The Tycho-Gaia Astrometric Solution (TGAS)

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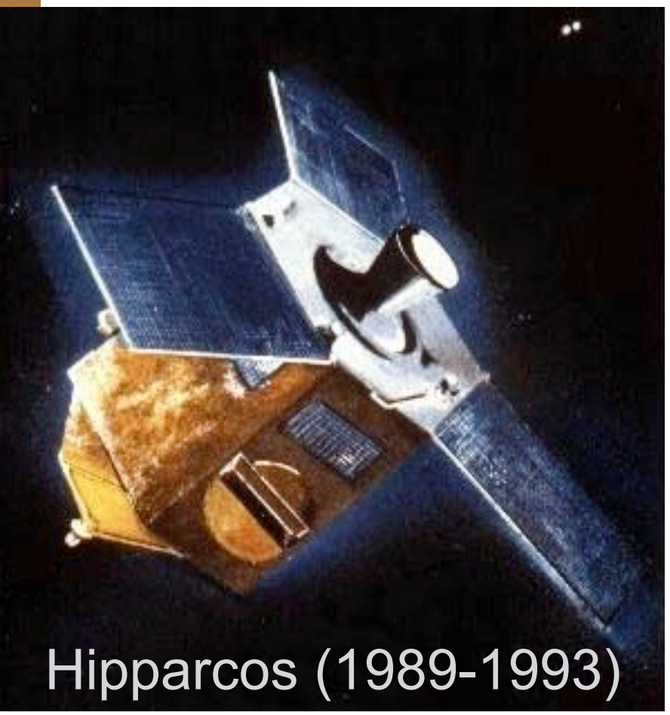
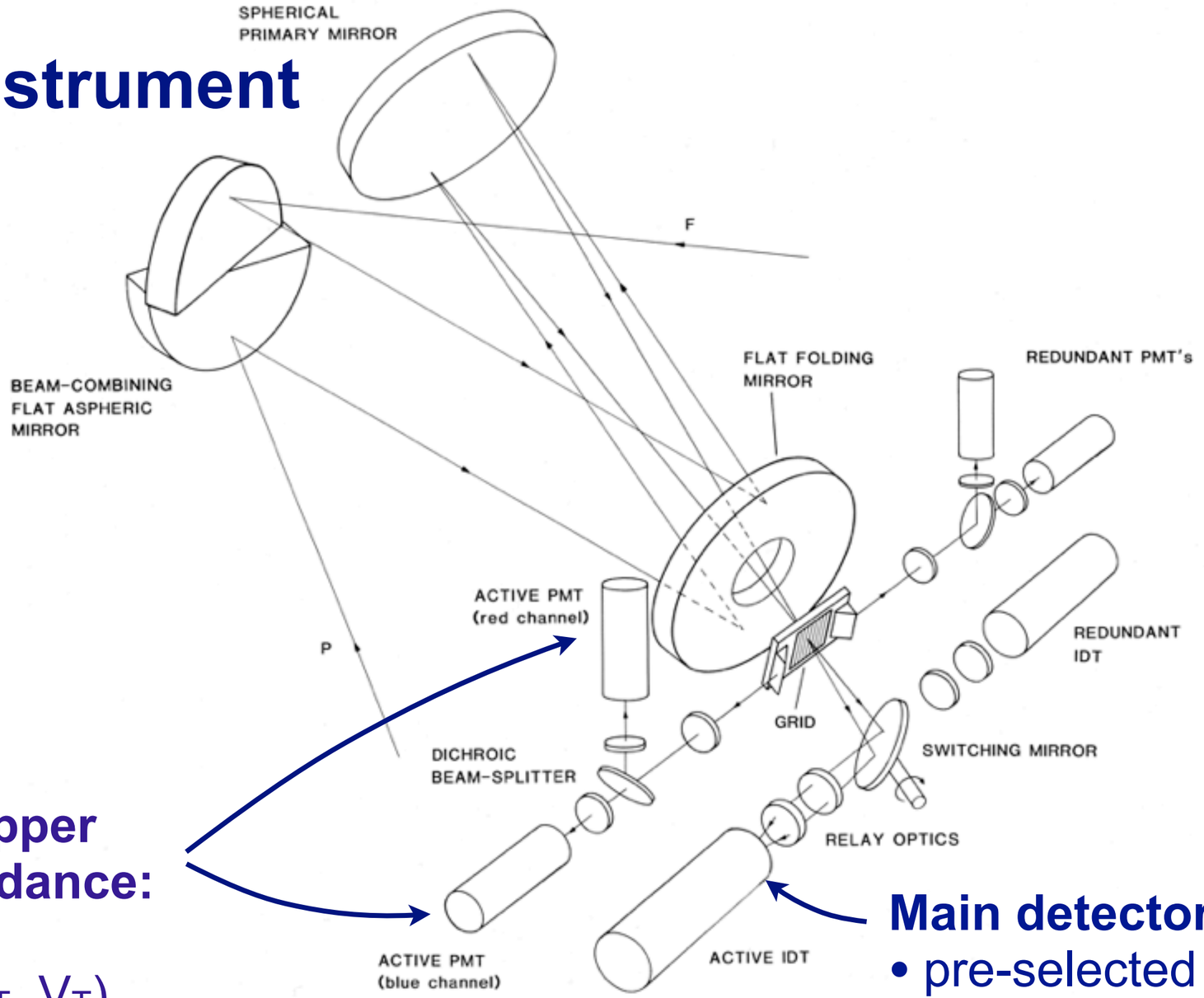
Outline of talk

- Historical background and concept
- Reference frame of TGAS
- Uncertainties
- Correlations
- Systematics
- Conclusions

The Hipparcos instrument


Hipparcos (1989-1993)



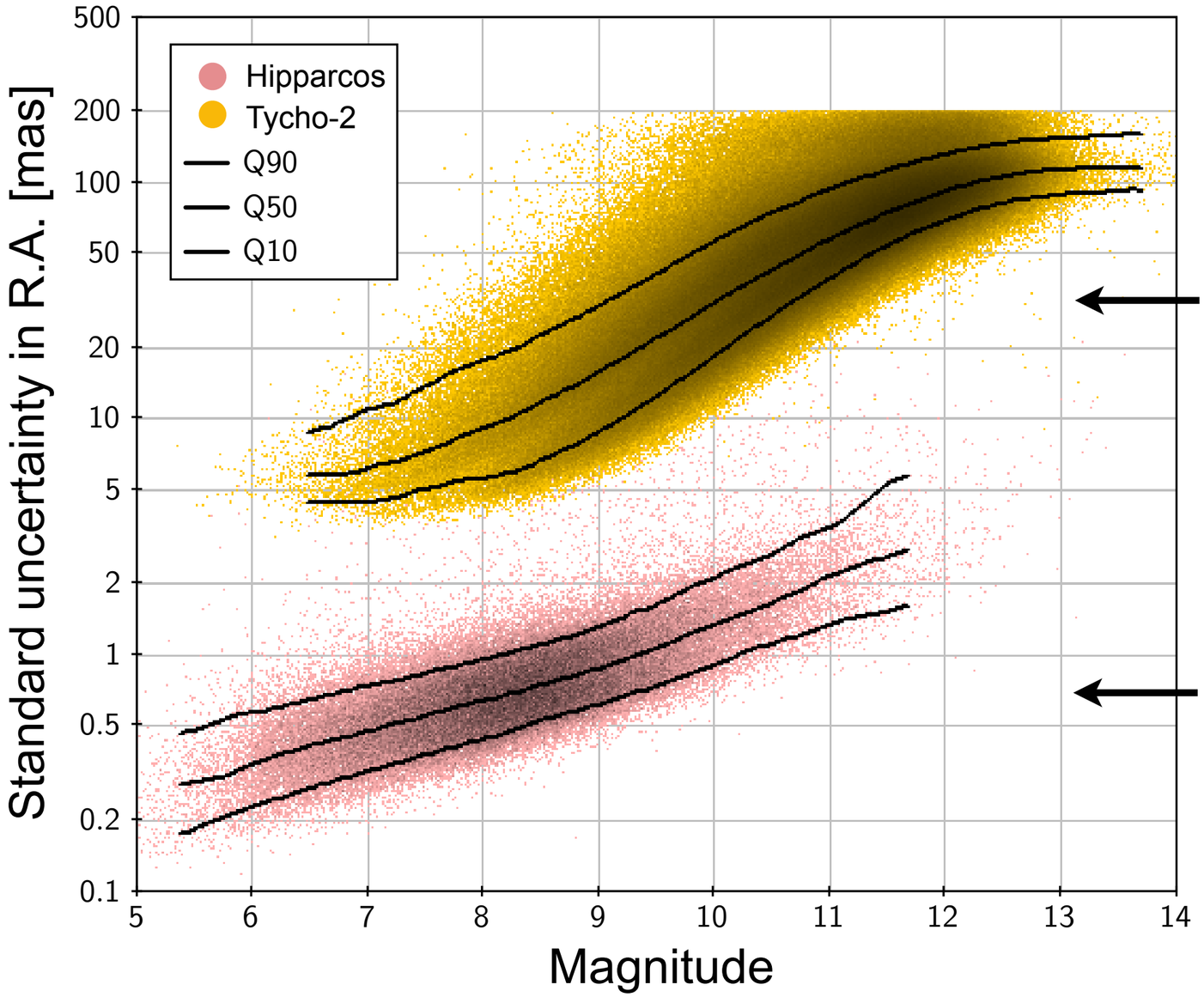
Auxiliary starmapper detectors for guidance:
- no pre-selection
- two channels (B_T, V_T)

➜ Tycho/Tycho-2 Catalogue

Main detector:
- pre-selected stars
- one channel (Hp)

➜ Hipparcos Catalogue

Hipparcos and Tycho-2: Positional errors at 1991.25



Tycho-2 Catalogue
2.5 million stars
(Høg et al. 2000)

Hipparcos Catalogue
118,000 stars
(van Leeuwen 2007)

From HTPM to TGAS

- In 2009 François Mignard proposed the ***Hundred Thousand Proper Motions (HTPM)*** project as an early “appetizer” for things to come from the Gaia mission

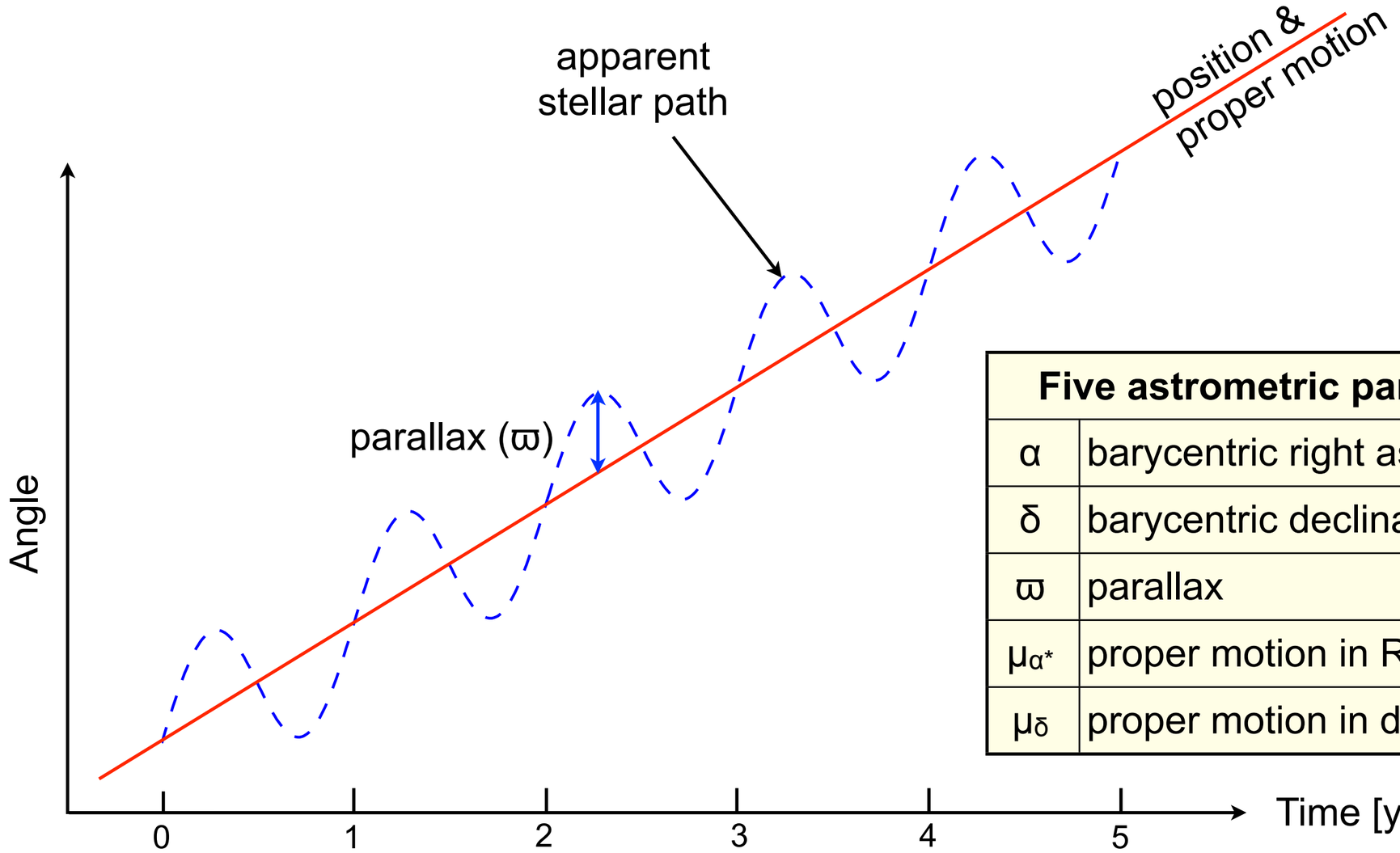
- Basic idea: to get a 10-fold improvement of the Hipparcos proper motions from early Gaia observations of Hipparcos stars, using the >20 yr epoch difference

- HTPM was adopted as part of Gaia DR1 in the official data release scenario

- A natural extension of HTPM is to use Tycho-2 positions as well
  ➜ ***Tycho-Gaia Astrometric Solution (TGAS)*** (Michalik et al., A&A 574, A115, 2015)

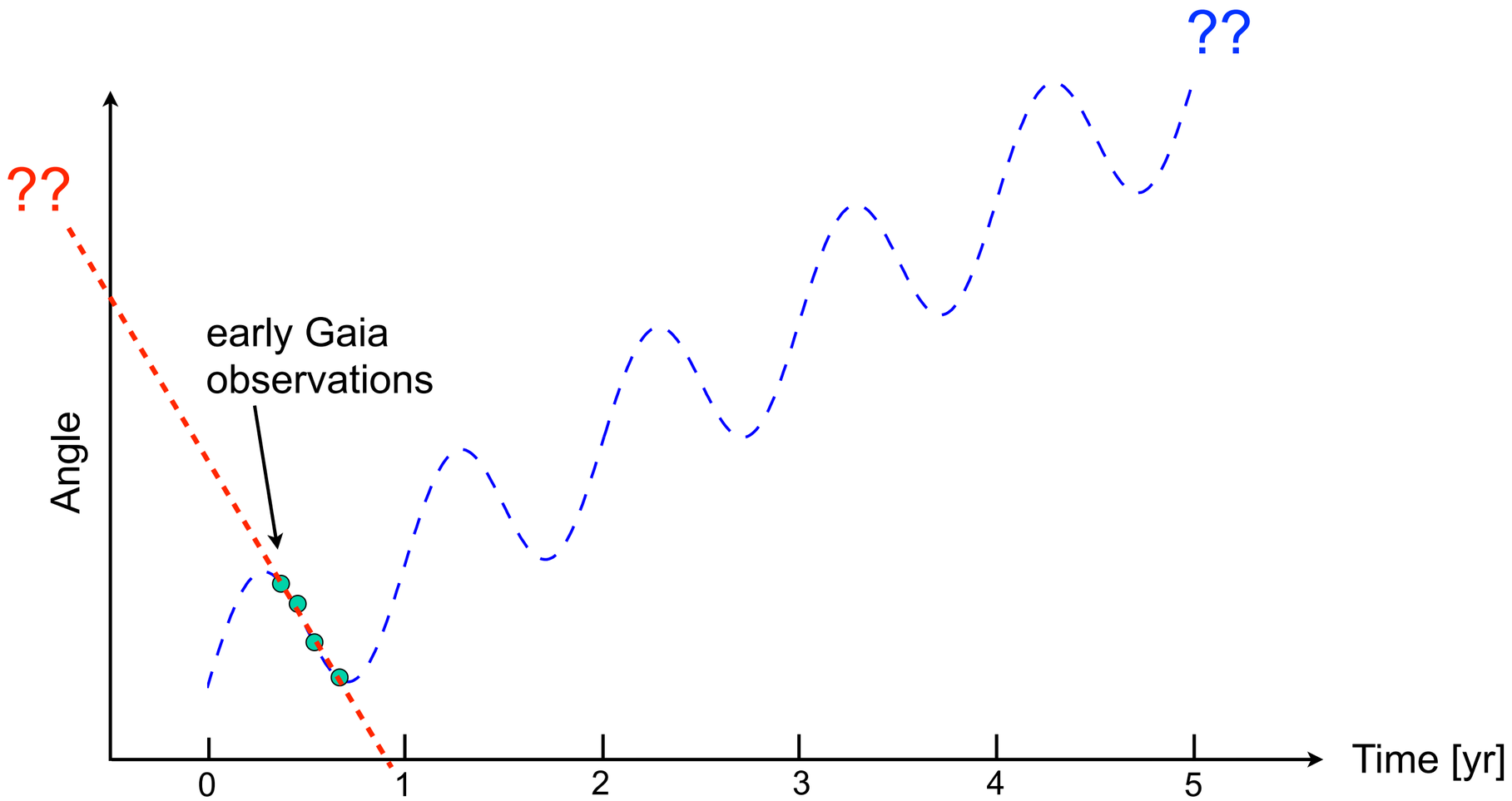
- TGAS allowed us to ***verify Gaia’s astrometric performance*** and ***improve the calibration models*** about 1 year earlier than otherwise possible

Astrometric model for a single star



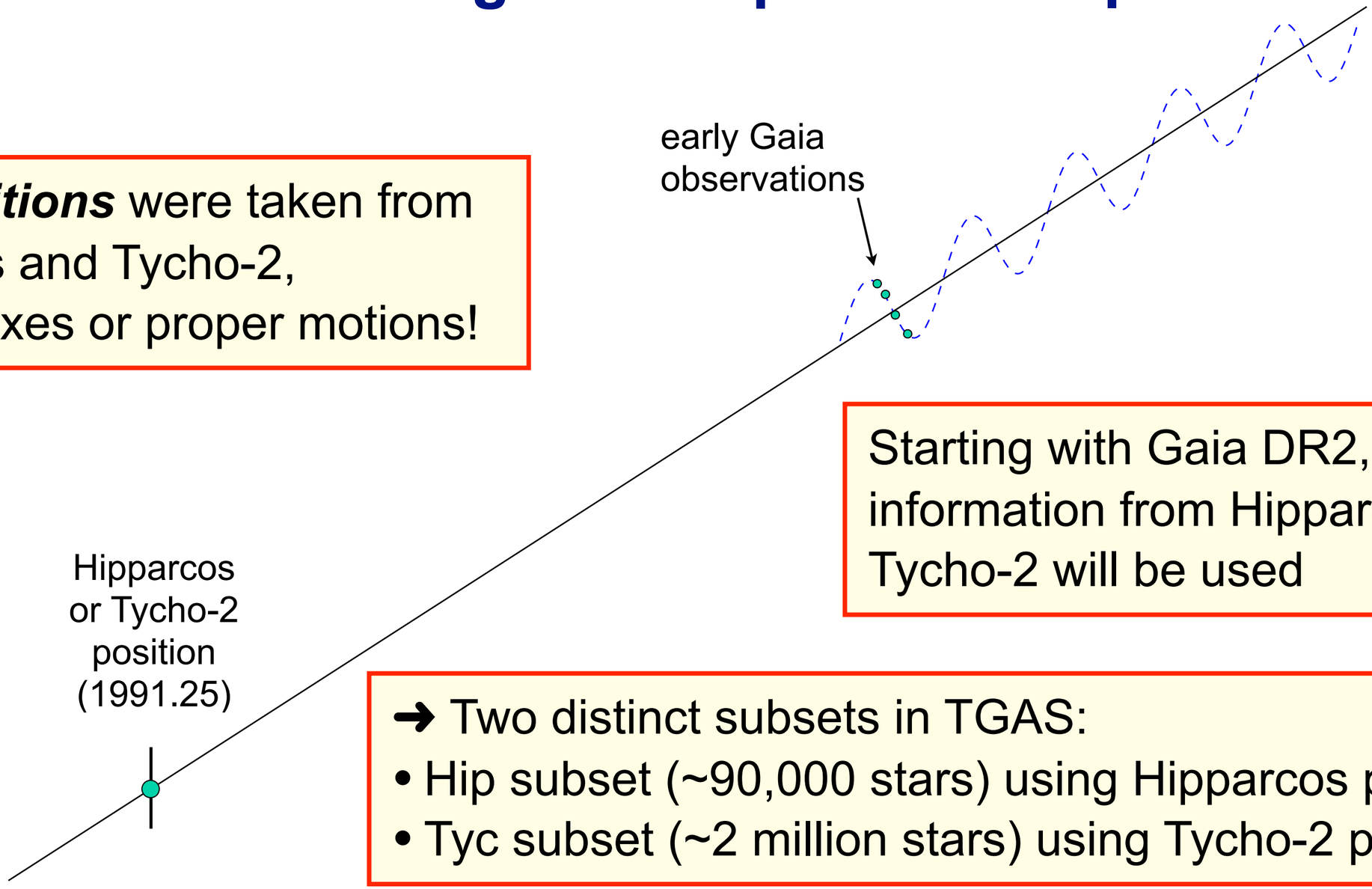
Five astrometric parameters per star	
α	barycentric right ascension at 2015.0
δ	barycentric declination at 2015.0
ϖ	parallax
μ_{α^*}	proper motion in R.A. (× cos δ)
μ_δ	proper motion in declination

Degeneracy for <1 yr of observations



TGAS: Using the old position as prior

Only ***positions*** were taken from Hipparcos and Tycho-2, no parallaxes or proper motions!



Starting with Gaia DR2, no prior information from Hipparcos and Tycho-2 will be used

➜ Two distinct subsets in TGAS:

- Hip subset (~90,000 stars) using Hipparcos positions
- Tyc subset (~2 million stars) using Tycho-2 positions

The reference frame of Gaia DR1

The ICRS = ***International Celestial Reference System*** (IAU 1997) is the basis for all modern astrometric catalogues (replacing FK4, FK5, equinox B1950, J2000, etc)

ICRS is ***non-rotating*** with respect to distant quasars − orientation defined by radio (VLBI) observations of ~300 quasars

Before Gaia, the ***Hipparcos Catalogue*** was the best ***optical*** realisation of the ICRS

Both Hipparcos and TGAS are nominally on ICRS

But we find that the ***Hipparcos Reference Frame rotates wrt ICRS by 0.24 mas/yr*** :

$$\mu_{\alpha*,\mathrm{ICRS}} = \mu_{\alpha*,\mathrm{HIP}} - 0.126 \sin\delta\cos\alpha + 0.185 \sin\delta\sin\alpha - 0.076\cos\delta$$

$$\mu_{\delta,\mathrm{ICRS}} = \mu_{\delta,\mathrm{HIP}} + 0.126 \sin\alpha + 0.185\cos\alpha$$

Uncertainties in TGAS

Five astrometric parameters per star:

$$\alpha,\ \delta,\ \varpi,\ \mu_{\alpha*},\ \mu_{\delta}$$

Gaia Archive:

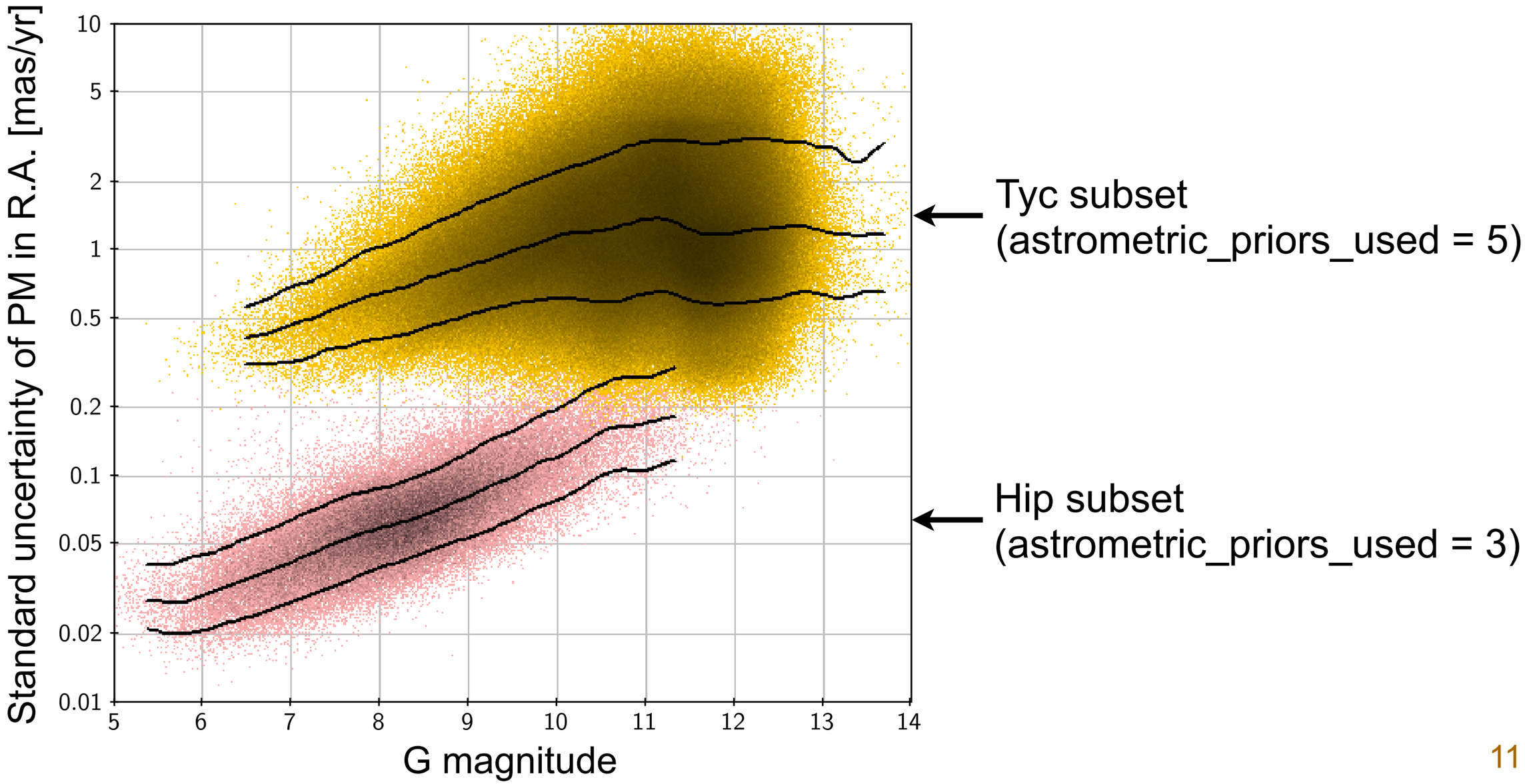
ra, dec, parallax, pmra, pmdec

Five standard uncertainties:

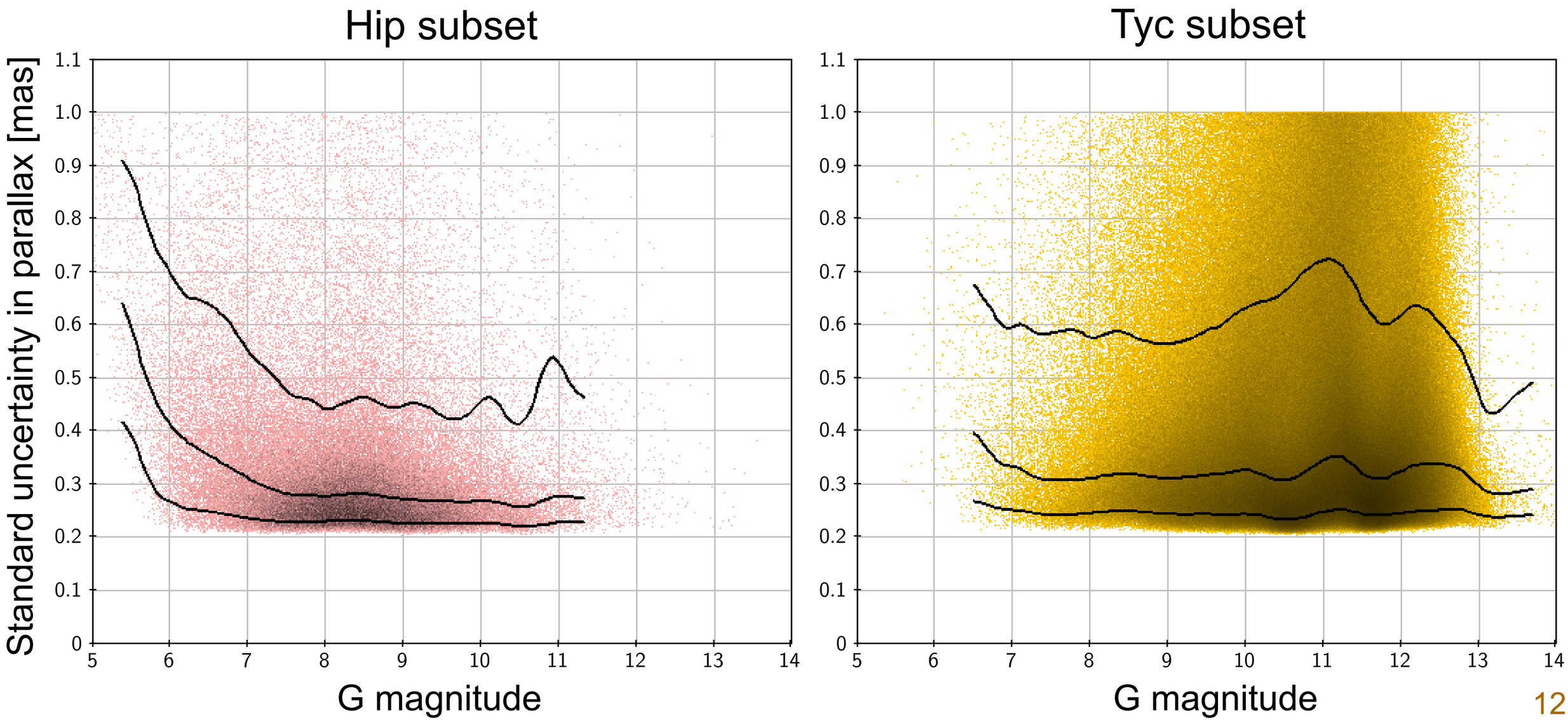
$$\sigma_{\alpha*},\ \sigma_{\delta},\ \sigma_{\varpi},\ \sigma_{\mu\alpha*},\ \sigma_{\mu\delta}$$

ra_error, dec_error, ...

Standard uncertainty in proper motion versus magnitude

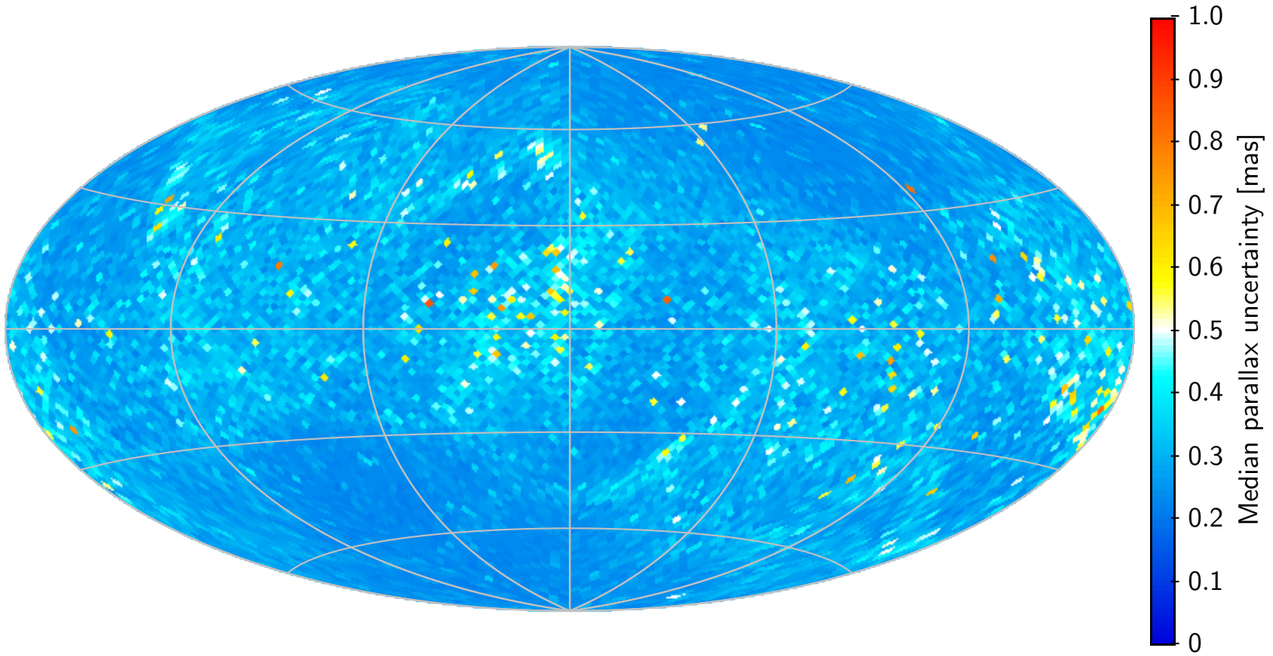


Standard uncertainty in parallax versus magnitude

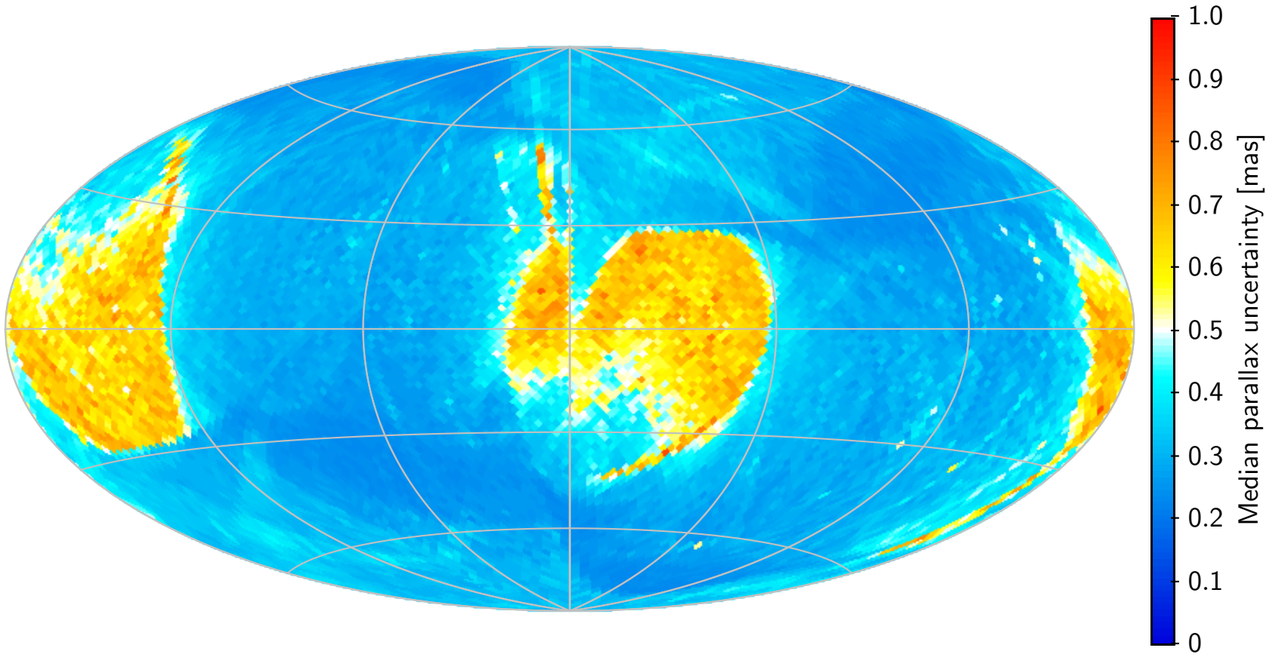


Median standard uncertainty in parallax versus position

Hip subset



Tyc subset



Correlations in TGAS

Five astrometric parameters per star:

$$\alpha,\ \delta,\ \varpi,\ \mu_{\alpha*},\ \mu_\delta$$

Gaia Archive:

ra, dec, parallax, pmra, pmdec

Five standard uncertainties:

$$\sigma_{\alpha*},\ \sigma_\delta,\ \sigma_\varpi,\ \sigma_{\mu\alpha*},\ \sigma_{\mu\delta}$$

ra_error, dec_error, ...

Ten correlation coefficients ($-1 < \rho < 1$):

$$\rho(\alpha,\delta),\quad \rho(\alpha,\varpi),\quad \rho(\alpha,\mu_{\alpha*}),\quad \rho(\alpha,\mu_\delta),$$
$$\rho(\delta,\varpi),\quad \rho(\delta,\mu_{\alpha*}),\quad \rho(\delta,\mu_\delta),$$
$$\rho(\varpi,\mu_{\alpha*}),\quad \rho(\varpi,\mu_\delta),$$
$$\rho(\mu_{\alpha*},\mu_\delta)$$

ra_dec_corr, ...

Correlations matter!

- Correlation coefficients (ρ) are needed for error propagation involving more than one astrometric parameter, e.g.:

$$v_\mathrm{T} = 4.7405\,\mu/\varpi \quad \Rightarrow \quad \left(\frac{\sigma_{v_\mathrm{T}}}{v_\mathrm{T}}\right)^2 = \left(\frac{\sigma_\mu}{\mu}\right)^2 + \left(\frac{\sigma_\varpi}{\varpi}\right)^2 - \underbrace{2\rho(\varpi,\mu)\left(\frac{\sigma_\mu}{\mu}\right)\left(\frac{\sigma_\varpi}{\varpi}\right)}$$

neglecting this can give very wrong σ_{vT}

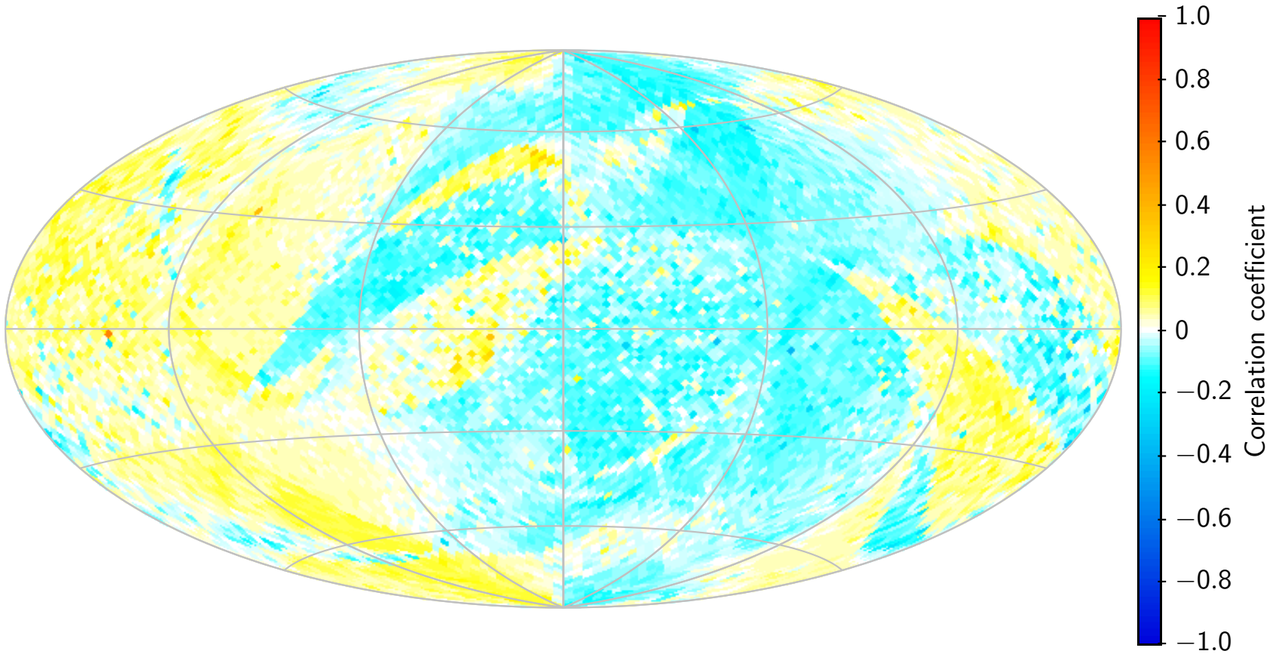
- Also when estimating model parameters (chi-square fitting, MLE, Bayesian analysis, ...):

$$\chi^2 = \begin{bmatrix}\Delta\mu_{\alpha*} & \Delta\mu_\delta & \Delta\varpi\end{bmatrix} \boldsymbol{C}^{-1} \begin{bmatrix}\Delta\mu_{\alpha*} \\ \Delta\mu_\delta \\ \Delta\varpi\end{bmatrix}$$

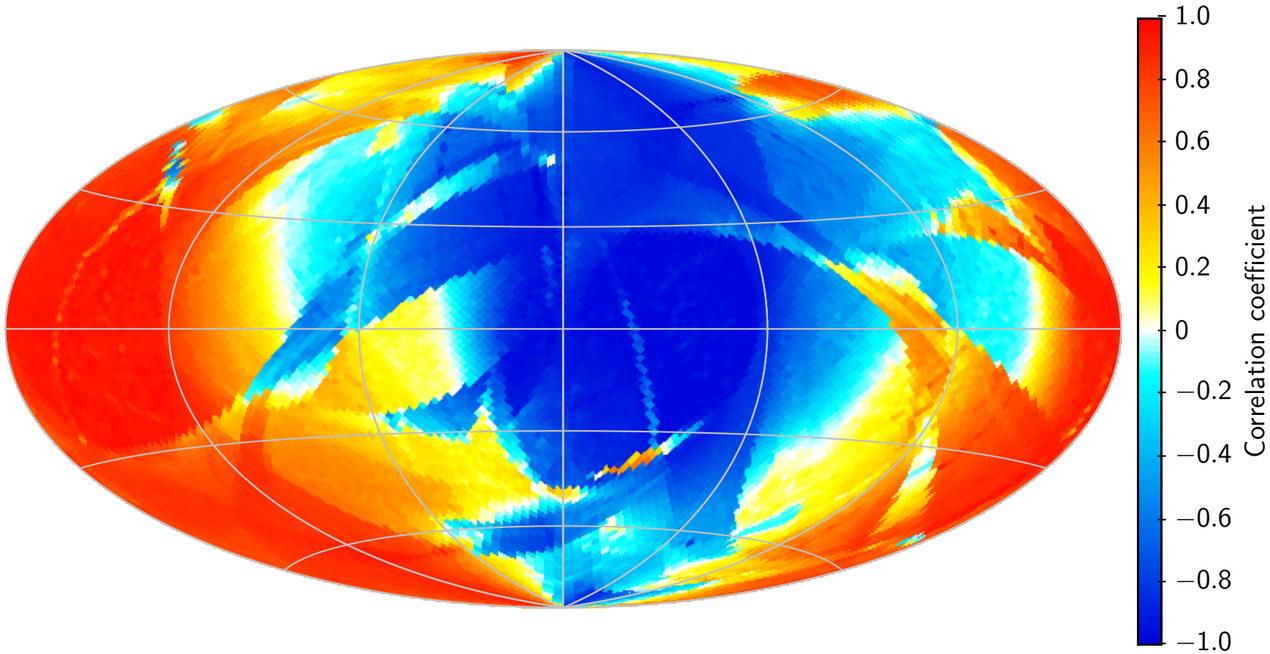
(***C*** = covariance matrix)

Median correlation coefficient (ϖ, μ_{α^*}) versus position

Hip subset

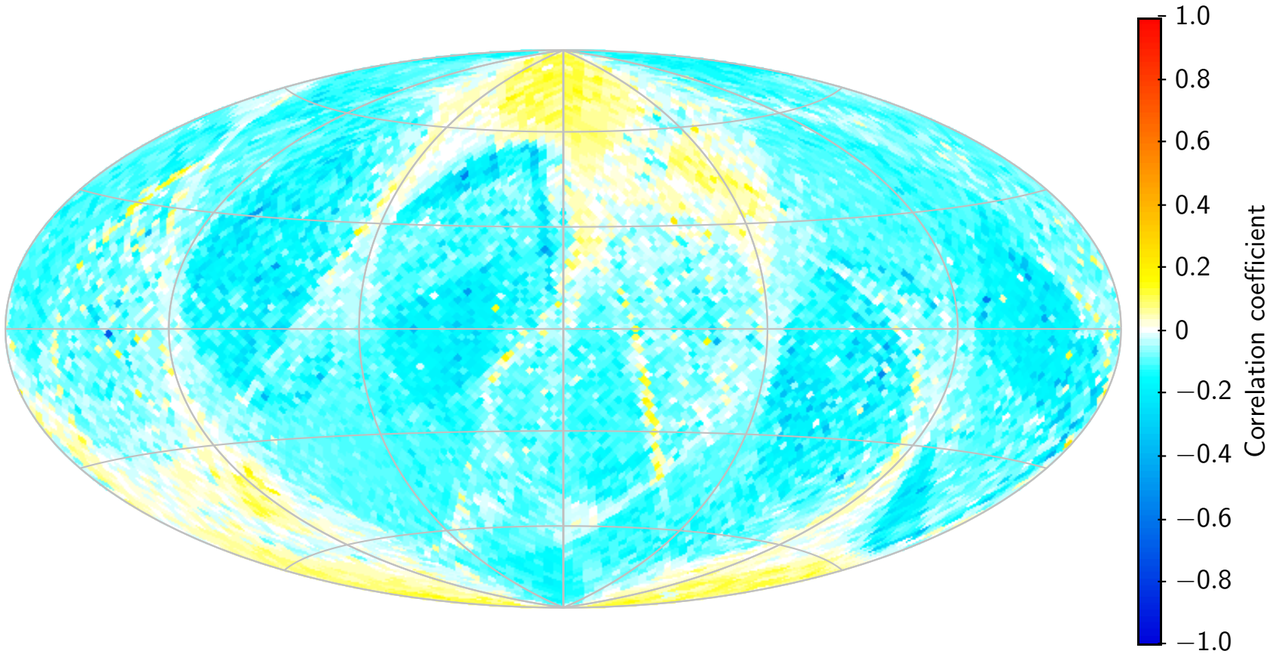


Tyc subset

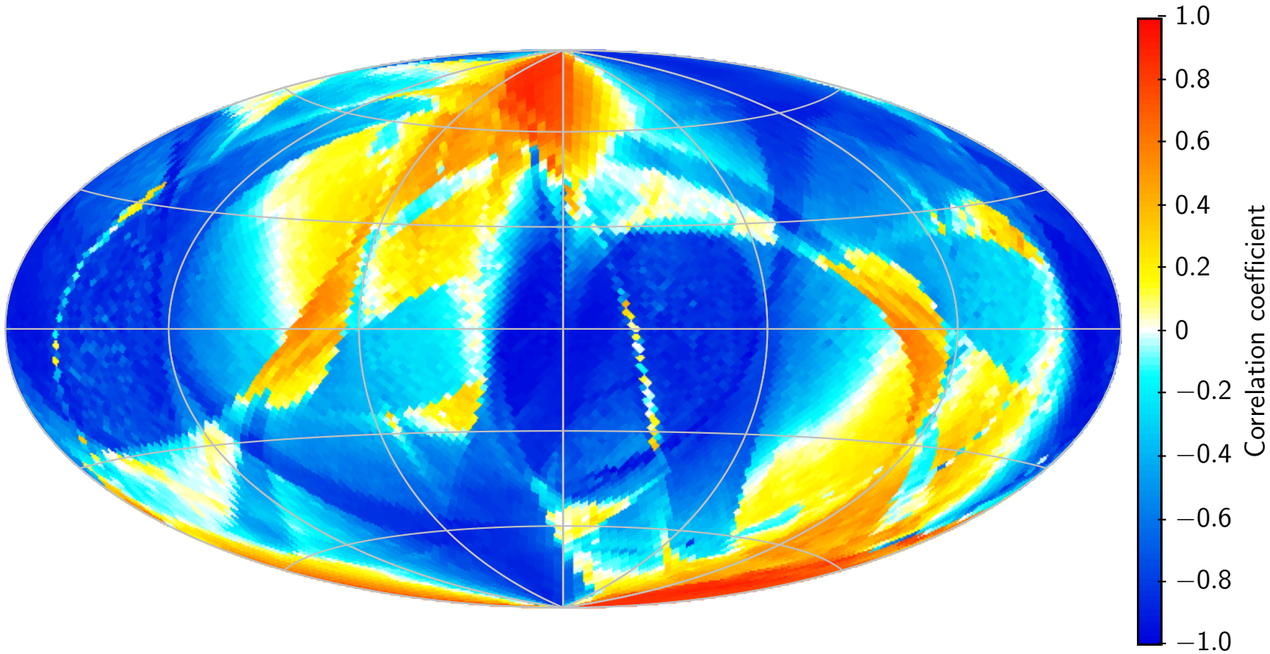


Median correlation coefficient (ϖ, μ_δ) versus position

Hip subset

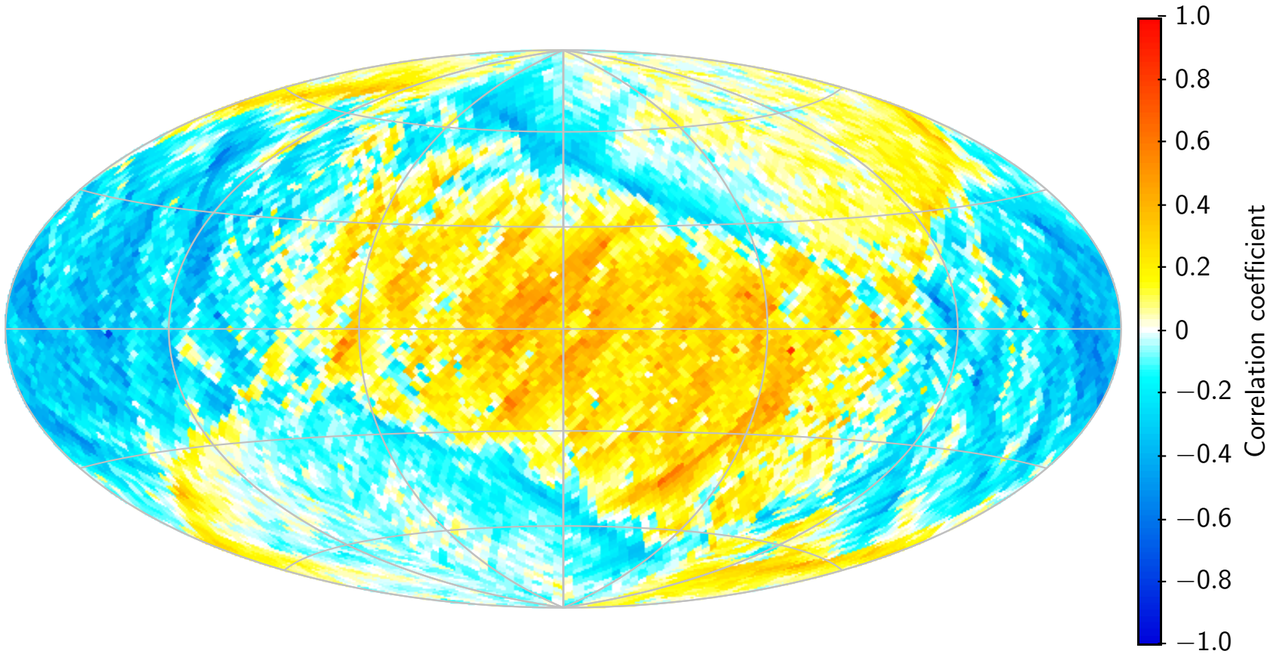


Tyc subset

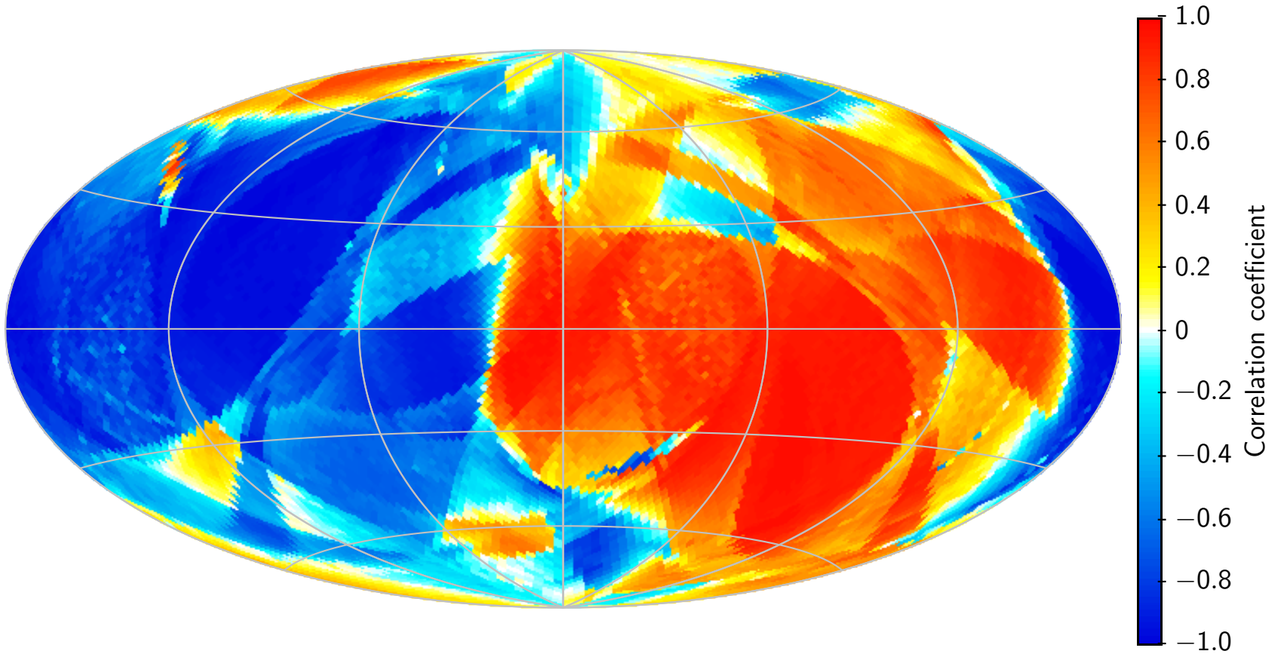


Median correlation coefficient (μ_{α^*}, μ_δ) versus position

Hip subset



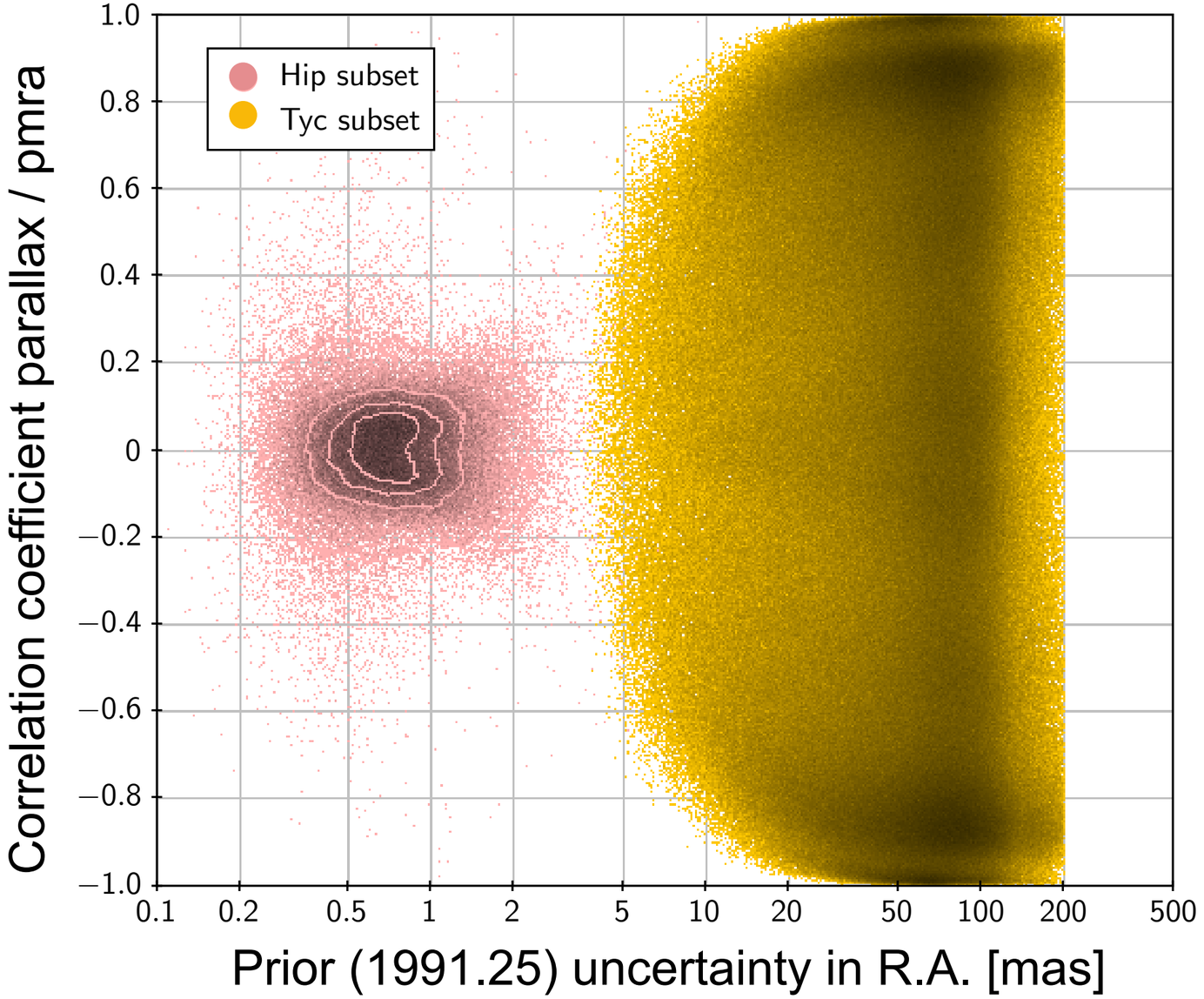
Tyc subset



Correlations often approach ±1 in the Tycho subset!

Correlations depend on the strength of the prior

strong prior ←



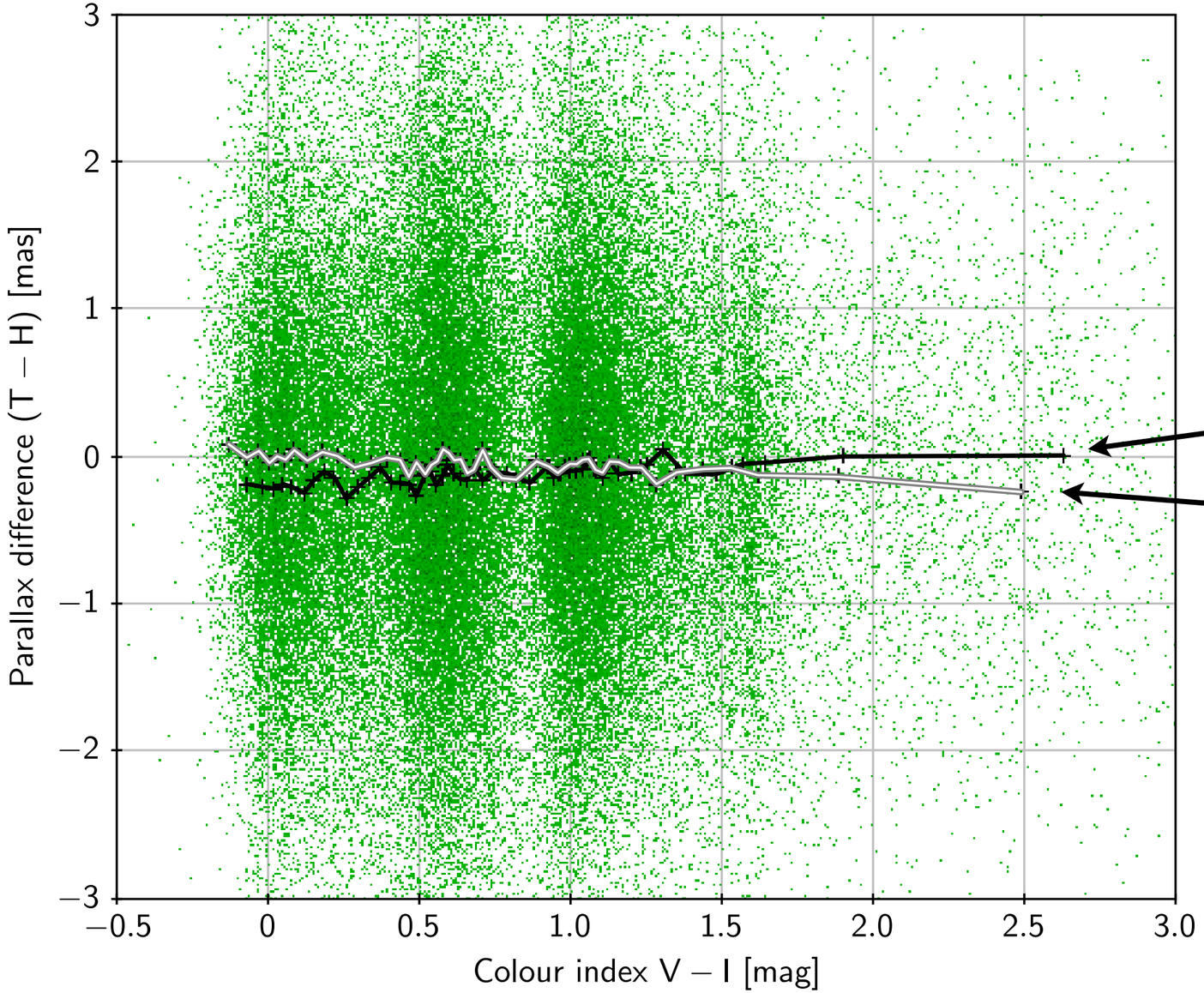
→ weak prior

Systematic errors in TGAS

- Systematic errors exist, and are complicated (largely unknown) functions of position, magnitude, colour, prior used, ...

- Systematics have been investigated through
  - comparison with external data (e.g. Hipparcos)

Example: $\varpi_{TGAS} - \varpi_{HIP}$ versus colour index



Median difference for:

β > 0 (ecliptic north)

β < 0 (ecliptic south)

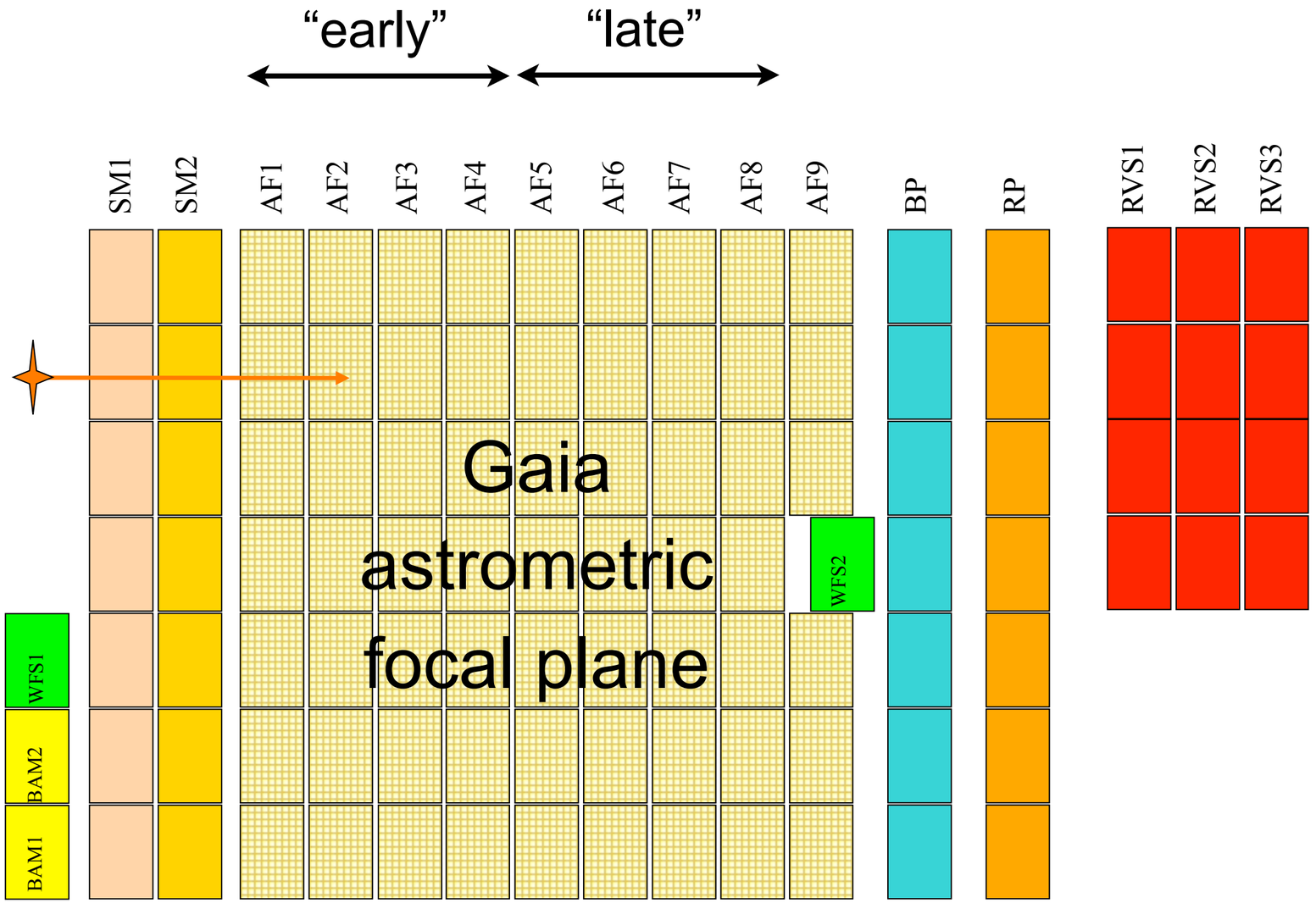
➜ Colour & position dependent systematics on the level ±0.1 mas

Systematic errors in TGAS

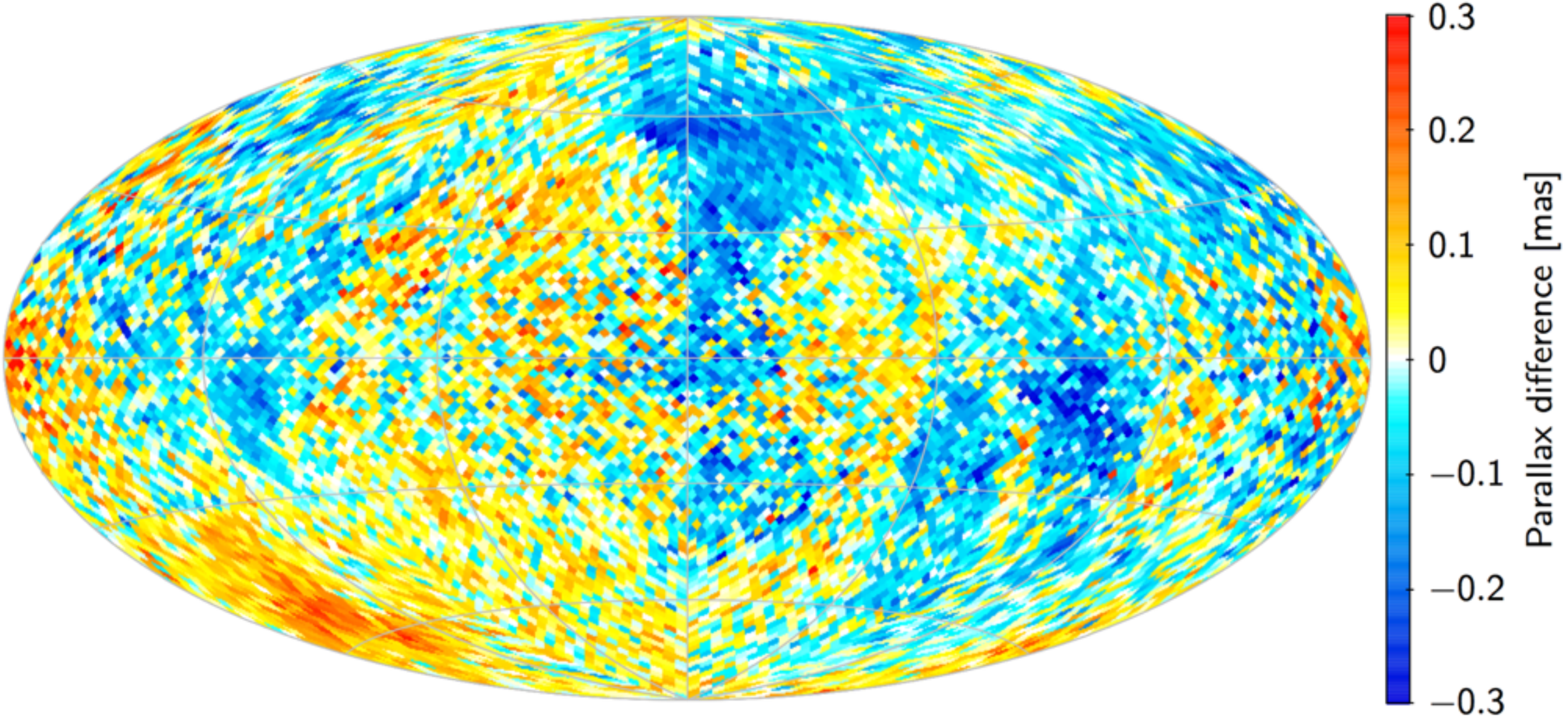
- Systematic errors exist, and are complicated (largely unknown) functions of the position, magnitude, colour, prior used, ...

- Systematics have been investigated through
  - comparison with external data (e.g. Hipparcos)
  - special validation solutions (e.g. splitting the data and making separate solutions)

Example: Splitting the observations in two datasets



Parallax difference between two validation solutions for “early” and “late” data



Systematic errors in TGAS

- Systematic errors exist, and are complicated (largely unknown) functions of the position, magnitude, colour, prior used, ...

- Systematics have been investigated through
  - comparison with external data (e.g. Hipparcos)
  - special validation solutions (e.g. splitting the data and making separate solutions)

- For the parallaxes
  - a global offset of ±0.1 mas may be present
  - there are colour dependent, spatially correlated errors of ±0.3 mas
  - in small areas even reaching ±1 mas

- These systematics are included in the standard uncertainties
  - see Gaia DR1 papers (A&A 595, 2016) for details

Conclusions

- The reference frame of Gaia DR1 is not the same as the Hipparcos Reference Frame (although both are nominally on ICRS)
- TGAS consists of two subsets: astrometric_priors_used = 3 (Hip) or 5 (Tyc), with very different properties − decisive factor is the strength of the prior
- Correlations in TGAS are very important, especially for weak priors (faint Tyc subset)
- Systematics are at the few 0.1 mas or mas/yr level, probably higher for weak priors
- Future Gaia data releases will tell us how good or bad TGAS really is!

gaia

Gaia DPAC