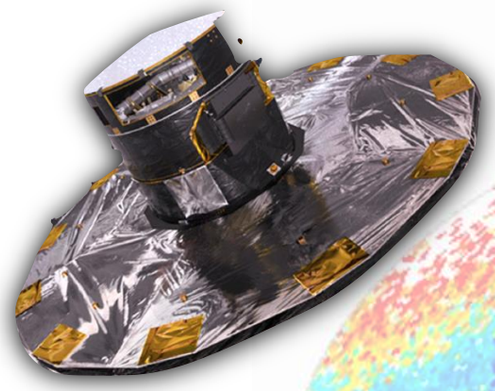
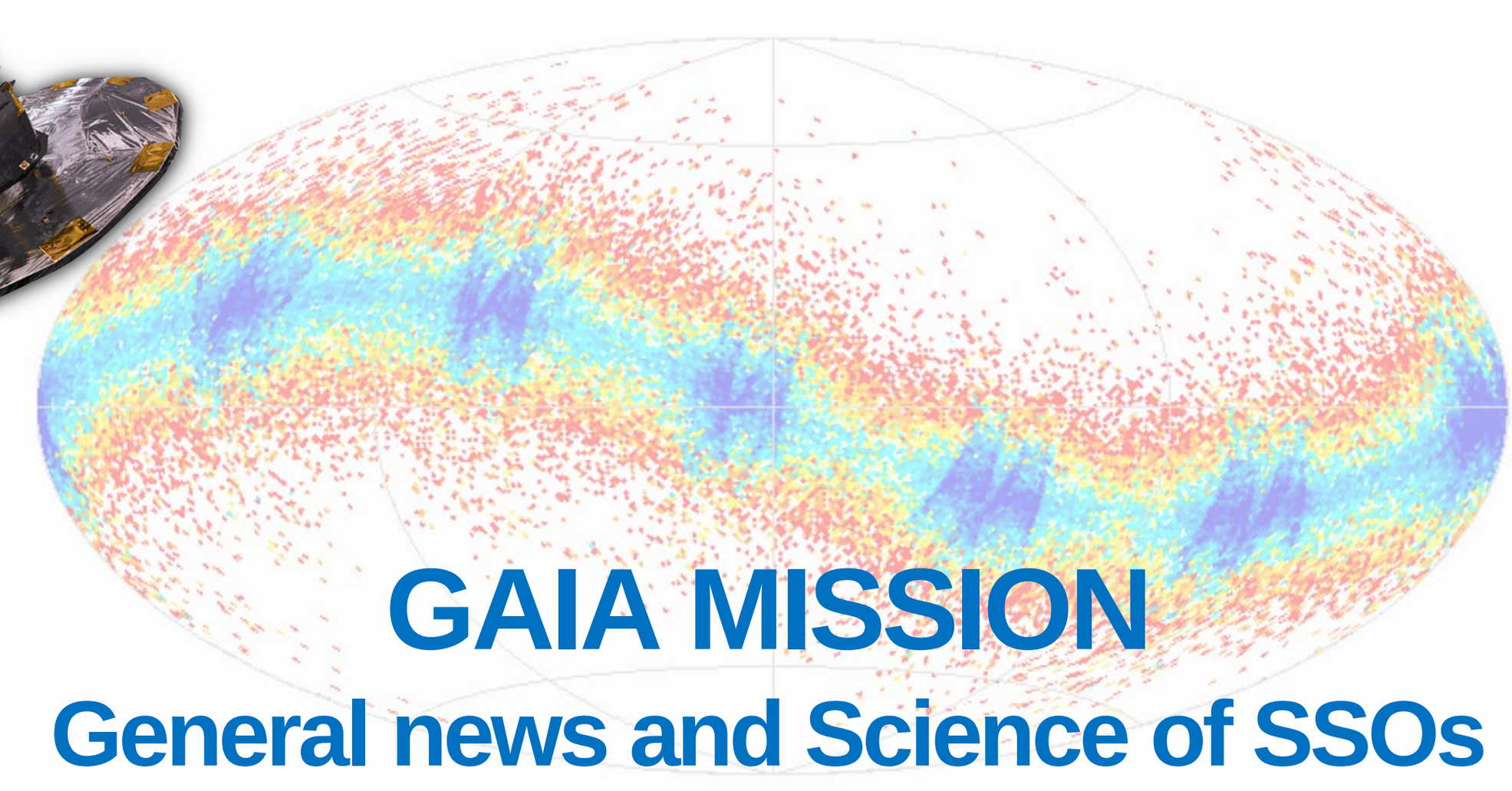




GAIA MISSION
General news and Science of SSOs

Daniel Hestroffer
& Gaia DPAC consortium

IMCCE/Paris observatory, univ. PSL, France
hestroffer@imcce.fr

Acknow.: P. Tanga, F. Spoto, F. Mignard, CU4-SSO

Jan. 2020 – ИПА, Санкт Петербург, Россия

Outline

- ***The Gaia mission, the satellite, the DPAC***
- ***Science - general results with DR2***
- ***SSOs (and exoplanets)***
- ***Future***

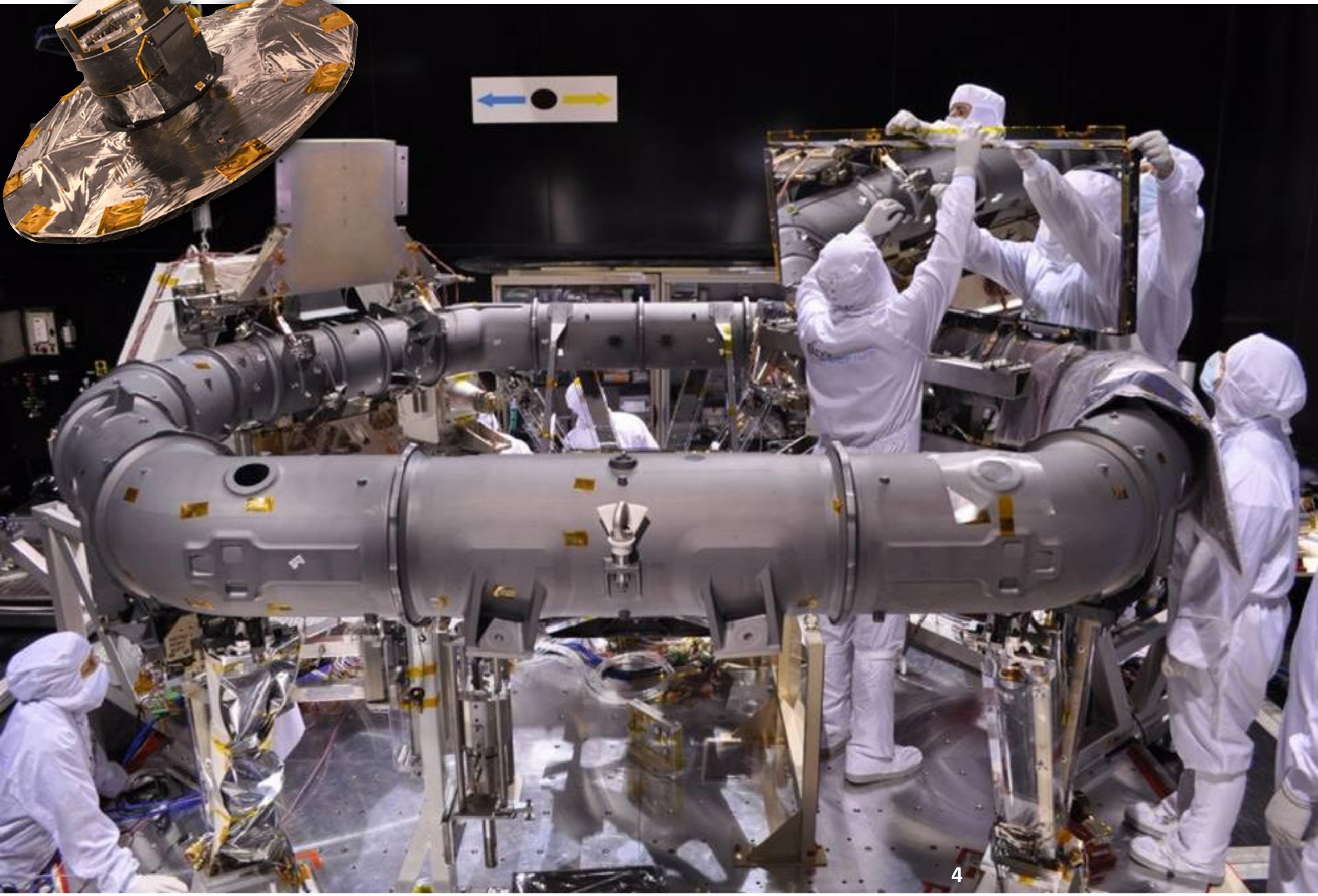
Gaia Mission

3D (6D) Census of the Milky Way
unravelling its dynamical and chemical history

Perform global astrometry with high precision (π, μ, rv)
Observing the whole sky (North and South) with same instrument
Continuously scanning the sky in space (no atmosphere),

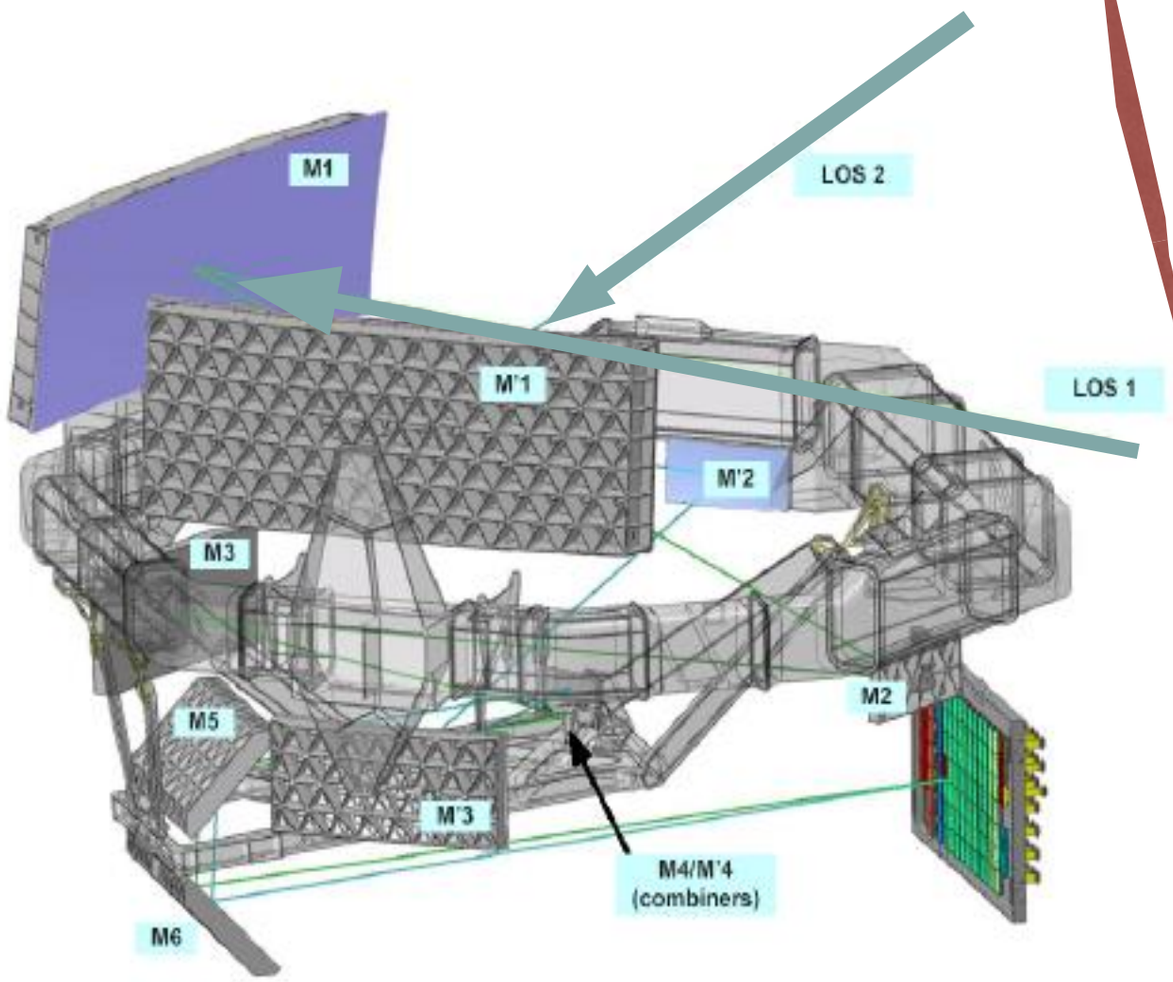
Measuring epoch positions & brightness over years
and their variation: motion & variability

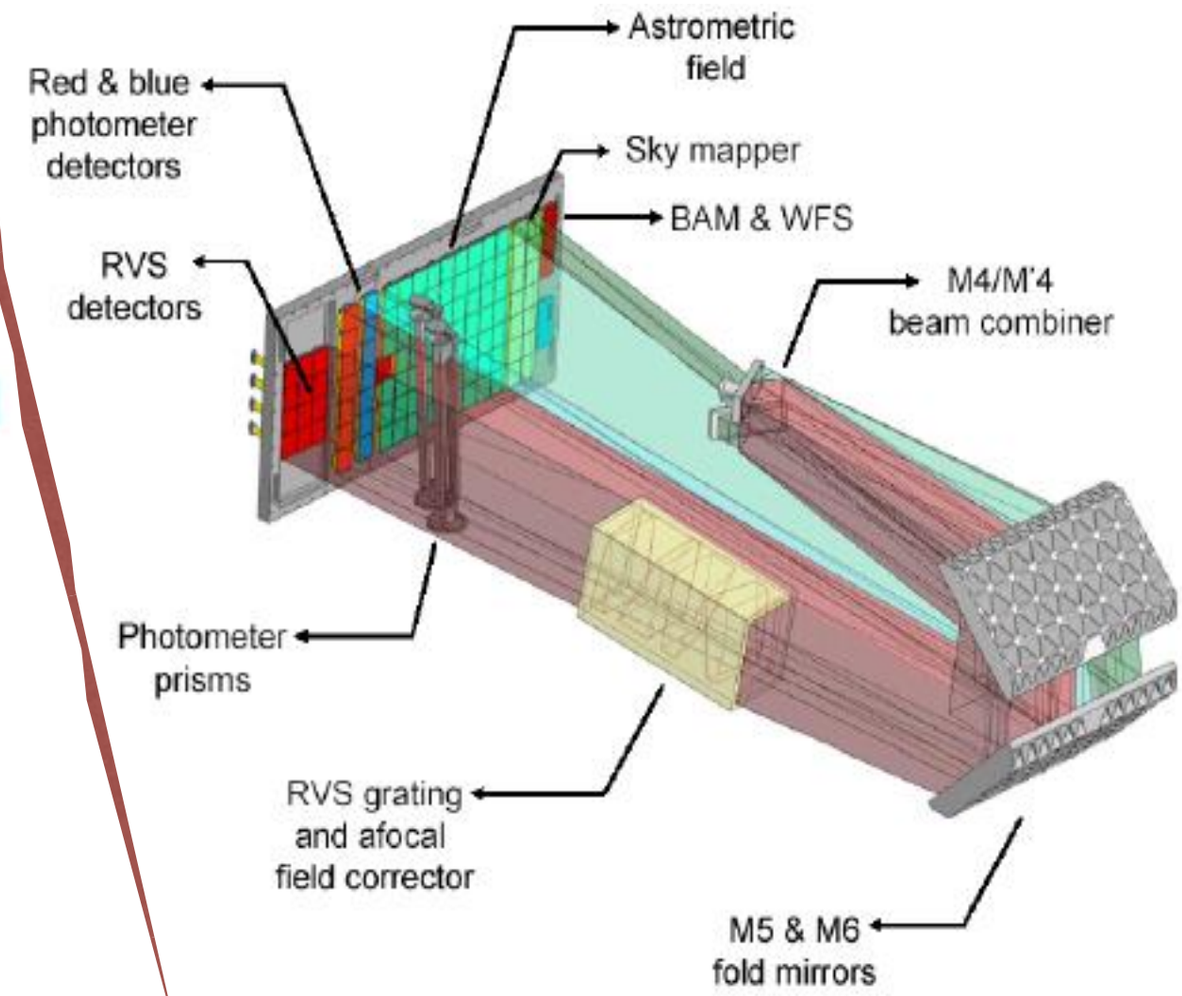
Installation of primary mirror M1



(@ASTRIUM)

Focal plane - Payloads

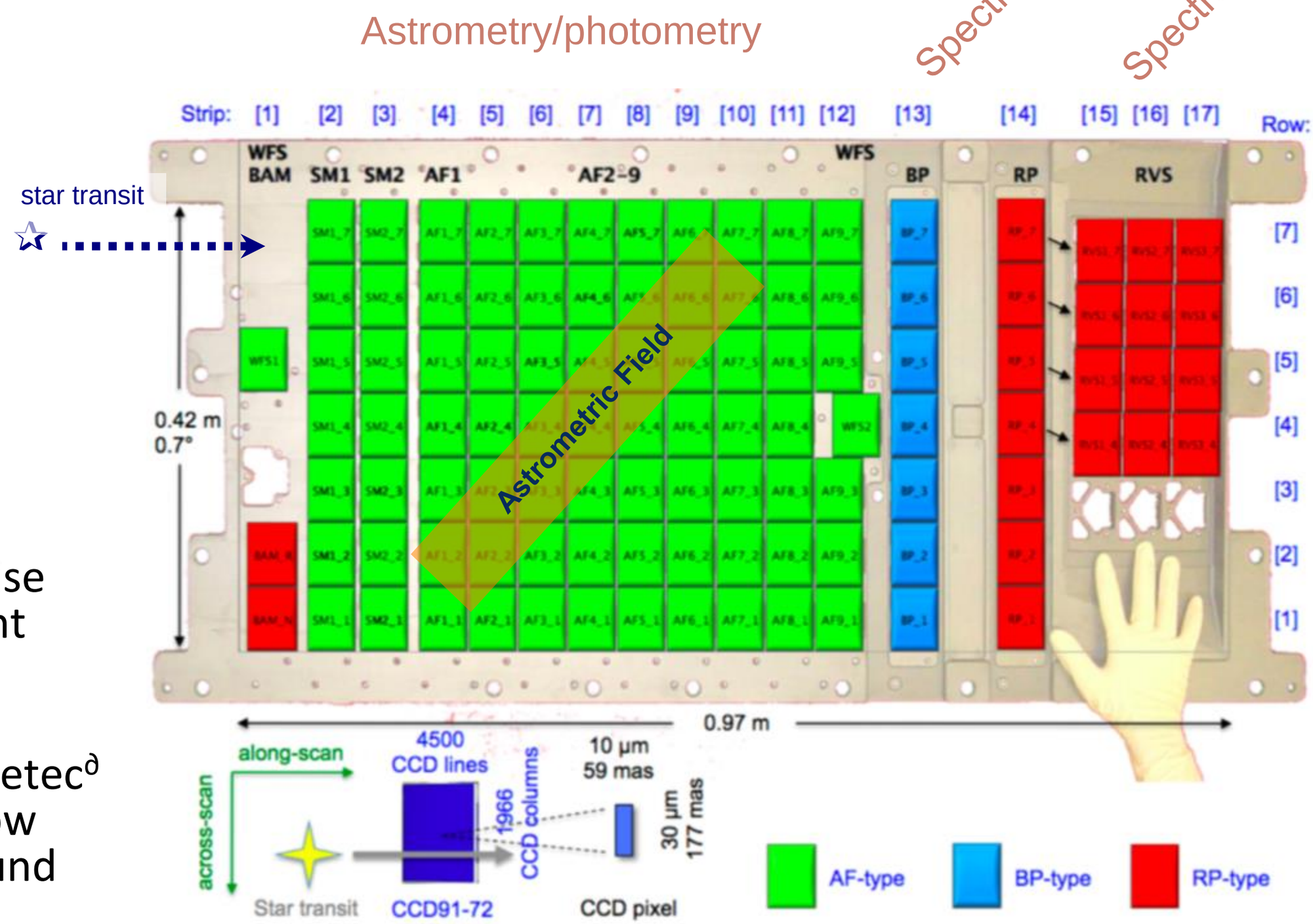




One single focal plane ; 3 instruments

astrometry,
spectro-photometry,
spectrometry

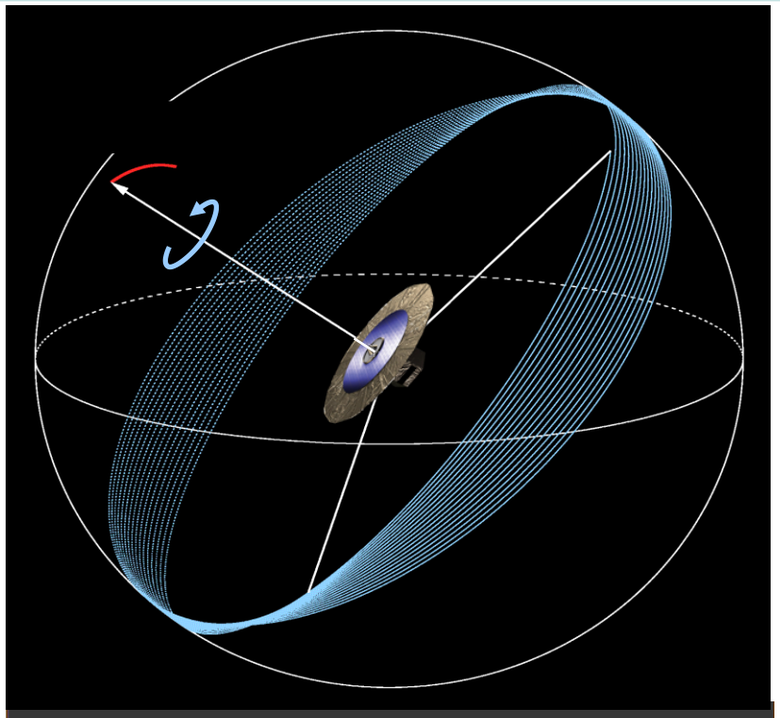
Focal plane - Payloads

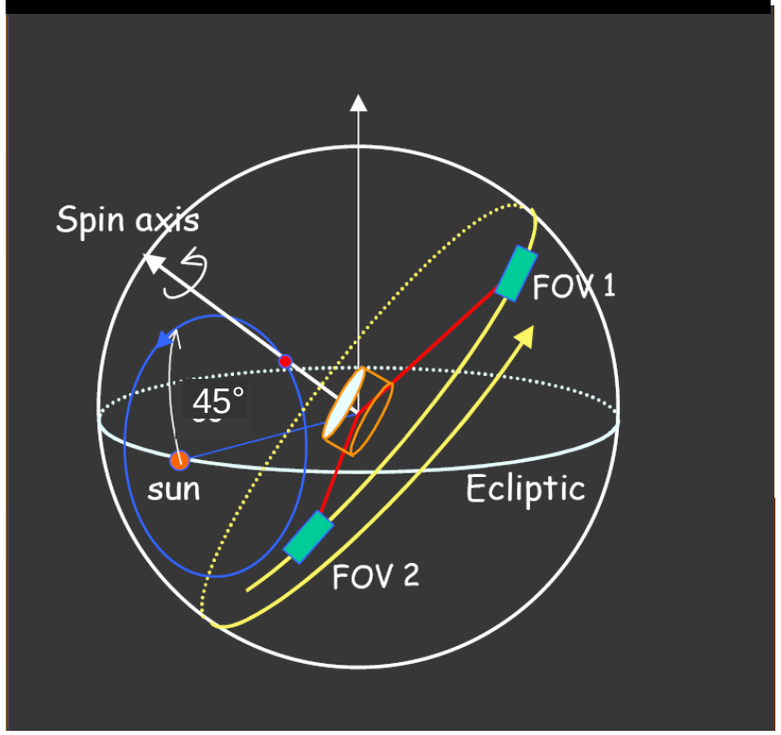


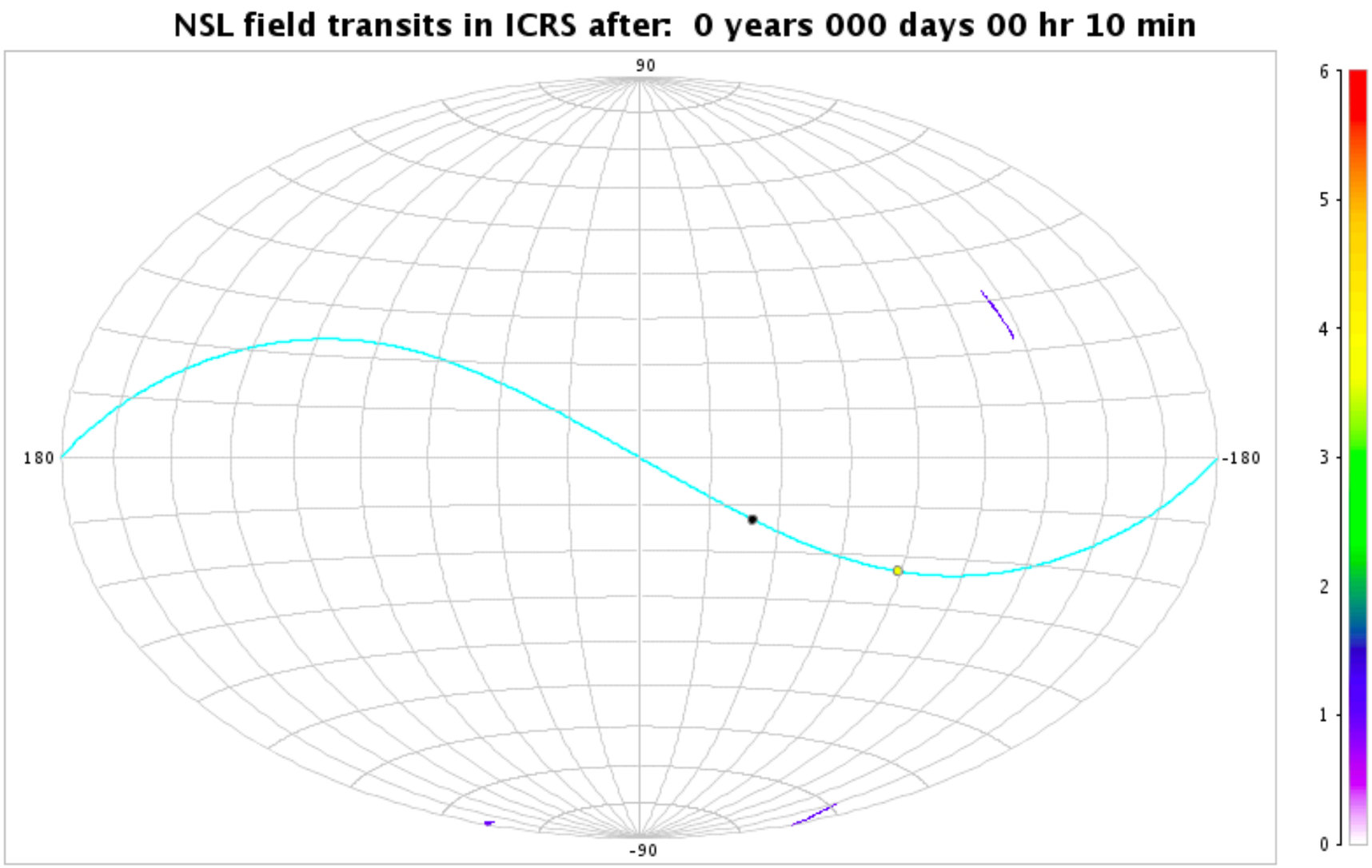
- Large mosaic >100 CCDs
- TDI mode
- Binning
  - Reduced noise photon count
  - 1D epoch astrometry
  - Automatic detec∂ patch window send to ground

Scanning law - Mapping

- *Scanning - no pointing*
- *2 FOVs - global astrom.*



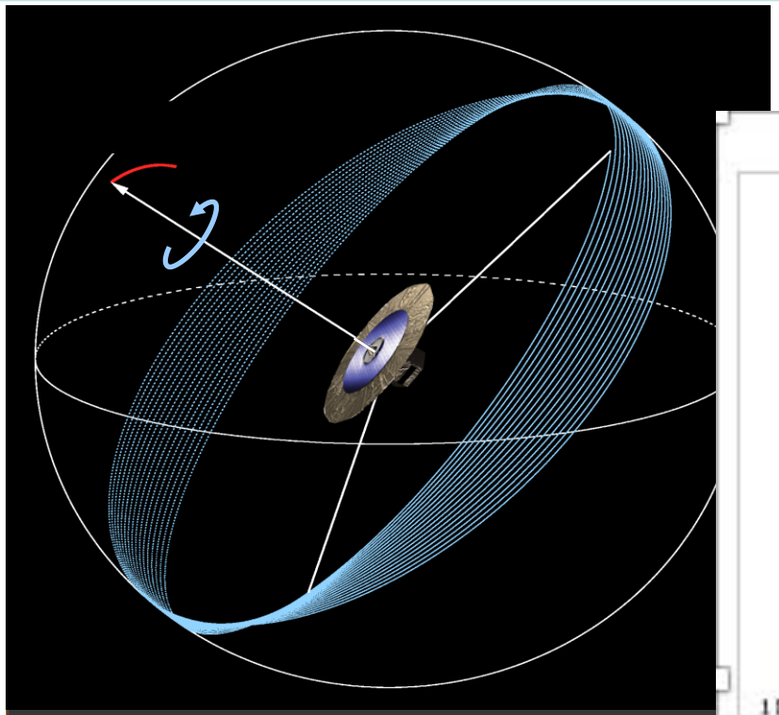


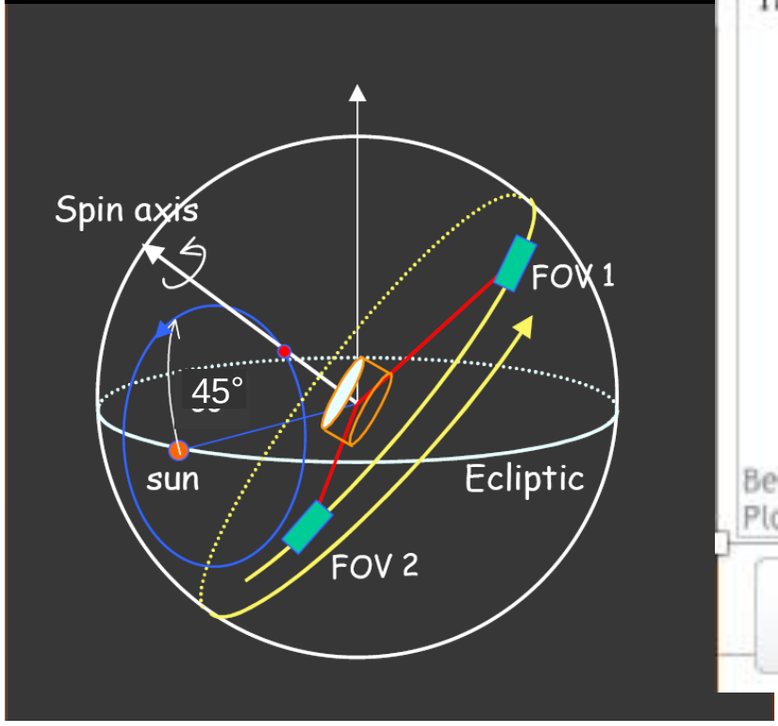


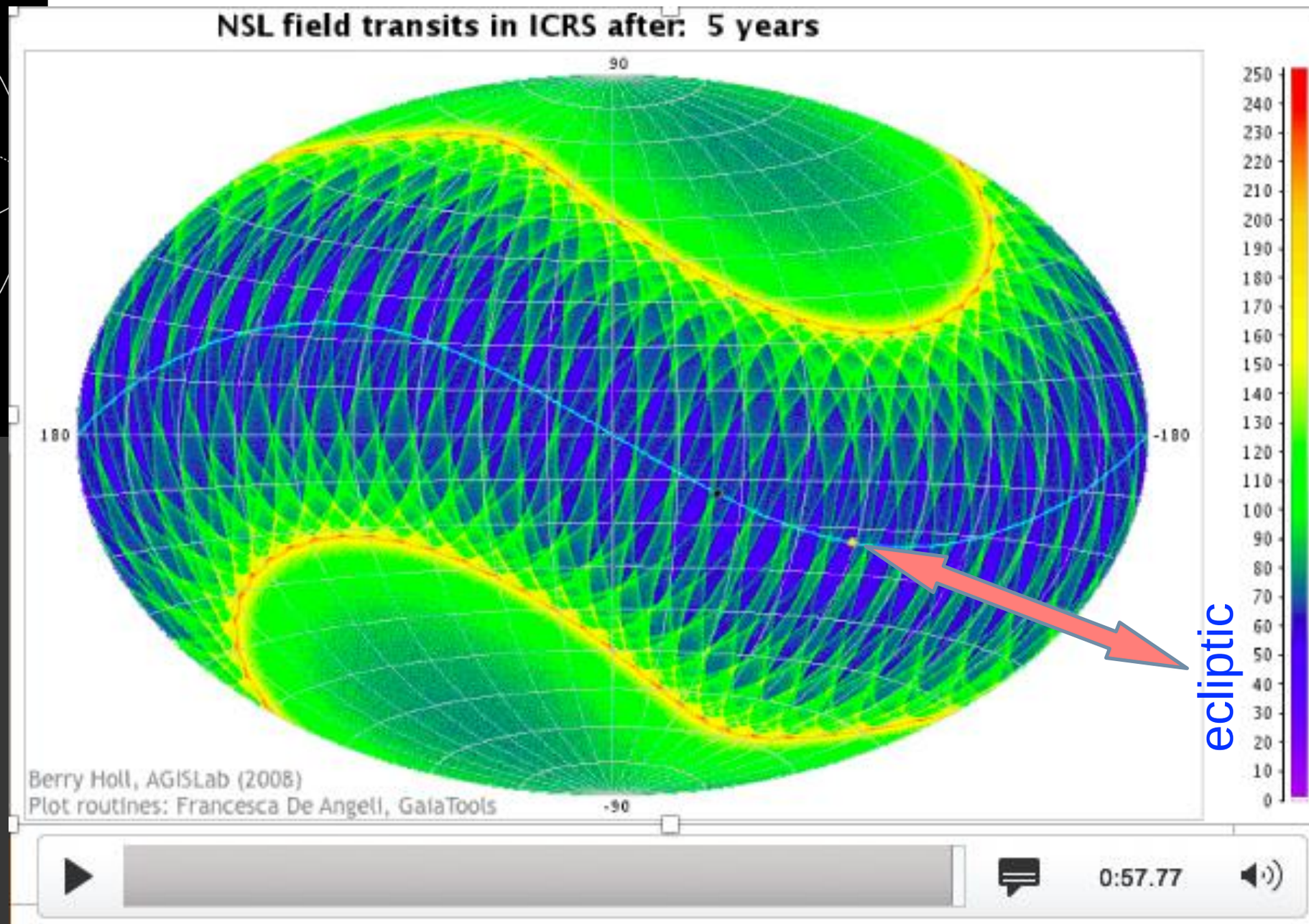
Scanning law - Mapping

- *Scanning - no pointing*
- *2 FOVs - global astrom.*

Movie showing sky coverage over time

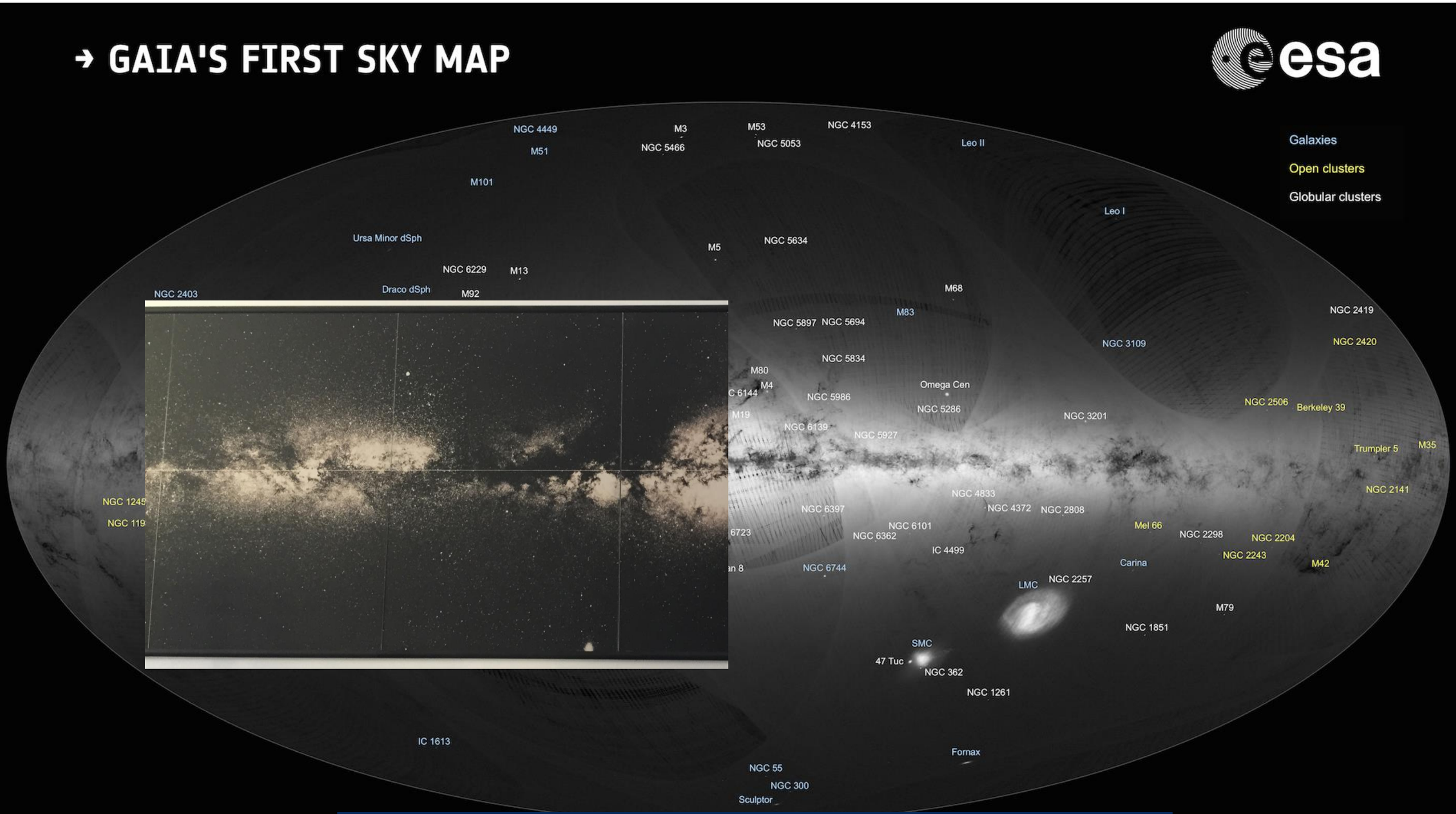






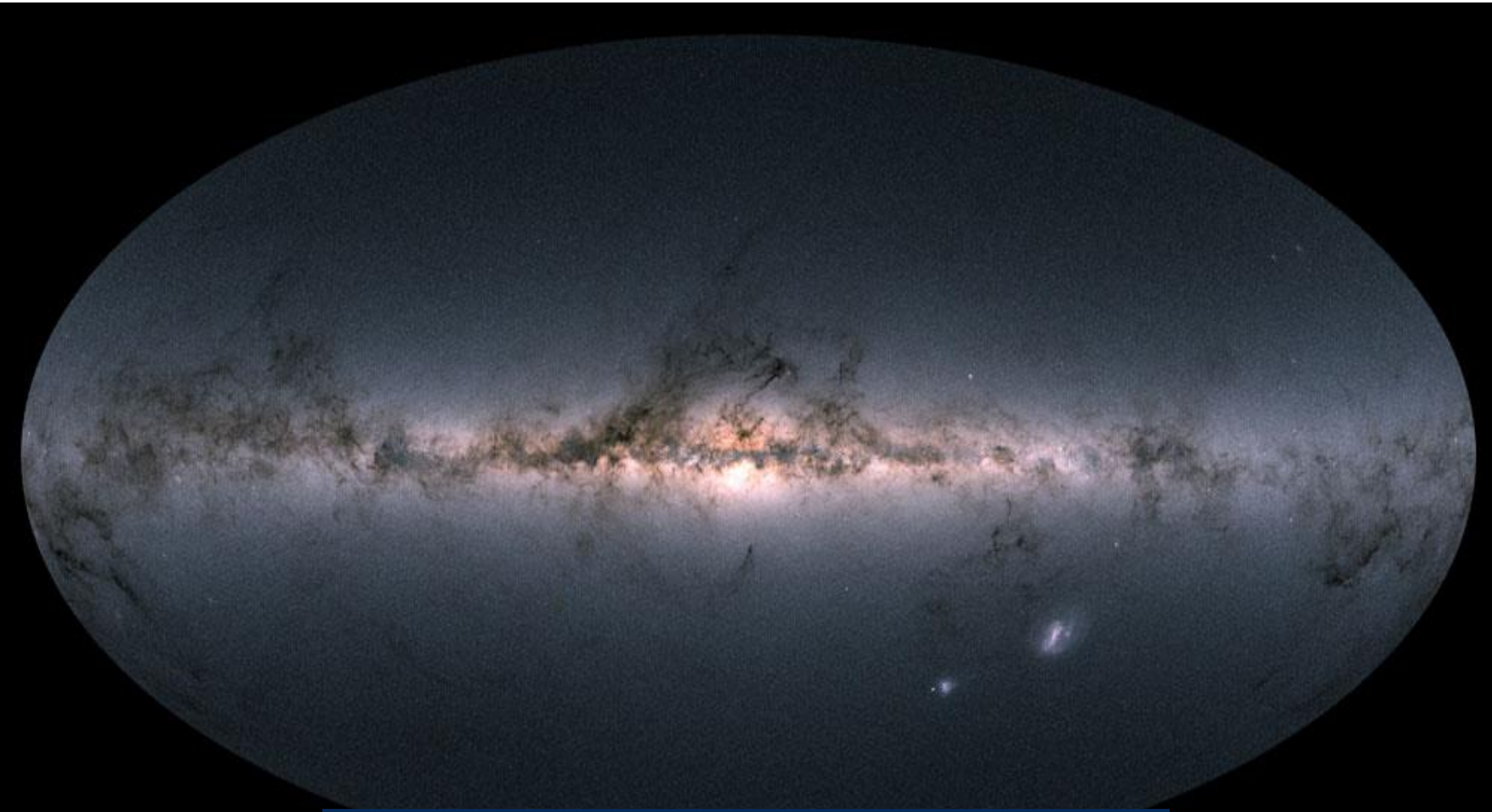
Gaia 2nd data release DR2
– overview –

Gaia DR1 (2017) – a teaser



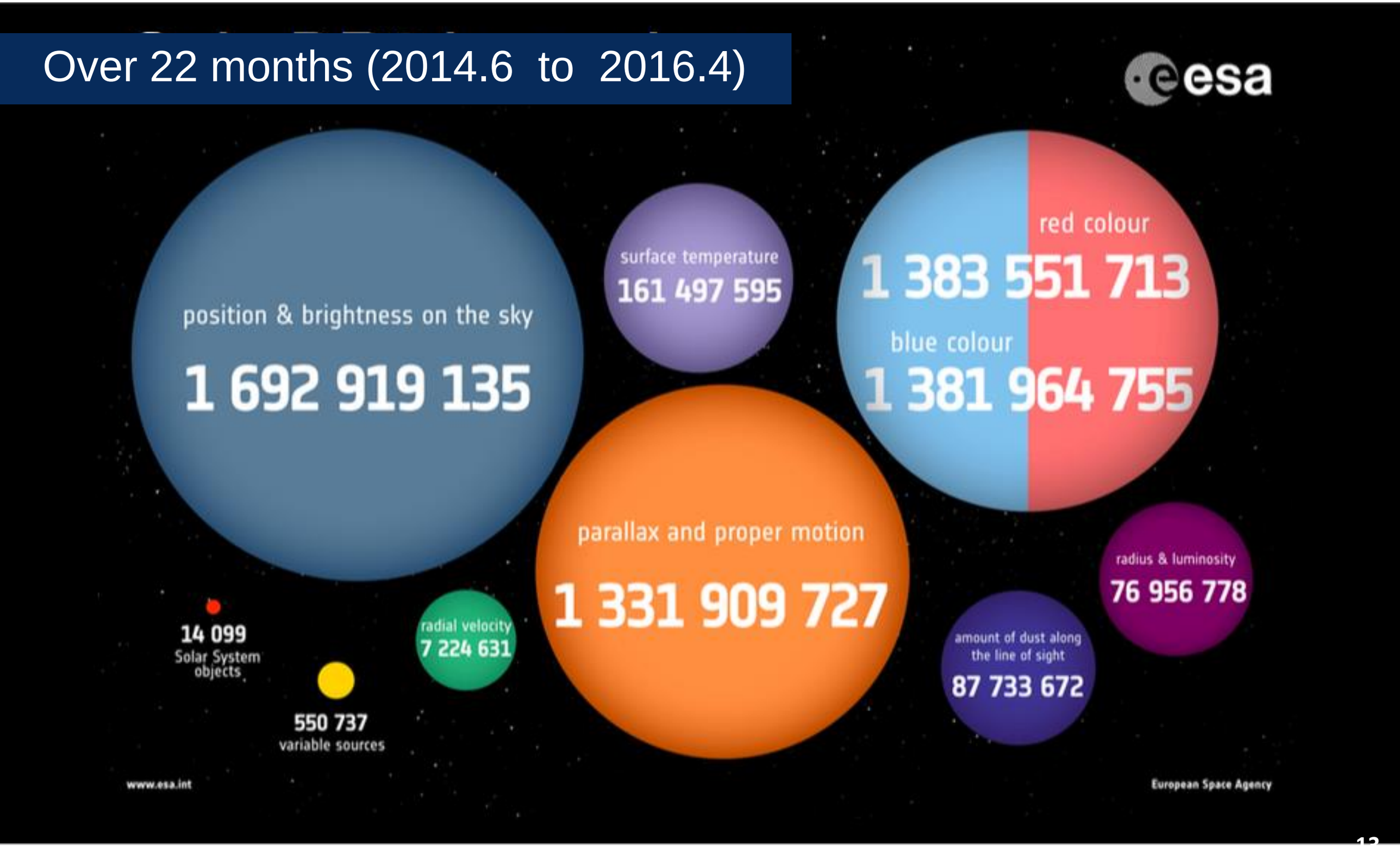
Mostly positions & magnitudes, TGAS

Gaia DR2 – April 2018

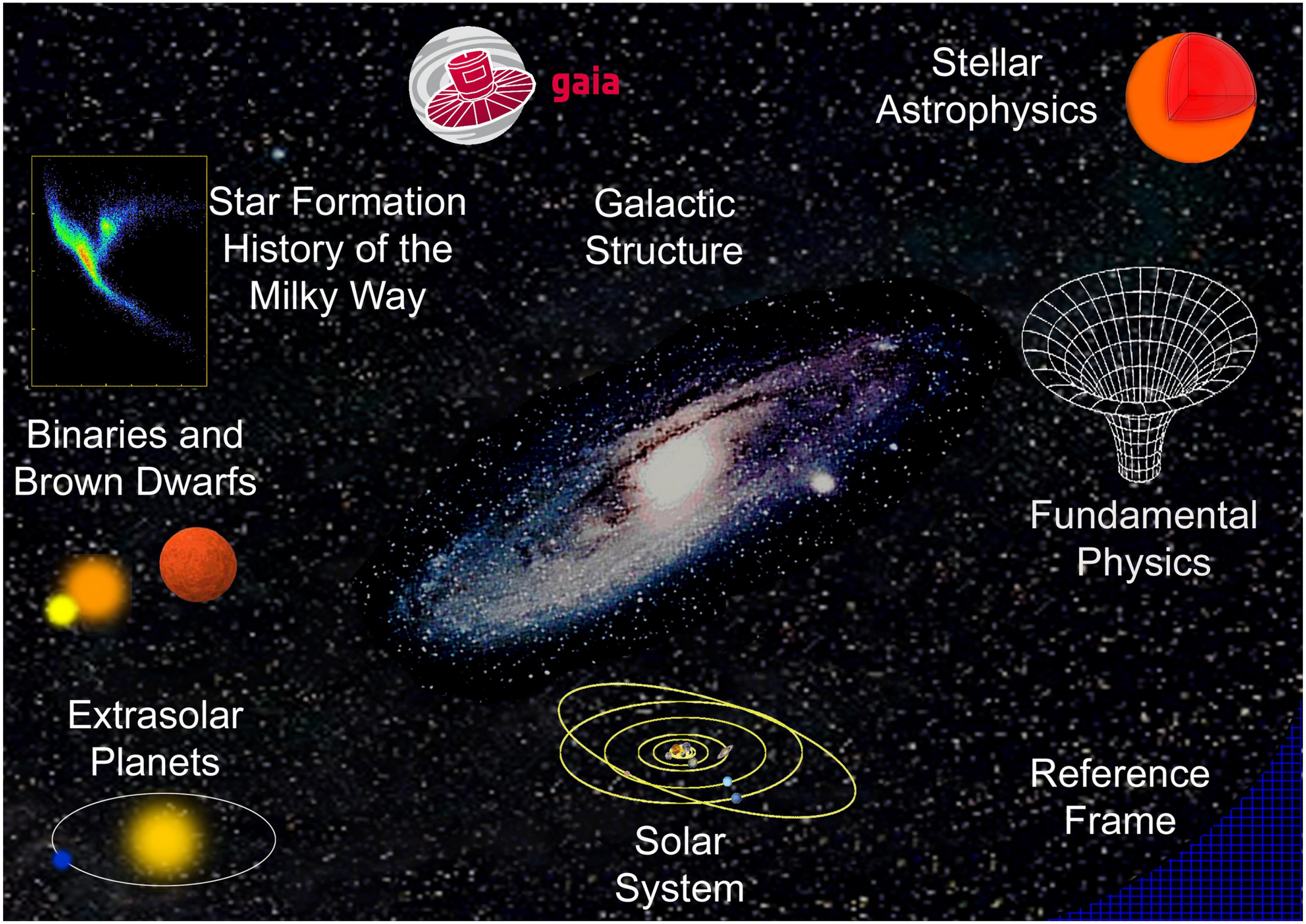


not only an image :: a map

Gaia DR2 – in numbers

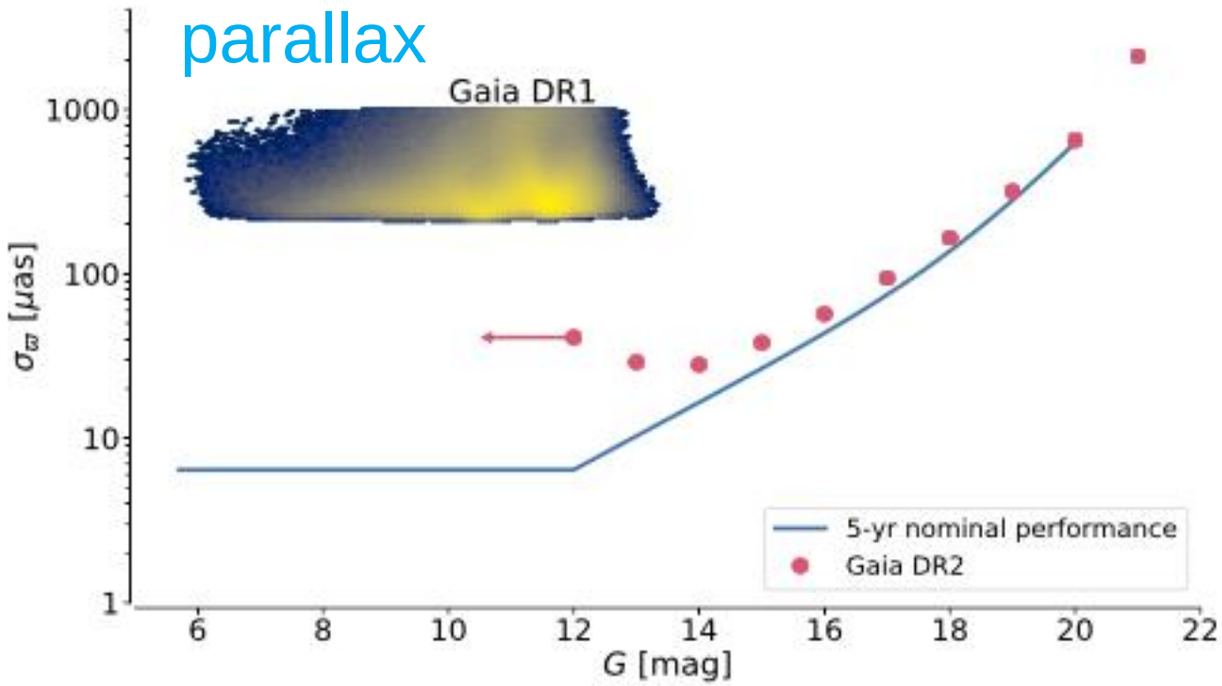


Gaia – Scientific Domains

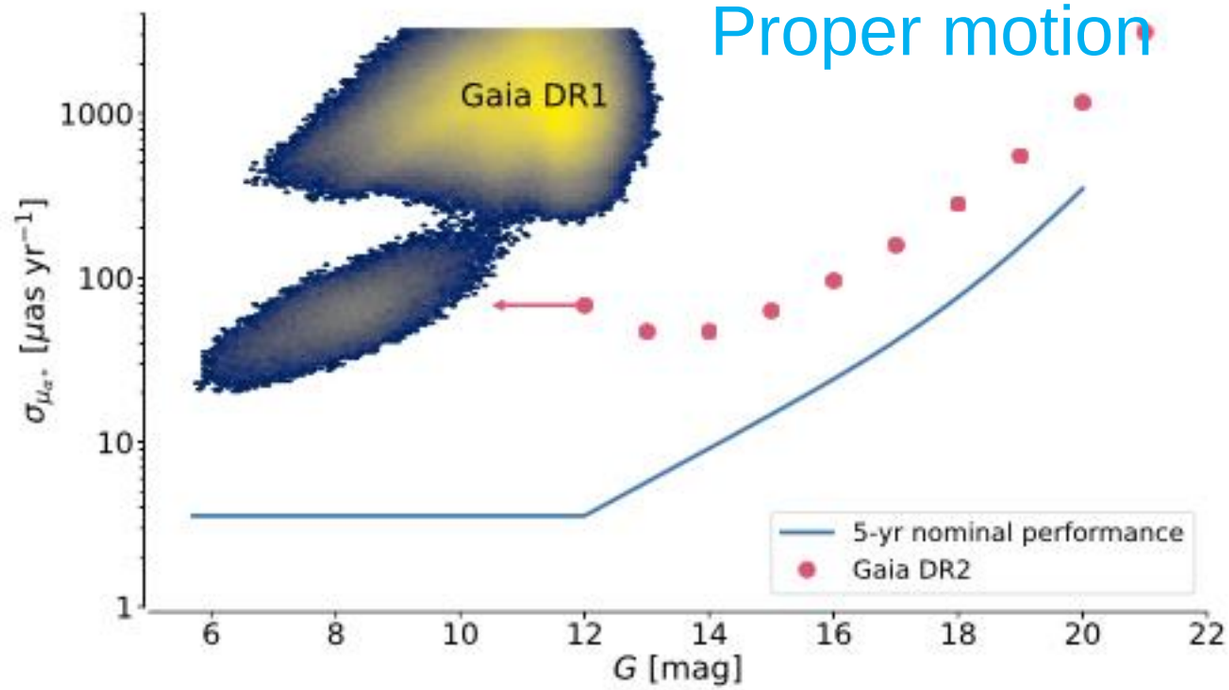


DR2 – Performances

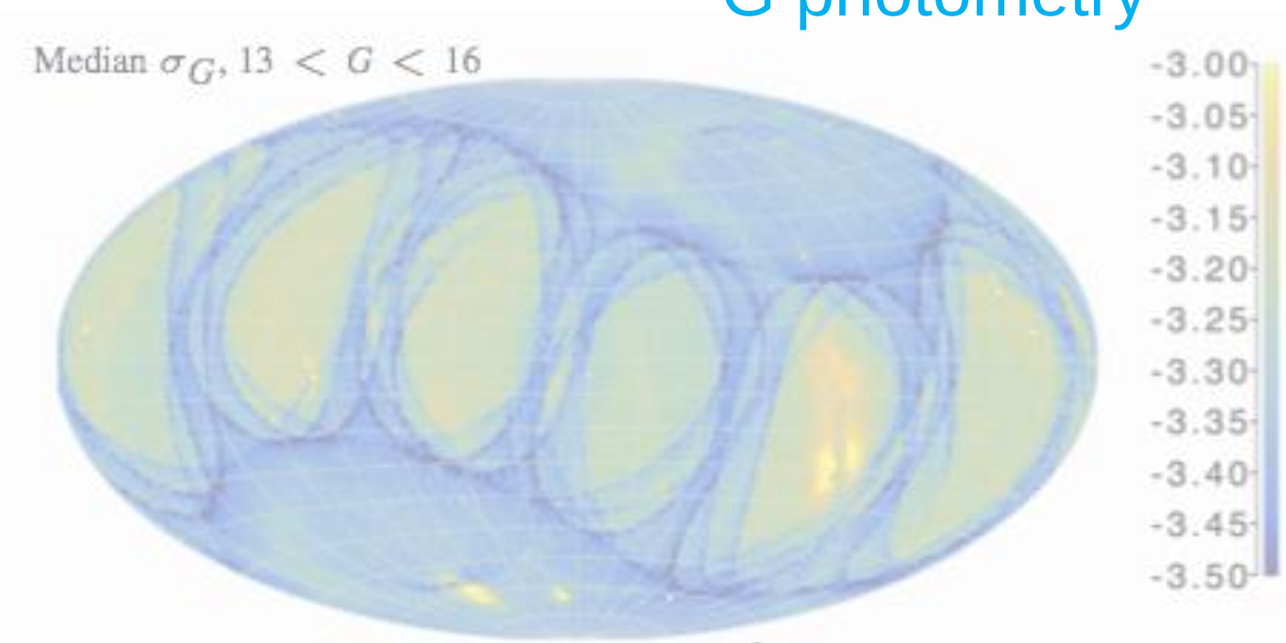
parallax



Proper motion

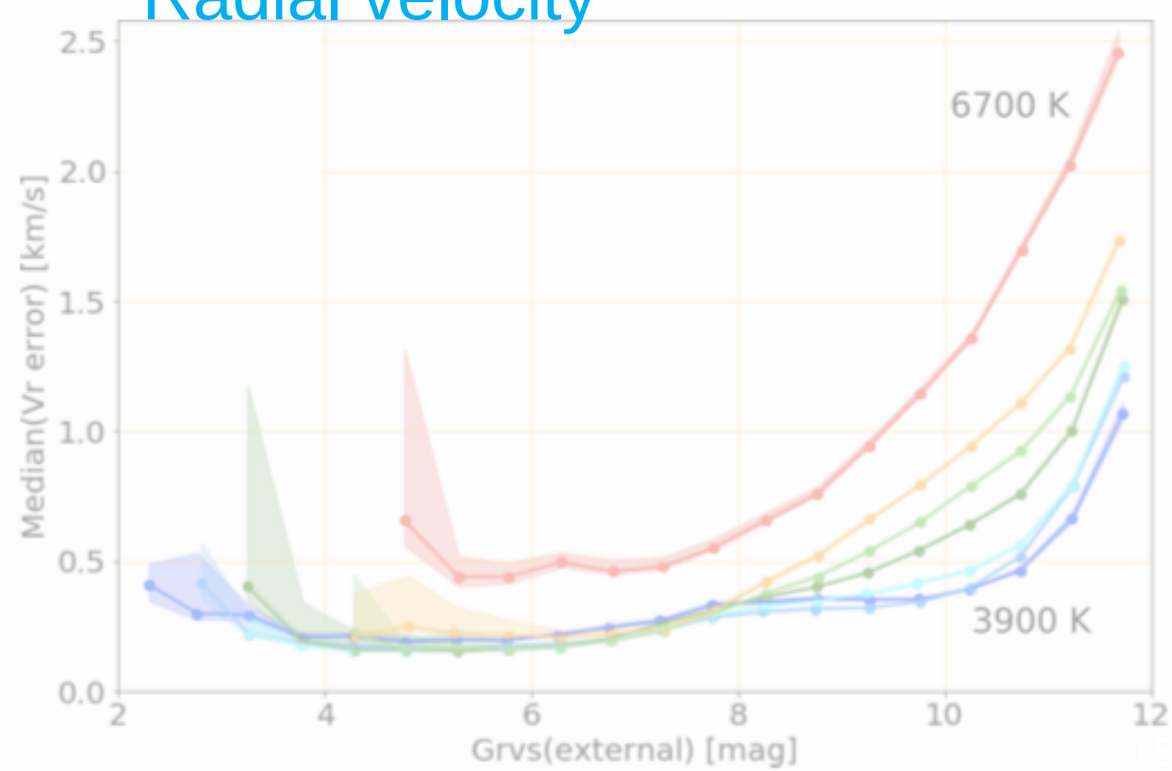


G photometry

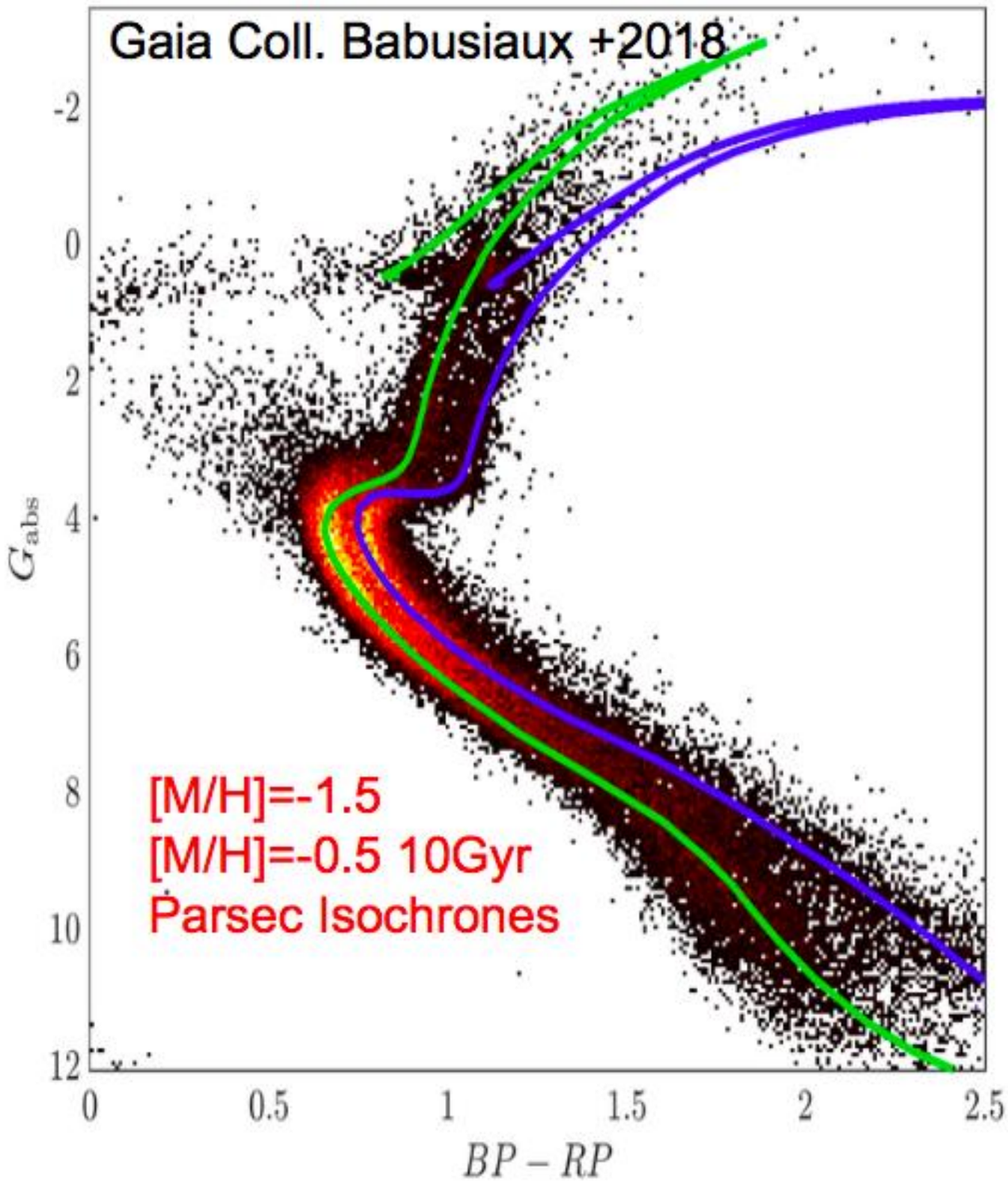


σ_G: 0.3–10 mmag

Radial velocity



Gaia DR2 – H-R Diagram



- Fine structures in H-R diagrams
- New views of
  - halo
  - Wdwarfs
  - clusters
  - mergers…
- Stellar evolution,
- Kinematics
- Extinction
- Combination with other surveys

(Babusiaux et al. 2018, A&A)

http://www.esa.int/Science_Exploration/Space_Science/Gaia/

SCIENCE & EXPLORATION

Gaia untangles the starry strings of the Milky Way

READ →

SCIENCE & EXPLORATION

Astronomers spy Europa blocking distant star – thanks to Ga...

READ →

SCIENCE & EXPLORATION

Gaia starts mapping our galaxy's bar

READ →

ENABLING & SUPPORT

Gaia's biggest operation since launch

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Observing Gaia from Earth to improve its star maps

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Gaia clocks new speeds for Milky Way-Andromeda collision

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Gaia reveals how Sun-like stars turn solid after their demi...

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Gaia spots stars flying between galaxies

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Gaia finds candidates for interstellar 'Oumuamua's home

READ →

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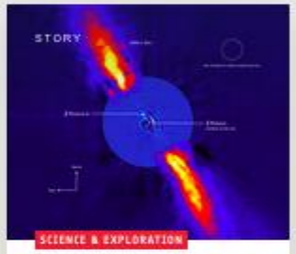
Gaia hints at our Galaxy's turbulent life

READ →



SCIENCE & EXPLORATION

Infant exoplanet weighed by Hipparcos and Gaia

READ →

SCIENCE & EXPLORATION

Gaia creates richest star map of our Galaxy – and beyond

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Call for media: Second data release from ESA's Gaia mission

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Close encounters of the stellar kind

READ →

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Artificial brain helps Gaia catch speeding stars

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The future of the Orion constellation

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Gaia's billion-star map hints at treasures to come

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Watch Gaia first data release media briefing

SCIENCE & EXPLORATION

Call for media: First data release from ESA's Gaia mission

SCIENCE & EXPLORATION

Celebrity comet spotted among Gaia's stars

SCIENCE & EXPLORATION

Gaia's first year of scientific observations

SCIENCE & EXPLORATION

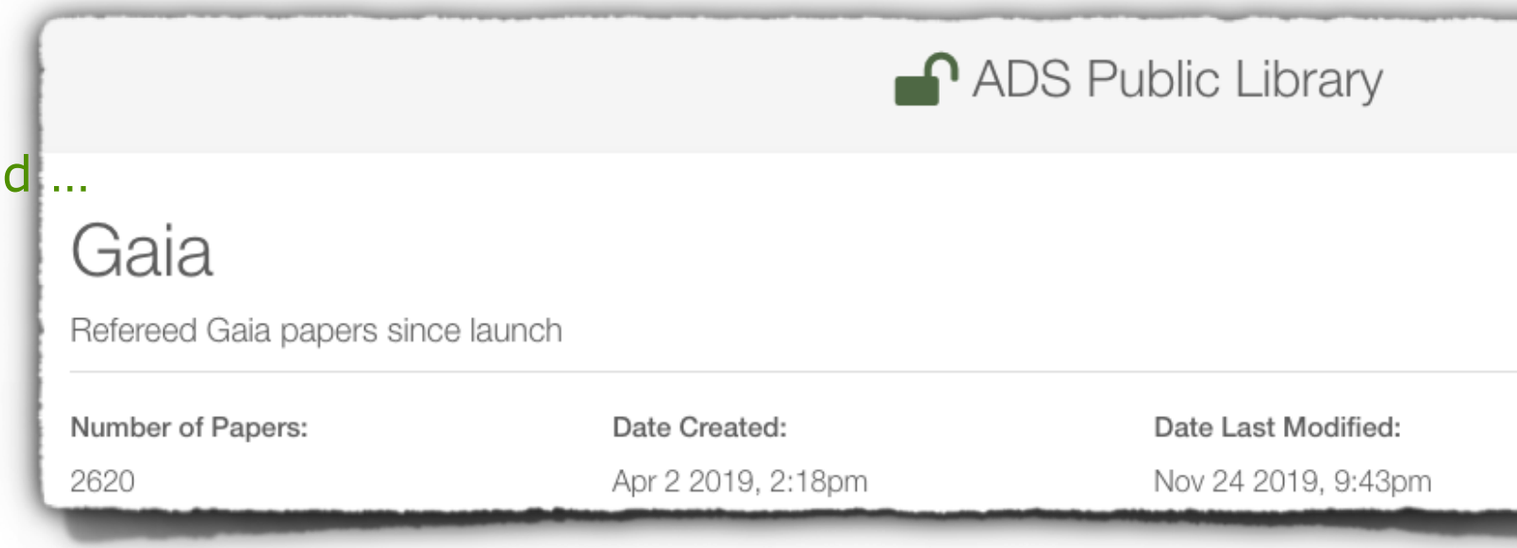
Counting stars with Gaia

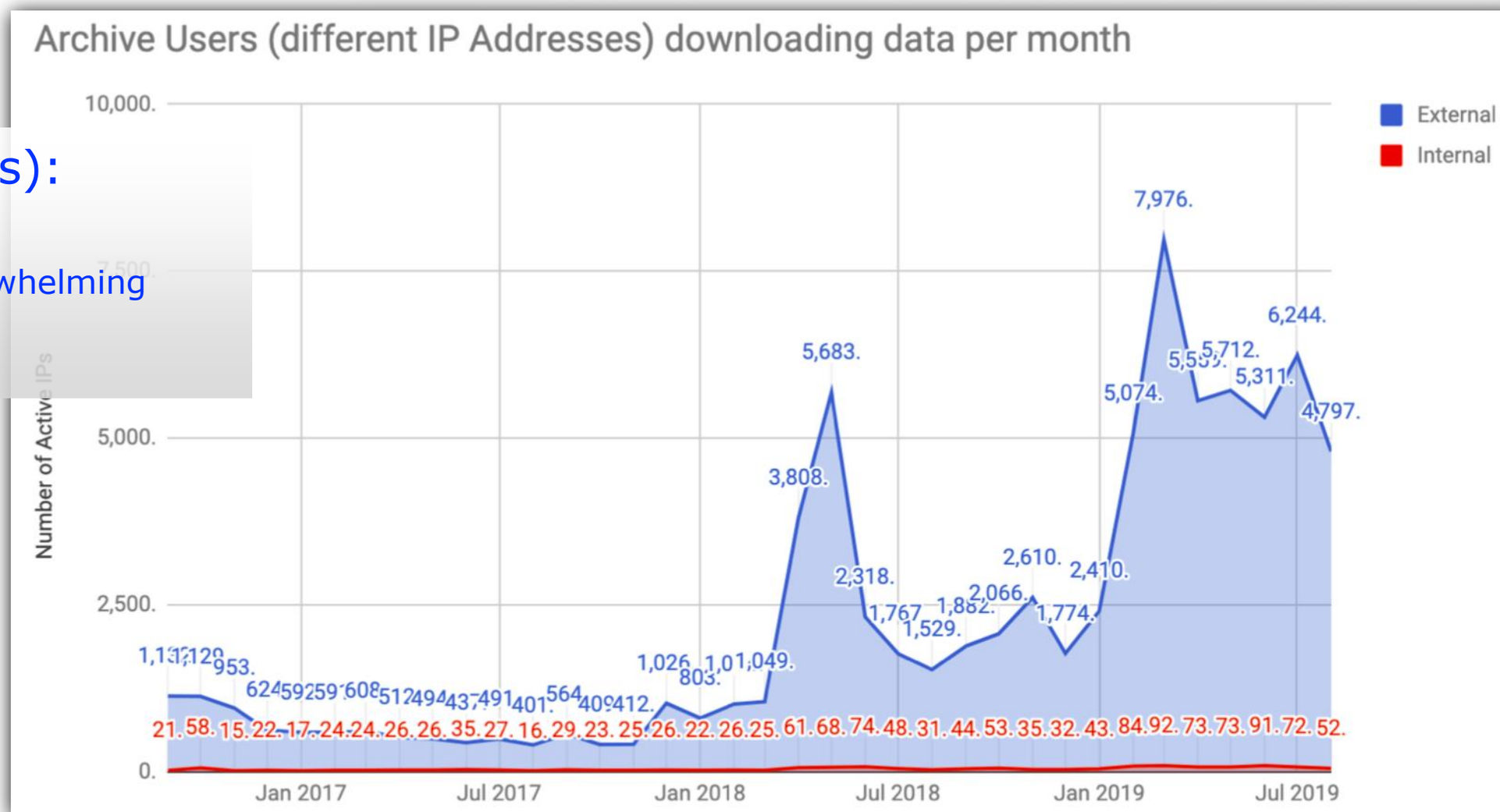
SCIENCE & EXPLORATION

Gaia discovers its first supernova

Gaia DR2 – in numbers

More than 2000 refereed papers
More than 300 arXiv preprints on the road …





T. Prusti (conclusions):

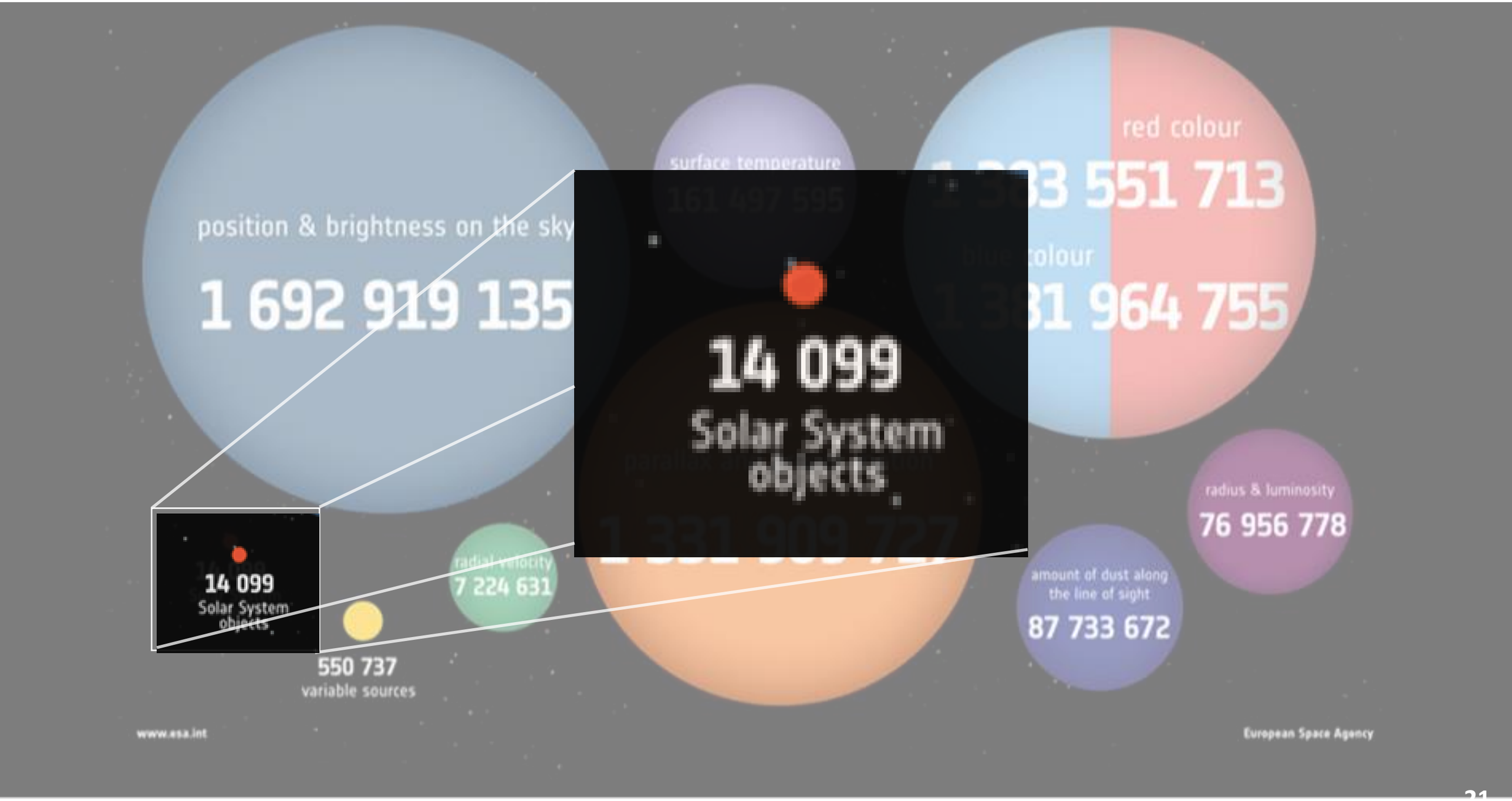
- Spacecraft is working
- Science production overwhelming

Solar System Objects +exoplanets

Treated in CU4 (a core unit of DPAC consortium)
With other peculiar objects
(NSS, extended objects, galaxies, gravitational lenses, etc.)

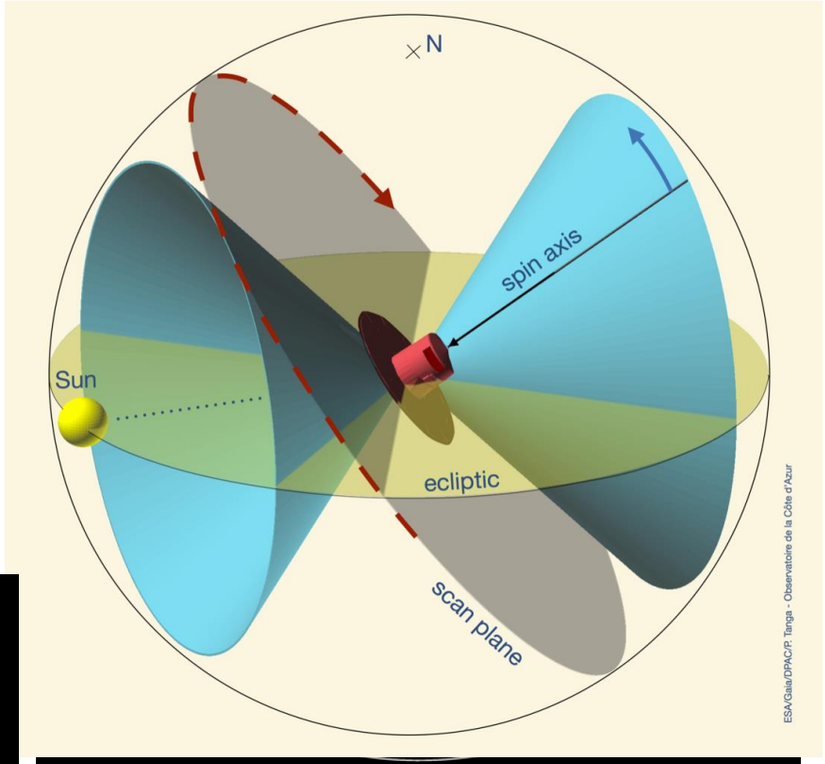
Gaia DR2

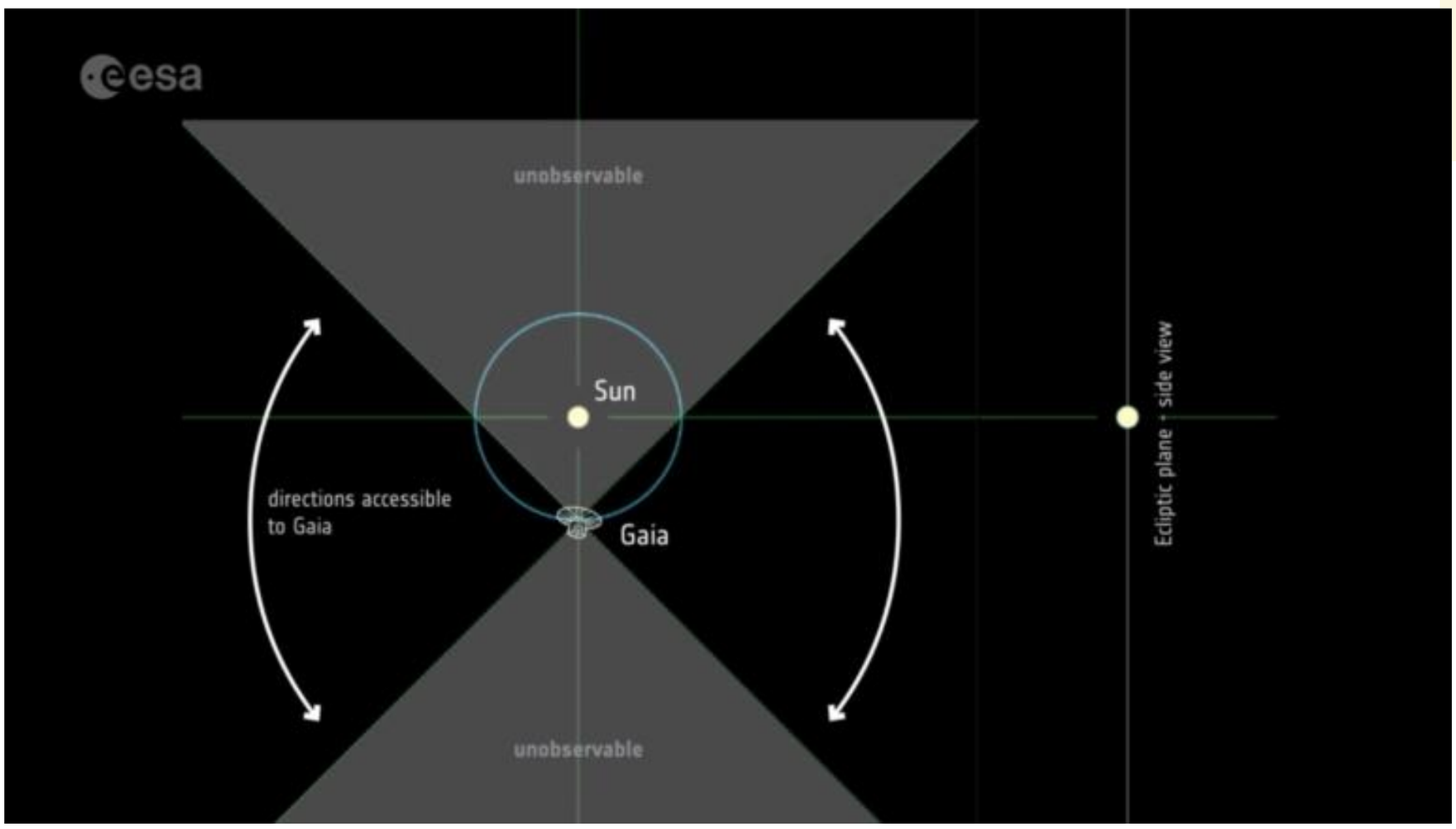
A teaser for SSOs

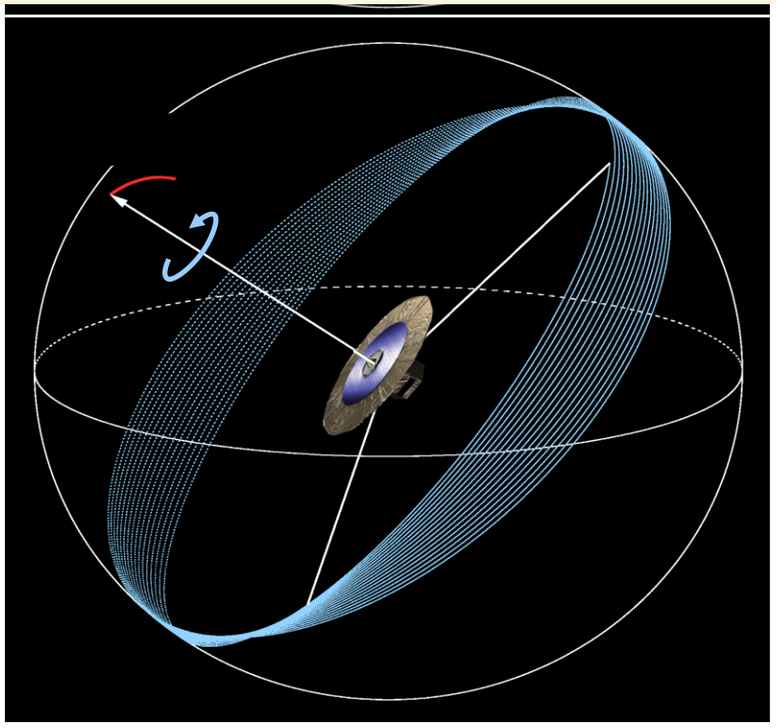


Gaia is observing SSOs

- Solar elongations 45° to 135°, with phase
- Limiting mag. V≈20.7
- 100,000 asteroid CCD obs. / day





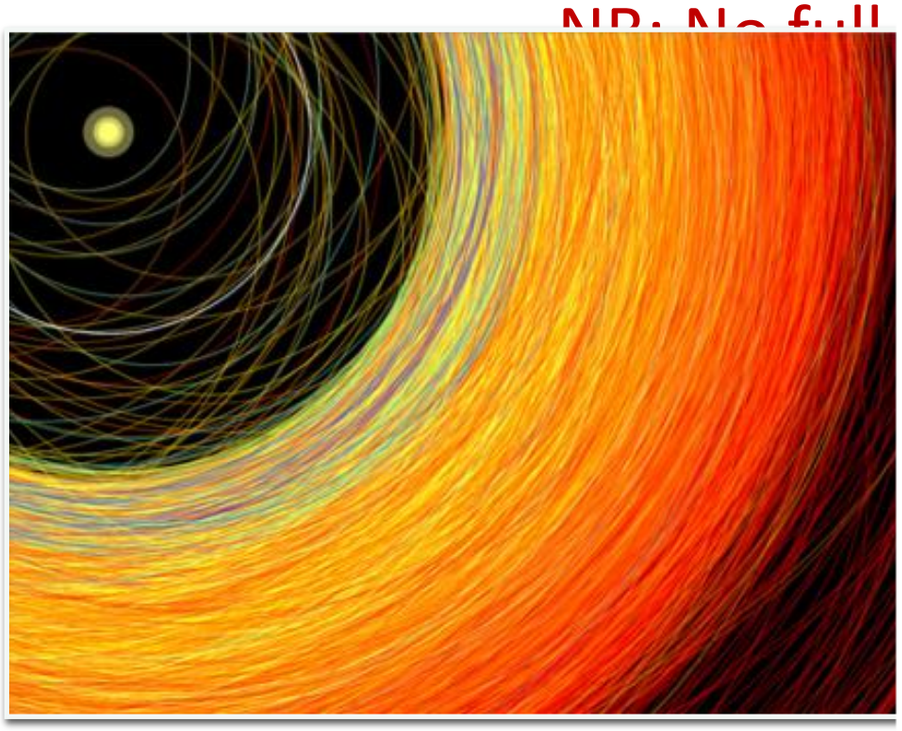


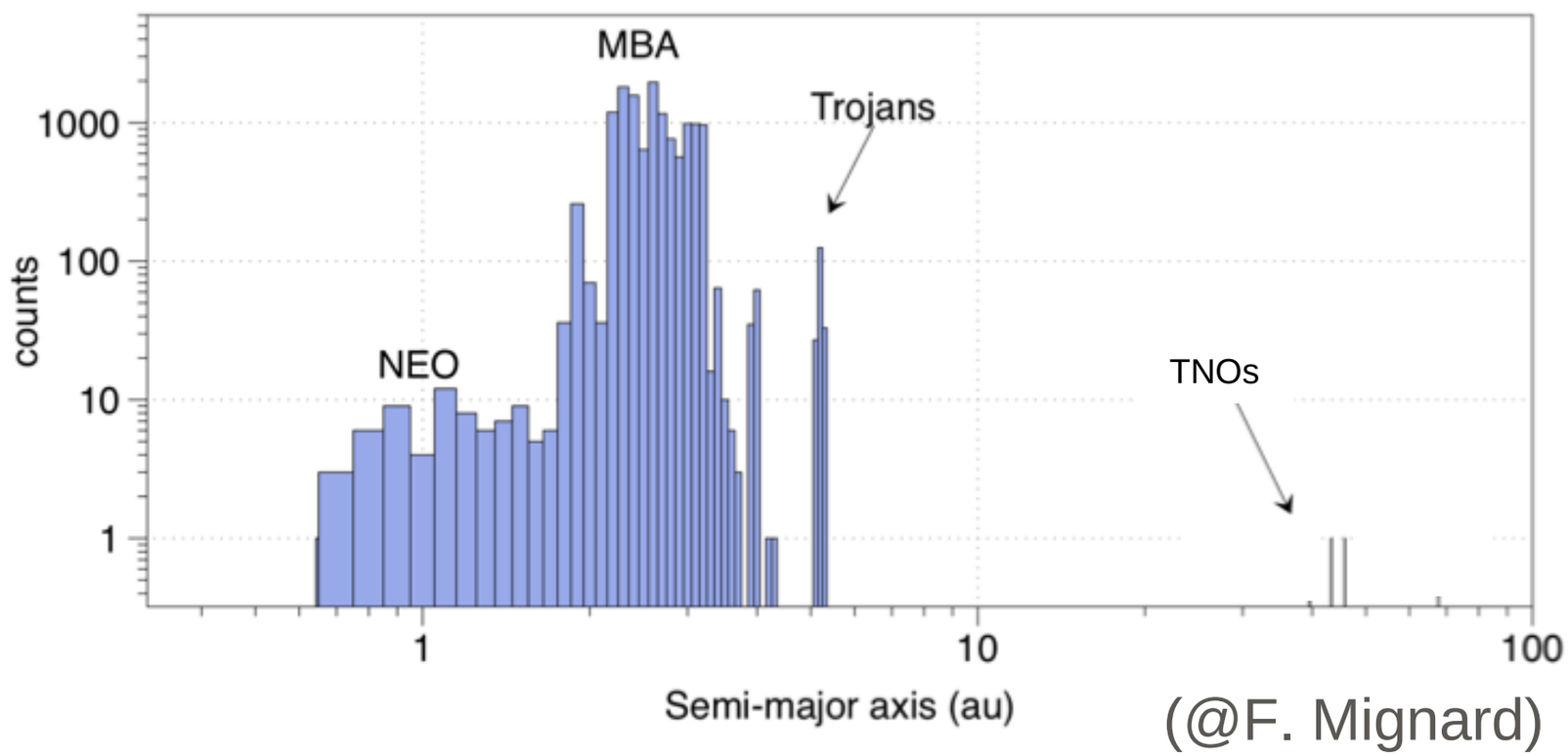
Gaia DR2 - Solar System

On the base of a *pre-selected* list of *known* objects (over ≈350,000)

> 10 FOV transits over the 22 months of DR2, V>10.5,

…





(@F. Mignard)

Objects	14 099	(*asteroids*)
Epoch astrometry	1 997 702	CCD positions
	287 904	transits (52% : photometry)
Accuracy	0.3–8 mas	(*along scan*)

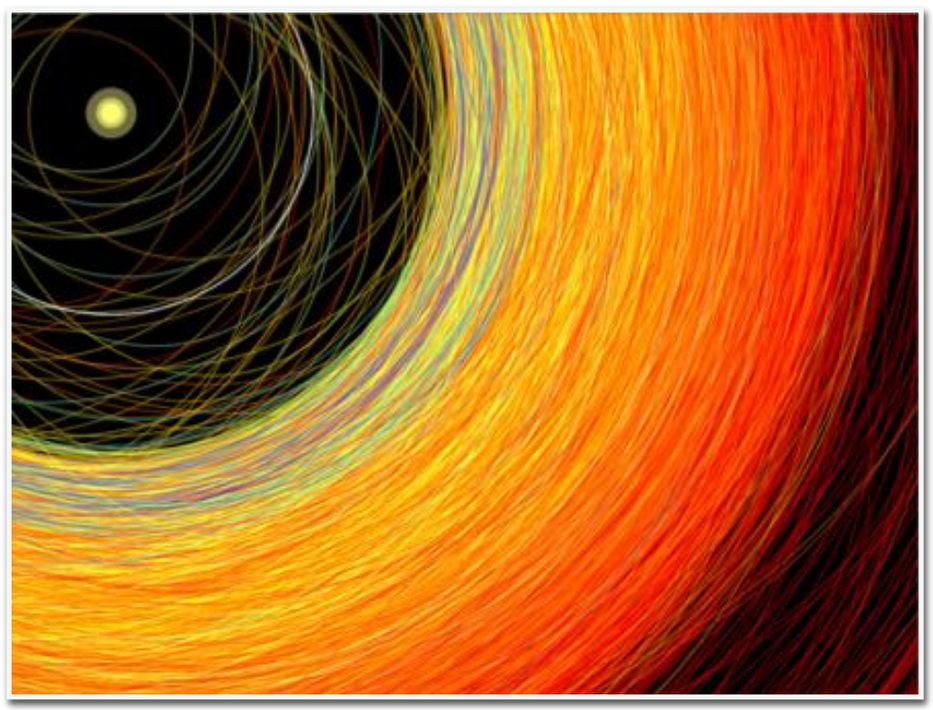
Gaia DR2 - Solar System

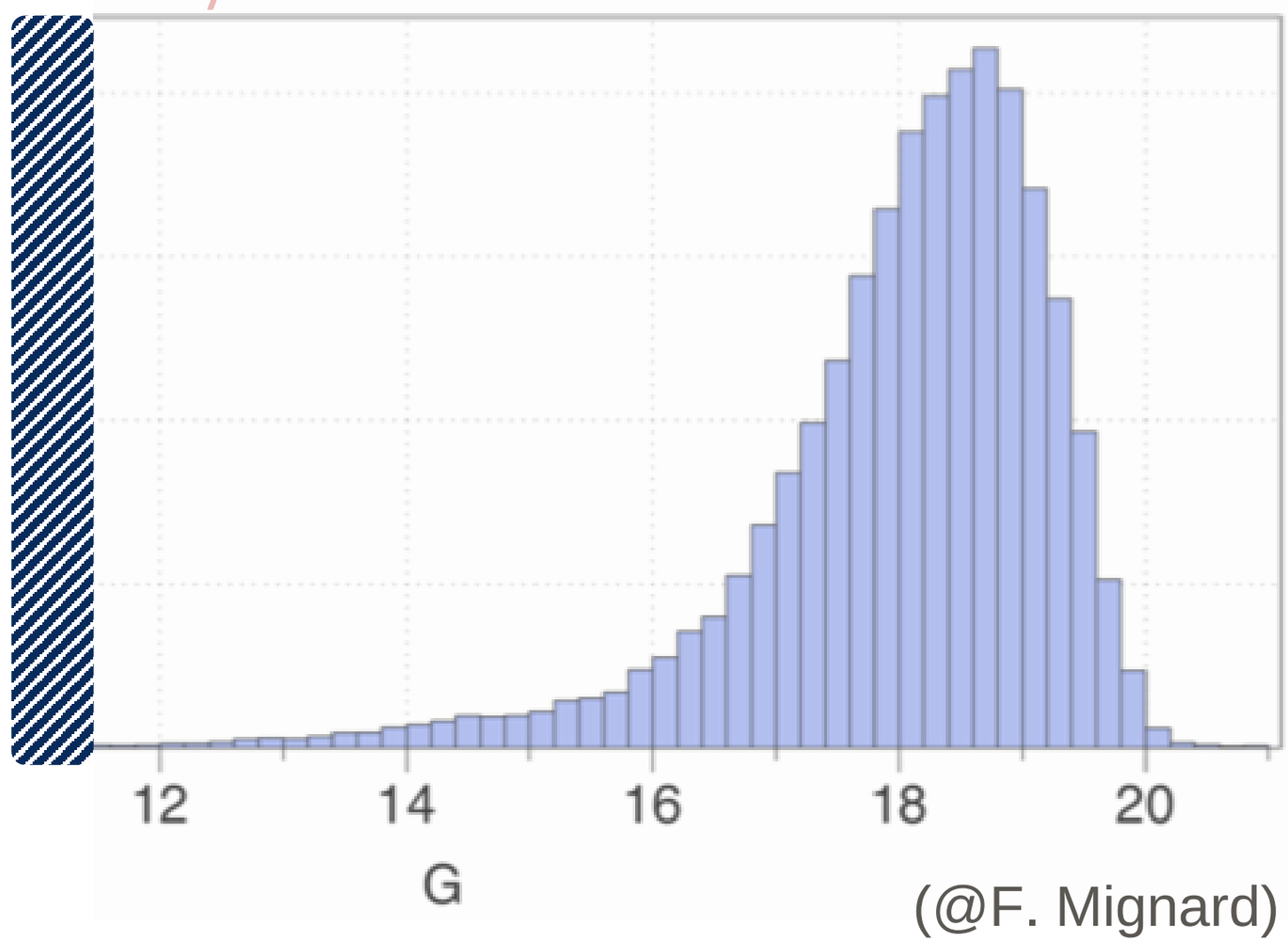
On the base of a *pre-selected* list of *known* objects

> 10 FOV transits over the 22 months of DR2, V>10.5,

…

NB: No full calibration yet !!





(@F. Mignard)

(some)
Results

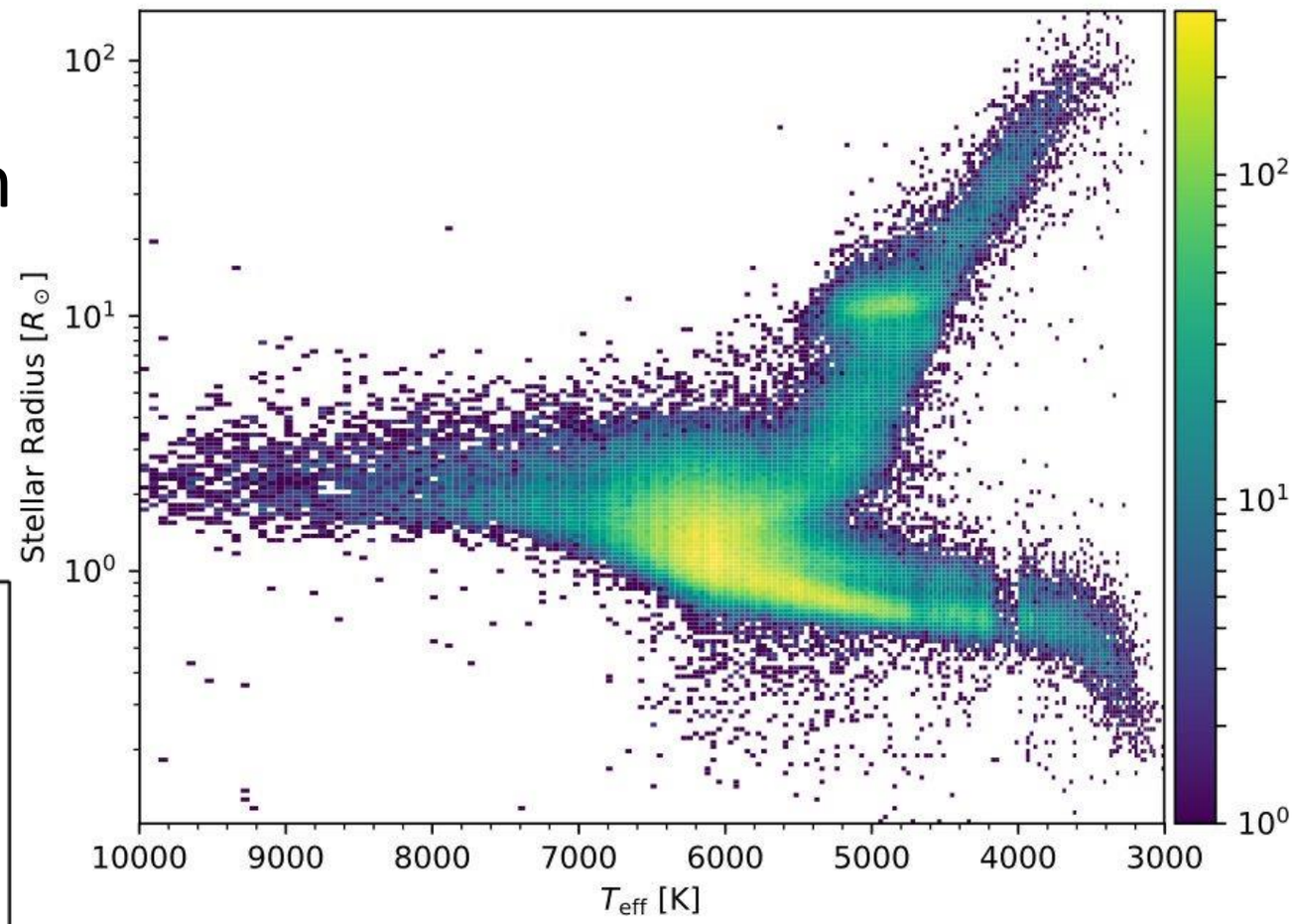
- **Catalogue of stars DR1, DR2**
- **Direct observations**
- **Combination Ground-based + Gaia**

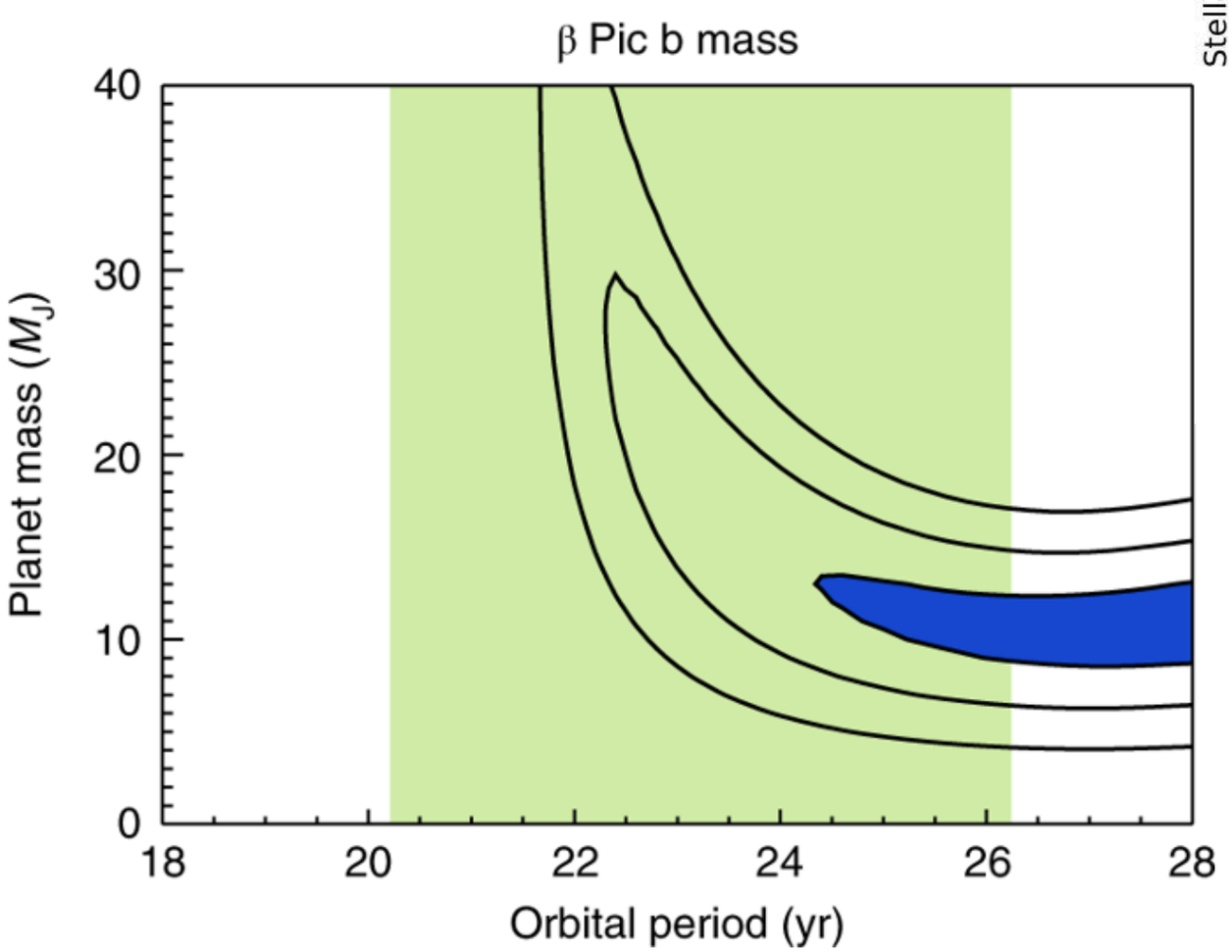
Exoplanets

(@A. Vallenari)

- No exoplanets yet, but… host stars
  - Stellar radii + mass for exoplanet characterisation

(Berger 2018 ApJ)

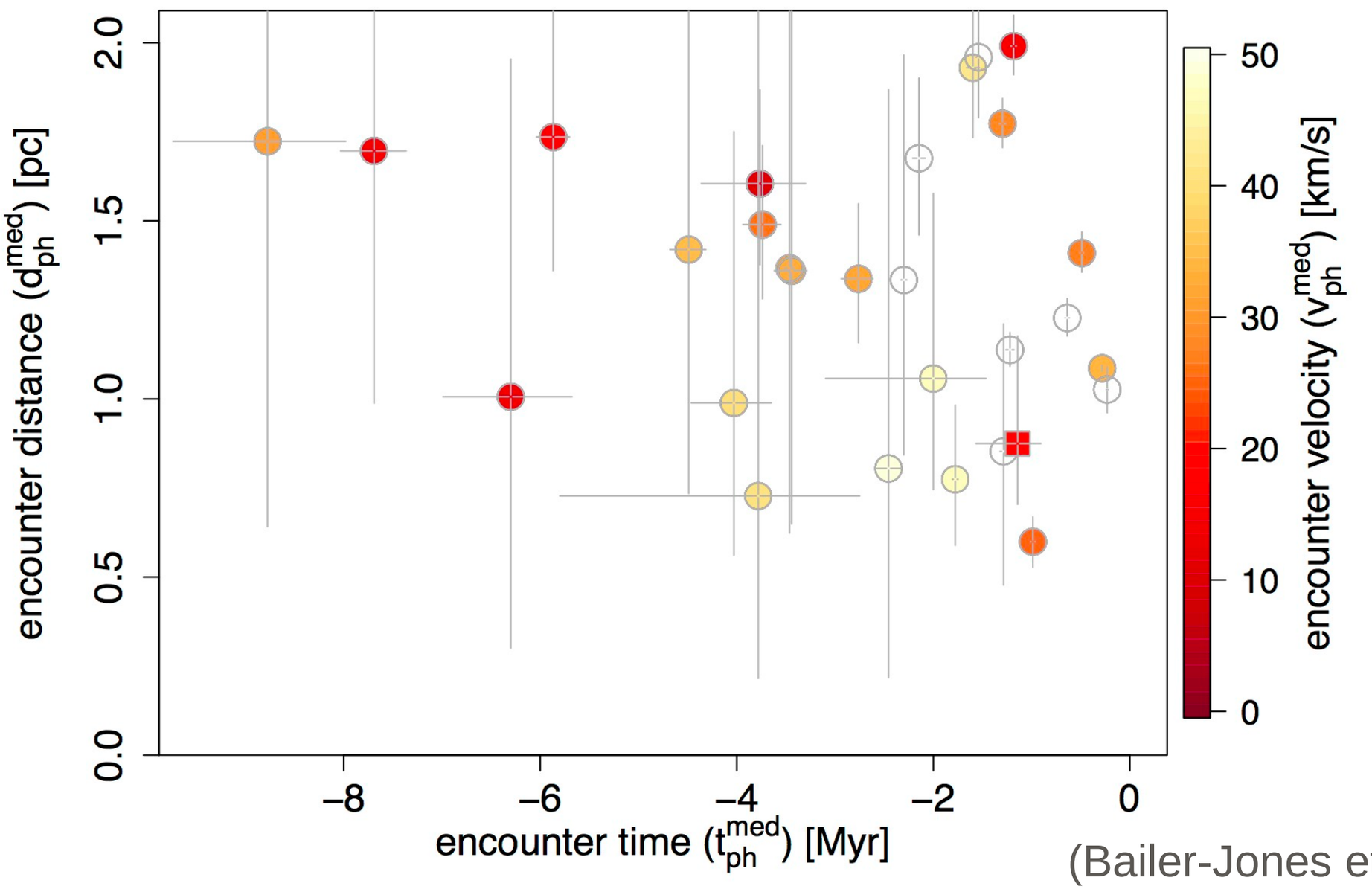




- Gaia + Hipparcos Mass of planet ß Pic b

(Snellen & Brown 2018 Nature)

‘Oumuamua ISO’s home



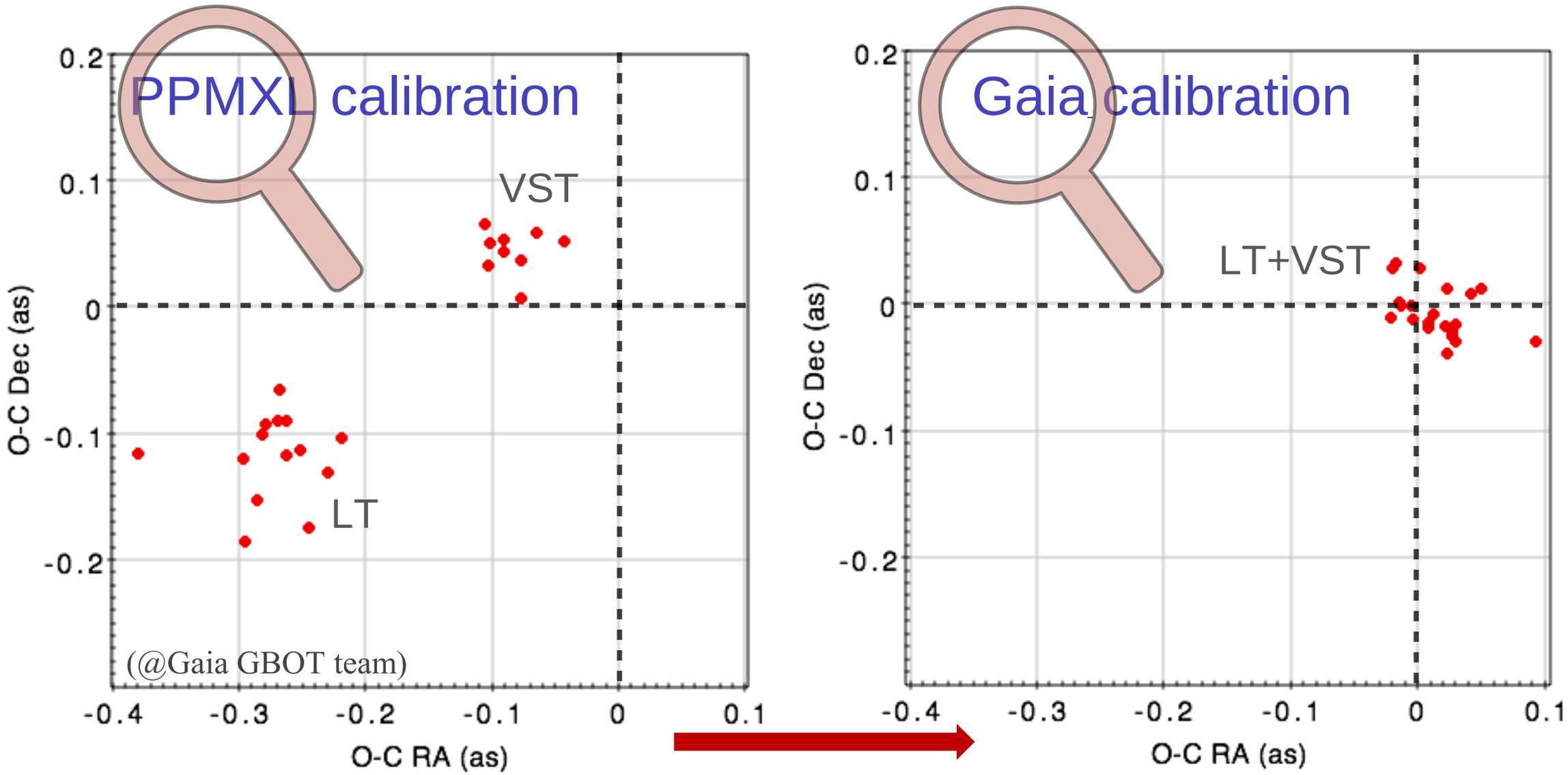
(Bailer-Jones et al. 2018 AJ)

Other stellar encounters at origin of LPC comets from Oort cloud

Gaia DR2 catalogue - calibration

Asteroid (1132) Hollandia **ground-based observations** (GBOT)

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



Use of DR2 stellar catalogue reduces errors

Gaia DR2 catalogue - calibration

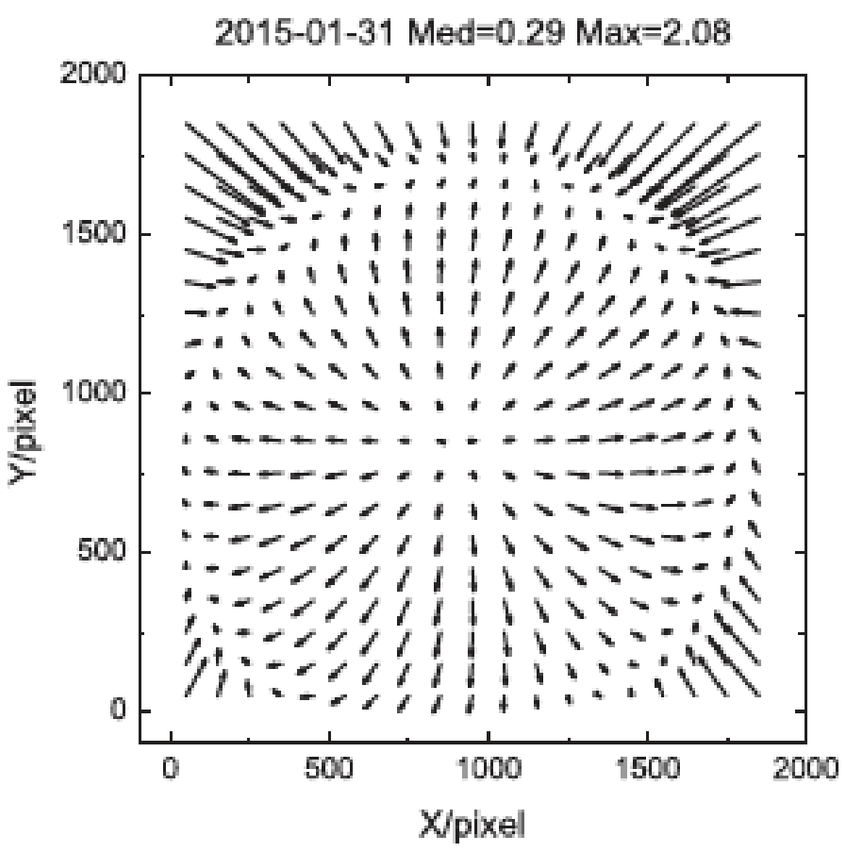
Many programmes NEOs, TNOs, …

Also for planetary satellites

(Wang et al. 2017 IAUs ; @Q.Peng Jinan univ.)

◇DR1
◇UCAC4

GDC
Geometric Distorsion Correction



Triton

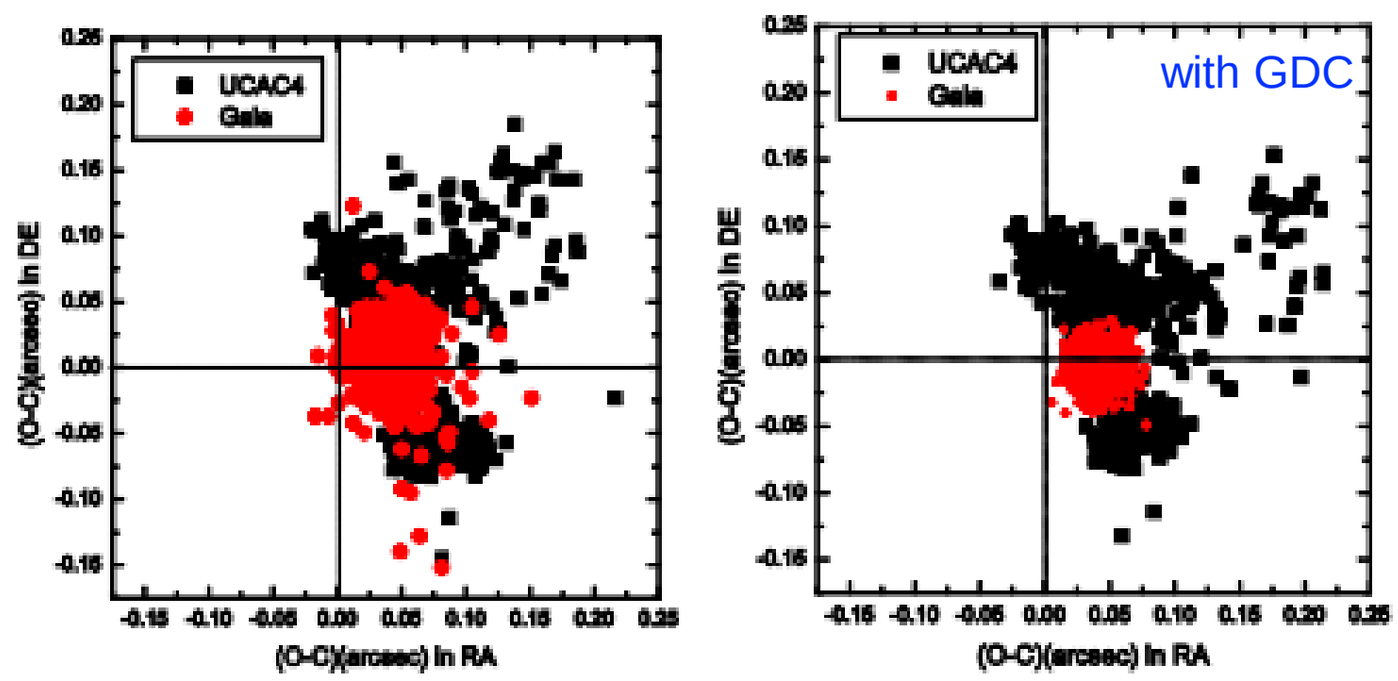
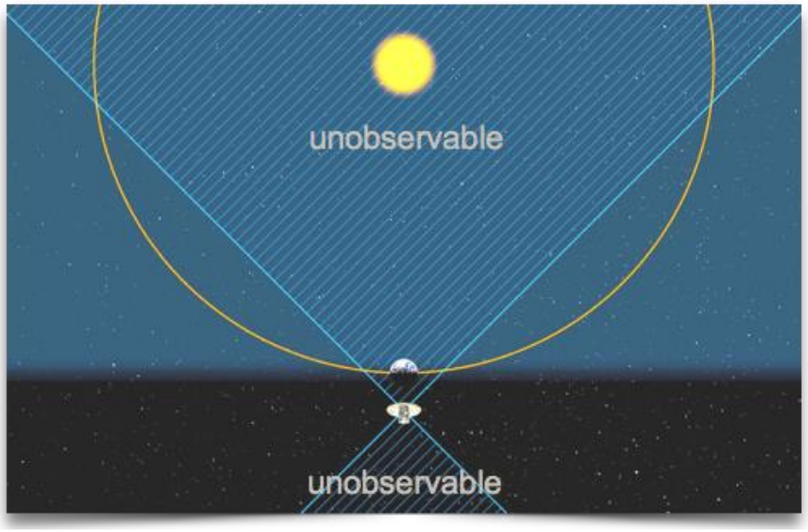
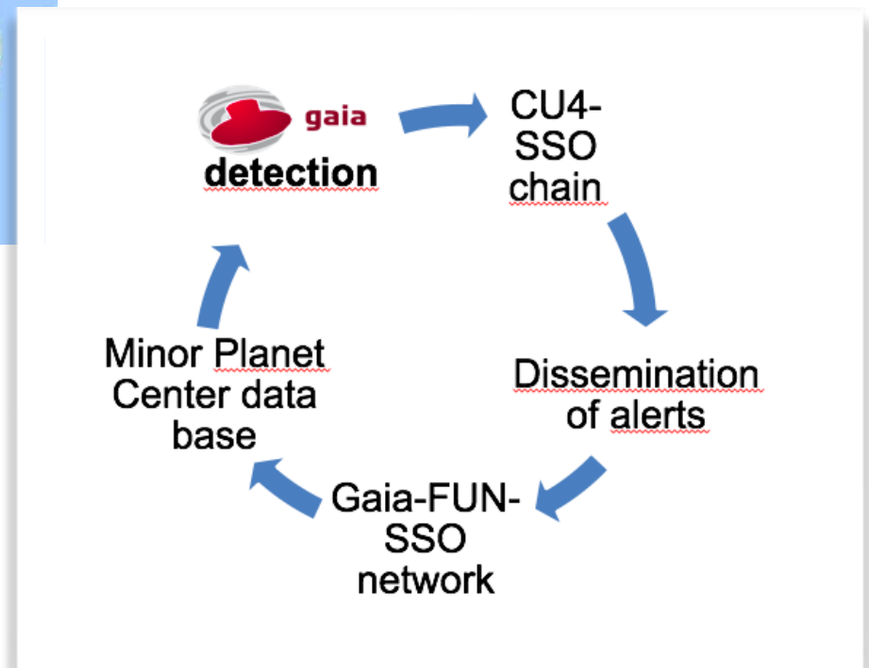


Figure 2.(O-C) residuals of Triton before and after Geometric Distortion Correction (GDC). The left panel shows the (O-C) residuals before GDC and the right panel after GDC.

Alerts Gaia-FUN-SSO

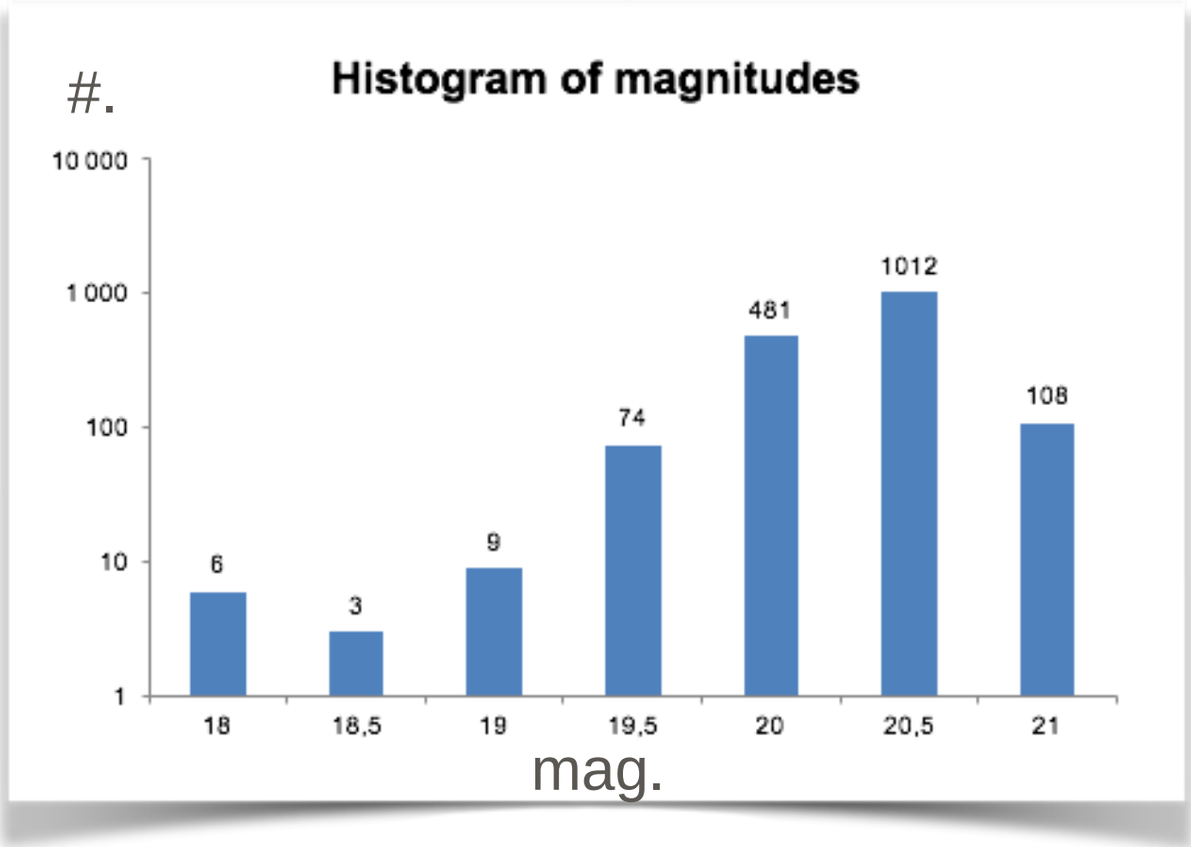
(@W. Thuillot)



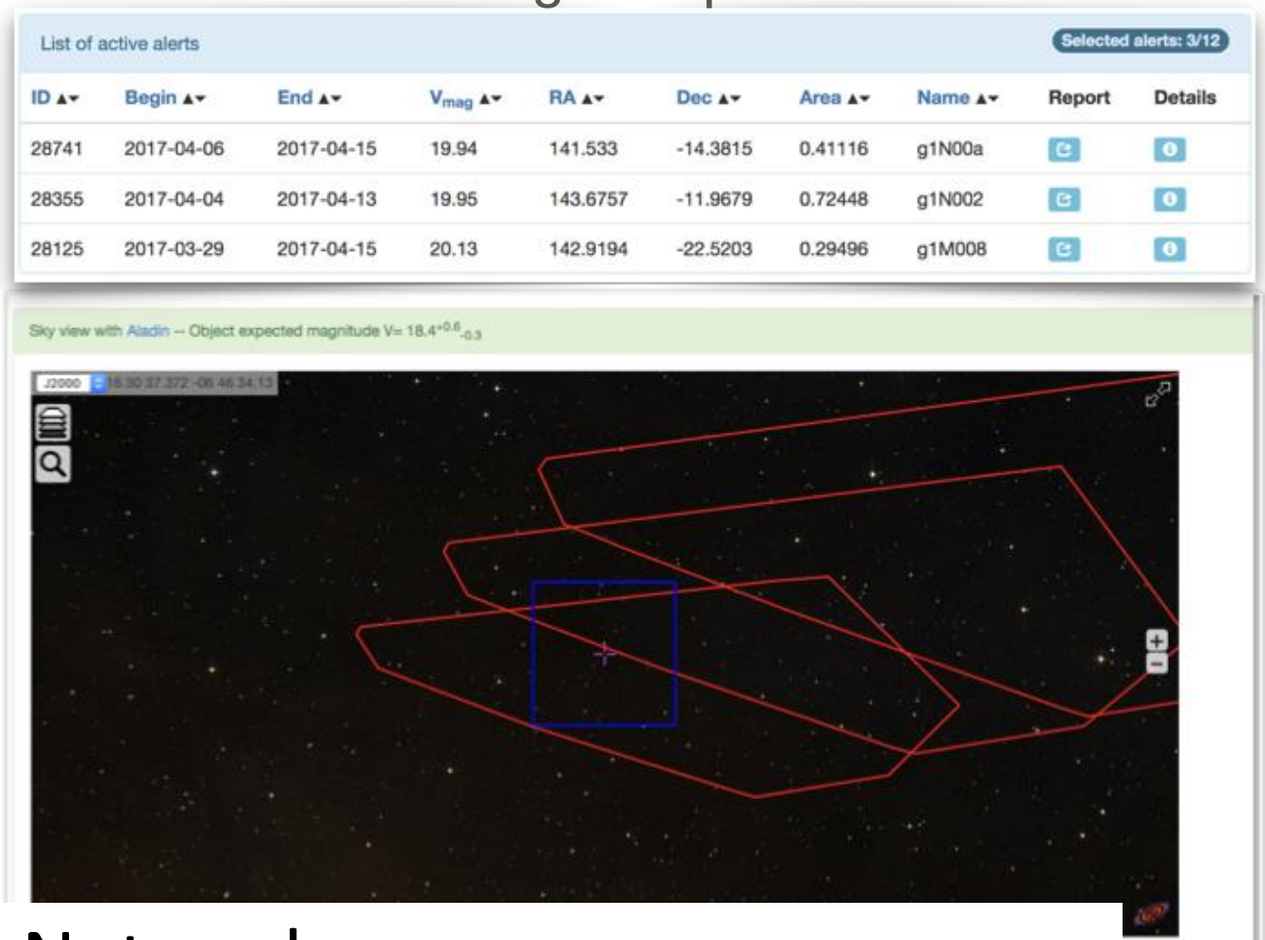


- Discovering new NEOs ans SSOs
- Ground-based Follow-Up Network
  - Gaia scans at low elongations (≈45°)
  - avoid loosing newly discovered objects
  - short term chain with MPC

Alerts Gaia-FUN-SSO



alerts logs & ephemeris

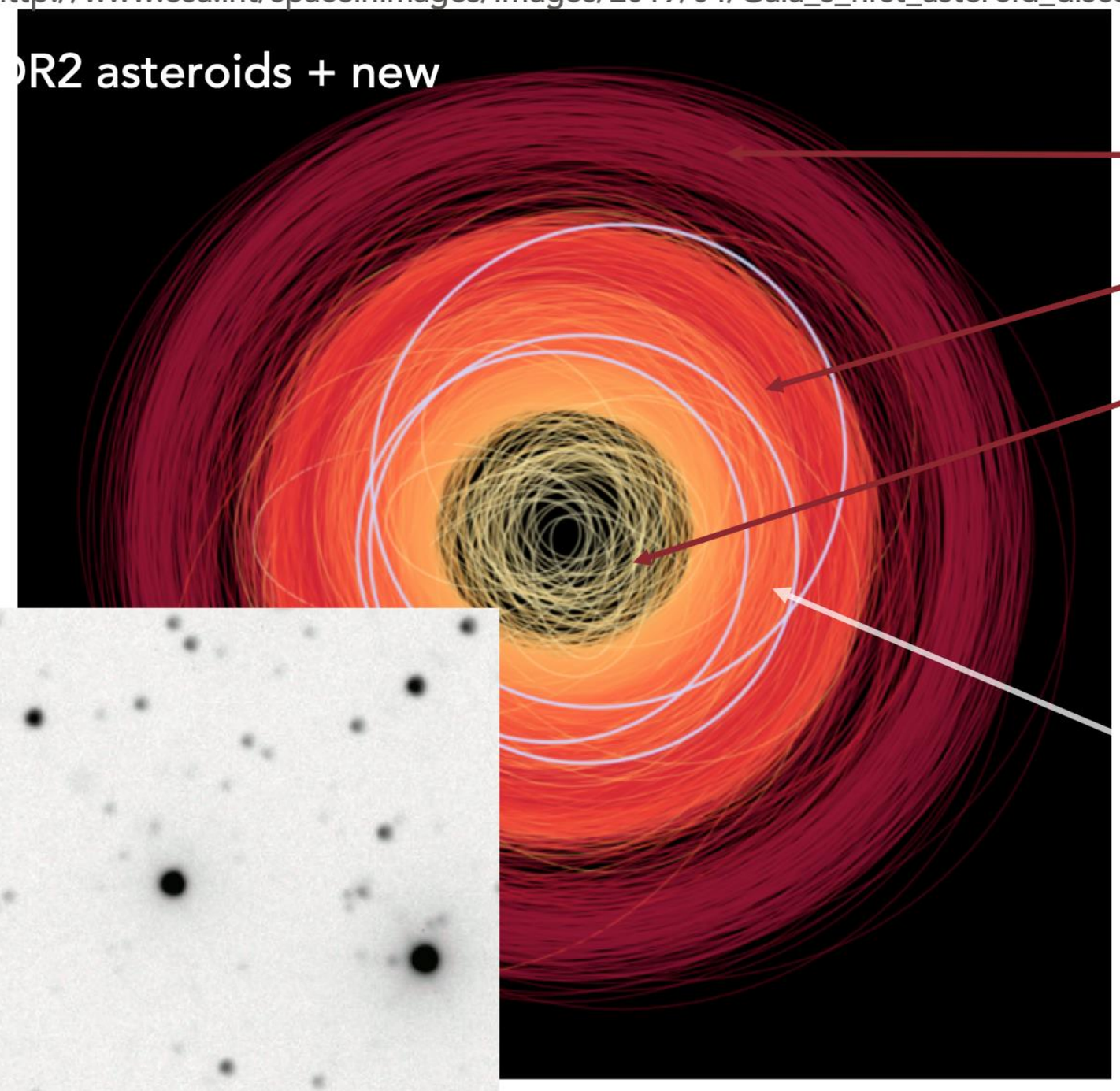


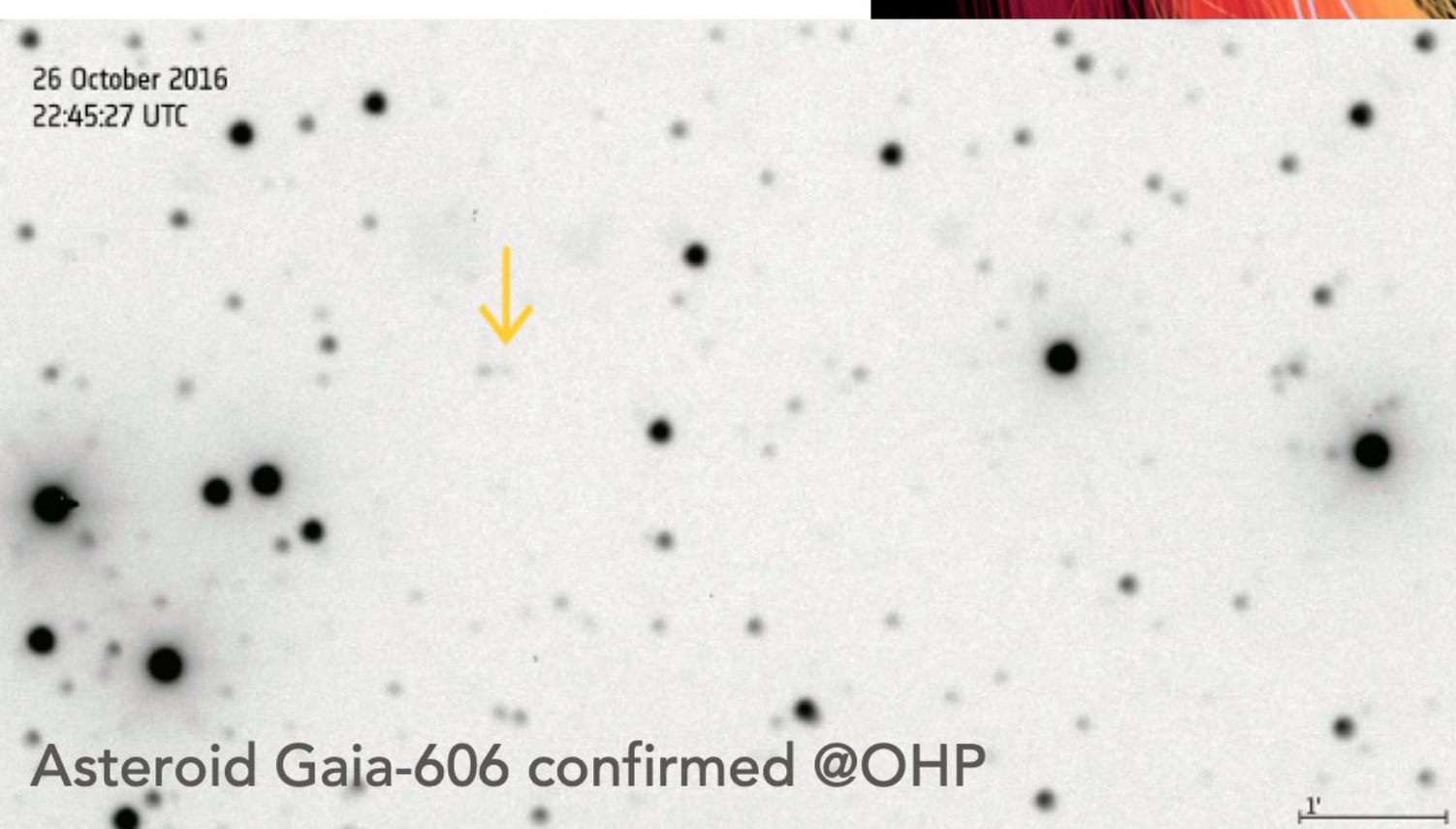
- Ground-based Follow-Up Network
  - ¡daily alerts posted ! ≈5/day
  - faint, mag. 20.5 >T1m telescopes wanted
  - contact gaia-fun-sso@imcce.fr

Alerts Gaia-FUN-SSO

http://www.esa.int/spaceinimages/Images/2019/04/Gaia_s_first_asteroid_discoveries

- Discovery of asteroids
- MBAs, mag >20
- high inclination >15°





Asteroid Gaia-606 confirmed @OHP

Scientific Objectives

– briefly –

AF astr.

- **astrometry**
  - Ref. frames, discovering/alerts, orbits: dynamics, relativity, masses, non-gravi. forces, ...

CCD

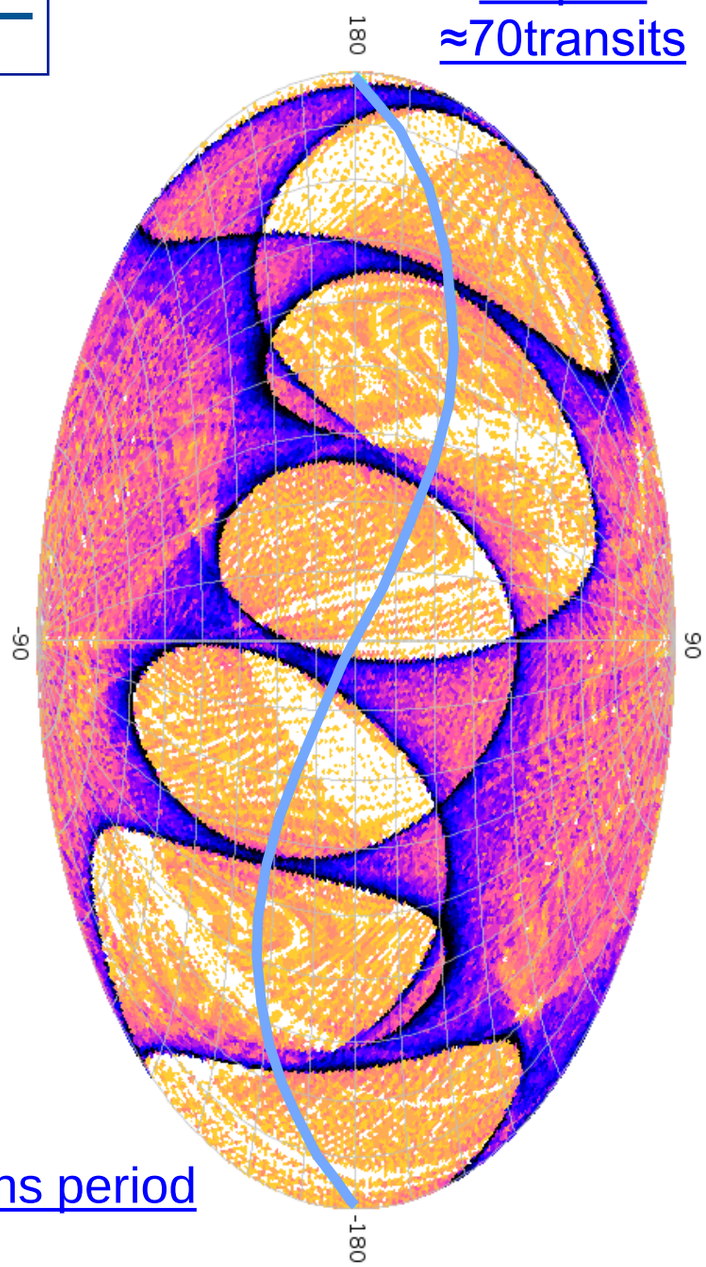
- **'imaging'**
  - size, shape, binaricity, ...

spectro-phot.

- **G, RP/BP photometry**
  - lightcurves : spin, shape, colours-taxonomy,...
  - albedo, density

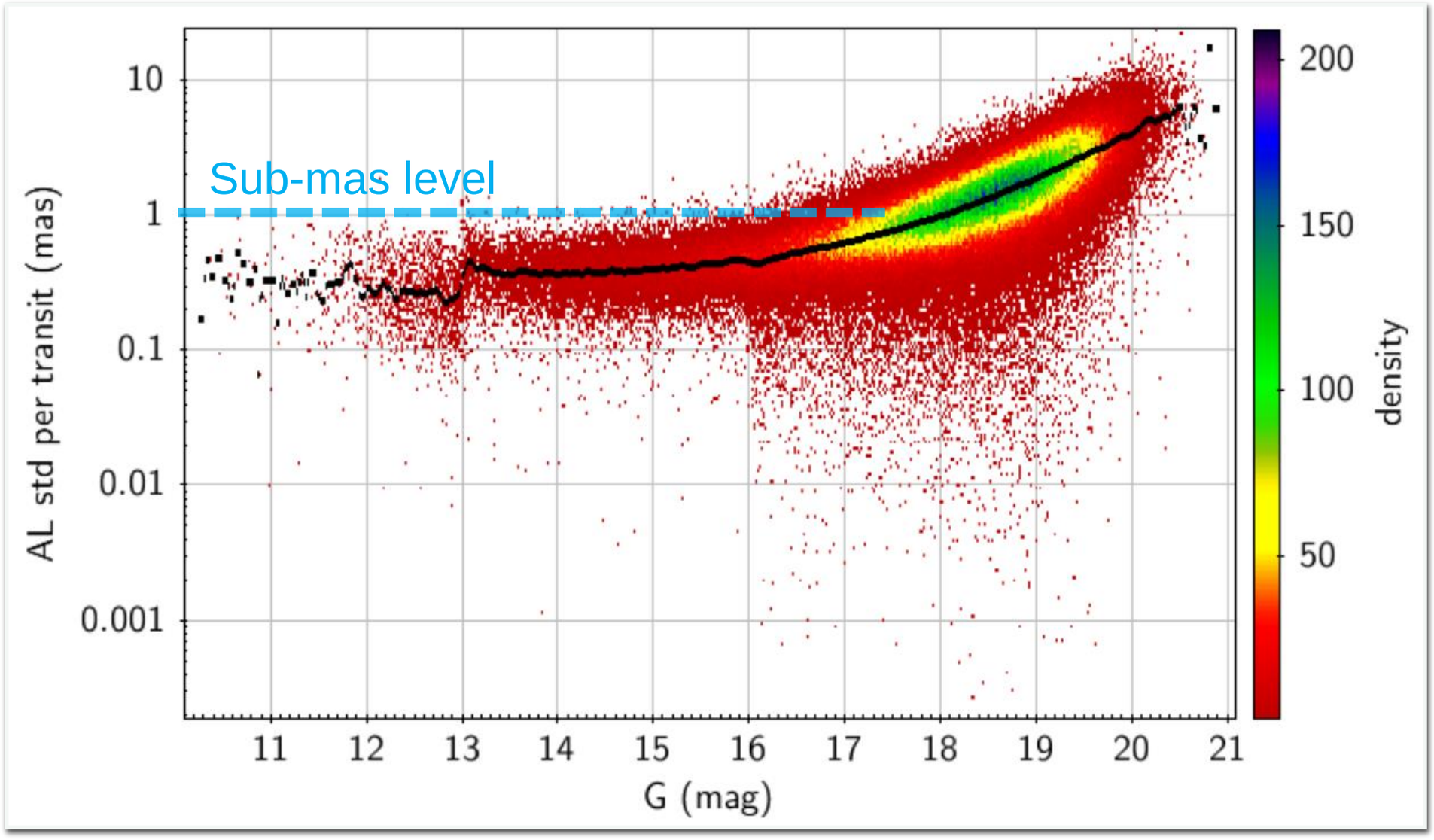
RVS

- *spectroscopy*
  - *calibration*



- not SNR limited, but telemetry limited

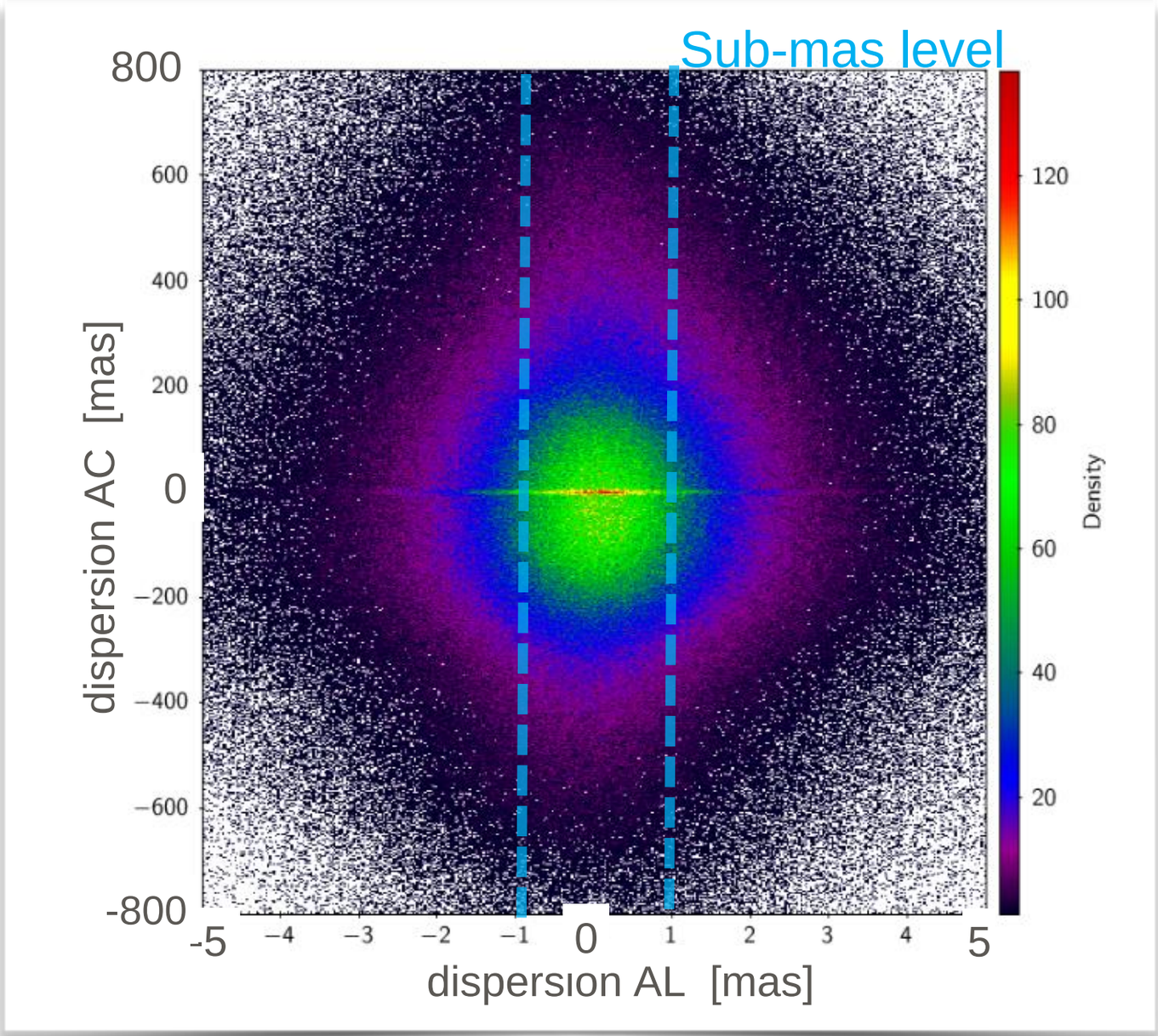
Gaia DR2 - SSO - transit astrometric performance



Residuals from the orbital fit of Gaia DR2 data only (along-scan direction)
(Spoto et al. 2018 A&A)

+ Improve past observations from stellar catalogue (GDR2 debiasing)

Gaia DR2 - SSO - transit astrometric performance

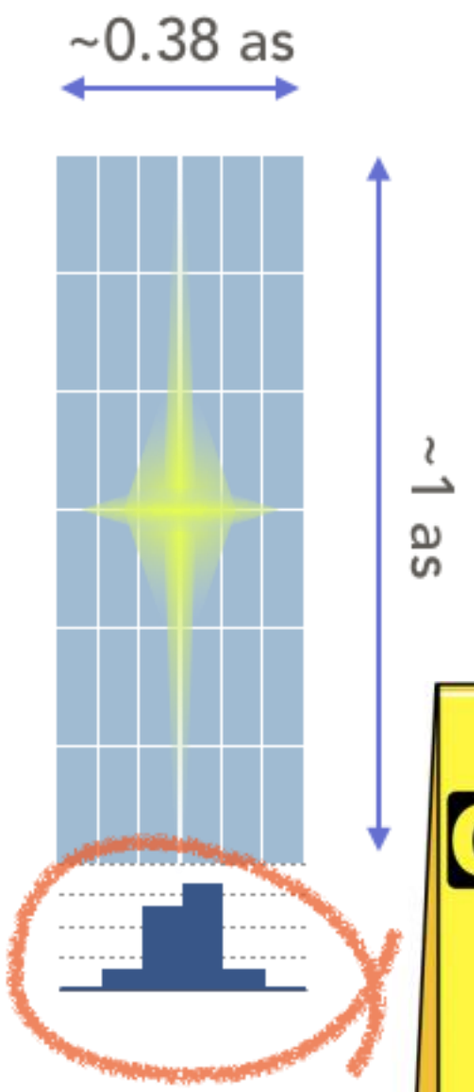


Residuals from the orbital fit of Gaia DR2 data only
AL + AC : note different scale!

+ Improve past observations from stellar catalogue (GDR2 debiasing)

Gaia DR2 – SSO

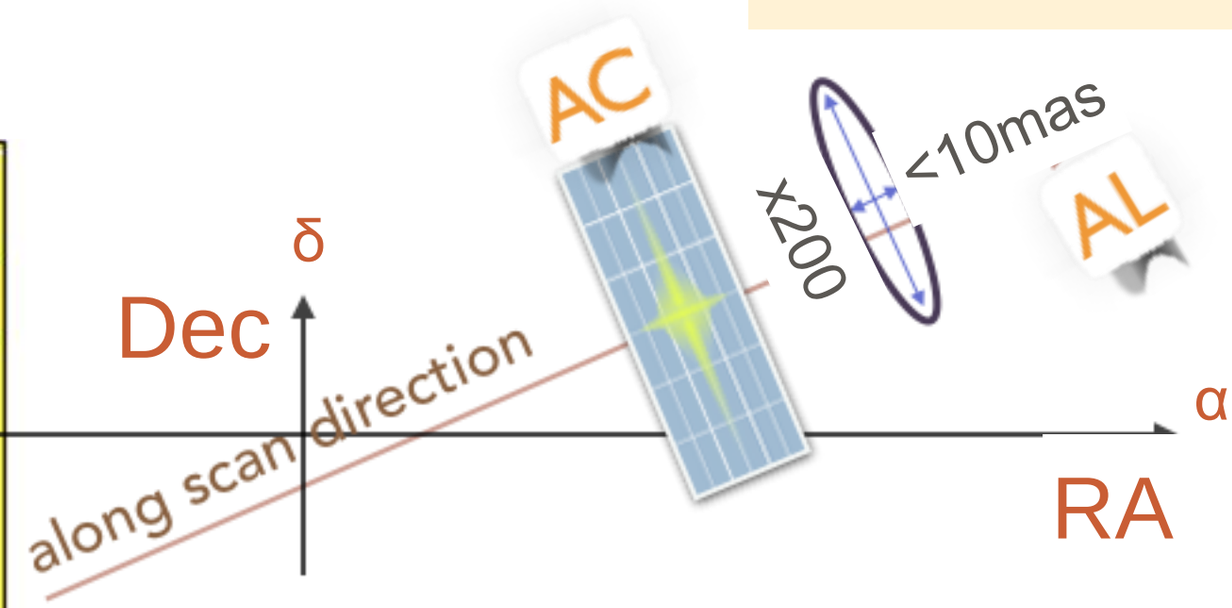
CAUTION



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

≈1D astrometry
no diagonal var/covar matrix

COR–
RELATIONS

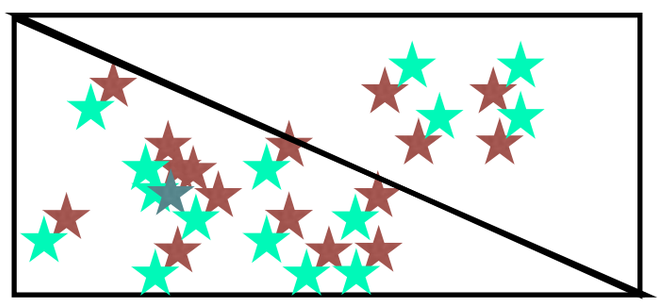


Gaia and the asteroids

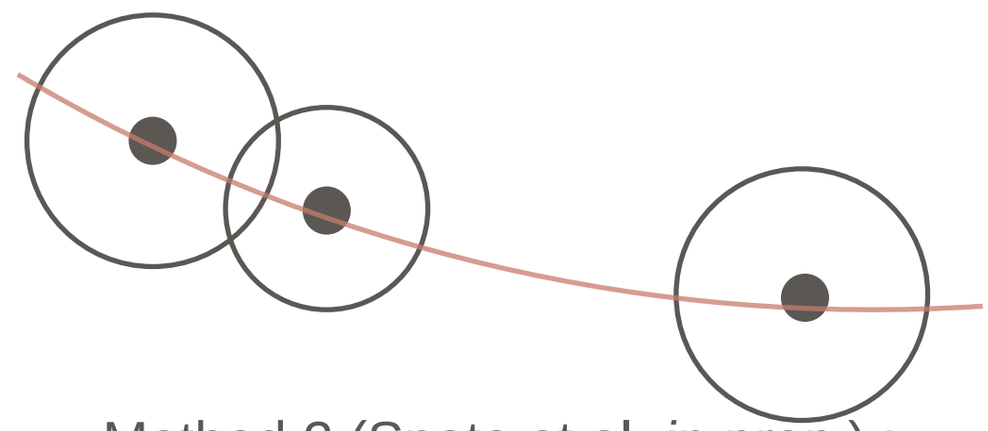
- **Before Gaia**
  - 1.9 x 10^8 measurements in the archives of the Minor Planet Center
    - mostly CCD imaging +reduction catalogues (USNOB, UCAC, PPMXL, …)
    - average accuracy: ≈400 mas
  - ≈2000 radar ranging measurements
    - equivalent accuracy : 1-50 mas
- With Gaia Challenges from sub-mass accuracy
  - How motion / size impacts precision & accuracy?
  - Can « 1D » measurements provide the expected orbit accuracy?
  - Is our dynamical Solar System model accurate enough?
  - How to combine Gaia and « pre-Gaia » astrometry?

Orbit improvement : DR2 + other observations

- Combining DR2+past observations: a factor ≈2 **(only)** average improvement (DR2=snapshot)
- But: GB data affected by systematics (zonal/calibration) errors of the pre-Gaia catalogs, and large difference in atrometric precision
- **Debiasing required for past observations!**
  - if possible = re-reduction
  - simplest way = ad-hoc method



Method 1 : Chesley, Farnocchia
Eggl et al. Icarus *accepted*
all catalogs referred to a reference
- corrections computed on a grid
(F2015 scheme)



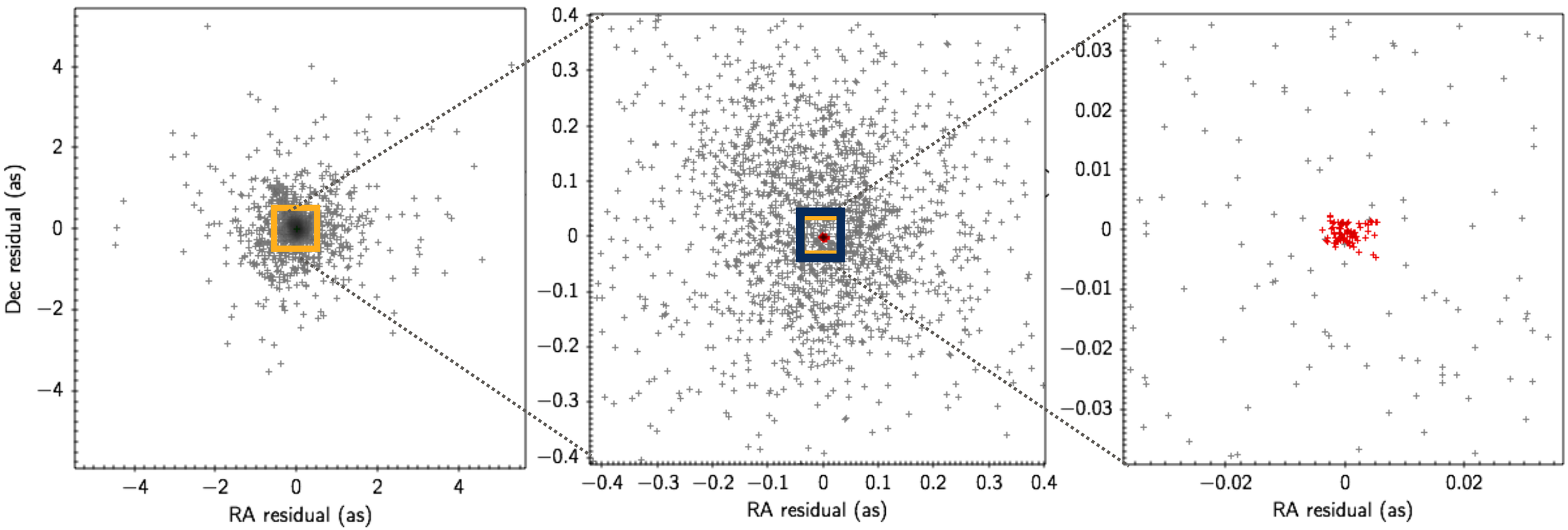
Method 2 (Spoto et al. *in prep.*) :
areas centered on archive asteroid observations
Reference: Gaia DR2
(DR2 scheme)

- **In all cases, precision and accuracy of past observations increased**

Asteroid (386) Siegena - residuals from orbital fit

Combining archive data (2776 obs.) to Gaia data

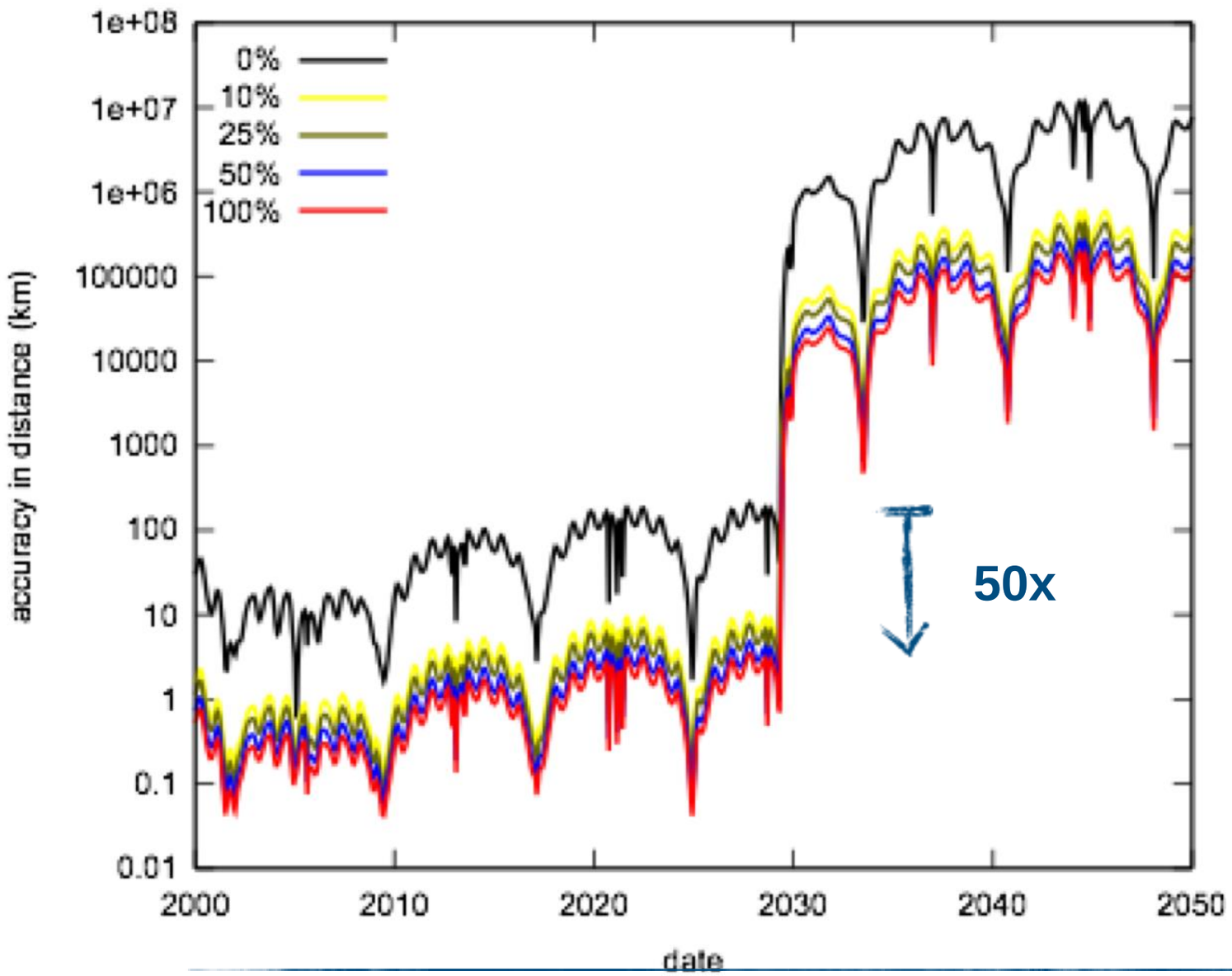
With GDR2 debiasing



factor 100 X improvement!

Orbit propagation

- re-reduction of <50% data

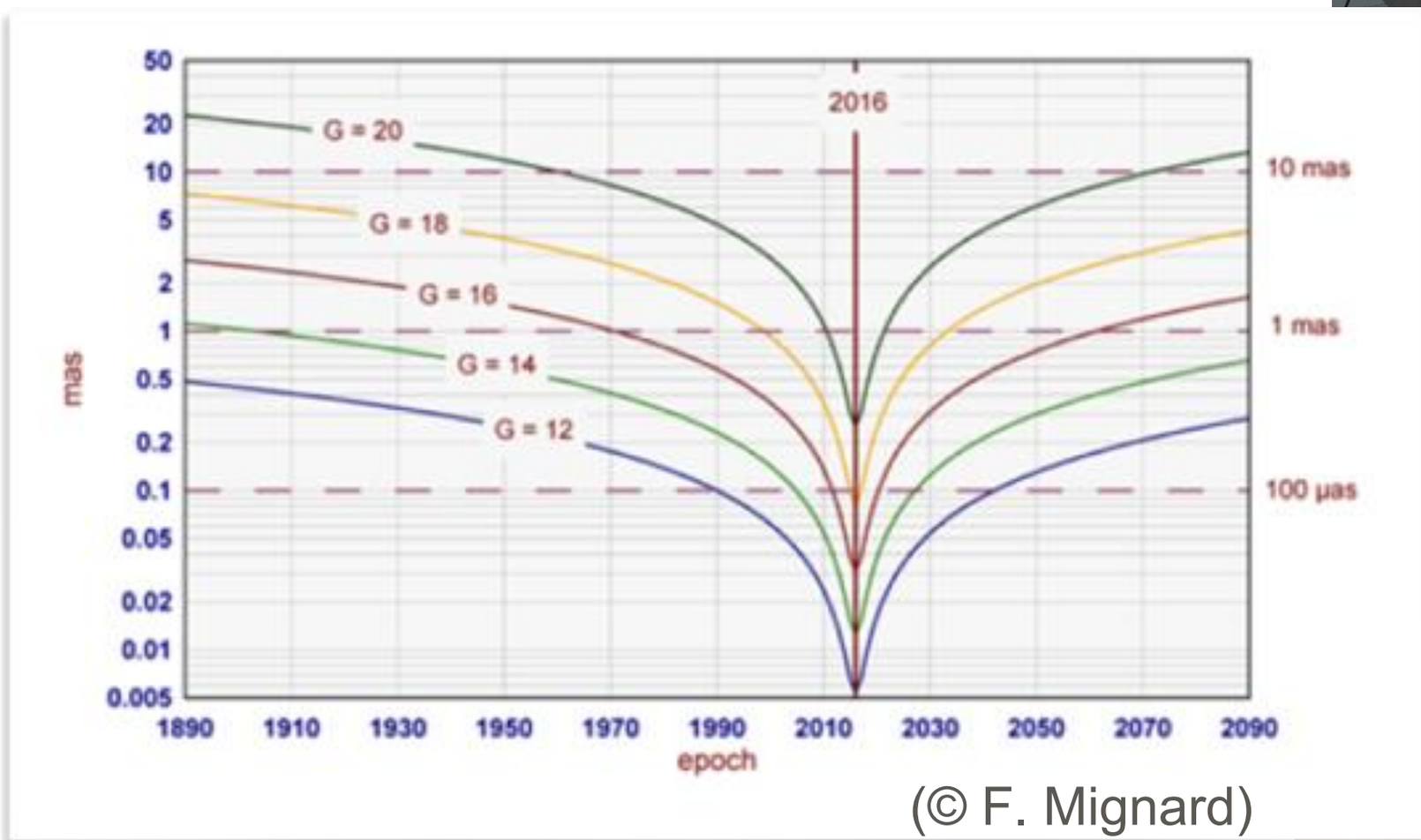


(Desmars et al. 2013)

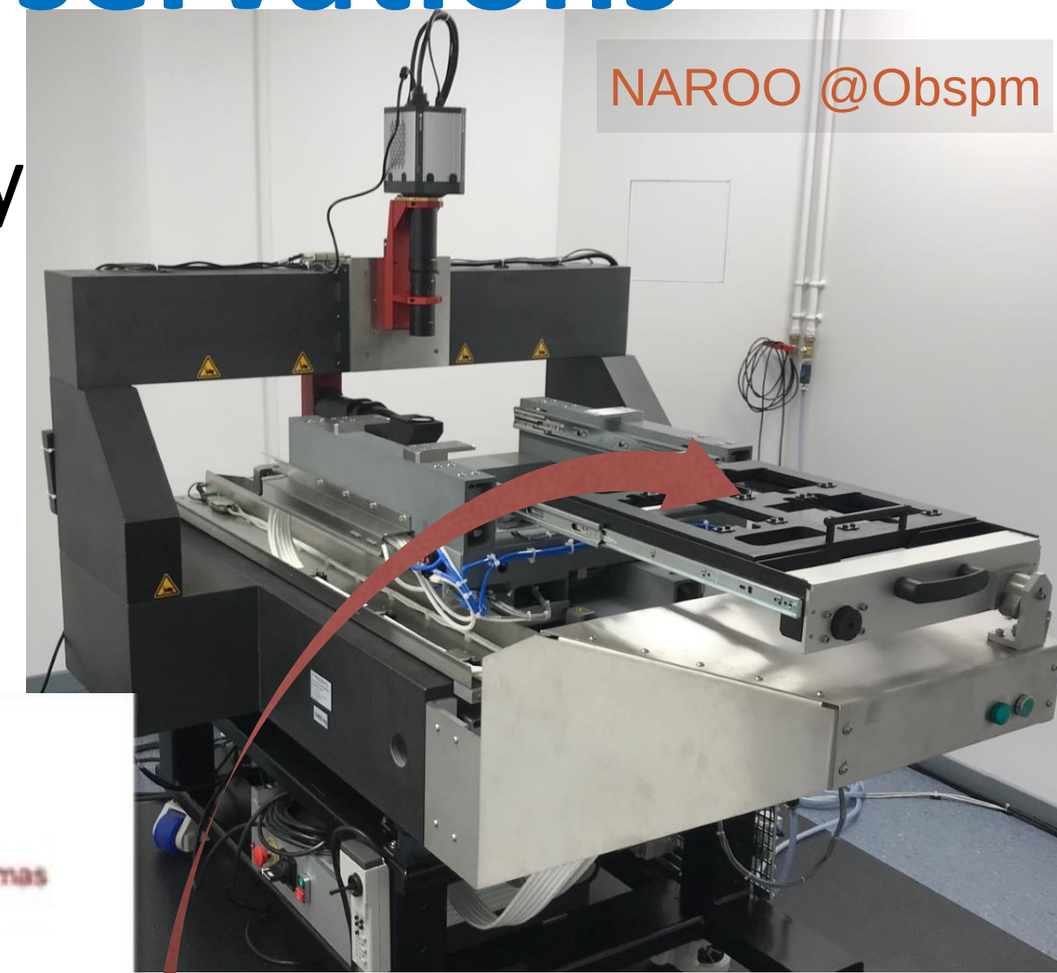
Apophis: position uncertainty reduced by factor 50
with only 10% of MPC data re-reduced

Revisiting past-observations

- Ad-hoc Debiasing MPC astrometry
- Recalibration
  GBOT, OSSOS, Pan-Starrs, etc.
- Photographic plates: NAROO

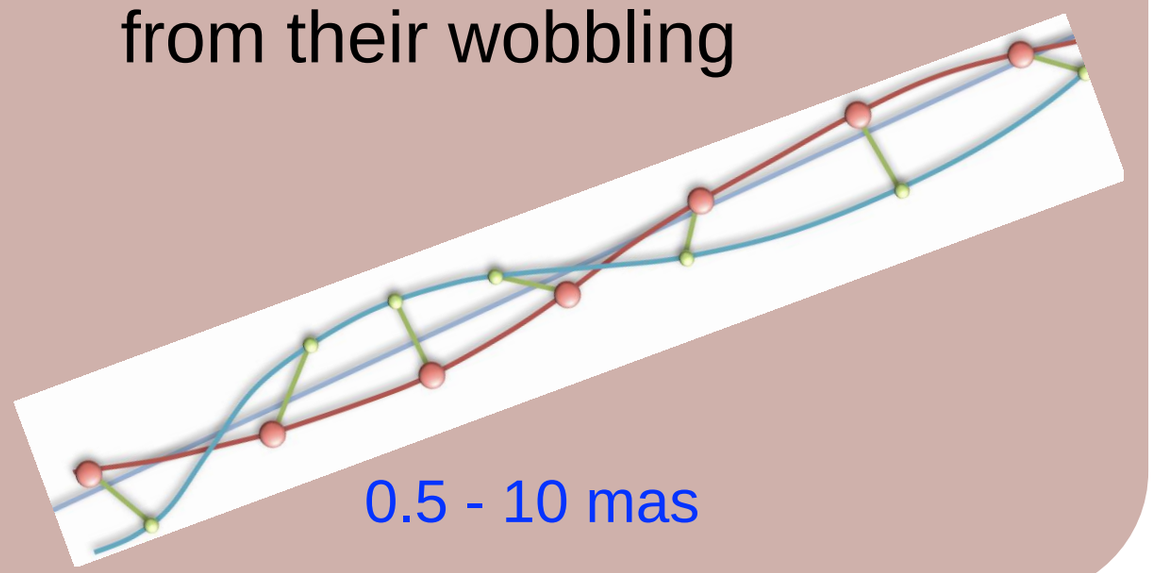


(© F. Mignard)



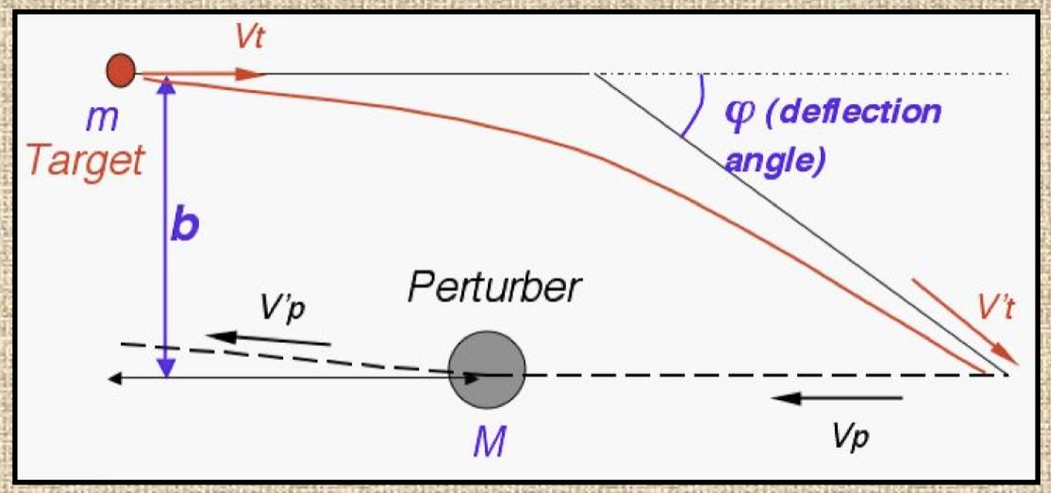
Some challenges for asteroid astrometry

Discover asteroid satellites from their wobbling

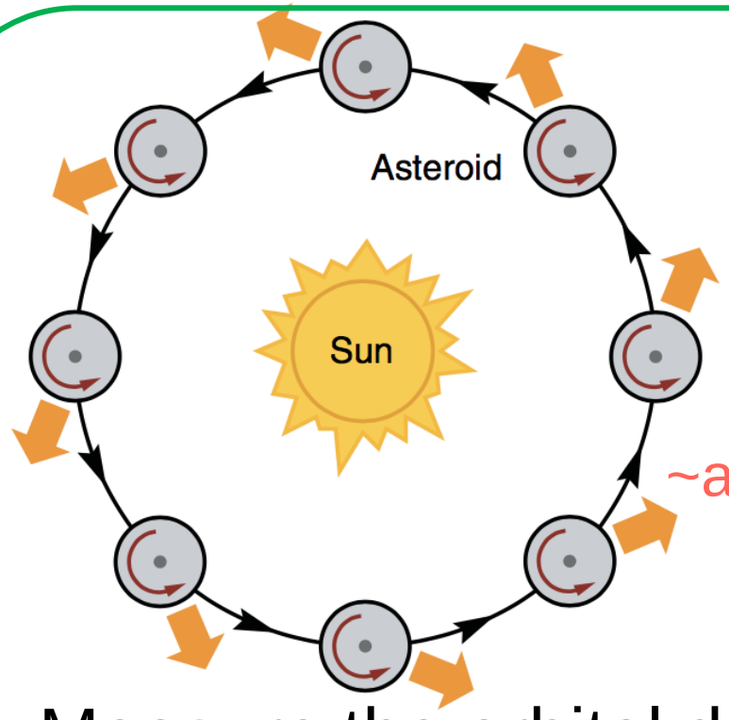


0.5 - 10 mas

New / precise asteroid masses



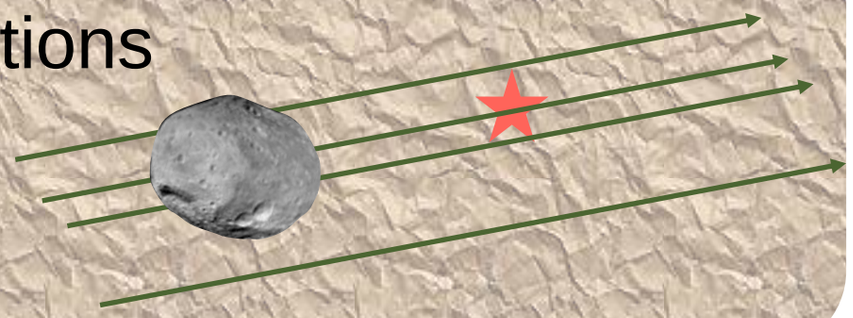
1000s encounters/year > 10 mas



~a few mas

Measure the orbital drift due to Yarkovsky force

Improve predictions of stellar occultations

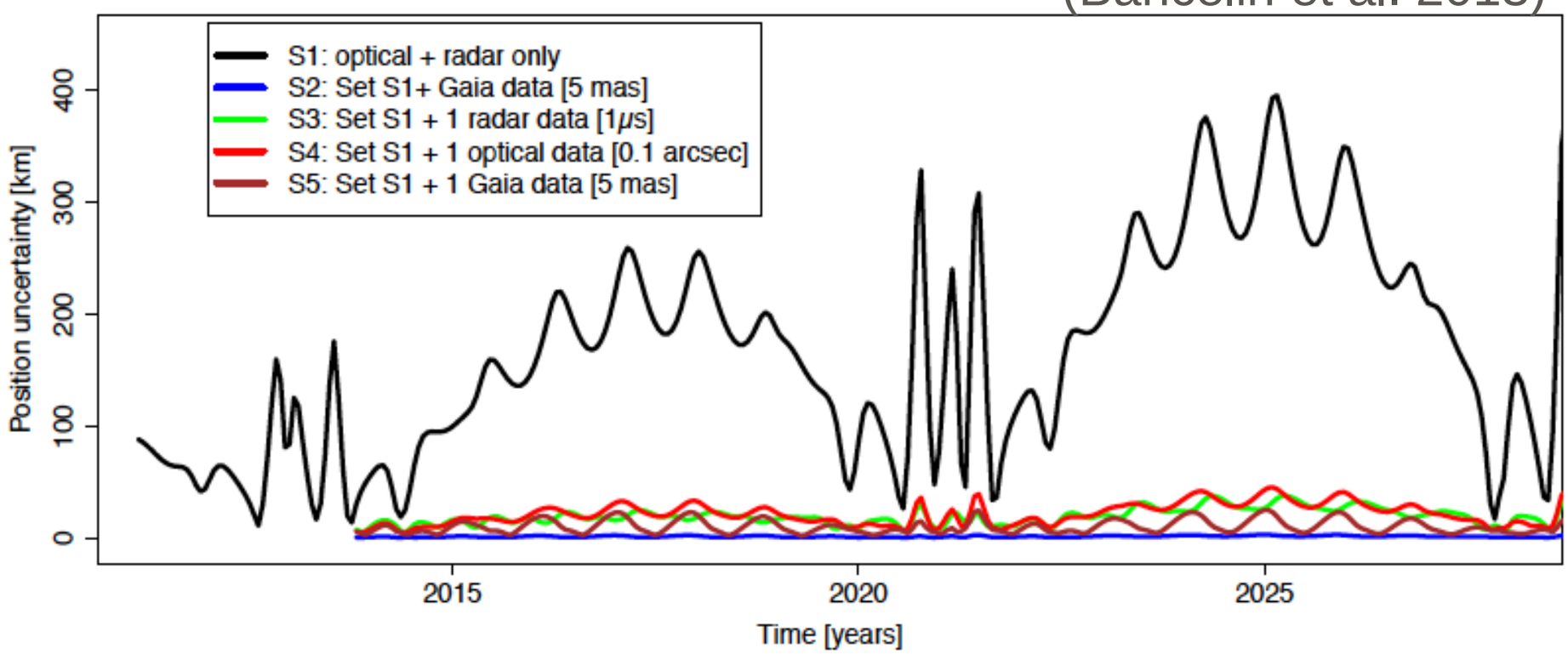


+ spectro-photometry, spin, taxonomy, sizes, …
+ reference frames, GR testing, …

NEO orbit propagation

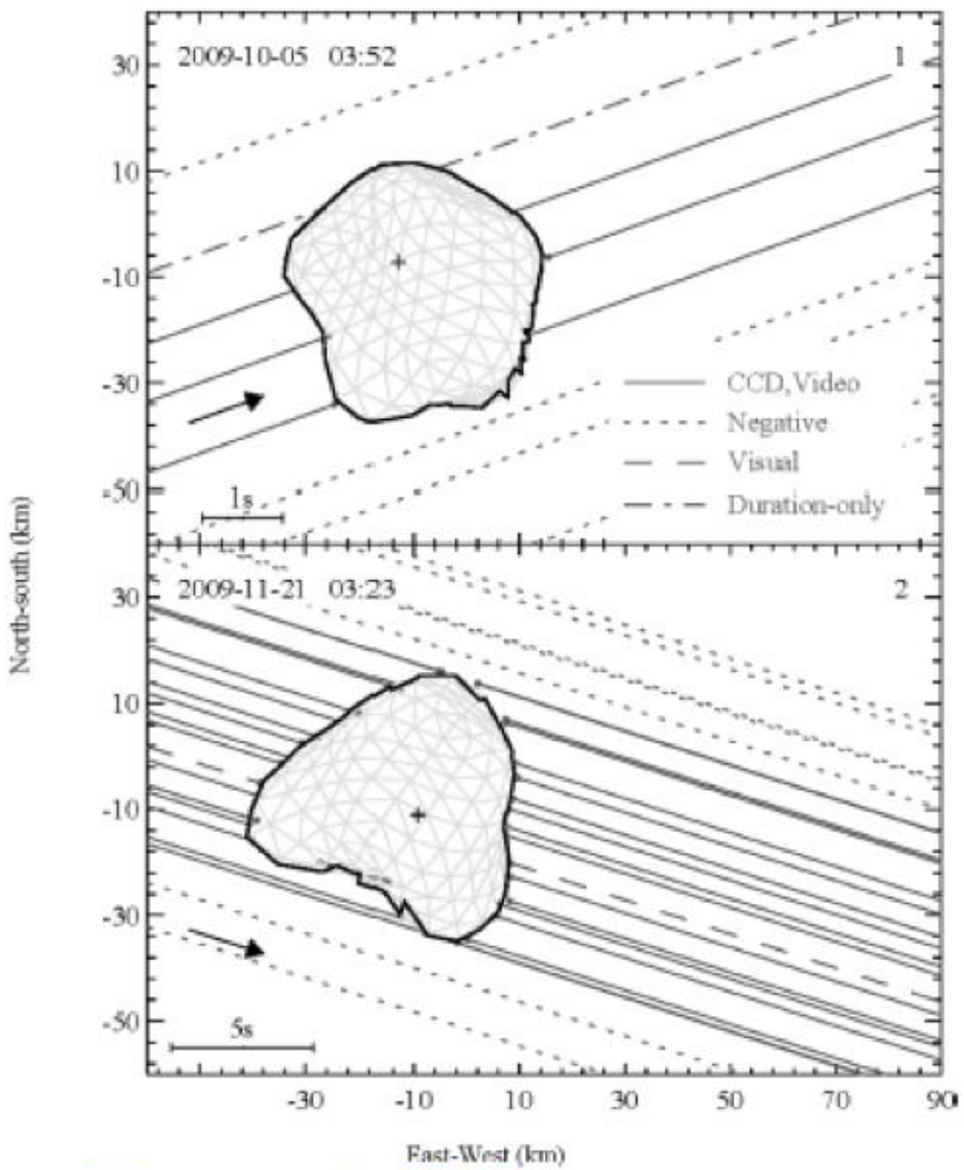
- Better – longer prediction of orbits, and IP

(Bancelin et al. 2013)



Apophis: position uncertainty reduced with Gaia at km level similar to best radar observations

Stellar occultations



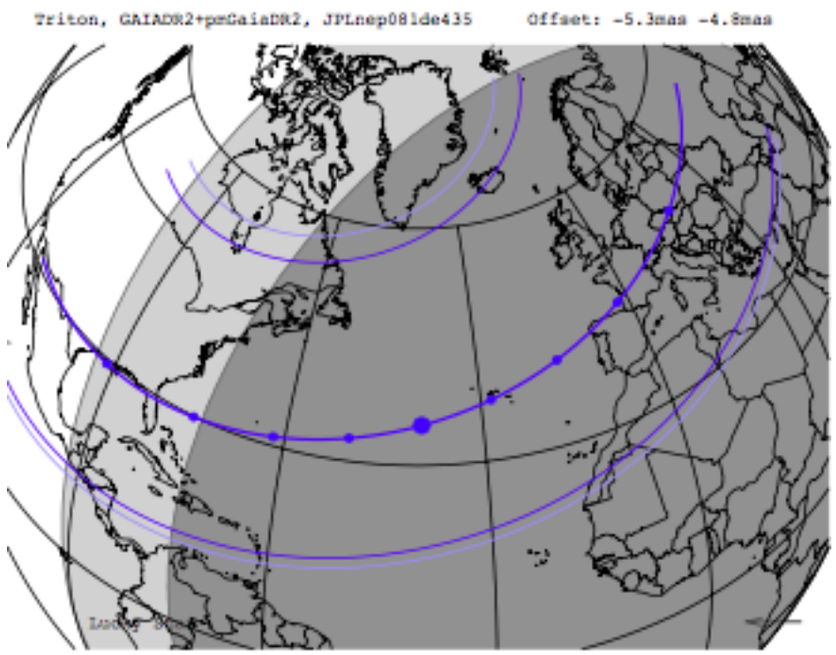
Tanga et al. 2015

Success!
better prediction => more chords
more chords => better science
Shape detailed and
direct size of small bodies

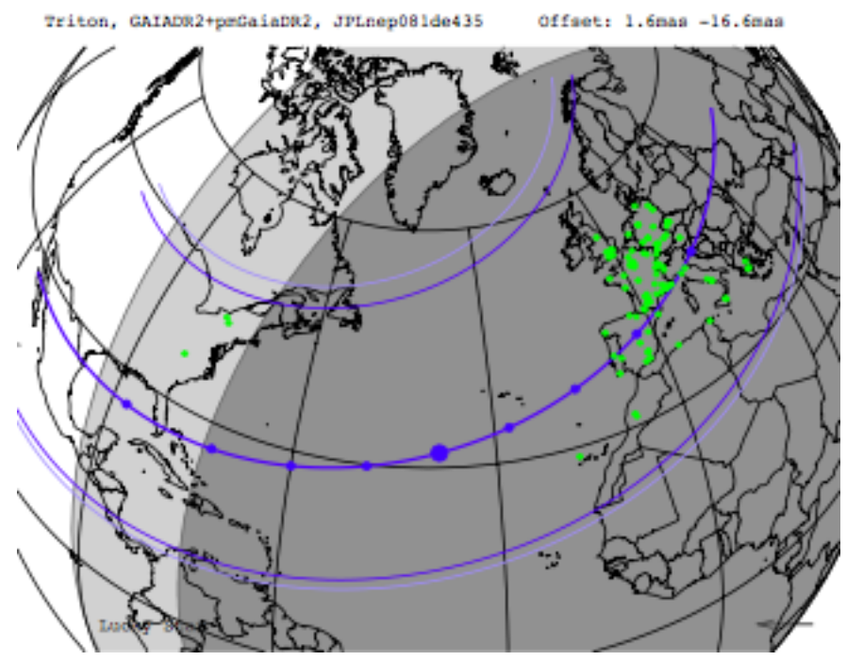
Stellar occultations with Gaia DR2

Triton occultation – 5 Oct. 2017

DR1 in Sep.



DR2 in Oct.



(@B. Sicardi et al.)

use of 119 preliminary DR2 stars

better positions of *both* Triton & occulted star

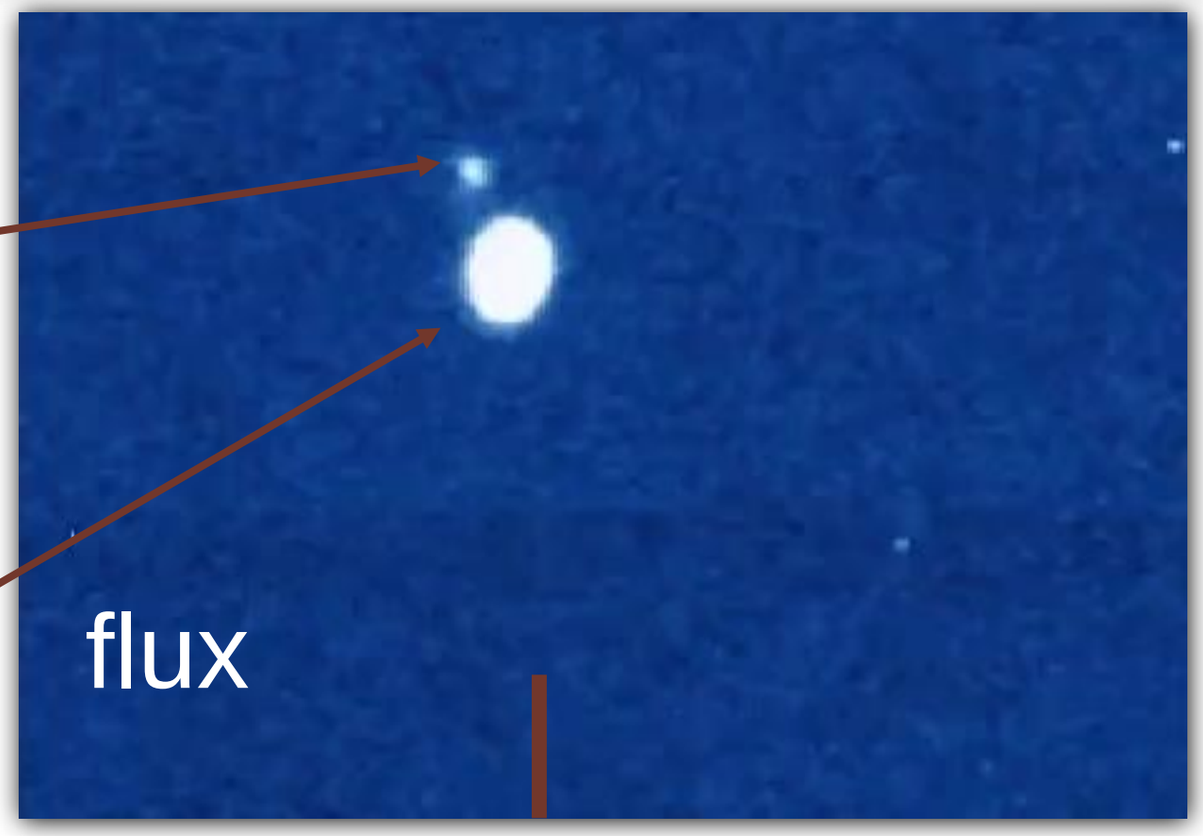
https://www.cosmos.esa.int/web/gaia/news_20170930

http://sci.esa.int/gaia/60015-central-flash-during-triton-occultation/

Stellar occultations with Gaia DR2

Triton occultation – 5 Oct. 2017

precision on ground
≈7s in time and ≈40km on path

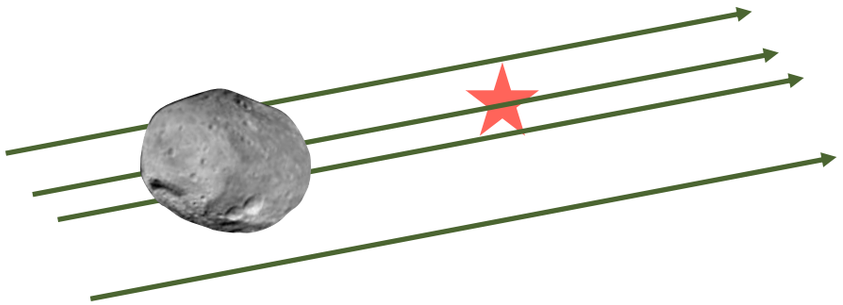


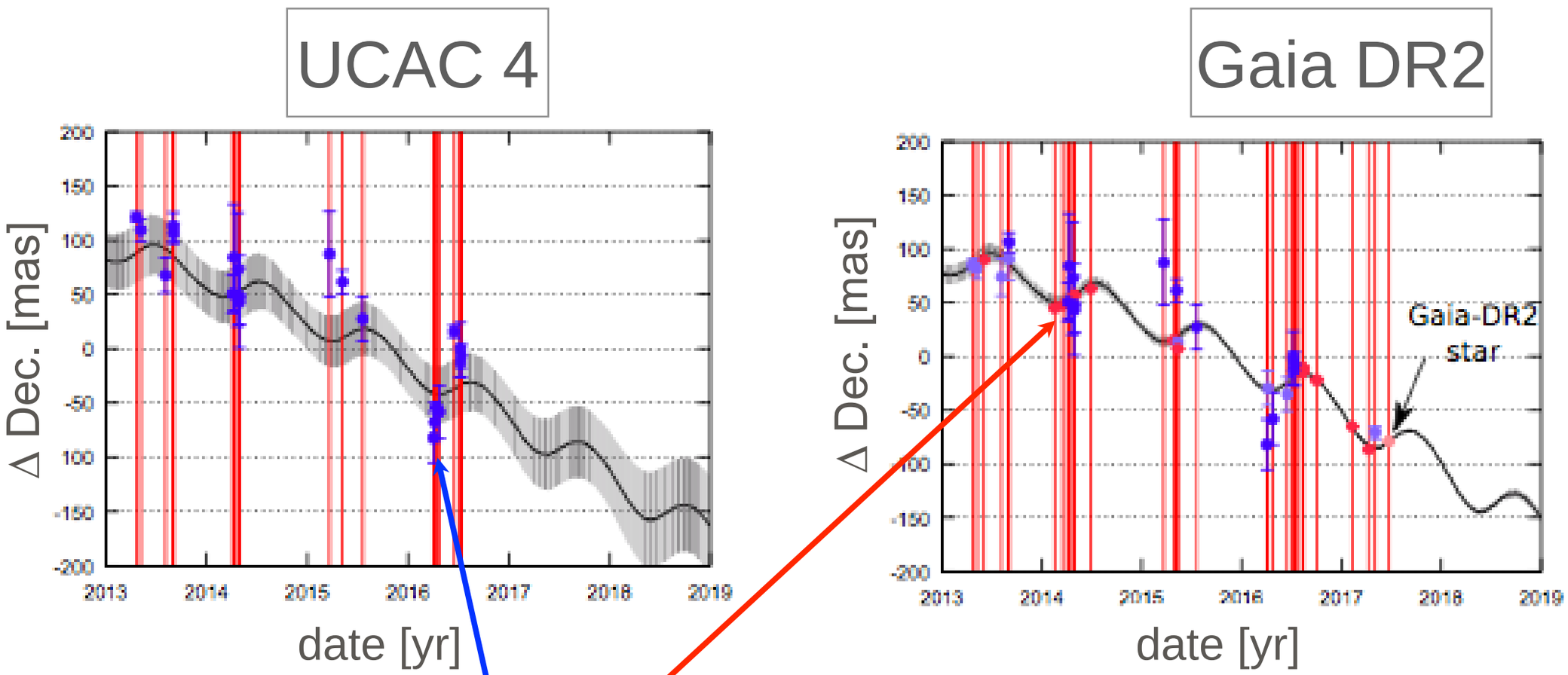
(© B. Sicardi et al.)

Central flash!! from satellite atmosphere

The occultation astrometry with Gaia

- DR2 successfully exploited
  - Triton (October 2017)
  - 2014 MU69 (V=27.5, 50 km KBO, ~1.4 mas)!!





red: SSO = DR star position

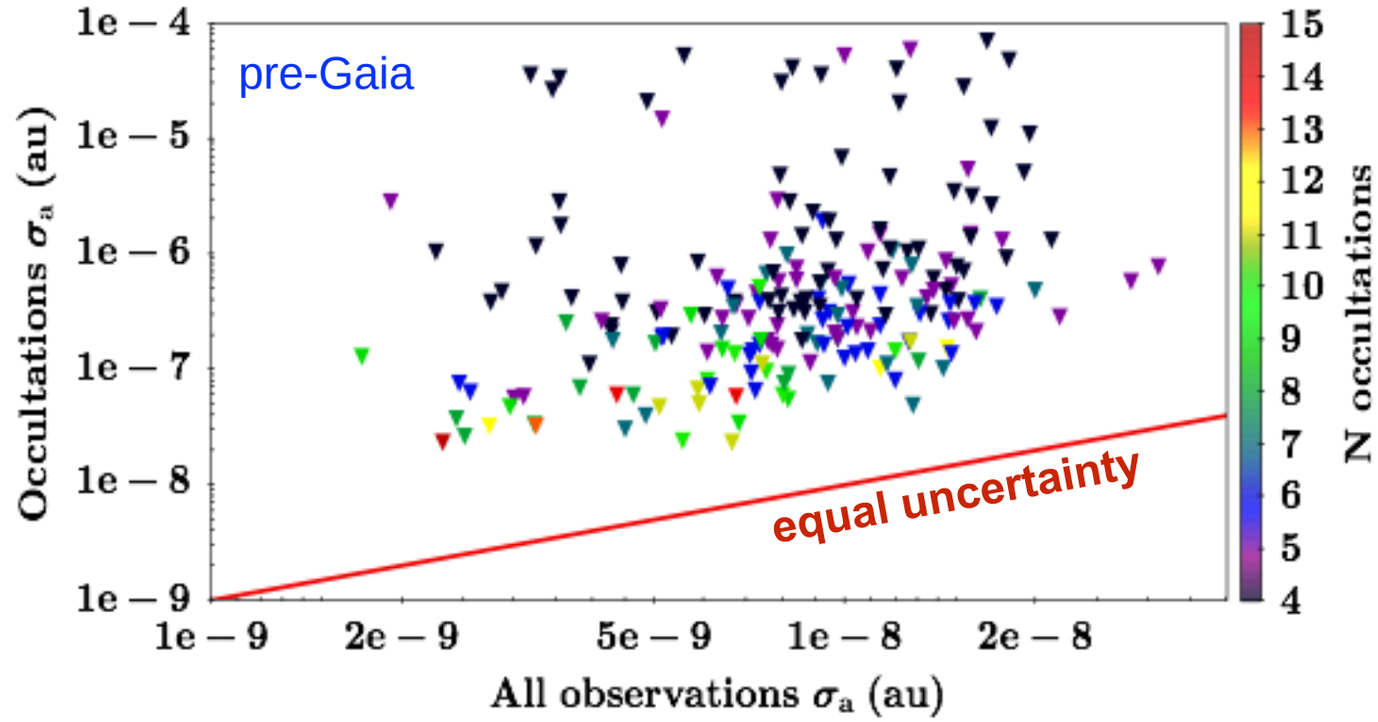
blue: classic astrometry

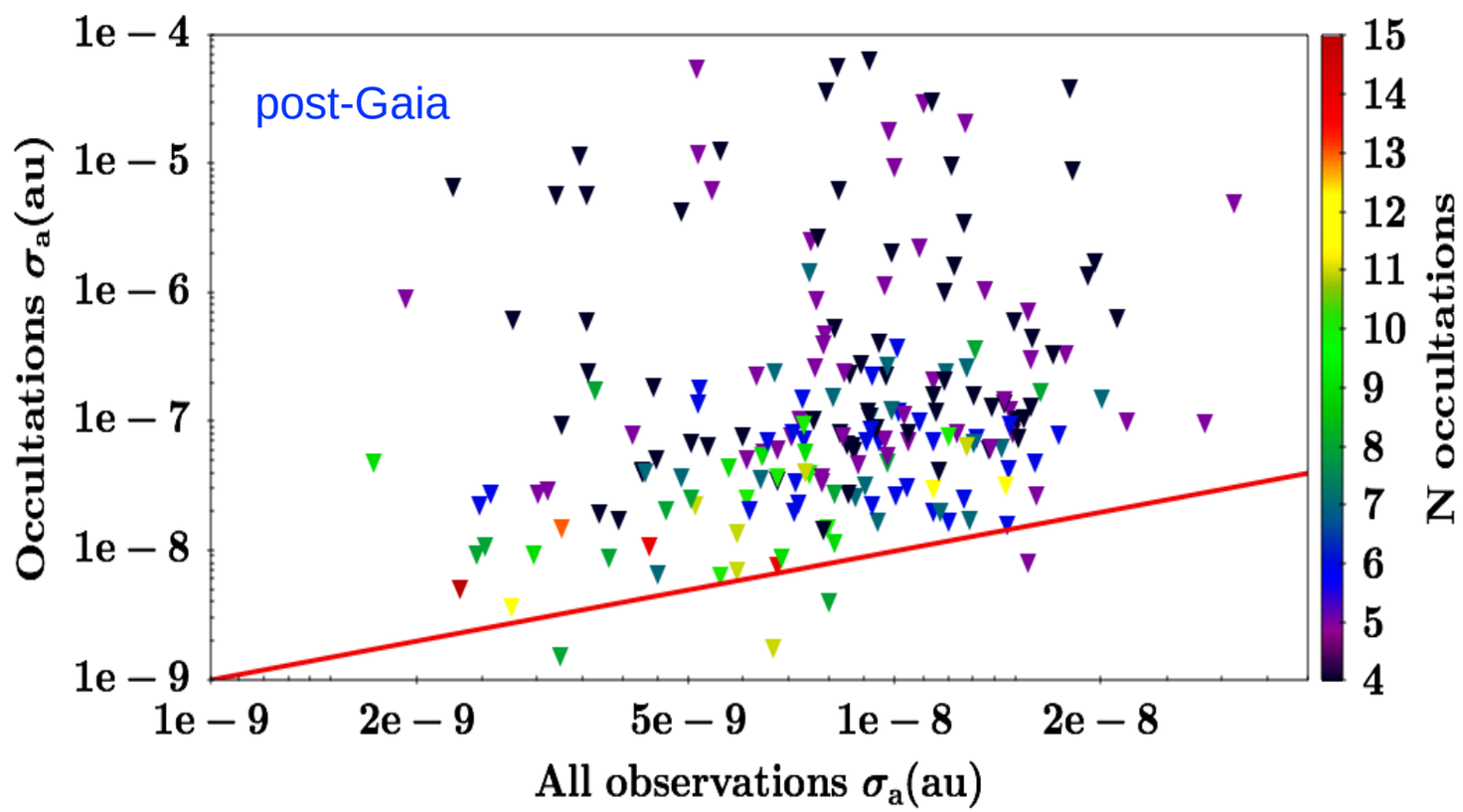
(© J. Desmars)

The occultation astrometry with Gaia

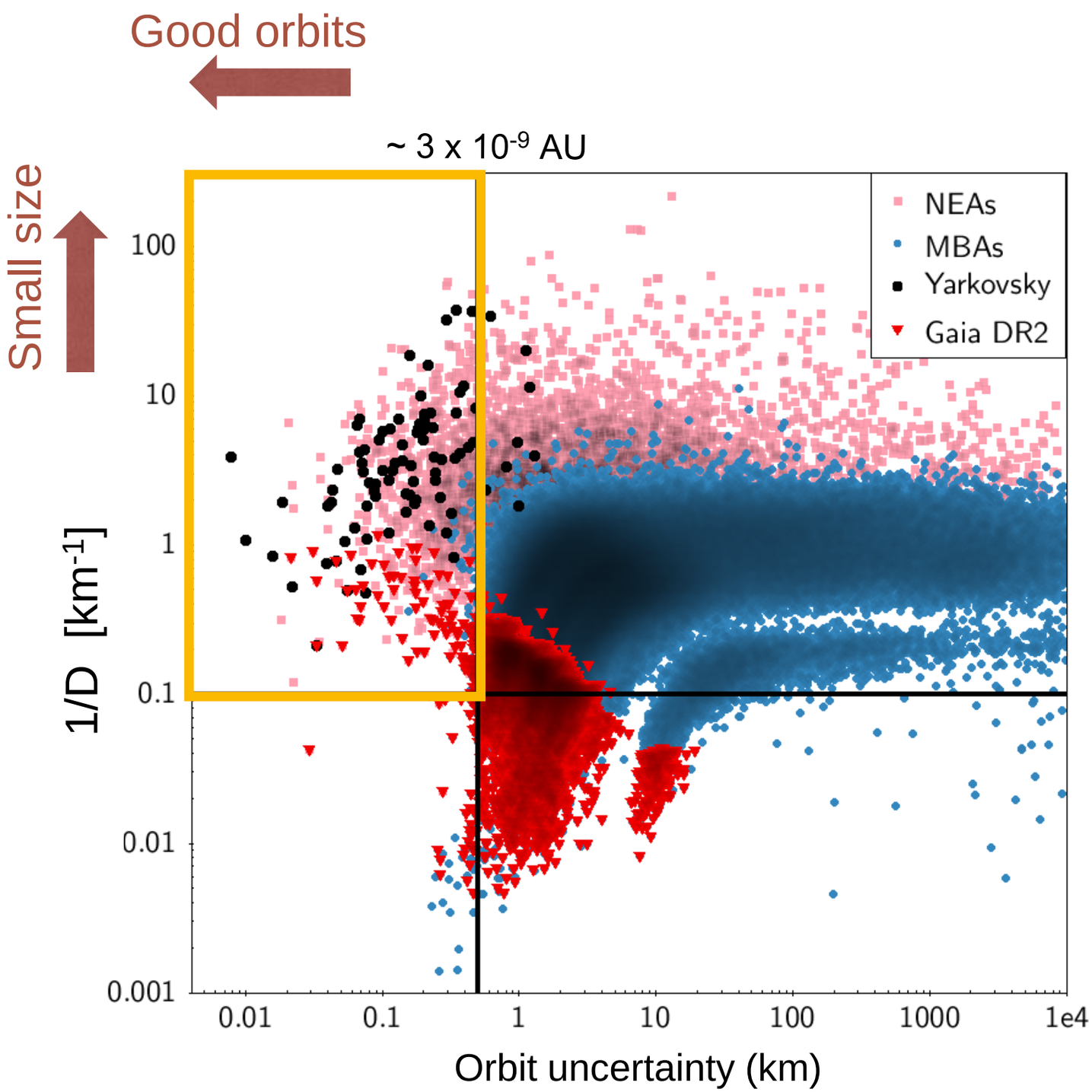
- Occultations: very accurate asteroid position at the level of the star astrometry (mas - µas)
- Comparison orbit precision
  - Few (past) occultations/object vs.
  - all (1000s) MPC data

- …beyond the duration of Gaia!
- Future of astrometry?
- ≈10,000 objects down to 20km





Yarkovsky effect



Pre-Gaia orbit quality (MPC data)

In DR2:

- 3 NEOs with measured Yarkovsky
- 5 NEOs with marginal detection
- about 20 good MB candidates

(@F. Spoto)

Mass determination

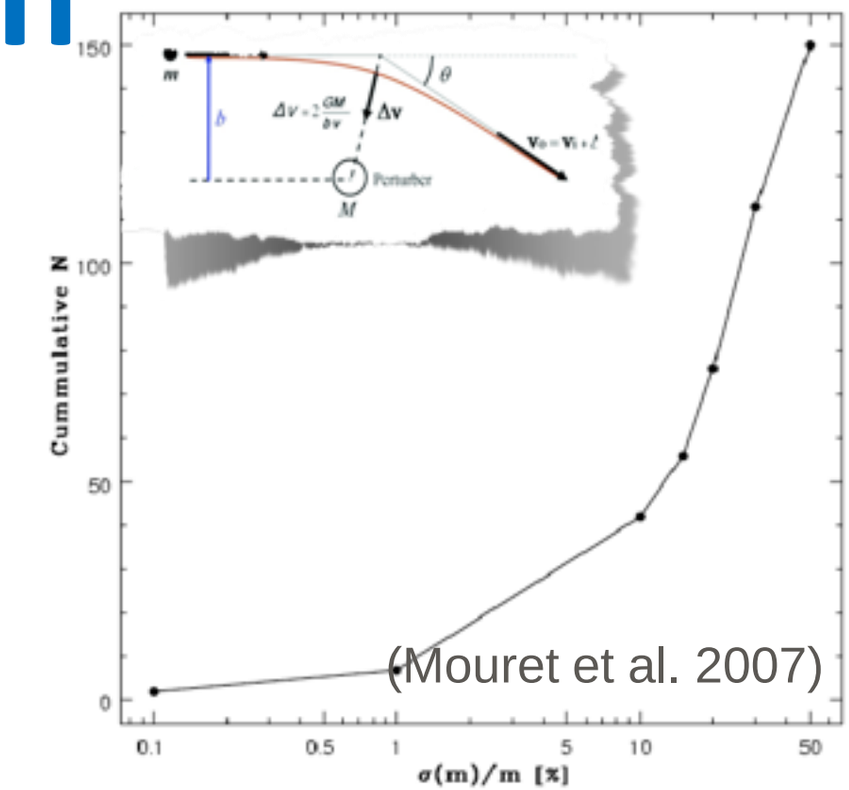
- Close encounters
  - ≈100 mass determination
  - from Gaia data alone

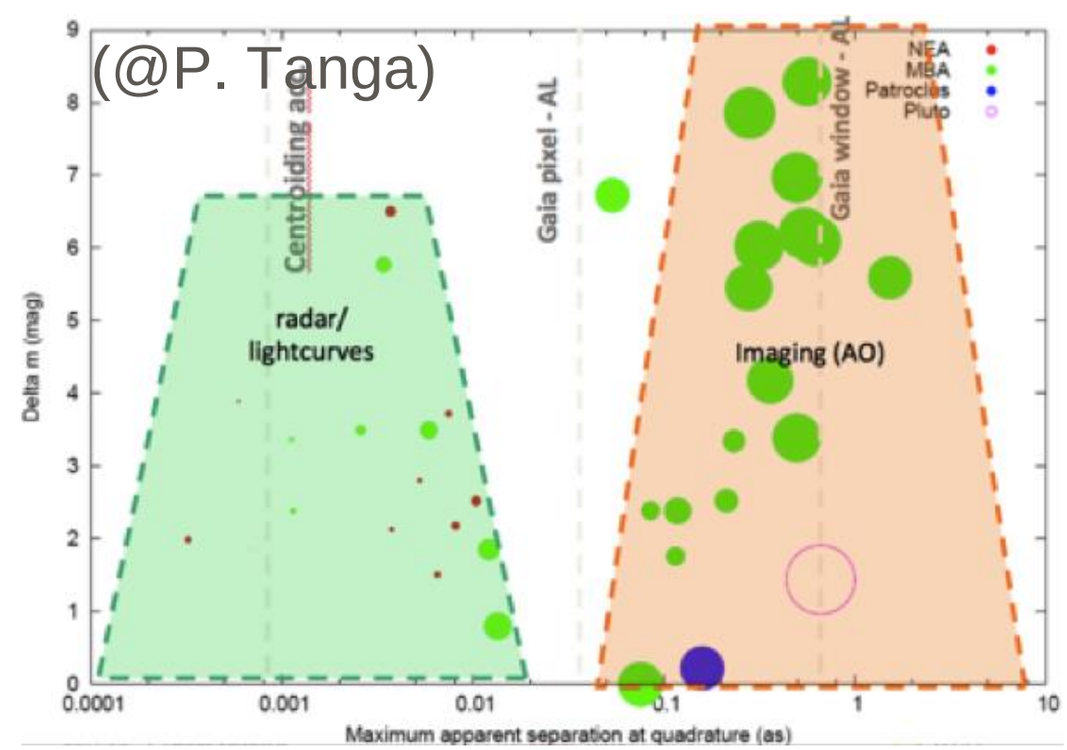
  (@Ivantsov et al.2017 IAUs 330)

- Binary asteroids
  - resolved binaries
  - astrometric binaries
  - MCMC inv. Code

  (@Kovalenko et al. 2016)

- With shape and size/albedo/taxo
  - bulk density
  - macro-porosity

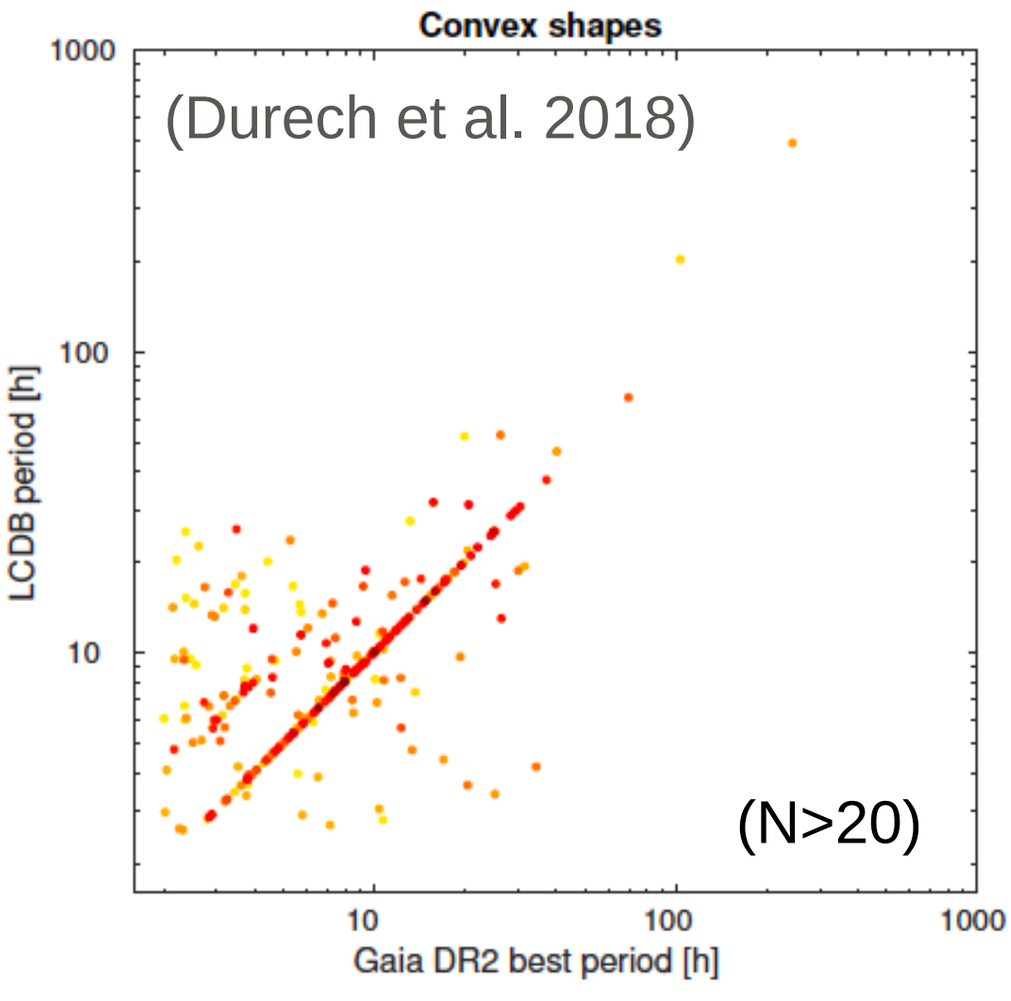




Photometry – lightcurve

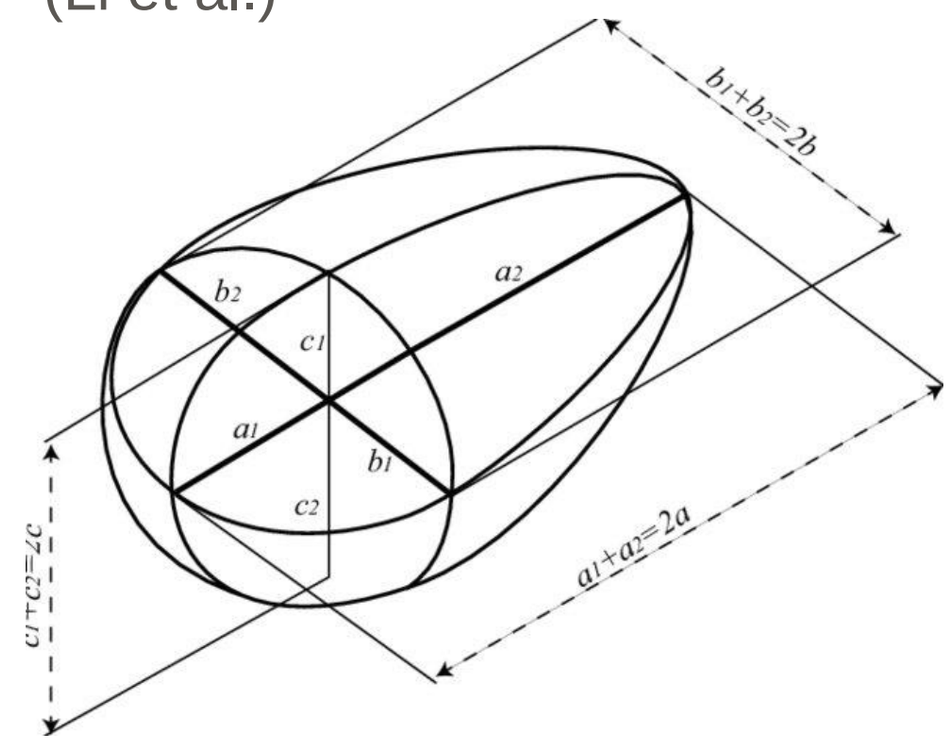
- sparse data – no full LC, yet over several years at milli-mag
- derive spin (period, direction), shapes
- valuable with N≥30 transits
- Also phase relation

topographic



Cellinoids

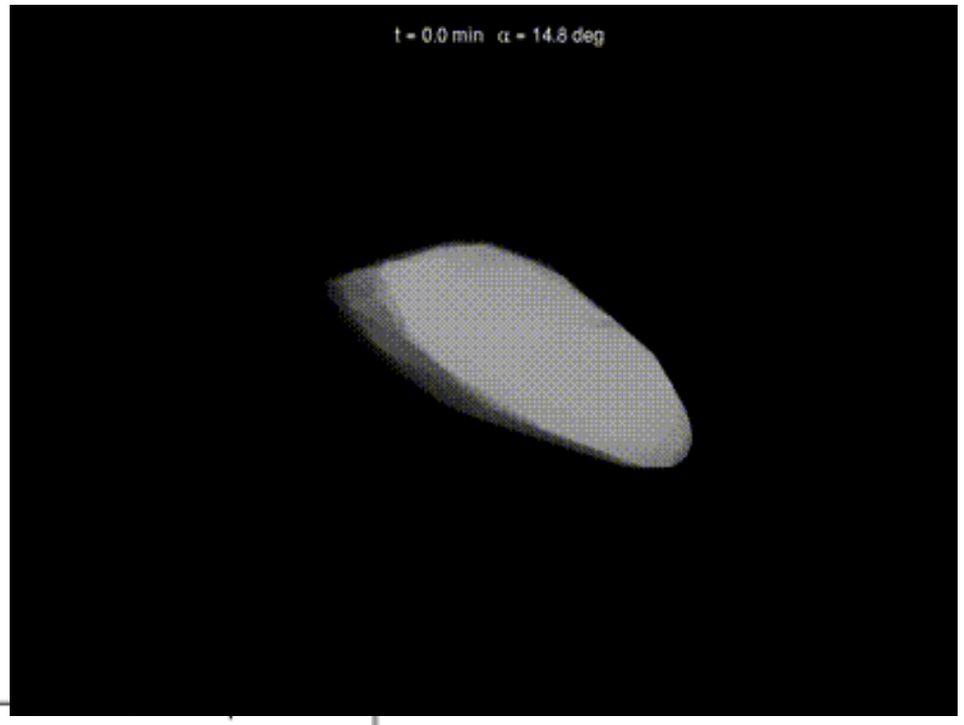
(Li et al.)

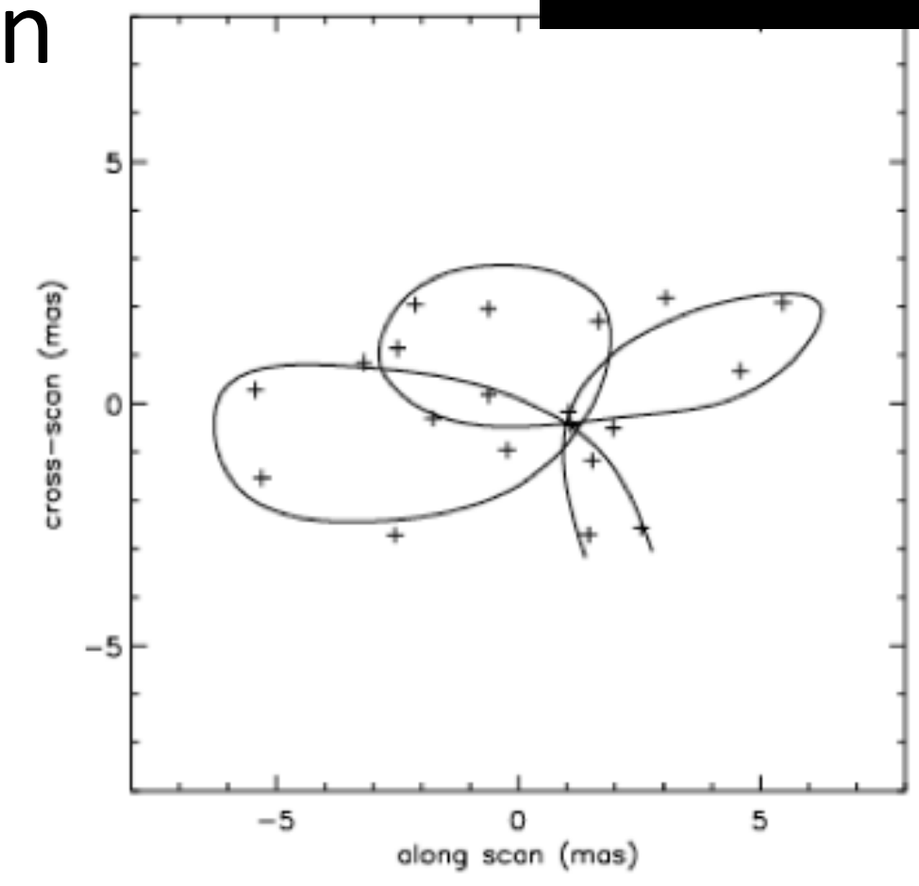


(combine Hipparcos+Gaia)

Photocentre offset

- Due to phase effect during rotation
  + propto size
  + shape
  + light-diffusion

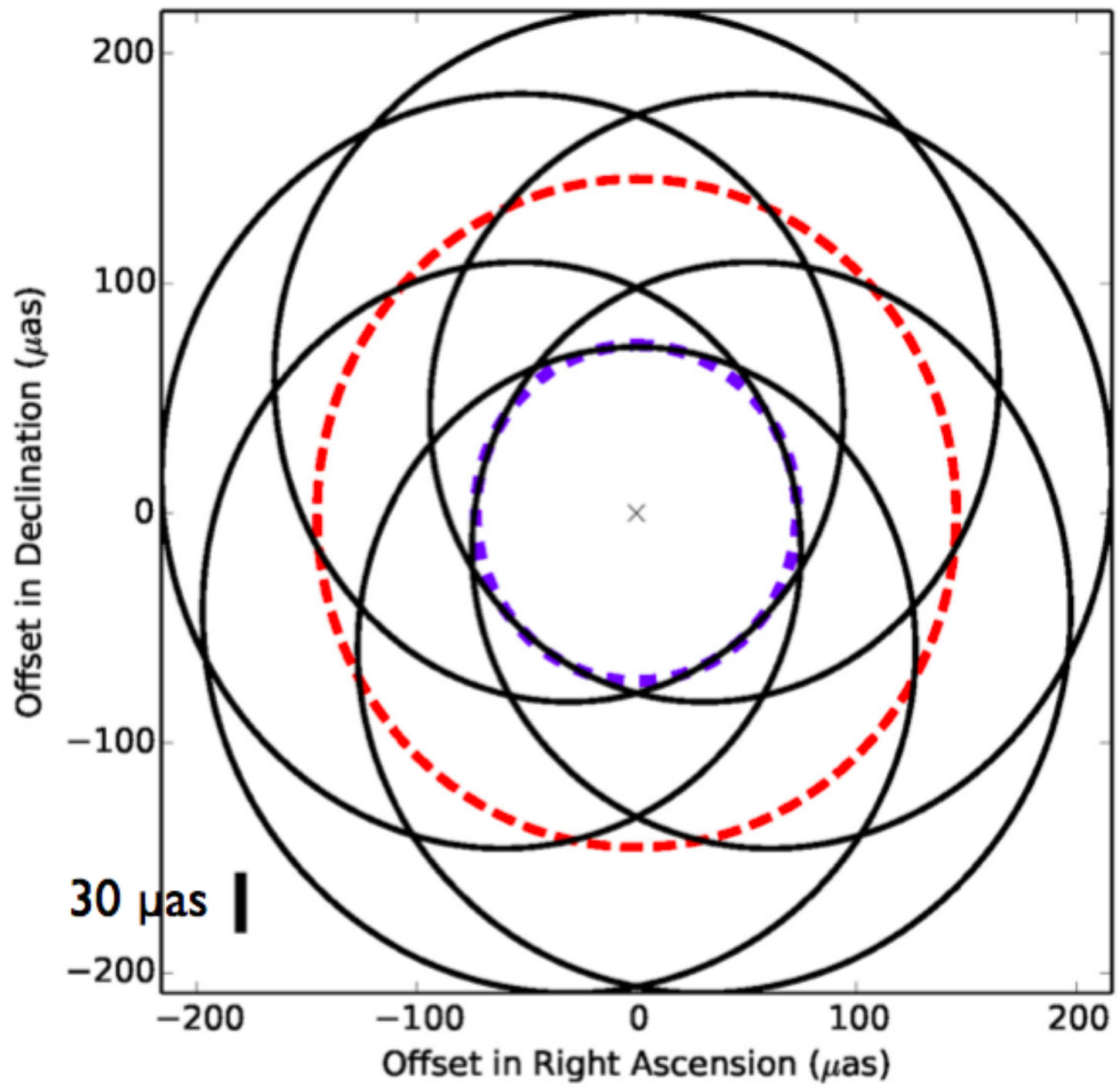




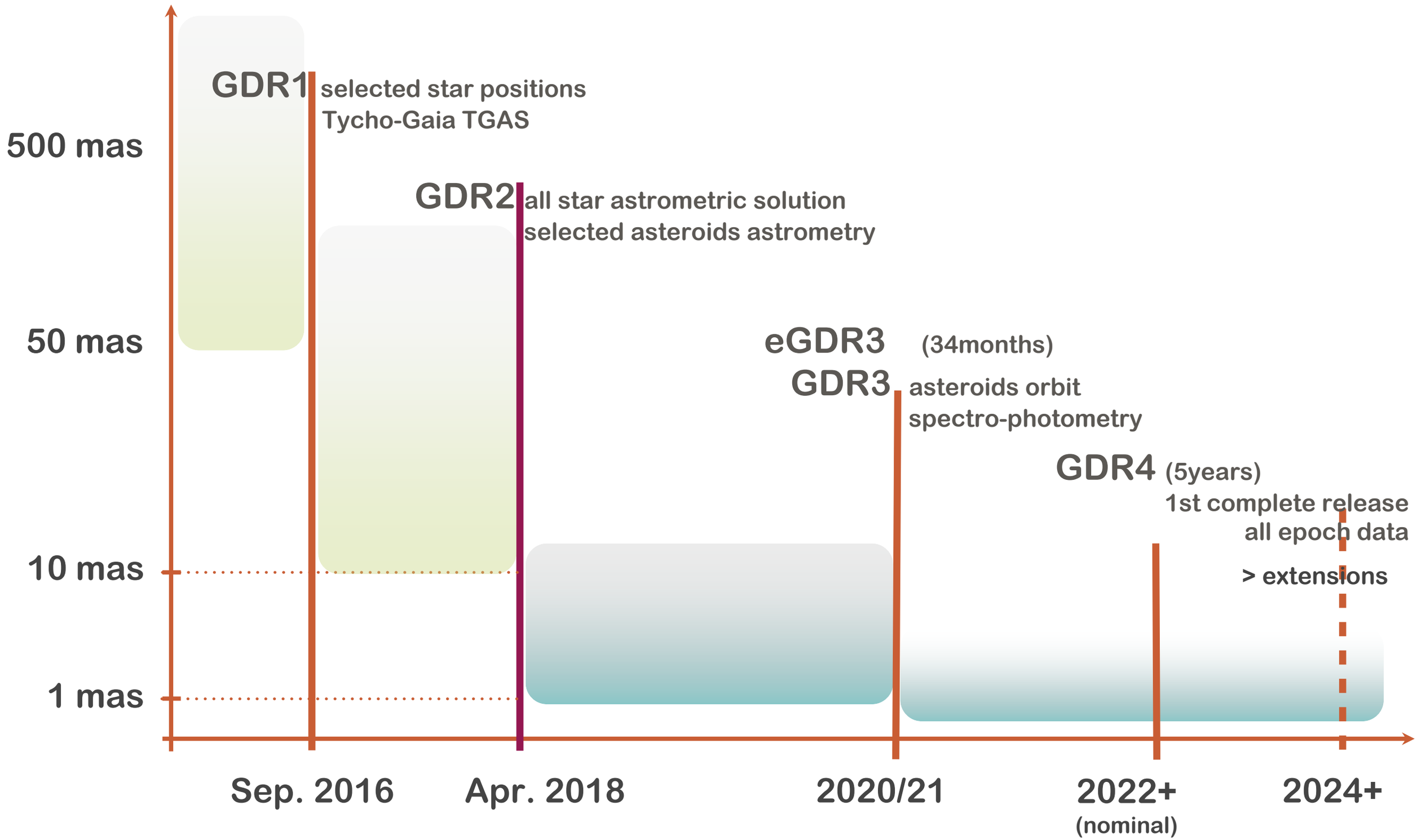
(Kaasalainen et al. 2004)

Exoplanets

- ≈1000's of exoplanets expected
- circumbinary planets
- 10% of tight binaries host one

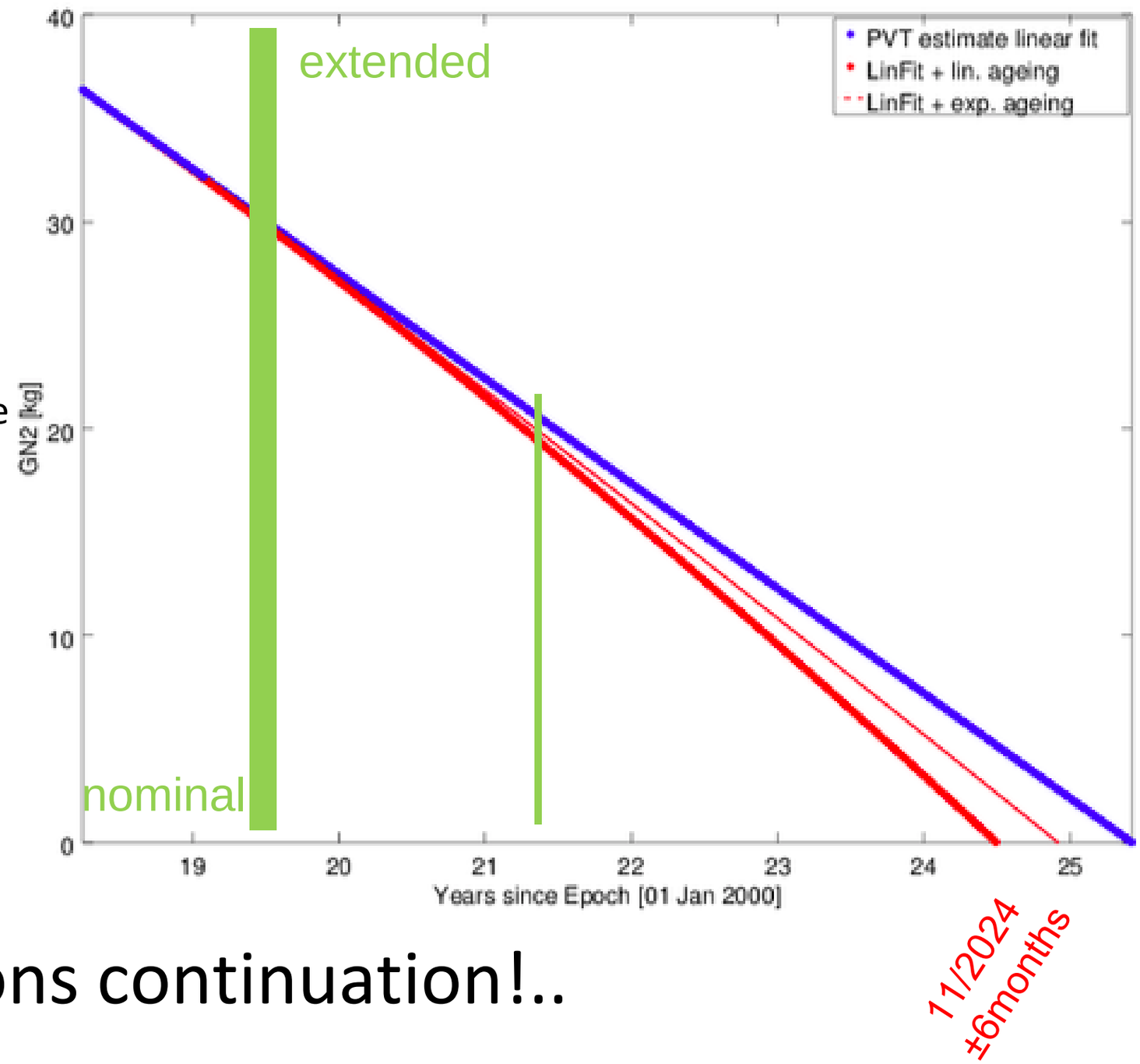


Timeline


GDR1
selected star positions
Tycho-Gaia TGAS
GDR2
all star astrometric solution
selected asteroids astrometry
eGDR3 (34months)
GDR3
asteroids orbit
spectro-photometry
GDR4 (5years)
1st complete release
all epoch data
> extensions
500 mas
50 mas
10 mas
1 mas
Sep. 2016
Apr. 2018
2020/21
2022+
(nominal)
2024+

Future - Extension

- Extension
  -> 10 years expected
  (depending cold-gas tank)
- More photons
  faint-end objects performance
- Good for dynamics
  - SSOs
  - Exoplanets
  - Binaries
  - …

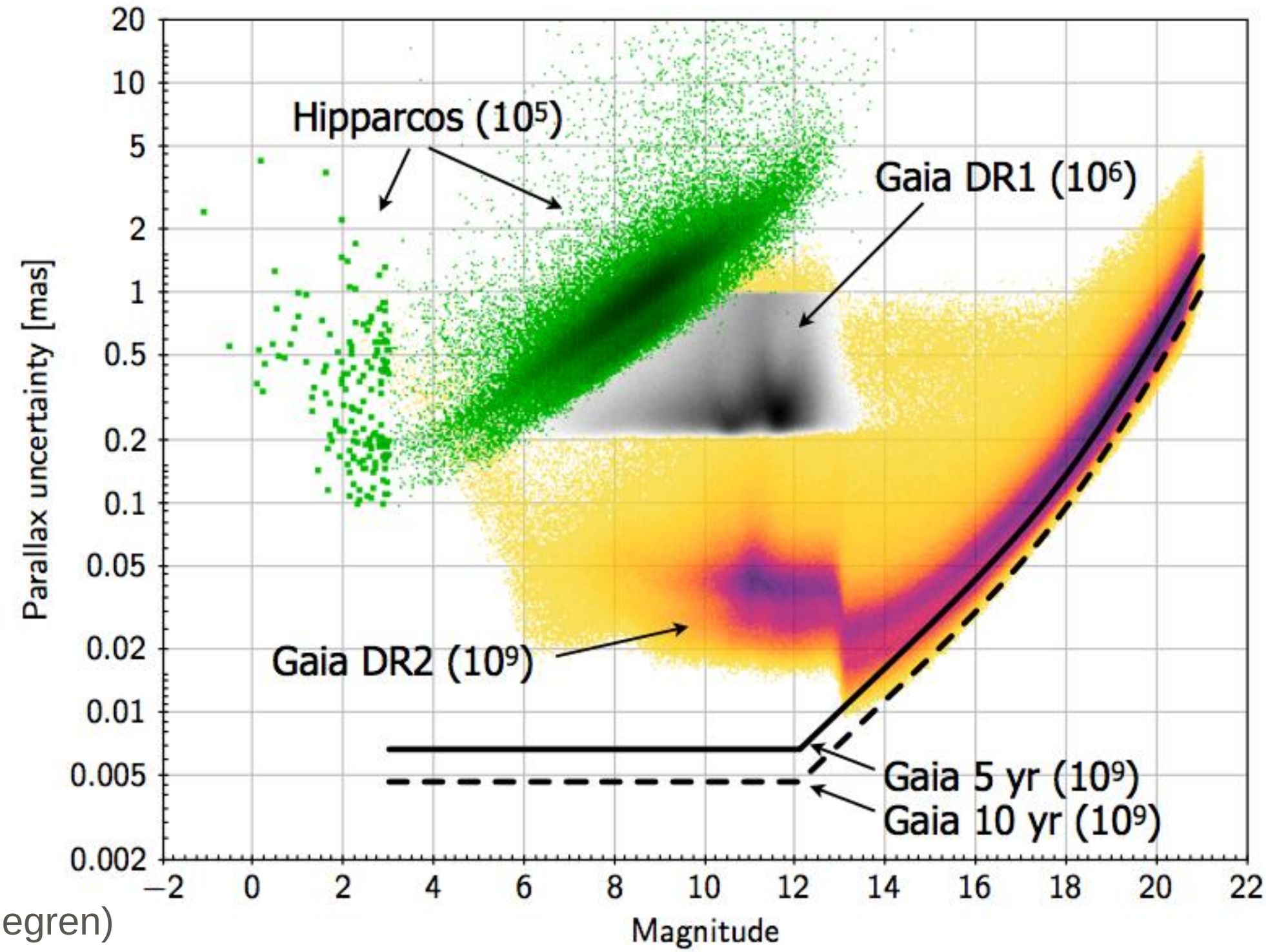


- Need of DPAC operations continuation!..

Future – Extension

Parallax

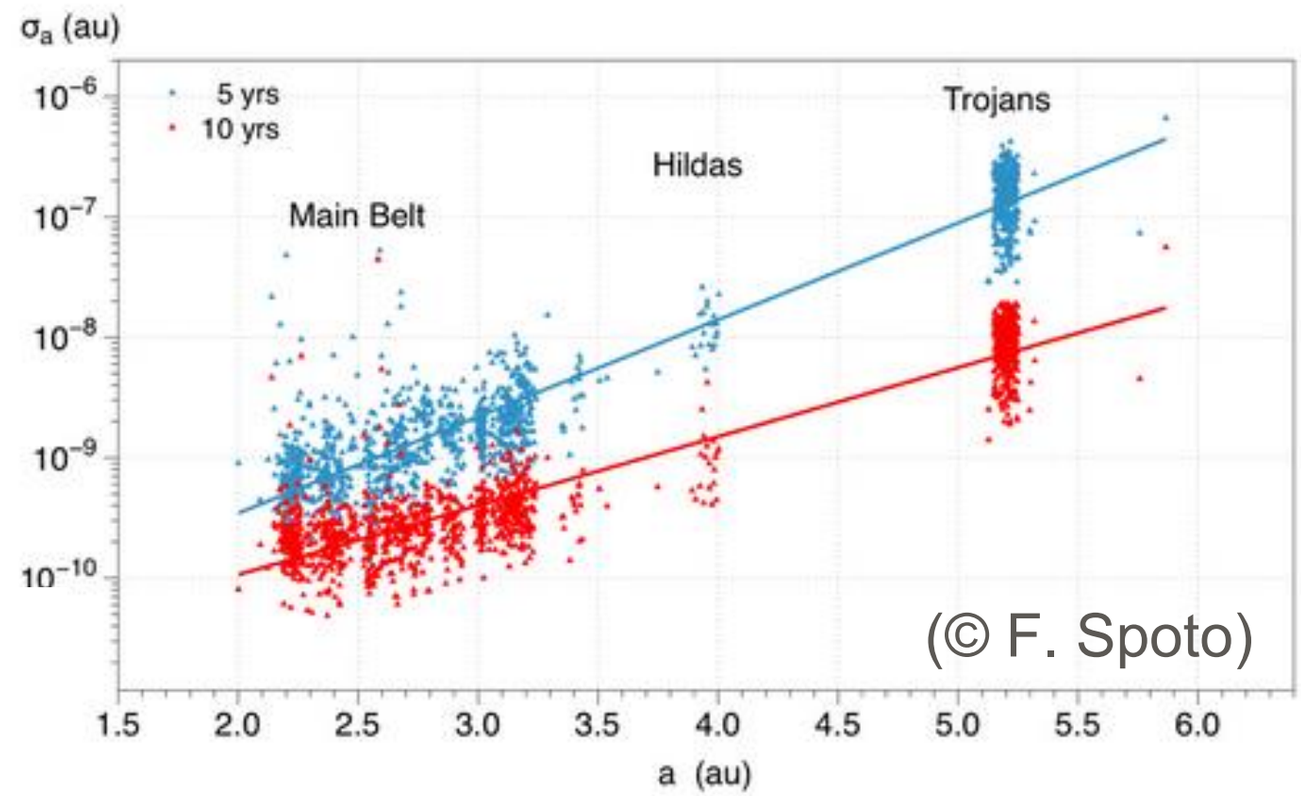
Proper motion improvement even better (^3/2)

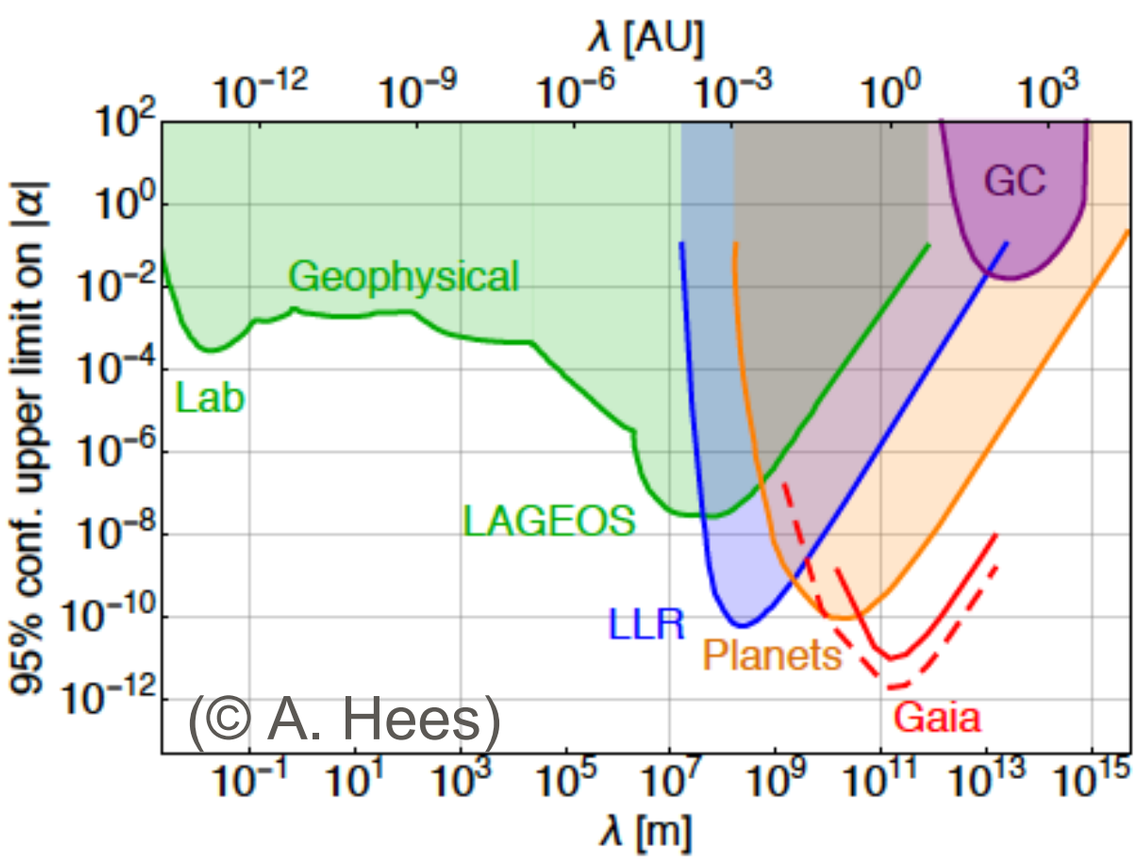


(@L. Lindegren)

Future - Extension

Dynamics of SSOs



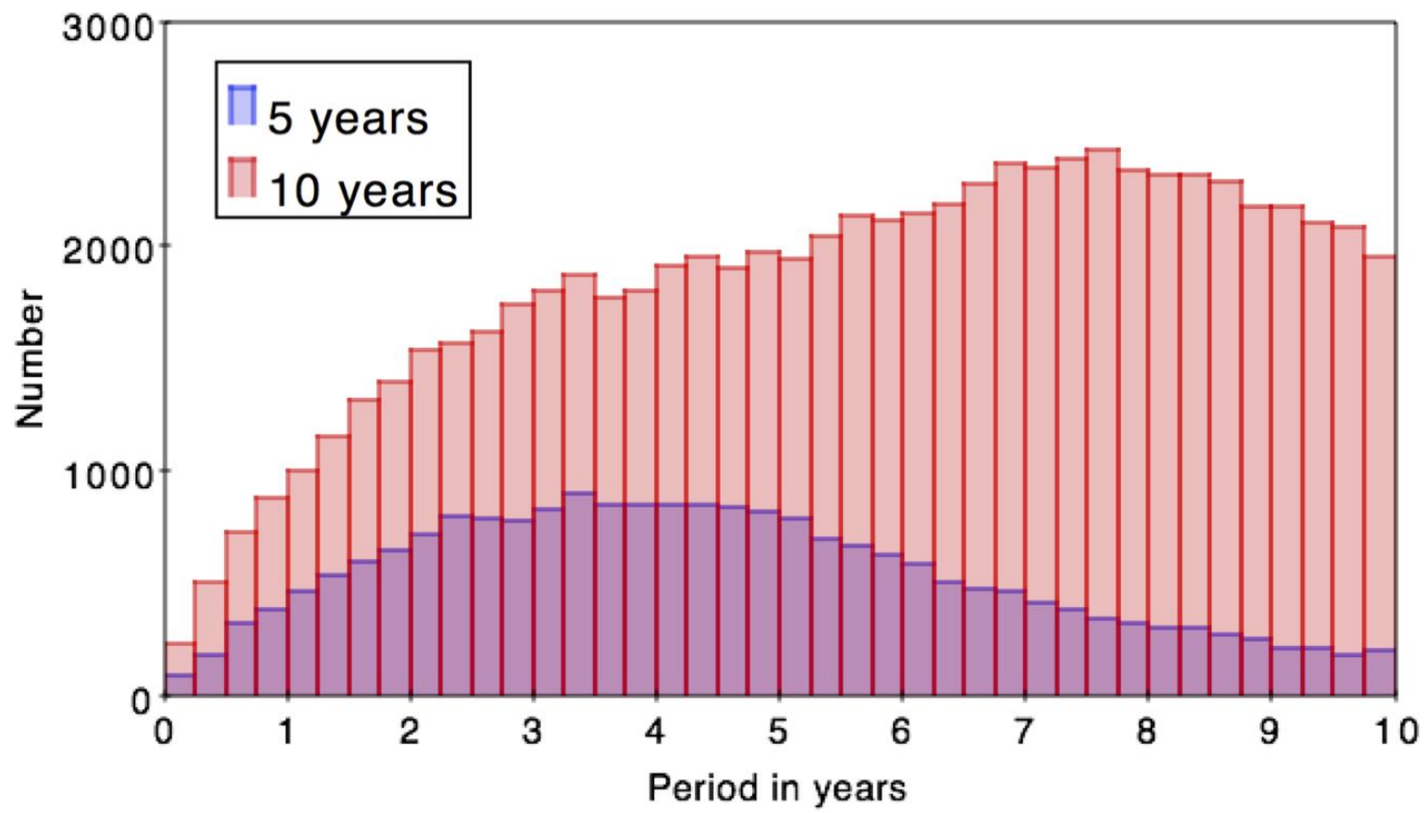


- SSOs orbits improvement
- Masses from encounters
- Tests of GR and gravitation

Future - Extension

- Gaia's strength is Neptune-Jupiter mass planets around stars
- Mission extension reveals population of giant planets above several AU distances from the parent star
  - giant planets before migration, systems with giant 'guarding' habitable zone
- Exoplanets research gains enormously from the improved parallaxes helping to describe the host star

Exoplanets



(@A. Brown)

Conclusions

- Gaia DR2 stars for occultations ; for catalogue astrometric corrections
- Gaia DR2 asteroid data: the first sample
  already useful to test some dynamical effects
  - general orbit improvement, stellar occultations, Yarkovsky, …

- Combination with other observations
- Past => accurate debiasing required (or re-reduction)
- Future ground-based spectro surveys, LSST, space astrometry in IR…

- Then DR3 &+, not only astrometry,
  not only asteroids !…

Gaia web & archive

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

Gaia web & archive

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

EUROPEAN SPACE AGENCY ABOUT ESAC SIGN IN

gaia archive

esa

HOME SEARCH STATISTICS VISUALISATION DOCUMENTATION HELP

Welcome to the Gaia Archive

Gaia is an ambitious mission to chart a three-dimensional map of our Gal
revealing the composition, formation and evolution of the Galaxy. Gaia wil
and radial velocity measurements with the accuracies needed to produce a
of about one billion stars in our Galaxy and throughout the Local Group. This
Galactic stellar population.

Top Features

Citation

How to cite and acknowledge Gaia.

Search

Query for Gaia sources using an ADQL (Astronomical Data Query Language) interface in an asynchronous mode (UWS).

Documents

Gaia Mission

Position File

Name
Equatorial

Target in Circle Box

Name for All Radius 5 arc sec

Search in: gaiadr2.sso_observation

Extra conditions

Display columns

solution_id	source_id	observation_id	number_mp	epoch
epoch_err	epoch_utc	ra	dec	ra_error_systematic
dec_error_systematic	ra_dec_correlation_systematic	ra_error_random	dec_error_random	ra_dec_correlation_random
g_mag	g_flux	g_flux_error	x_gaia	y_gaia
z_gaia	vx_gaia	vy_gaia	vz_gaia	position_angle_scan
level_of_confidence				

Select All / None

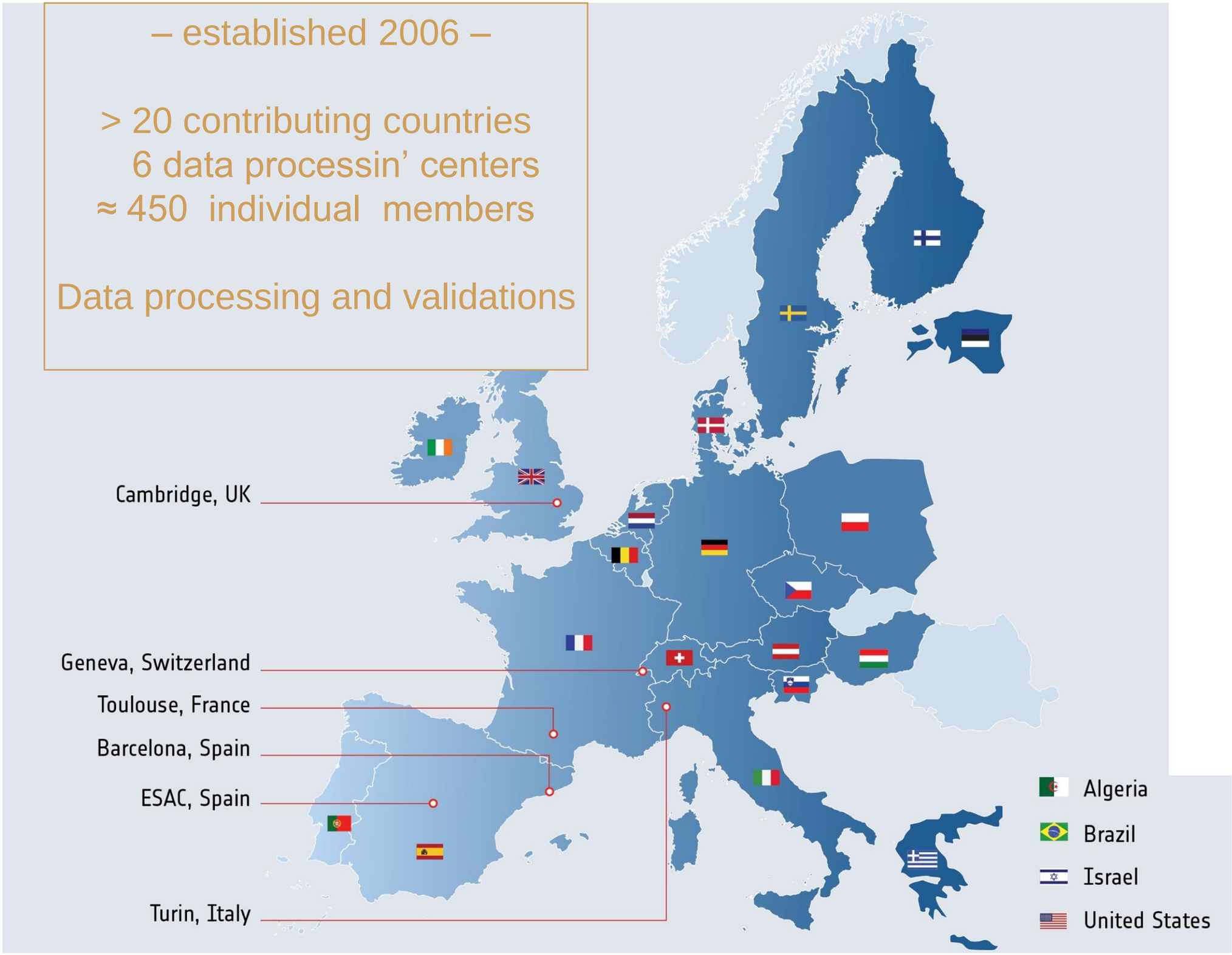
Max. number of results: 500 Reset Form Show Query Submit Query

DPAC consortium

– established 2006 –

> 20 contributing countries
6 data processin' centers
≈ 450 individual members

Data processing and validations



Thanks to DPAC

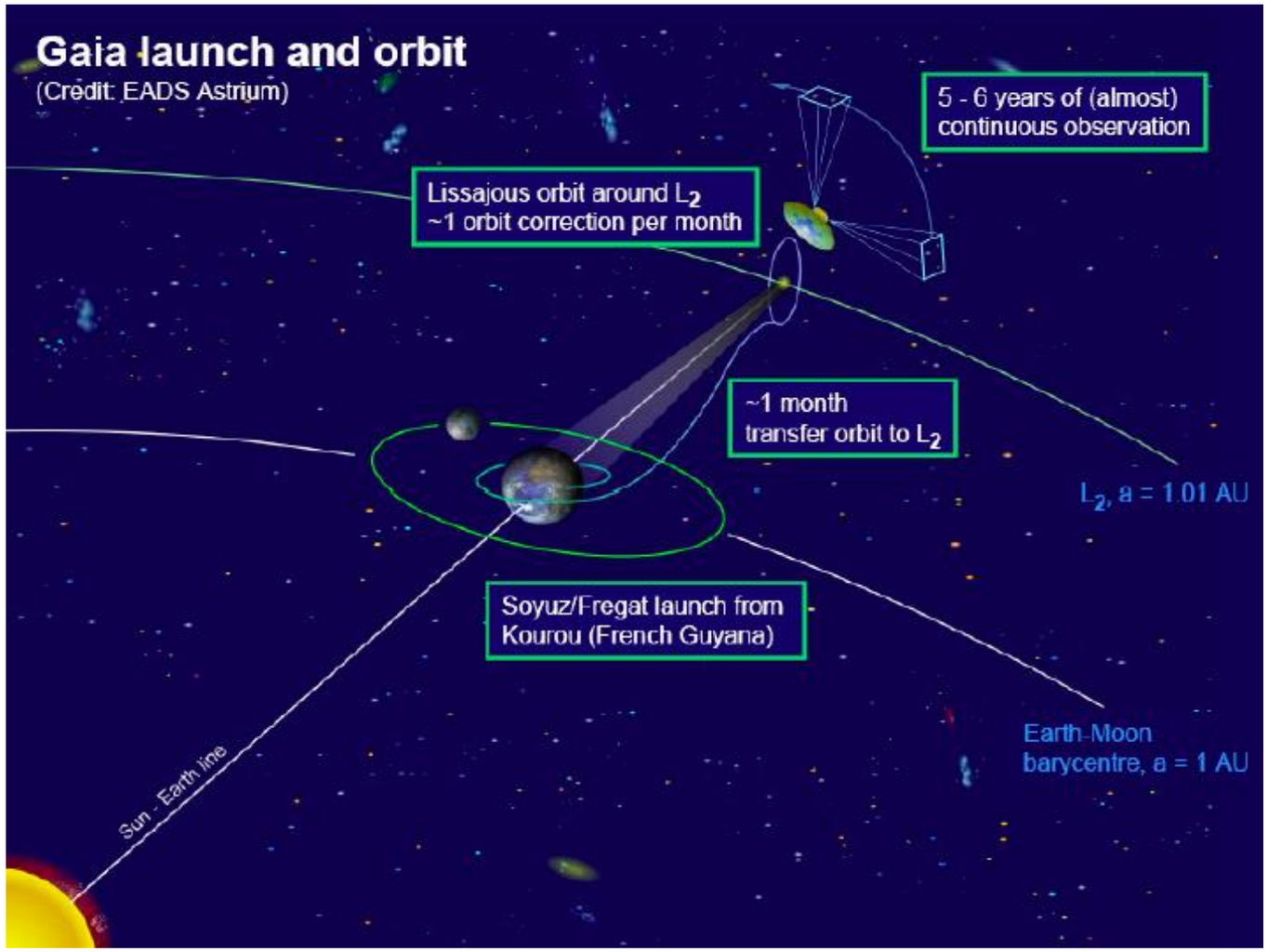
‘At the back of your paper’: You too, acknowledge DPAC !

Citation

How to cite and acknowledge Gaia.

“This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), …”

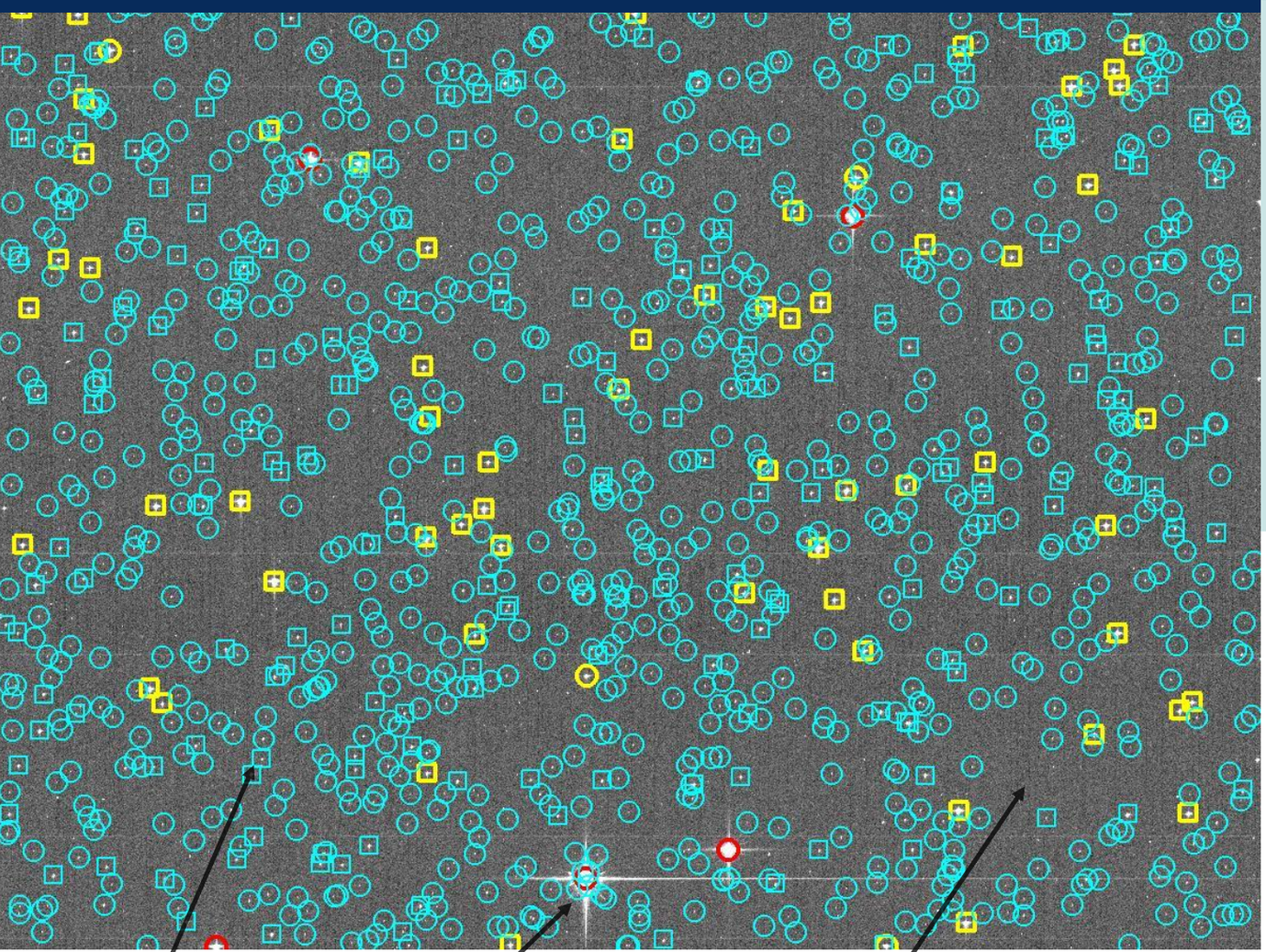
Operations



- Send to L2
- Science since mid-2014
  now 56months
- Everything works fine
  - stray light - did impact RVS
  - contamination – OK, managed
  - radiation damage – factor 6 below expectations
  - micro-meteorites & micro-clanks

Focal plane - Payloads

Automatic source detection



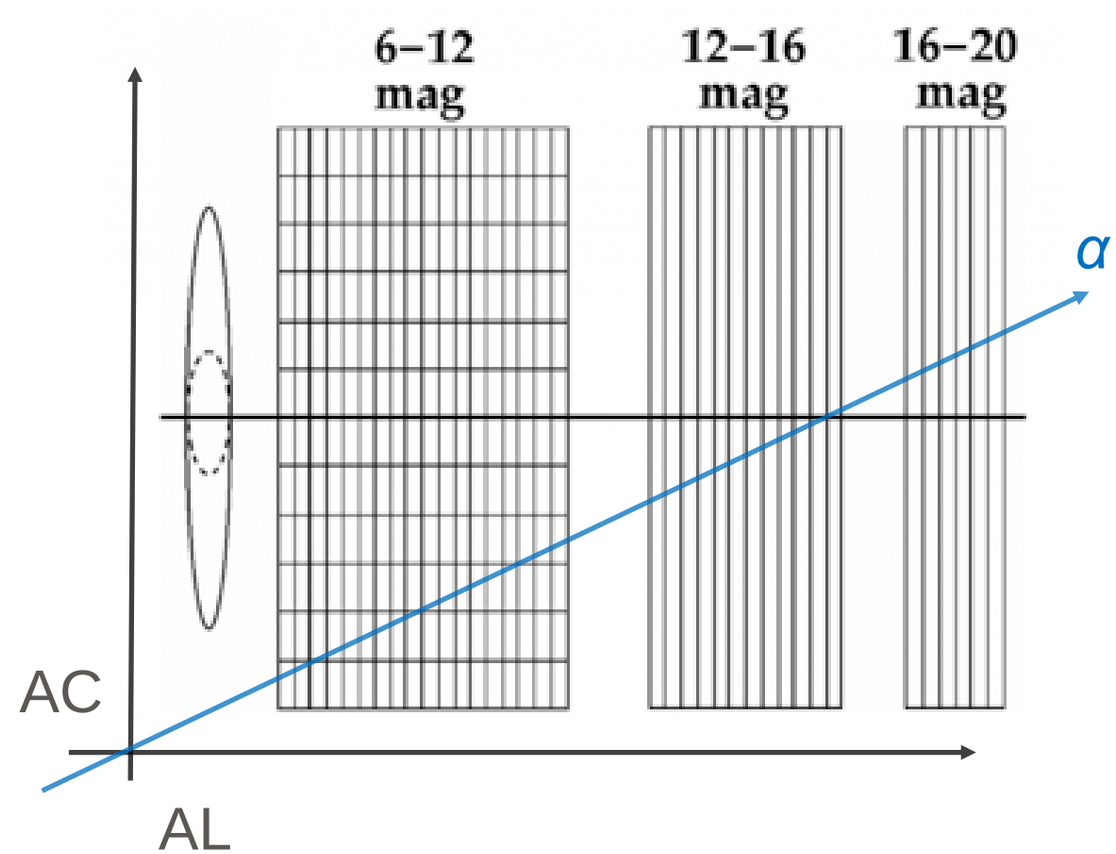
deal with confusion

window sent to ground

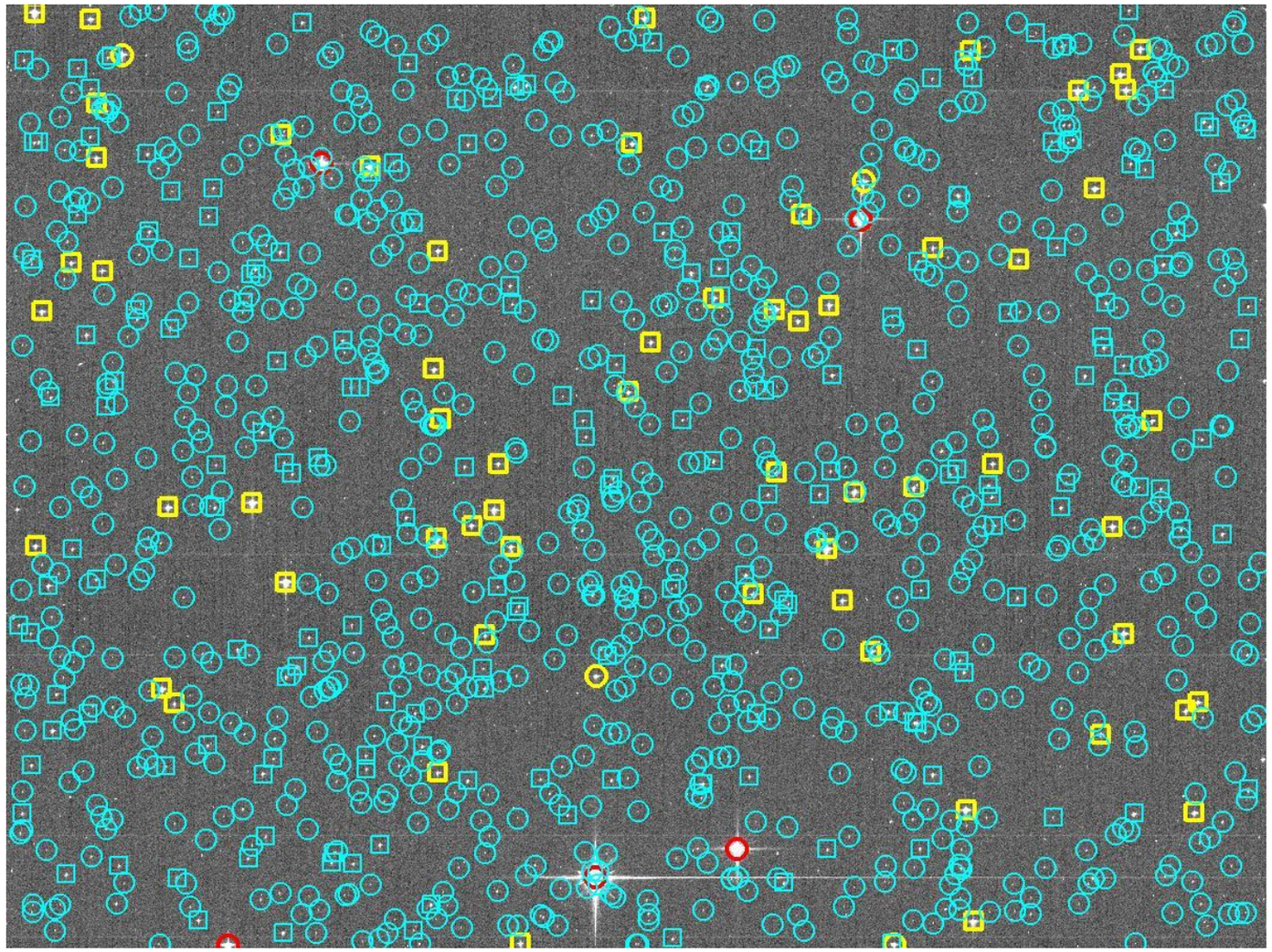
pixel not sent

Windows and patches

- *no data compression*
  not all Gpix. sent to ground
- *adapted to stars motion and TDI*
  not adapted to fast moving objects
- *pixels binning => 1D signal*
  highly correlated (α,δ)



Automatic detection

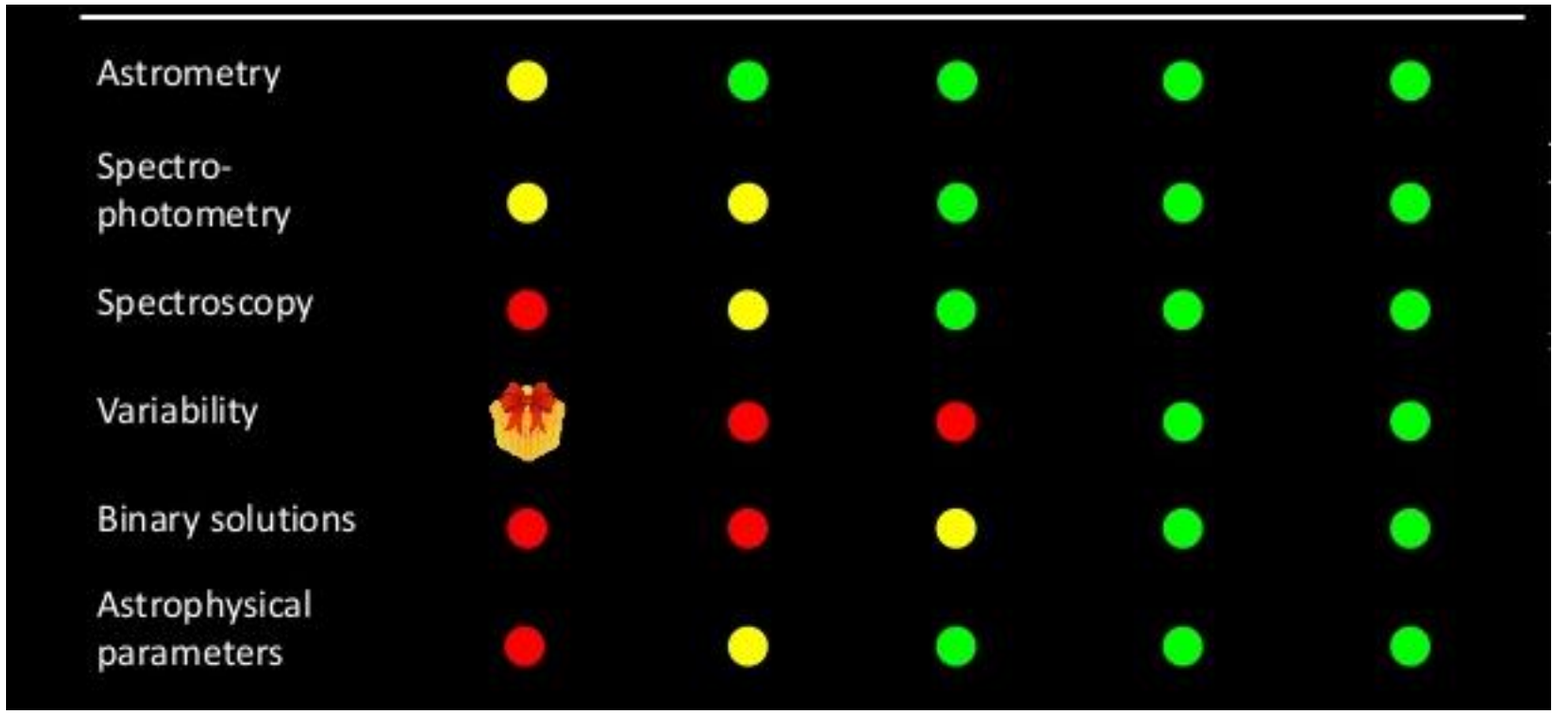


- Sky mapper detection
  based on PSF pick
  not SNR limited
- Patch around source
  transmitted to ground
  based on scanning
- No large source (≈0.9”)
- No blurred source
- TDI mode not adapted for fast moving objects

Summary - Future

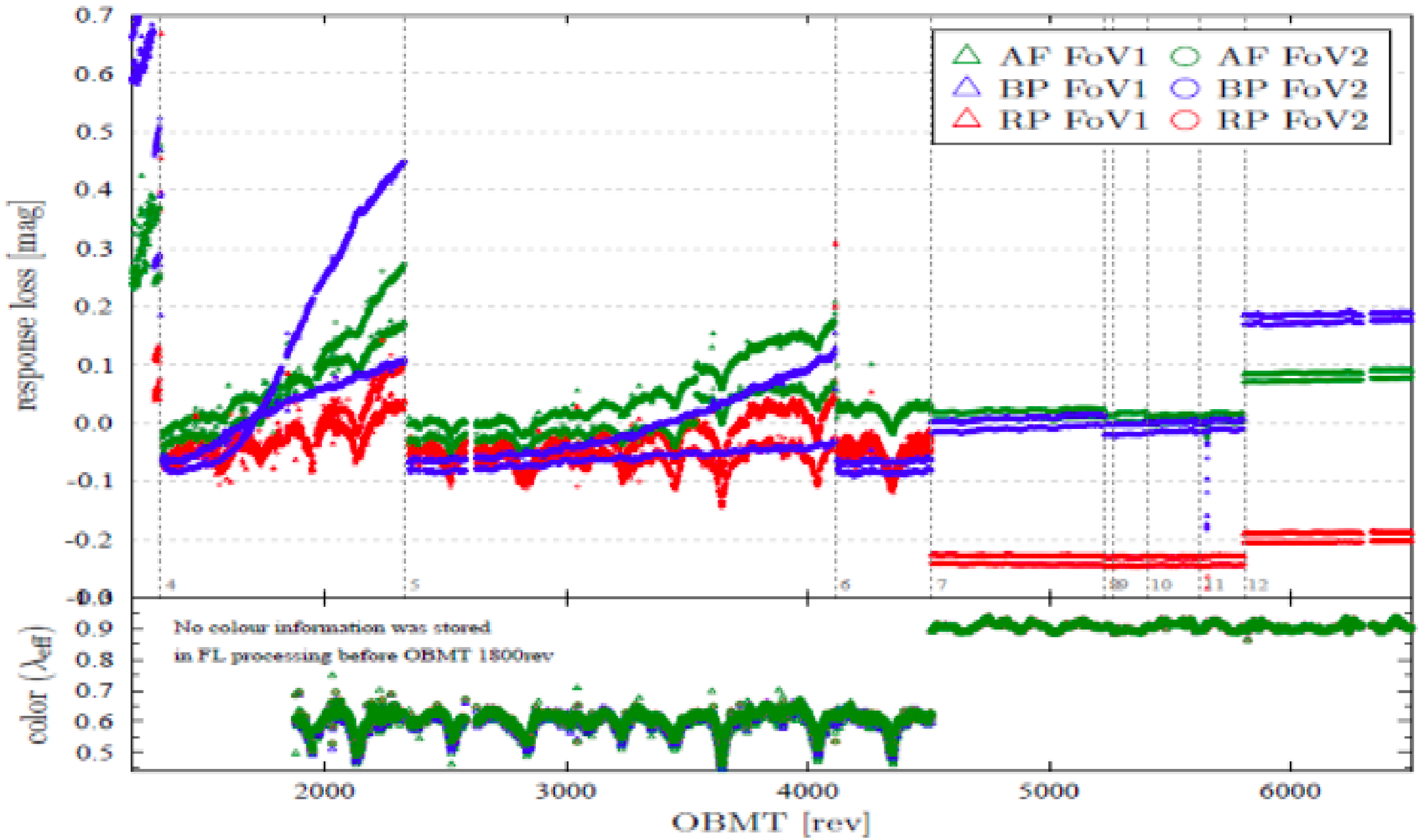
- Much more about DR2 https://www.cosmos.esa.int/web/gaia/data-release-2
- Gaia archive http://gea.esac.esa.int/archive/
- Recent IAU Div.A days session https://www.iau.org/science/scientific_bodies/divisions/A
- Conf. ESLAB#53 The Gaia Universe 8-12 April 2019
  https://www.cosmos.esa.int/web/the-gaia-universe/home

- Future GDRs
  - Incremental, improvement
  - More data! and solutions
  - Astrophys. parameters
  - Exoplanets
  - Asteroids, satellites, comets
  - All epoch and transit data

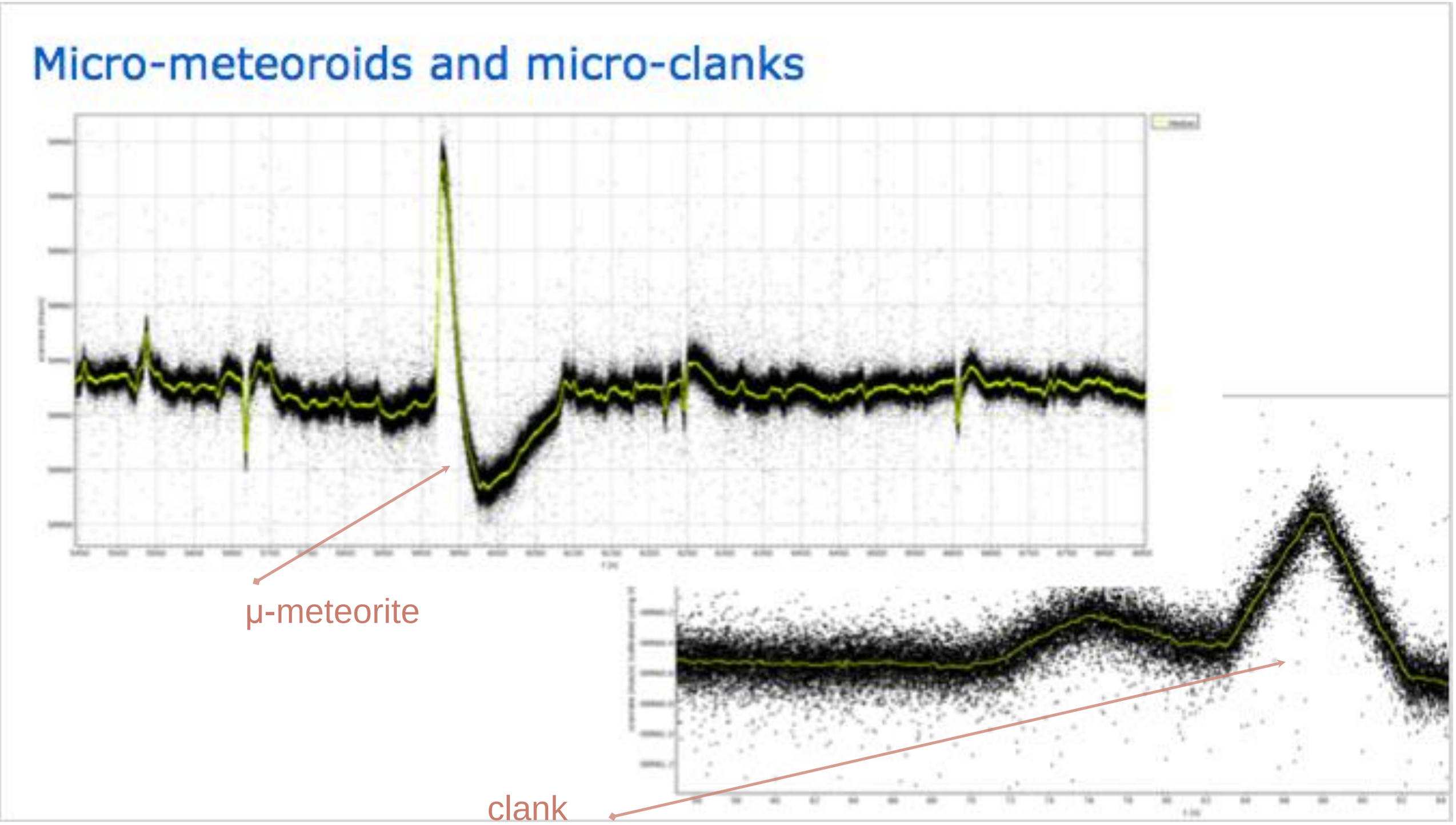


- Ground-based spectroscopic surveys, LSST
  - deeper Northern survey - Continuation to faint end
  - high accuracy epoch astrometry + photometry
  - 37 billion stars+galaxies, 10 years , 15Pb
- Space astrometry in IR

Contamination

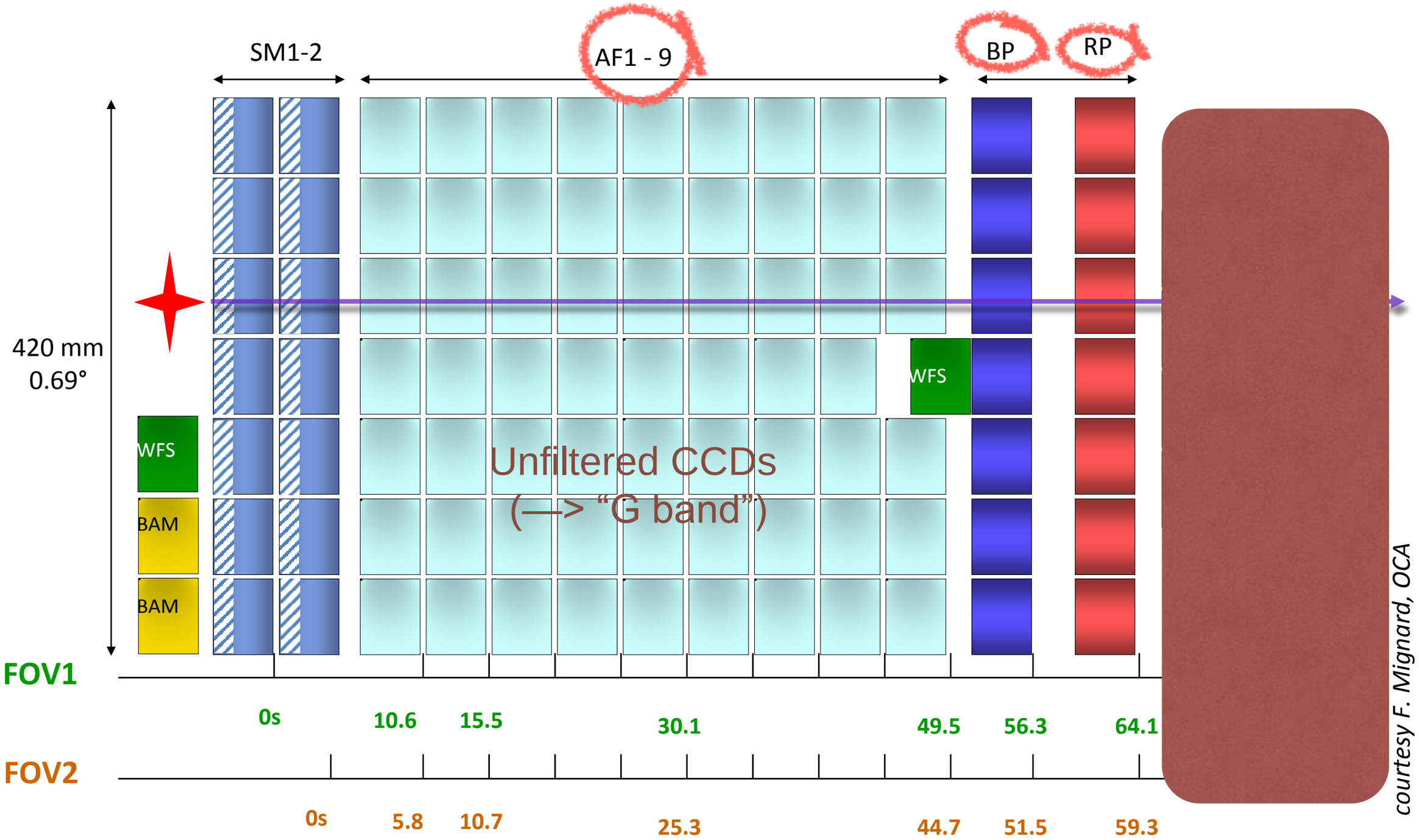


Fine tuning of scan



Probably common on s/c, but Gaia is the first one to be able to measure it!

An observation = a transit
= 10 positions + spectro-photometry



courtesy F. Mignard, OCA

First Yarkovsky measurement by Gaia: (2062) Aten

- ground-based observations from 1955 to 2017
- good pre-Gaia orbital fit with Yarkovsky measurement

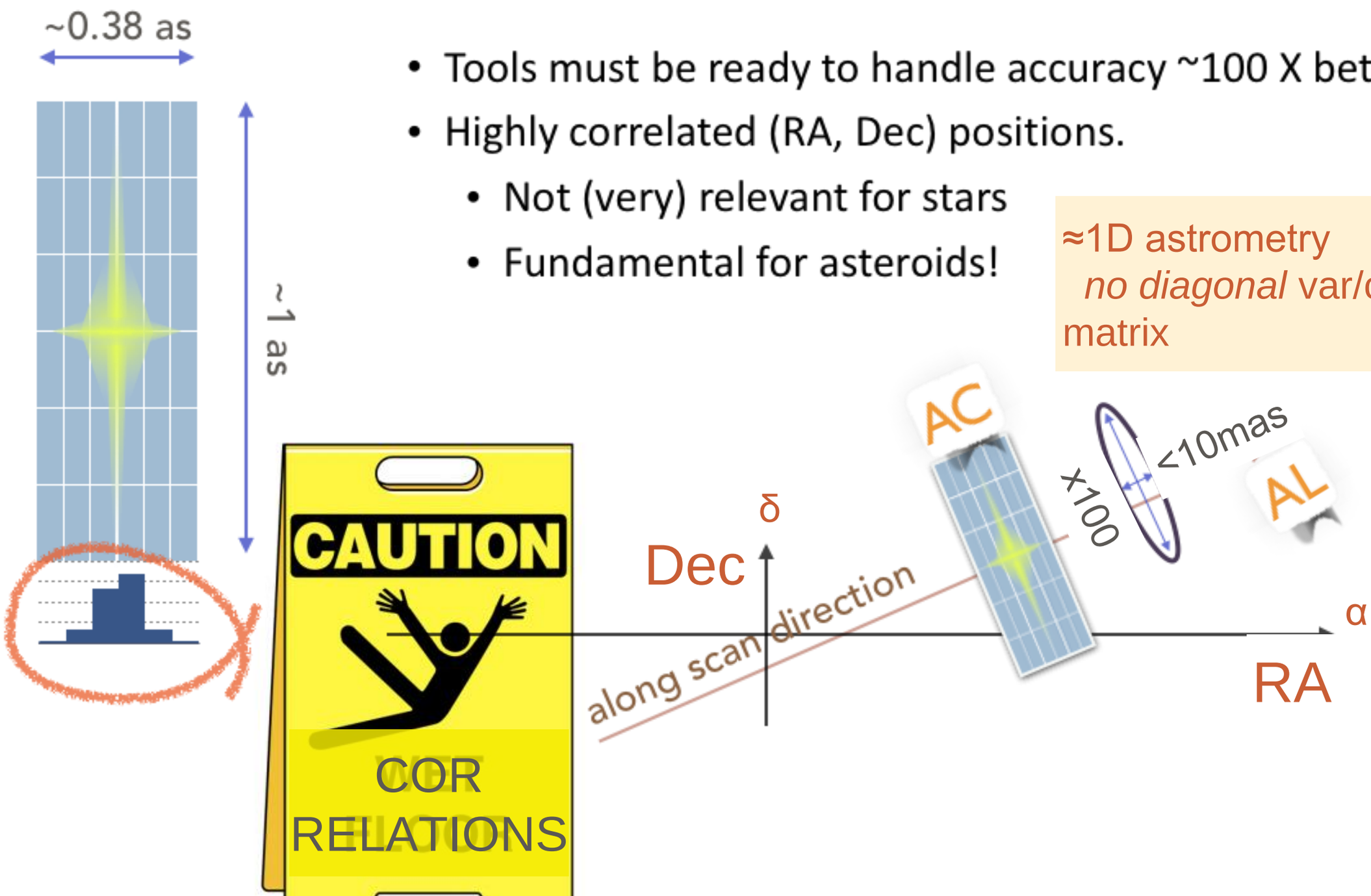
	SNR_{A2}	da/dt $10^{-4} au/Myr$
69 Gaia + 959 optical + 7 radar	14.63	-4.90 ± 0.34
959 optical + 7 radar	8.64	-5.98 ± 0.68

Spoto et al. 2018

- The combination of Gaia + other data significantly changes the value and improves SNR
- A coherent debasing is fundamental: only the *DR2 scheme* correctly combines Gaia + other observations (—> no rejection of DR2 astrometry)
- Note: $\sigma_a = 1 \times 10^{-10}$ au !!!

Gaia DR2 – SSO

CAUTION



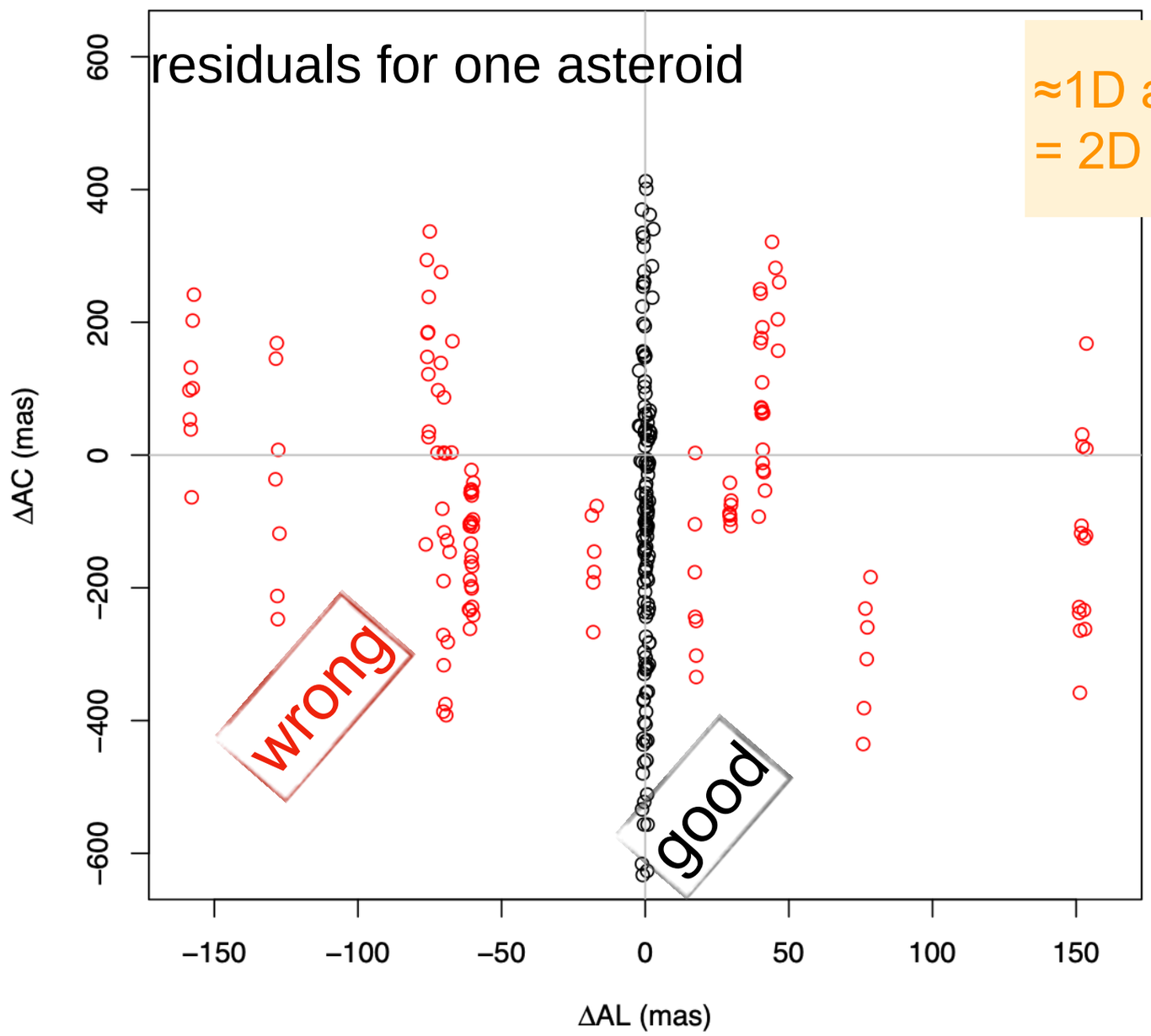
- Tools must be ready to handle accuracy ~100 X better
- Highly correlated (RA, Dec) positions.
  - Not (very) relevant for stars
  - Fundamental for asteroids!

≈1D astrometry
no diagonal var/covar matrix

Gaia DR2 – SSO

CAUTION

o W = diagonal
o W = var/covar



≈1D astrometry in (AL, AC)
= 2D var/covar matrix (α, δ)

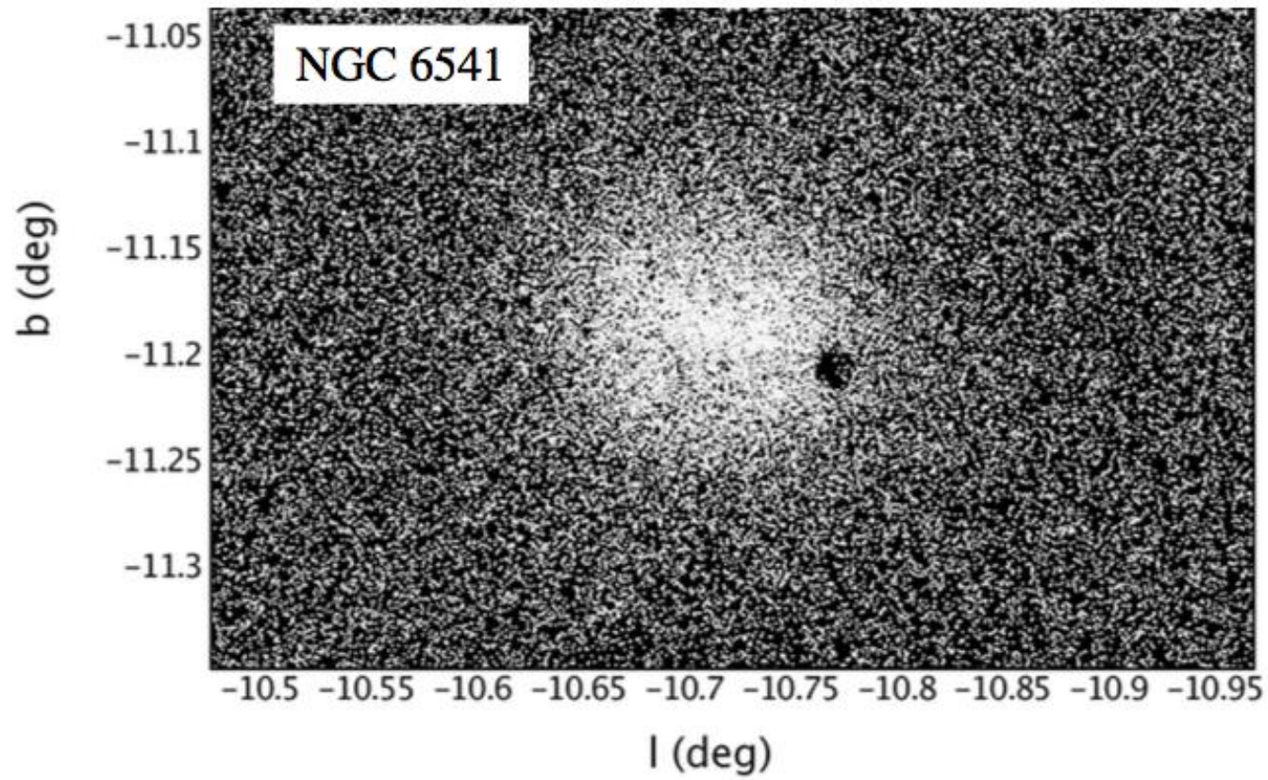
Conclusions

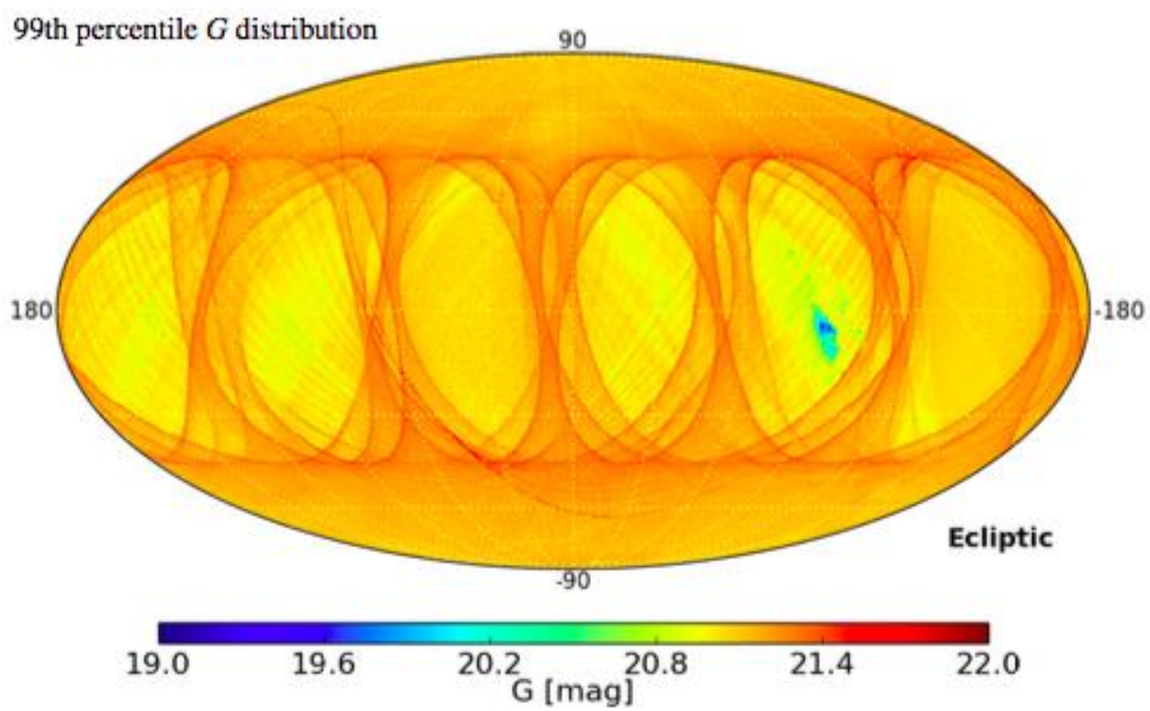
- Gaia DR2 asteroid data: the first sample, already useful to test subtle dynamical effects
  - Yarkovsky determination
  - general orbit improvement
  - application to stellar occultations
    - Combination with other observations: it starts to work…
      - but weighting of the data is critical
      - accurate debiasing is required
      - a new method successfully implemented and tested

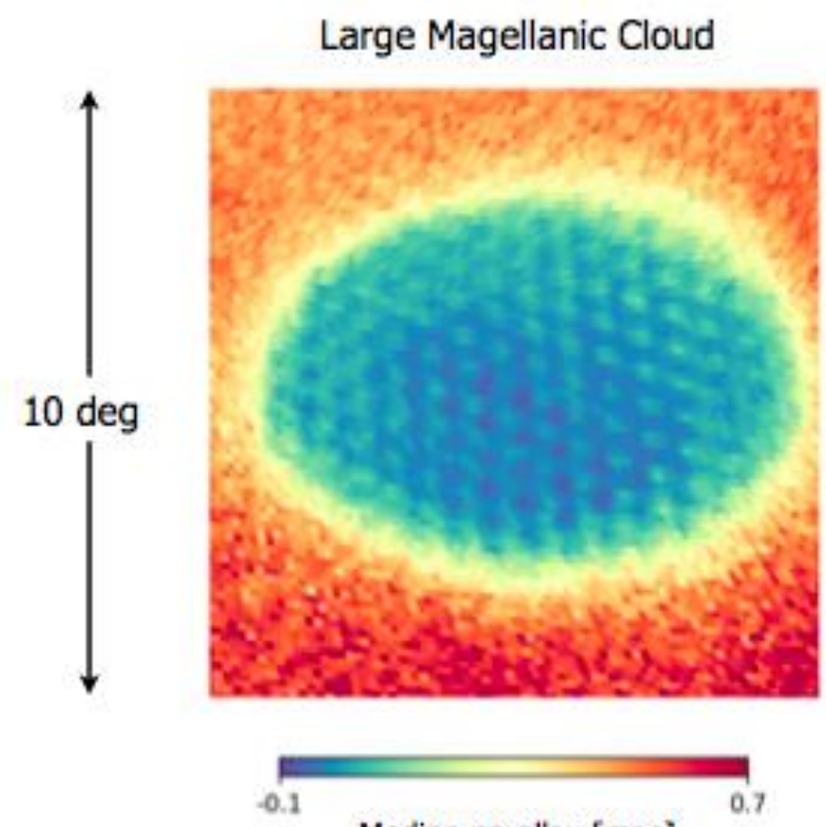
- Yarkovsky detection *in the Main Belt* is getting closer…
- Other dynamical effects to come!
- Then, not only astrometry, not only asteroids !…

DR2 - Shortcomings

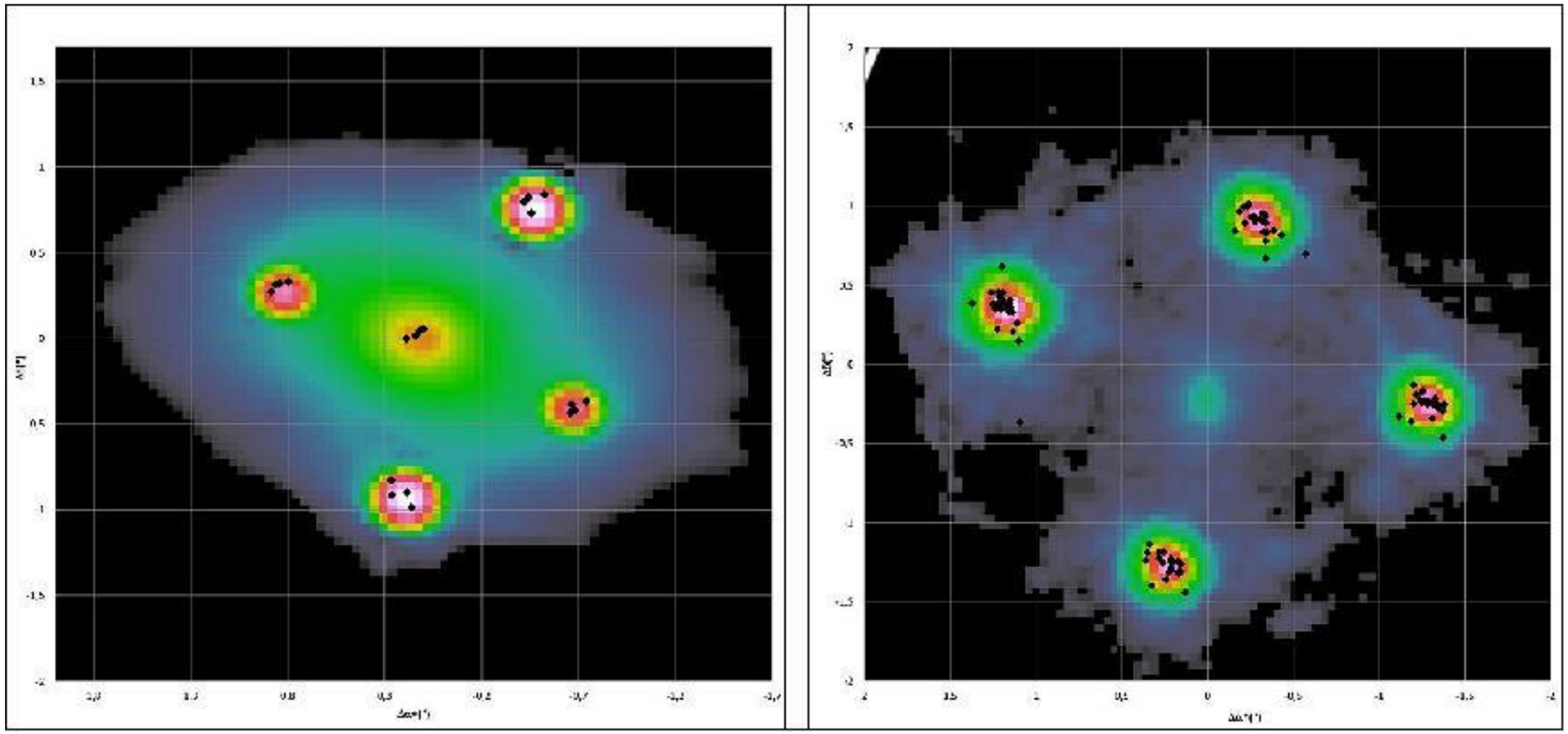
- Some caveats
  - bright stars calibration
  - crowded regions,
  - fast moving stars
  - scanning law systematics
  - Varying magnitude limit







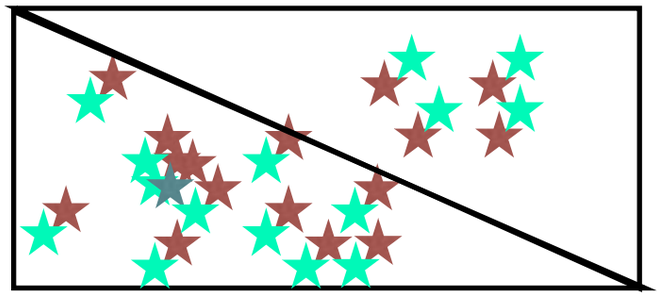
Gravitational lenses multi-imaged QSO



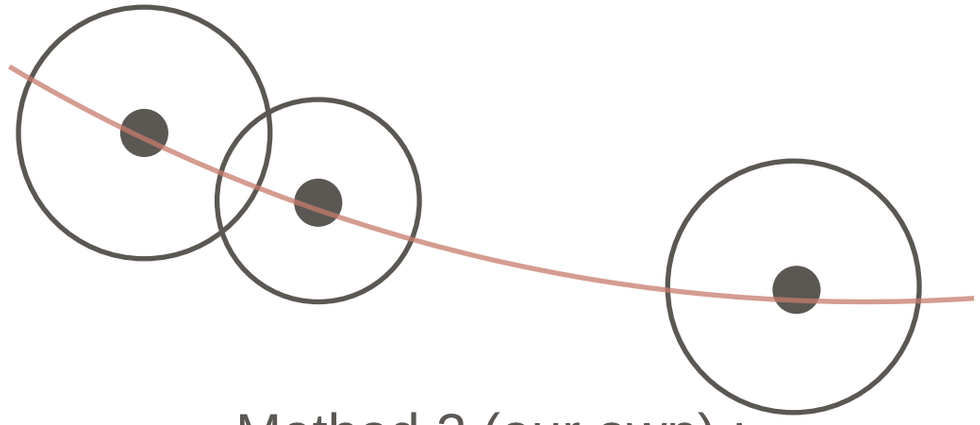
Einstein Cross (left) and HE0435-1223 (right) (@C. Ducourant)
with Gaia astrometric positions placed over HST images and galaxy visible at centre

Orbit improvement : DR2 + other observations

- 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
- **Debiasing required!**
  - exploit the catalog information provided by MPC with the asteroid data
  - compute local biases per catalog (positions and pm) and correct observations



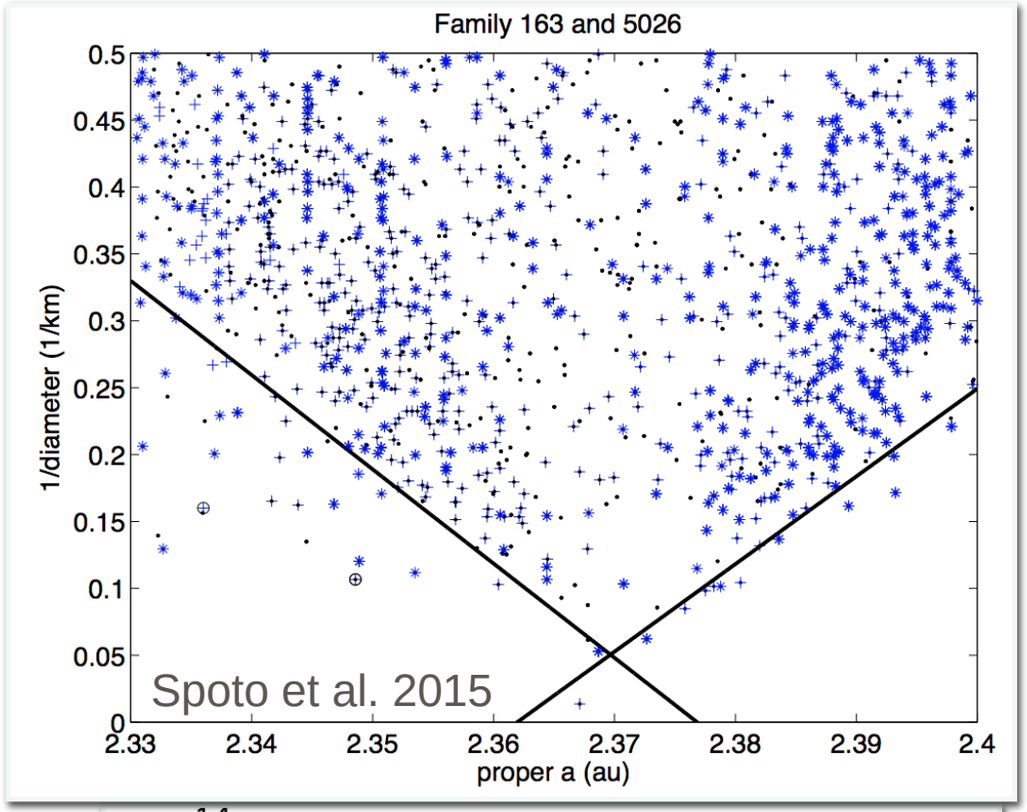
Method 1 : Farnocchia et al. (2015)
all catalogs referred to PPMXL
corrections computed on a grid
(F2015 scheme)



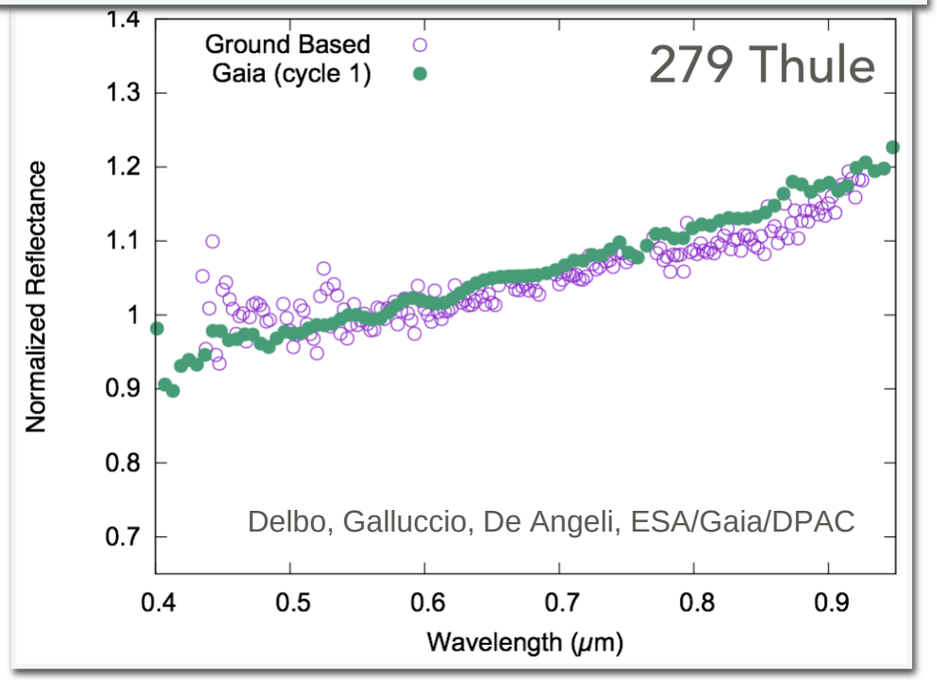
Method 2 (our own) :
areas centered on archive asteroid observations
Reference: Gaia DR2
(DR2 scheme)

Yarkovsky effect: why we care

- Yarkovsky applications:
  - NEO and meteorite transport
  - physical properties (spin, density…)
  - family dispersion, ages



- connection to spectro- photometry by Gaia:
  - low-res spectra: taxonomy in the visible
  - *mmag* photometry: shape determinations
- Large sample by end of mission: ≈ 350k



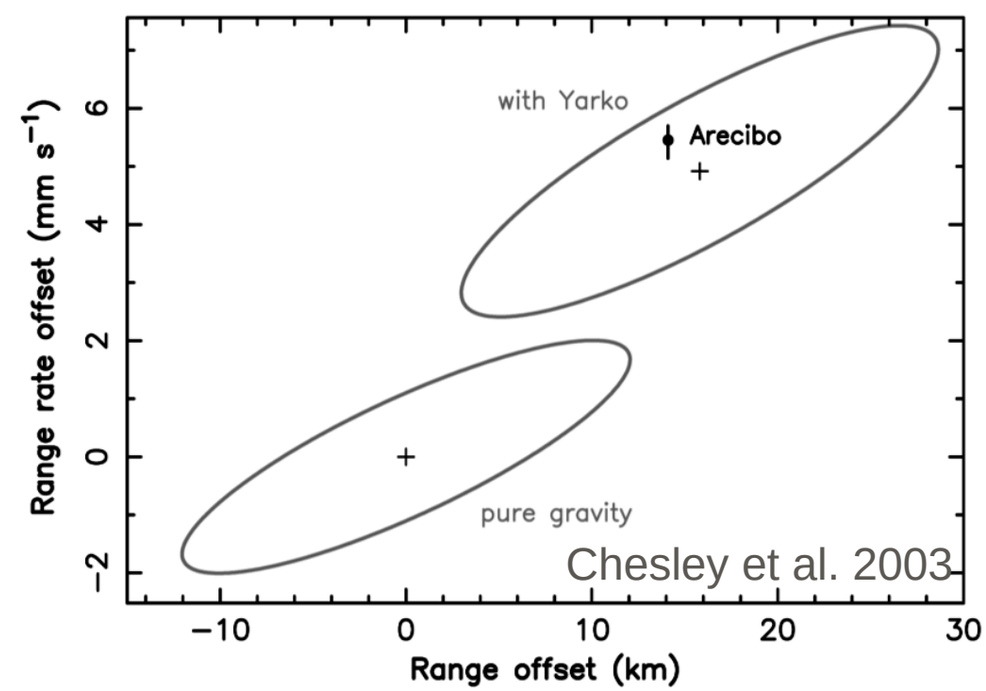
The problem of measuring Yarkovsky

- Weak semi-major axis drift ~10^{-4} au/Myr (at 1 au)
  – decreasing with size (1/D) and distance ($1/r_2$)
- It requires:
  – accurate observations
  – …spanning a « large » interval of time
  – accurate weighting

- Results:
  – **36 NEOs** with *valid* detections (SNR>3)
  – **4 with SNR > 10** (Vokrouhlický et al. 2015)
  – ….radar observations essential !!

- for a small fraction of asteroids, only, $\sigma_a < 10^{-9}$ au

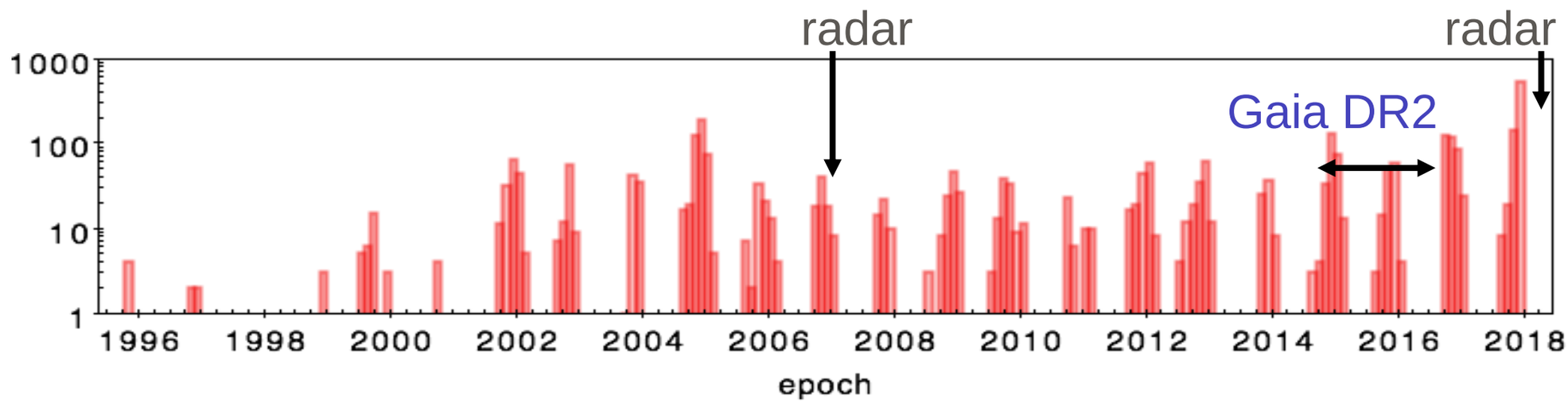
6489 Golevka



Chesley et al. 2003

Another important case: (3200) Phaethon

- B-type, associated to the Geminid meteor stream
- Close encounter in Dec. 2017 (radar + many optical data)



- Without Gaia : SNR ~ 3.4 (JPL)
- By using Gaia DR2 observations:

$$da/dt = -9.22 \pm 1.27 \ (10^{-4} \text{ au/Myr}) \quad \text{- SNR} \sim 16$$

- A large amount of low-quality observations in 2017 « pollutes » the result