Gaia DR2 astrometry

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Main references

A18 F. Arenou et al. (2018):
Gaia DR2: Catalogue validation (link)

L18 L. Lindegren et al. (2018):
Gaia DR2: The astrometric solution (link)

\+ New material

An extended version of this presentation is on the ESA web page

Gaia → Gaia Data → Data Release 2 → Known issues:
`www.cosmos.esa.int/web/gaia/dr2-known-issues`

Outline

1. Random and systematic errors
2. Quality indicators
3. Spurious and anomalous parallaxes
4. Conclusions and outlook

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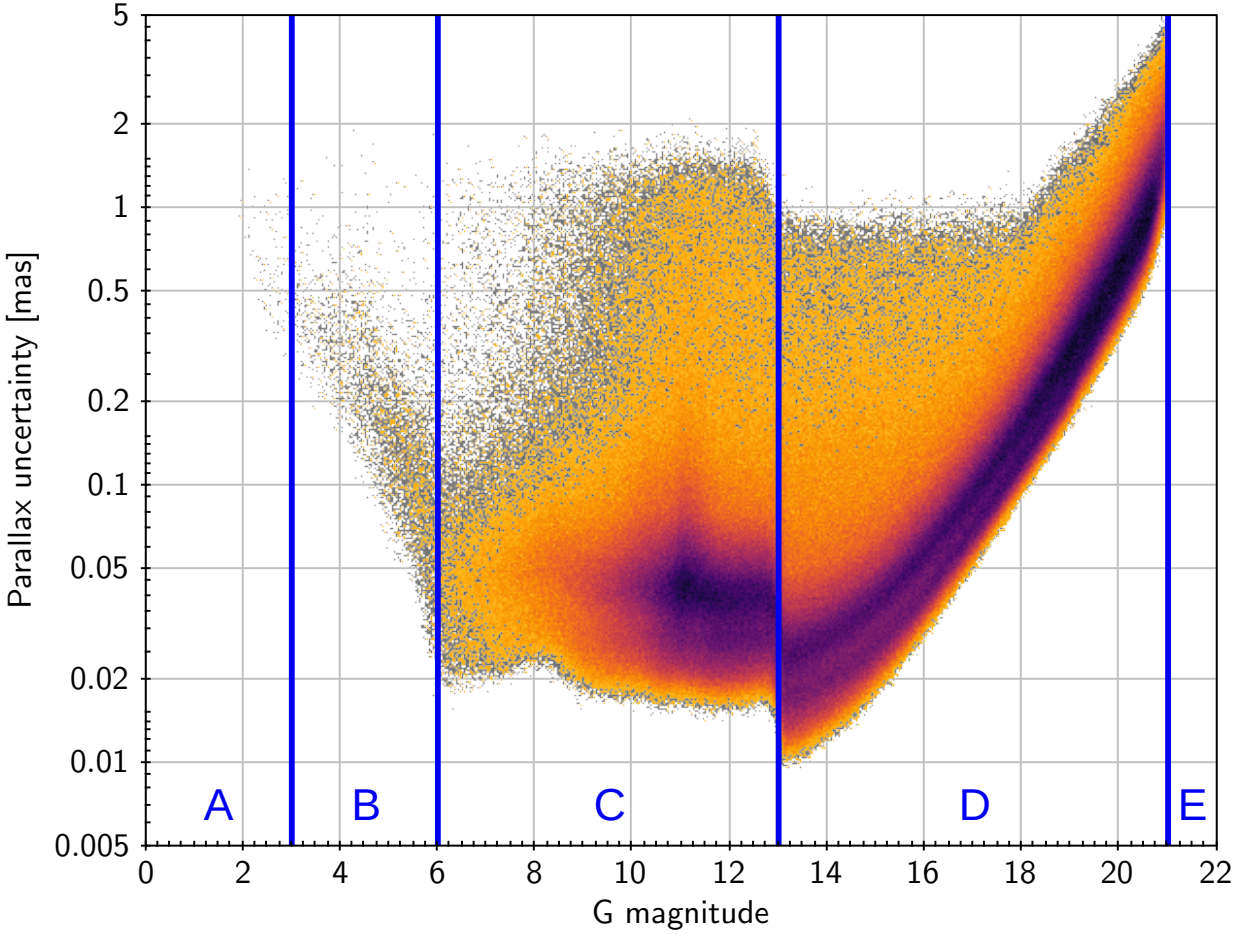
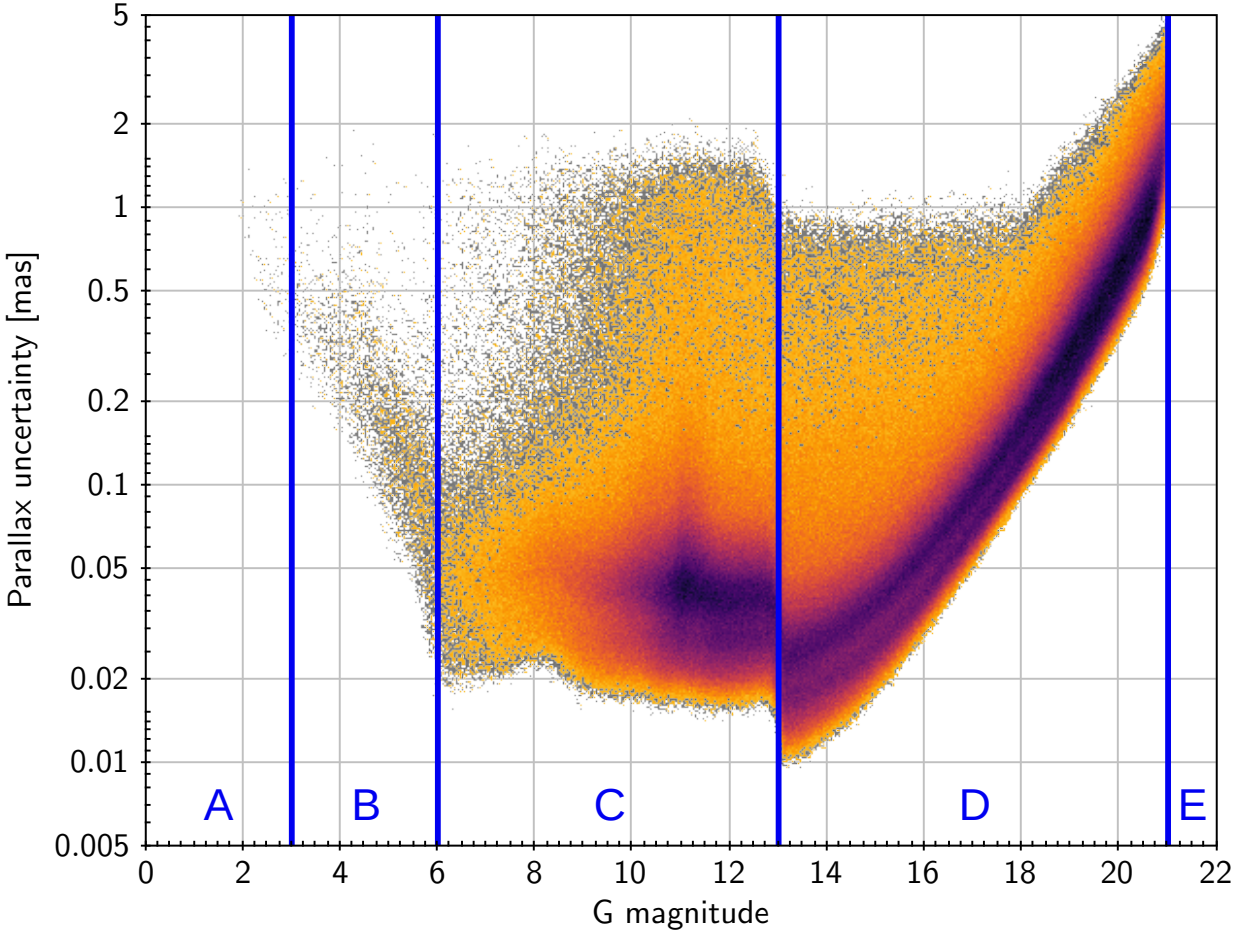
Formal uncertainty in parallax



Regimes of G:

- A: Too bright
- B: Partly saturated (unreliable)
- C: Detector and calibration limited
- D: Photon limited
- E: Too faint (not published)

Formal uncertainty in parallax



Regimes of G:

- A: Too bright
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Formal uncertainties in *Gaia* DR2 were estimated from the internal consistency of measurements and do not represent the total error

Random and systematic errors

A useful model for the total (external) error in parallax for source i is

$$\varpi_i^{\mathrm{DR2}} - \varpi_i^{\mathrm{true}} = r_i + s(\alpha, \delta, G, C, \dots) \tag{1}$$

Random error r_i:

- On average zero, uncorrelated between different sources
- Formal uncertainty σ_i is a (possibly underestimated) estimate of its standard deviation: $\sigma_r = k\sigma_i$ with correction factor $k \gtrsim 1.0$

Systematic error s:

- May depend on several variables (position, magnitude, colour, ...)
- Same for sources with sufficiently similar position, magnitude, etc
- Mean value is the parallax zero point ϖ_0
- Variance is σ_s^2

Random and systematic errors

In this model the external (total) uncertainty becomes

$$\sigma_{\text{ext}} = \sqrt{k^2\sigma_i^2 + \sigma_s^2} \tag{2}$$

- Astrophysical applications using likelihood or Bayesian methods require the probability density of the total error $e_i = \varpi_i^{\text{DR2}} - \varpi_i^{\text{true}}$
- Most conservative assumption:
  e_i is Gaussian with mean value ϖ_0 and standard deviation σ_{ext}

External data must be used to "calibrate" the model
by estimating ϖ_0, k and σ_s (see next slides)

Values may depend on the sample used

Parallax zero point (ϖ_0)

The zero point ϖ_0 is the expected measured parallax for a source at infinity; it should thus be *subtracted* from the catalogue value.

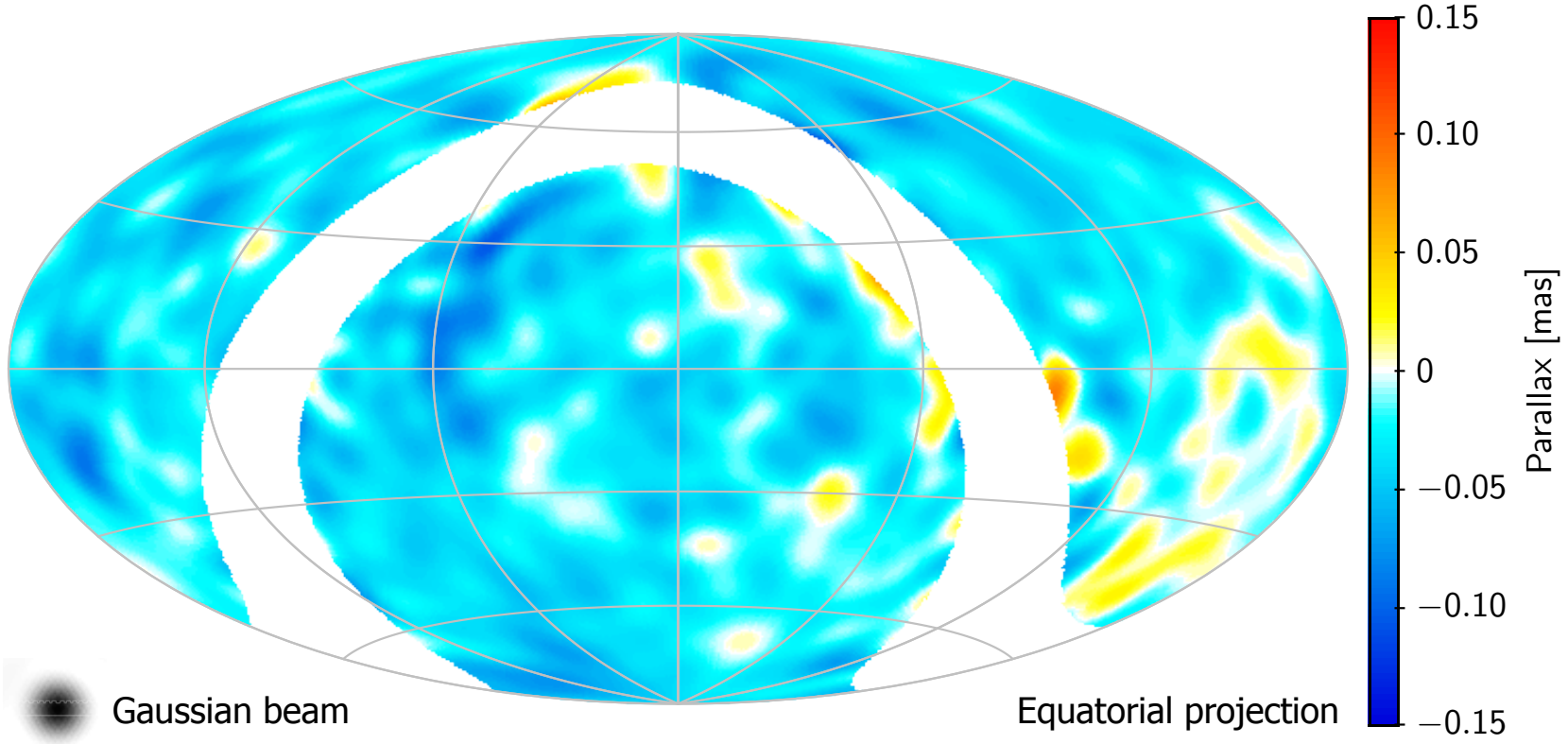
As a global average, $\varpi_0 \equiv \langle s \rangle \simeq -0.03$ mas, but:

- s definitely depends on (α, δ)
- s probably depends of G
- s may depend of $C = G_{\mathrm{BP}} - G_{\mathrm{RP}}$
- the dependence is probably multivariate, $s(\alpha, \delta, G, C, \ldots)$

No general recipe can be given
for the correction of the zero point

Systematics $s(\alpha, \delta)$ on large scales

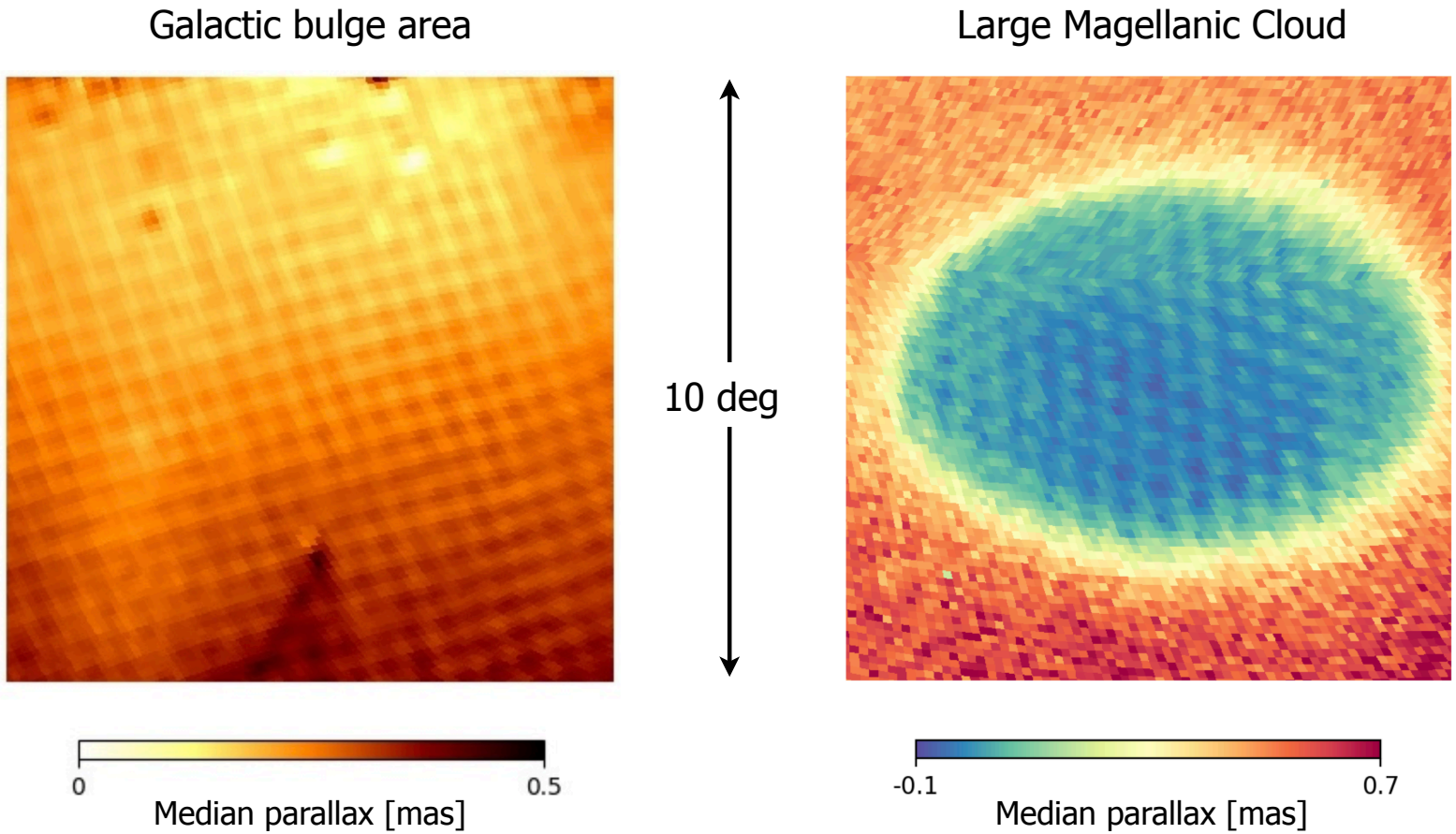
QSO parallaxes smoothed by a Gaussian beam ($\sigma = 3.7°$)
(only $|\sin b| > 0.2$ shown)



Mean value = −0.030 mas, RMS of smoothed values = 0.020 mas

Systematics $s(\alpha, \delta)$ on small scales

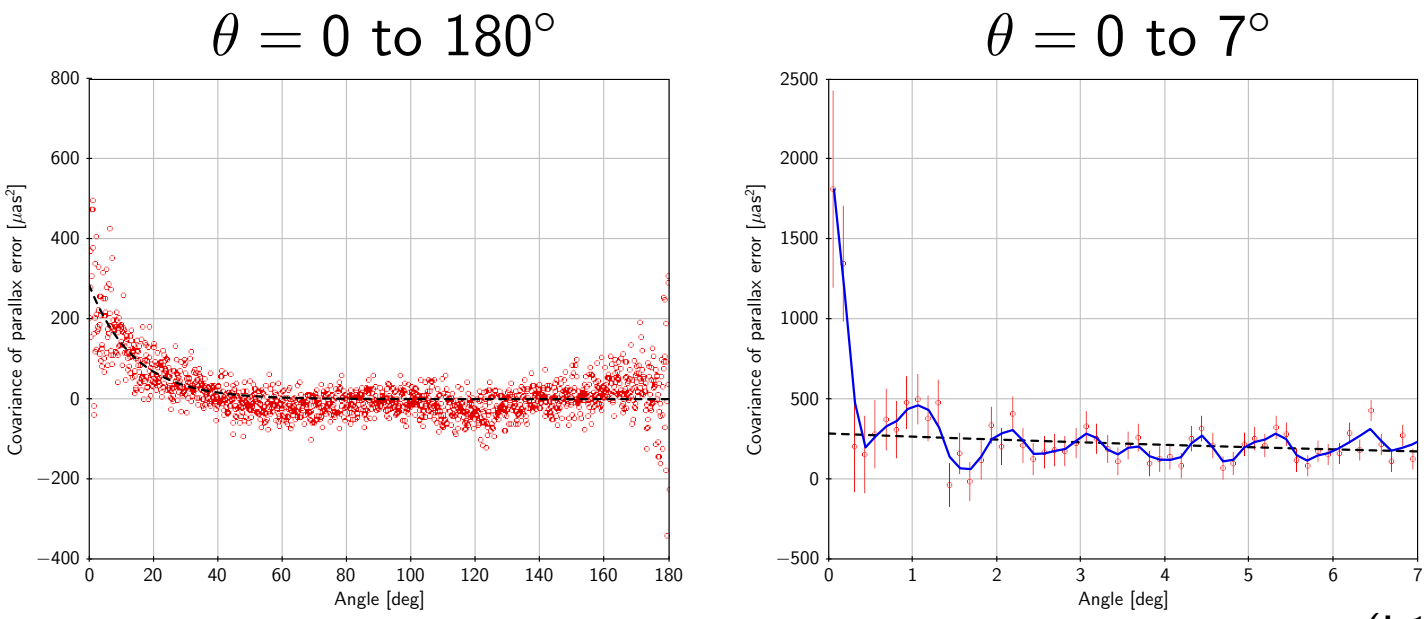
Quasi-periodic patterns imprinted by the *Gaia* scanning law



Characteristic period $\simeq$ 0.6 deg, RMS variation $\simeq$ 0.02–0.04 mas

(A18, Figs. 12–13)

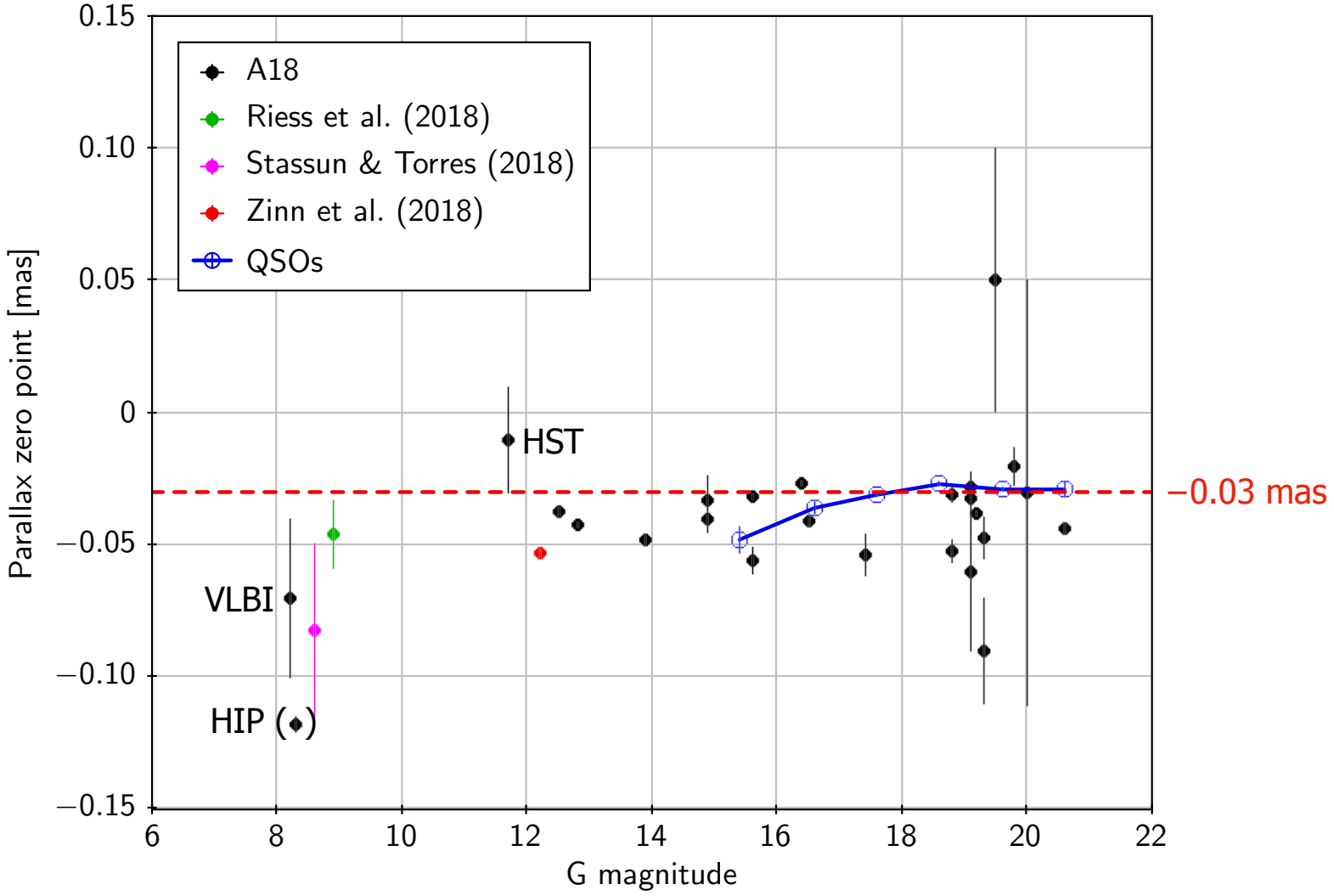
Spatial covariance function $V_\varpi(\theta)$



(L18, Fig. 14)

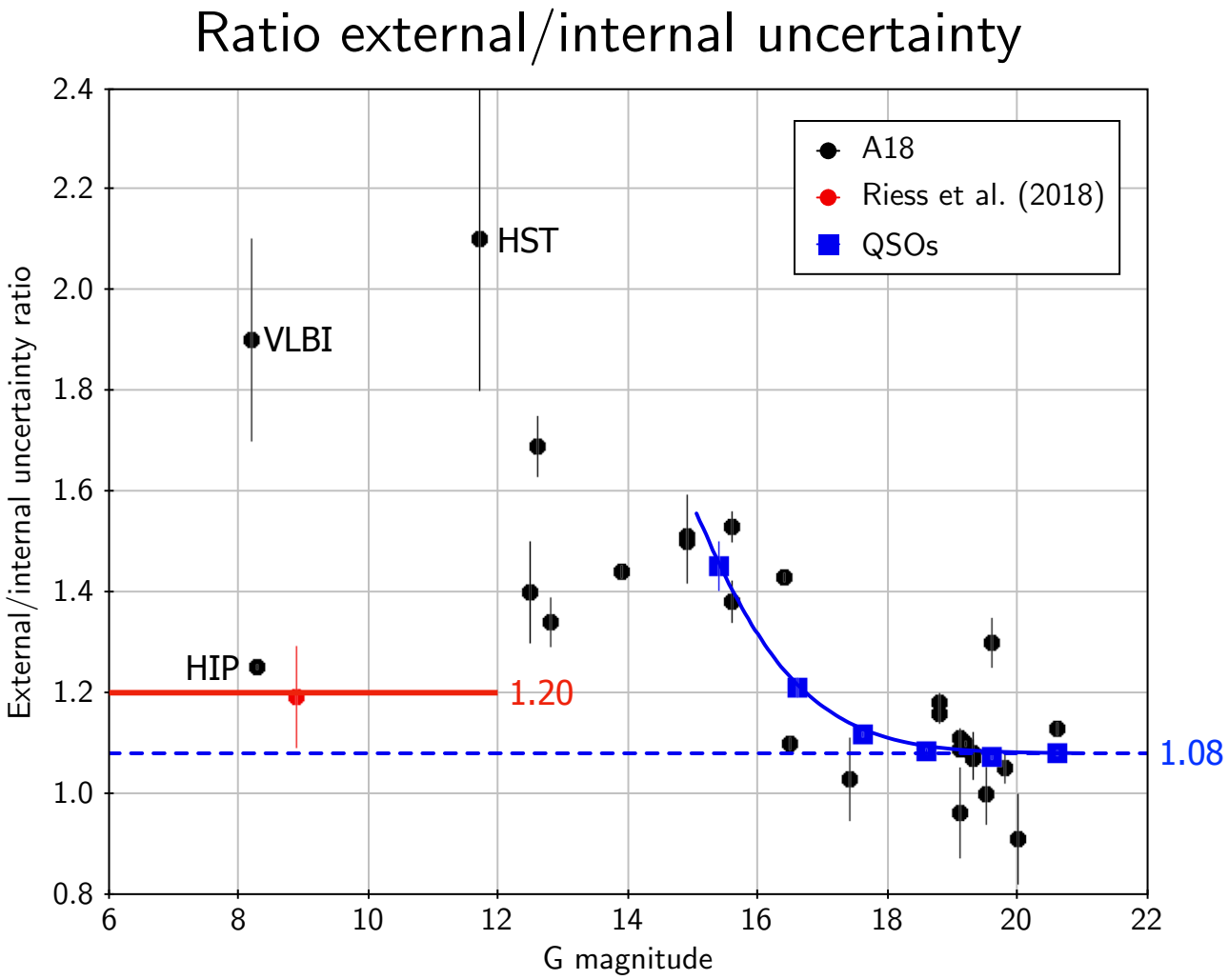
- $V_\varpi(\theta)$ is a statistical description of the systematic error $s(\alpha, \delta, \ldots)$ on different scales, equivalent to an angular power spectrum
- The total variance is $V_\varpi(0) = \sigma_s^2$, from which $\sigma_s = 0.043$ mas
- $V_\varpi(\theta)$ and $V_\mu(\theta)$ make it possible to estimate the systematic uncertainty of the mean parallax or proper motion of a cluster (see the extended version for details)

Parallax systematics vs. magnitude



A more negative zero point may apply to sources brighter than the QSOs

Estimating k and σ_s



k and σ_s estimated from $\sigma_{\text{ext}}/\sigma_i$ vs. G:

Quasars (blue):

$k = 1.08$

$\sigma_s = 0.043$ mas

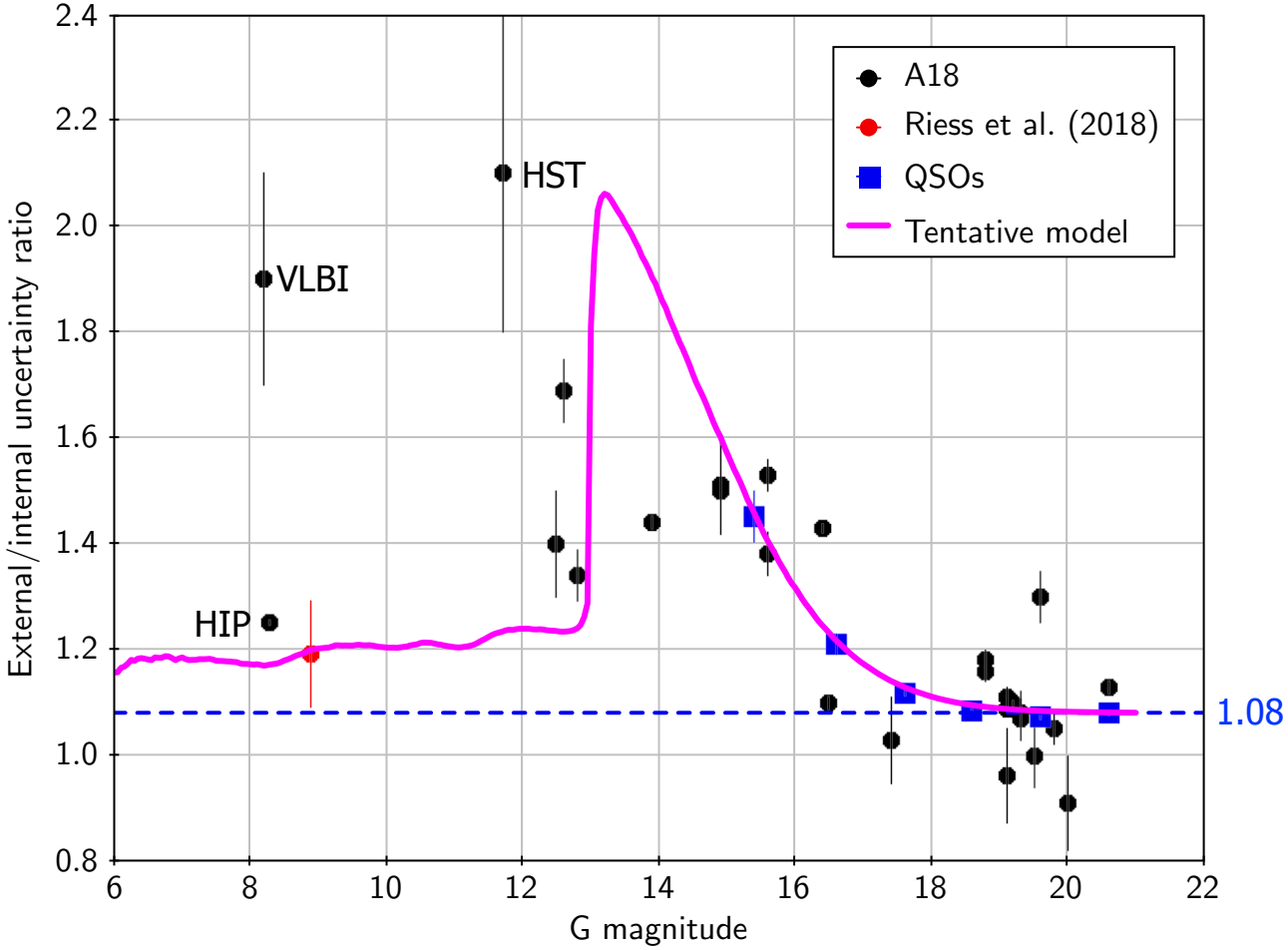
Bright stars (red):

$k = 1.08$ (assumed)

$\sigma_s = 0.021$ mas

A tentative external "calibration"

Ratio external/internal uncertainty



$$\sigma_{\rm ext} = \sqrt{k^2\sigma_i^2 + \sigma_s^2}$$

Faint ($G \gtrsim 13$):

$k = 1.08$

$\sigma_s = 0.043$ mas

Bright ($G \lesssim 13$):

$k = 1.08$

$\sigma_s = 0.021$ mas

The model may be too pessimistic for $G \simeq 13$ to 15

Systematics in proper motions

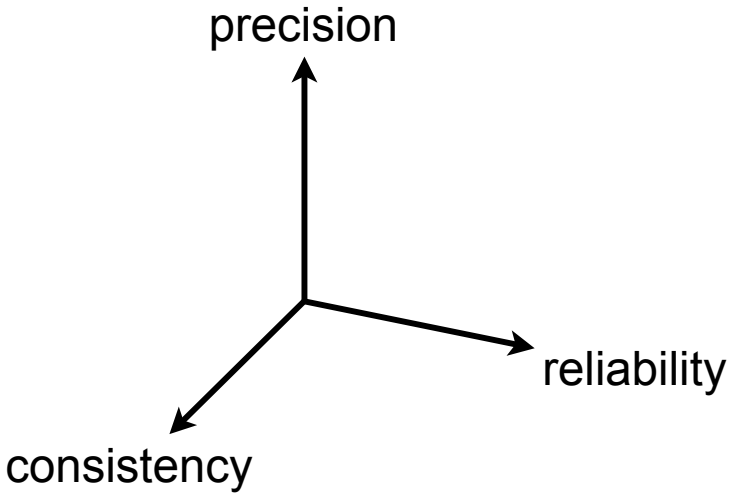
Main points:

- Systematics exist on large and small scales similar to the parallax
- For faint sources the reference frame is effectively non-rotating
- For $G \lesssim 12$ the proper motions have a significant ($\sim$0.15 mas yr^{-1}) rotation bias

For details see the extended version at

www.cosmos.esa.int/web/gaia/dr2-known-issues

Quality indicators for the astrometry



- Precision: `parallax_error`, `pmra_error`, `pmdec_error`, etc. → OK
- Reliability: `visibility_perods_used` ($\geq$ 6 for full solutions) → OK
- Consistency (goodness of fit to the 5-parameter model):
  - ▷ `astrometric_n_bad_obs_al`
  - ▷ `astrometric_gof_al`
  - ▷ `astrometric_chi2_al`
  - ▷ `astrometric_excess_noise`
  - ▷ `astrometric_excess_noise_sig`

  } → not recommended

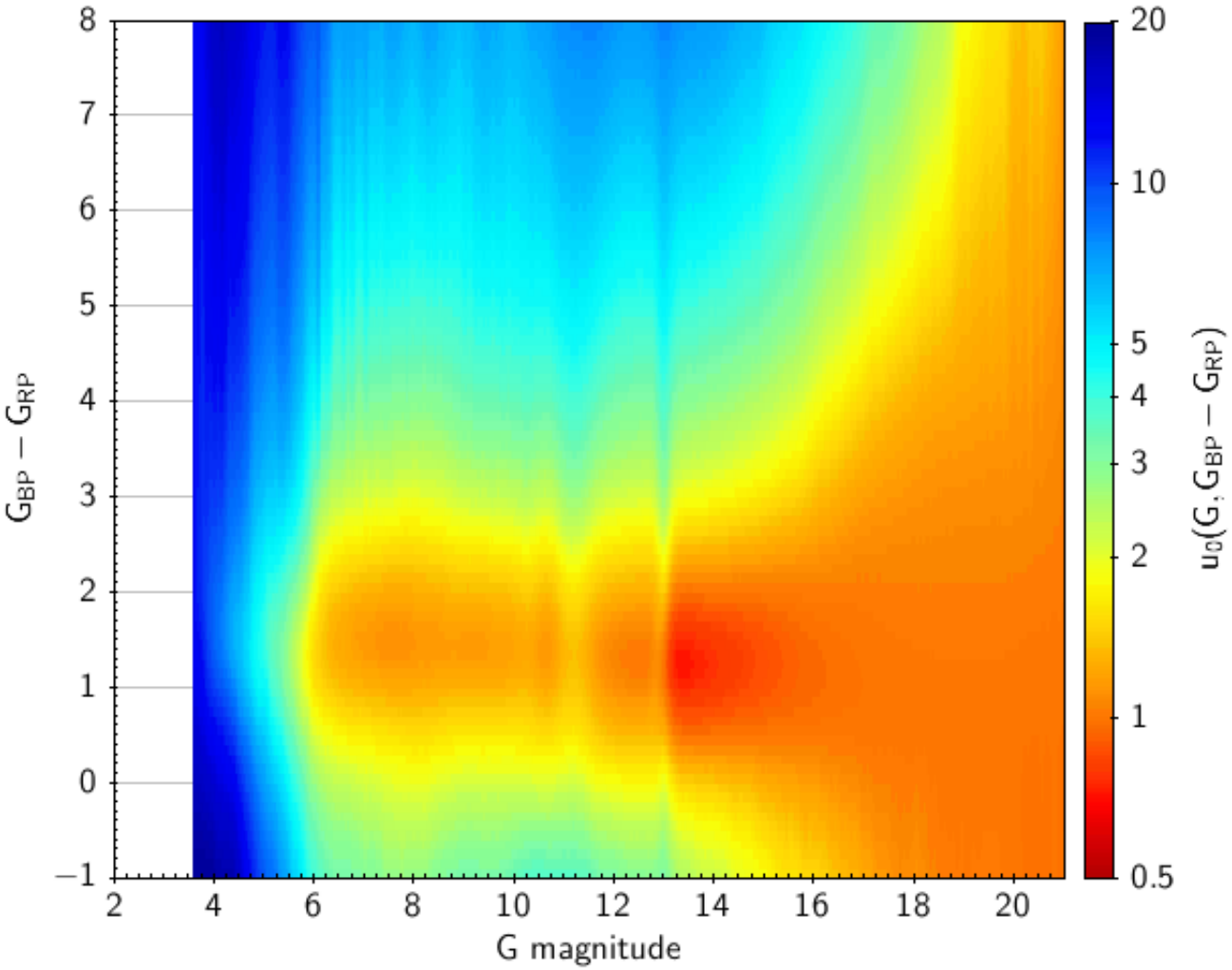
Renormalised Unit Weight Error

- Recommended GoF indicator for *Gaia* DR2 astrometry
- Not given directly in the *Gaia* Archive
- Can be computed from the quantities:

$$\chi^2 = \texttt{astrometric\_chi2\_al}$$
$$N = \texttt{astrometric\_n\_good\_obs\_al}$$
$$G = \texttt{phot\_g\_mean\_mag}$$
$$C = \texttt{bp\_rp} \quad \text{(if available)}$$

- Unit weight error UWE $= \sqrt{\chi^2/(N-5)}$
- Renormalised unit weight error RUWE $=$ UWE$/u_0(G, C)$
- $u_0(G, C)$ is an empirical normalisation factor, provided as a lookup table on the ESA *Gaia* DR2 Known issues page

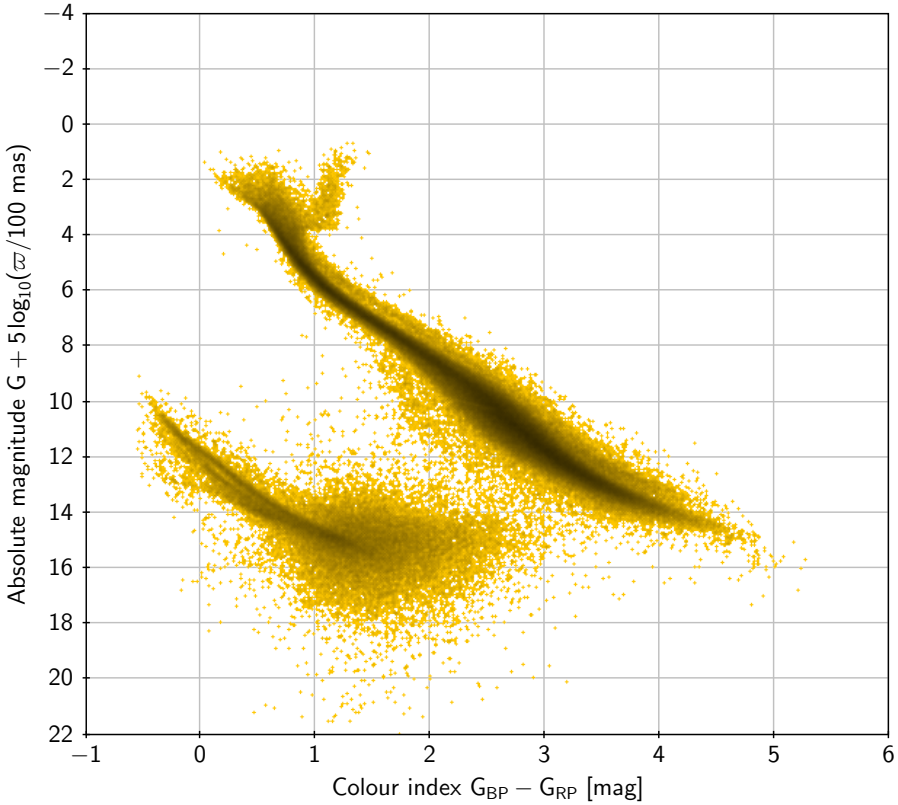
Normalisation factor $u_0(G, C)$



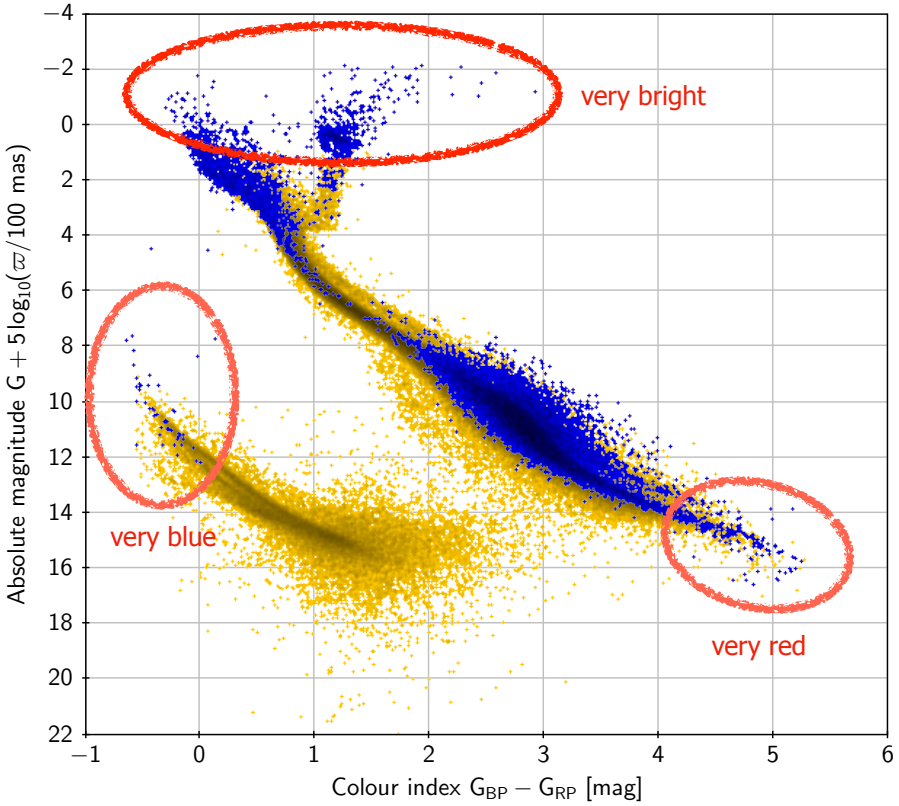
This is essentially the "typical" UWE for a given magnitude and colour

HRD filtered by UWE and RUWE

UWE < 1.96



RUWE < 1.40



Limits chosen to retain the same number of sources

Filtering by RUWE gives a cleaner HRD

Blue dots are sources missing in the left diagram

Spurious parallaxes

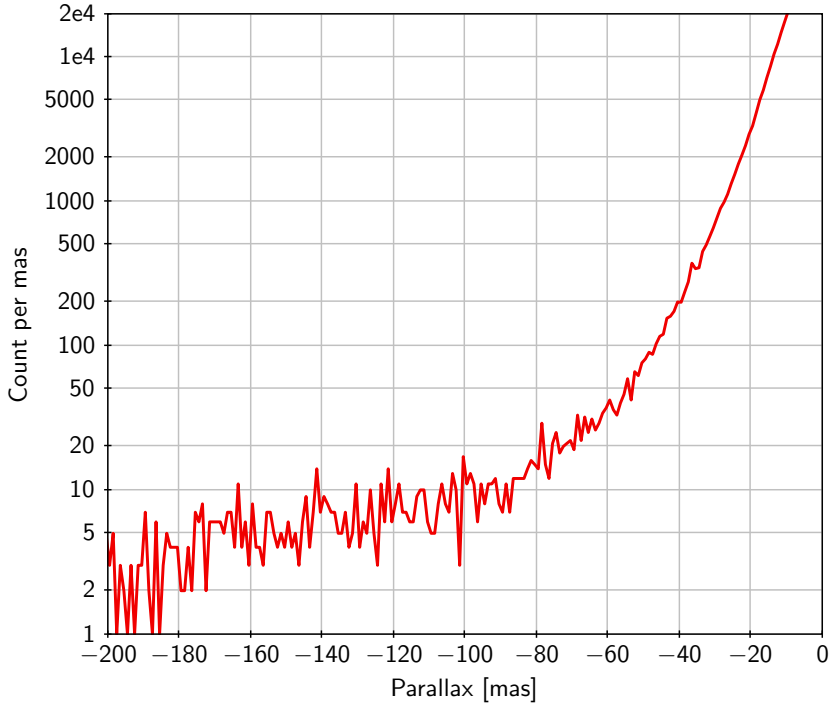
Gaia DR2 contains some parallaxes that are horrendously wrong

Source ID	G	parallax	RUWE
4062964299525805952	19.63	1851.88 ± 1.29	1.44
4065202424204492928	19.88	1847.43 ± 1.87	1.01
4051942623265668864	19.35	1686.27 ± 1.47	1.63
4048978992784308992	19.78	1634.28 ± 1.97	1.50
$\vdots$	$\vdots$	$\vdots$	$\vdots$
4089303169338901632	20.35	-1621.17 ± 1.83	0.92
4059697925504813440	20.76	-1706.70 ± 1.99	1.17
4052499285375616384	20.00	-1787.00 ± 1.45	1.24
4090728411324689792	20.00	-1856.58 ± 2.72	1.72

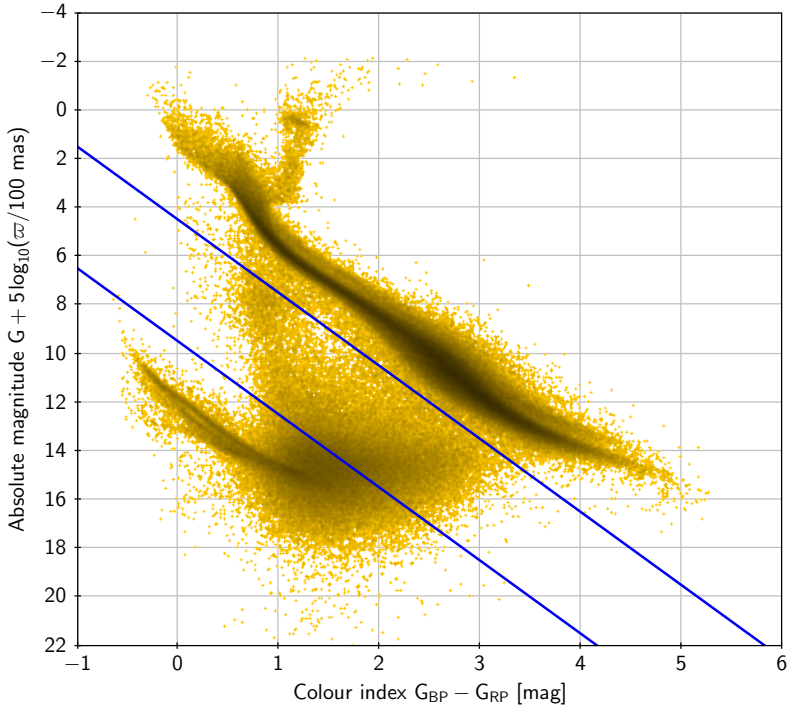
The really big errors ($> 1''$) are probably cross-matching errors causing spurious parallax solutions – these are typically faint sources

Anomalous parallaxes

Tail of negative parallaxes



HRD for $\varpi > 10$ mas



In the HRD most sources between blue lines have parallax errors >10 mas

Sources with anomalous parallaxes (wrong by ± 10 to ± 100 mas) are usually partially resolved doubles ($\rho \simeq 0.2$–$1''$, $\Delta G < 2$ mag)
$\Rightarrow$ need dedicated processing (future releases)

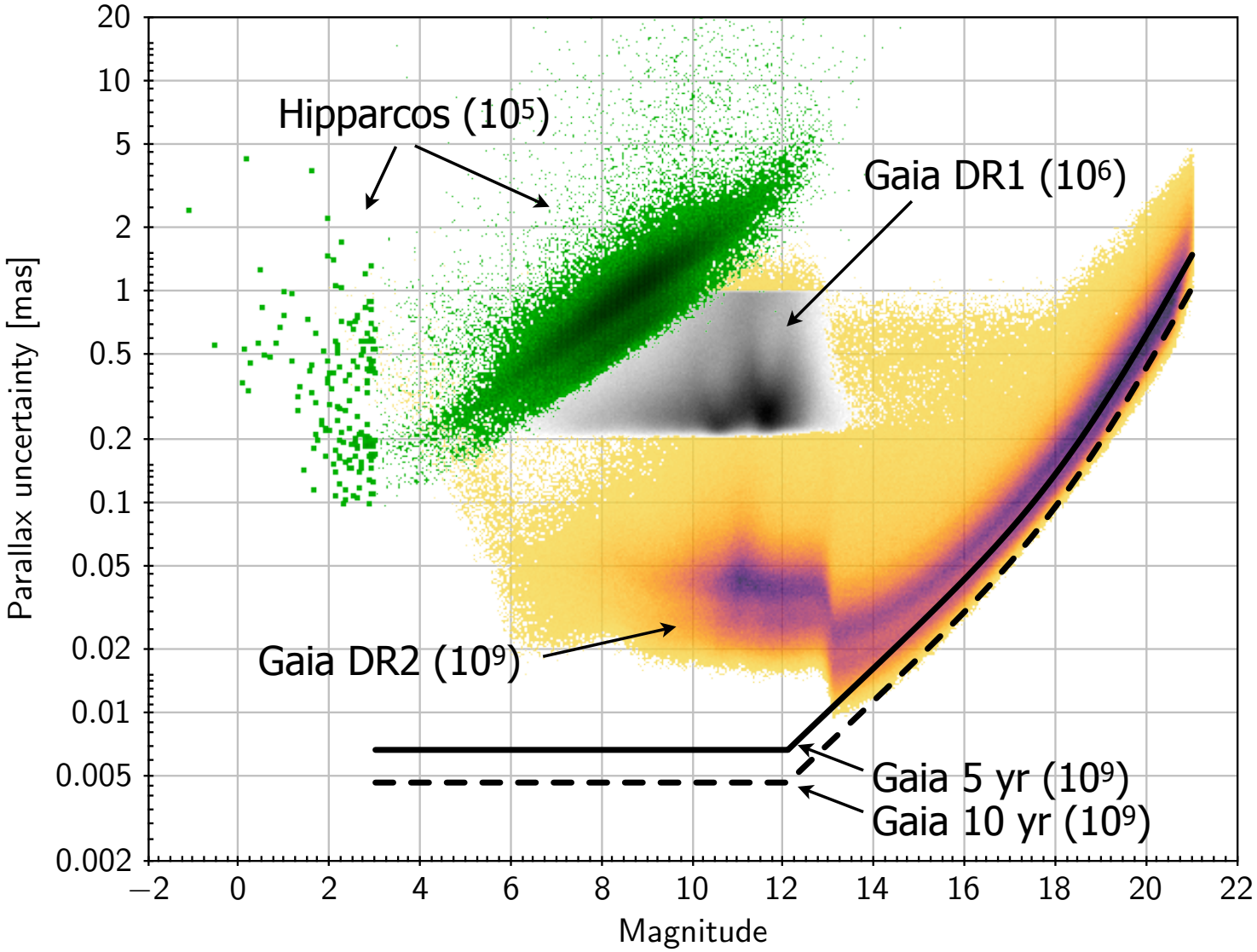
Conclusions and outlook

- This talk focused on peculiarities and deficiencies in *Gaia* DR2
- Knowing about them will help users make optimum use of the data
- Conversely, feedback from users will help us to understand the data
- Future releases will benefit from the accumulated insight

This should not obscure the tremendous advances made:

Gaia DR2 = A giant leap for astronomy!

Formal uncertainty in parallax



Thank you!

For more information please check the extended version at

ESA Gaia → Gaia Data → Data Release 2 → Known issues

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