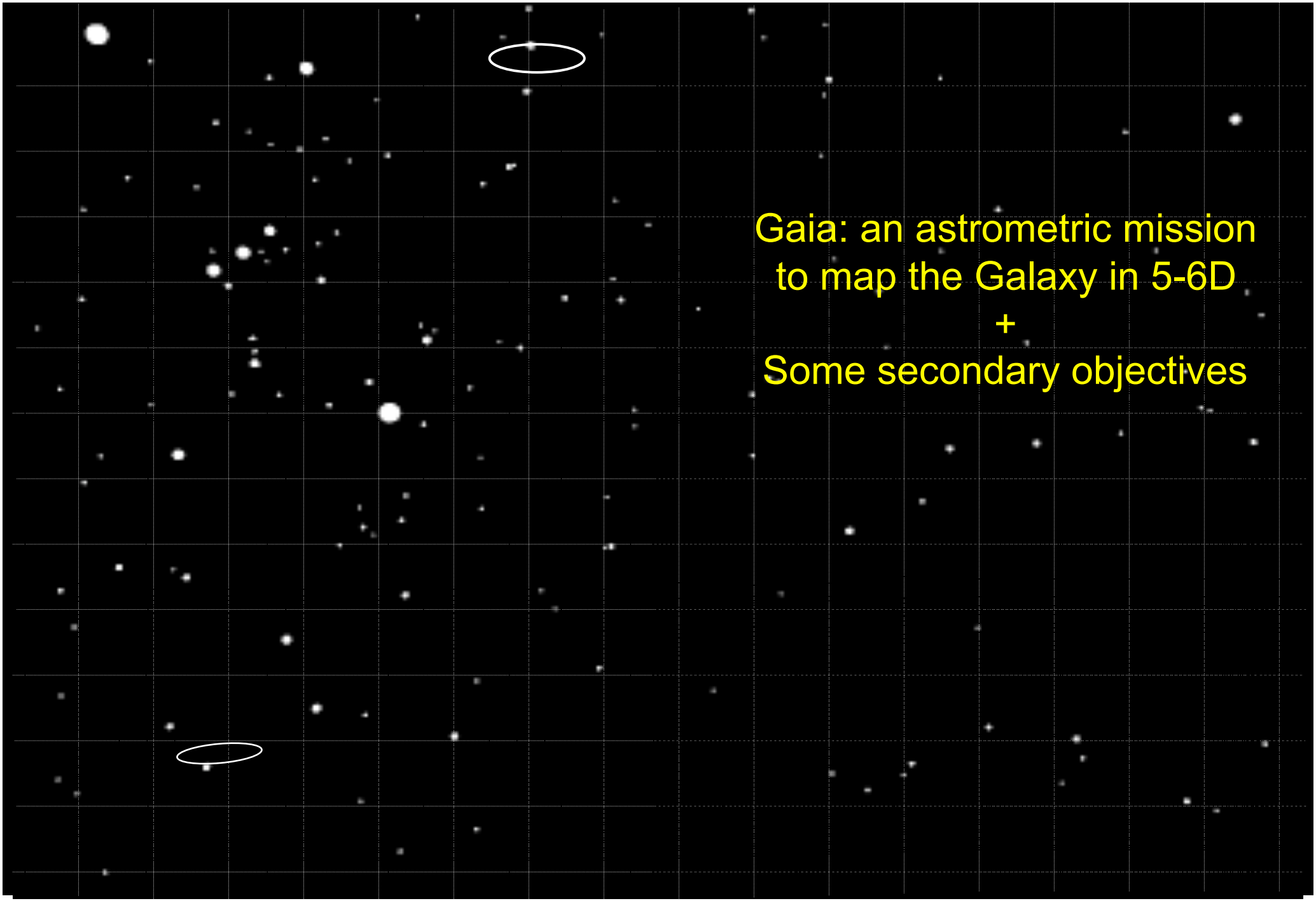
The Gaia mission

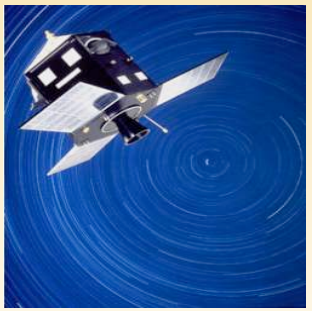
F. Thévenin

Observatoire de la Côte d'Azur


Gaia: an astrometric mission
to map the Galaxy in 5-6D
+
Some secondary objectives

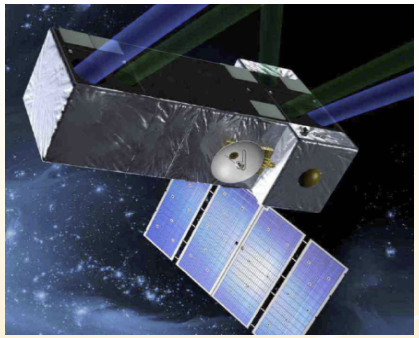
Space Astrometry: Past & Present

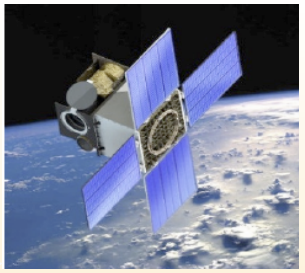
1 mas = 5 nrad 10 μas = 50 prad

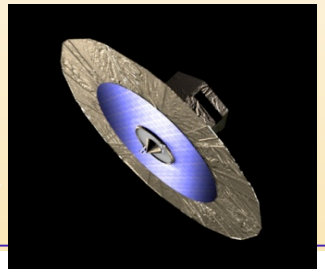


- A successful forerunner: HIPPARCOS (ESA)
  - accuracy of 1 mas ~ a coin @ 1000 km
- The unfortunate followers
  - accuracy of 0.1 mas ~ a nail @ 1000 km
  - Roemer, FAME-1, FAME-2, DIVA, Lomonossov, AMEX

    ESA US US DE RU US
- Study phase
  - JASMINE (Japan) in the IR
- Delayed > 2015
  - SIM-lite (US) with 1 μas accuracy
- Funded – launch 2012 - 2013
  - NanoJasmine [4 mas], J-MAPS (US) [1mas]
  - Gaia (ESA) : 25 μas (a hairwidth @ 1000 km)







Astrometry for Astrophysique

- Immediat and direct product
  - Positions, parallaxes & proper motions for a large sample of stars
    - 1 mas (Hipparcos) to 1 μas (SIM)
  - Photometry multi-epoch from UV to near IR
  - Radial velocity with few km/s of accuracy
  - Solar System Object Studies
  - Detection, measures of visual & spectroscopiques binaries

Secondary product: Stellar Physics & galactique structure

Assets of Gaia

- A single mission with three nearly synchronous data taking by 3 instruments: astro, BP/RP and RVS
  - Astrometric, photometric and spectroscopic data
- GAIA is a scanning mission
  - no pointing, no change in the schedule Uniform coverage of the sky
- Quasi regular time sampling over 5 years
  - ~ 80 observations ➔ photometry, orbits of binaries, asteroids
- Internal and autonomous detection system to G = 20
- Global astrometry of staggering precision
  - Internal metrology, thermal and mechanical stability

The 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	7-8	13	24	34	55	90	155	300	μas
Proper motion	5	7	11	18	30	50	80	145	μas / an
Position	6	10	16	25	40	70	115	205	μas

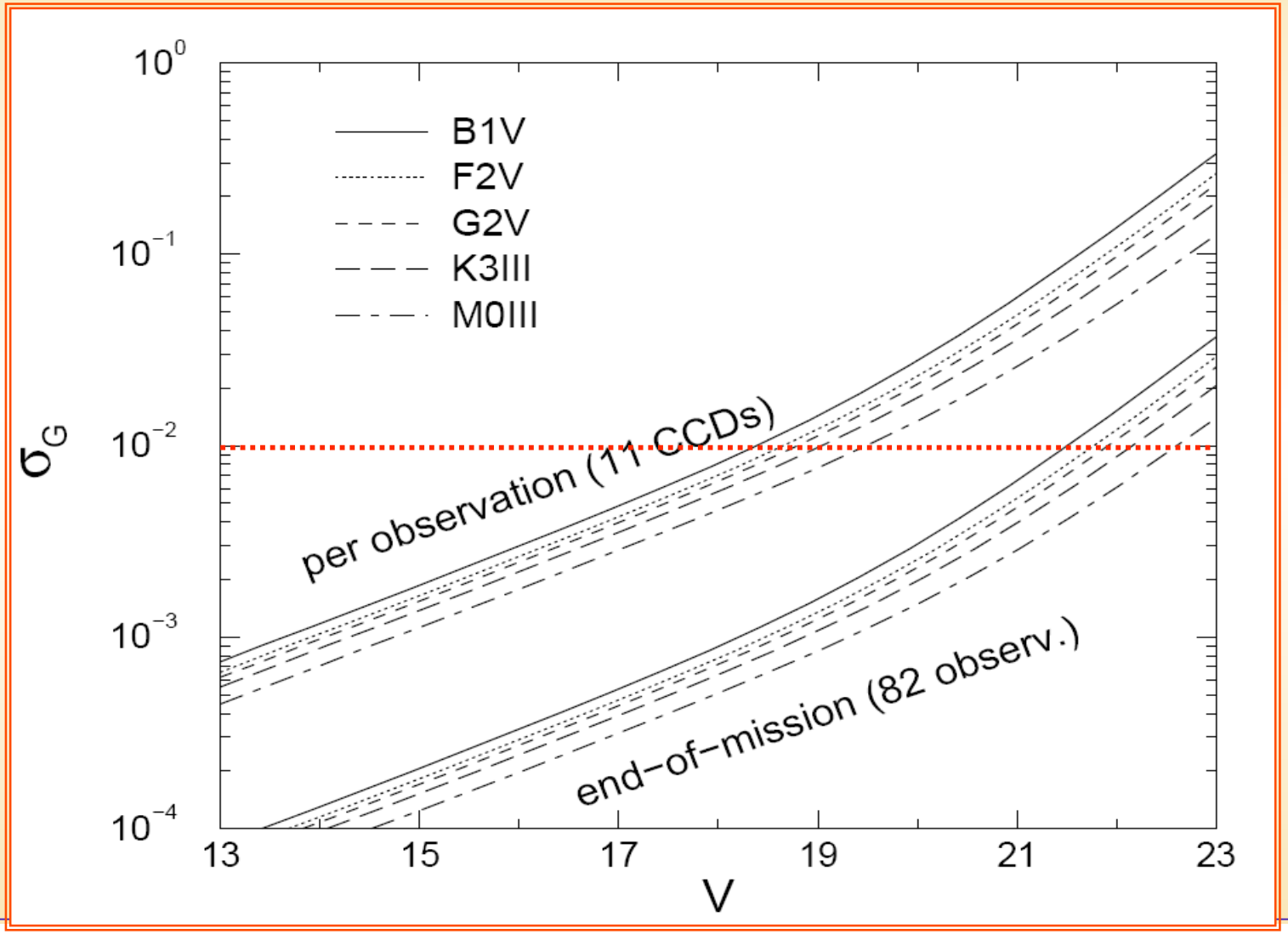
Notes:

- Radiation-damage effects on CCDs not fully taken into account
- Estimates include a 20% margin (factor 1.2) for unmodelled errors

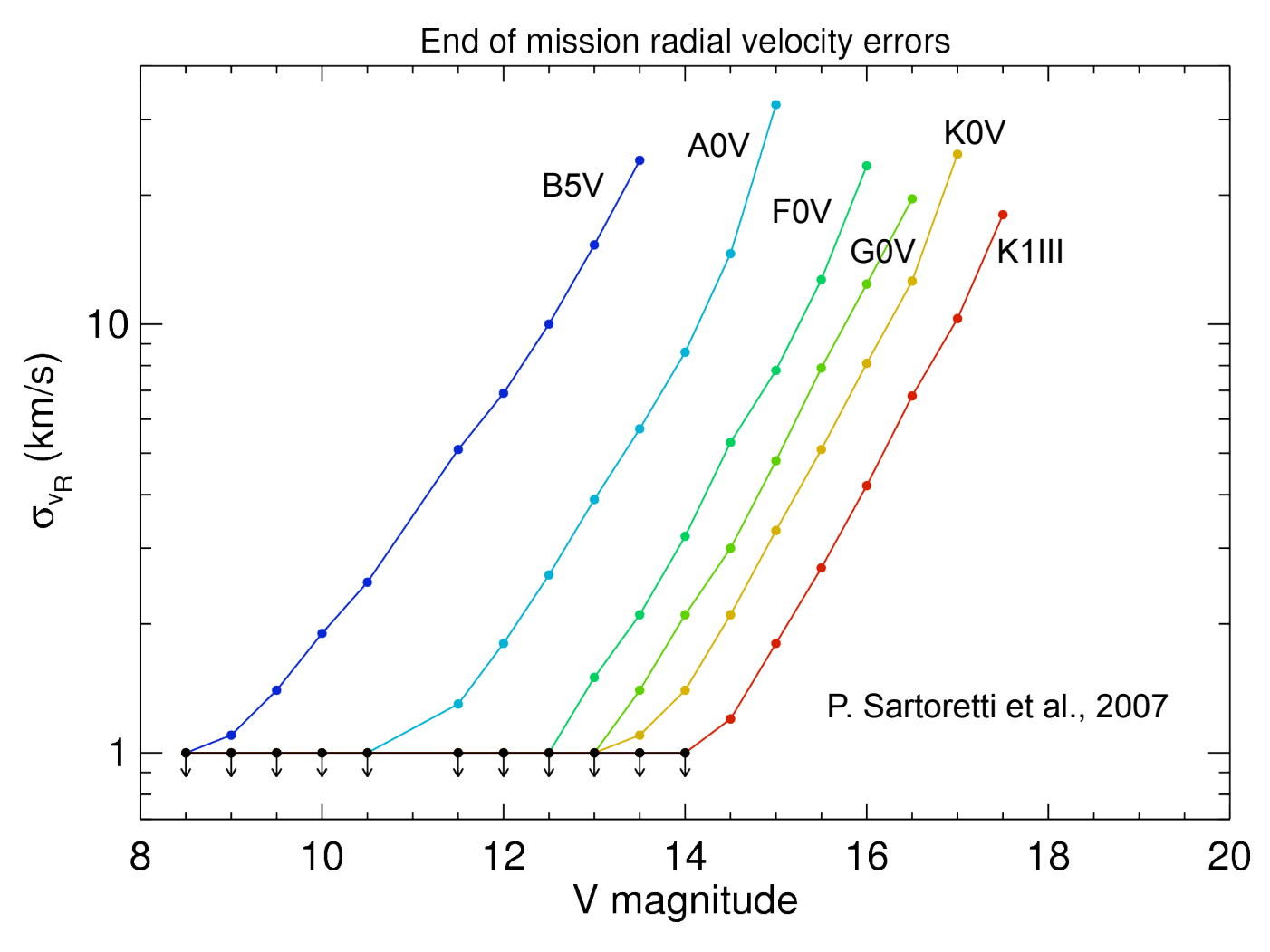
Photometric performance (no radiation dammage)

Photometric band V	V(mag)	B1V	G1V	M6V
C1M344	15	< 10 mmag	< 15 mmag	< 100 mmag
	20	< 150 mmag	< 1000 mmag	-
C1M410	15	< 10 mmag	< 10 mmag	< 20 mmag
	20	< 60 mmag	< 200 mmag	< 1100 mmag
C1M549	15	< 8 mmag	< 8 mmag	< 8 mmag
	20	< 120 mmag	< 120 mmag	< 120 mmag
C1M965	15	< 20 mmag	< 10 mmag	< 10 mmag
	20	< 400 mmag	< 150 mmag	< 10 mmag

… and for the G-band photometry (no radiation damage)



Radial velocity accuracy



RAVE : $\langle V_r \rangle$ ~ 2 km/s, 9<I<12

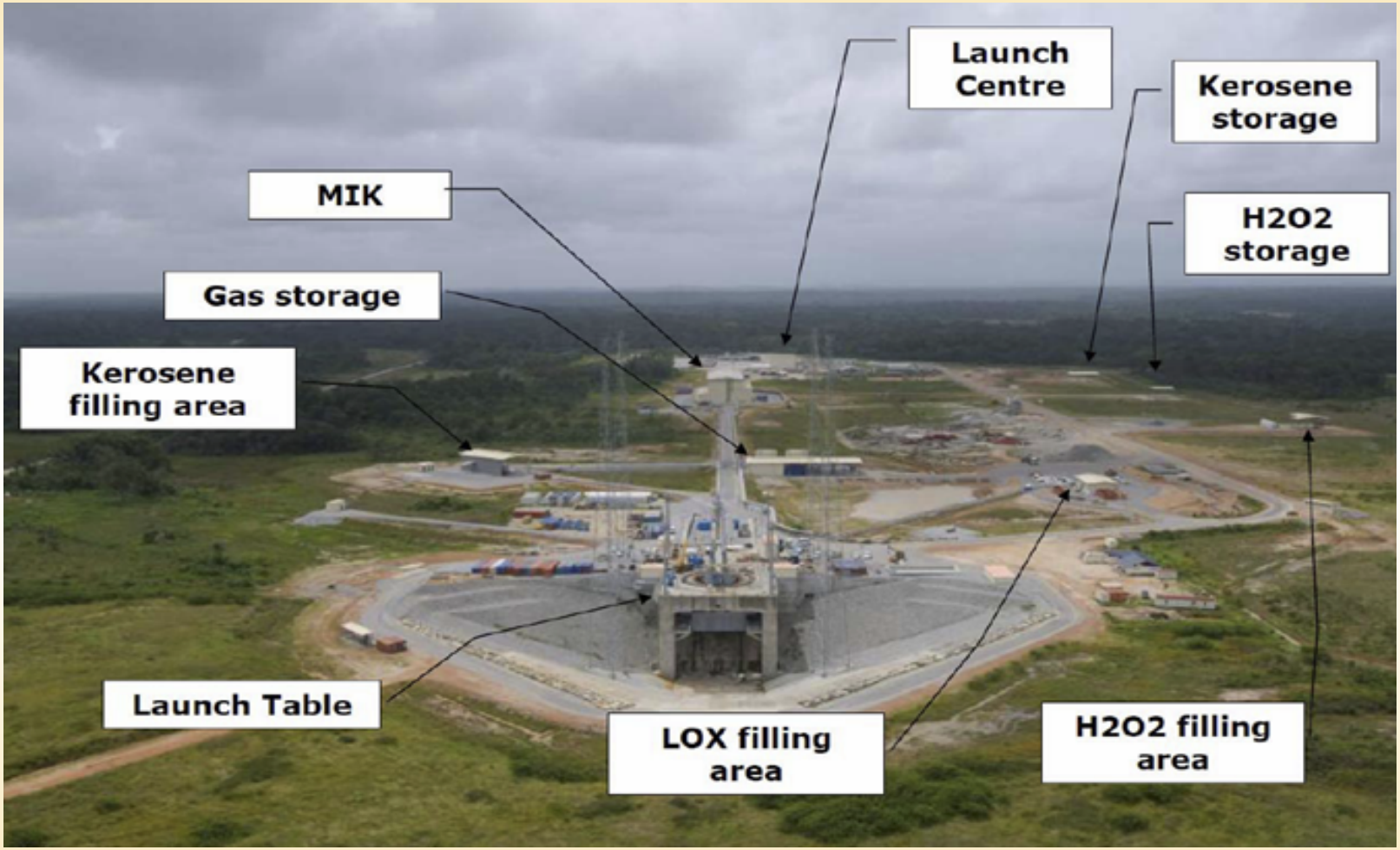
Gaia Real Science: very broad coverage

- The real science return for the DPAC scientists sounds more like
  - Mapping of the Milky-way
  - Stellar physics (classification, M, L, Ln g, T_{eff}, [Fe/H], variability)
  - Galactic kinematics and dynamics
  - Distance scale (geometric to 10 kpc, HR diagram, cepheids, RR Lyr)
  - Age of the Universe (cluster diagrams, distances, luminosity)
  - Dark matter (potential tracers)
  - Reference frame (Quasars, astrometry)
  - Planet detection (~ M_J, astrometry and photometric transits)
  - Fundamental physics (Relativity experiments, $\gamma \sim 2 \times 10^{-6}$, $\beta \sim 5 \times 10^{-4}$)
  - Solar Physics ($J2_{sun} \sim 5 \times 10^{-7}$)
  - Solar system science (Taxonomy, Masses, Orbits, 3×10^5 bodies)

The Gaia machine

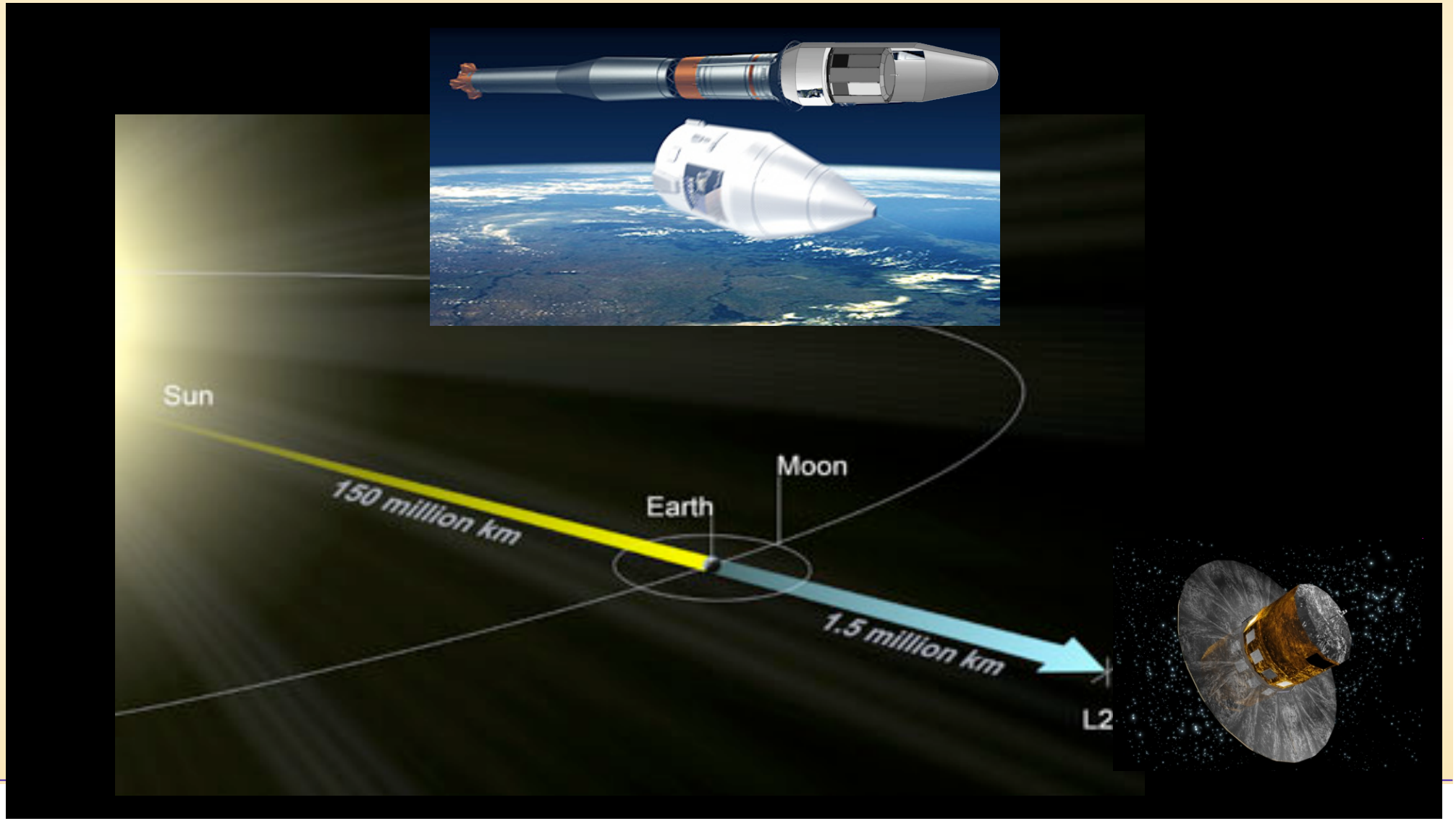
in few pictures

Soyouz Launchpad near Kuru



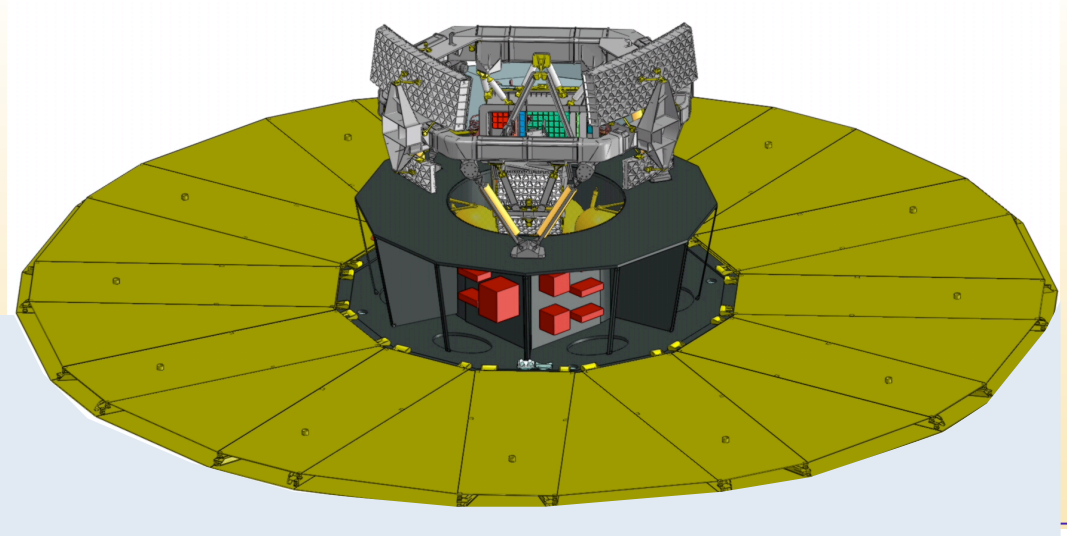
Launch August 2012

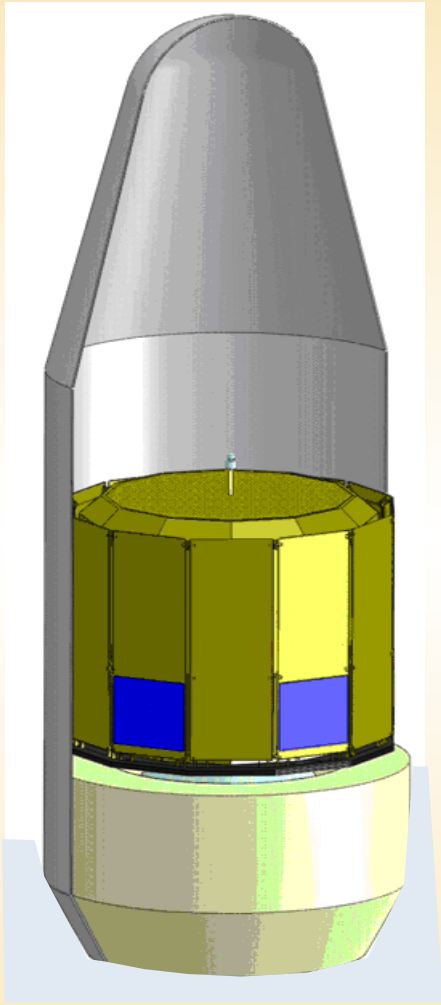
Orbite au point L2



Main characteristics

- S/C masse at launch : 2 t
- Power available : 2 kW
- Size : 3 m
- Shield diameter : ø = 10 m
- - pupil of telescopes : 1.45 x 0.5 m
-
-

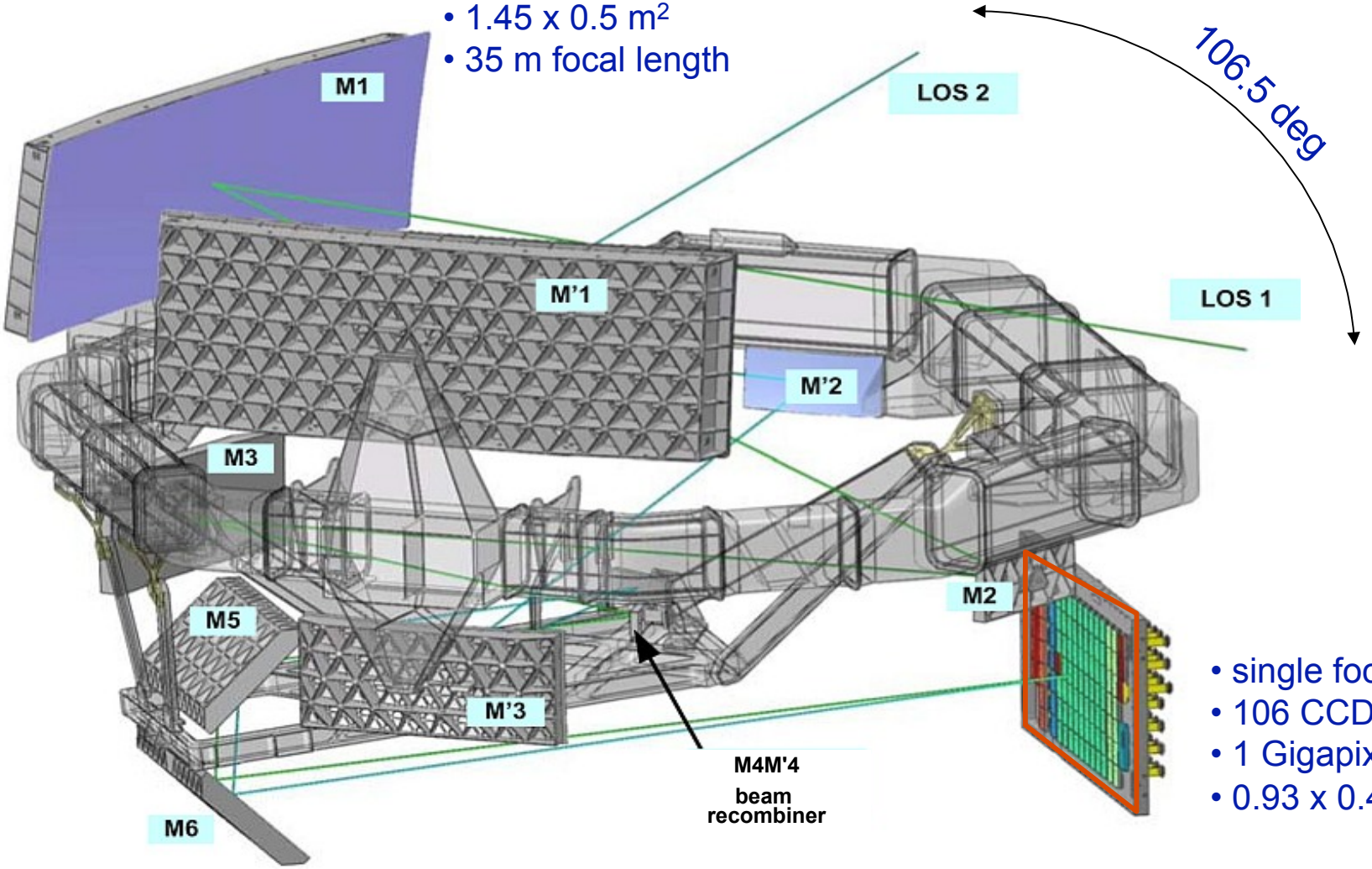




Schield of 10m ø

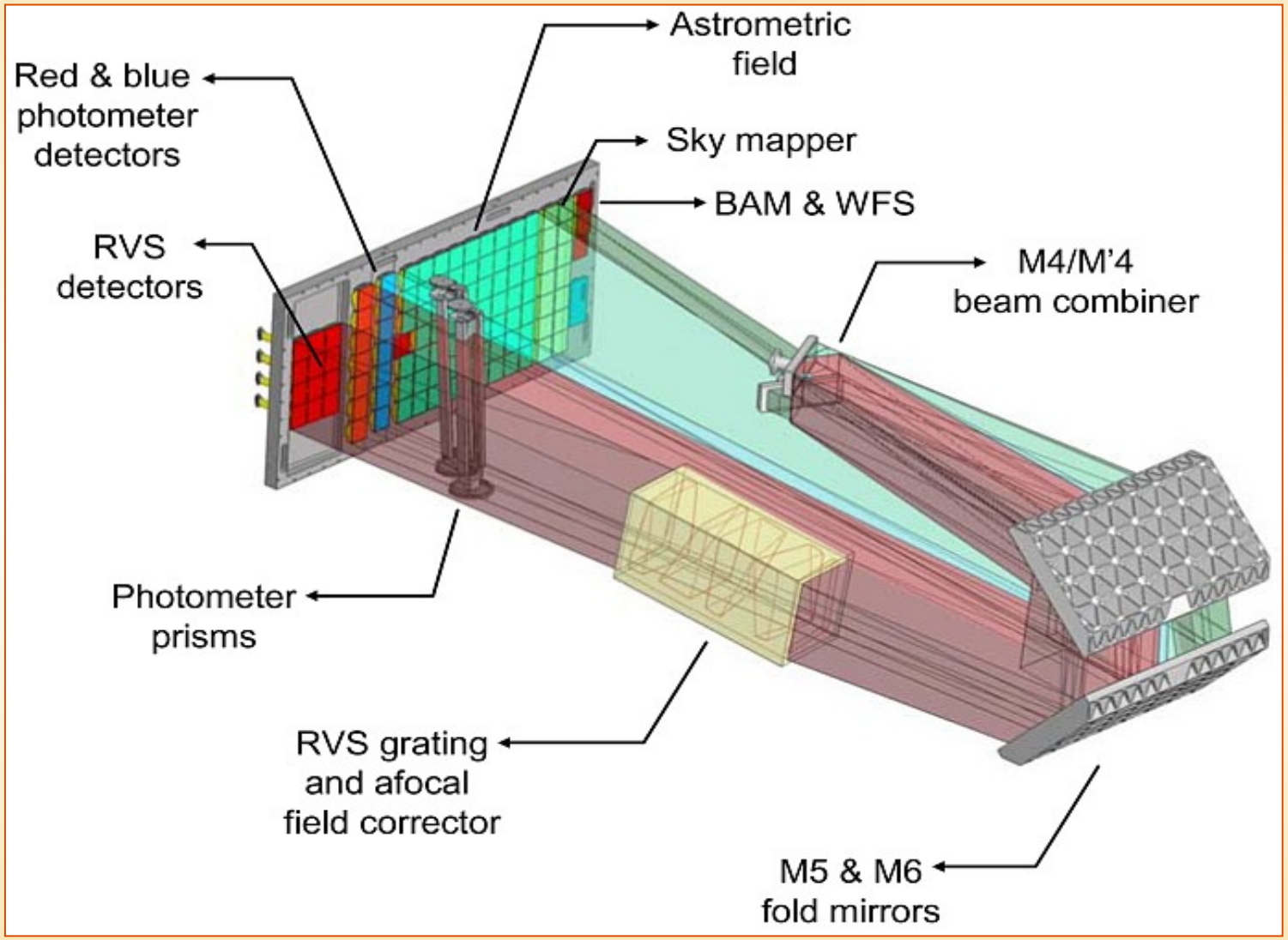
Gaia : telescopes and detector

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



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

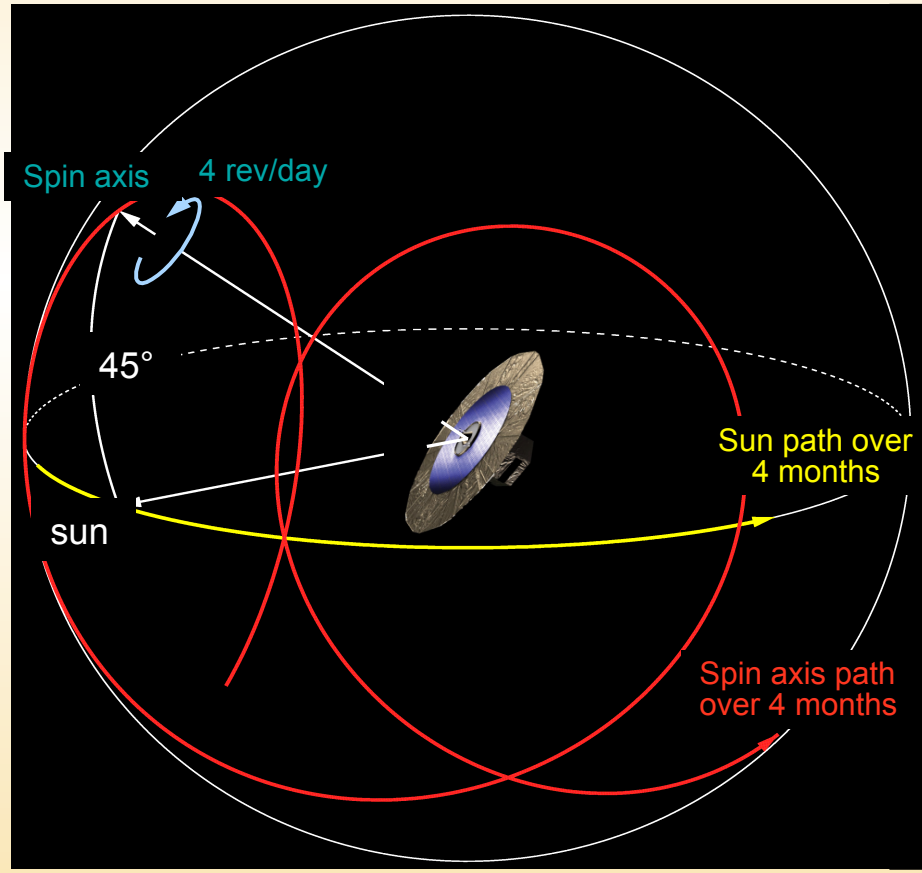
BP/RP & RVS Instruments in the P/L



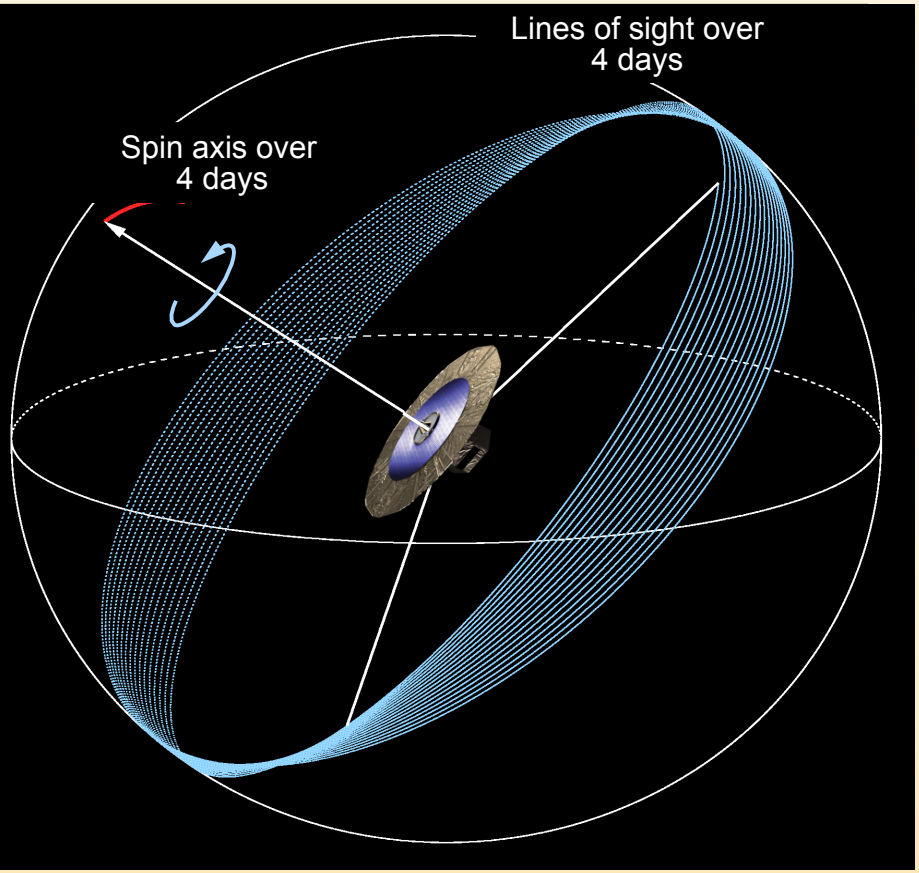
Gaia : Scanning

Gaia DPAC

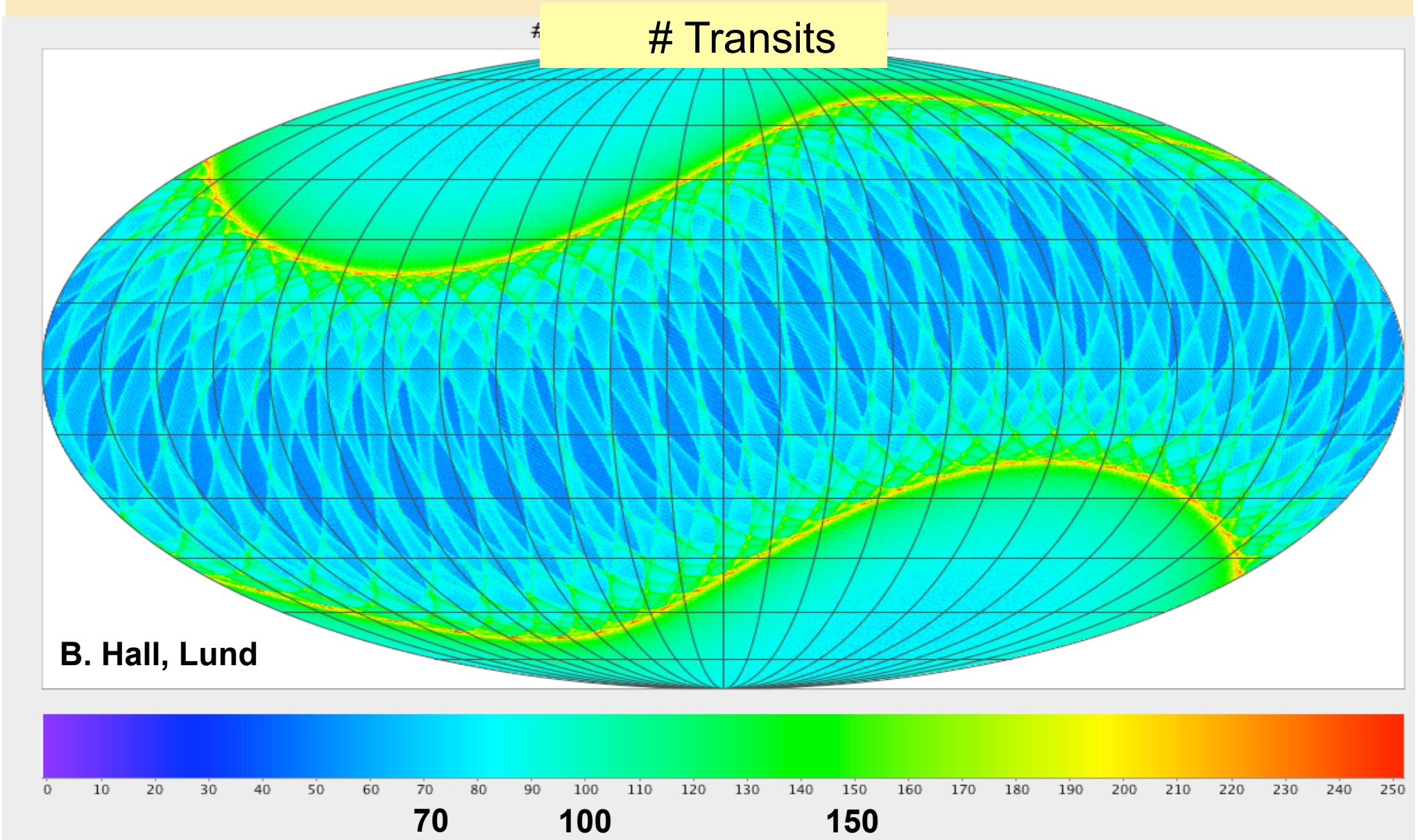
Motion of the spin axis



Sky covered over 4 days

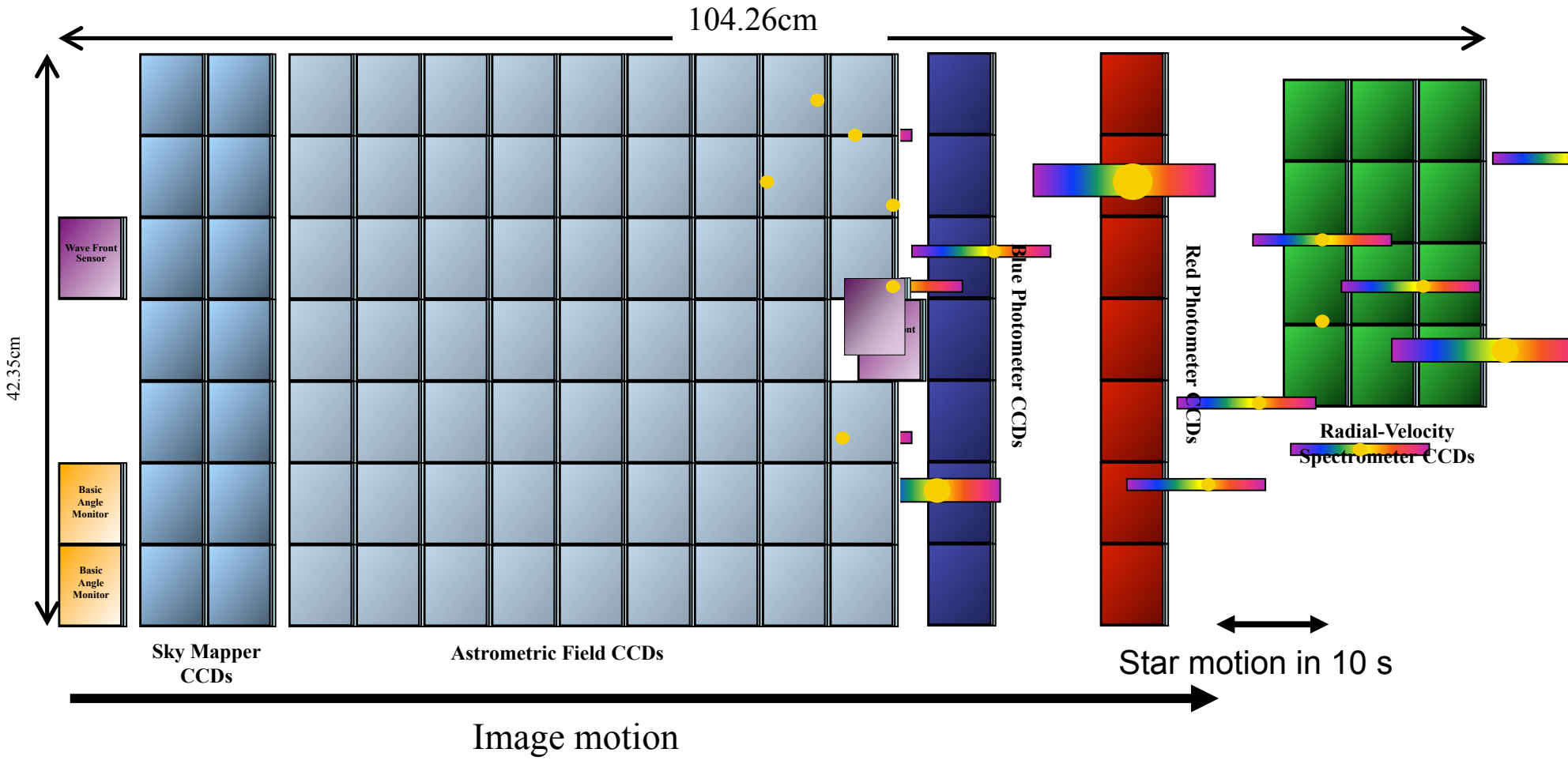


Sky coverage



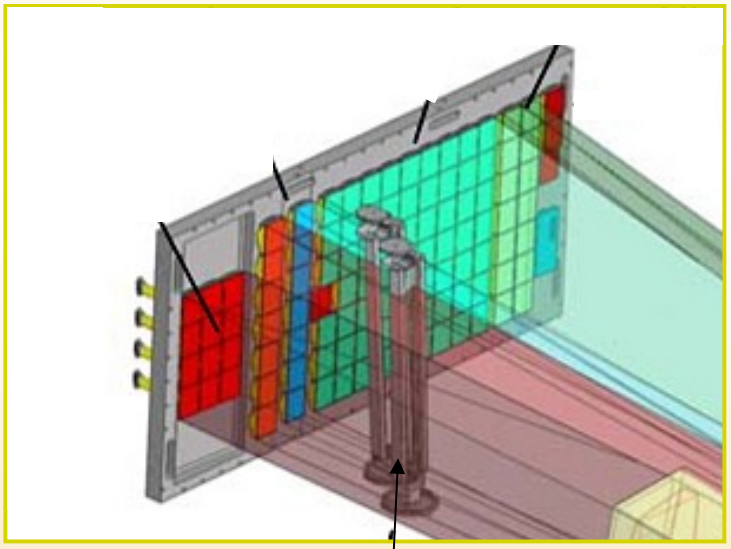
Multiplexing observations

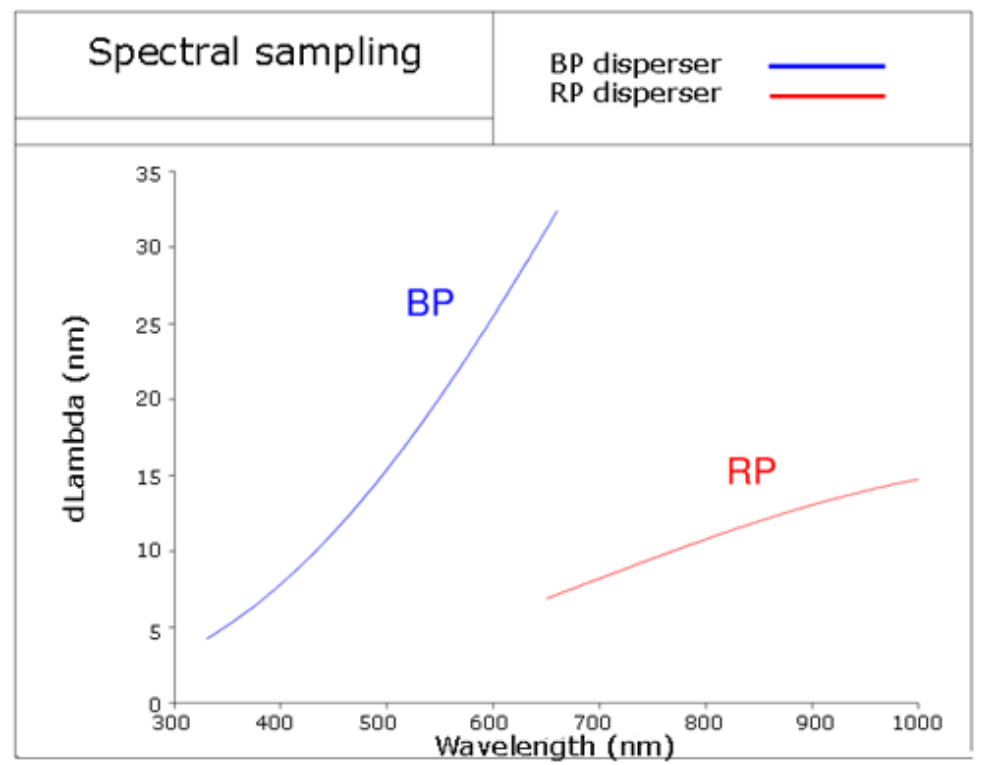
106 CCDs , 938 million pixels, 2800 cm^2



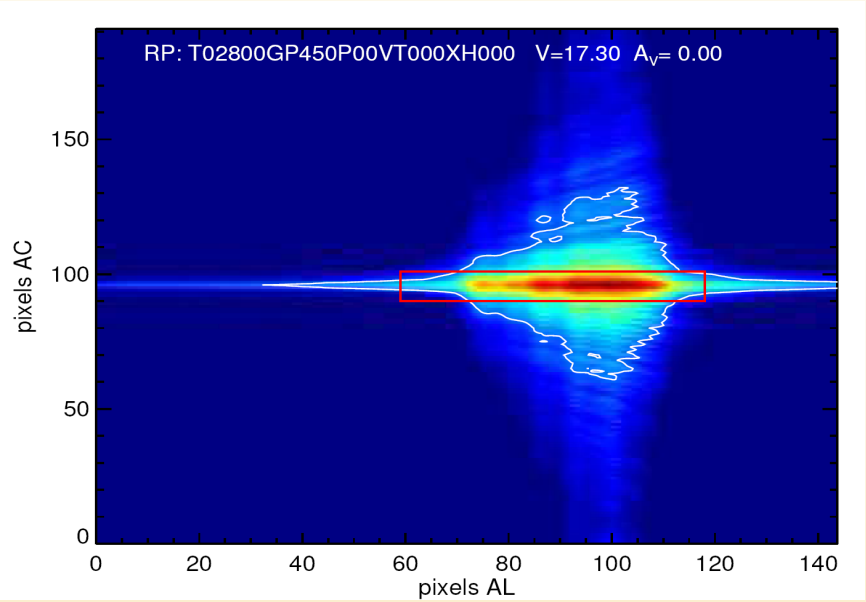
Spectrophotometer

- Two photometers with dispersed images
  - R ~ 50 with time delay mode integration
- Red and Blue enhanced detectors





2 prisms: blue & red gives a covarage of
330 -1100 nm
Pixels varying from ~3 to 30 nm



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

Very low dispersion

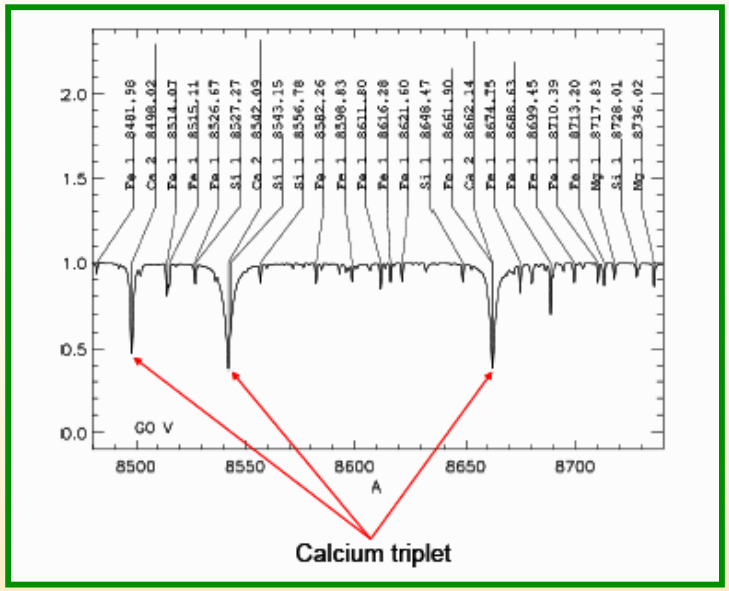
Figures courtesy Anthony Brown

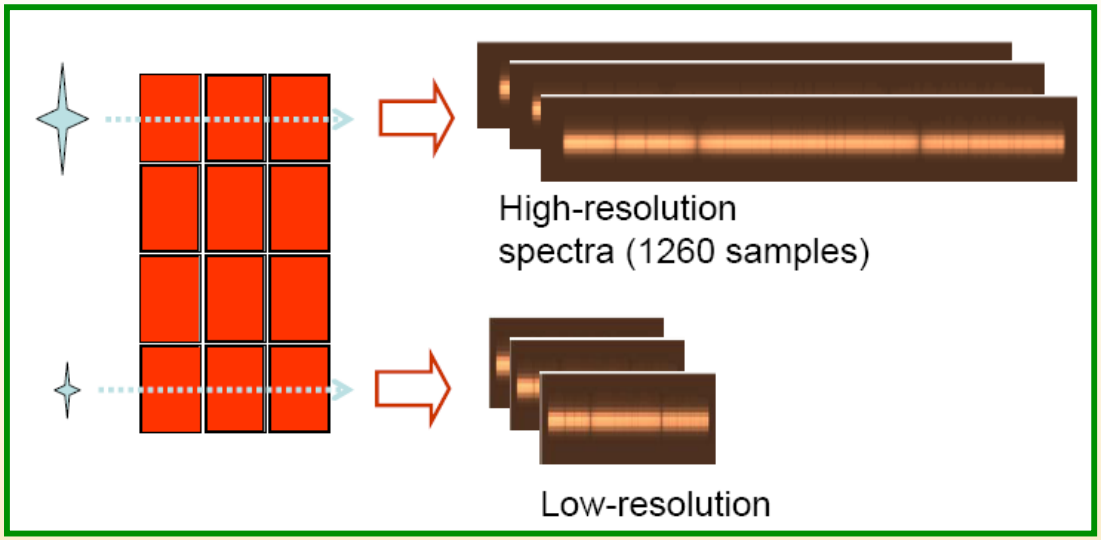
The Radial Velocity Spectrometer

- A prism-grating system in the band 849 – 875 nm R~11500

  Choiced because CaT and Paschen lines for Vr and DIB

  Problem: hard region to simulate for astrophysical studies

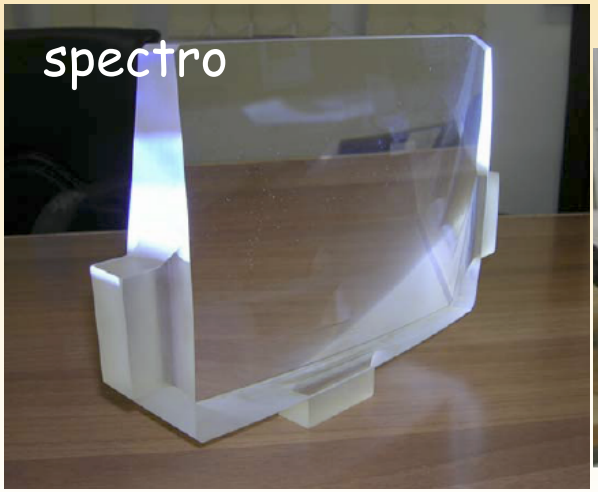


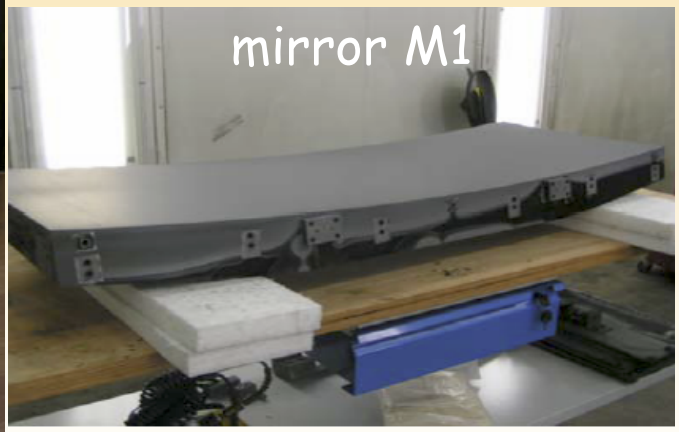


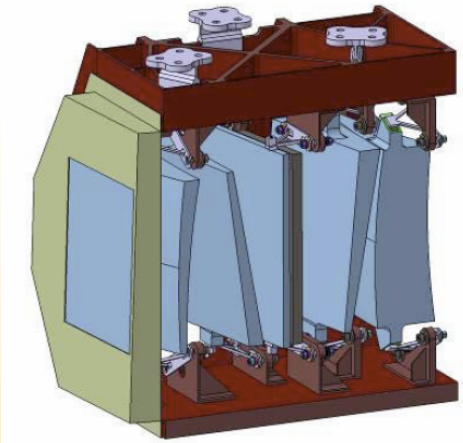
Primary goal Vr & Vsini (expected V=16)

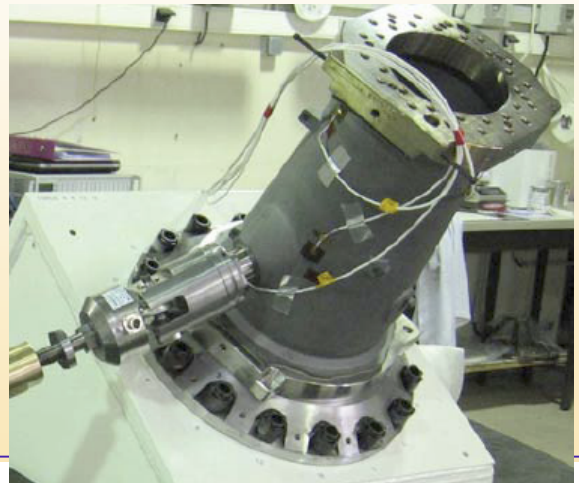
If some problems can be calibrated: some detailed abundances

‘Hard stuff ' already manufactured

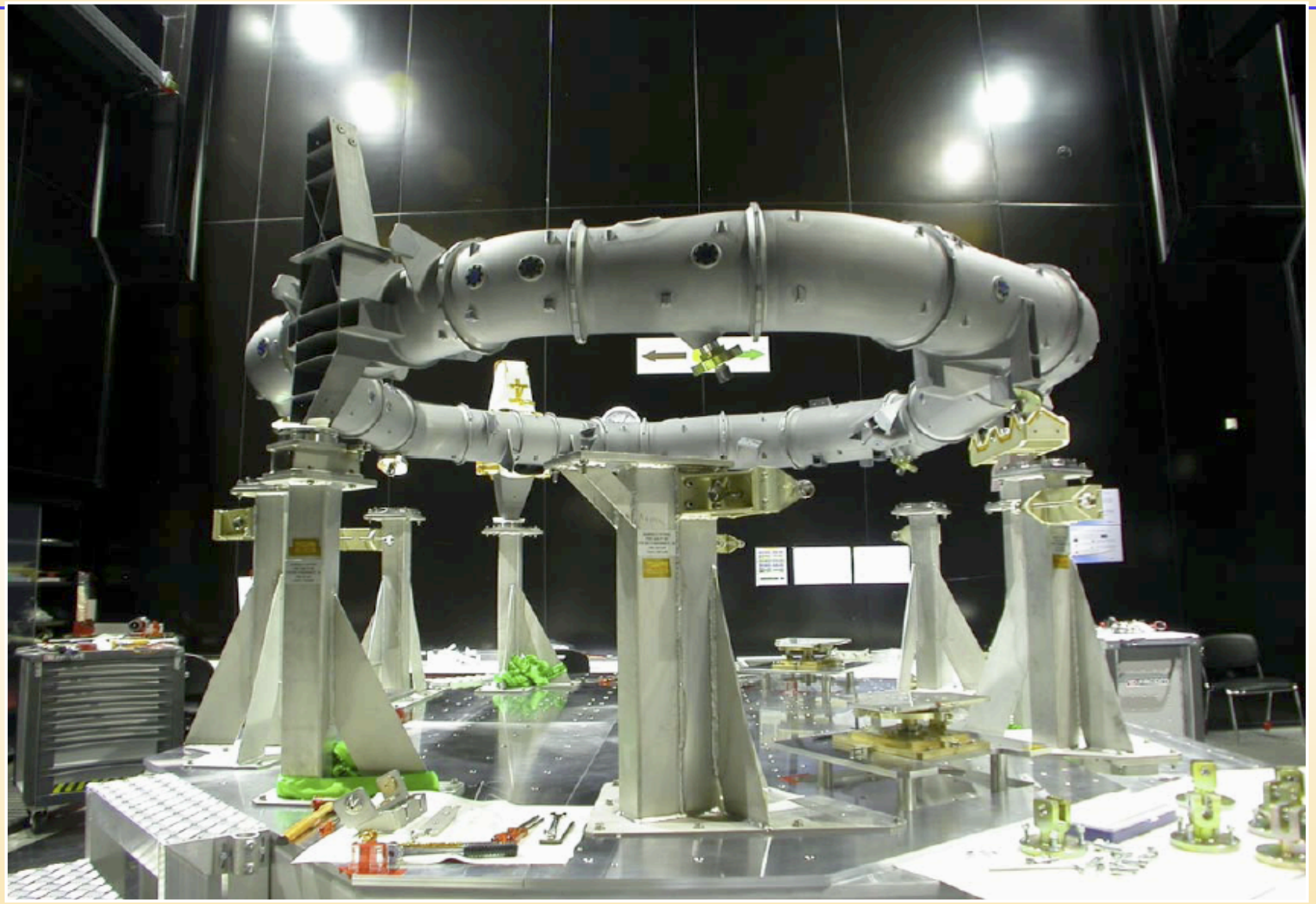




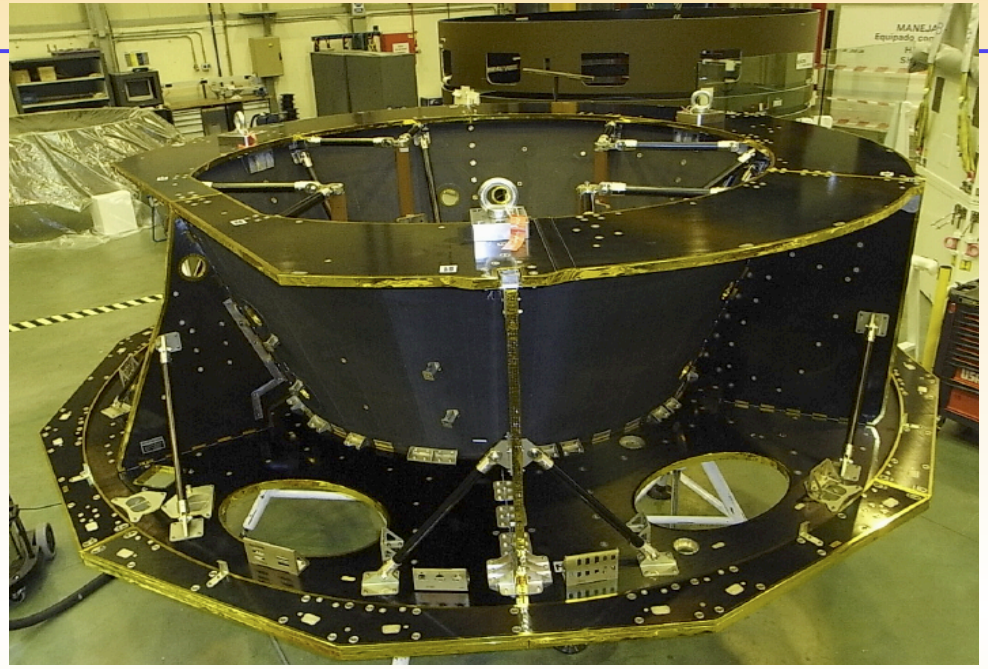




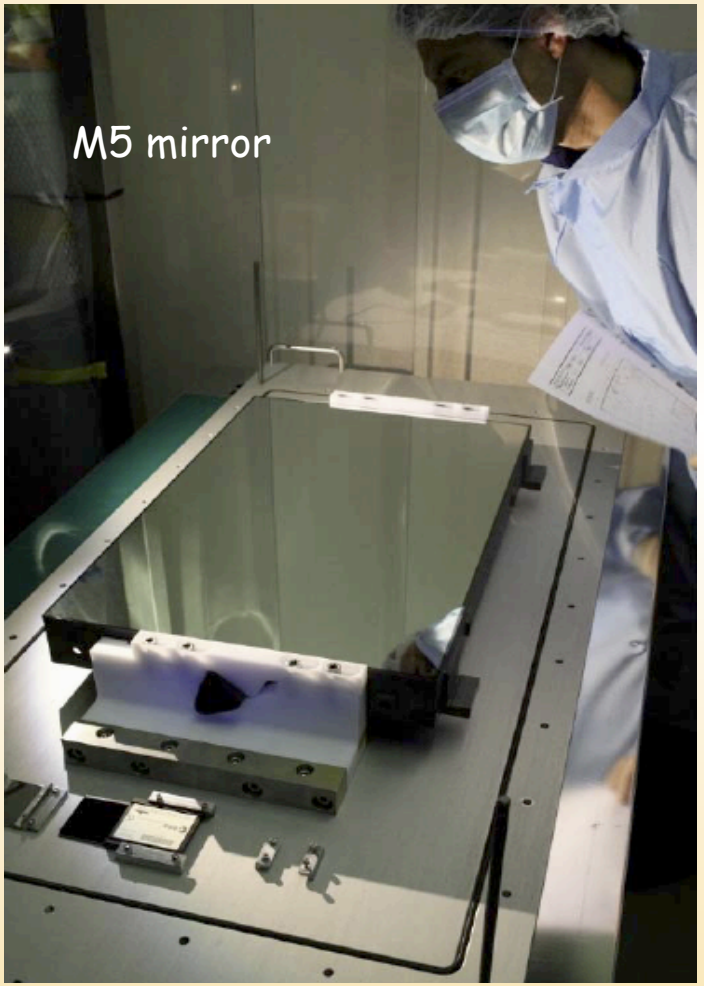
Gaia: Brased torus in place (SiC like the mirrors)

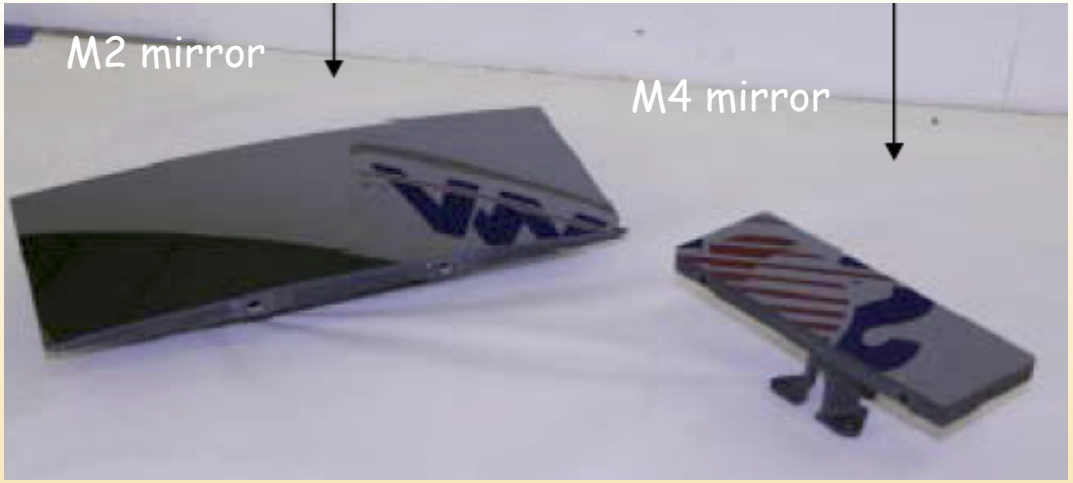


Gaia in construction

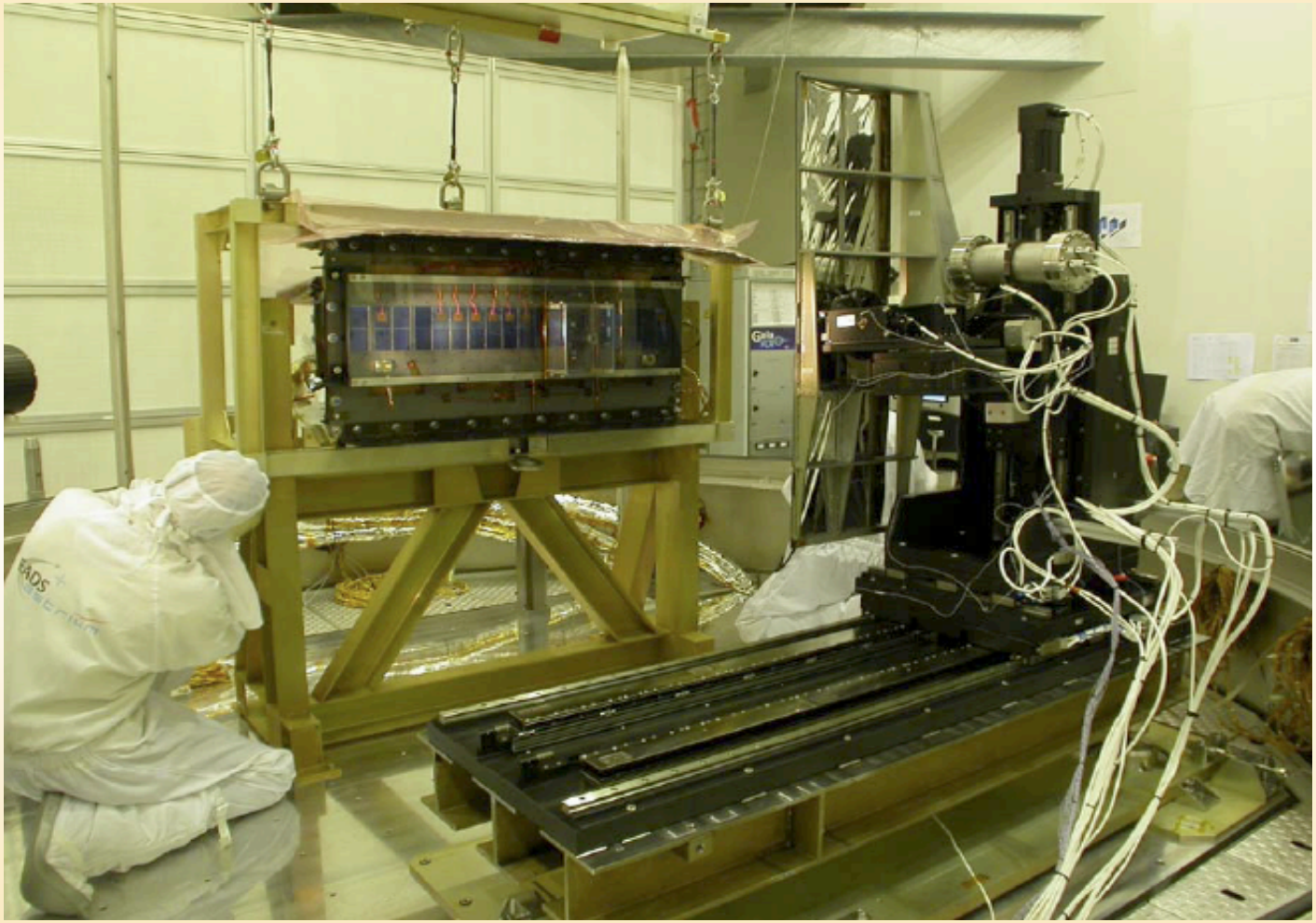


Service Module structure





Testing CCD acquisition mode



EADS Astrium

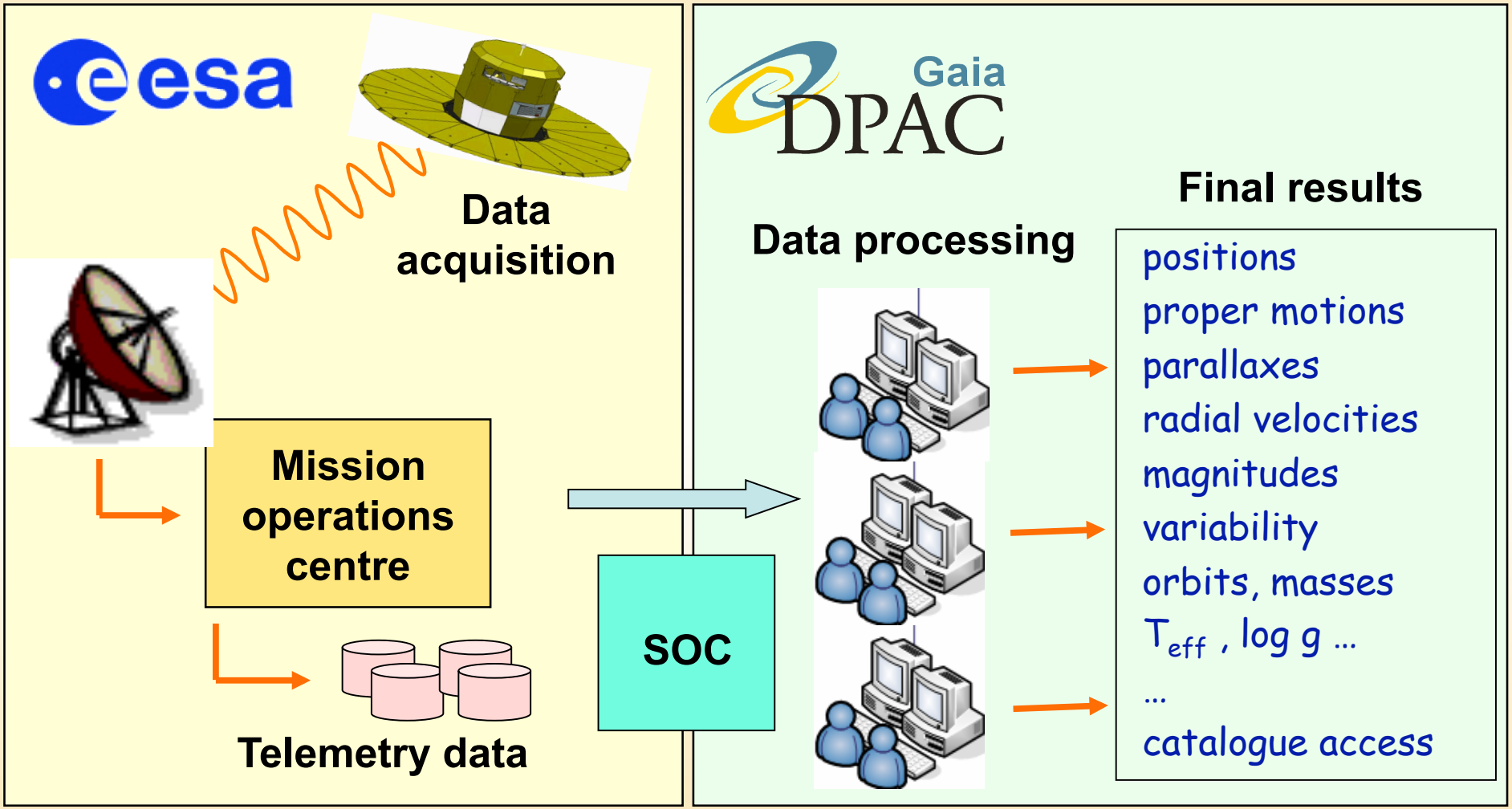
Ephemeris and Tracking

- Accuracy requirements
  - velocity
    - < 2.5 mm/s random
    - < 1mm/s systematic
  - position
    - < 150 m rms
  - distance to Earth
    - < 300 m
- Important efforts of ground base observations for the tracking (GBOT activity)

Data Processing Organization

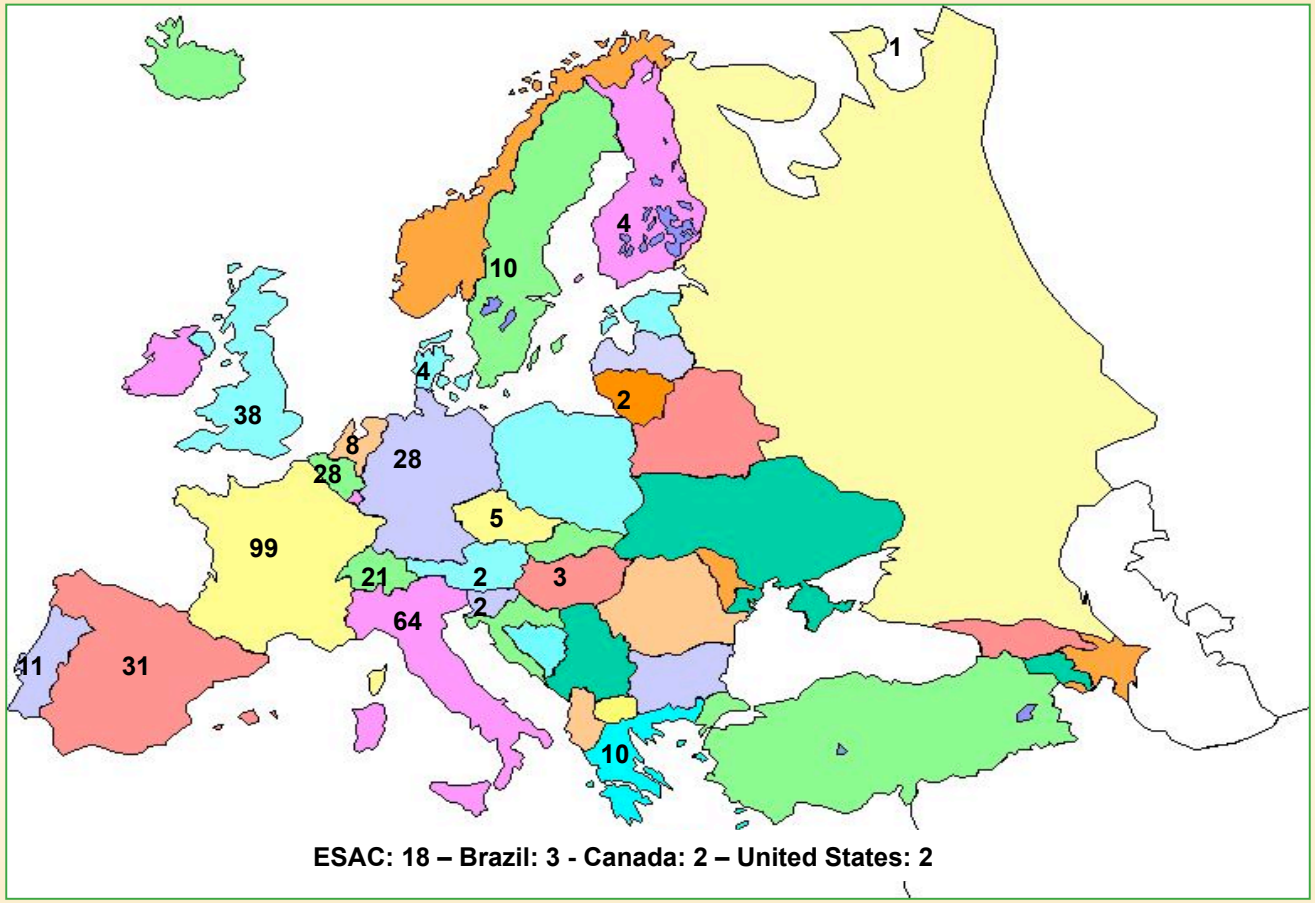
The DPAC

ESA & DPAC Responsibilities



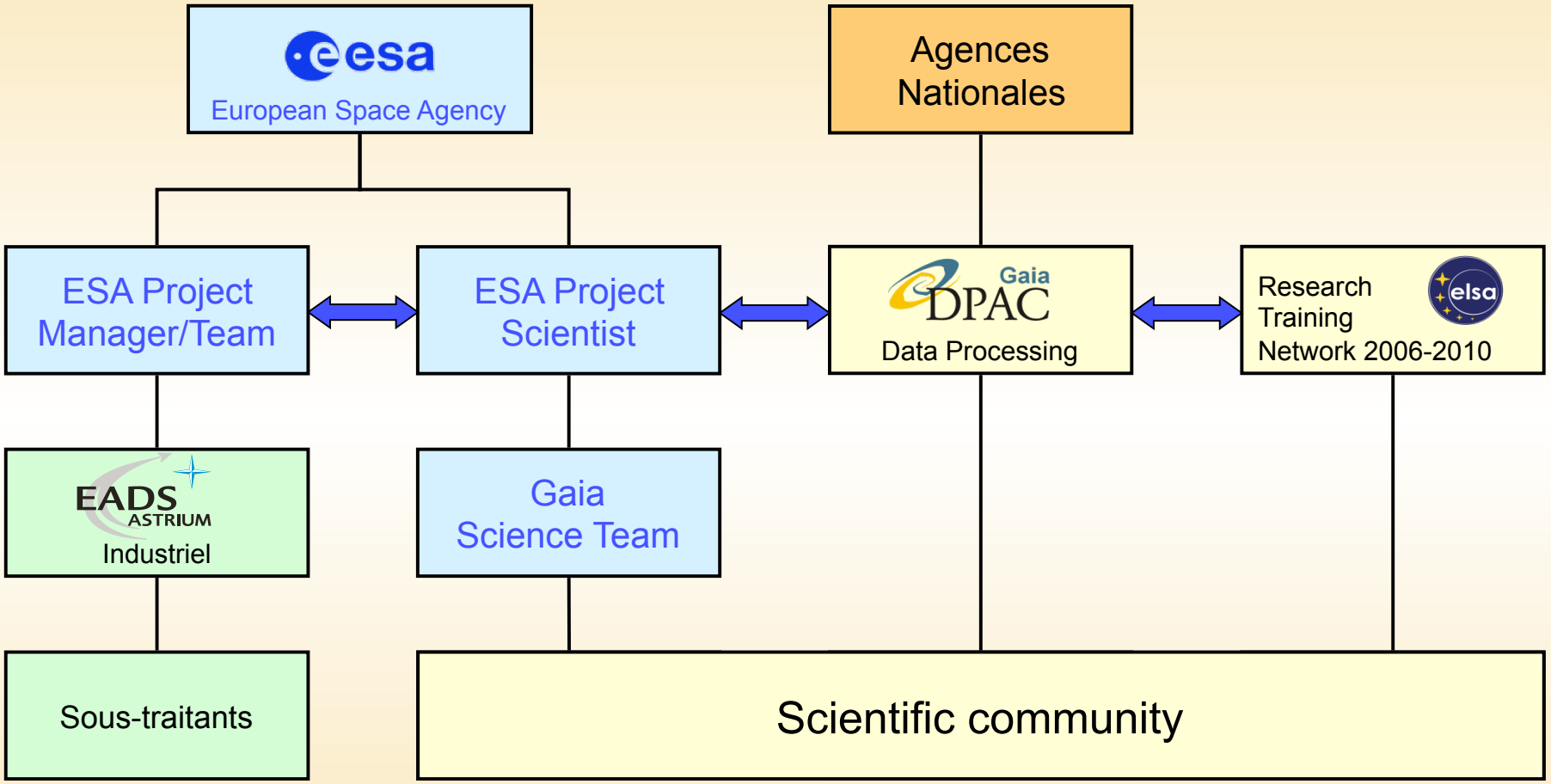
DPAC active members 2009

- 430 members
- 22 Funding agencies

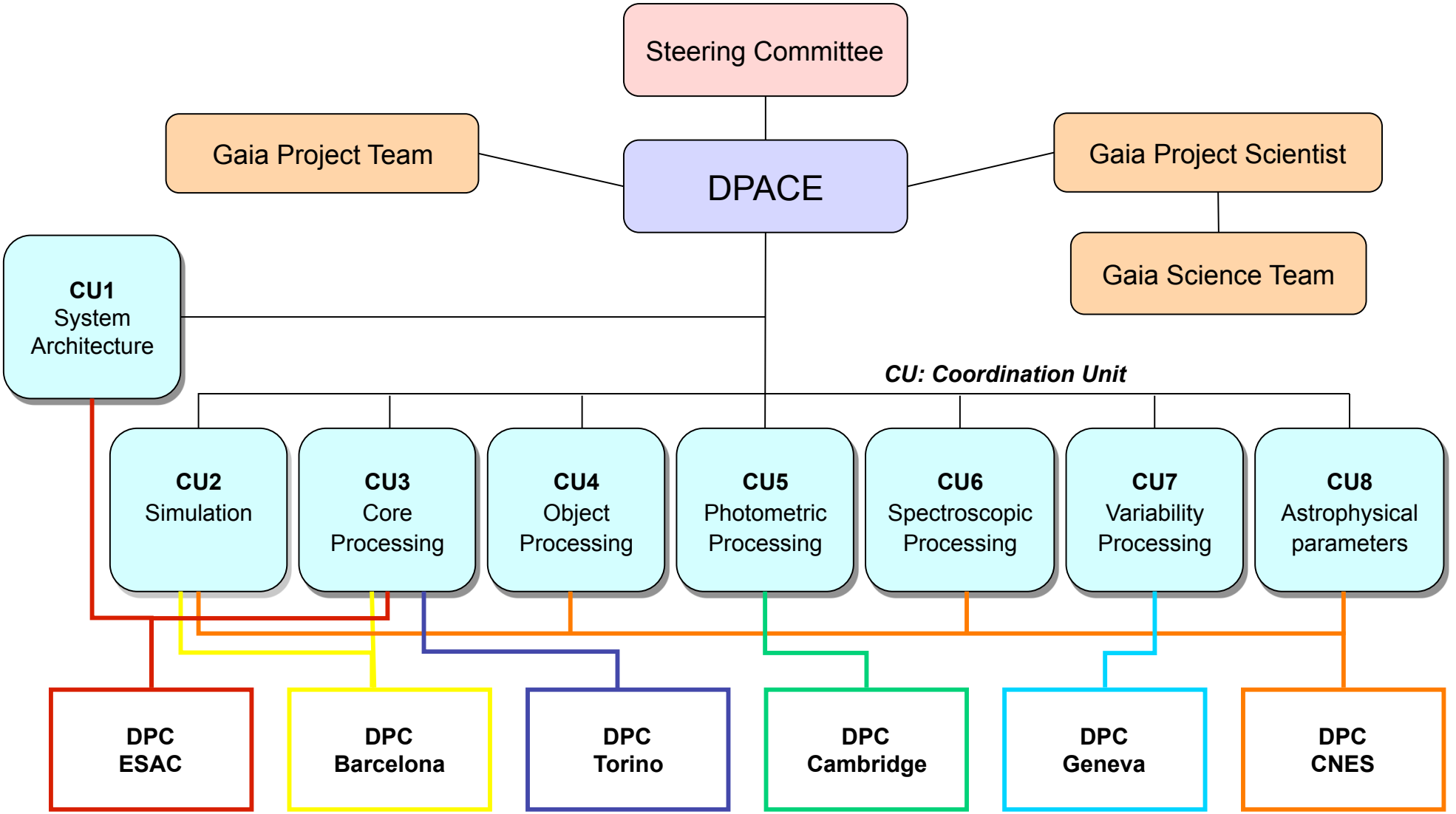


ESAC: 18 – Brazil: 3 - Canada: 2 – United States: 2

The DPAC in the mission overall chart



”Gaia People Finder” recense environ 500 personnes (excluant l'industrie)


Steering Committee
Gaia Project Team
DPACE
Gaia Project Scientist
Gaia Science Team
CU1
System
Architecture
CU: Coordination Unit
CU2
Simulation
CU3
Core
Processing
CU4
Object
Processing
CU5
Photometric
Processing
CU6
Spectroscopic
Processing
CU7
Variability
Processing
CU8
Astrophysical
parameters
DPC
ESAC
DPC
Barcelona
DPC
Torino
DPC
Cambridge
DPC
Geneva
DPC
CNES
DPC: Data Processing Centre

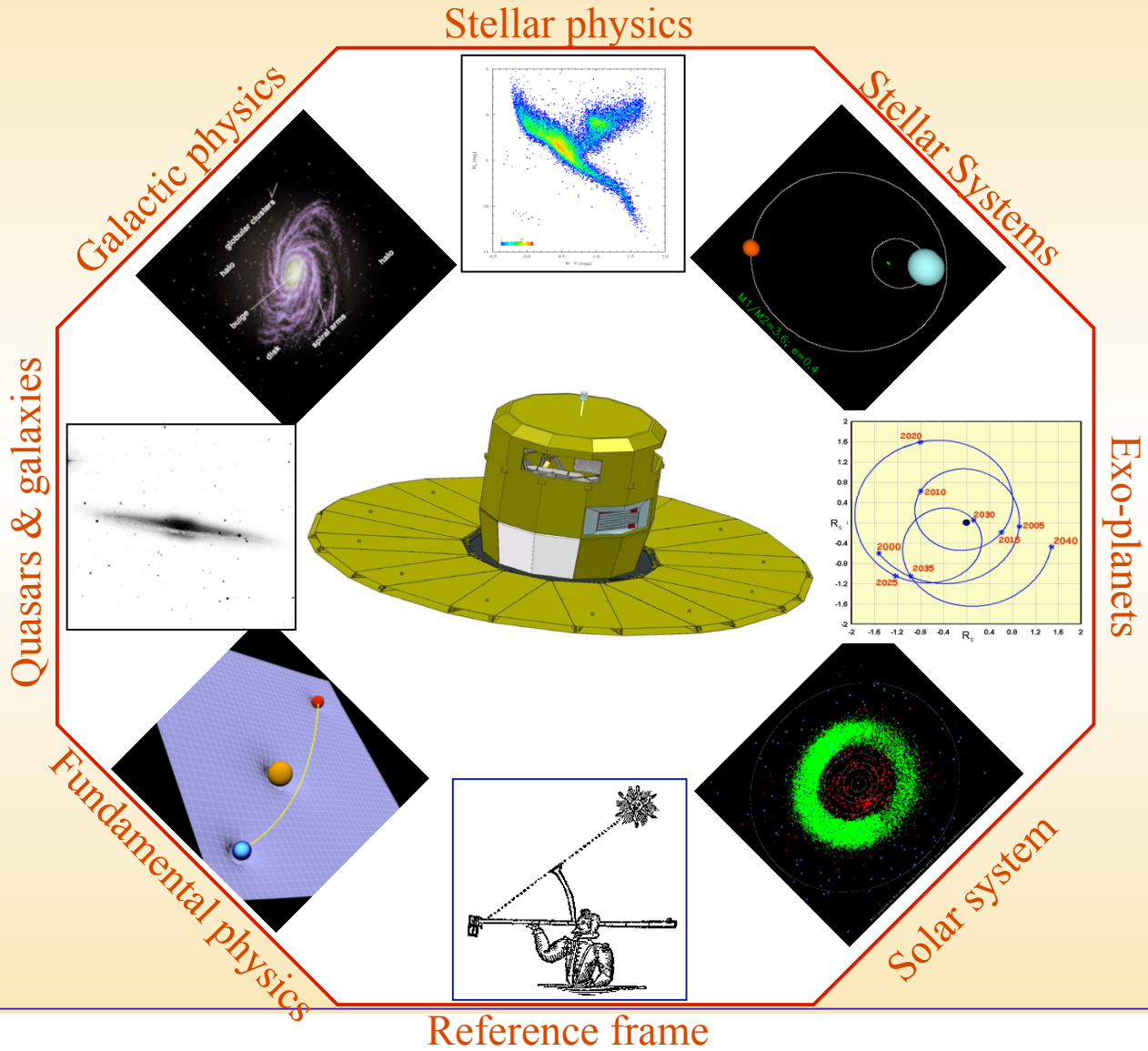
We need the help of ground based telescopes for calibrations

In particular in the ecliptique poles and for ~500 stellar calibrators

The effort will be on a long time but

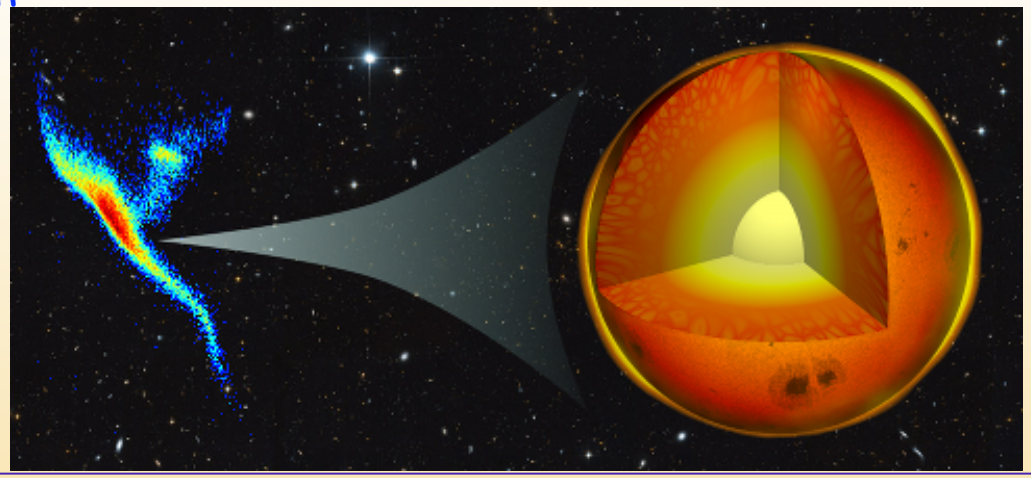
it is mandatory for Gaia and the Astronomy

Science with Gaia



Stellar physics: HR diagram

- Accurate distances across the HR diagram
  - luminosity calibration
    - calibration photometric and spectroscopic distance indicators
  - tests of stellar interior models and stellar evolution: convection & rotation
  - initial mass function, census of multiplicity
  - fundamental parameters for rare stellar types
  - astrometric detection of stellar, sub-stellar and planetary companions
  - 3-D mapping of interstellar extinction



Masses and Ages of single stars and clusters

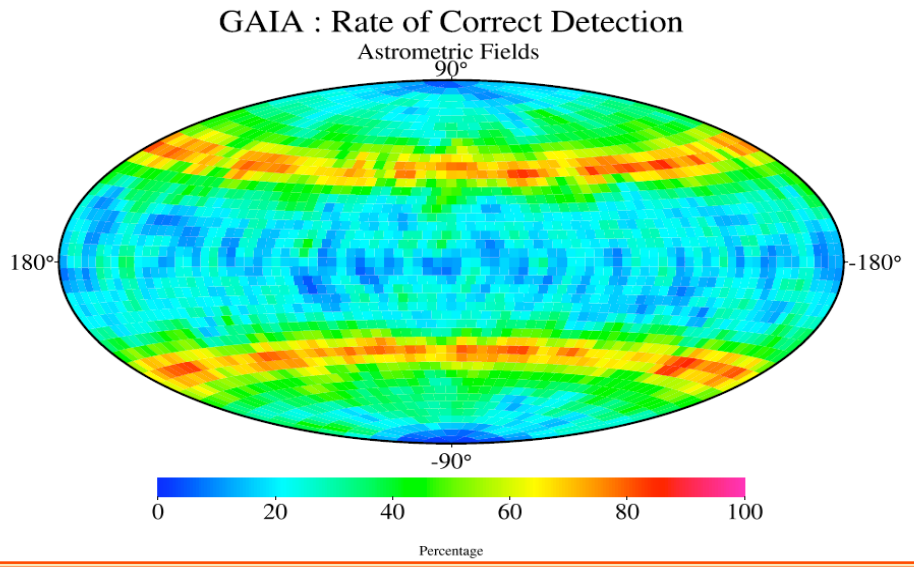
- Will give a relation between Age & Fe/H
- Astrometric and spectrographic binaries will offer an opportunity to have precise ages for about 5000 binaries

Need ground based observations in complement for the best objects

Stellar physics: Variable stars

- 90% of variable stars V< 12 not yet identified (Paczynski, 2000)
- Currently Hipparcos remains the largest all-sky survey
  - 10% of the Catalogue , amplitude > 0.02 mag
- Other GB surveys are under-way (Pan Starrs, LSST, OGLE)
  - deeper than Hipparcos but not 4π coverage
- Objective for Gaia
  - ~ 80 epoch survey over 5 years
  - mmag accuracy of single observation
- Qantitative impact
  - 20×10^6 classical variables
  - 1 – 5 million eclipsing binaries
  - ~ 5000 cepheids, 70,000 RR Lyr
  - 6,000 SNe Ia to G =19

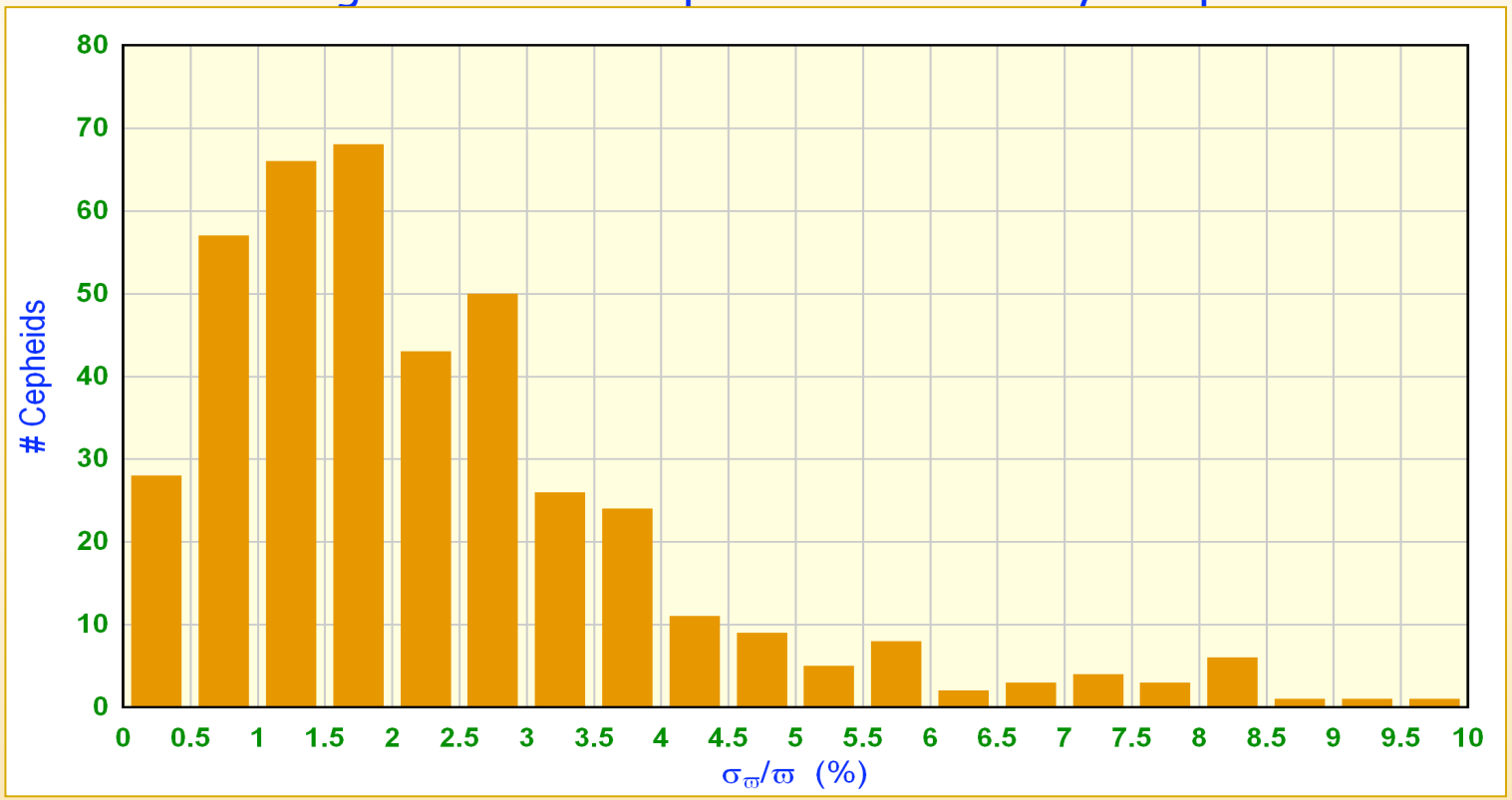
Example: S/N= 0.75, Per=0.2 day



Eyer & Mignard, 2005

Cepheids with Gaia: impact on the physics of these stars and on the masses of the Cepheids.

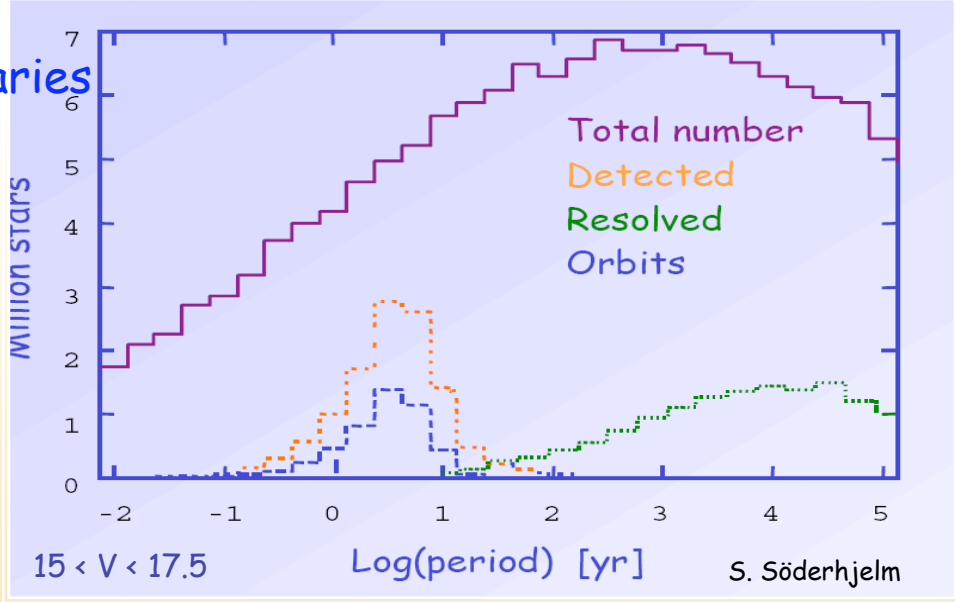
- 15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc
  - bright enough (V < 14)
- In the plot : 400 galactic cepheids from David Dunlap DB
  - distance and magnitude ➔ Gaia predicted accuracy for parallax



F. Mignard 2002, 2009

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 various categories of binaries
    - 10^7 resolved within 250 pc (long period)
    - 10^7 astrometric binaries
    - $10^{6\text{-}7}$ eclipsing binaries, 10^6 spectro
  - 50% complete census to 250 pc
  - masses to 1% for 10^4 stars
  - constraints on evolutionary models



Spectroscopic survey with the RVS

- Stellar and interstellar parameters *(conservative estimates)*

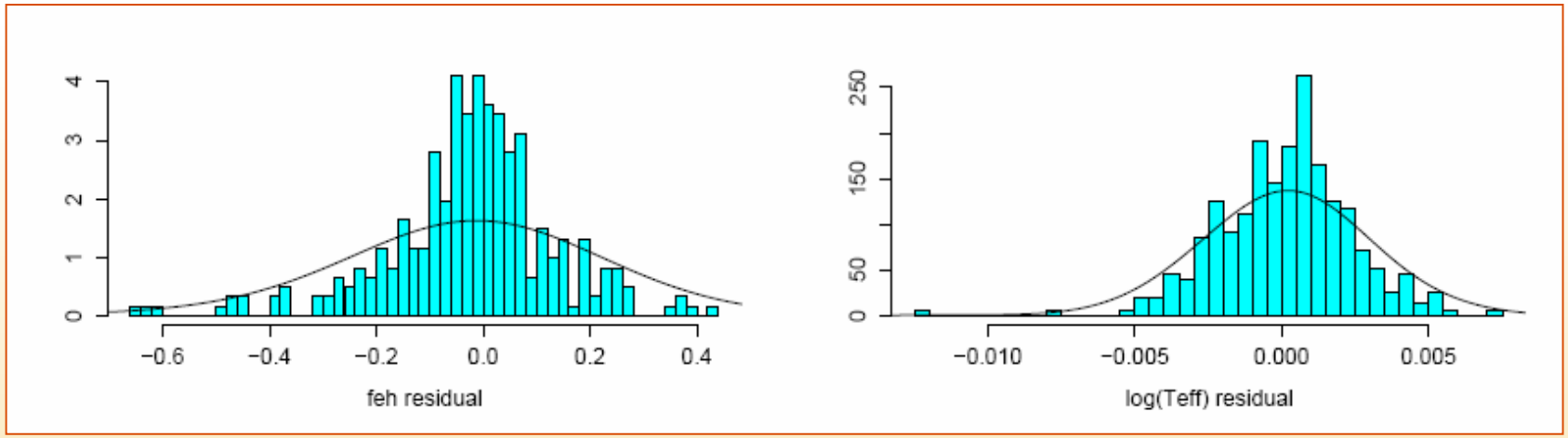
◆ Radial velocities	V ≤ 17.0	~ 150x10^6 *
◆ Rotational velocities	V≤13	~ 5x10^6
◆ Atmospheric parameters.	V≤13	~ 5x10^6
◆ Abundances	V≤12	~ 2x10^6
◆ Interstellar reddening	V≤13	~ 5x10^6

- Diagnostics
  - ◆ Binarity/multiplicity, variability
  - ◆ ~ 10^6 spectroscopic binaries
  - ◆ ~ 10^5 eclipsing binaries (~25% SB 2 → masses)
  - ◆ Long period classical cepheids σ_{vr}< 7 km/s ➔ 20-30 kpc

Performances AP: BP/RP

	T_{eff}	Ag	log g	[M/H]	[α/Fe]
G<16	<5%	0.05-0.2	0.2-0.3	0.2-0.4	0.2
G=18	5-15%	0.05-0.3	0.2-0.5	0.5-0.7	?

- Ranges in errors reflect the influence of the spectral type, metallicity



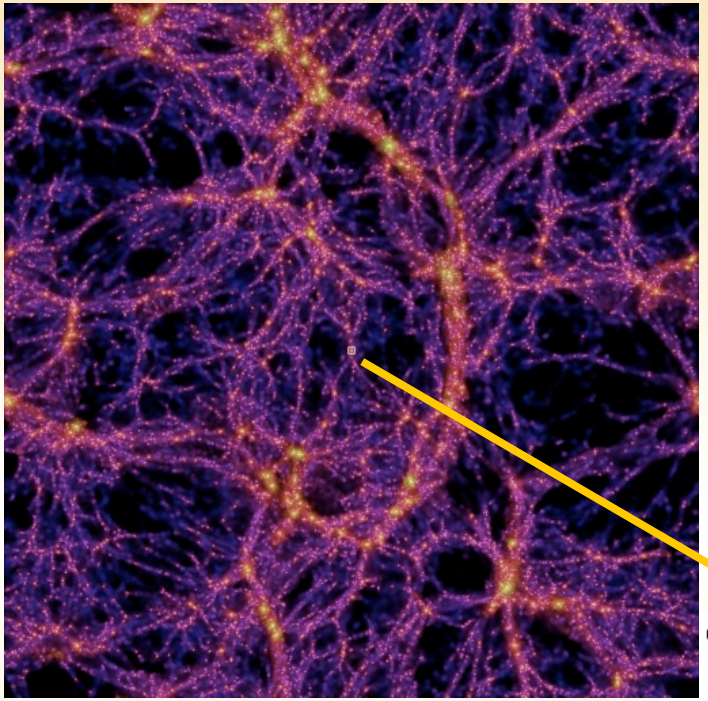
dwarfs, G = 15, T < 7000 K, [Fe/H] > -2

C. Bailer-Jones, GAIA-C8-TN-MPIA-CBJ-043

Galactic physics

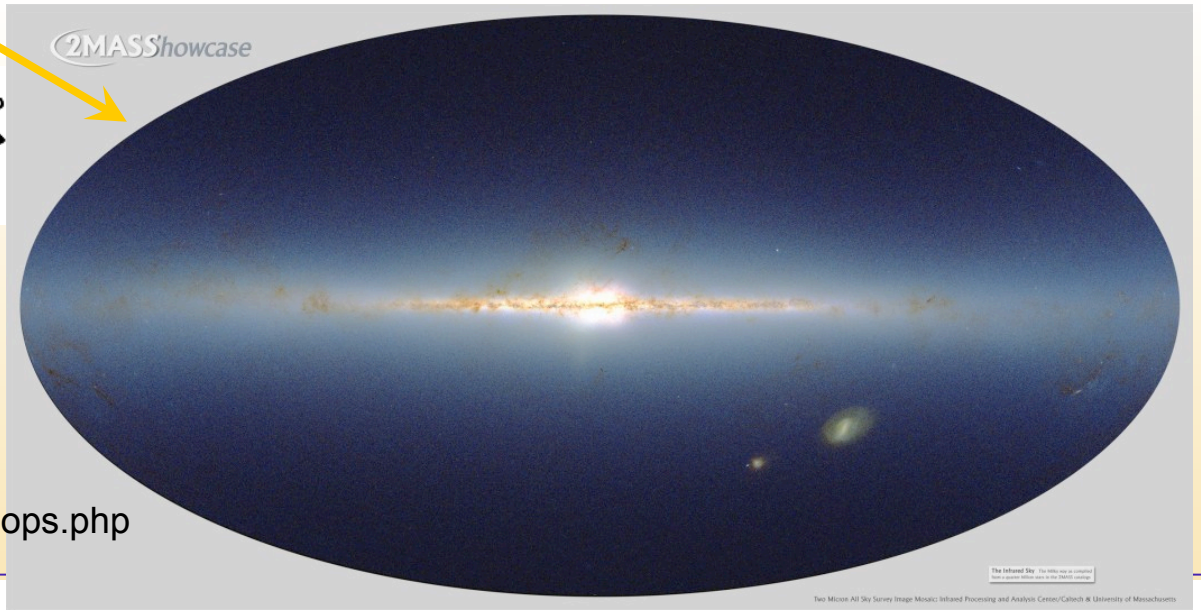
- First survey providing 6D phase space (**r**, **v**)
- Photometry for very large magnitude-limited samples of stars
  - Distances + magnitudes & colours + kinematics
    - **spatially and kinematically resolved distributions** (luminosity, age, metallicity)
    - history of **star formation**
    - **chemical enrichment** history
  - Number density and kinematics of tracer stars
    - refined galactic rotation model
    - mapping the **galactic potential**
    - **distribution of (dark) matter**
    - **disk dynamics** (bar, spirals)
  - Phase space (or E, Lz) structures in halo
    - history of **galactic mergers**
- Colour/mag diagrams for dwarf galaxies in the local group
  - astrometry and photometry of individuals stars

Galactic physics



Aquarius project

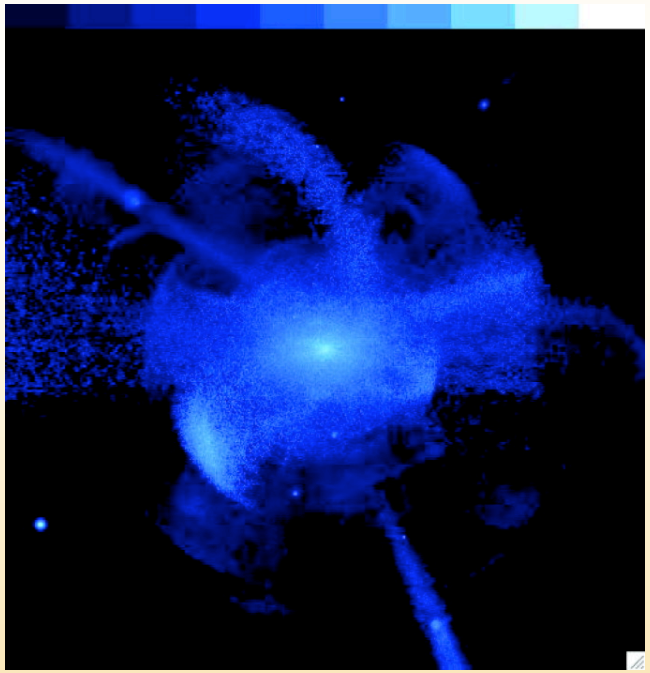
- which stars form and where?
- mass distribution throughout Galaxy?
- spiral structure?
- mass cycling?
- how universal is initial mass function?
- impact of metal-free stars on Galaxy evolution?
- merging history?
- Galaxy consistent with ΛCDM?

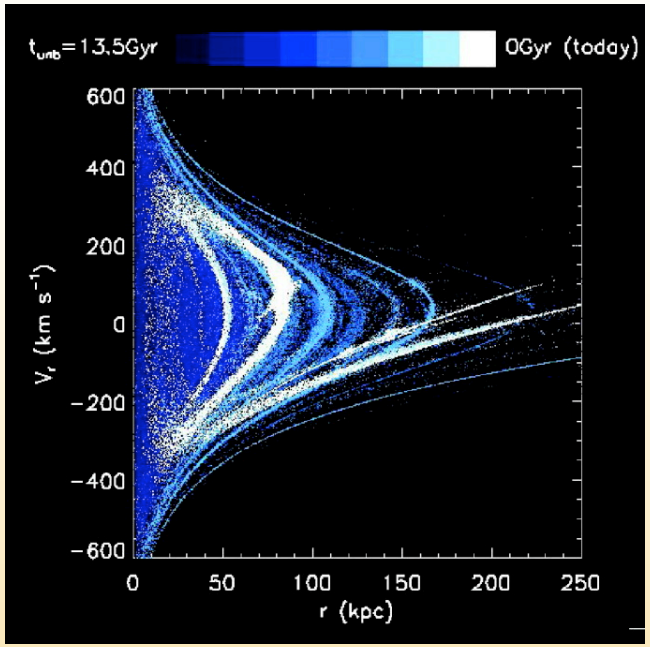


see: www.stecf.org/coordination/esa-eso/galpops.php

Galaxy and local group: Gaia's impact

- First survey providing 6D phase space (**r**, **v**)
  - all-sky and large-volume coverage
  - accurate and robust spatial/kinematic separation of structural components
  - phase-space mapping (E, Lz, J, etc)
  - detailed properties of bulge, thin/thick disk, halo (substructure), spiral arms



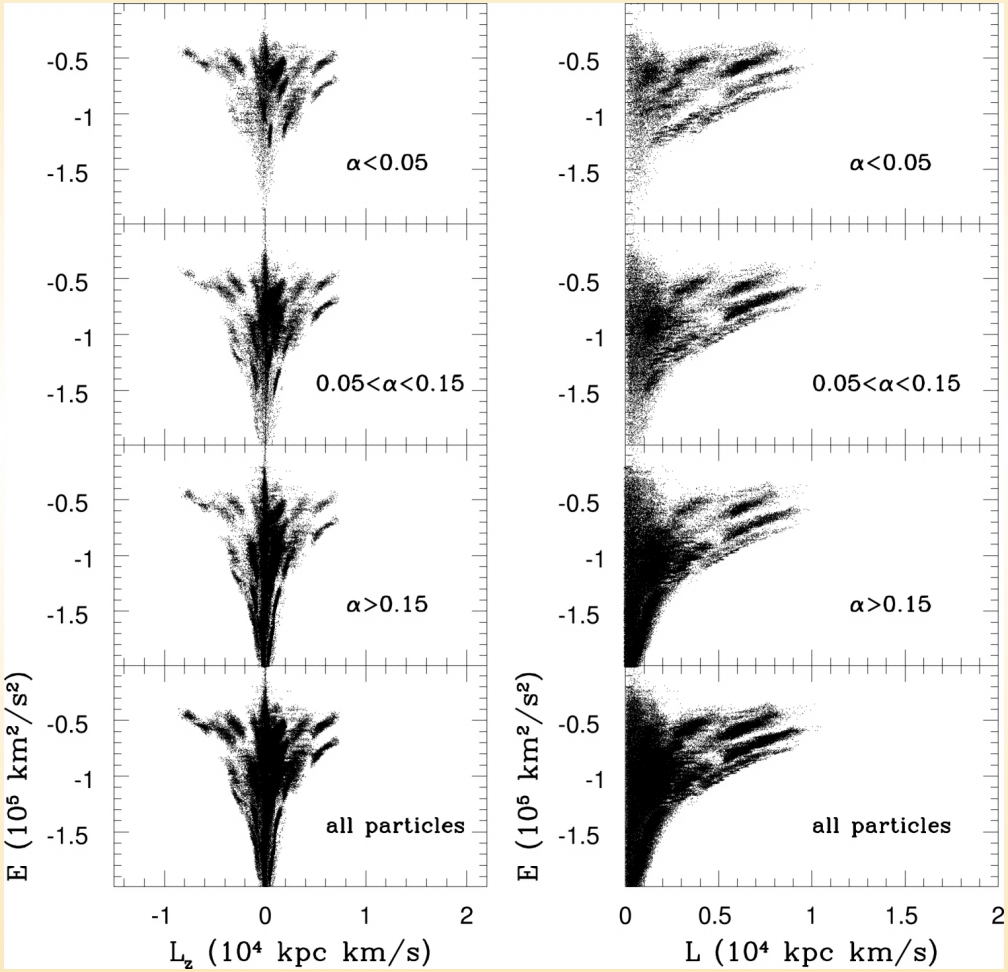


Bullock & Johnston 2005

Galaxy and local group: Gaia's impact

- Accurate mapping of HR-diagram
  - accurate luminosities
  - improved stellar structure and atmosphere models
  - age and chemical composition determinations
  - detailed characterization of stellar populations
  - star formation history and chemical evolution

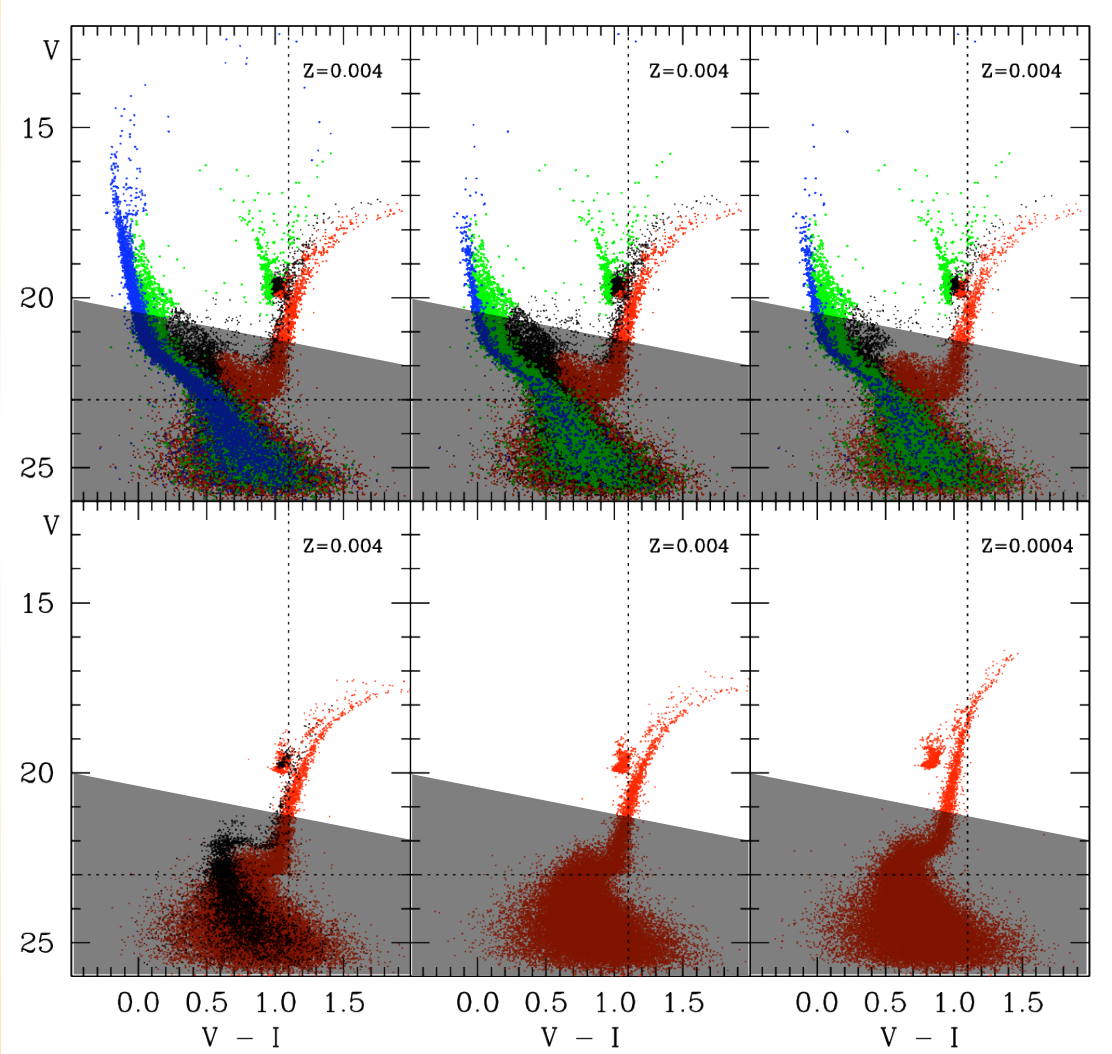
For more details on the impact of Gaia on the past history of the galaxy see papers by A. Helmi



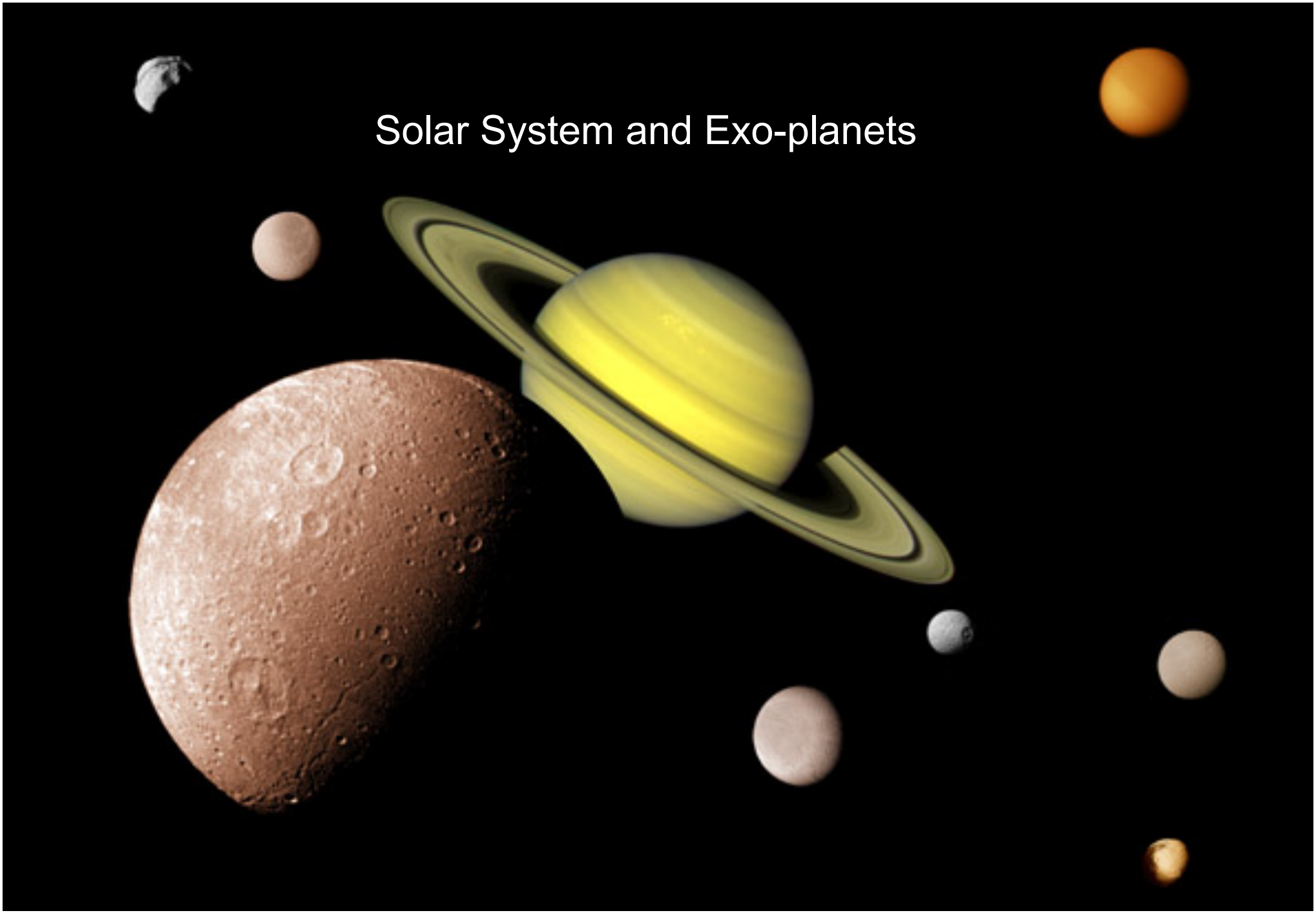
Font et al. 2006

Galaxy and local group: Gaia's impact

- Astrometry/photometry for **individual** stars in local group dwarf galaxies
- G=20 corresponds to V=20-22

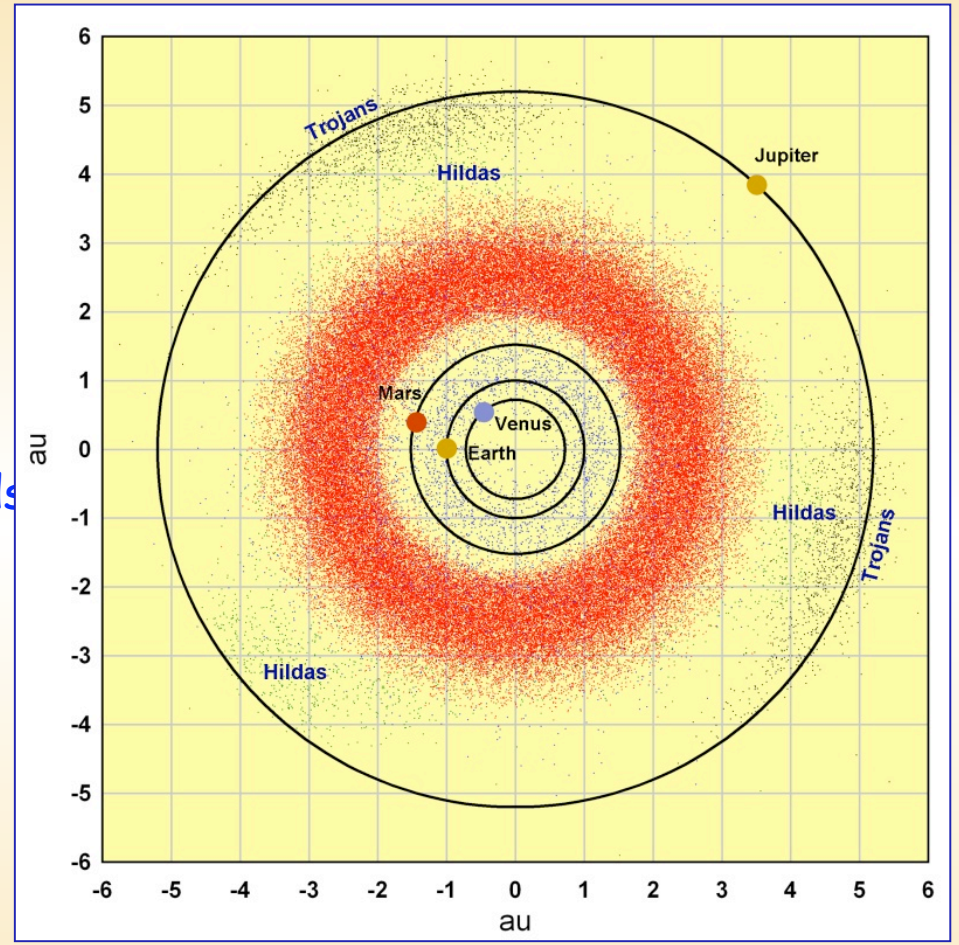


Tolstoy, Hill, Tosi 2009


Solar System and Exo-planets

Solar system

- Objects observed,
  - 6< V <20, size <200 mas
- ~70 observations / object
  - < 1mas accuracy for individual transits
- Astrometry and photometry for:
  - 3×10^5 Main Belt & Near Earth Asteroids
    - 50,000 new objects expected
  - Jupiter Trojans
  - Comets and TNOs
  - small planetary satellites
- Spectroscopic properties
  - limited to bright end (V<13)



Solar system at time of Gaia launch, F. Mignard 2009

Solar System Science: final products

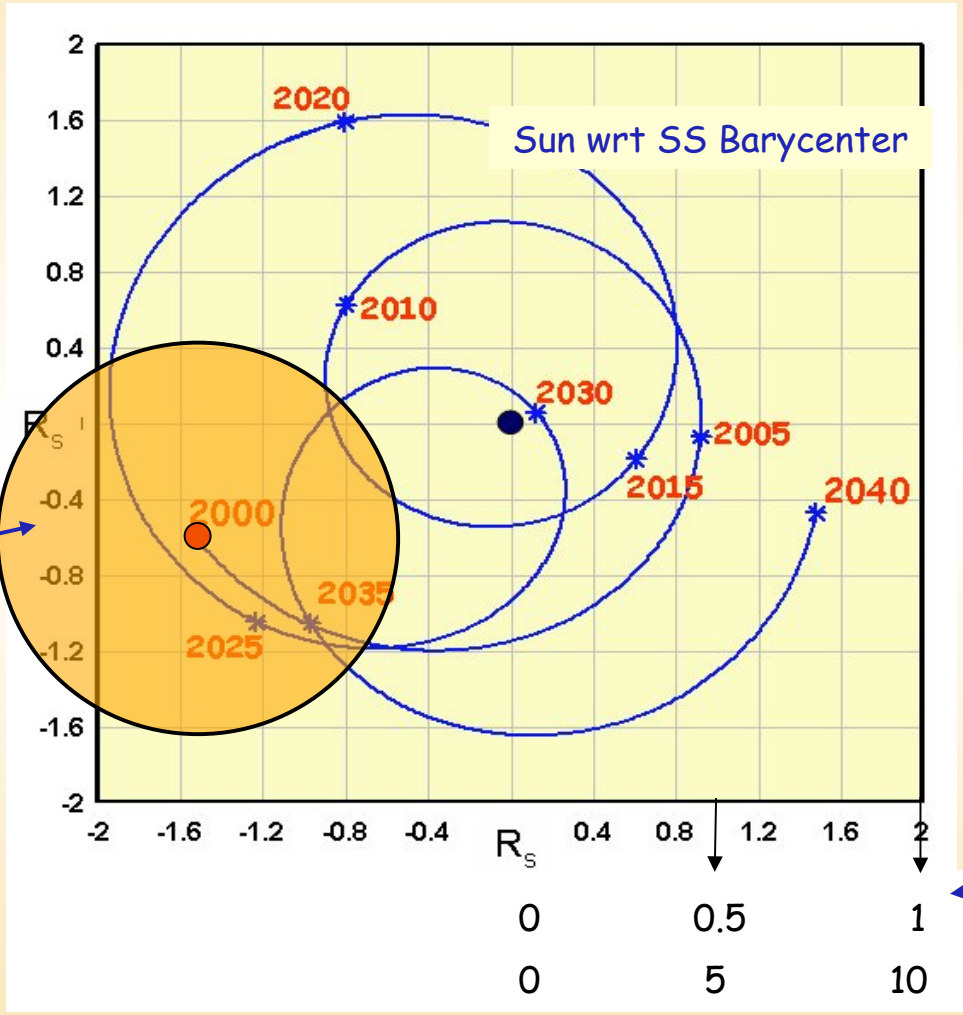
Gaia Solar System Astrometry

ground-based	Gaia single measurement
0.1 - 1 arcsec	*0.1 – 1 mas*

- Systematic survey down to 20 mag ~ 3x10^5 objects
  - Observations at high ecliptic latitudes and to within 45° from Sun ➔ exotic orbits
- Orbits : virtually all object observed - x30 better than now
- Masses from close encounters ~ 100 masses expected
- Diameter for over 1000 asteroids : shape, density
- Photometric data in several bands : albedo, taxonomic classification
- Light curves over 5 years : rotation, pole, shape
- Space distribution vs. physical properties
- Perihelion precession for 300 planets : GR testing, solar J2

Exo-planet search

Sun reflex motion

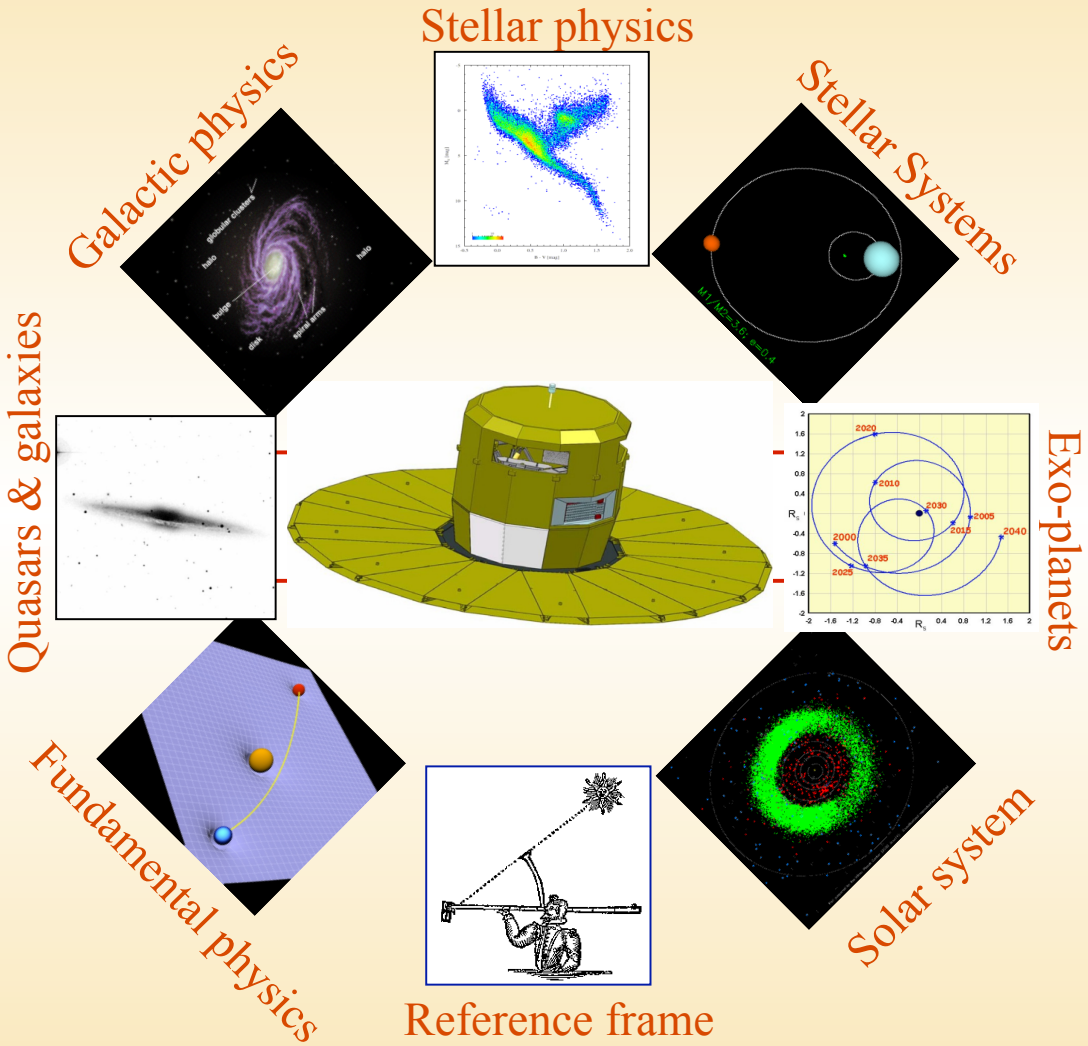


- Full solar system
- Reflex motion of the Sun
- Period 10-30 yrs
- Wobble dominated by Jupiter and Saturn
- Planet ~M_J detectable

Reference Frames

- Dense (> 1500 stars /deg^2) net of reference stars
  - Direct observations of extragalactic sources
    - ~ 500,000 quasars observable
    - **kinematically non-rotating system** (~0.3 muas/yr)
    - **acceleration** of the Solar System Barycentre in cosmological frame
  - Long-lived reference system:
    - based on a clean subset ~ 20,000 QSOs V < 18
    - 18 mag positions good to <1 mas over 1995 - 2035
- QSO physics
  - largest homogeneous survey to V ~ 20
  - Investigation of transverse motion to 20 muas/yr (individual), <1muas/yr (systematic)

More information: August 2012



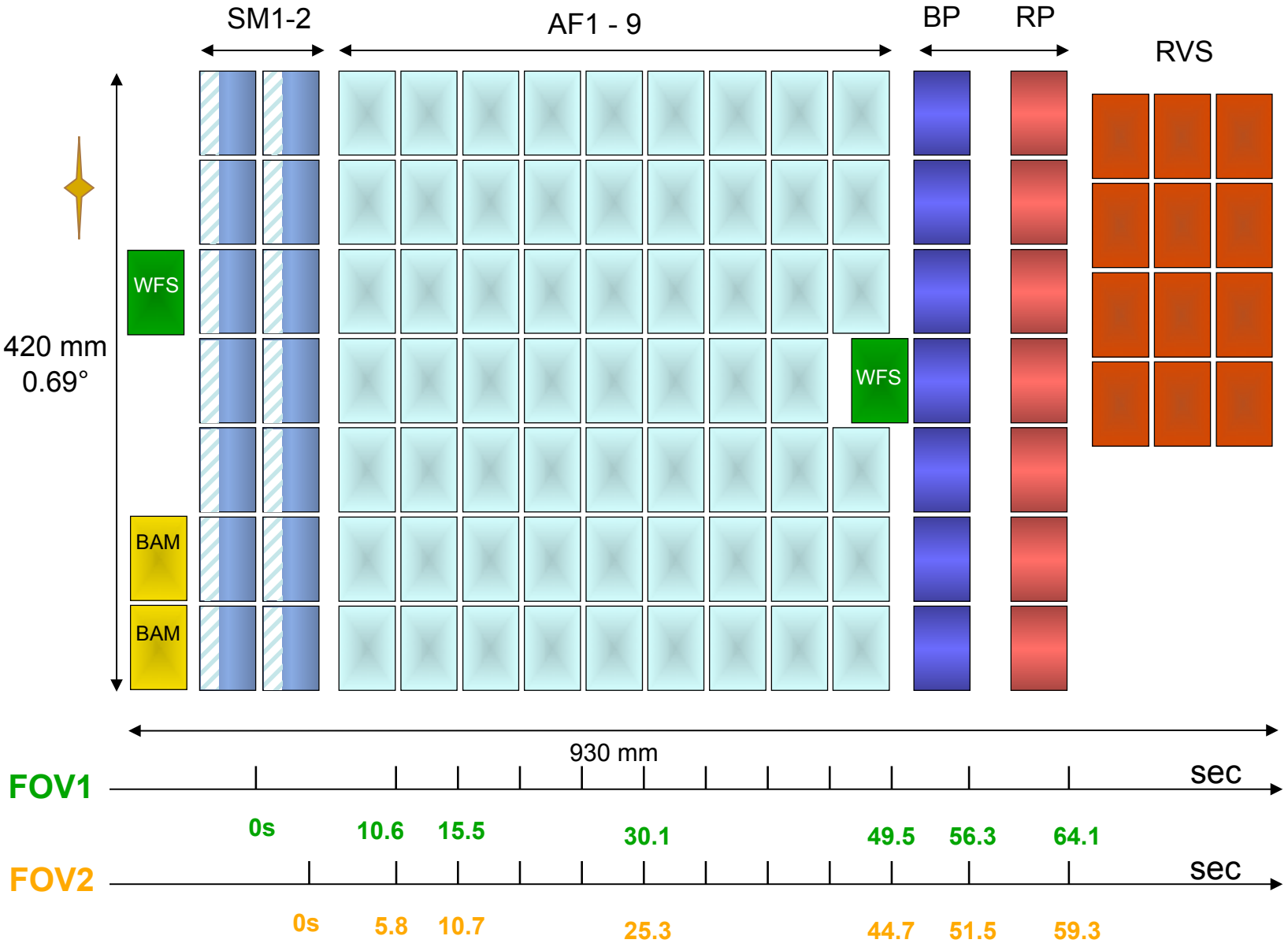
Synergy with E-ELT, JWST

- Easy to imagine
- But one have to look at km basis interferometers
  - to explore radius of stars on top of HR diagram of clusters

- Plato will take benefits of the Gaia catalogue

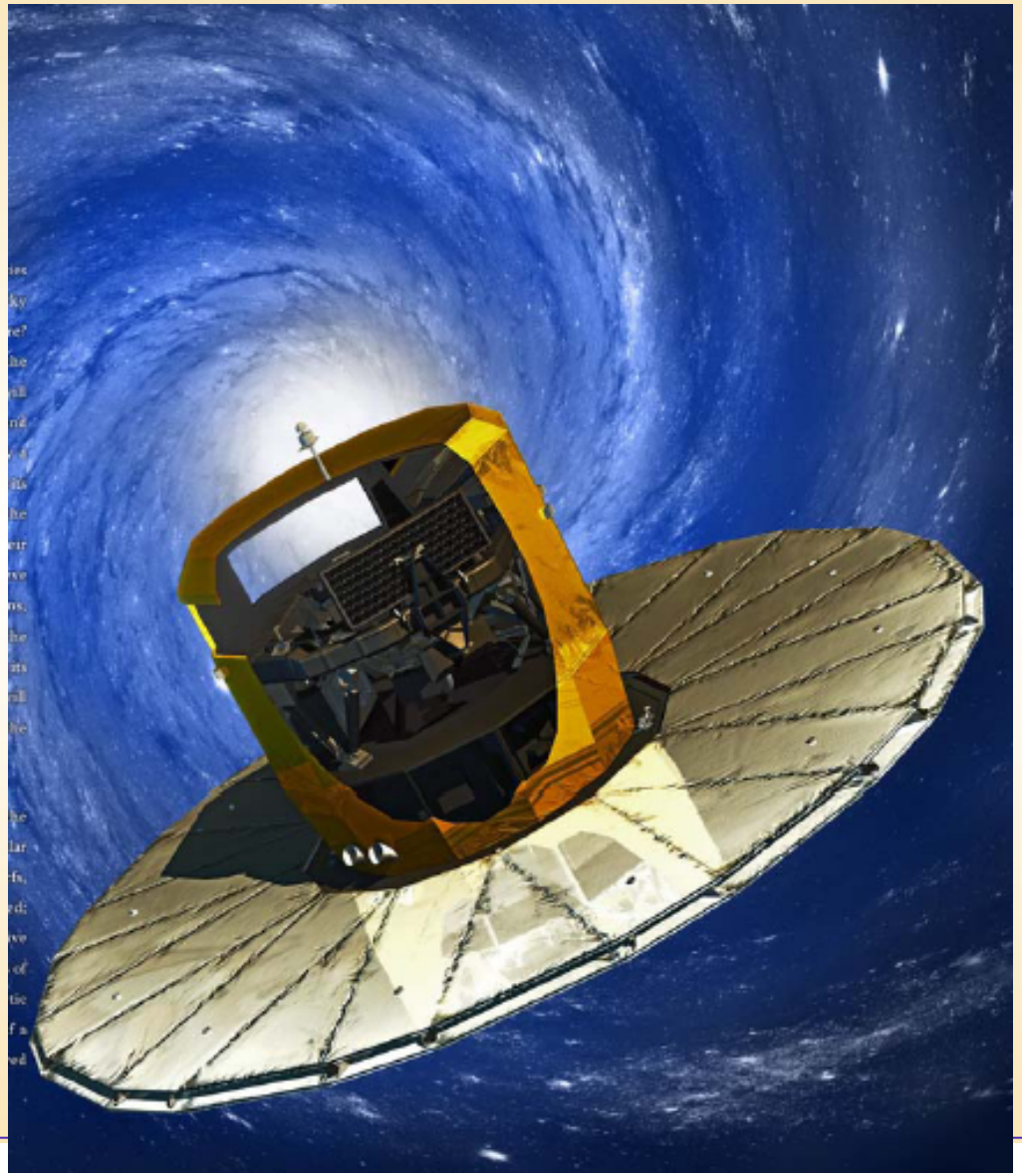
Thank you

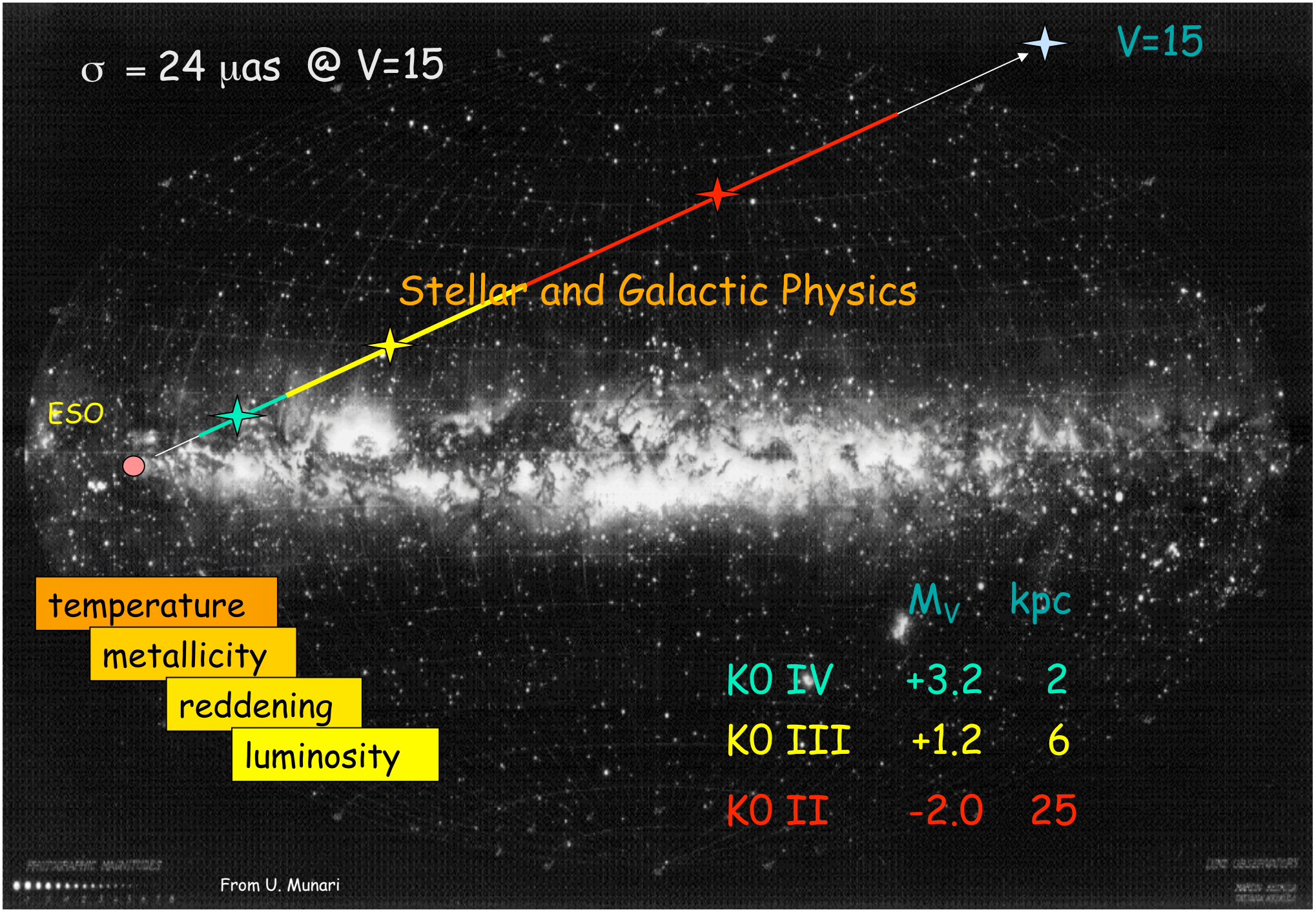
Focal Plane Assembly



Outline

- Gaia: Present status
- Data Analysis
- Science with Gaia
  - stellar and galactic physics
  - solar system
  - exo-planets survey
  - reference frame
  - fundamental physics




σ = 24 μas @ V=15
V=15
Stellar and Galactic Physics
ESO
temperature
metallicity
reddening
luminosity
M_V kpc
K0 IV +3.2 2
K0 III +1.2 6
K0 II -2.0 25
From U. Munari