Gaia DPAC
Data Processing & Analysis Consortium

INAF

ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI TORINO

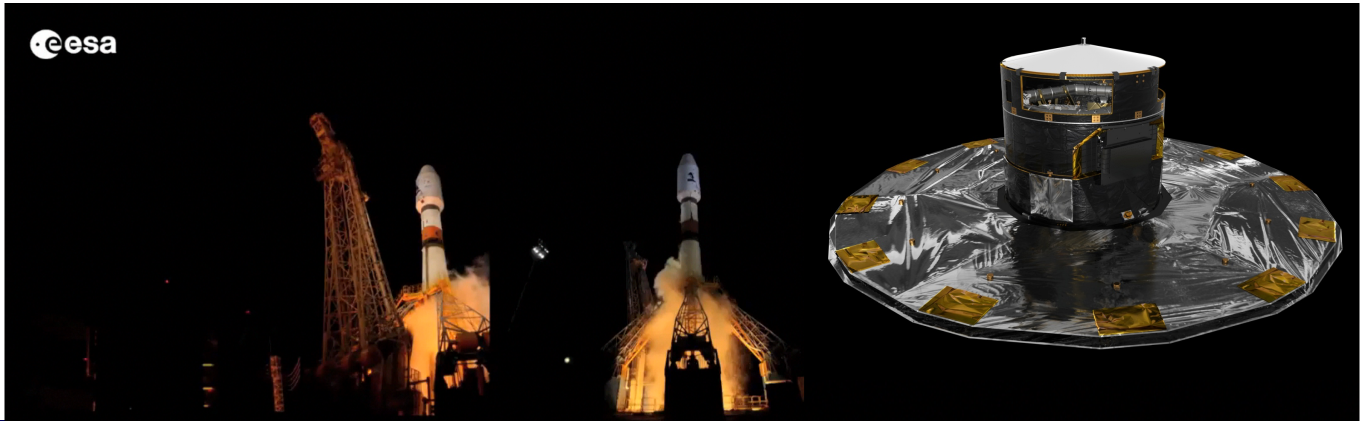
agenzia spaziale italiana

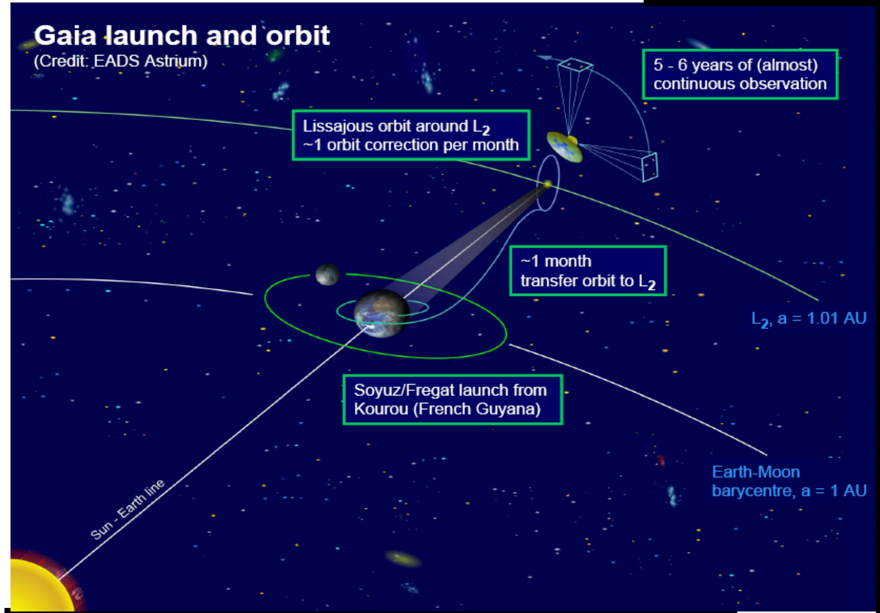
GR21 New York 2016, 10-15 July

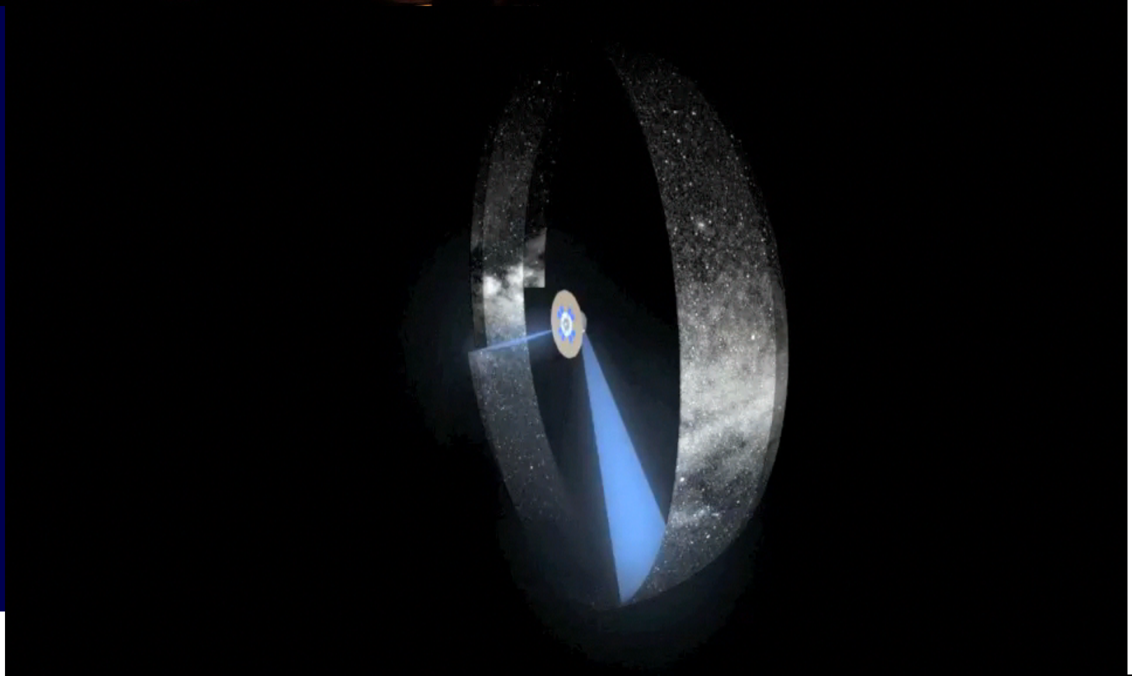
esa

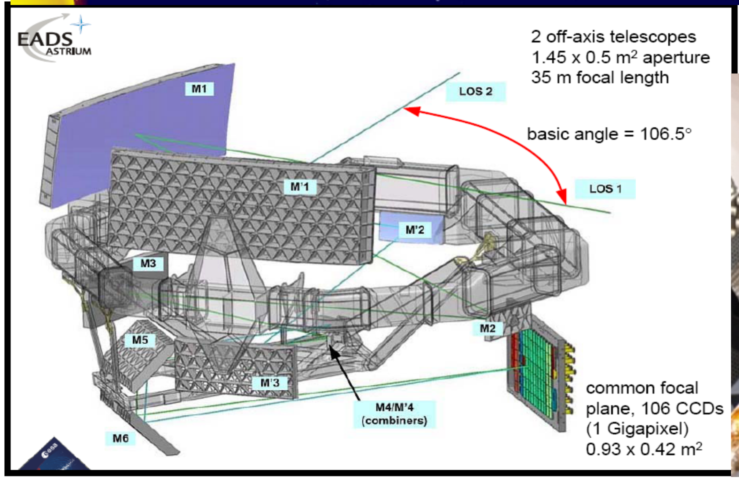
Gaia

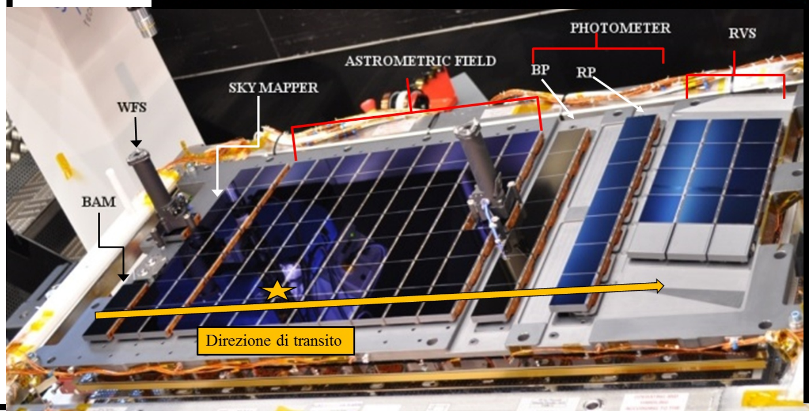
gaia

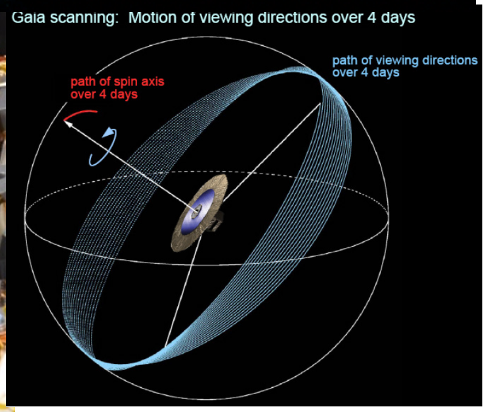












Gaia – main characteristics and status

science with **one billion objects in 3 dimension**

- from structure and evolution of the MW to general relativity

Astrometry, photometry, spectroscopy (RVS)

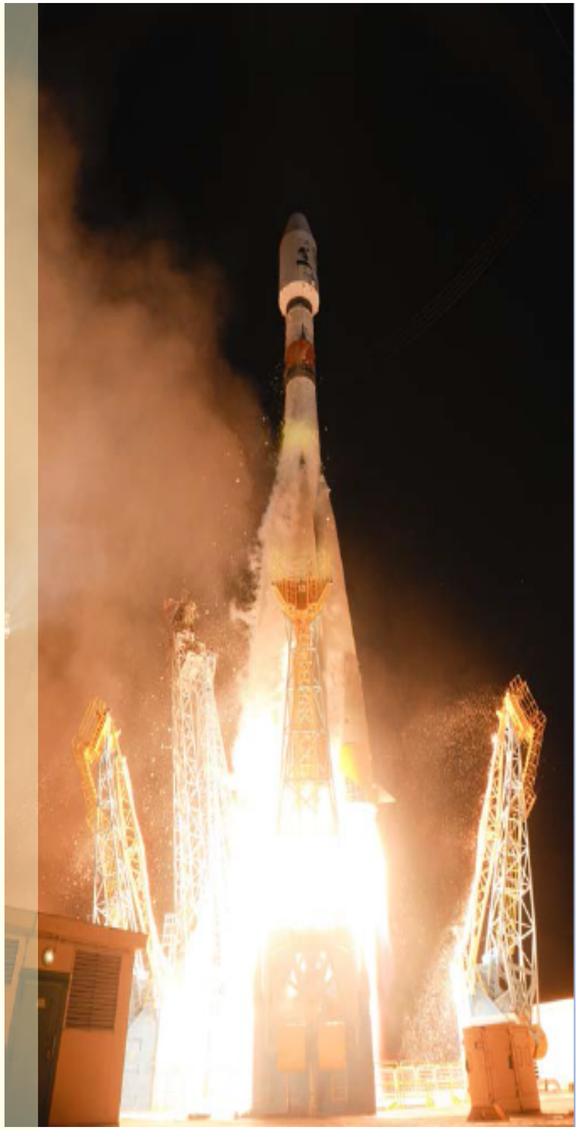
- Astrometry and photometry G < 20.7 mag
- Stars brighter than G=3 captured with Sky Mapper imager
- Spectra still G_{RVS}=16.2

Satellite (including payload) by industry, management and operations by ESA, data processing by scientists (DPAC)

✓ Now in 5-year routine operations (since 25/7/2014)

✓ First DR planned for September, science alerts started

✓ Data validation started



(Courtesy of M.G. Lattanzi - OATo)

Data Release Scenario (http://www.cosmos.esa.int/web/gaia/release)

First release end of summer 2016 - Subject to successful validation:

- **Positions** (α, δ) and **G magnitudes** for all stars with acceptable formal standard errors on positions
- **Photometric data** of RR **Lyrae and Cepheids** from high-cadence measurements
- The **five-parameter astron** motions – for stars in **common b**

2 million stars complete to V=1
associations, moving groups, (

Sub milliarcsec accuracy (10 % at 300 pc)

The *Tycho-Gaia* astrometric solution

How to get 2.5 million parallaxes with less than one year of *Gaia* data

Daniel Michalik, Lennart Lindegren, and David Hobbs

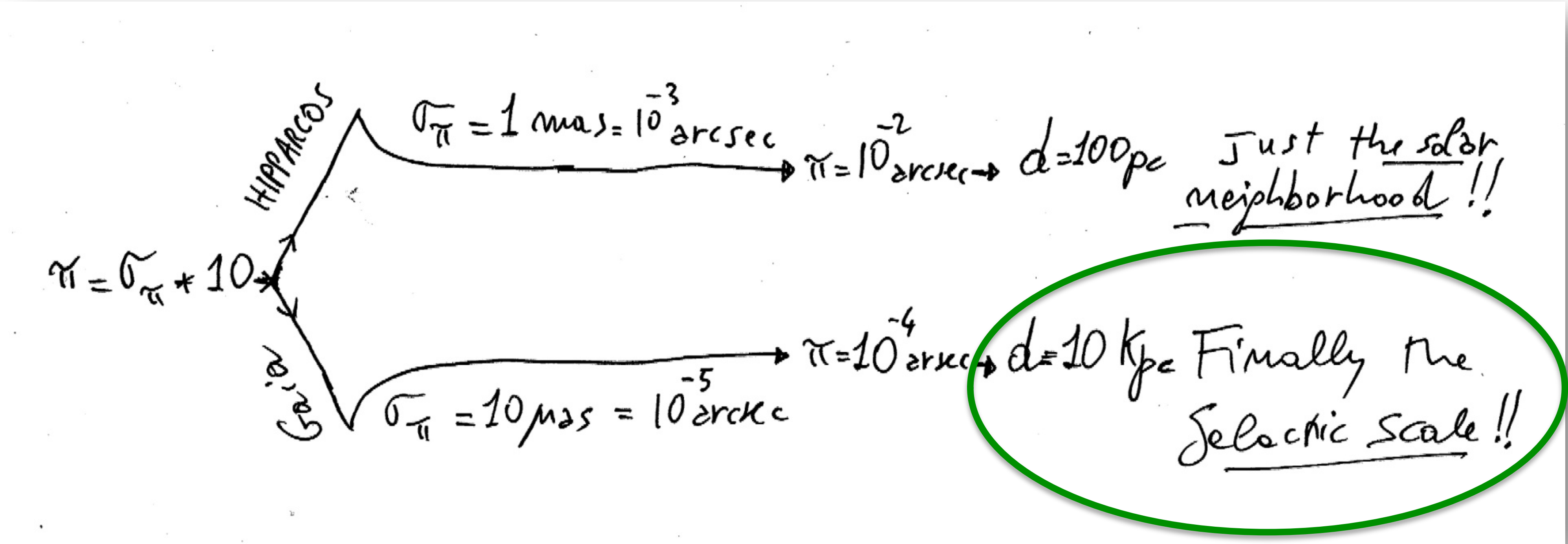
Second release summer 2017 - Potentially:

- **Five-parameter astrometric solutions** of objects with single-star behaviour
- Integrated **BP/RP photometry,** for sources where basic astrophysical parameter estimation has been verified
- **Mean radial velocities** will be released for "well behaved objects" objects

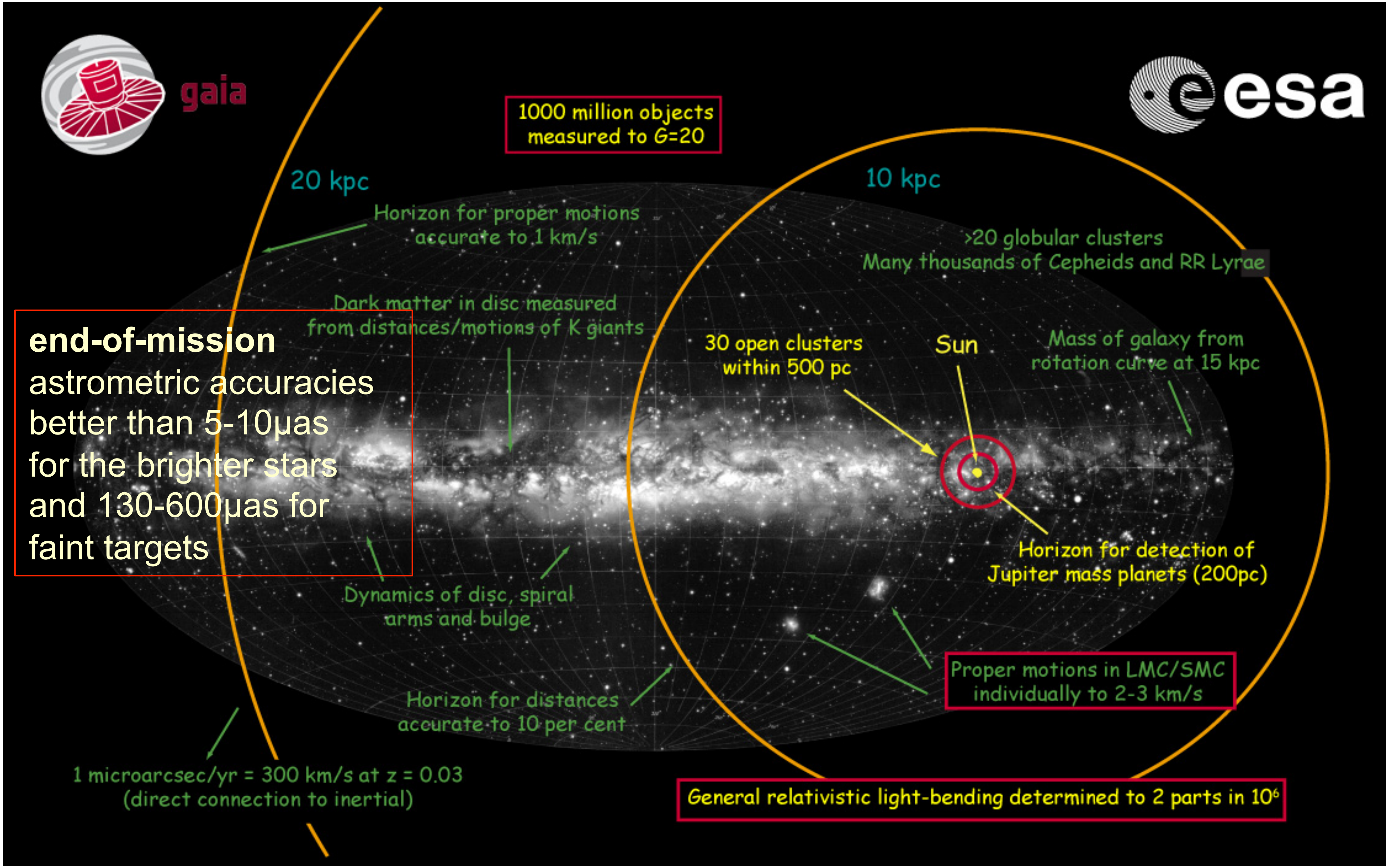
Third release summer 2018 (TBC)….

(Courtesy of M.G. Lattanzi - OATo)

THE LOCATION OF AN OBJECT IN ASTROMETRY IS CONSIDERED RELIABLE IF ITS RELATIVE ERROR IS LESS 10%

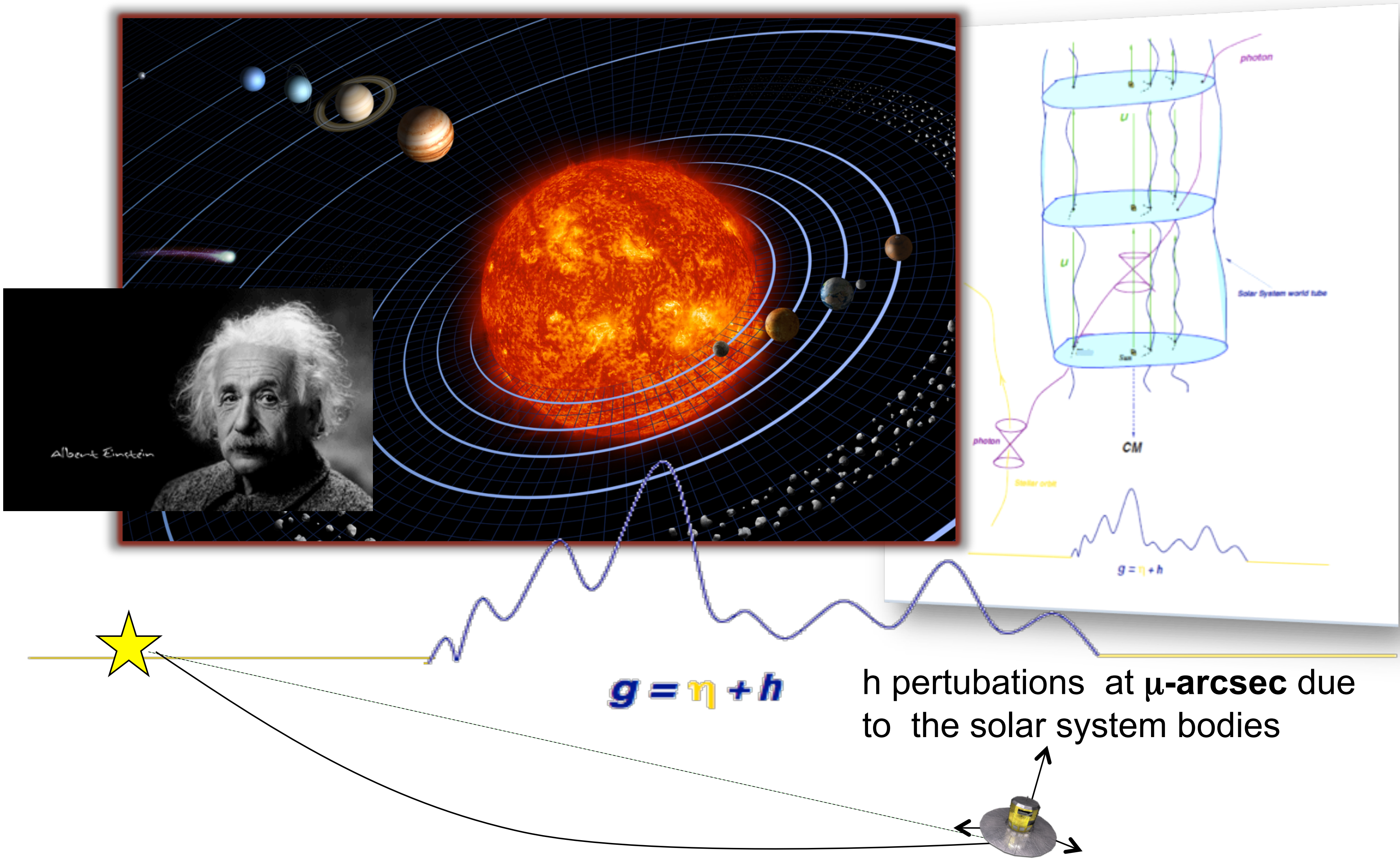


The Gaia's look into the Milky Way



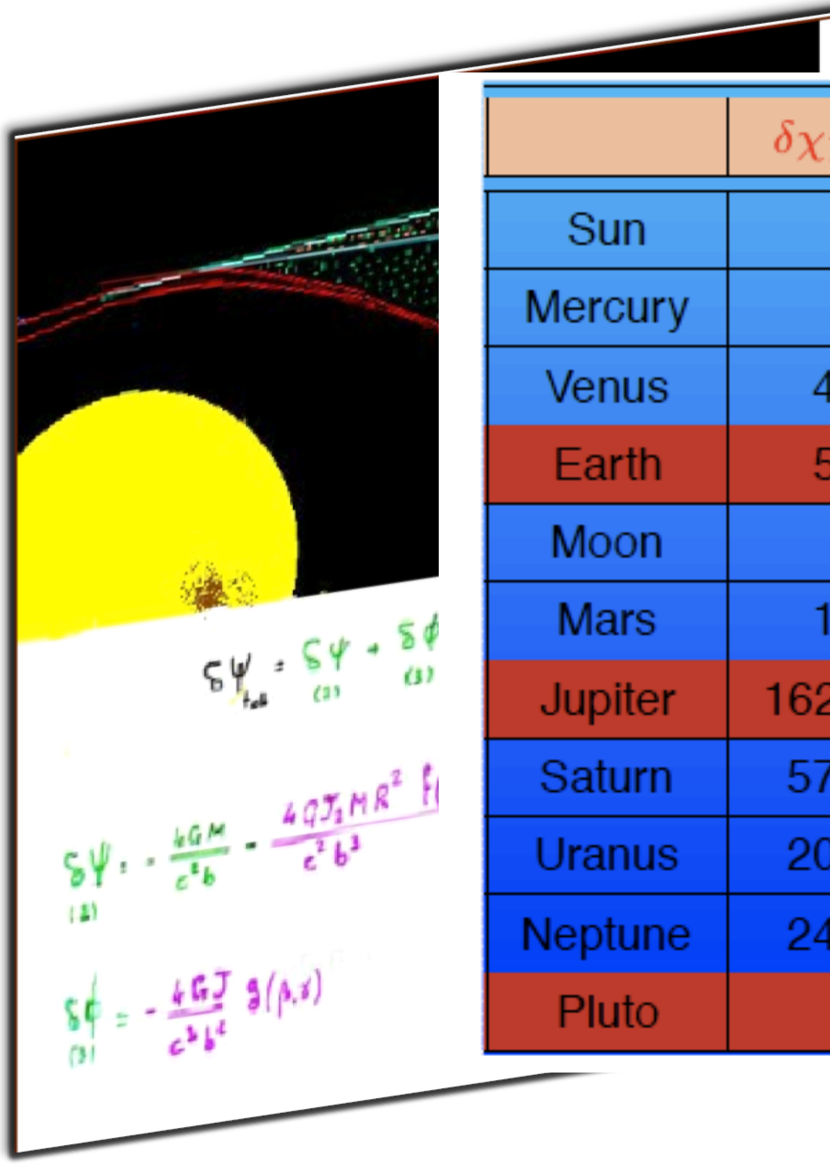
http://www.cosmos.esa.int/web/gaia/science

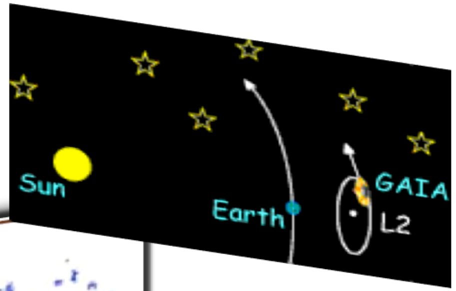
Our laboratory: the Solar System



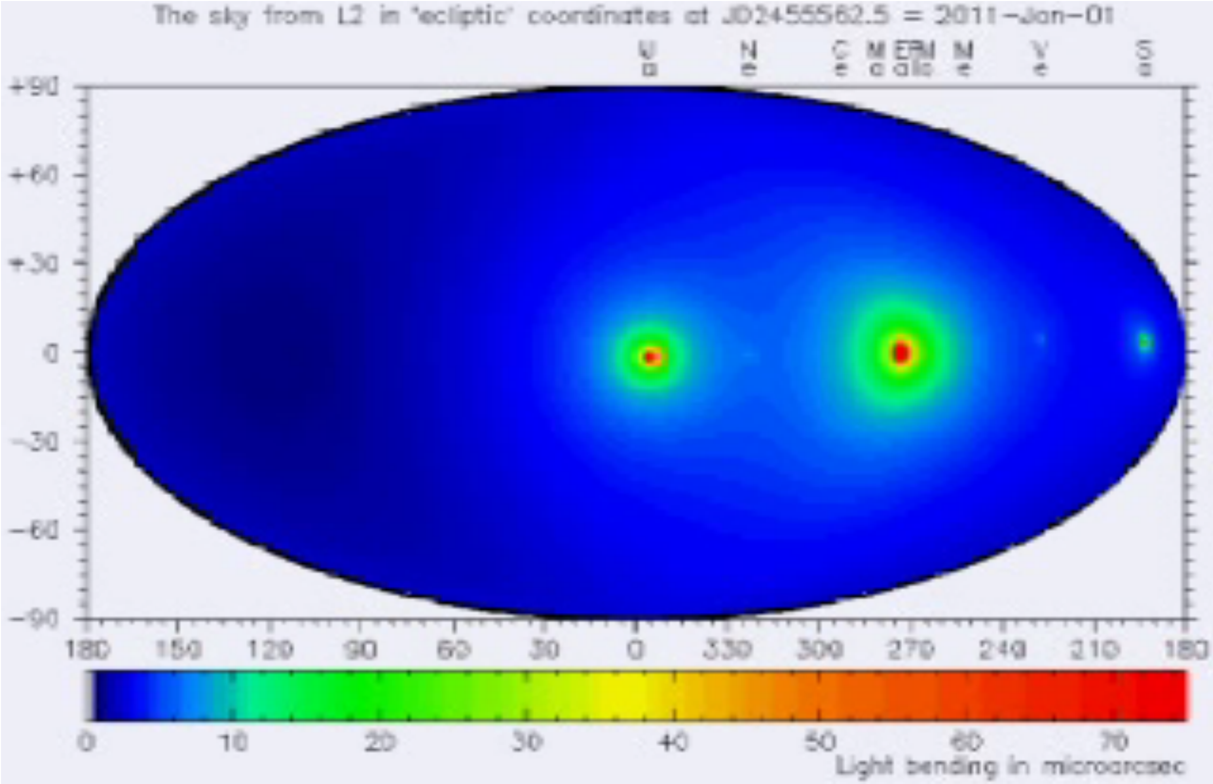
h pertubations at μ-**arcsec** due to the solar system bodies

Detectable relativistic deflections at L2





	$\delta\chi_{\rm PN}$	$\delta\chi_{J_2}$	$\delta\chi_L$	$\chi_{\max}$
Sun	$1''.75$	$\sim 1\ \mu$as	$0.7\ \mu$as	(180°)
Mercury	$83\ \mu$as	–	–	$(7')$
Venus	493	–	–	(4.0°)
Earth	574	0.6	–	(101°)
Moon	26	–	–	(2.3°)
Mars	116	0.2	–	$(17')$
Jupiter	16290	240	0.2	$(87^\circ/3')$
Saturn	5772	94	–	$(16^\circ/51'')$
Uranus	2030	7	–	$(67'/4'')$
Neptune	2487	8	–	$(50'/3'')$
Pluto	7	–	–	$(0''.3)$



J. de Bruijne © ESA

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta} + O(h^2)$$

$$h_{00} = \sum_a \frac{2M_{(a)}}{r_{(a)}} + O(\epsilon^4)$$

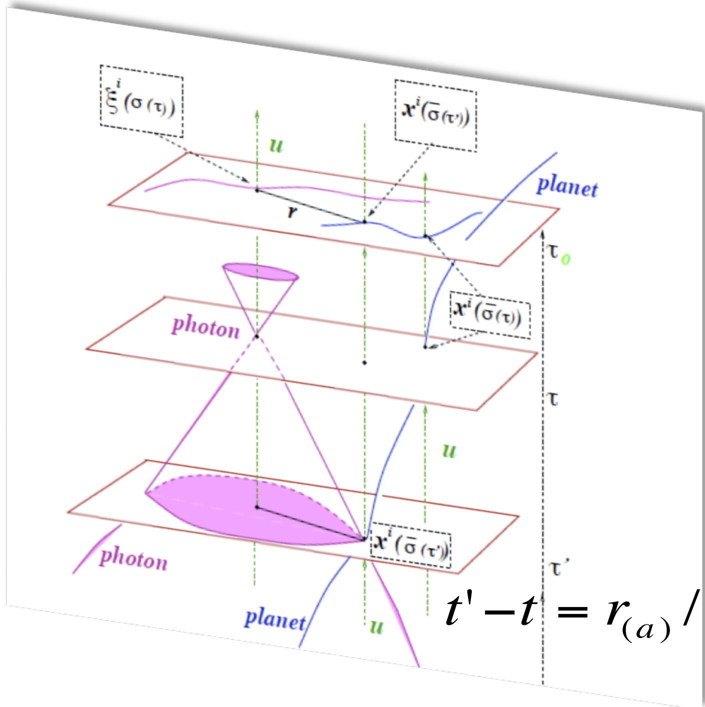
$$h_{0i} = -\sum_a \frac{4M_{(a)}}{r_{(a)}} \tilde{\beta}_{i(a)} + O(\epsilon^5)$$

$$h_{ij} = \sum_a \frac{2M_{(a)}}{r_{(a)}} \delta_{ij} + O(\epsilon^4),$$

$$\tilde{\beta}^j = (1 - h_{00}/2)\tilde{v}^i(\tilde{\sigma}) + O(h^2)$$

IAU resolutions for BCRS metric

micro-arcsecond accuracy+
dynamical gravitational fields,
relativistic models of
Light propagation:
RELATIVISTIC ASTROMETRY



$$t' - t = r_{(a)}/c$$

M. Crosta, GR21, C4, New York 2016, 10-15 July

Gaia,
WG REMAT: RElativistic Models And Tests

Inside the Consortium constitued for the Gaia data reduction (Gaia CU3, Core Processing, DPAC), two models have been developed:

1. **GREM** (Gaia RElativistic Model) , baselined for the Astrometric Global Iterative Solution for Gaia (AGIS)

2. **RAMOD** (Relativistic Astrometric MODel) implemented in the Global Sphere Reconstruction (GSR) of the Astrometric Verification Unit (AVU) at the Italian data center (DPCT)

Italian Data Processing Center

All Gaia operations activities (daily and cyclic) done in Italy are implemented at the DPCT, the Italian provided HW and SW operations system designed, built and run by ALTEC (To) and INAF-OATo for ASI.

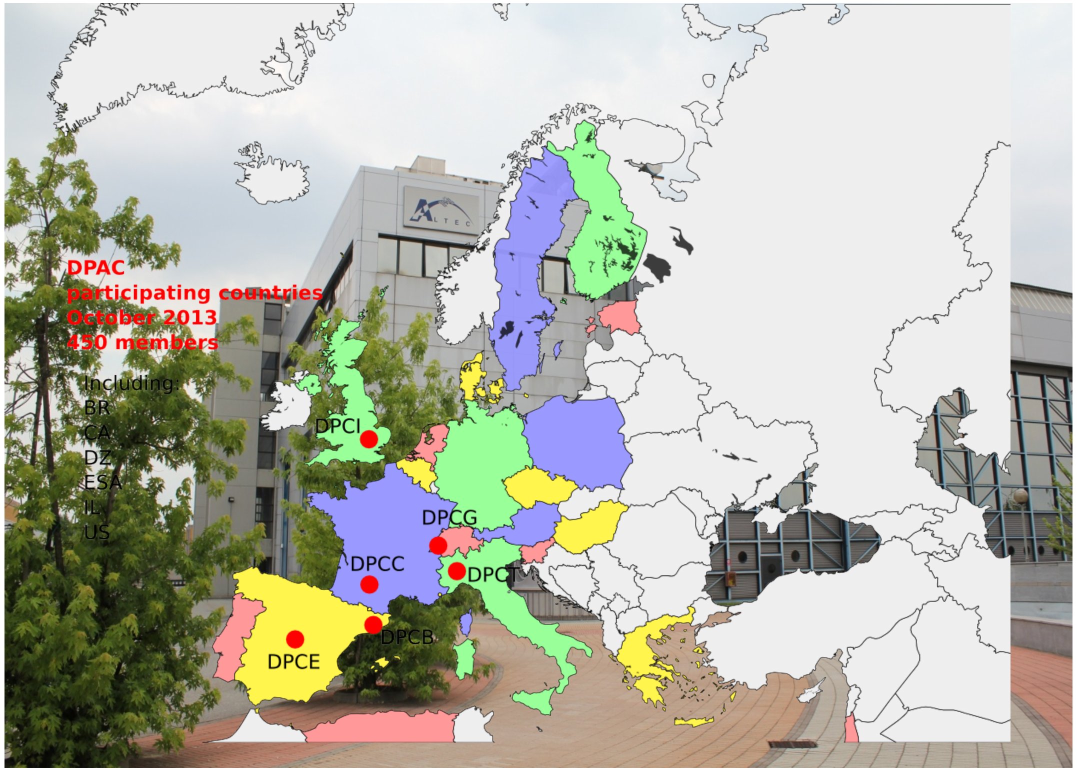
DPCT at full capacity. Accumulated other than 50 TB of data

Size at completion ~ 1.2 PB

The DPCT host the systems AVU:

- CCD-level precision and accuracy (Astrometric Instrument Monitoring - AIM)
- Accuracy at the Optical System level (Basic Angle Monitoring - BAM/AVU)
- Precision & accuracy on the celestial sphere (Global Sphere Reconstruction - GSR)

Essential components of Gaia's astrometric error budget

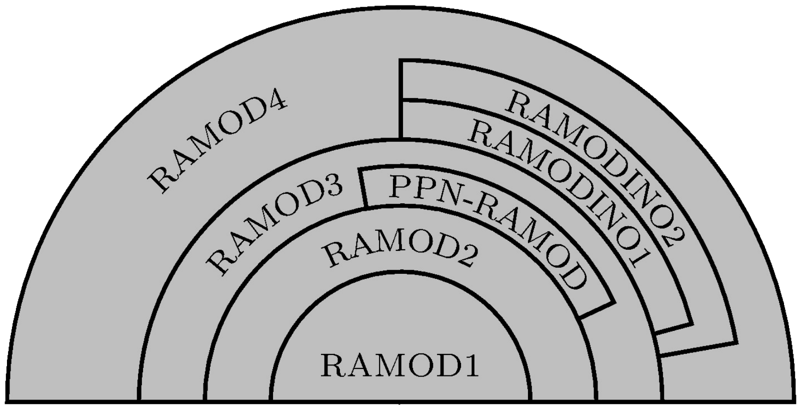


DPCT was established through a specific ASI contract via a partnership between INAF-OATo and ALTEC S.p.A.

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

This is the only Data Processing Center, within the network of 6 DPCs dedicated to Gaia, which specializes in the treatment of the satellite astrometric data

RAMODs&Gaia: from the "measurement" to the star



RAMOD is a framework of general relativistic astrometric models

with increasing intrinsic accuracy, adapted to many different

observer's settings, **interfacing numerical and analytical relativity**

RAMOD applies the measurement protocol (MP) in GR

de Felice, F. & Bini, D. 2010, Classical Measurements in Curved Space-Times, Cambridge University Press

1. RAMOD1: a static non-perturbative model in the Schwarzschild metric of the Sun (de Felice et al., 1998, A&A,332,1133)
2. RAMOD2: a dynamical extension of RAMOD1 (parallaxes and proper motion, de Felice et al., 2001, A&A,373,336)
3. PPN-RAMOD: recasting RAMOD2 in the PPN Schwarzschild metric of the Sun (Vecchiato et al.,2003, A&A, 399,337)
4. RAMOD3: a perturbative model of the light propagation in the static field of the Solar System (milliarcsecond, de Felice et al., 2004, ApJ, 607, 580)
5. RAMOD4: the extension of RAMOD3 to the microarc-second level of accuracy, (de Felice et al., 2006, ApJ, 653, 1552)
6. RAMODINO1-2-3: satellite-observer model for Gaia (Bini et al., 2003, Class.Quantum Grav., 20, 2251/4695); ray tracing error budget (de Felice, F.; Preti, G. 2006CQGra..23.5467D and 2008CQGra..25p5015D)
7. RAMOD vs PM/PN approach: Crosta 2011 Class. Quantum Grav. 28 235013;
8. RAMOD analytical solutions for Gaia-like case : 2015 Crosta, Vecchaito, de Felice , Lattanzi Classum Quantum Gravity

DETAILS on POSTER sess. A2
"The dawn of Relativistic Astrometry..."

The observational target

Local line-of-sight

$$\ell^\alpha = P^\alpha_\beta(u) k^\beta(\tau)$$

Tangent to null geodesic

(MP step 6) Identify the **frame components** of those quantities which are the **observational targets**.

$$P(u')_{\alpha\beta} = g_{\alpha\beta} + u'_\alpha u'_\beta$$

Projector operator in the rest-space of **u**

$$k^\alpha k_\alpha = 0, \quad \frac{dk^\alpha}{d\lambda} + \Gamma^\alpha_{\rho\sigma} k^\rho k^\sigma = 0$$

→

Master Equations

$$\frac{d\ell^\alpha}{d\sigma} = F^\alpha(\partial_\beta h(x,y,z,t), \ell^i(\sigma(x)))$$

A general solution $\bar{\ell}^i(\sigma) = \bar{\ell}^i(\bar{\boldsymbol{\ell}}(\sigma_0), h_{\alpha\beta}(\sigma))$ depends on the observed ℓ^k_{obs}

✓**boundary condition to solve uniquely the differential equations**
✓link to the parameters of the star in the astrometric measurements (condition equation)

$$\frac{d\bar{\ell}^k}{d\sigma} + \bar{\ell}^k \left(\frac{1}{2} \bar{\ell}^i h_{00,i} \right) + \delta^{ks} \left(h_{sj,i} - \frac{1}{2} h_{ij,s} \right) \bar{\ell}^i \bar{\ell}^j - \frac{1}{2} \delta^{ks} h_{00,s} = 0.$$

STATIC CASE

$$\frac{d\bar{\ell}^0}{d\sigma} - \bar{\ell}^i \bar{\ell}^j h_{0j,i} - \frac{1}{2} h_{00,0} = 0$$

DYNAMICAL CASE

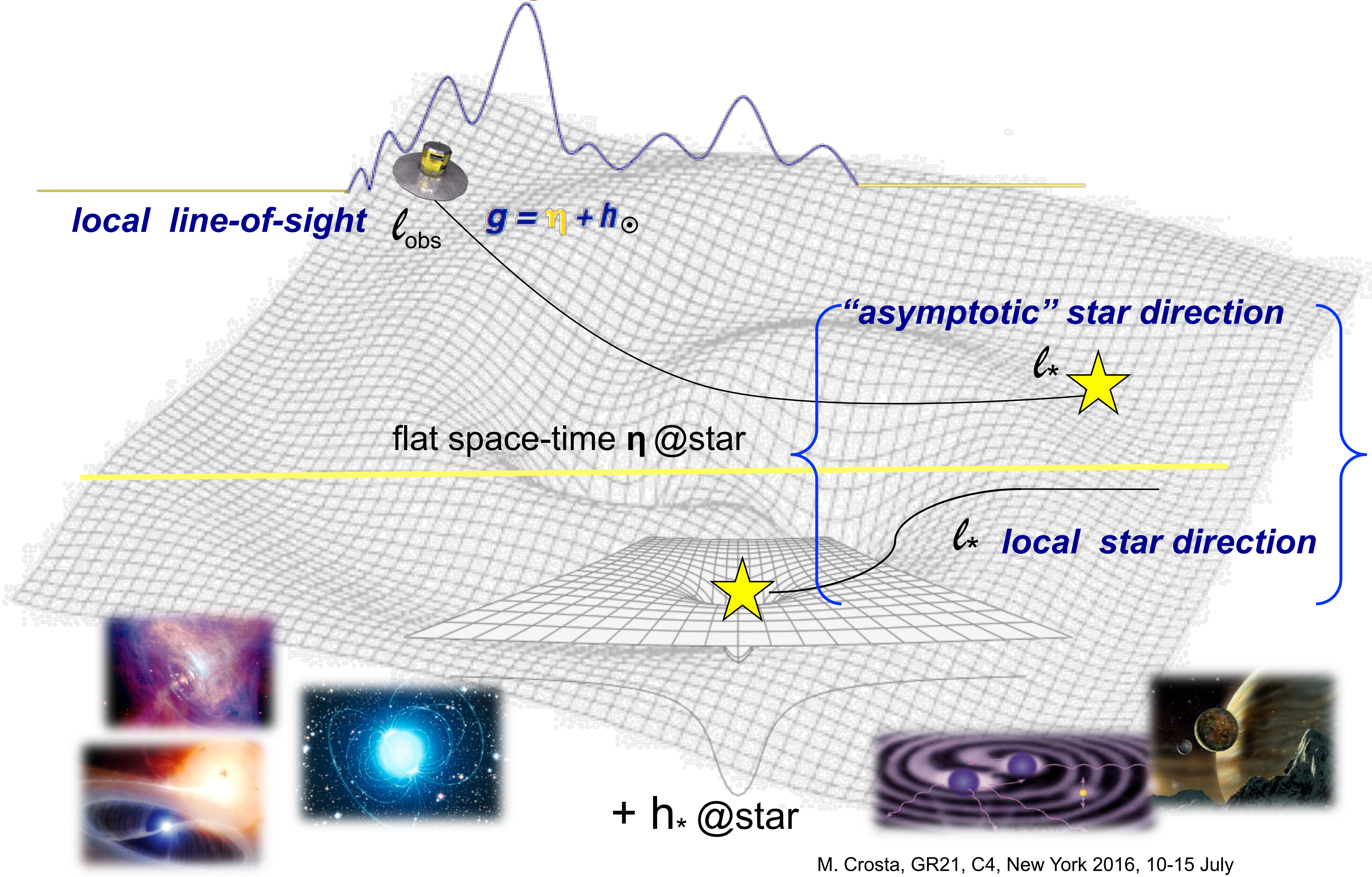
$$\frac{d\bar{\ell}^k}{d\sigma} - \frac{1}{2} \bar{\ell}^k \bar{\ell}^i \bar{\ell}^j h_{ij,0} + \bar{\ell}^i \bar{\ell}^j \left(h_{kj,i} - \frac{1}{2} h_{ij,k} \right) + \frac{1}{2} \bar{\ell}^k \bar{\ell}^i h_{00,i} + \bar{\ell}^i \left(h_{k0,i} + h_{ki,0} - h_{0i,k} \right) - \frac{1}{2} h_{00,k} - \bar{\ell}^k \bar{\ell}^i h_{0i,0} + h_{k0,0} = 0.$$

One more equation to integrate: spatial time component!

With appropriate assumptions adapted to the case of the Solar System and the accuracy of a Gaia-like observer there exists analytical solutions:

R.A.MOD. models (Crosta et al., Classum Quantum Gravity, 32 (2015) 1655008 and references thererein)

from the local line-of-sight to the local star direction



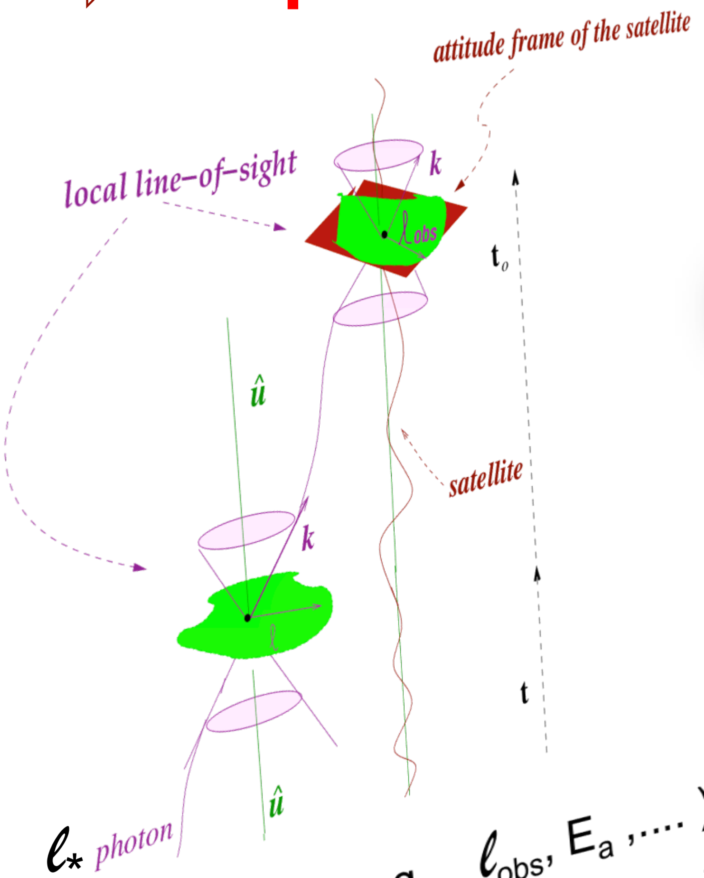
aberrated (gravitational) direction

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

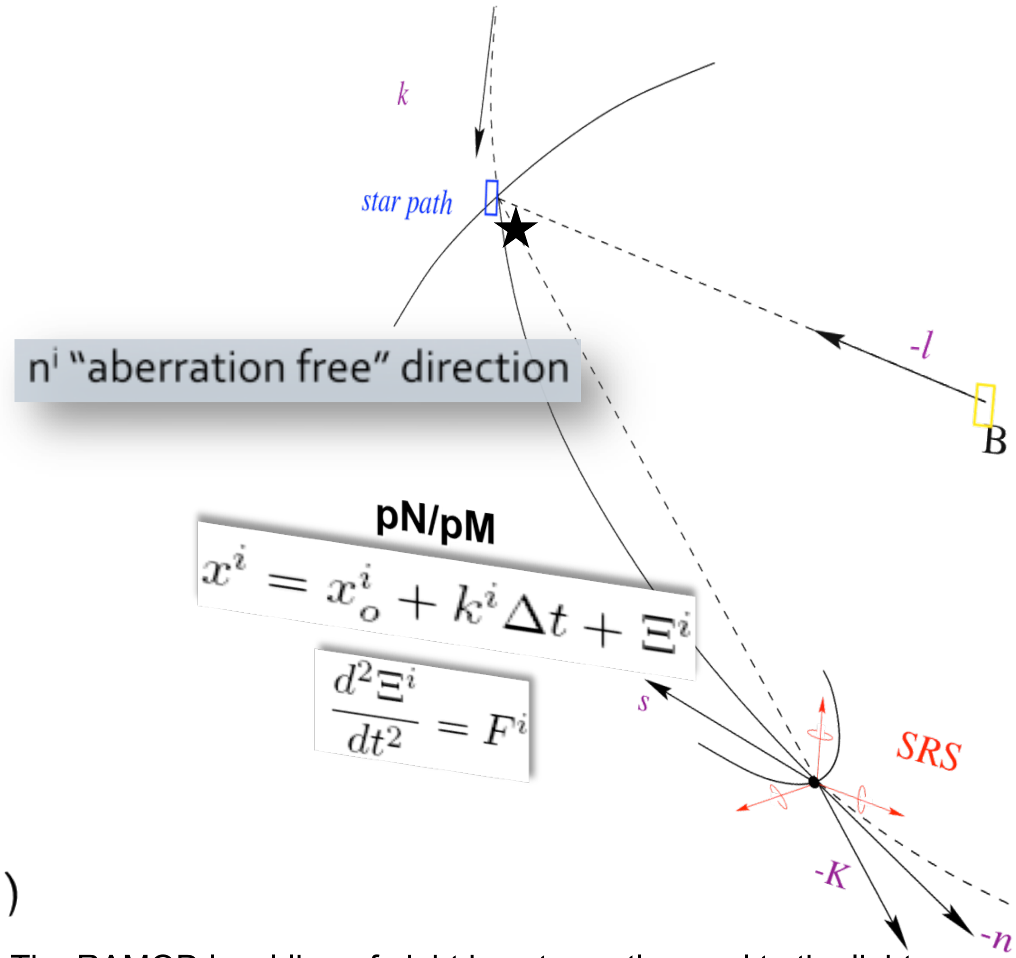
$h_{00}/2 \approx U/c^2$ (local potential)[IAU solution]

⇒ **100 µas!**

(MP step 8) Verify the degree of the residual ambiguity in the interpretation of the measurements and decide the strategy to evaluate it (i.e. comparing what already is known).

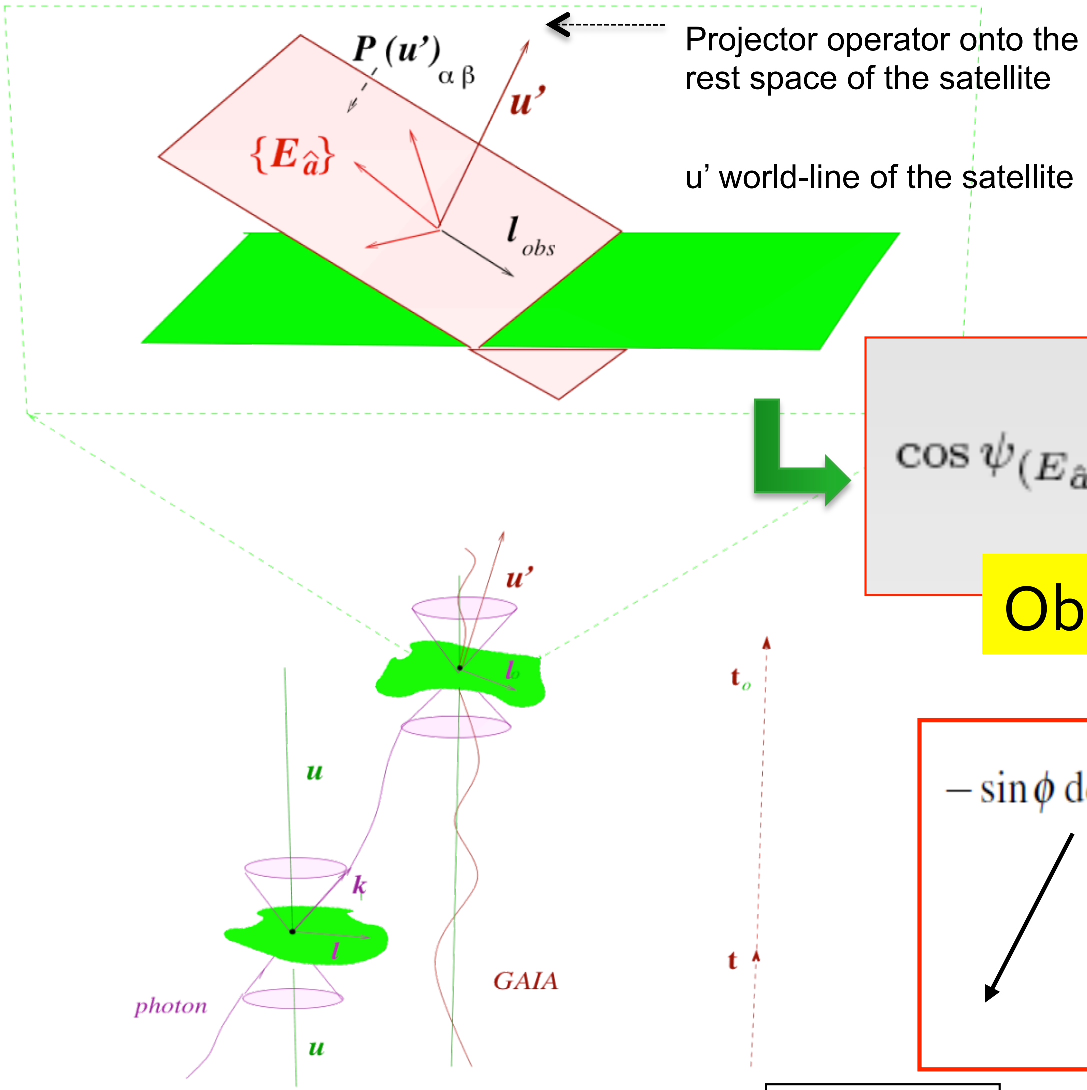


$$x_* = F(x_{obs}, g_{\mu\nu}, \ell_{obs}, E_a, \ldots.)$$



The RAMOD local-line-of-sight is not exactly equal to the light direction used in the semi-classical approximation

The astrometric observable in RAMOD/AVU



E_α^β "attitude tetrad"-> ESSENTIAL to define the boundary condition (Bini , Crosta, and de Felice, Class.Quantum Grav. 20, 4695, 2003

$$\cos\psi_{(E_{\hat{a}},\ell_{obs})} \equiv \mathbf{e}_{\hat{a}} = \frac{P(u')_{\alpha\beta}\,\ell_{obs}^{\alpha}\,\boldsymbol{E}_{\hat{a}}^{\beta}}{(P(u')_{\alpha\beta}k^{\alpha}k^{\beta})^{1/2}}$$

Observation equation

$$-\sin\phi\,d\phi = \underbrace{\frac{\partial F}{\partial \alpha_*}\delta\alpha_* + \frac{\partial F}{\partial \delta_*}\delta\delta_* + \frac{\partial F}{\partial \varpi_*}\delta\varpi_* + \cdots}_{\text{Astrometric parameters}}$$

$$\sum_{ij}\frac{\partial F}{\partial \sigma_i^{(j)}}\delta\sigma_i^{(j)} + \sum_i \frac{\partial F}{\partial c_i}\delta c_i + \frac{\partial F}{\partial \gamma}\delta\gamma + \cdots$$

$$\phi_{obs} - \phi_{calc}$$

All derivatives are calculated at appropriate "catalog" values

The concept of the Global Sphere Reconstruction

$$\cos\phi \equiv F\left(\underbrace{\alpha_*,\delta_*,\varpi_*,\mu_{\alpha*},\mu_{\delta*}}_{\text{Astrometric parameters}},\underbrace{\sigma_1^{(1)},\sigma_2^{(1)},\sigma_3^{(1)},\sigma_1^{(3)},\sigma_2^{(3)},\sigma_3^{(3)}}_{\text{Attitude parameters}},\underbrace{c_1,c_2,\ldots,}_{\text{Instrument}}\underbrace{\gamma,\ldots}_{\text{Global}}\right)$$

DETAILS on posters: sess. B2 "The AVU/ GSR pipeline in the Gaia Mission" and sess.C4 "ASTRA"

Solving the linearized GSR sphere in the Least-Squares sense

Known **Unknown** **Unknown**

$$\sin\psi_i^{(1)}\,\Delta\psi_i^{(1)} = \frac{\partial f}{\partial\alpha_i}\Delta\alpha_i + \frac{\partial f}{\partial\delta_i}\Delta\delta_i + \frac{\partial f}{\partial\pi_i}\Delta\pi_i + \cdots + \frac{\partial f}{\partial\gamma}\Delta\gamma$$

$$\sin\psi_i^{(2)}\,\Delta\psi_i^{(2)} = \frac{\partial f}{\partial\alpha_i}\Delta\alpha_i + \frac{\partial f}{\partial\delta_i}\Delta\delta_i + \frac{\partial f}{\partial\pi_i}\Delta\pi_i + \cdots + \frac{\partial f}{\partial\gamma}\Delta\gamma$$

• • • • • •

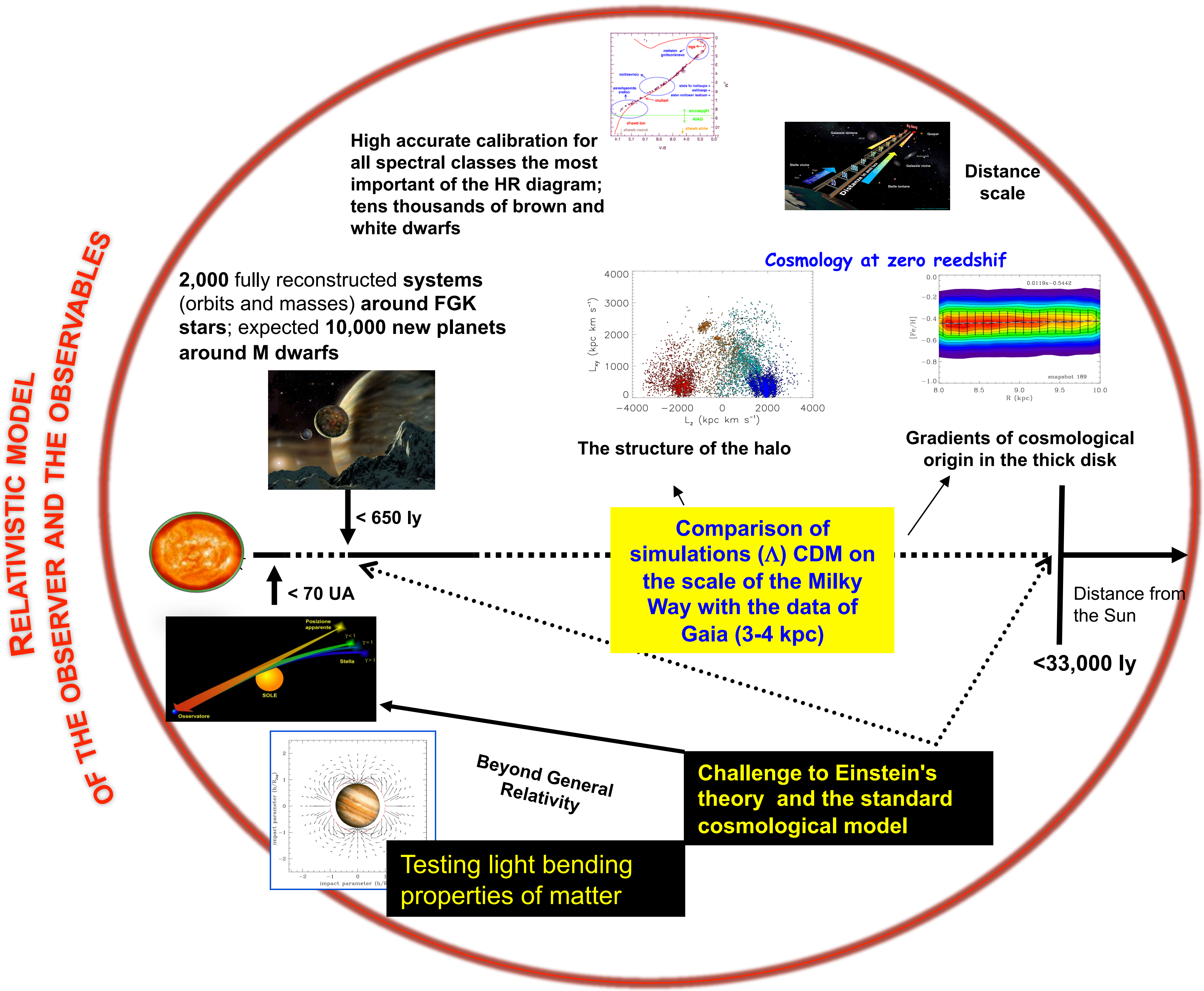
$$\sin\psi_i^{(n)}\,\Delta\psi_i^{(n)} = \frac{\partial f}{\partial\alpha_i}\Delta\alpha_i + \frac{\partial f}{\partial\delta_i}\Delta\delta_i + \frac{\partial f}{\partial\pi_i}\Delta\pi_i + \cdots + \frac{\partial f}{\partial\gamma}\Delta\gamma$$

1 obs. $\Rightarrow$ 1 condition eq.

(linearized) system of solution with dimensions $\sim 10^{10} \times 10^{8}$

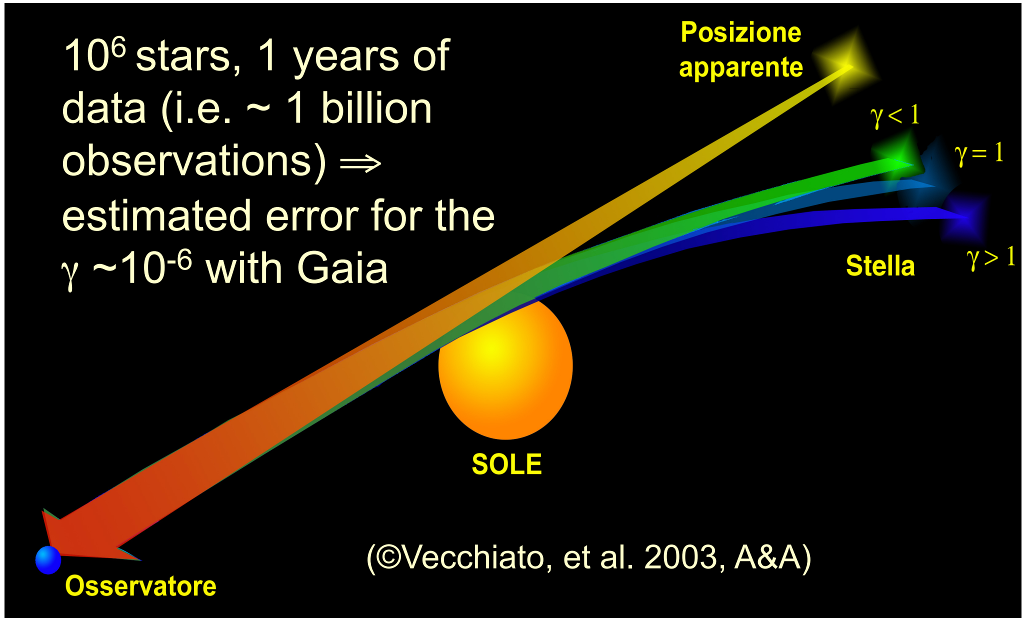
iterative method (LSQR, Paige, C. & Saunders, M. A. 1982, ACM Trans. Math. Software, 8, 43)

→ A real Galilean experiment in space: a massive repetition of the Eddington et al. astrometric test of GR with 21st century technology, thank to the interfacing of analytical&numerical relativity methods


RELATIVISTIC MODEL
OF THE OBSERVER AND THE OBSERVABLES
High accurate calibration for all spectral classes the most important of the HR diagram; tens thousands of brown and white dwarfs
Distance scale
2,000 fully reconstructed systems (orbits and masses) around FGK stars; expected 10,000 new planets around M dwarfs
Cosmology at zero reedshif
The structure of the halo
Gradients of cosmological origin in the thick disk
< 650 ly
< 70 UA
Comparison of simulations (Λ) CDM on the scale of the Milky Way with the data of Gaia (3-4 kpc)
Distance from the Sun
<33,000 ly
Posizione apparente
Stella
SOLE
Osservatore
Beyond General Relativity
Challenge to Einstein's theory and the standard cosmological model
Testing light bending properties of matter

Fundamental Physics tests

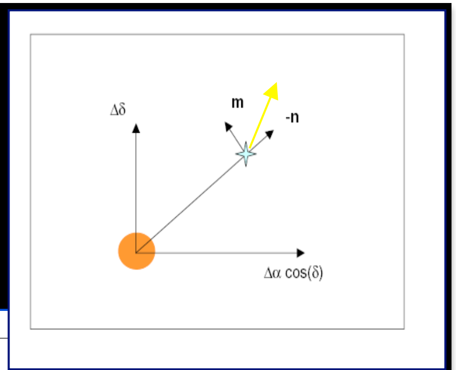
poster (C4) "High-precision astrometry.."

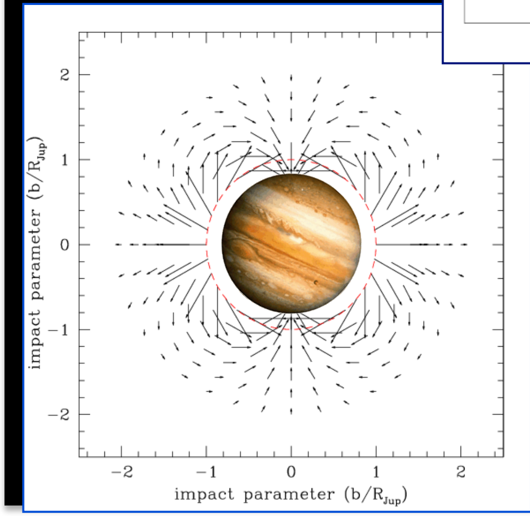


Future improvements of light deflection measurements in Solar System allow 10^{-8}!

poster (C4) "The Gaia Rel...GAREQ"

detection of the light deflection due to the quadrupole of Jupiter





3 to 10σ level

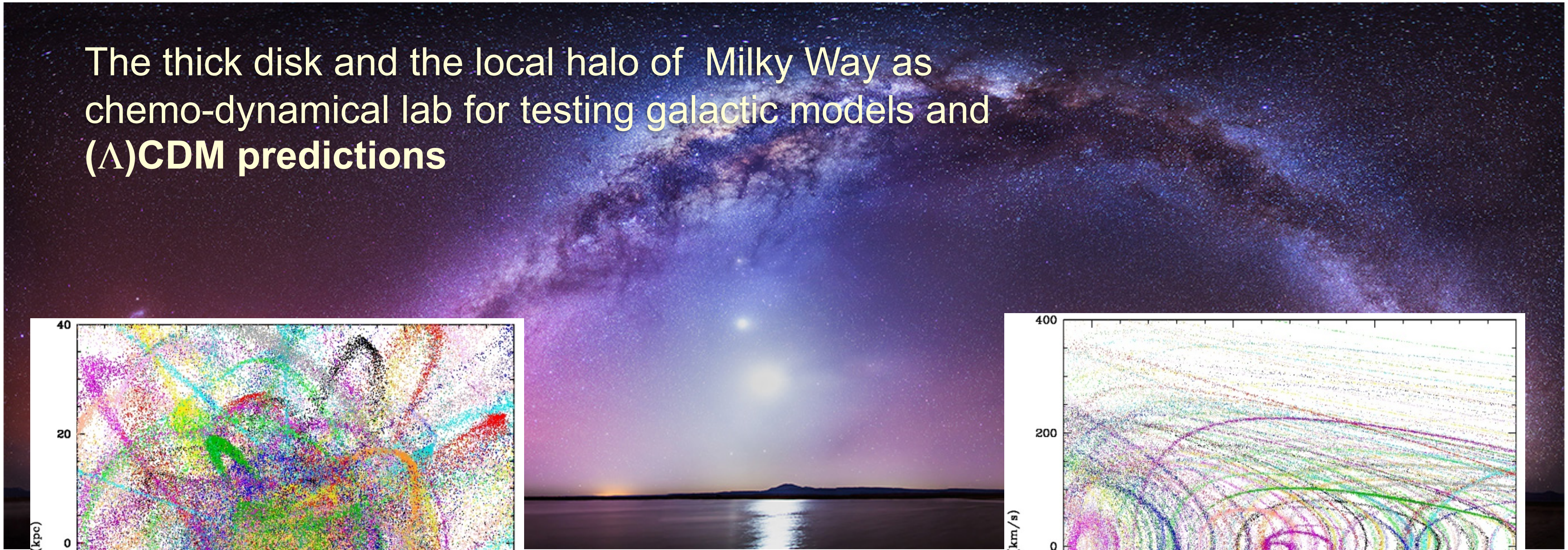
Global astrometry: the evaluation of deviations from GR depends on the particular scalar-tensor theory adopted -> quantum theory of gravity, verification of inflationary models, violation of the principle of equivalence, constancy of the physical constants, low-energy limits of string theories, f (R) gravity with no need of dark matter and dark energy, accelerated cosmological expansion, Galaxy cluster dynamics, Galaxy rotation curves and DM halos

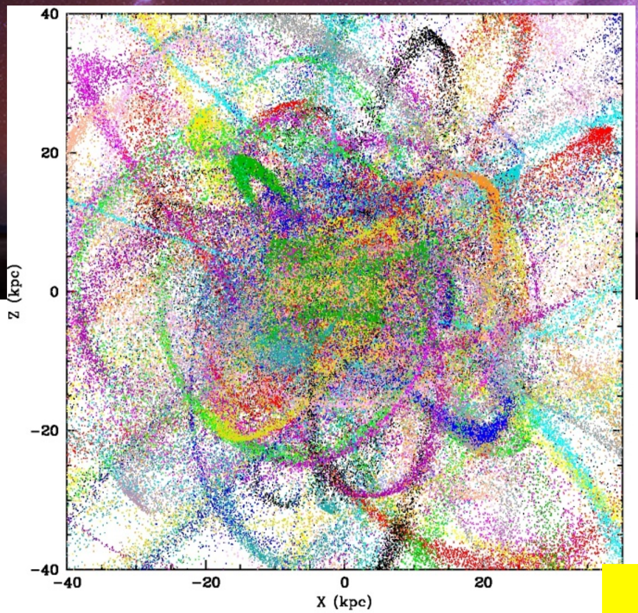
Differential Astrometry:

extrapolation of the evaluation of the quadrupole contribution to second order deflection effects, gravitomagnetic and post-Newtonian effects of higher order

Milky Way..relativisticlly tuned (kinematically)

The thick disk and the local halo of Milky Way as chemo-dynamical lab for testing galactic models and **(Λ)CDM predictions**

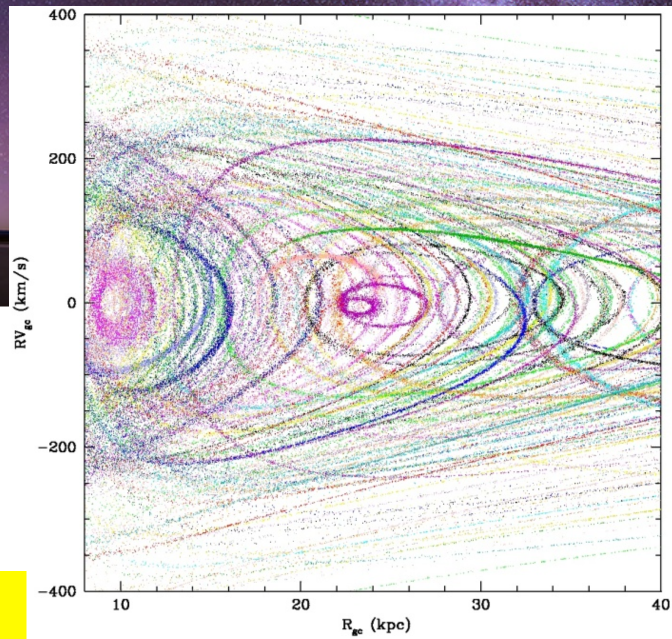




©P. Harding e H. Morrison

POSITION / POSITION

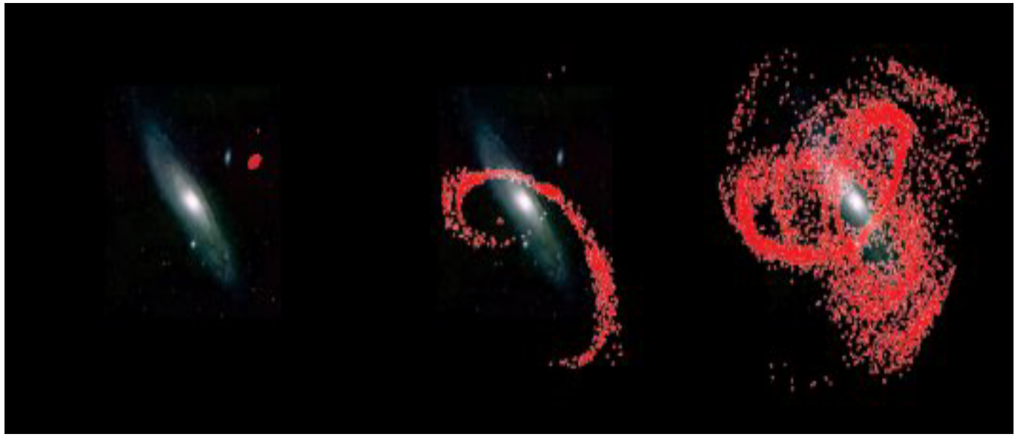
Comparison of simulations Lambda-CDM on the scale of the Milky Way with the data of Gaia (3-4 kpc)



POSITION / VELOCITY

©P. Harding e H. Morrison

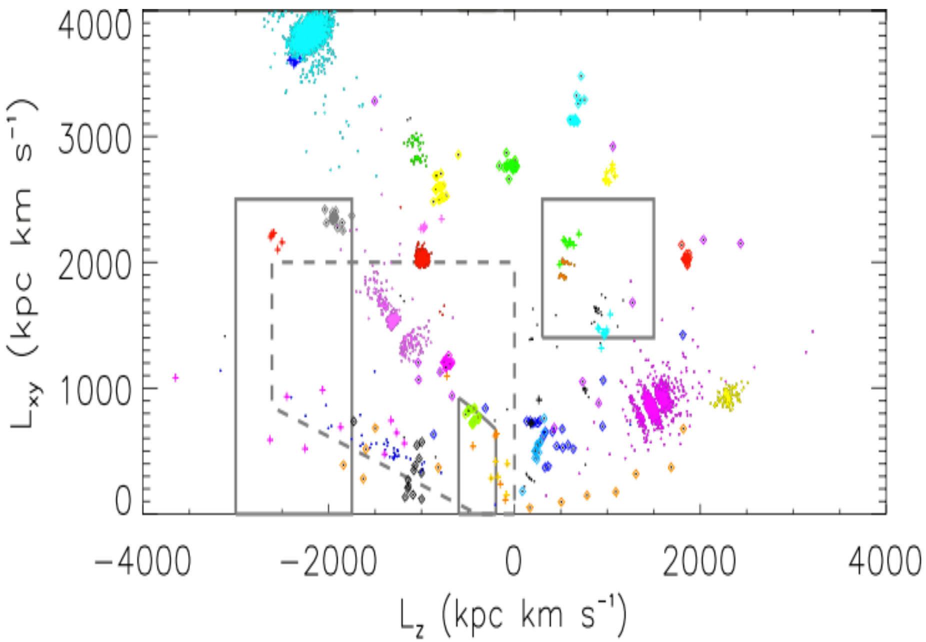
(Courtesy of A. Spagna - OATo)



Finding (and counting!) streams in the Galactic inner halo (<u>within 3-5 kpc from the Sun</u>)

- Simulations -

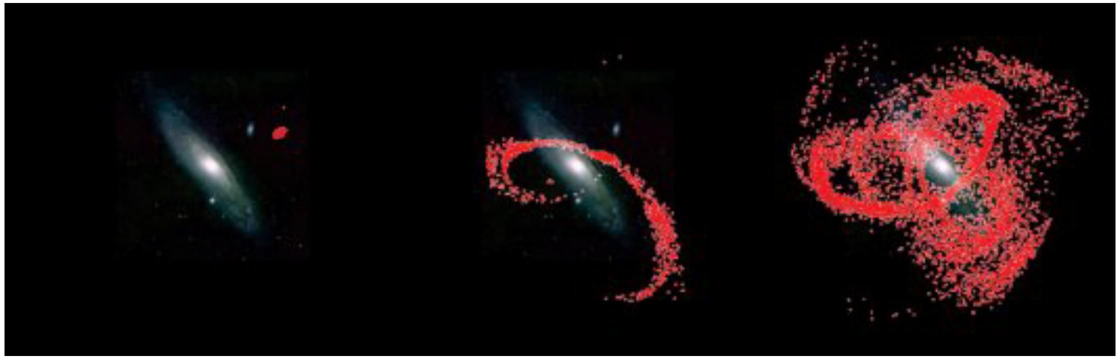
True 'simulated' data set →



Simulations from *Sanderson et al. (2014)*

(Courtesy of A. Spagna - OATo)

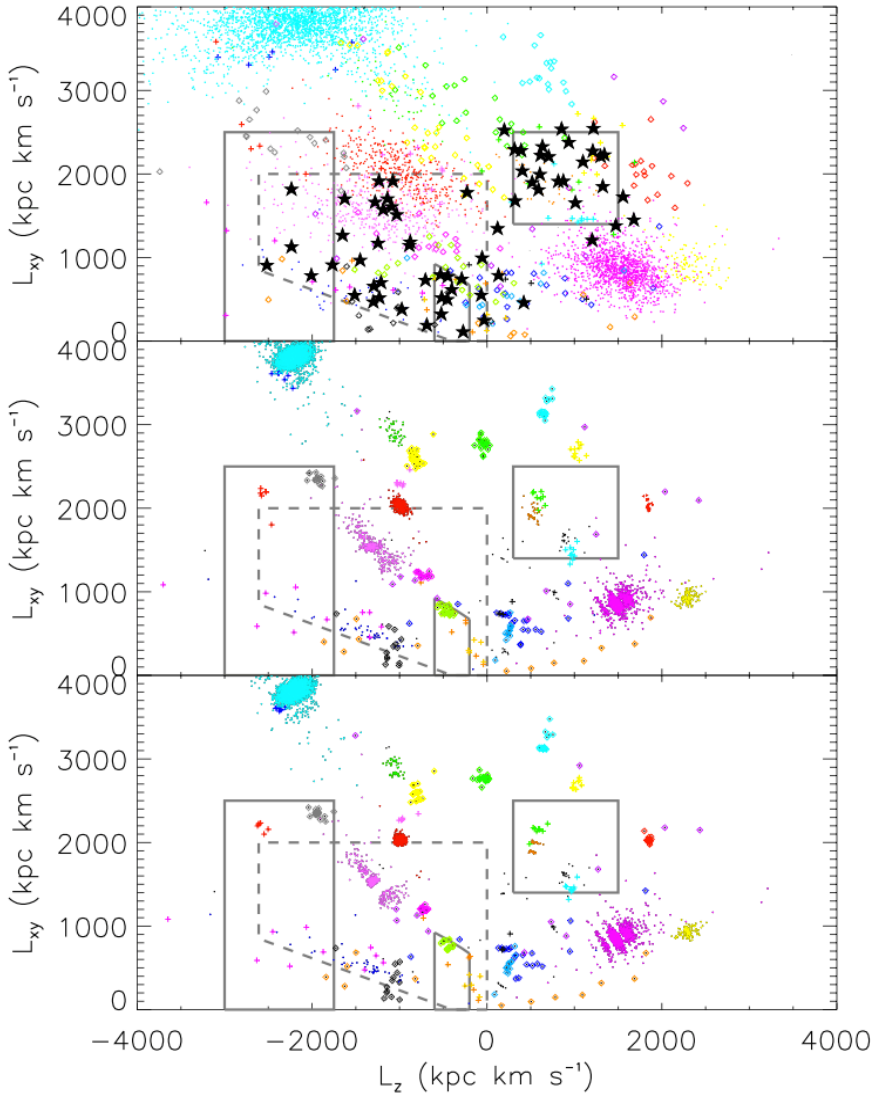
Finding streams in the Galactic inner (within 3 kpc from the Sun) halo - *Simulations* -



Accuracy of the current ground-based catalogs

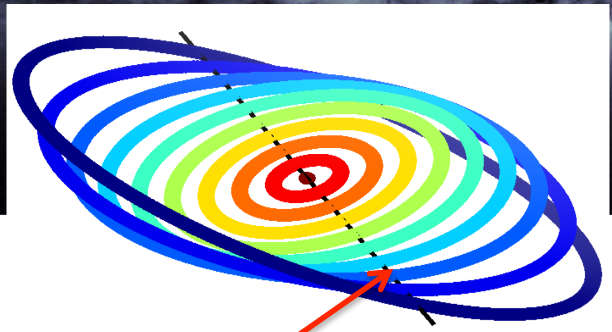
Expected Gaia observations

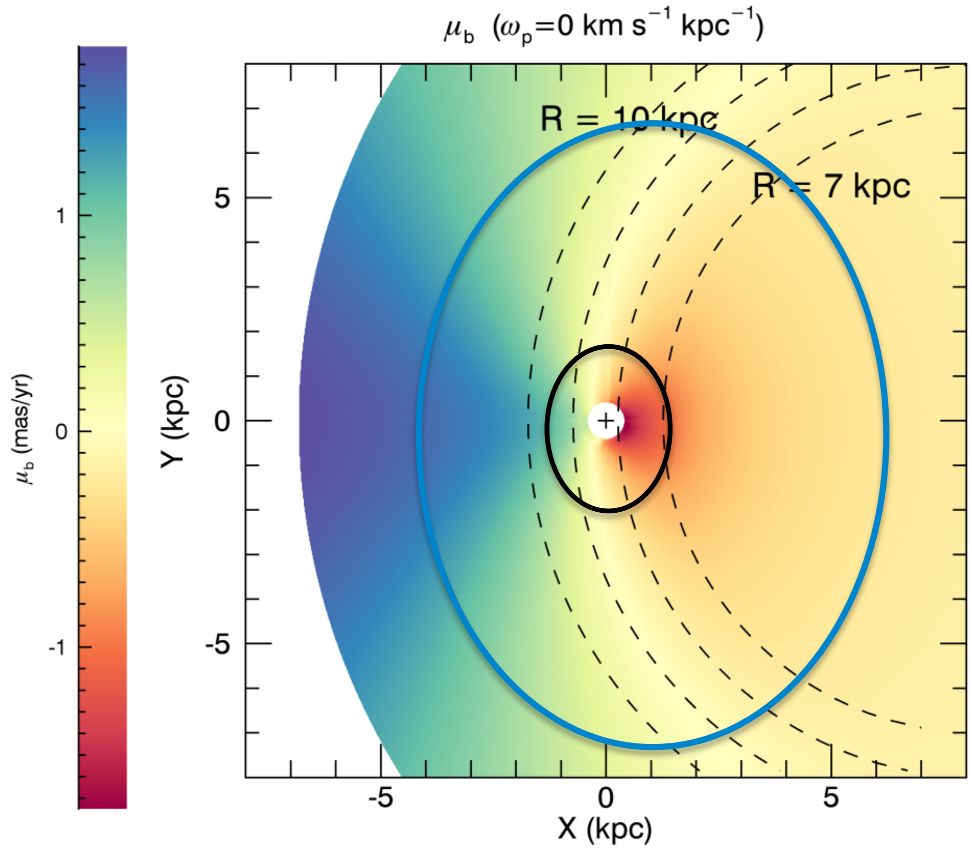
True 'simulated' data set

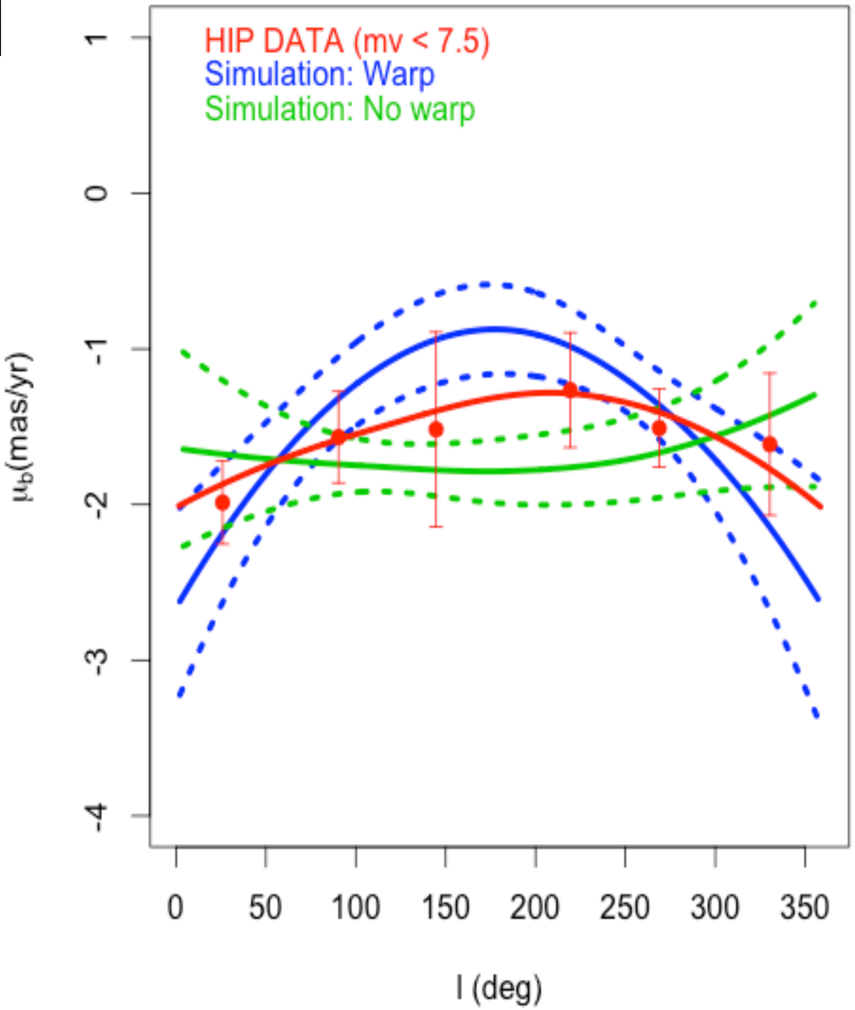


Simulations from *Sanderson et al. (2014)*
and error model from *Re Fiorentin et al. (2015)*

The Galactic Warp (via O-B stars)







(Courtesy of R. Drimmel - OATo)

✓Conclusions

- DR1 processing and validation is indicating that the Gaia mission is fulfill most of the science promised
  - ❖ DR1 is **only** the first Gaia data release and full confirmation has to wait for the next DR (i.e., for a **full-Gaia-only solution**).

Reaching 10-20 μas accuracy on individual parallax and annual proper motions for bright stars (V<16) is the key

➢**possibly to perform the largest GR experiment ever attempted from space:**

the realization of the celestial sphere is not only a scientific validation of the absolute parallax and proper motions in Gaia, but also, *given the number of celestial objects (a real Galilean method applied on the sky!) and directions involved (the whole celestial sphere!), the largest experiment in General Relativity ever made with astrometric methods (since 1919)*

➢to fully probe the MW (outer) halo (mass content and distribution) and compare the prediction of Lambda-CDM models

✓Conclusions

- But all the goals of Gaia will not be achieved without the correct characterization and exploitation of the ``relativistic'' astrometric data.

  The Gaia-like observer is positioned inside the Solar System, a weak gravitational regime which turns out to be "strong" when one has to perform high accurate measurements

- Any discrepancy between the relativistic models, if it can not be attributed to errors of different nature, will mean either a limit in the modeling/ interpretation - that a correct application of GR should fix - and therefore a validation of GR, or, maybe, a clue that we need to refine our approach to GR

✓Conclusions

- in tracing back light rays we need to keep consistency, at any level of approximations, with GR
- this implies a new rendition of the astronomical observables and it may open, at the sub-muas level, a new detection window of many subtle relativistic effects naturally folded in the light while it propagates through the geometry of space-time up to the "local" observer

- **Beyond the micro-arcsecond? <u>Gaia represents ONLY the 0-step</u>**… increasing the level of the measurement precision requires to refine consistently the metric of the solar system, the solution for the null geodesic and so on..
- <u>Once a relativistic model for the data reduction has been implemented, any subsequent scientific exploitation should be consistent with the precepts of the theory underlying such a model</u>

One century after General Relativity we must rethink the Mach's principle: how much the local universe can affect on our knowledge of the global universe?

The method introduced by RAMOD extends beyond the scope of Gaia, after Gaia Astrometry becomes part of the fundamental physics and, in particular, in that of gravitation