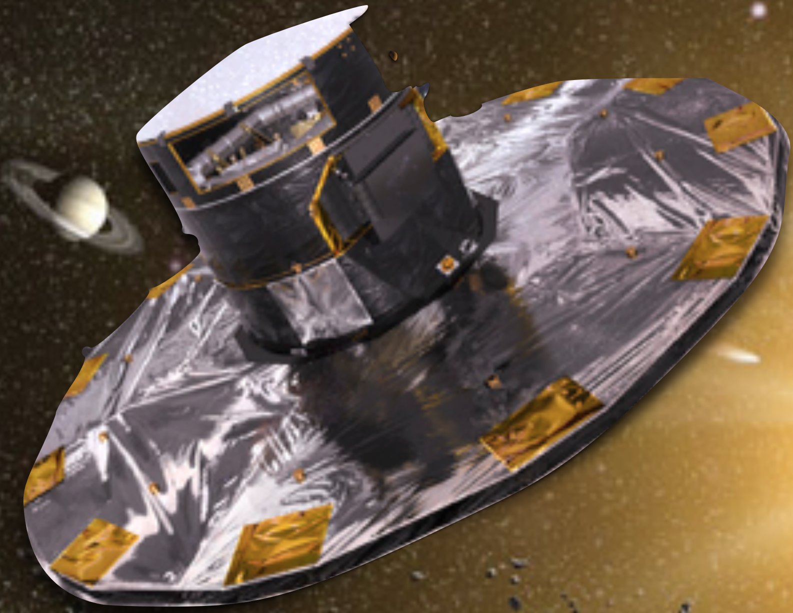
March 16, 2017



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

P. Tanga

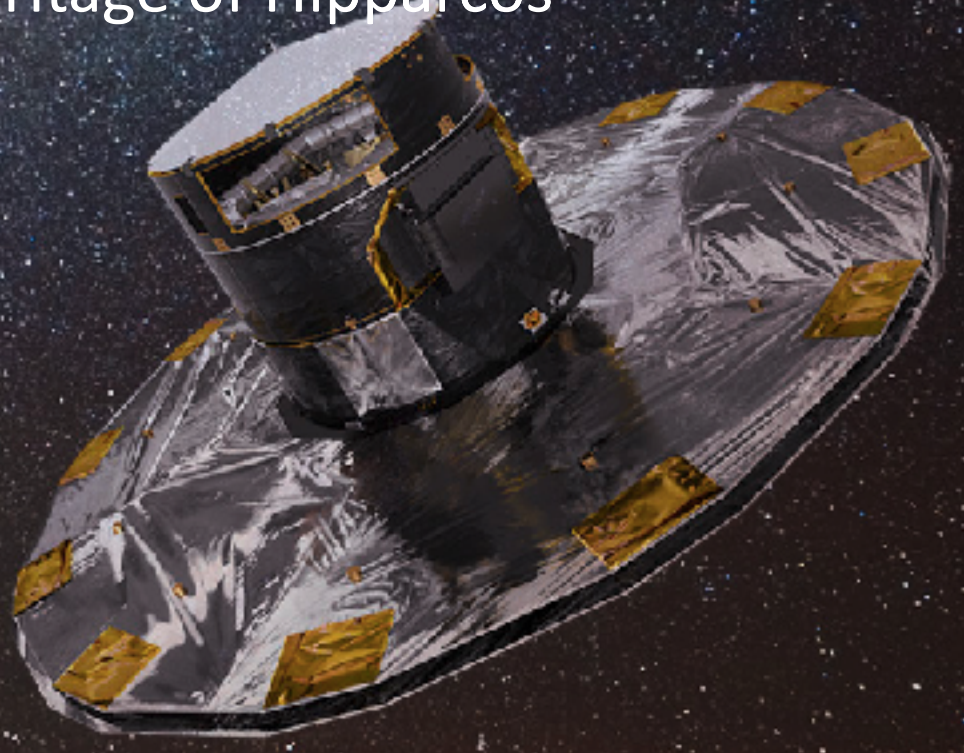
Laboratoire Lagrange,

Observatoire de la Côte d’Azur, France

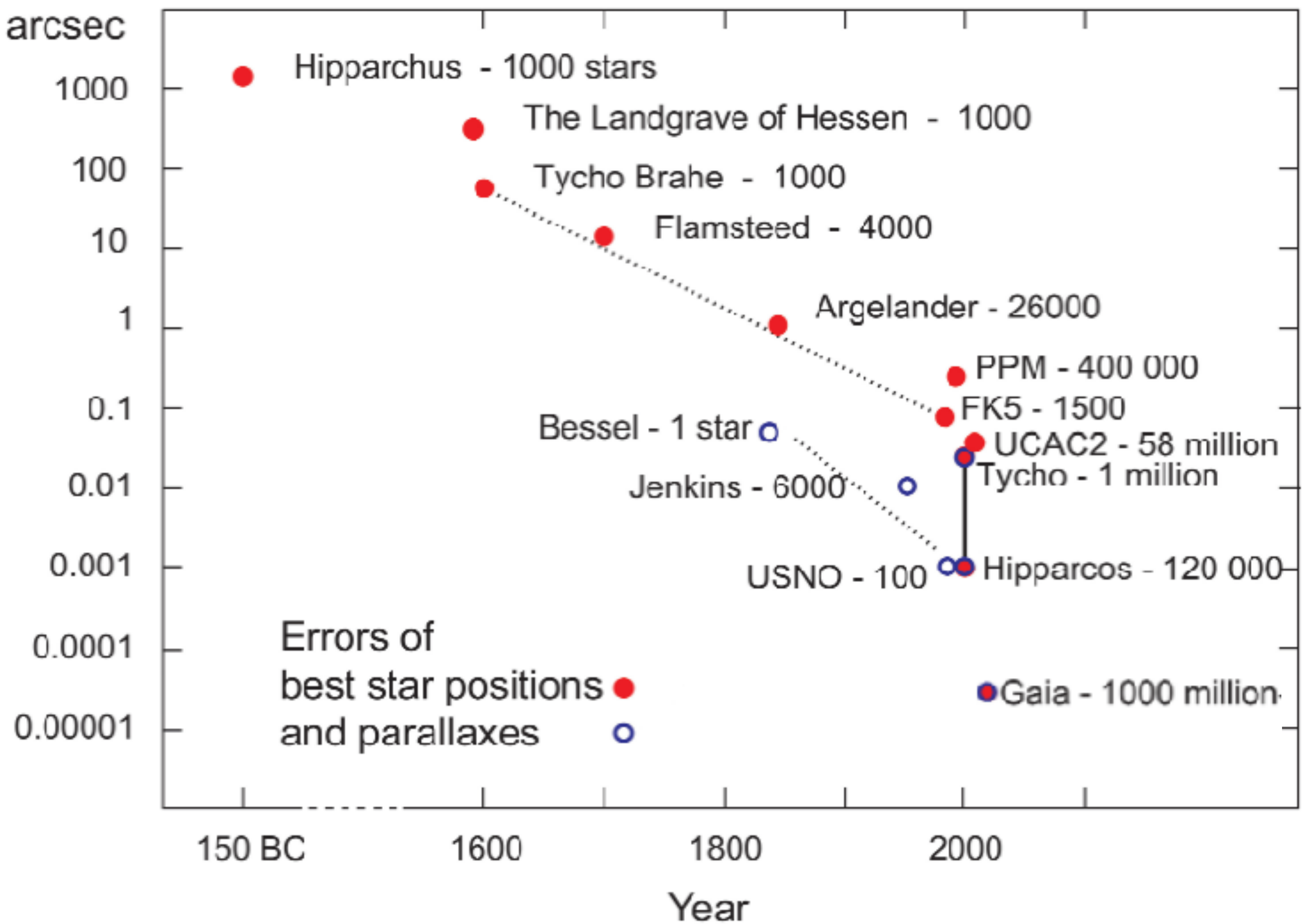
Gaia ID card

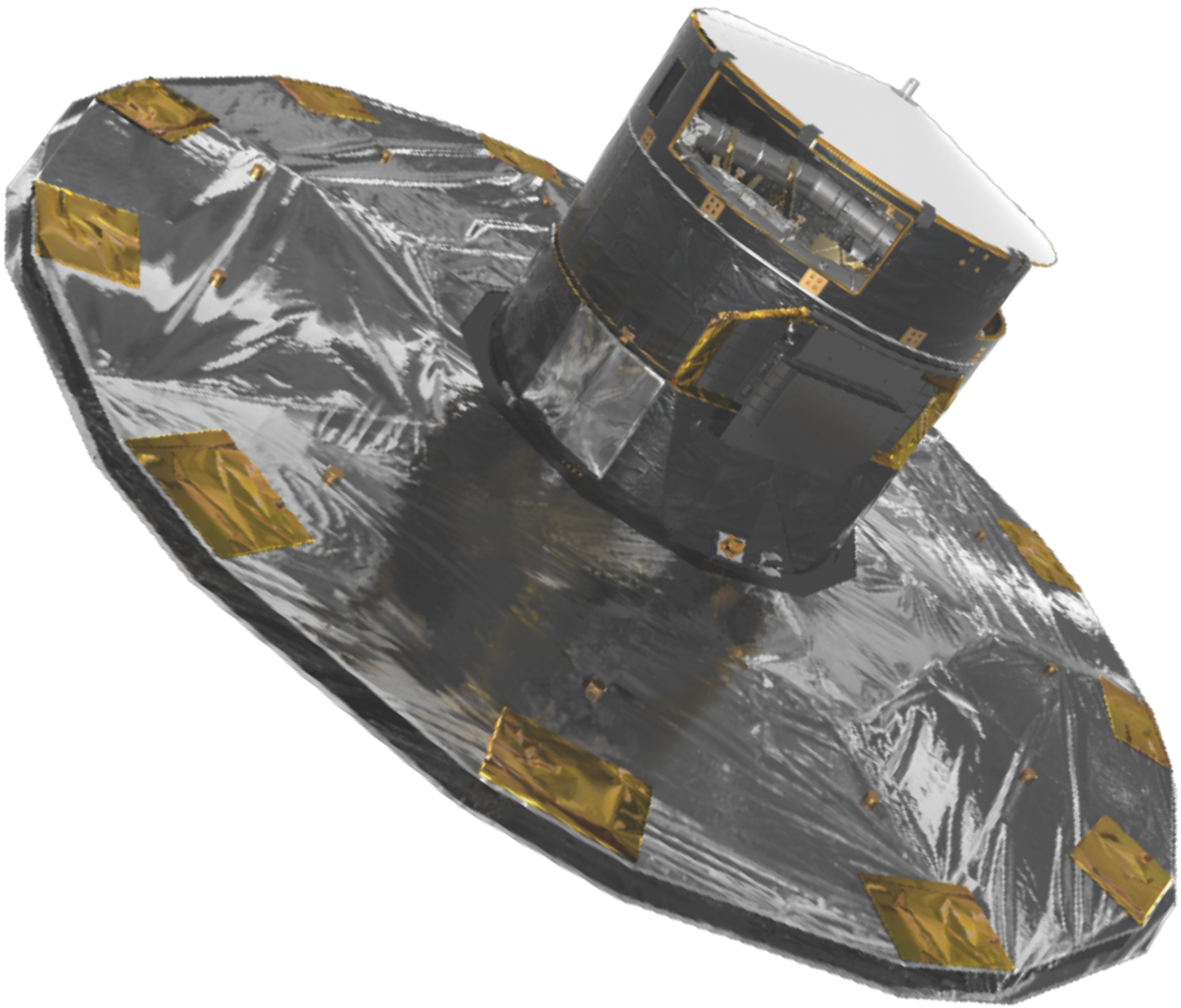
- It is a **ESA** cornerstone **scientific mission**:
  - ESA: building, operation
  - Scientific community: data reduction
  - No instrument PI, no proprietary period
- **Astrometry**:
  - 10^9 stars, V<20
  - 25 μas at V~15
  - uniform sky coverage (70-100 obs./ source)
- **Physical observations**:
  - Spectro-photometry
  - Radial velocities, hi-res spectra (V<16.5)
- **5 years** of observations

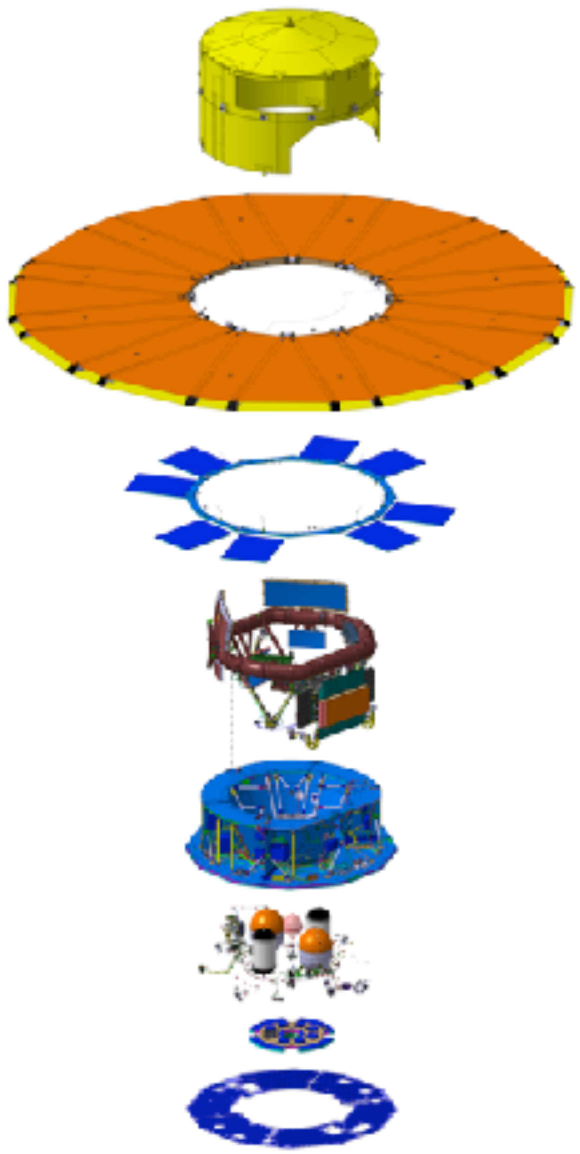
  (nominal mission started in July 2014)
- **Positioned around L2**
- **automated selection of sources , on input catalog**
- Self-monitored, onboard metrology
- Heritage of Hipparcos



Gaia in the history of astrometry







ESA/Gaia/DPAC/Airbus DS

Optics

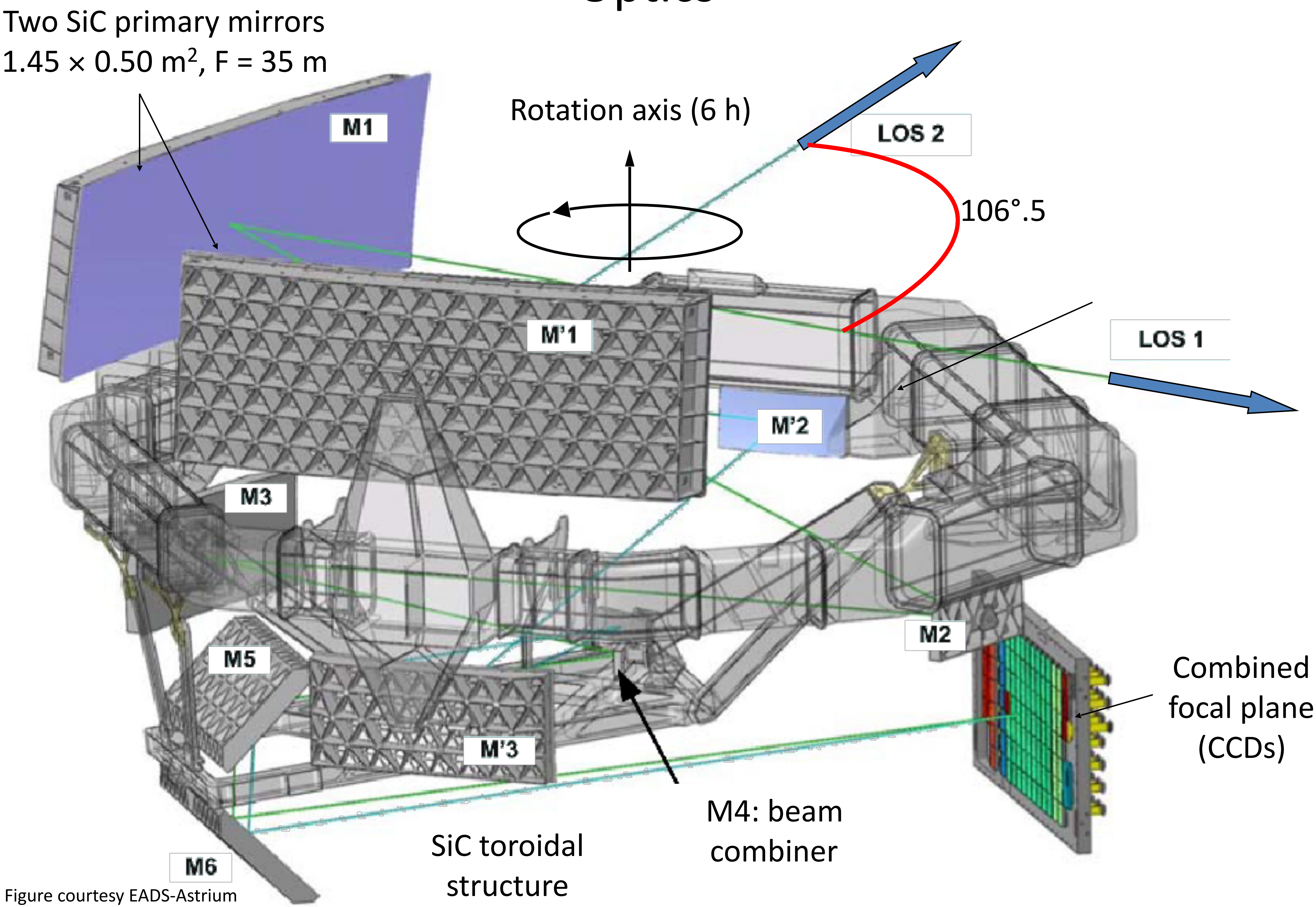
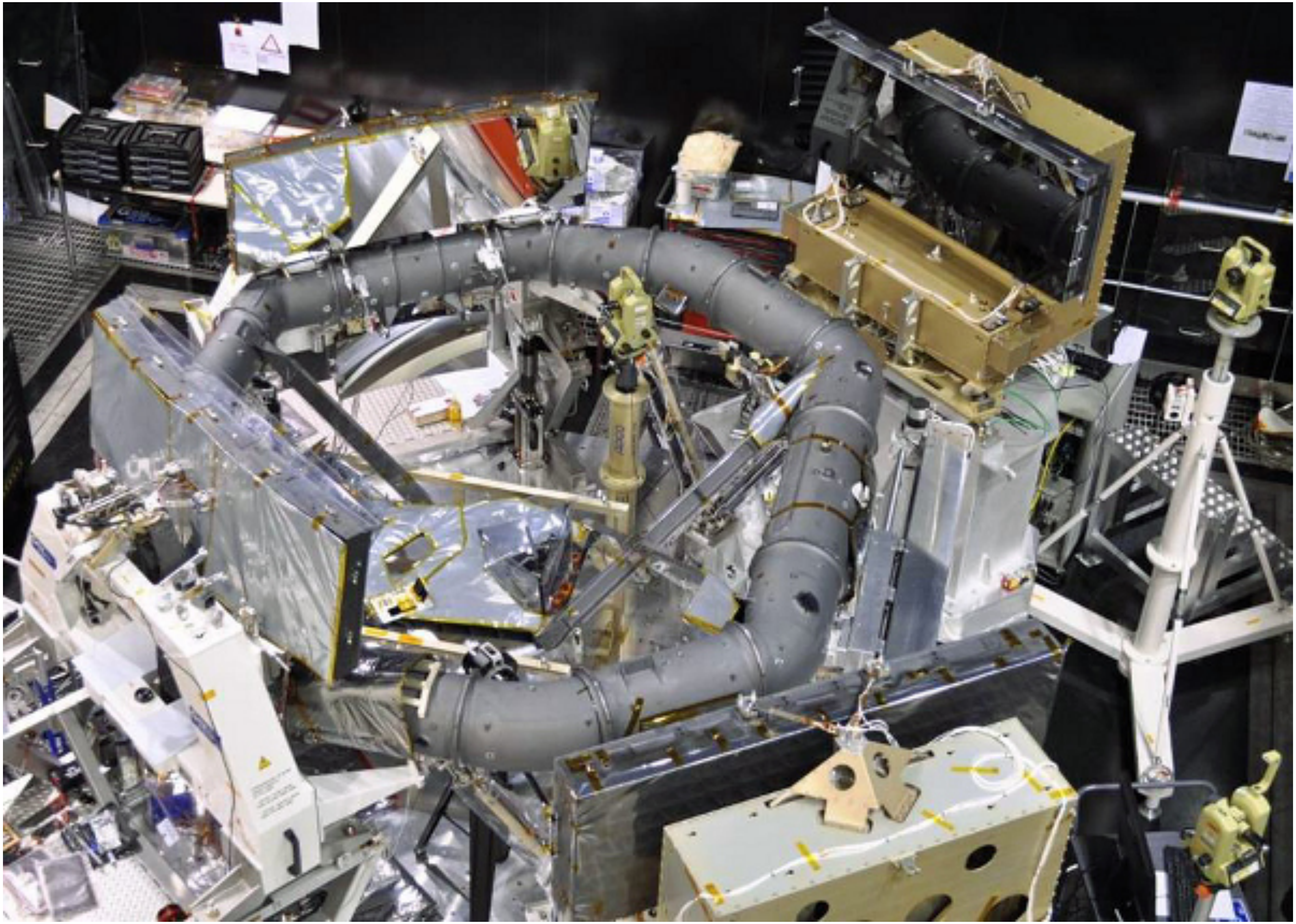


Figure courtesy EADS-Astrium



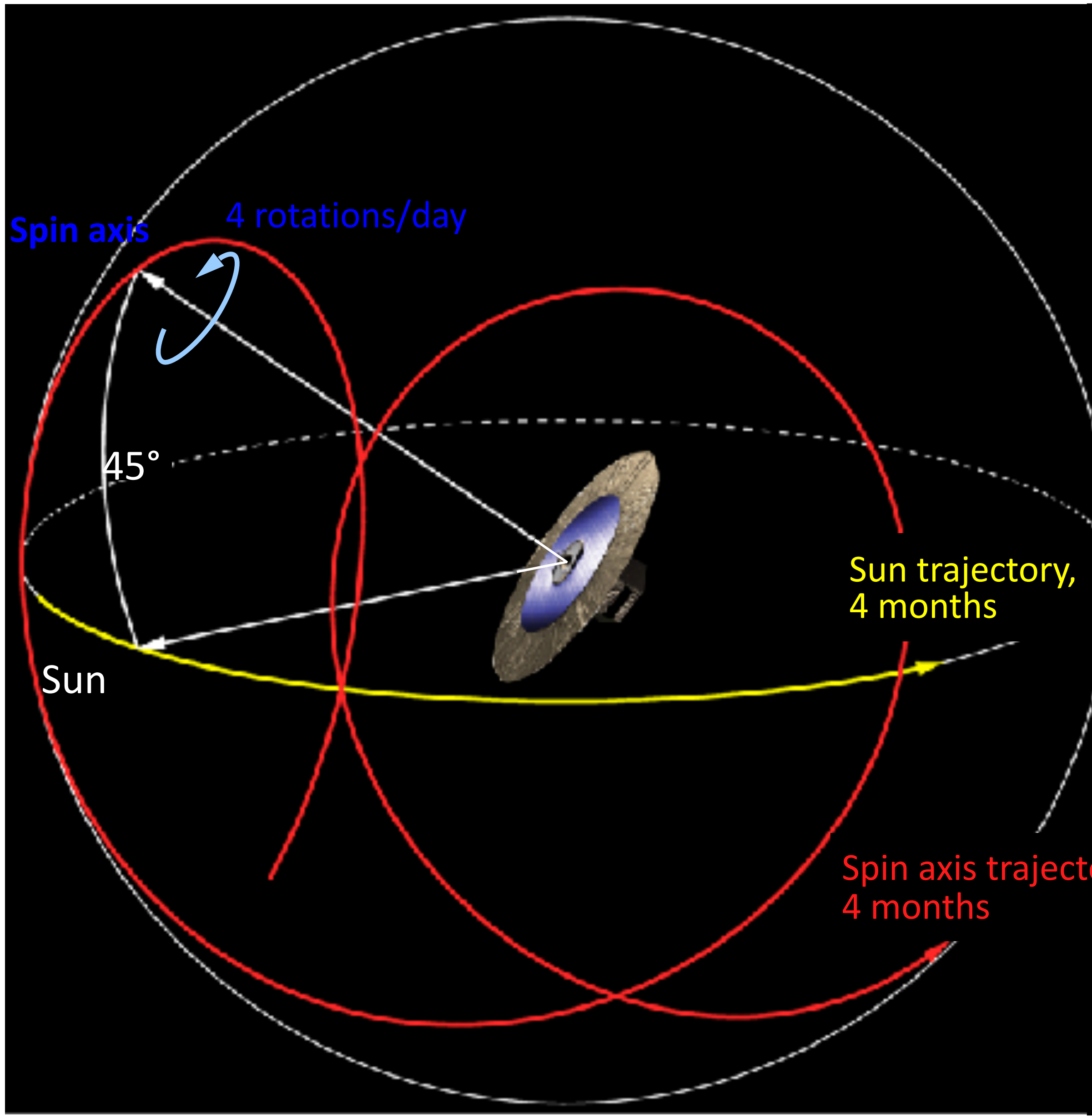
ESA/Gaia/DPAC/Airbus DS

Sunshield deployment test – Oct. 2011

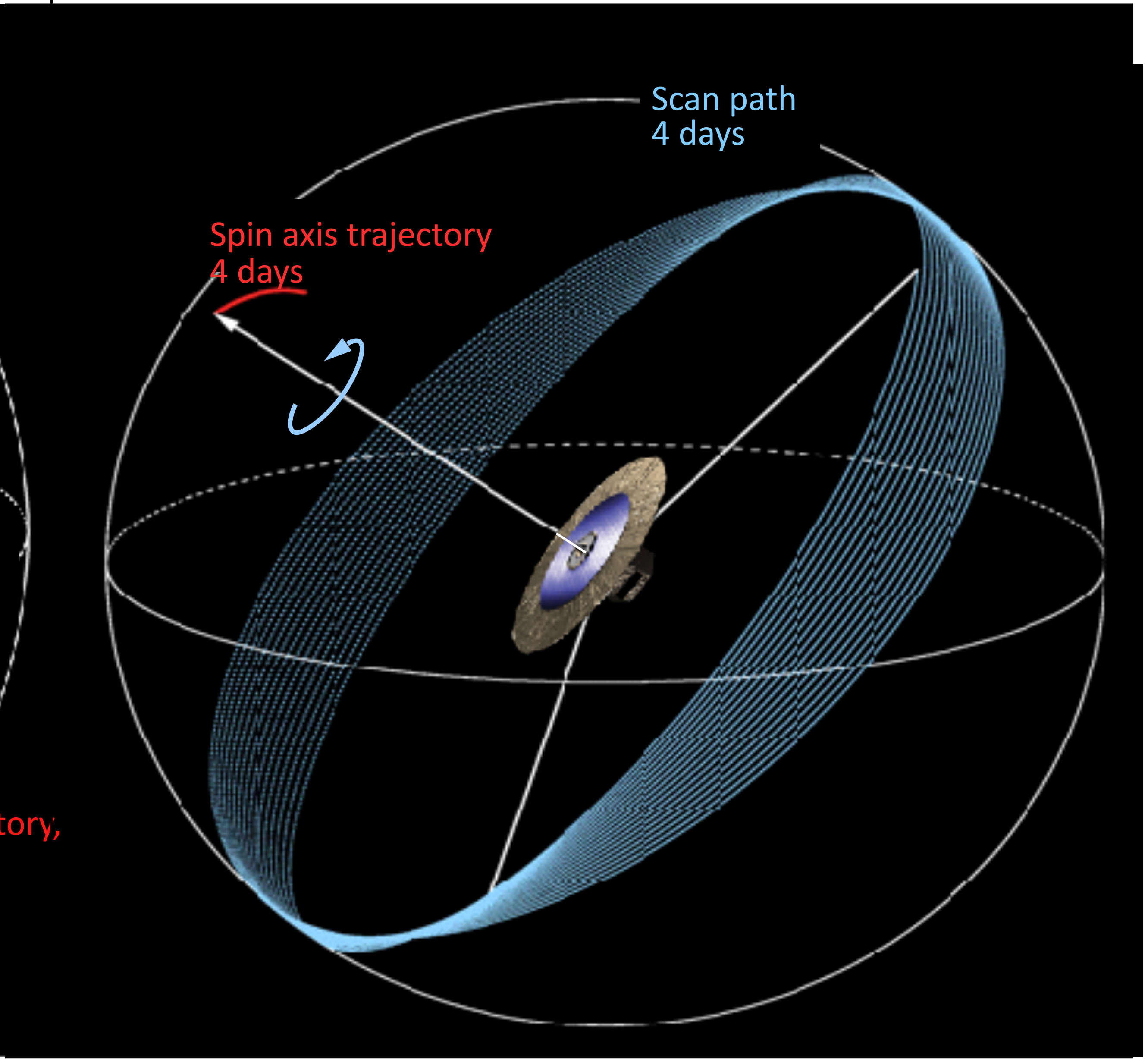

December 19, 2013

The scanning law

Rotation axis movement



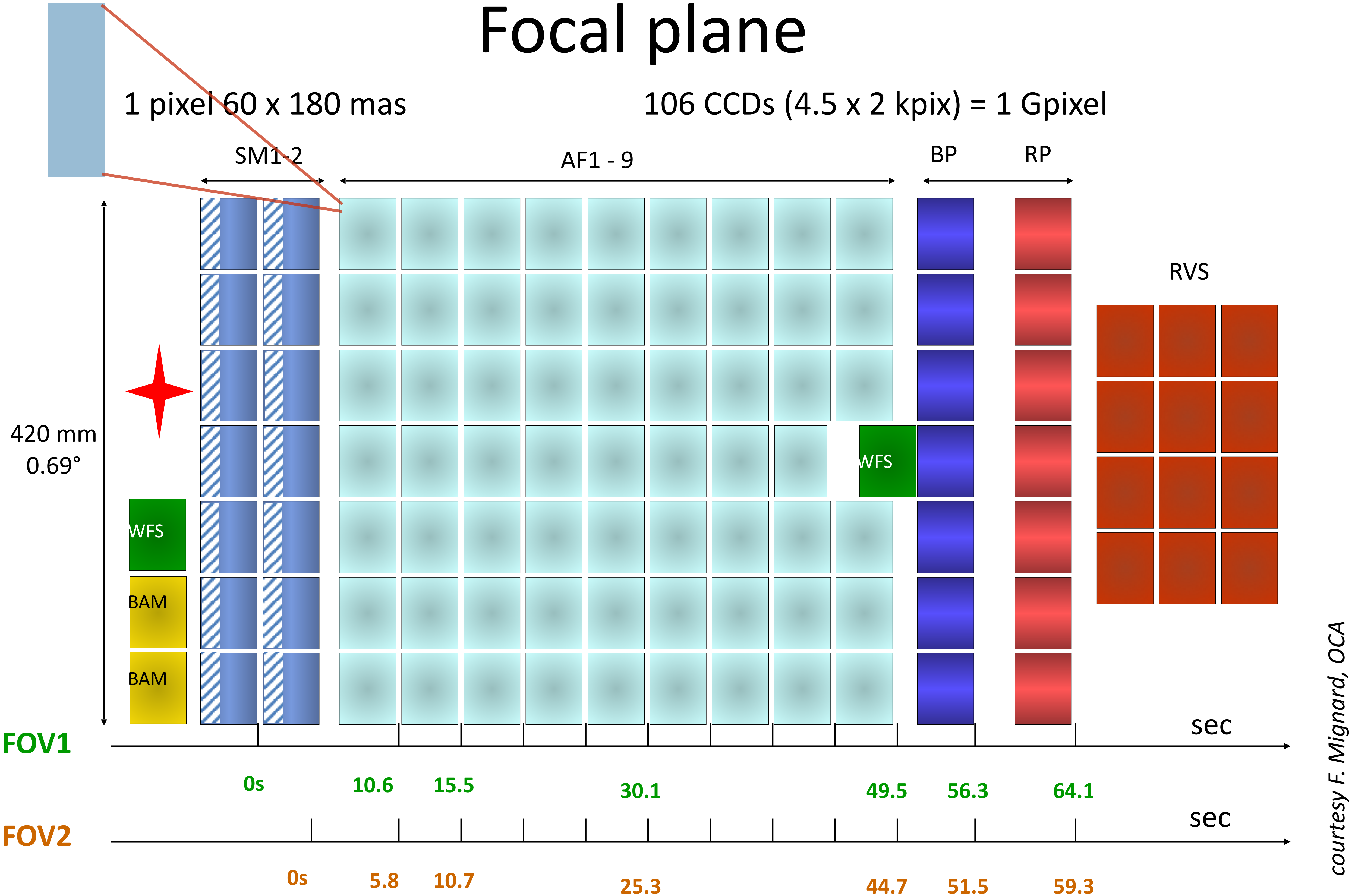
Scan path in 4 days



Focal plane

1 pixel 60 x 180 mas

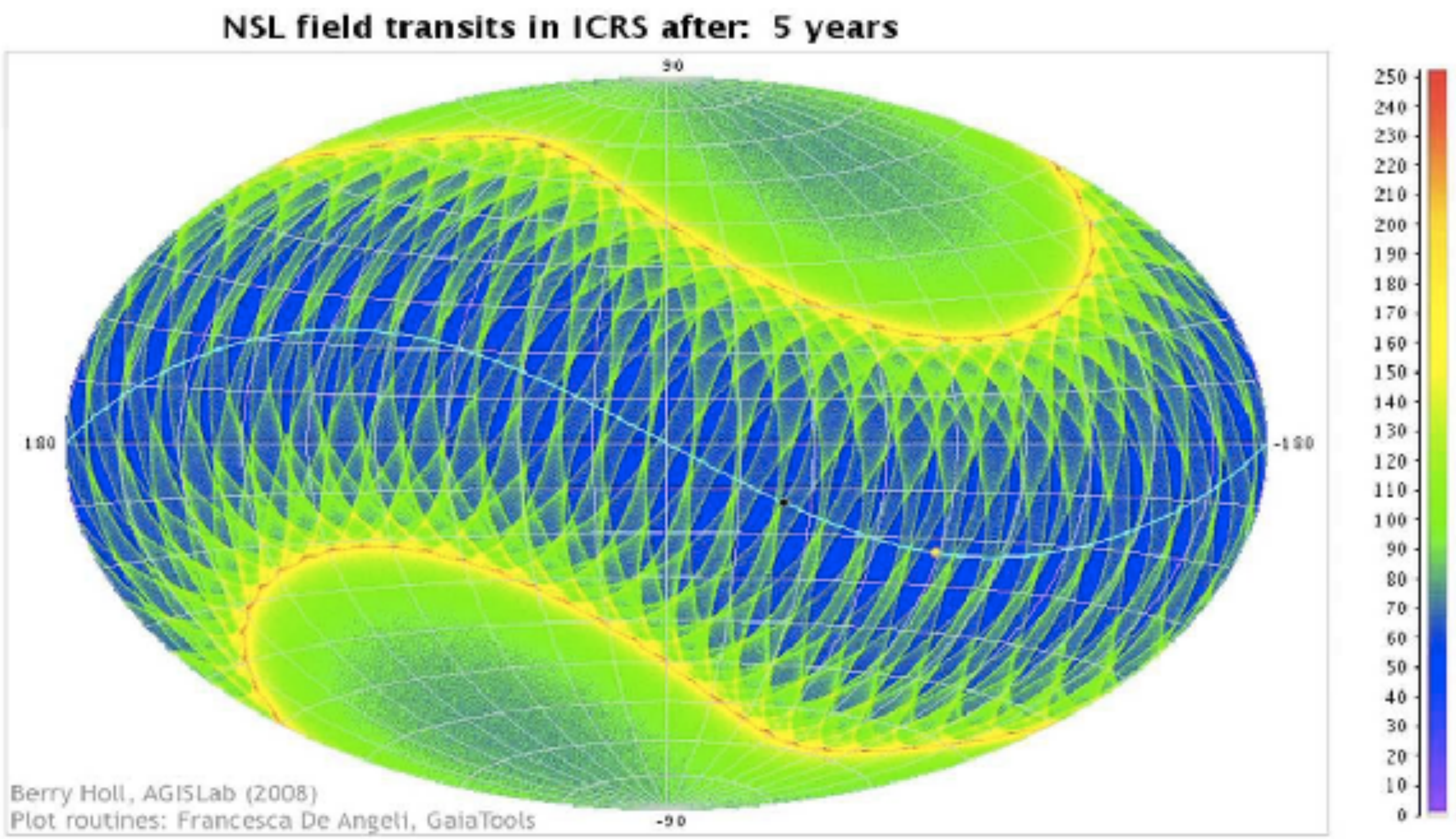
106 CCDs (4.5 x 2 kpix) = 1 Gpixel



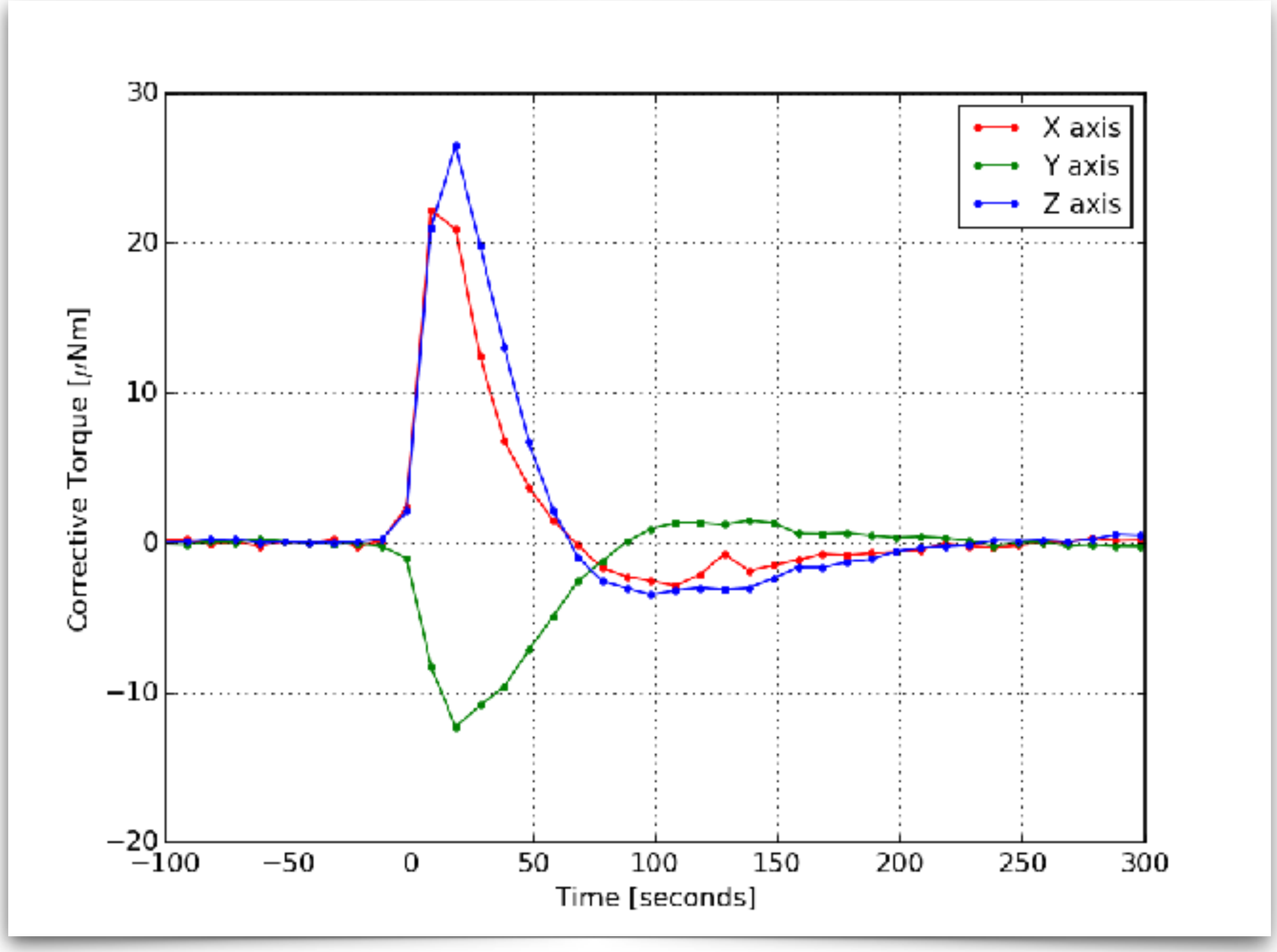
The Astrometric Global Iterative Solution (AGIS)

- 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

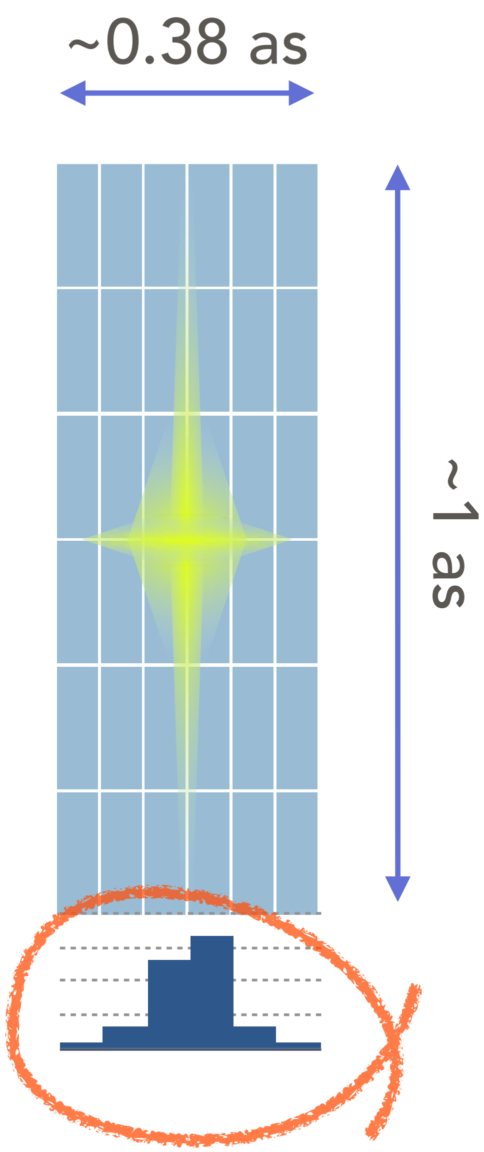
- Astrometry:
  - Accurately measure relative positions at large angles —> no zonal error
  - Measure time instead of positions (and control very accurately the transformation)
  - Average the signal over several 10.000s pixels (good for photometry too)
- Spectro-photometry
  - provide colors and low-resolution 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

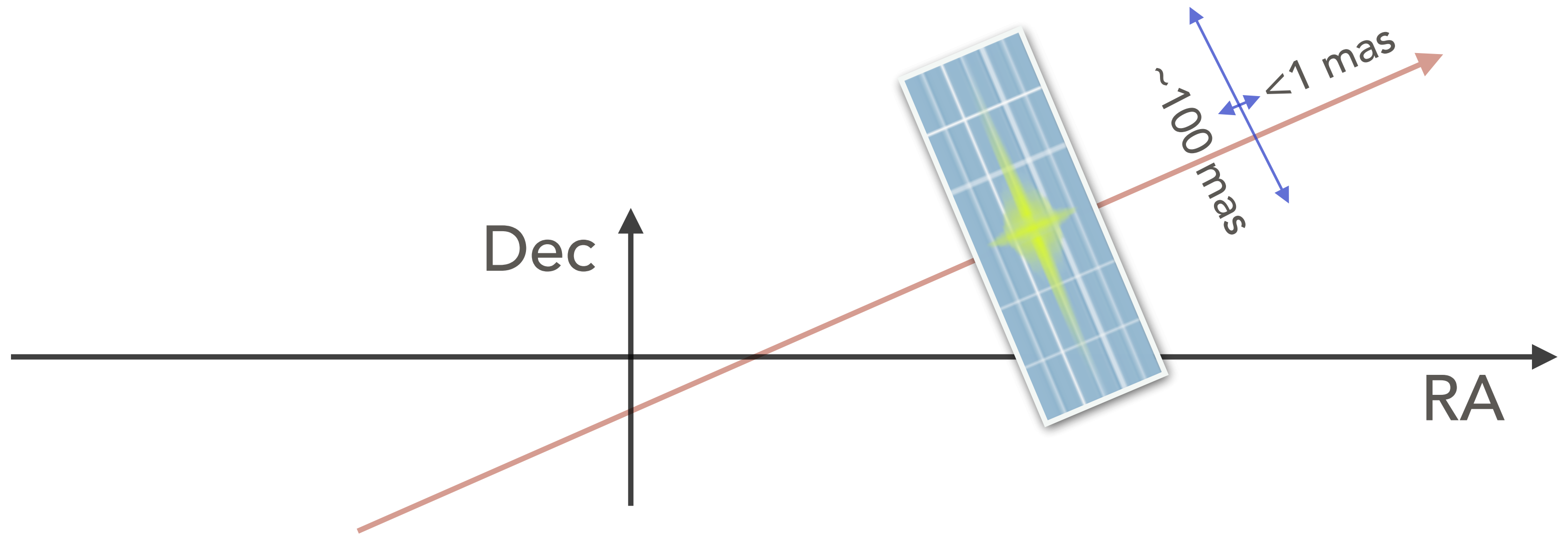
- (Except for testing in a special mode)
- Operates in TDI mode (line period 1 ms)
- Small windows read from the CCD around the sources
- 2D windows are binned across scan —> 1 D data sample (typ. 6 pixels)
- on board lossless compression

- Fundamental measurement: crossing time of a fiducial line on the CCD by the brightness peak of a source



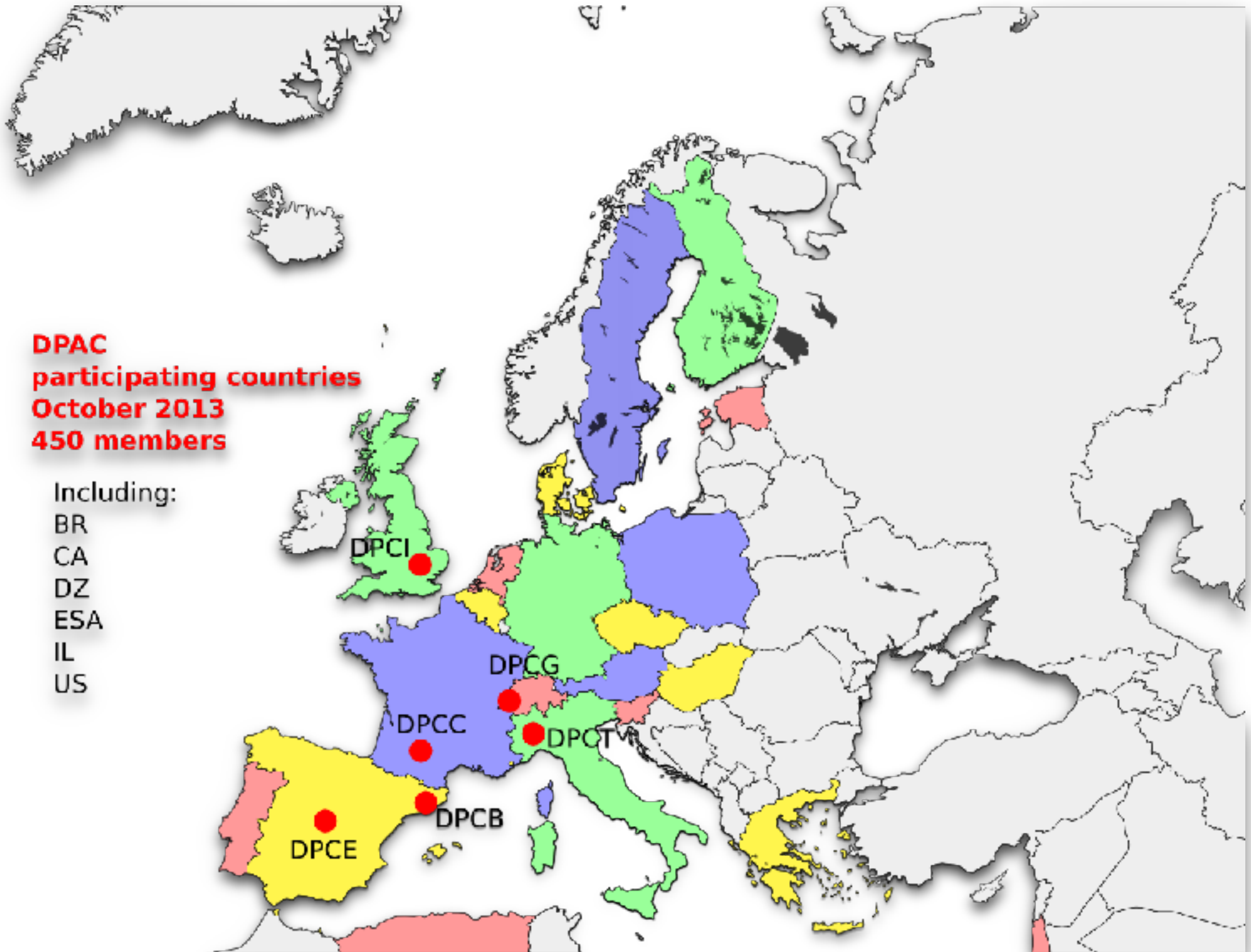
Gaia produces unusual epoch astrometry

- 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)

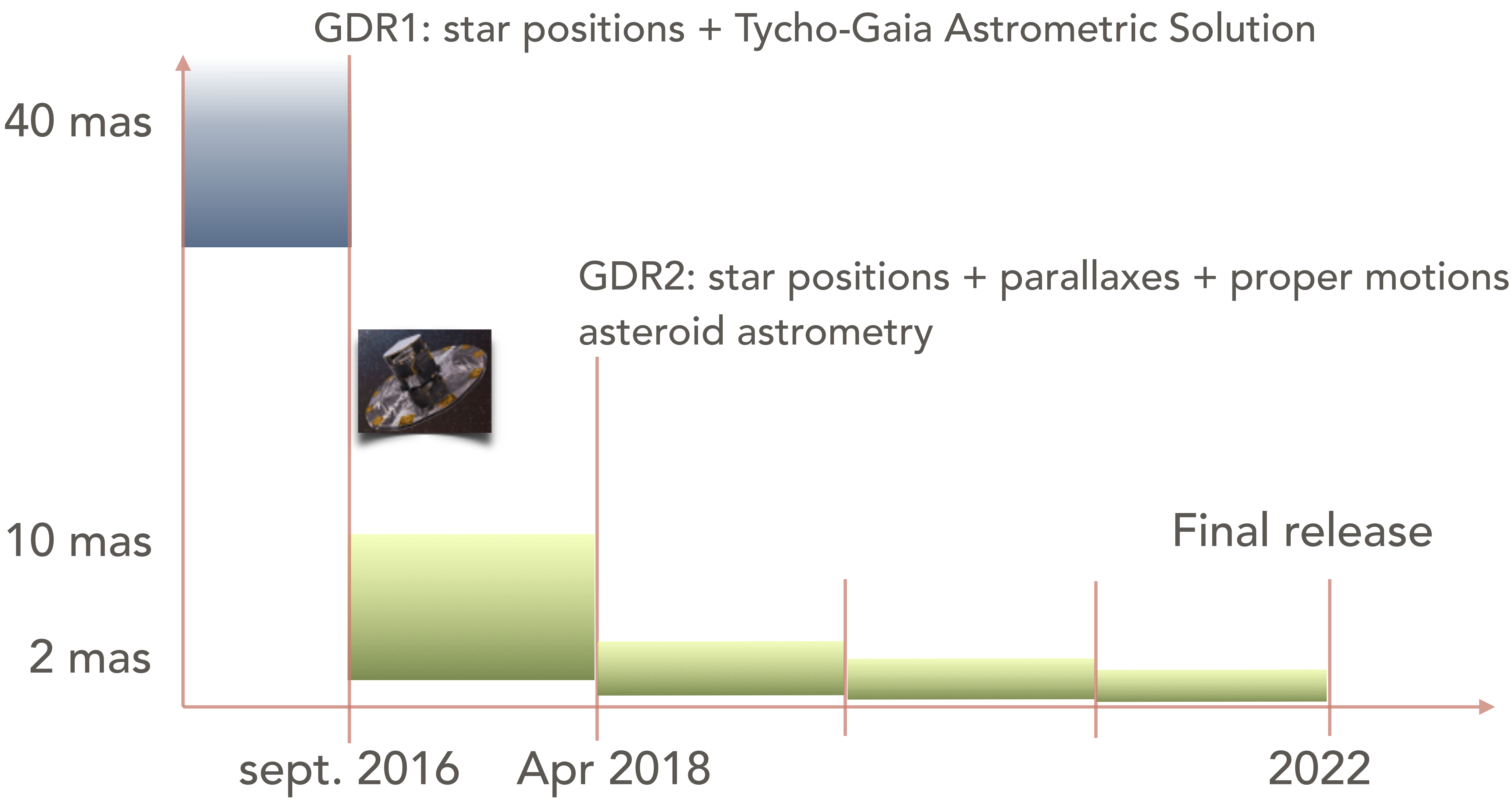


- When rotated to (RA, dec) this results in highly correlated uncertainties
- This is not (very) relevant for stars
- It is fundamental for asteroids! Pay attention to the covariance matrix

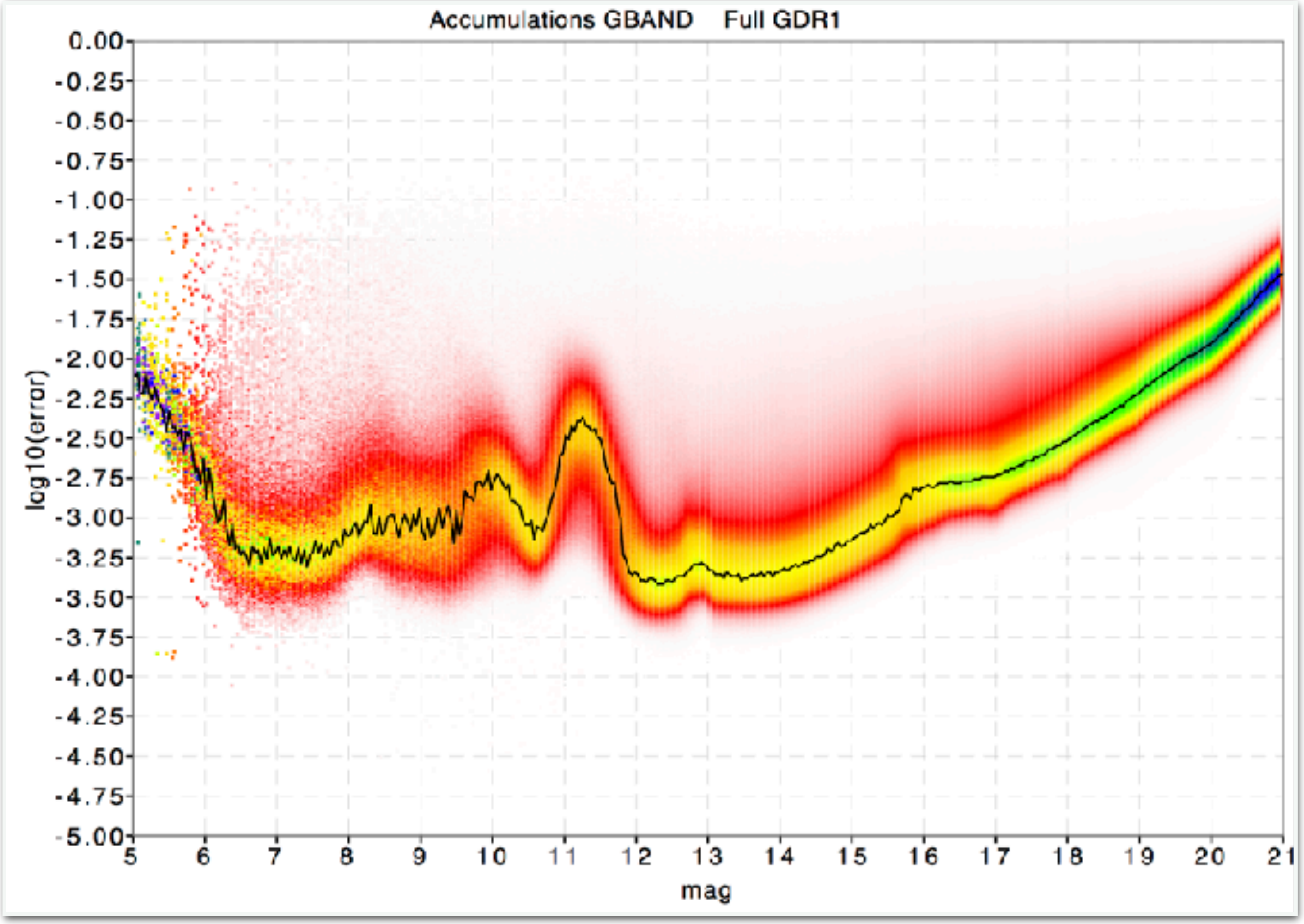
The Data Processing and Analysis Consortium - since 2007



Gaia data - when?

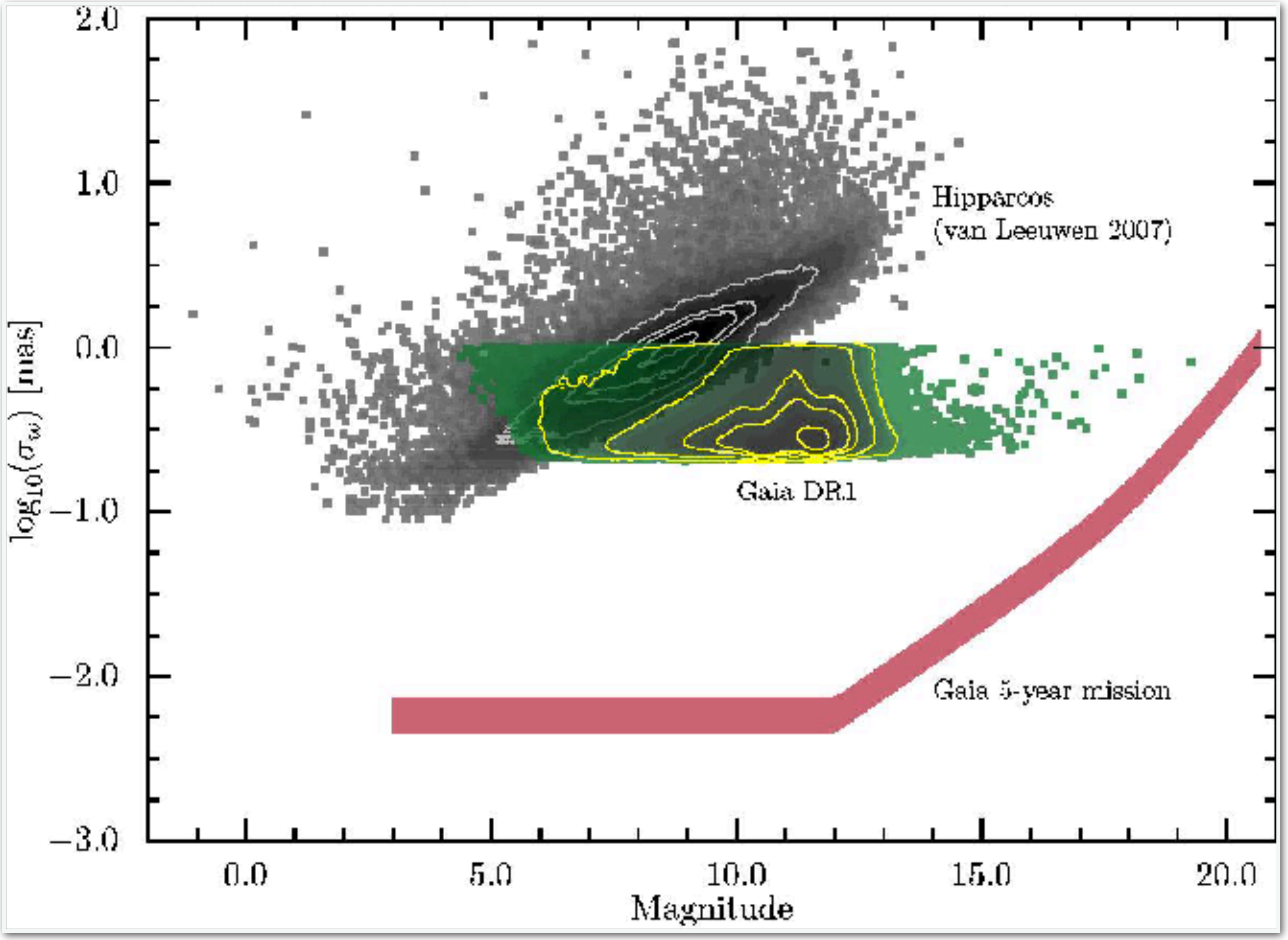


GDR1: brightness accuracy

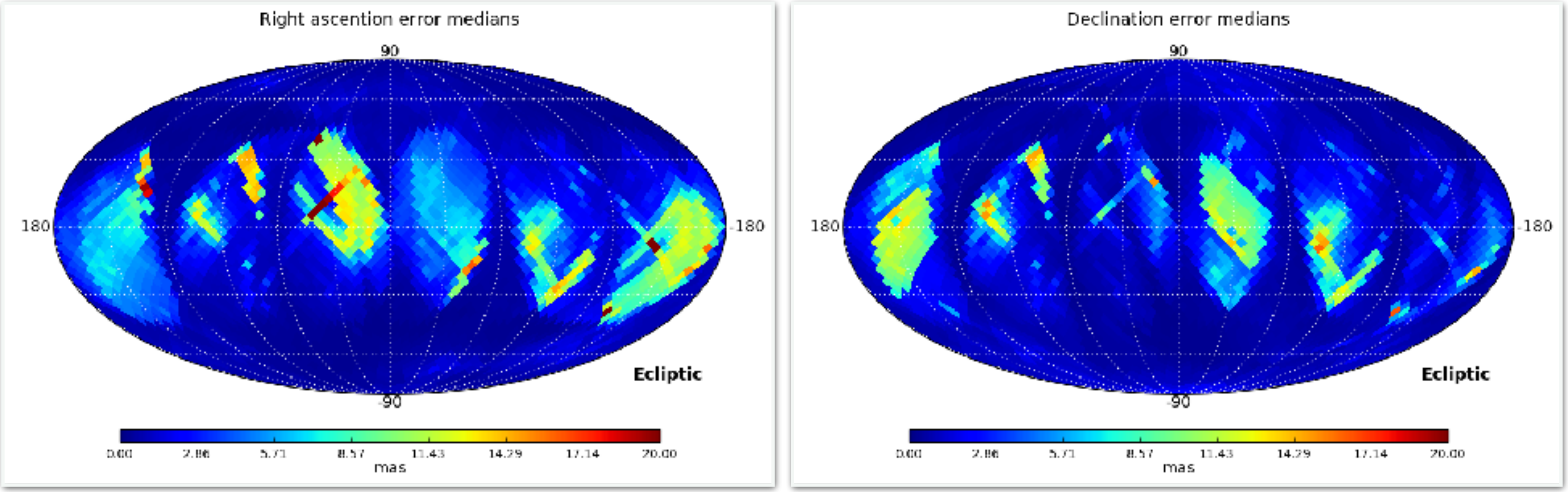


This plot shows the distribution of the estimated uncertainties on the weighted mean G-band photometry as a function of magnitude. The colours indicate the density of data points, from low (red) to high (blue) on a logarithmic scale. Credits: ESA/Gaia/DPAC

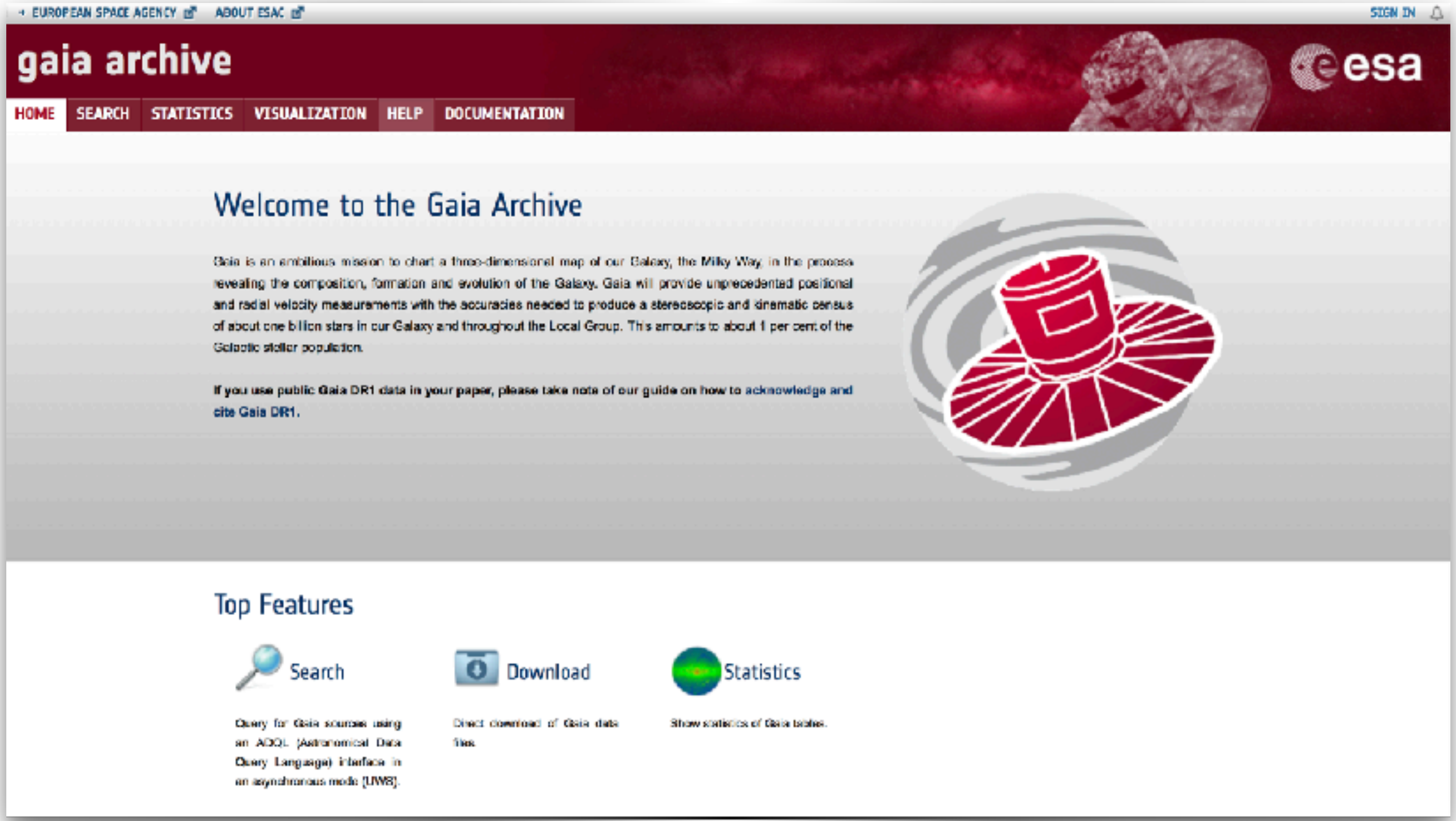
GDR1: parallax accuracy (TGAS)



GDR1: position errors



Gaia Archive



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

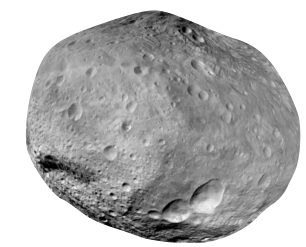
The Solar System and Gaia

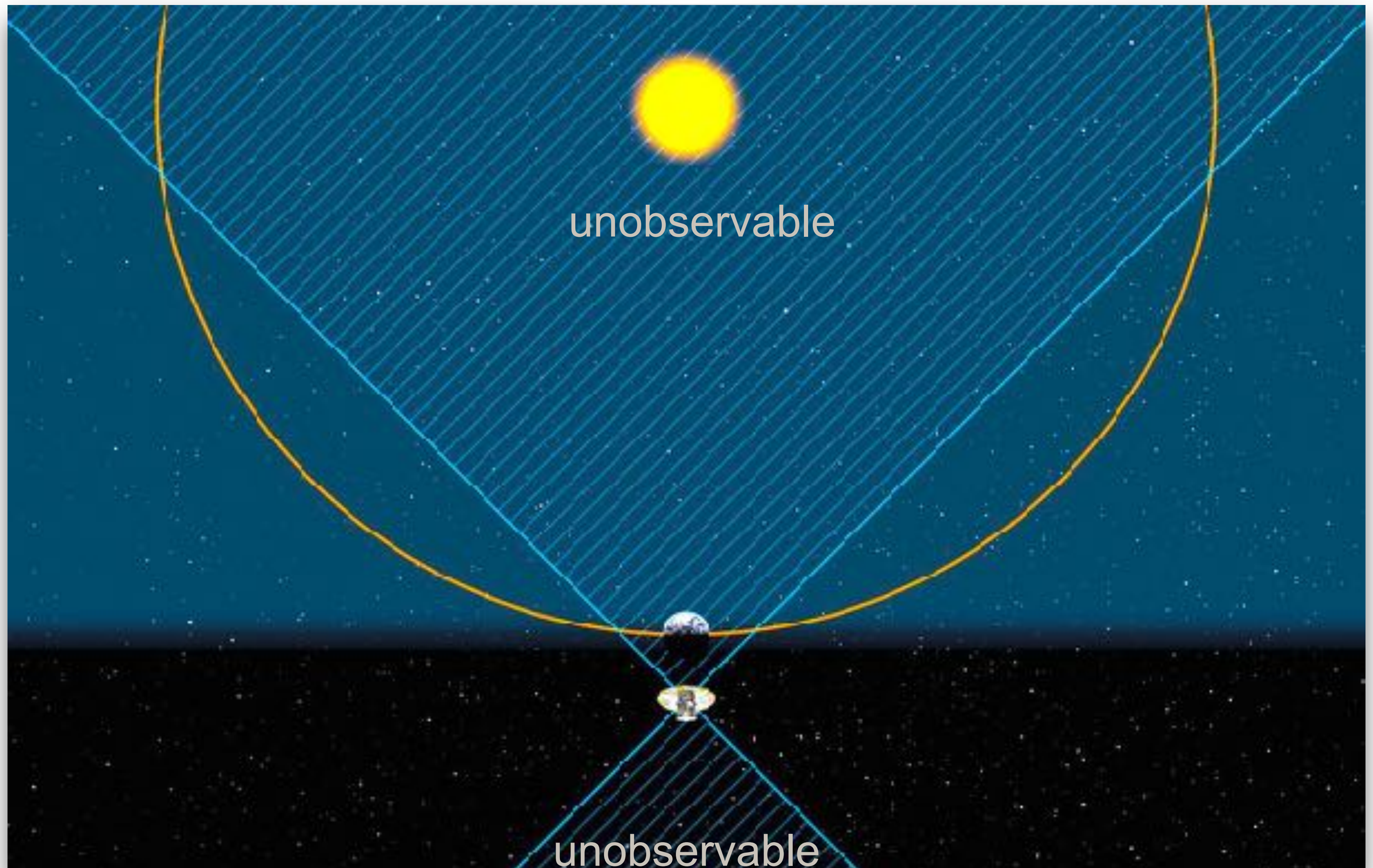
What Gaia observes

- **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

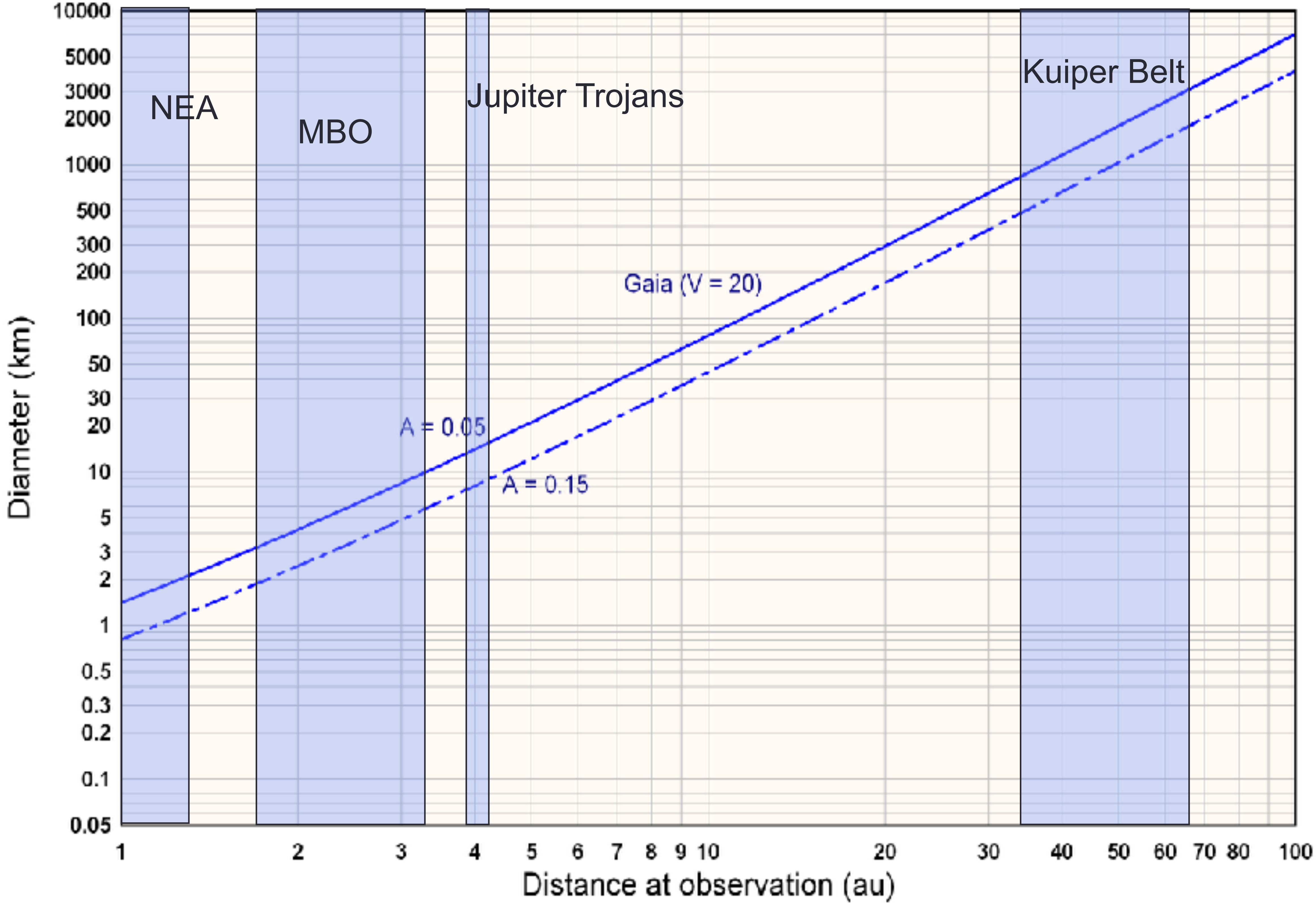




~70 observations per object

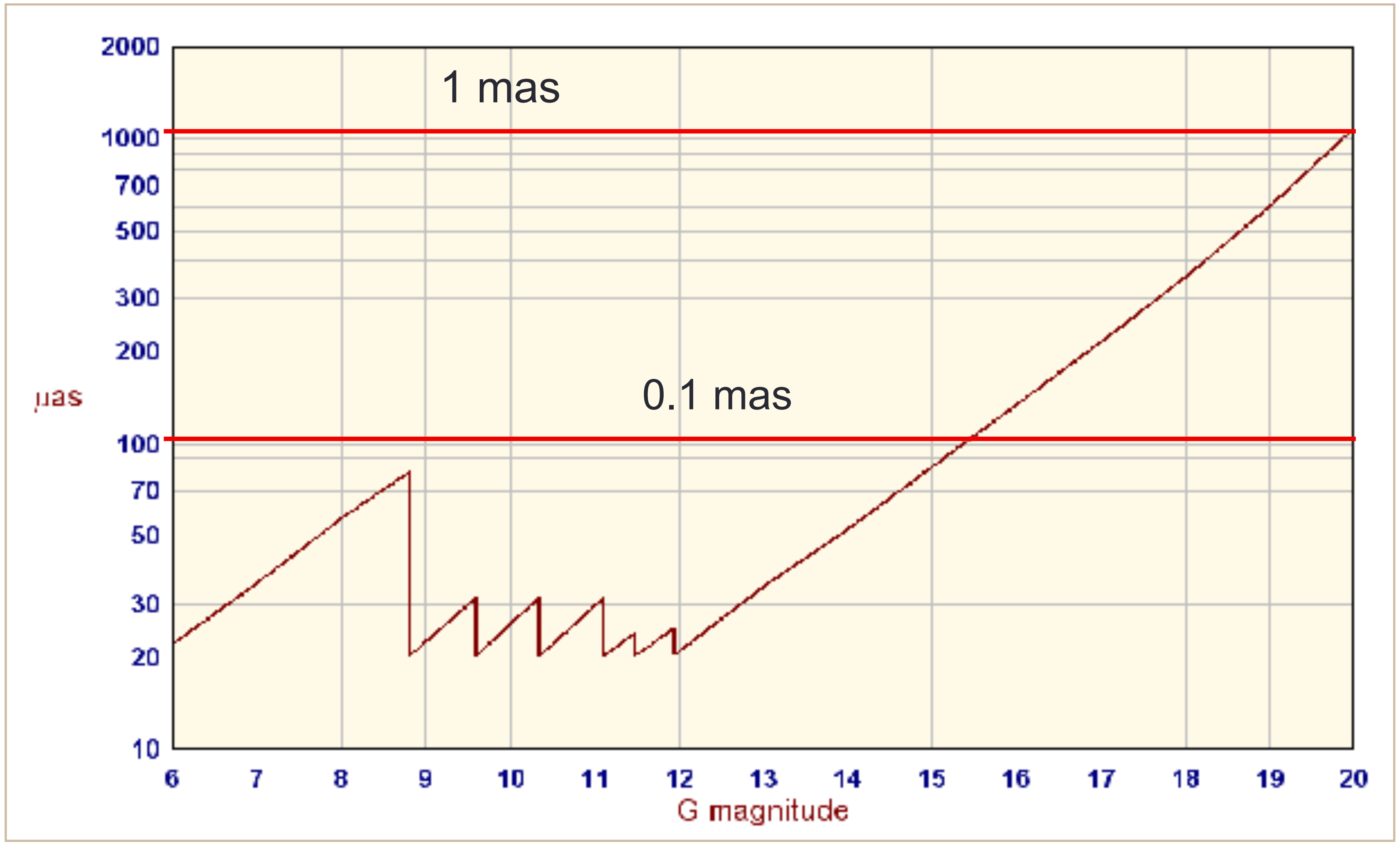
- Discovery space:
  - Low elongations (~45-60°)
  - Inner Earth Objects (~unknown)
  - Other NEOs
  - Some MBAs

What Gaia observes: how big



Gaia single-epoch astrometric accuracy

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

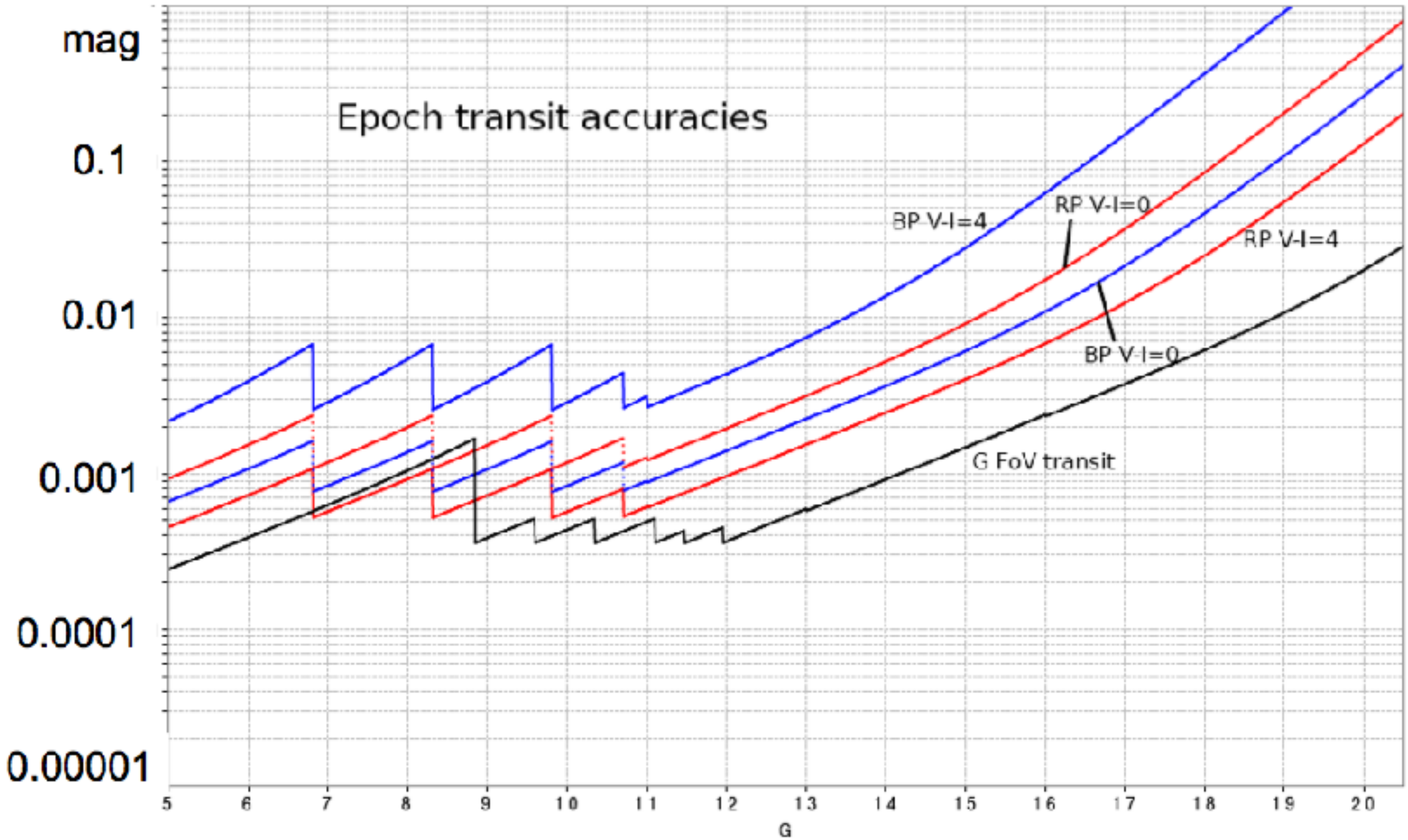


Type	Name	Number of measurement	Percentage of accepted measurement	Accuracy	
C	CCD	79 569 190	99.49%	0.388	arcsec
S	Wise	1 526 466	99.86%	0.583	arcsec
S	*Hubble* Space Telescope	867	96.54%	0.585	arcsec
S	*Spitzer*	48	33.33%	1.673	arcsec

random errors + systematic

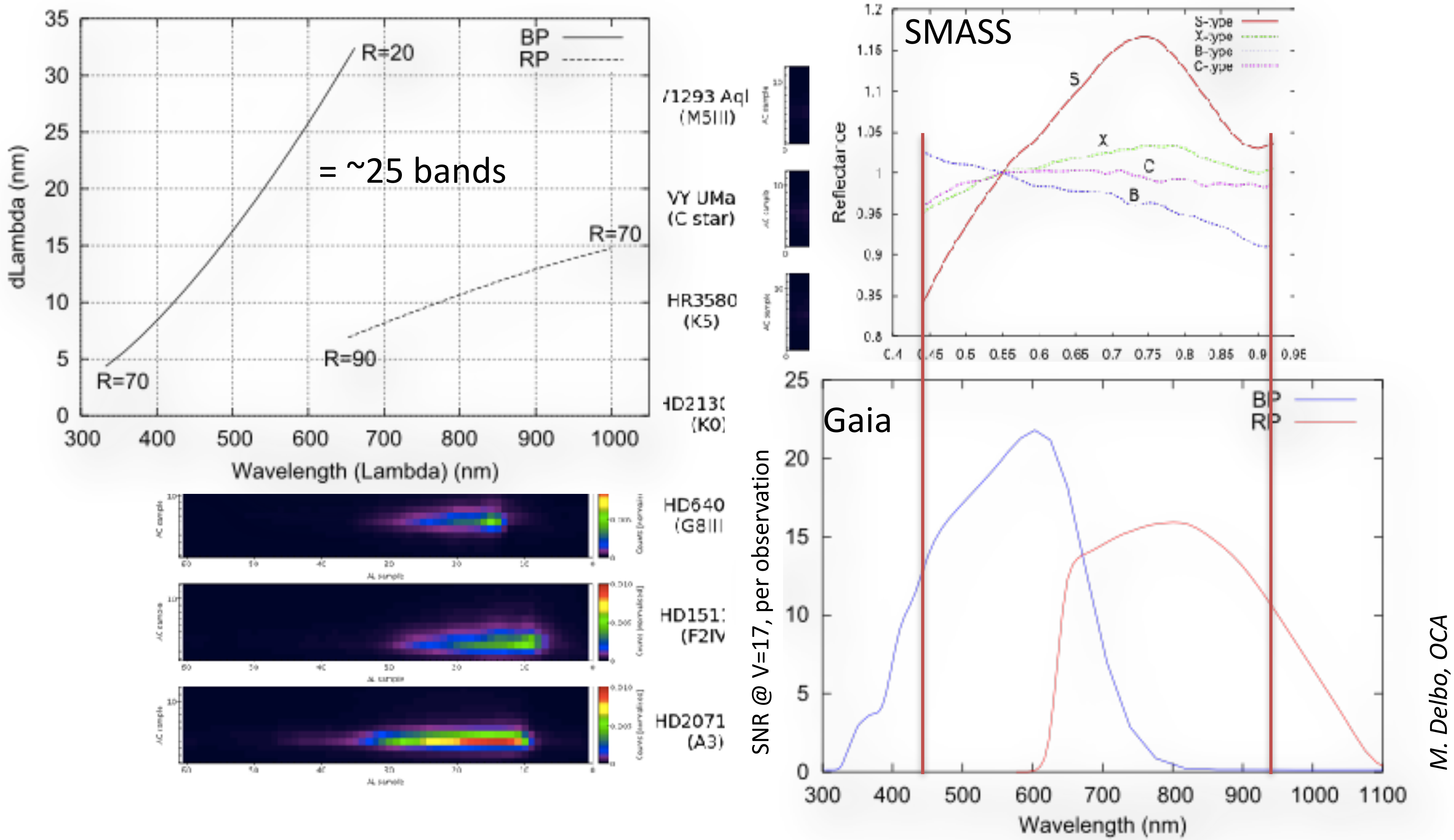
Observations in the AstDys service (Univ. Pisa)

Photometric accuracy



(courtesy D. Evans)

Low-resolution spectroscopy



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

Astrometry

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

Ground-based follow-up
Search for binaries
Asteroid occultations
Re-processing of "old" astrometry

resolution

- Diameter ~1000 asteroids

→more sizes, masses
→densities

spectro-photometry

- Composition, taxonomy
- Shape, pole, rotation period

Asteroid families
Differentiation signatures
Collisional evolution

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

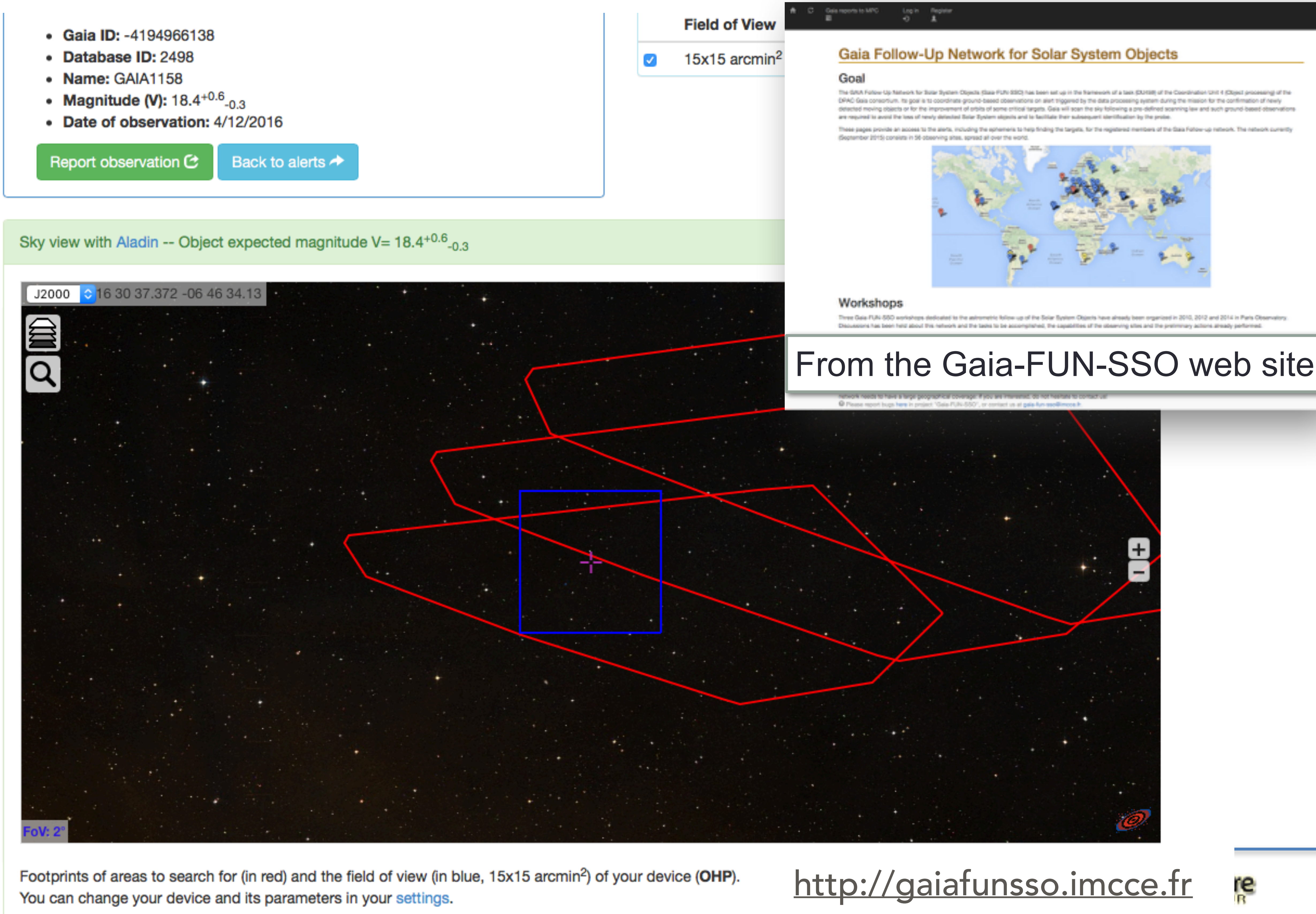
→ ground-based alert network

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

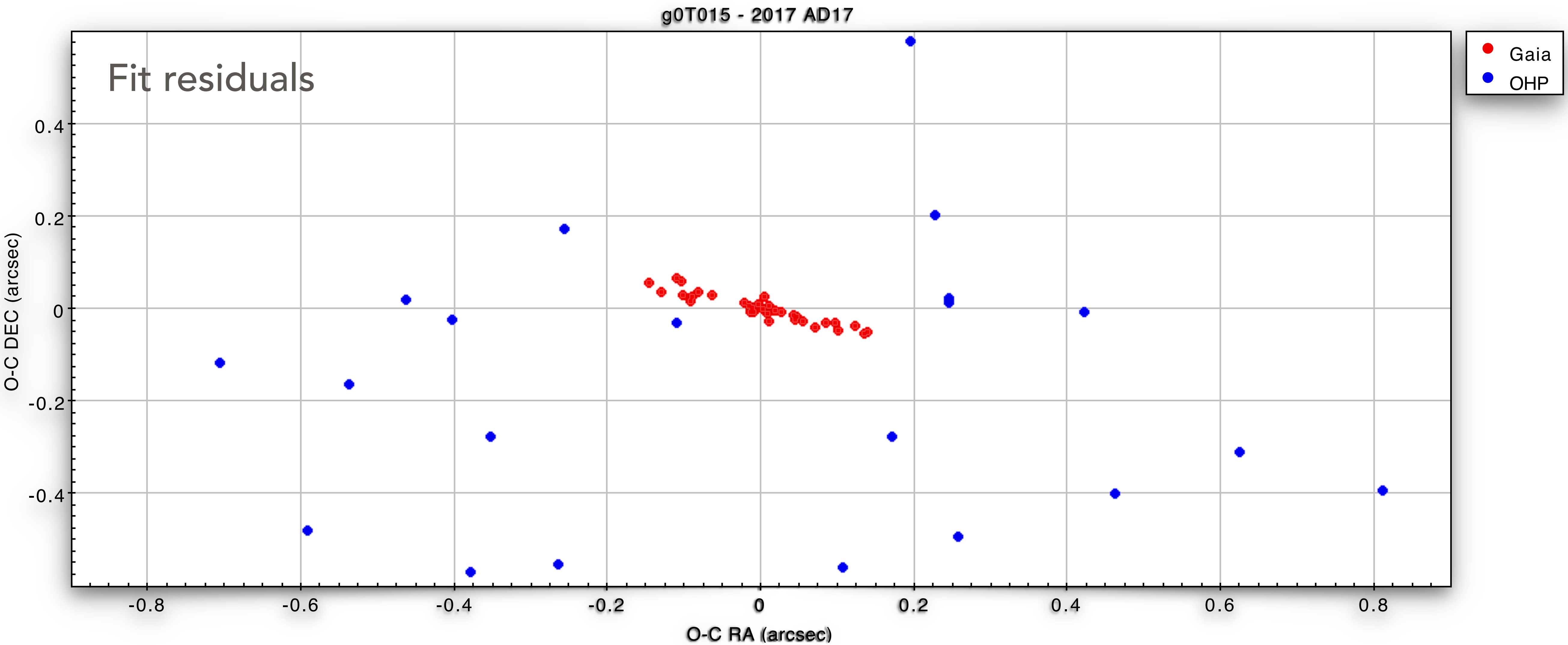


From the Gaia-FUN-SSO web site

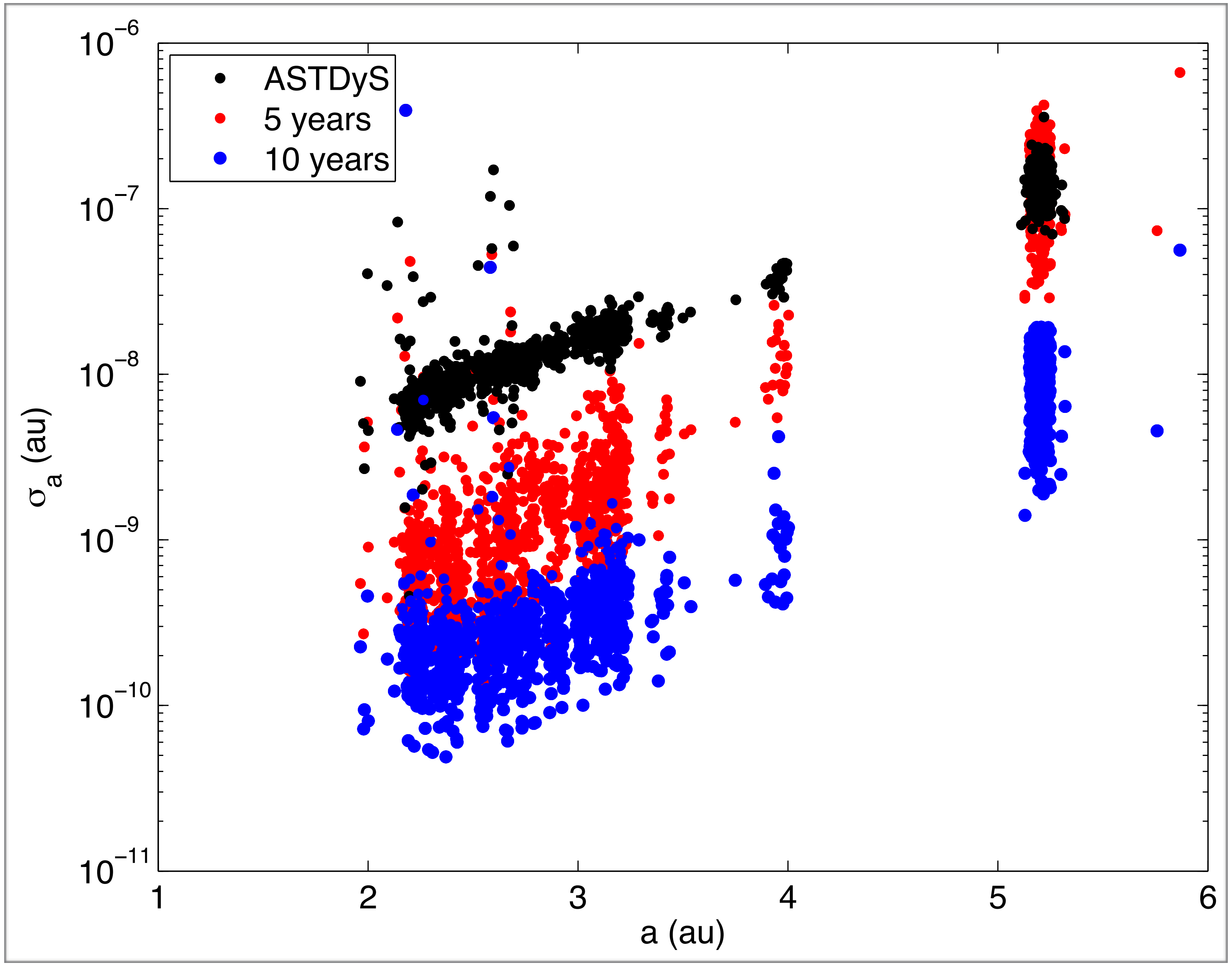
http://gaiafunsso.imcce.fr

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

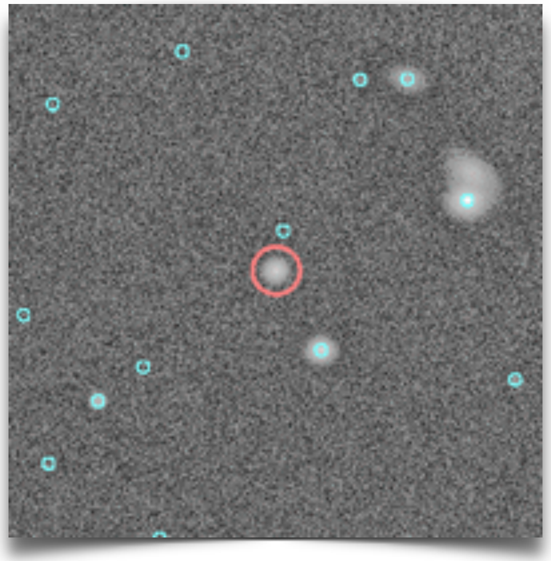
But we don't have asteroid astrometry by Gaia, yet!

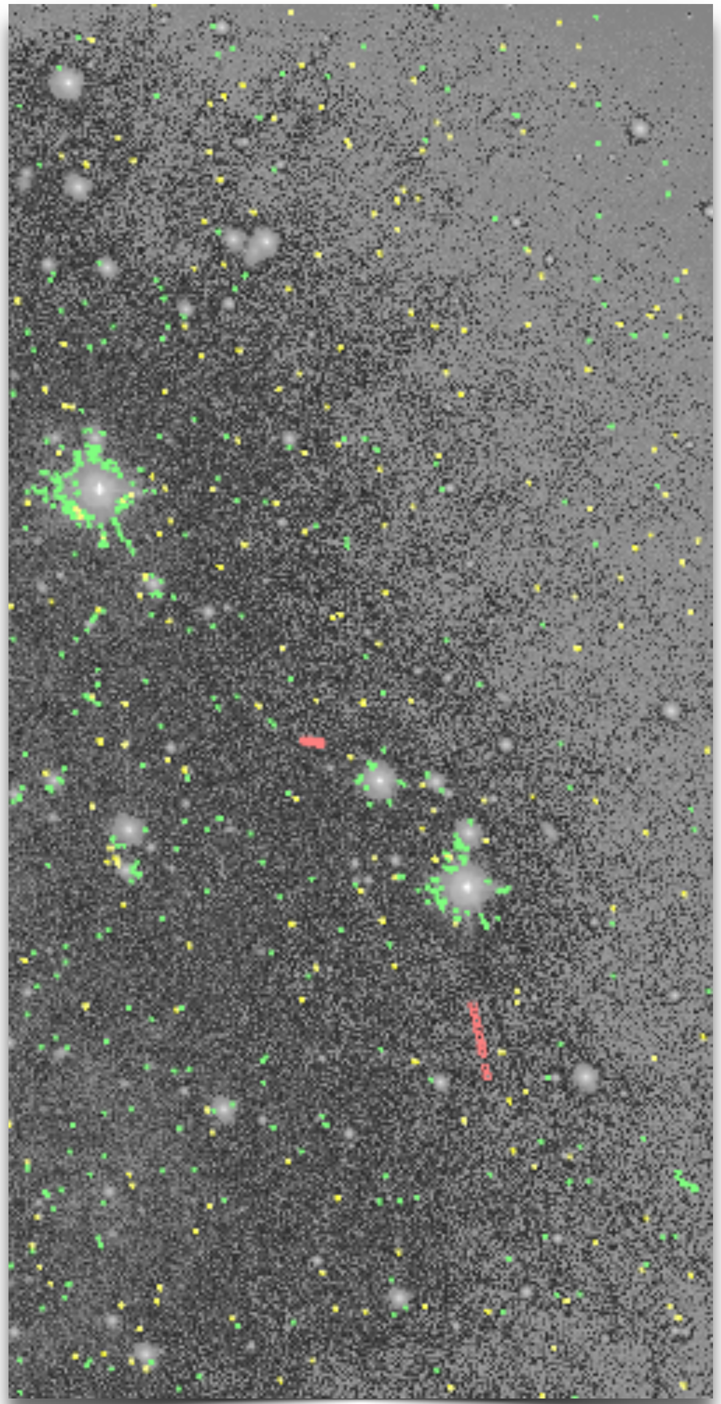
So, what can we do?

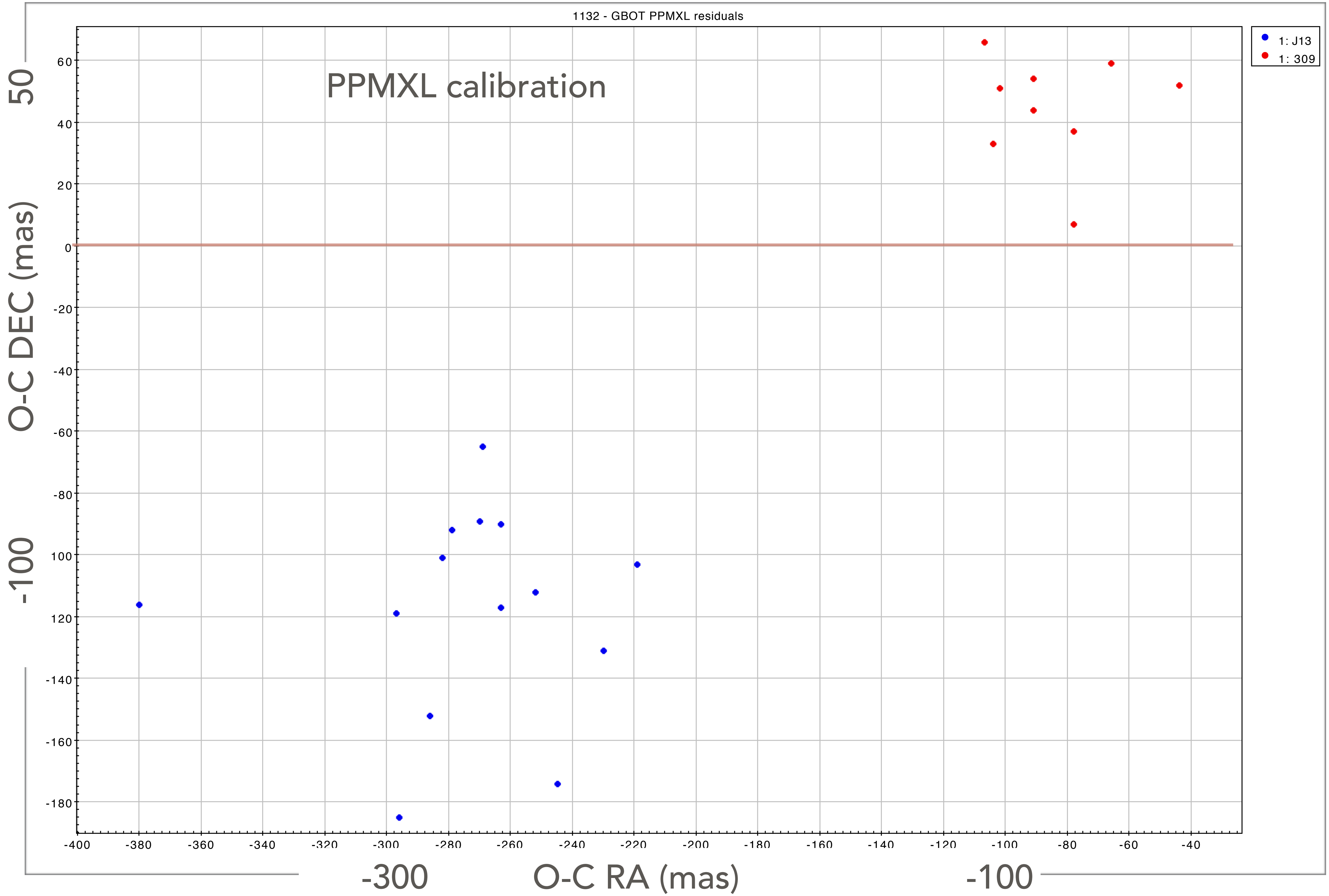
Exploit the stars in GDR1 !

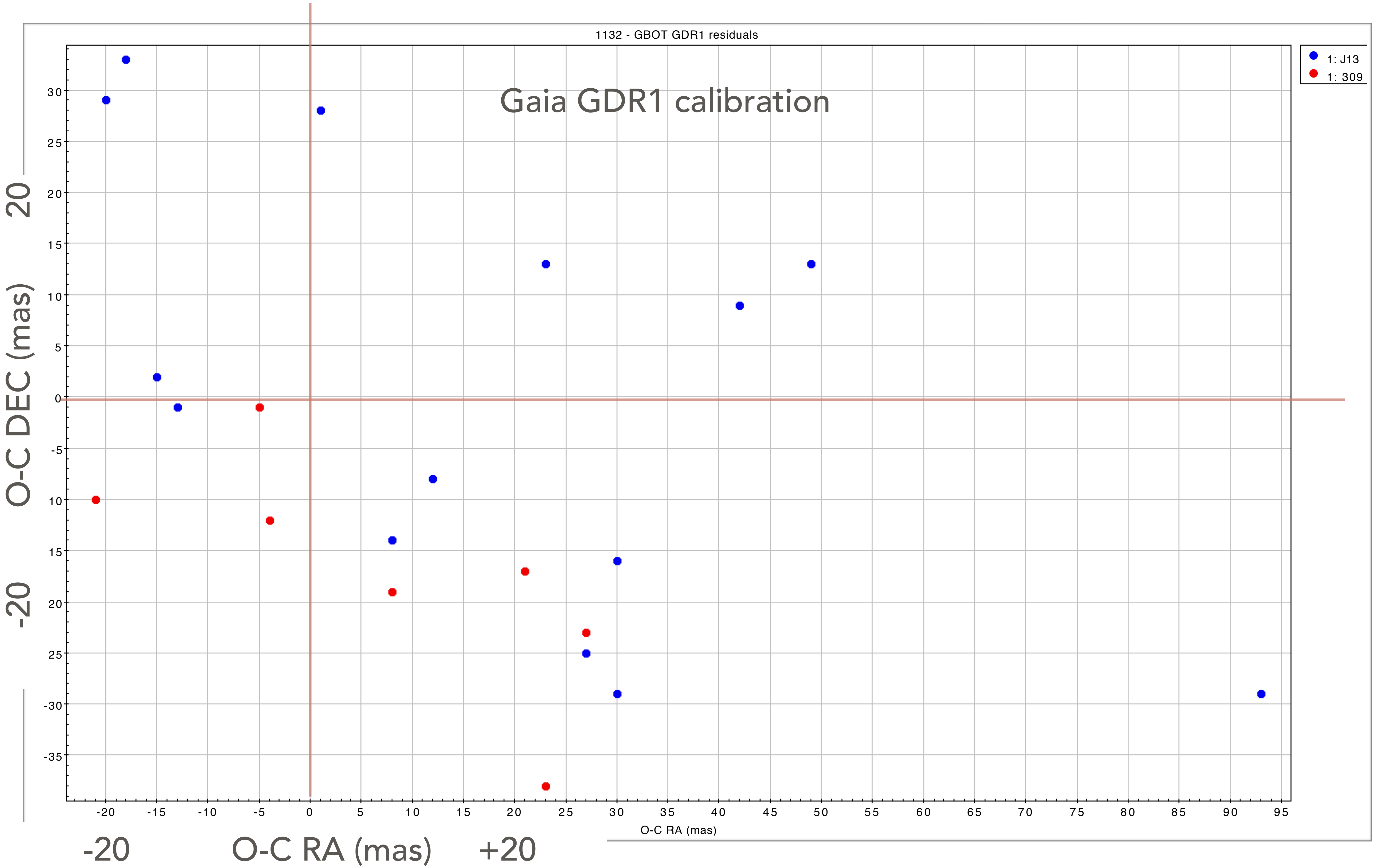
Re-calibration of ground-based astrometry

- 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



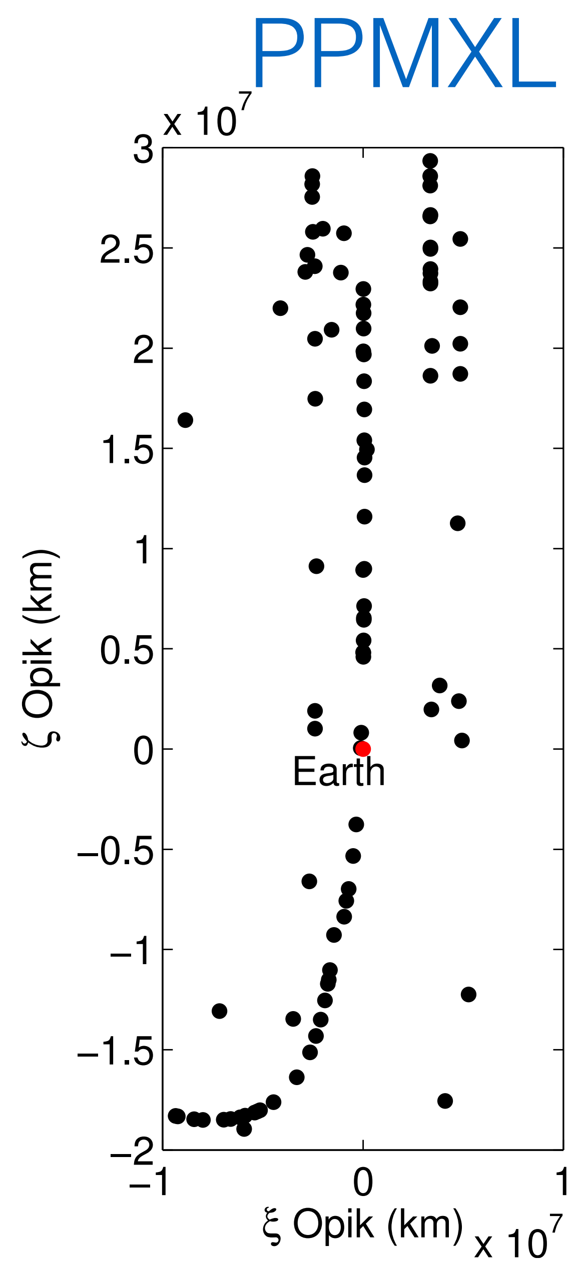


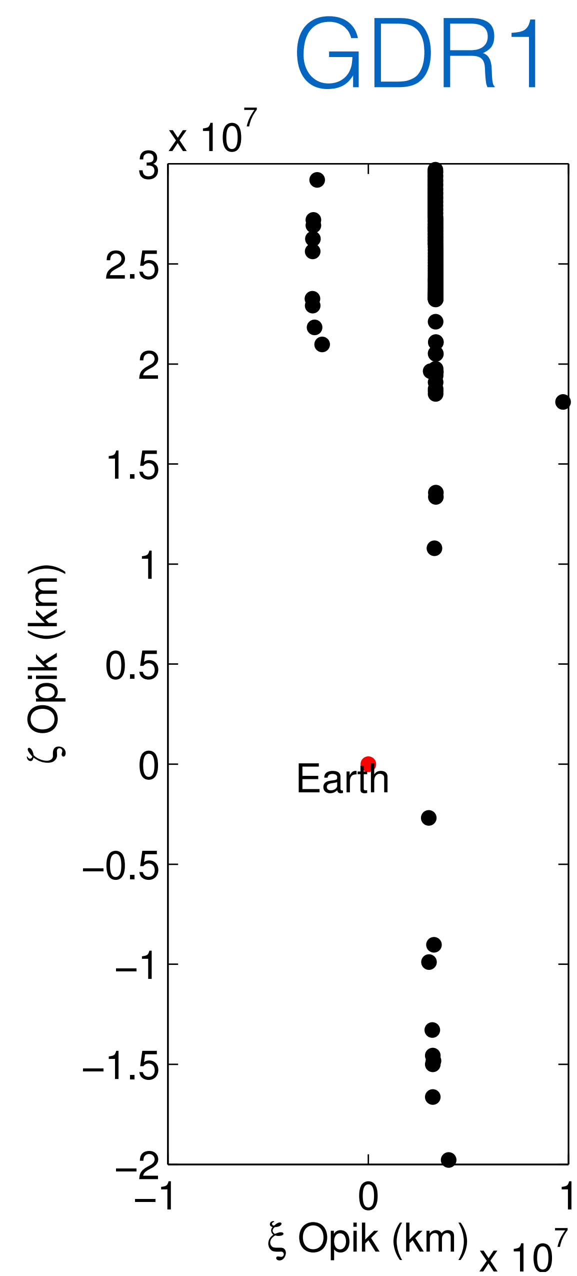

1132 - GBOT PPMXL residuals
PPMXL calibration
1: J13
1: 309
O-C DEC (mas)
50
-100
60
40
20
0
-20
-40
-60
-80
100
120
-140
-160
-180
-400
-380
-360
-340
-320
-300
-280
-260
-240
-220
-200
-180
-160
-140
-120
-100
-80
-60
-40
-300
O-C RA (mas)
-100


1132 - GBOT GDR1 residuals
1: J13
1: 309
Gaia GDR1 calibration
O-C DEC (mas)
20
-20
O-C RA (mas)
-20
O-C RA (mas)
+20

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





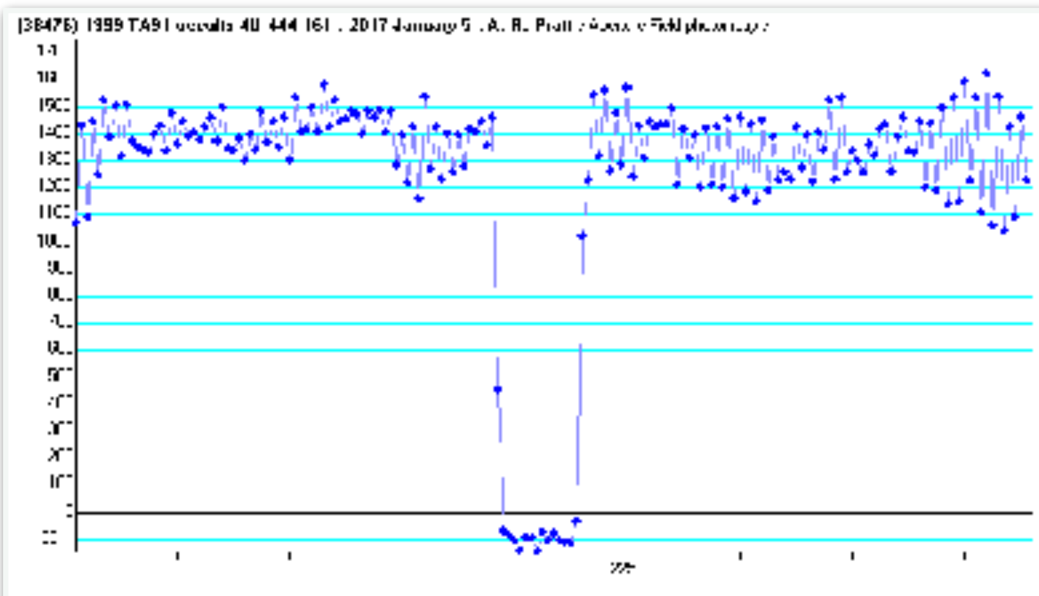
The revolution in astrometry

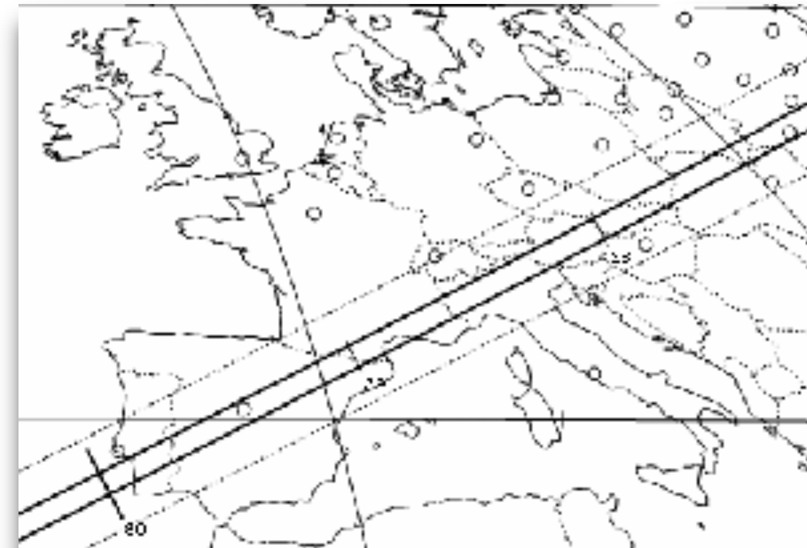
- …does not come for free!
- Tools must be ready to handle accuracy ~100 X better
- An appropriate, careful weighting of the observations is necessary

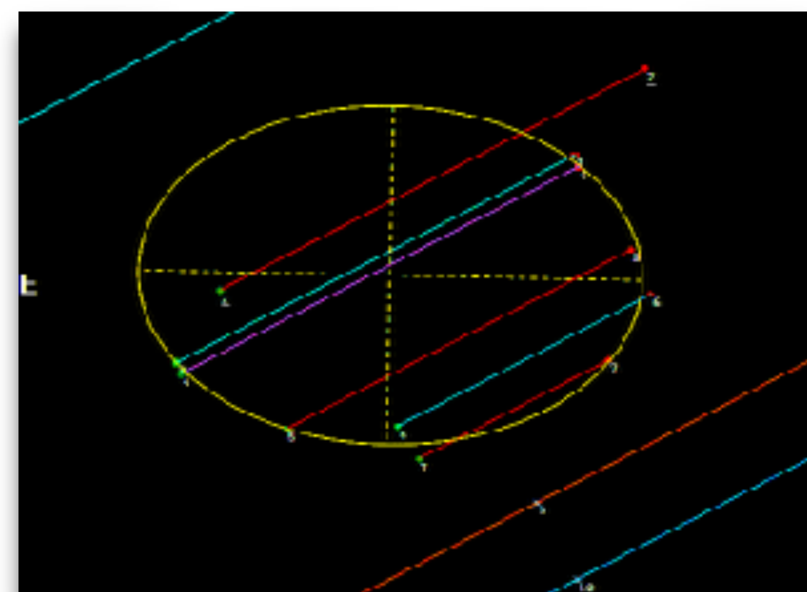
- A factor 10 X improvement is accessible with GDR1
- More to come…!

Stellar occultations: potential with Gaia

- predictions based on GDR1 available since end 09/2015



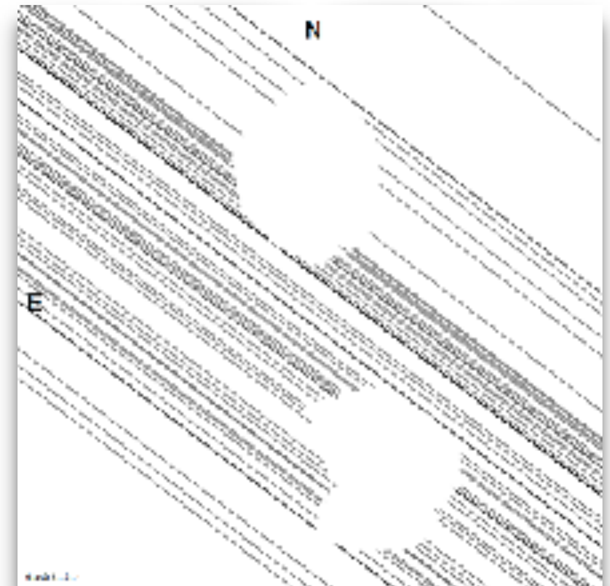




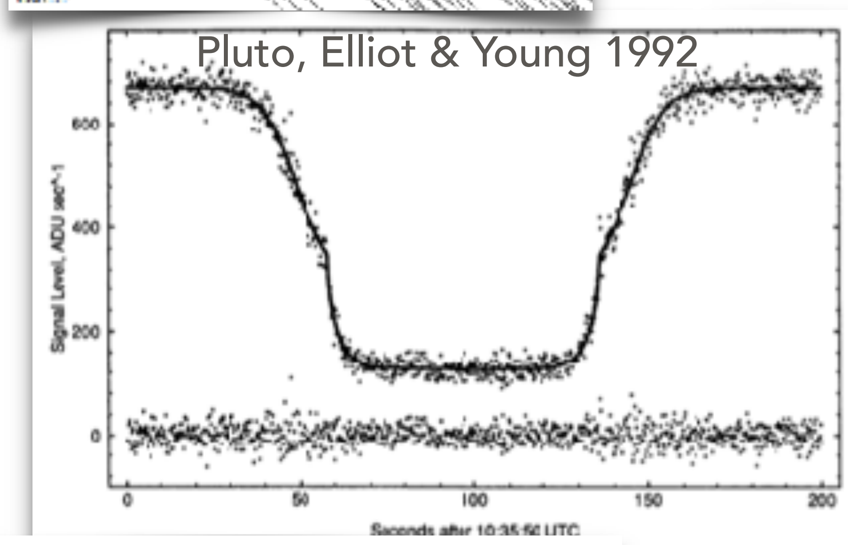
The duration of the occultation can be transformed into a chord length.
Typ. AL accuracy of the occultation ~0.1-0.2 s = 1 - 3 km

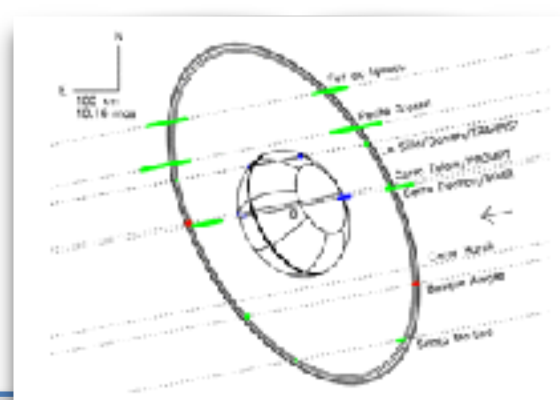
Occultations: science case

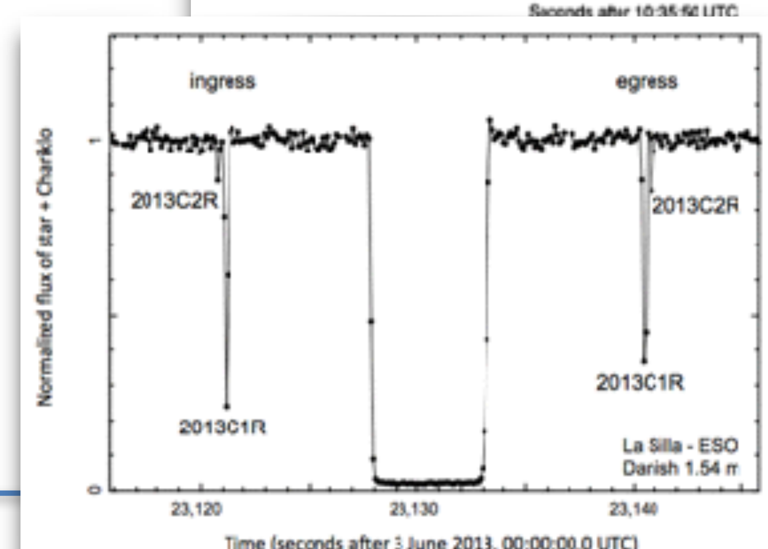
- Determine asteroid sizes, shapes
  - discriminate among spin pole solutions
  - calibrate indirect size determination methods (thermo-physical modeling)
  - complement photometric inversion (”KOALA”)
  - the only efficient method for TNO size determination
- Measure binary systems
  - separations,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



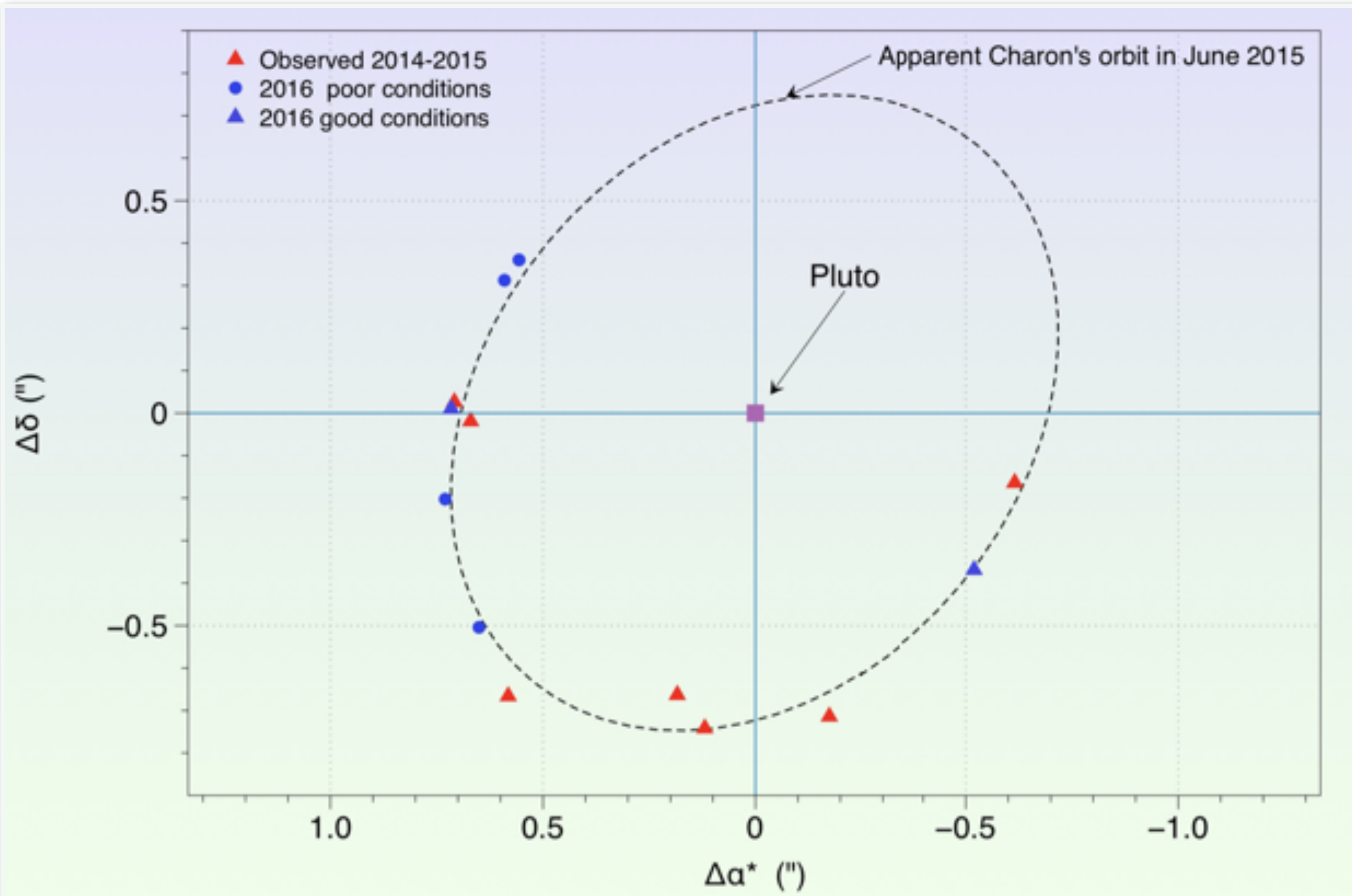
90 Antiope



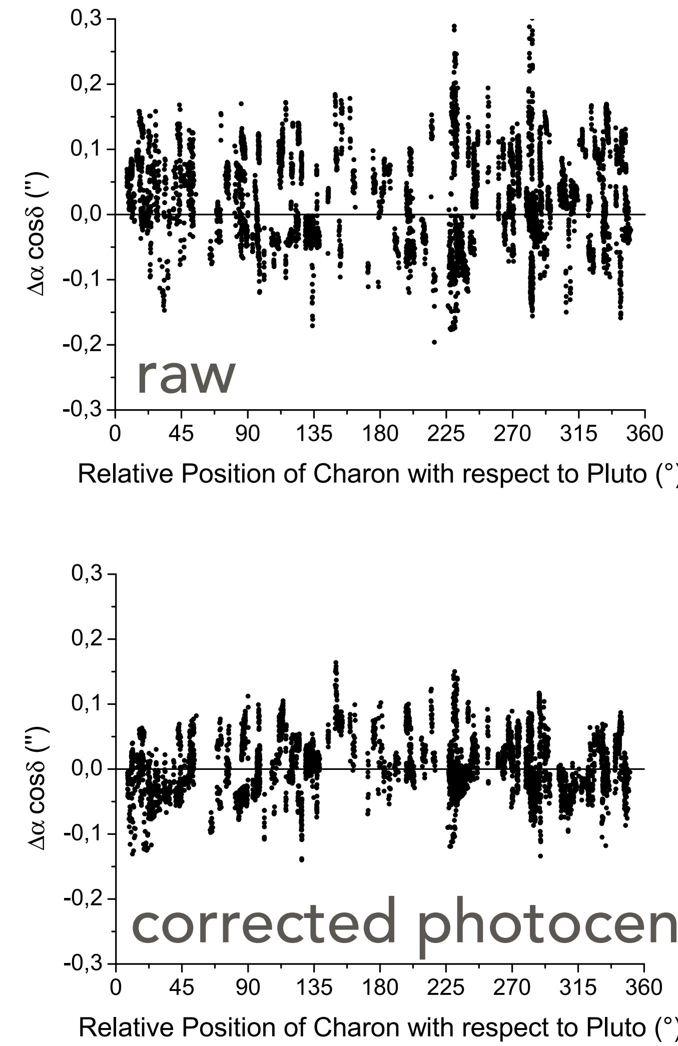




Pluto and Charon from *daily astrometric calibration (~70 mas)*



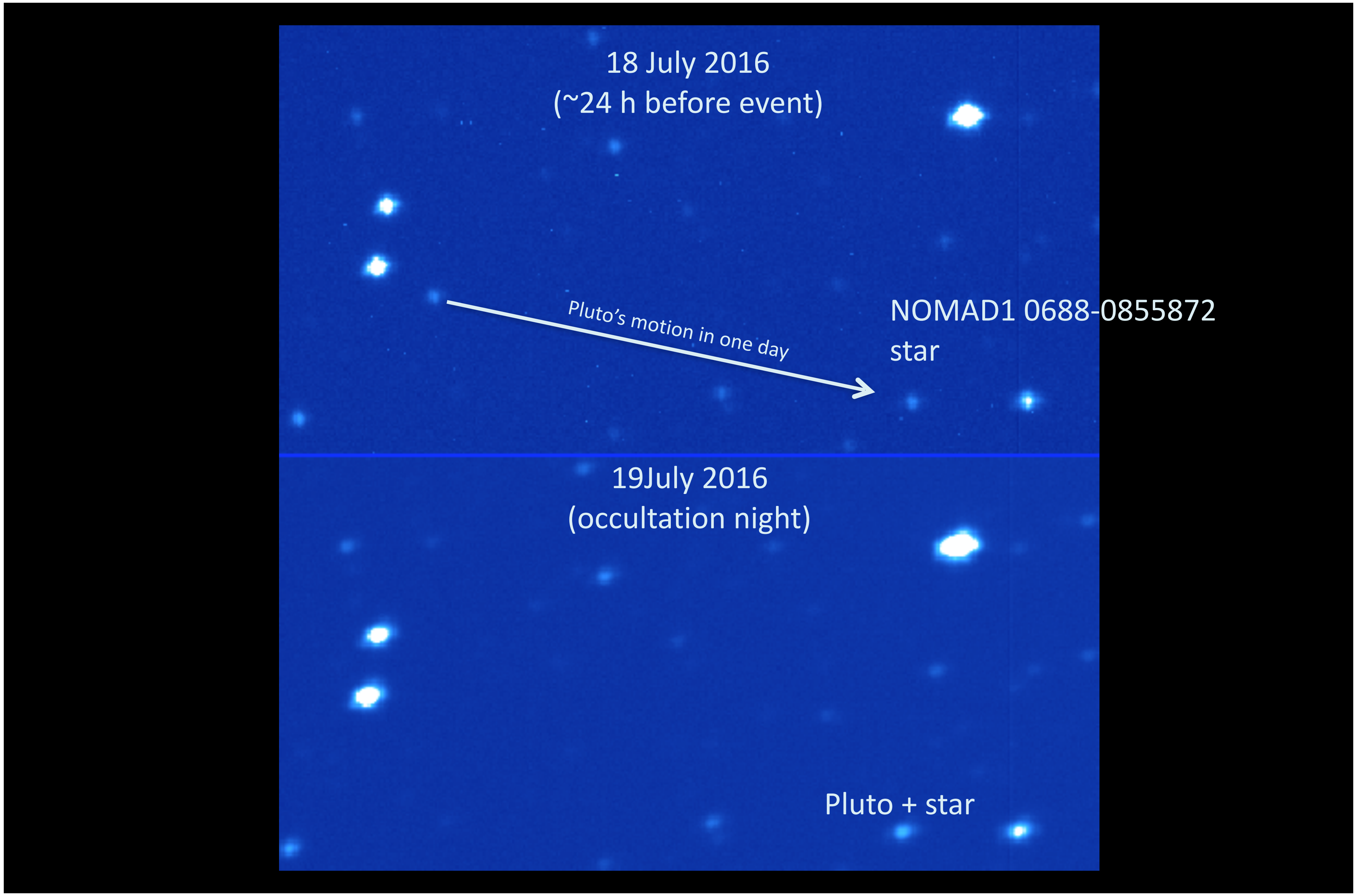
from the ground - 19 years



Benedetti-Rossi et al. 2014

motion around barycenter ~100 mas
photocenter wobbling ~10 mas
variations linked to albedo changes ~?~

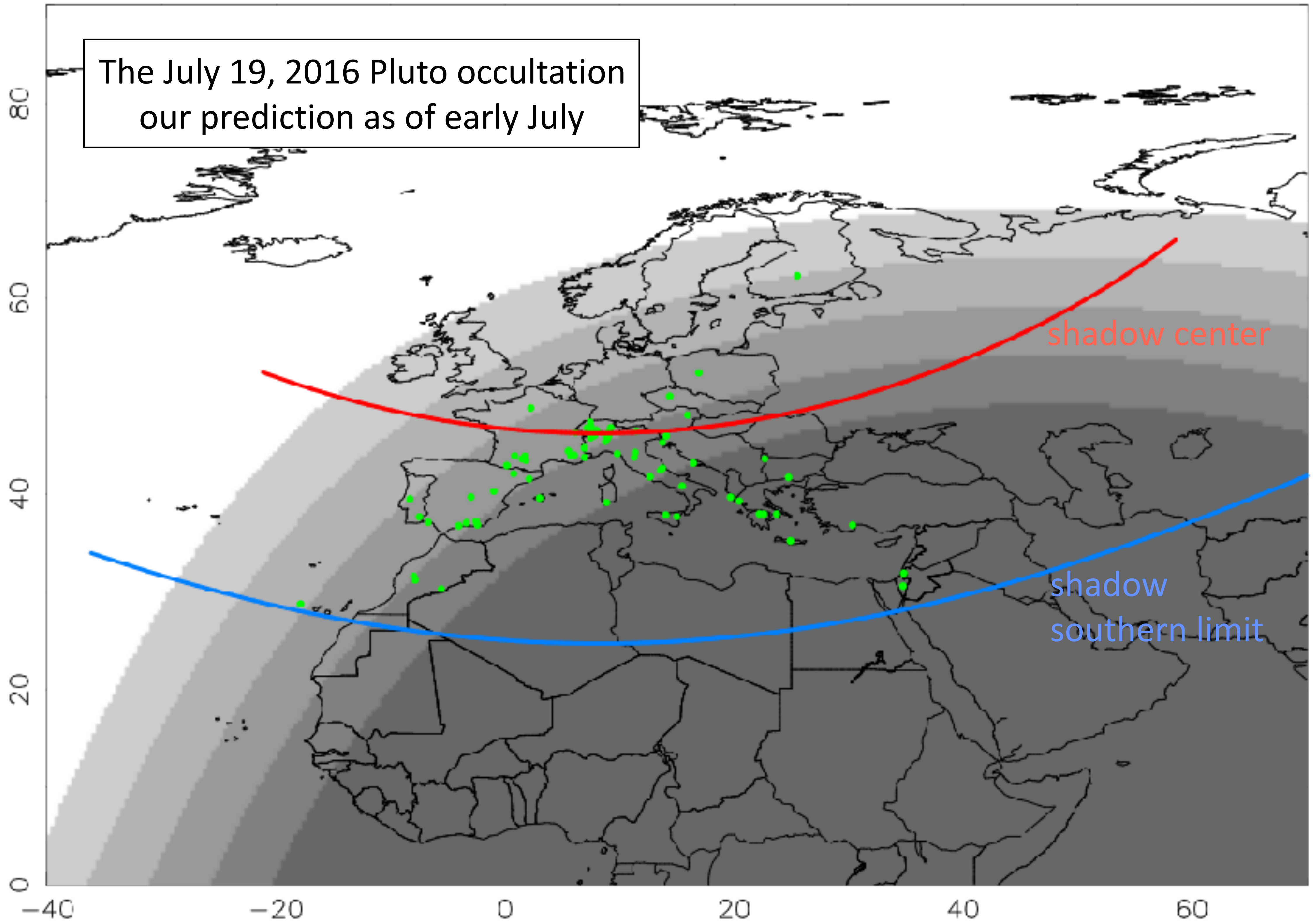
Example - Prediction of stellar occultations: Pluto



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

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

Example - Prediction of stellar occultations: Pluto



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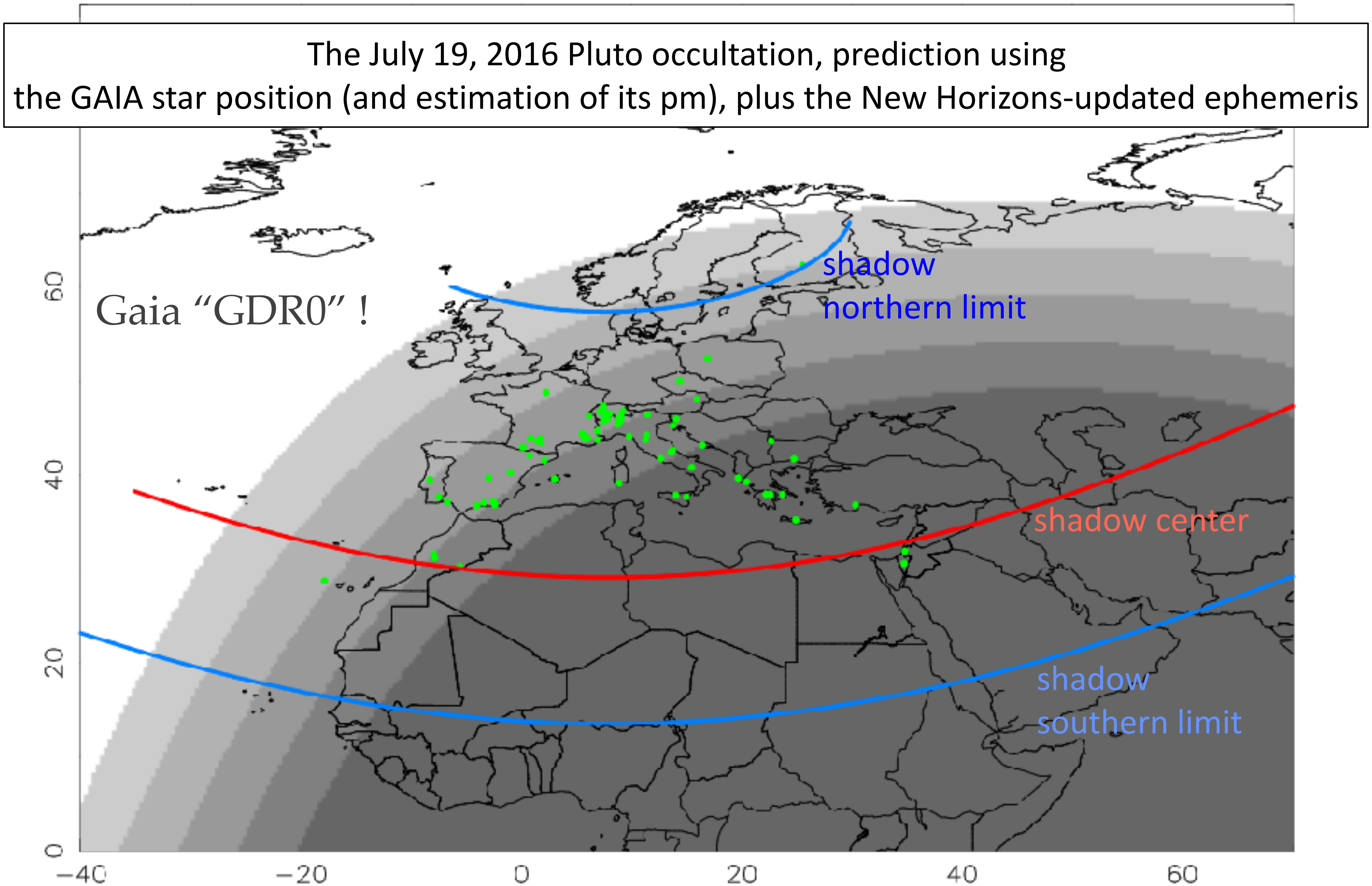

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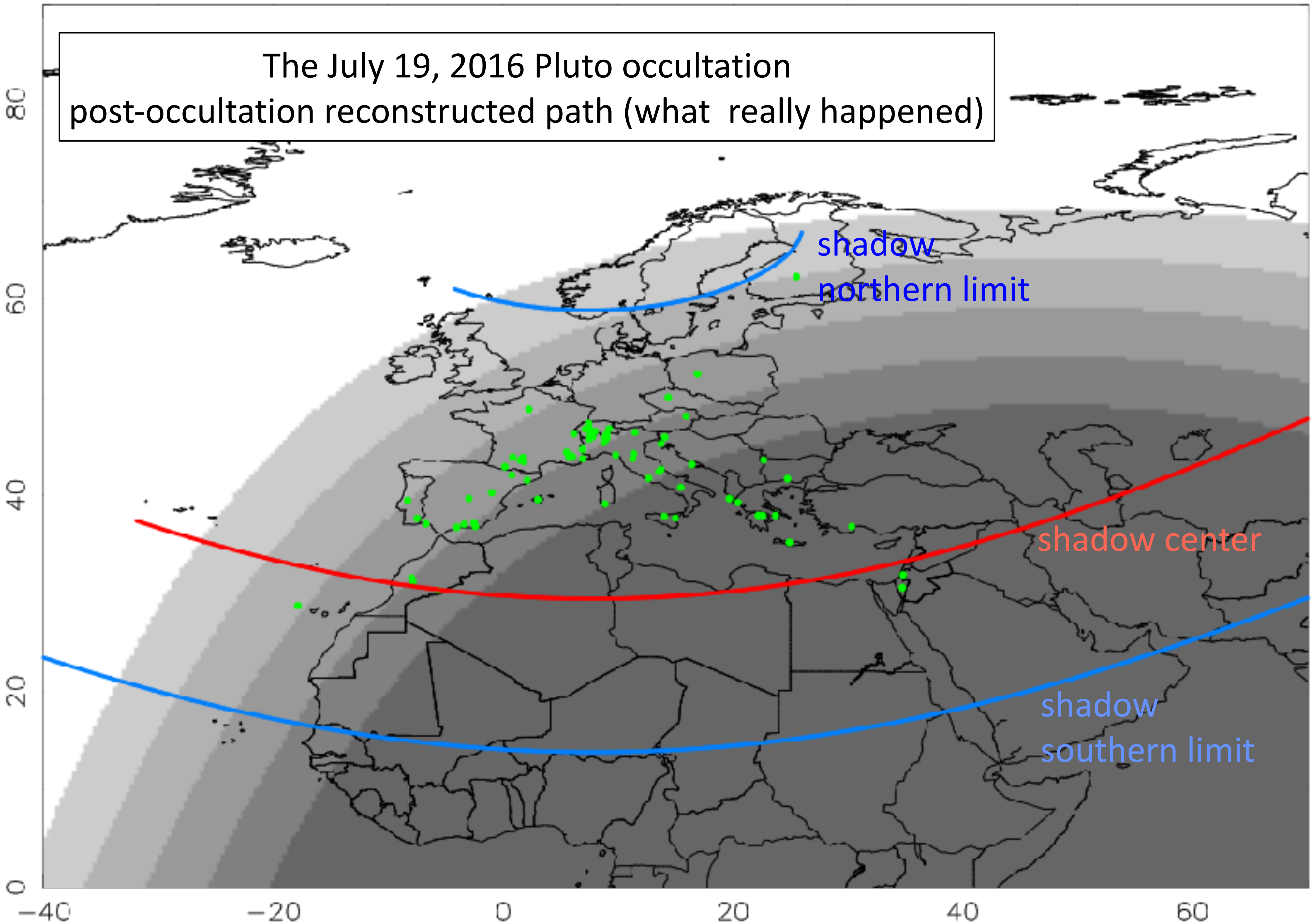
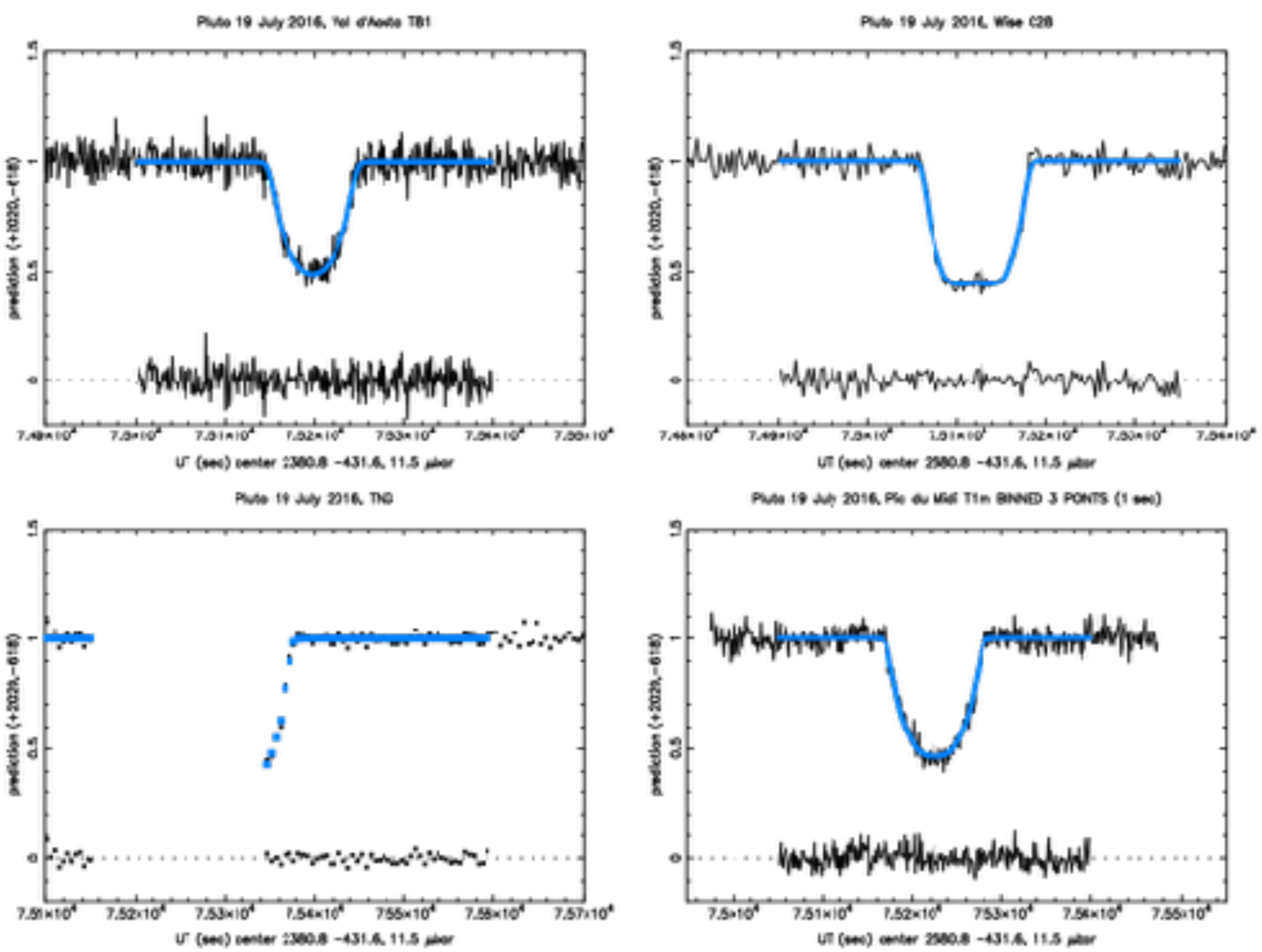
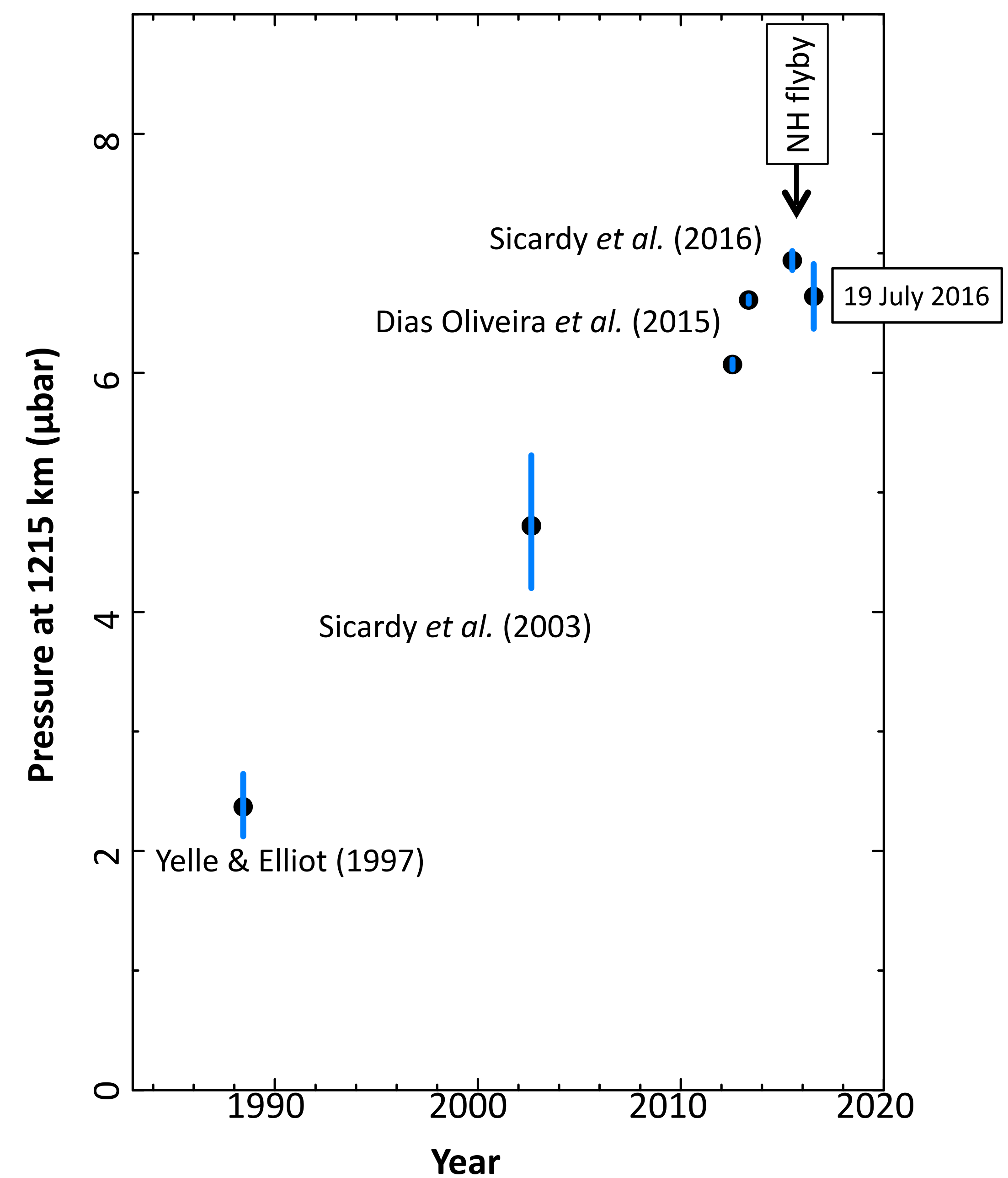


green dots: sites involved in the campaign (not all got data!)

Example - Prediction of stellar occultations: Pluto



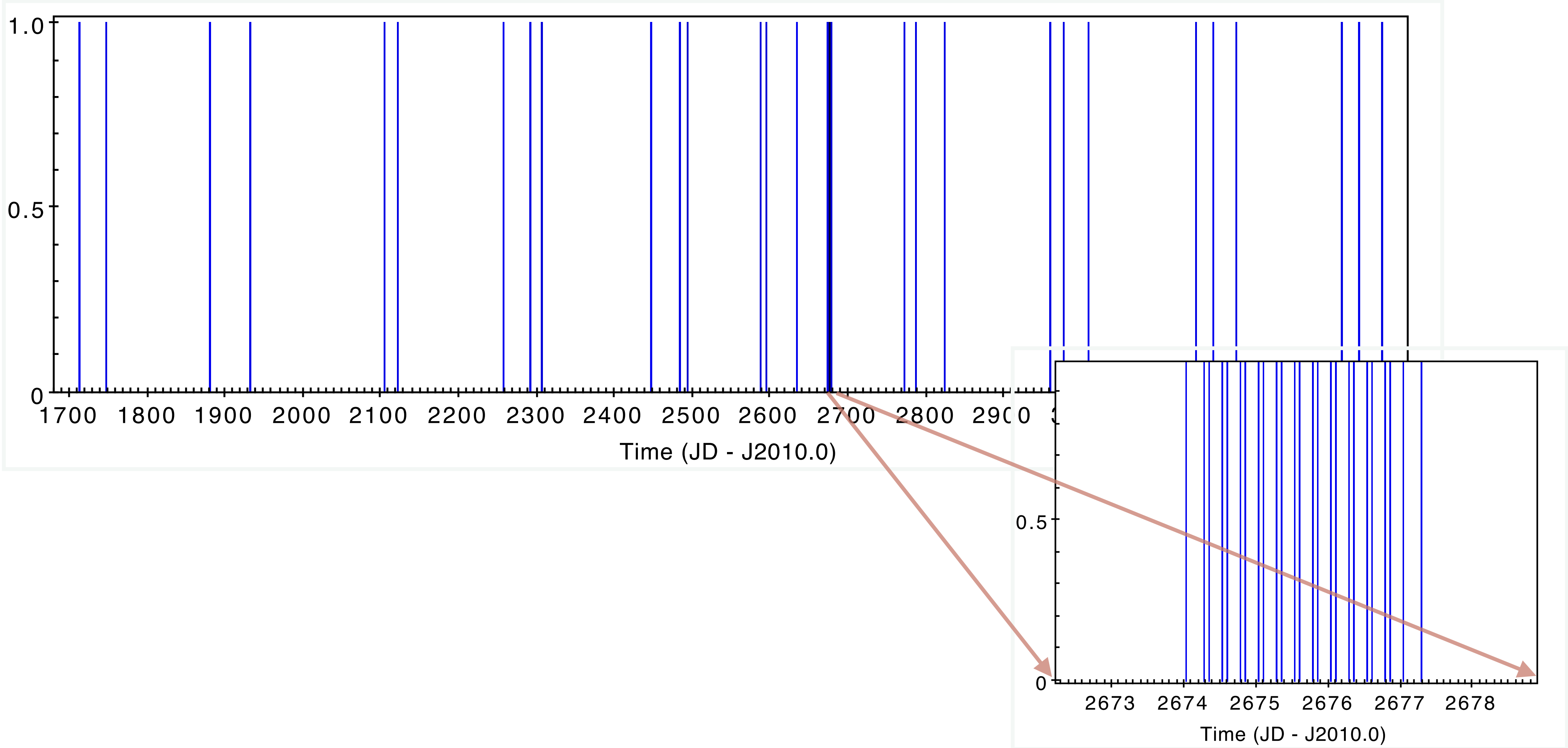
Courtesy: B. Sicardy, LESIA, Obs. de Paris

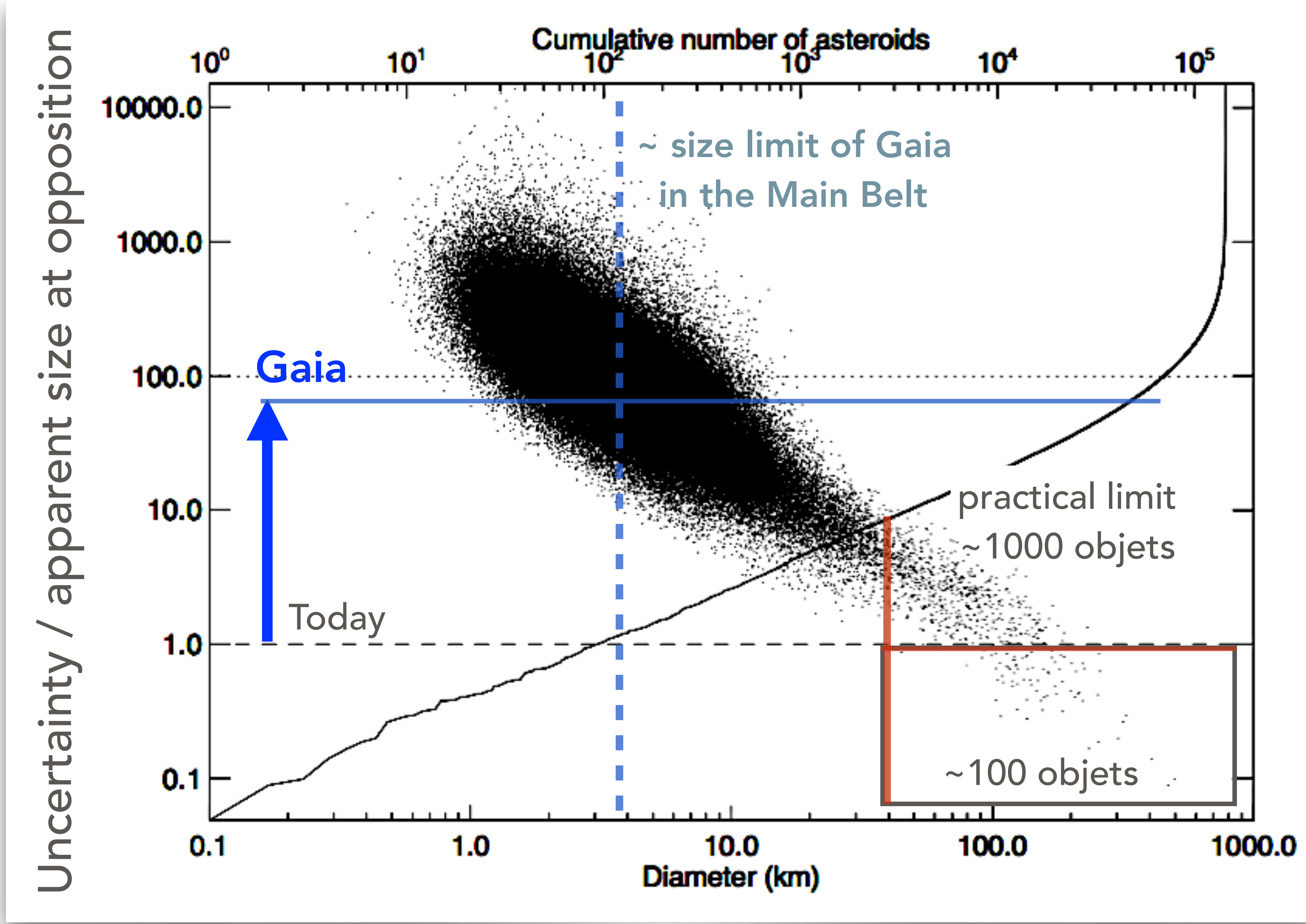


(B. Sicardy, presented at DPS 2016)

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:





At 1.4 AU, 1 km ~1 mas

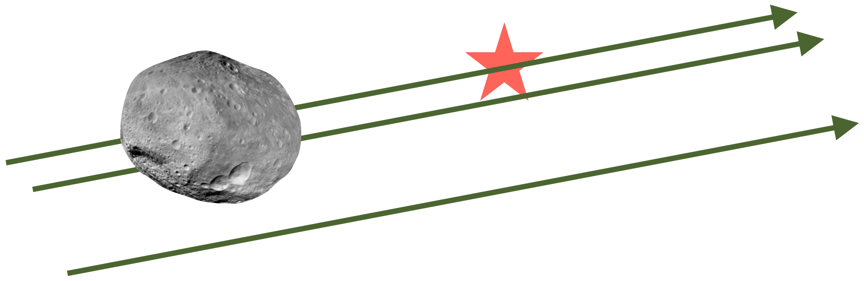
Tanga & Delbo' 2007

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 ~ 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

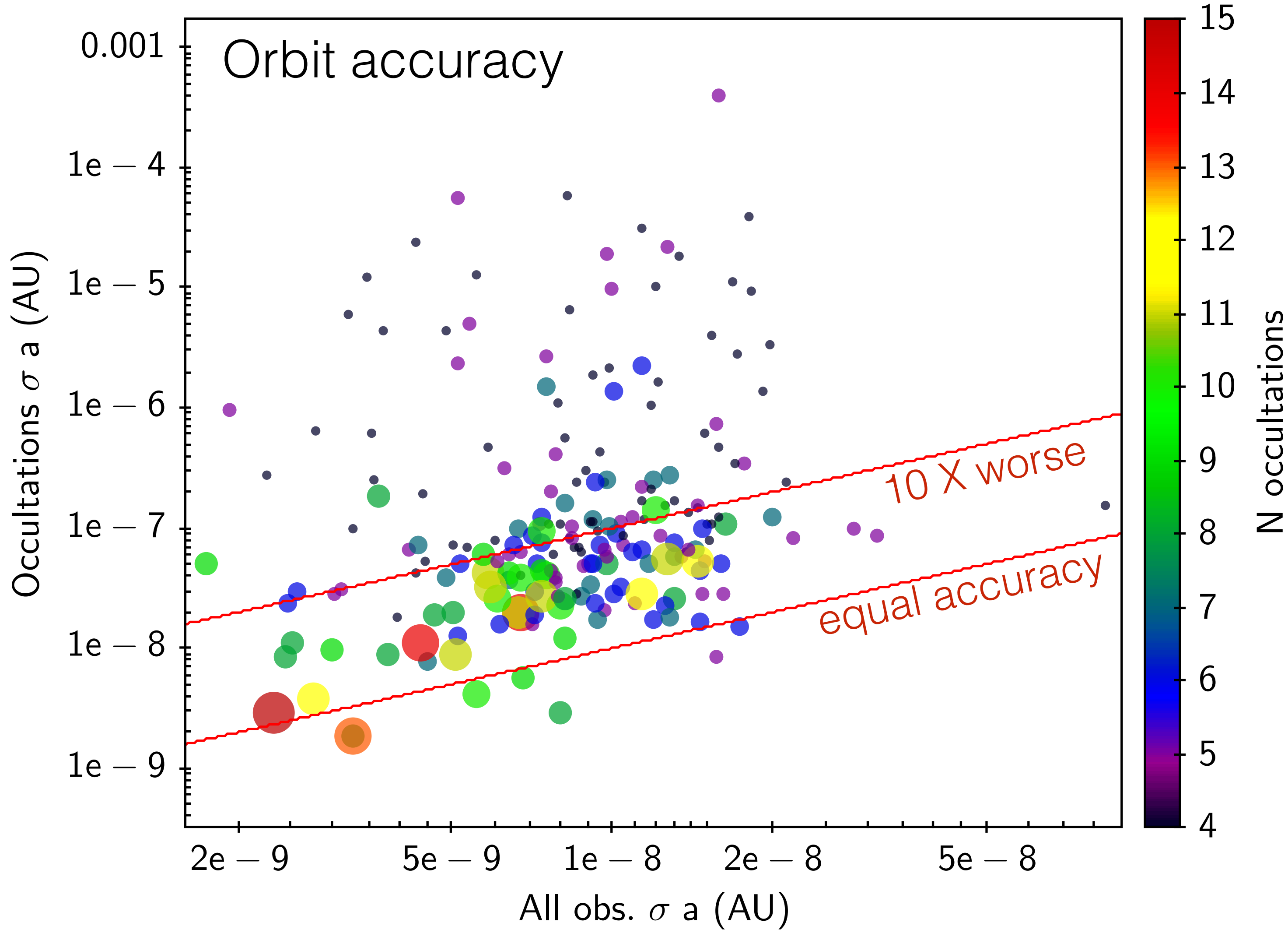
Occultation astrometry: a new approach



- 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

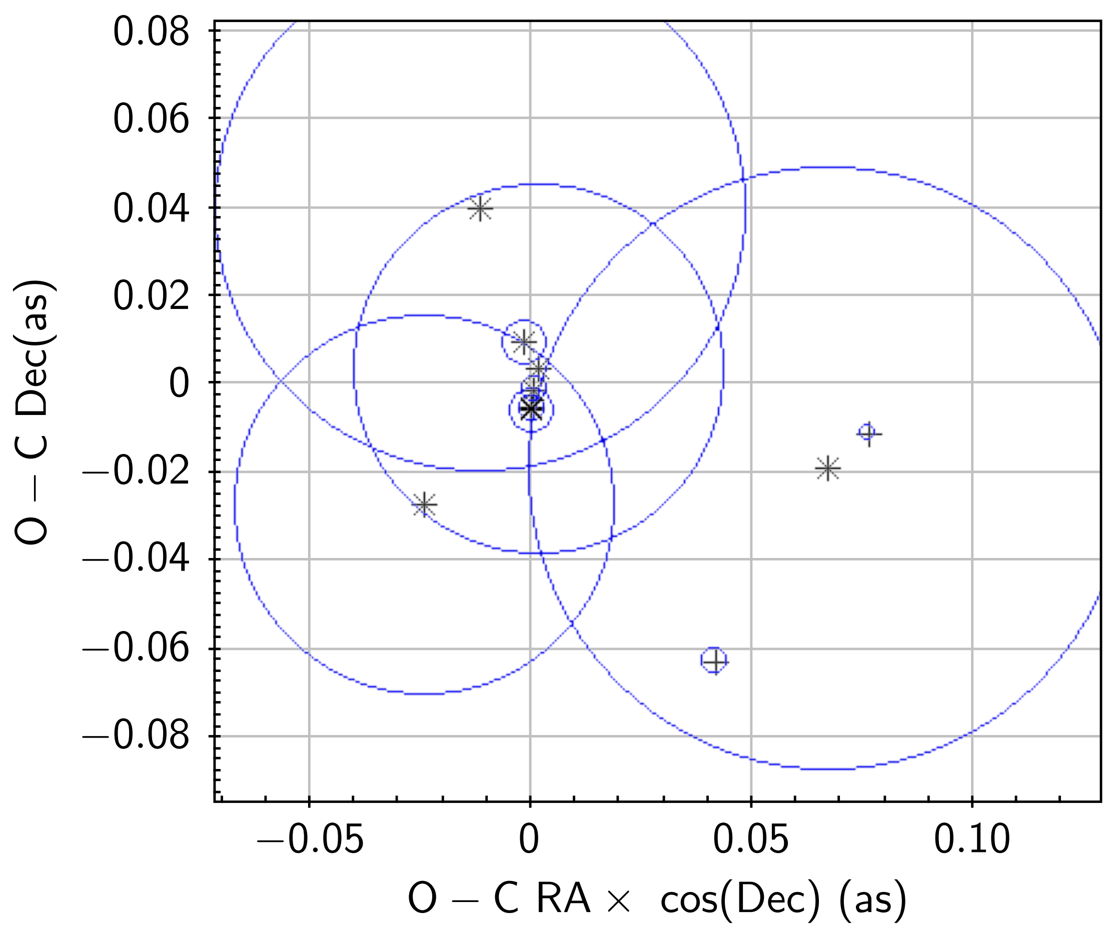
Dream becoming true: the *occultation astrometry of asteroids*

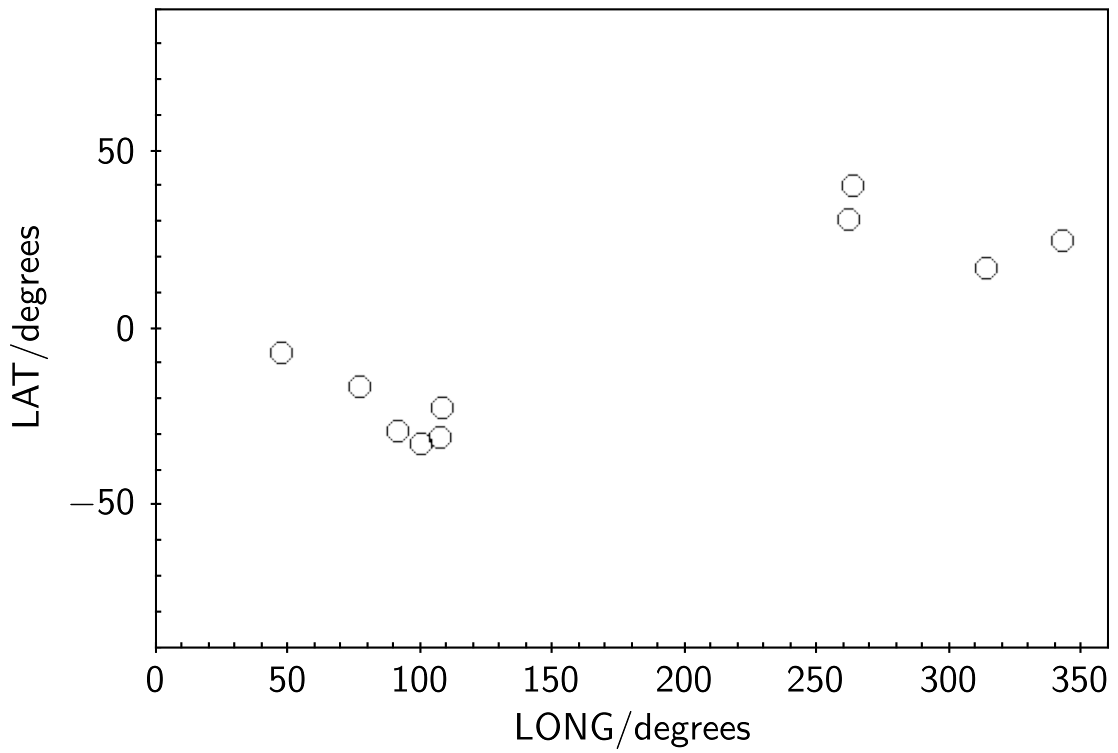


F. Spoto, OCA

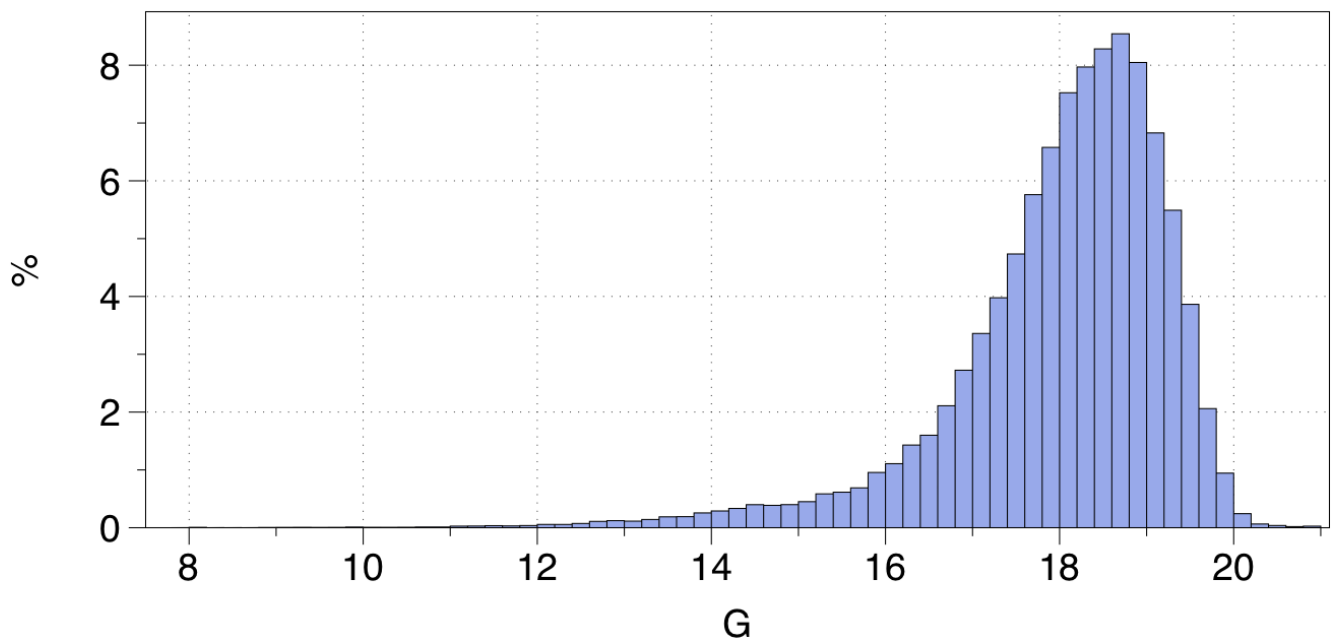
Occultation residuals

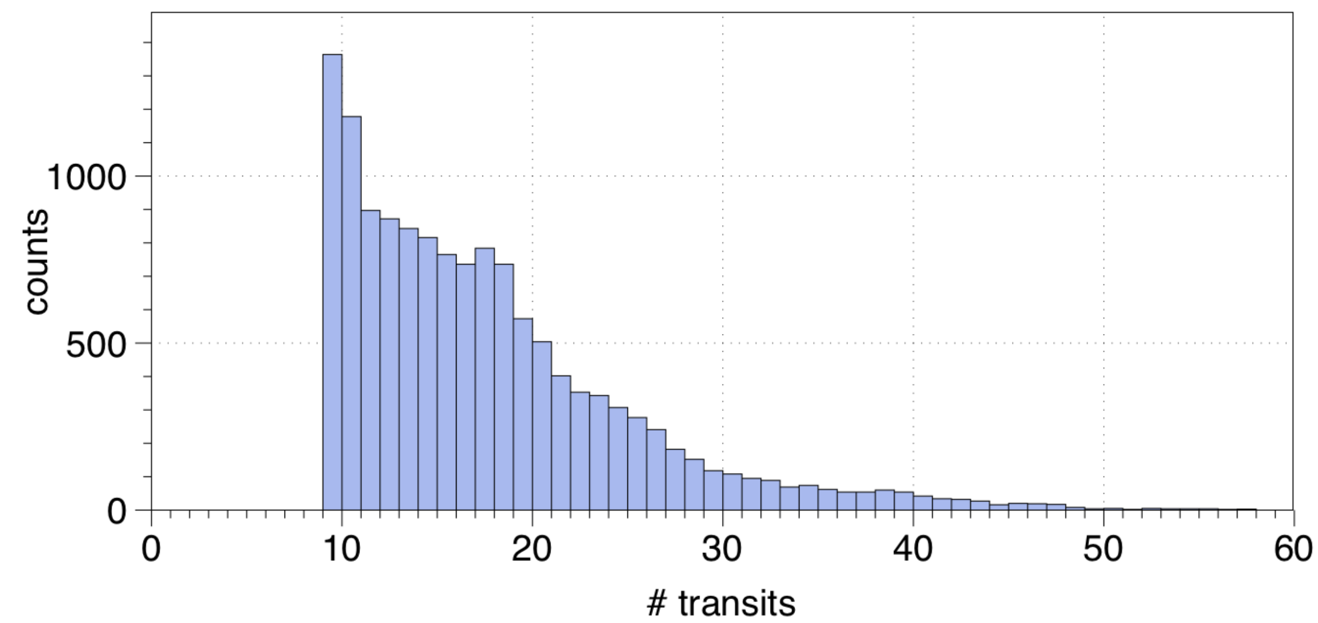
- Asteroid 105 Artemis

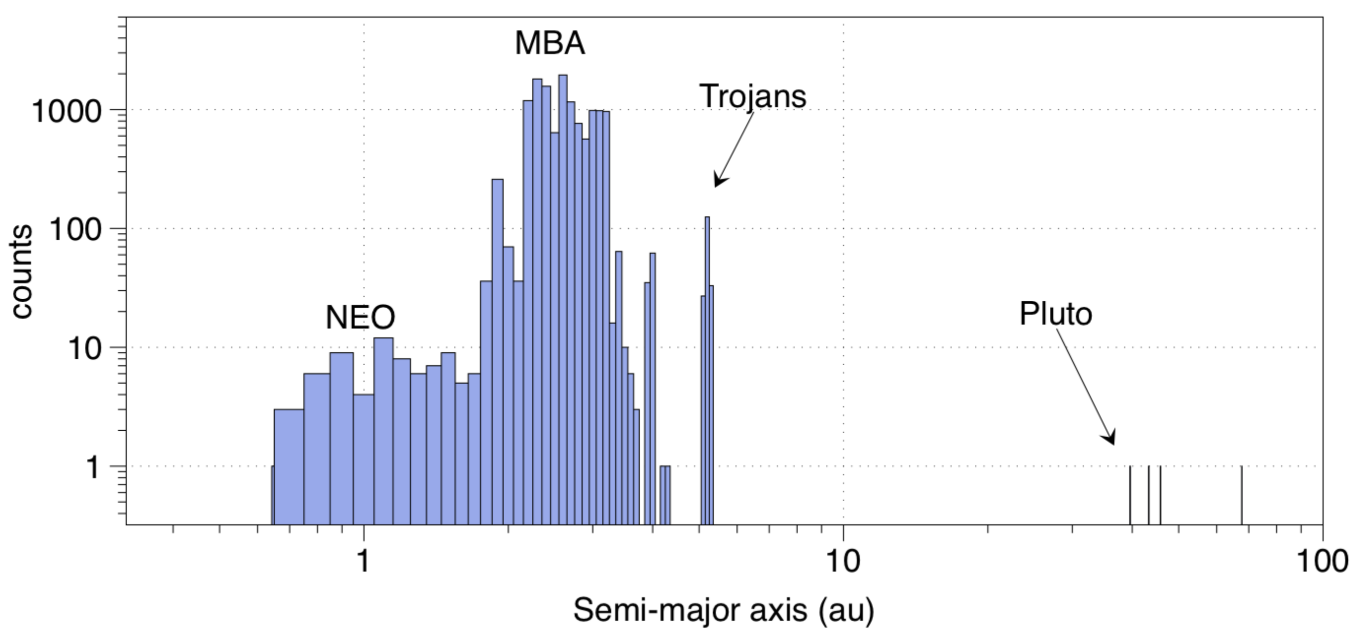




Selection for the Gaia Data Release 2 (Apr. 2018)







- 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!