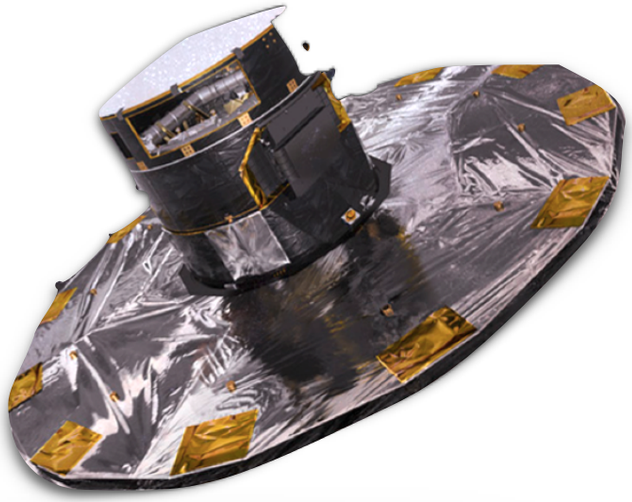
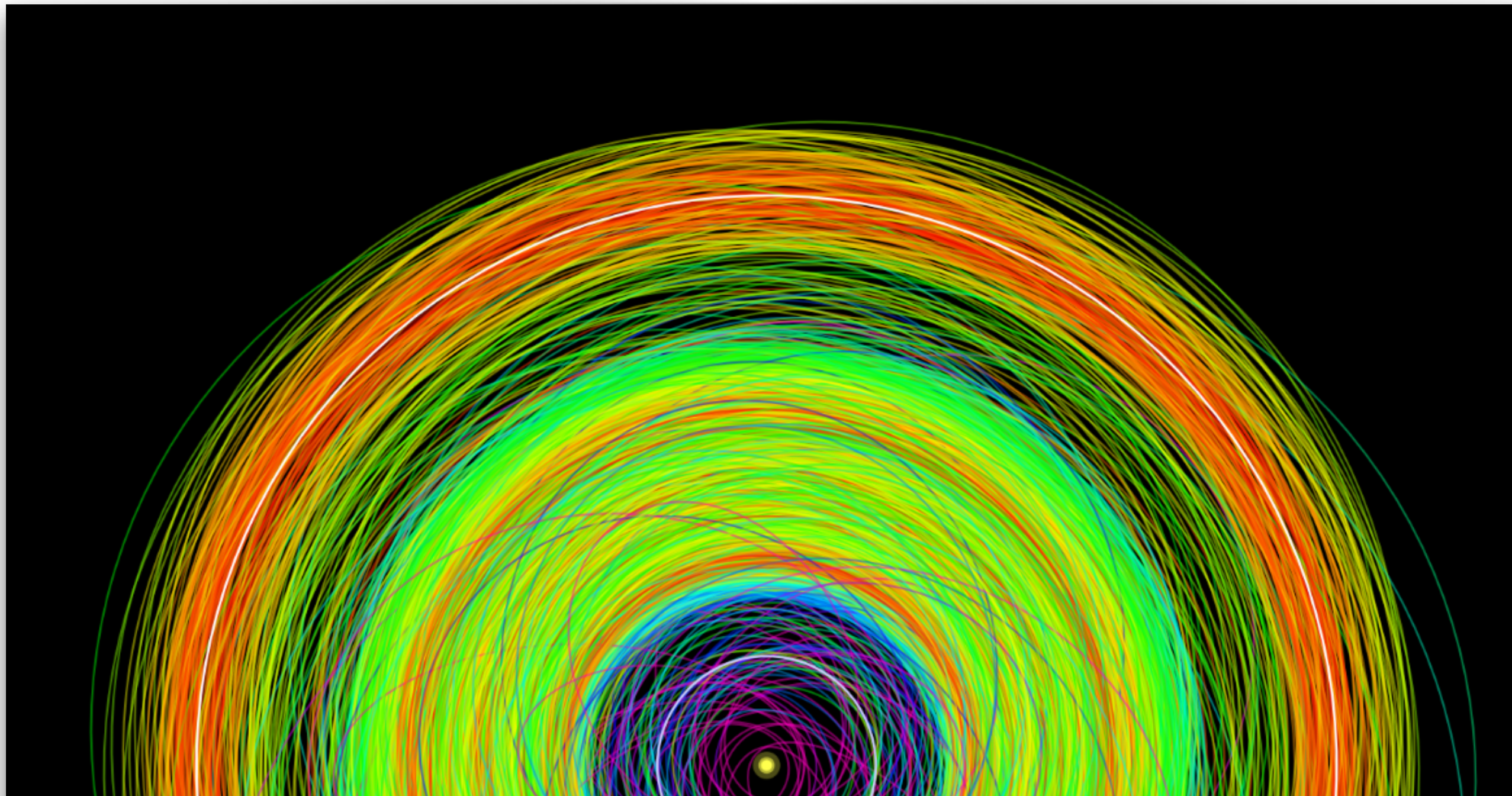


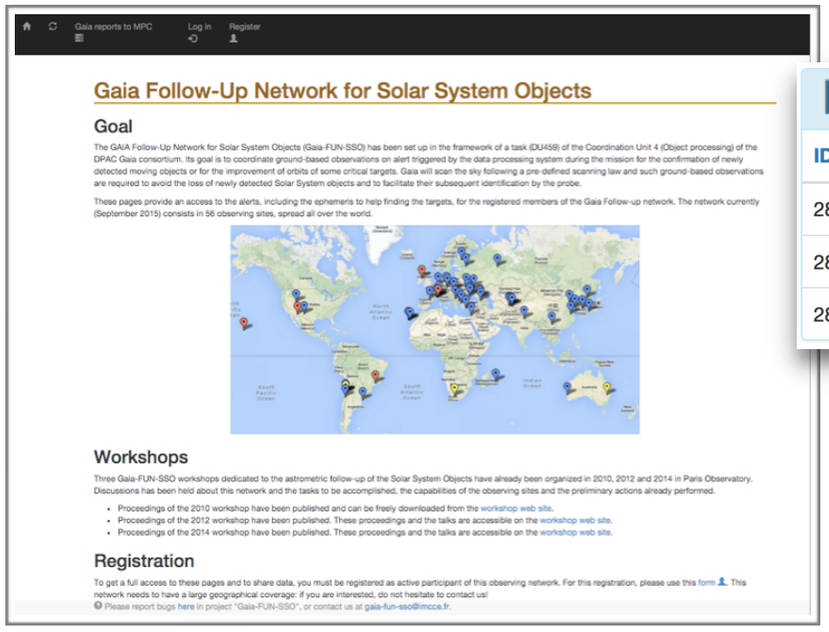
# GAIA
# ASTEROID OBSERVATIONS

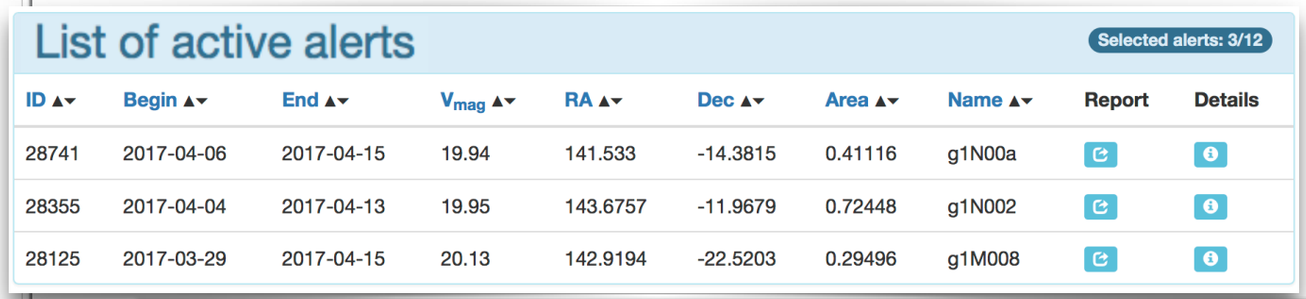
**P. Tanga**

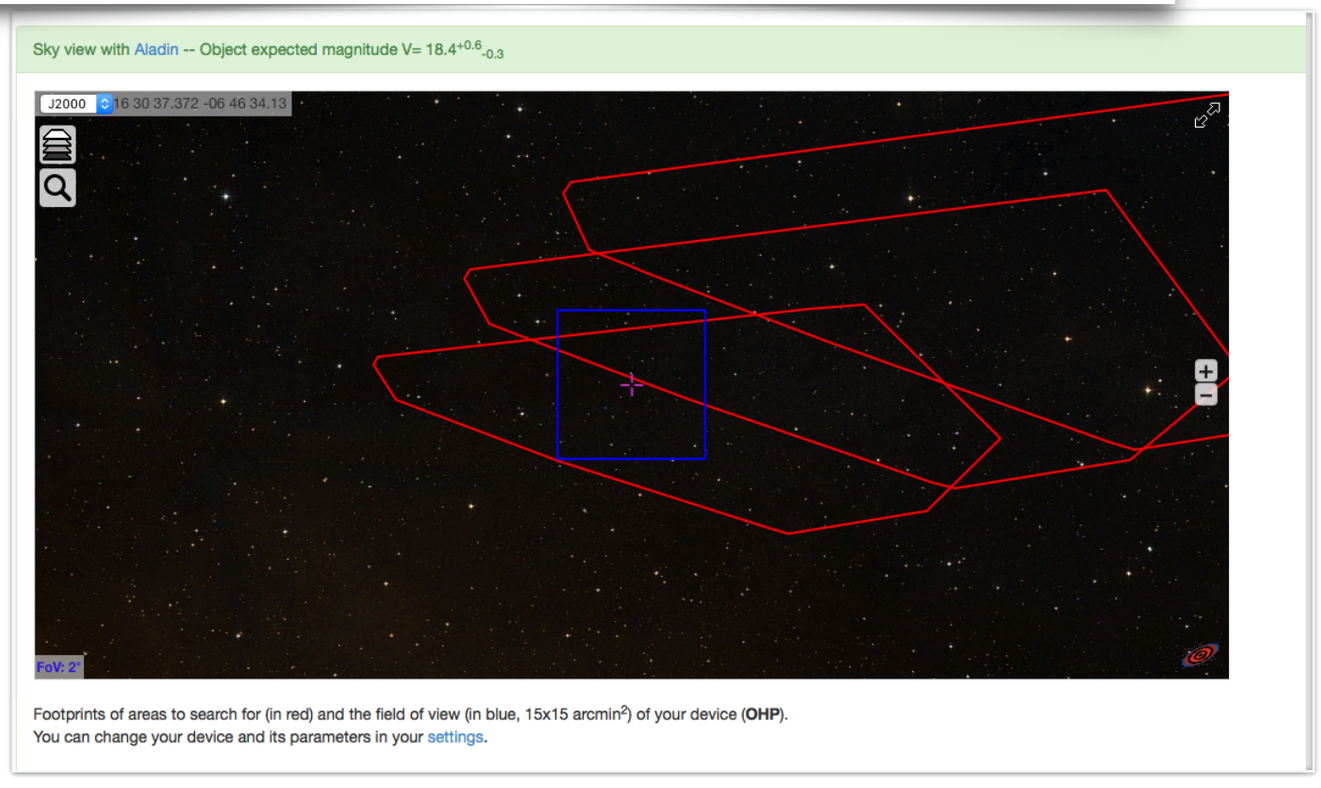
Observatoire de la Côte d'Azur, Nice, France



# Diffusion of asteroid alerts




**http://gaiafunsso.imcce.fr**

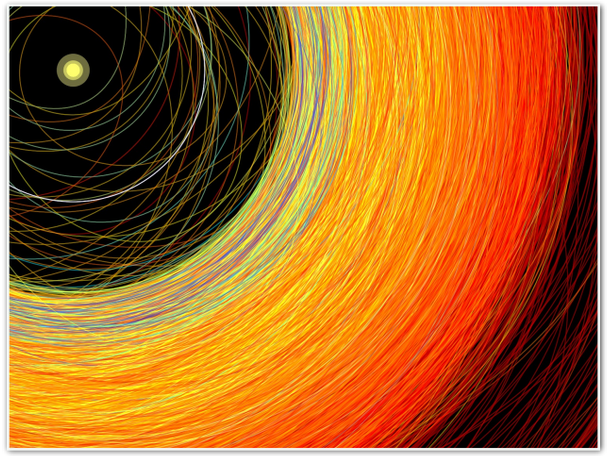
B. Carry (OCA), W. Thuillot (IMCCE)

**Register and contribute!**

# Gaia DR2 - Solar System

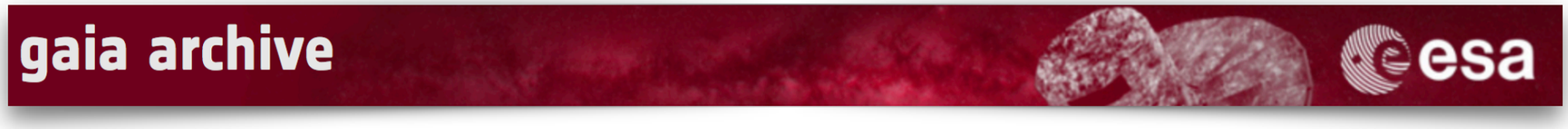
On the base of a pre-selected list of known objects

> 10 FOV transits over the 22 months of DR2
August 5, 2014 - May 23, 2016



| | | |
|---|---|---|
| **Objects** | 14 099 | |
| **Epoch** | 1 997 702 | CCD positions |
| | 287 904 | transits (52% : |
| **Typ. accuracy** | <1 mas | (along scan) |

# Asteroids DR2 data




- asteroid ID and BCRS positions (Ra, Dec) as seen by Gaia
- barycentric positions of Gaia
- TCB gaiacentric epochs for the positions
- uncertainties & correlation:
  - systematic component <— constant along a transit
  - random component <— uncorrelated over a transit
- brightness (1 per transit): G magnitude, flux and uncertainty

# The result of a >15 years effort

In the frame of the Data Processing and Analysis Consortium (DPAC)

Main contributors to processing :

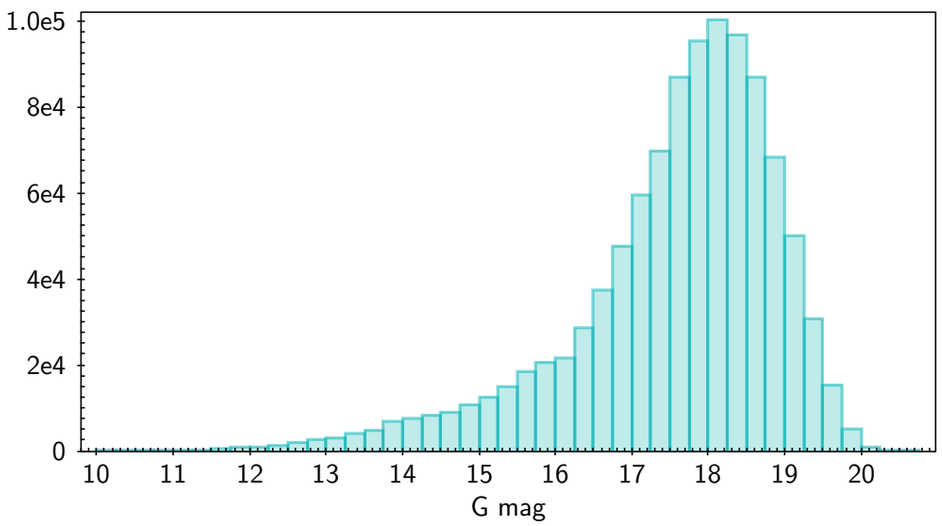
| | |
|---|---|
| IMCCE, France: | J. Berthier, P. David, D. Hestroffer, W. Thuillot |
| INAF, Italy: | A. Cellino, A. Dell'Oro |
| UTINAM, France: | J.M. Petit |
| OCA, France: | M. Delbo, L. Galluccio, F. Mignard, Ch. Ordenovic, F. Spoto, P. Tanga |
| ORB, Belgium: | Th. Pauwels |
| U. Helsinki, Finland: | K. Muinonen, G. Fedorets |

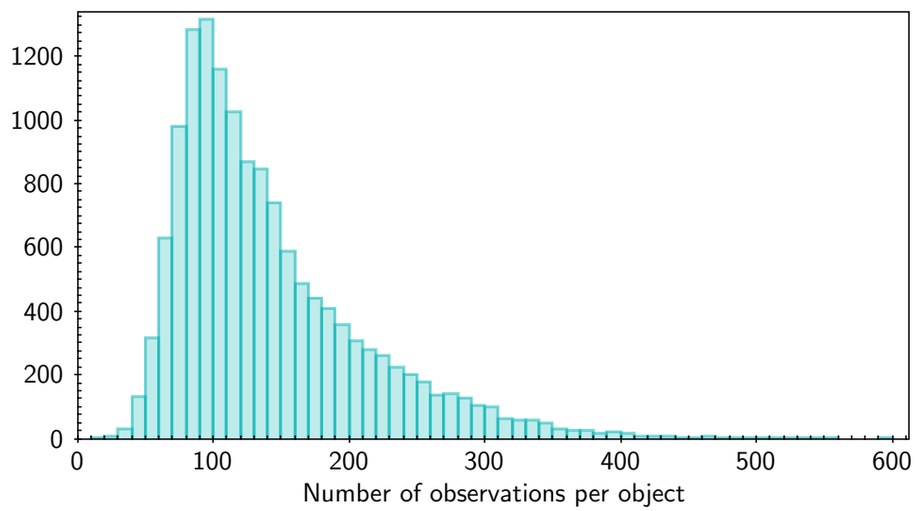
Validation :

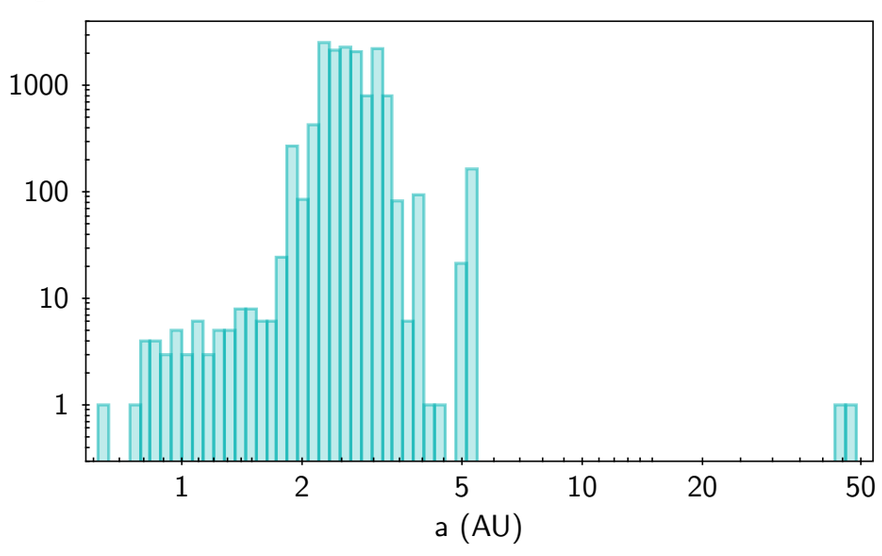
| | |
|---|---|
| OCA, France: | F. Spoto, A. Cellino |

Now preparing DR3!

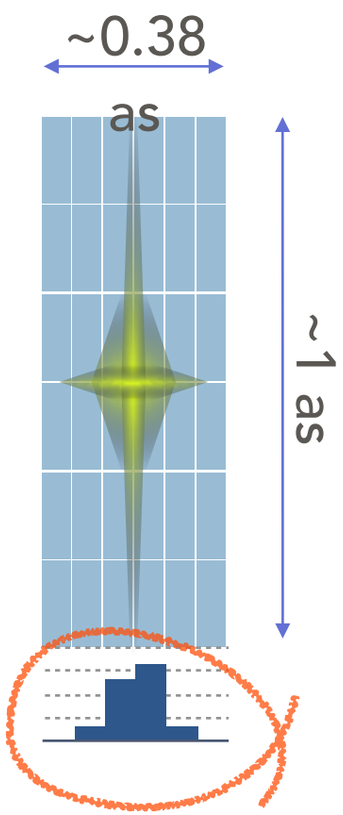
# Gaia DR2 - Solar System statistics



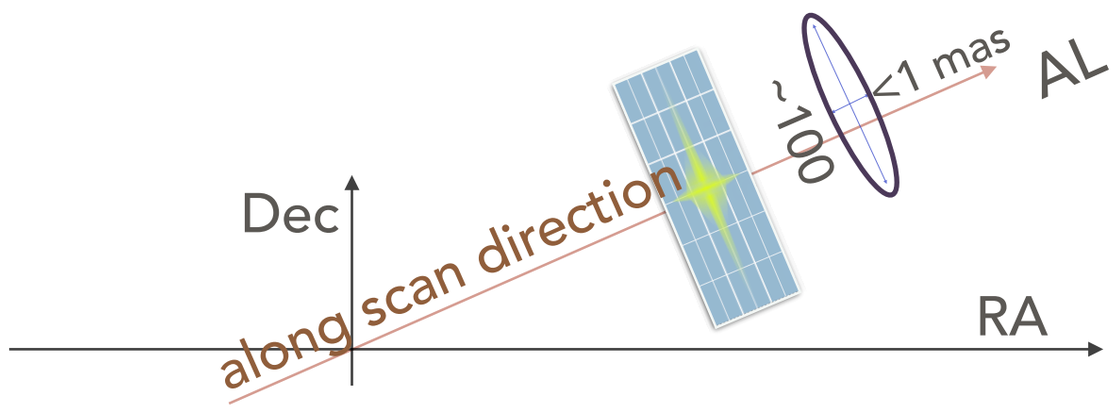



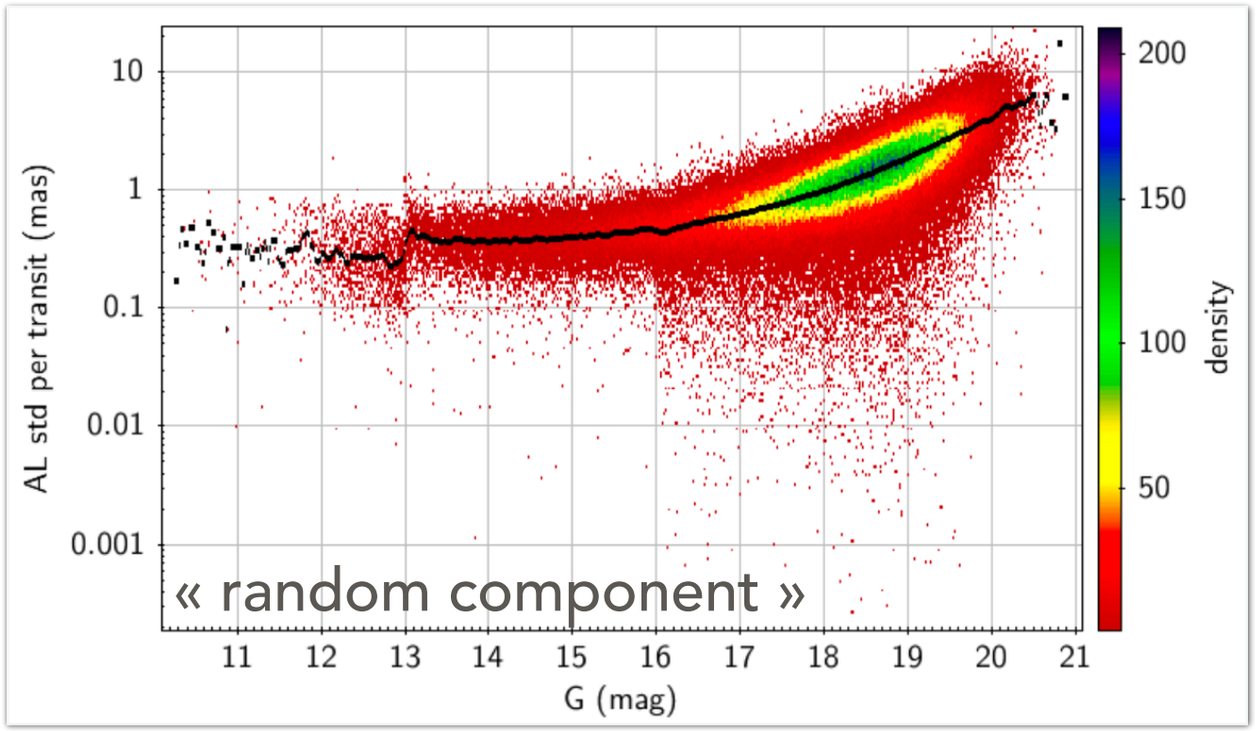



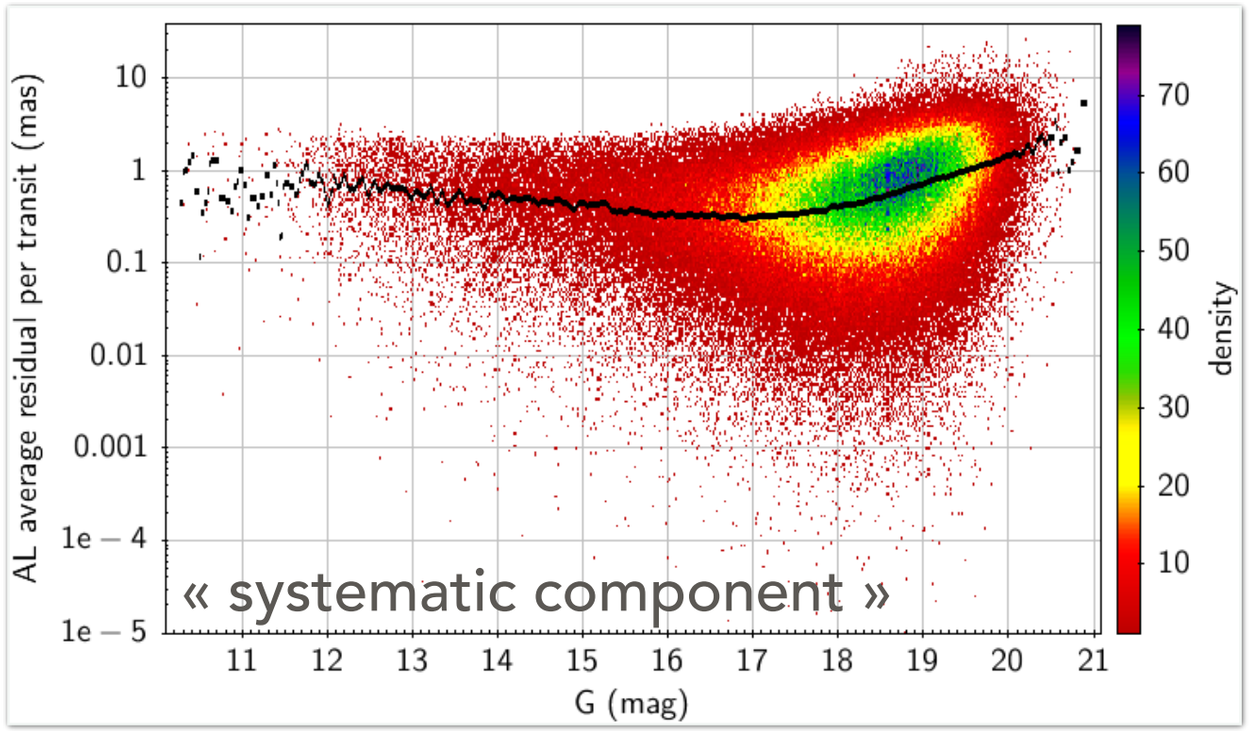
# Gaia elementary observation: highly correlated errors




- Tools must be ready to handle accuracy ~100 X bette
- Highly correlated (RA, Dec) positions.
  - Not (very) relevant for stars
  - Fundamental for asteroids!
- Random and systematic components given



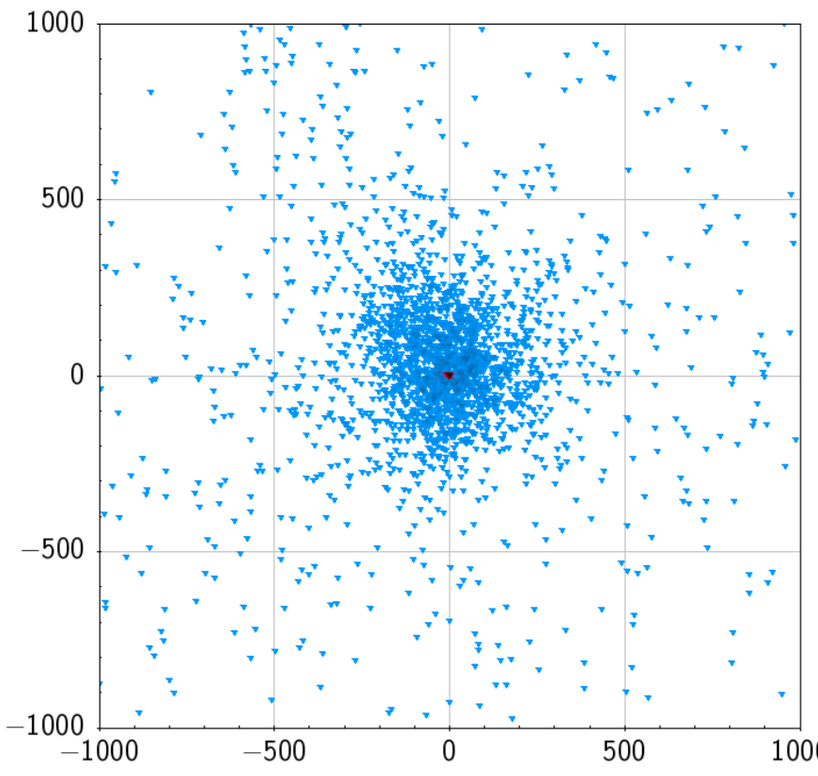



# Residuals from the orbital fit of Gaia DR2 data only (AL direction)

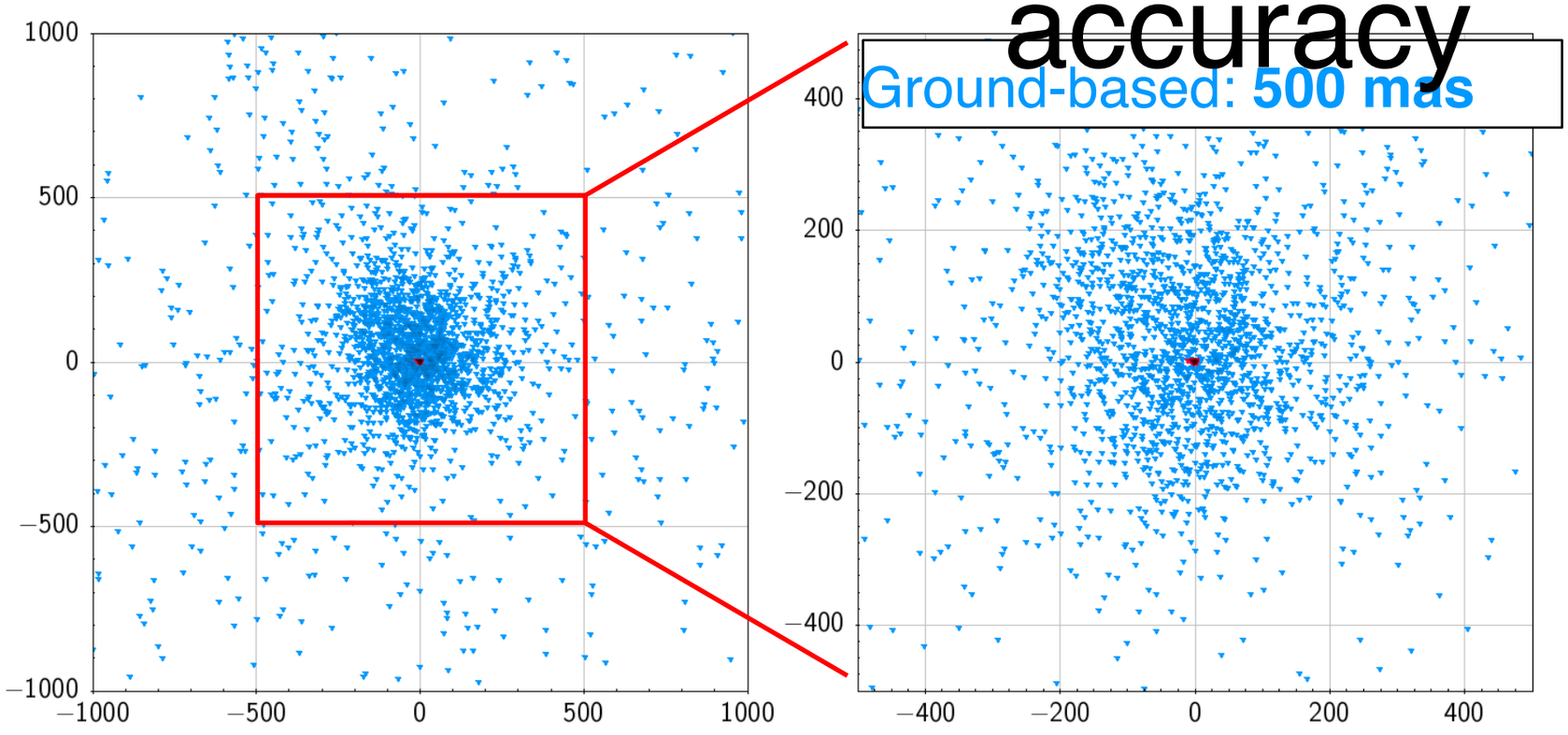
The Gaia collaboration: Spoto et al. 2018

# Gaia DR2- asteroid observation accuracy



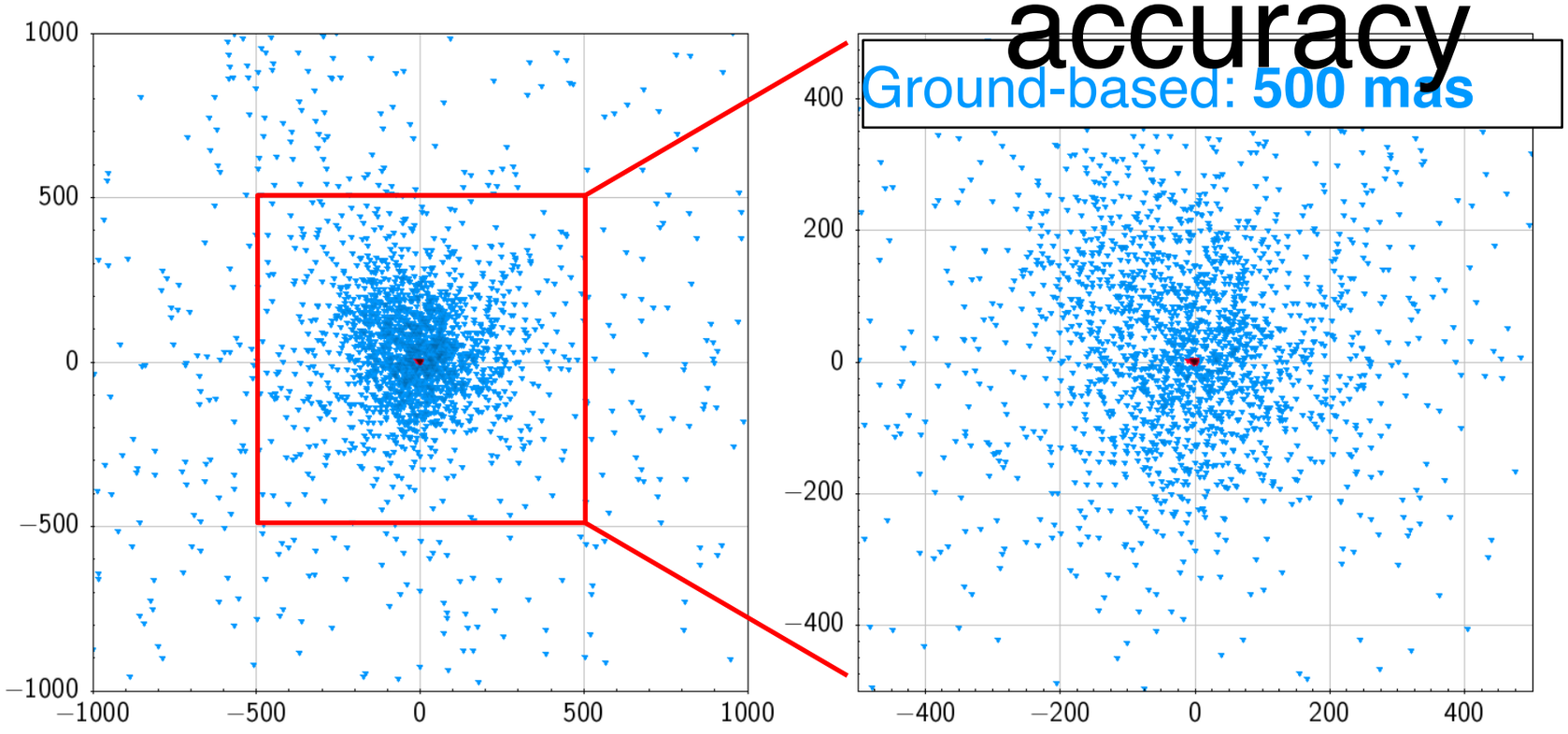

**Post-fit residuals αcos(δ)**

# Gaia DR2- asteroid observation accuracy




## Post-fit residuals αcos(δ)

# Gaia DR2- asteroid observation accuracy

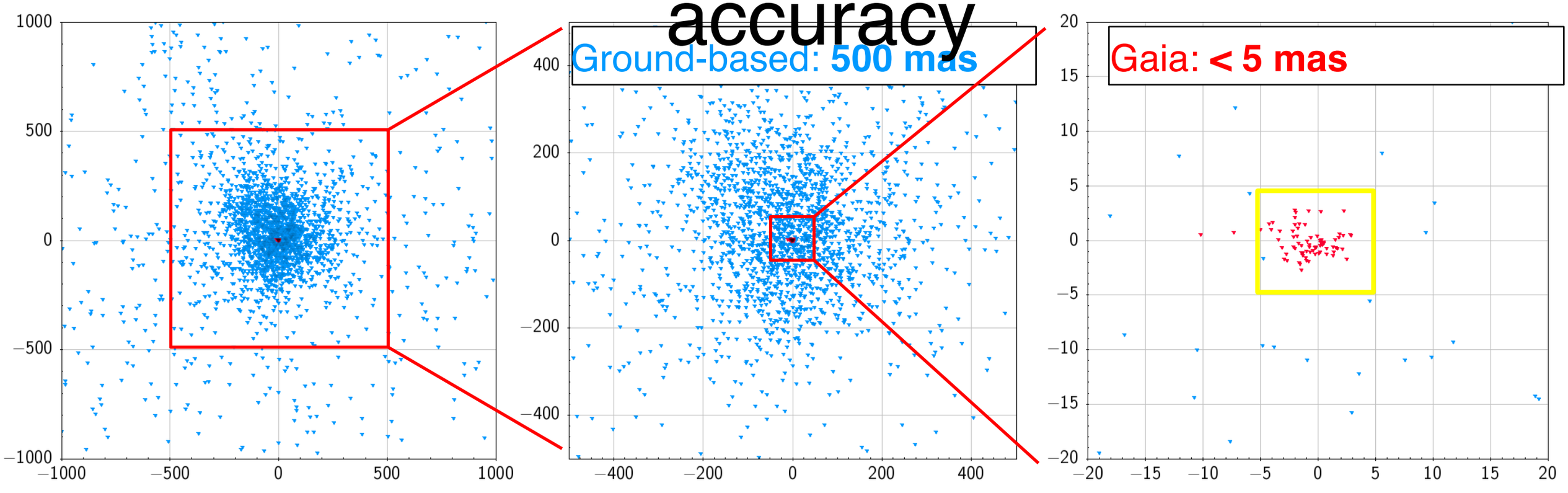



**Post-fit residuals αcos(δ)**

## Available ground-based astrometry

- **200 millions** of observations (mid Feb. 2019)
- Typical accuracy: between **400** and **500 mas**
- **2 000** accurate observations (mostly radar)

# Gaia DR2- asteroid observation accuracy




**Post-fit residuals αcos(δ)**

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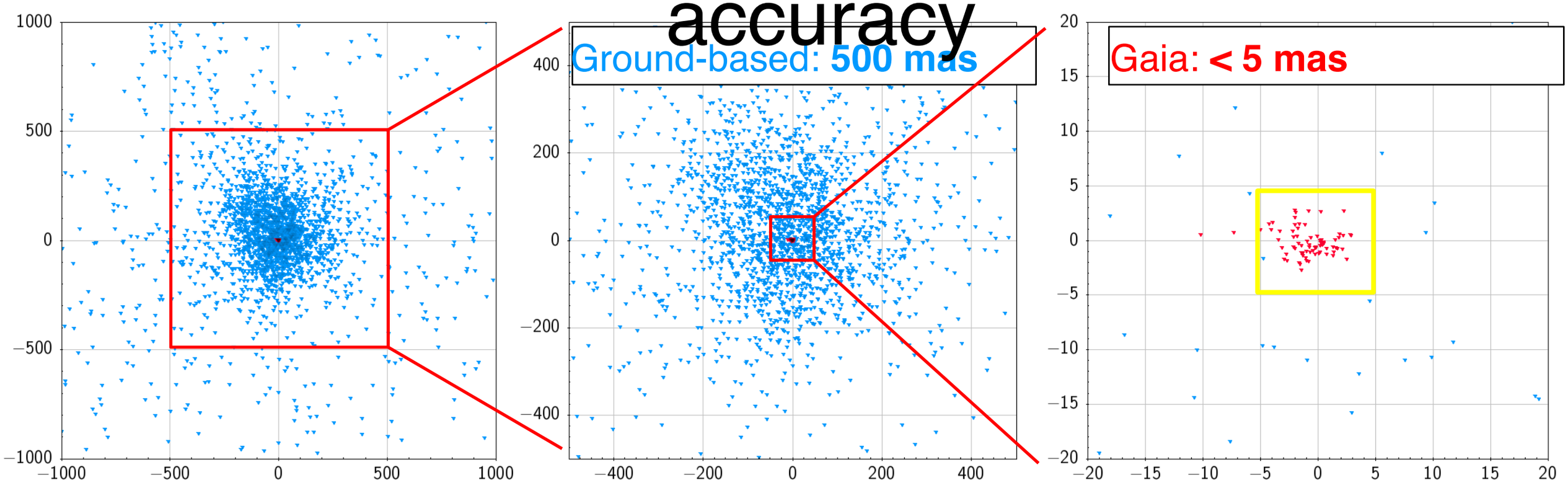
# Gaia DR2- asteroid observation accuracy




**Post-fit residuals αcos(δ)**

## Available ground-based astrometry

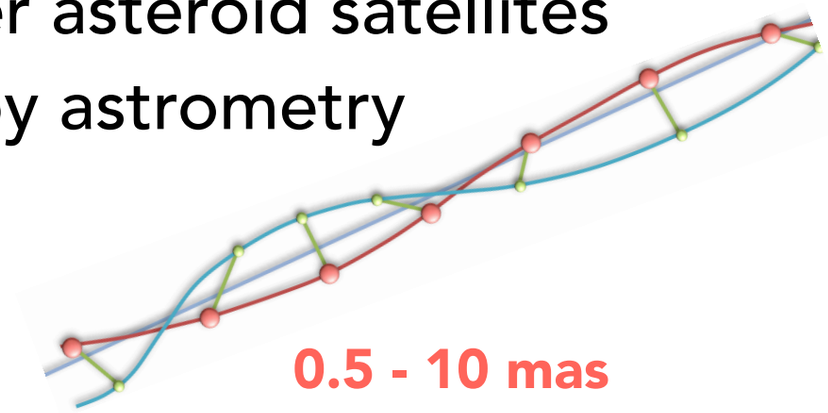
- **200 millions** of observations (mid Feb. 2019)
- Typical accuracy: between **400** and **500 mas**
- **2 000** accurate observations (mostly radar)

## Gaia DR2 (Gaia Collaboration et al. 2018)

- **1 977 702** observations
- Accuracy between **2** and **5 mas** (V~20.5)
- Accuracy at the **sub-mas** level (bright objects)

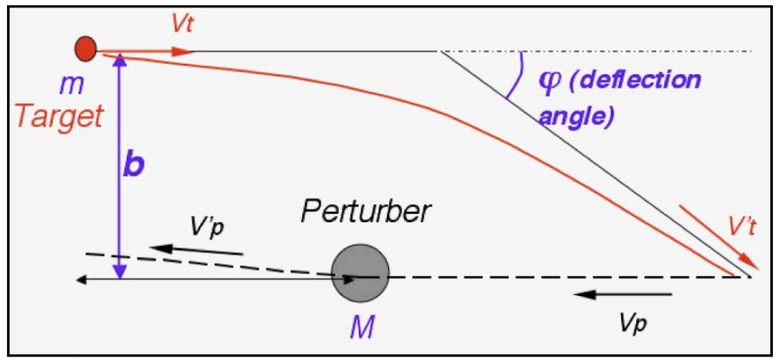
# Some challenges for asteroid astrometry require long observational arcs

## Discover asteroid satellites by astrometry

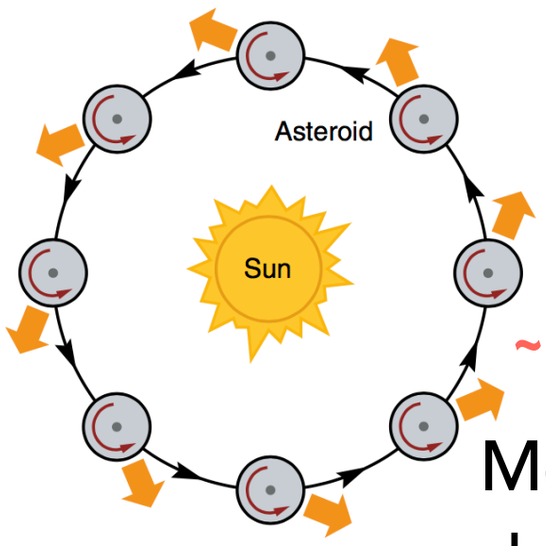


**0.5 - 10 mas**

## New / precise asteroid masses



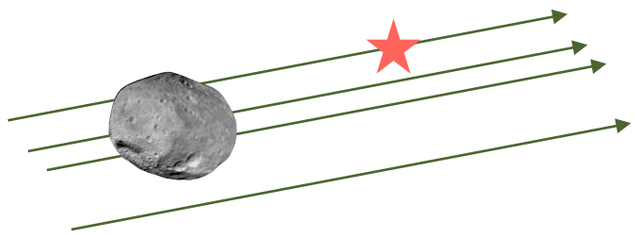

**~ 10 mas**



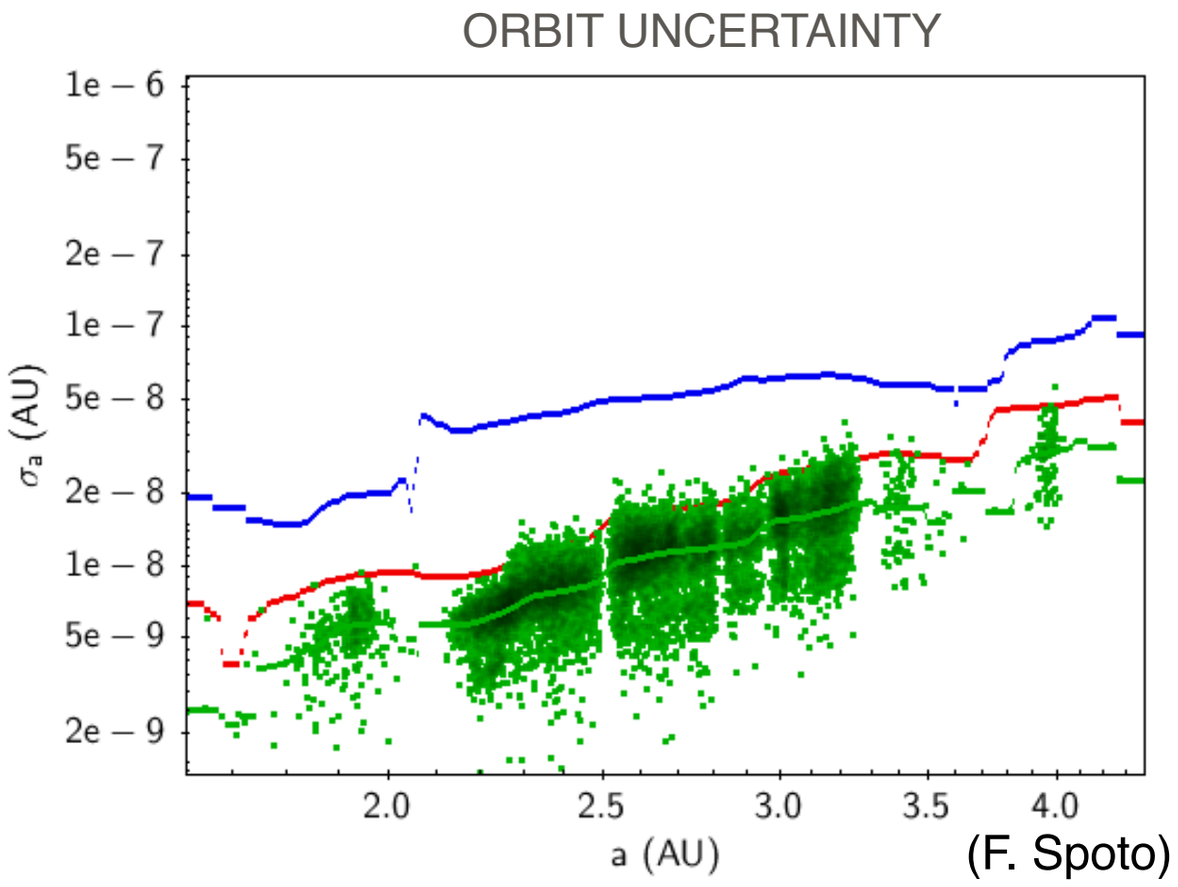

**~a few mas**

Measure the orbital drift due to *Yarkovsky force*

## Improve predictions of stellar occultations



# « Tentative » orbit improvement by DR2




(F. Spoto)

Gaia DR2 only

MPC non-Gaia astrometry

Gaia DR2 + MPC non-Gaia

DR2 has a strong weight (100s better accuracy).

- A factor ~2 (only) average improvement by using DR2 + all other data
- But: most other data are affected by systematic (zonal) errors of the pre-Gaia catalogs

# Data sources

- Minor Planet Center
  - 200 million astrometric positions, for ~800k asteroids
  - starting in 1802
  - different techniques (visual, photography, meridian circles, CCD…)
  - data include the telescope used, filter, calibration catalogue (for a large fraction)

- Gaia DR2
  - ~2 million CCD-level, epoch positions for 14.099 asteroids
  - over 22 months
  - Gaia DR3 —> ~100.000 asteroids
  - Gaia final —> ~350.000 asteroids

# Typical errors

- Minor Planet Center

| | Fraction | Average residuals |
|---|---|---|
| CCD | 94.1 % | 380 mas |
| WISE, HST... | 4.2 % | 580 mas |
| pre-CCD | 1.2 % | 500-1000 mas |
| Hipparcos, occultations, radar | 0.5 % | 10-150 mas |

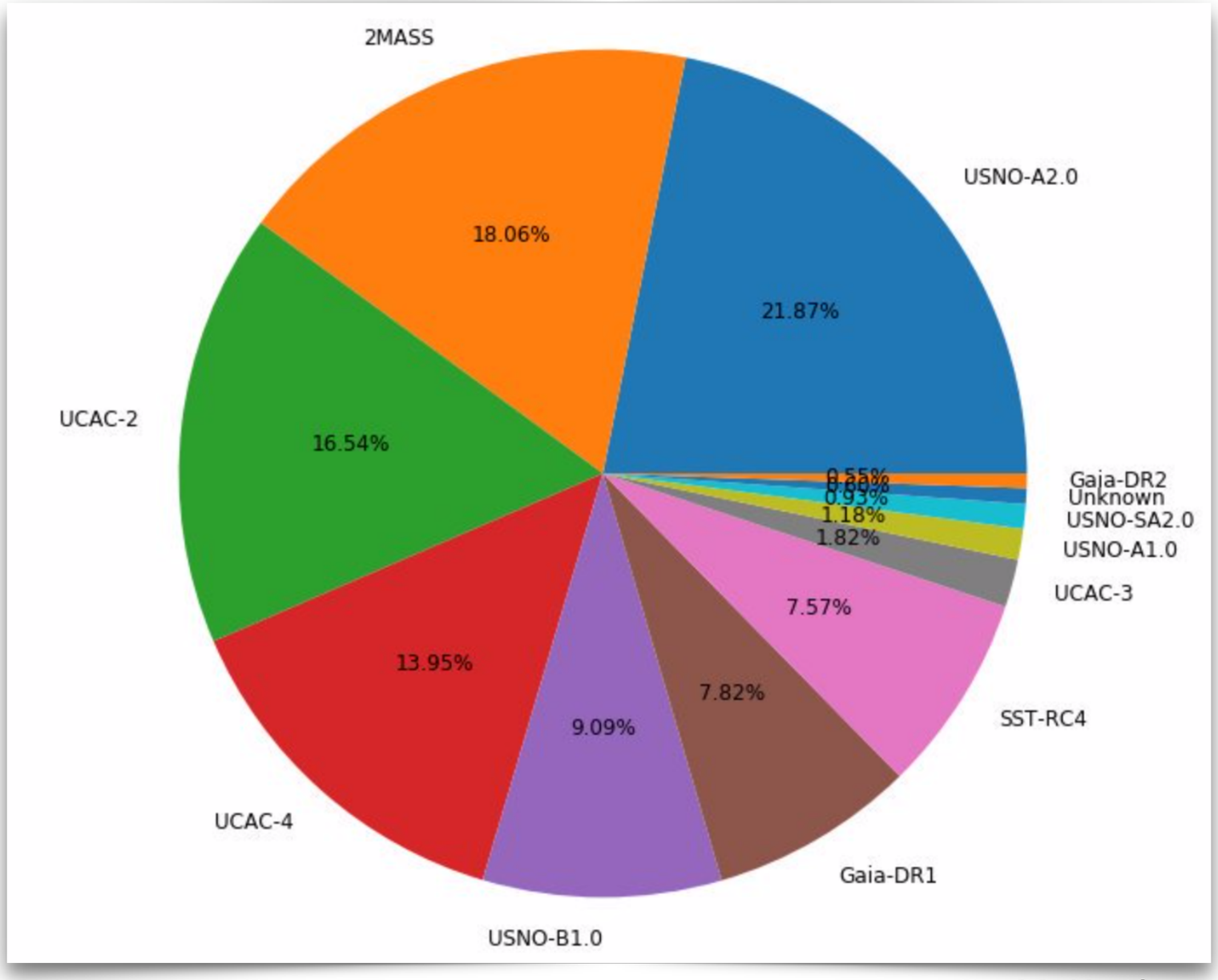
Desmars et al. 2013

- Gaia DR2 (14.099 asteroid set)

| Fraction | Residuals |
|---|---|
| 52 % | < 1 mas |
| 96 % | < 5 mas |

# Catalogue used in MPC data

- ~191 million positions, updated at Oct 2018




courtesy M. Kretlow

# The problem

An appropriate use of Gaia + pre-Gaia astrometry (calibrated by “old” catalogs)
requires
the correction of systematic effects present in old catalogs

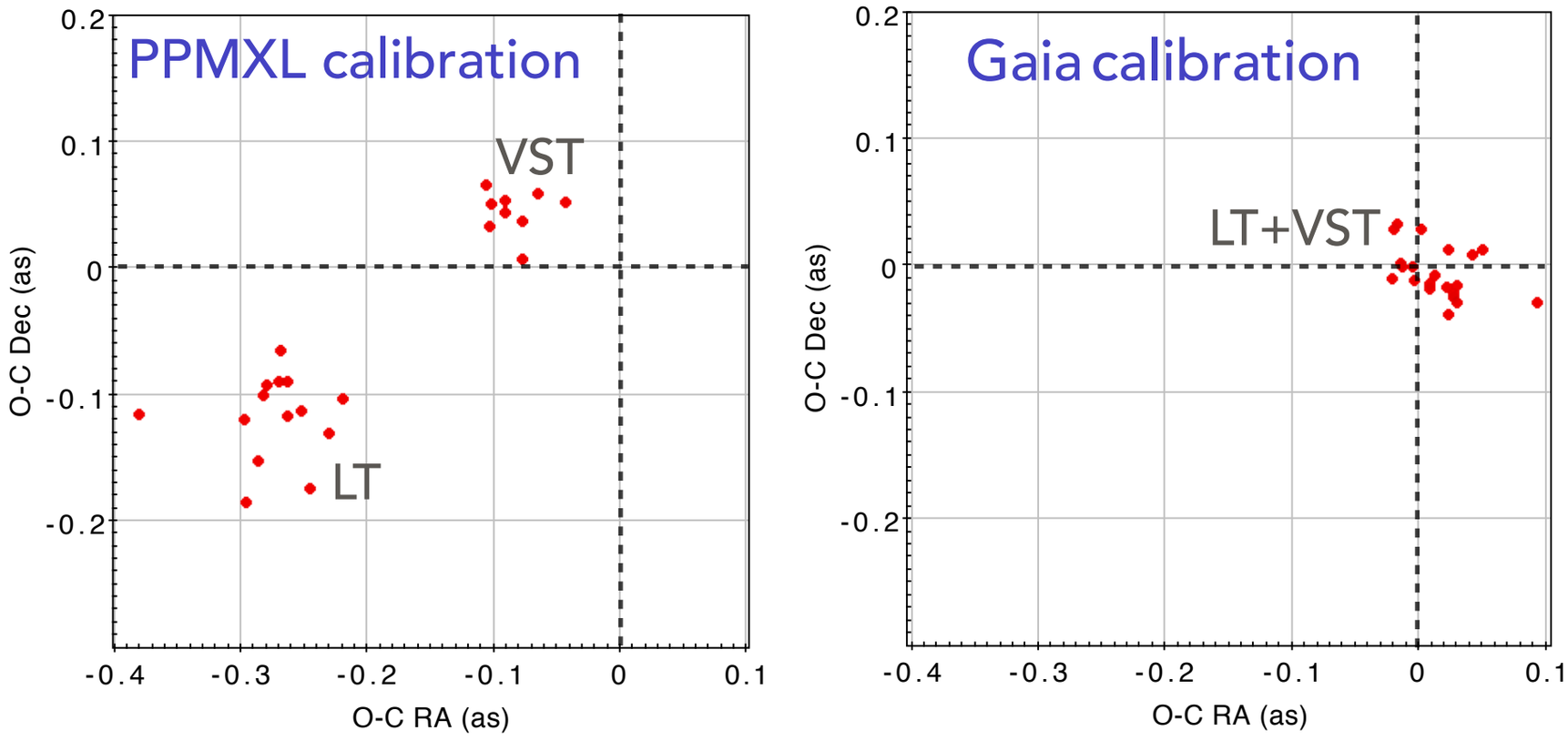
- Such effects can be:
  - different definitions of the reference system/frame
  - local (zonal) discrepancies, mostly due to:
    - ~plate size used for astrometric imaging
    - errors inherited in proper motions from pre-existing astrometry

- Going back to old raw data (plates, CCD images) and performing a new data reduction solves (nearly) all problems but it is not applicable to all the observations available (!)

# Bias example: joint exploitation Gaia + pre-Gaia astrometry

Asteroid (1132) Hollandia

Liverpool Telescope + VST (8 hours apart) & MPC ground-based data (~1900 positions)




(credits: Gaia GBOT team)

# Correction of catalogue errors: “de-biasing”

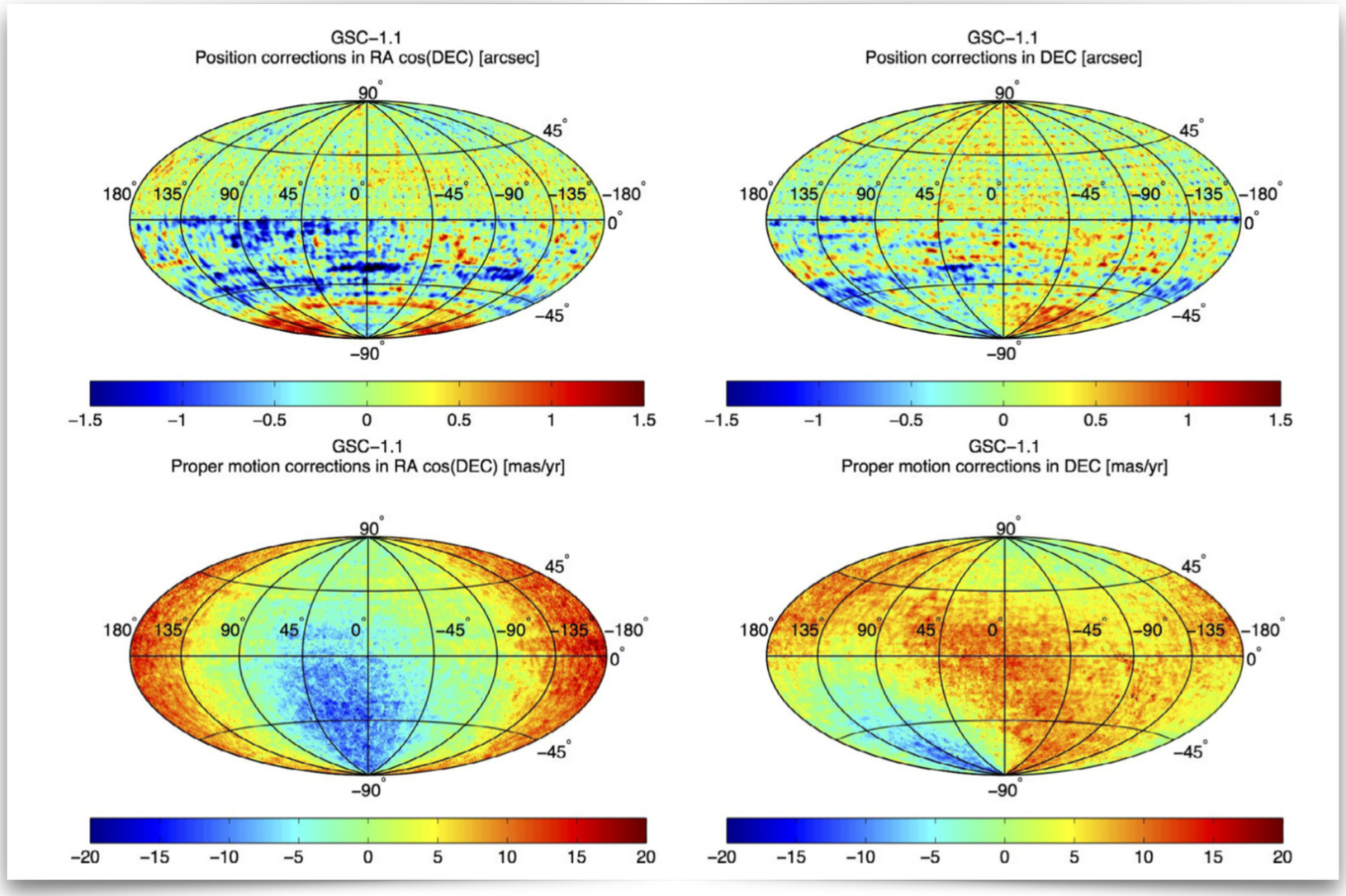
- The idea is to use the “best” available catalogue as a reference
- “Local” positions of stars in the old catalogs, at a given epoch t, can be compared to the same stars in the reference (here assumed at t = J2000.0):
  - the average difference in position $\Delta RA_{2000}, \Delta DEC_{2000}$ is computed
  - an additional contribution, the difference in proper motion $\Delta\mu_{RA}, \Delta\mu_{DEC}$, must be included (at t of each observation)

$$\Delta\mathrm{RA} = \Delta\mathrm{RA}_{2000} + \Delta\mu_{\mathrm{RA}}(t - 2000.0)$$
$$\Delta\mathrm{DEC} = \Delta\mathrm{DEC}_{2000} + \Delta\mu_{\mathrm{DEC}}(t - 2000.0)$$

# Standard approach: Farnocchia et al. 2015

Correction computed on healpix tassellation of the sky.

Reference: a subset of PPMXL, in common with 2MASS.



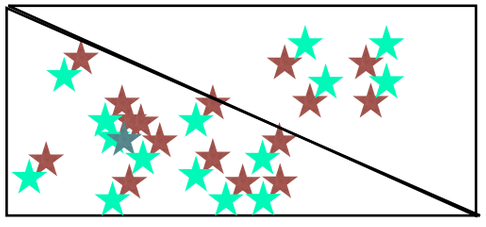

Example of resulting corrections for GSC-1.1

- Advantages:
  - Fast
  - Computed once, applicable to old/new data.
- Limitations:
  - Rigid (tassellation is fixed)
  - Discontinuities between adjacent zones.
  - No relation to the real observing conditions.

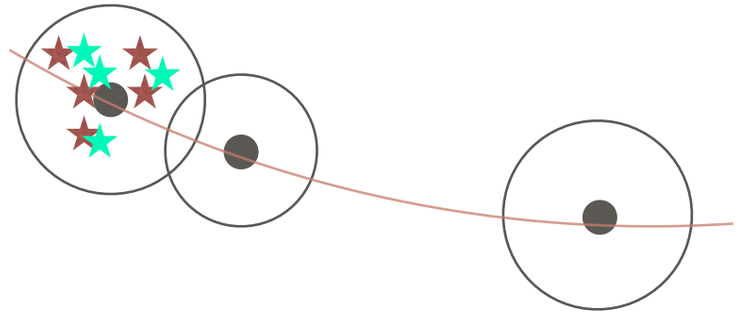
# New approach (our own)

- No tassellation: differences are computed around each astrometric position of an asteroid (source: MPC).
- Advantages, flexibility
  - large discontinuities are avoided
  - domain size and limiting magnitude can be adapted for each observation
- Limitations
  - large amount of data to correct, need to query many catalogues several times
  - overhead of computation on overlapping regions

# Quick look comparison



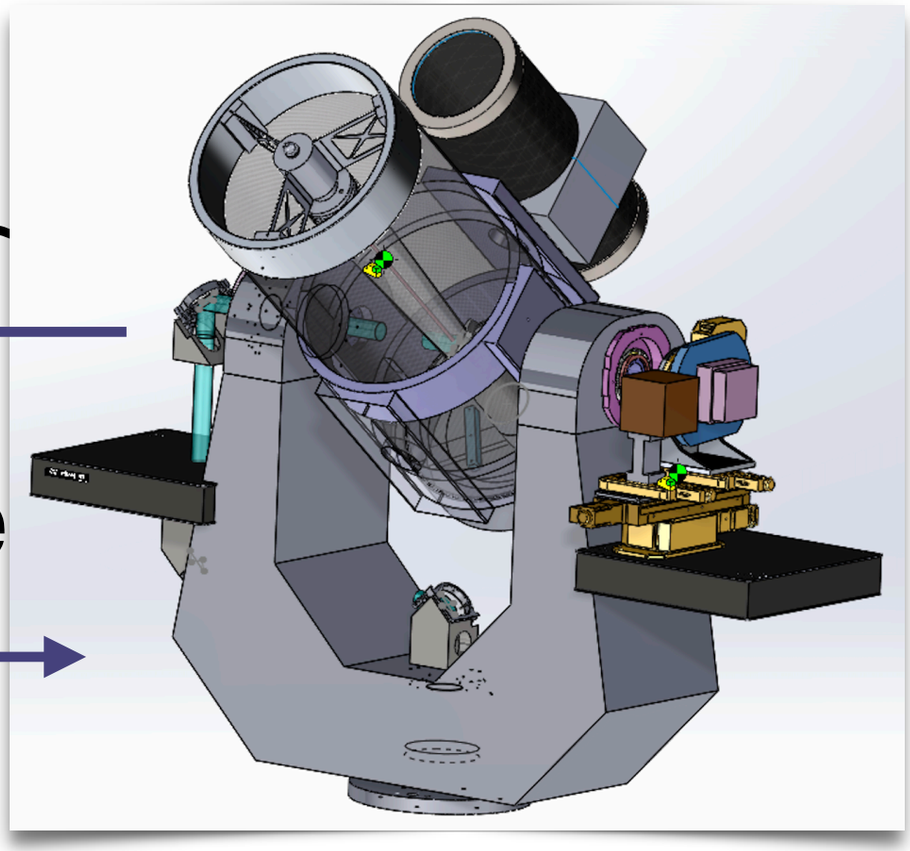
Method 1 (used up to now): corrections of catalogs computed on a healpix tassellation of the sky (Farnocchia et al. 2015)



Method 2 (our own) : corrections of single archive observations referred to Gaia DR2

# Robotic observations of asteroid occultations

- Extension to faint magnitudes and small asteroids
- Only method providing ~ accuracy
- 50 cm robotic telescope France



ASTROMETRIC DATA

OBSERVATIO

EXPLOITATION: YARKOVSKY IMPROVED DYNAMICAL

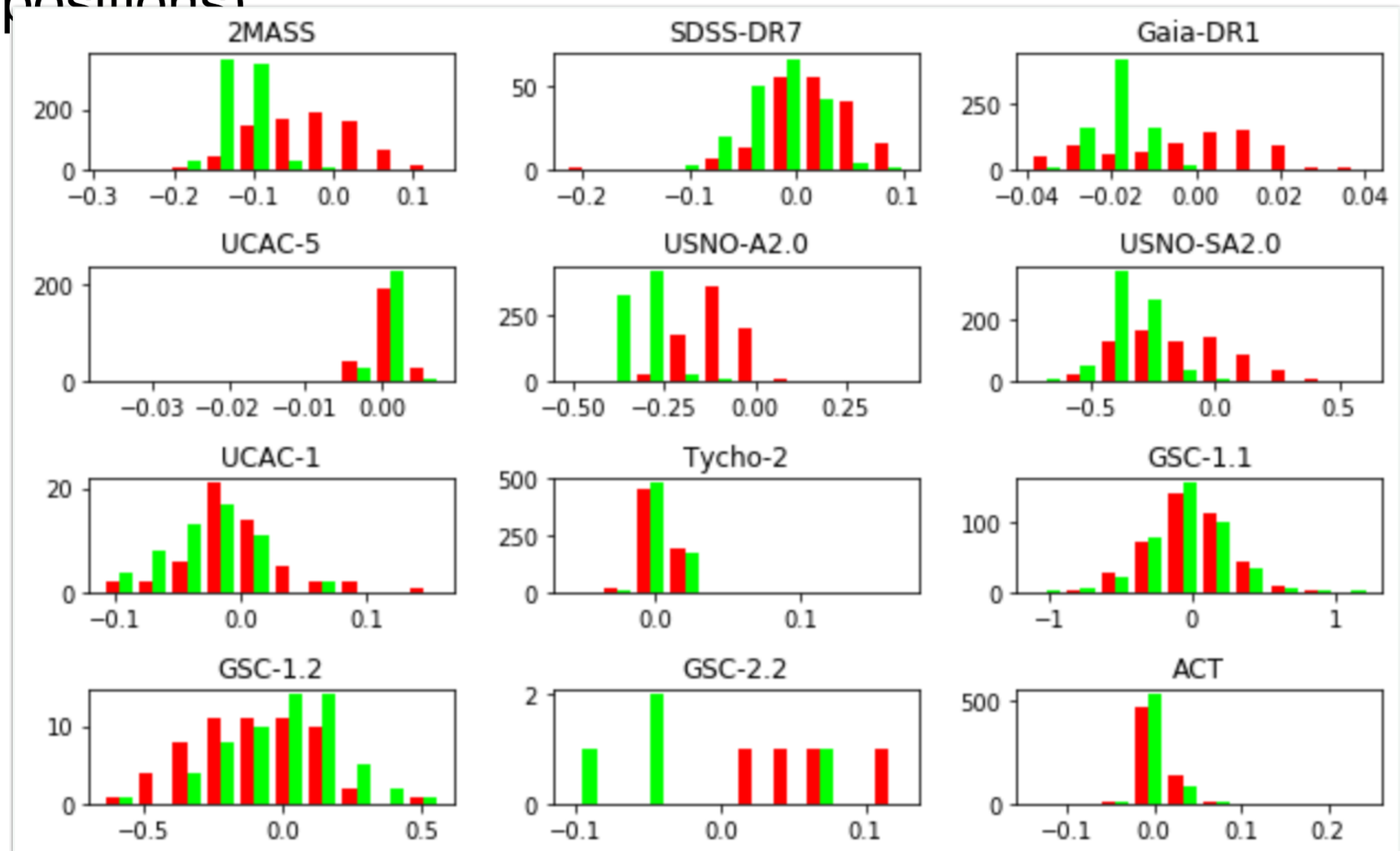
OCCULTATION

# New approach: preliminary version

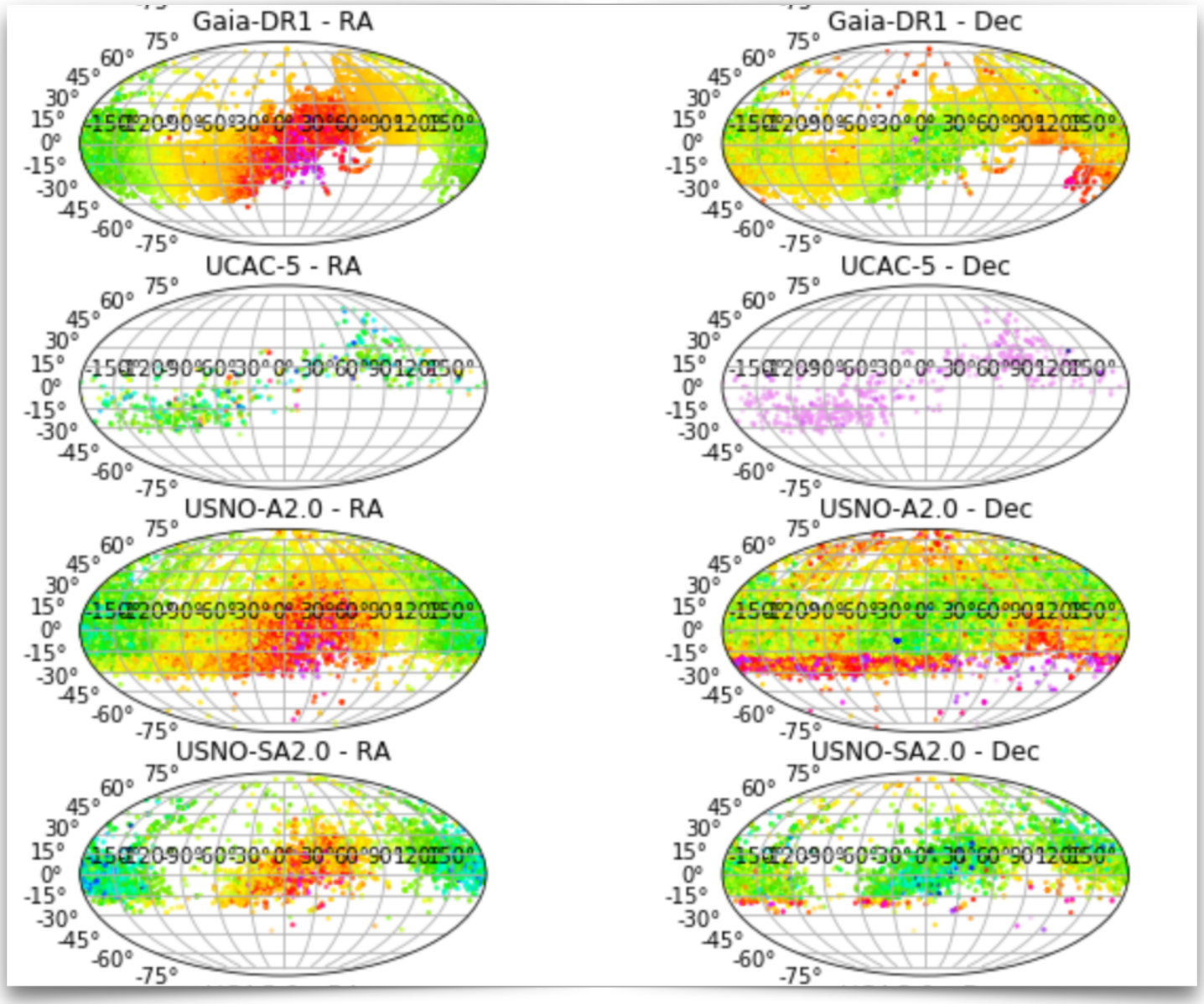
ACT
USNO-A2.0
USNO-SA2.0
USNO-B1.0
CMC-14
UCAC-1
UCAC-2
UCAC-3
UCAC-4
UCAC-5
GSC-ACT
GSC-1.1
GSC-1.1
GSC-2.2
Tycho-2
2MASS
PPMXL
SDSS-DR7
Gaia-DR1

## Current magnitude limit V<15

Bias distribution (arcsec): ~3000 asteroids (~1 million positions)



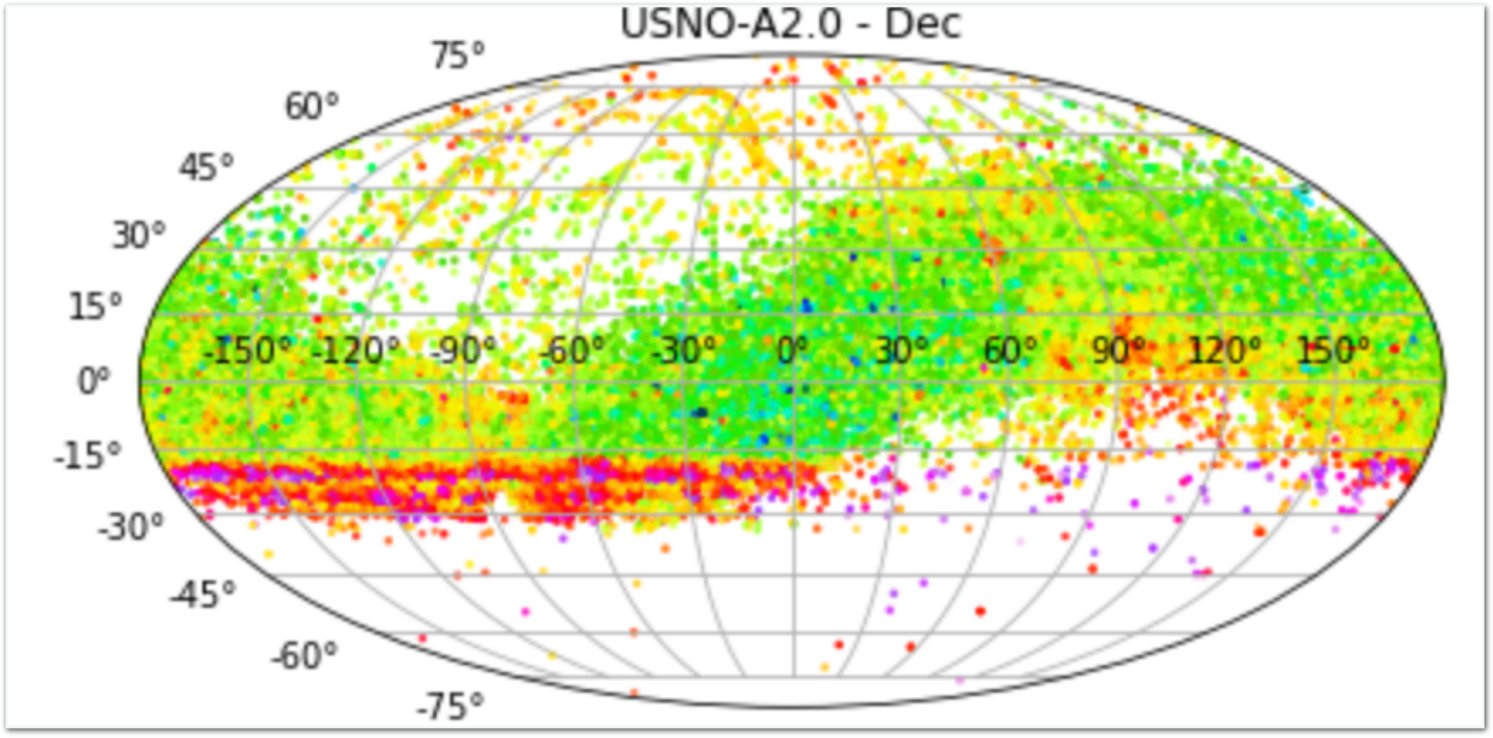
# New approach: preliminary version




Sky distribution: example on 4 catalogues

position difference at J2000.0

# A detailed look: declination bands




amplitude ~50 mas

# New approach : current (and future) implementation

- Current (test) version:
  - Corrections on 20 catalogues
  - 30 arcmin field radius around each position
  - limiting magnitude G<15

- New version for massive exploitation:
  - FOV tuned on ~40 telescopes/surveys
  - adapted limiting magnitude

# Conclusions

- Correction of local systematics is required if old astrometric positions of Solar System objects are used.
- The new method works
  - The final validation of the correction can be done by an orbital fit
  - Comparison of residuals, prediction (or post-diction) of stellar occultations
- Limitations:
  - deterioration of proper motion accuracy strongly affects the result
    - when faint stars are involved
  - lack of information on the original astrometric calibration
- Debiasing methods cannot replace direct DR2 calibration
  - but are the best we can do for all other astrometric data