L'Italia in Gaia

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For the Italian participation in the mission

Overview

- ❑ **Gaia in a nut-shell**
- ❑ Mission Status: where are we at?
- ❑ The Italian contribution

Gaia in a nutshell

- All-sky astrometric survey carried out **end 2013 – end 2018**
  - ⇒ final results around **2021- early 2022**

- All point objects between magnitude 6 and 20
  - ⇒ stars, asteroids, quasars, extragalactic supernovae, etc
  - ⇒ about 10^9 objects

- Using Hipparcos principle (continuous scanning, two fields of view)
  - ⇒ stellar astrometric parameters α, δ, ϖ, μ_α, μ_δ

- Positional accuracy from 6 μas (bright stars) to 200 μas (faint)
  - ⇒ tied to the extragalactic frame via ~500,000 quasars

- Complementary spectrophotometry and spectroscopic radial velocity
  (to ~ milli-mag and ~ Km/sec precision/accuracy)

Three experiments on board

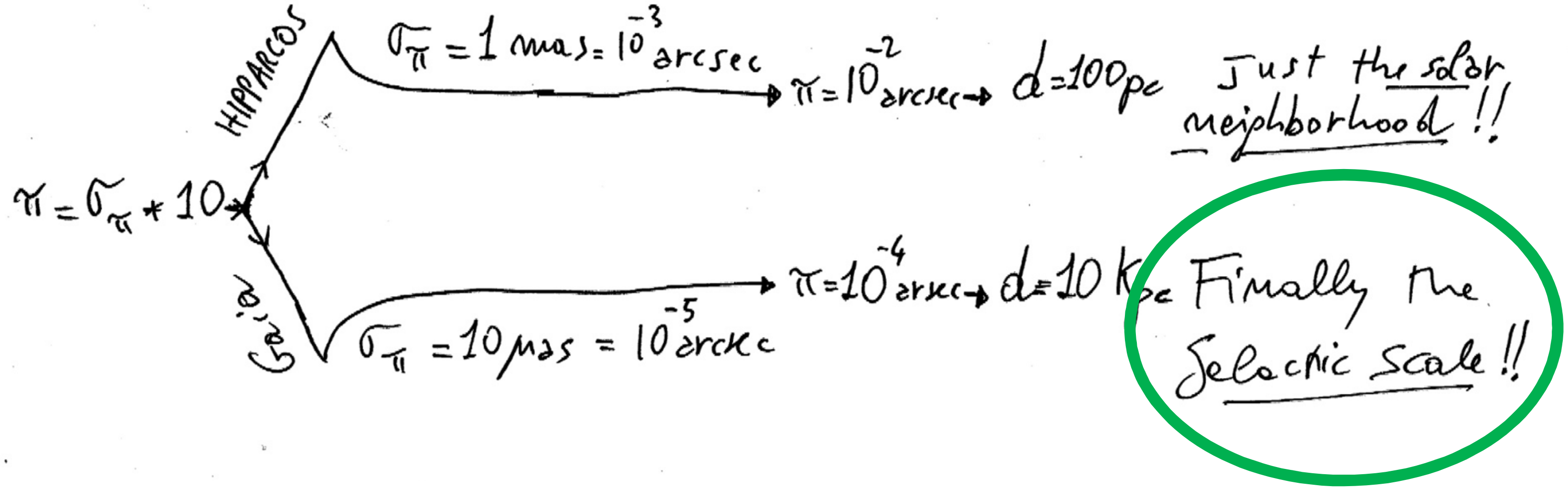
1. Astrometry (< 20 mag):
   - unbiased and complete to 20 mag ⇒ 10^9 stars
   - 10 – 25 μarcsec precision at 15 mag
   - scanning satellite with two viewing directions ⇒ global accuracy
   - global astrometric reduction, as for Hipparcos

2. Photometry (< 20 mag):
   - astrophysical diagnostics (spectro-photometry) + chromaticity
   - T_{eff} to ~200 K, log(g) to 0.2 dex, [Fe/H] to 0.2 dex, extinction, …

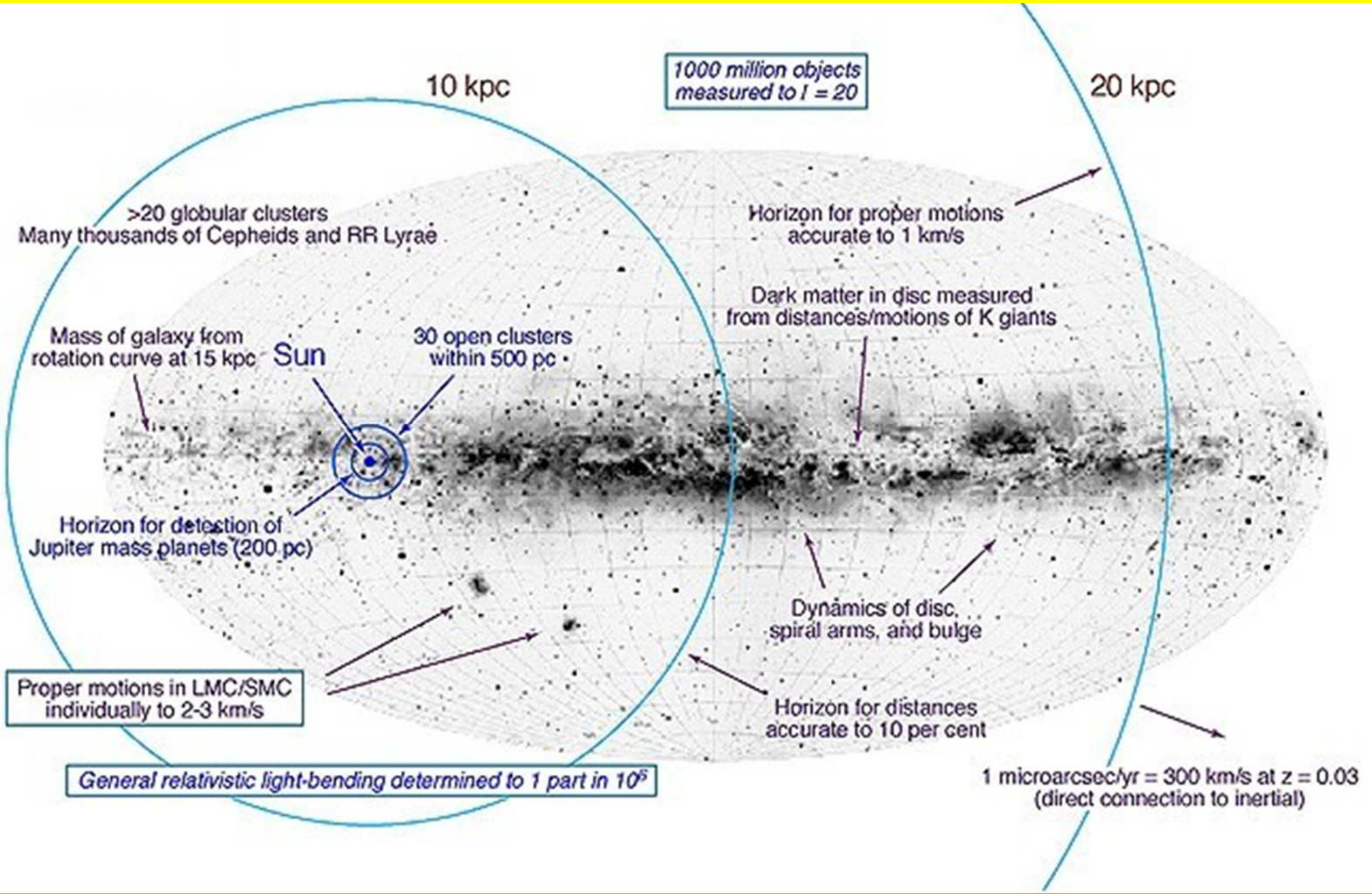
3. Spectroscopy (< 17 mag):
   - slitless spectroscopy of Ca triplet (847 – 874 nm) at R = 11,500
   - radial velocities with 15 km s^{-1} precision at 17 mag
   - third component of space motion, perspective acceleration, binaries, chemistry, rotation, …

Parallax (π) relative error is the same as relative error in distance (**d**).

The location of an object in astrometry is considered reliable if its error is less than 10%: $\frac{\sigma_\pi}{\pi} = 0.1$



Gaia: the ultimate Milky Way "machine"



Science with Gaia (examples)

(From the original science case)

- **Stellar astrophysics:**
  - accurate (< 1%) parallax distances to millions of stars
    - ⇒ intrinsic properties of stars, test of stellar structure models
  - astrometric detection of (large) planetary companions
- **Galactic astrophysics:**
  - space motions of large, volume-complete samples of stars
    - ⇒ galactic potential ⇒ distribution of (dark) matter
  - combined luminosity / colour / velocity data for large samples
    - ⇒ history of star formation and how the Galaxy was put together
- **Solar system physics:**
  - about 300,000 asteroids observed
  - about 50 observation epochs per object, 35-1000 μas per epoch
    - ⇒ orbit families, dynamical evolution, masses of individual asteroids
- **Reference frame and fundamental physics:**
  - dense and accurate optical frame directly tied to the extragalactic frame

- ESA-only mission (prime EADS Astrium SAS)
- Launcher: Soyuz–Fregat from CSG (Guiana)
- Orbit: L2 Lissajous orbit (1.5 million km from Earth, one-month travel time after launch)
- Lifetime: 5 years (1 year potential extension)
- Ground stations: Cebreros + New Norcia + Malargüe
- Downlink rate: 4 – 8 Mbps (~50 GB day^{-1})
- Only scientific data reduction contracted out to DPAC (European consortium)

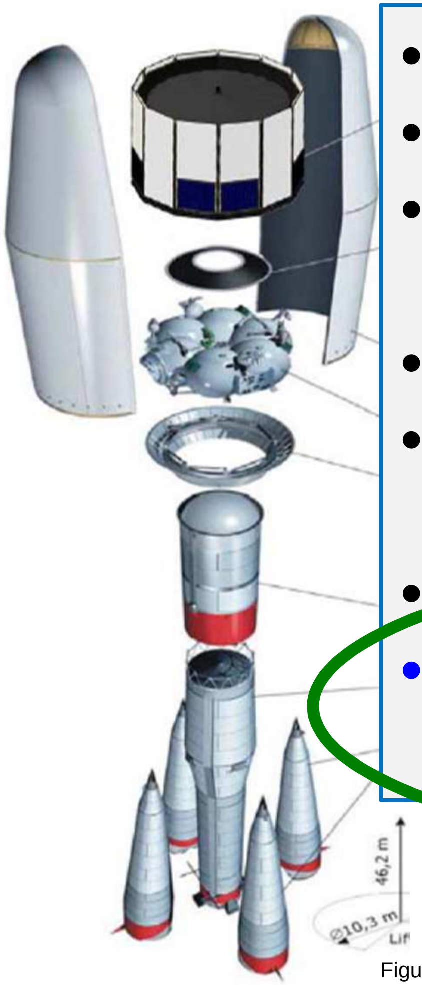
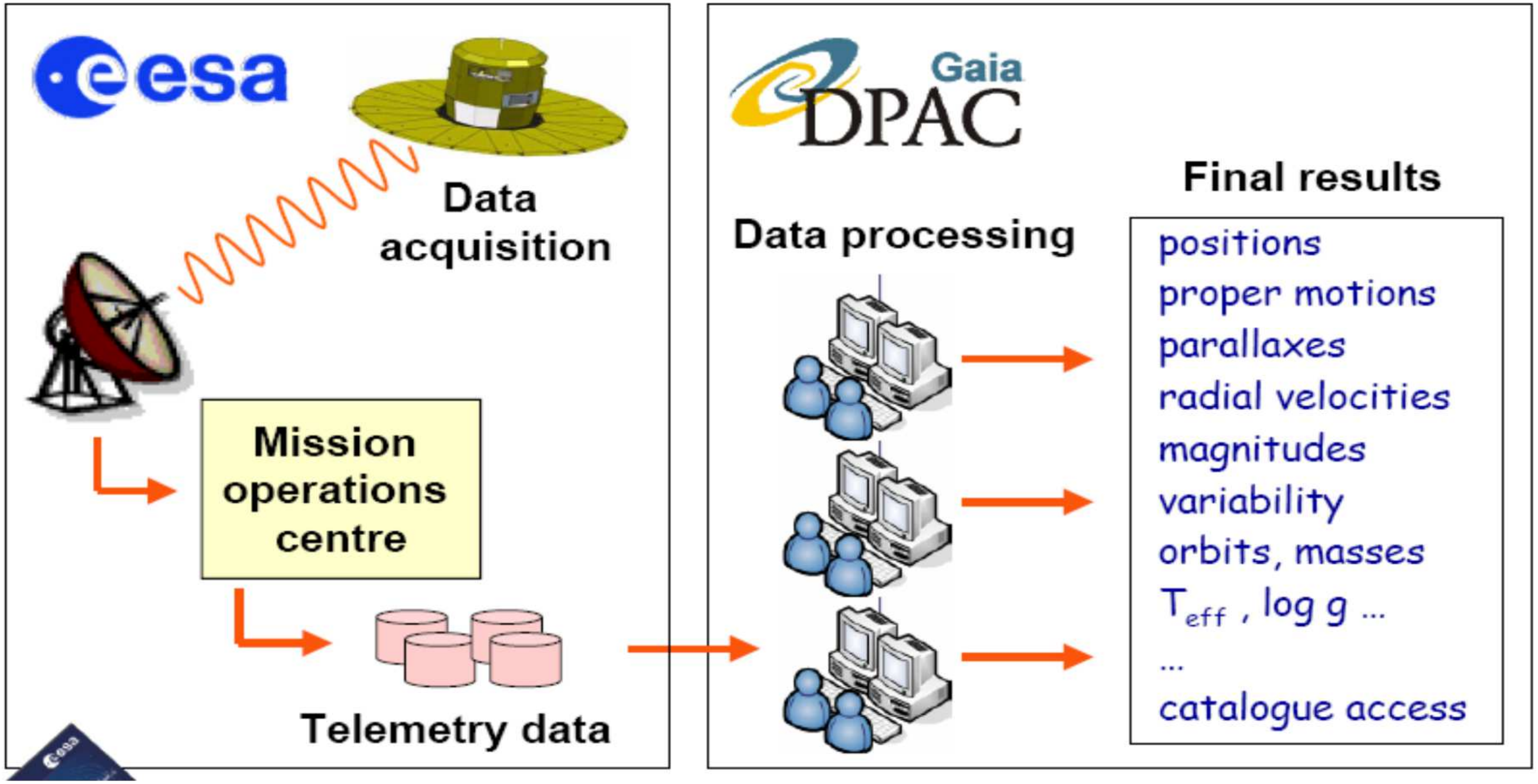


Figure courtesy EADS Astrium

ESA and DPAC responsibilities



Final catalog release expected in late 2021:

no proprietary data rights. Immediate release to community at large.

Intermediate data releases:

starting from ~ 16 months after science verification (4 to 6 months); immediate release as for final catalog

Examples:

- Variability
- "Local" Relativity experiments (GAREQ)
- Spectra of brighter objects
- Astrometry of "nearby" stars (e.g., the new Hipparcos)
- …….

Gaia Intermediate Data Release *Scenario*

Four intermediate releases before the final data release:

- **Launch+22 months release:**
  - Positions and G magnitudes *for single stars*
  - HTPM: proper motions for Hipparcos stars
- **Launch+28 months release:**
  - 5 parameter astrometric solution *for single stars*
  - Integrated photometry BP/RP
  - Mean radial velocities for brightest stars
- **Launch+40 months release:**
  - Improved estimates of previously released quantities
  - Orbital solutions for binaries with periods between ~2 to 12mo
  - Object classification and astrophysical parameters
  - BP/RP spectra and/or RVS spectra used for the above
- **Launch+65 months release:**
  - Improved estimates of previously released quantities
  - Variable star classification and epoch photometry used
  - Solar System object parameters and epoch observations used
  - Non-single star catalogues (incl. Extrasolar planet candidates)

Final Release 3 yrs after end of satellite operations.

Parallel Initiatives (outside DPAC):

- Developed for ground-based support and preparation for scientific exploitation

Gaia-ESO Survey (GES):
Spectroscopic survey at VLT
For supporting MW and stellar population studies

G. Gilmore, S. Randich (Co-Pis)

(specific presentation by Randich)

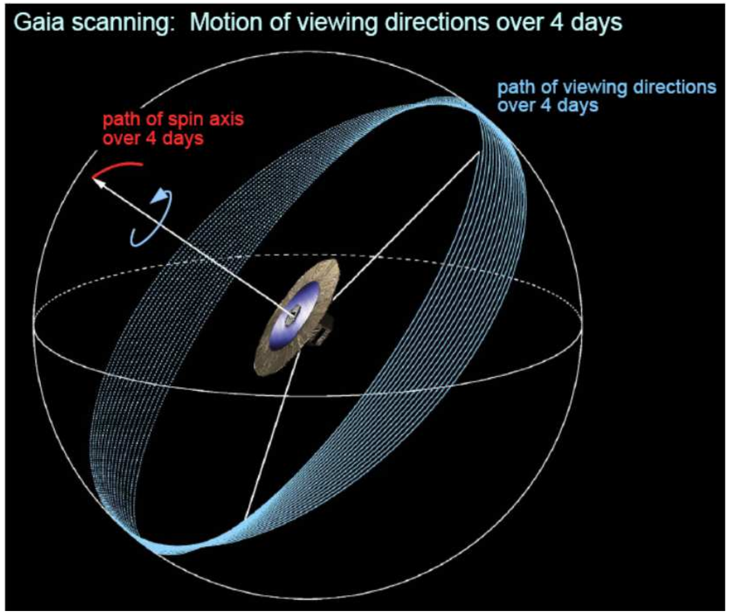
GREAT initiative (ESF, ITN-FP7)
Scientific exploitation preparation in all major areas of the Gaia science case.

N. Walton (PI), G. Clementini (Co-I, for INAF)

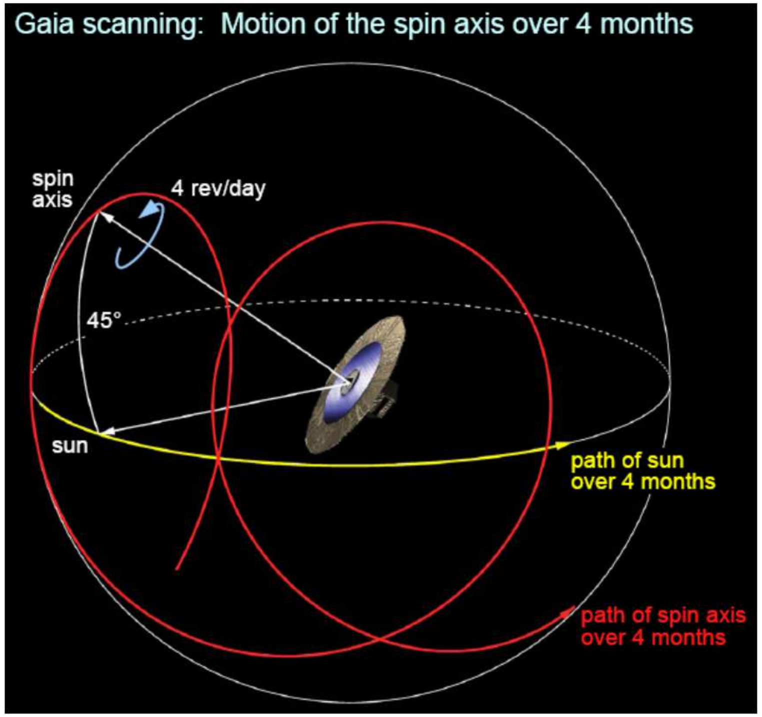
(specific presentation by Clementini)

Mission Essentials

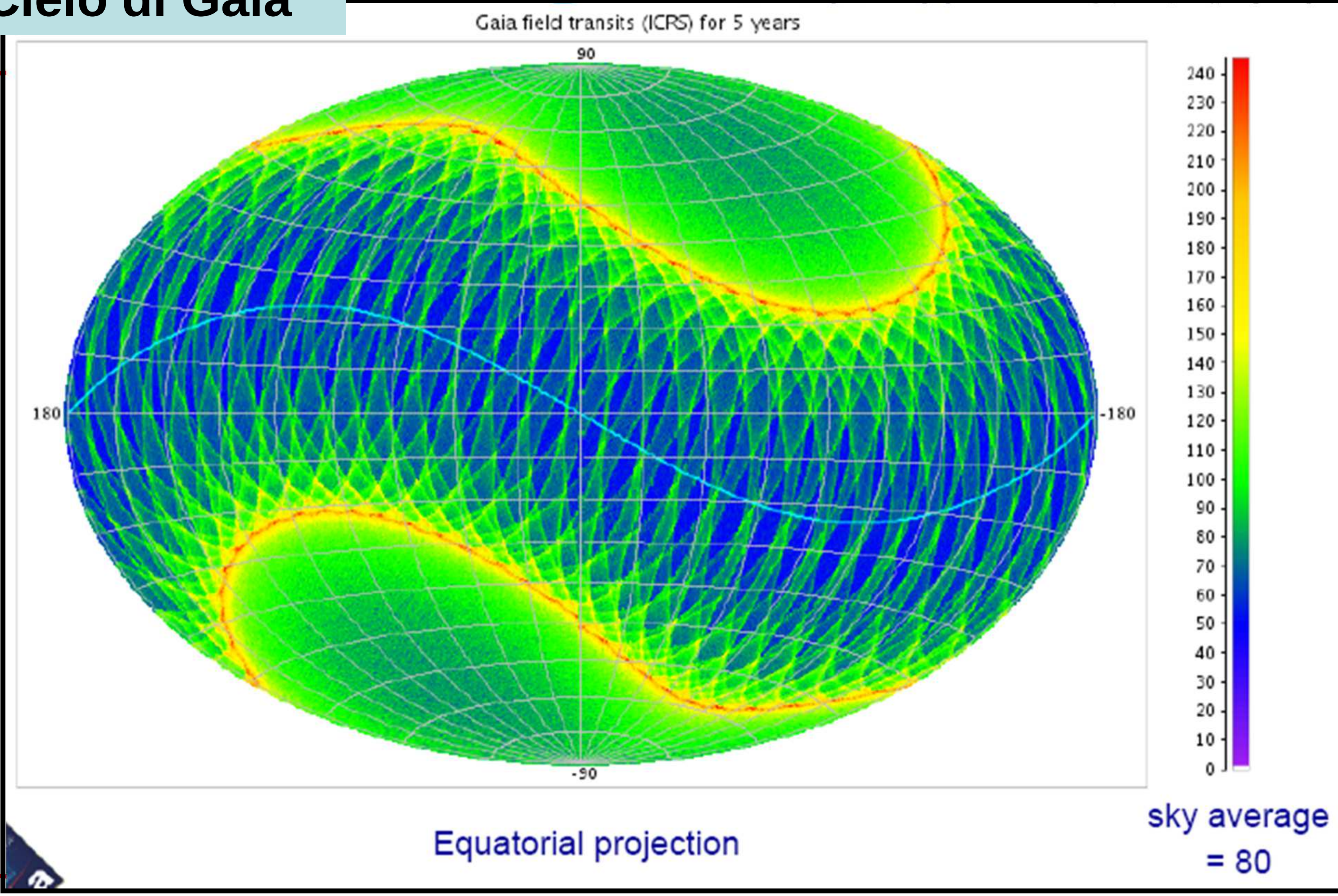
Scanning satellite

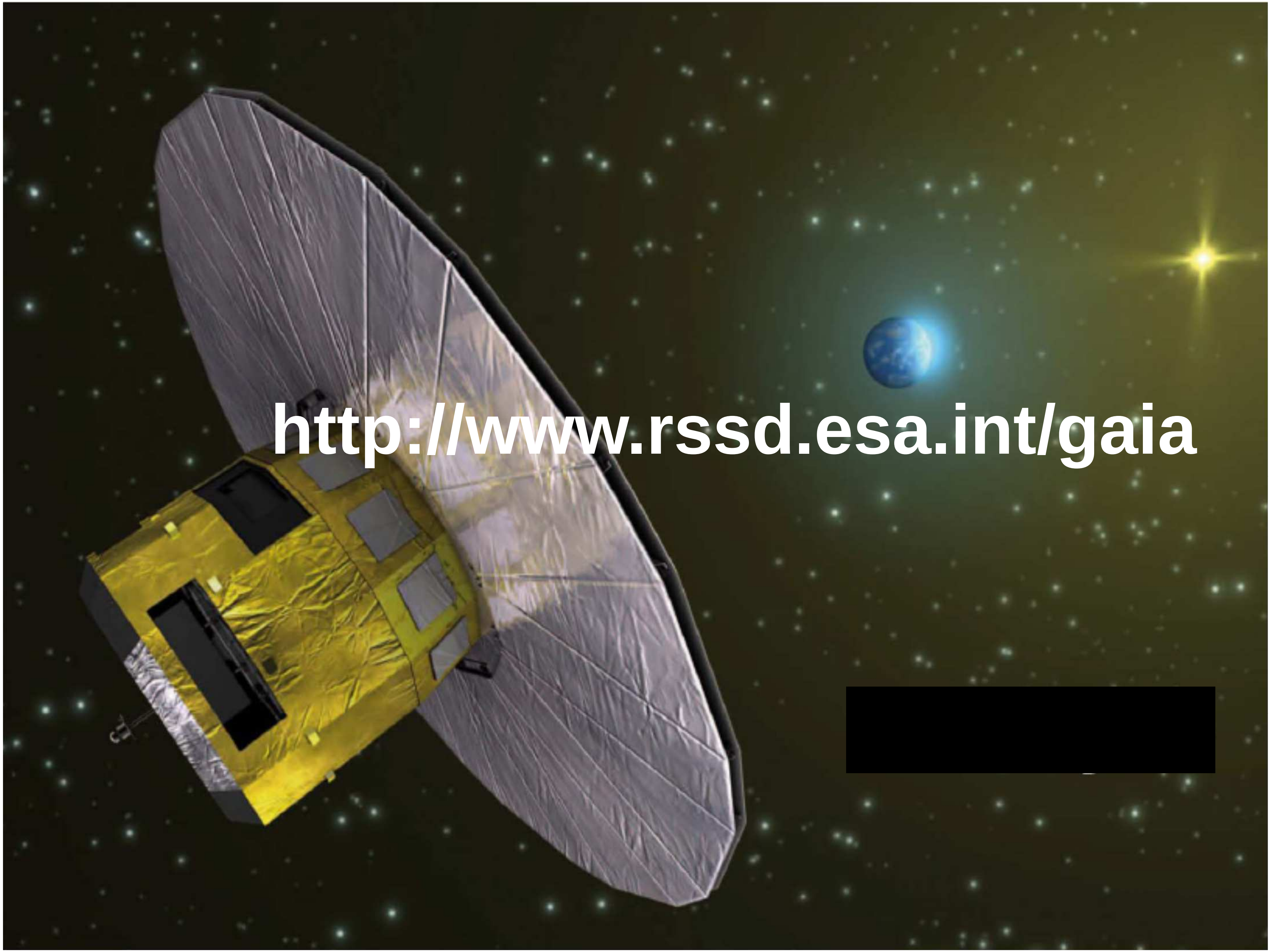


Precession at fixed angle to the Sun ensures sky coverage



Il Cielo di Gaia




http://www.rssd.esa.int/gaia
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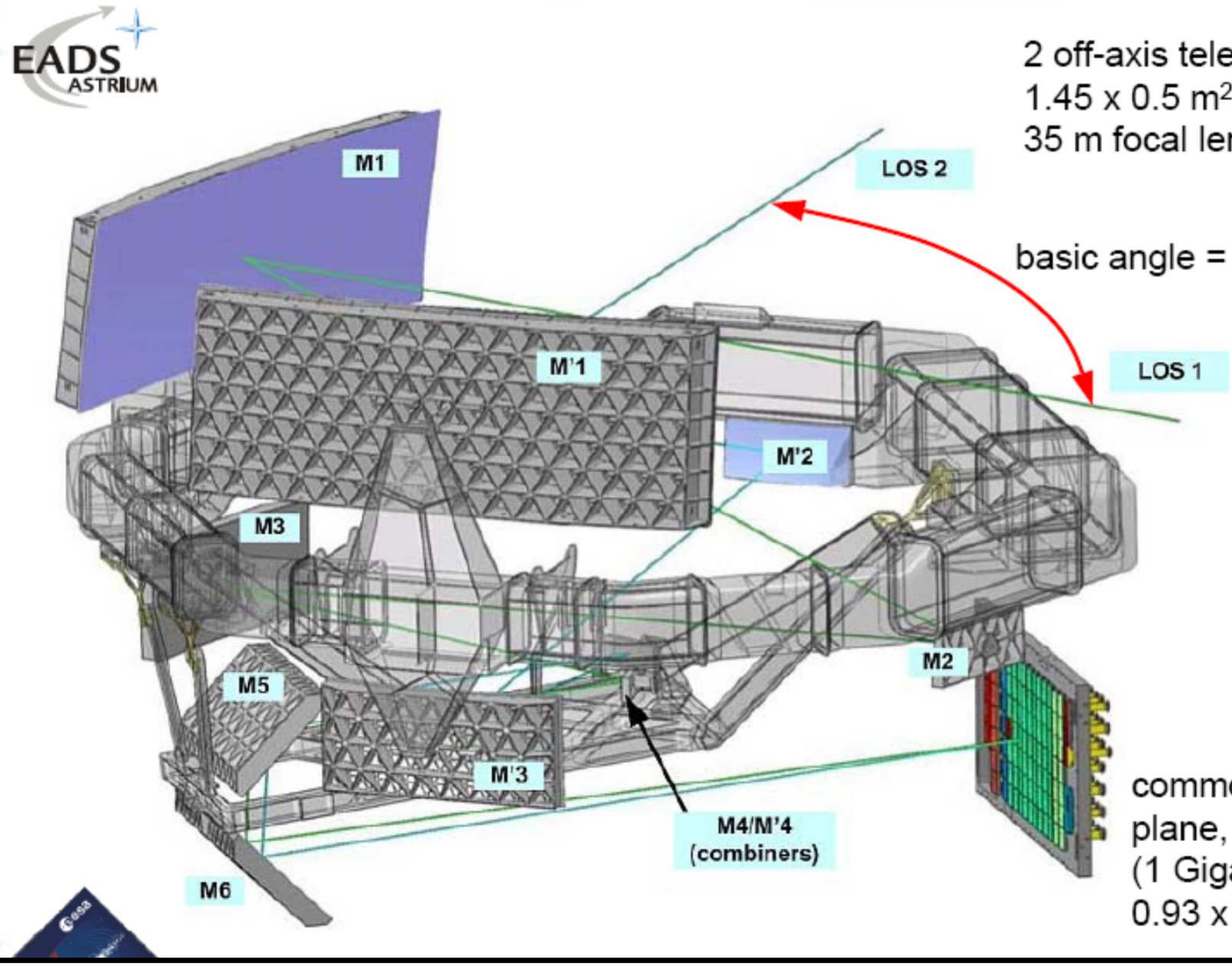
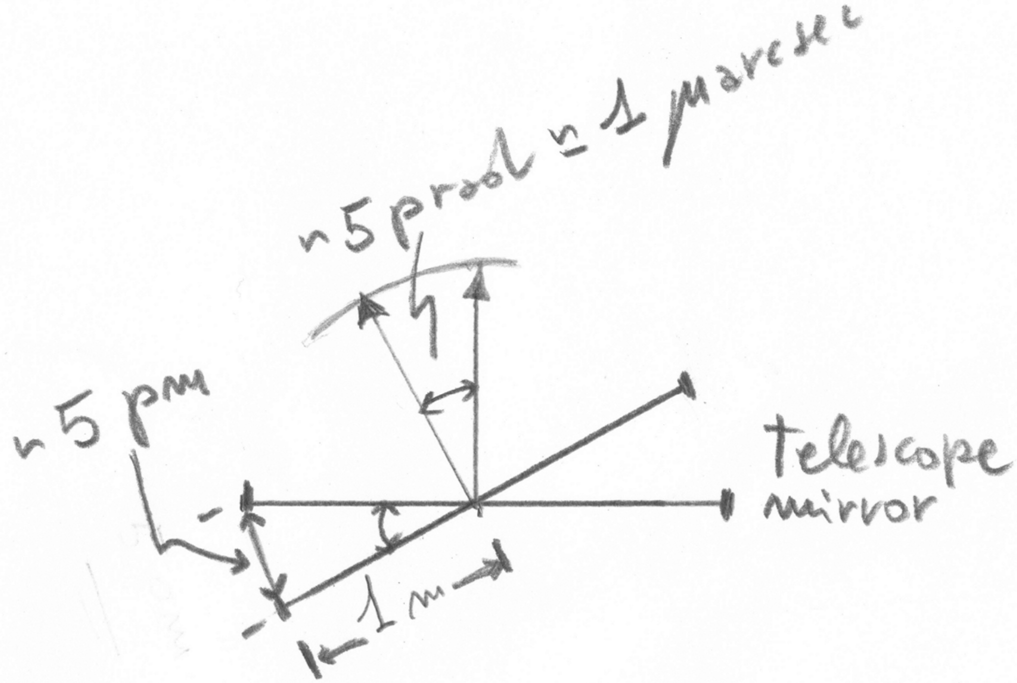
Mission Challenges



2 off-axis telescopes
1.45 x 0.5 m² aperture
35 m focal length

common focal plane, 106 CCDs (1 Gigapixel)
0.93 x 0.42 m²

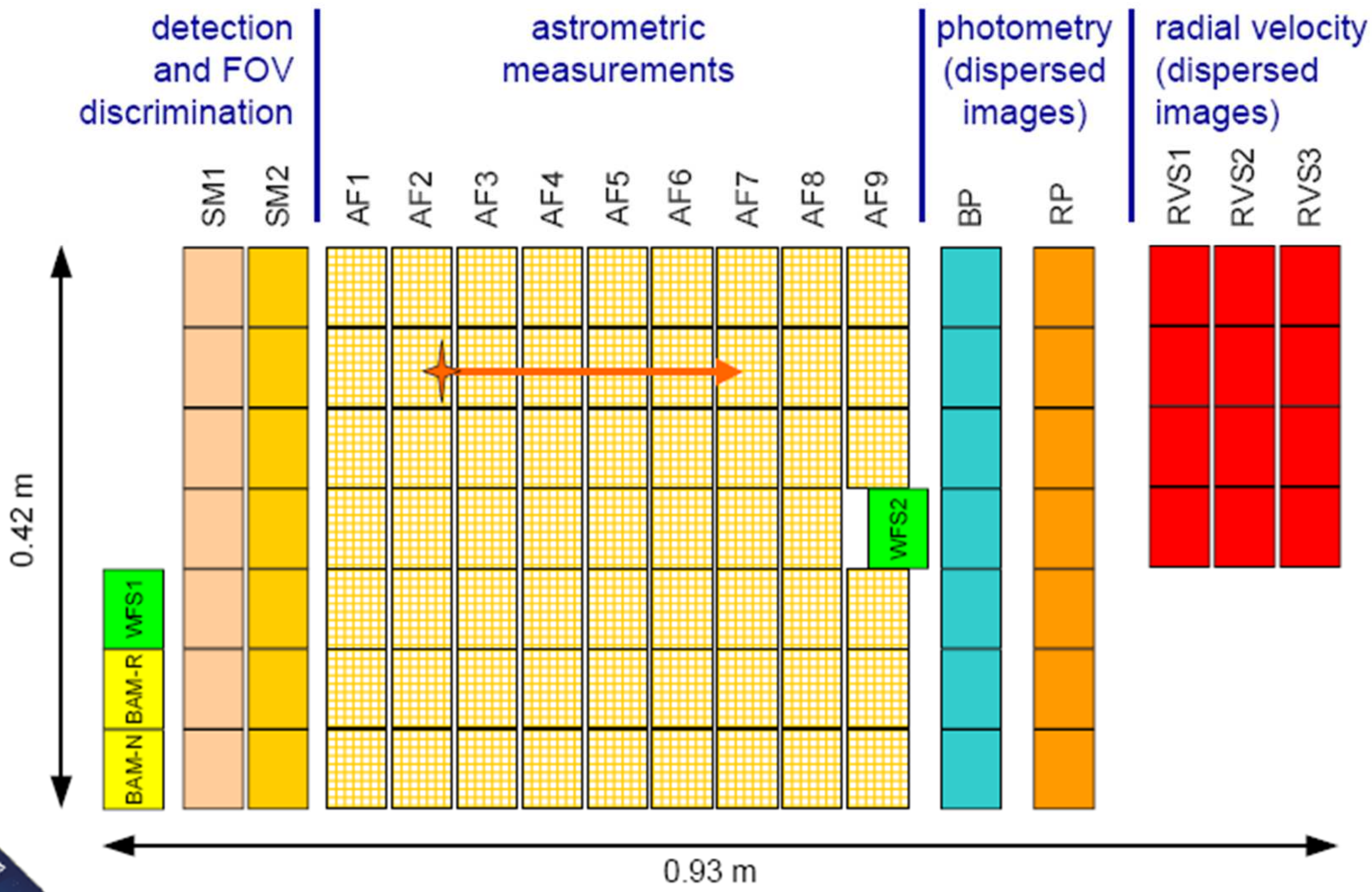
One μas: 1 micro-arcsec ……… What is it?



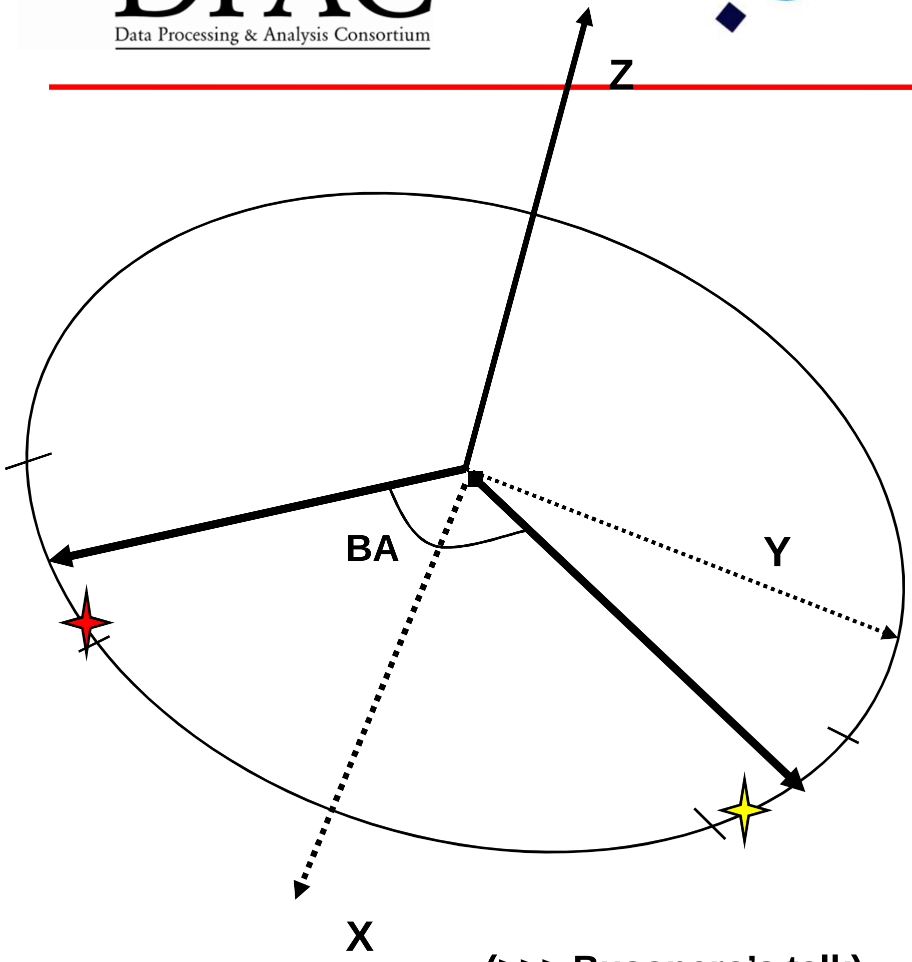
…. Atomic dimensions are of the order af 1 Angstrom = 10^{-10} m !!

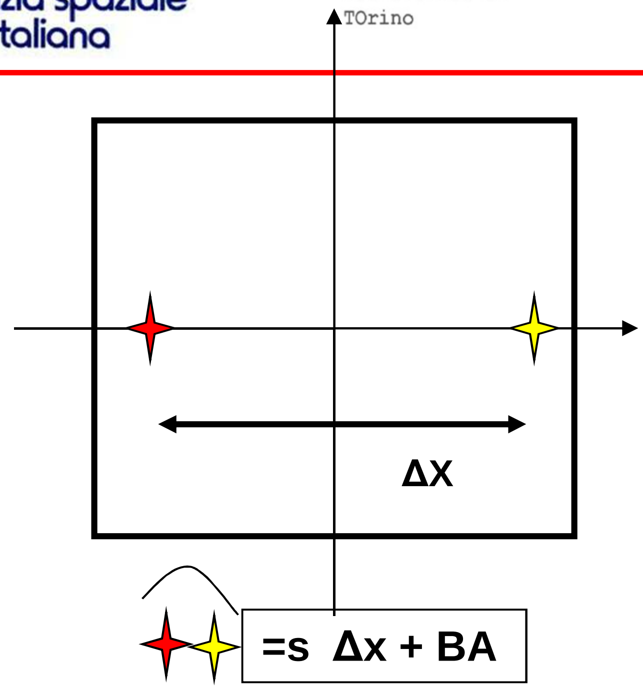
Think also of the thermal stabilities that need to be reached over volumes of tens of cubic meters! [as in the case of the Gaia payload.

Gaia focal plane (106 CCDs)



BAM = basic angle monitor, WFS = wavefront sensor





$$\left\{ \begin{array}{l} \sigma_{**}^2 = s^2 \sigma_{\Delta x}^2 + \sigma_{BA}^2 \\ \delta_{**} = \Delta x \delta_s + \delta_{BA} \end{array} \right.$$

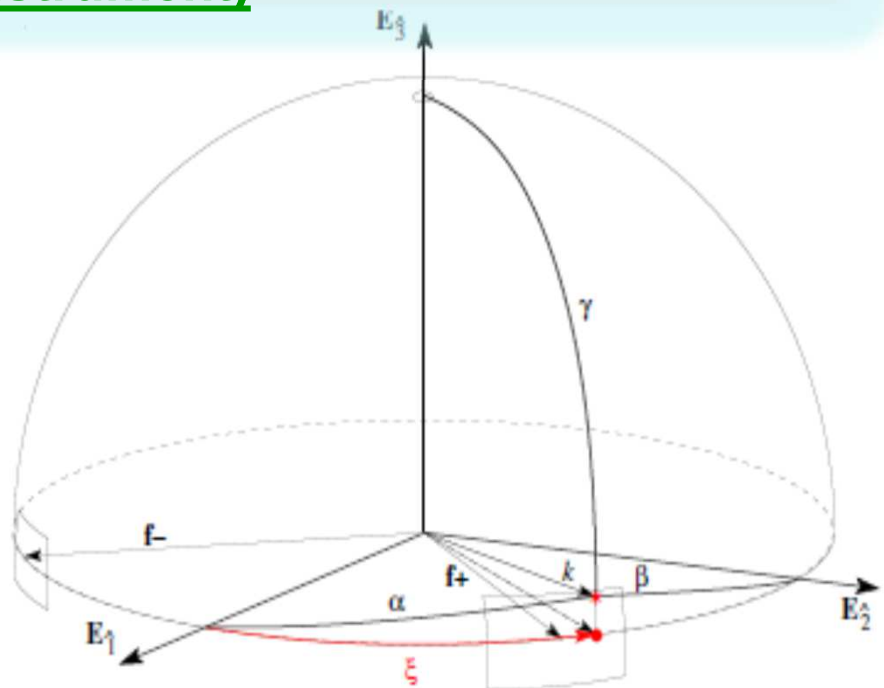
(>>> Busonero's talk)

The astrometric principle exploits the **< closure condition >** in the elementary (geometric) **observation equation**: the same star field is re-observed after one complete revolution of the scanning satellite: over the short period it takes for a complete revolution (~ 6 h) any astrometric change in the stellar scene, i.e. angles among objects, must be of instrumental nature **(self-calibrating instrument)**

$$\cos\xi = \frac{\cos\psi_{(\hat{1},k)}}{\sqrt{1-\cos^2\psi_{(\hat{3},k)}}}$$

Telescope and focal plane properties (**C**)

Stellar and attitude parameters (**S** and **A**)



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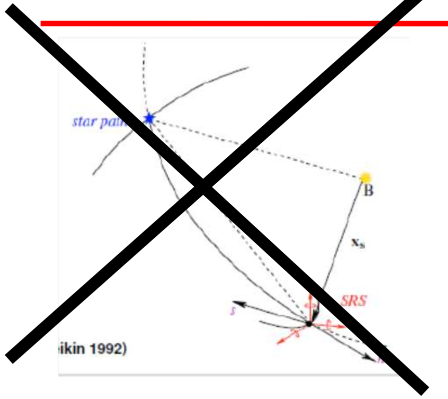


(v/c) classical aberration term ~20 arcsec so:

$(v/c)^2$ ~ 2 milli-arcsec, or mas (Hipparcos)

$(v/c)^3$ ~ 0.2 µ-arcsec, or µas (Gaia)

>>> Right?

WRONG!

In the Solar System: $1 >> (v/c)^2 \sim \omega^2/c^2 \geq |h_{\alpha\beta}|$ where ω is the potential $\omega = GM/R$ and h the perturbation to Minkoskian (flat) space.

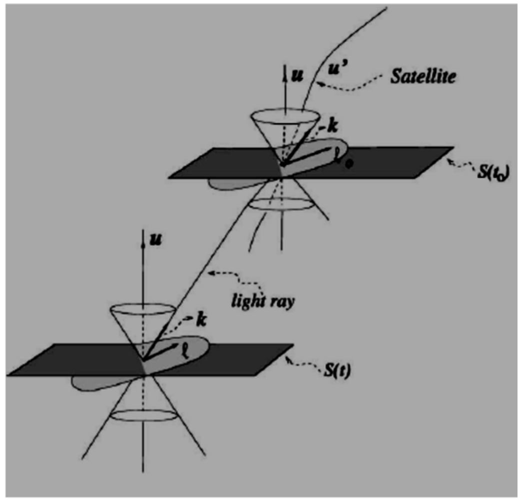
Basic equation of relativistic astrometry

$$\bar{l}^i = n^i\left(1 - \frac{h_{00}}{2}\right) + O\left(\frac{v^4}{c^4}\right)$$

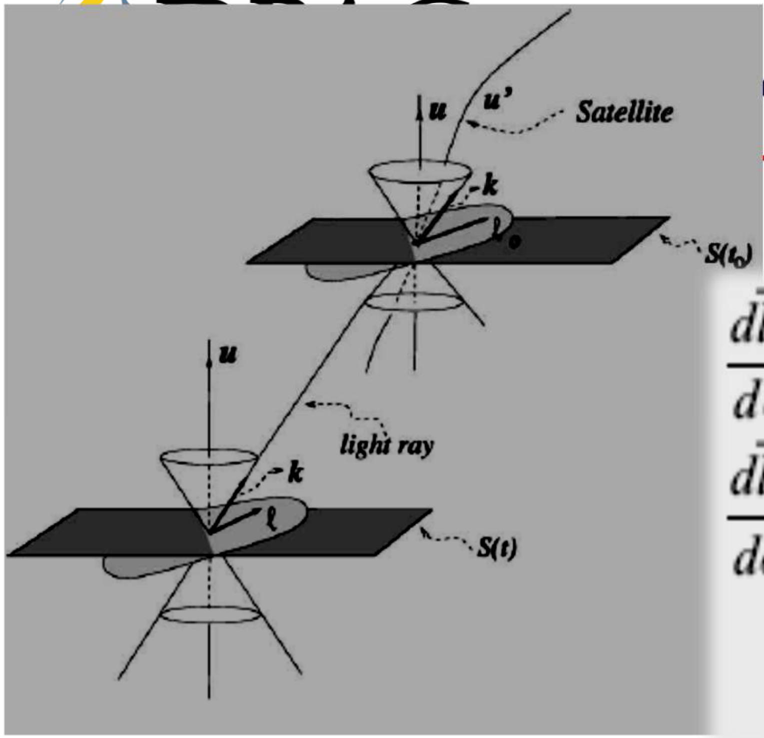
$h_{00} = 2\omega/c^2$

The spatial light direction $\bar{l}^i$ is expressed in terms of its Euclidean counterpart, $\boldsymbol{n}^i$, at the satellite location in the gravitational field of the solar system.

(Crosta, Vecchiato 2010; Crosta 2012)



(>> Crosta/de Felice' presentation)



At the micro-arcsec ………

$$
\frac{d\bar{l}^0}{d\sigma} - \bar{l}^i\bar{l}^j\partial_i h_{0j} - \frac{\partial_0 h_{00}}{2} = 0,
$$

$$
\frac{d\bar{l}^k}{d\sigma} - \bar{l}^k\bar{l}^i\bar{l}^j\frac{\partial_0 h_{ij}}{2} + \bar{l}^i\bar{l}^j\left(\partial_i h_{kj} - \frac{\partial_k h_{ij}}{2}\right) + \bar{l}^k\bar{l}^i\frac{\partial_i h_{00}}{2}
+ \bar{l}^i(\partial_i h_{k0} + \partial_0 h_{ki} - \partial_k h_{0i}) - \frac{\partial_k h_{00}}{2} = 0.
$$

$$
h_{00}^{(a)} = \left(\frac{2G\mathcal{M}^{(a)}}{c^2 r^{(a)}}\right)(1 + \tilde{\boldsymbol{v}}^{(a)}\cdot\hat{\boldsymbol{n}}^{(a)}) + O(1/c^4),
$$

$$
h_{jk}^{(a)} = \left(\frac{2G\mathcal{M}^{(a)}}{c^2 r^{(a)}}\right)(1 + \tilde{\boldsymbol{v}}^{(a)}\cdot\hat{\boldsymbol{n}}^{(a)})\delta_{jk} + O(1/c^4),
$$

$$
h_{0j}^{(a)} = w_j^{(a)} + O(1/c^4),
$$

…….. Astrometry <u>and satellite attitude</u>, they both become **fully relativistic!!**

Astrometric solution for Gaia: The problem

- The basic measurement is the "time of observation" for each star's crossing a CCD
  - ⇒ 10^{12} measurements in total

(>>> Vecchiato's presentation)

- Unknown parameters to estimate:
  - 5 astrometric parameters per star
  - attitude (celestial orientation) of instrument as function of time
  - instrument calibration parameters (basic angle, CCD positions, etc)
  - possibly additional parameters (incl. PPN-γ)
  - ⇒ 5×10^9 unknowns in total

- Not all stars are suitable for simple modelling (binaries, etc)
  - a subset of "primary stars" is used for the astrometric solution
  - aim to use at least 100 million primary stars (10% of all)
  - the rest are "secondary stars", can be treated offline
  - ⇒ astrometric solution needs 5×10^8 unknowns

Hardware

- **Large and complex all-SiC structure (including mirrors)**
- **Largest CCD mosaic ever built**
- **On-board monitoring of micro-arc-second angular variations (measurements of BA via BAM device)**

Software

- Formidable numerical problem for the sphere reconstruction, in the least squares sense, at the micro-arcsec level
- All-relativistic formulation of light travel from within the Solar System including satellite attitude (italian contribuition here…)
- Extremely complex IT infrastructure with 6 different Data Processing Centers
- Dealing with radiation damage

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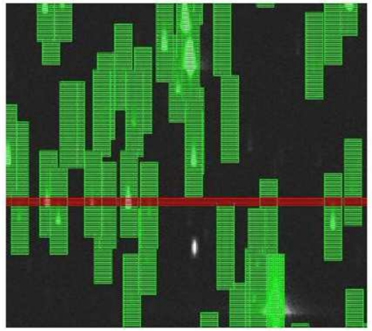
Astrometry and Spectro-photometry have similar measurement principles (and, therefore, face similar challenges:

$$f_{obs}(u) = \int_0^\infty R(\lambda) \cdot L_\lambda(u - u_0(\lambda)) \cdot S(\lambda)\; d\lambda$$

Photometric model for elementary measurements on focal plane.



(>>> <u>Cacciari and Giuffrida' presentations)</u>

$$I_k = f \int_{k(pixel)} L_\lambda (x_x - x_0) \qquad dx$$

Astrometric model for elementary measurements on focal plane.

(>>> <u>Busnero's presentation)</u>

The difference is on the expected (final) errors……..

Predicted Errors

(of the ‘as-built’ system)

End-of-mission photometric errors, in units of milli-magnitude:

	B1V			G2V			M6V		
G [mag]	**G**	**BP**	**RP**	**G**	**BP**	**RP**	**G**	**BP**	**RP**
6 - 13	1	4	4	1	4	4	1	4	4
14	1	4	4	1	4	4	1	5	4
15	1	4	5	1	4	4	1	6	4
16	1	4	5	1	5	5	1	9	4
17	2	5	7	2	5	5	2	20	5
18	2	7	14	2	9	8	2	49	5
19	2	13	34	2	18	18	2	120	8
20	3	29	83	3	43	43	3	301	17

$\sigma_{p_{cal}}$ = 30 milli-mag at CCD-level

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End-of-mission radial-velocity robust formal errors $\sigma_{v_{rad}}$ [km s^{-1}]

	B1V	G2V	K1III - MP
V=7	0.6	0.6	0.6
V=12	8.5	0.6	0.6
V = 13	21	0.6	0.6
V = 14	-	2	1
V = 16	-	7.8	5
V = 17	-	20	13.3

Astrophysical Parameters predicted accuracy (CU8):
>>For zero extinction stars:
Teff accuracy 0.3% at G=15 and 4% at G=20
[Fe/H] ~ 0.1-0.4 dex for stars G< 18.5
log g ~ 0.1-0.4 dex for stars G<18.5

>>as extinction varies:
[Fe/H] ~0.3-0.5 dex at G=15
log g ~ 0.3-0.5 dex at G=15
Teff and Av 3-4% accuracy, but strong degeneracy

End-of-life astrometric performance

µas	B1V		G2V		M6V	
	Req.	Perf.	Req.	Perf.	Req.	Perf.
V < 10 mag	< 7	8.4	< 7	8.6	< 7	10.6
V = 15 mag	< 25					9.4
V = 20 mag	< 300					97.7

Very little or none of comparable quality is available for external comparisons!

Sky-averaged parall… …rc (µas)

$\sigma \sim \sqrt{720}$ **worse, on average, at the single CCD-level transit**

- ✓ Gaia in a nut-shell
- ❑ **Mission Status: where are we at?**
- ❑ The Italian contribution

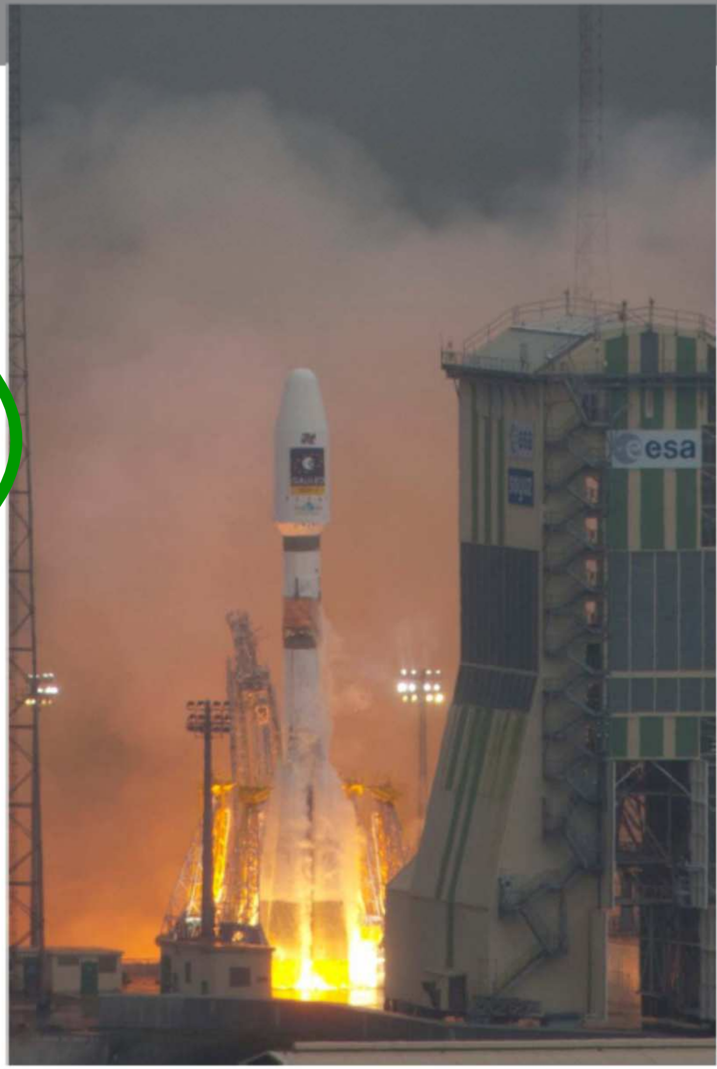
• **Payload Module is being delivered to ESA by Astrium (after TV/TB test of flight unit) for final integration. This is a key milestone and a big (press) event > beginning of March.**

• **Satellite delivery to ESA (PLM + SVM) expected for late Sprig, then ready for shipment to launch site.**

• **DPAC will undergo Operation Rehersals specifically devoted to supporting commissioning phase (first in Dec 2012) and GSRR in April.**

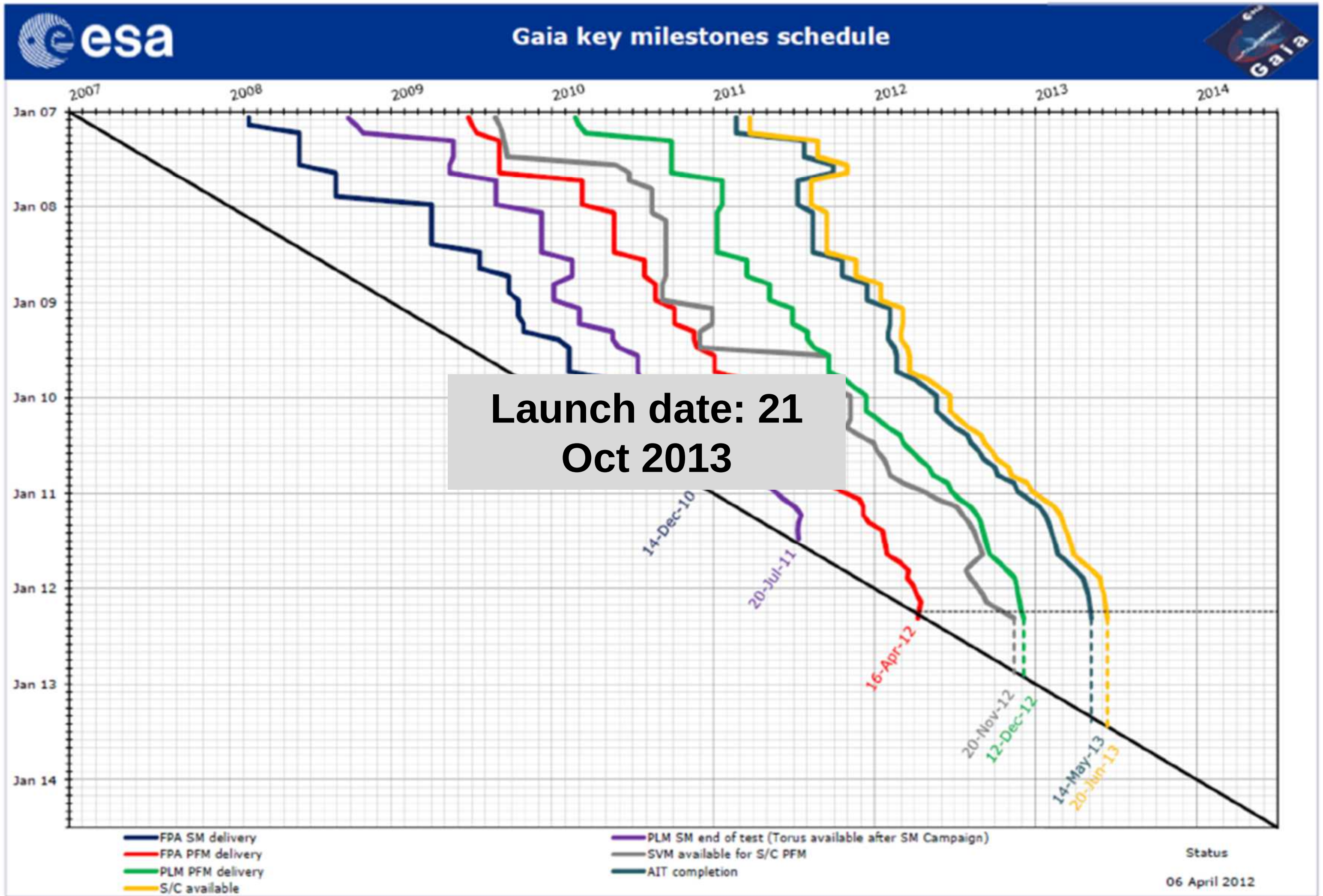
Gaia : Soyuz Launcher and Launch Site

- The launch vehicle configuration which will be used for Gaia was qualified by the Galileo IOV-M1 launch in October 2011.
- The launch vehicle assigned to Gaia is Sz 013 (Soyuz 2.1.b three stages) and 133-01 for the Fregat MT upper stage. This means that the manufacturing has started
- The launcher adaptor is ready and its fit check with the Service Module is planned in September
- The activities for the Launch Campaign preparation are on going



G. Sarri | MOC-CU3_13-14.6.2012_Gaia | Slide 9

Schedule trend



Launch date: 21 Oct 2013

✓ Gaia in a nut-shell

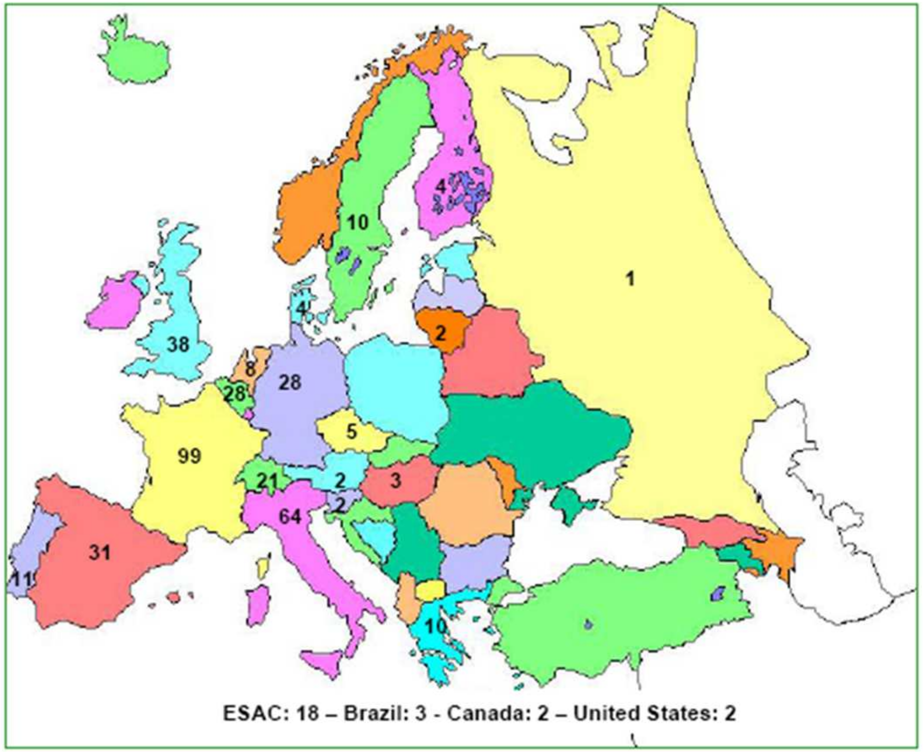
✓ Mission Status: where are we at?

❑ **The Italian contribution**

Gaia Data Processing and Analysis Consortium (DPAC)

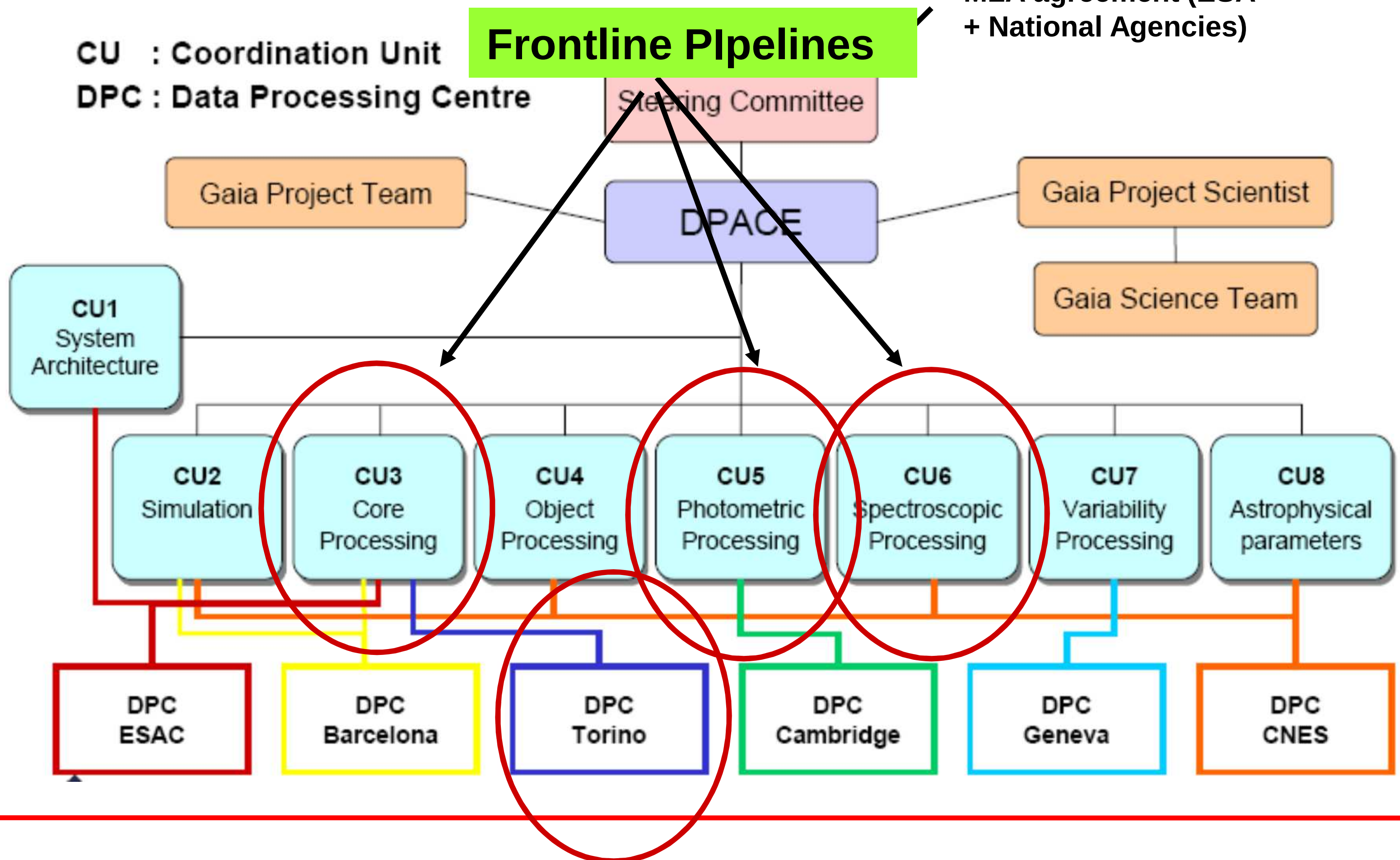
Formed 2006 in response to an "Announcement of Opportunity" issued by ESA

- Consists of individual persons organized in an ad hoc structure
- Currently (Feb 2009) 396 members
- 22 funding agencies
- 6 data processing centres



DPAC organization

CU : Coordination Unit
DPC : Data Processing Centre



CU9

- **The last CU to join DPAC was CU9. This was done through a special call by ESA.**

One proposal was submitted in January 2013 after a 1-year DPAC preparatory study (the GAP initiative) and it has been just approved by ESA SPC.

CU9 deals with the Gaia Archive preparation that will be released to the community at large and includes exploitation tools (**Data Access**).

The Italian contribution is coordinated by ASDC (see Marrese's presentation)

The Italian contribution to DPAC is (numerically) first with that of France at approx. 18-19 % of the total effort:

~ 25 FTE/yr of staff personnel (spread over just more than 60 colleagues!!) + 12 FTE/yr of contract personnel

M. Castronuovo (RC, MLA-SC repr.)
B. Negri (EOS)

ASI

DPCT
(@ALTEC, To)

CU9

INAF

Project Office
(@ OATo)

Coordination Group

Parallel initiatives:

- GES (S. Randich)
- GREAT (G. Clementini)
- ASDC Gaia's team (P. Marrese)

MGL PS (CU3, CU4)
Drimmel, PM (CU8)
Morbidelli, RSO@DPCT
Sarasso, Contract Coordinator

C. Cacciari (OABo; CU5, CU7)
A. Lanzafame (OACt; CU7, CU8, CU3
A. Piersimoni (OATe; CU5)
L. Pulone (OARm; CU5)
V. Ripepi (OANa; CU7)
A. Vallenari (OAPd; CU8)

Randich is Member of the GST, Vallenari is DPAC Deputy Chair

Contribution to CU3
Core Processing@ESAC

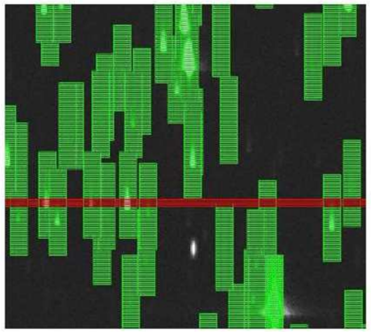
- Initial Source catalog
- Object naming and observations threading (**OATo**)

Contribution to CU4
Object Processing@CNES

- Minor planets identification (**OAFi**) and Phot. Classification (OATo)
- Exoplanets identifications and characterization (OATo)

Contribution to CU5
Photpipe@Cambridge

- Absolute flux calibration and monitoring (OABo)
- Crowded fields (**OARm**, **OATe**, **ASDC-Gaia team**)



(>>>> Afternoon session)

Contribution to CU7

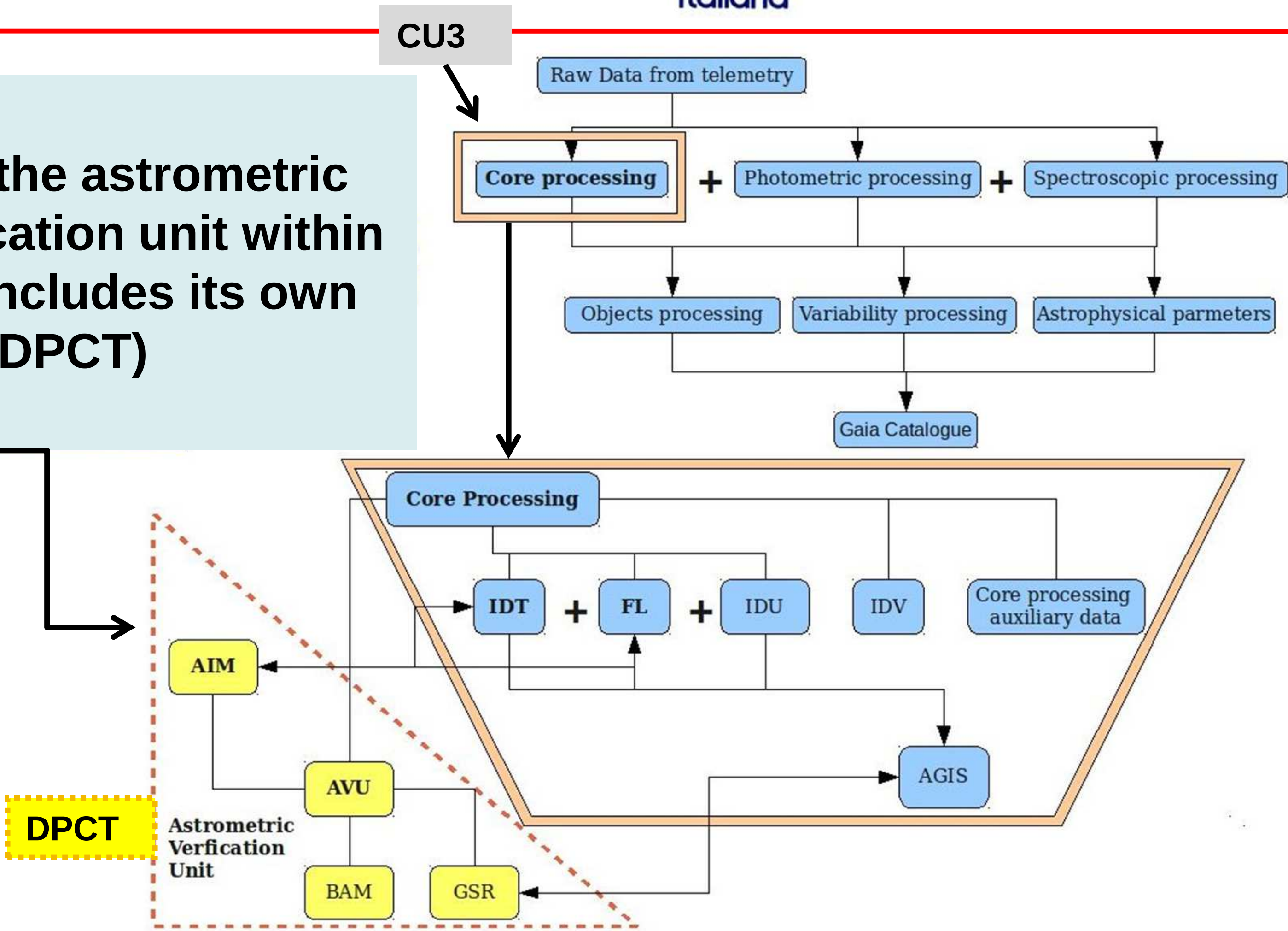
Variability Processing @ Geneva

- Cepheids, RR Lyrae, Solar-like, … (**OABo**, **OACt**, **OANa**)

Contribution to CU8
Astrophysical characterisation@CNES

- Stellar parameters (OACt, **OAPd**)
- Interstellar absorption (OATo)

AVU: the astrometric verification unit within CU3 includes its own DPC (DPCT)



Astrometric Verification Unit (AVU)@DPCT

- Can pipeline-process data from the astrometric portion of the focal plane at the single CCD level with different methods and monitor evolution of main (astrometric) electro-optical system (AVU/AIM).
- Can pipeline process data from the Basic Angle Monitoring Device (BAMD) and monitor evolution of angle between lines of sight over all time scales (AVU/BAM)

} (Busonero)

- Complete independent reconstruction of the Celestial Sphere (GSR) as defined by the Primary Sources (common to baseline AGIS).

→ (Vecchiato)

AVU is a unique (only) tool to validate the astrometry of Gaia at all levels down to the quality of the all-sky astrometric reconstruction (to ≥10 μas, depending on magnitude) expected for the final catalog.

- **Fully relativistic [to $(v/c)^3$] new astrometric model (RAMOD)**

(Crosta , Vecchiato 2010; Crosta 2011; Vecchiato et al. 2007; de Felice et al. 2001, Vecchiato, Lattanzi et al. 2003,)

- **New representation for satellite relativistic attitude**

(Bini, Crosta, de Felice 2003)

- **Completely different approach to numerical analysis for least squares solution including fully parallel version for HPC systems**

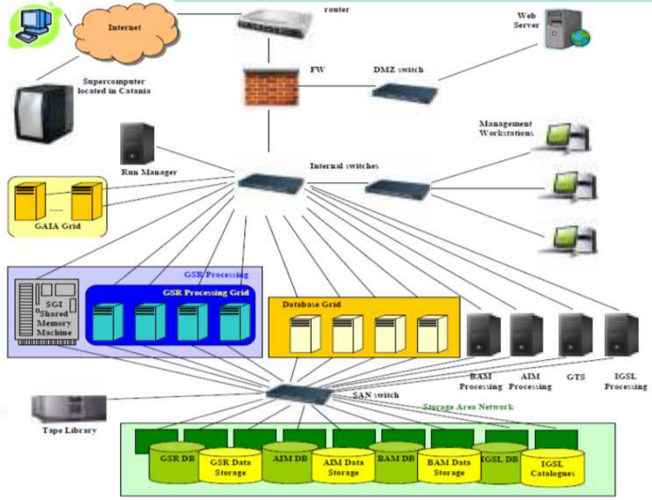
(M. Bandieramonte, U. Becciani, A. Vecchiato, M. Lattanzi and B. Bucciarelli)

- **Up to 2 million primaries in house (at DPCT) as trial (optimization) runs**
- **Up to 100 million primaries at CINECA (via DPCT) supercomputer center on the new IBM BLU GENE Q [10,000 computing nodes (16 processing elements each)]**

DPCT @ ALTEC (Torino) : size and scope

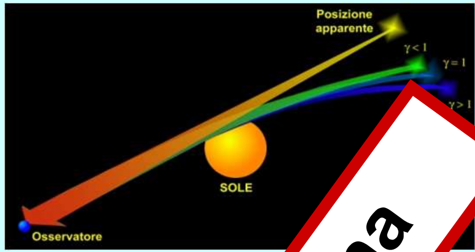
- Following initial investment for operational HW (early 2013, current contract), which will provide 250 TB of DB storage, system will grow to 1 PB; Oracle-based DBMS, through INAF-Oracle Italia special agreement; High speed connection to ESAC and CINECA (provided by ASI);
- Pipeline processing of AVU systems throughout DPAC operations (5+3 years since launch)
- Host copy of the Mission Data Base (MDB)
- Extended reprocessing capability from MDB and catalog extraction beyond final catalog release (**strategic legacy**).
- **A unique space-like instrument made possible by ASI for the INAF community to continue to exploit!!**

DPCT operational HW Architecture



Gaia's challenges

Beyond Einstein?

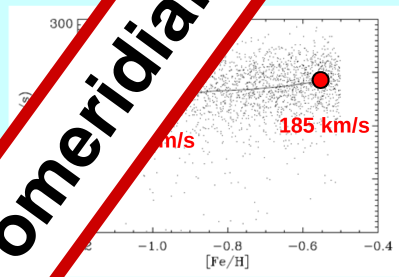


Deviations from GR to **3*10^{-7} detectable**: presence of residual scalar field from within the Solar System?

(Vecchiato, Lattanzi et al 2003)

Challenging GR and Concordance Model

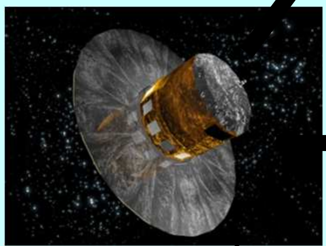
Local cosmology



Circular velocity-metallicity relation in the Galaxy Thick Disk

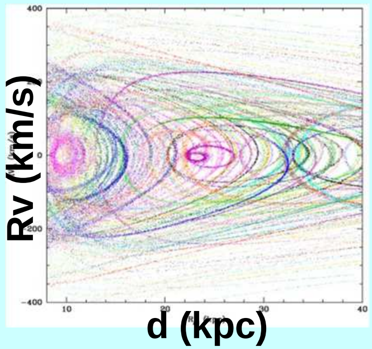
(Spagna, Lattanzi et. Al 2010, Curir, Lattanzi, et al 2012))

(Vϕ) vs. [Fe/H] : **50 ± 5 km/s /dex**



Testing light b…
properties o…

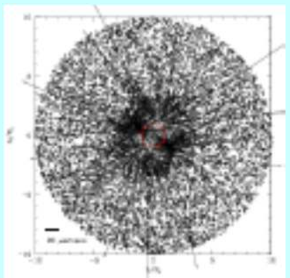
Sessione Pomeridiana



(Λ)CDM prediction for the Galactic halo. Structure in phase space: **true?**

Extrasolar planets

2,000 fully reconstructed **systems** (orbits and masses) **around FGK stars**; expected **10,000 new planets around M dwarfs**.



First detection of light deflection by Jupiter's quadrupole (J_2)

Epilogue

- Gaia: a unique opportunity for physics and astronomy, possibly a new beginning for MW studies and Local Cosmology.
- Large potential for unexpected discoveries

- The Gaia legacy: delivering the catalog/archive will not be the end of the story > A treasury DB, like a space instrument but with a much longer 'lifetime' (!), will await at DPCT for full exploitation and leaving laboratory (new theories and/or new reduction methods to try, data mining, space science and space engineering research) for many decades to follow … All of that will be available through ASDC (data access and exploitation of catalogs for astrophysics) and DPCT (MDB investigations and reprocessing/recalibration capabilities).