The Gaia DR2 Reference System

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Gaia‘s second star catalogue

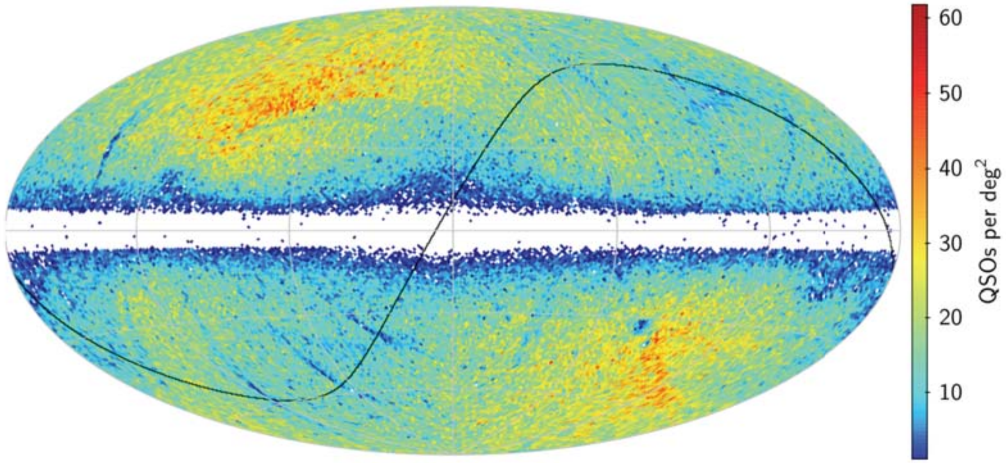
from Twitter

Gaia Data Release 2: The Celestial reference frame (Gaia-CRF2)

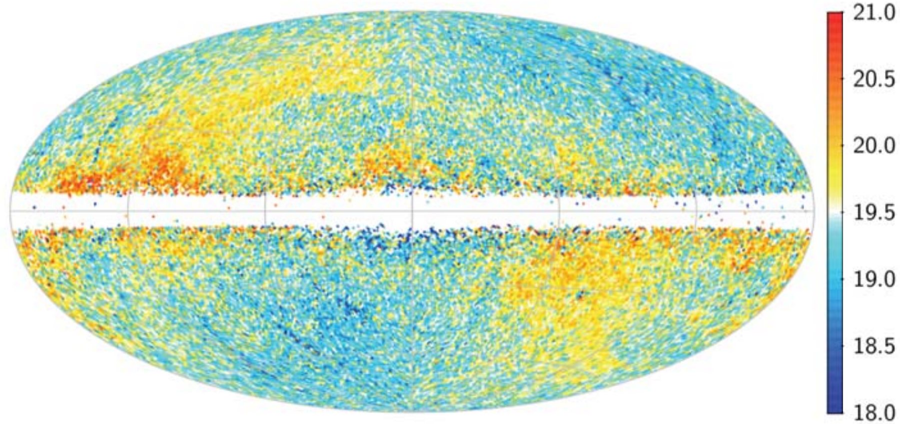
- Key science objectives of *Gaia* mission: Build a rotation-free, dense highly accurate celestial reference frame in the optical wavelength range
- *Gaia* Celestial Reference Frame (*Gaia*-CRF)
- Axes are fixed with respect to quasars.
- Coincide with the International Celestial Reference Frame (ICRF 3) established by VLBI observations of selected quasars.

Gaia Data Release 2: The Celestial reference frame (Gaia-CRF2)

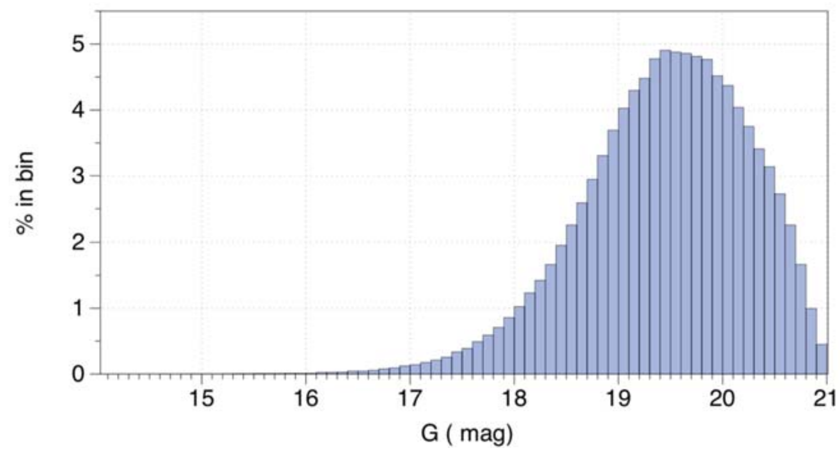
- Gaia DR2 (*Gaia* Collaboration et al. 2018)
- Complete astrometric data (positions, parallaxes, and proper motions) for more than 550 000 quasars.
- 30th General Assembly of IAU, Resolution B2 "The Third Realization of the ICRS Frame", valid from January 2019
- Gaia DR2 astrometric solution avoided rotation and aligned axis against prototype version of 3rd realization of ICRS/ICRF (Lindegren et al. 2018)



Sky density per square degree for the quasars of *Gaia*-CRF2 on an equal-area Hammer–Aitoff projection in Galactic coordinates. The Galactic centre is at the origin of coordinates (centre of the map), Galactic north is up, and Galactic longitude increases from right to left. The solid black line shows the ecliptic. The higher density areas are located around the ecliptic poles.



Sky distribution of the *Gaia*-CRF2 source magnitudes. Median values of cells of ≈0.84 deg^2



Gaia Data Release 2: The Celestial reference frame (Gaia-CRF2)

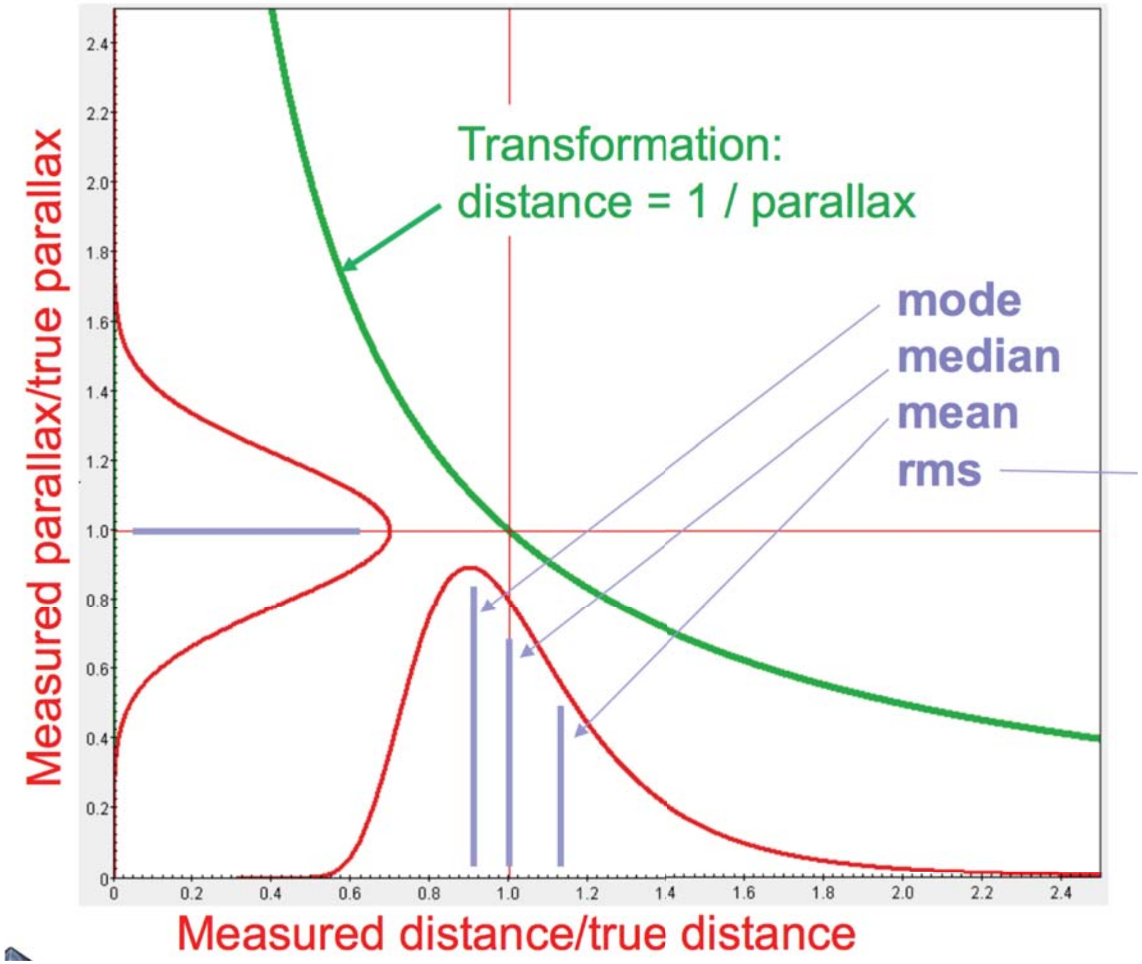
- *Gaia*-CRF2 first optical realisation of a reference frame at sub-milliarcsecond (mas) precision, using a large number of extragalactic objects
- Ten quasars per square degree (except in the Milky Way band)
- 100-fold increase in the number of objects from the current realisation at radio wavelengths, i.e. the ICRF2 (Fey et al. 2015)
- *Gaia*-CRF2 is bound to replace the HCRF (Hipparcos Celestial Reference Frame)
- Positions and proper motions of the $\simeq$ 1.3 billion stars in *Gaia* DR2 are nominally in the same reference frame
- Gaia Collaboration., 2018, A&A 616, 14, "Gaia Data Release 2: The Celestial reference frame (Gaia-CRF2)"

Reference for measuring the Hubble constant

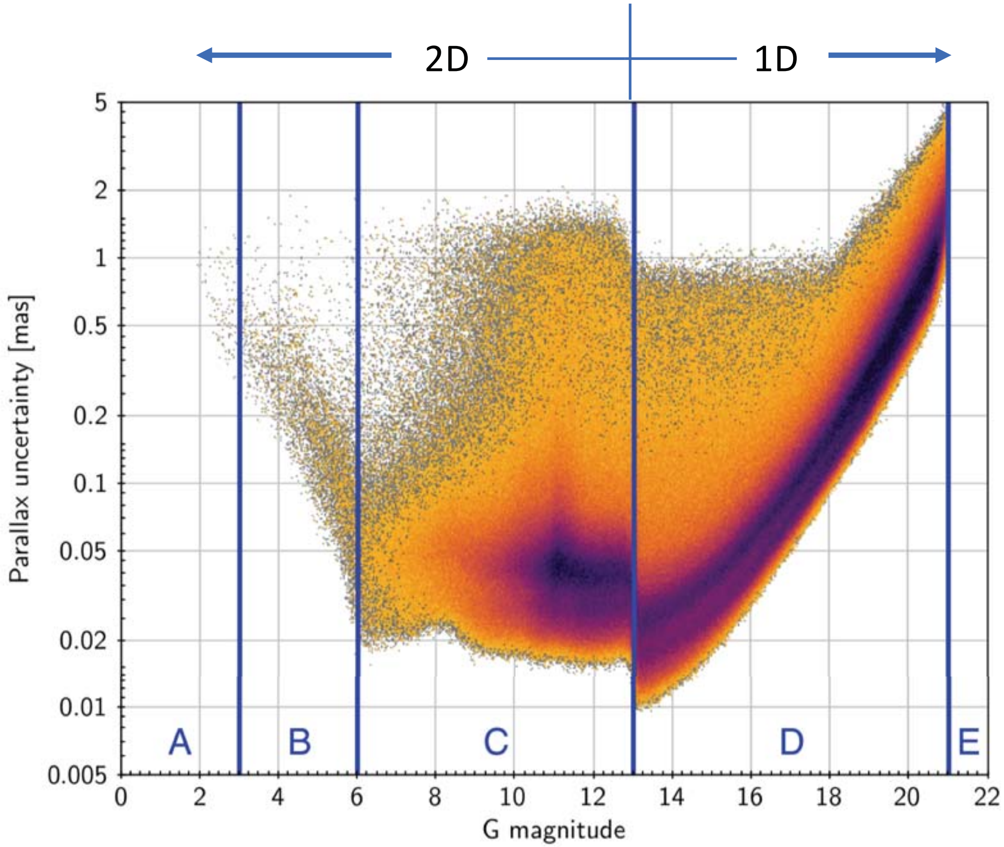
Of particular importance for this conference:

- Accuracy of the Gaia parallaxes:
  - Random errors
  - Systematic errors, in particular the Gaia parallax zero point
  - Best method to obtain a "clean" sample

Parallax to distance



Formal uncertainty in parallax (random errors)



Regimes of G:

A: Too bright

B: Partly saturated (unreliable)

C: Detector and calibration limited

D: Photon limited

E: Too faint (not published)

Formal uncertainties in *Gaia* DR2 were estimated from the internal consistency of measurements and do not necessarily represent the total error

after Lindegren

https://www.cosmos.esa.int/documents/29201/1770596/Lindegren_GaiaDR2_Astrometry_extended.pdf/1ebddb25-f010-6437-cb14-0e360e2d9f09

Random and systematic errors of parallaxes

- **Random error** ← published uncertainty in Gaia DR2
  - on average zero, standard deviation $\boldsymbol{\sigma_i}$
  - in order to account for possible underestimation: $\sigma_r = k\sigma_i$ with $k \gtrsim 1.0$

- **Systematic error**
  - may depend on position, magnitude, colour, ...
  - standard deviation $\boldsymbol{\sigma_s}$
  - mean value is parallax zero point ϖ_0

External calibration

- **External (total) uncertainty**

$$\boldsymbol{\sigma_{ext}} = \sqrt{k^2\sigma_i^2 + \sigma s^2}$$

see https://www.cosmos.esa.int/documents/29201/1770596/Lindegren_GaiaDR2_Astrometry_extended.pdf

Random and systematic errors of parallaxes

$$\frac{\sigma_{\text{ext}}}{\sigma_i} = \sqrt{k^2 + \left(\frac{\sigma_s}{\sigma_i}\right)^2}$$

Estimating k:
– in the faint limit photon noise dominates ($\sigma_i \gg \sigma_s$) so $\gg \sigma_{\text{ext}}/\sigma_i \rightarrow k$
Estimating σ_s (two methods):
– from $\sigma_{\text{ext}}/\sigma_i$ of brighter sources when k is known
– from the spatial covariance $V_\varpi(\theta)$, using that $V\varpi(0) = {\sigma_s}^2$

- **Random error** ← published uncertainty in Gaia DR2
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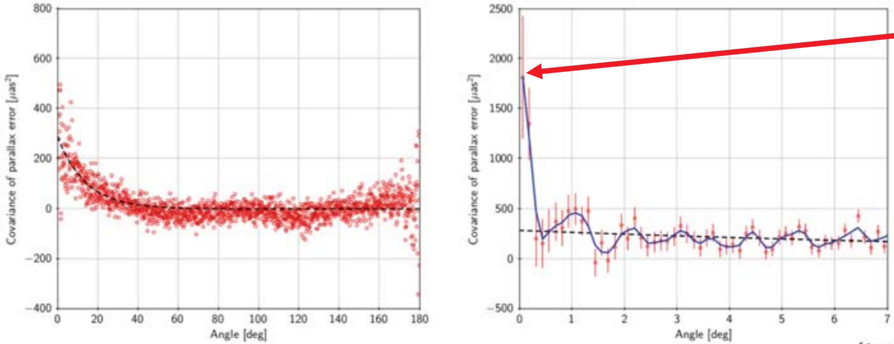
  - standard deviation σ_s
  - mean value is parallax zero point ϖ_0

External calibration

- **External (total) uncertainty** $\sigma_{\text{ext}} = \sqrt{k^2\sigma_i^2 + \sigma s^2}$

$\theta = 0$ to $180°$ | $\theta = 0$ to $7°$



$V\varpi(0) = 1849\ \mu as^2 {\sigma_s}^2 \Rightarrow \sigma_s \approx 43\ \mu as^2$

(L18, Fig. 14)

Random and systematic errors of parallaxes

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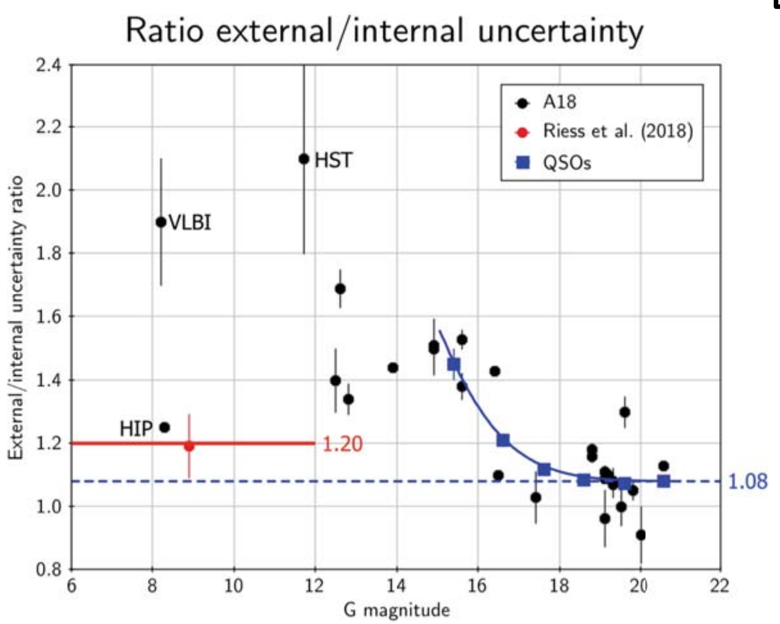


k and σ_s estimated from σ_{ext}/σ_i vs. G:

Quasars (blue):

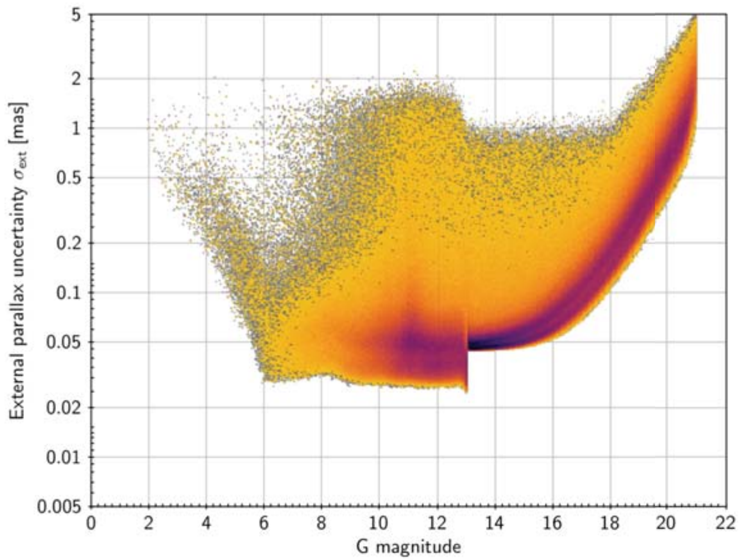
$k = 1.08$

$\sigma_s = 0.043$ mas

Bright stars (red):

$k = 1.08$ (assumed)

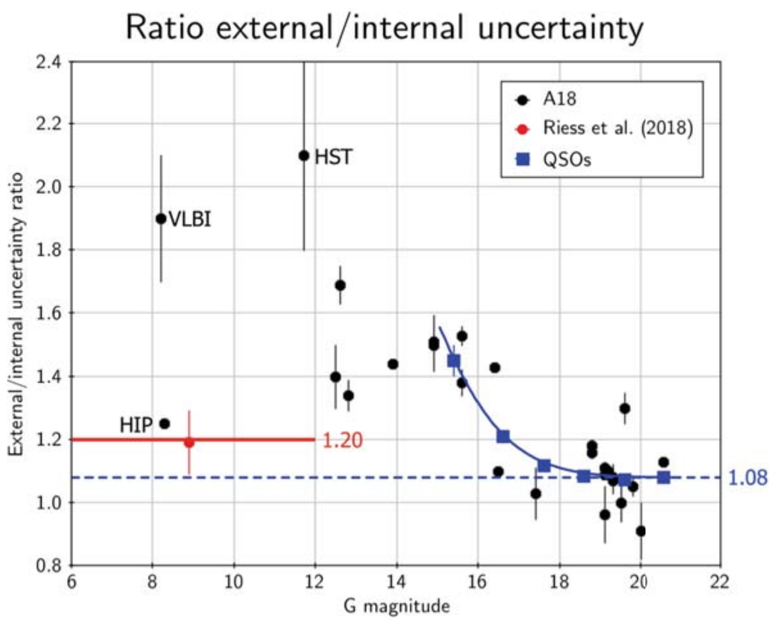
$\sigma_s = 0.021$ mas



see https://www.cosmos.esa.int/documents/29201/1770596/Lindegren_GaiaDR2_Astrometry_extended.pdf

Random and systematic errors of parallaxes

The external errors were estimated assuming that the uncertainties given in the various catalogues are correct (which we know is often not true)!



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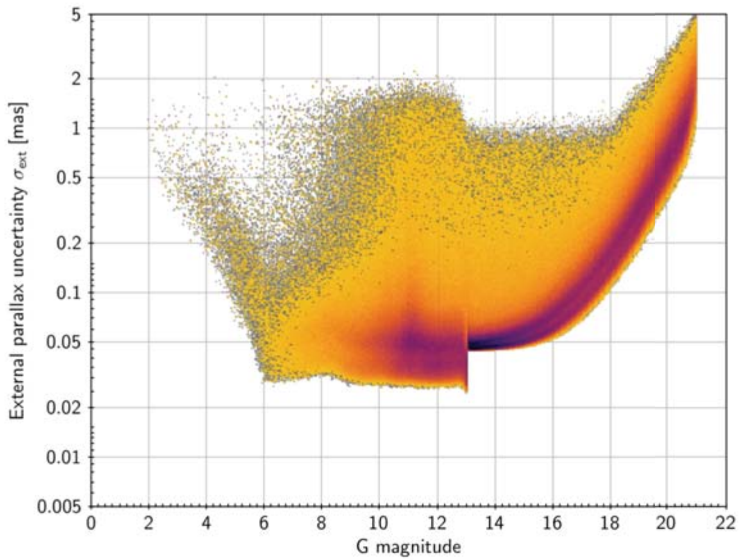

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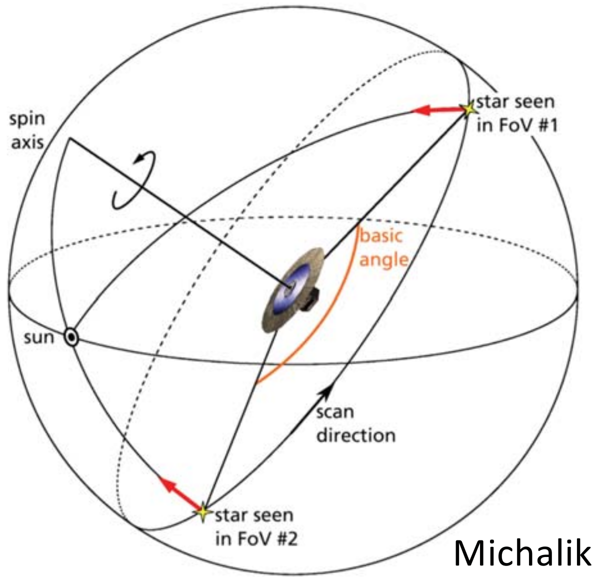
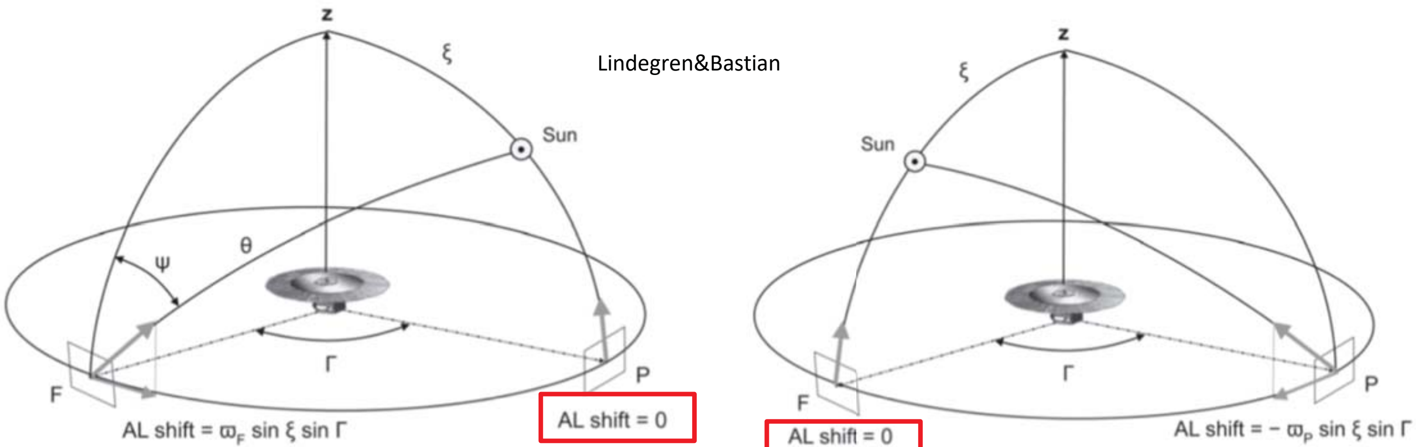
Parallax zero point

- The zero point ϖ_0:
  - – expected measured parallax for a source at infinity
  - – to be added to the catalogue value
  - – should be zero for a perfect Gaia with a stable basic angle



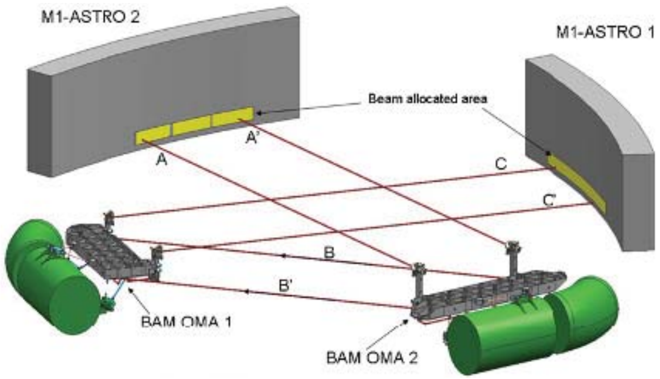
Michalik



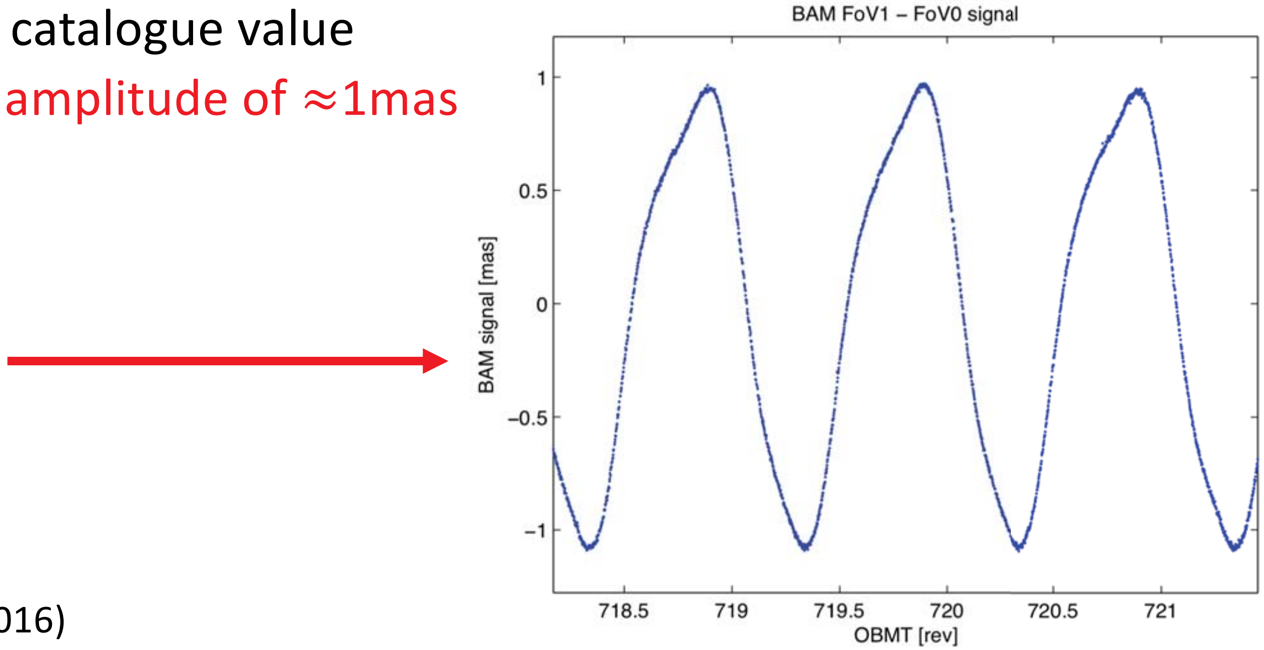
Lindegren&Bastian

Parallax zero point

- The zero point ϖ_0:
  - expected measured parallax for a source at infinity
  - to be subtracted from the catalogue value
  - basic angle varies with an amplitude of ≈1mas

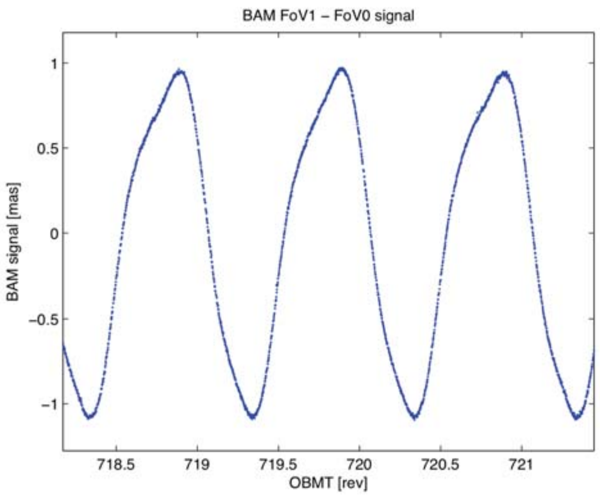


Gaia Basic-Angle Monitor, Fabricius et al. (2016)



Basic Angle Variation

- Spin-related distortion model



$$\Delta\Gamma(t) = d(t)^{-2} \sum_{k=1}^{8} \Big(\big[C_{k,0} + C_{k,1}(t - t_{\mathrm{ref}})\big] \cos k\Omega(t) + \big[S_{k,0} + S_{k,1}(t - t_{\mathrm{ref}})\big] \sin k\Omega(t) \Big)$$

- heliotropic spin phase $\Omega(t)$
- $d(t)$ is the Sun–*Gaia* distance in au
- t_{ref} = J2015.5

	Coefficient [μas]		Derivative [μas yr^{-1}]	
	BAM	Corr.	BAM	Corr.
→ C_1	+909.80	–	+73.34	+1.37
C_2	−110.50	−23.38	+1.86	−1.59
C_3	−68.39	−4.65	+1.37	−0.33
C_4	+17.61	−2.53	−0.79	−1.53
C_5	+2.79	−1.15	−0.25	−2.86
C_6	+3.67	+1.47	+0.40	−0.18
C_7	+0.12	+0.38	−0.34	+0.42
C_8	−0.51	−0.44	−0.01	+0.61
S_1	+668.41	−25.42	+19.78	+1.49
S_2	−90.95	+34.46	−10.68	+5.23
S_3	−63.47	+4.63	+3.02	+0.97
S_4	+18.11	+3.32	+1.20	−1.33
S_5	−0.11	−0.55	+0.79	−1.61
S_6	+0.02	−1.11	−0.69	+0.38
S_7	+0.18	−0.05	−0.27	−0.14
S_8	−0.49	+0.25	+0.09	−0.32

$\delta\Gamma(t) = C_1 d(t) \cos\Omega(t)$ almost indistinguishable from $\delta\varpi = C_1/[2 \sin\xi \sin(\Gamma/2)] \simeq 0.883 A_1$.

Parallax Zero Point

- Lindegren et al., 2018, A&A 616, A2, "Gaia Data Release 2: The astrometric solution"

Parallax zero point from 492,928 quasars with small errors:

-29 μas

= 3 percent of basic angle variation amplitude

Quasar parallaxes <0.0025 µas for redshifts $z > 0.1$

"… the actual offset applicable for a given combination of magnitude, colour, and position may be different by several tens of µas."

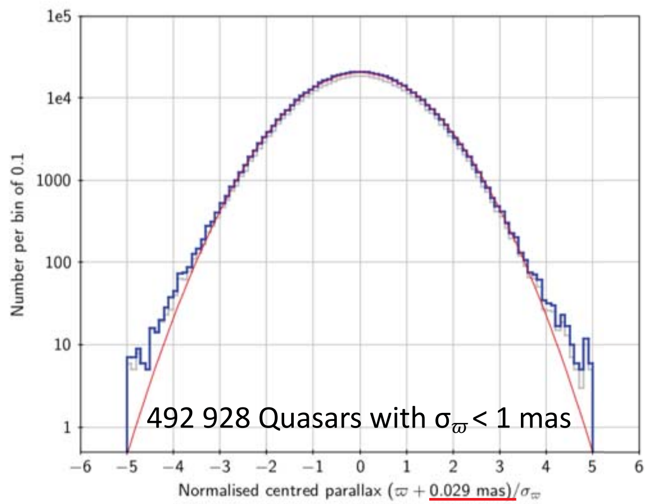


Fig. 8. Distributions of the normalised centred parallaxes for the same samples as in Fig. 6. The red curve is a Gaussian distribution with the same standard deviation (1.081) as the normalised centred parallaxes for the full sample.

Parallax Zero Point

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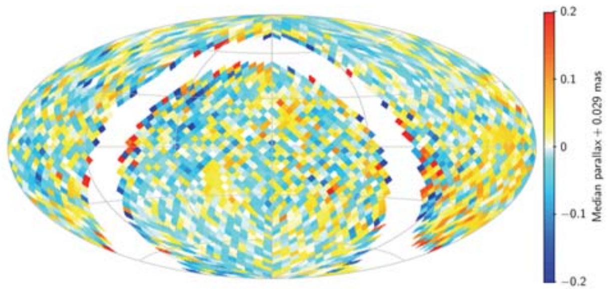


Fig. 12. Map of the median parallaxes for the full quasar sample, showing large-scale variations of the parallax zero point. See Fig. 5 for the coordinate system and density of sources. Median values are calculated in cells of about 3.7×3.7 deg^2. Only cells with $|\sin b| > 0.2$ are plotted.

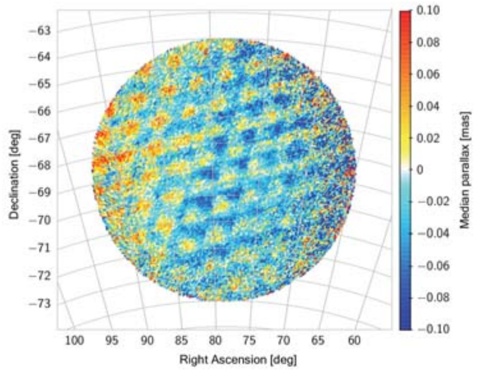


Fig. 13. Map of the median parallaxes for a sample of sources in the LMC area, showing small-scale variations of the parallax zero point. Median values are calculated in cells of about 0.057×0.057 deg^2.

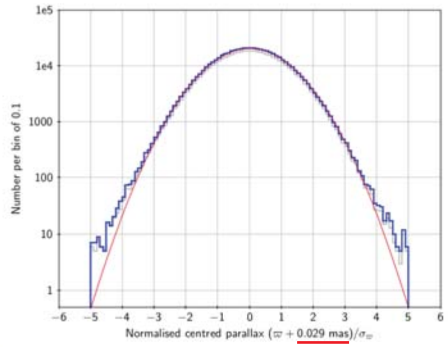


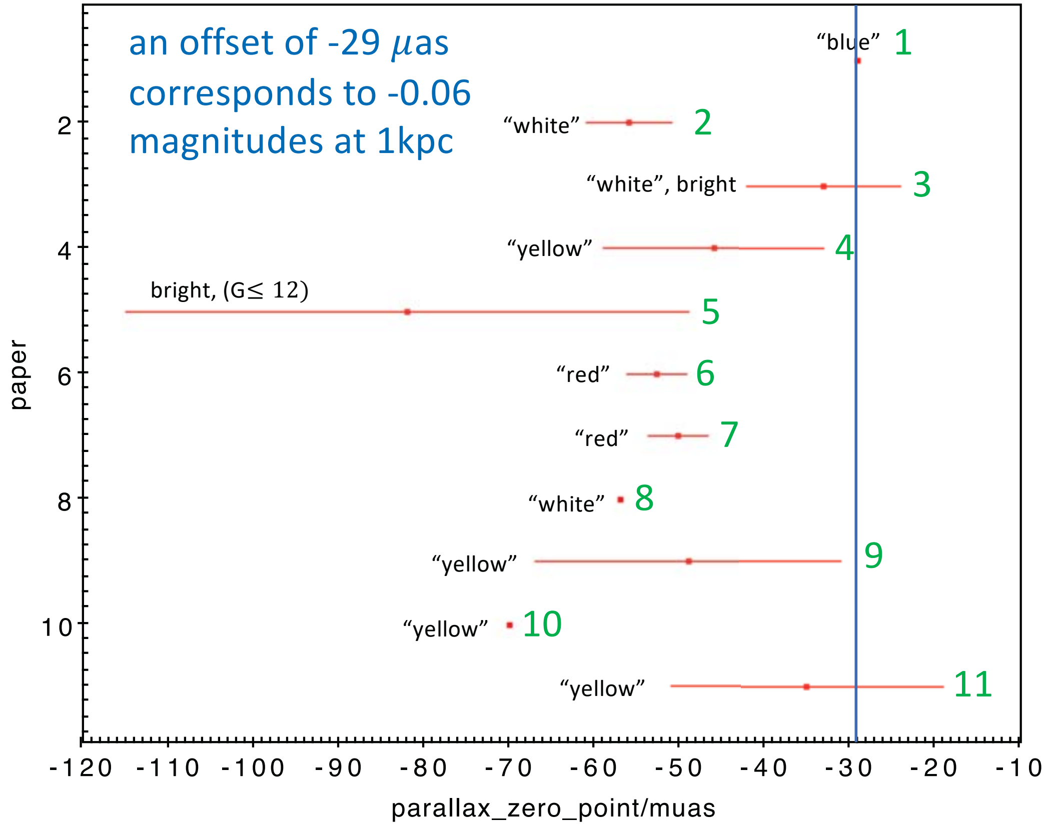
Fig. 8. Distributions of the normalised centred parallaxes for the same samples as in Fig. 6. The red curve is a Gaussian distribution with the same standard deviation (1.081) as the normalised centred parallaxes for the full sample.

Several areas of a few tens of degrees where the parallaxes are systematically offset by about ±50 μas from the global mean.

Period of about 0.6° and a typical amplitude of about ±(20-30) μas.

Other Papers discussing the Gaia DR2 parallax zero point

- Lindegren et al., 2018, A&A 616, A2, “Gaia Data Release 2: The astrometric solution”, -29 μas (1)
- Arenou et al., 2018, A&A 616, A17, “Gaia Data Release 2: Catalogue Validation”: -56±5 μas (2) from Gaia DR2 RR Lyrae stars, -33±9 μas (3) from GCVS RR Lyrae stars
- Riess et al, 2018, ApJ 861, 126, “Milky Way Cepheid Standards for Measuring Cosmic Distances and Application to Gaia DR2: Implications for the Hubble Constant“: 50 Cepheids: -46 ±13μas (4)
- Stassun & Torres, 2018, ApJ 862, 61, “Evidence for a Systematic Offset of −80 μas in the Gaia DR2 Parallaxes“, Eclipsing Binaries: -82 ±33μas (5) for (G≤ 12).
- Zinn et al., 2018, ApJ, arXiv:1805.02650, “Confirmation of the zero-point offset in Gaia Data Release 2 parallaxes using asteroseismology and APOGEE spectroscopy in the Kepler field“: RGB stars: 52.8±2.4(stat.)±1(syst.) μas (6), Red Clump: 50.2 ± 2.5(stat.) ± 1(syst.)μas (7)
- Muraveva et al., 2018, MNRAS 481, 1195: “RR Lyrae stars as standard candles in the *Gaia* Data Release 2 Era“: -57 μas (8)
- Groenewegen, 2018, A&A in press, arXiv:1802.05796: “The Cepheid period -- luminosity -- metallicity relation based on Gaia DR2 data“: 9 Cepheids: -49 ± 18μas (9)
- Ripepi et al., 2018, AA, arXiv:1810.10486: “A re-classification of Cepheids in the *Gaia* Data Release 2“: -70 μas (10)
- Sahlholdt &Silva Aguirre. 2018, MNRAS 481, L125, “Asteroseismic radii of dwarfs: new accuracy constraints from *Gaia* DR2 parallaxes“, dwarfs: -35 ±16μas (11)



How to filter stars with ”good” astrometric solutions?

$$\texttt{astrometric\_chi2\_al} = \chi^2 = \sum_{l=1}^{N} \left(\frac{R_l}{\tilde{\sigma}_l} \right)^2$$

R_l = along-scan residuals
$\tilde{\sigma}_l$ = standard uncertainties of along-scan residuals

$$u = \sqrt{\frac{\chi^2}{N-5}} = \sqrt{\frac{\texttt{astrometric\_chi2\_al}}{\texttt{astrometric\_n\_good\_obs\_al} - 5}}$$

“unit weight error” (UWE)

L. Lindegren, LL-124

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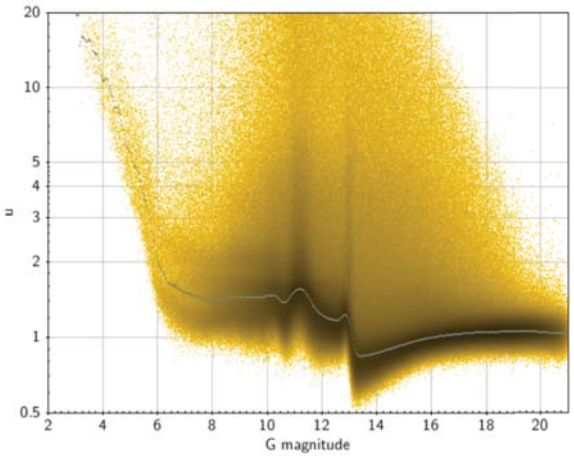

FIGURE 2: UWE (u) for a subset of five-parameter solutions in *Gaia* DR2 as a function of the G magnitude. The yellow dots are for the individual solutions; the grey curve is the (slightly smoothed) median. The subset include all sources for $G \leq 11$ mag, and an exponentially decreasing random fraction of the fainter sources.

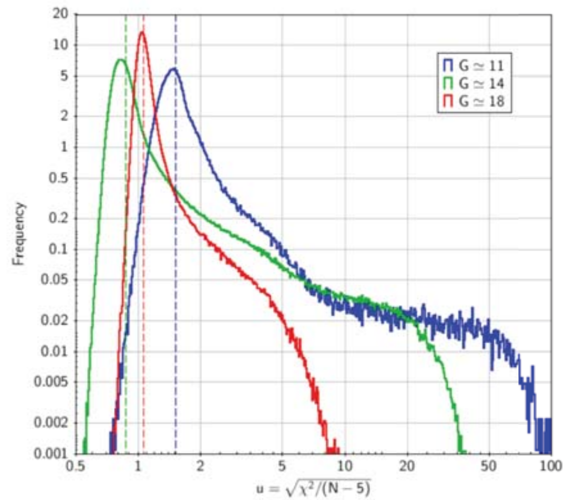

FIGURE 1: Histogram of the UWE (u) for five-parameter solutions of sources in *Gaia* DR2 with G magnitude in the ranges 10.8–11.2, 13.9–14.1, and 17.995–18.005. The dashed vertical lines show the medians of the distributions.

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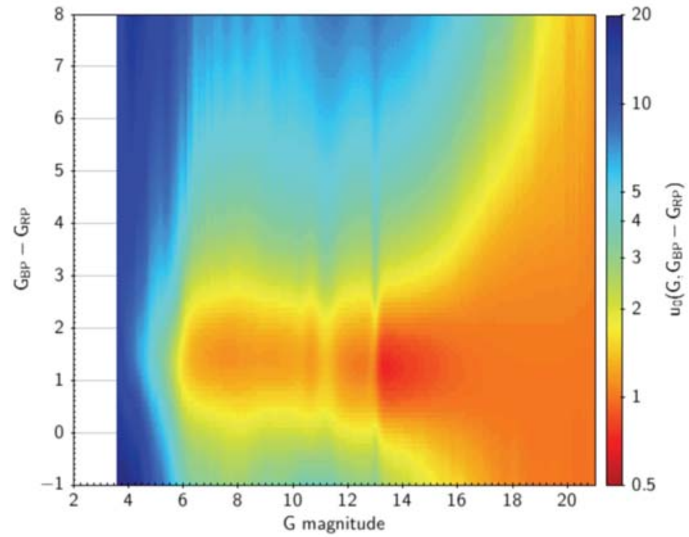

Normalisation function u_0

The function u_0 was determined by sampling *Gaia* DR2 in bins of magnitude and colour, estimating the “typical” UWE (taken as the 41st percentile of the UWE) per bin, and fitting a semi-analytical function.

$$RUWE = \frac{u}{u_0(\text{magnitude,colour})}$$

„Re-normalised Unit Weight Error“

u_0 can be obtained from ”Known issues”:
https://www.cosmos.esa.int/documents/29201/1769576/DR2_RUWE_V1.zip

L. Lindegren, LL-124

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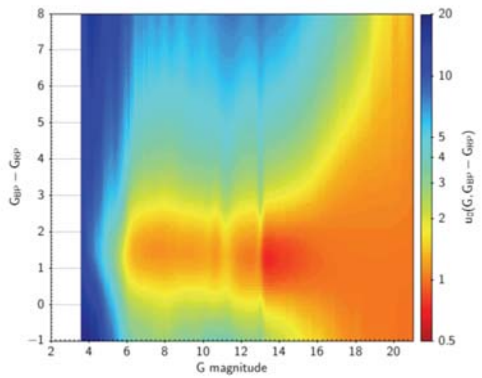
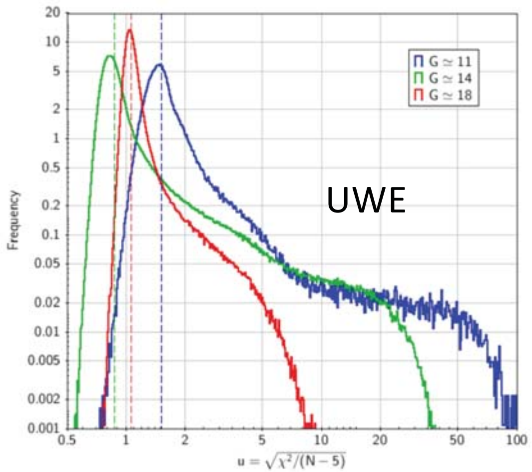
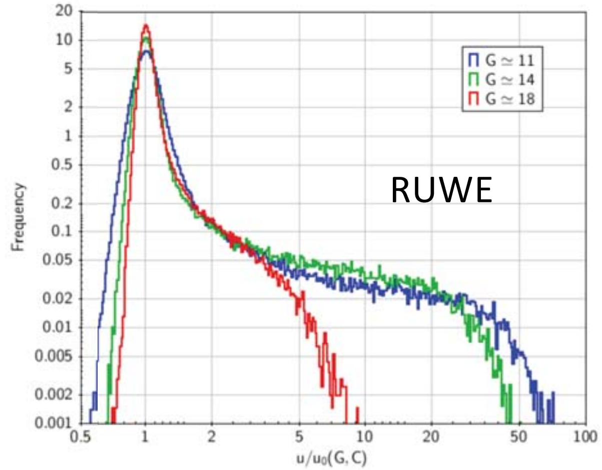


Normalisation function u_0





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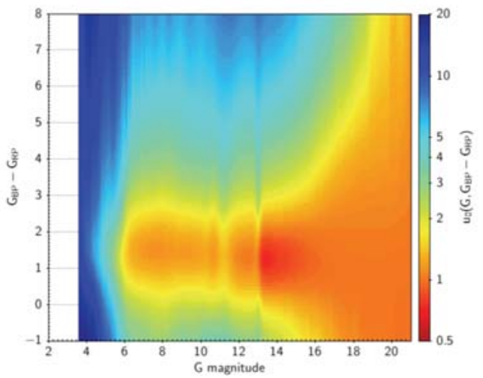

Normalisation function u_0

Recommendation for clean filtering:

- RUWE≤ 1.4
- visibility_periods_used > 8
- $1.0 + 0.015(G_{BP} - G_{RP})^2$ < flux_excess_noise < $1.3 + 0.06(G_{BP} - G_{RP})^2$

Gaia's Schedule

- **May 1993: First proposal for Gaia at ESA**
- **2000: Accepted as "Cornerstone Mission" by ESA**
- **2006: Start of the industrial phase**
- **2007-2013: Various reviews**
- **December 19, 2013: Launch**
- **Until 18 July 2014: "Commissioning" (test) phase**
- **August 2014: Start of regular measurements**
- **14 September 2016: First Gaia Catalogue**
- **25. April 2018: Second (first "real") Gaia Catalogue**
- **2019: End of the nominal mission (5 years time)**
- **2019-2020: Approved extended mission (1.5 years)**
- **2021 (first half): Third Gaia catalogue**
- **2020-2024: Expected extended mission (3.5 years)**
- **2023?: Fourth catalogue due to the nominal mission**
- **2026?: Fifth catalogue due to extended mission**

Gaia is European Teamwork