

GAIA AND THE ASTEROID POPULATION: A REVOLUTION ON EARTH, COMING FROM SPACE

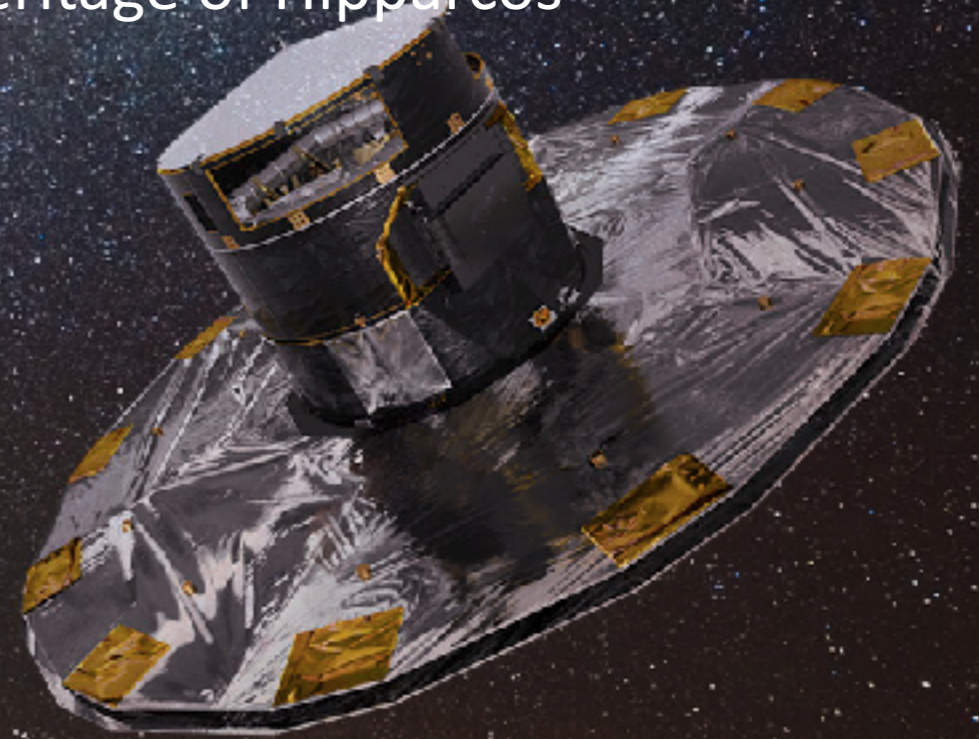
P. Tanga

Laboratoire Lagrange,
Observatoire de la Côte d'Azur, France

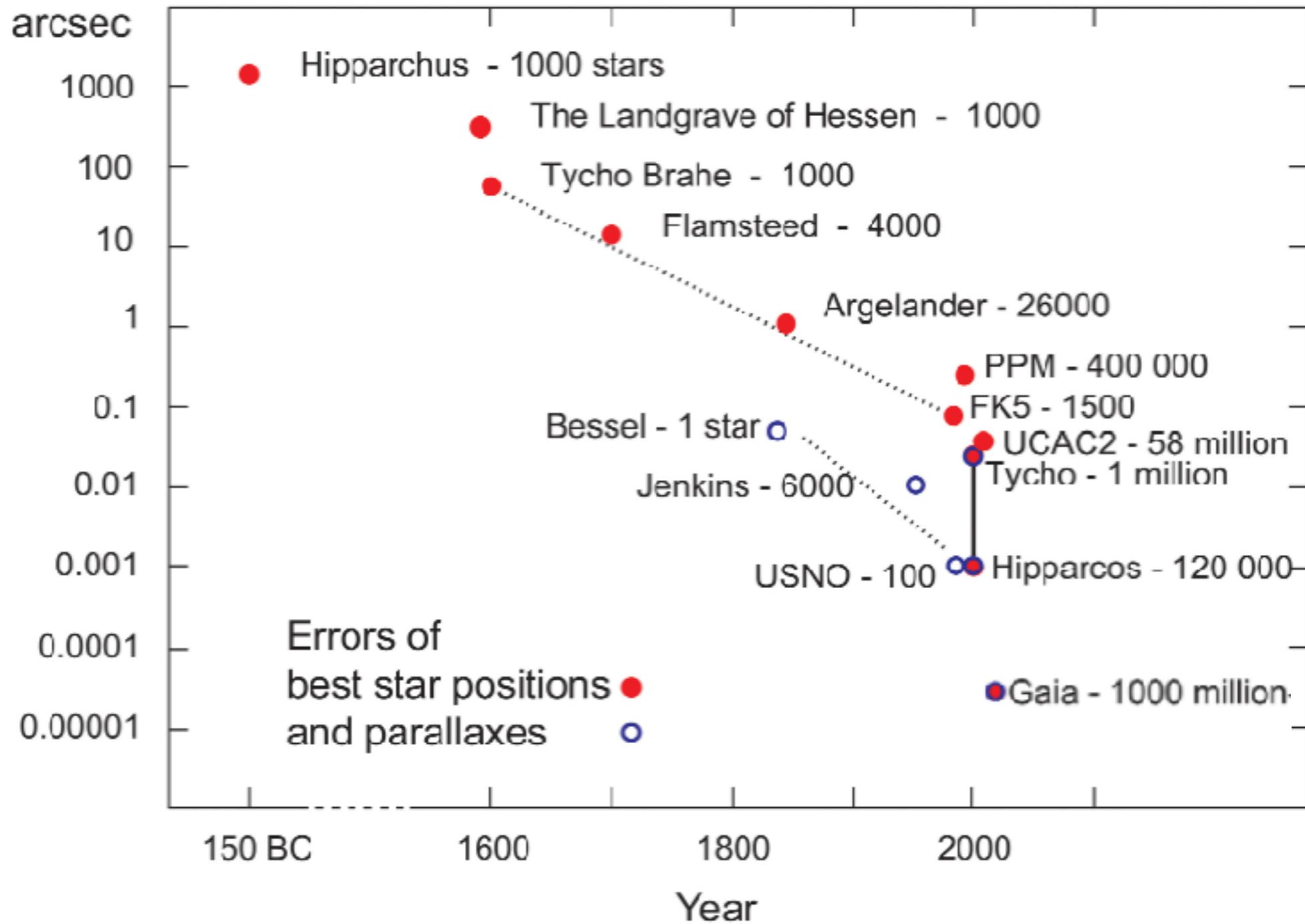


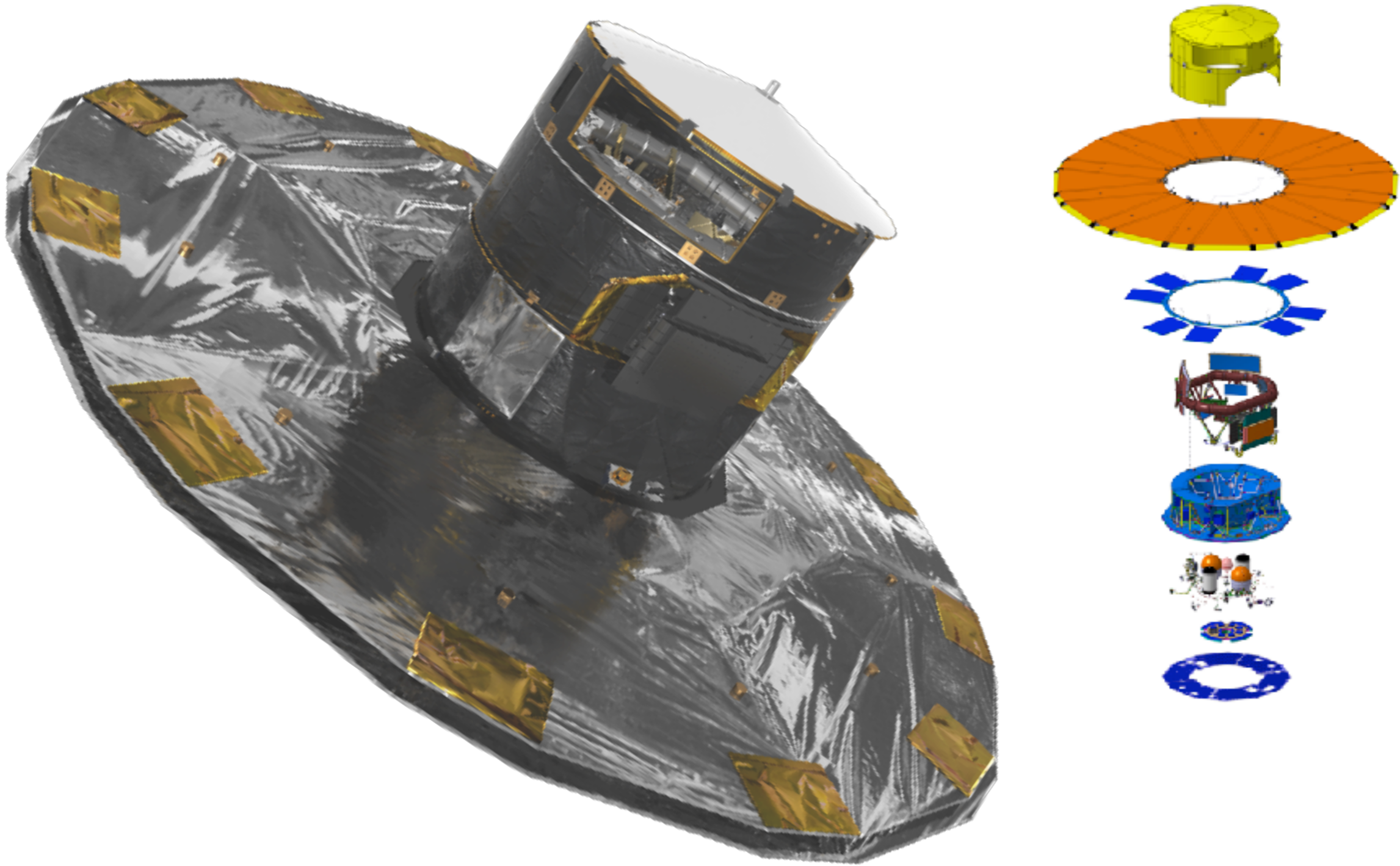
Gaia ID card

- It is a **ESA** cornerstone **scientific mission**:
 - ESA: building, operation
 - Scientific community: data reduction
 - No instrument PI, no proprietary period
- **Astrometry**:
 - 10^9 stars, $V < 20$
 - $25 \mu\text{as}$ at $V \sim 15$
 - uniform sky coverage (70-100 obs./source)
- **Physical observations**:
 - Spectro-photometry
 - Radial velocities, hi-res spectra ($V < 16.5$)
- **5 years** of observations (nominal mission started in July 2014)
- **Positioned around L2**
- **automated selection of sources , on input catalog**
- Self-monitored, onboard metrology
- Heritage of Hipparcos



Gaia in the history of astrometry





ESA/Gaia/DPAC/Airbus DS

Optics

Two SiC primary mirrors
 $1.45 \times 0.50 \text{ m}^2$, $F = 35 \text{ m}$

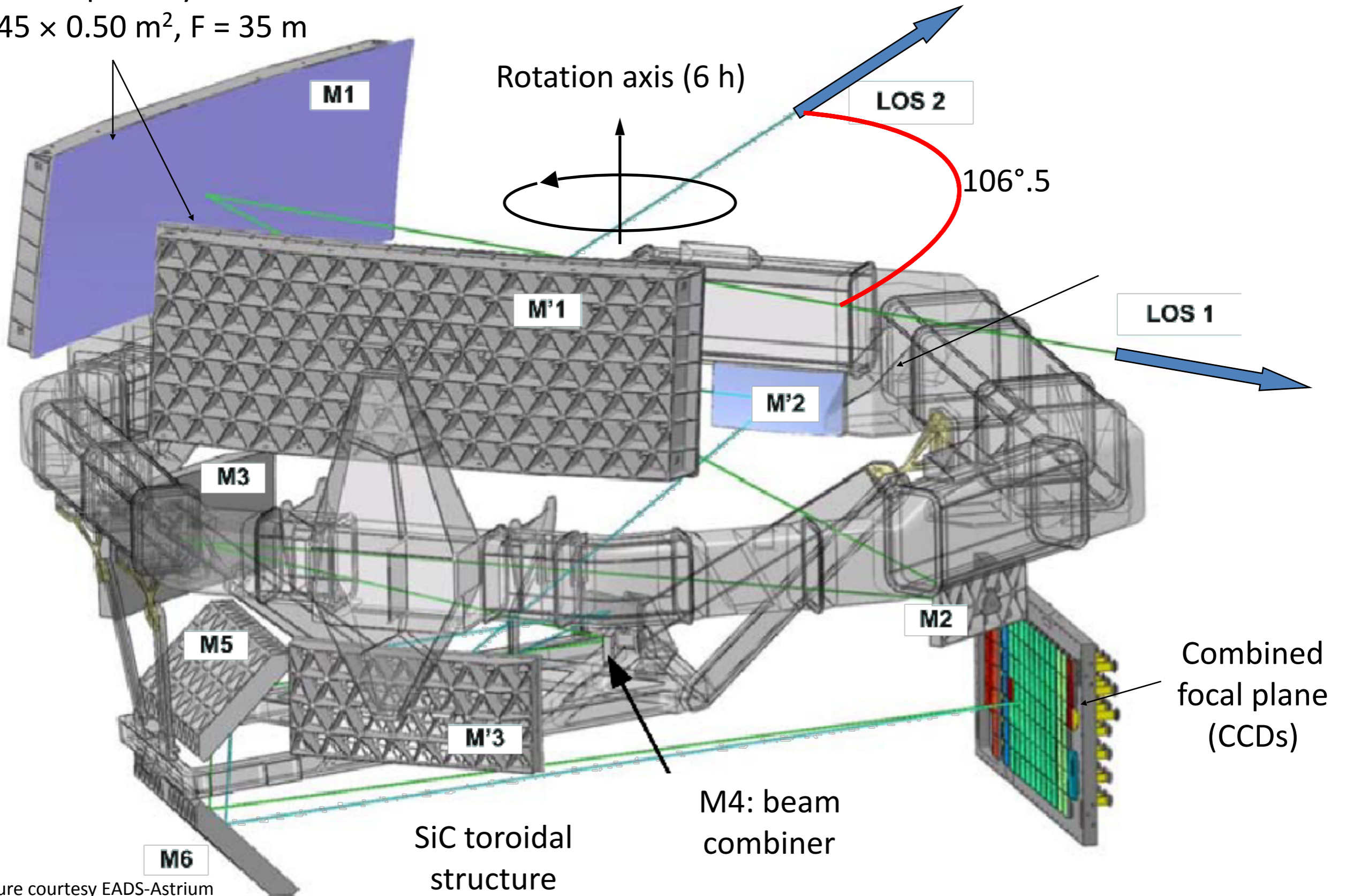
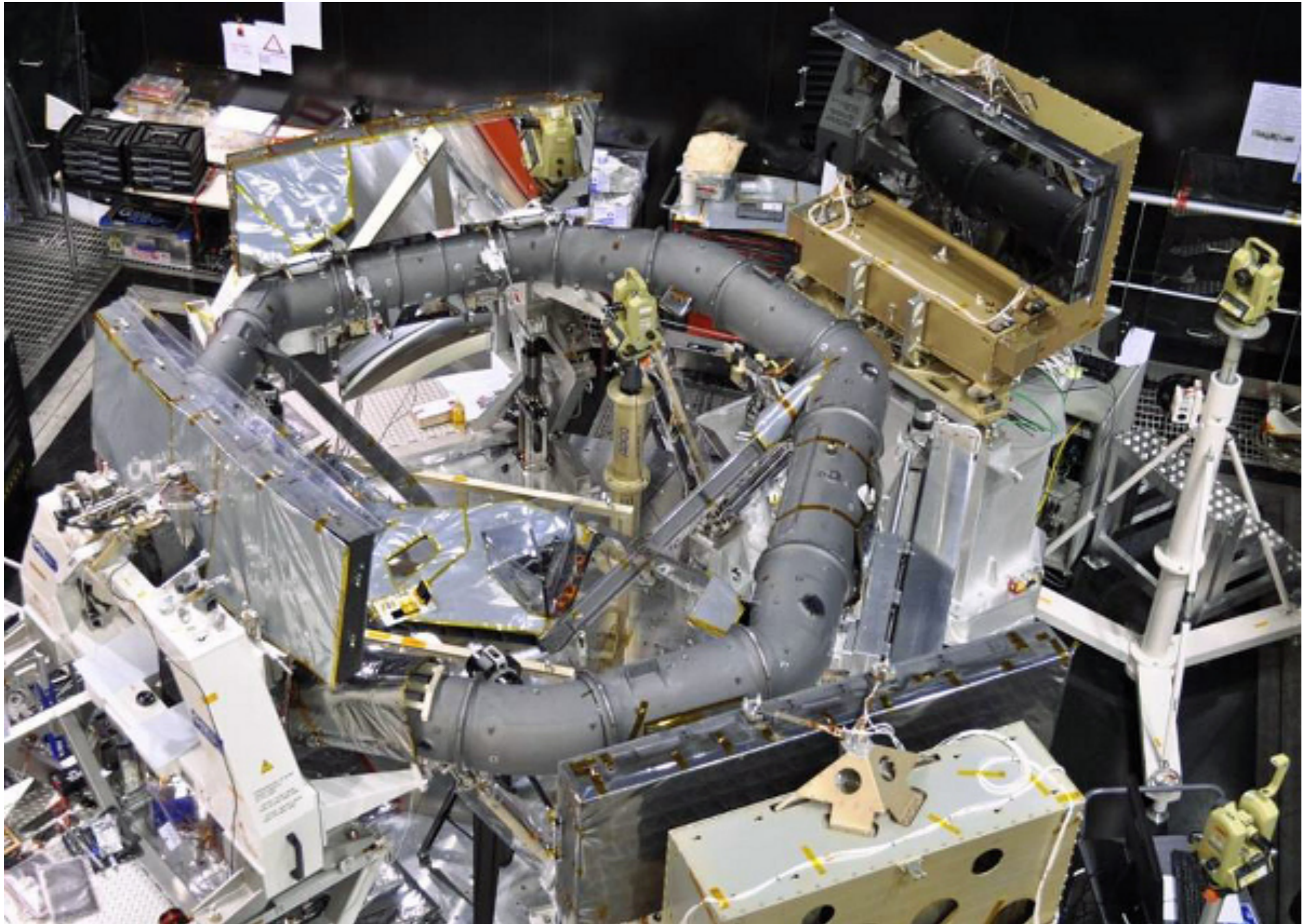


Figure courtesy EADS-Astrium

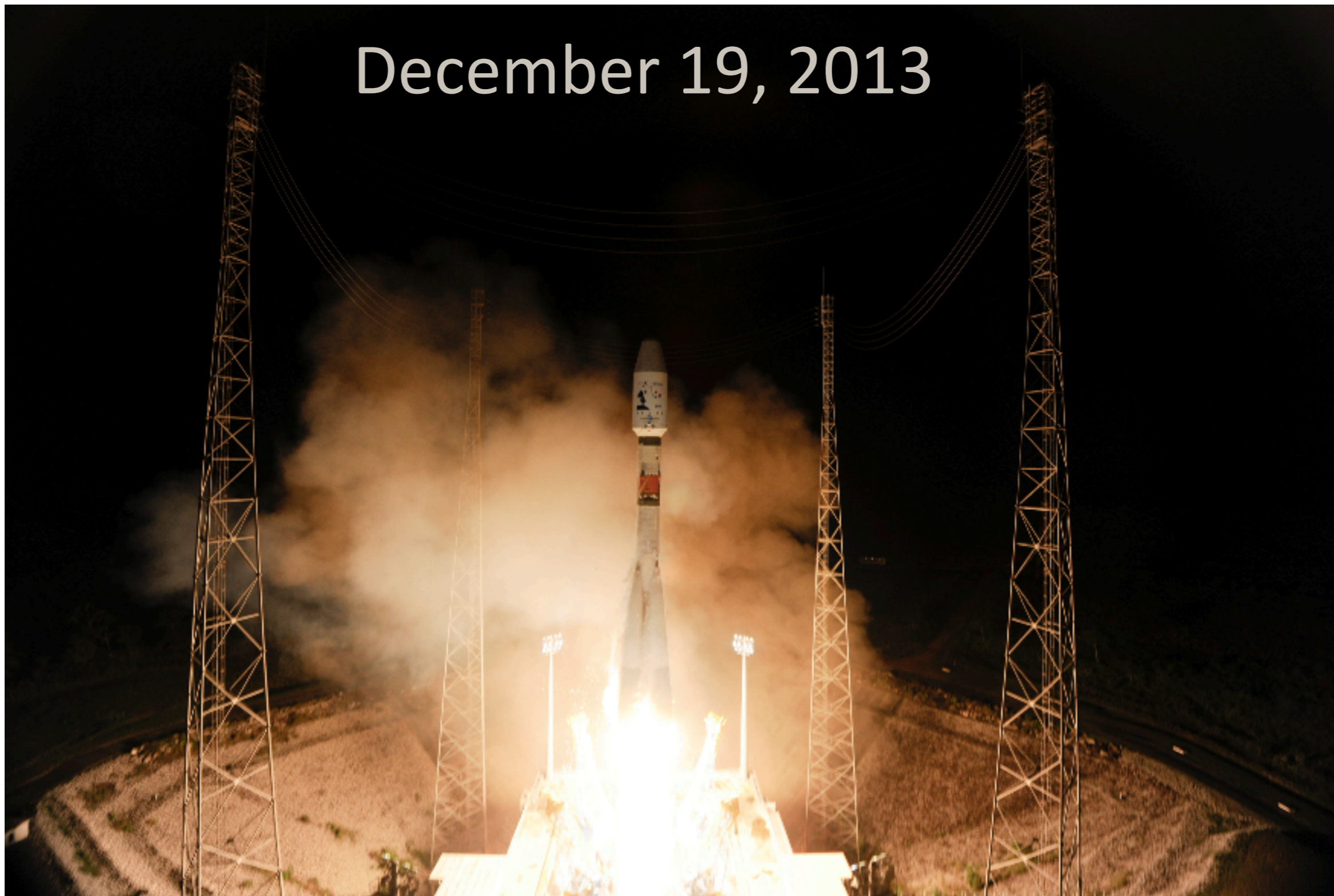


ESA/Gaia/DPAC/Airbus DS

Sunshield deployment test – Oct. 2011



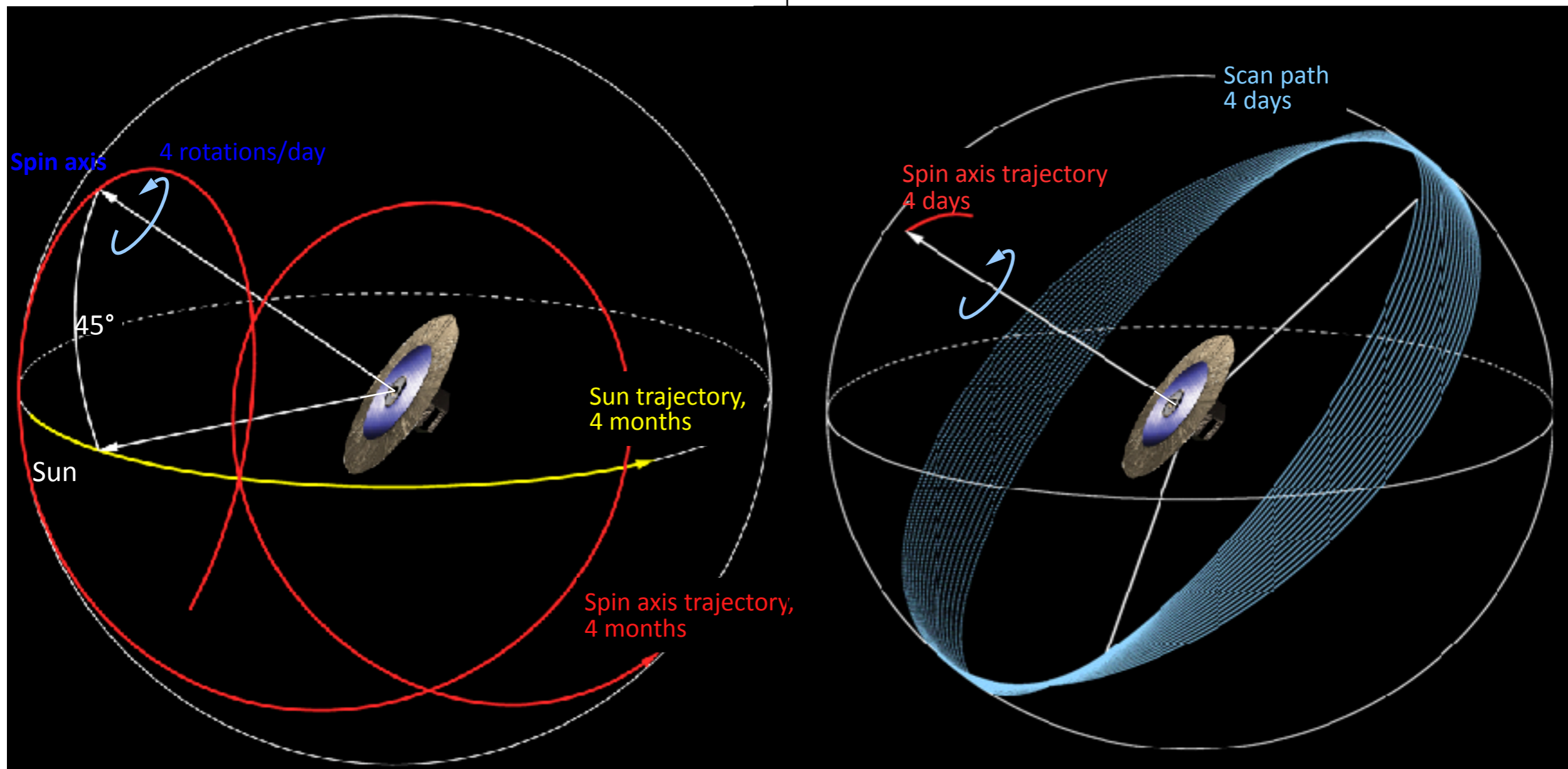
December 19, 2013



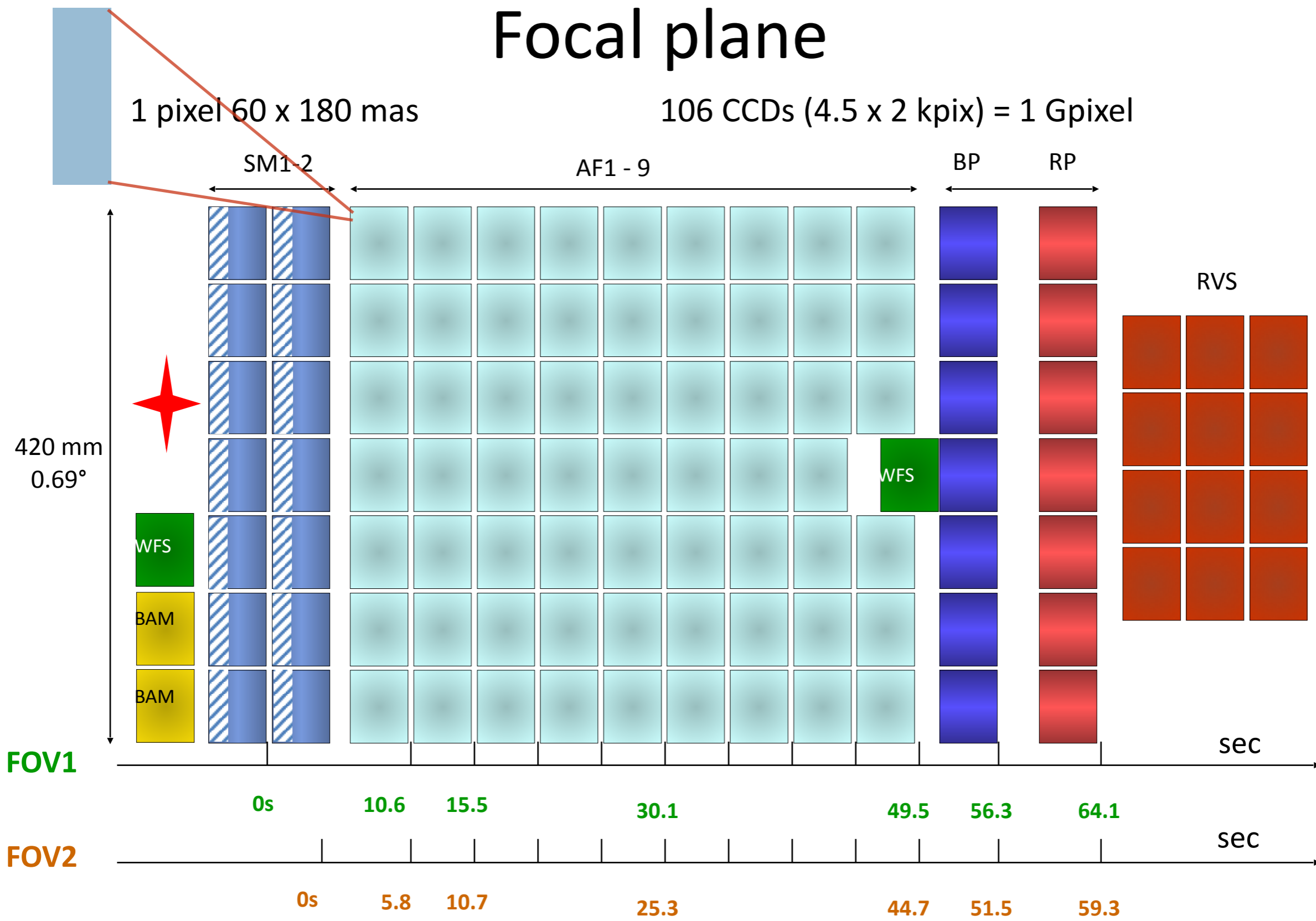
The scanning law

Rotation axis movement

Scan path in 4 days



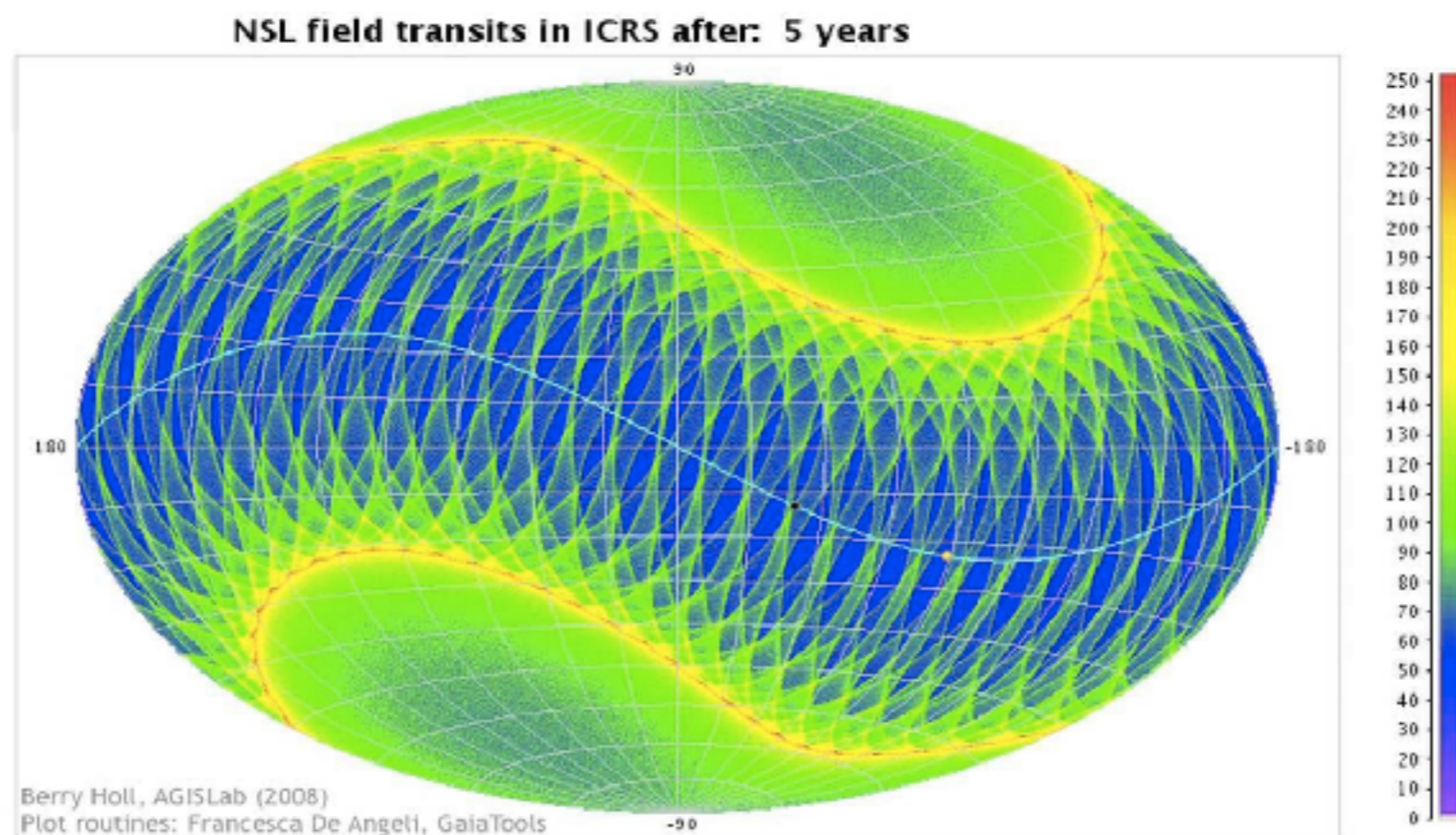
Focal plane



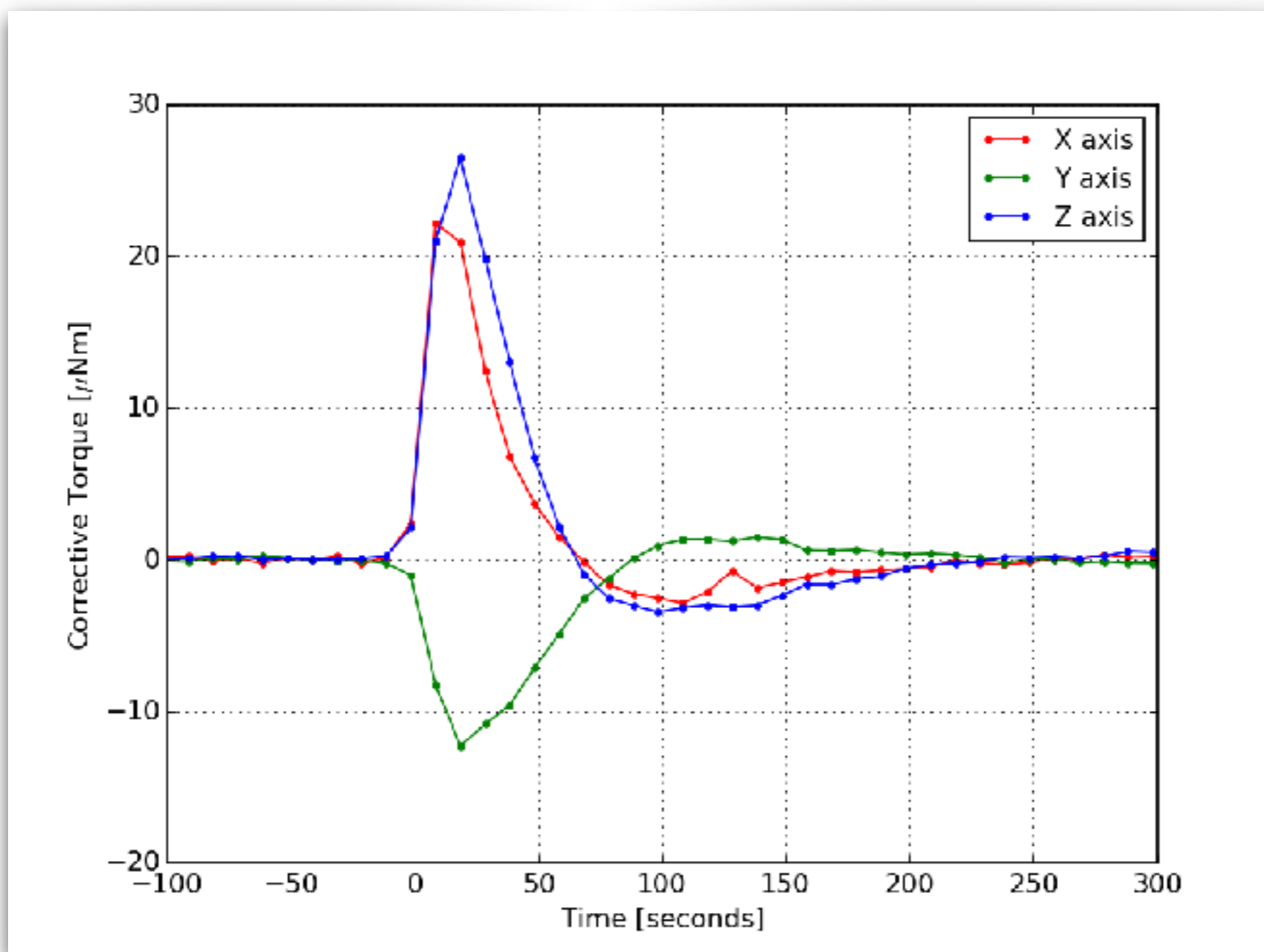
courtesy F. Mignard, OCA

The Astrometric Global Iterative Solution (AGIS)

- Simultaneous all-sky solution of positions, parallaxes, proper motions, physical parameters (e.g. color) and instrument calibration parameters
- Link to ICRS by VLBI sources directly observed by Gaia
—> All aspects of the data reduction are deeply connected



Gaia as Micro-meteorite detector



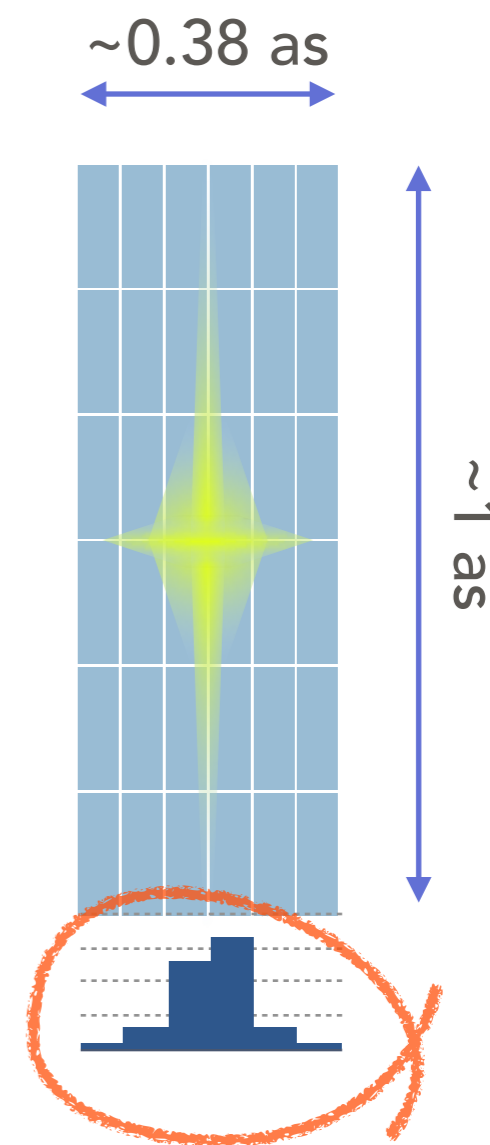
Corrective torques applied to recover spacecraft attitude after a meteoroid strike (Perseid activity peak).

The strengths of Gaia

- Astrometry:
 - Accurately measure relative positions at large angles → no zonal error
 - Measure time instead of positions (and control very accurately the transformation)
 - Average the signal over several 10.000s pixels (good for photometry too)
 - Spectro-photometry
 - provide colors and low-resolution spectra (→ classification) for all sources
 - Radial velocities
 - Add the 3rd dimension of motions in the Galaxy
- + automated source detection on board

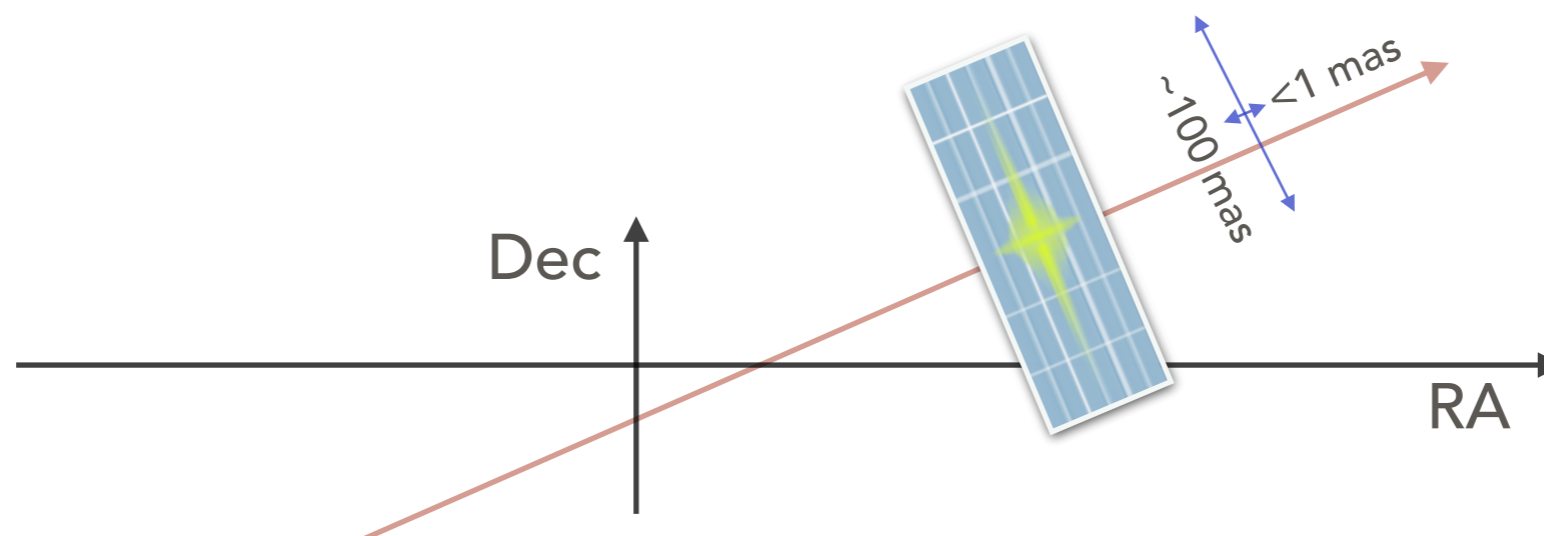
Gaia does not produce images

- (Except for testing in a special mode)
- Operates in TDI mode (line period 1 ms)
- Small windows read from the CCD around the sources
- 2D windows are binned across scan \rightarrow 1 D data sample (typ. 6 pixels)
- on board lossless compression
- Fundamental measurement: crossing time of a fiducial line on the CCD by the brightness peak of a source



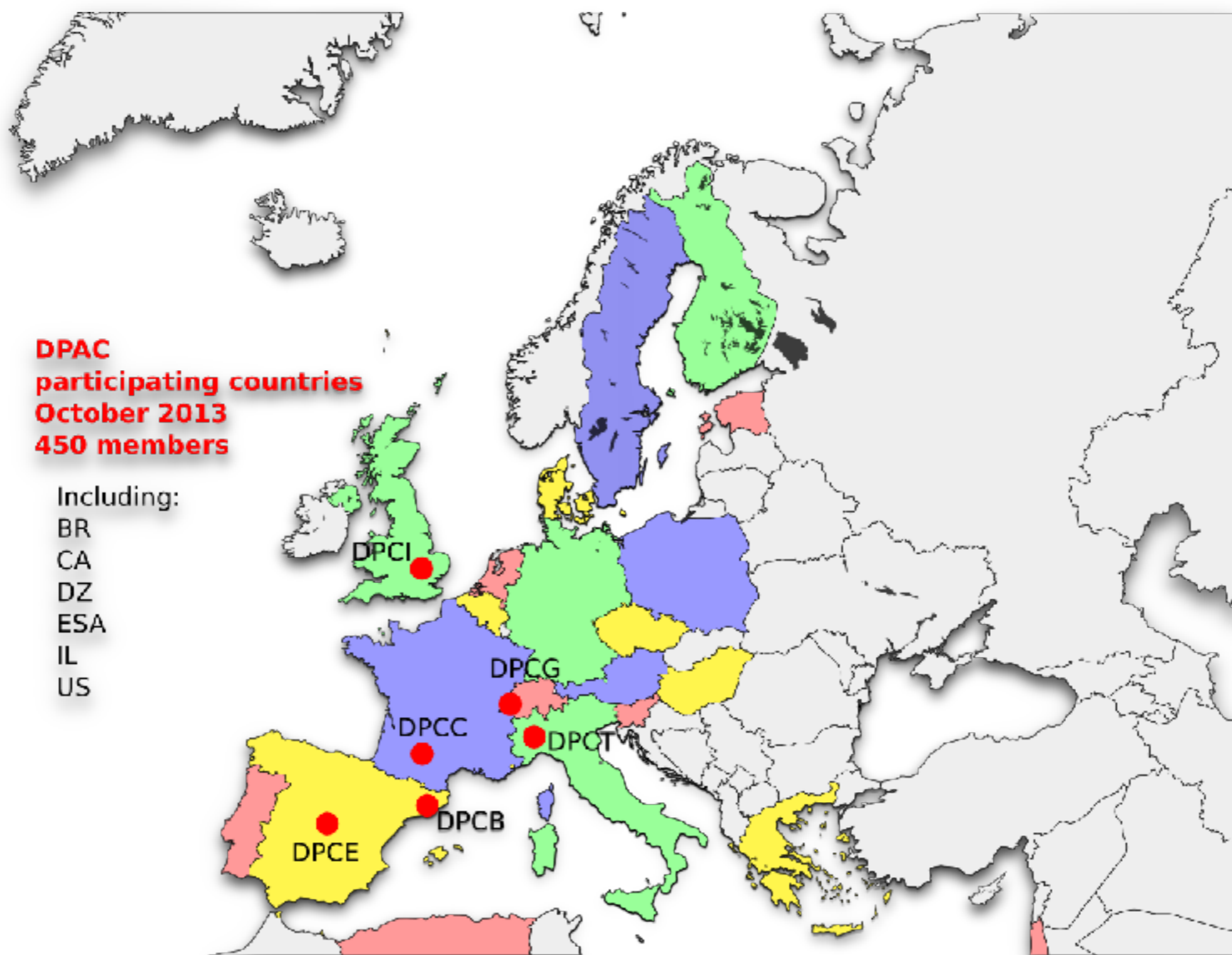
Gaia produces unusual epoch astrometry

- In the along scan direction the typical accuracy is a small fraction of a pixel (~ 1 mas)
- Across scan it is of the order of a pixel (~ 100 mas)

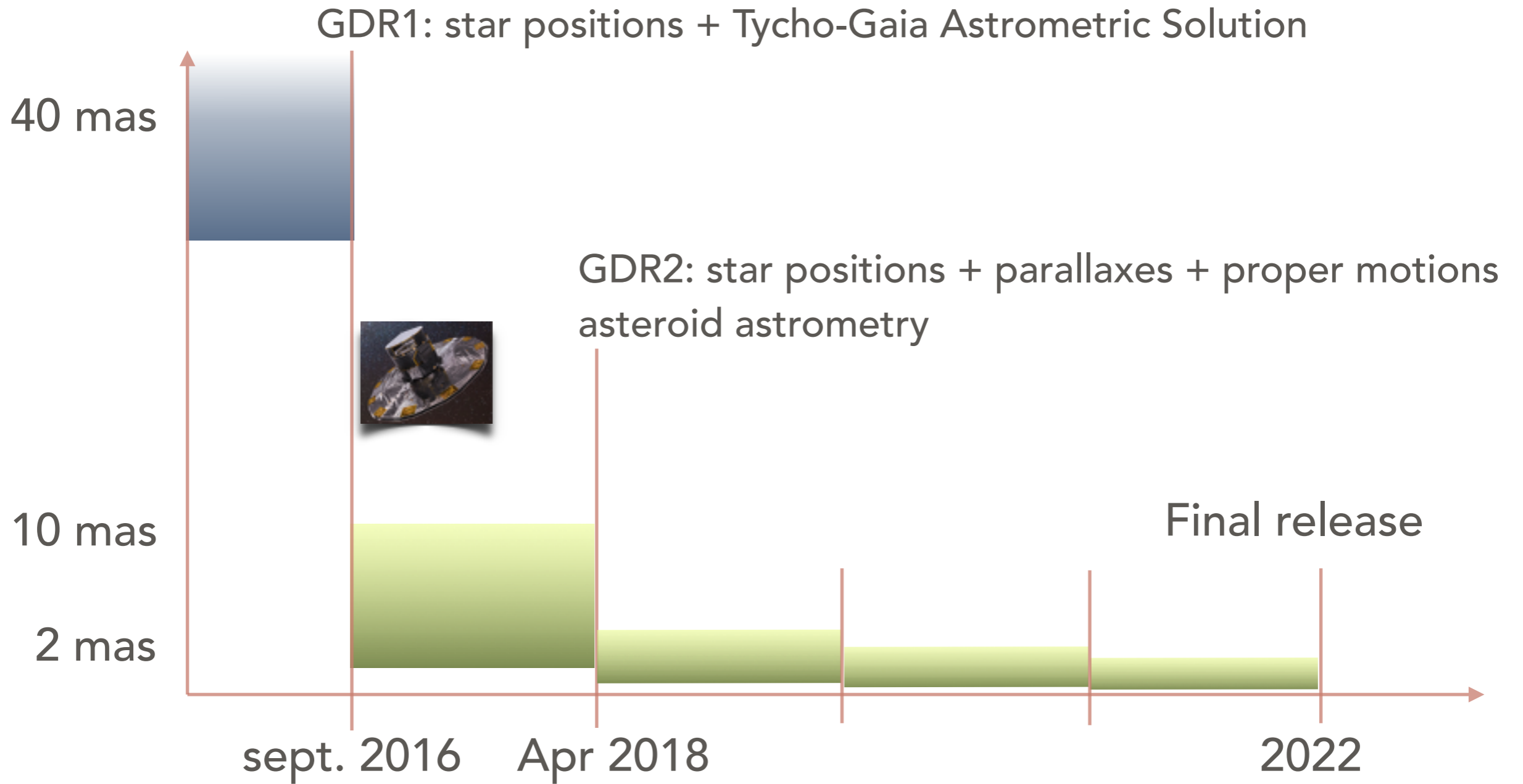


- When rotated to (RA, dec) this results in highly correlated uncertainties
- This is not (very) relevant for stars
- It is fundamental for asteroids! Pay attention to the covariance matrix

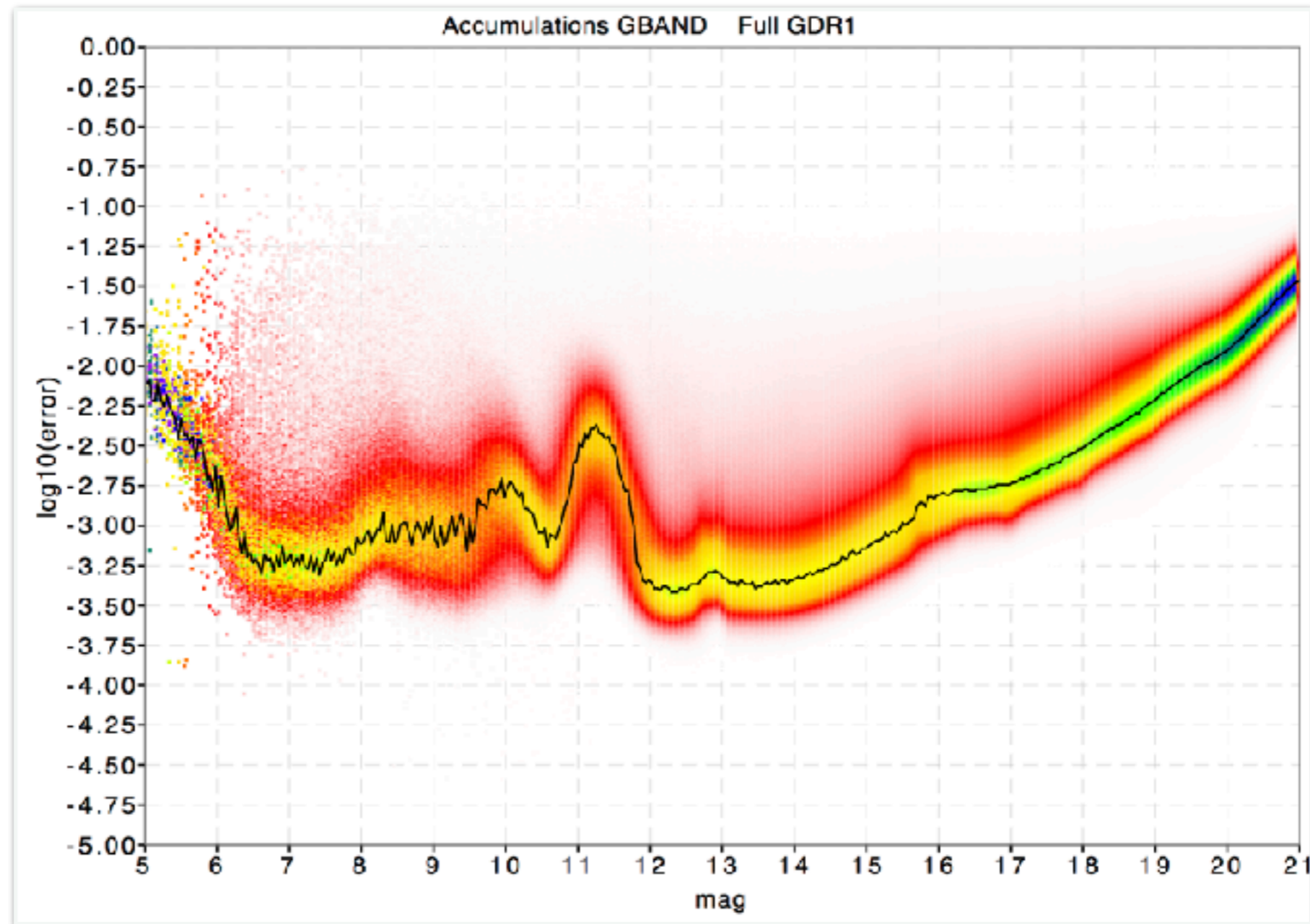
The Data Processing and Analysis Consortium - since 2007



Gaia data - when?

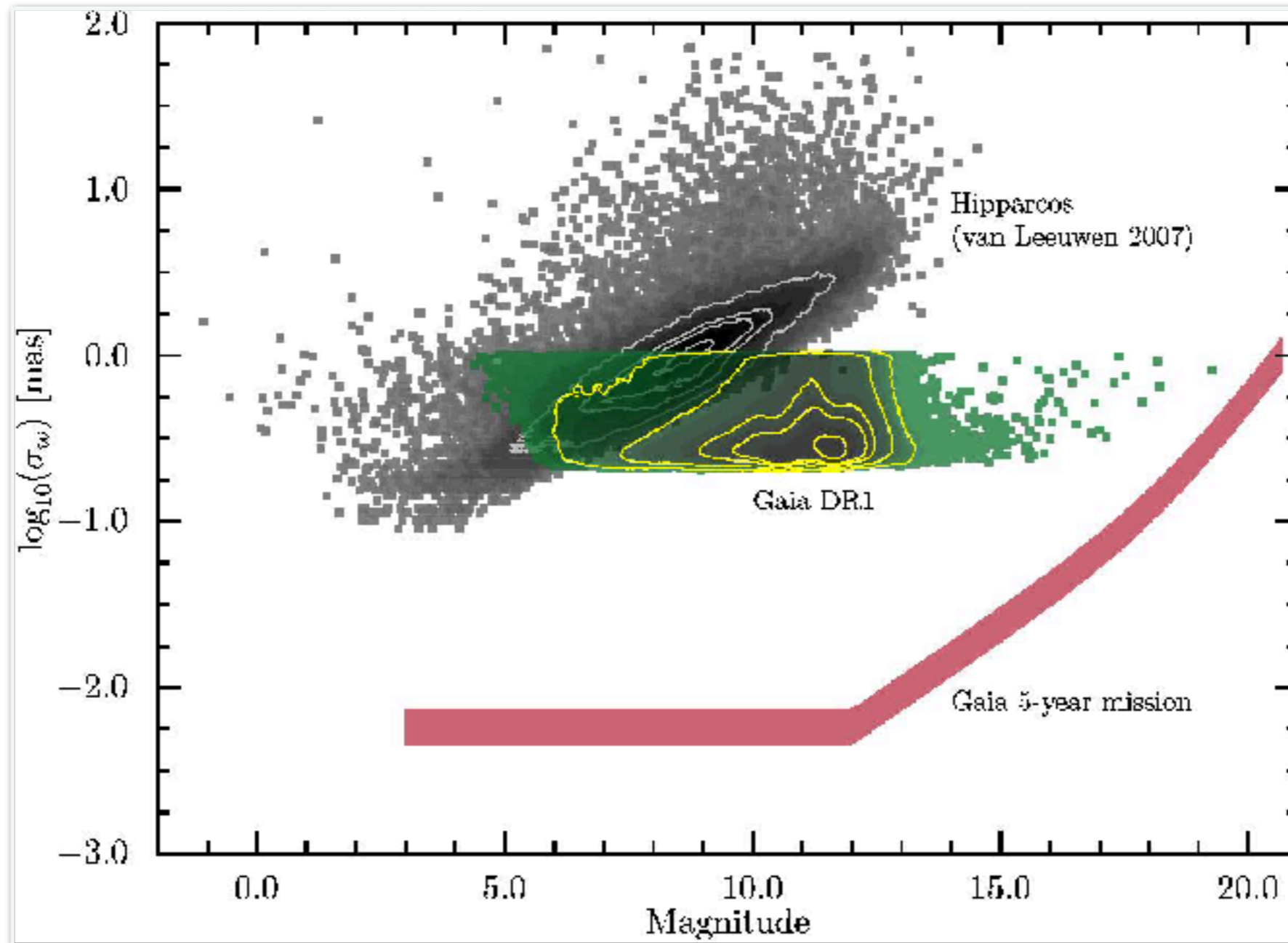


GDR1: brightness accuracy

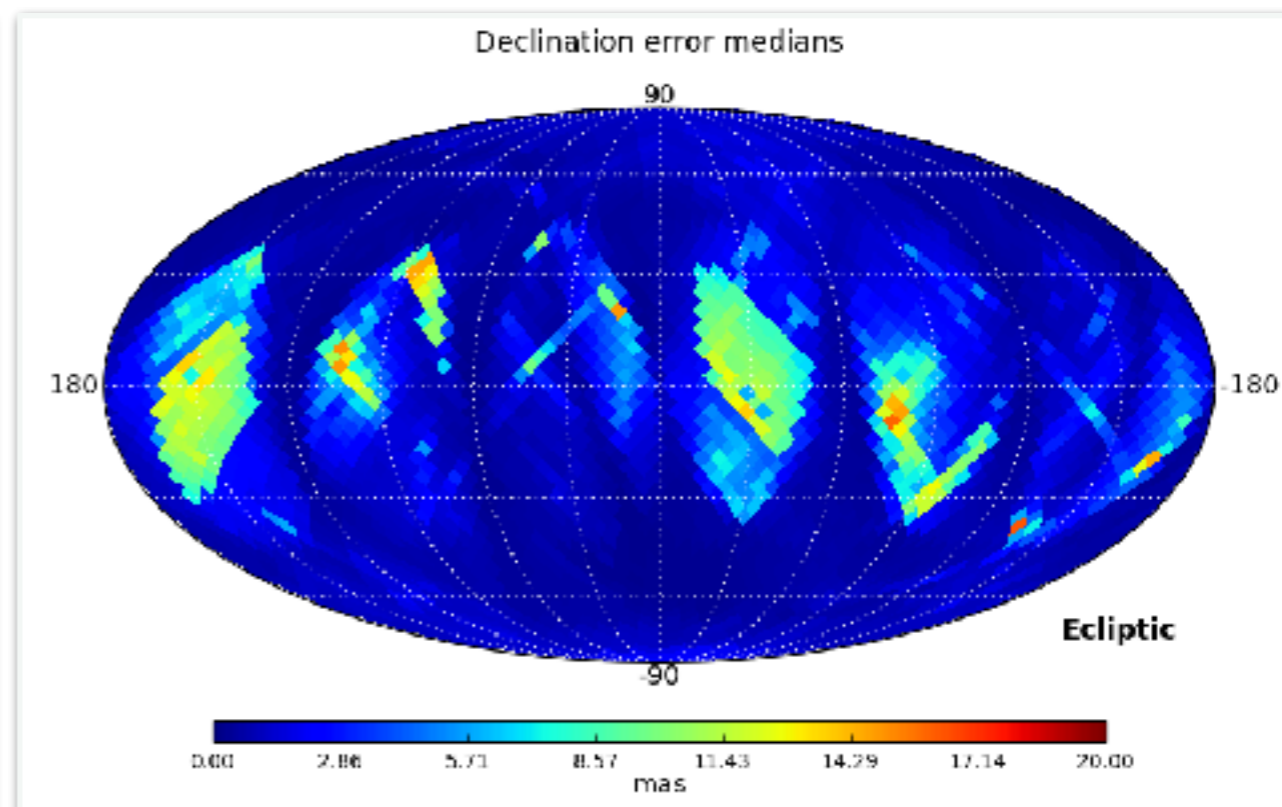
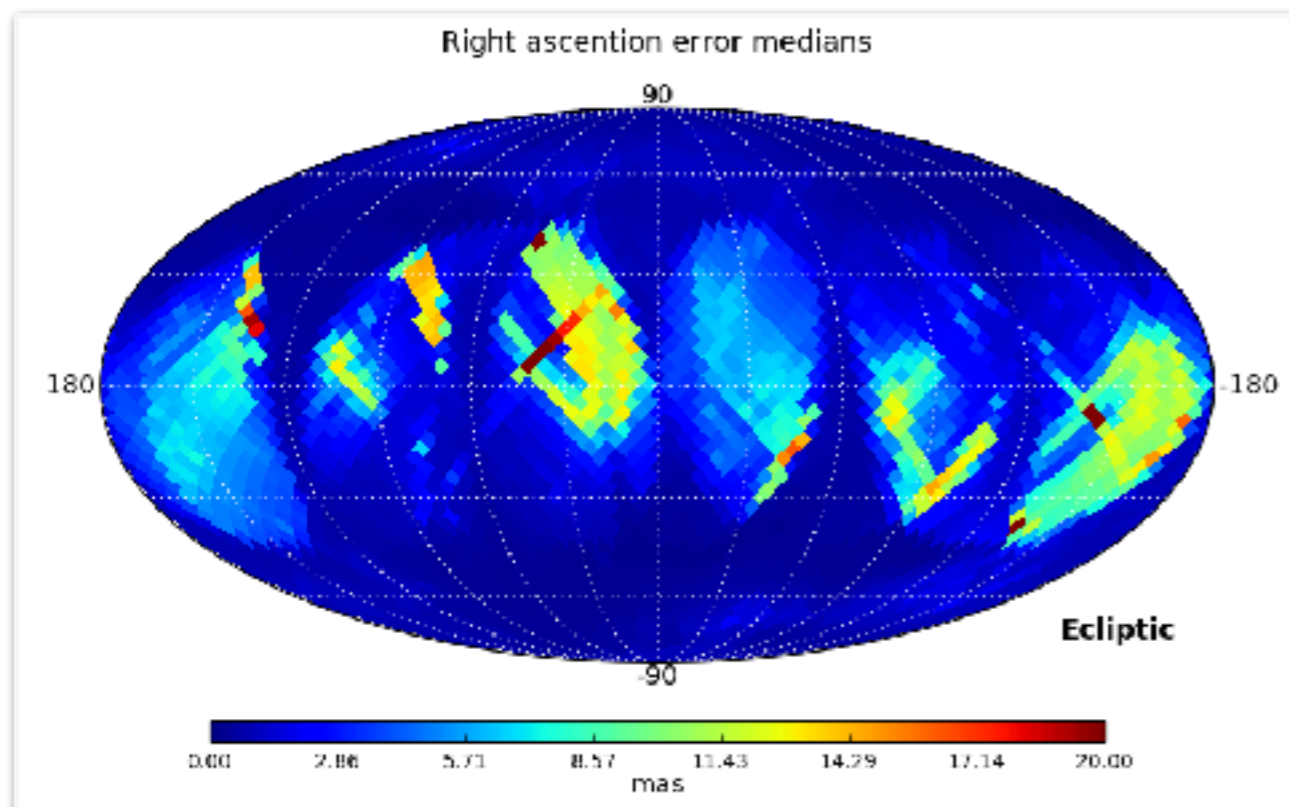


This plot shows the distribution of the estimated uncertainties on the weighted mean G-band photometry as a function of magnitude. The colours indicate the density of data points, from low (red) to high (blue) on a logarithmic scale. Credits: ESA/Gaia/DPAC

GDR1: parallax accuracy (TGAS)



GDR1: position errors



Gaia Archive

EUROPEAN SPACE AGENCY ABOUT ESAC SIGN IN

gaia archive

HOME SEARCH STATISTICS VISUALIZATION HELP DOCUMENTATION

Welcome to the Gaia Archive

Gaia is an ambitious mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy. Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and throughout the Local Group. This amounts to about 1 per cent of the Galactic stellar population.

If you use public Gaia DR1 data in your paper, please take note of our guide on how to acknowledge and cite Gaia DR1.

Top Features

- Search**
Query for Gaia sources using an ADQL (Astronomical Data Query Language) interface in an asynchronous mode (LWS).
- Download**
Direct download of Gaia data files.
- Statistics**
Show statistics of Gaia tables.

<https://gea.esac.esa.int/archive/>

The Solar System and Gaia

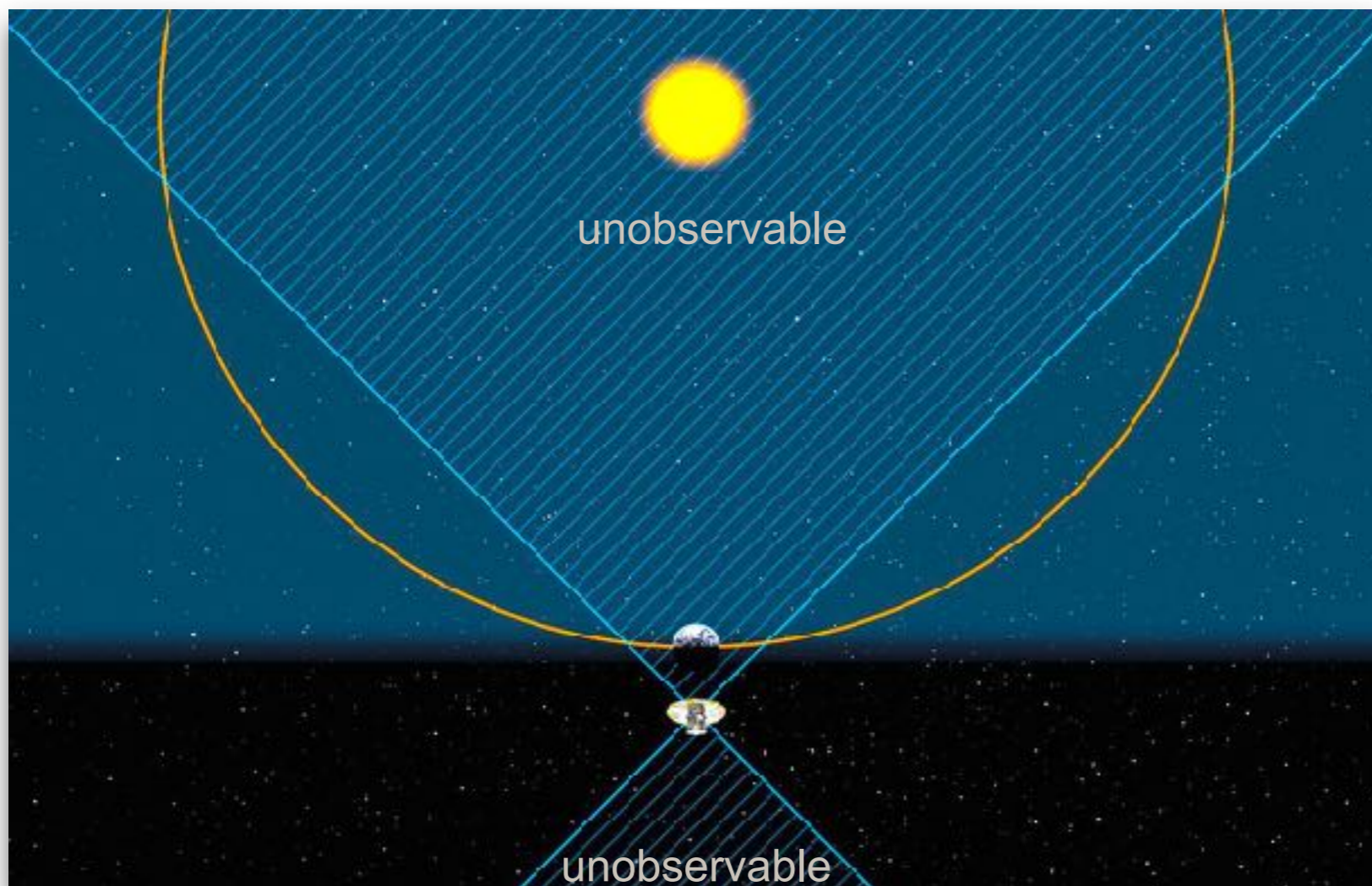


What Gaia observes



- **What Gaia observes = all small objects at $V < 20.5$**
 - 350.000 asteroids(>700.000 known today)
 - comets, TNOs
 - small planetary satellites
- **Why we are interested**
 - small bodies record the history of the Solar System
 - very poorly known properties:
 - a few 1000s spectra, 10s masses, 100k sizes, ~400 shapes

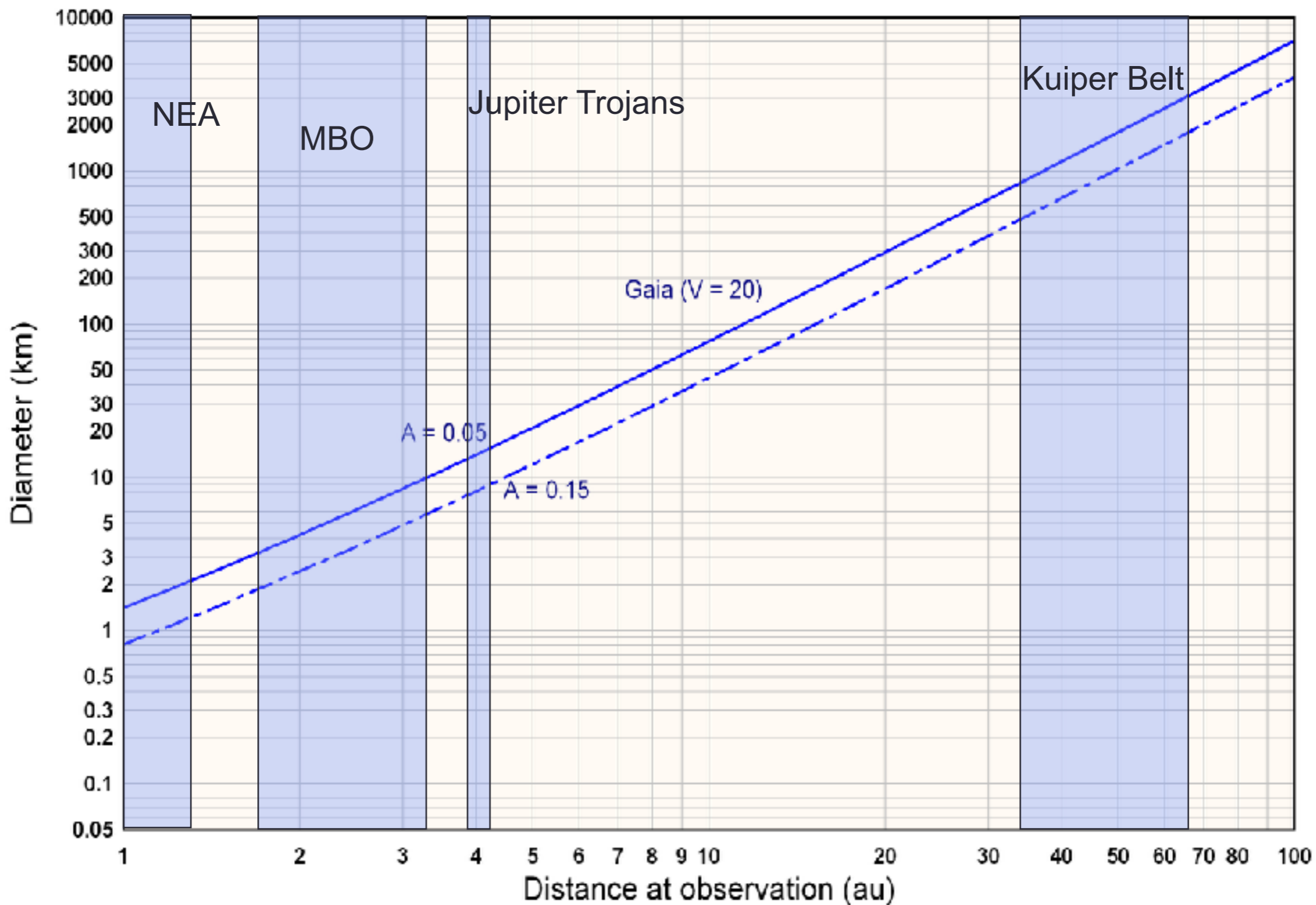
Where Gaia observes



~70 observations per object

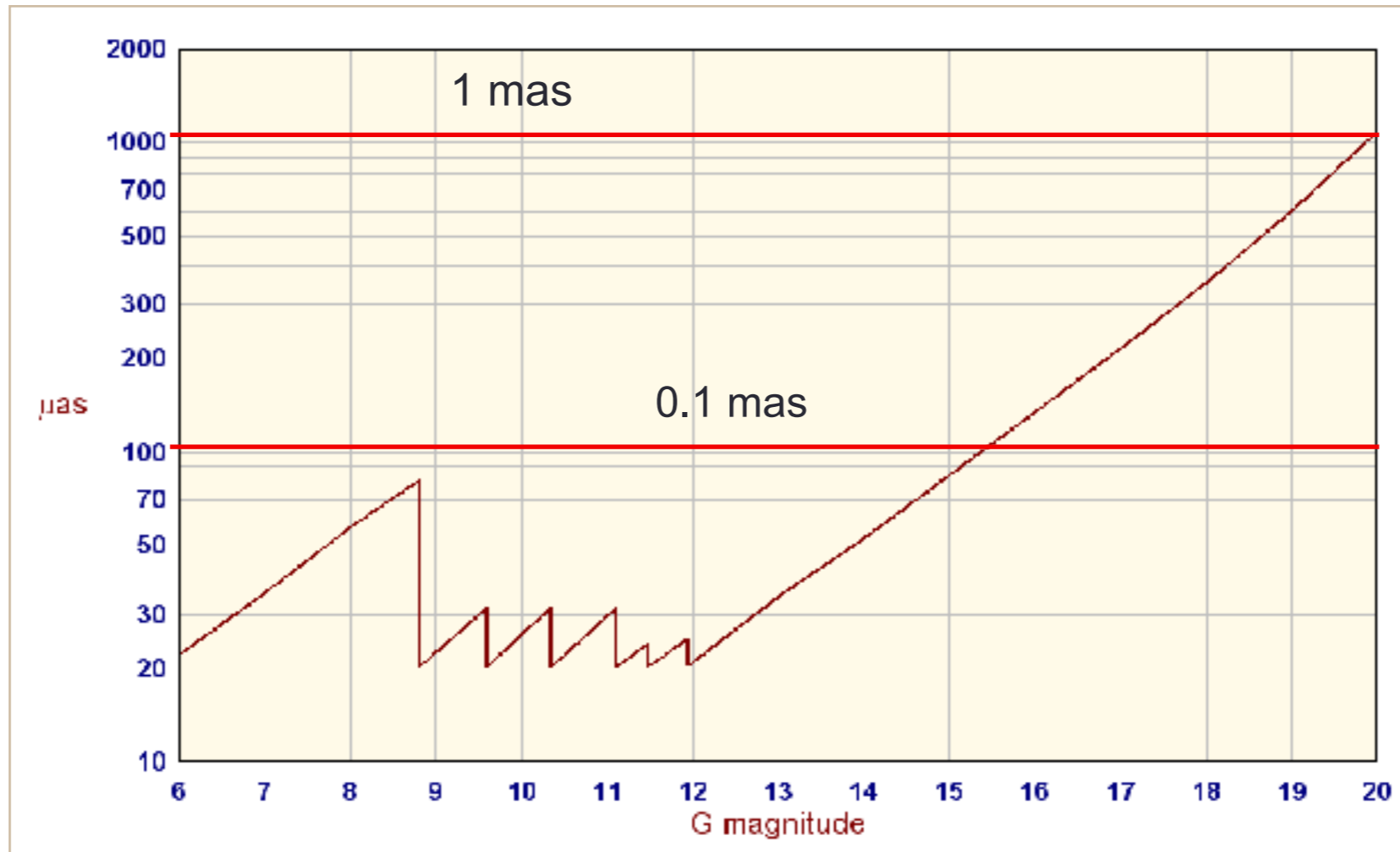
- Discovery space:
 - Low elongations ($\sim 45-60^\circ$)
 - Inner Earth Objects (\sim unknown)
 - Other NEOs
 - Some MBAs

What Gaia observes: how big



Gaia single-epoch astrometric accuracy

final attitude and calibration, single FoV (9 positions) transit, point-like source

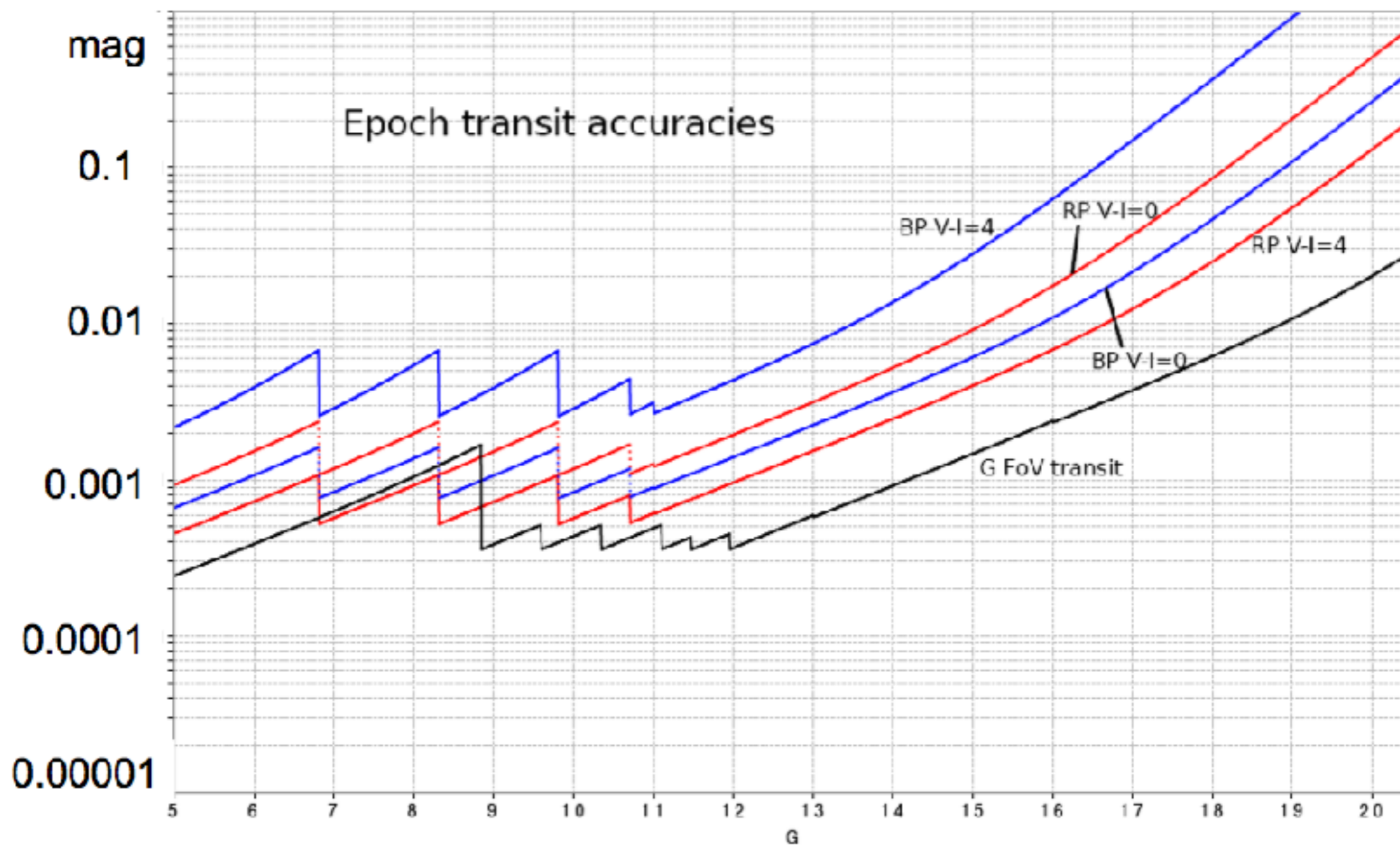


Type	Name	Number of measurement	Percentage of accepted measurement	Accuracy
C	CCD	79 569 190	99.49%	0.388 arcsec
S	Wise	1 526 466	99.86%	0.583 arcsec
S	<i>Hubble</i> Space Telescope	867	96.54%	0.585 arcsec
S	<i>Spitzer</i>	48	33.33%	1.673 arcsec

random errors
+ systematic

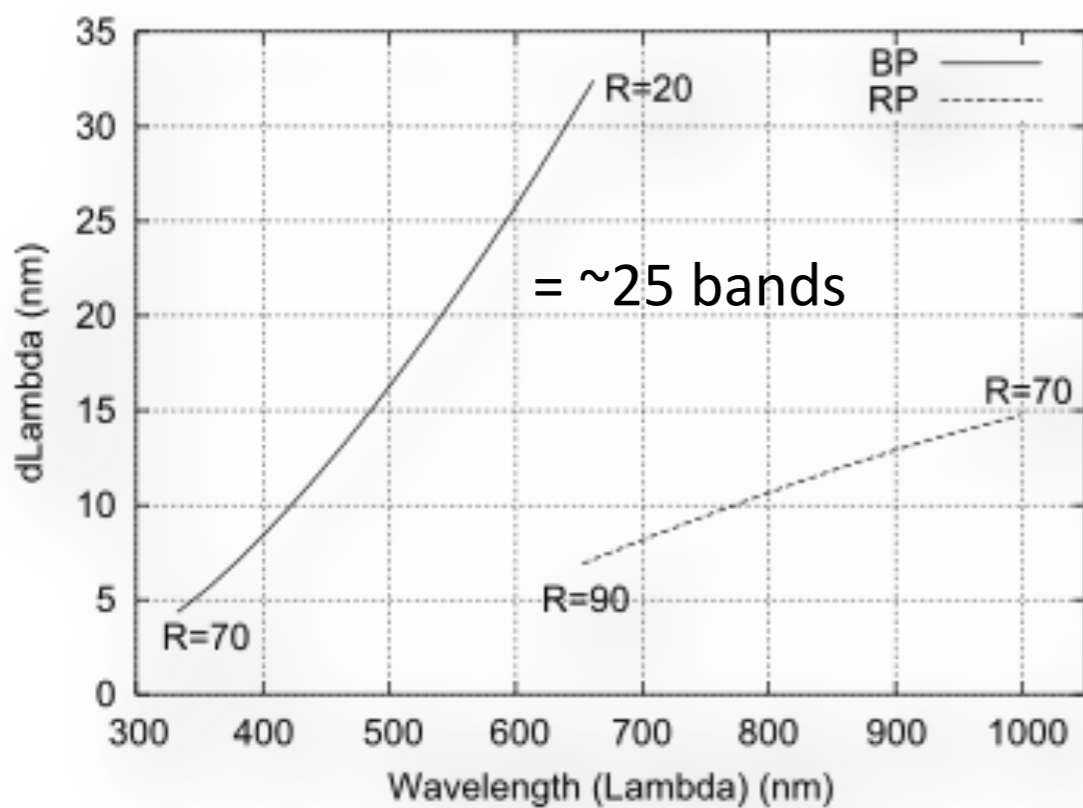
Observations in the AstDys service (Univ. Pisa)

Photometric accuracy



(courtesy D. Evans)

Low-resolution spectroscopy



HD 1293 Aql (M5III)

VY UMa (C star)

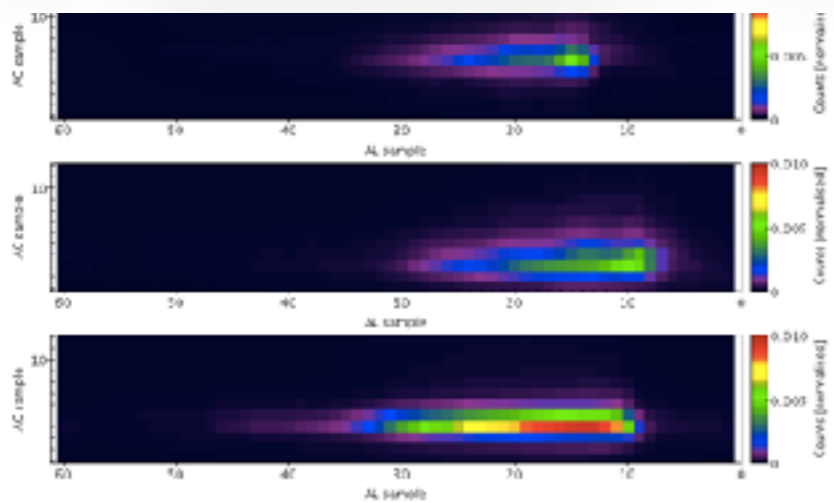
HR3580 (K5)

HD2130 (K0)

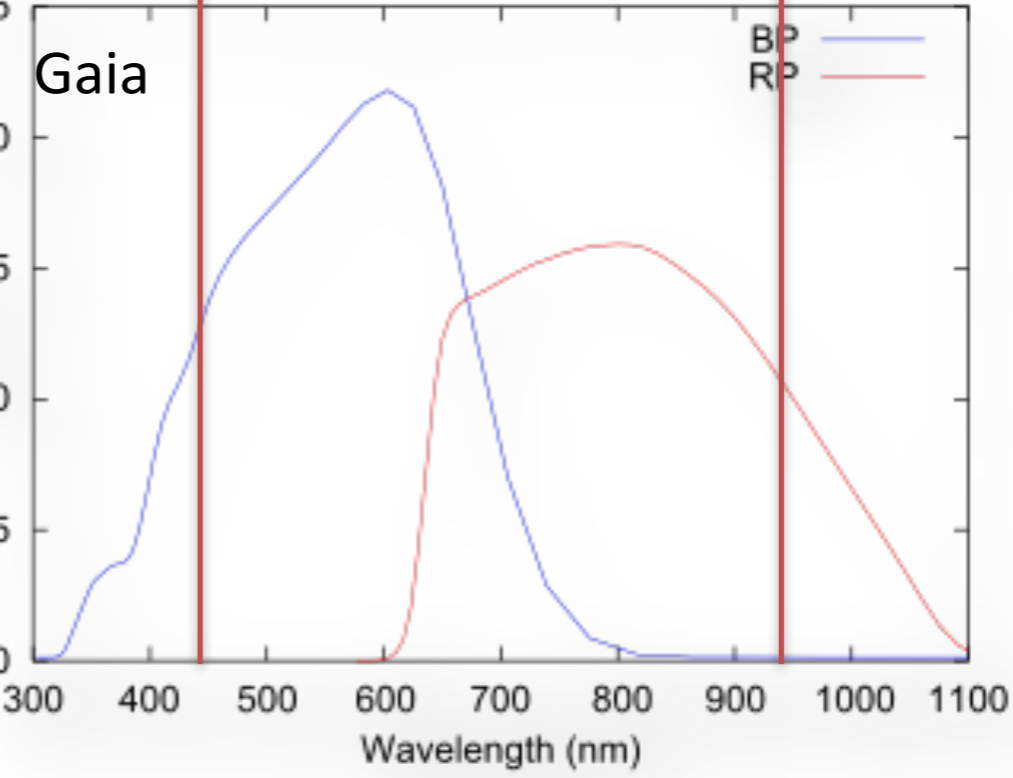
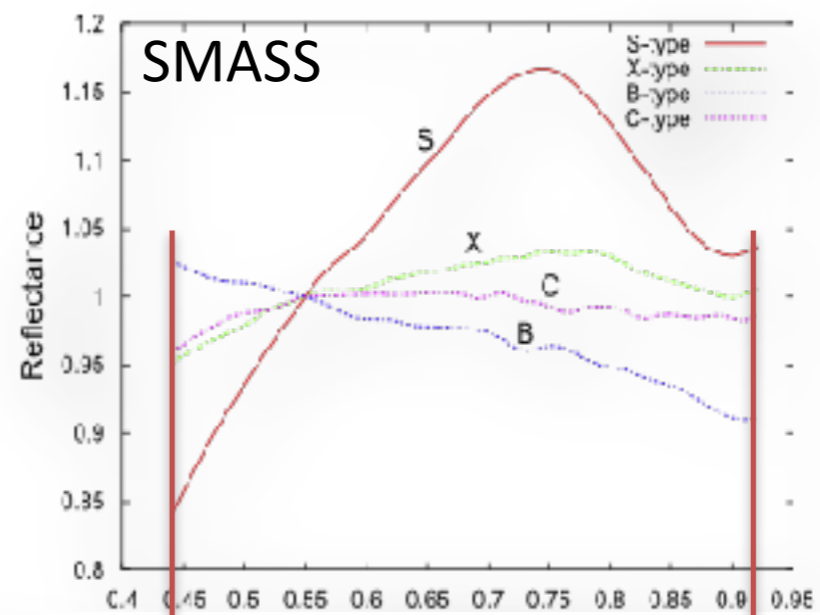
HD640 (G8III)

HD1510 (F2IV)

HD2071 (A3)



SNR @ V=17, per observation



M. Delbo, OCA

Science goals for the end of the mission

Astrometry

- Complete the sample (discoveries)
- Orbits : X 100 improvement
- Precession: Gen. Relativity tests
- 100 masses from close encounters

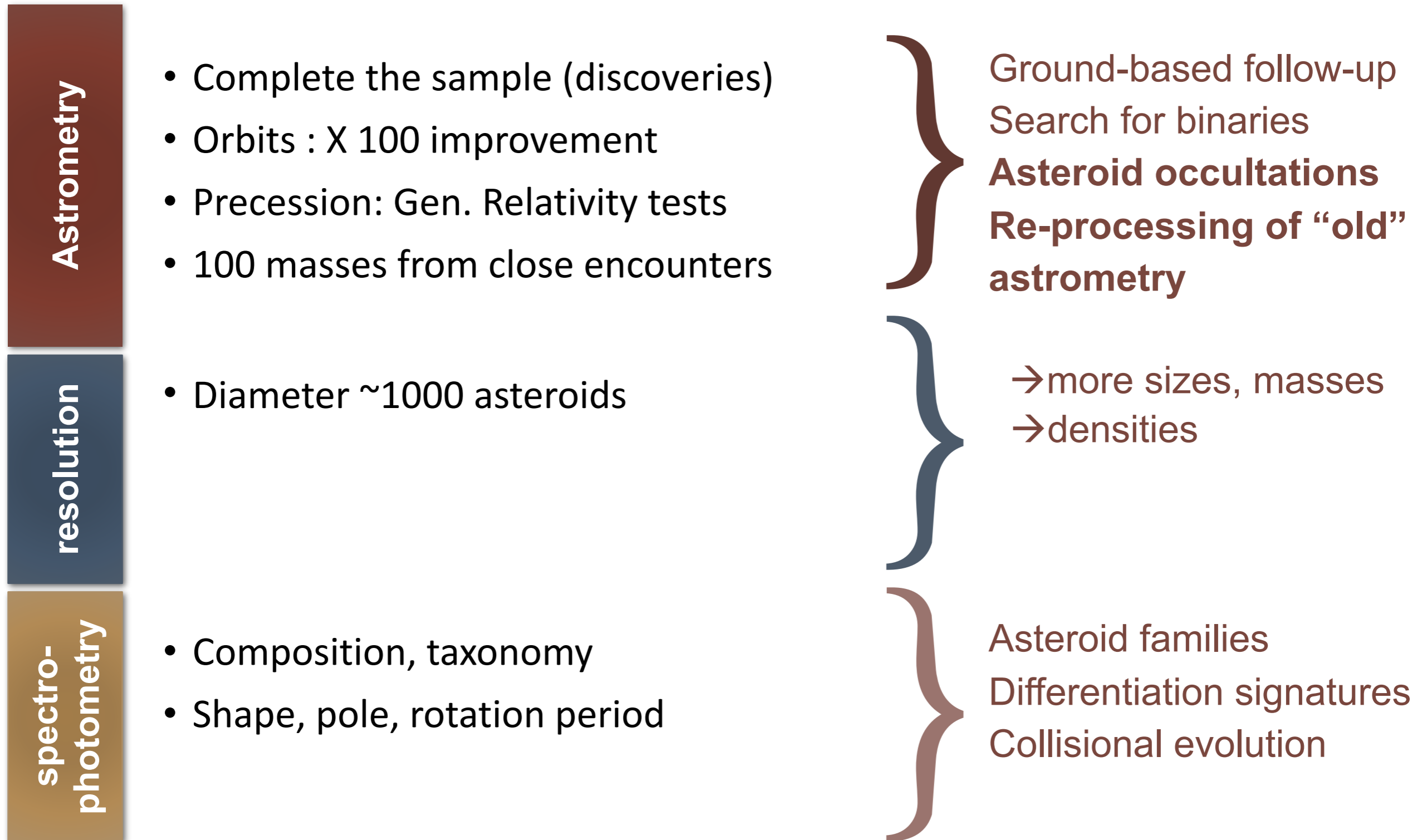
resolution

- Diameter ~1000 asteroids

spectro- photometry

- Composition, taxonomy
- Shape, pole, rotation period

From data reduction ...to scientific exploitation



Our knowledge – before and after Gaia

Property	today	Gaia
astrometry	~ 0"5	0"005
ephemeris precision	50-200 mas	> 20 times better
shape, pole	500	~100,000
rotation period	4000	~100,000
satellites	~ 50 (MBA)	1000s ?
spectral type	~ 1000	~200,000
mass, $\sigma < 50\%$	~ 50	150
size	100,000	~1000

Solar System in DPAC Coordination Unit 4

Manager: D. Pourbaix (Univ. Brussels)

Deputy: P. Tanga (OCA, France)

DU450 Management

DU451 Auxiliary data

DU452 Identification of known objects

DU453 CCD processing

DU454 Astrometric reduction

DU455 Object threading

DU456 Orbital inversion

DU457 Global Effects on Dynamics

DU458 Physical parameters

DU459 Ground-based observations

DU460 Simulation



CU4: two pipelines for the science goals

Daily processing

Processing of « new » asteroids
Per-object, on 48h time frames
Preliminary astrometry (OGA1)
Preliminary calibration

ground-based alert
network

Long-term processing

All sources
Best calibrations, best astrometric model
Take into account shape and motion
Devoted to obtain the best possible final
output of the mission

epoch astrometry
refined orbits
dynamical and physical
parameters

Diffusion of asteroid alerts

- **Gaia ID:** -4194966138
- **Database ID:** 2498
- **Name:** GAIA1158
- **Magnitude (V):** $18.4^{+0.6}_{-0.3}$
- **Date of observation:** 4/12/2016

Report observation ↻

Back to alerts →

Field of View

15x15 arcmin²

Gaia Follow-Up Network for Solar System Objects

Goal

The GAIA Follow-Up Network for Solar System Objects (Gaia FUN SSO) has been set up in the framework of a task (SU158) of the Coordination Unit 4 (Object processing of the DPAC Gaia consortium. Its goal is to coordinate ground-based observations or alert triggered by the data processing system during the mission for the confirmation of newly detected moving objects or for the improvement of orbits of some critical targets. Gaia will scan the sky following a pre-defined scanning law and such ground-based observations are required to avoid the loss of newly detected Solar System objects and to facilitate their subsequent identification by the probe.

These pages provide an access to the alerts, including the ephemeris to help finding the targets, for the registered members of the Gaia Follow-up network. The network currently (September 2015) consists in 56 observing sites, spread all over the world.



Workshops

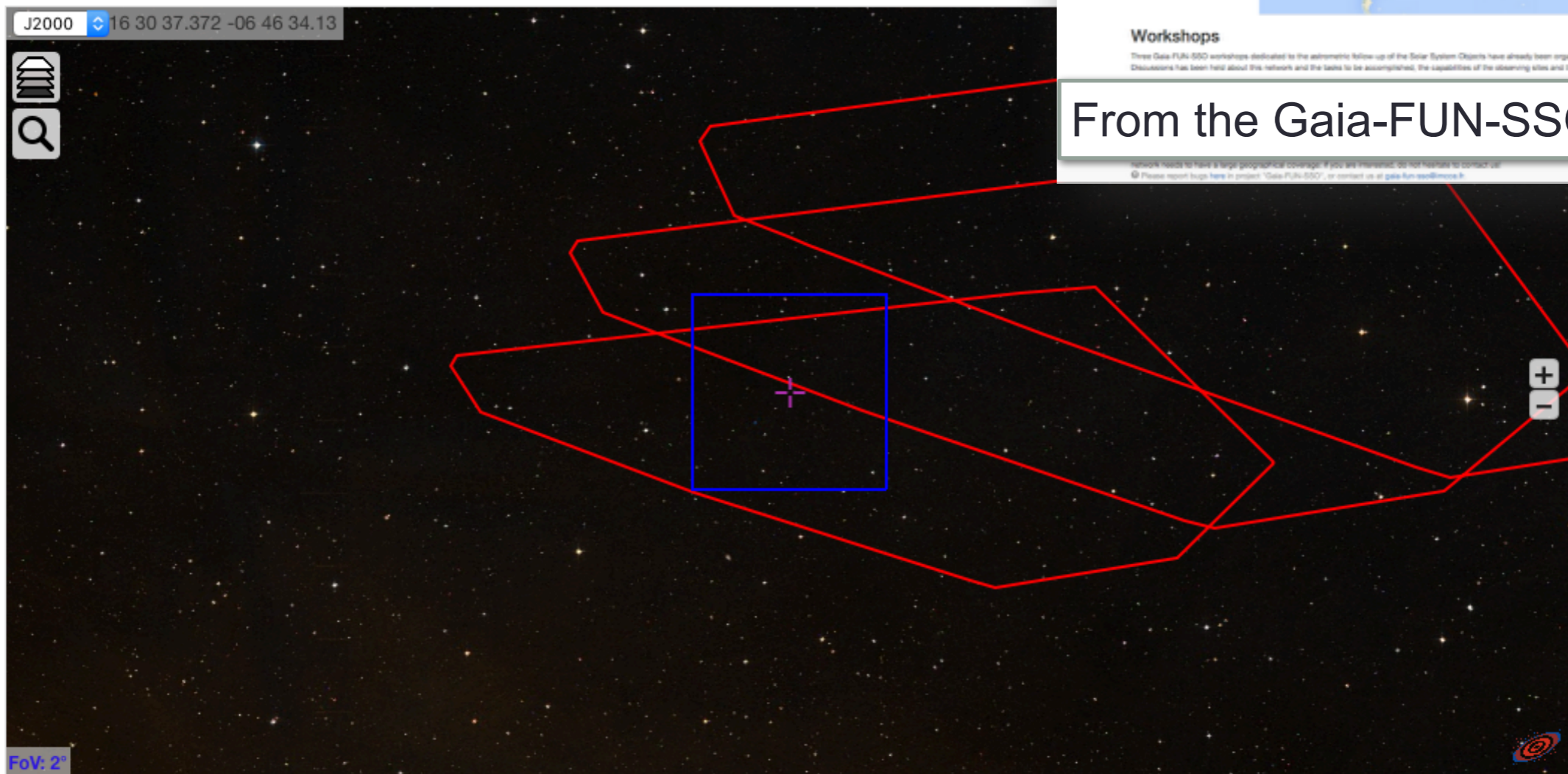
Three Gaia FUN SSO workshops dedicated to the astrometric follow-up of the Solar System Objects have already been organized in 2010, 2012 and 2014 in Paris Observatory. Discussions have been held about this network and the tasks to be accomplished, the capabilities of the observing sites and the preliminary actions already performed.

From the Gaia-FUN-SSO web site

Network needs to have a large geographical coverage! If you are interested, do not hesitate to contact us!
 © Please report bugs [here](#) in problem "Gaia FUN SSO", or connect us at gaia.fun.sso@imcce.fr

Sky view with Aladin -- Object expected magnitude $V=18.4^{+0.6}_{-0.3}$

J2000 16 30 37.372 -06 46 34.13



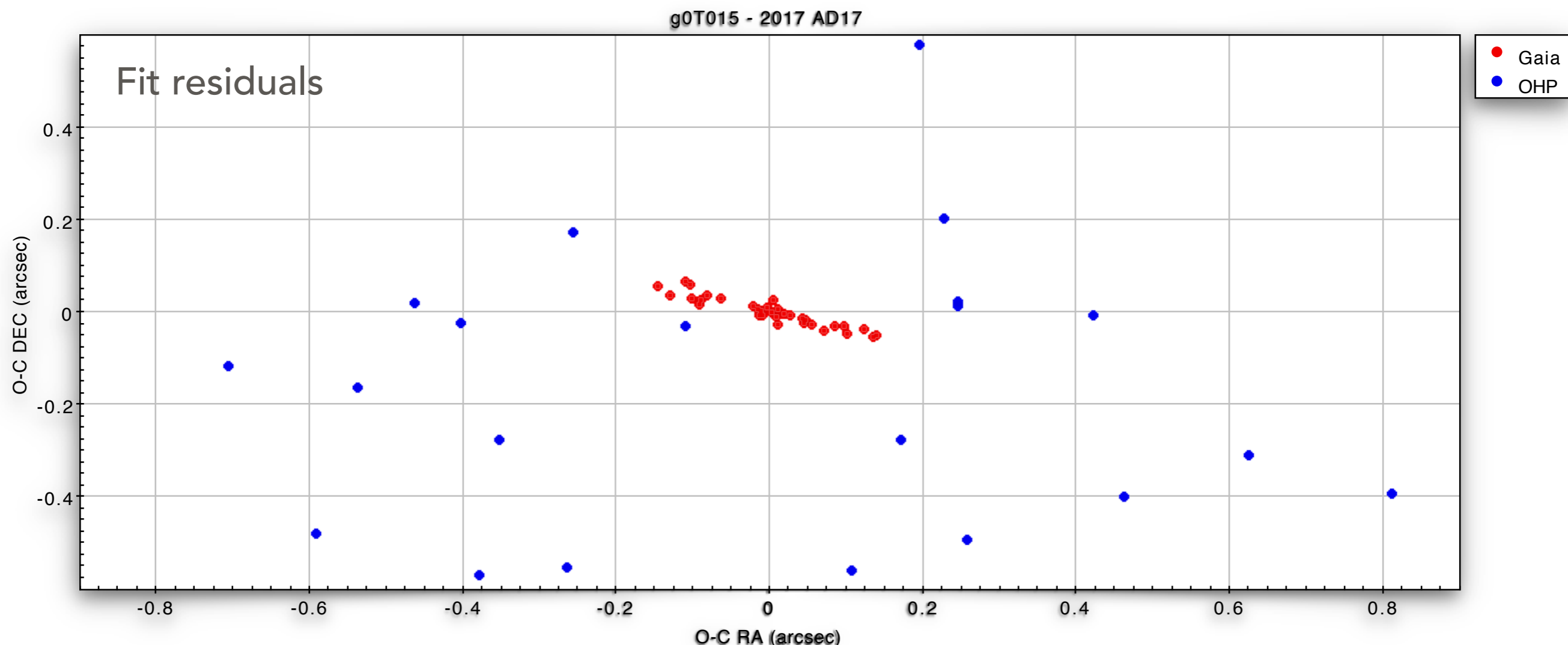
FoV: 2°

Footprints of areas to search for (in red) and the field of view (in blue, 15x15 arcmin²) of your device (OHP).
 You can change your device and its parameters in your [settings](#).

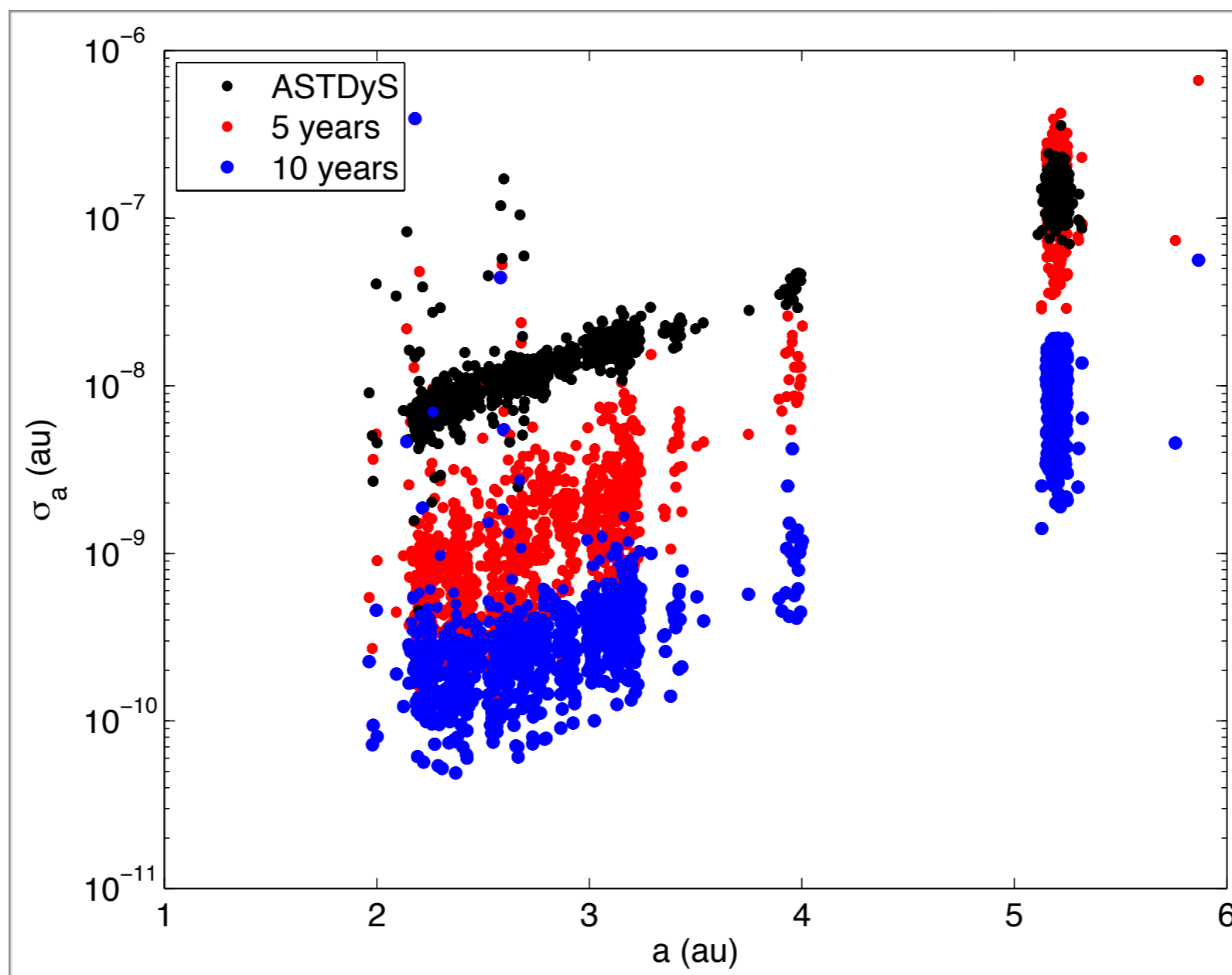
<http://gaiafunssso.imcce.fr>

First confirmation of an asteroid alert

- Orbit computation from Gaia and from the ground (OHP, France)
- Observations on Dec. 29 (Gaia - 4 transits) and Jan. 3-4 (OHP, 2 nights)
- resulting uncertainty $\sigma_a \sim 10^{-3}$



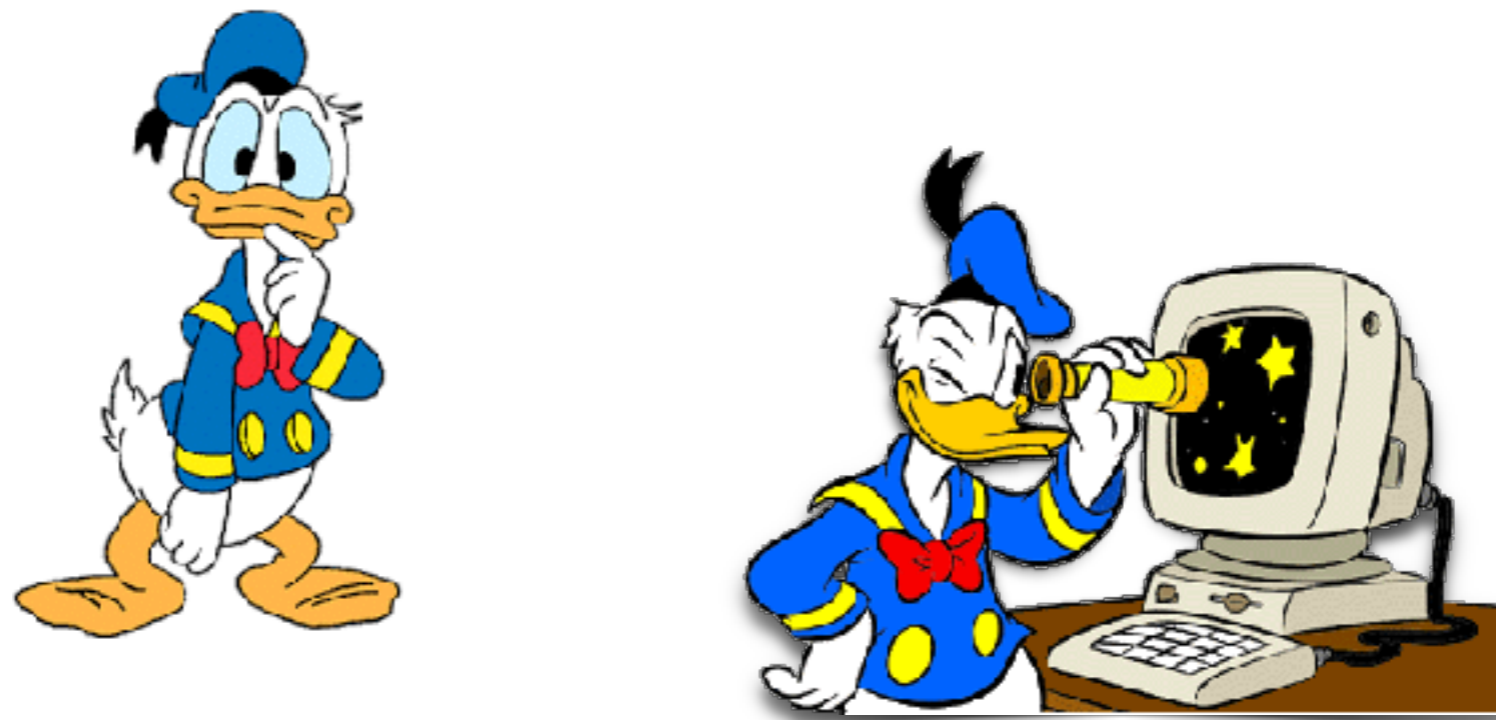
Looking forward to long-term processing: asteroid orbits by Gaia ONLY - accuracy



F. Spoto, F. Mignard, P. Tanga, OCA

But we don't have asteroid astrometry by Gaia, yet!

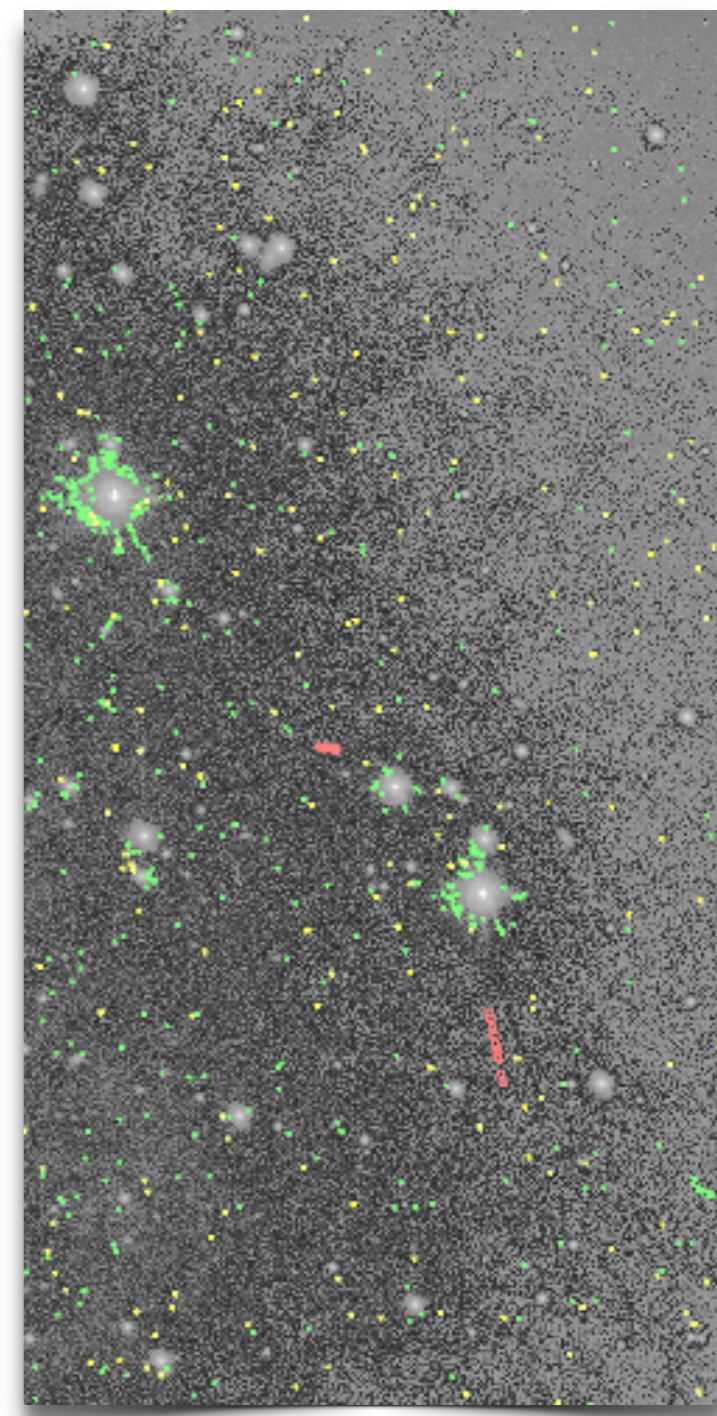
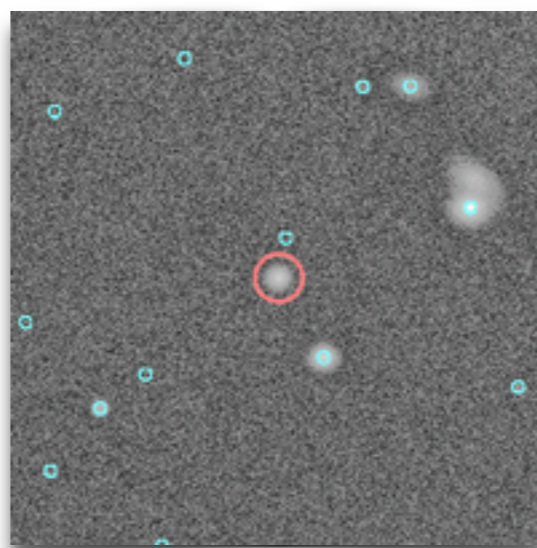
So, what can we do?

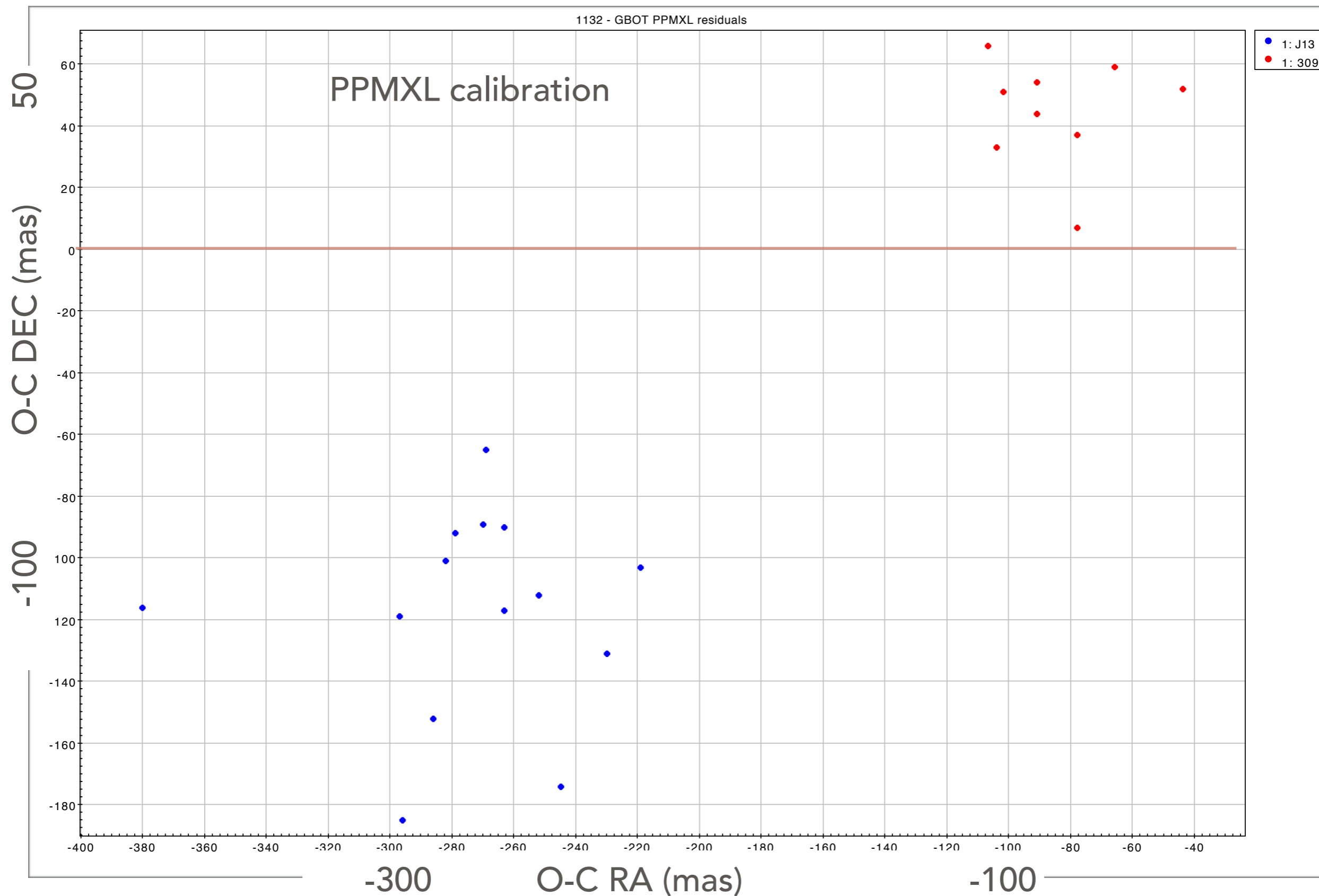


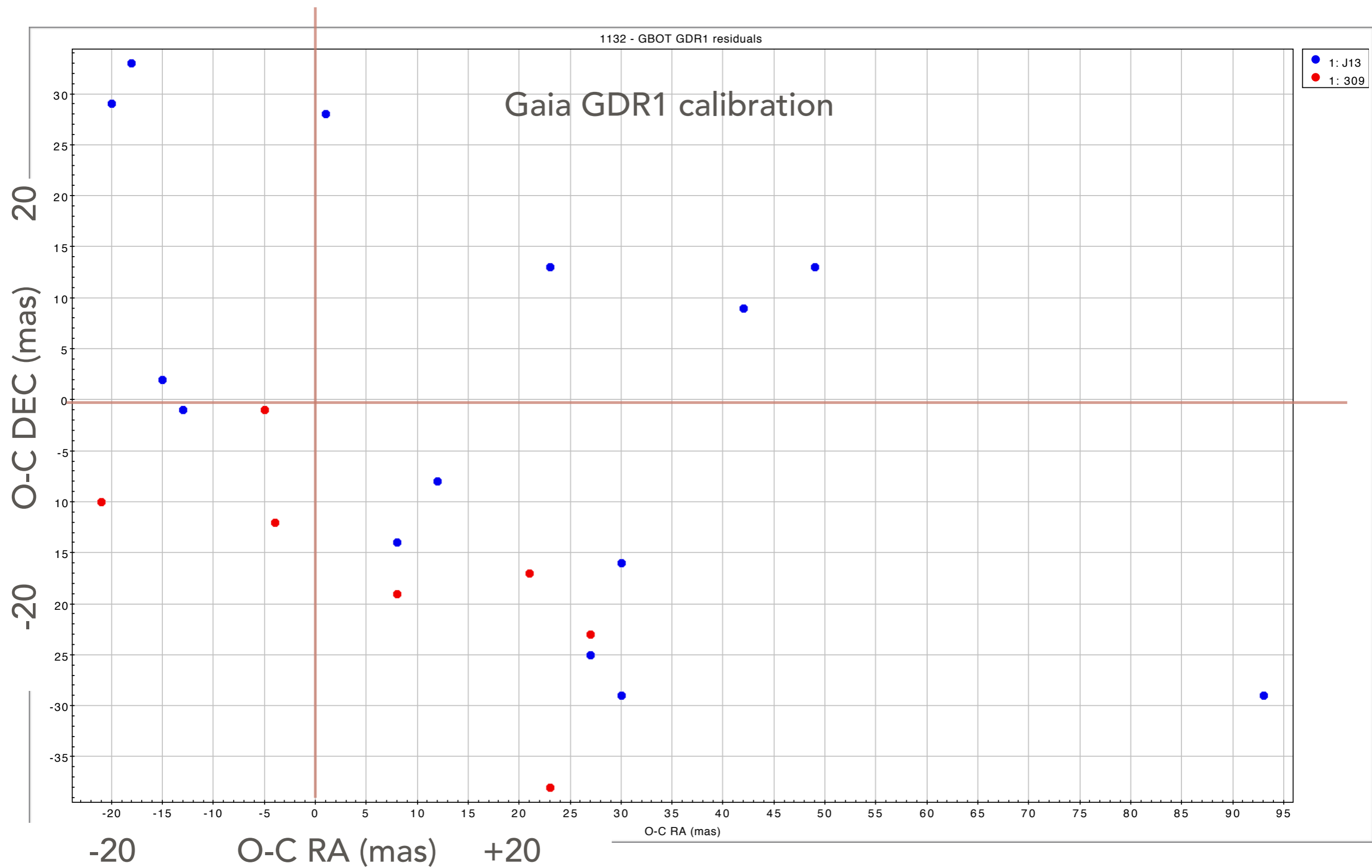
Exploit the stars in GDR1 !

Re-calibration of ground-based astrometry

- Asteroid observations from the Ground-Based Optical Tracking of Gaia (GBOT)
 - VST - Paranal
 - Liverpool robotic - Canary Isl.
- Several 10s asteroids observed each night
- Data reduction with PPMXL and Gaia DR1
- Typical sequence: 10 images over ~15 minutes, once

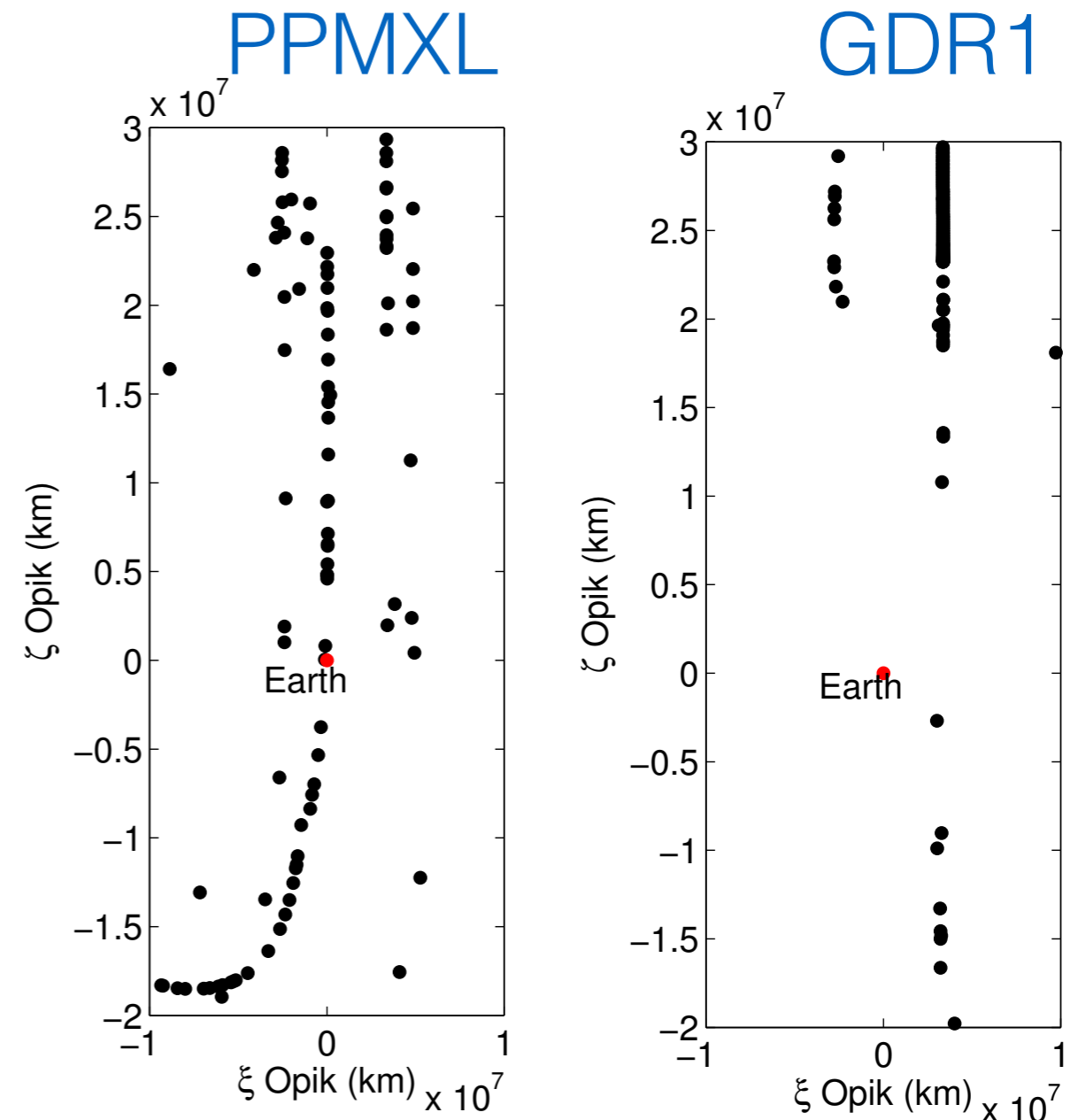






Potential “impactor” NEA 2016EK85

- Discovered by GBOT (8 observations by VST, 20 by LT, March 9-10, 2016)
- On the impact risk list with low probability for Feb. 22, 2102
- New observations from Mauna Kea (March 16, 2016) rule out impact
- If GDR1 were available, the object would have never been on the risk list



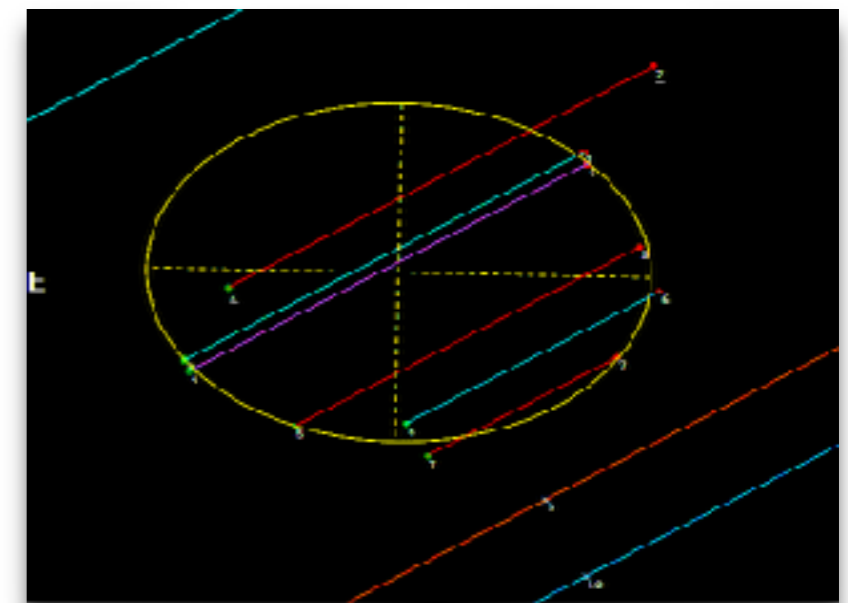
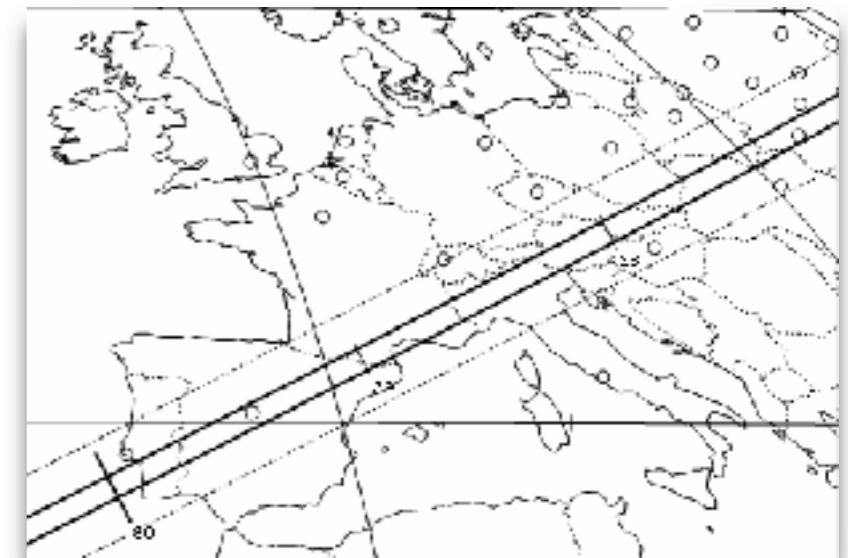
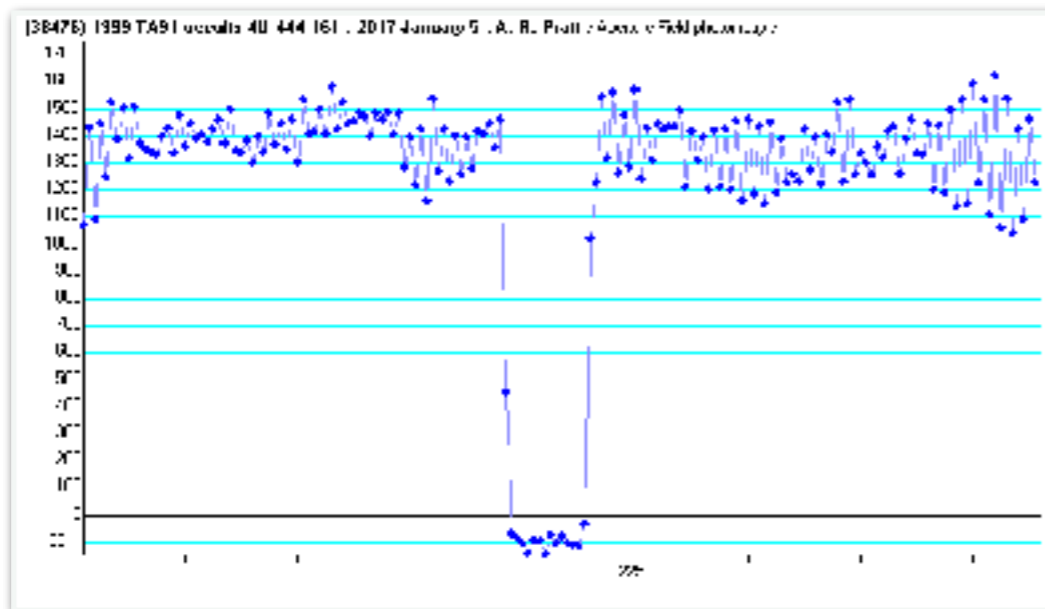
The revolution in astrometry

- ...does not come for free!
- Tools must be ready to handle accuracy ~ 100 X better
- An appropriate, careful weighting of the observations is necessary

- A factor 10 X improvement is accessible with GDR1
- More to come...!

Stellar occultations: potential with Gaia

- predictions based on GDR1 available since end 09/2015

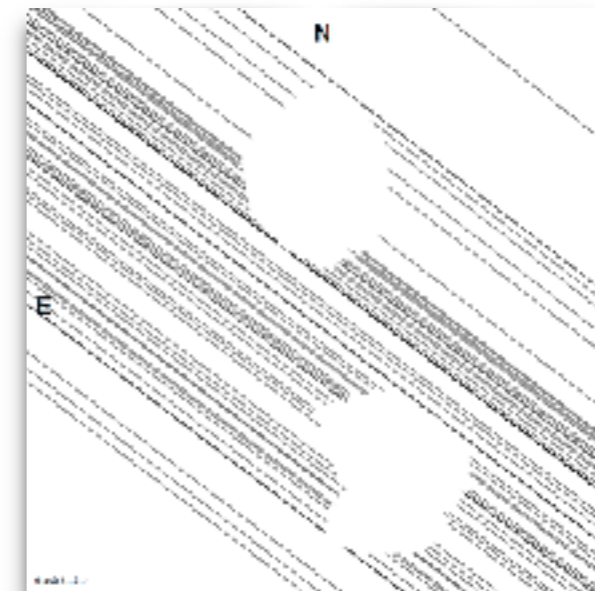


The duration of the occultation can be transformed into a chord length.

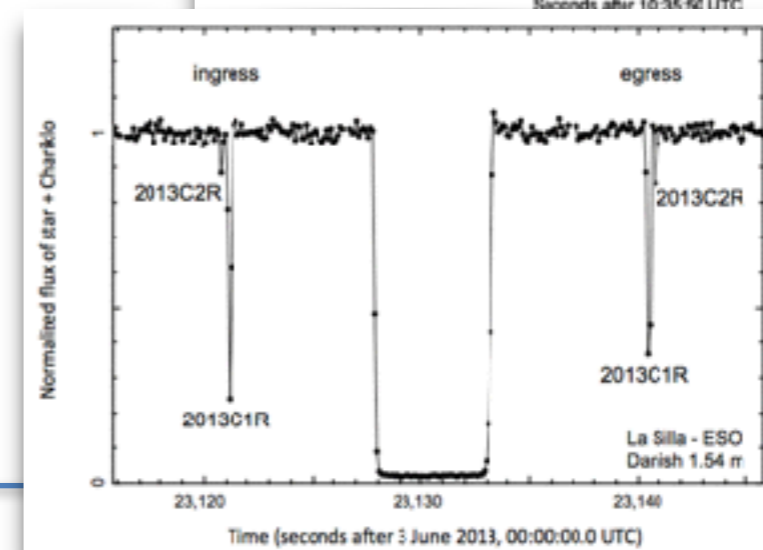
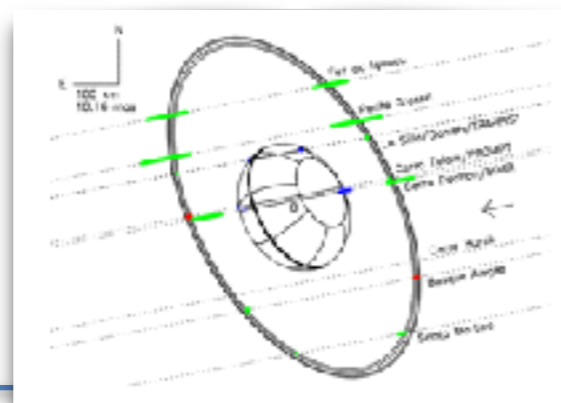
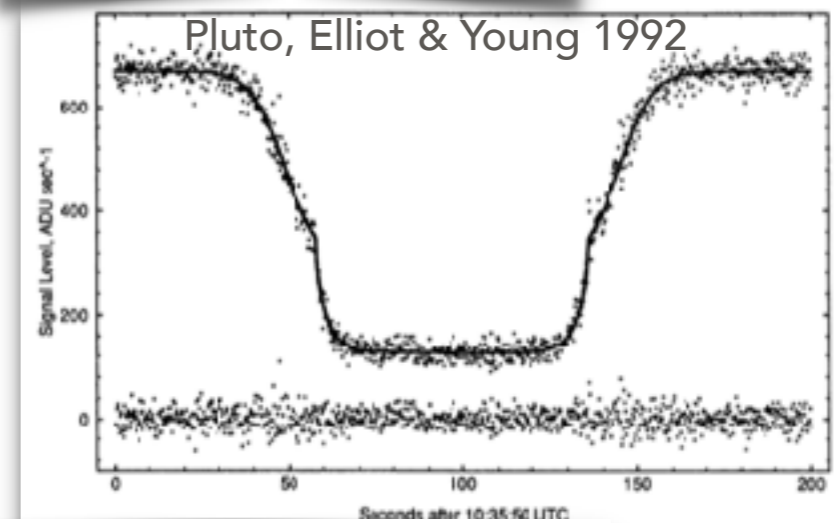
Typ. AL accuracy of the occultation $\sim 0.1-0.2$ s = 1 - 3 km

Occultations: science case

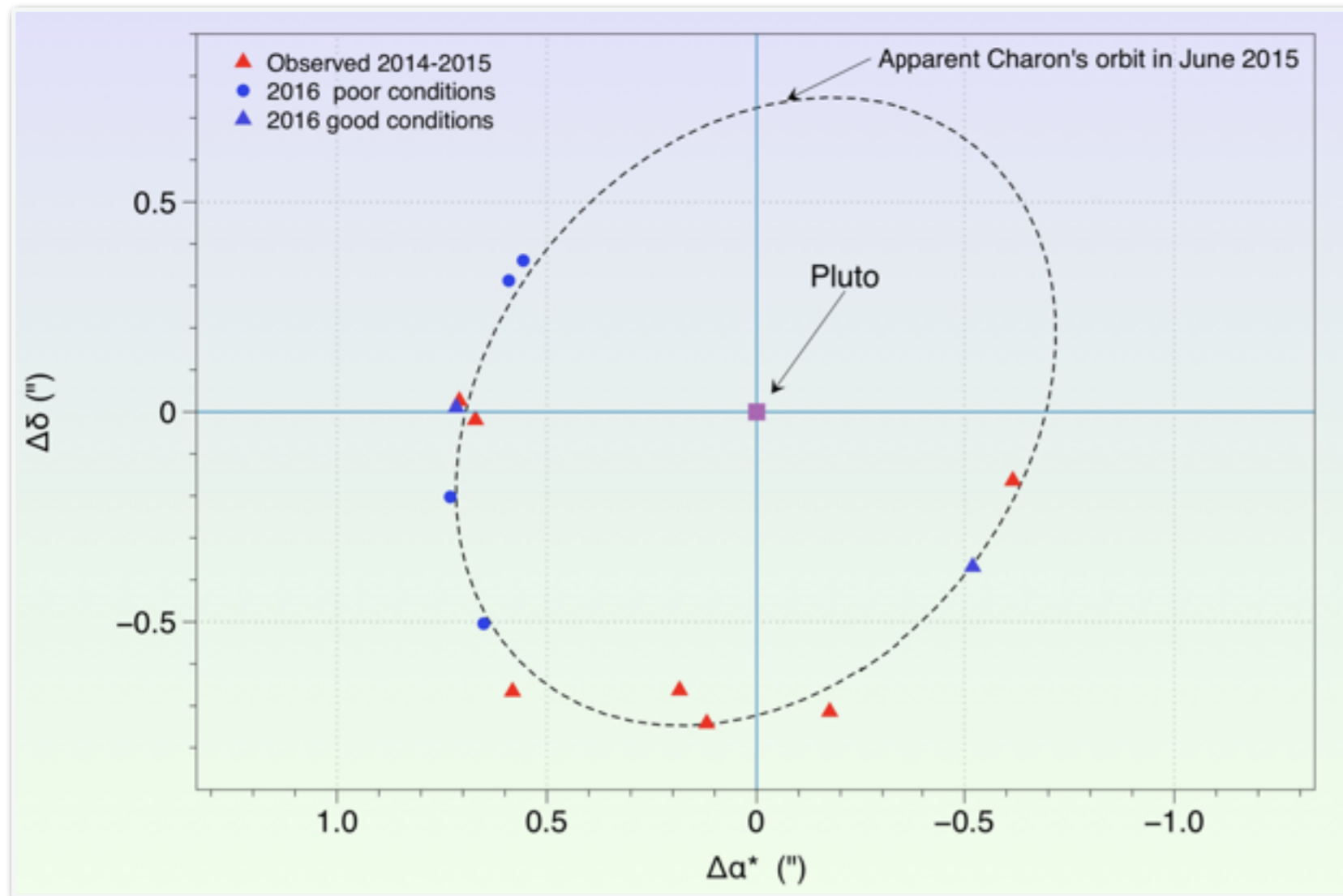
- Determine asteroid sizes, shapes
 - discriminate among spin pole solutions
 - calibrate indirect size determination methods (thermo-physical modeling)
 - complement photometric inversion (“KOALA”)
 - the only efficient method for TNO size determination
- Measure binary systems
 - separations, primary/secondary size → mass, density (!!)
- Detect thin atmospheres
 - on Pluto, large satellites (Titan), TNOs



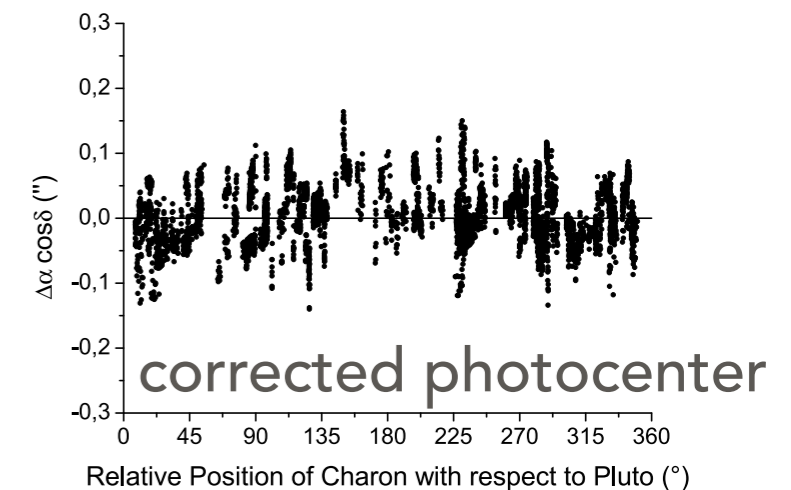
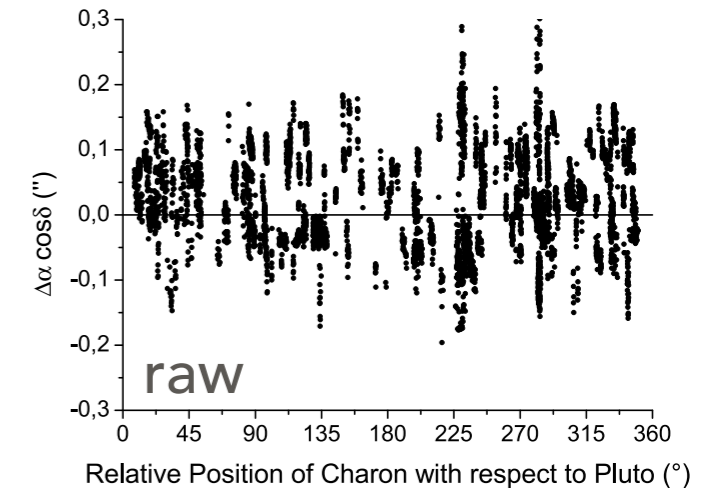
90 Antiope



Pluto and Charon from *daily astrometric calibration* (~ 70 mas)



from the ground - 19 years



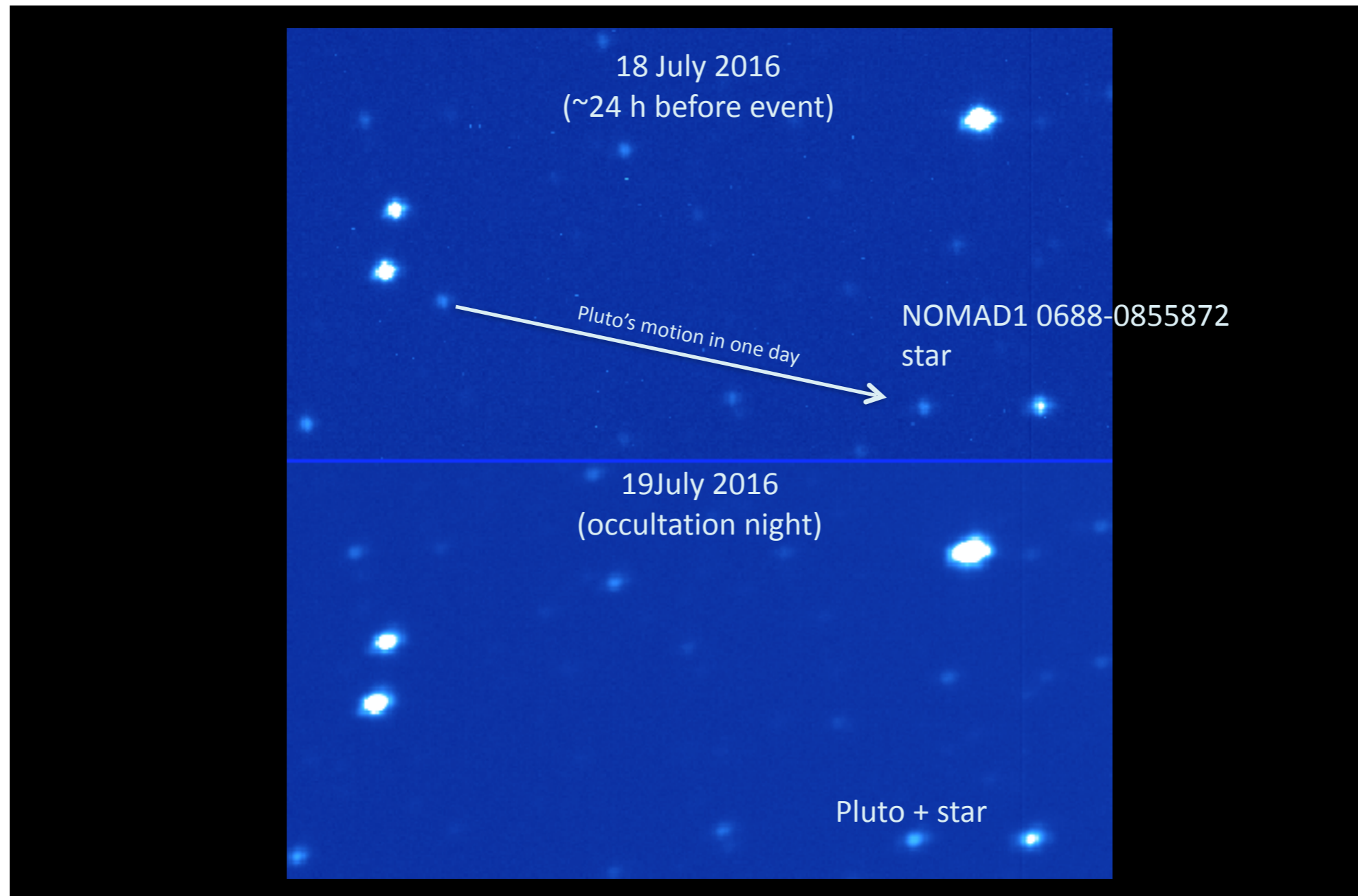
Benedetti-Rossi et al. 2014

motion around barycenter
 photocenter wobbling
 variations linked to albedo changes

~ 100 mas
 ~ 10 mas
 $\sim ? \sim$



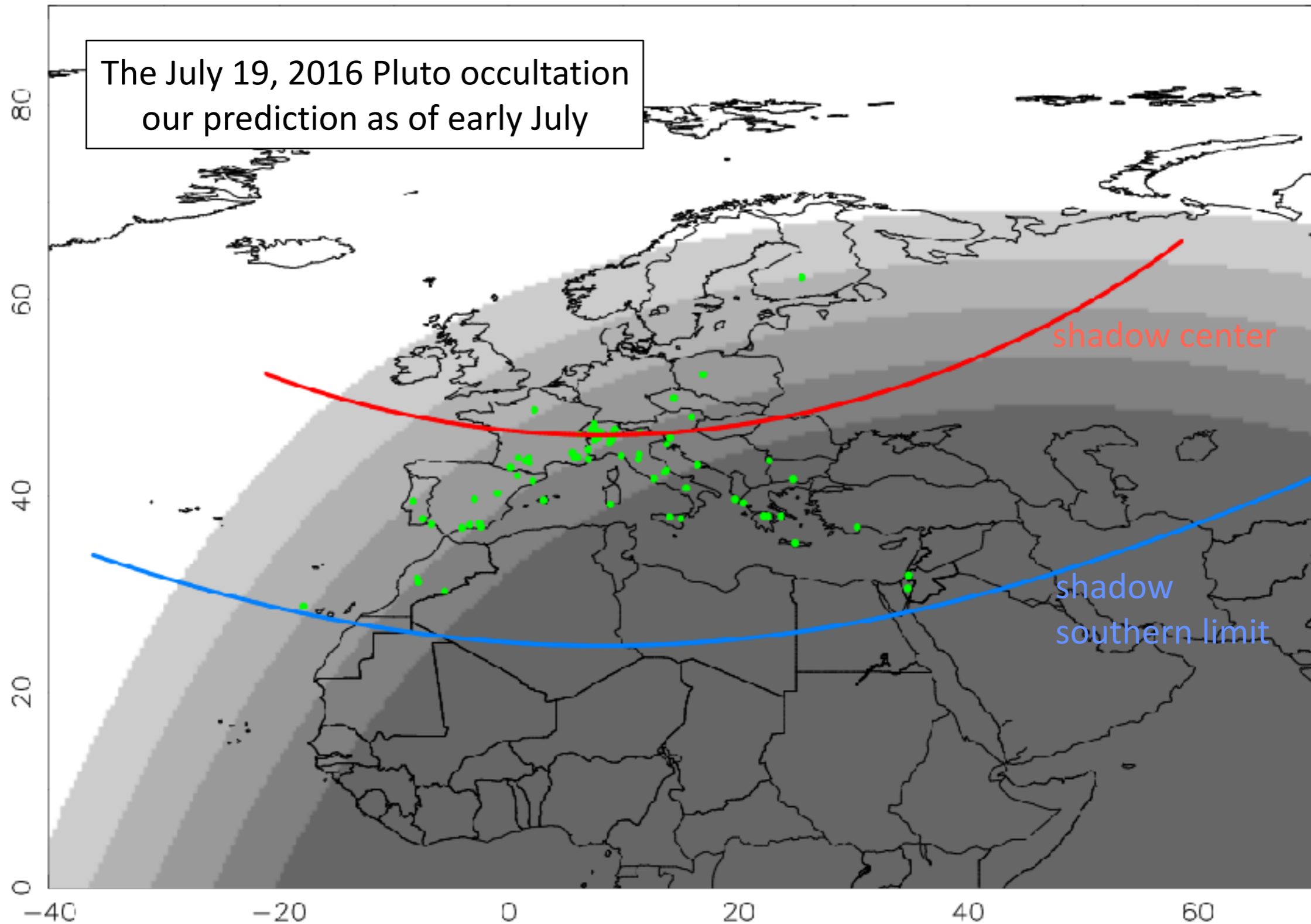
Example - Prediction of stellar occultations: Pluto



Observatory Valle d'Aosta, Saint Barthélémy, July 19, 2016

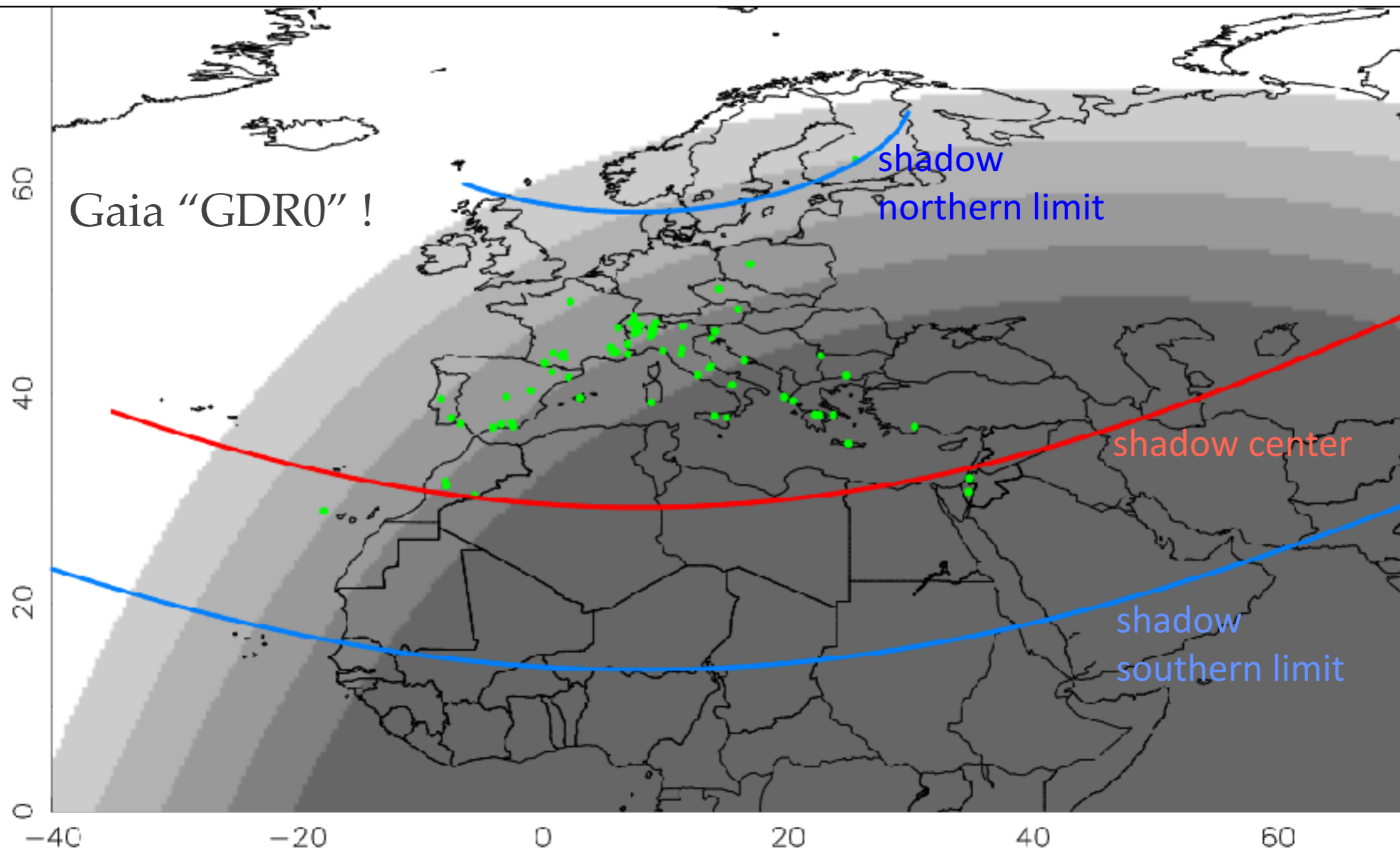
Courtesy: B. Sicardy, LESIA, Obs. de Paris

Example - Prediction of stellar occultations: Pluto

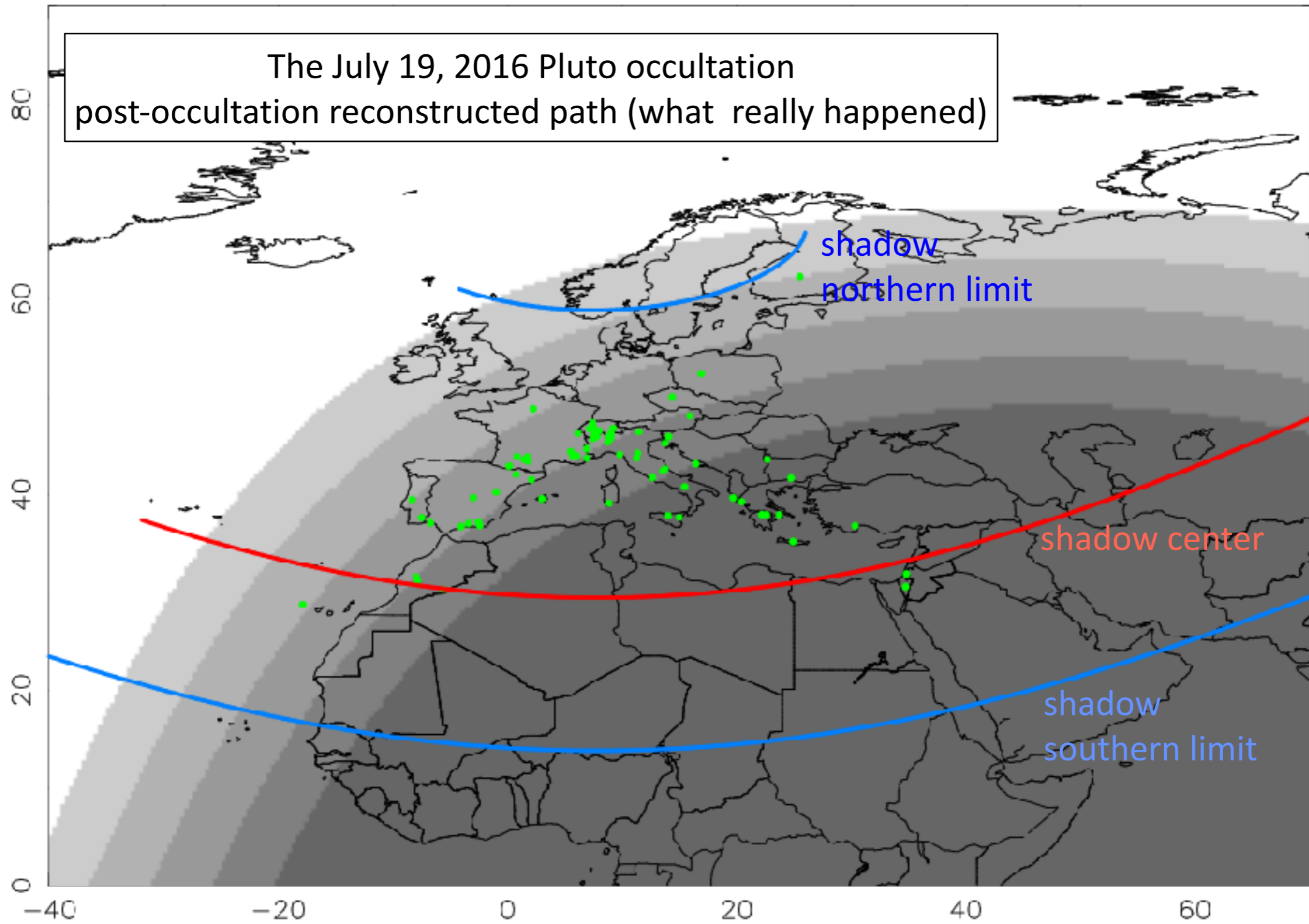


Example - Prediction of stellar occultations: Pluto

The July 19, 2016 Pluto occultation, prediction using the GAIA star position (and estimation of its pm), plus the New Horizons-updated ephemeris

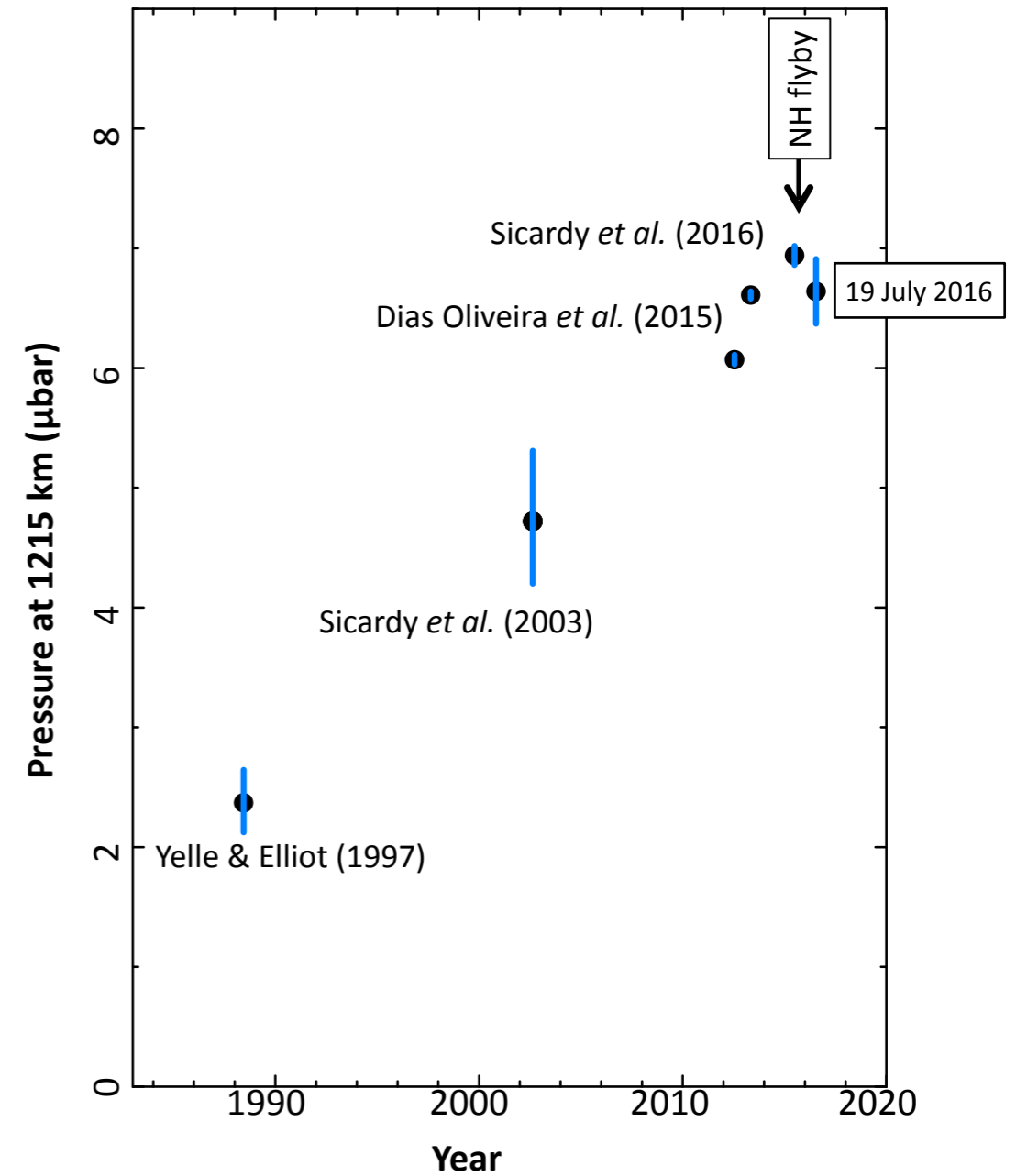
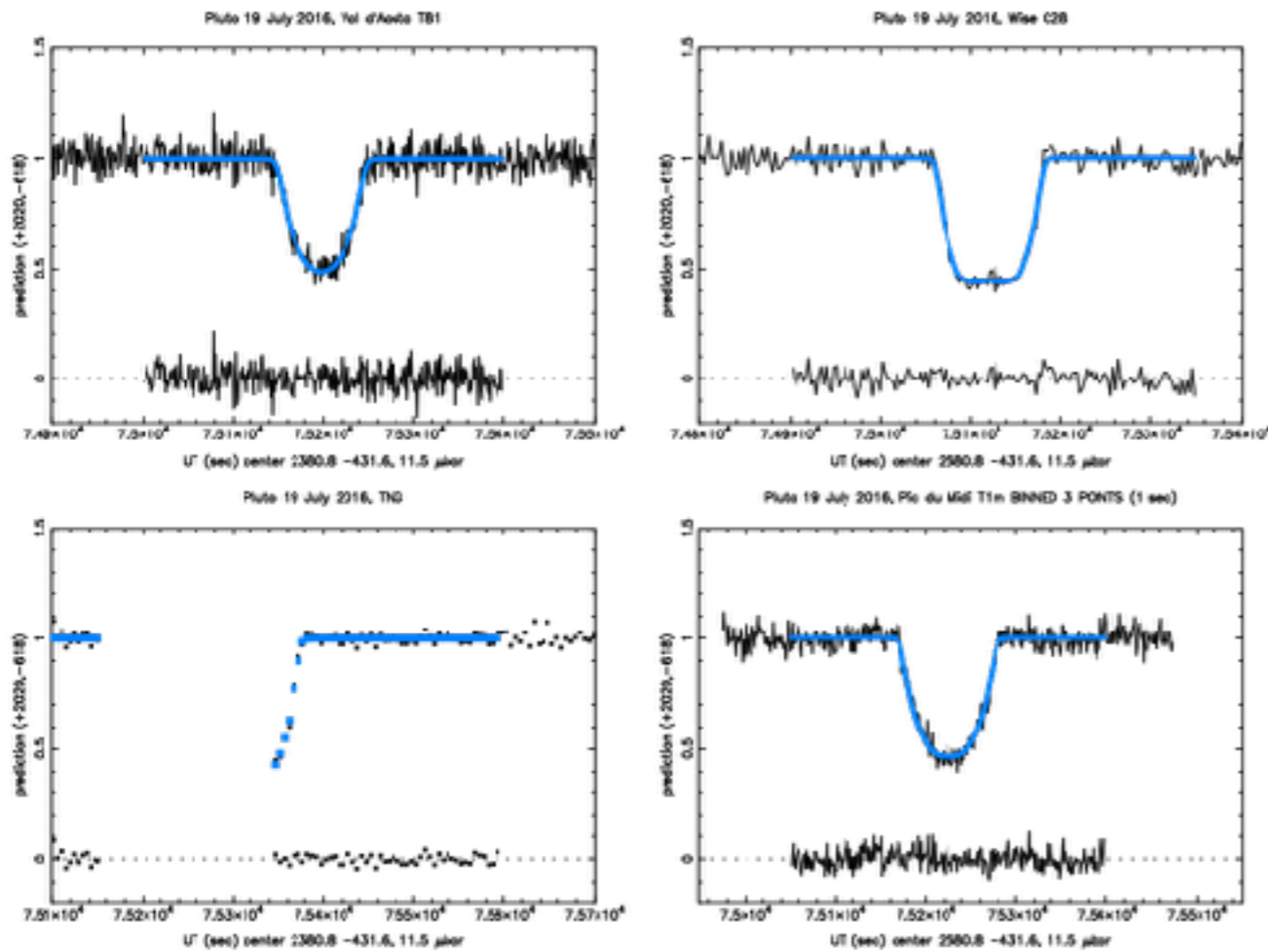


Example - Prediction of stellar occultations: Pluto



green dots: sites involved in the campaign (not all got data!)

Example - Prediction of stellar occultations: Pluto

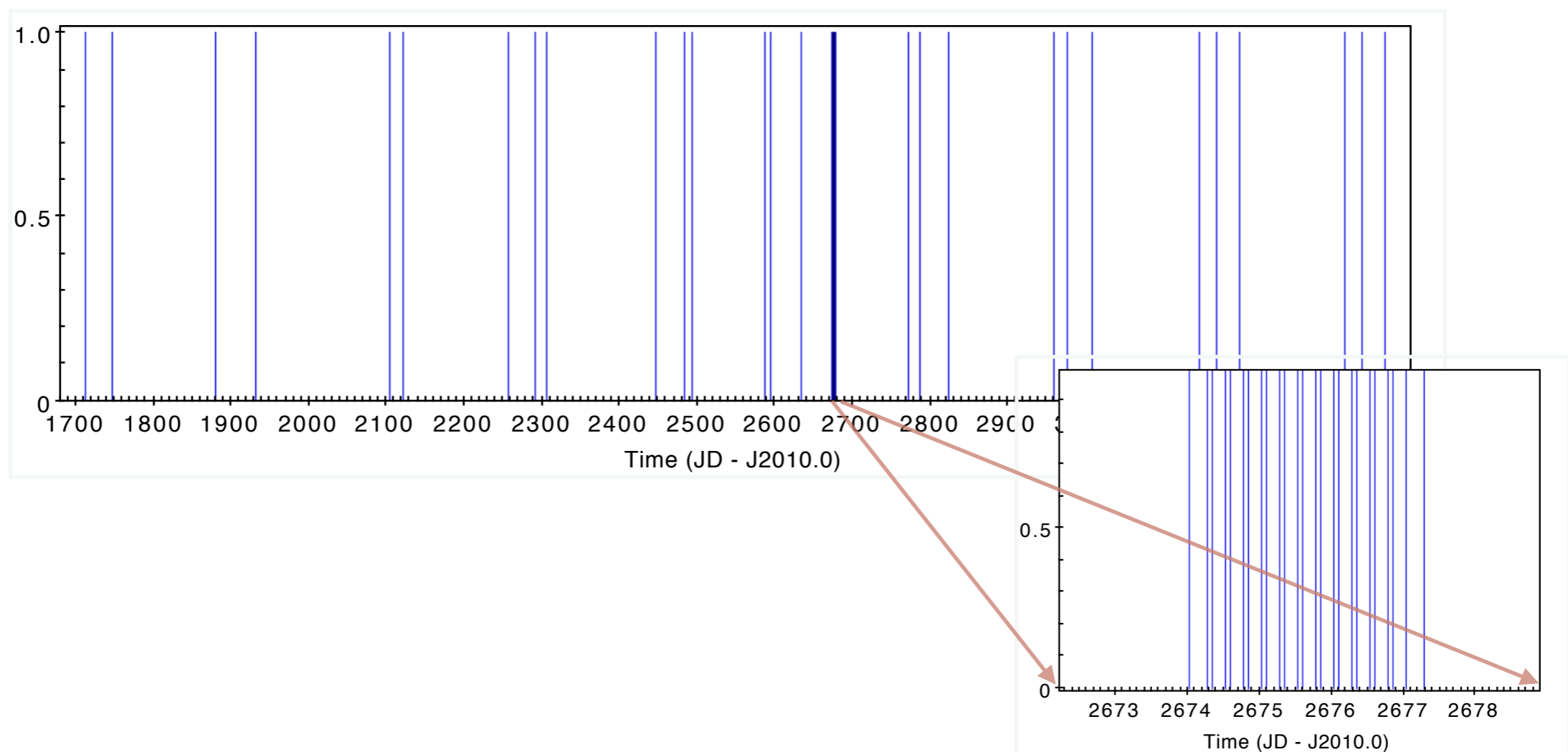


Courtesy: B. Sicardy, LESIA, Obs. de Paris

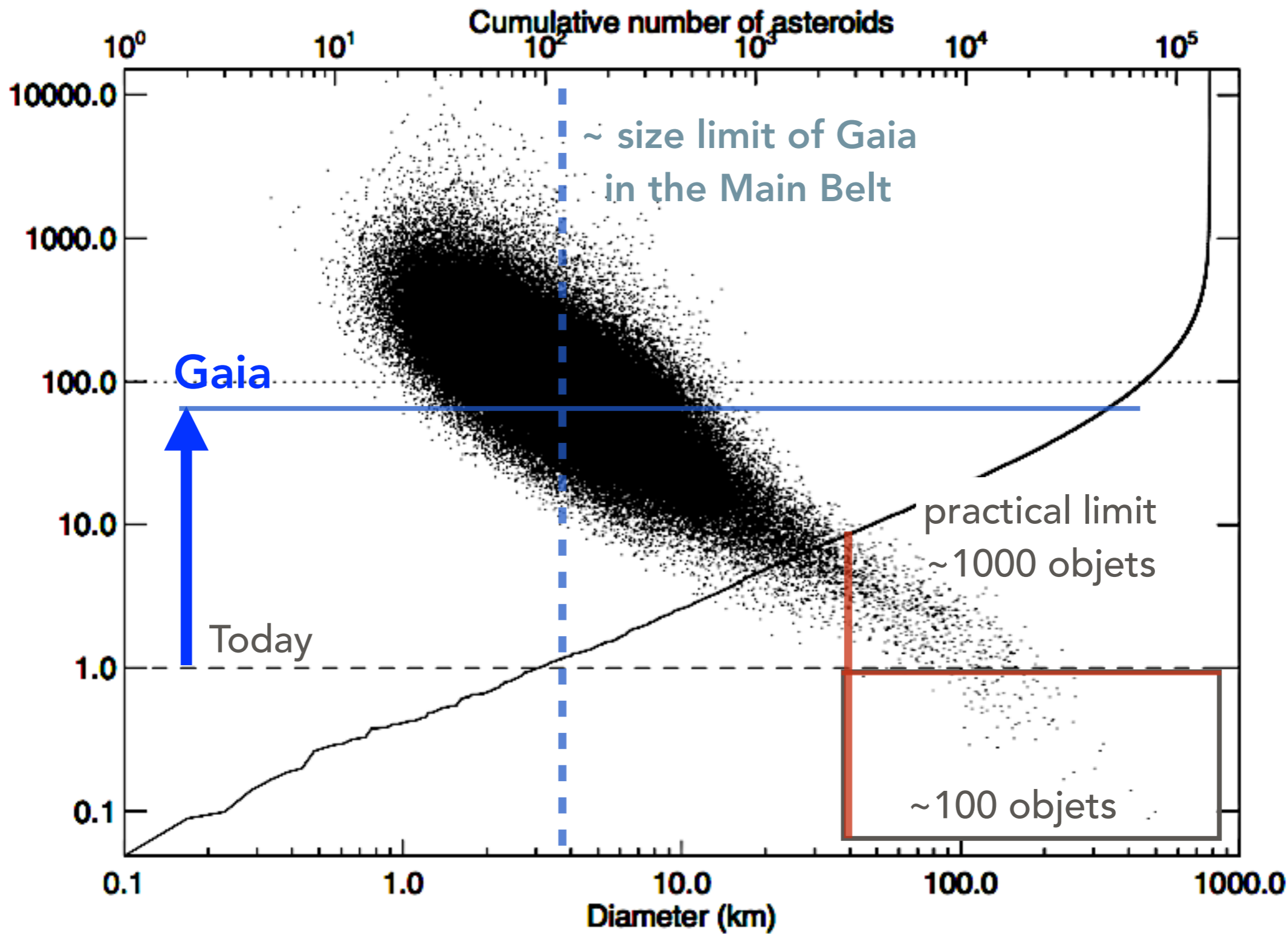
(B. Sicardy, presented at DPS 2016)

TNO detections

- 30 TNOs (in theory) below the $V=20.5$ threshold
- accuracy per transit probably 2-3 mas (along scan)
- example of time distribution:



Uncertainty / apparent size at opposition



At 1.4 AU, 1 km ~1 mas

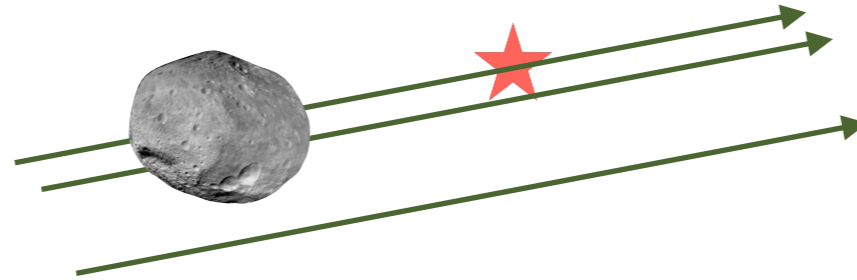
Tanga & Delbo' 2007

Impact of Gaia on stellar occultations

- Predictions possible (in principle) for ~ 1 billion stars
 - in practice: limited by delta-mag
- Path width = uncertainty at $D \sim 5-15$ km
- Many 10s events observable per night from any site for $V < 15$ (star)

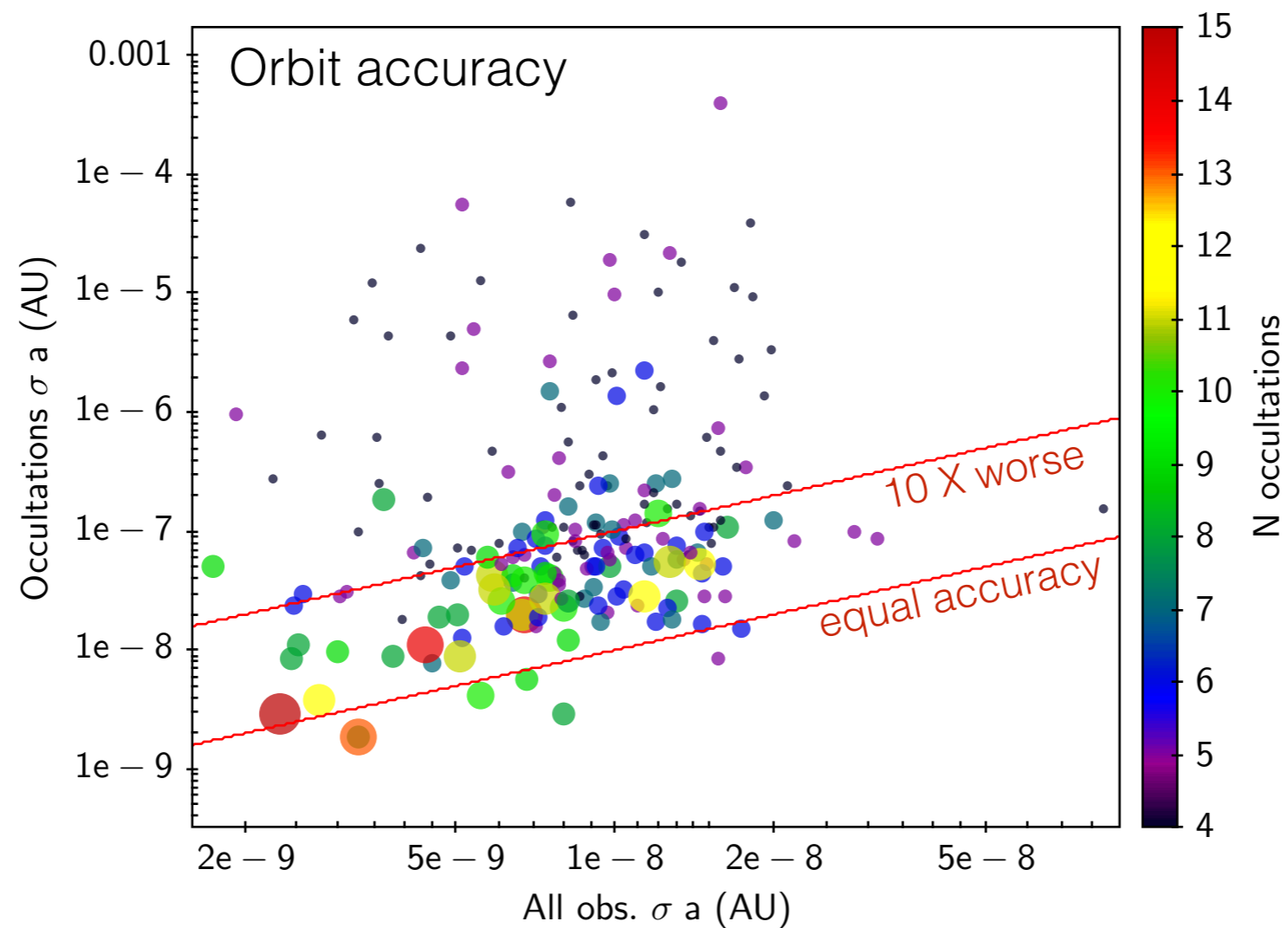
- New tools to be developed
 - not a task for humans!
 - accurate prediction at ~ 100 m level on the ground
 - introduction of a probabilistic description of the results

Occultation astrometry: a new approach



- Is it possible to calculate optimized asteroid orbits from occultations ONLY?
- Well-observed occultations can be very accurate astrometric positions for asteroids
 - at the level of the stellar astrometry
 - ...but possible *before* and *after* Gaia

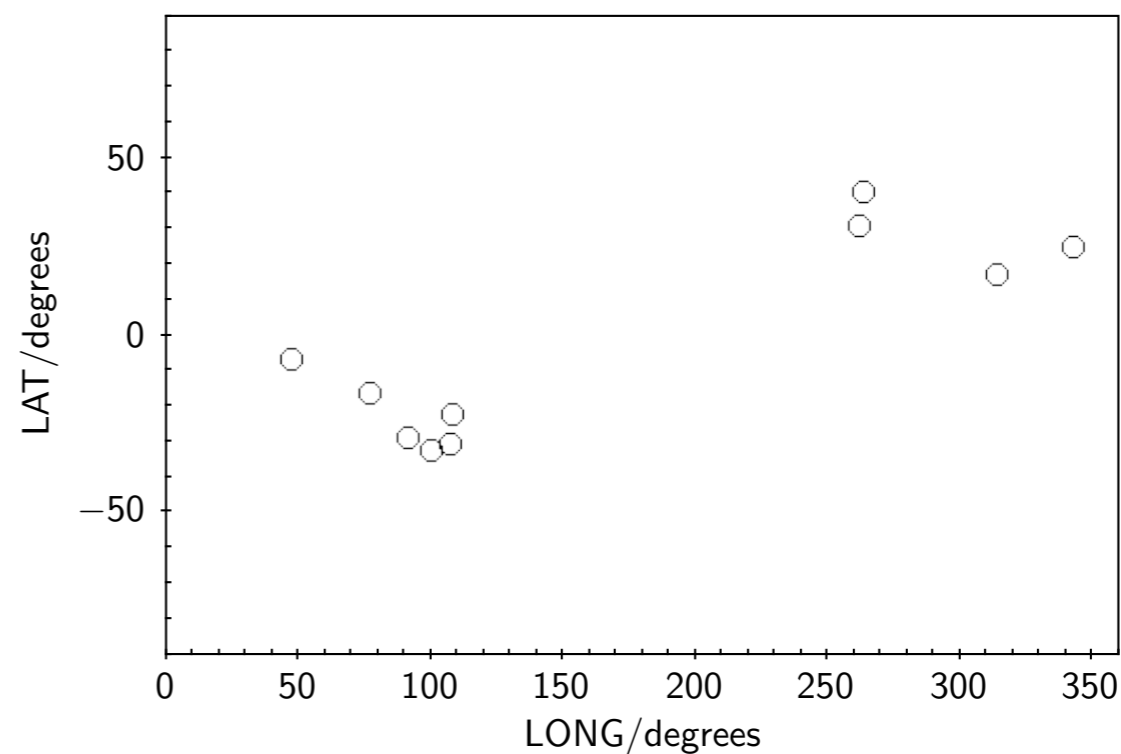
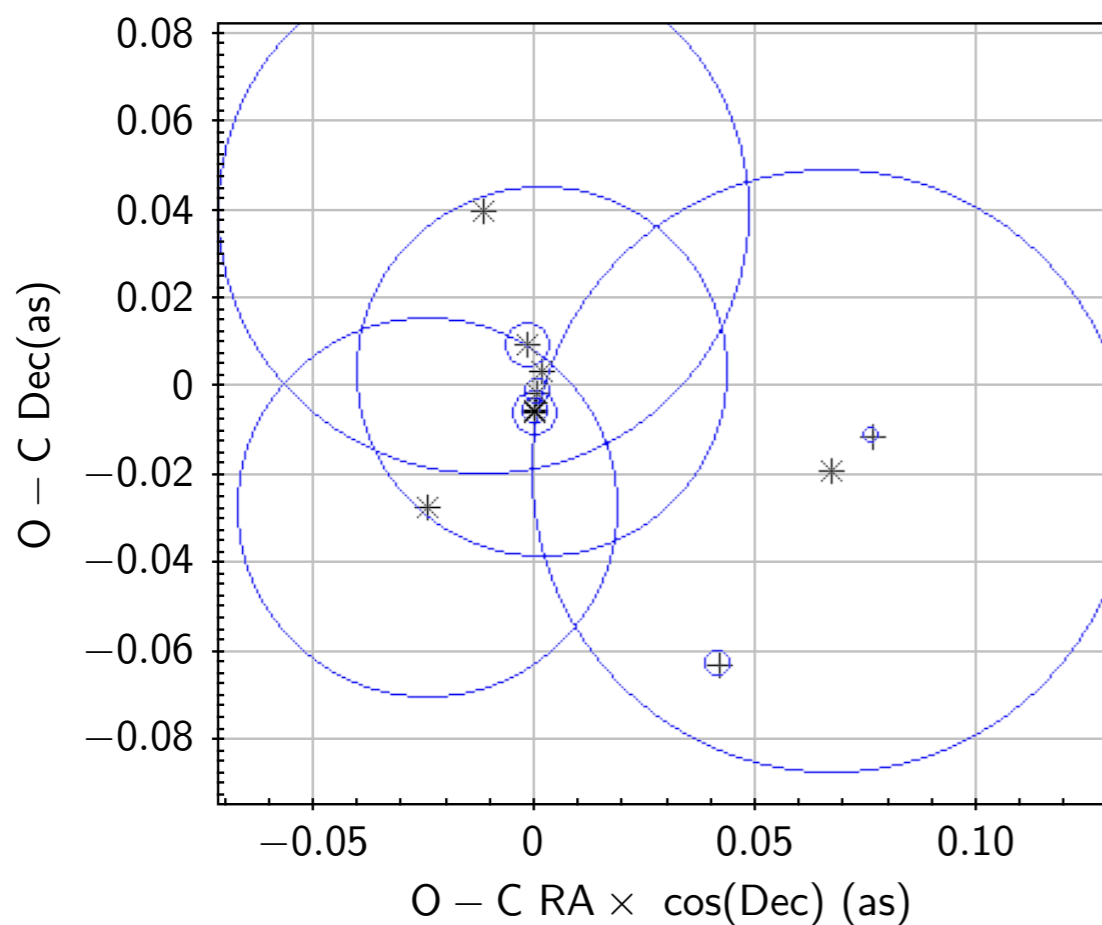
Dream becoming true: *the occultation astrometry of asteroids*



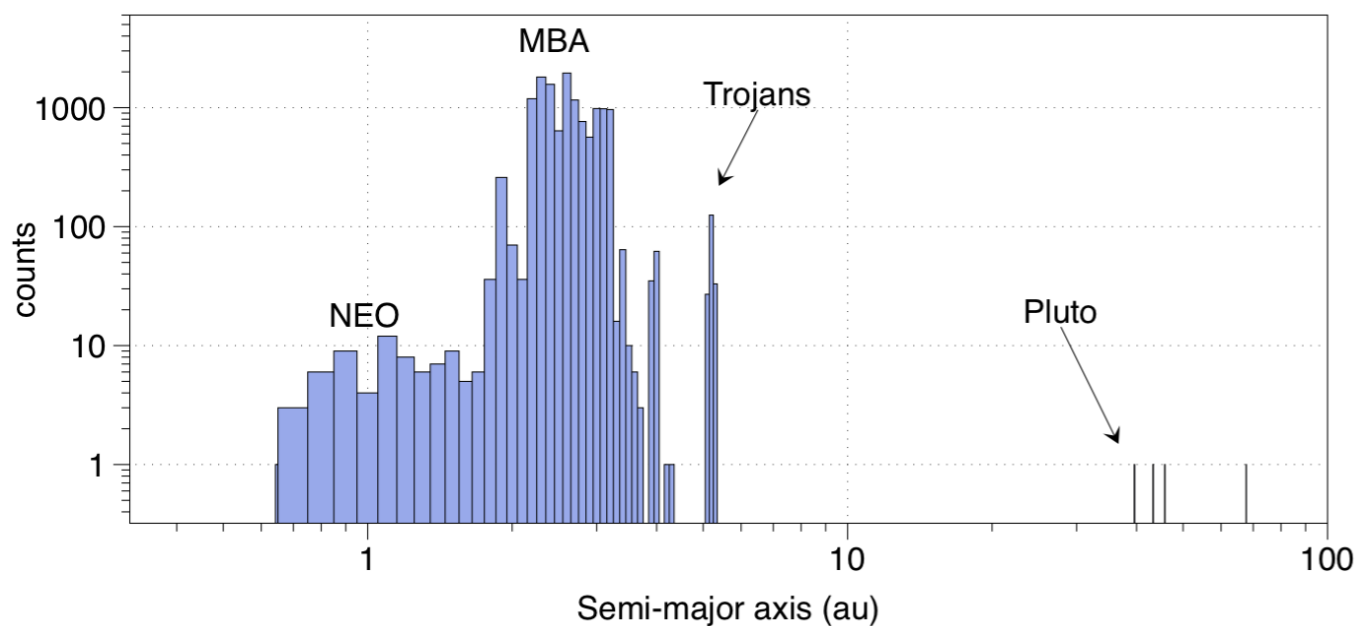
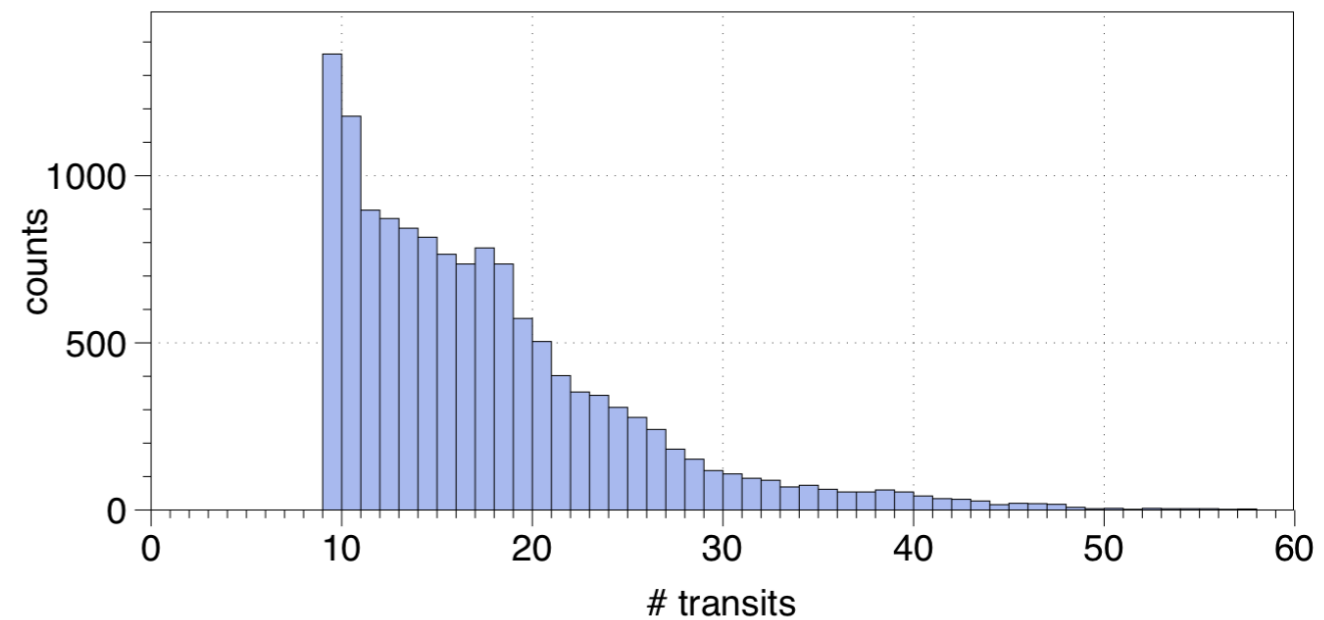
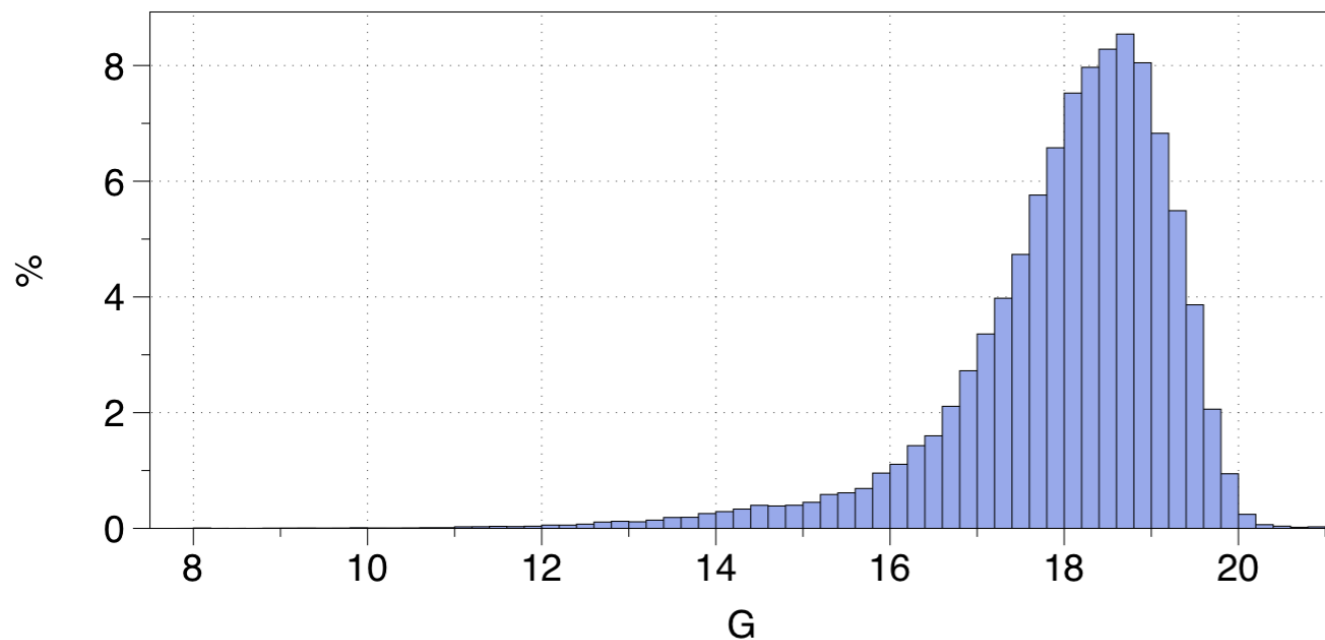
F. Spoto, OCA

Occultation residuals

- Asteroid 105 Artemis



Selection for the Gaia Data Release 2 (Apr. 2018)



- Last version (January 8):
 - no transit loss for the included asteroids
 - asteroids with less than 9 transits are excluded
 - 13,400 planets (195,000 transits)

F. Mignard, OCA

Conclusions

- Gaia data are delivering the expected resolution
 - stellar data already interesting for Solar System science
- Big potential in asteroid data: sensitivity to shape/satellites, subtle dynamical effects
- “old” approaches are being renovated: asteroid occultations is the example of excellence

Thank you!

