Gaia

C. Cacciari
INAF - Osservatorio Astronomico, Bologna

The primary objective of Gaia is the Galaxy: to observe the physical characteristics, kinematics and distribution of stars over a large fraction of its volume, with the goal of achieving a full understanding of the MW dynamics and structure, and consequently its formation and history.
(Concept and Technology Study Report, ESA-SCI(2000)4

Reconstructing the Milky Way's History: Spectroscopic Surveys, Asteroseismology and Chemodynamical Models
1 - 5 June 2015, Physikzentrum Bad Honnef, GERMANY

Gaia in a nutshell

- ESA cornerstone mission building on the Hipparcos heritage
- Satellite & payload by industry
  management & operations by ESA
  data processing by scientists (DPAC)
- Launch 19 Dec 2013 with Soyuz from Kourou
- 5 years of operations at L2
- Commissioning completed 18 July 2014
- Data collection: up to 21 million transits per square deg up to end of March

- all sky survey to R_{lim} = 20 – 21, ≥ 10^9 sources
- μas accuracy astrometry (parallaxes, positions, proper motions)
- optical spectrophotometry (luminosities, astrophysical parameters)
- spectroscopy to V = 15-16 (radial velocities), to V= 11-12 (rotation, chemistry)

Lissajous orbit around L2

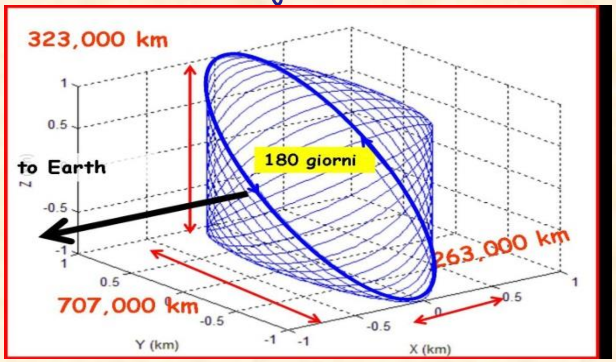


Figure courtesy A. Buzzoni

www.cosmos.esa.int/web/gaia

Payload and Telescope

Two SiC primary mirrors
1.45 × 0.50 m² at 106.5°

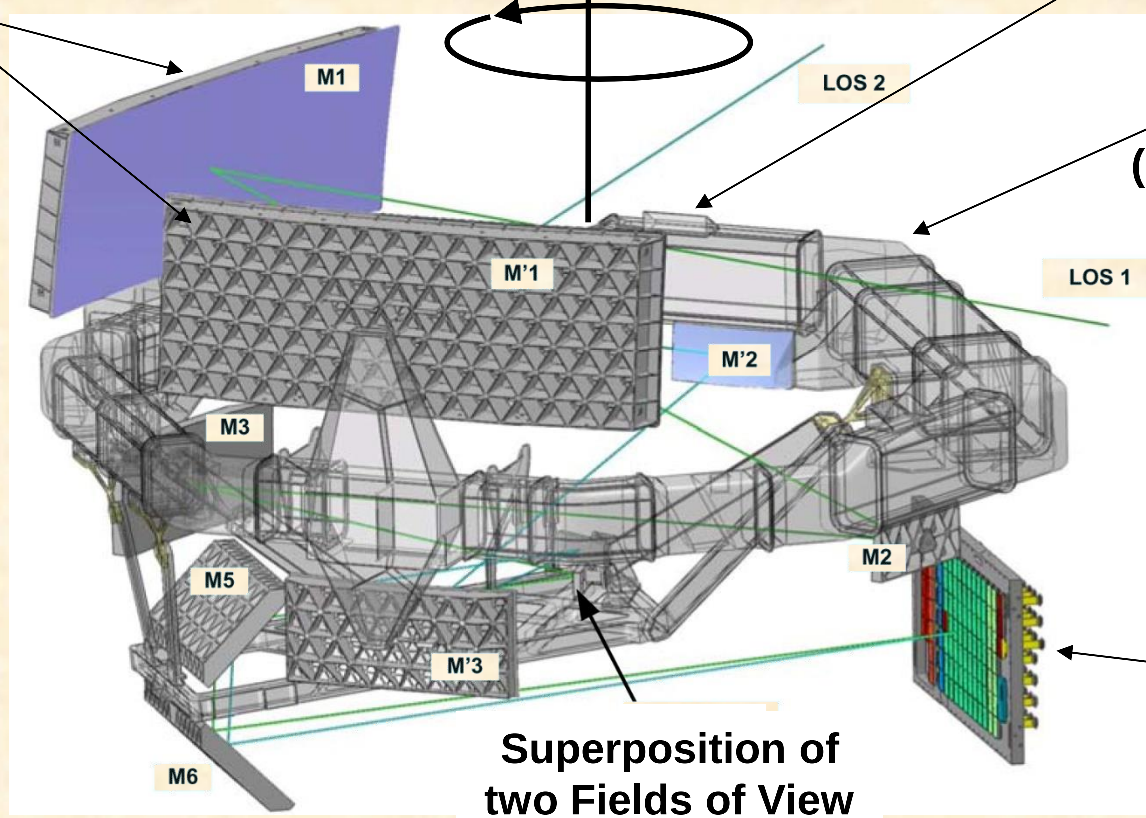
FoV

1.7° x 0.6°

Rotation axis (6 h)

Basic angle monitoring system

SiC toroidal structure (optical bench)

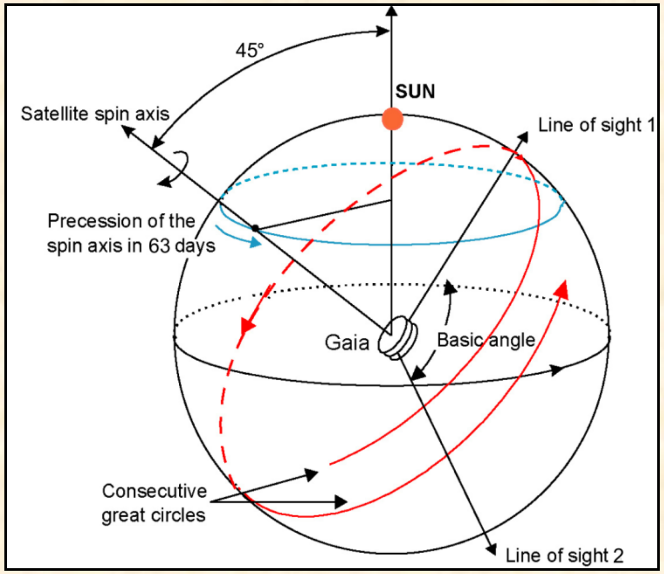


Combined focal plane (CCDs)

Superposition of two Fields of View (FoV)

AIRBUS DEFENCE & SPACE

Sky Scanning Principle



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

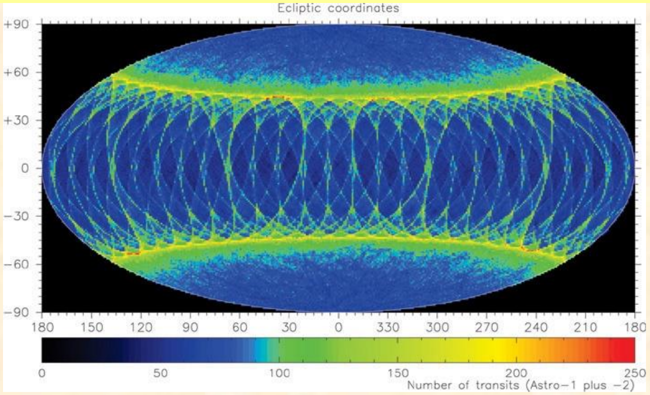
FoV-1: t_0 & t_0 + 6hr

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

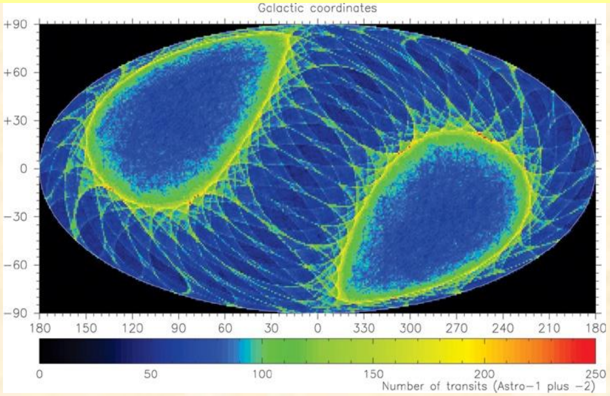
repeated 10-30 days later

Precession of spin axis around solar direction in 63 days ➔ 29 revolutions in 5 yr

End of mission sky-average number of transits: ~ 70
(max $\geq$ 200 at $|\beta|$ = 45° $\pm$ 10°)



Ecliptic coordinates

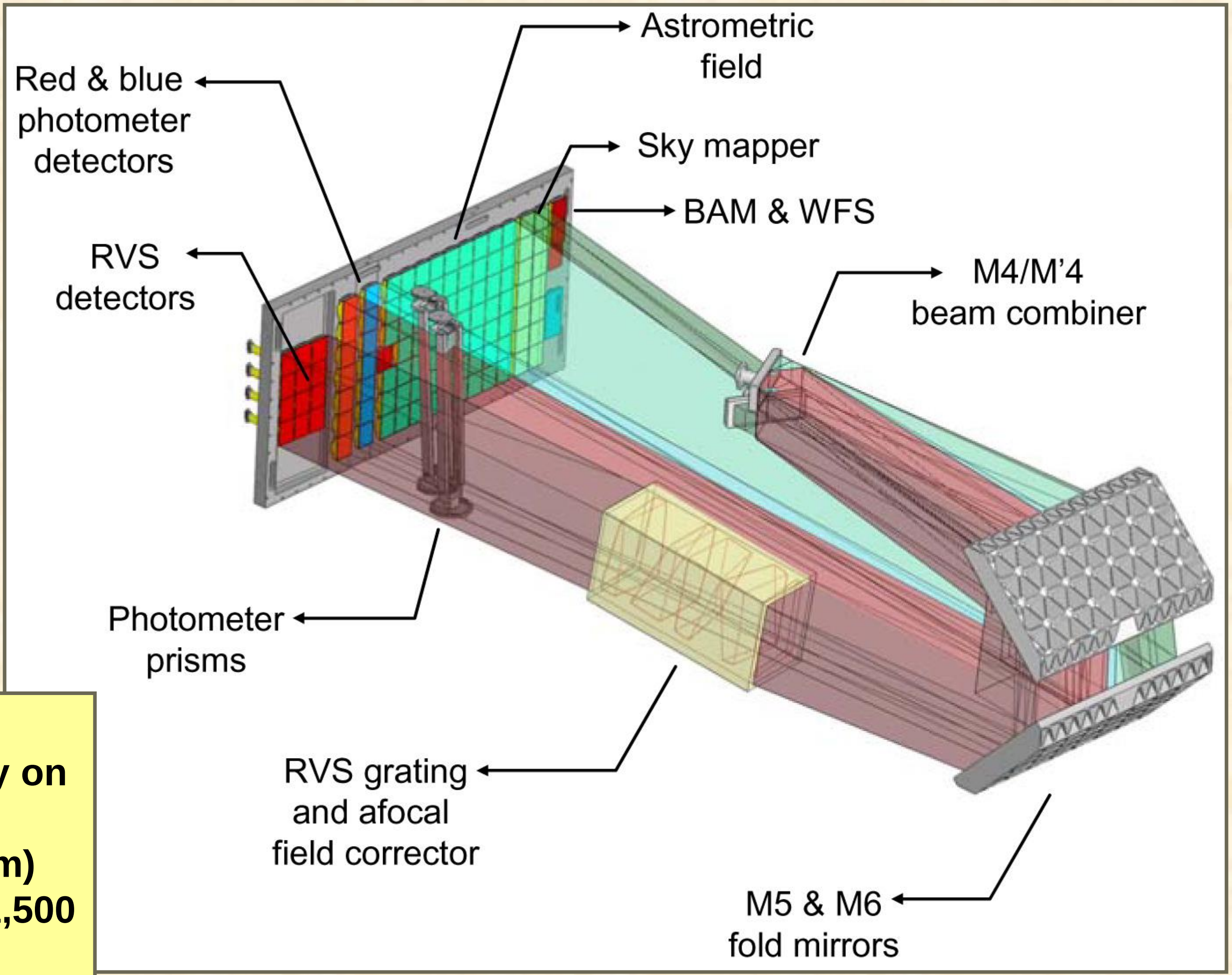


Galactic coordinates

The instruments

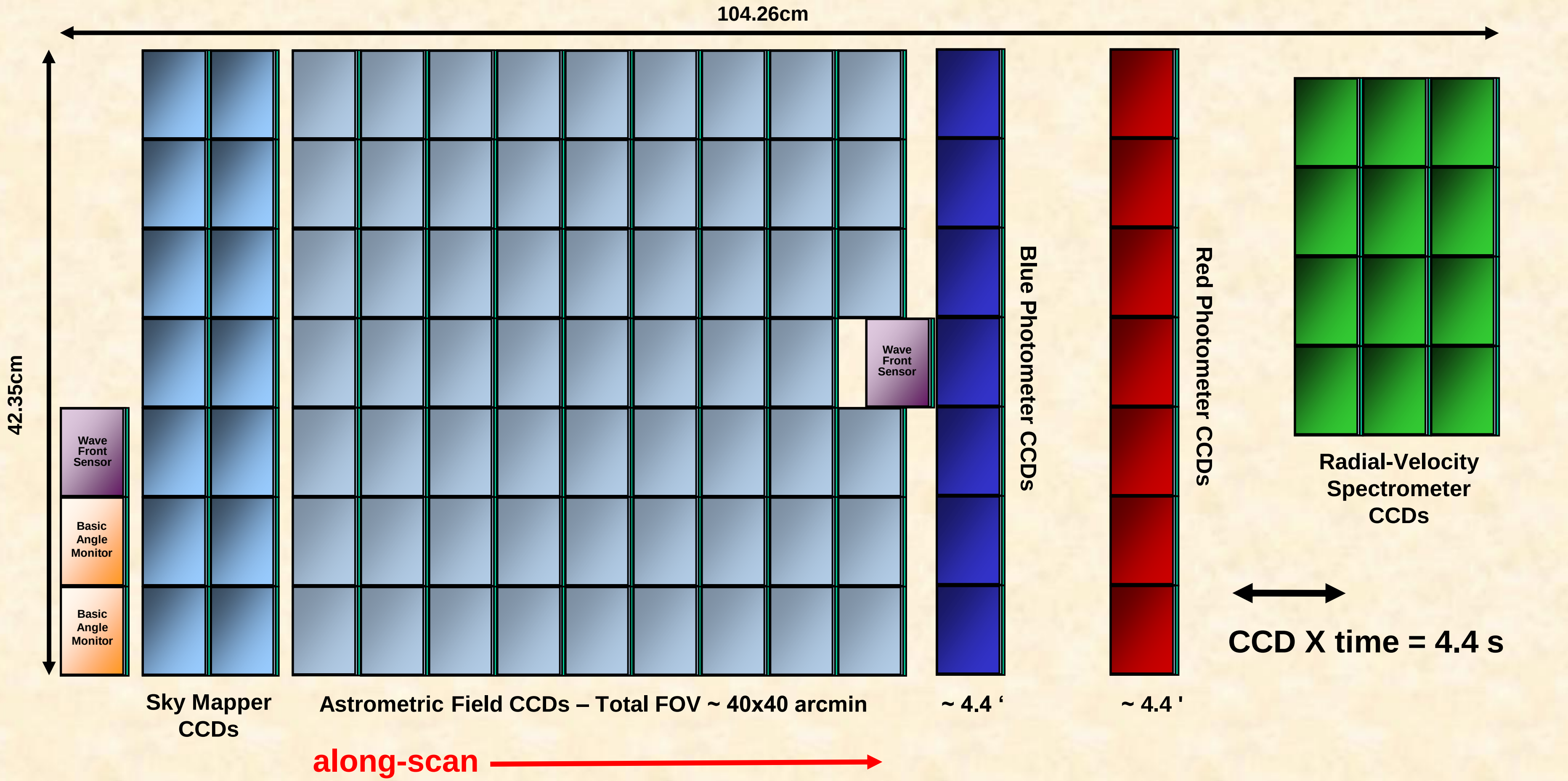
R ~ 80 – 20

R ~ 90 – 70



Slitless spectroscopy on Ca triplet (845–872 nm) Resolution 11,500

Focal Plane



Total field:
- active area: 0.75 deg^2
- CCDs: 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

Gaia science products: census of …

Stellar pops in the Galaxy

(based on the Besançon Galaxy model - *Robin et al. 2003, 2004*)

- Disk: 9.0×10^8
- Thick disk: 4.3×10^8
- Spheroid: 2.1×10^7
- Bulge: 1.7×10^8

Special objects in the Galaxy

- Solar System bodies (3×10^5)
- exoplanets (a few 10^4)
- binaries & rare stellar types (fast evolutionary phases)
- WDs ($\sim 2 \times 10^5$), BDs ($\sim 5 \times 10^4$)

Outside the Galaxy

- brightest stars in nearby (LG) galaxies
- supernovae and burst sources ($\sim 2 \times 10^4$)
- galaxies (10^6 - 10^7)
- QSOs ($\sim 5 \times 10^5$)
- gravitational lensing events: $< 10^2$ photometric; a few 10^2 astrometric

Fundamental Physics

- γ to $\sim 5 \times 10^{-7}$ (10^{-4} - 10^{-5} present)

One billion stars in 5D (6D … 9D) will provide:

in the Galaxy …

positions & distances, velocity distributions and astrophysical parameters (APs) of all **stellar populations in the MW** to unprecedented accuracy, allowing to:

- map the **spatial and dynamical structure** of bulge, disk(s) and halo(s)
- derive **formation and chemical history** (e.g. accretion and/or interaction events) of the MW & star formation history throughout
- obtain the trigonometric calibration of primary distance indicators (**RR Lyraes, Cepheids**) ➔ accurate and robust definition of the **cosmic distance scale**

and beyond the Galaxy …

- QSO detection and definition of rest frame
- structure & stellar population studies in nearby galaxies

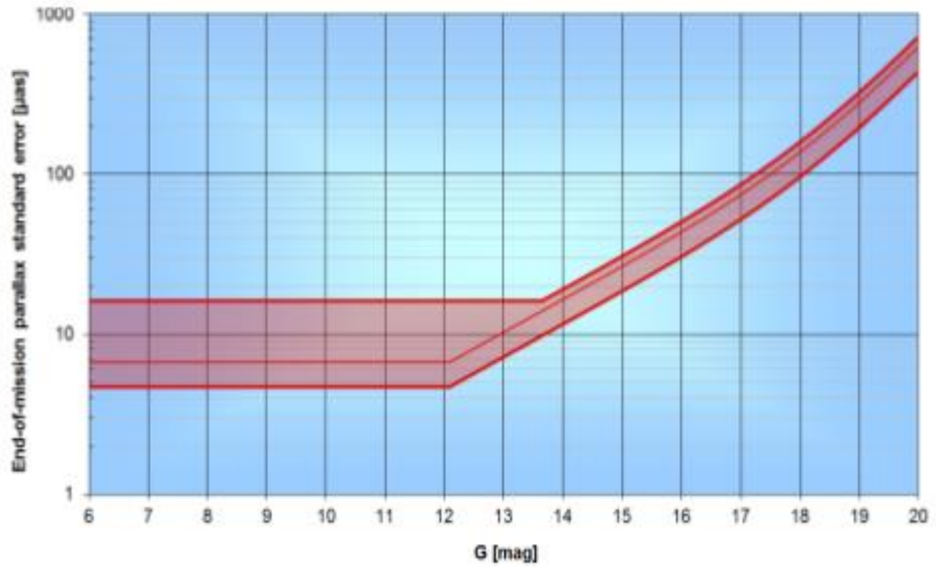
Astrometric performance

- **Sky-averaged end-of-mission parallax standard error** in units of **μas**
- Upper and lower curves show expected variations due to position on the sky, star colour, and bright-star observing conditions (TDI gates, onboard mag-estimation errors etc.)
- The slight upturn of the linear relation in log space starting at ~ 17 mag is mainly caused by straylight

$\sigma_{pos}=0.74\ \sigma_{\omega}$

$\sigma_{\mu}=0.53\ \sigma_{\omega}$

unreddened G2V star (middle curve)



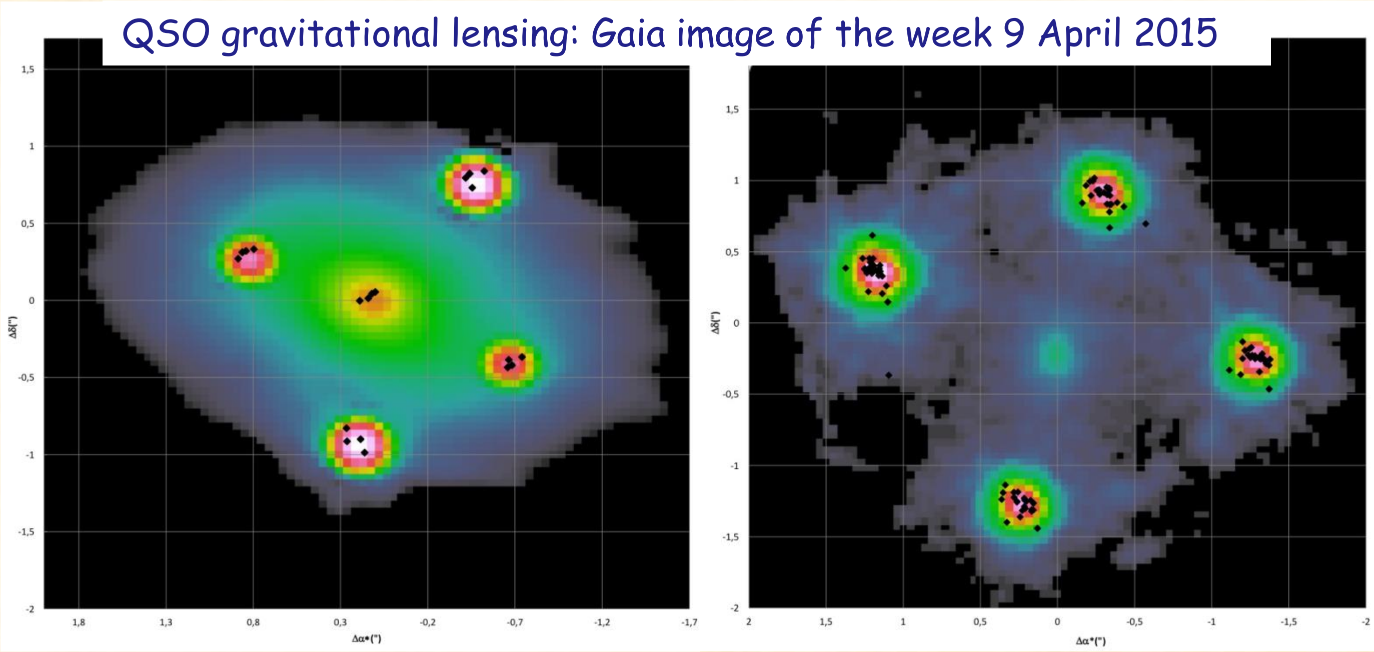
σ_{ω}	V
540μas	20
137μas	18
24μas	15
5-14μas	3-12

(J. De Bruijne , arXiv:1502.00791)

Preliminary results: astrometry

Lensed images
17-19 mag

Image position accuracy for Einstein Cross
~ 50 mas
(better for HE0435-1223) .



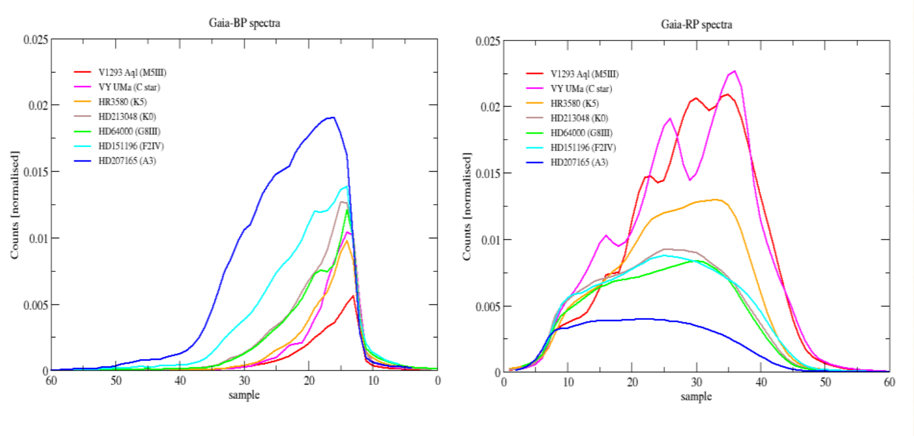
Einstein Cross (Q2237+030) **(z=1.7)** **HE0435-1223**

Gaia astrometric positions placed over HST images. Gaia positions from Initial Data Treatment in a routine mode, with a very preliminary attitude determination.
9 new observations of Q2237+030 and 16 for HE0435-1223 by end 2015 + improved attitude determination ➔ much better accuracy

Credits: ESA/Gaia/DPAC/C. Ducourant, J-F. Lecampion (LAB/Observatoire de Bordeaux), A. Krone-Martins (SIM/Universidade de Lisboa, LAB/Observatoire de Bordeaux), L. Galluccio, F. Mignard (Observatoire de la Côte d'Azur, Nice)

Photometric performance

Figure courtesy C. Jordi & J.-M. Carrasco



	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

End-of-mission photometric errors, in units of **mmag**, considering all known instrumental effects including straylight, as well as a 20% science margin

- **Astrophysical parameters (AP)** can be derived using Gaia spectro-photometric data, sometimes in combination with astrometric and spectroscopic data.
- Preliminary internal accuracy (rms residuals) of AP estimates – **to be reassessed on real data** - on F, G, K, M dwarfs and giants for a wide range of metallicites and interstellar extinctions are (Bailer-Jones+2013, A&A 559, A74):

	T_{eff}	Av	logg	[M/H]
G=15 (V~15-17)	**~ 100 K**	**0.1 mag**	**0.25 dex**	**0.2 dex**

The accuracy is a strong function of the parameters themselves, varying by a factor of more than two up or down over this parameter range

Preliminary results: photometry I
RR Lyraes in the LMC

G-band light curves of RRL stars in the LMC observed by Gaia during the Ecliptic Pole scanning (July 2014)

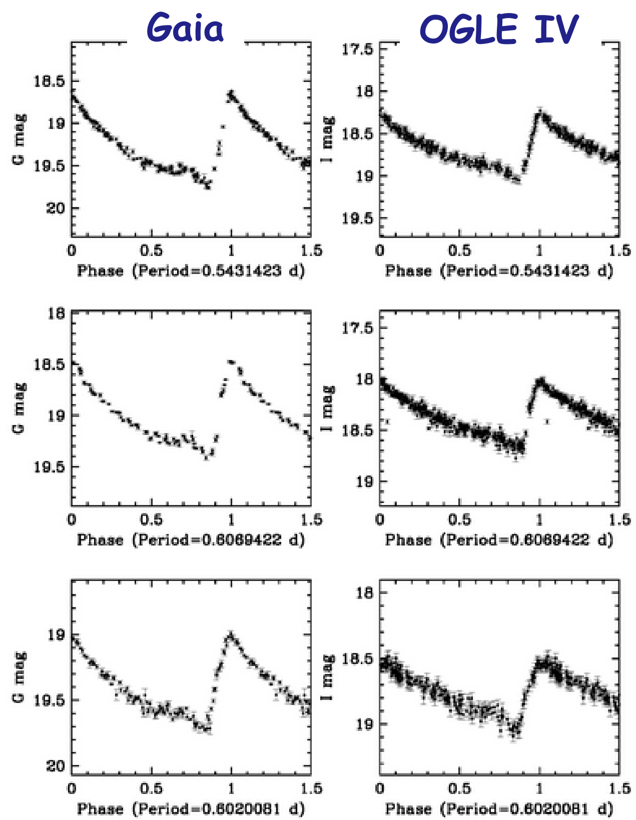
-- Data points from 118 and 96 observations spread over 28 days

-- median uncertainty of measurements ~ 0.02 mag

› 800 measured, including some hundreds new discoveries, with typical average mag G ~ 19.5

Gaia image of the week 5 March 2015

RR LYRAE STARS IN THE LARGE MAGELLANIC CLOUD AS SEEN BY GAIA



I-band light curves obtained by OGLE IV for the same stars

ESA/Gaia/DPAC/CU5/CU7/INAF-OABo, G. Clementini, D. Evans, L. Eyer, K. Nienartowicz, L. Rimoldini and the Geneva CU7/DPCG and CU7/INAF-OACN teams

Preliminary results: photometry II
Cepheids in the LMC

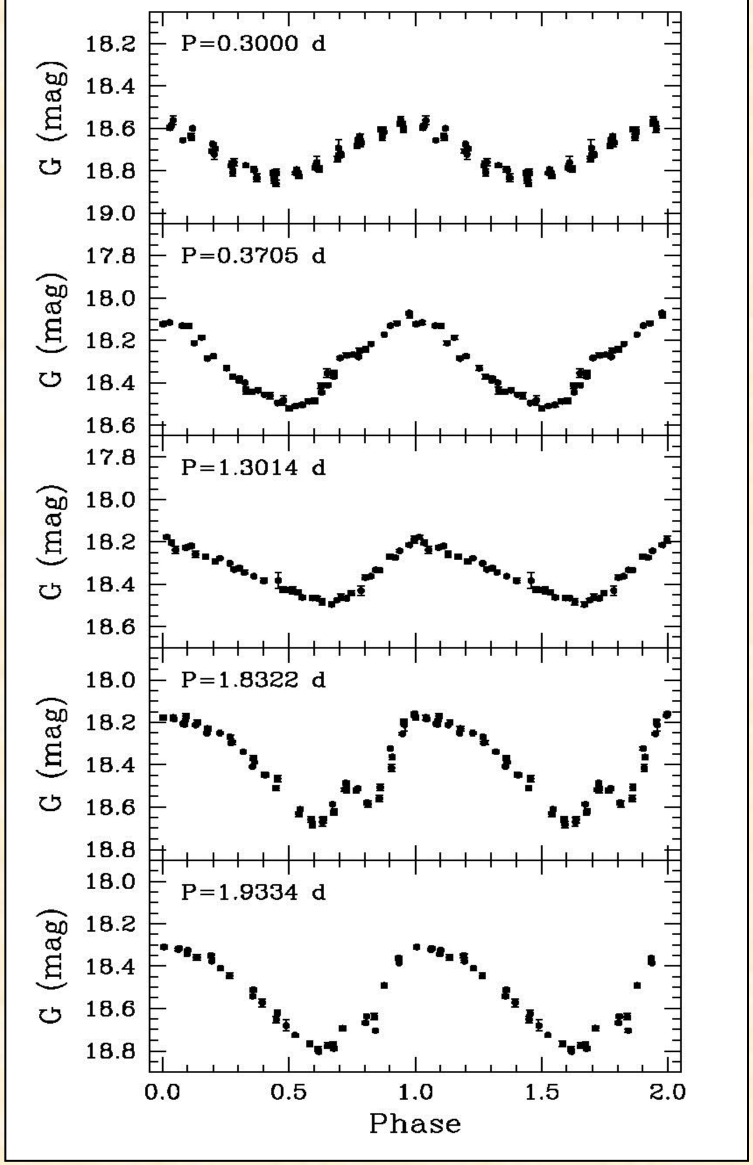
G-band light curves of **short period/faint (G = 18.3-18.7)** Cepheids in the LMC observed by Gaia during the Ecliptic Pole scanning (July 2014)

-- Data points from 31 to 56 observations each star, spread over 32 days

-- median uncertainties of the measurements ~ 10-15 mmag

-- Cepheid magnitude distribution peaks at G ~ 15.5 mag (Mv ~ -3, P ~ 3–5 days)

Gaia image of the week 28 May 2015

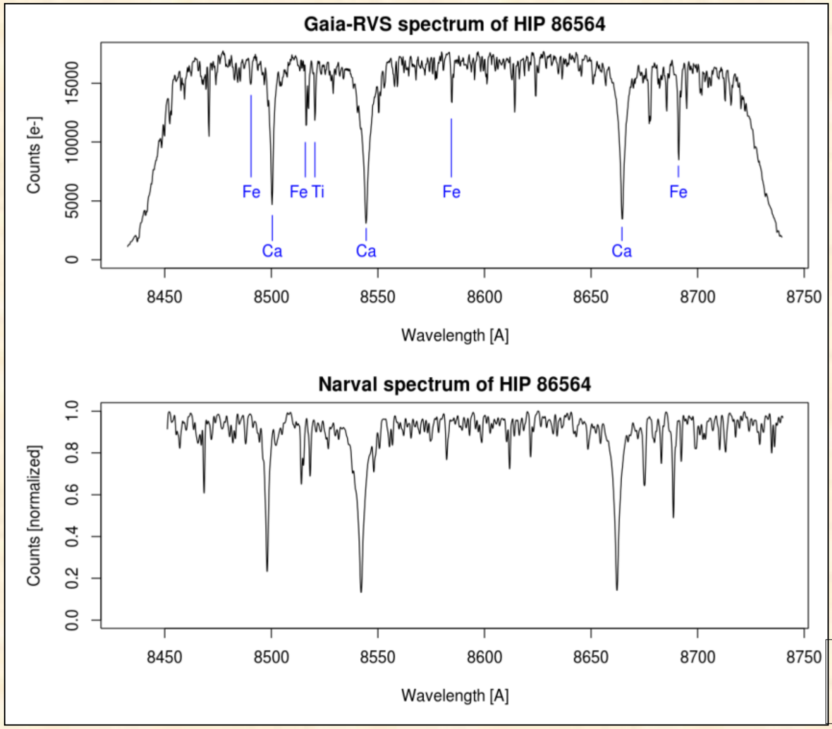


Credits: ESA/Gaia/DPAC/CU5/DPCI/CU7/INAF-OABo/INAF-OACn G. Clementini, V. Ripepi, S. Leccia, L. Eyer, L. Rimoldini, I. Lecoeur-Taibi, N. Mowlavi, D. Evans, Geneva CU7/DPCG and the whole CU7 team. The photometric data reduction was done with the PhotPipe pipeline at DPCI; processing data were received from the IDT pipeline at DPCE.

Spectroscopic performance

End-of-mission radial-velocity errors, considering all known instrumental effects including straylight as measured during the in-orbit commissioning phase, as well as a 20% science margin

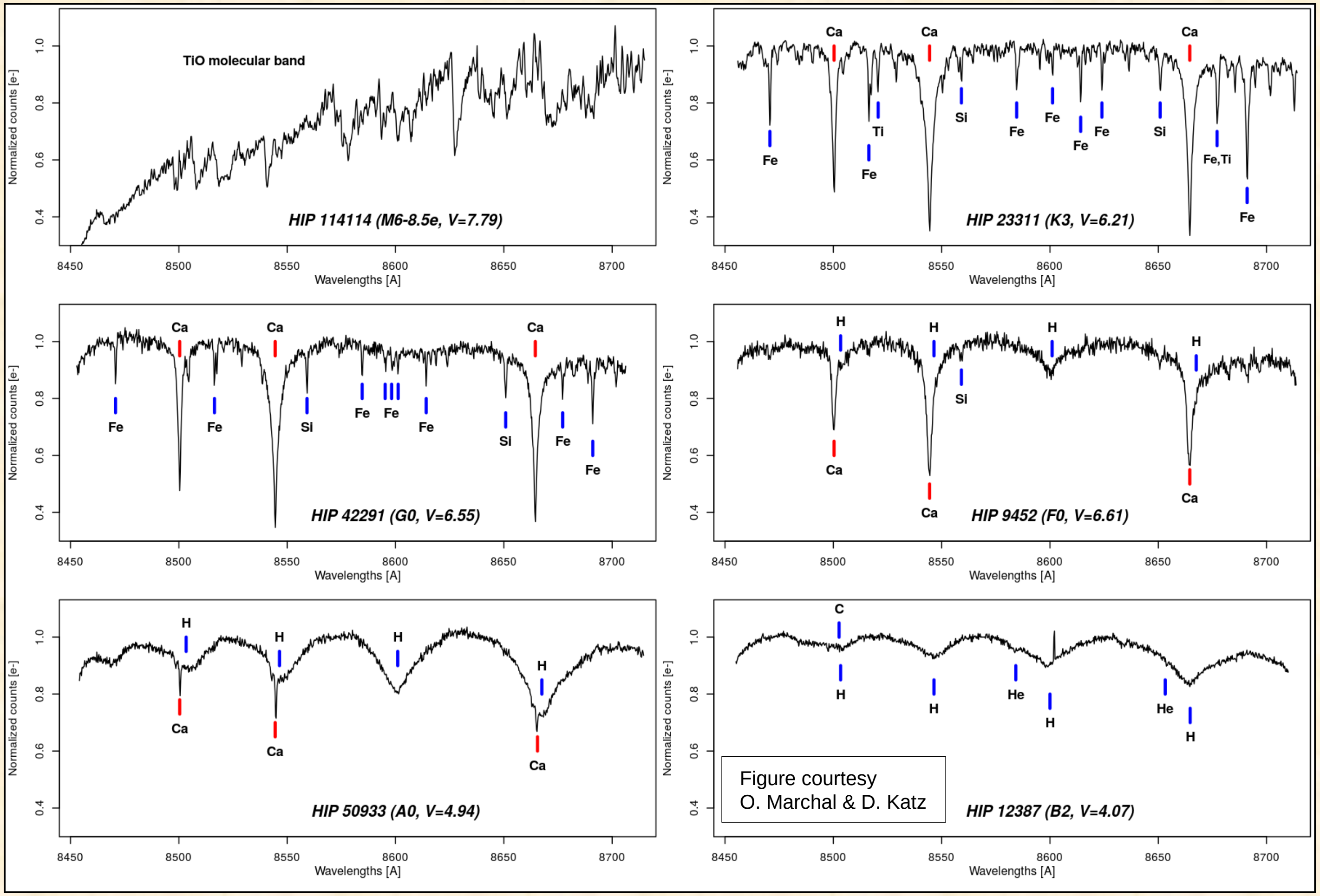
Spectral type	V [mag]	Radial-velocity error [km s^{-1}]
B1V	7.5	1
	11.3	15
G2V	12.3	1
	15.2	15
K1III-MP (metal-poor)	12.8	1
	15.7	15



HIP 86564
K5 V=6.64

Figure courtesy D. Katz, O. Marchal, C. Soubiran

Preliminary RVS results at bright end



Data processing & distribution

- Data Processing and Analysis Consortium (DPAC): ≥ 450 people from 20 European countries and ESA
- No proprietary data rights
- Science alerts (e.g. SNe) data released immediately
- **Final catalogue ~ 2020–22**
- Intermediate data releases:

  GDR1: Mid-2016 Positions + G magnitude (~ 90% sky, single stars)
  Includes more often scanned Ecliptic Pole regions (~ 1 deg)
  Hundred Thousand Proper Motions (HTPM Hipparcos-Gaia, ~ 50 μas/yr)
  GDR2: Early 2017 radial velocities for bright stars, two-band photometry, and full astrometry (α, δ, ω, μ_{α}, μ_{δ},) where available

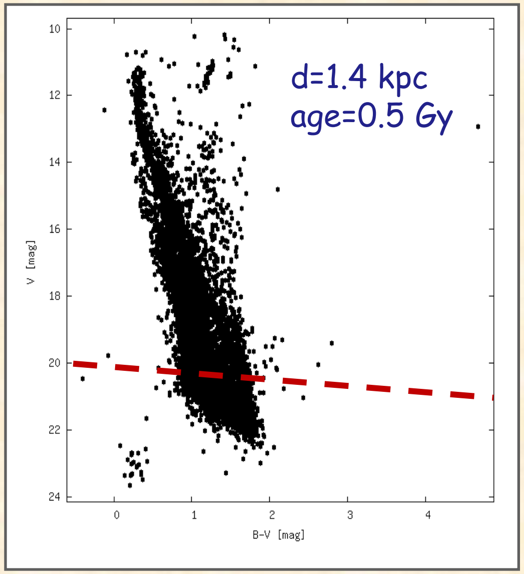
  Two more intermediate releases (2017/18 and 2018/19) TBD

Stellar populations of the MW

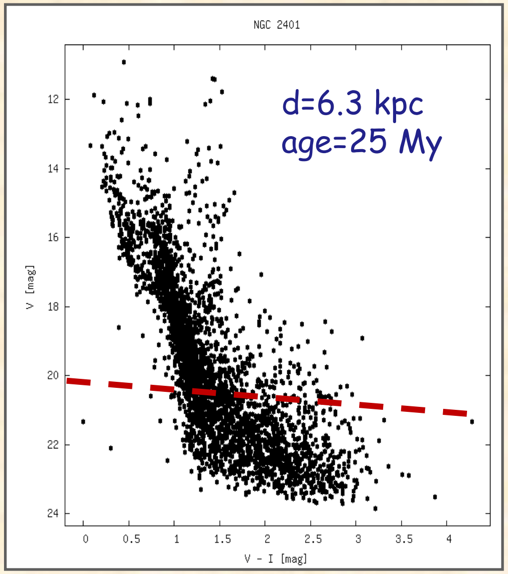
Some selected **kinematic tracers**: σ_{vel} = velocity dispersion of MW component

MW component	Tracer	Mv mag	Av mag	D kpc	V mag	σ_{vel} km/s	Gaia σ_{μ} µas/yr - km/s
Bulge	gM (M0III) HB (A5V) MS-TO (G2V)	-1 +0.5 +4.5	5 5 2	8 8 5	18.5 20 20	100 100 100	67 – 2.5 324 – 12 290 – 6.9
Thin disk warp	gK (K3III) gM (M0III)	0 -1	2 2	10 10	17 16	10-20 10-20	33 – 1.6 20 - 0.9
Thick disk	gK (K3III) HB (A5V) gK (K3III) HB (A5V)	0 +0.5 0 +0.5	2 2 2 2	8 8 15 15	16.5 17 18 18.5	50-60 50-60 30 30	25 – 1.0 39 – 1.5 59 - 4.2 100 – 7.1
Spiral arms	Cepheids (F8) SgB (B0I) SgM (M7III)	- 3 - 5 - 5	5 5 5	10 10 10	17 15 15	10-20 10-20 10-20	37 – 1.8 14 - 0.7 4 - 0.2
Inner Halo Outer	gK (K3III) HB (A5V) MS-TO (G2V) gK (K3III) HB (A5V)	- 1 +0.5 +4.5 -1 +0.5	0 0 0 0 0	10 10 10 30 30	14 15.5 19.5 16.5 18	100 100 100 100 100	8 - 0.4 18 - 0.9 193 – 9.1 25 – 3.6 71 - 10

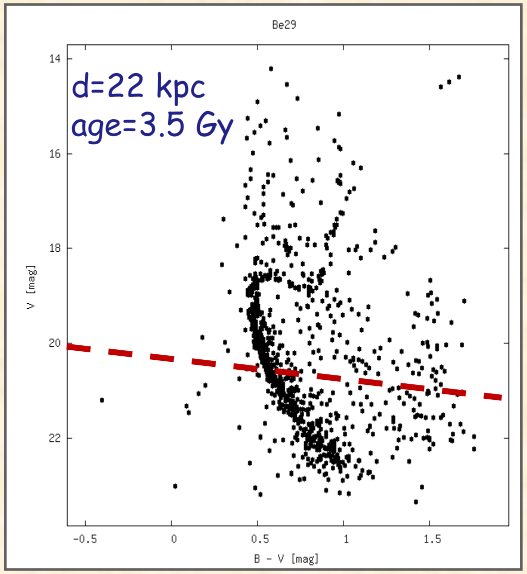
The disk: open clusters



NGC 2099 - Kalirai et al. 2001



NGC 2401 - Baume et al. 2006



Be 29 - Tosi et al. 2004

All the MW open clusters will be observed by Gaia

The distance scale: Galactic RR Lyraes

GEOS database photometry:

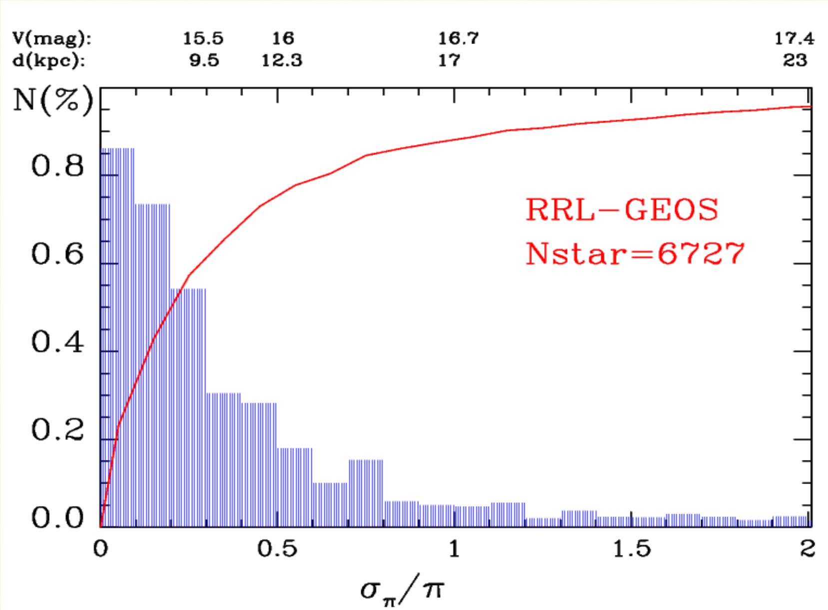
$M_V = 0.52$ (~ [Fe/H]=-1.5 dex)
V-I=0.50
$\langle V \rangle = (V_{max} + V_{min})/2$
Zero reddening

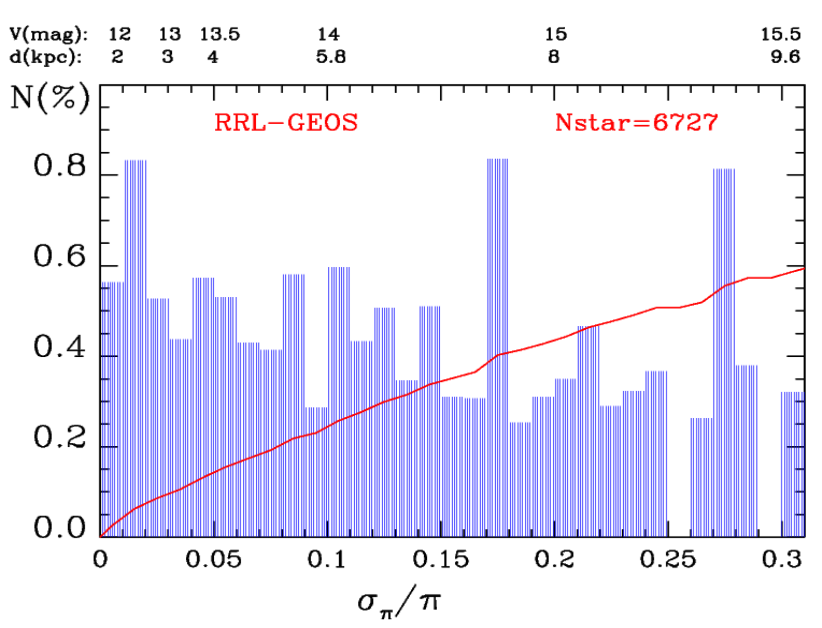
➔ Individual end-of-mission σ_π/π estimates

n. stars	σ_π/π	D(kpc)
~ 5 % (~ 340)	≤ 1%	≤ 2
~ 15 % (~ 1000)	≤ 5%	≤ 4
~ 26 % (~ 1750)	≤ 10%	≤ 6
~ 43 % (~ 2900)	≤ 20%	≤ 8
~ 60 % (~ 4000)	≤ 30%	≤ 10

Expected from Gaia
- ~ 15-40 10^3 bulge
- ~ 70 × 10^3 halo
- › 25 × 10^3 LMC

(Eyer & Cuypers, 2000)





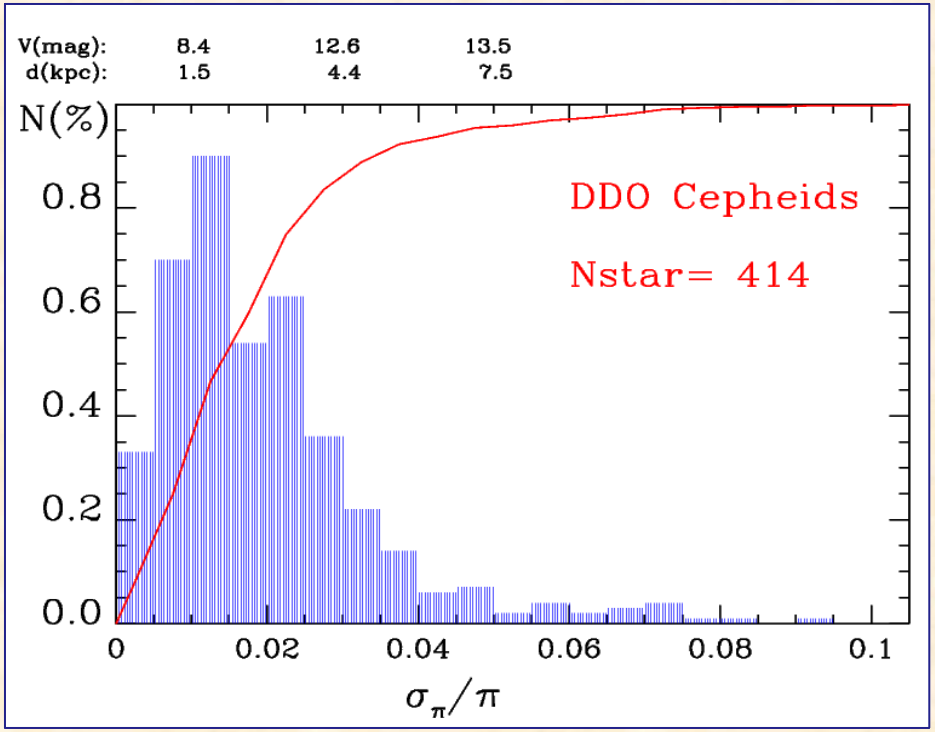
The distance scale: Galactic Cepheids

Fernie et al. (1995)

Only ≲ 1000 Galactic Cepeheids are known – most are located in the Solar neighbourhood

~ 400 Galactic Cepheids from David Dunlap Observatory DB
➔ photometry, reddening, distance, magnitude

Gaia predicted accuracy
≲ 1% for 145 stars (35%)
≲ 2% for 290 stars (70%)
≲ 4% for 390 stars (95%)

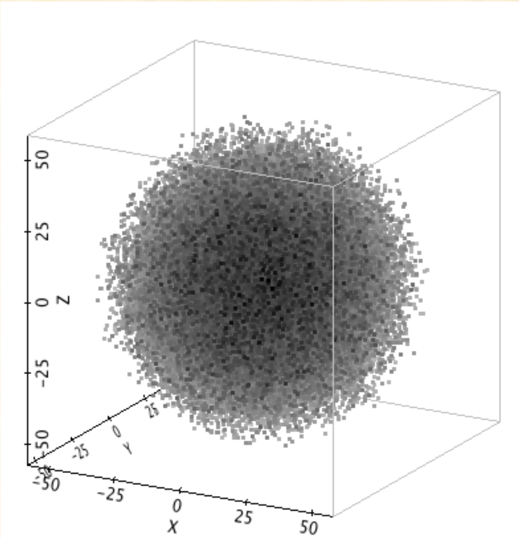


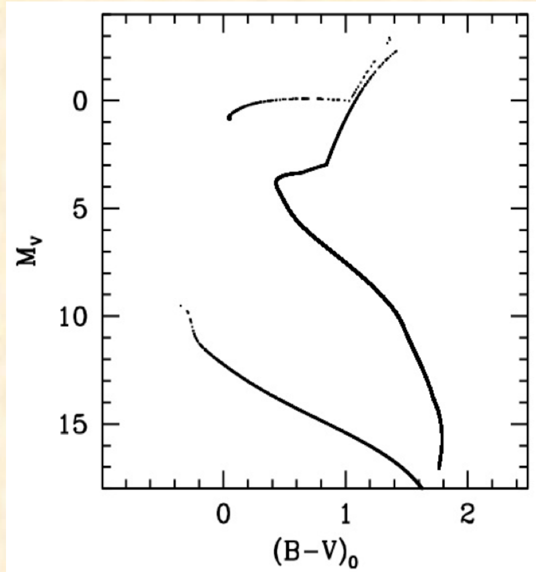
Presently, there are only ~ 250 Cepheids with parallax & photometry
➔ ~ 100 with σ_π ≲ 1 mas (Hipparcos) - 10 with HST parallax

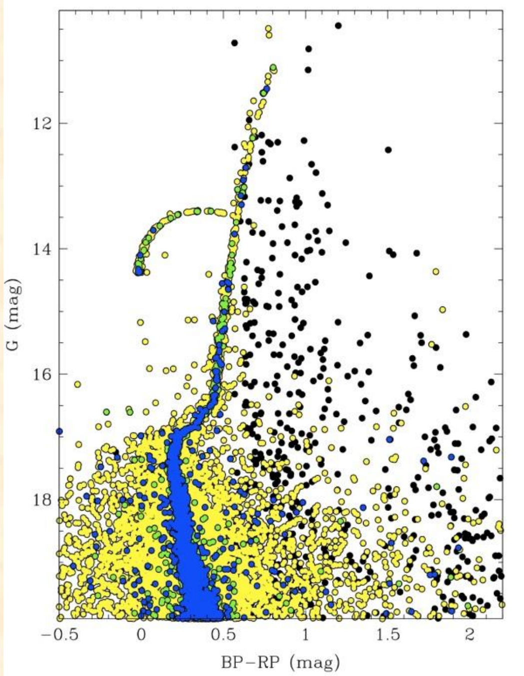
Estimated MW Cepheids for Gaia: 2–9 × 10^3 (Eyer & Cuypers, 2000; Windmark 2011)

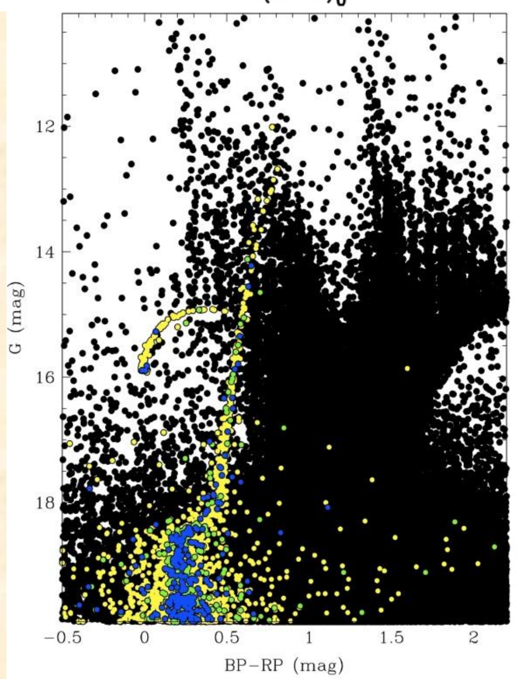
➔ direct (trigonometric) calibration of local standard candles for the cosmological distance scale

Case 1: globular clusters









Pancino, Bellazzini, Marinoni 2013, MemSAIt, 84, 83

Simulation tool

Produce a full 3-D synthetic cluster at dynamical equilibrium

Assign magnitudes to all stars from appropriate stellar models: old & metal-poor

Place it at a given distance

Add reddening and contamination by field stars [from a Galactic model: Besançon]

Simulate the process of Gaia observation [end of mission] including crowding

Astrometry: systemic motion

Easy cluster M_V=-7.6

$\mu_{RA/Dec}$ = 5000 μas/yr = 118 km/s
Distance = 5 kpc

With (de)blends (16838):
μ_{RA} = 4998.7 ± 0.8 μas/yr
μ_{Dec} = 5000.2 ± 0.7 μas/yr
π = 199.7 ± 0.7μas
D = 5.007 ± 0.007 kpc

Difficult cluster

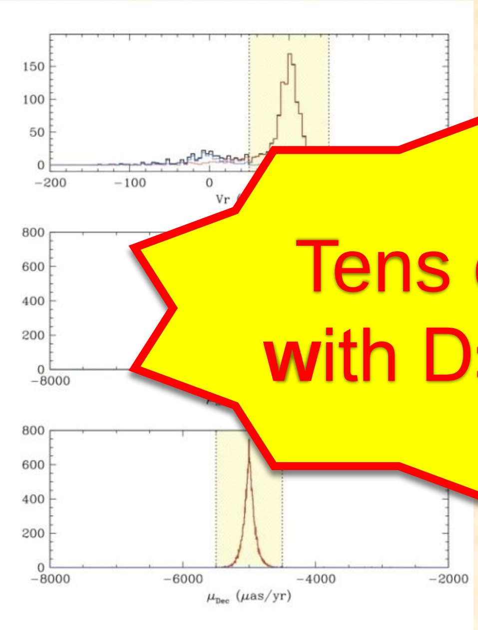
$\mu_{RA/Dec}$ = 5000 μas/yr = 237 km/s
Distance = 10 kpc

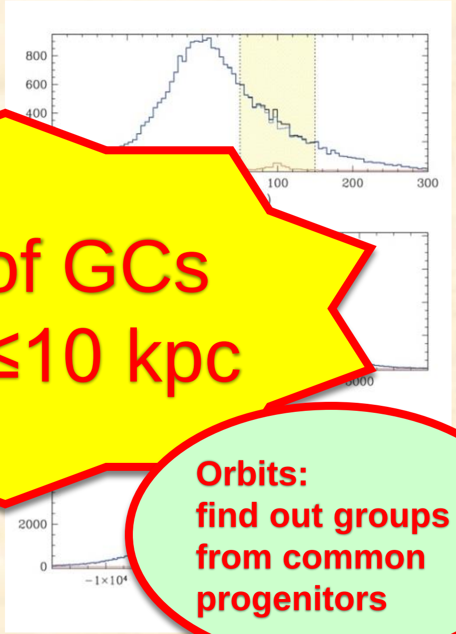
With deblends (3513):
μ_{RA} = 4993 ± 3 μas/yr
μ_{Dec} = 4994 ± 3 μas/yr
π = 101.2 ± 1.4 μas
D = 9.997 ± 0.017 kpc

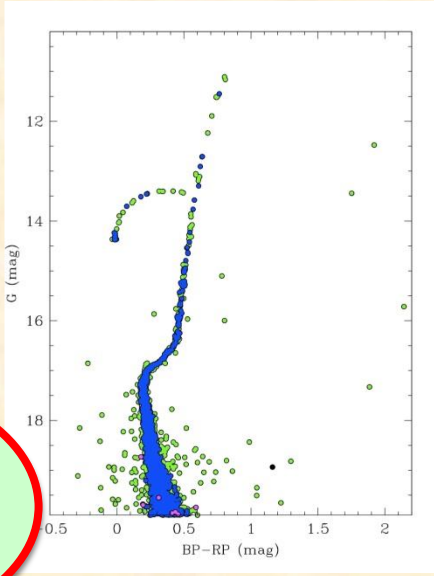
< 1 km/s

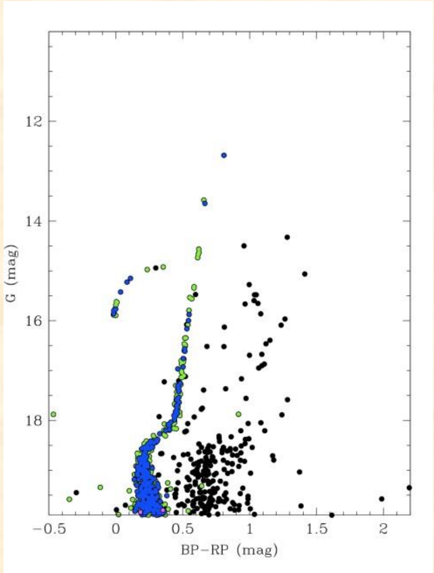
< 20 pc

Credits: Elena Pancino (INAF-OABo)









Tens of GCs with D≤10 kpc

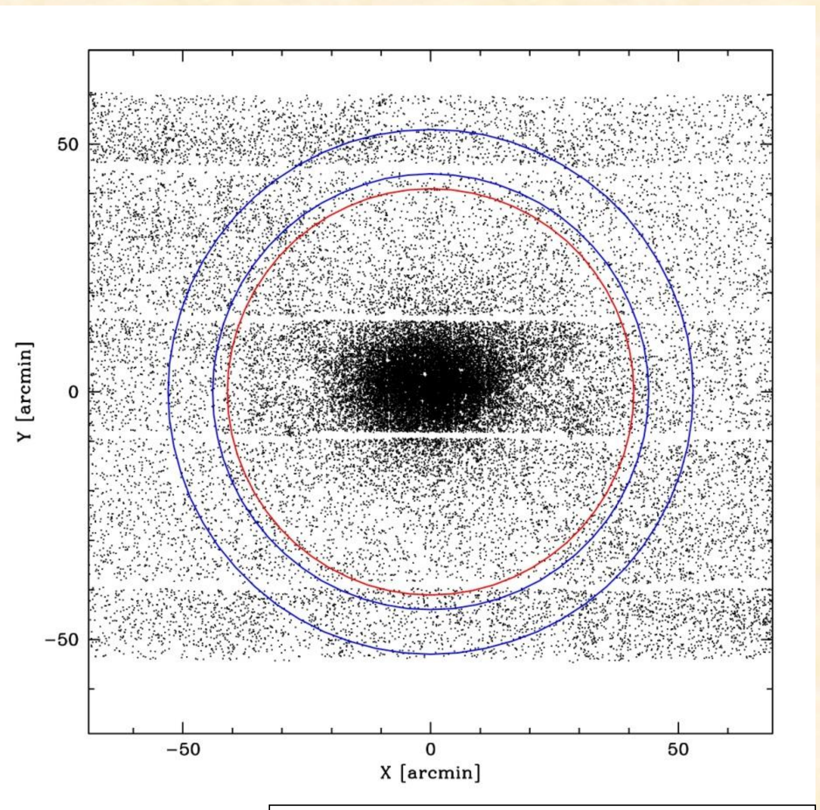
**Orbits:
find out groups
from common
progenitors**

Case 2: dwarf spheroidal galaxy Draco

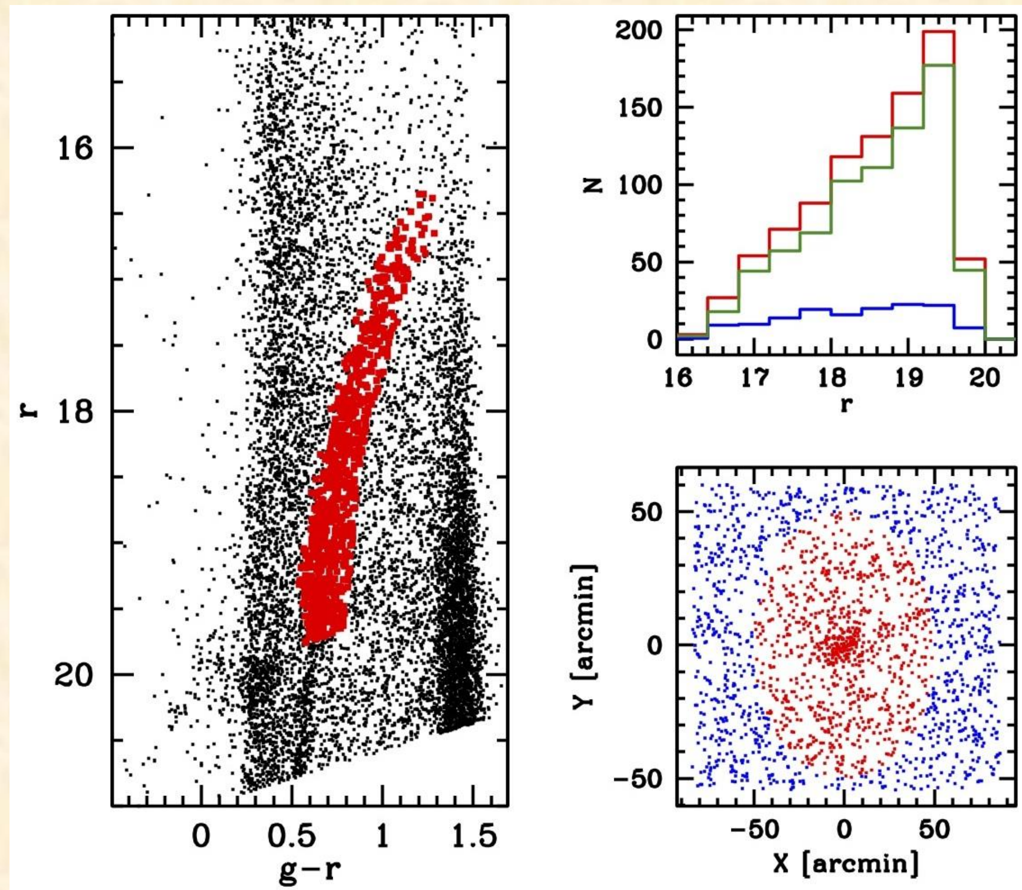
M_V=-9.0 $\mu_{V,0}$=25.0 mag/arcsec^2 D = 93 kpc

2º×2º CFHT photometry from Segall et al 2007

After statistical decontamination ➔ 750 RGB stars with V≤ 20



Courtesy Michele Bellazzini, OABo



Case 2: dwarf spheroidal galaxy Draco

Simulating Gaia observations of real Draco stars (motions - velocity dispersion)

To each of the 750 Draco member stars observable by Gaia I associate :

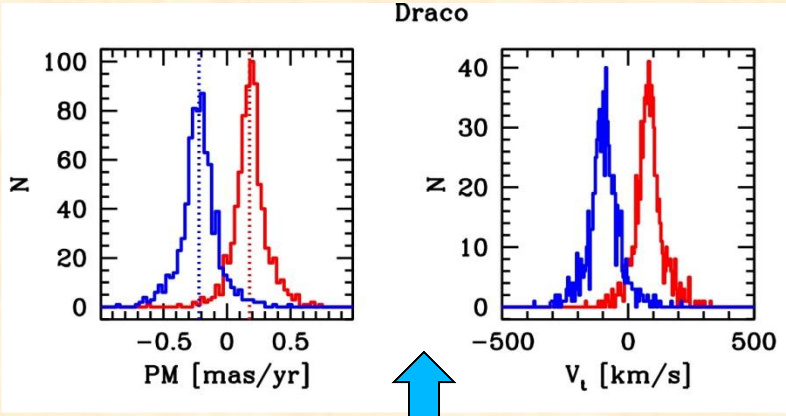
- **A realistic SYSTEMIC tangential motion (amplitudes from HST estimates)**
- **A realistic velocity dispersion (9.1 km/s, assuming isotropy)**
- **Observational errors from de Bruijne's model**
- **To simulate non-perfect knowledge of individual observational errors a Gaussian component of amplitude 10% is added to the error**

For each star observed by Gaia I obtain realistic:

PMRA ± ePMRA & PMDE ± ePMDE

Case 2: dwarf spheroidal galaxy Draco

Maximum Likelihood estimate of systemic proper motion and velocity dispersion using a simple gaussian model. In input PMRA ± ePMRA & PMDE ± ePMDE



State of the art systemic PM with HST: uncertainty = 0.063 mas/yr (Pryor et al. 2015)

N_*/M_V	Error inaccuracy	TRUE <PMRA>	Measured <PMRA>	TRUE <PMDE>	Measured <PMDE>	TRUE σ	Measured σ	Gaia/HST
750/-9.0 in mas/yr	10%	0.177	0.175 ±0.0033	-0.221	-0.217 ±0.0031	0.0206	0.0210 ±0.0054	~19
750/-9.0 in km/s	10%	78.0	77.1 ±1.4	97.4	-95.6 ±1.4	9.1	9.2 ±2.4	
75/-6.5 in mas/yr	10%	0.177	0.172 ±0.0119	-0.221	-0.217 ±0.0093	0.0206	0.0420 ±0.0156	~6
10/-4.3 in mas/yr	10%	0.177	0.180 ±0.030	-0.221	-0.185 ±0.030	0.0206	-------	~2

Summary – Conclusions

- In the Galaxy Gaia will provide the distances, velocity distributions and APs of all stellar populations to unprecedented accuracy as far as 10 kpc (and beyond), allowing to:
  - map the spatial and dynamical structure of the MW components
  - identify merger debris, streams etc. (evidence of accretion and/or interaction events), and derive the MW formation and chemical history
  - derive the star formation history throughout the Galaxy
  - obtain the trigonometric calibration of primary distance indicators ➔ a definitive and robust definition of the cosmic distance scale
- Comparable astrometric accuracy may be achieved by other present (future) space- & ground-based facilities, but on **small areas** of the sky
- **Several surveys** (especially the high-resolution **spectroscopic** ones, see talk by Carlos Allende-Prieto) will be very important: none will provide all-sky coverage, but all will contribute to complement and extend the scientific potential of the Gaia data

more information on Gaia at

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

Thank you !