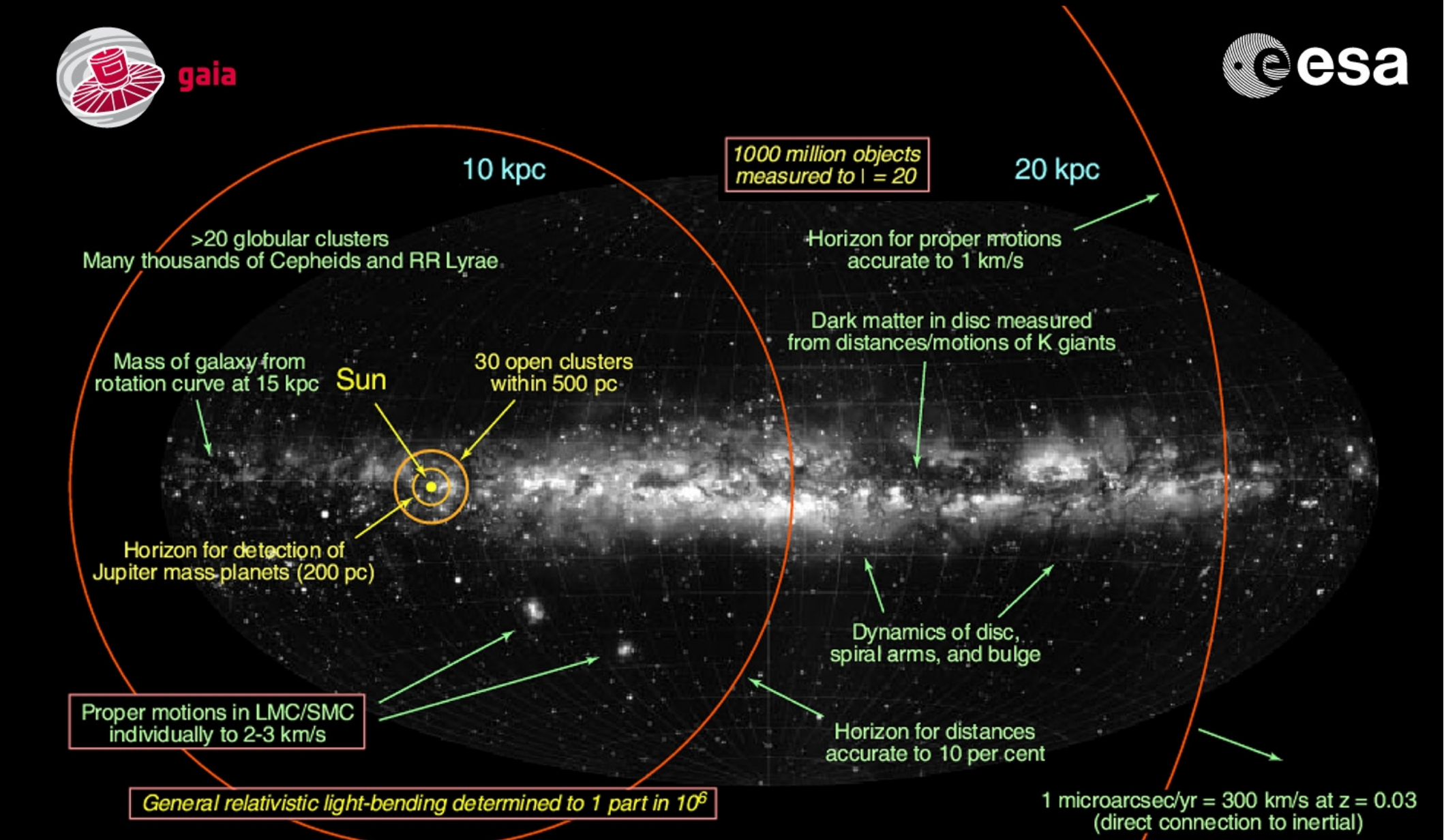
- A star with a parallax of 1 arcsec has a distance of one parsec
  - Nearest star: Proxima Centauri → parallax of 0.76", thus at a distance of 1.31 pc
- Hipparcos (satellite in the 90s) measured parallaxes to accuracies of milli arcsec → distances to 1 kpc
  - Catalogue of ~120,000 stars to V=12 mag
  - See: van Leeuwen, ASSL 350, 2007
- HST astrometry
  - Typically 0.2 milli arcsec errors
  - But calibration gives relative not absolute astrometry
- These just reach a few nearby Cepheids stars

# The Distance Scale

Indirect distances all based on the fundamental measurement of nearby stars

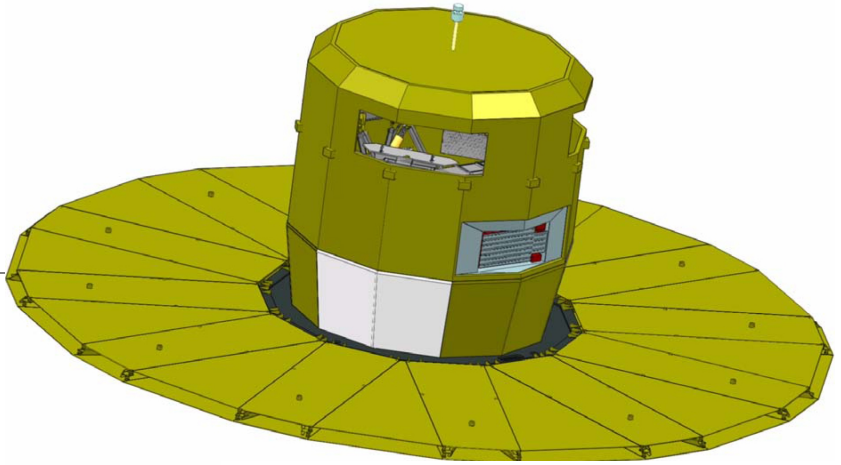


# The Promise of Gaia
## transformational science

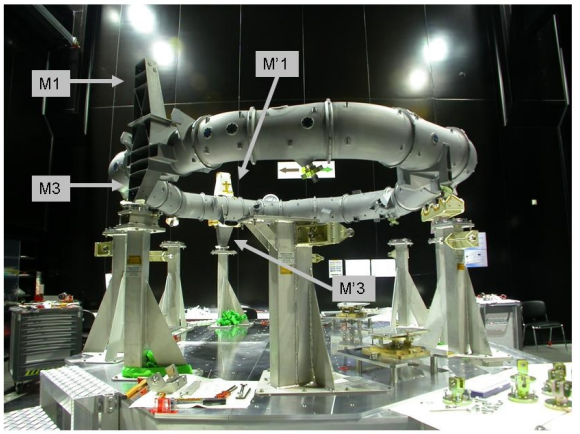


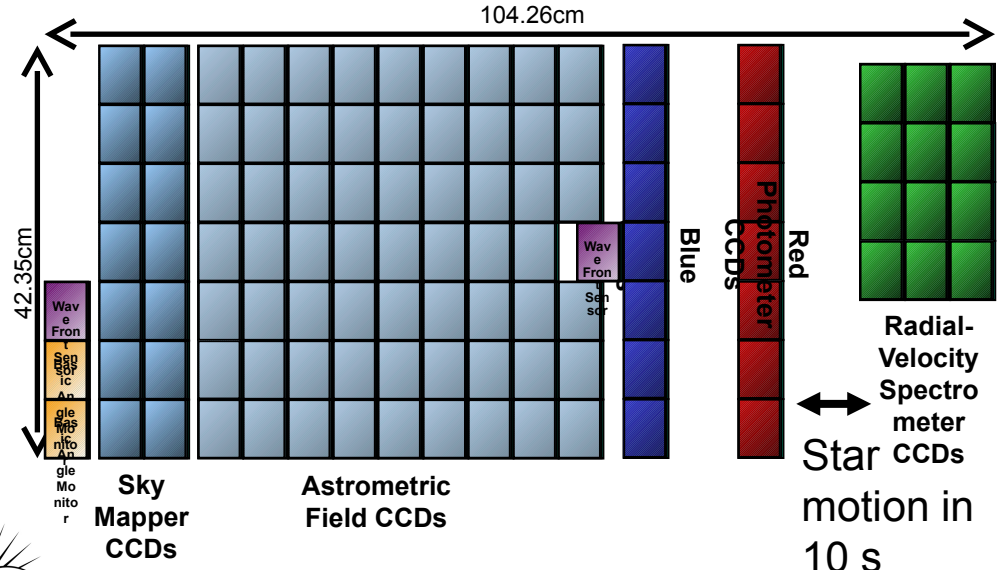
# Gaia: mapping the Universe
## launches May 2013

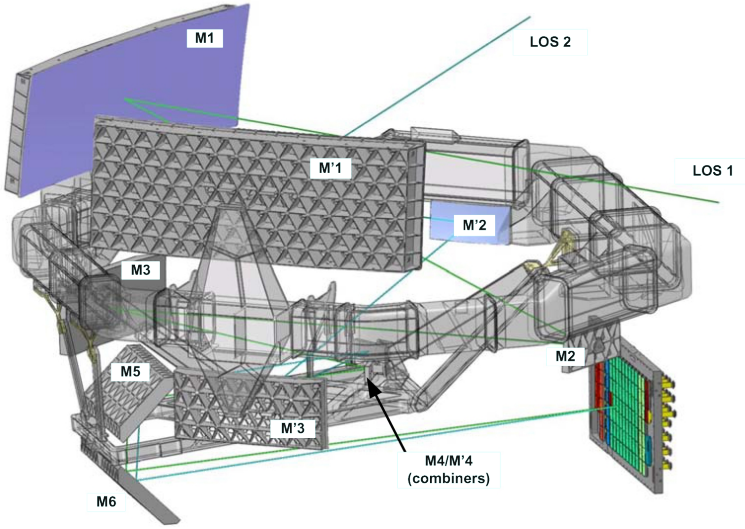
| | Hipparcos | Gaia |
|---|---|---|
| Magnitude limit | 12 | 20 mag |
| Completeness | 7.3 – 9.0 | 20 mag |
| Bright limit | 0 | 6 mag |
| Number of objects | 120 000 | 26 million to V = 15<br>250 million to V = 18<br>1000 million to V = 20 |
| Effective distance | 1 kpc | 1 Mpc |
| Quasars | None | $5 \times 10^5$ |
| Galaxies | None | $10^6 – 10^7$ |
| Accuracy | 1 milliarcsec | 7 μarcsec at V = 10<br>10-25 μarcsec at V = 15<br>300 μarcsec at V = 20 |
| Photometry | 2-colour (B and V) | Low-res. spectra to V = 20 |
| Radial velocity | None | 15 km/s to V = 16-17 |
| Observing | Pre-selected | Complete and unbiased |



Images: ESA



# … not so far away now …

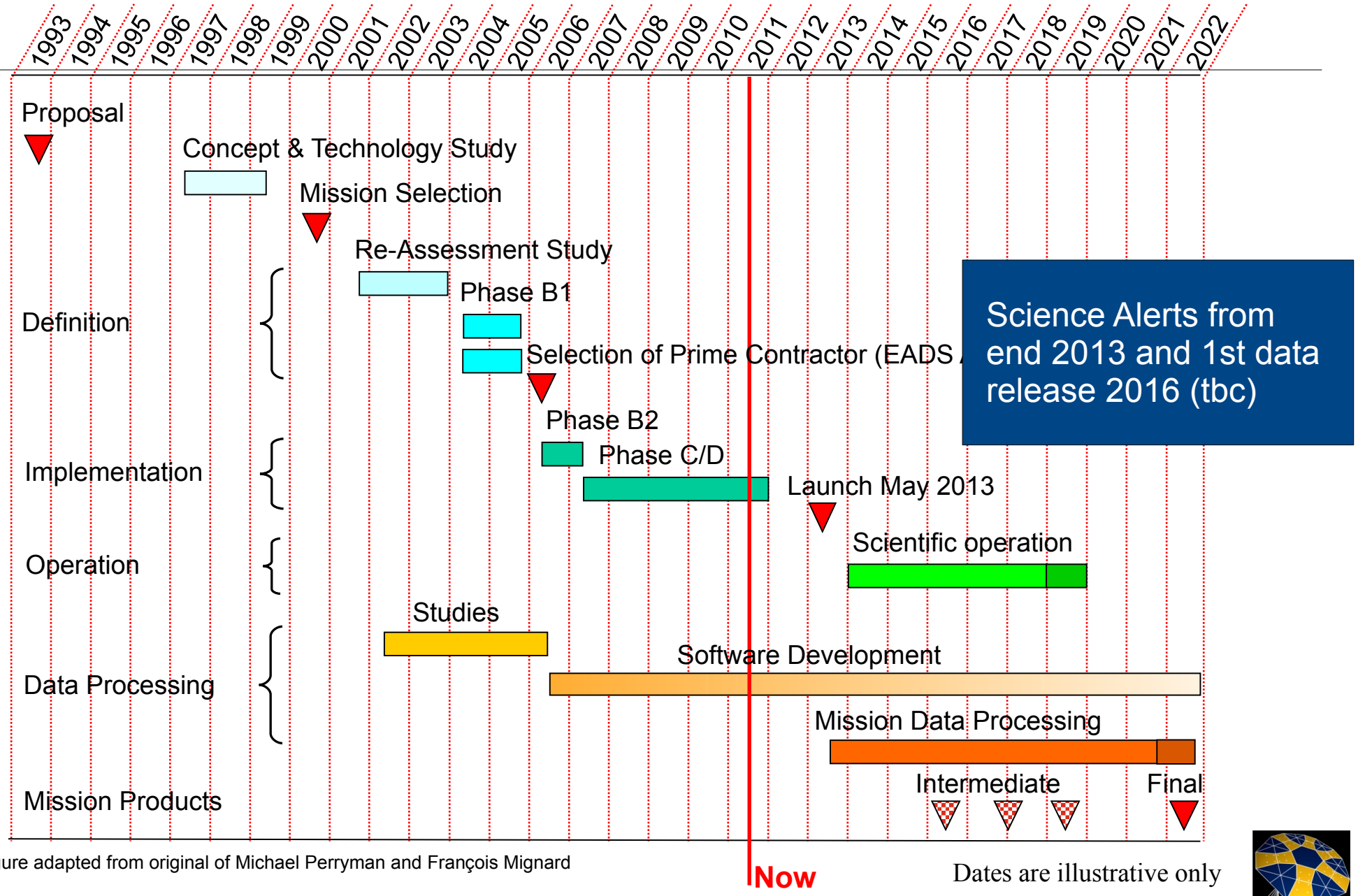



Figure adapted from original of Michael Perryman and François Mignard

Dates are illustrative only

# What's driving Gaia?

- Towards a more precise understanding of the current structure and history of our galaxy:
  - Distributions of mass, energy and angular momentum
    - Missing mass, dark matter?
  - Signatures of mergers
    - Dwarf galaxies within the local group
  - History of star formation and enrichment of the inter-stellar dust and gas
- In a nutshell – map the Galaxy and Local Universe
  - a billion stars, μ arcsec astrometry, to V=20 mag
  - one μarcsec : 'resolve a finger nail on the moon!'

# What's required for this mapping?

- Accurate positions and velocities of stars over a large volume of space
  - size of the galaxy implies a Radius ~10 to 20 kpc (dist.mod: 15.0 to 16.5)
- Complete survey down to a limiting magnitude
  - Approximately $20^{th}$ magnitude, $10^9$ objects
- Complementary data required to 'sort' the objects
  - effective temperature
  - surface gravity
  - metallicity
  - luminosity

# Gaia: Design Considerations

- Astrometry (< 20 mag):
  - completeness to 20$^{th}$ mag (with on-board detection) → 10$^{9}$ stars
  - accuracy: 10–25 μarcsec at 15$^{th}$ mag (c.f. Hipparcos: 1 mas at 9$^{th}$ mag)
  - scanning satellite, two viewing directions → ***global accuracy, with optimal use of observing time***
  - principles: global astrometric reduction (as for Hipparcos)
- Photometry (< 20 mag):
  - astrophysical diagnostics (low-dispersion photometry)/ chromaticity
    - $T_{eff}$ ~ 200 K, log g, [Fe/H] to 0.2 dex, extinction …
- Radial velocity (< 17 mag):
  - application:
    - third component of space motion, perspective acceleration
    - dynamics, population studies, binaries
    - spectra: chemistry, rotation
  - principles: slit less spectroscopy using Ca triplet (847–874 nm)
    - R = 11,500 with radial velocities at 15 km s$^{-1}$ precision

# Gaia: Complete, Faint, Accurate

| | Hipparcos | Gaia |
|---|---|---|
| Magnitude limit | 12 | 20 mag |
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| Photometry photometry | 2-colour (B and V) | Low-res. spectra to V = 20 |
| Radial velocity | None | 15 km/s to V = 16-17 |
| Observing programme | Pre-selected | Complete and unbiased |

source: ESA

# Gaia Accuracy: 10μas is very small!

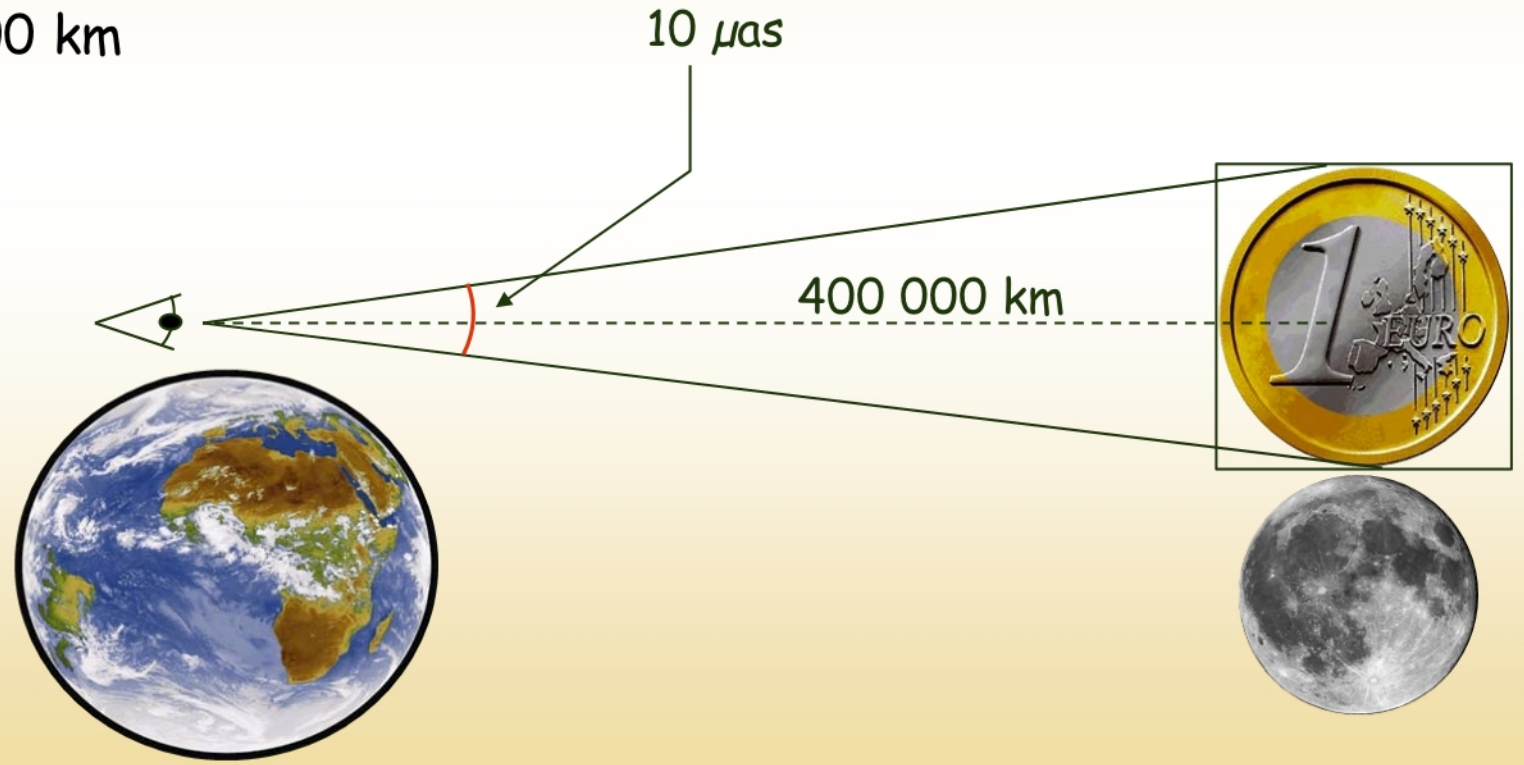
0.3 mm displacement on the Earth

Displacement of a 100 mas/yr star in one hour

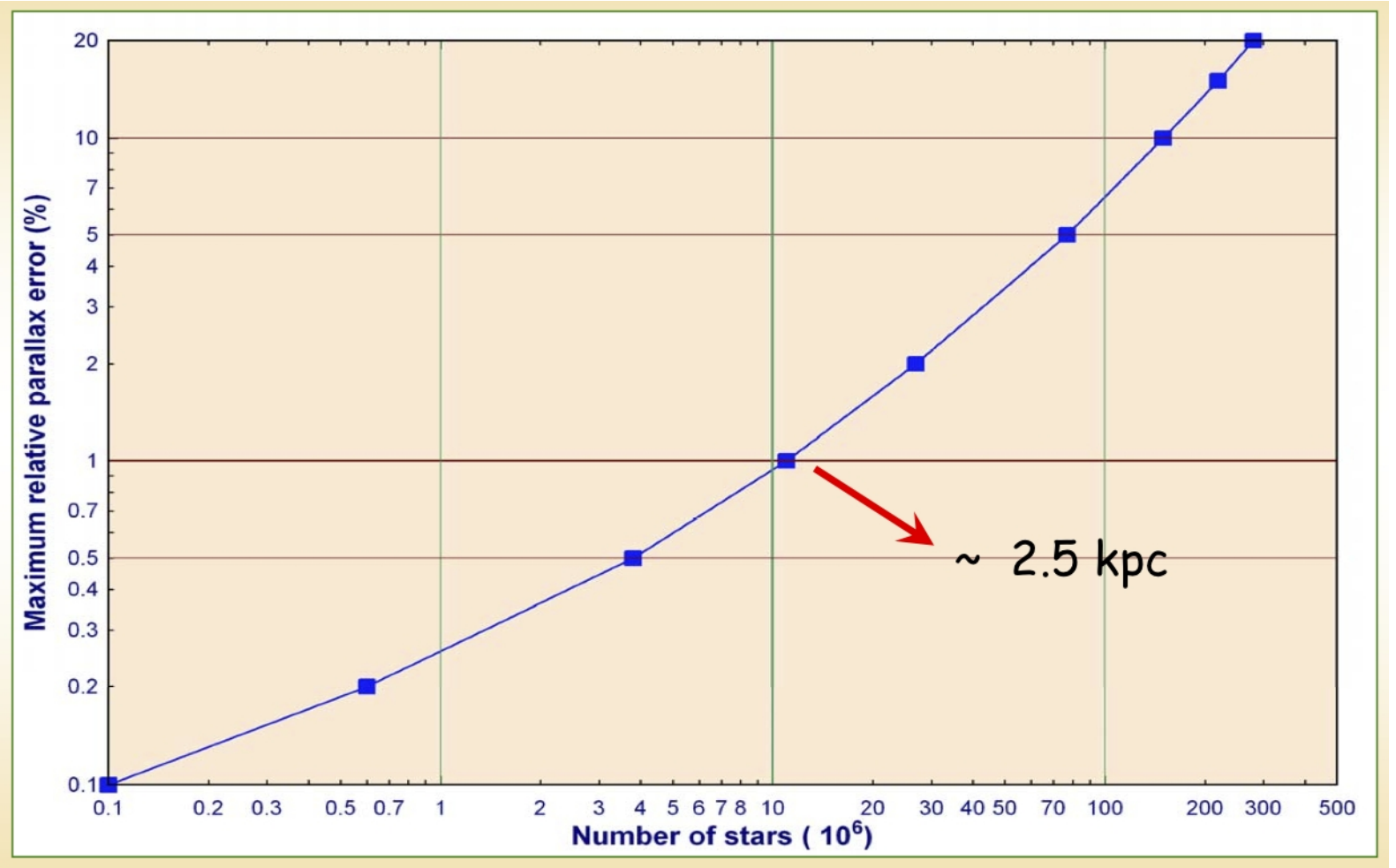
Motion of a fast moving minor planet in 100 μs

edge-on sheet of paper @ 2000 km

1 hair @ 1000 km



# And what 10 uas gets you ...




1% errors on distances out to ~2.5 kpc

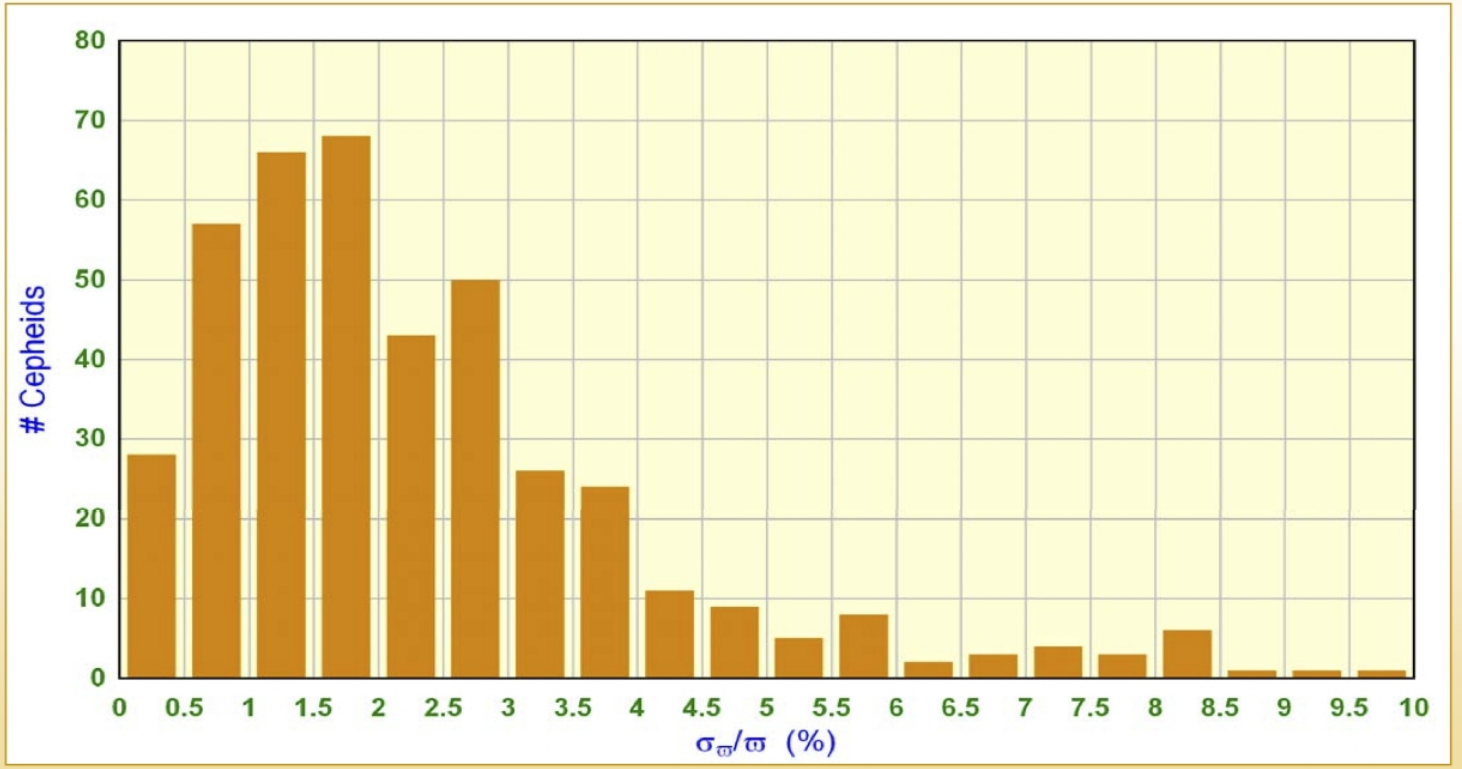
# Thus Gaia will give direct distances to Cepheid variables (a key 2$^{ry}$ indicator)

15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc

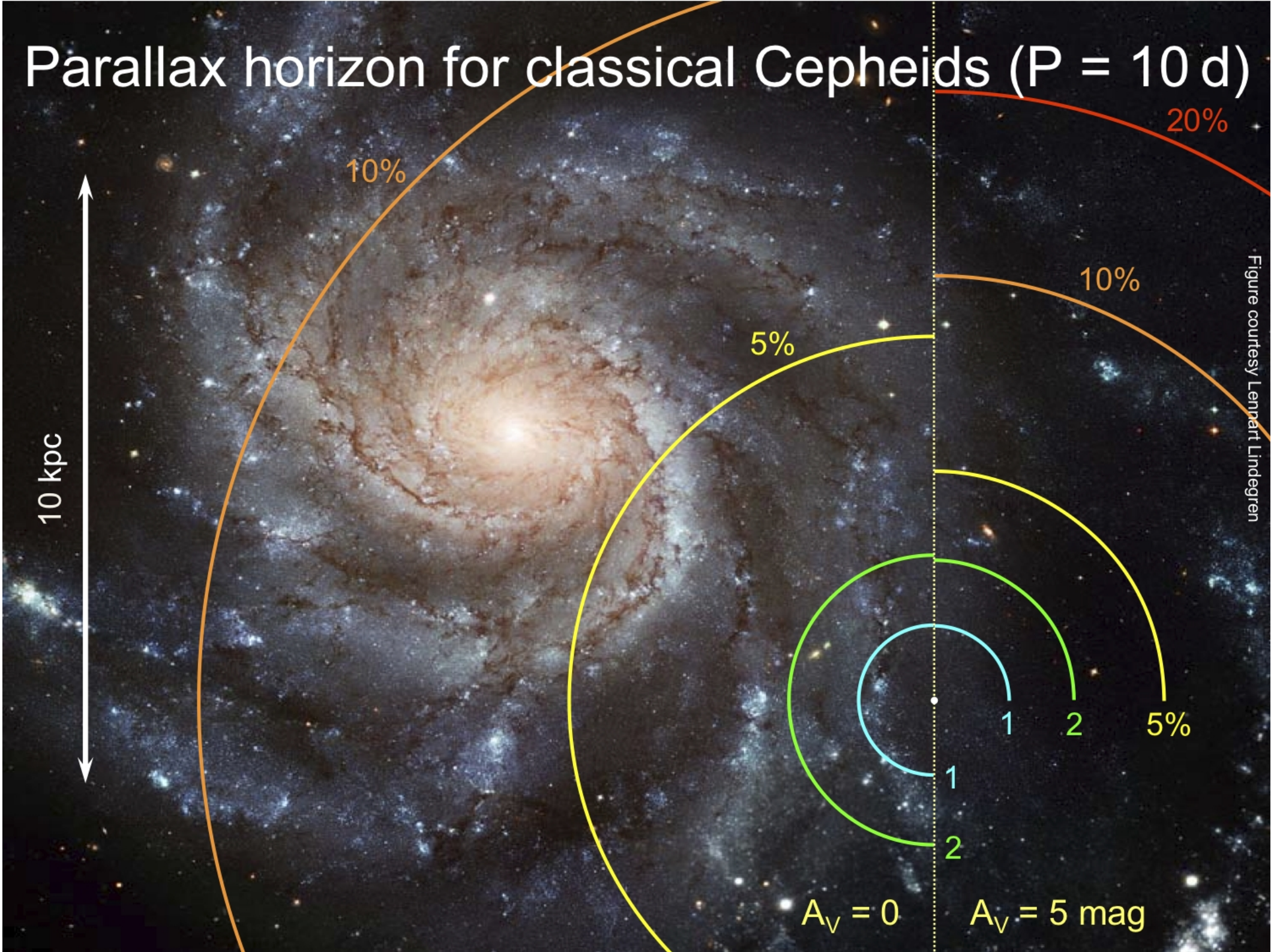
- bright enough ( V < 14)

In the plot : 400 galactic cepheids from David Dunlap DB

- distance and magnitude ➔ Gaia predicted accuracy for parallax




F. Mignard 2002, 2009


Parallax horizon for classical Cepheids (P = 10 d)
20%
10%
10%
5%
10 kpc
1
2
5%
1
2
$A_V$ = 0
$A_V$ = 5 mag
Figure courtesy Lennart Lindegren

# Gaia & other Astrometric missions

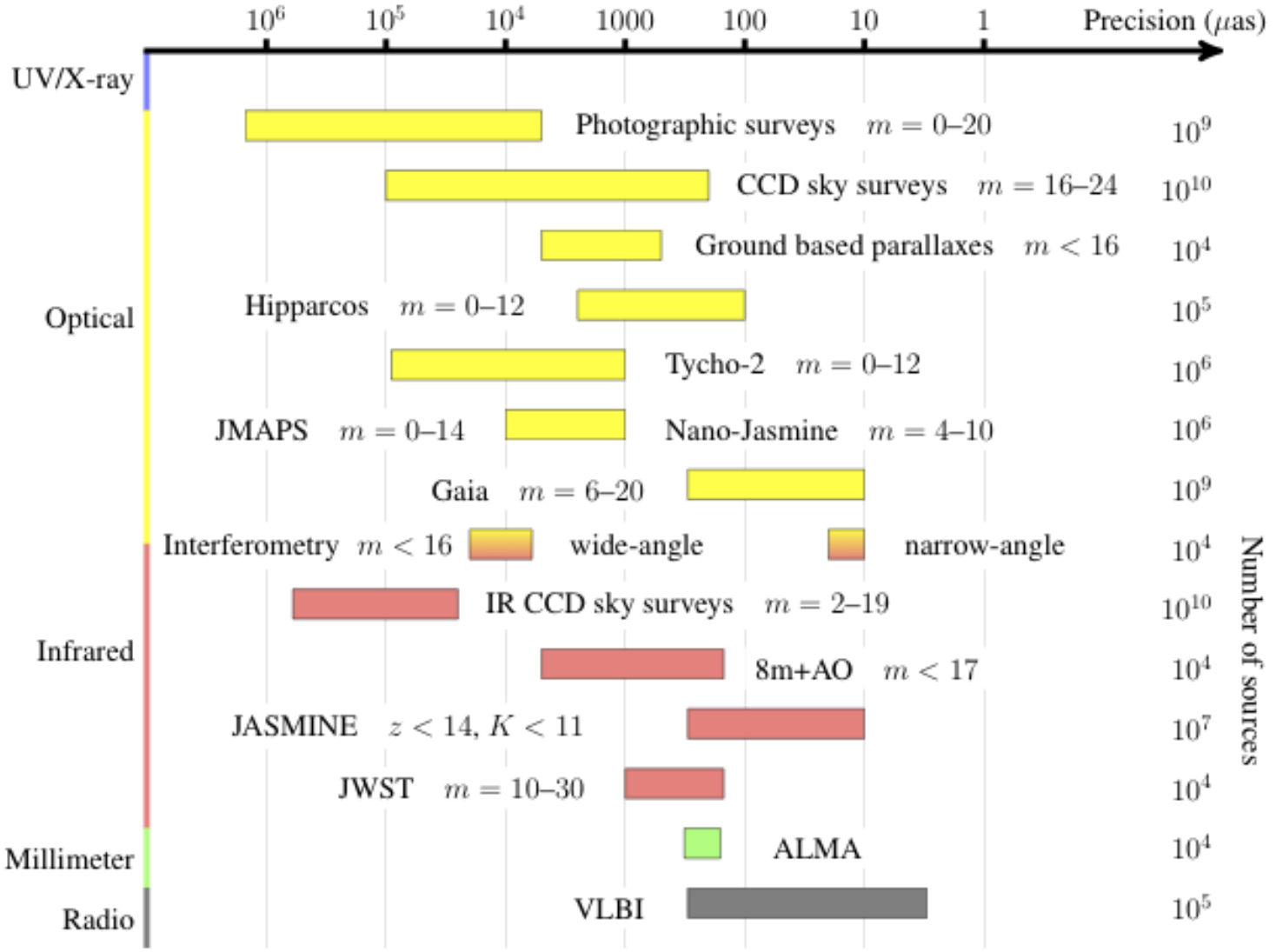



Figure: Anthony Brown

# GAIA: Some Science Objectives

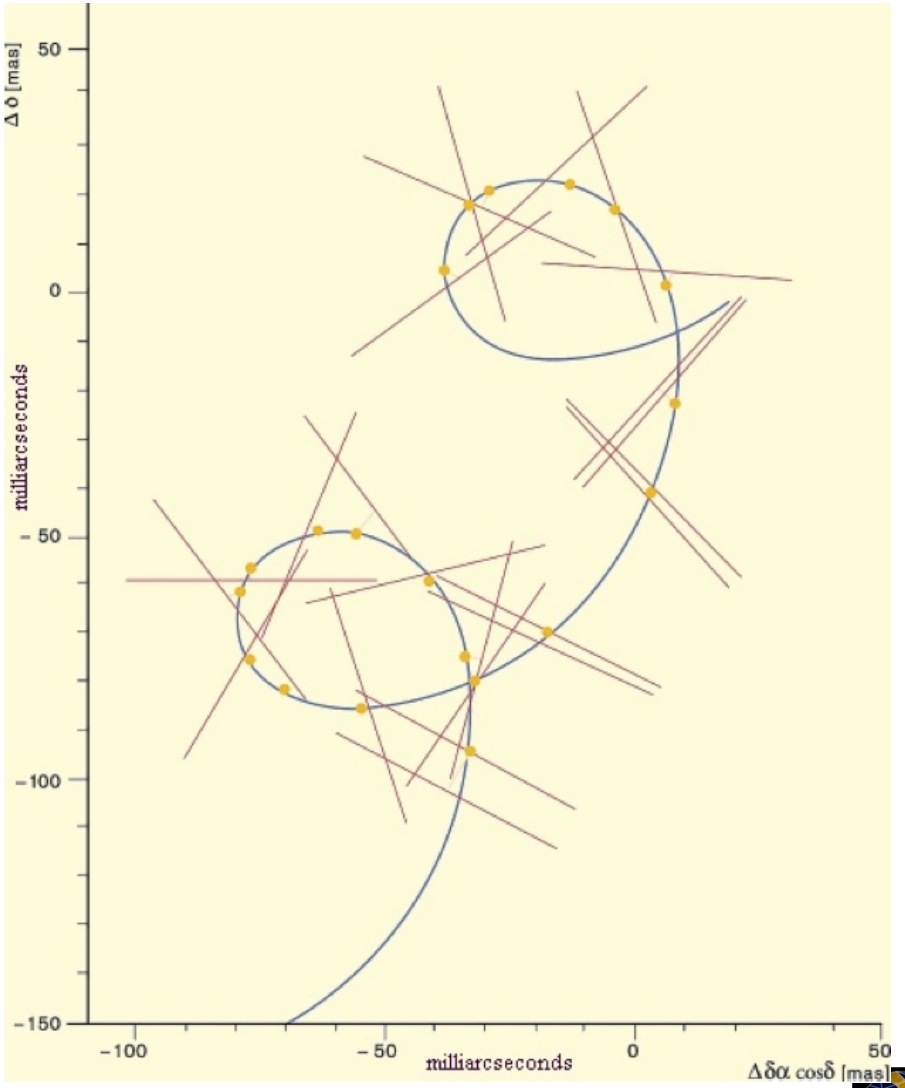
- Structure and kinematics of our Galaxy:
  - shape and rotation of bulge, disk and halo
  - internal motions of star forming regions, clusters, etc
  - nature of spiral arms and the stellar warp
  - space motions of all Galactic satellite systems
- Stellar populations:
  - physical characteristics of all Galactic components
  - initial mass function, binaries, chemical evolution
  - star formation histories
- Tests of galaxy formation:
  - dynamical determination of dark matter distribution
  - reconstruction of merger and accretion history

# One Billion Stars in 3-D will Provide …

- **in our Galaxy …**
  - the distance and velocity distributions of all stellar populations
  - the spatial and dynamic structure of the disk and halo
  - its formation history
  - a detailed mapping of the Galactic dark-matter distribution
  - a rigorous framework for stellar-structure and evolution theories
  - a large-scale survey of extra-solar planets (~7,000)
  - a large-scale survey of Solar-system bodies (~250,000)
- **… and beyond**
  - definitive distance standards out to the LMC/SMC
  - rapid reaction alerts for supernovae and burst sources (~20,000)
  - quasar detection, redshifts, microlensing structure (~500,000)
  - fundamental quantities to unprecedented accuracy: e.g. relativistic light bending due to gravity: PPN $\sigma_\gamma$ ~$2\times10^{-6}$ (~$2\times10^{-5}$ present)

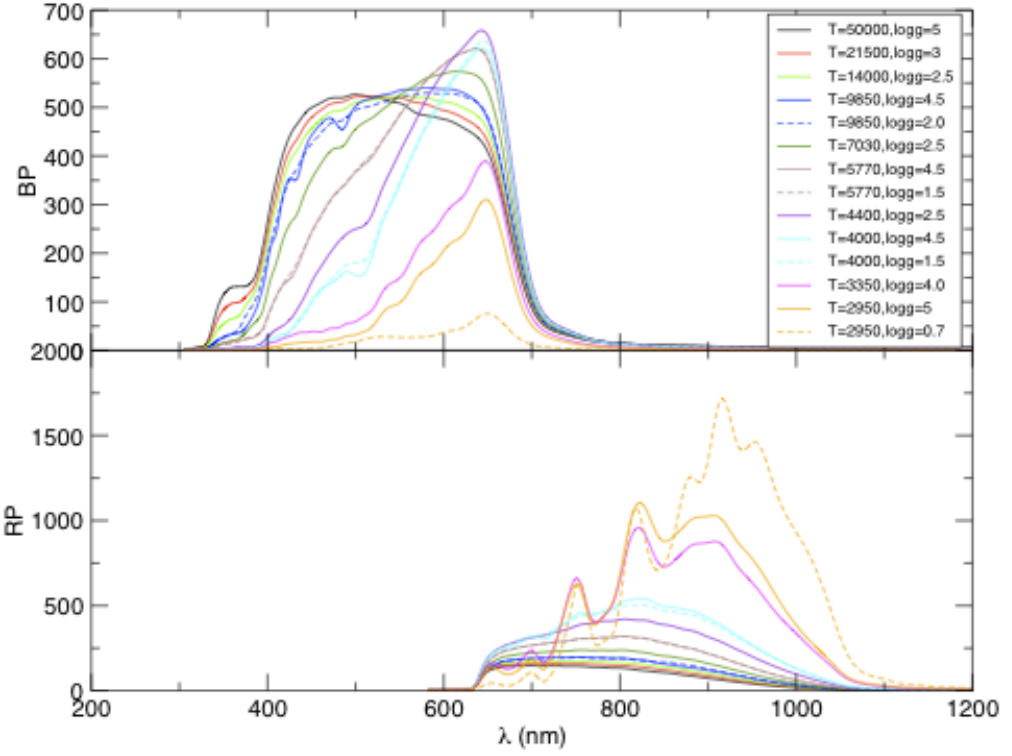
# Gaia Science: Astrometry

- σ~5-14 μas for V <12
- σ~10-25 μas for V <15
- σ~100-300 μas for V <20
- 25,000 stars/deg$^2$ with max ~10$^6$ stars/deg$^2$
- ~5,000 extrasolar planets to 200pc
- 3x10$^5$ minor bodies in the solar system
- 5x10$^5$ QSOs



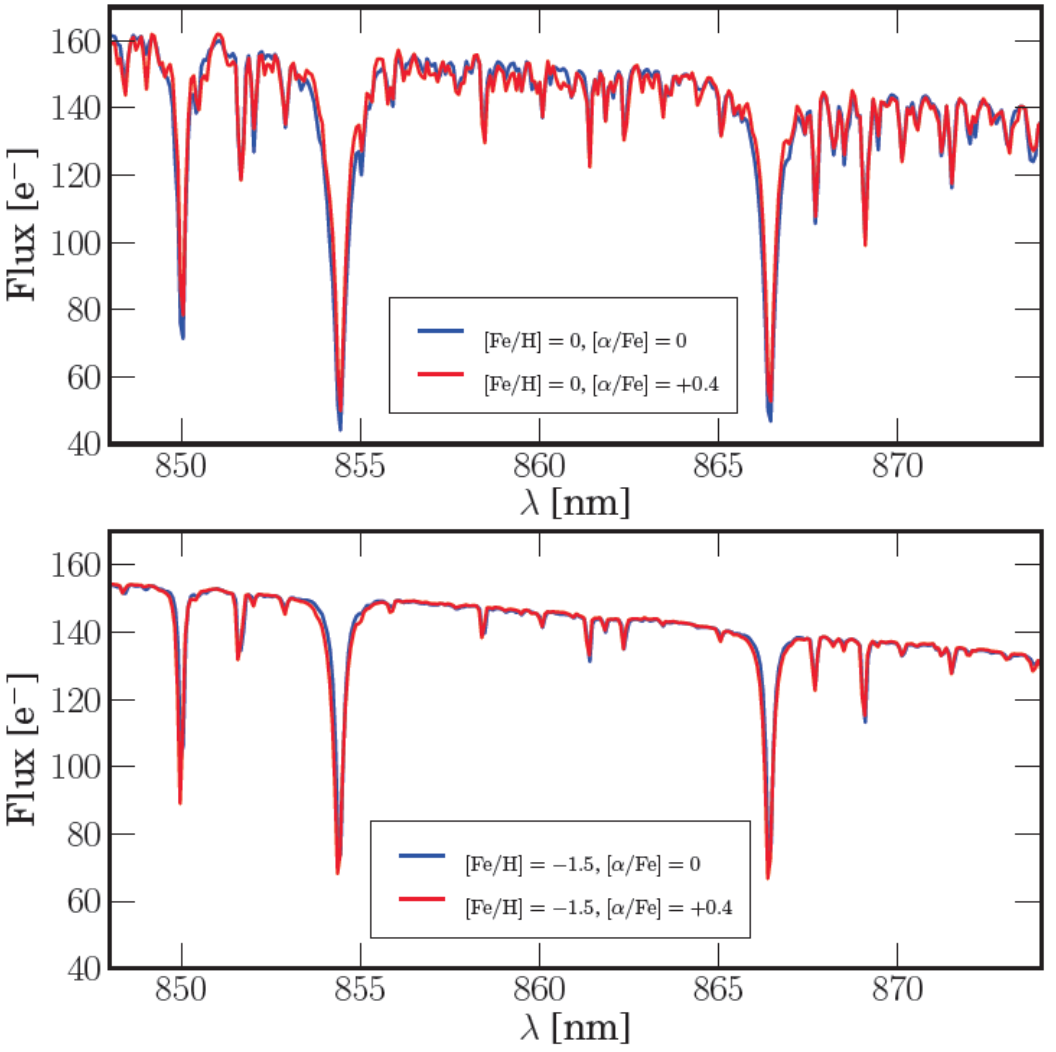
# Gaia Science: Photometry

- Two channels: 330-680 nm (BP), 640-1000nm (RP)
- Low resolution (~3-30 nm/pix) prism spectra
- Allows derivation of $A_v$, $T_{eff}$, log $g$, [M/H] and [α/H] for brighter stars



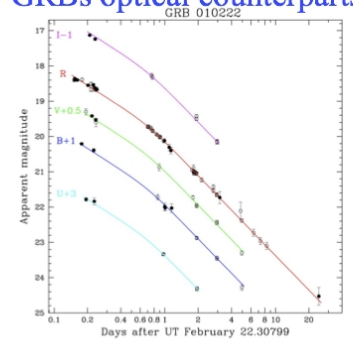
# Gaia Science: Spectroscopy

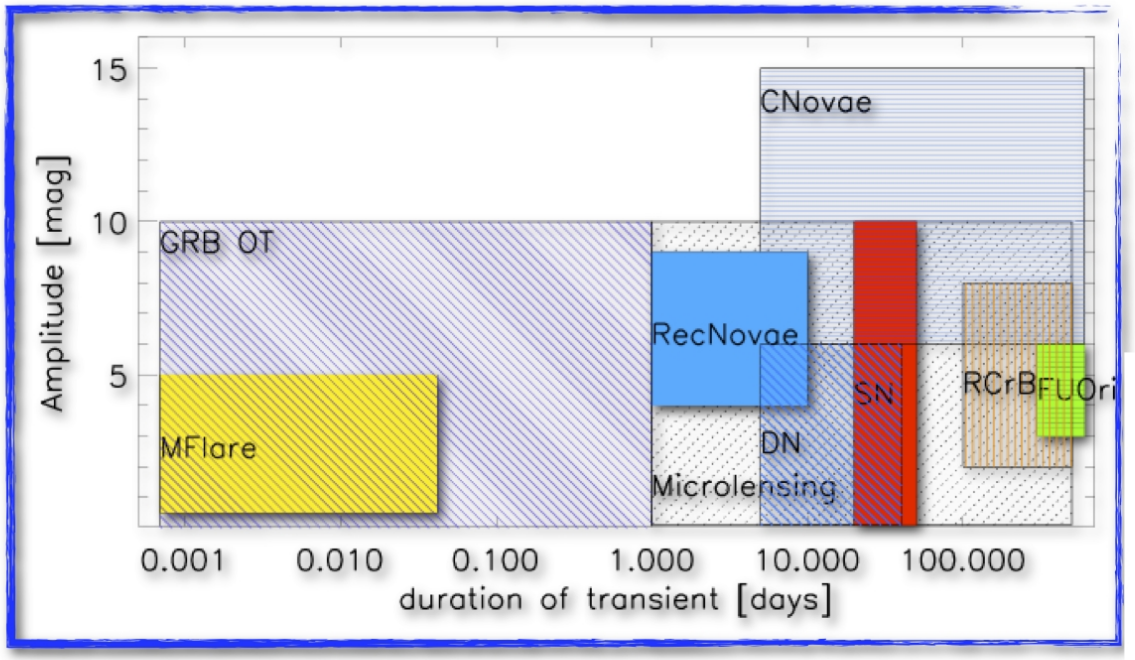
- Binarity, variability
- ~$10^6$ spectroscopic binaries
- ~$10^5$ eclipsing binaries
- Long period classical Cepheids to 20-30 kpc



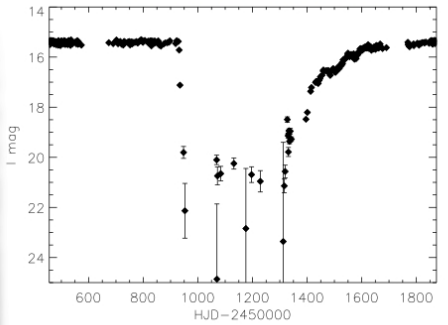
# Gaia will also observe the transient sky

GRBs optical counterparts

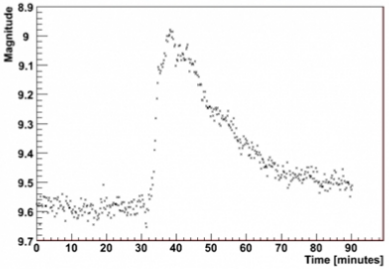


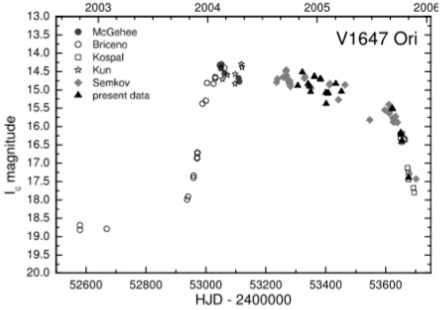

R Coronae Borealis



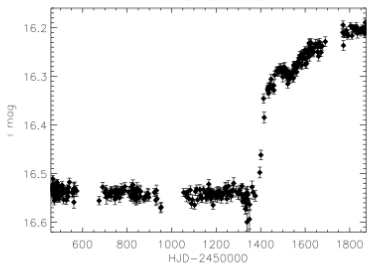

M-dwarf flares



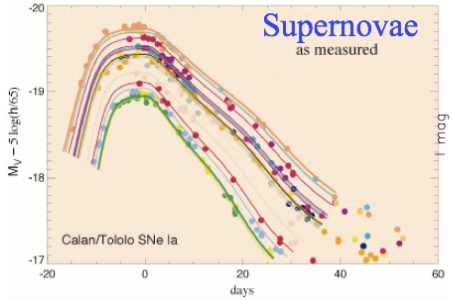

FU Orionis and similar

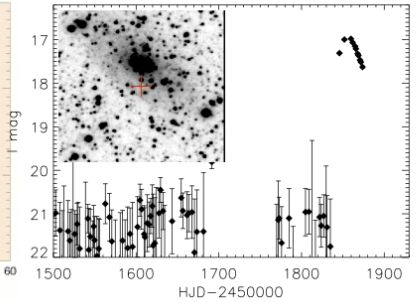



Be stars

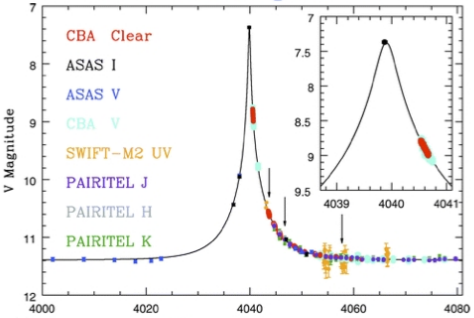



Supernovae

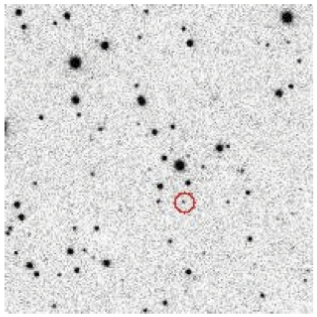


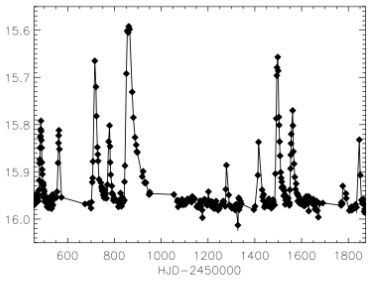

Microlensing events



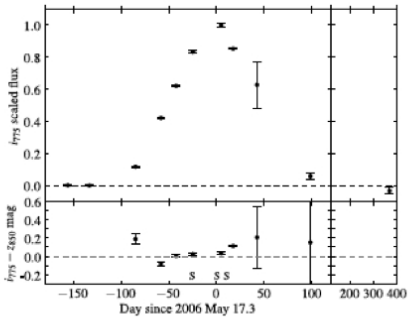

Asteroids



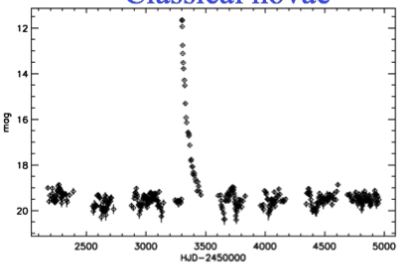
Dwarf novae



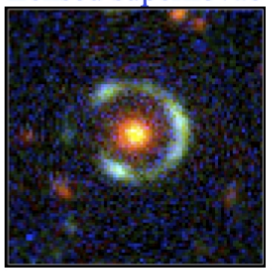

NEW THINGS??




Classical novae




Lensed supernovae



# The Gaia Spacecraft

Payload Module

Service Module

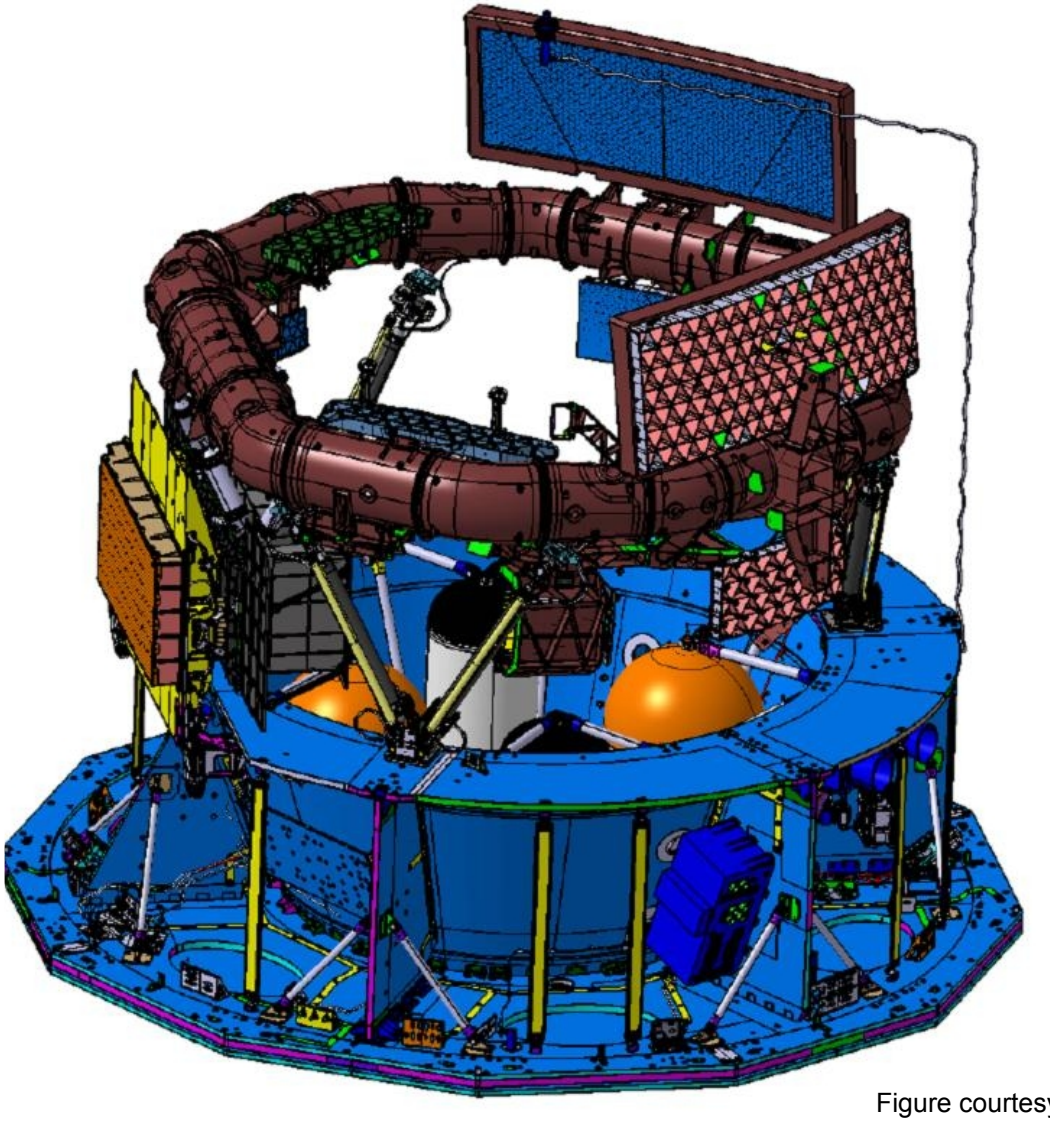
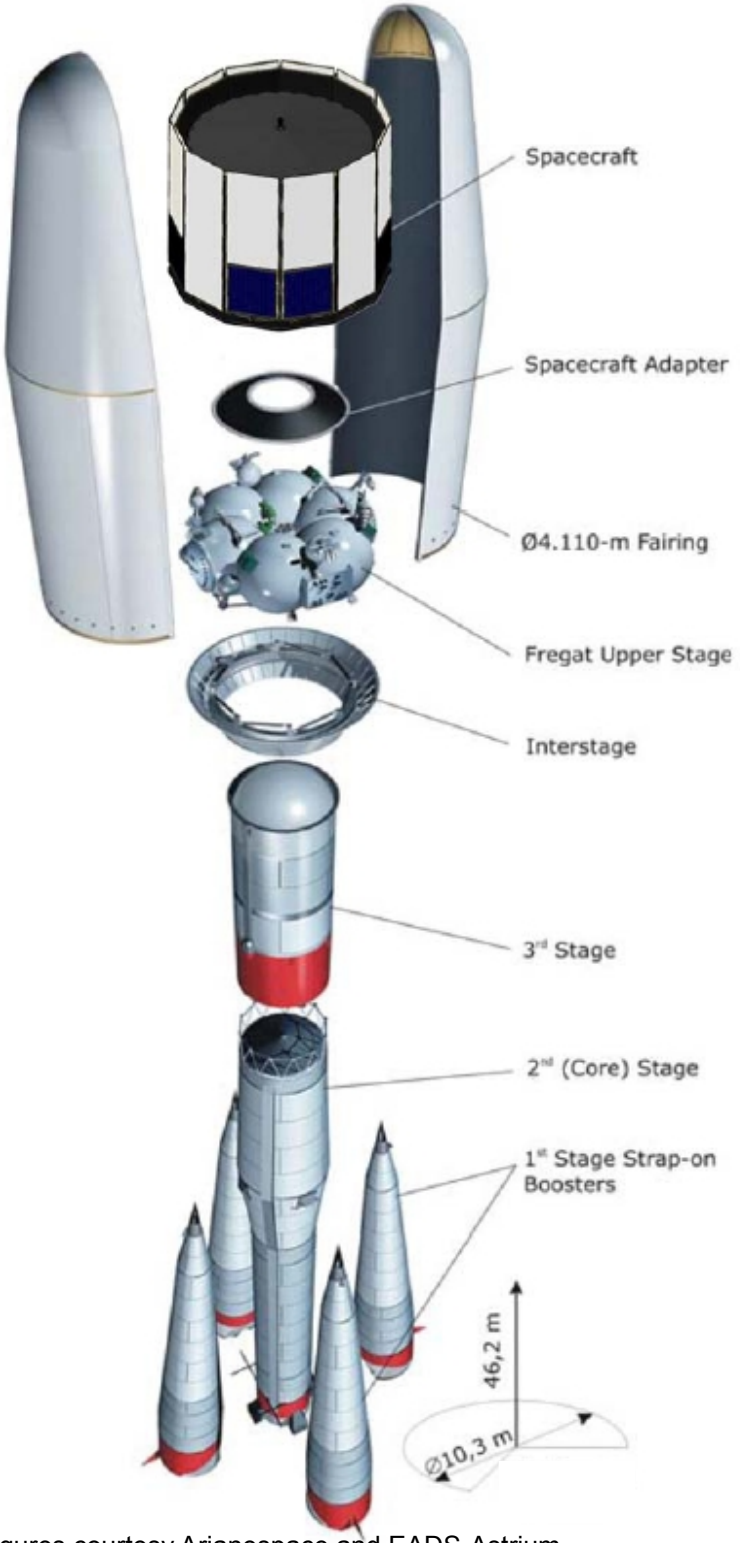


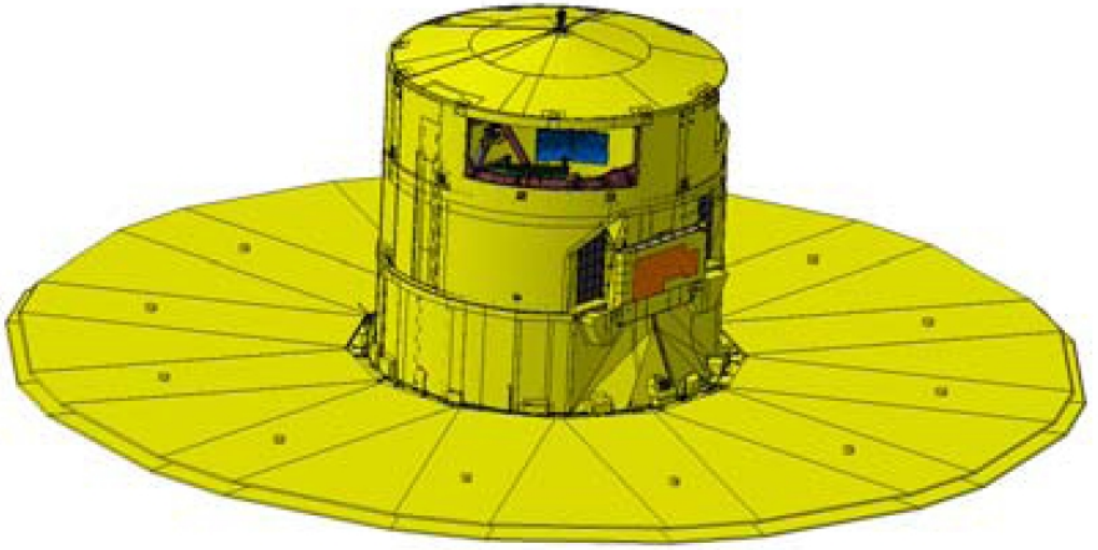
Figure courtesy EADS-Astrium

# Satellite and System

- ESA-only mission
- Launch: May 2013
- Launcher: Soyuz–Fregat from Kourou
- Orbit: L2 Lissajous orbit
- Ground stations: Cebreros + New Norcia
- Lifetime: 5 years (1 year potential extension)
- Downlink rate: 4 – 8 Mbps




Figures courtesy Arianespace and EADS-Astrium



# Downlink


- Using Cebreros (35M)
  - 3-8Mb/s downlink
    - depends on encoding
    - which depends on weather
  - ~ 30GB/day → ~100TB
  - so download 'windows' around objects
- occasionally New Norcia
  - during Galactic plane scans
  - data accumulated onboard downlinked later
- Data is compressed encoded and requires a lot of processing (~$10^{21}$ FLOP)

# Payload and Telescope

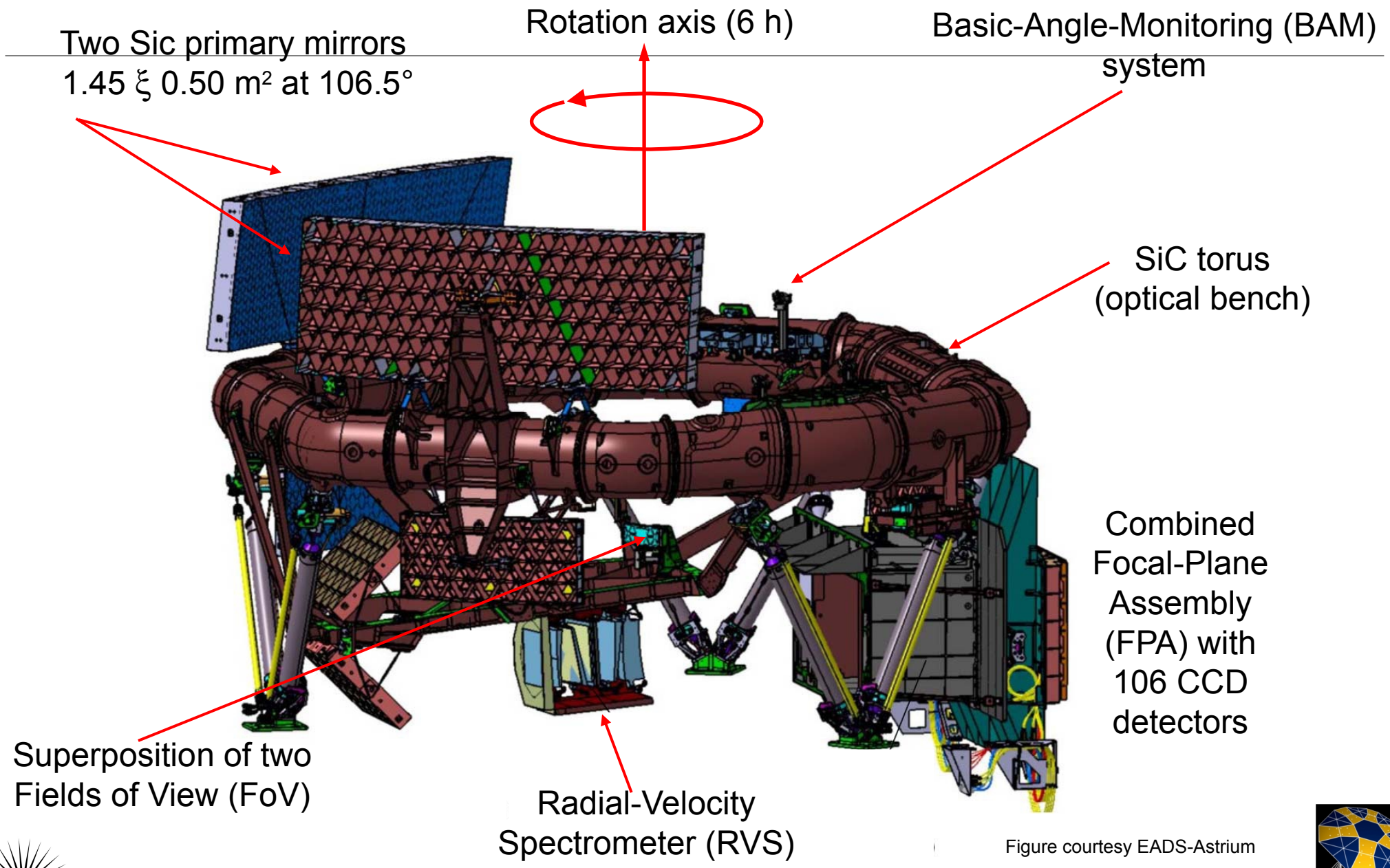
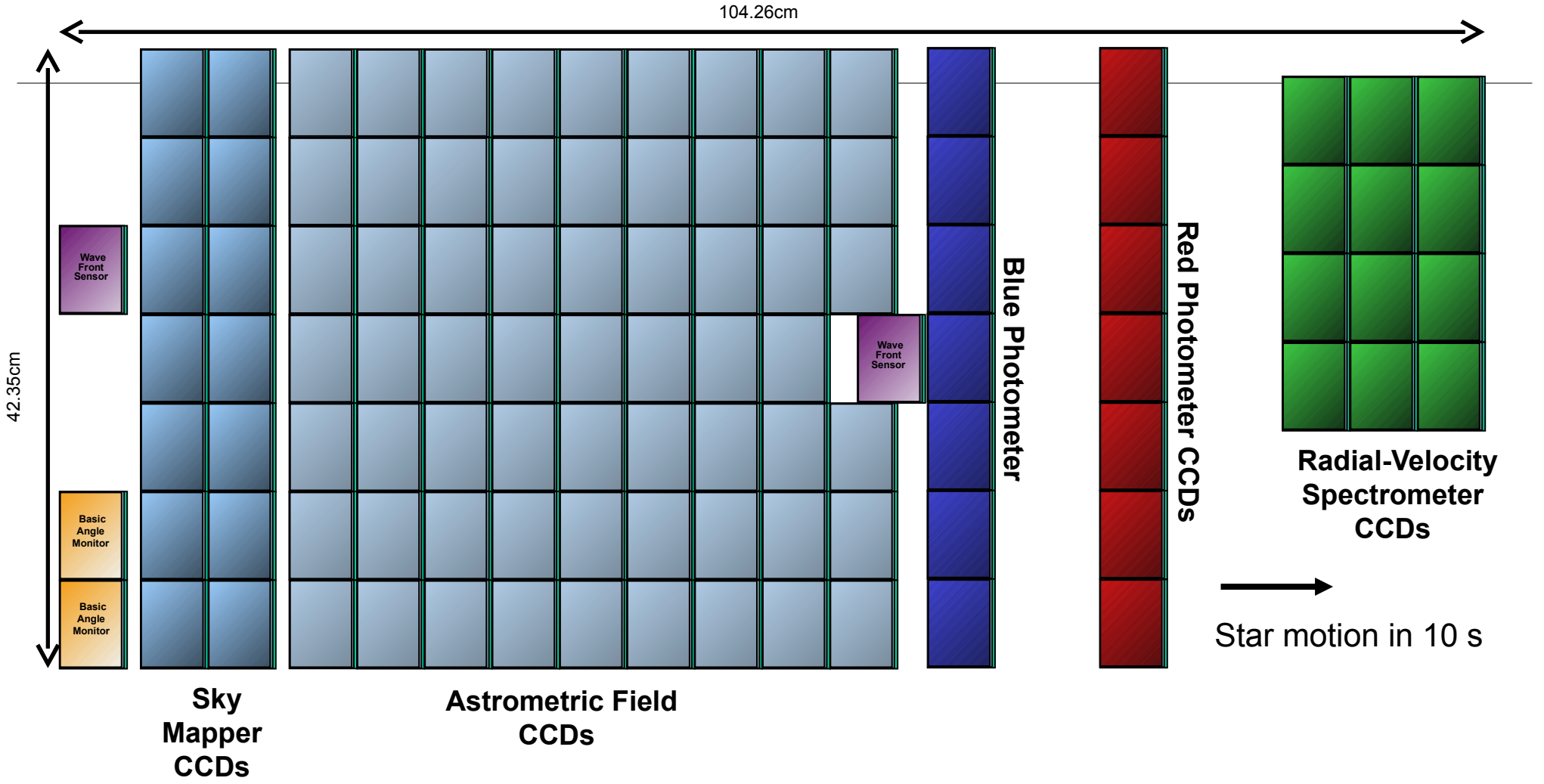



Figure courtesy EADS-Astrium

Figure courtesy Alex Short

# Focal Plane




## Total field:

- active area: 0.75 deg$^2$
- CCDs: 14 + 62 + 14 + 12 (+ 4)
- 4500 x 1966 pixels (TDI)
- pixel size = 10 μm x 30 μm
  = 59 mas x 177 mas

## Sky mapper:

- detects all objects to 20 mag
- rejects cosmic-ray events
- field-of-view discrimination

## Astrometry:

- total detection noise ~ 6 e$^-$

## Photometry:

- spectro-photometer
- blue and red CCDs

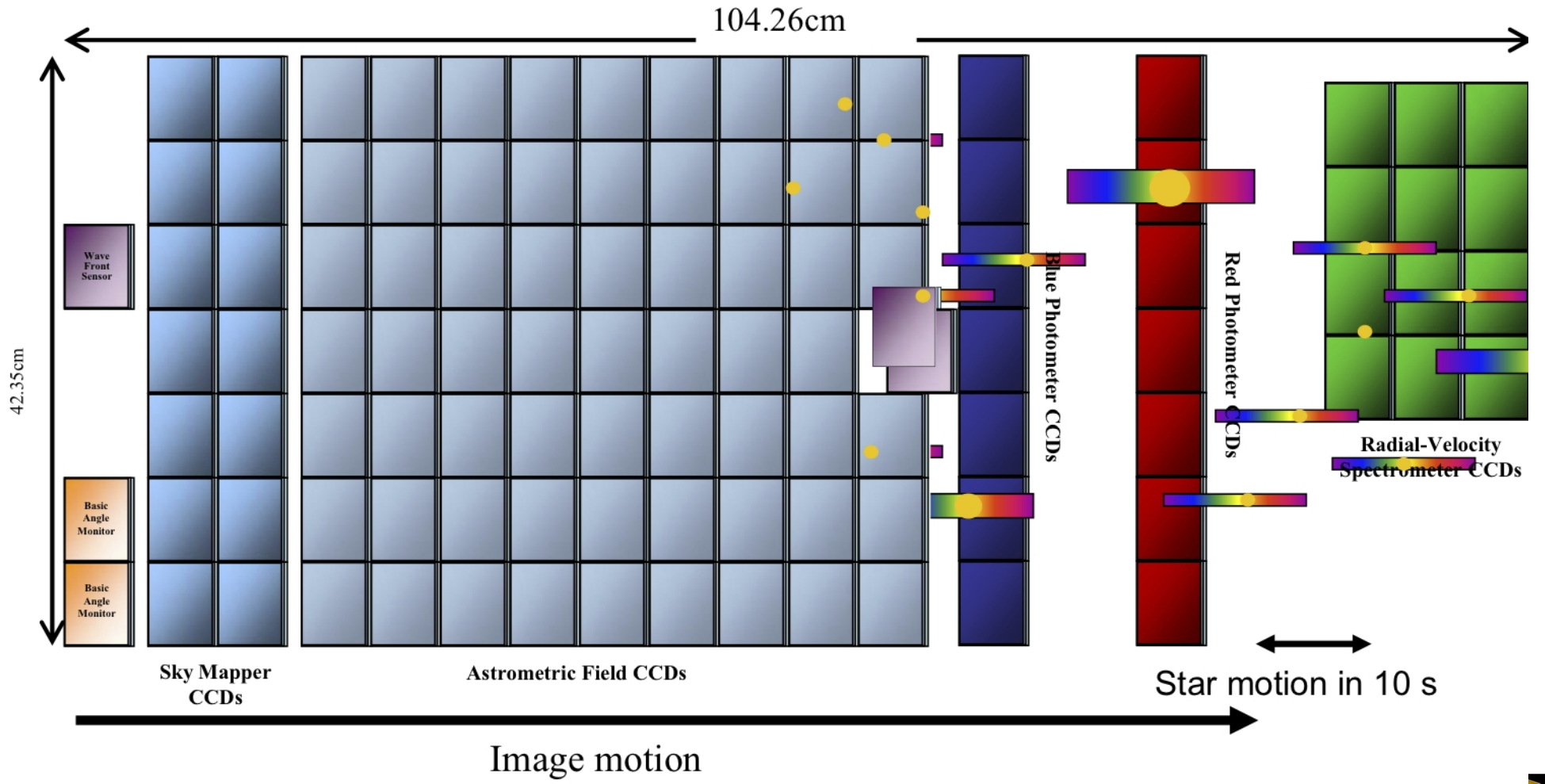
## Spectroscopy:

- high-resolution spectra
- red CCDs

# Focal Plane: multiplexing

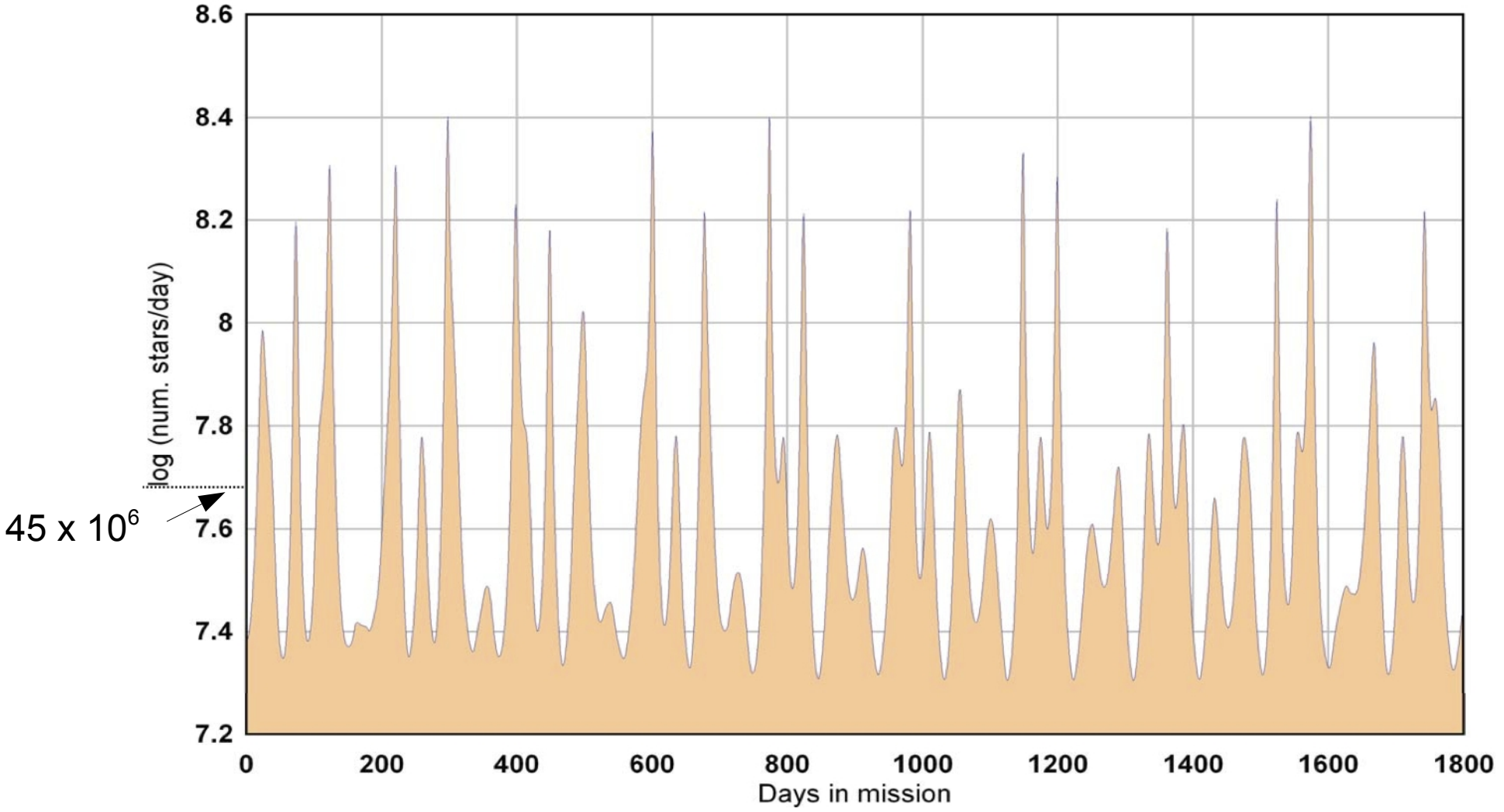
**106 CCDs , 938 million pixels, 2800 cm²**

Figure courtesy Alex Short/ Wil O'Mullane



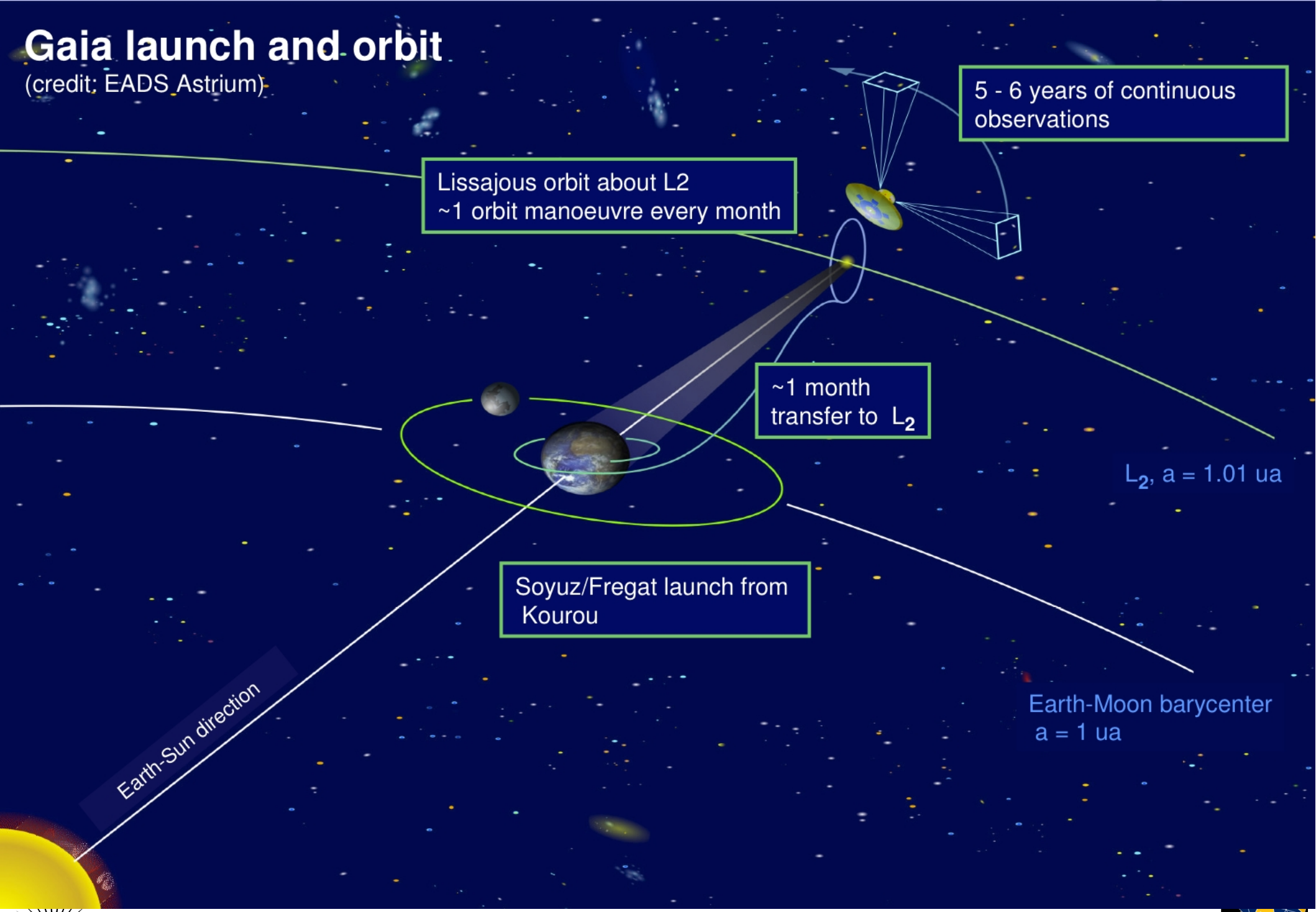
# Number of Sources per day

## about 1000 deg$^2$ scanned per day

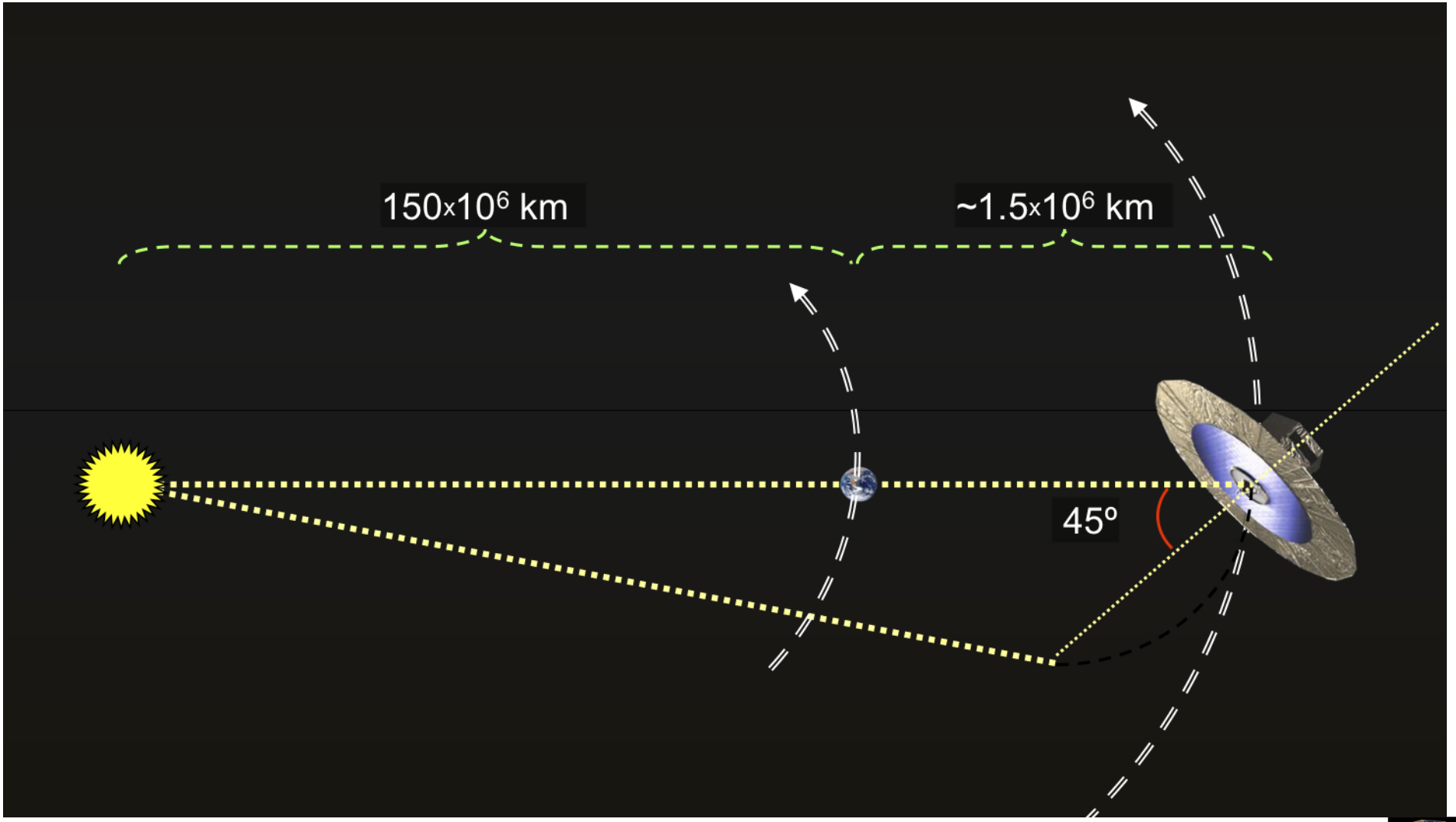


# Gaia launch and orbit

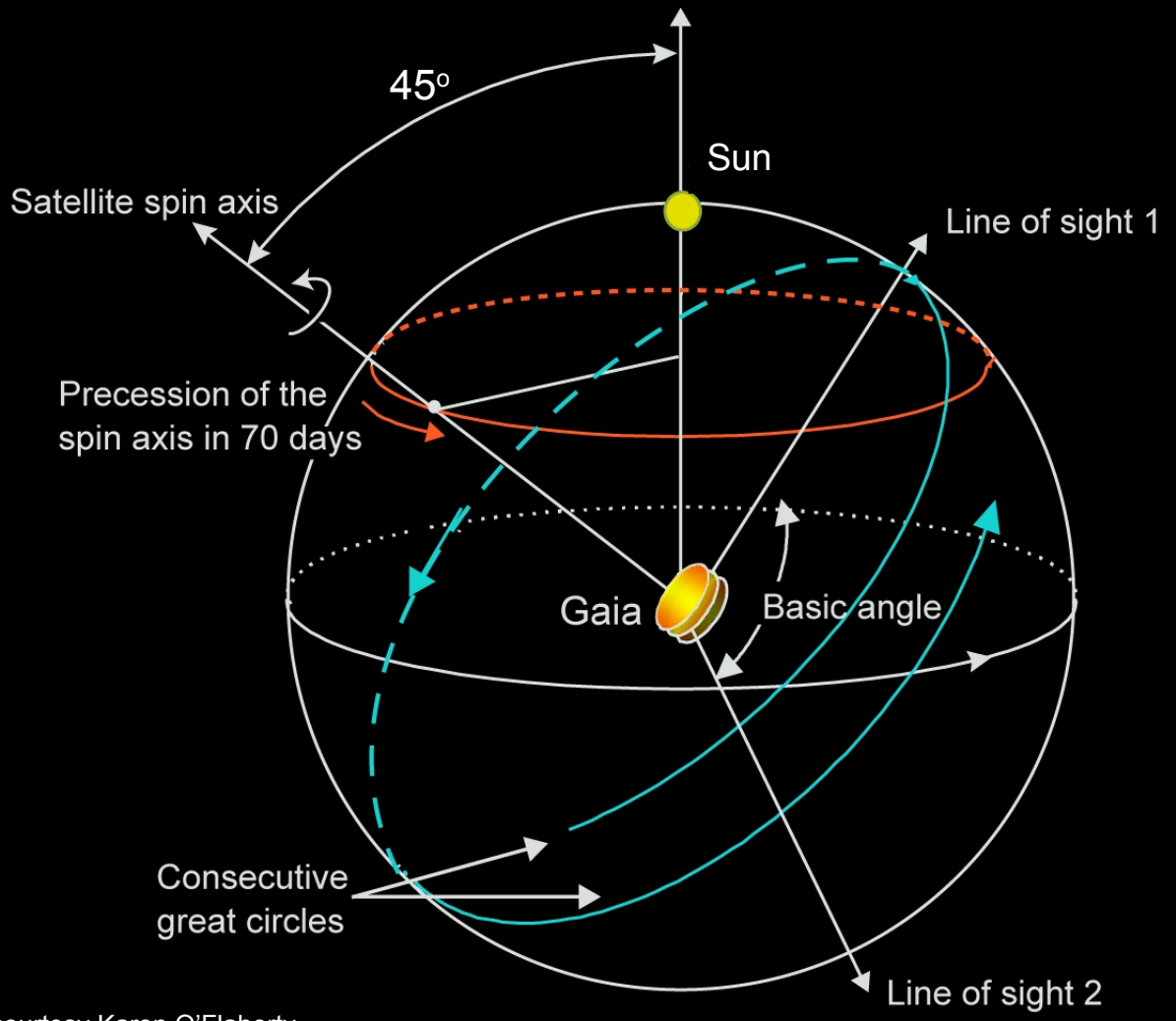
(credit: EADS Astrium)



# Gaia Orbit



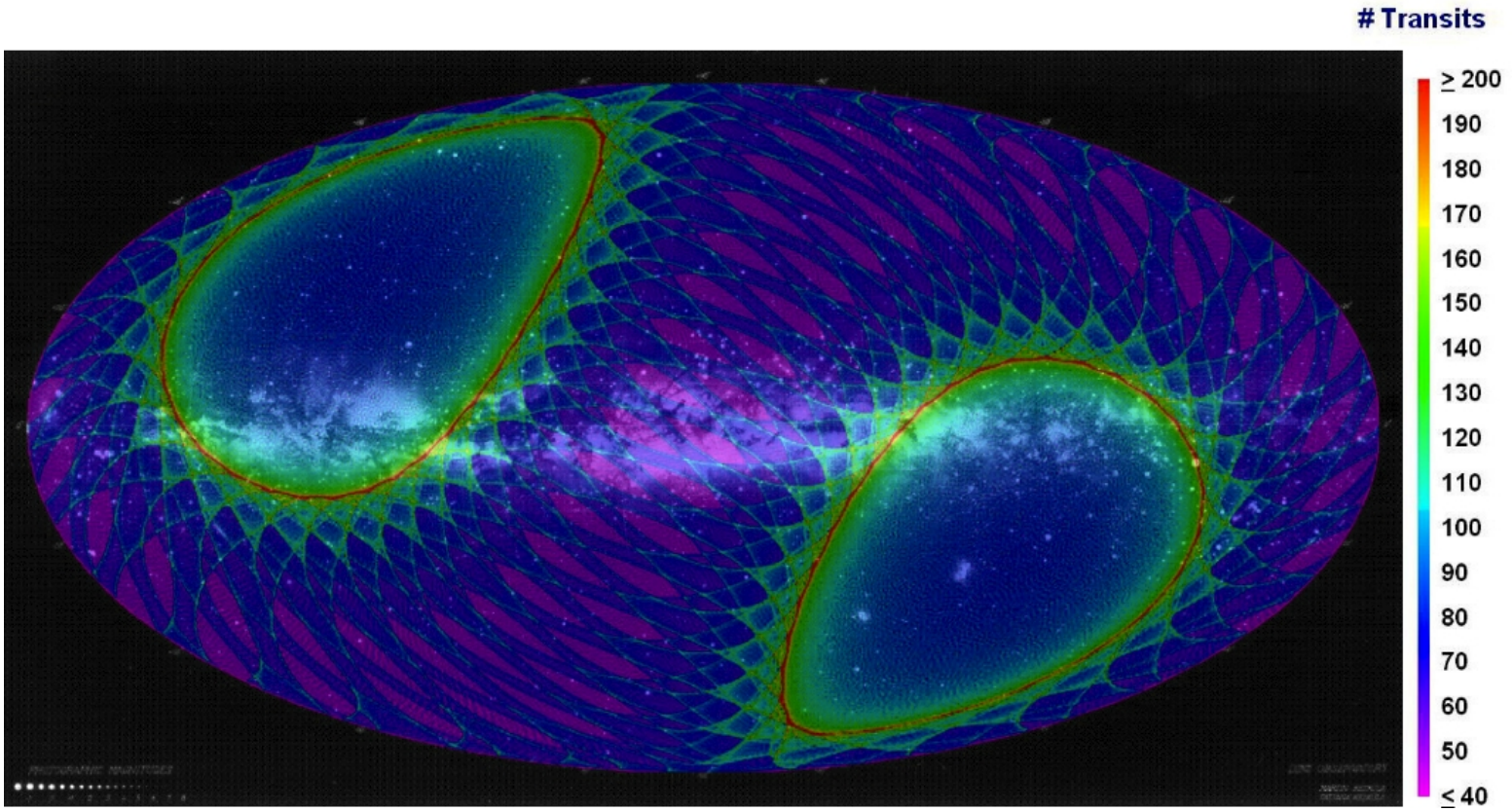
# Sky-Scanning Principle




| | |
|---|---|
| Spin axis | 45° to Sun |
| Scan rate: | 60 arcsec $s^{-1}$ |
| Spin period: | 6 hours |

Figure courtesy Karen O'Flaherty

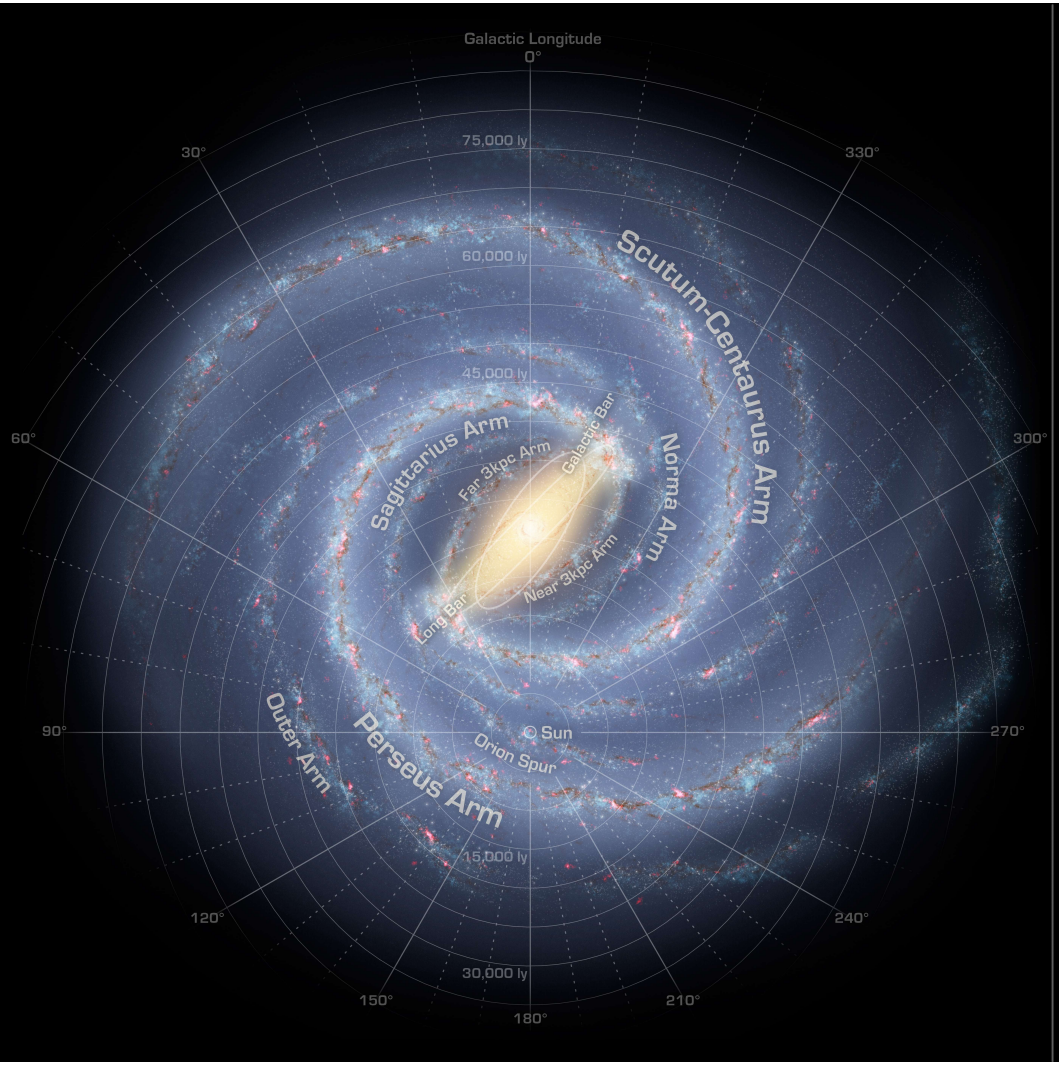
# Gaia: Sky Coverage



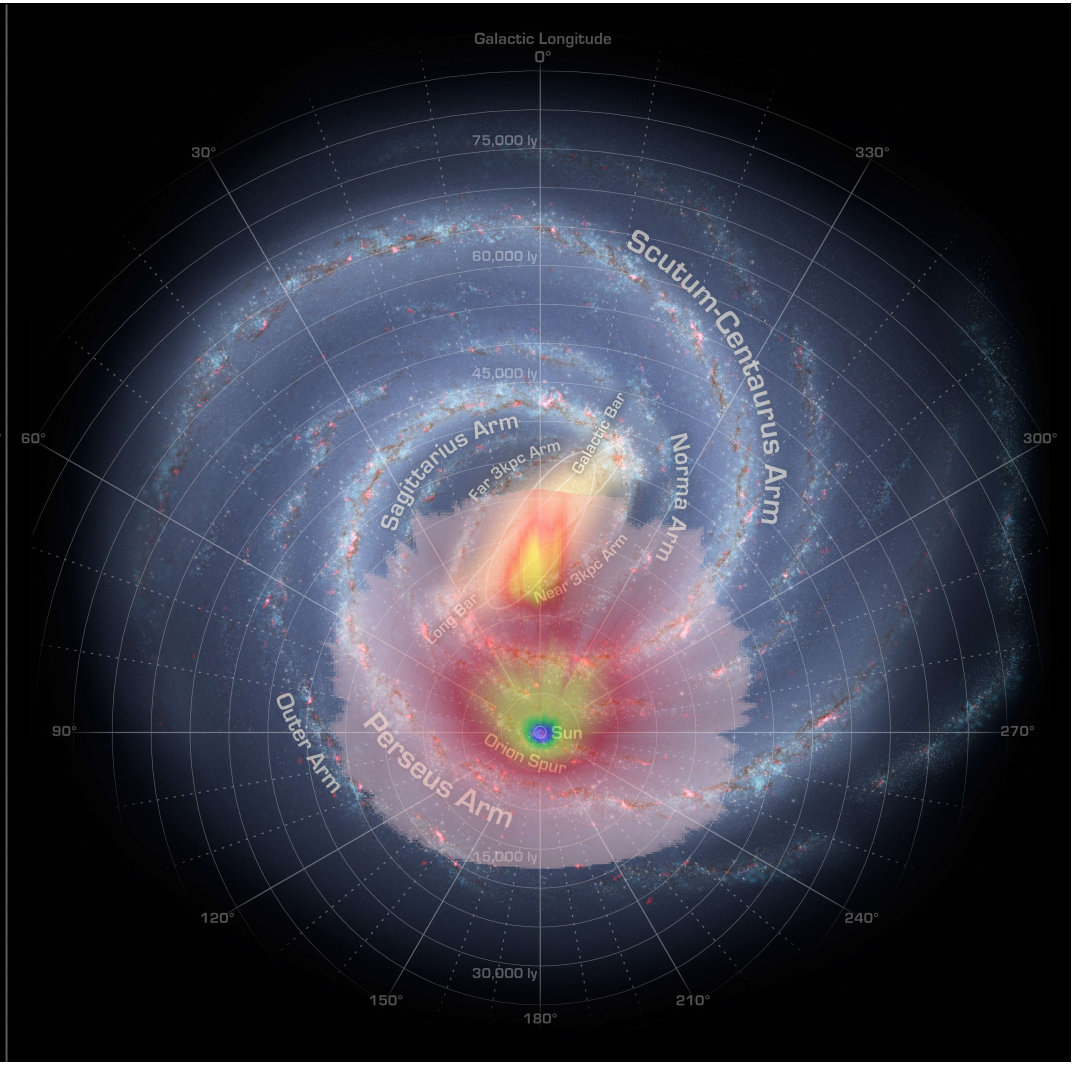

Each point: $t_0$, $t_0$ + 106 mins, $t_0$ + 6hrs, $t_0$ + 6hrs + 106 mins, repeated 10-30 days later

# What will Gaia see?

## Colours correspond to density of objects

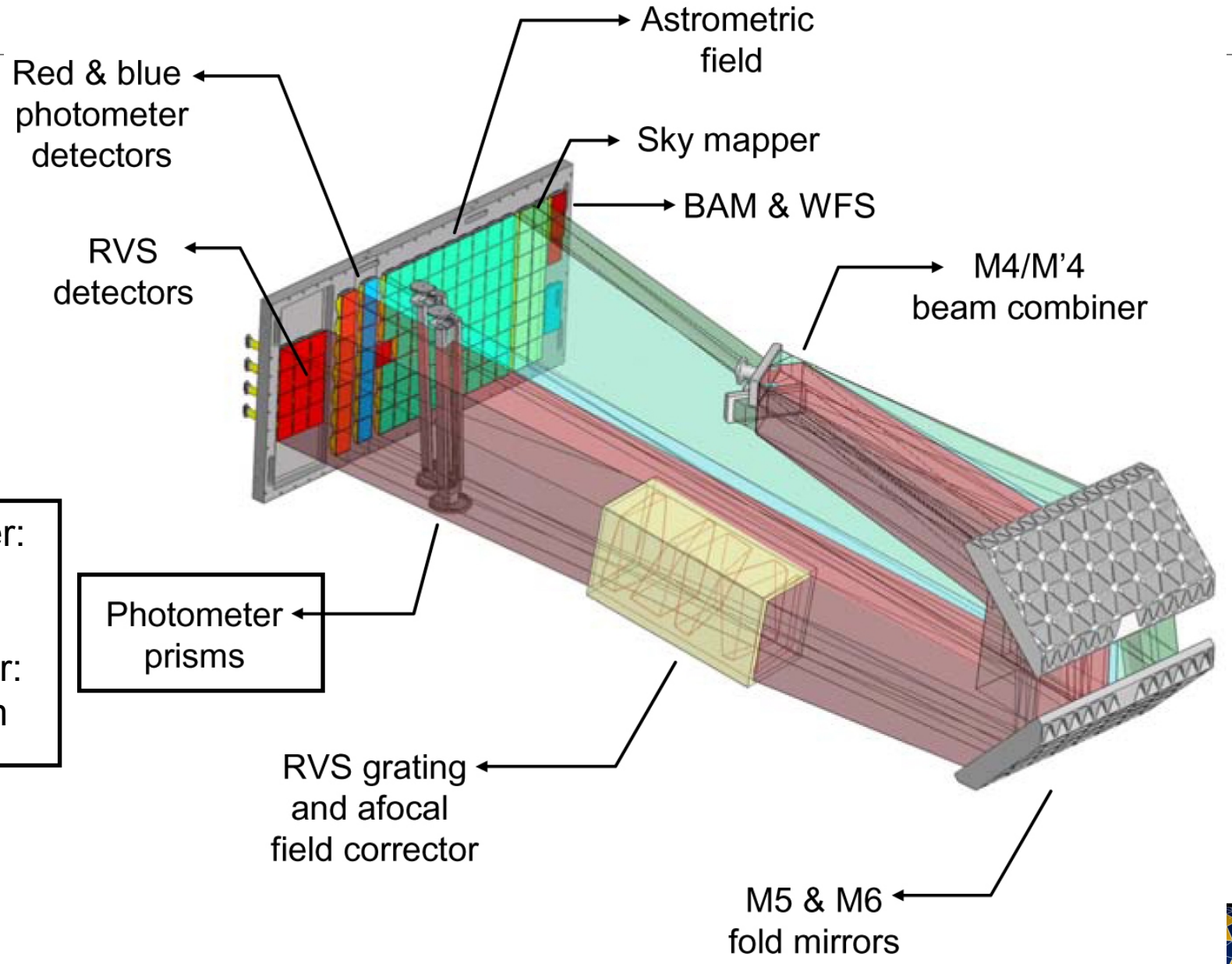



artistic top view of our galaxy (NASA/JPL-Caltech/R. Hurt)




X. Luri & the DPAC-CU2. Simulations based on an adaptation for Gaia of the Besançon galaxy model (A. Robin et al.)

# Photometry Measurement Concept (1/2)

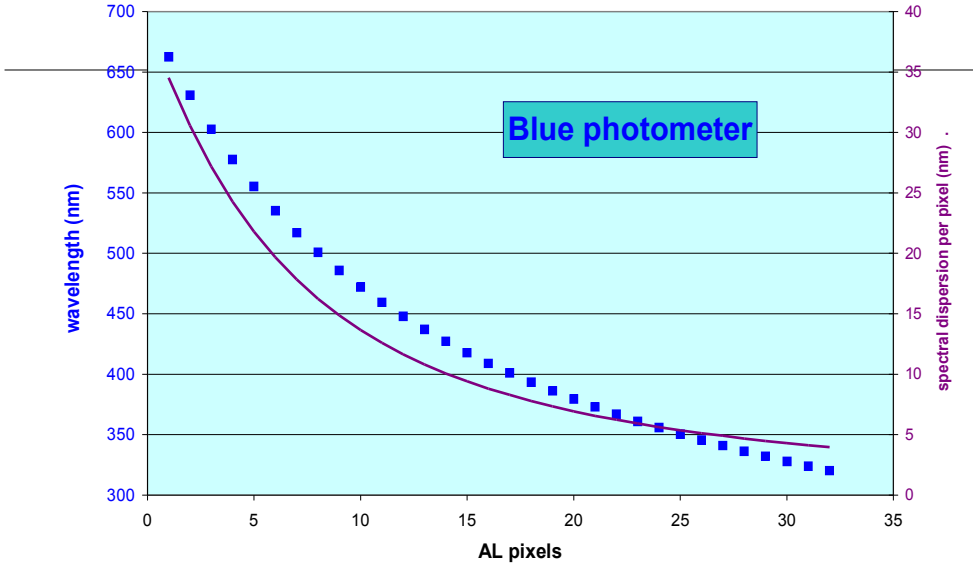


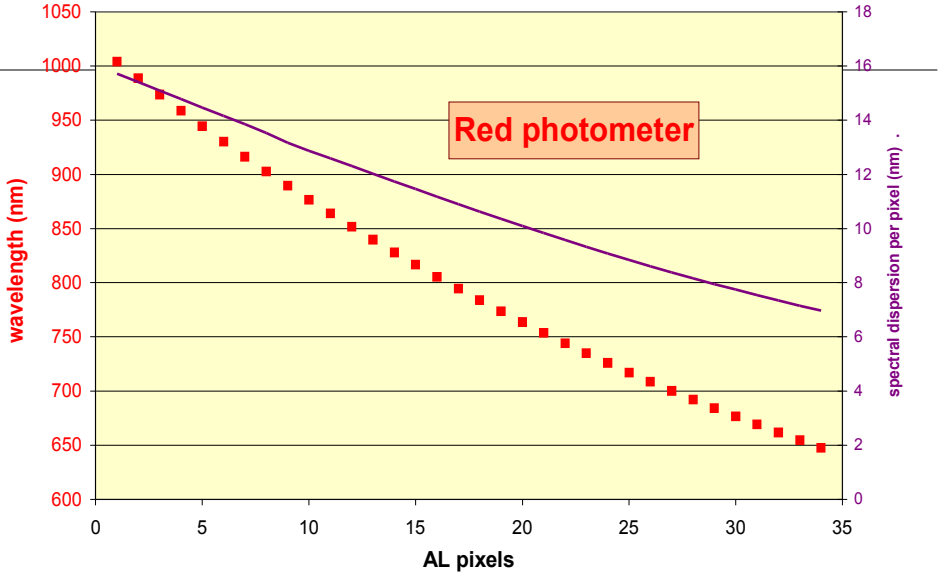

Blue photometer:
330 – 680 nm

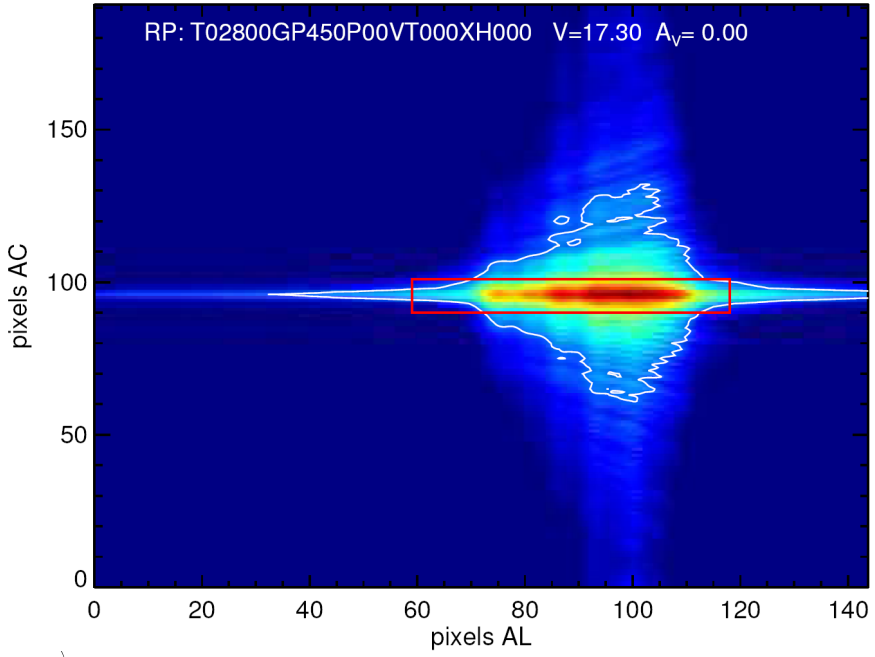
Red photometer:
640 – 1000 nm

Figure courtesy EADS-Astrium

# Photometry Measurement Concept (2/2)




Figures courtesy Anthony Brown

RP spectrum of M dwarf (V = 17.3 mag)
Red box: data sent to ground
White contour: sky-background level
Colour coding: signal intensity

# Radial-Velocity Measurement Concept (1/2)

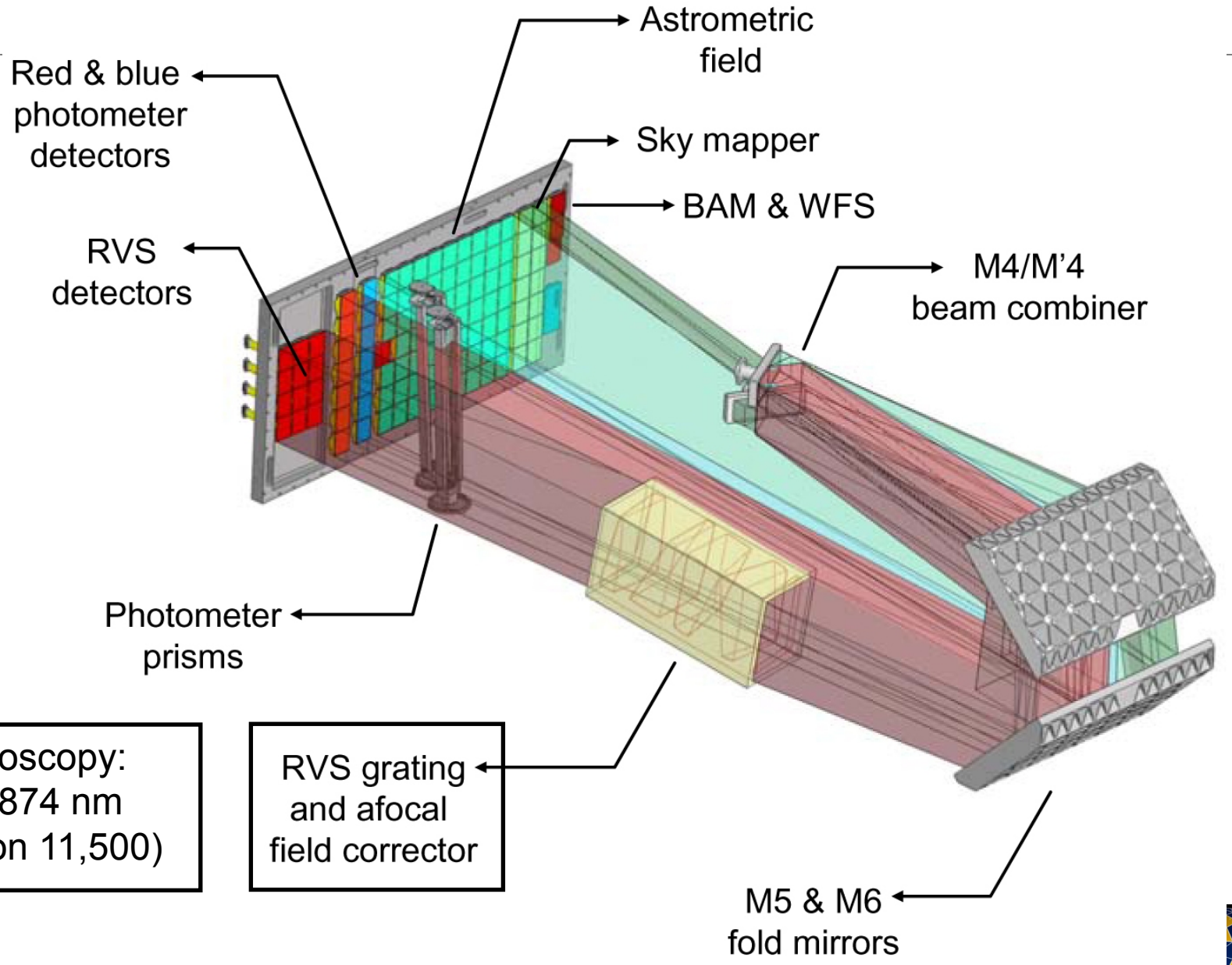
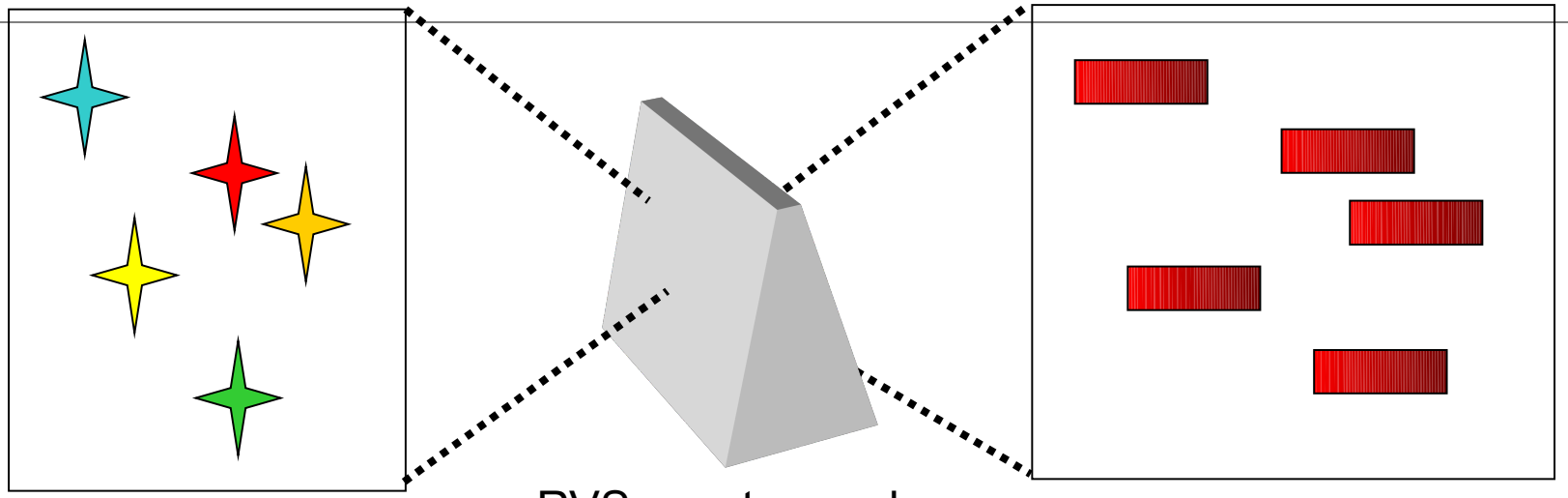
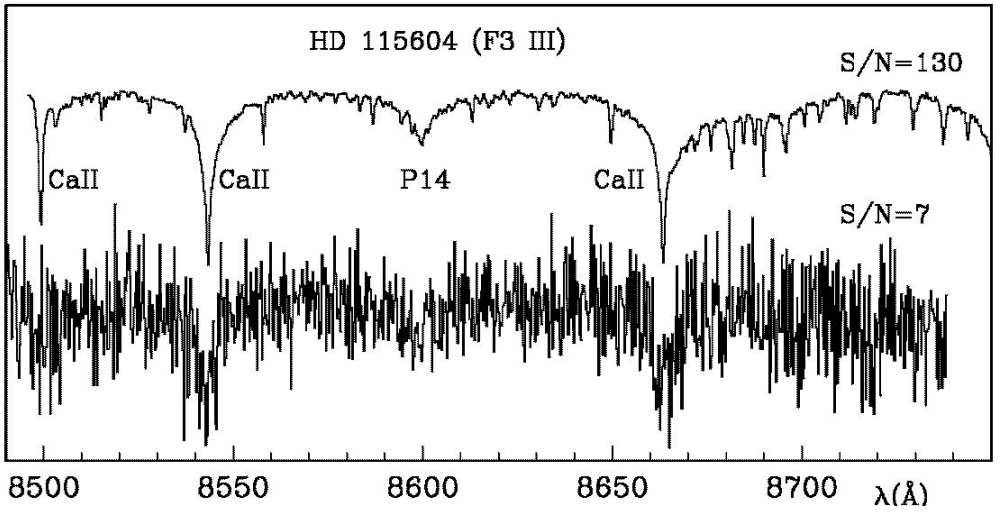



Figure courtesy EADS-Astrium

Spectroscopy:
847 – 874 nm
(resolution 11,500)

# Radial-Velocity Measurement Concept (2/2)




RVS spectra of F3 giant (V = 16 mag)
S/N = 7 (single measurement)
S/N = 130 (summed over mission)

Figures courtesy David Katz

# Data-Reduction Principles

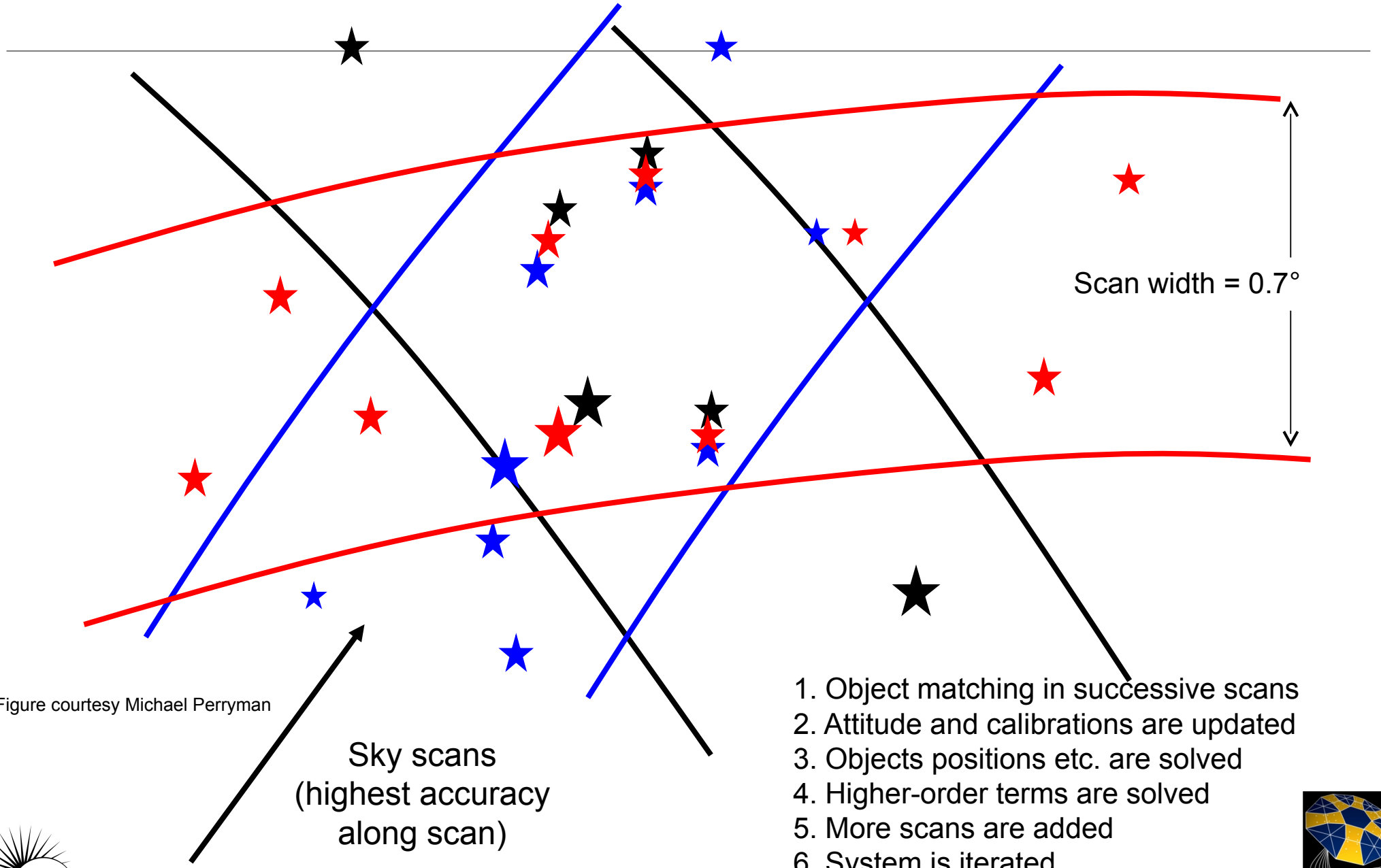
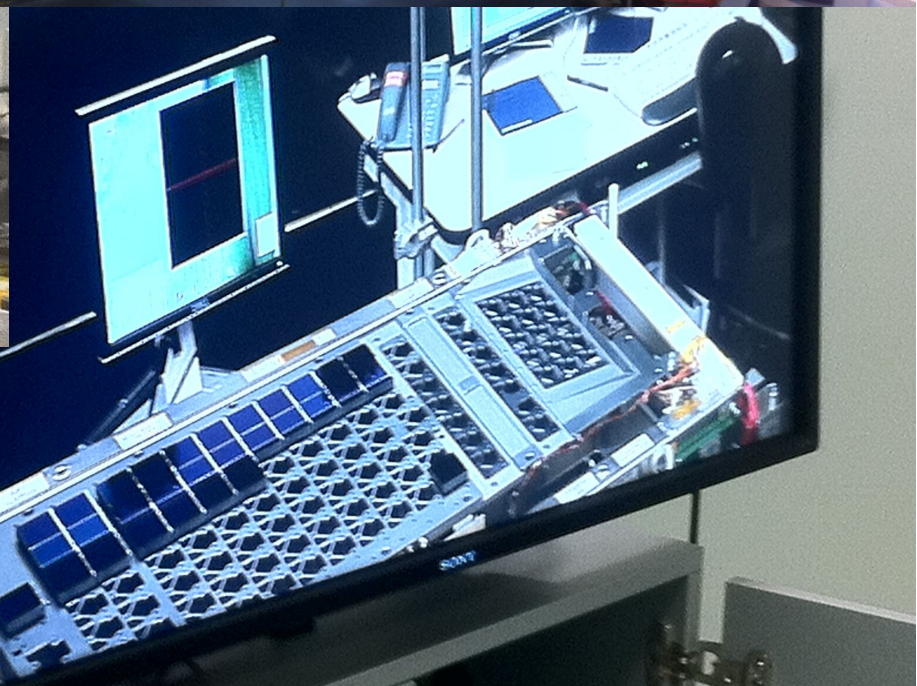



Figure courtesy Michael Perryman

1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc. are solved
4. Higher-order terms are solved
5. More scans are added
6. System is iterated

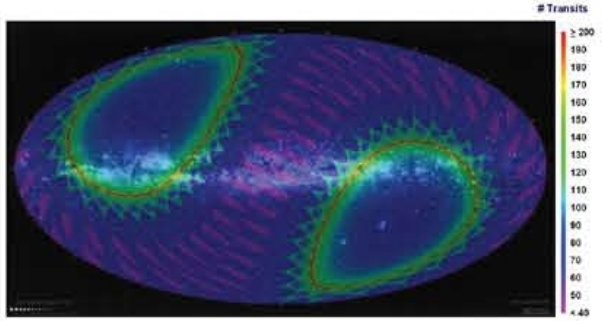
# Gaia In Build



# Gaia Image Gallery

http://www.rssd.esa.int/index.php?project=GAIA&page=Image_gallery

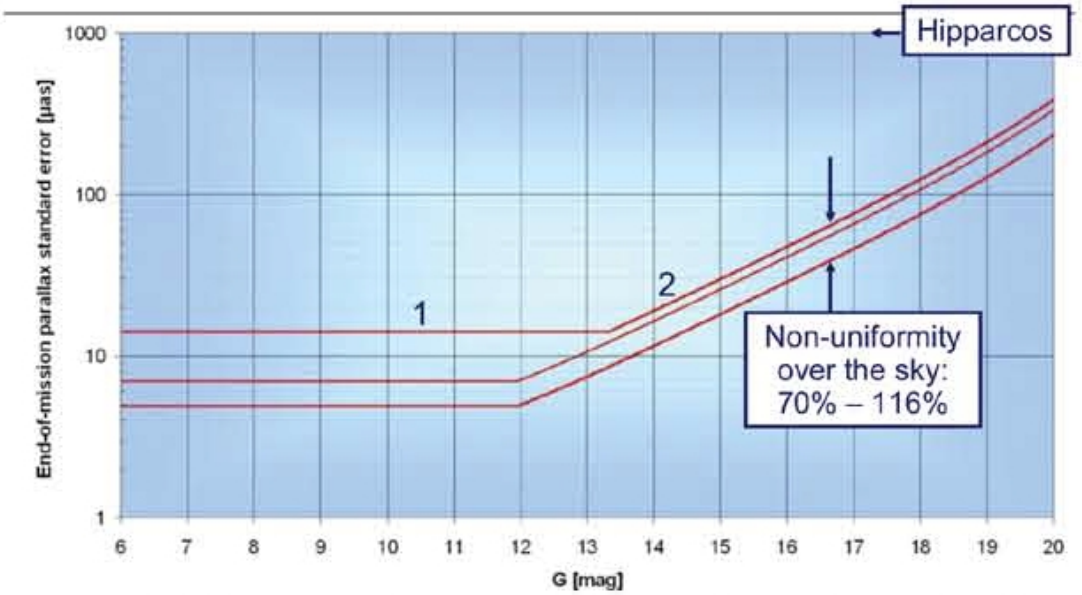



This shows the expected coverage for a 5 year mission. Each location of the sky will be observed in multiple blocks of four observations - these spaced a t_0, t_0 + 106 mins, t_0 + 6hrs, t_0 + 6hrs + 106 mins, with these then being repeated 10 to 30 days later. This temporal coverage of the sky leads to opportunities to discover an characterise various transient objects. Credit: A Brown / ESA.

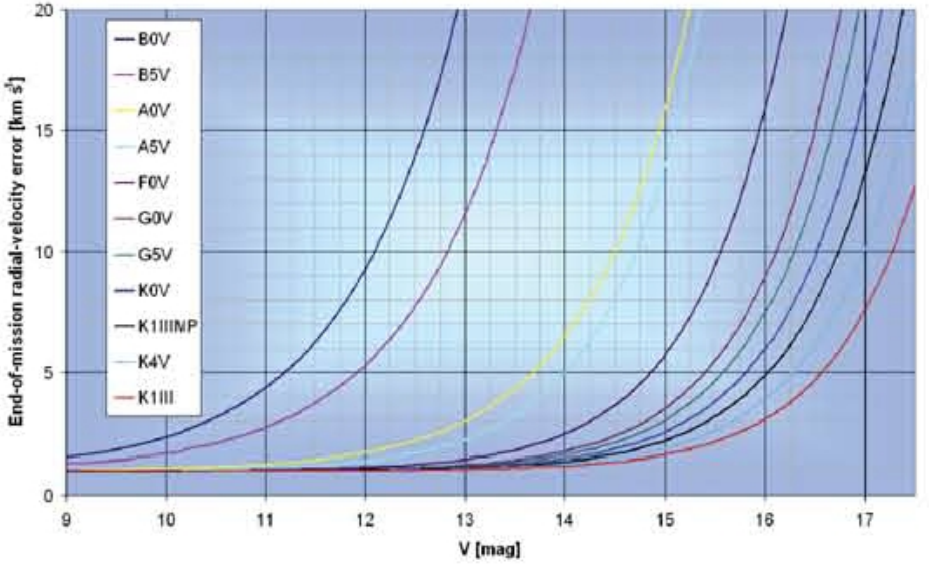
## Summary of Gaia Science Products

- $10^9$ stars
- $10^6$ at V=12, $30x10^6$ at V=15, $250x10^6$ at V=18
- Sigma ~10μas V<12, 22μas V=15, 220μas V=20
- 25,000 stars/ deg$^2$ with max ~$10^6$ stars/ deg$^2$
- $150x10^6$ radial velocities
- Accurate stellar classification for all classes and types
- Recalibration of the distance scale
- Variability analysis for over $10^8$ stars
- 10,000 stellar masses with $\sigma < 1\%$
- Extrasolar planets to 200pc
- $3x10^5$ minor bodies of the solar system
- ~$5x1^{05}$ QSOs + z + photometry, ICRF in the visible
- PPN gamma to ~ $2x10^{-6}$

## End-of-life parallax errors

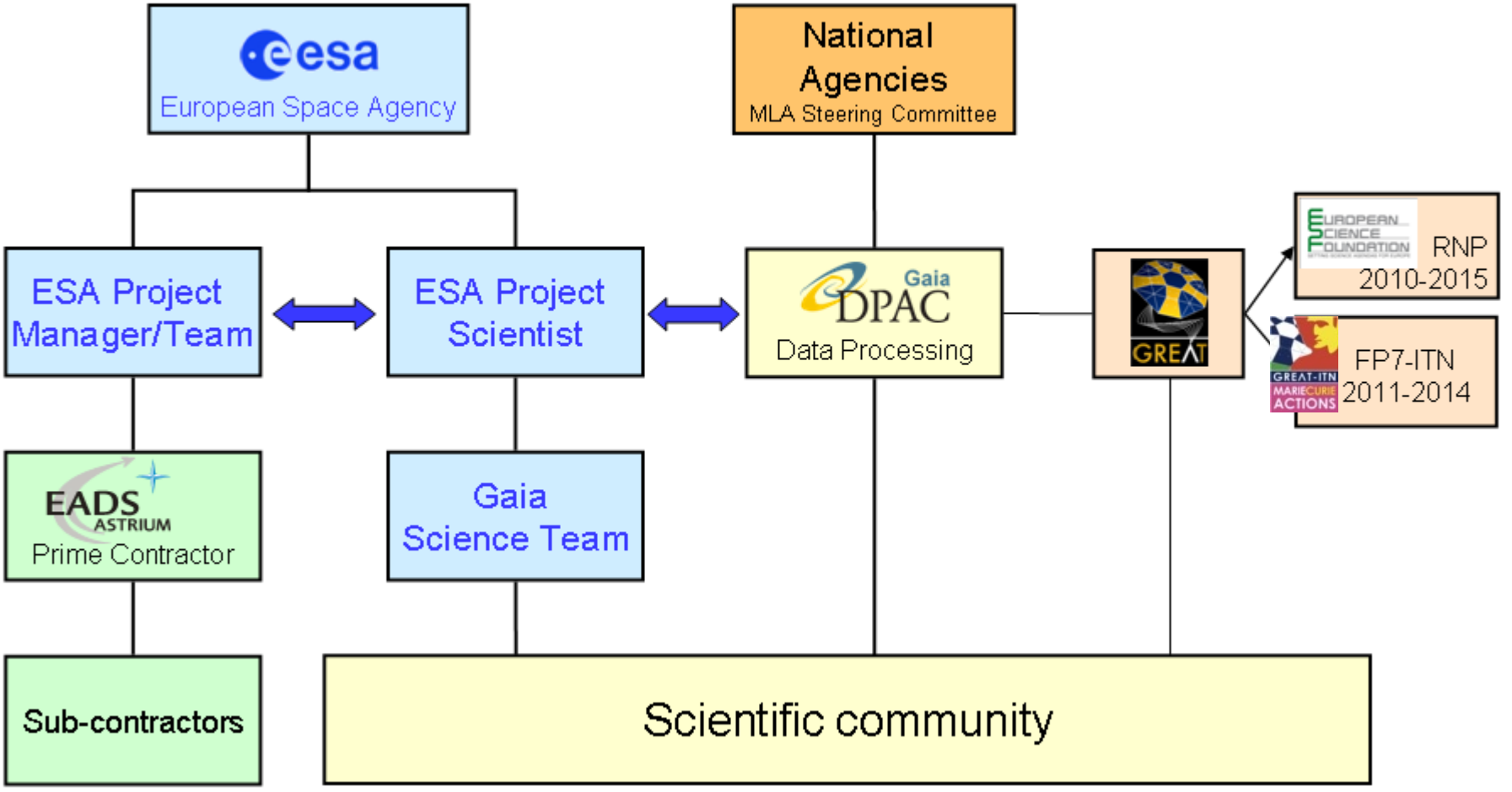



1. 6 < G < 12: bright-star regime (calibration errors, CCD saturation)
2. 12 < G < 20: photon-noise regime, with sky-background noise and electronic noise setting in around G ~ 20 mag



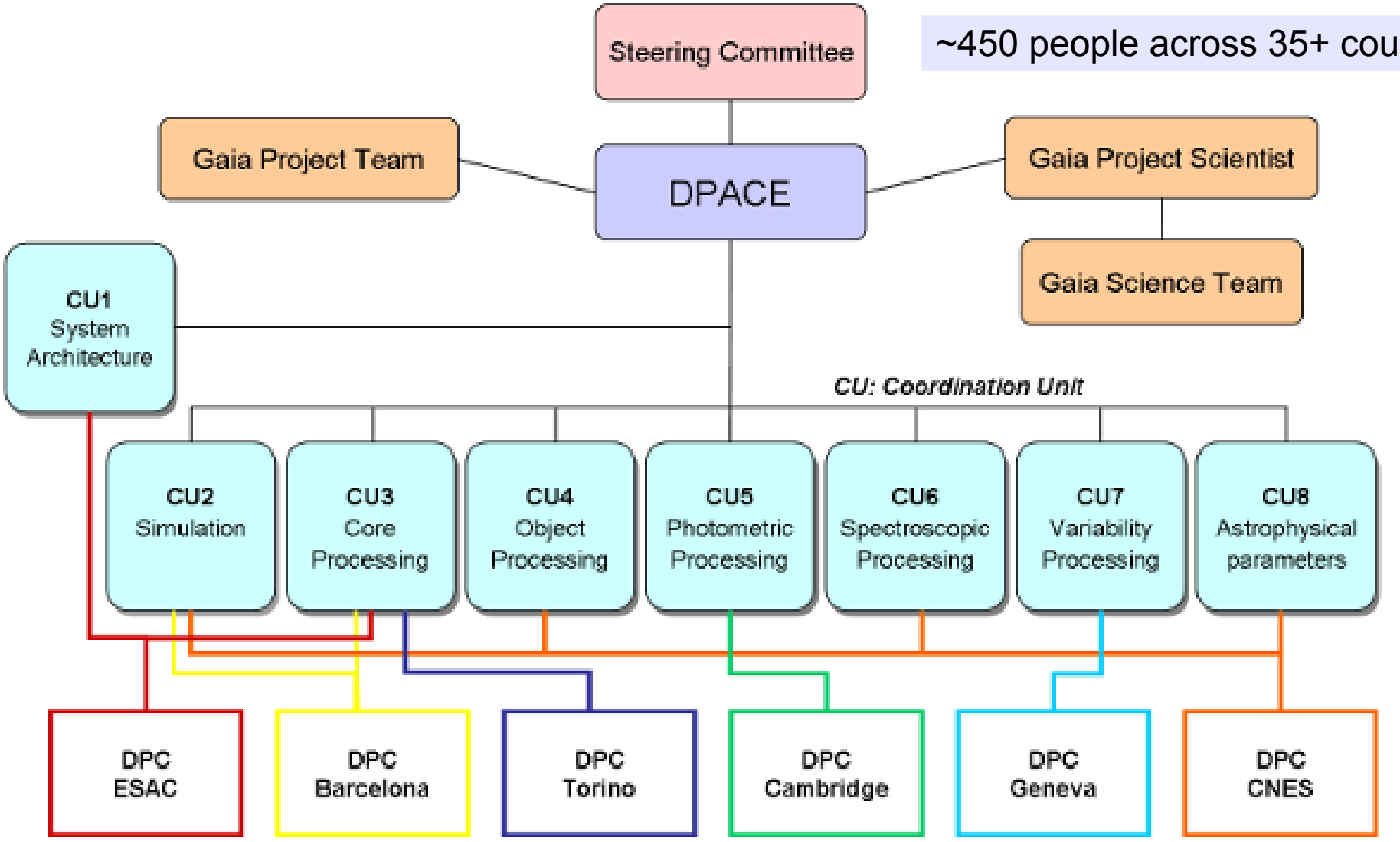
# The Gaia Project

## a complex mission on budget, on time (more or less)



# The Data Reduction Challenge

## DPAC: Data Processing & Analysis Consortium



# Overall chart of the data processing

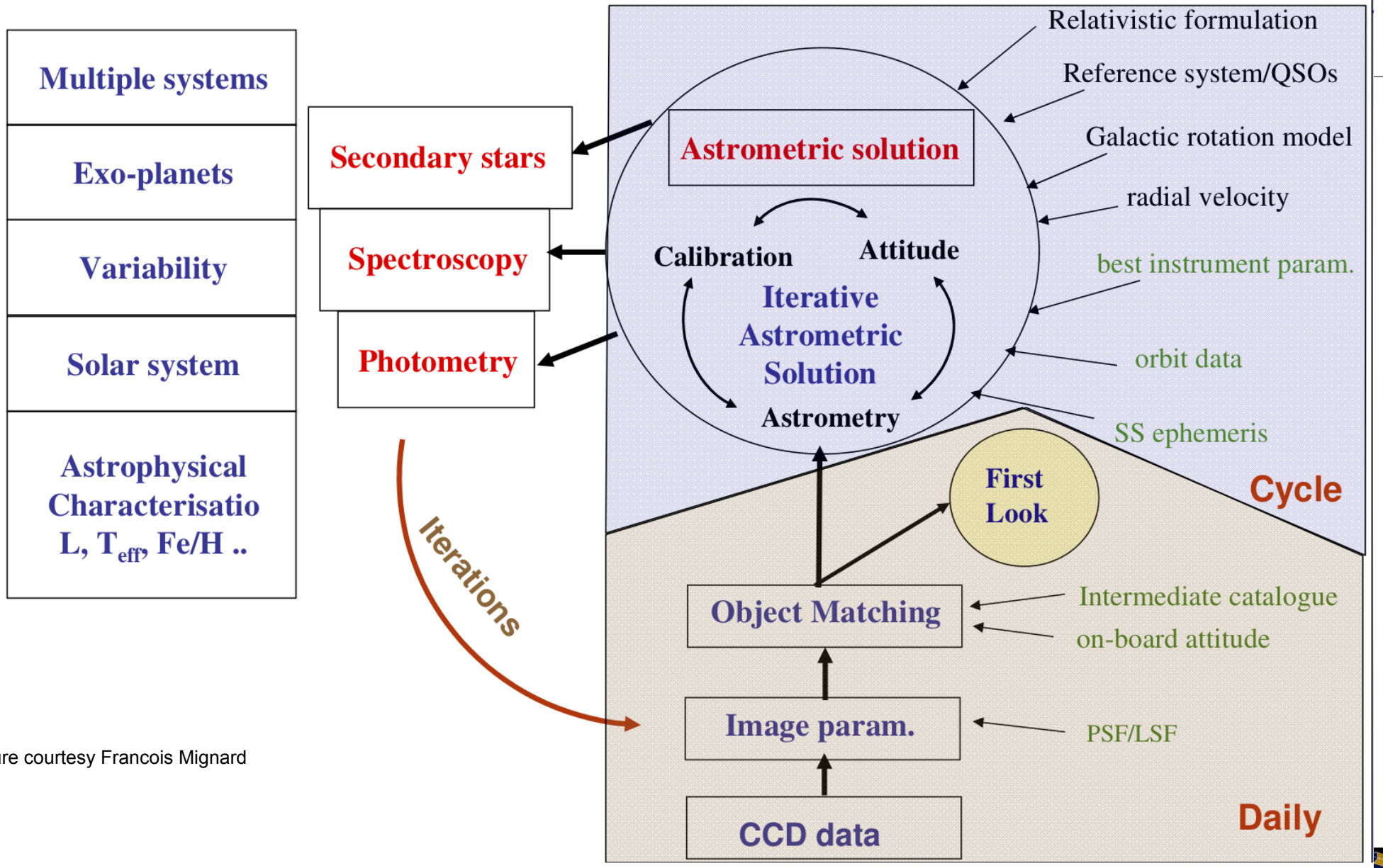



Figure courtesy Francois Mignard

# GREAT ESF RNP
## Scientific Community Building

- Development led by team from ESA Gaia Science Team and Data Processing & Analysis Consortium
- Funds conferences, workshops, exchanges, schools
- Key science remit inclusive across Gaia science
  - Origin, structure, evolution of the Milky Way
  - Stellar Astrophysics
  - Galactic Dynamics
  - Galactic Archaelogy
  - Star formation and evolution
  - Fundamental physics
  - Extrasolar planets and non single stars
  - Solar system
  - The IT data challenge
- Opportunity for students

# GREAT ESF Research Network Programme

- Provides funds for the GREAT research network:
  - Feb 2010 – Jan 2015 with a budget of ~€750K
- The Programme provides financial support for the following activities:
  - Science meetings (workshops, conferences or schools) organised either by the Programme Steering Committee or following an open call for proposals
  - Grants for short and exchange visits awarded following an open call for applications
  - Publication of information brochures and leaflets, scientific books and meeting proceedings etc

# ESF RNP

- ESF networking programmes are 'Open'
  - Encouraged to involve the wider community
  - Ideal for the concept of including those that are not co-applicants in other network activities
- Period of call is science over 2010 – 2015
  - Thus, can factor in access to 'early' Gaia data releases
  - Access to Gaia science alert streams
  - Can also consider science programmes requiring preparatory work (theory, simulations, observational)
- Calls are published at http://www.great-esf.eu
  - Short visits can be proposed at any time, whilst for workshops/ conferences/ exchanges: two calls/year

# GREAT-ESF Meetings 2011

## range of topics to be covered

**GREAT-ESF Workshop** *Orbiting couples: "pas de deux" in the Solar System and the Milky Way*, 10 - 12 October 2011, Paris Observatory, Paris, France

**GREAT-ESF Workshop** *The Interstellar Medium in Three Dimensions with Gaia*, 11 - 14 July 2011, The Lorentz Centre, Leiden University, Leiden, The Netherlands (workshop website)

**GREAT-ESF Workshop** *Stellar Atmospheres in the Gaia Era: Quantitative Spectroscopy and Comparative Spectrum Modelling*, 23 - 24 June 2011, Free University Brussels (Vrije Universiteit Brussel - VUB), Campus Etterbeek, Brussels, Belgium (workshop website)

**GREAT PLENARY** *4th Great Plenary Meeting*, 21 - 23 Jun 2011, Brussels, Belgium (Plenary website)

**GREAT-ESF Workshop** *QSO Astrophysics, Fundamental physics, and Astrometric Cosmology in the Gaia era*, 6 - 9 June 2011, Faculty of Sciences, University of Porto, Porto, Portugal (workshop website)

**GREAT-ESF Summer School and Workshop** *Astrostatistics and Data Mining in Astronomical Databases*, 30 May - 3 June 2011, La Palma, (school website)

**GREAT-ESF Workshop** *Asteroid dynamic and physical studies during and after the Gaia mission*, 4 - 6 May 2011, Pisa, Italy (workshop website)

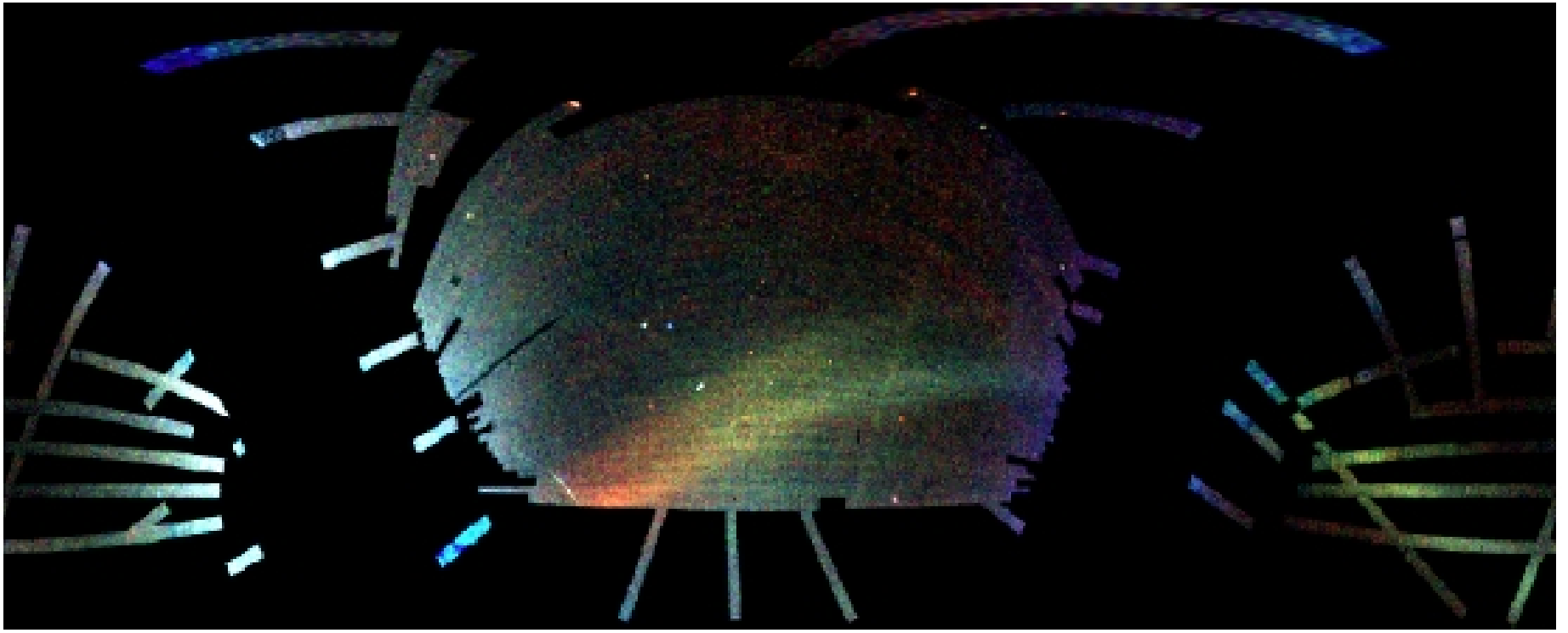
**GREAT-ESF CONFERENCE** *The Fundamental Cosmic Distance Scale: State of the Art and the Gaia Perspective*, 3 – 6 May 2011, Osservatorio Astronomico di Capodimonte, Naples, Italy (conference website)

**GREAT-ESF CONFERENCE** *Assembling the puzzle of the Milky Way*, 17 – 22 April 2011, Le Grand-Bornand, France (conference website)

**GREAT-ESF Workshop** *Gaia and the End States of Stellar Evolution*, 11 - 14 April 2011, The University of Leicester, UK (workshop website)

http://great.ast.cam.ac.uk/Greatwiki/GaiaScienceMeetings
See this link also for the final reports from each meeting

# Galaxy substructure and satellite accretion



Belokurov et al (2006 etc) – this figure is the SDSS DR7 release. This shows turnoff stars (selected by colour) – where blue is closer, red further

# Gaia-ESO Survey: Supporting Spectra

## Galactic Astrophysics via VISTA Imaging, Gaia Astrometry, and Eso SpectrOscopy

- Large scale survey → ground based spectroscopy for Gaia:
  - Mass Distribution of the Galaxy
  - Galaxies formation and evolution traced by chemistry
- Key aims: kinematic studies of the halo, chemistry of the disk
  - Quantify thick disk and halo abundance and kinematic gradients
  - Distribution functions due to the inner bar and spiral arms
- Determine the relative importance of assembly and accretion
- Bulge-disk interface: (secular) origin of the thick disk
- Halo-disk interface: (merger) origin of the halo & thick disk
- Direct constraints on the disk and halo potential

# Gaia-ESO Survey

## Open Star Clusters: the path from molecular clouds to the MW disc population

- Large survey also includes stellar astrophysics …
  - Clusters and star formation and evolution
- Key aims: kinematic and chemical studies of a large sample of Open Clusters and cluster members – to:
  - understand how clusters form; evolve, dissolve, and populate the Milky Way
  - calibrate complex physics that affect stellar evolution;
  - measure the Galactic metallicity gradient at different ages with unprecedented accuracy, thereby setting constraints on models of disc formation
- Survey VLT FLAMES/UVES → 300 nights: 2012 to 2017
- See http://www.gaia-eso.eu

# Conclusions and Links

More on the below in presentations at the GREAT Plenary – June 2011:
http://great.ast.cam.ac.uk/Greatwiki/GreatMeet-20110621

- Gaia set to revolutionise our understanding of the nearby Universe
- The European galactic astronomy community well organised through the GREAT network
- Ambitious supporting survey and instrument programmes now underway:
  - Gaia-ESO survey
  - MOONS, 4MOST, WEAVE
- ESA Gaia: http://www.rssd.esa.int/gaia
- GREAT: http://www.great-esf.eu