Gaia and variable stars

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With special thanks to:
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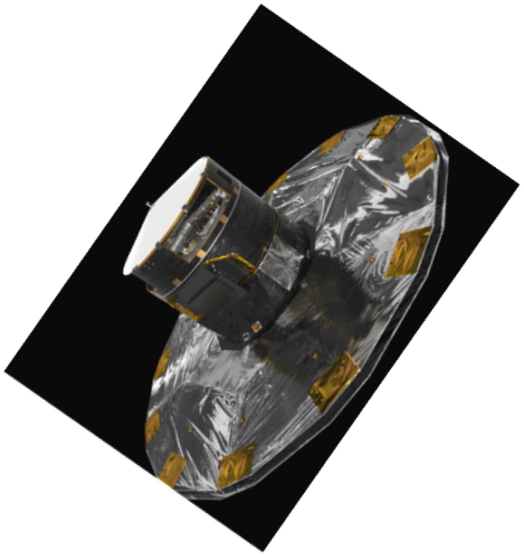
D. Evans, C. Cacciari & all DPAC members

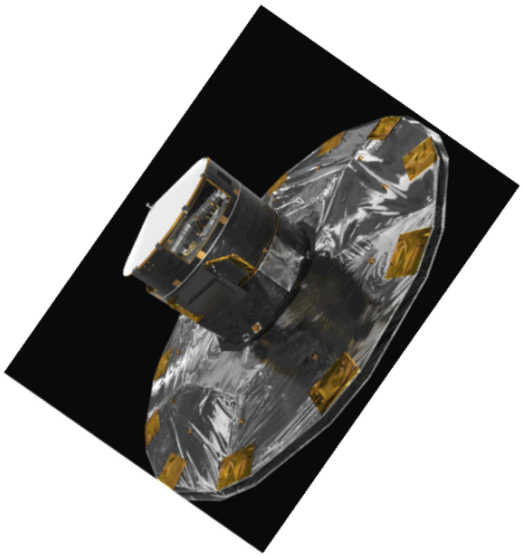
Bologna, 24 September 2015

Gaia in a nutshell



- ESA cornerstone mission building on the Hipparcos heritage
- all sky (i.e. ~ 40,000 deg^2) survey complete to G_{lim} = 20.7 mag
  ➔ ~ science with one billion sources in three dimensions
- high (μas) accuracy astrometry (parallaxes, positions, proper motions)
- optical spectrophotometry (luminosities, astrophysical parameters)
- spectroscopy (radial velocities, rotation, chemistry) to G = 16.2 mag
- 5D (some 6D …) phase space survey over a large fraction of the Galaxy volume

Gaia science topics



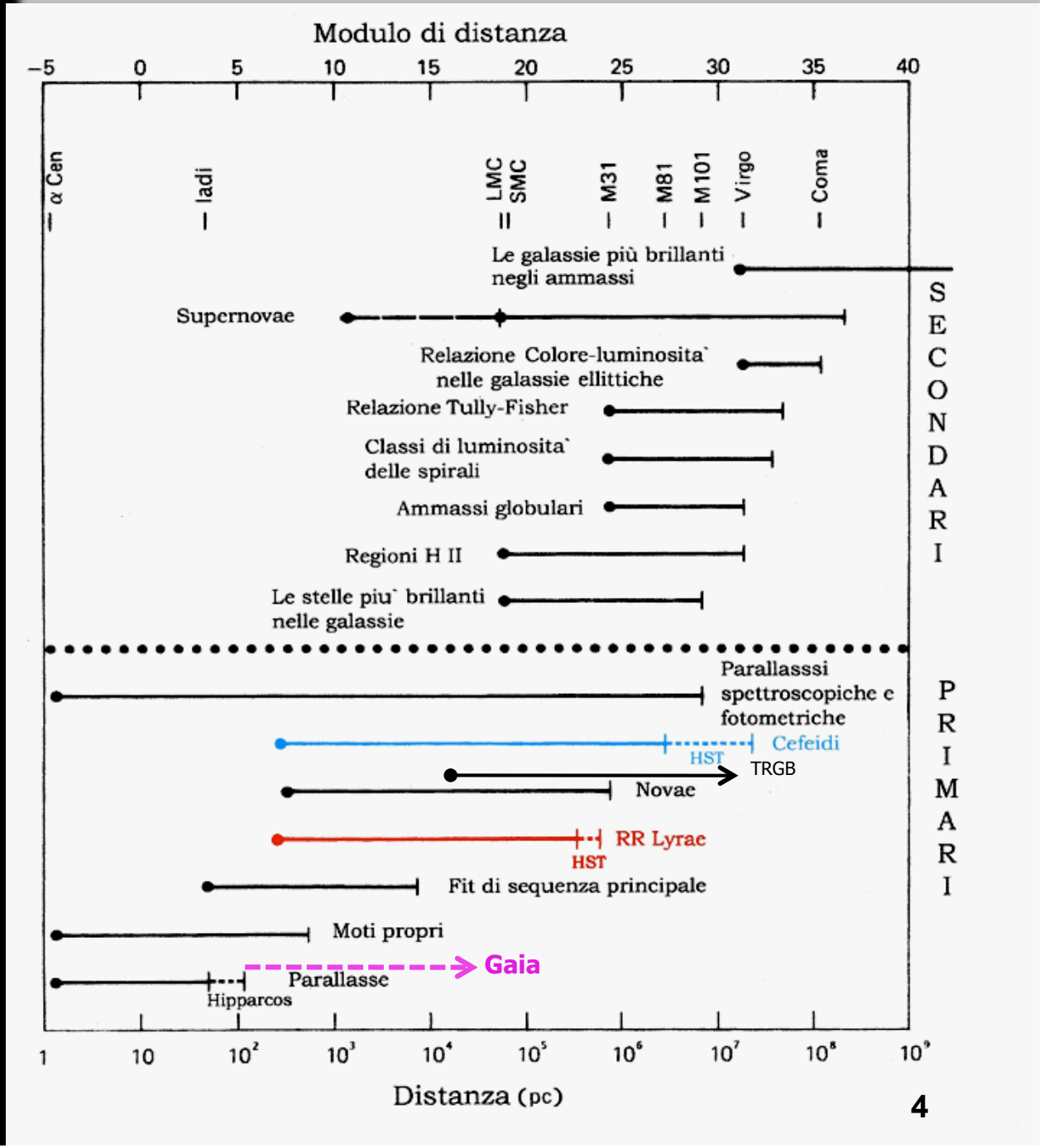
- Structure and dynamics of the Galaxy
- Star formation history of the Galaxy
- Stellar astrophysics
- Binaries and multiple stars
- Brown dwarfs and planetary systems
- Solar system
- Galaxies, Quasars and the Reference Frame
- Fundamental physics: General relativity

Multi-epoch all sky survey: discovery of thousands of new variable sources

Absolute calibration of fundamental standard candles of the Cosmic Distance Ladder

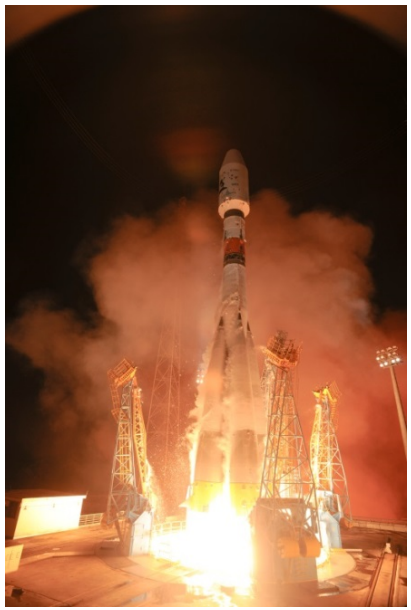
Distance Ladder

"Given the range spanned by the astronomical distances, the astronomical distance ladder is made by overlapping techniques and distance indicators, starting from the most closeby **that we can calibrate directly.**"



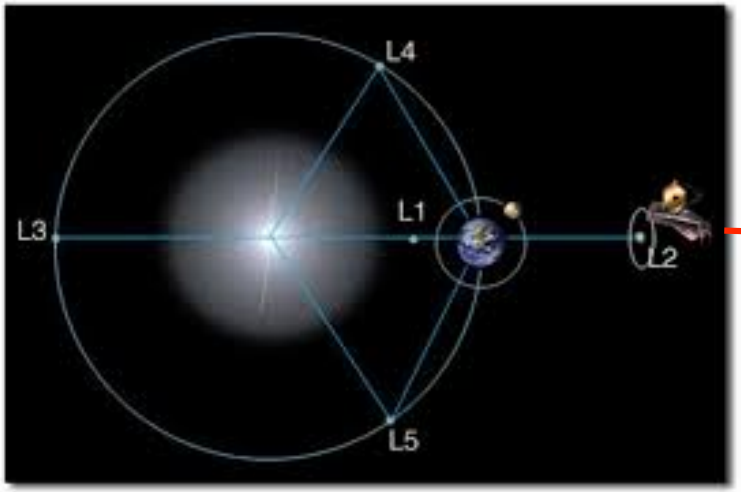
Satellite and System

ESA-only mission (Airbus DS contractor)
Satellite, including payload by industry
Management & operations by ESA
Data processing by scientists (DPAC)
Lifetime: 5 yr (+ 1yr + ?) in L2



Launched on 19 December 2013 from Kourou (French Guiana)
Launcher: Soyuz-Fregat
Commissioning formally completed 18 July 2014

L2 (gravitational equilibrium
1.5 million km from Earth away from Sun)



Lissajous orbit around L2

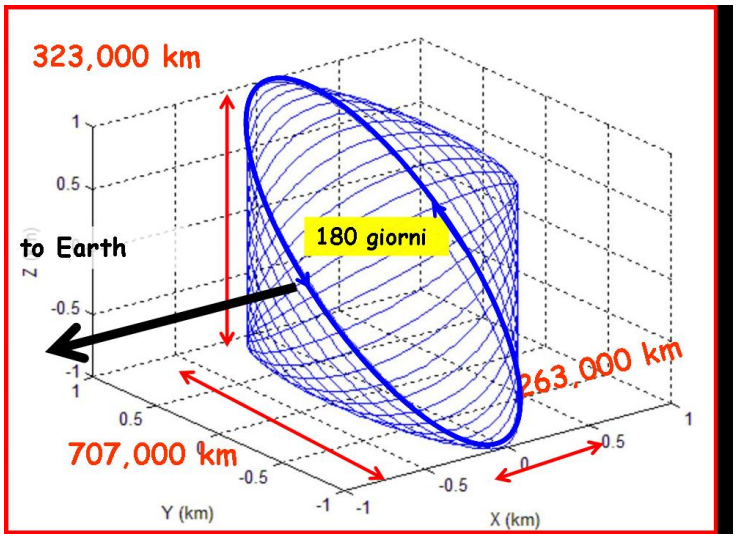
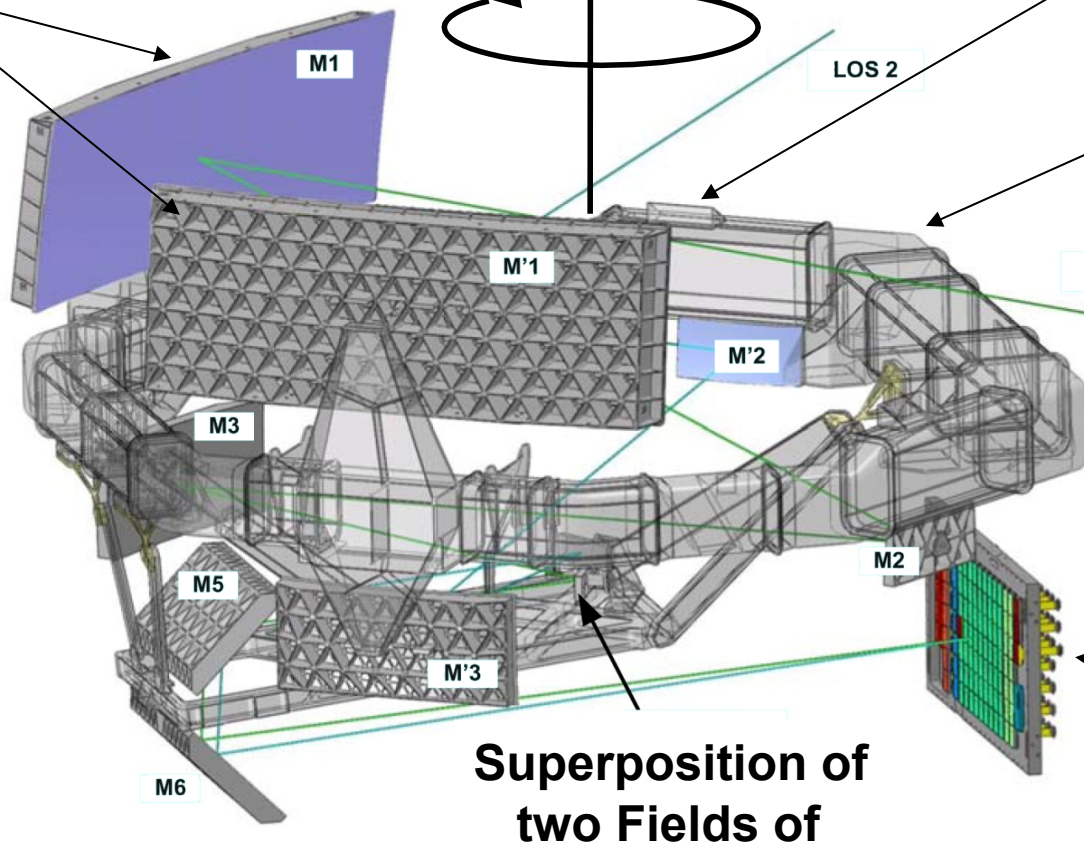


Figure courtesy A. Buzzoni

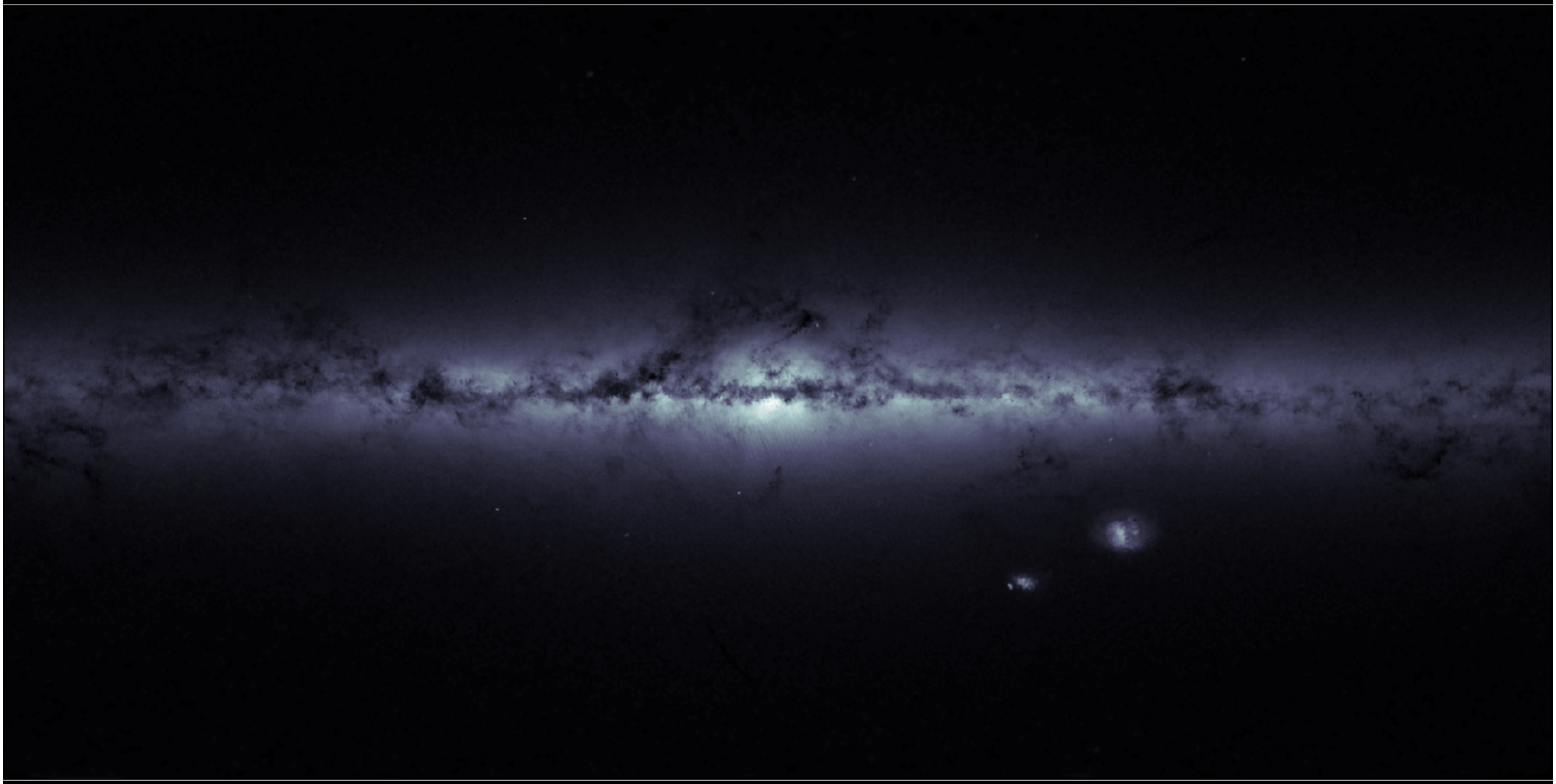
Video: Gaia launch to orbit
http://www.esa.int/spaceinvideos/Videos/2013/12/Gaia_launch_to_orbit

Payload and Telescope



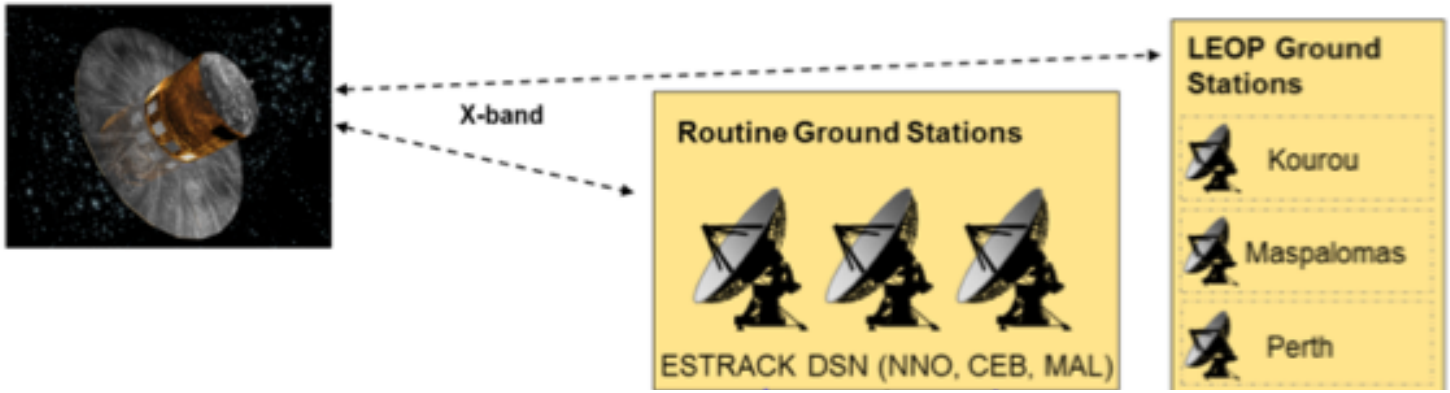
Video: Gaia scanning the sky
http://www.esa.int/spaceinvideos/Videos/2013/06/Gaia_scanning_the_sky

Counting stars with Gaia



Gaia's ground stations

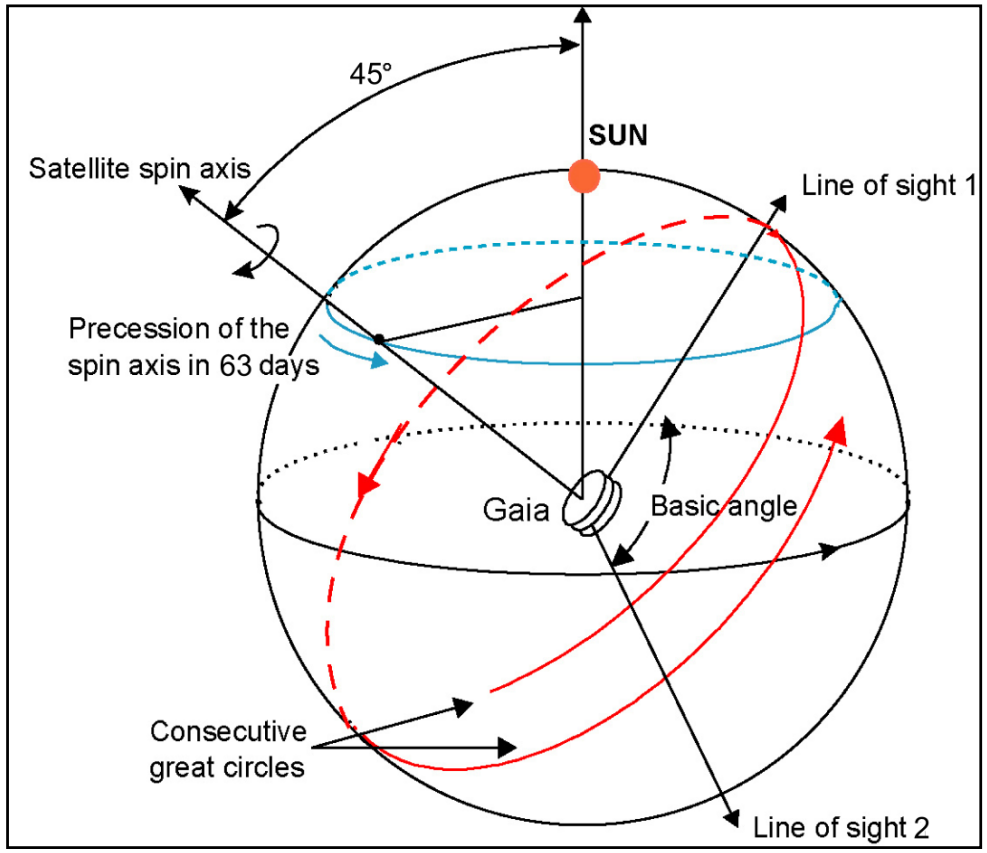
ESA's most powerful ground stations, the 35 m deep-space stations in New Norcia, **Australia (DSA 1), Cebreros, Spain (DSA 2), and Malargüe, Argentina (DSA 3),** are used to send commands to Gaia and receive the high volume of science data. During the critical Launch and Early Orbit Phase (LEOP), additional ground station support was provided by ESA's 15 m-diameter stations at Kourou, Maspalomas and Perth.



Gaia's tracking from the ground

The orbit of Gaia must also be determined to very high accuracy. The traditional radiometric methods are supplemented by optical observations from **VST@Paranal** and **LT in Canary Islands** which take pictures of Gaia against the background stars. During the commissioning phase multiple DSA stations were used to precisely determine the position with respect to Quasars.

Sky Scanning Principle



Spin axis: 45° to Sun
Scan rate: 60 arcsec/s
Spin period: 6 hr

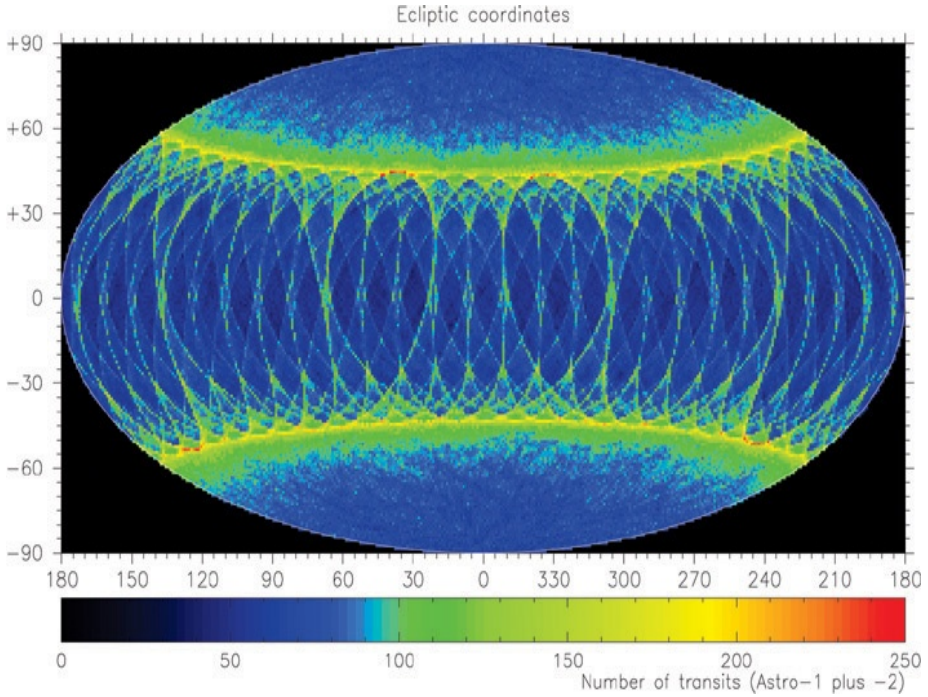
FoV-1: t_0
t_0 + 6hr

FoV-2: t_0 + 106.5m
t_0 + 106.5m + 6hr

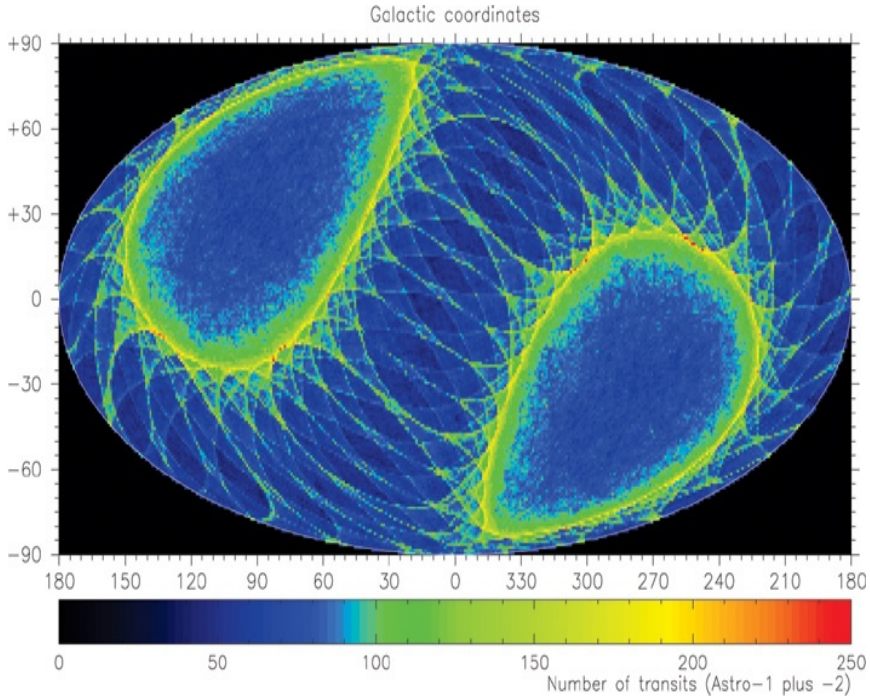
repeated 10-30 days later

29 revolutions of spin axis around solar direction in 5 yr

Transit maps



Ecliptic coordinates

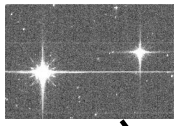


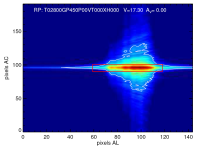
Galactic coordinates

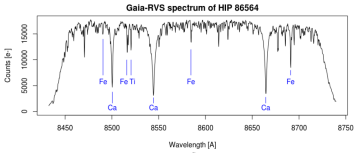
Each object observed 10 – 250 times

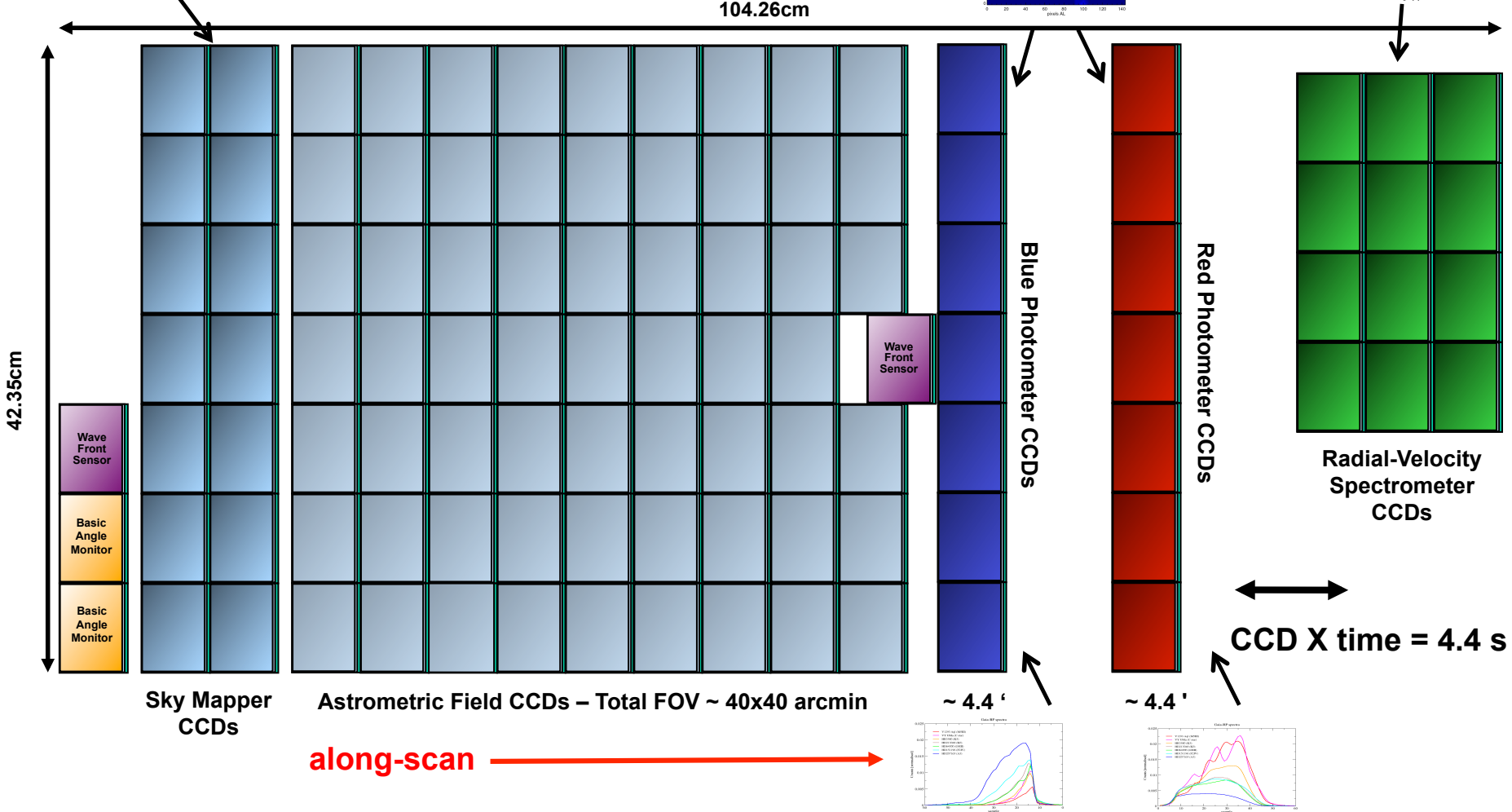
End of mission (5 yr) sky-average number of transits: ~ 70 (RV=40)
(max ≥ 200 at $|\beta|$ = 45° ± 10°)

Focal Plane









Total field:

- active area: 0.75 deg^2
- CCDs: 4 + 14 + 62 + 14 + 12
- each CCD: 4500x1966 px (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
- FoV discrimination

Astrometry:

- total detection noise: 6 e$^-$

Photometry:

- spectro-photometer
- blue and red CCDs

Spectroscopy:

- high-resolution spectra
- red CCDs

Photometric bandpasses: G, BP, RP & RVS

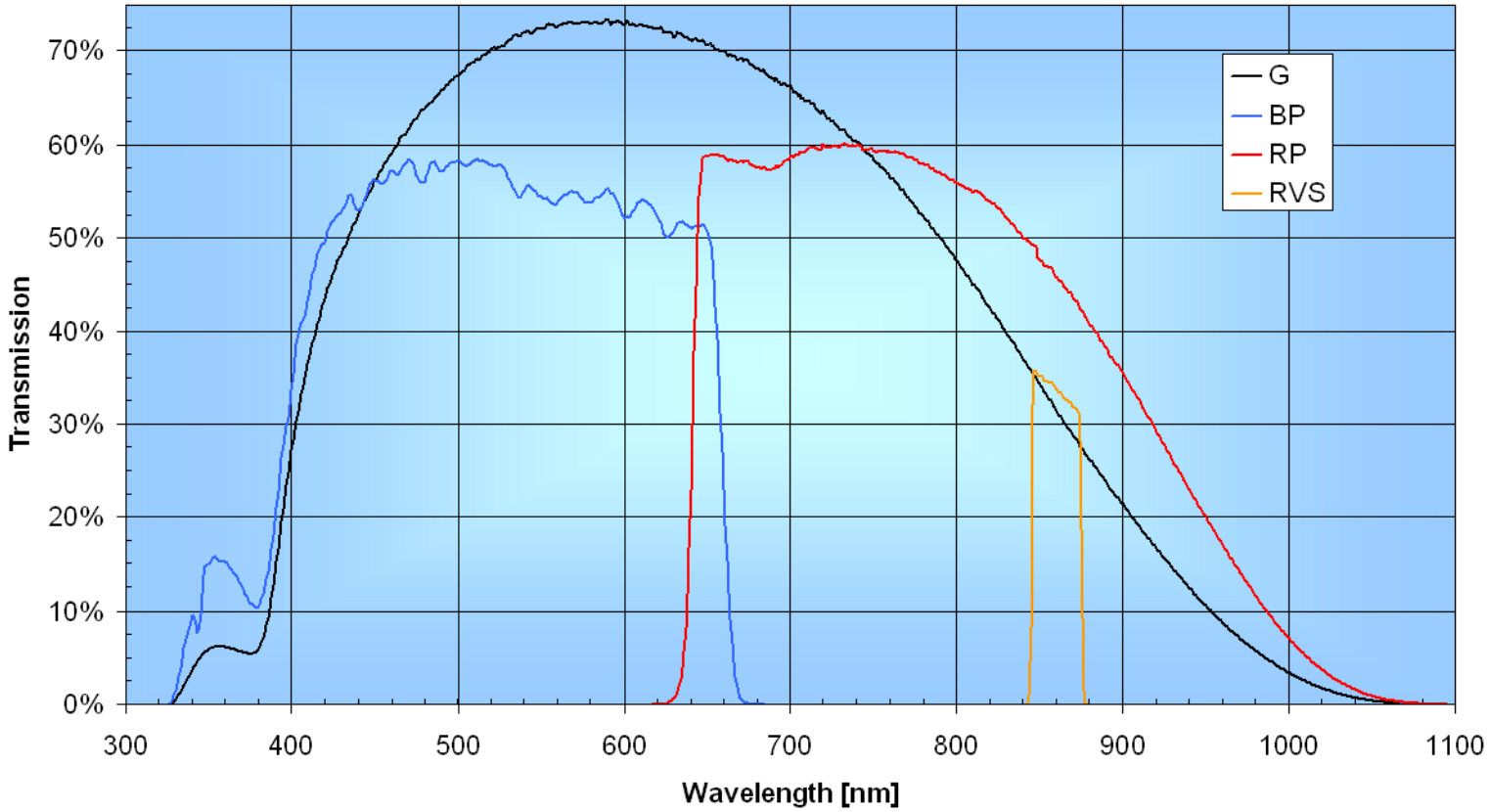
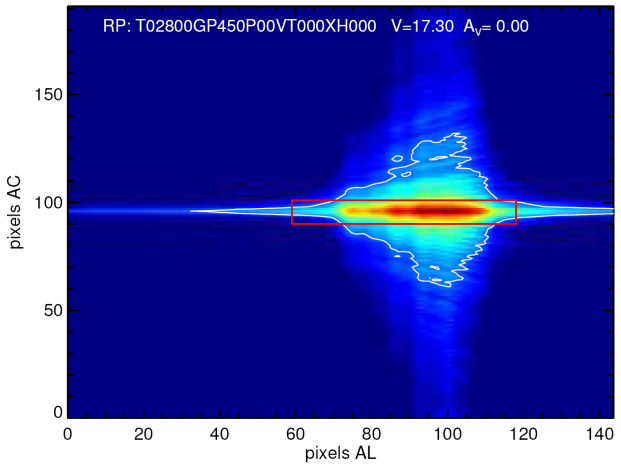


Figure courtesy ESA

Gaia photometry measurement concept: spectro-photometry (G ≤ 20.7 mag)

- **Integrated:**
  - ➔ white-light (G-band, 330-1050 nm) from the Astrometric Field

- **Dispersed:**
  - ➔ Blue (BP, 330-680 nm) & Red (RP, 640-1050 nm) low resolution spectra (R~20-90)

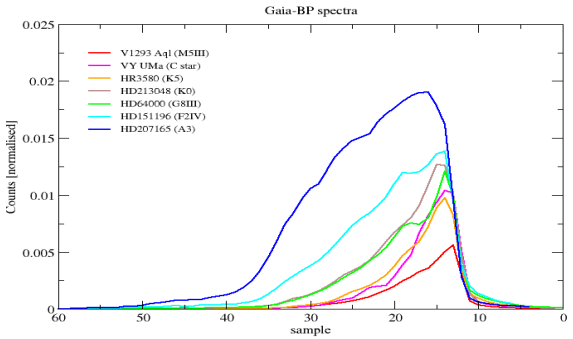


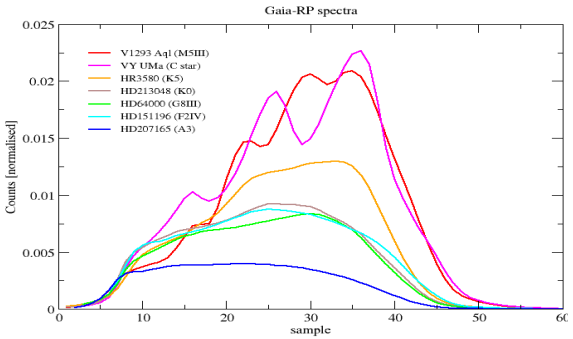
RP spectrum of M dwarf (V = 17.3 mag)
Red box: data sent to ground
White contour: sky-background level
Colour coding: signal intensity

Figures courtesy Anthony Brown

dispersion

4-32 nm/px



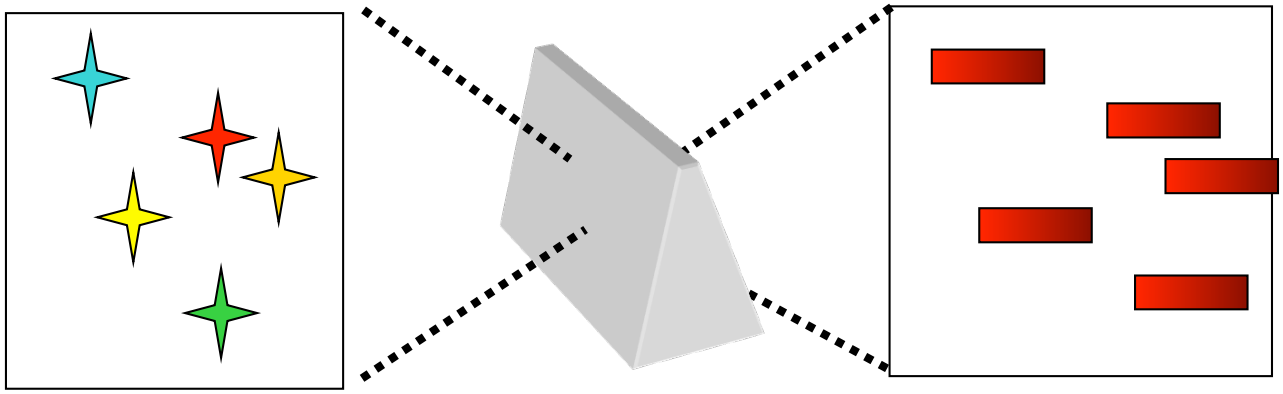


dispersion

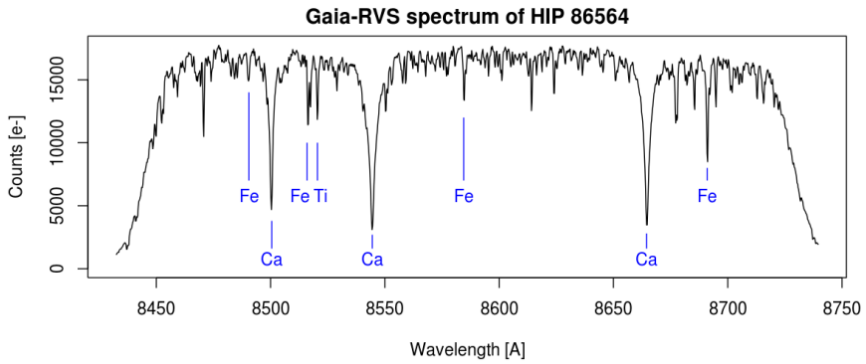
7-15 nm/px

Gaia Radial-Velocity Measurement Concept

Slitless spectroscopy on Ca triplet (847–874 nm)
Resolution 11,500



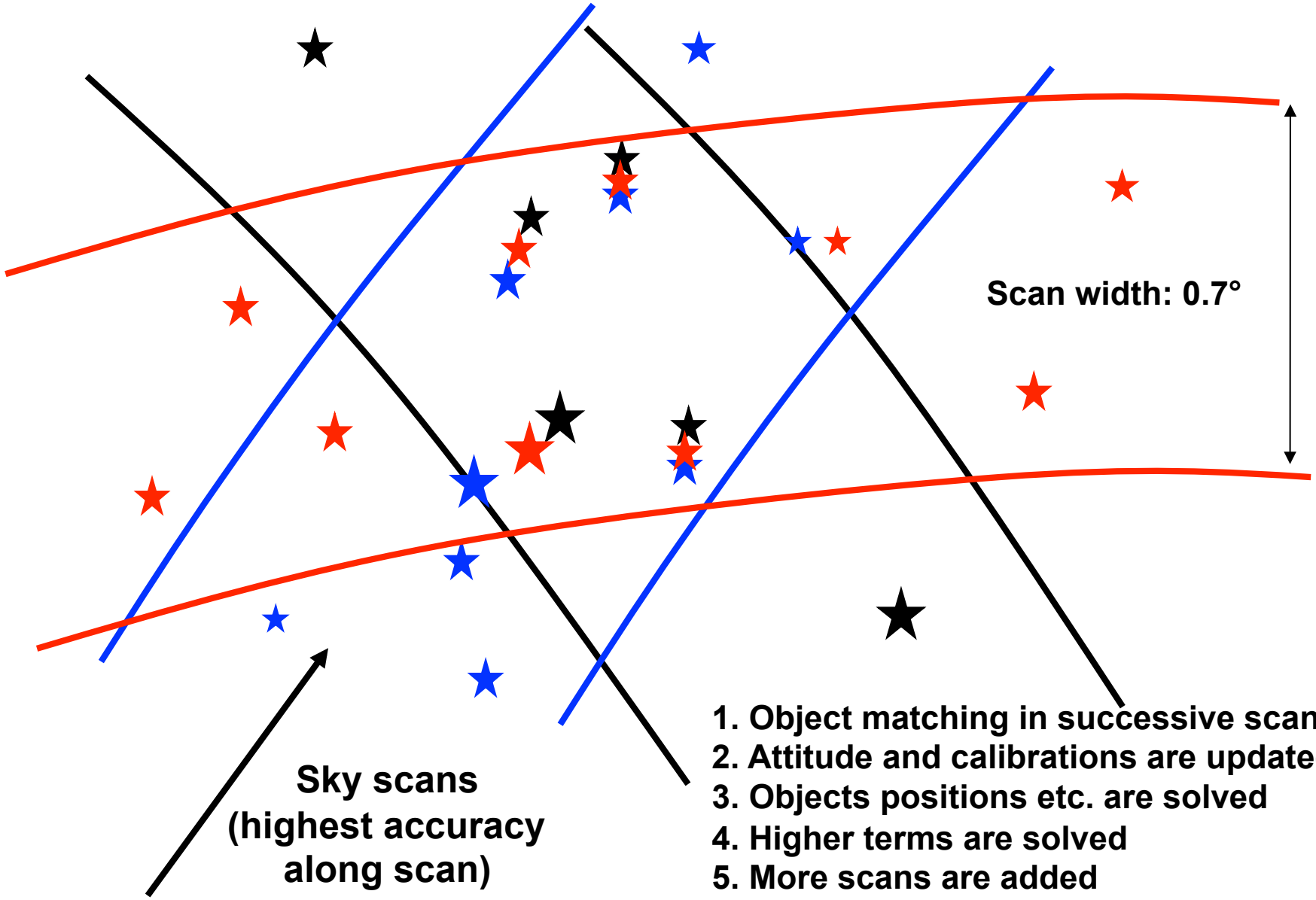
Courtesy David Katz



Spectra of the star HIP 86564

Gaia-RVS on FoV 0, CCD row 4 strip 15

Astrometry: data reduction principles



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

Figure courtesy Michael Perryman

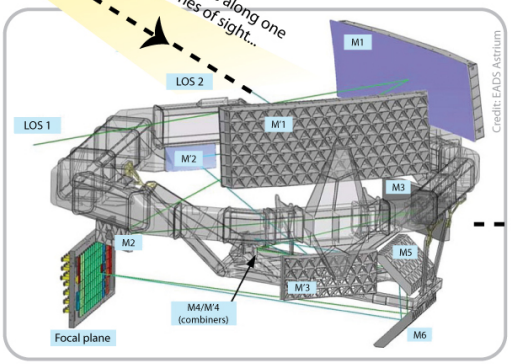
Star

Gaia will detect all celestial bodies down to the very faint magnitude 20, amounting to about a billion objects. This catch-all survey will naturally observe many objects beside stars, including minor Solar System bodies, brown dwarfs, quasars and supernovae.

1. Starlight travels along one of Gaia's lines of sight...

Payload

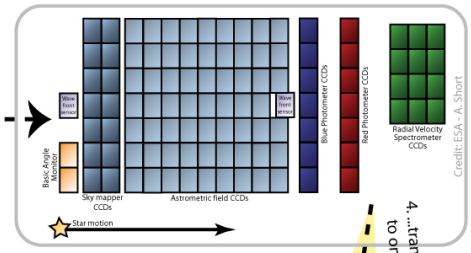
Light from a celestial object enters Gaia's payload arrangement through one of the two viewing apertures, striking the large primary mirror opposite (M'1 in the case pictured). The light is bounced by a series of mirrors along a total focal length of 35m. The light paths from the two viewing directions meet at the M4/M'4 beam combiner before finally reaching the shared focal plane.



2. ...enters Gaia's instruments, and is reflected along a 35m focal length to hit...

Focal plane

At the focal plane is a large mosaic of sophisticated charge-coupled devices (CCDs). Containing 106 of these light detectors, the focal plane assembly comprises a total of nearly one billion pixels - a 'gigapixel'.



3. ...the CCDs of the focal plane assembly, thereby being detected before...

4. ...transmission by low gain antenna to one of Gaia's ground stations...

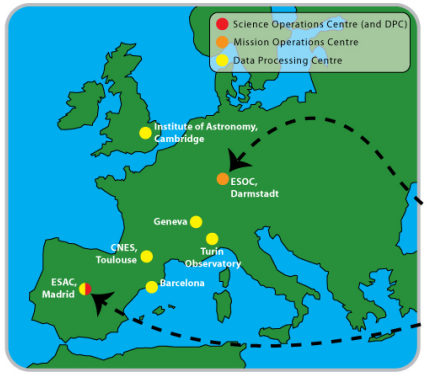
Gaia DPAC
Data Processing & Analysis Consortium

Science Operations Centre

Gaia's Science Operations Centre is based at ESA's European Space Astronomy Centre (ESAC) in Spain. ESAC receives all of Gaia's science telemetry for preliminary processing in the Initial Data Treatment. Also carried out here is Detailed First Look processing, Gaia's regular science 'health check'.

Data Processing Centres

Following the preliminary processing, the data passes to Gaia's Data Processing Centres (DPCs). Data processing is the task of DPAC, the Data Processing and Analysis Consortium. DPAC draws its membership of about 450 scientists and developers from all over Europe; the processing itself takes place at these six DPCs.



5. ...the telemetry is then transmitted onto the Mission and Science Operation Centres...

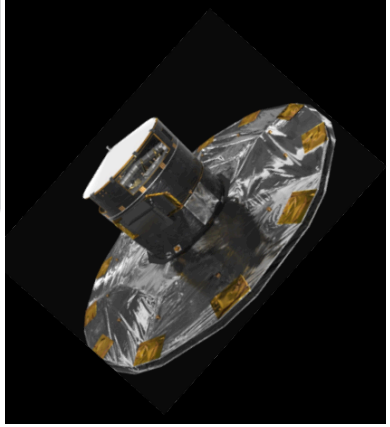
Ground station

Gaia will be making use of three ground stations, each with 35m deep space dish antennae: Cebreros in Spain, New Norcia in Australia and Malargüe in Argentina.

6. ... and processed by DPAC into the final...

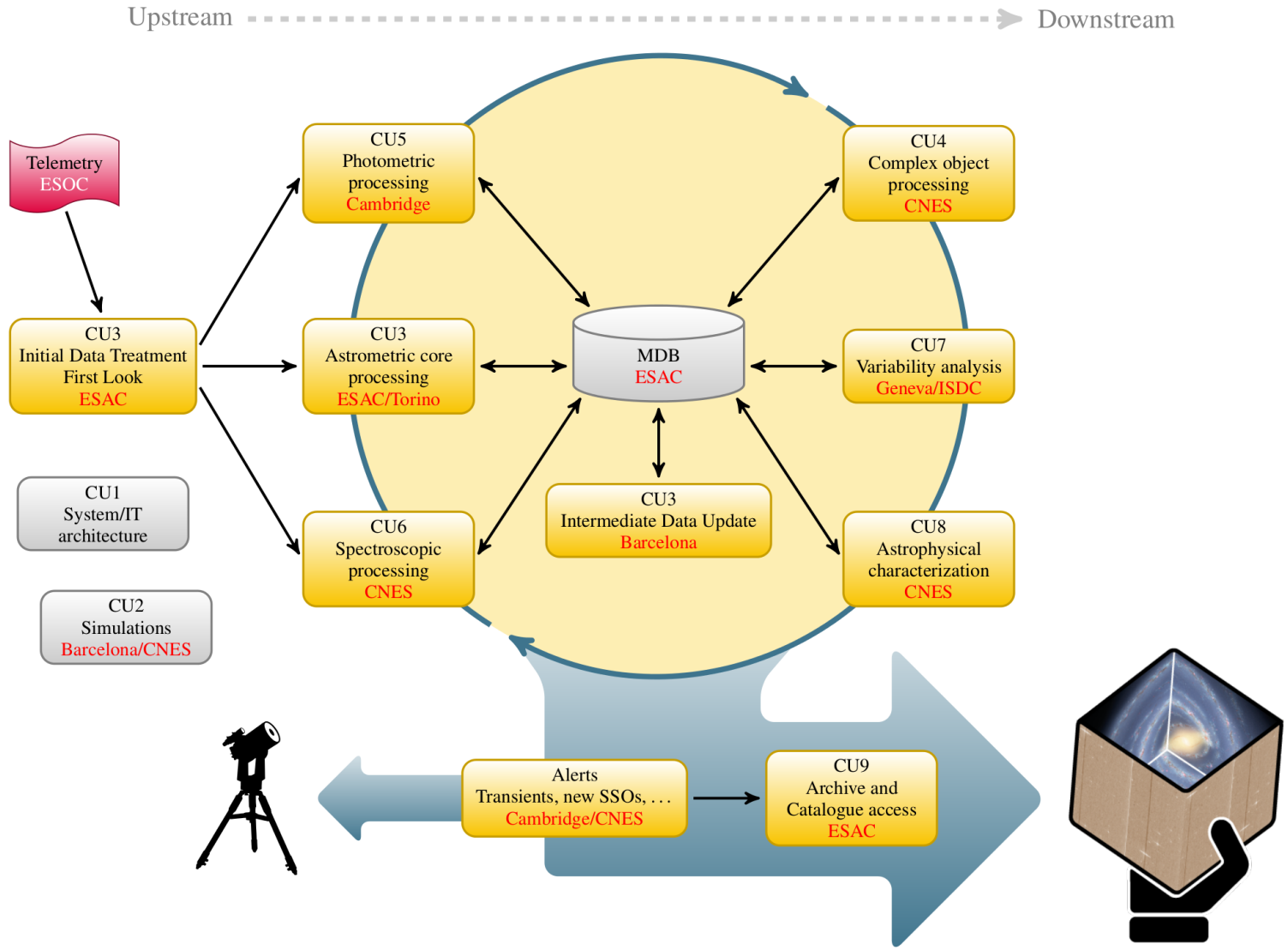
Gaia Catalogue

The final Gaia Catalogue, containing the precise astrometric, photometric and spectroscopic details of about a billion celestial objects, is scheduled for publication in 2022. Gaia's processed data will then immediately be freely available for investigation by the world's scientific community.



Data processing

Data Processing and Analysis Consortium (DPAC): more than 500 people from 20 European countries and ESA

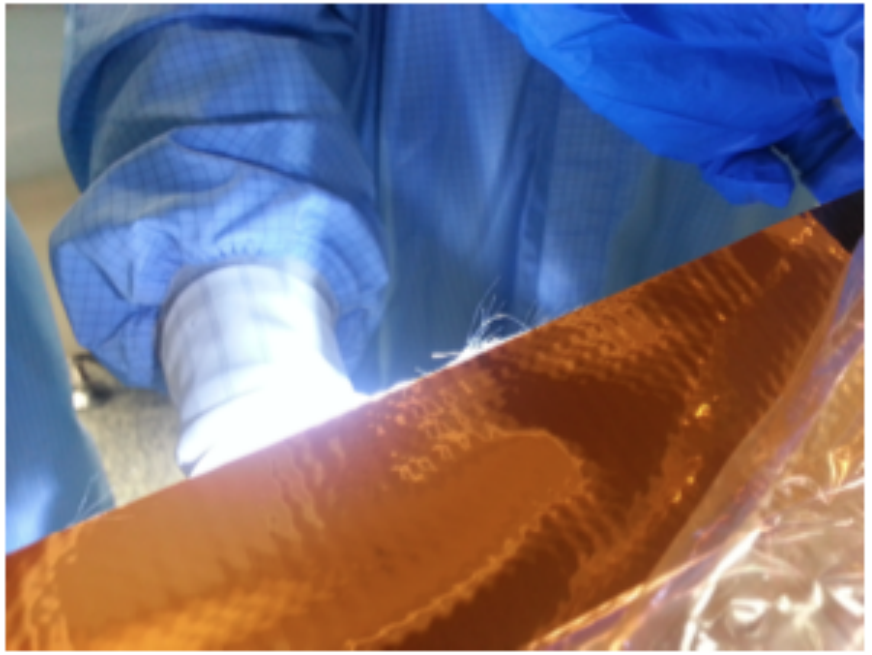


Cyclic processing

Unwanted surprises

- Stray light both from astronomical sources and the Sun

- **Due to scattering at the edge of the Sun shield**
- **Impacts faint stars and especially RVS**
- **Attempt to recover RVS magnitude loss with improved background – subtraction algorithms and on-board s/w modifications to change the across-scan window width size**



A flight-spare blanket of the Gaia sun shield lit with a torch from the back to enhance the effect of scattered light from fibres protruding from the edge.

Unwanted surprises

- Transmission loss due to continuing contamination of mirrors by water
  - **A new decontamination procedure involving a short heating of mirrors executed in September followed by re-focusing**
- Basic Angle variation larger than expected
  - **Working group established to chase the root of the variations**

Post-launch photometric & radial velocity performance

End-of-mission photometric standard errors of the integrated G-band, BP-band, and RP-band, in units of **milli-magnitude**, as a function of Gaia G mangitude for 3 reference stellar types. The standard-error calculation includes all known instrumental effects, including stray light as measured during the in-orbit commissioning phase, as well as a 20% science margin.

	B1V			G2V			M6V		
G [mag]	**G**	**BP**	**RP**	**G**	**BP**	**RP**	**G**	**BP**	**RP**
15	1	4	4	1	4	4	1	7	4
18	2	8	19	2	13	11	2	89	6
20	6	51	110	6	80	59	6	490	24

Predicted end-of-mission radial-velocity robust formal errors

Spectral type	V [mag]	Radial-velocity error [km s^{-1}]
B1V	7.5	1
	11.3	15
G2V	12.3	1
	15.2	15
K1III-MP (metal-poor)	12.8	1
	15.7	15

Post-launch astrometric performance

Sky-averaged, end-of-mission, astrometric standard errors, in units of **μas**, for position, parallax, and proper motion, as a function of Gaia G magnitude, for an unreddened G2V star (V-I=0.75 mag and V-G=0.16 mag).

G [mag]	3–12.09	13	14	15	16	17	18	19	20
σ_0 [μas]	5.0	7.7	12.3	19.8	32.4	55.4	102	208	466
σ_ϖ [μas]	6.7	10.3	16.5	26.6	43.6	74.5	137	280	627
σ_μ [μas yr^{-1}]	3.5	5.4	8.7	14.0	22.9	39.2	72.3	147	330

De Bruijne et al. 2015, arXiv1502.00791

Timeline 1

- Routine phase started with 28 days of Ecliptic Pole Scanning
- Now operating in optimised Nominal Scanning Law **(since 18 July 2014)**

- Magnitude limits
  - Astrometry and photometry between $2 < G < 20.7$ mag
  - Stars brighter than $G = 3$ mag captured with Sky Mapper imaging
  - Spectra till $G_{RVS} = 16.2$ mag (and $G > 2$ mag)

Timeline 2

- Gaia has now covered the whole sky in every direction at least once and has been surveying the Milky Way since the start of the mission (mid July 2014) to a faint limit of G=20.7 mag
- The satellite is fully operational and on average collecting data for 50 million stars per day (peak day above 250 million)
- As of end May 2015: 225 billion astrometric CCD transits, 45 billion photometric, 4.5 billion spectroscopic
- DPAC cyclic processing tested on the EPSL-28 data
- A first set photometric calibrations produced by CU5, covering both the white light G-band and the low resolution prism spectrophotometry
- Gaia on-board processing software optimized to mitigate RVS losses due to stray light
- The first trials of the global astrometric solutions have started, results look promising so far.

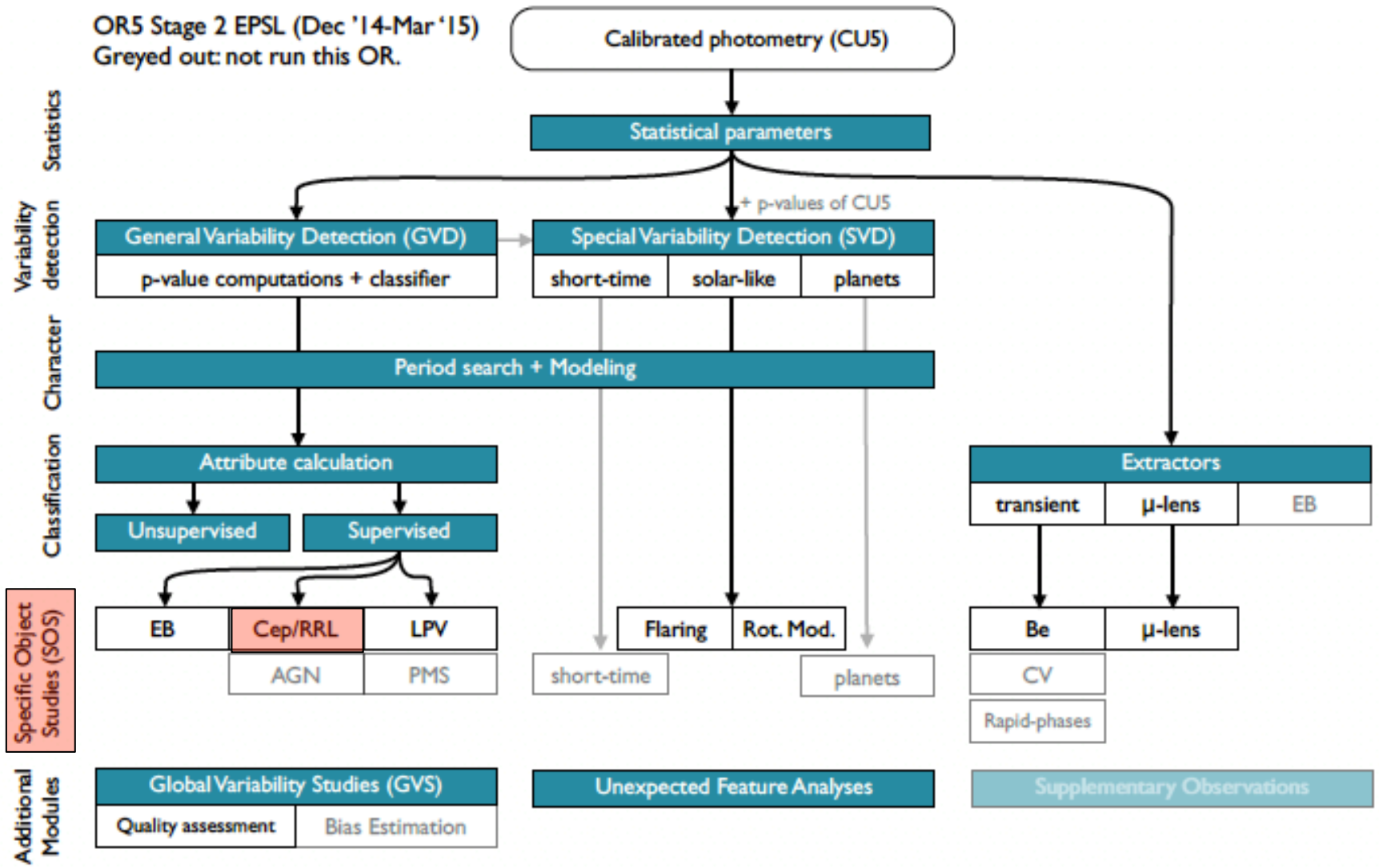
Variability processing

DPAC Coordination Unit 7 (CU7) – DPCG (Geneva)

DPAC CU7 members, responsible of the **Cepheid & RRLyrae** pipeline development:

G. Clementini (leader), V. Ripepi, S. Leccia, M. Marconi, I. Musella

CU7 processing chain



Courtesy of B.Holl

Operation Rehearsals

Satellite has been in operation (since July 2014)

Variability Processing and Analysis is **not** "in operation" **(yet)**

We have been training.... on

- "Gaia" Simulated data
- some real data (Hipparcos, OGLE, EROS)

And now on

- **Real Gaia Ecliptic Pole Scanning Law data**

This exercise/training is called **Operation Rehearsal (OR5 stage 2)**

(courtesy of L.Eyer)

The Operation Rehearsal data

Data set {
- 28 days of Ecliptic Scanning law
- 3 days of Nominal Scanning law

69 million sources
received from Photometric Processing (Cambridge University)

↓

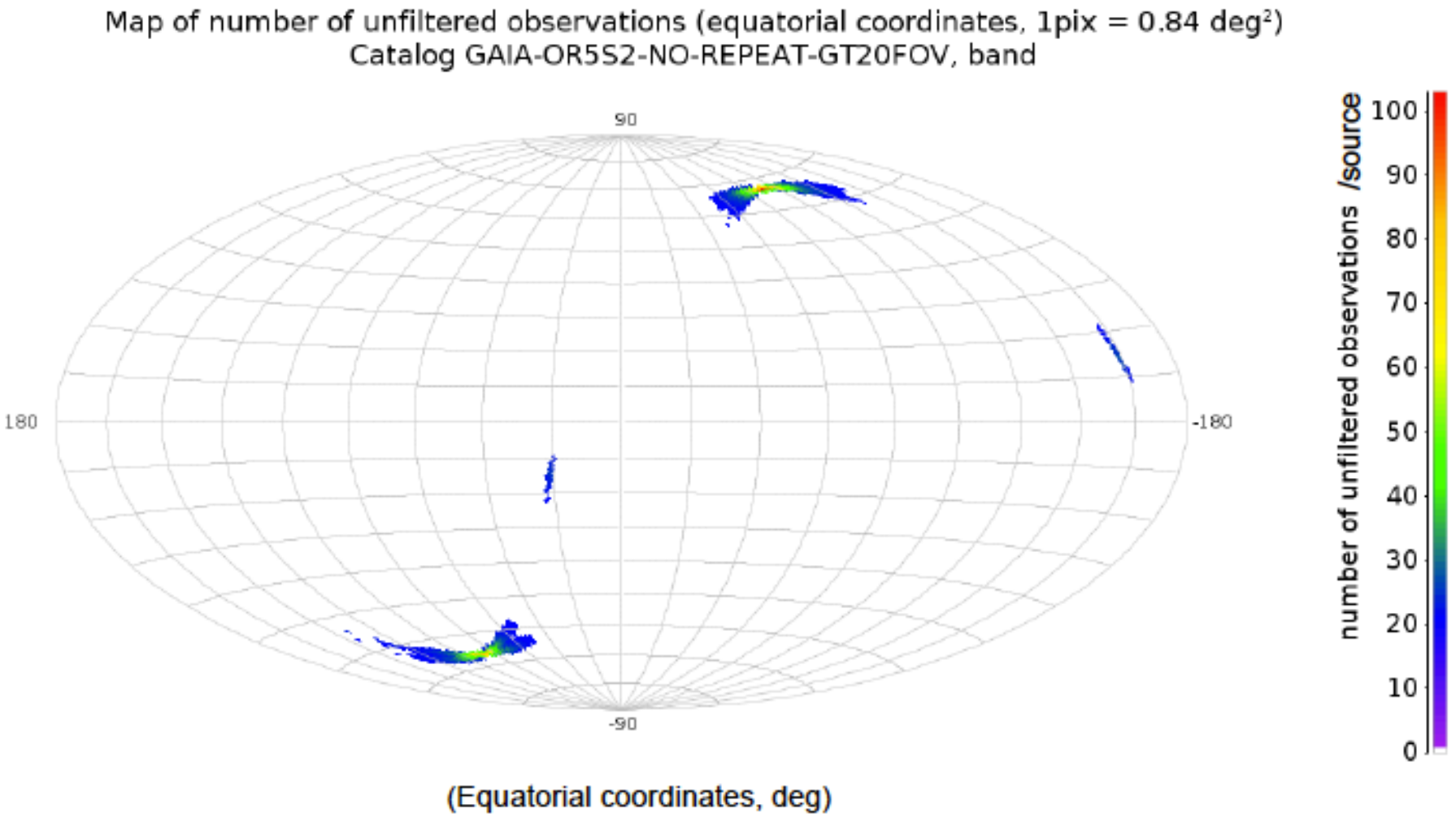
Selection:
20 measurements in either G, BP, RP
No repeated observations within 100 minutes

↓

790,000 sources

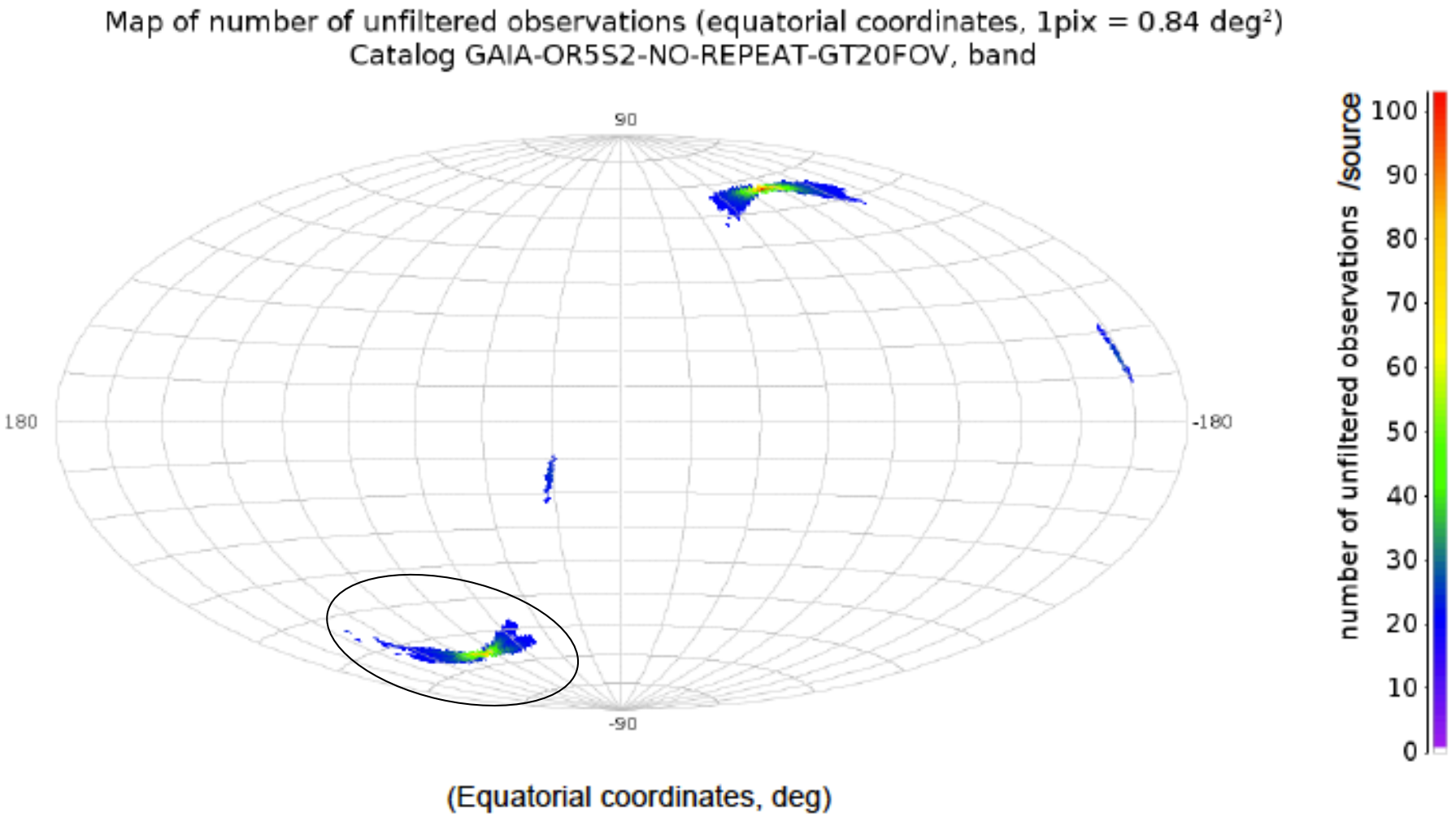
(courtesy of L.Eyer)

Mean number of obs/source (789K)



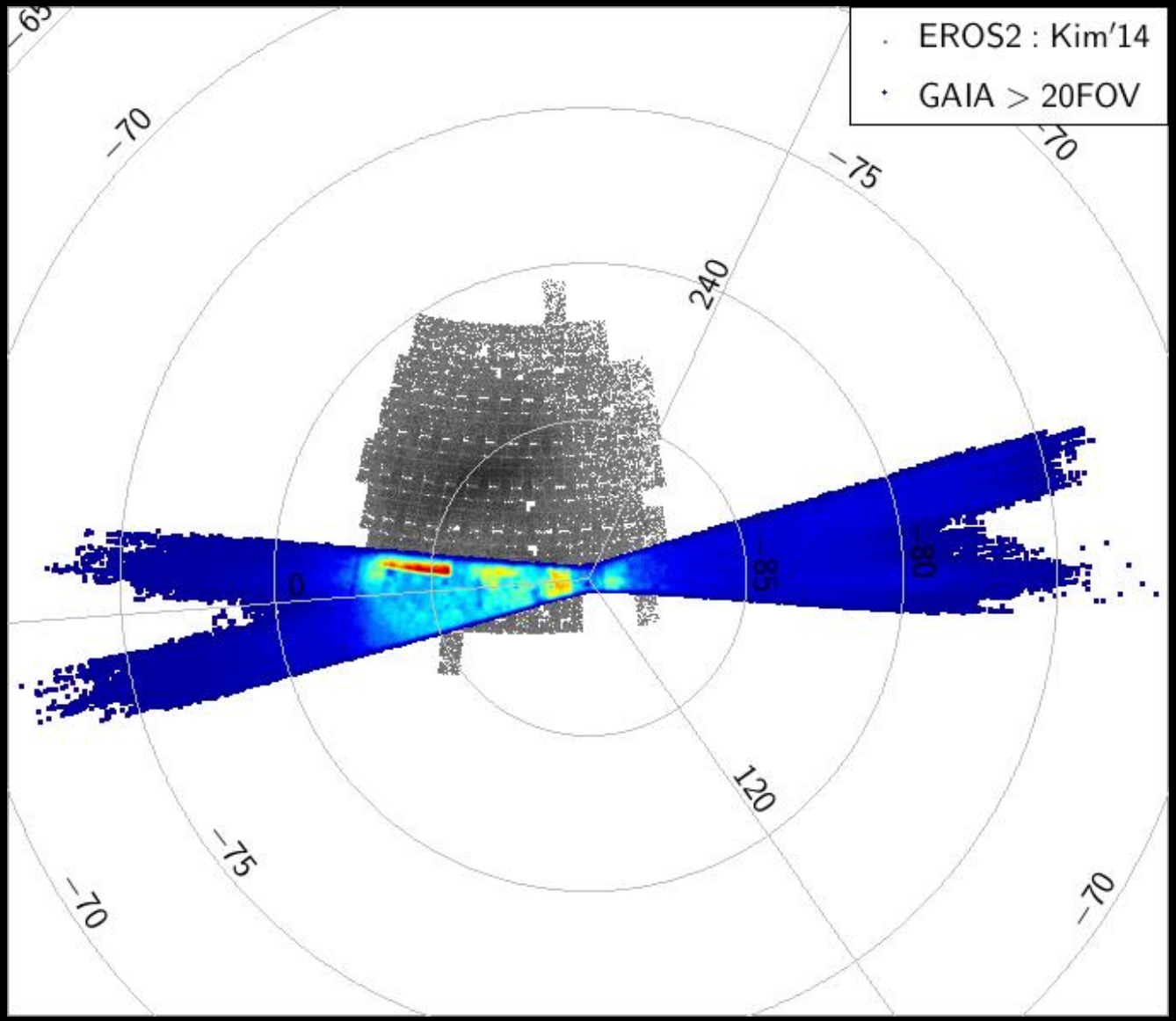
(courtesy of L.Rimoldini)

Mean number of obs/source (789K)

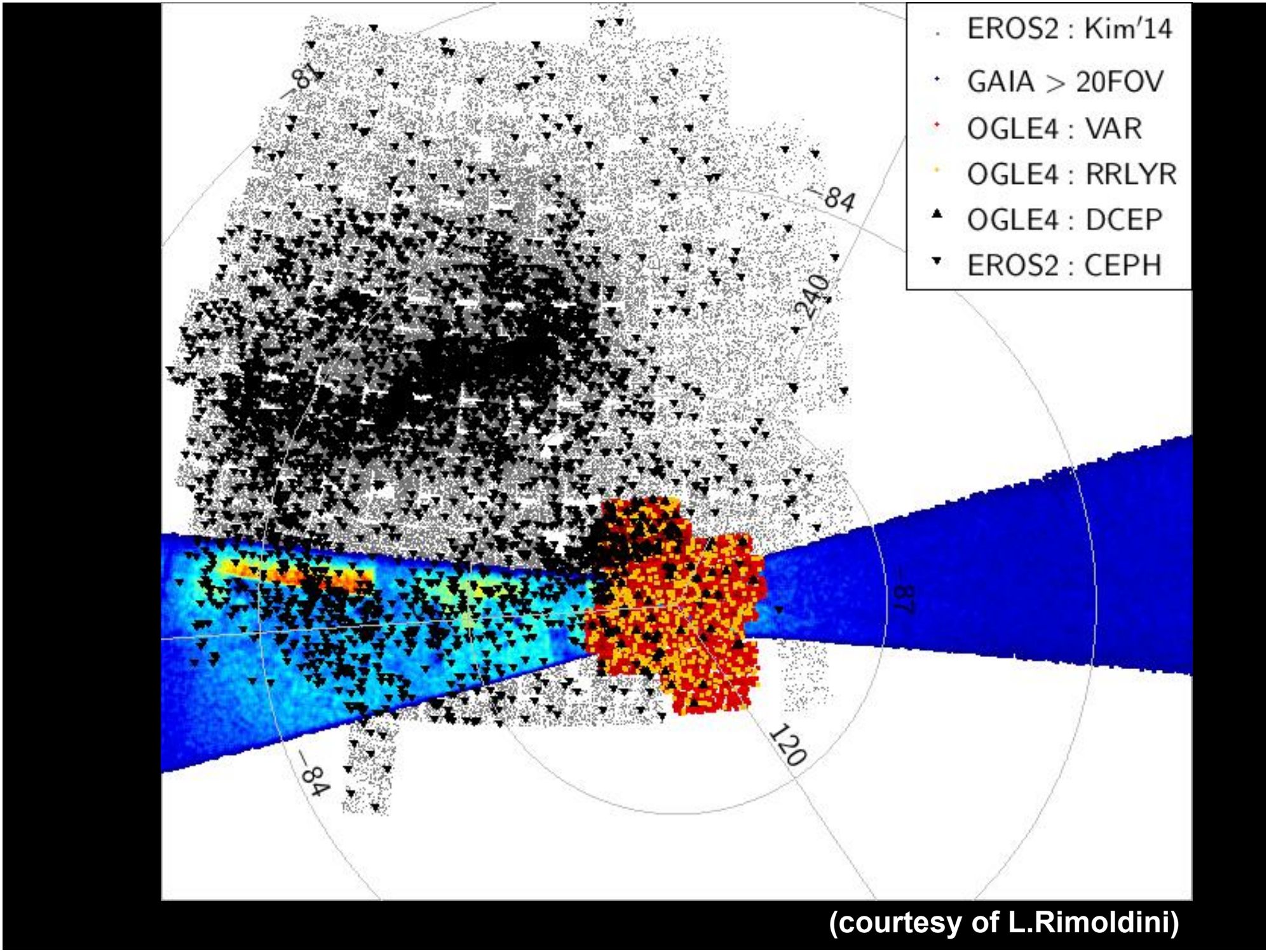


(courtesy of L.Rimoldini)

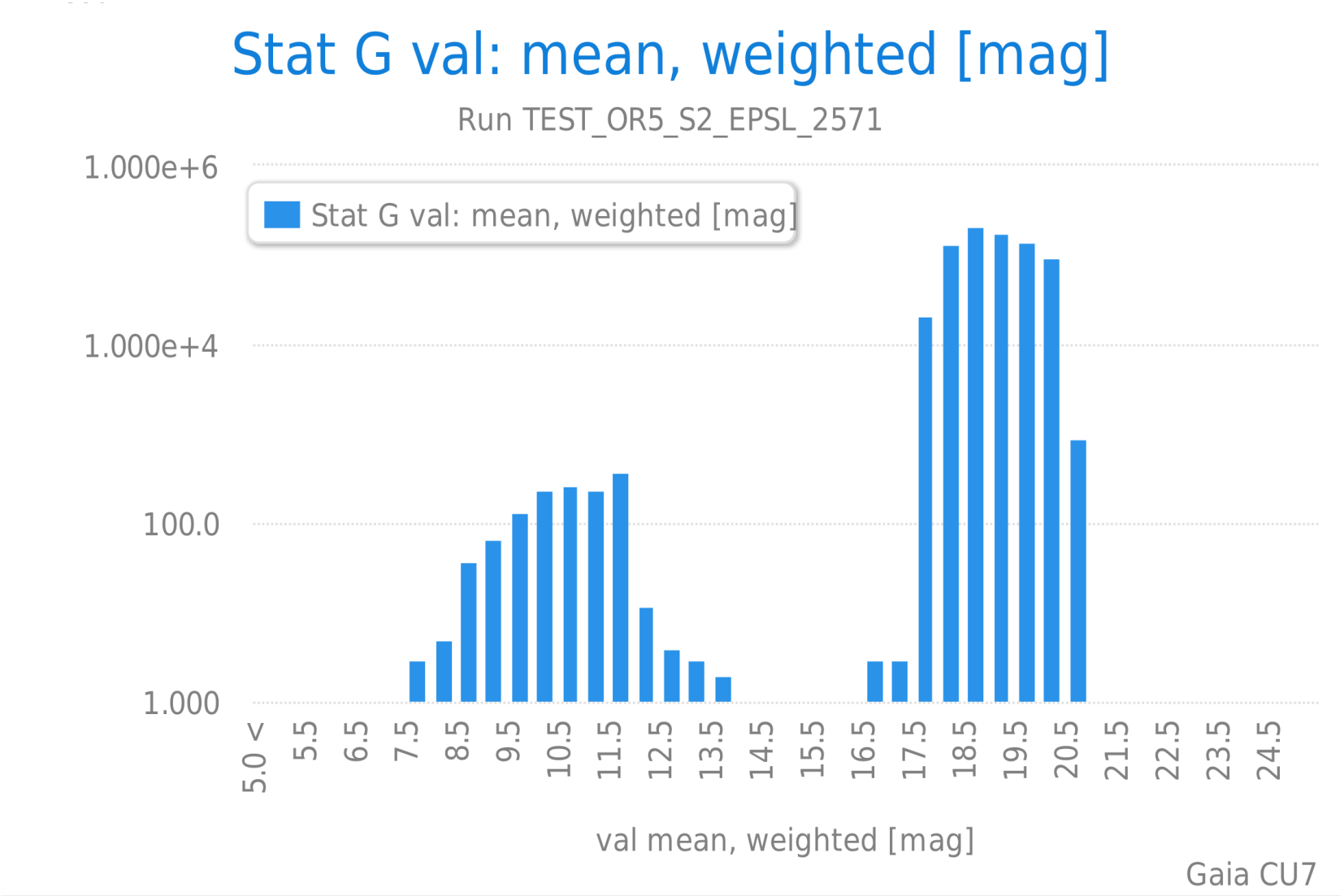
Gaia SEP

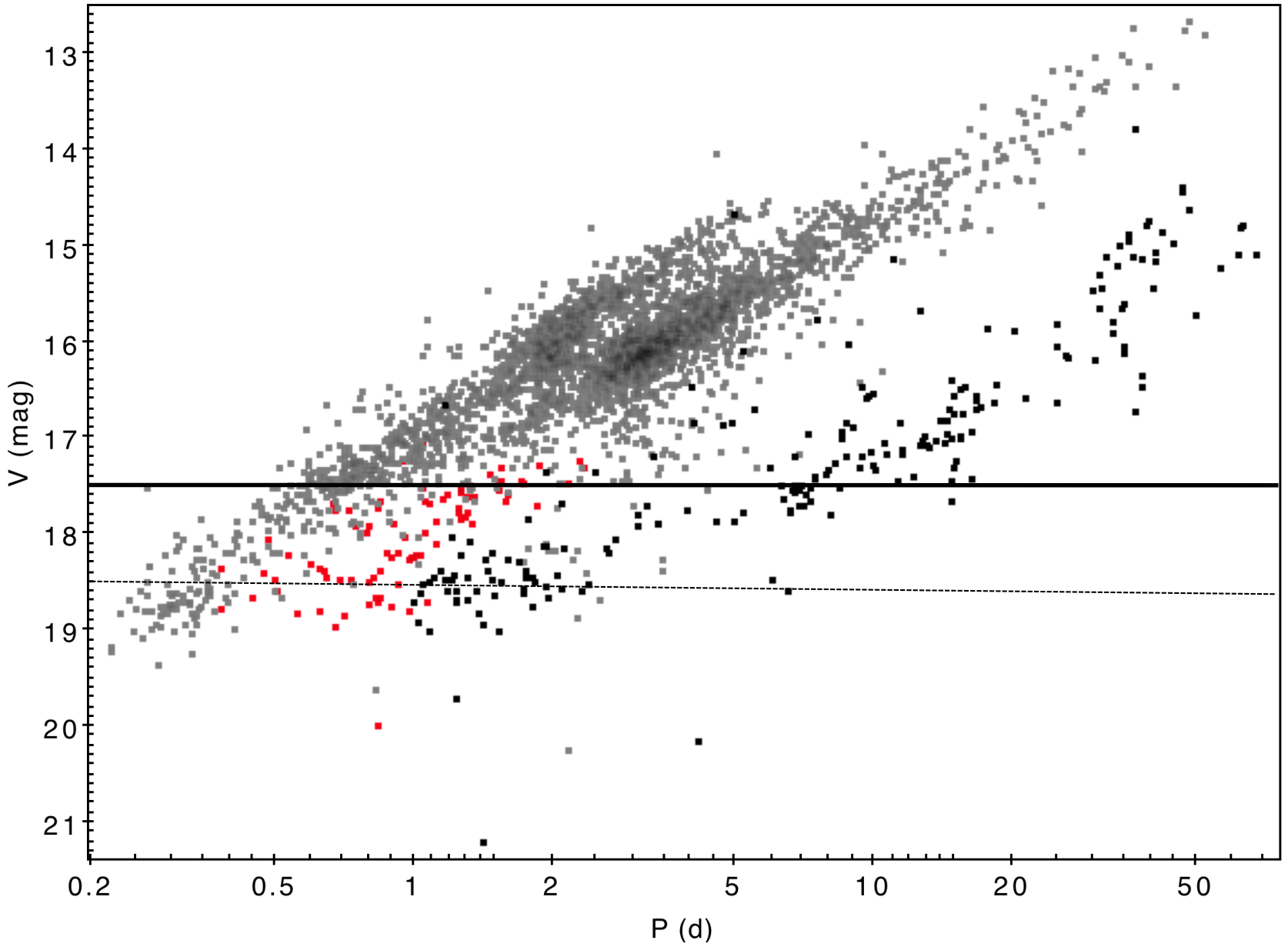


(courtesy of L.Rimoldini)



(courtesy of L.Rimoldini)


Stat G val: mean, weighted [mag]
Run TEST_OR5_S2_EPSL_2571
1.000e+6
1.000e+4
100.0
1.000
Stat G val: mean, weighted [mag]
5.0 <
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
22.5
23.5
24.5
val mean, weighted [mag]
Gaia CU7



Period-Luminosity relation of the LMC Cepheids based on OGLE III and OGLE IV catalogues (courtesy of M.I. Moretti)

The Operation Rehearsal data

Data set {
- 28 days of Ecliptic Scanning law
- 3 days of Nominal Scanning law

69 million sources
received from Photometric Processing (Cambridge University)

↓

Selection:
20 measurements in either G, BP, RP
No repeated observations within 100 minutes

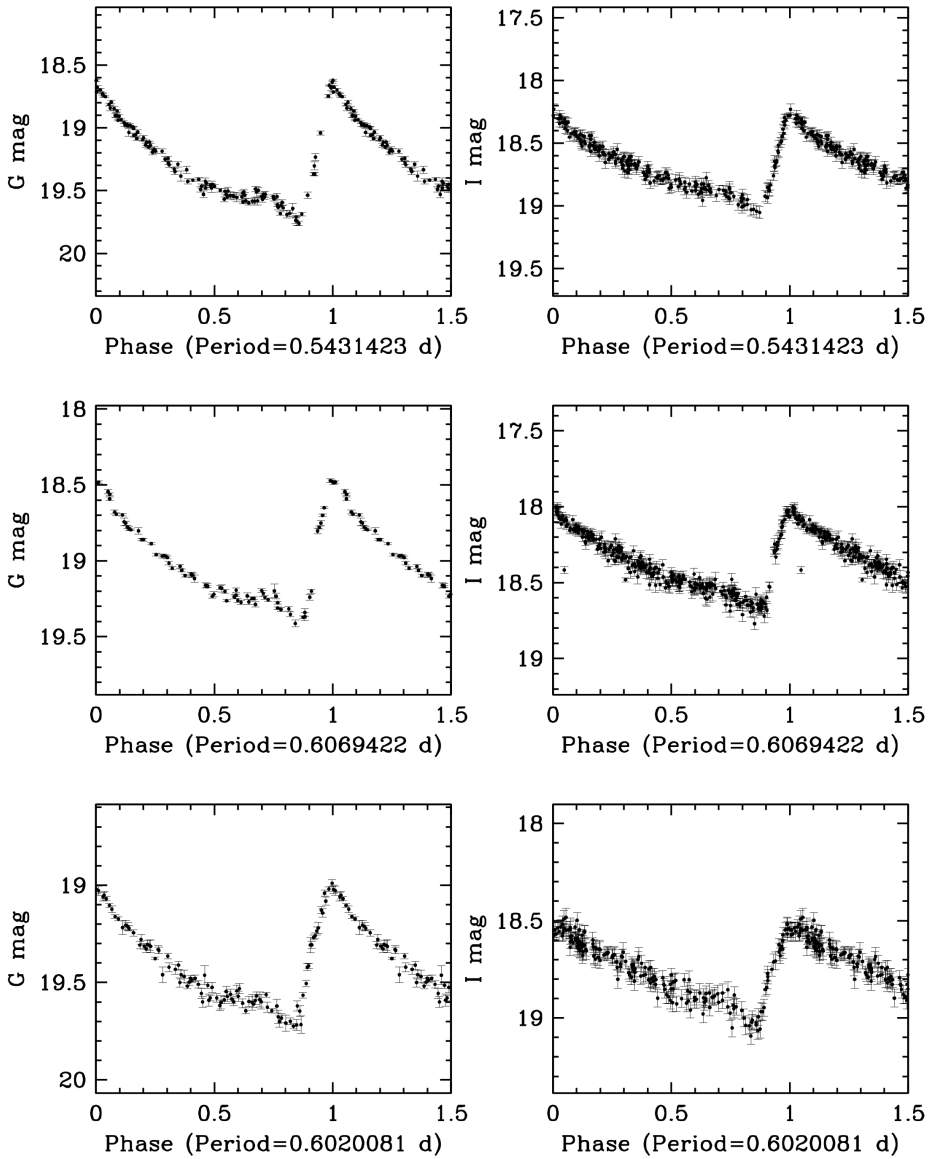
↓

790,000 sources

1282 sources classified as candidate RR Lyrae (1280) /Cepheids (2) fed into the Cep&RRL SOS WP: ~1200 RRLs + ~20 Ceps detected and characterized

RR Lyrae stars in the LMC as seen by Gaia

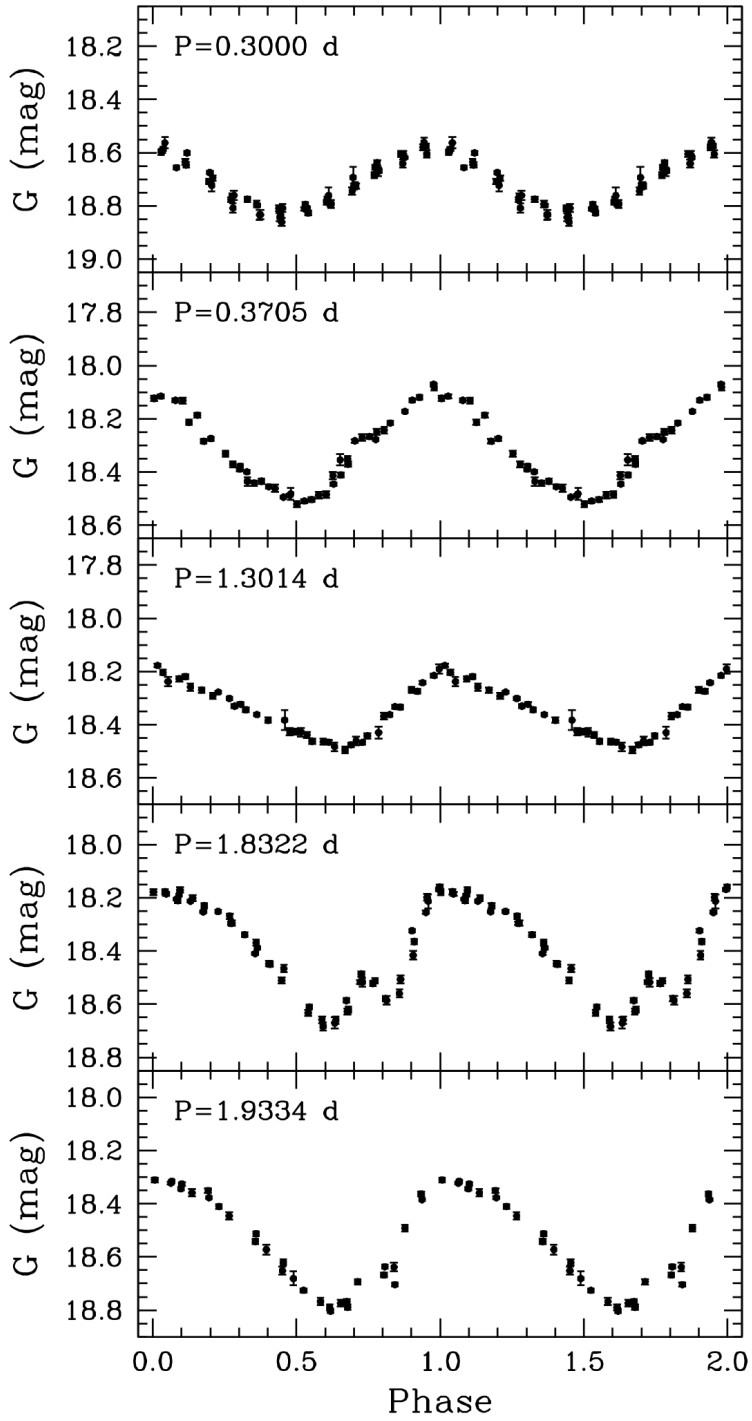
http://www.cosmos.esa.int/web/gaia/iow_20150305



Gaia's Image of the Week March 5th, 2015

Credits: ESA/Gaia/DPAC/CU5/CU7/INAF-OABo
Gisella Clementini, Dafydd Evans, Laurent Eyer, Krzysztof Nienartowicz, Lorenzo Rimoldini and the
Geneva CU7/DPCG and CU7/INAF-OACN teams.

Left panels: G-band light curves of RR Lyrae stars in the Large Magellanic Cloud observed by Gaia during the EPSL scanning. *Right panels*: I-band light curves obtained for the same stars by the OGLE IV survey.



Short period/faint magnitude Cepheids in the LMC observed by Gaia

http://www.cosmos.esa.int/web/gaia/iow_20150528

Gaia's Image of the Week May 28th, 2015

Credits: ESA/Gaia/DPAC/CU5/DPCI/CU7/INAF-OABo/INAF-OACn
Gisella Clementini, Vincenzo Ripepi, Silvio Leccia, Laurent Eyer,
Lorenzo Rimoldini, Isabelle Lecoeur-Taibi, Nami Mowlavi,
Dafydd Evans, Geneva CU7/DPCG and the whole CU7 team.
The photometric data reduction was done with the PhotPipe pipeline at DPCI; processing data were received from the IDT pipeline at DPCE.

Pulsating variables with Gaia

	Hipparcos	Gaia
Classical Galactic Cepheids	273 observed (2 new) P: 2 to 36 days $\sim$ 100 with $\sigma_\pi < 1$ mas	Census of galactic Cepheids with $G \leqslant 20$: $\sim$ 9000 Cepheids All periods, colours and metallicities Up to 1-2 kpc with $\sigma_\pi/\pi < 1\,\%$ All galactic Cepheids with $\sigma_\pi/\pi < 10\,\%$ Cluster membership
Population II Cepheids	$\sim$ 30	$\sim$ 2000
LMC Cepheids	None	1000-2000 Cepheids with $\sigma_\pi/\pi \sim 50 - 100\,\%$ Mean distance of groups of Cepheids expected to 10 % Mean distance of LMC expected to 0.5 % Depth of LMC expected to 1 %
RR Lyrae	186 observed (9 new) Only RR Lyr with accurate π 126 with $\sigma_\pi/\pi \sim 30\,\%$	All galactic RR Lyrae: $\sim$ 70 000 **+15000-40000 in the Bulge** All metallicities Up to 1 kpc with $\sigma_\pi/\pi < 1\,\%$ In globular clusters: mean $\sigma_\pi/\pi < 1\,\%$
All pulsating variables		Extensive surveys of all types of variables Astrometry, photometry and spectroscopy Extensive sampling versus period, colour, metallicity Determination of the zero-points and slopes the P-L(-C) relations Determination of the intrinsic dispersion of the P-L(-C) relations Cluster membership

adapted from Turon et al. 2012, ApSS 341, 15

Data distribution

- Final catalogue ~ 2022
- Intermediate data releases – tentative schedule:

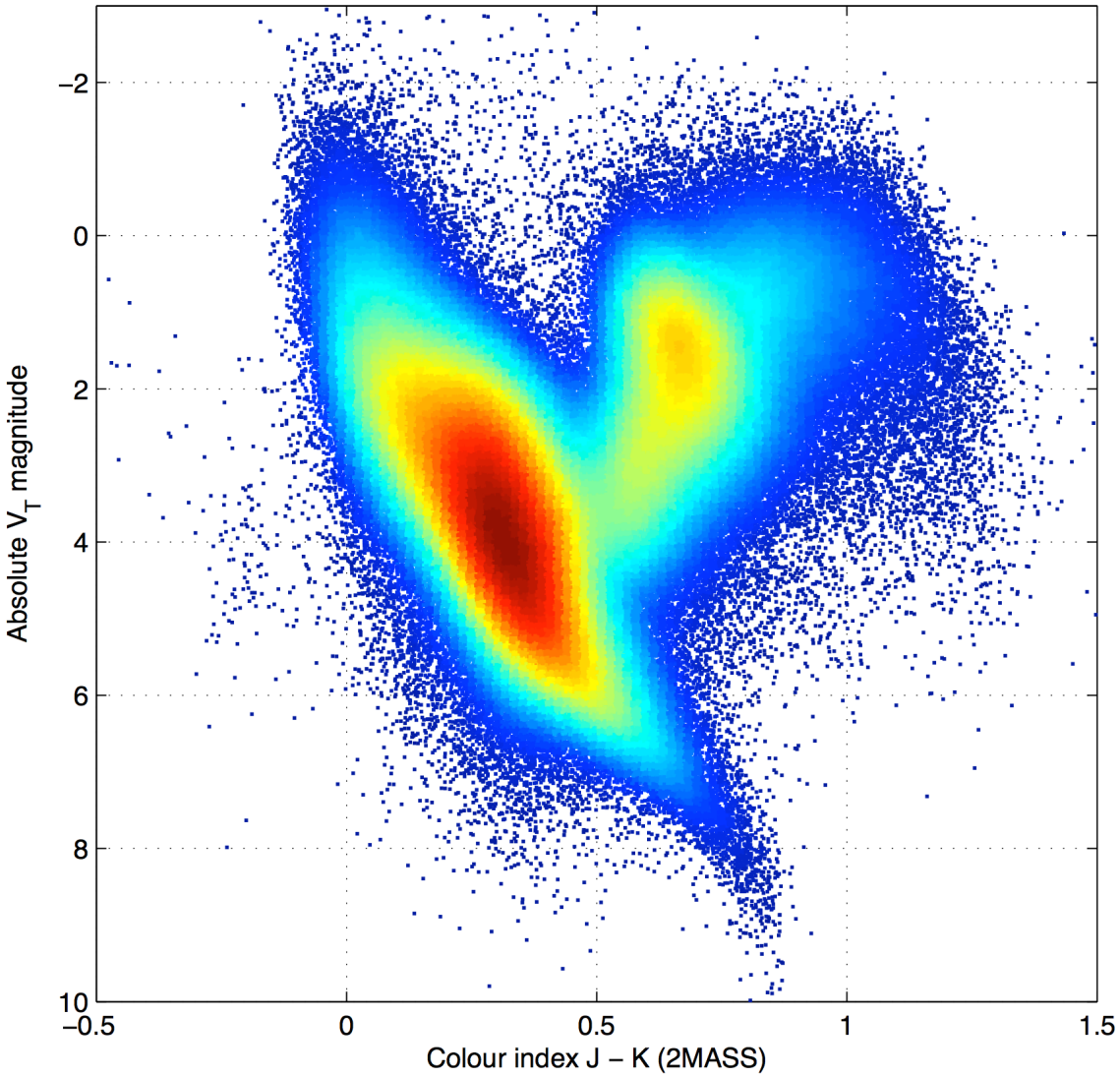
GDR1: Mid-2016 Positions + G magnitude ($\sim$ all sky, single stars)

- Includes more often scanned Ecliptic pole regions
- Hundred Thousand Proper Motions (Hipparcos-Gaia, $\sim$ 50 μas/yr)
- **Includes the EPSL RR Lyrae stars and Cepheids**
- **May include TGAS (to be decided in the next weeks)**

GDR2: Early 2017 radial velocities for bright stars, two-band photometry, and full astrometry (α, δ, ϖ, $\mu_{\alpha*}$, μ_δ) where available.

- Science alerts data released immediately
- No proprietary data rights

Astrometry: TGAS



More information on Gaia at

http://www.cosmos.esa.int/web/gaia

Thank you !