Differential Astrometry with Gaia

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Seminar @ LineA
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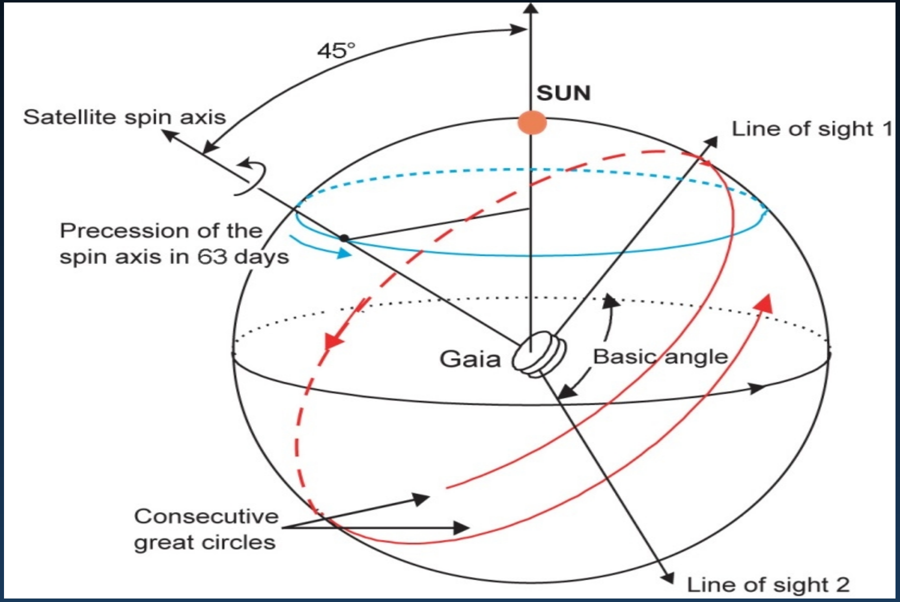
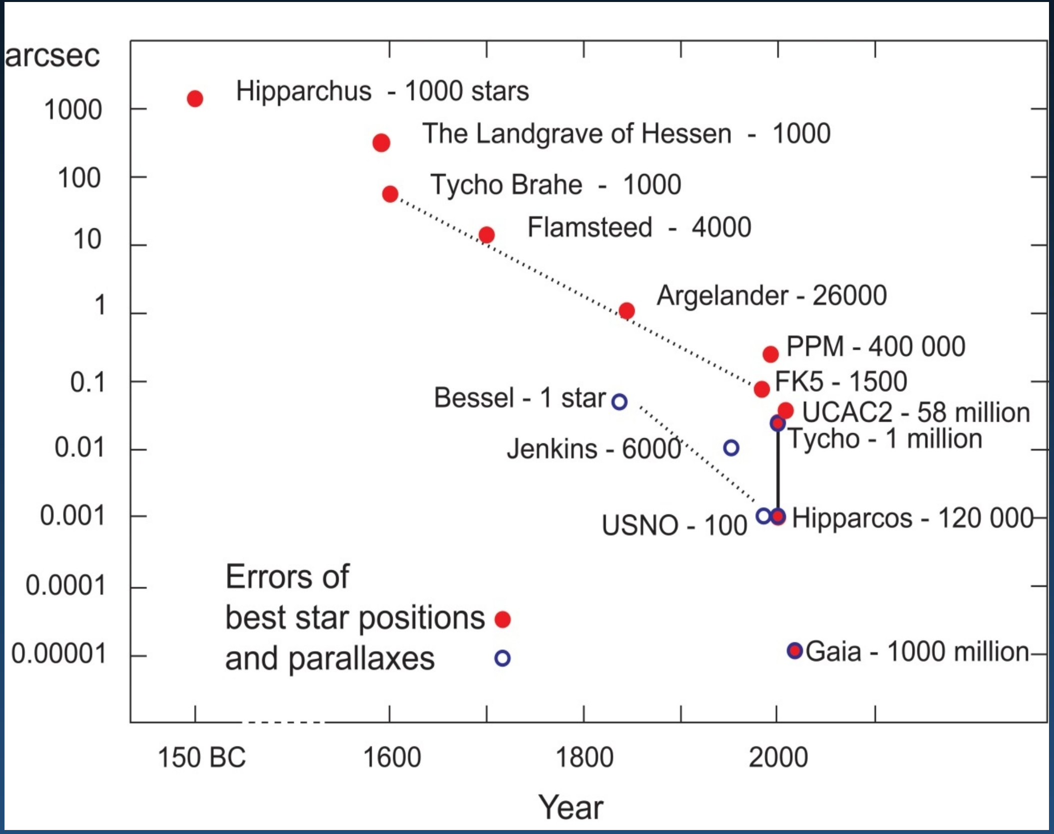
Outline

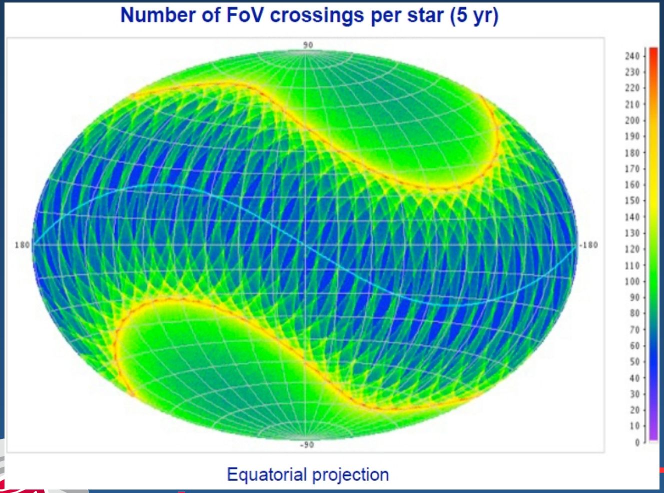
- *The Gaia Space Mission*
- *Principles of differential astrometry*
- *Challenges*
- *Systematic Effects*
- *Obtaining a muas stable reference frame*
- *GAREQ experiment*

Gaia
A Space Astrometry Revolution!



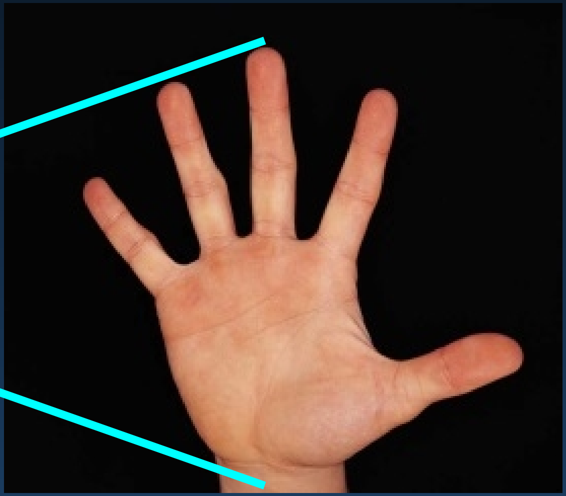
At Gaia's G=20.7 survey limit: >1.5x10^9 stars





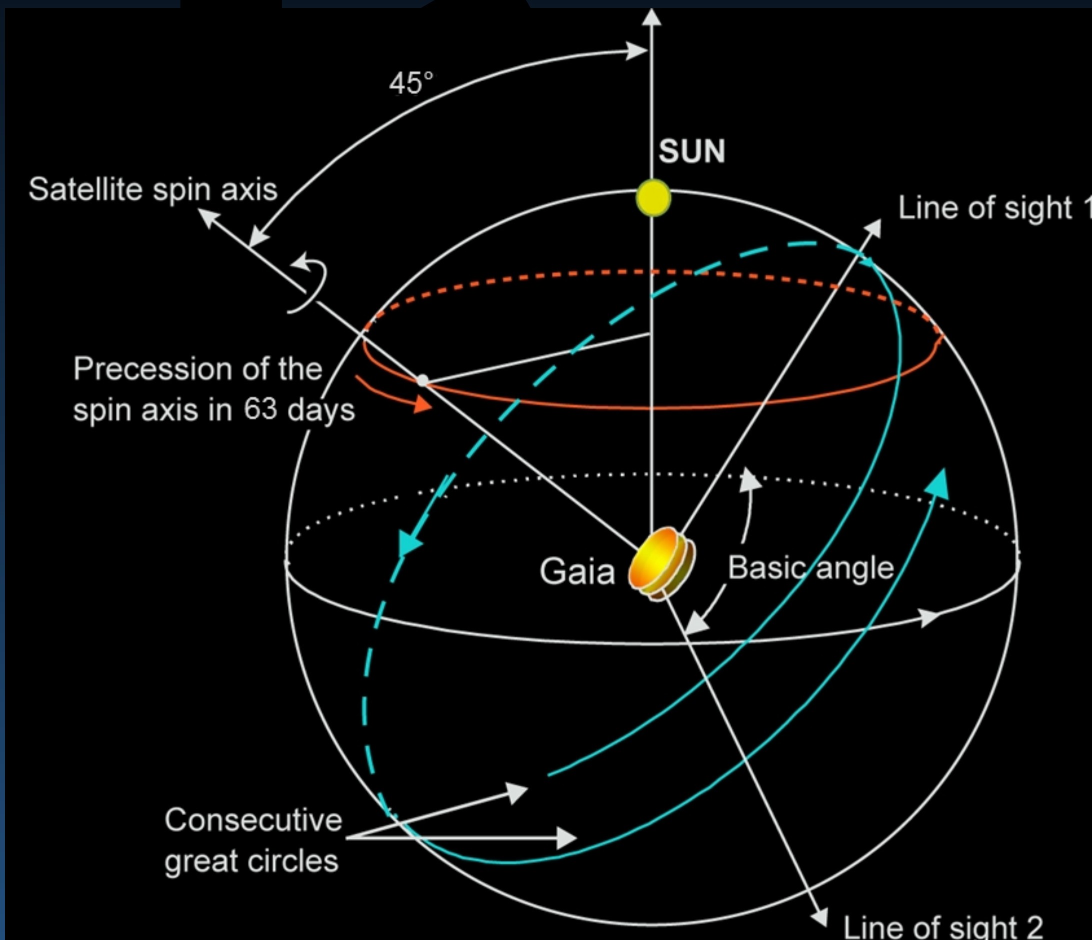
*** 2834 days in science operations**
*** 200 billion transits observed**

10 muas Astrometry



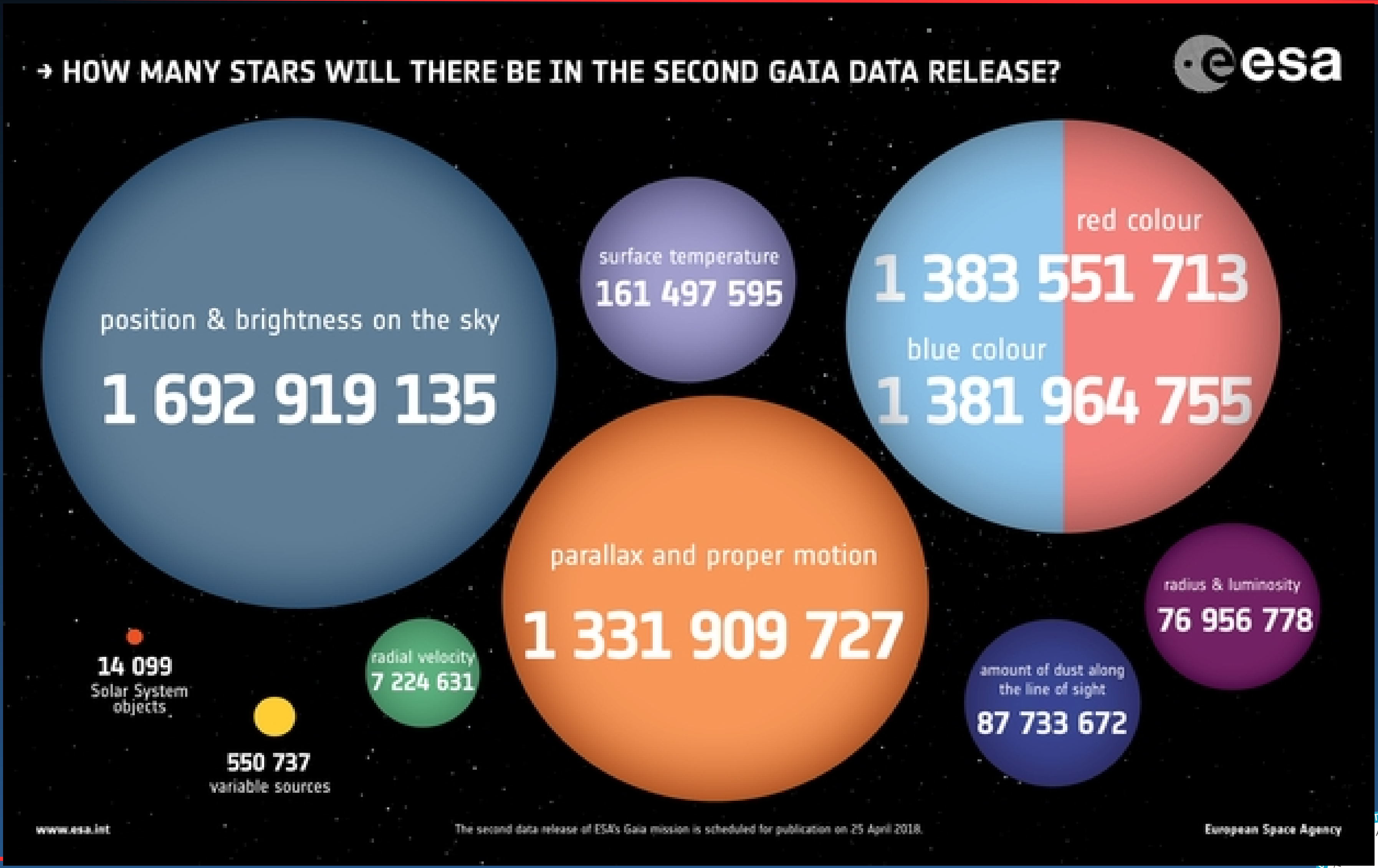
Gaia’s precision (enough to measure the size of your hand from the moon!)

Sky Scanning Principle

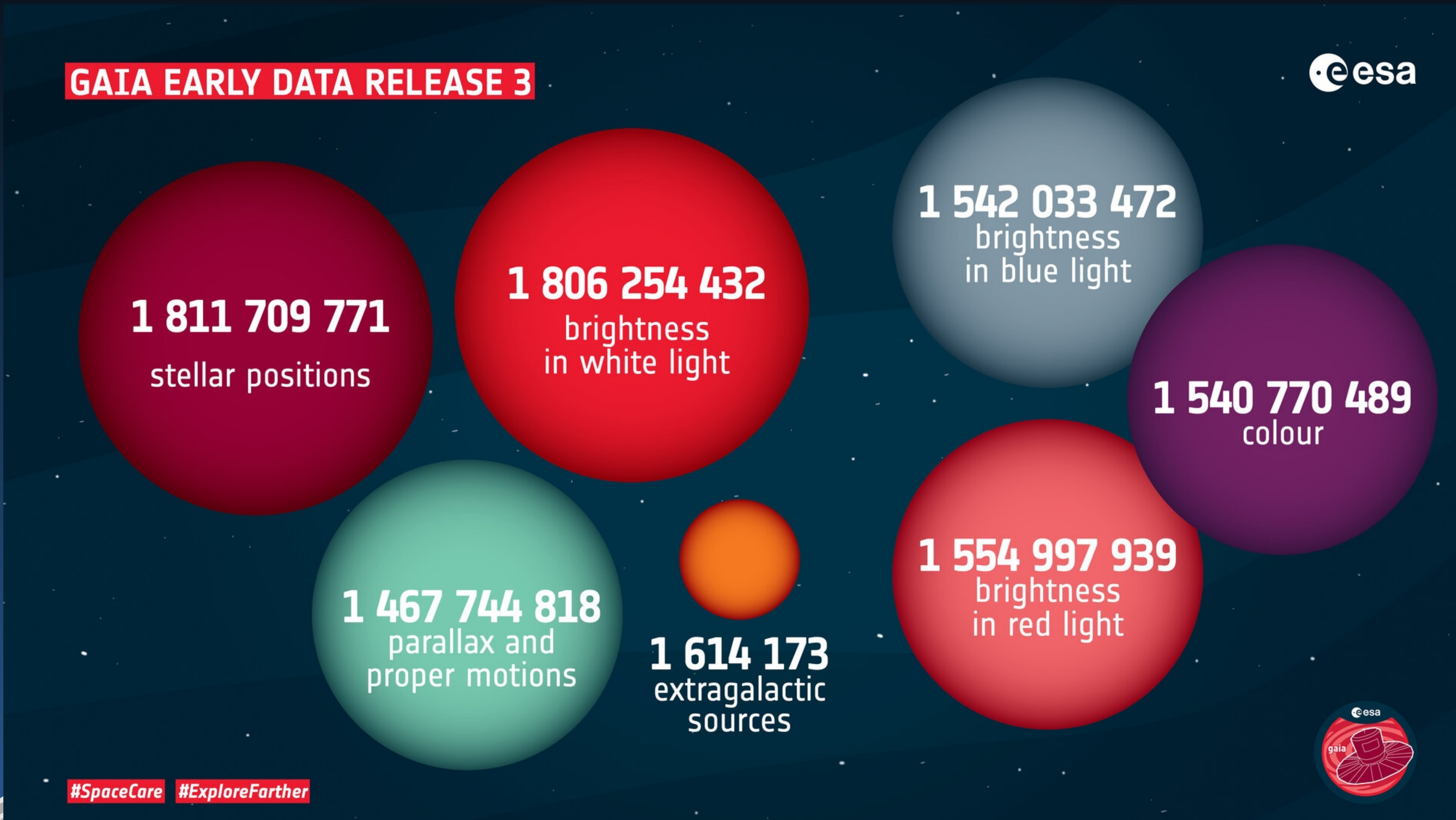


Spin axis	45° to Sun
Scan rate:	60 arcsec s^{-1}
Spin period:	6 hours

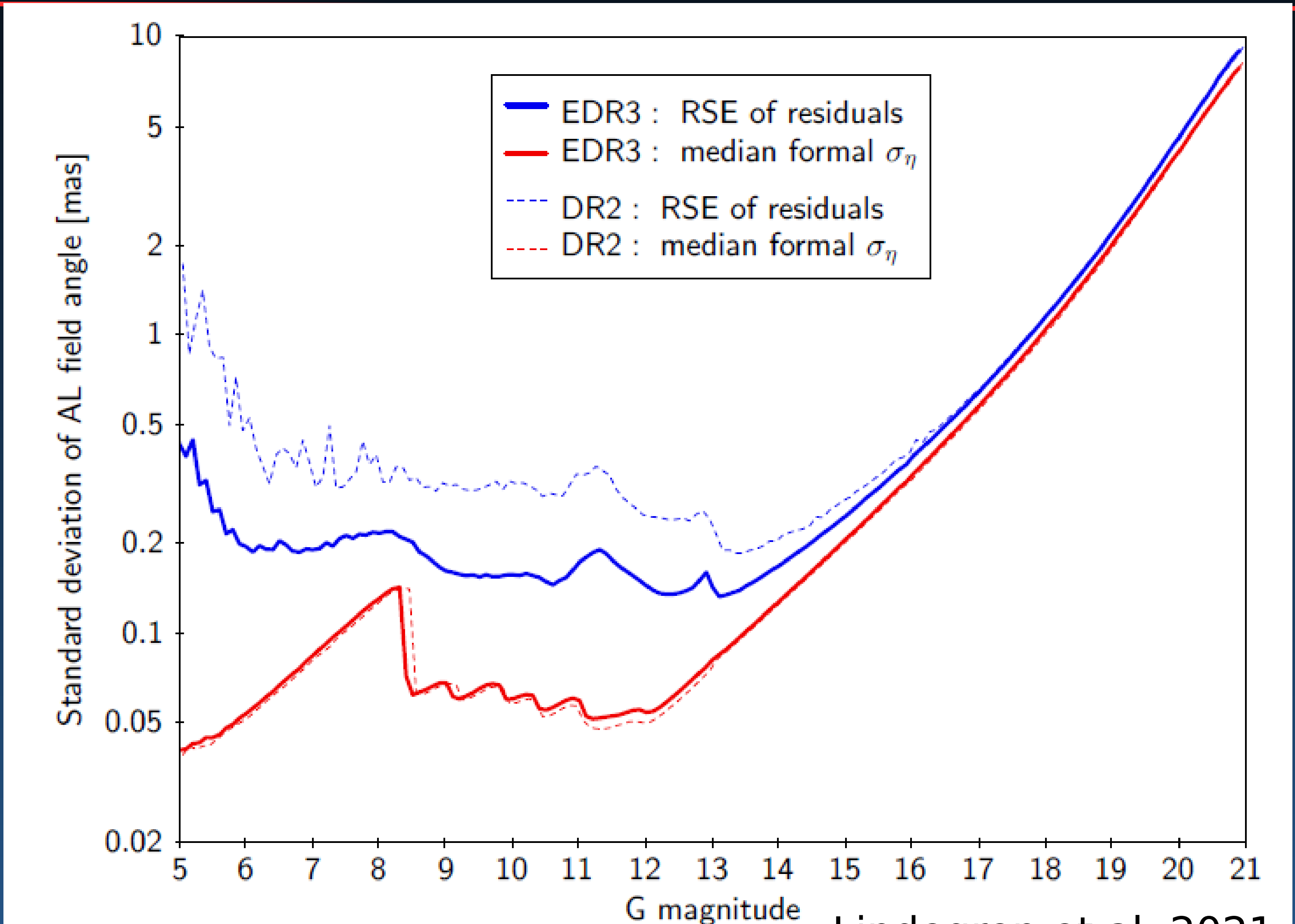
Gaia DR2: 25 April 2018



Gaia EDR3: 3 December 2020



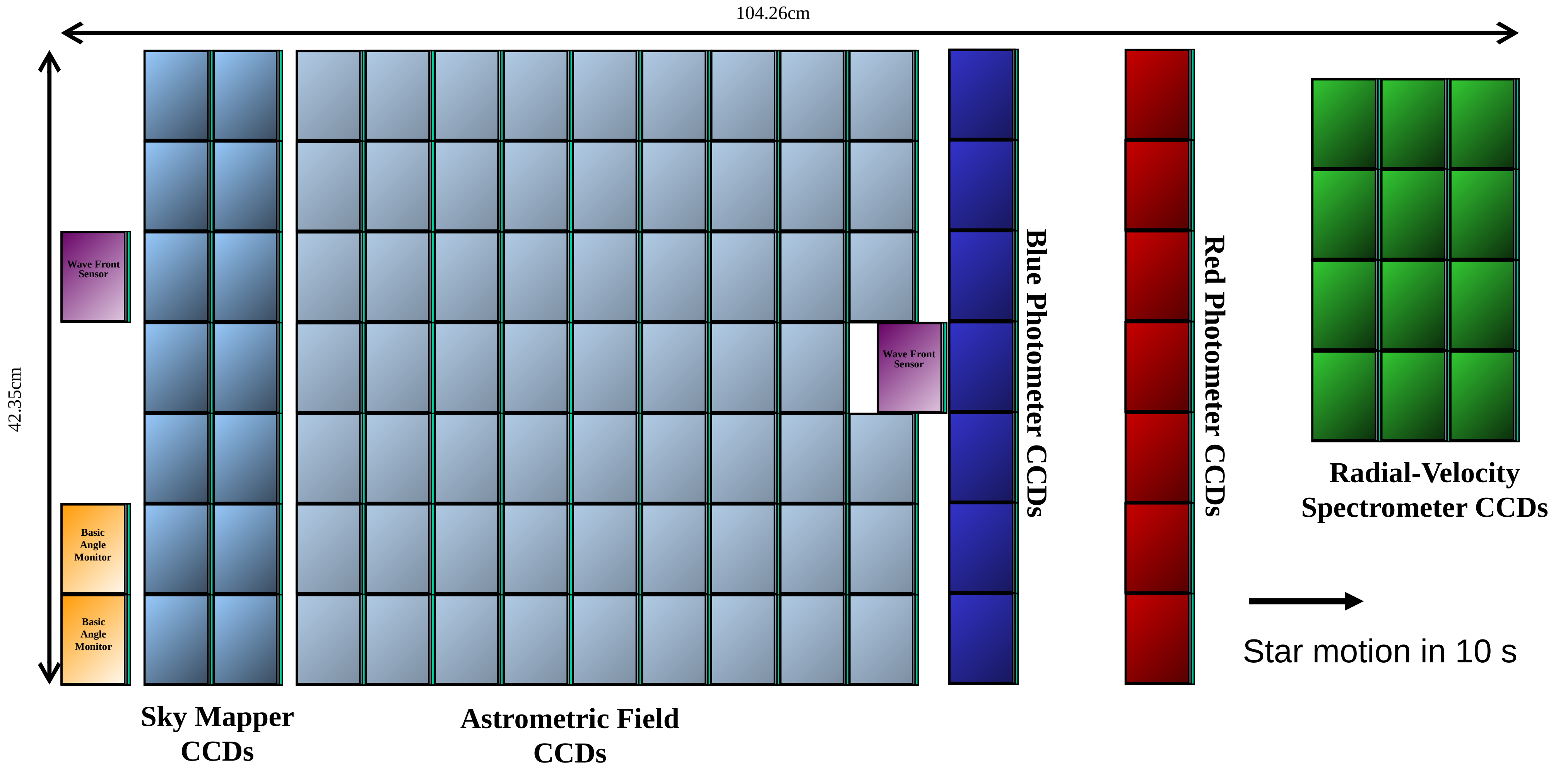
Gaia EDR3 - Astrometry



Lindegren et al. 2021

Figure courtesy Alex Short

Focal Plane



Total field:
- active area: 0.75 deg^2
- CCDs: 14 + 62 + 14 + 12 (+ 4)
- 4500 x 1966 pixels (TDI)
- pixel size = 10 µm x 30 µm
  = 59 mas x 177 mas

Sky mapper:
- detects all objects to G=20 mag
- rejects cosmic-ray events
- field-of-view discrimination

Astrometry:
- total detection noise ~ 4 e$^-$

Photometry:
- spectro-photometer
- blue and red CCDs

Spectroscopy:
- high-resolution spectra
- red CCDs

Star to Image to Astrometry

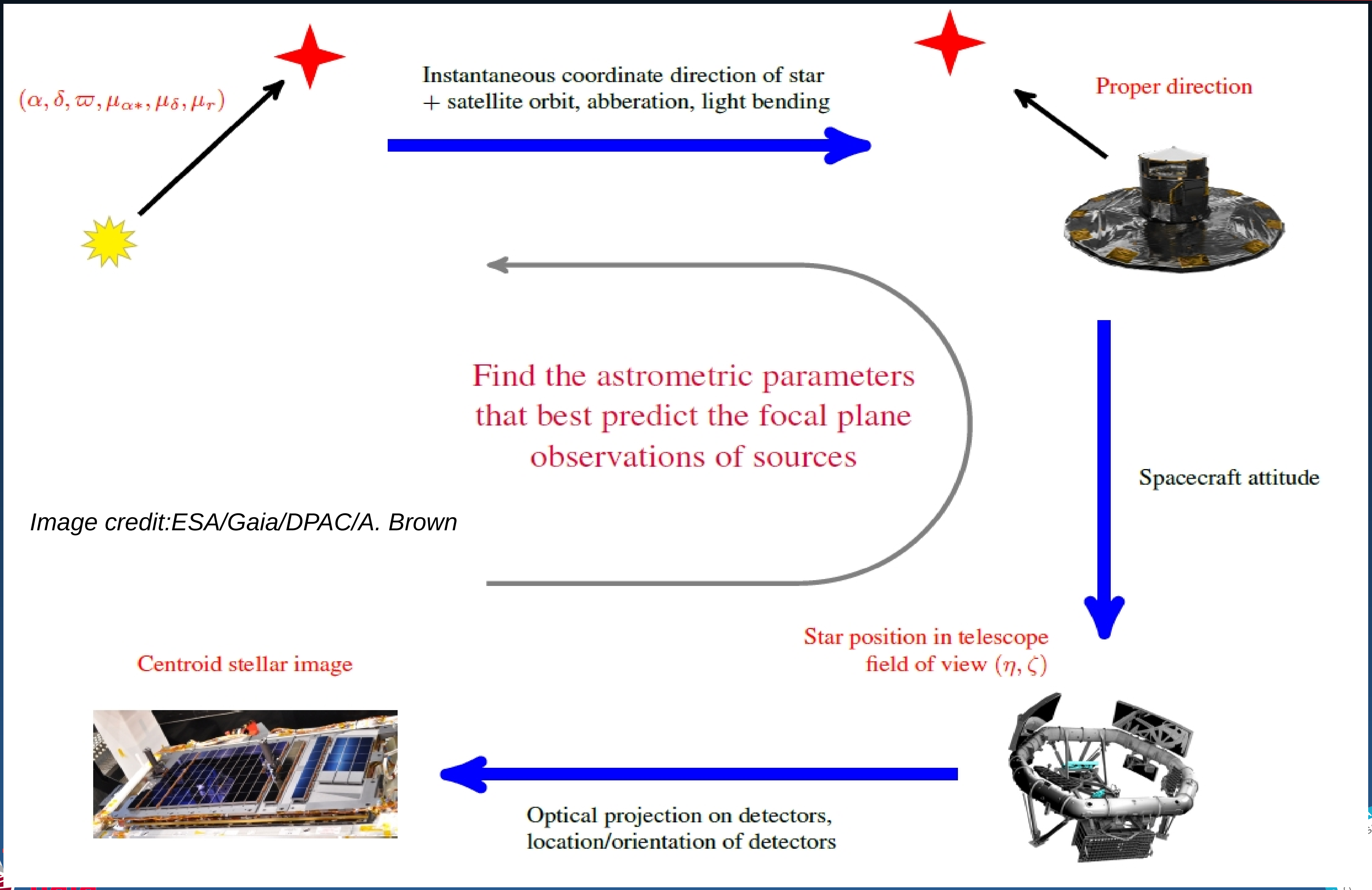


Image credit:ESA/Gaia/DPAC/A. Brown

Challenges to Differential Astrometry

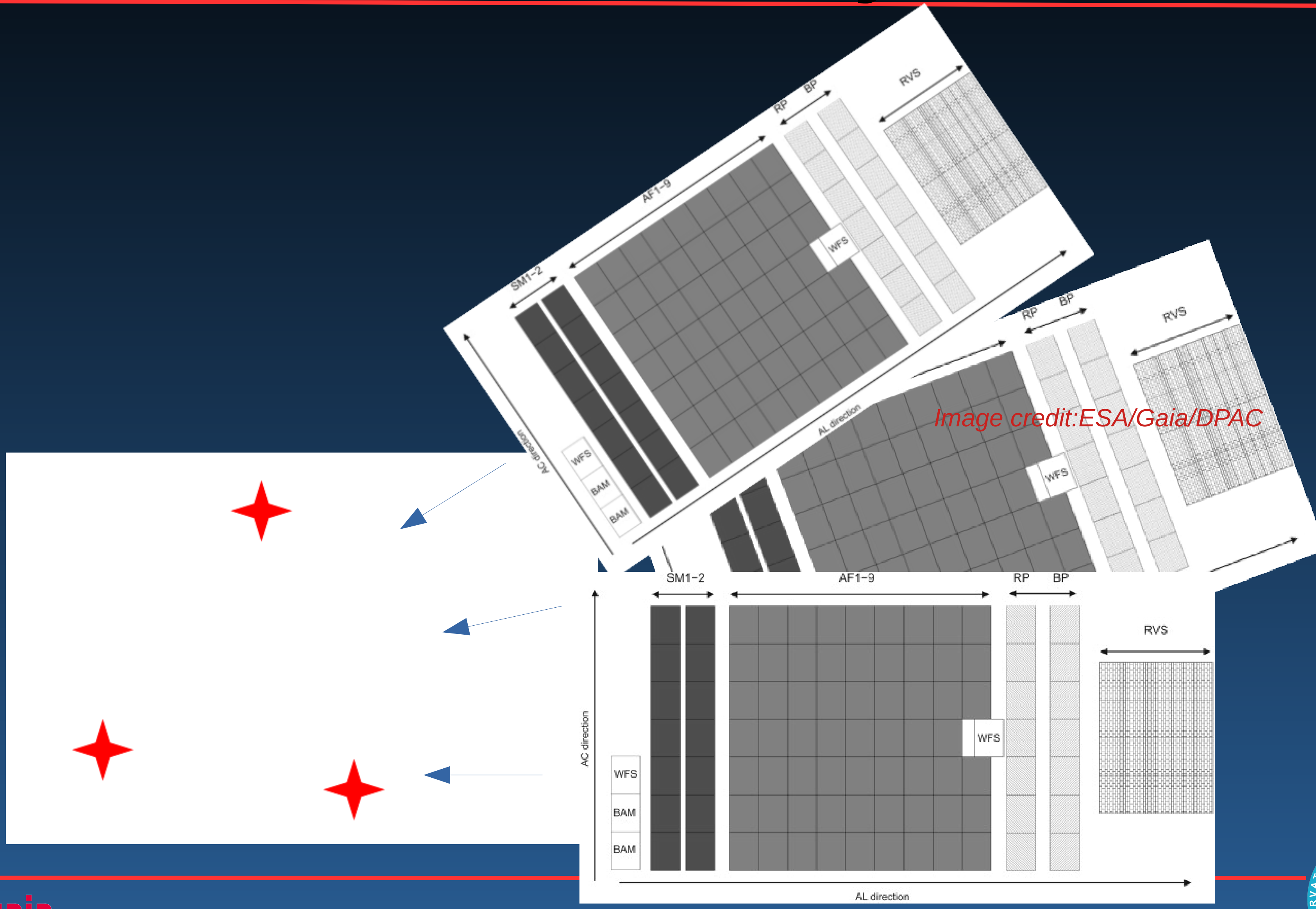


Image credit:ESA/Gaia/DPAC

Systematic Effects

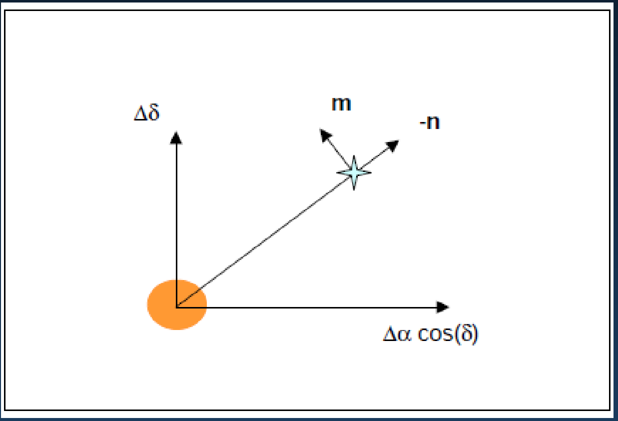
Physical Effects 1

- ***Gravitational deflection of light** due to Solar System Objects, e.g. due to Jupiter (Crosta & Mignard 2006):*

$$\Delta\mathbf{\Phi} = \Delta\Phi_1\mathbf{n} + \Delta\Phi_2\mathbf{m},$$

$$\Delta\Phi_1 = \frac{2(1+\gamma)M}{b}\left[1 + J_2\frac{R^2}{b^2}\left(1 - 2(\mathbf{n}\cdot\mathbf{z})^2 - (\mathbf{t}\cdot\mathbf{z})^2\right)\right]$$

$$\Delta\Phi_2 = \frac{4(1+\gamma)MJ_2R^2}{b^3}(\mathbf{m}\cdot\mathbf{z})(\mathbf{n}\cdot\mathbf{z}).$$



- ***Aberration** due to motion of Observer wrt barycenter of the Solar System (Klioner & Kopeikin 1992):*

$$\delta\theta_{ab} = \frac{v}{c}\sin\theta\left[1 + \frac{1}{c^2}(1+\gamma)w(x_0) + \frac{1}{4}\frac{v^2}{c^2}\right] - \frac{1}{4}\frac{v^2}{c^2}\sin 2\theta + \frac{1}{12}\frac{v^3}{c^3}\sin 3\theta + O(c^{-4})$$

Physical Effects 2

- ***Effect due to the AL-AC motion of a star*** *(Lindegren 2004)***:**

$$\eta(t_t) = \eta(t_s) + \frac{d\eta}{dt} * (t_t - t_s)$$
$$\zeta(t_t) = \zeta(t_s) + \frac{d\zeta}{dt} * (t_t - t_s)$$

$$\frac{d\eta}{dt} = -\omega_z + [\omega_x \cos\varphi + \omega_y \sin\varphi] \tan\zeta$$
$$\frac{d\zeta}{dt} = -\omega_x \sin\varphi + \omega_y \cos\varphi$$

- ***Star's Proper Motion*** *leads to differential effects of several tens of micro-arcsec (Abbas et al. 2017).*

Instrumental Effects

- *Time-dependent instrument model describing the layout of the CCDs (Lindegren et al. 2012, 2016):*
- *physical geometry of each individual CCD and its configuration in the Focal plane assembly*
- *the distortions and aberrations in the optical system*
- *nominal values of the focal length and basic angle*

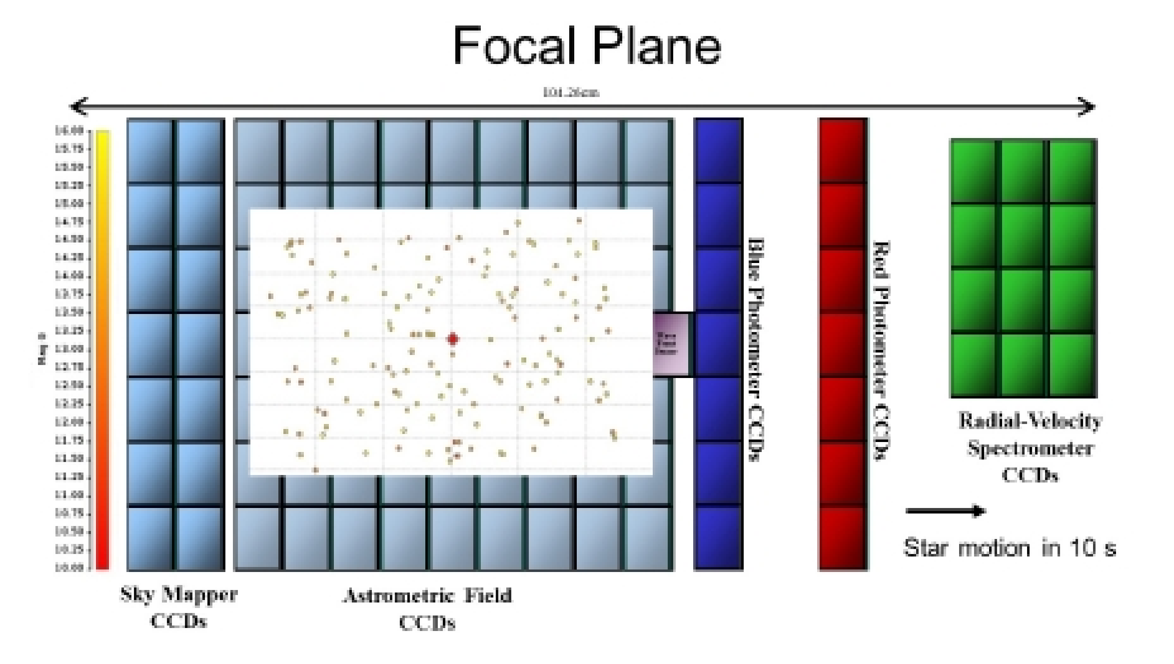
$$\eta_{fn}(\mu, t) = \eta_n^0 + \sum_{r=0}^{2} \Delta\eta_{rfn} L_r^*(\frac{\mu - 13.5}{1966})$$

Stability of the Reference Frame

Importance of stability

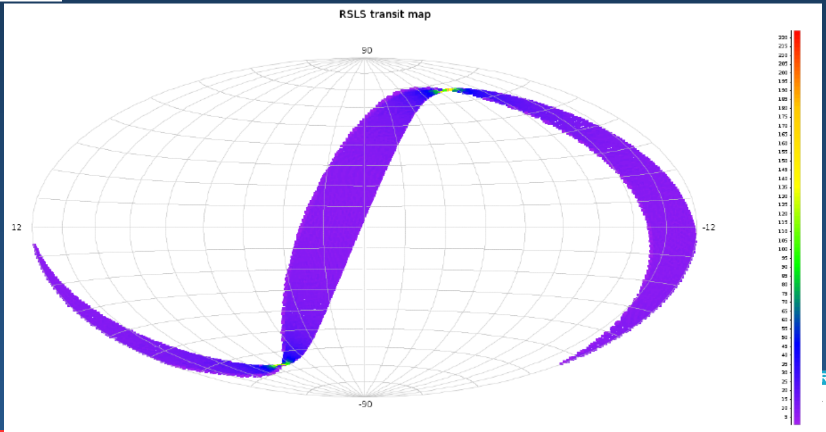
- *The stability is given by the rms scatter of repeated observations of the positions of the objects.*
- *Many observations help to fix the local reference frame and allow to decrease the random error.*
- *Pre requisite for studies of various science cases over different characteristic time scales; 1 day, 1 year, 5 years etc.*

The Star Field & Simulation



- *Gmag<16 stars in 0.6x0.4 sq deg around the North Ecliptic Pole from* ***IGSL catalogue***.
- *Obtain EPSL observations of them with* ***AGISLab*** *for 1 day as seen by Gaia.*

#Transits during the 28 days undisturbed EPSL



Transformation procedure

FOR EACH PLATE:

- *A-priori removal of star proper motions and parallaxes*
- *Pre-rotation onto the (1,0,0) Gaia's optical axis vector*
- *Gnomonic transformation to the tangent plane with tangent point (0,0)*
- *Taylor series expansion around the fiducial position*

WITH ALL PLATES:

Plate transformation (typically linear) using an Astrometric model

The Astrometric model

$$\eta'_{ij} = \eta_{ij} + \sum_{r=0}^{2} \Delta\eta_{rfnk} L_r^*\left(\frac{\mu - 13.5}{1966}\right)$$

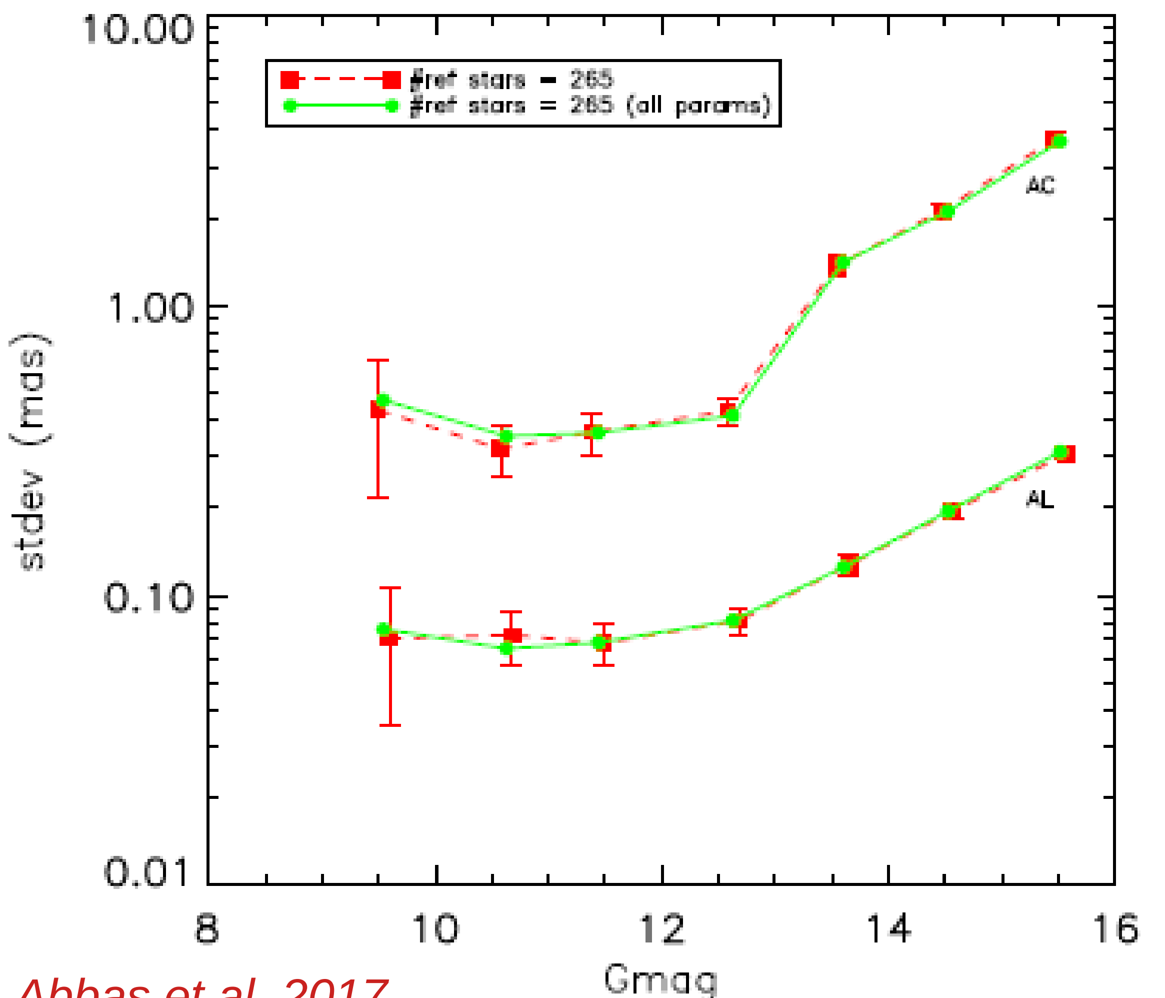
$$\zeta'_{ij} = \zeta_{ij} + \sum_{r=0}^{2} \Delta\zeta_{rfnk} L_r^*\left(\frac{\mu - 13.5}{1966}\right)$$

$$\eta'_{0j} = a_i\eta'_{ij} + b_i\zeta'_{ij} + c_i - \mu_{\eta j}\Delta t_{ij} - P_\eta \pi$$

$$\zeta'_{0j} = d_i\eta'_{ij} + e_i\zeta'_{ij} + f_i - \mu_{\zeta j}\Delta t_{ij} - P_\zeta \pi$$

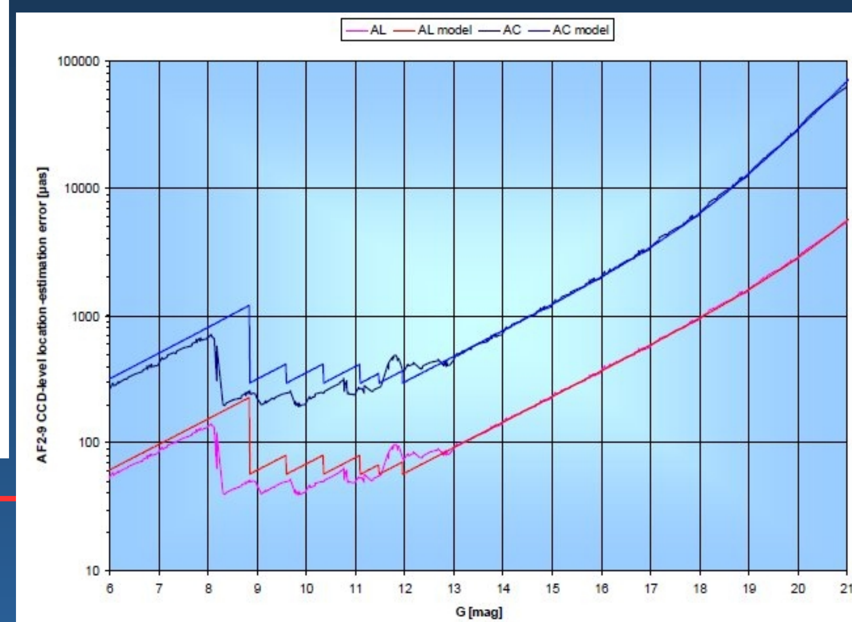
Parameters estimated using GaussFit: robust least squares estimator

Stdev vs Gmag

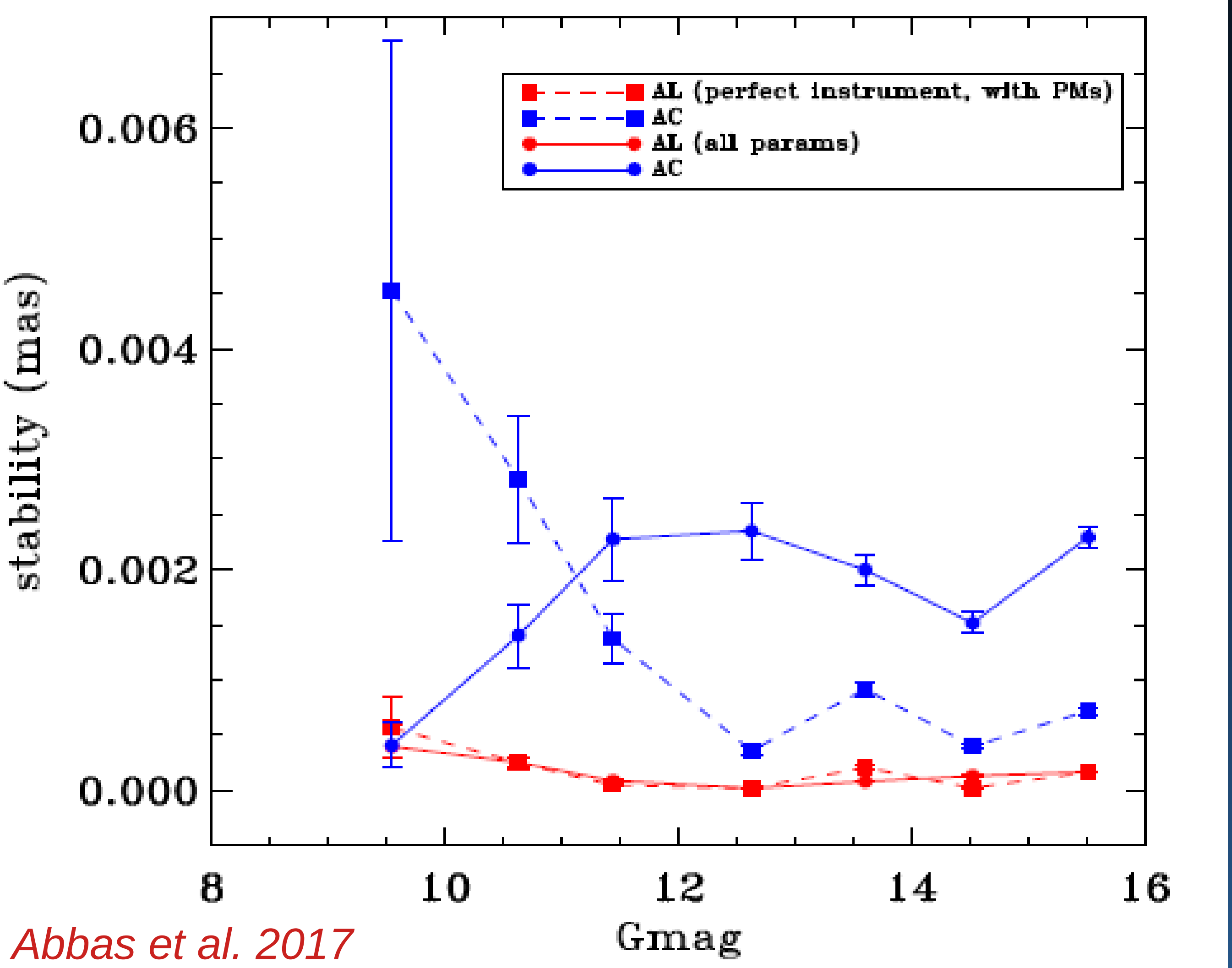


Abbas et al. 2017

- *The standard deviations (here for linear model) as a function of G-mags.*
- *The input errors follow standard CCD-level location estimation errors.*



Muas Stability of the RF



Abbas et al. 2017

- *Systematic errors are reliably estimated to the muas level even in fields with a modest number of 37 stars with G <13 mag for a perfect instrument.*
- *The inclusion of the geometric instrument model requires fainter stars down to G = 14 mag without diminishing the accuracy of the reference frame.*

GAREQ Experiment

Possible Science Cases

Study various science cases over different time scales:

- *1 day (relativistic deflection of light),*
- *few months (microlensing events)*
- *several years (detection of extrasolar planets) etc.*

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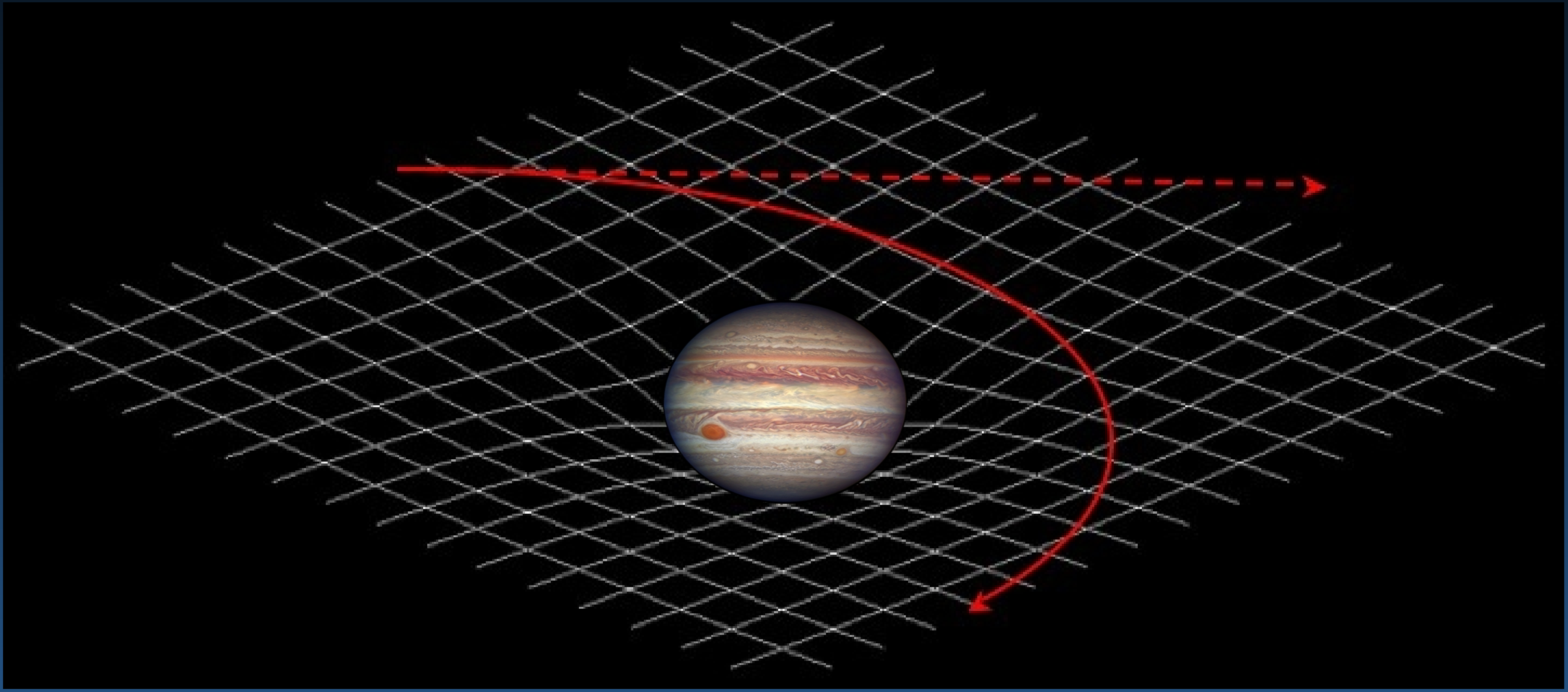
Study various science cases over different time scales:

- *1 day (relativistic deflection of light),* → ***GAREQ***
- *few months (microlensing events)*
- *several years (detection of extrasolar planets) etc.*

GAia Relativistic Experiment on Jupiter's Quadrupole



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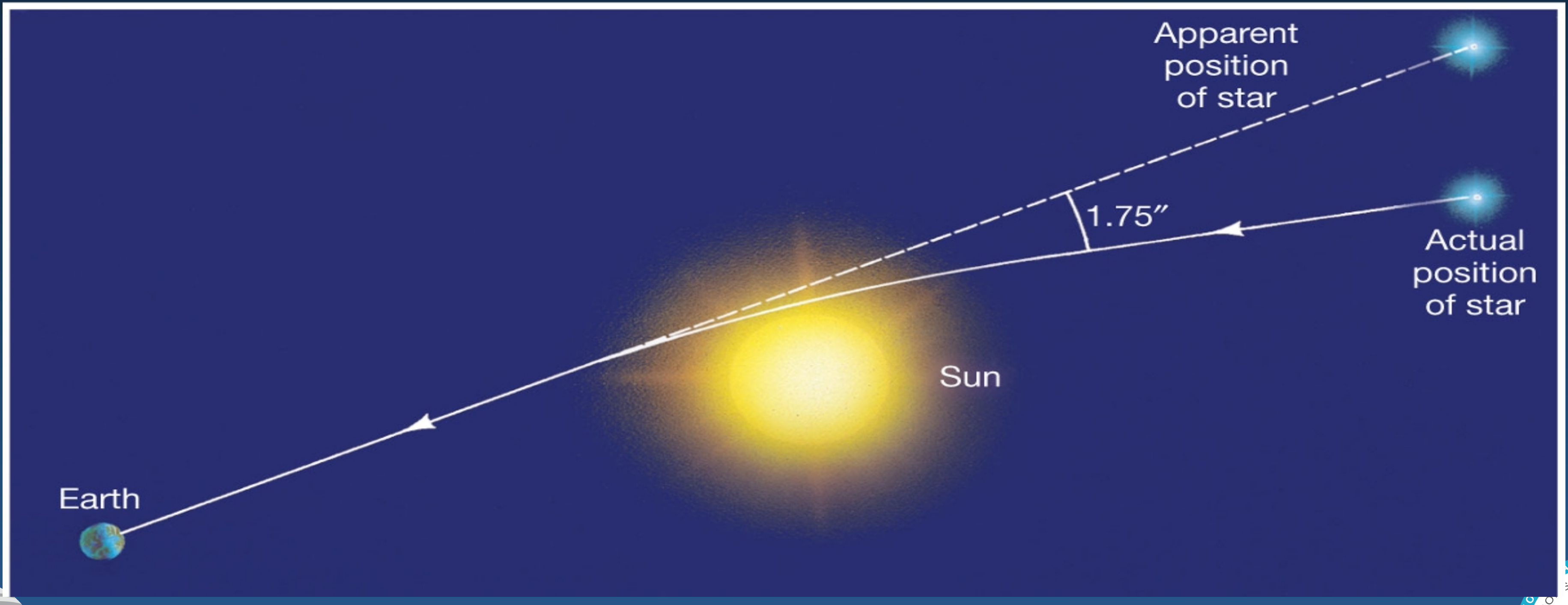
Eddington light experiment

- *In 1919 Arthur Eddington & Andrew Crommelin took photos of the solar eclipse.*
- *Verified Einstein's theory to 30%!*



Effect on Astrometry

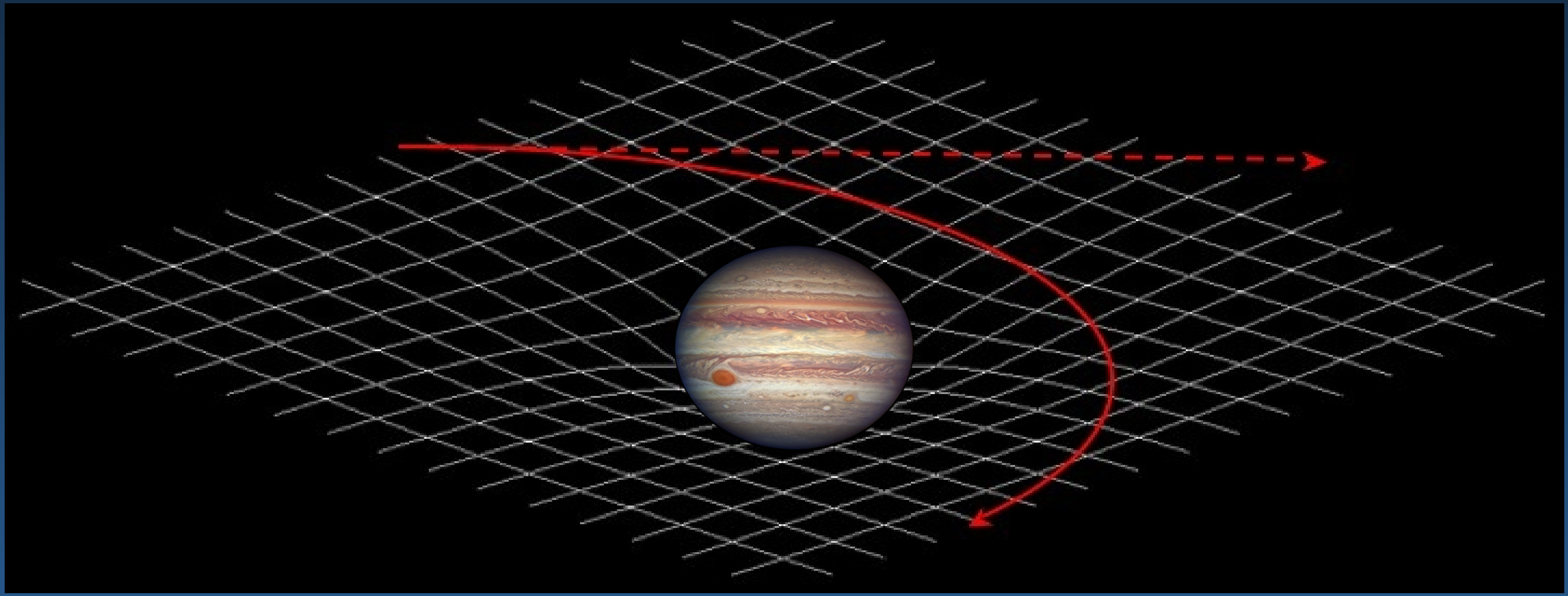
- *The entire sky is slightly distorted by light deflection around the Sun and Planets*
- *~4 milliarcseconds perpendicular to the Earth-Sun direction.*
- *Accounted for by modern astrometric satellites such as Hipparcos and Gaia.*

Deflection in the Solar System

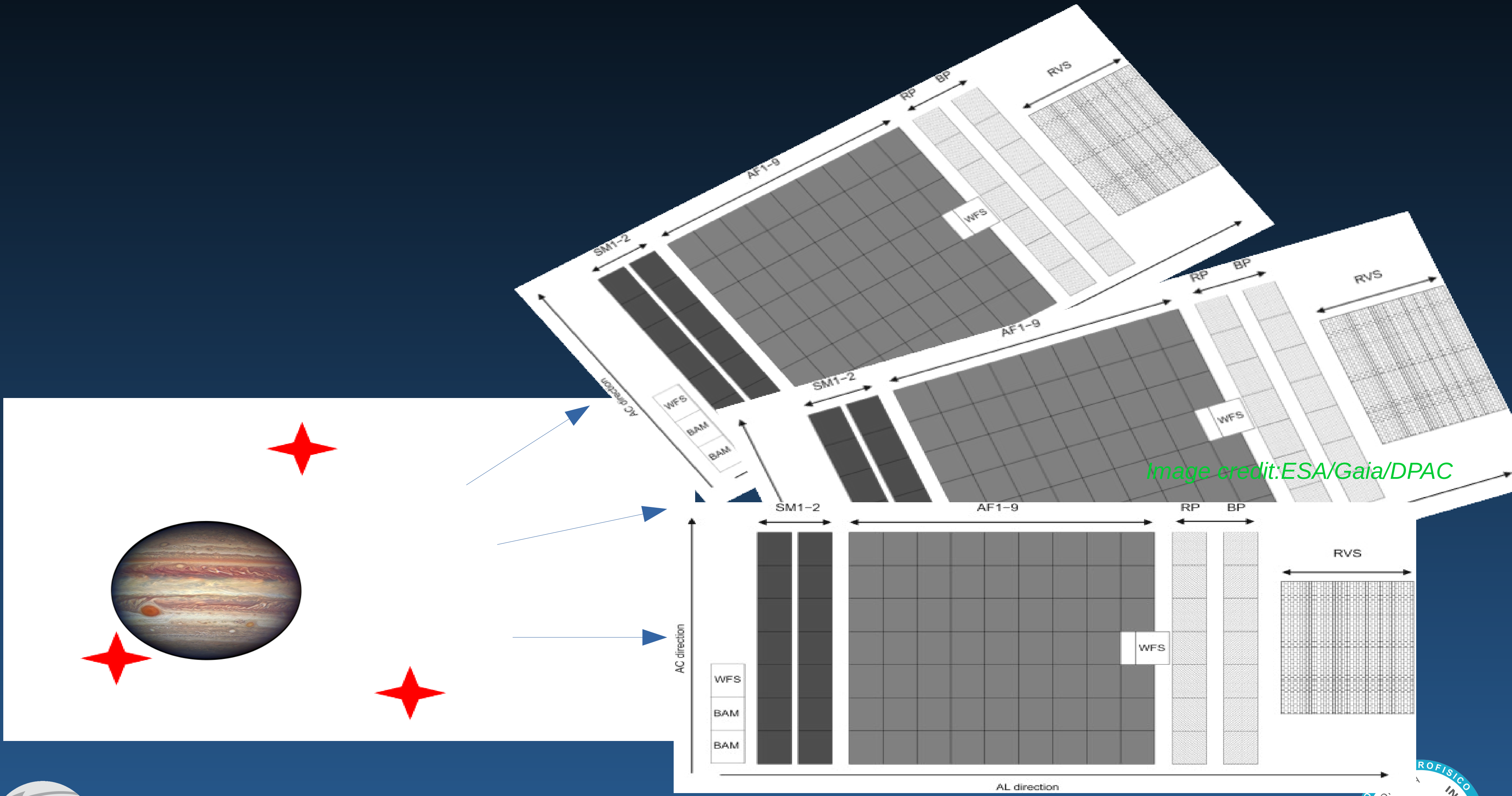
Body	Monopole		Quadrupole	
	grazing	χ	grazing	χ
	mas	$\delta\theta = 1\ \mu$as	μas	$\delta\theta = 1\ \mu$as
Sun	17,000	180°		
Mercury	0.083	0.15°		
Venus	0.49	4.5°		
Mars	0.12	0.4°		
Jupiter	16.3	90°	240	8 R_J
Saturn	5.8	17°	95	4 R_S
Uranus	2.1	1.2°	8	2 R_U
Neptune	2.5	0.9°	10	2 R_N

GAREQ experiment around Jupiter

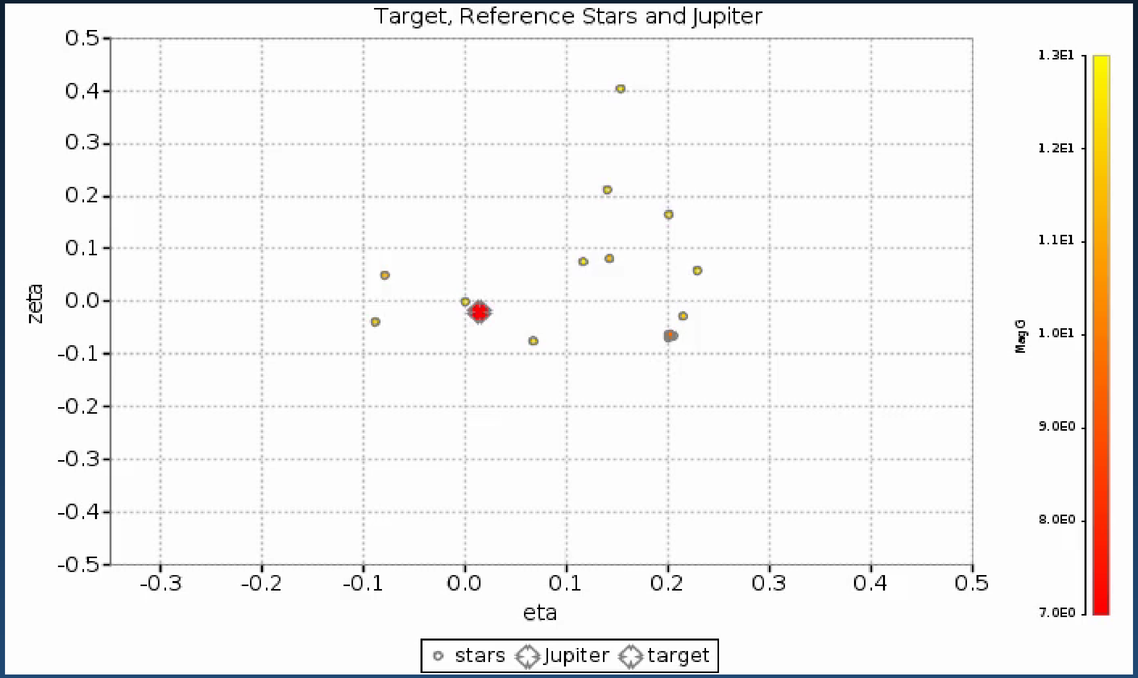
- *First-time deflection of light by Jupiter in the optical.*
- *At the 20muas level possible to measure deflection due to Jupiter's quadrupole!*



GAREQ with Gaia

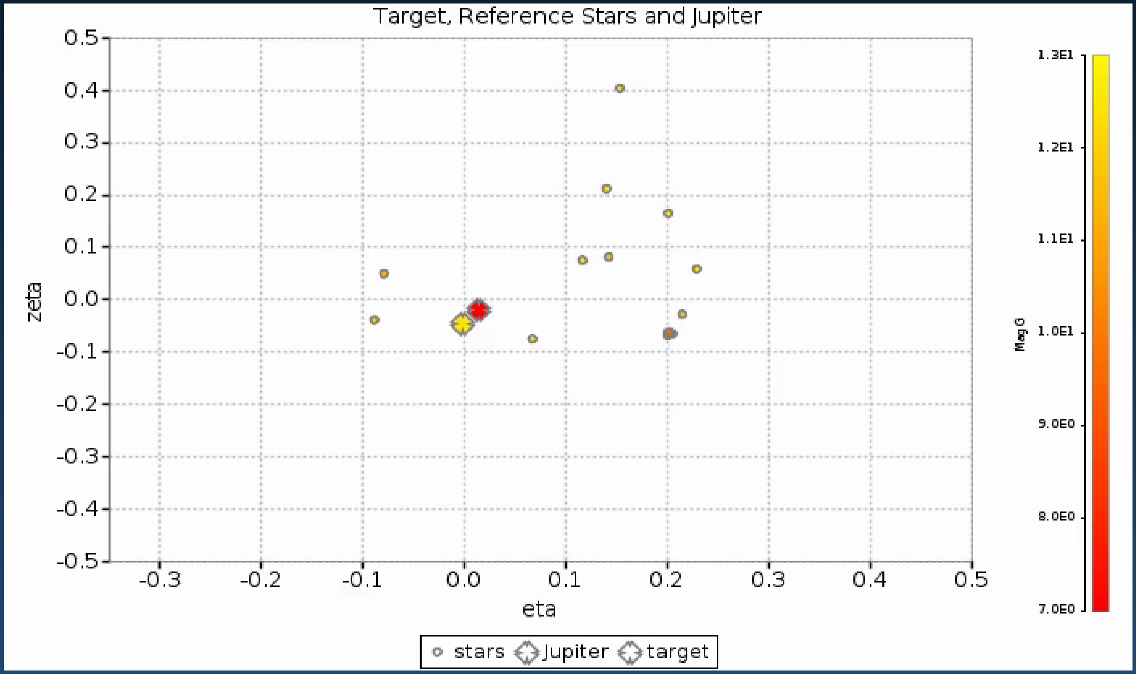


Simulated Star Field



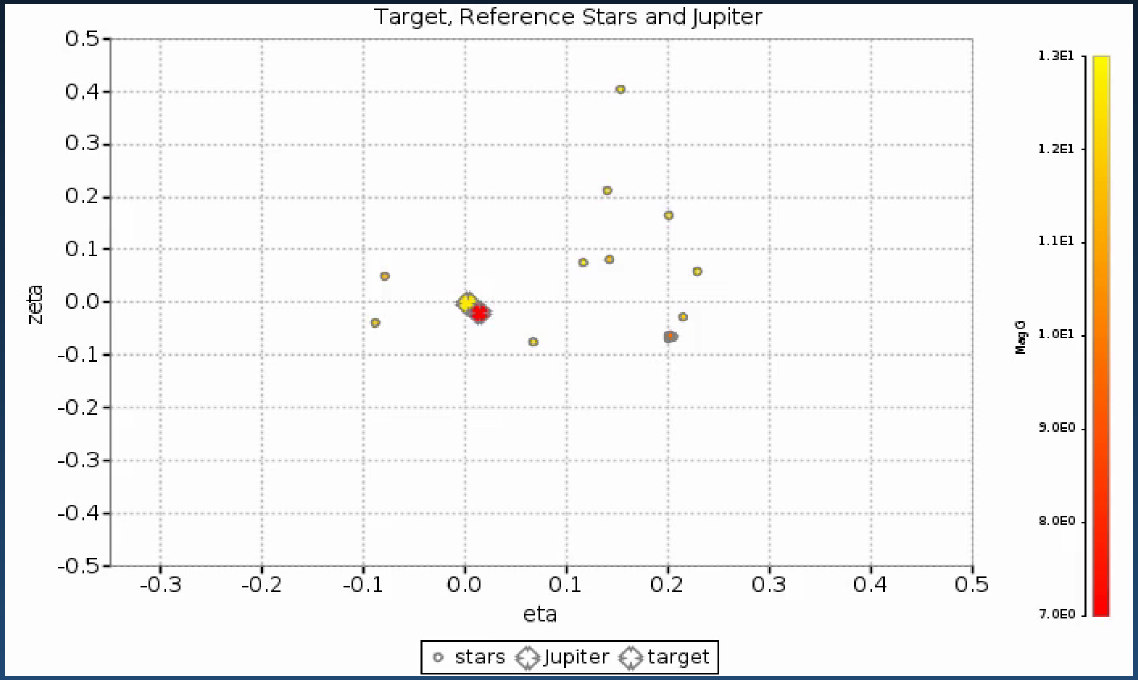
The star field (G<13 mag) as seen by Gaia (simulation) on a succession of transits (15 transits chosen around the time of closest approach by the target) along with the motion of Jupiter.

Simulated Star Field with Monopole Effect



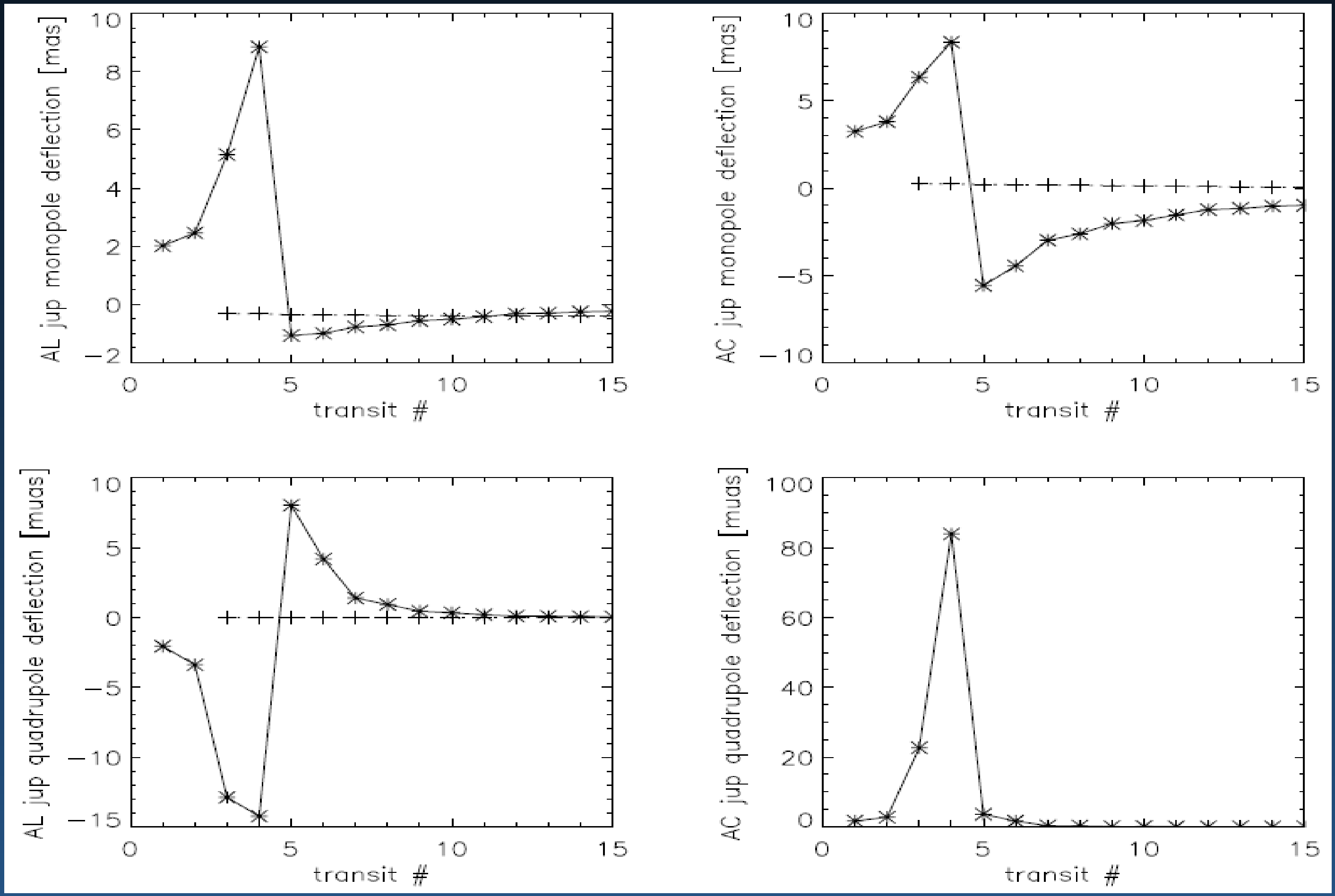
Simulation of the monopole deflection effect shown here enlarged by a factor of 50,000.

Simulated Star Field with Quadrupole Effect



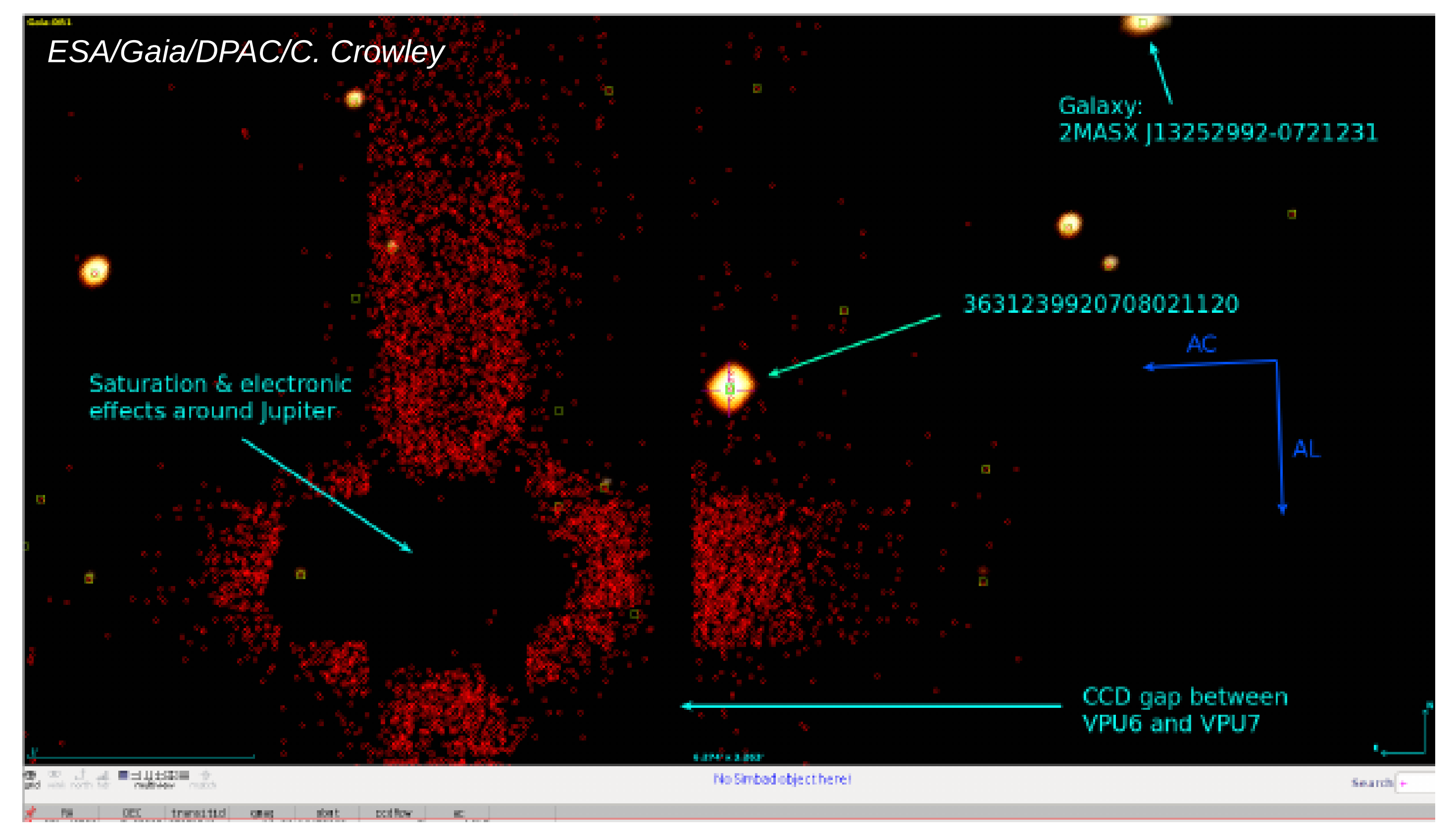
*Simulation of the quadrupole deflection effect shown here enlarged by a factor of 70*50,000.*

Deflection Signal



Upper panels show the simulated AL/AC monopole deflection signal and lower panels the quadrupole deflection signal.

Observation of GAREQ event



Scene around the target star successfully detected onboard during a transit on 2017-02-22T19:08:12.954 (UTC) at a predicted angular distance of 67.65" from Jupiter's limb.

Summary

- *DA can be used to establish a muas-stable reference frame + study science cases over different time scales.*
- *The astrometric modeling needs to take into account physical effects due to the aberration, AL-AC motion and proper motions of the stars, as well as instrumental calibrations.*
- *High cadence EPSL observations allow to construct a small field differential reference frame over short timescales*
- *The Gaia scanning law optimized for the GAREQ experiment has led to observations of a highly favorable configuration of a bright star close to Jupiter that can be studied with DA.*
- *Data analysis is ongoing and results are promising – soon to be submitted!*

Thank you!