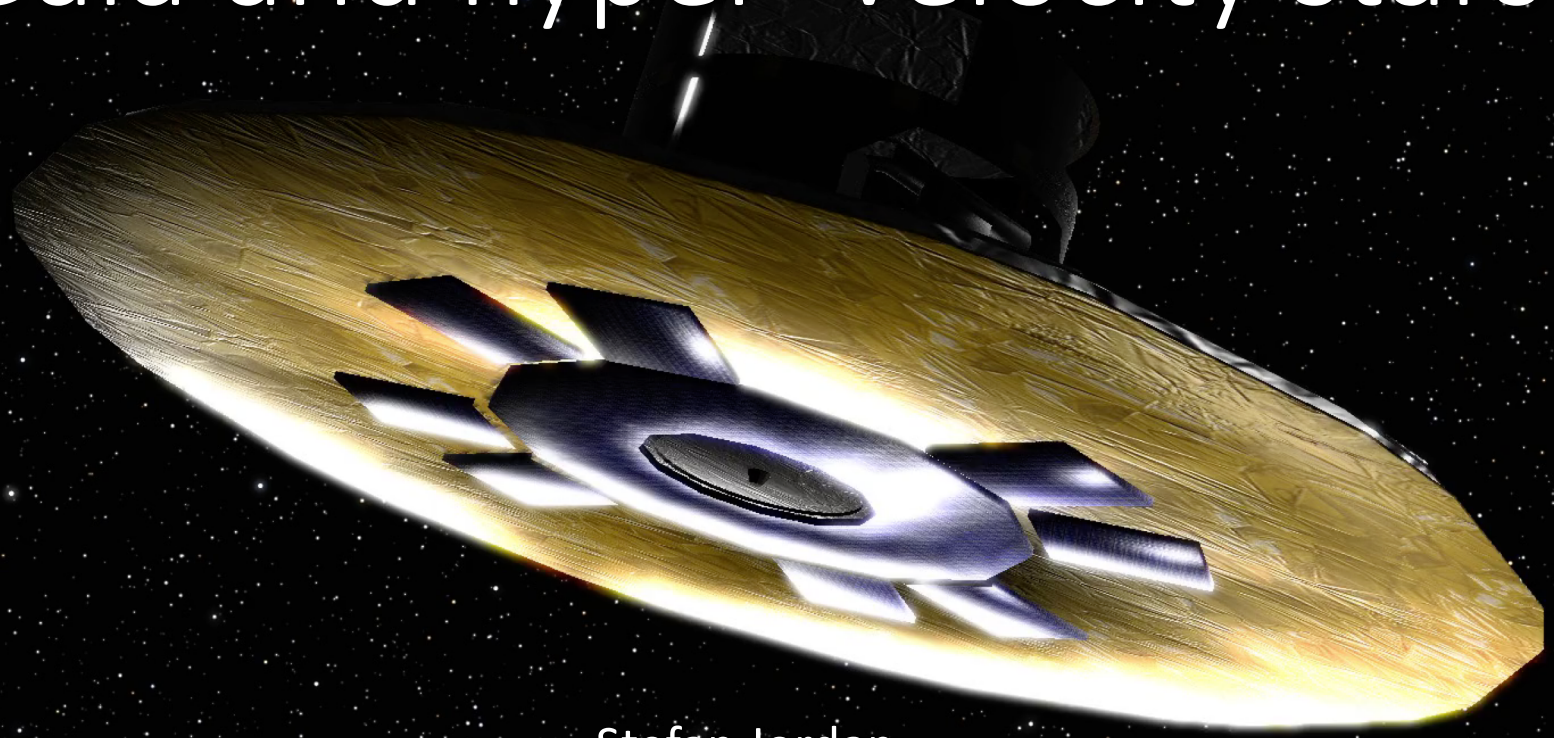
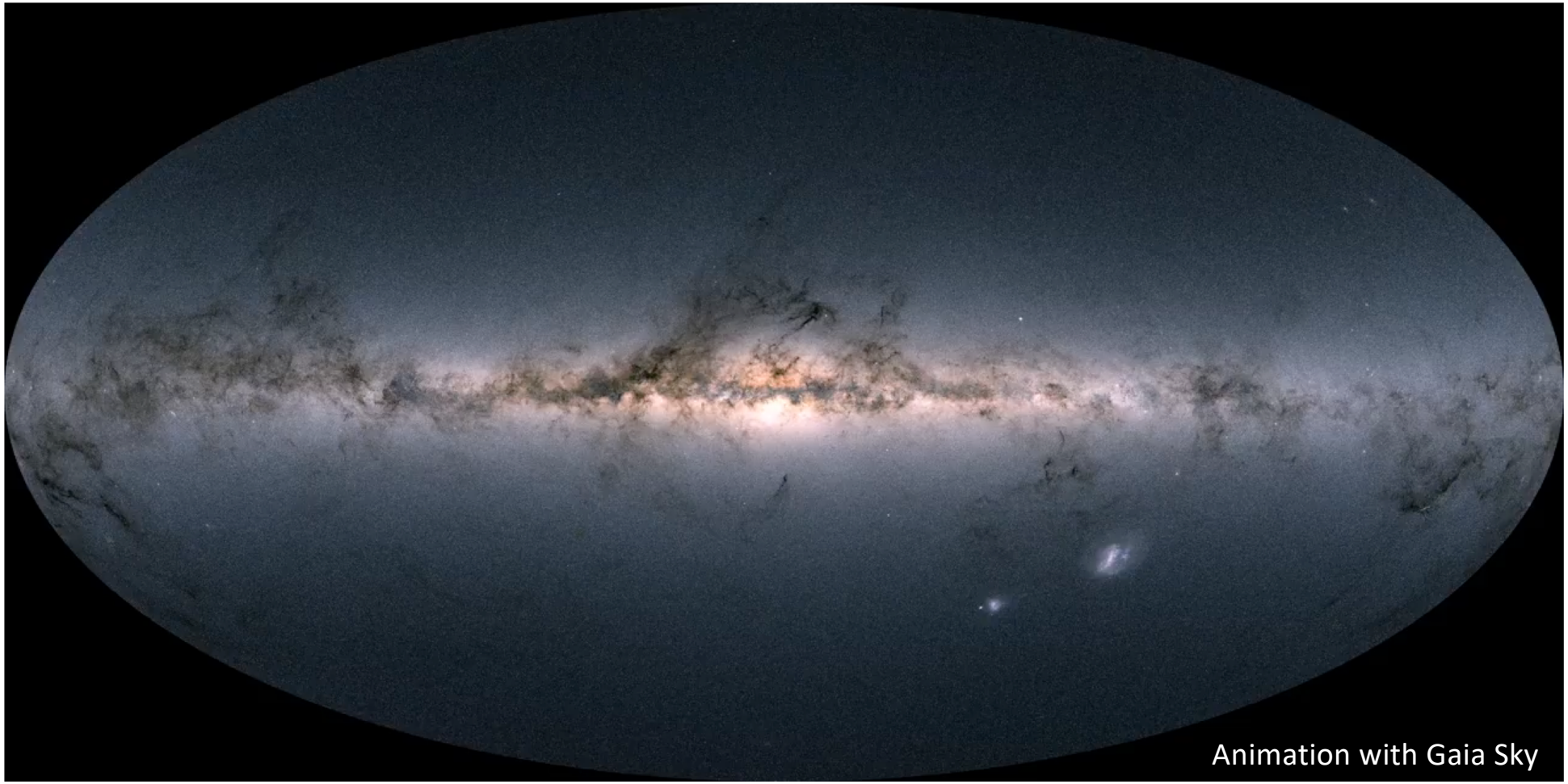
Gaia and hyper- velocity stars



Stefan Jordan
Astronomisches Rechen-Institut
Zentrum für Astronomie
Universität Heidelberg

Stars on the run in Gaia DR2 (astrometry)



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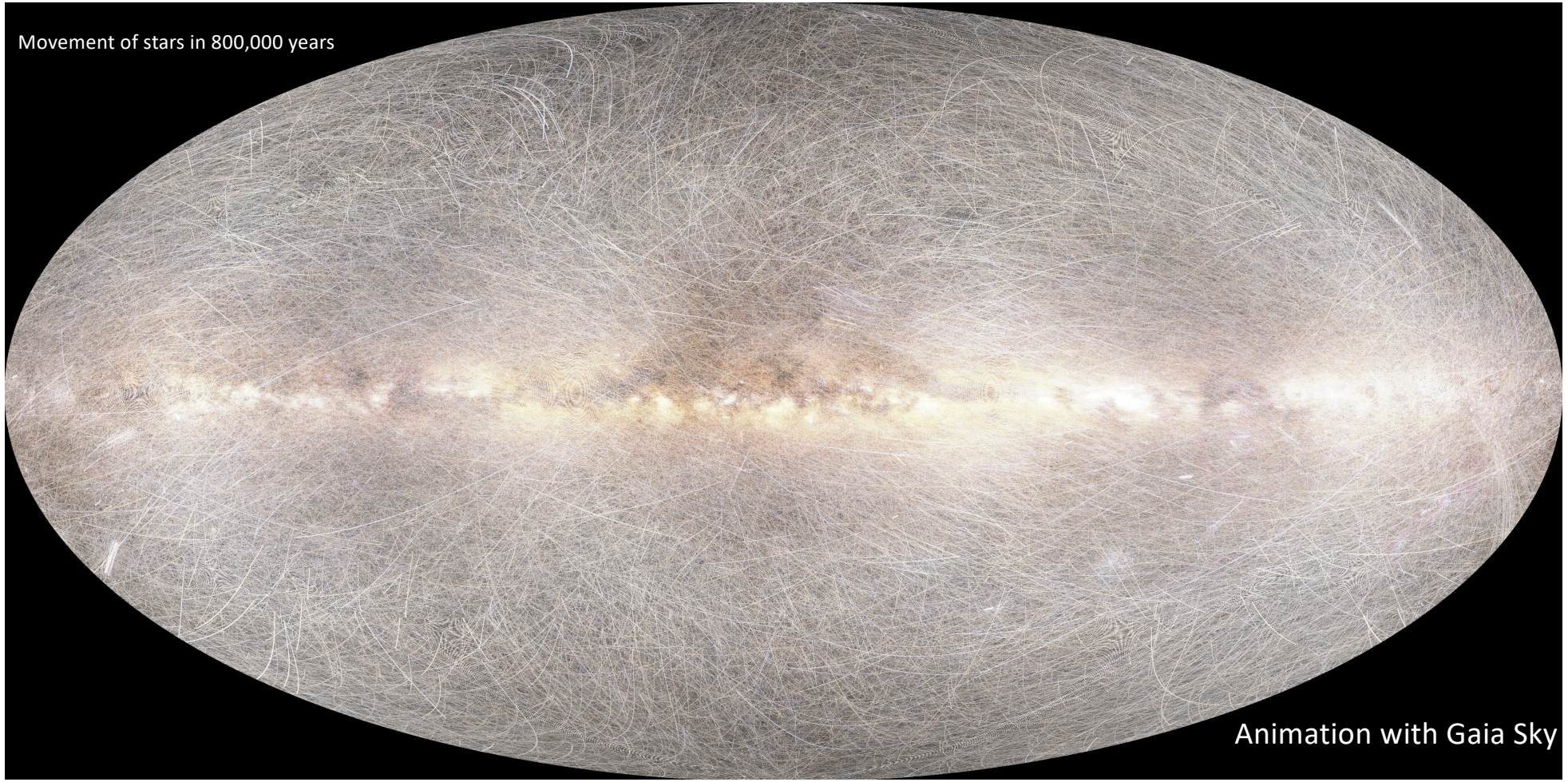
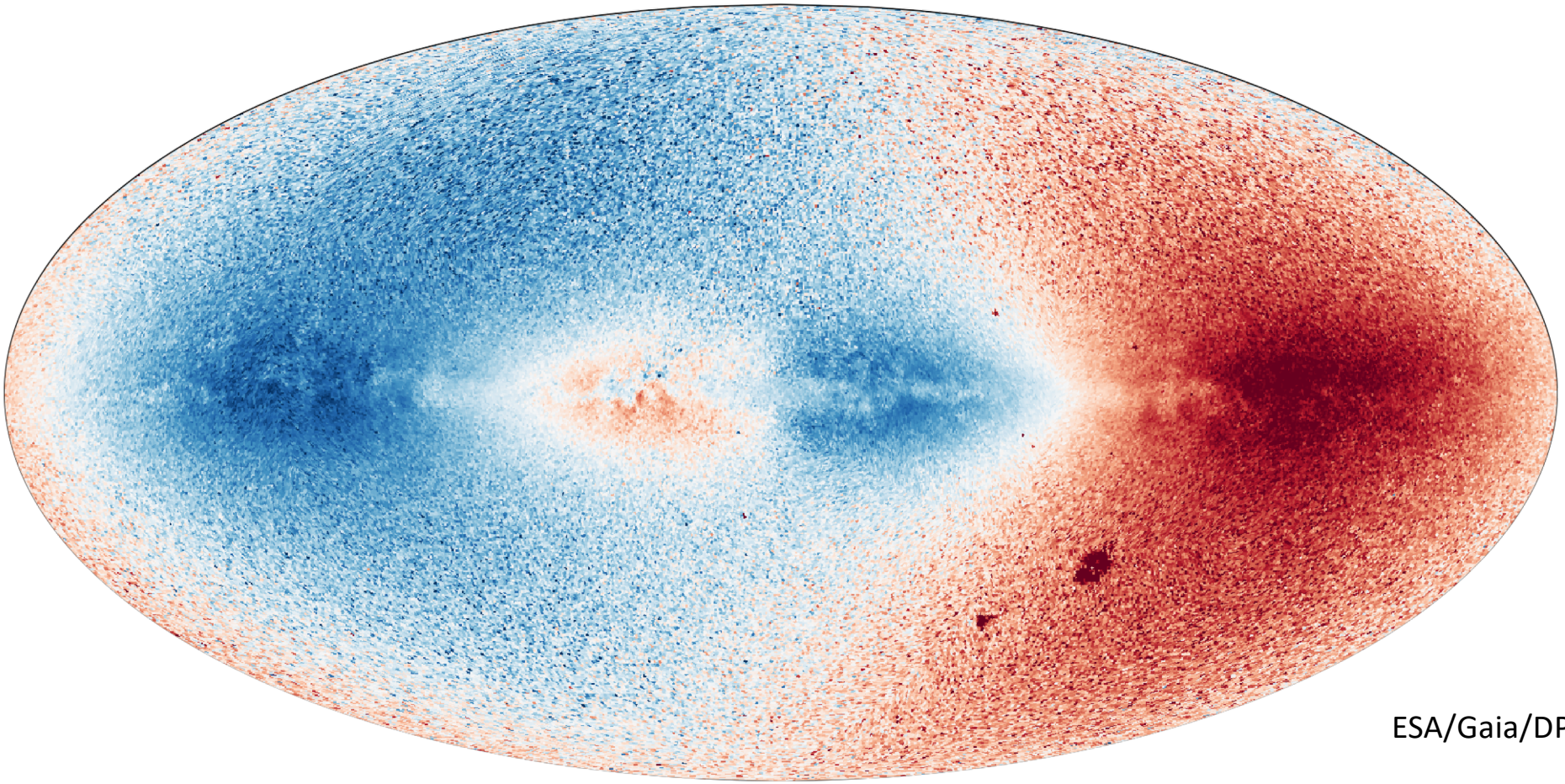
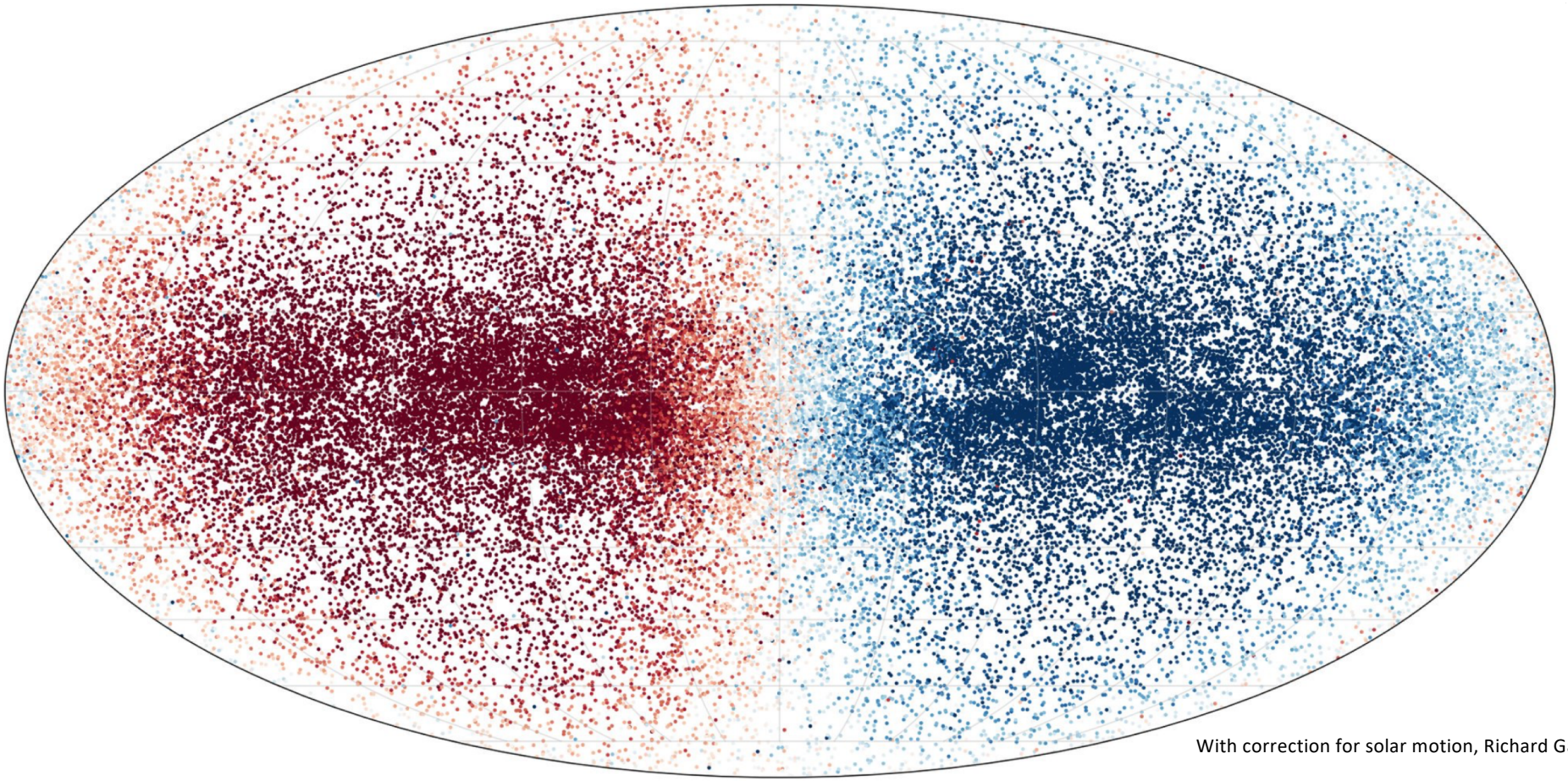


Radial velocities



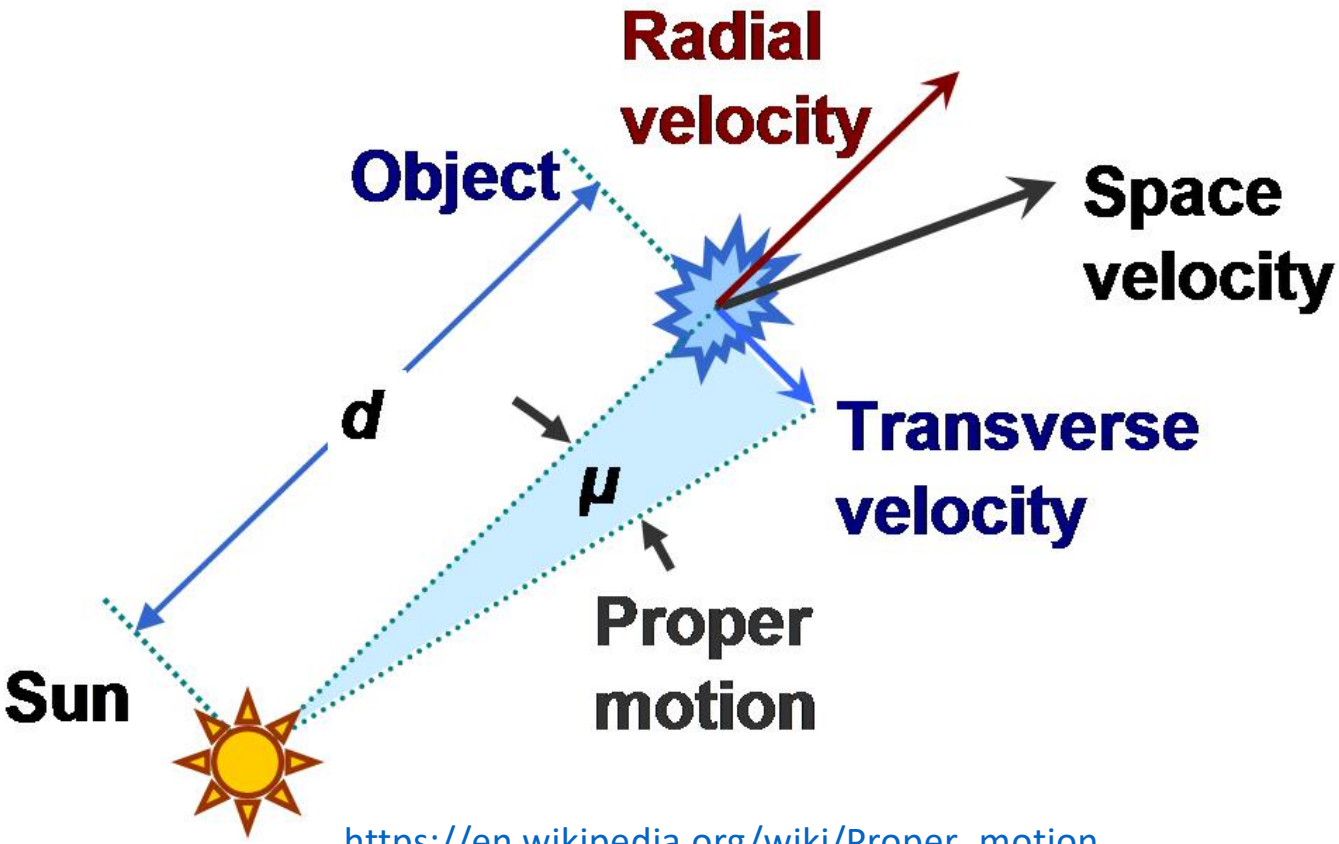
ESA/Gaia/DPAC

Radial velocities



With correction for solar motion, Richard Galvez

Space velocity



https://en.wikipedia.org/wiki/Proper_motion

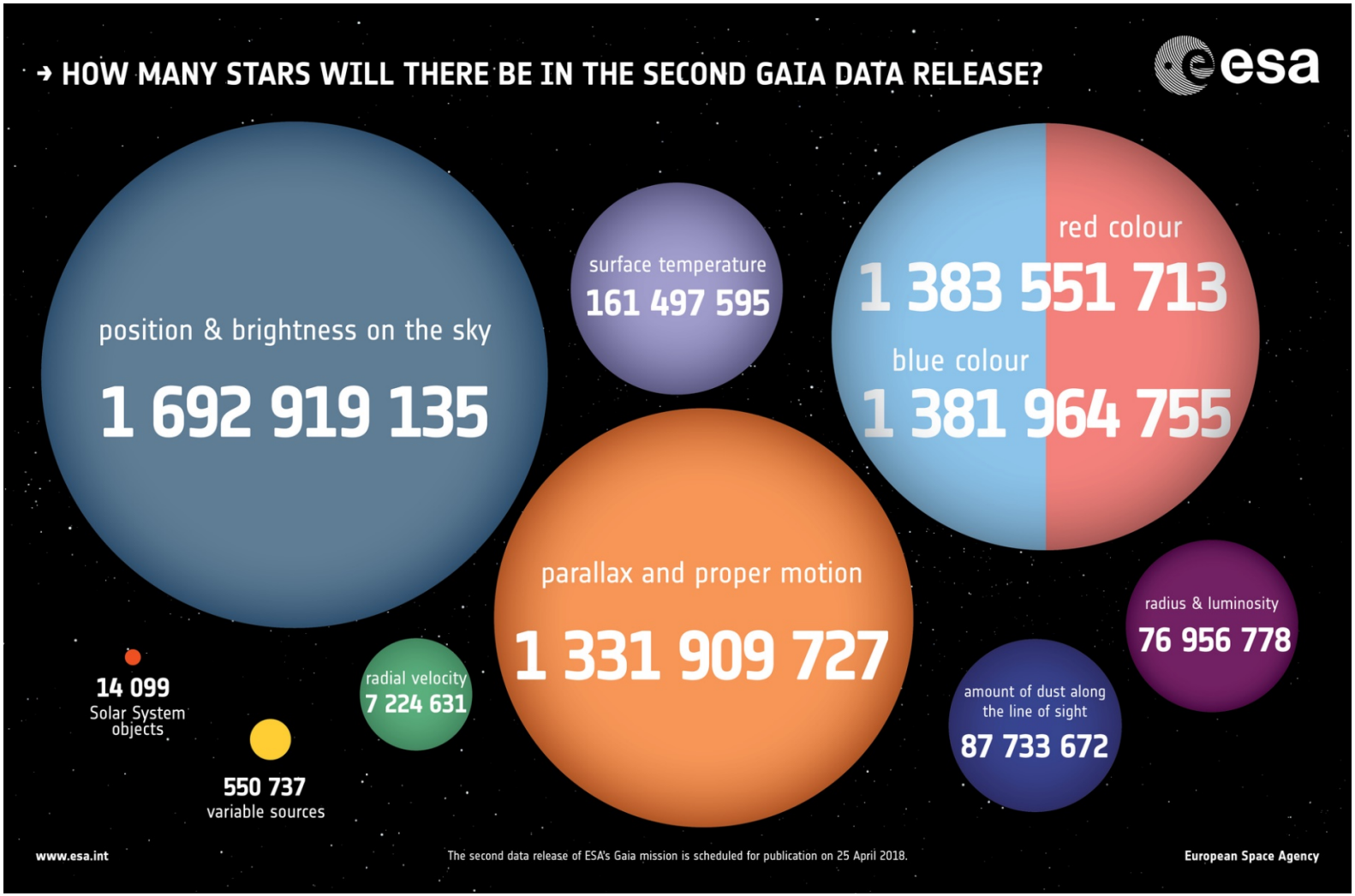
$$v_T = 4.75 \frac{\mu}{\varpi}$$

μ = Proper Motion in arcsec/yr

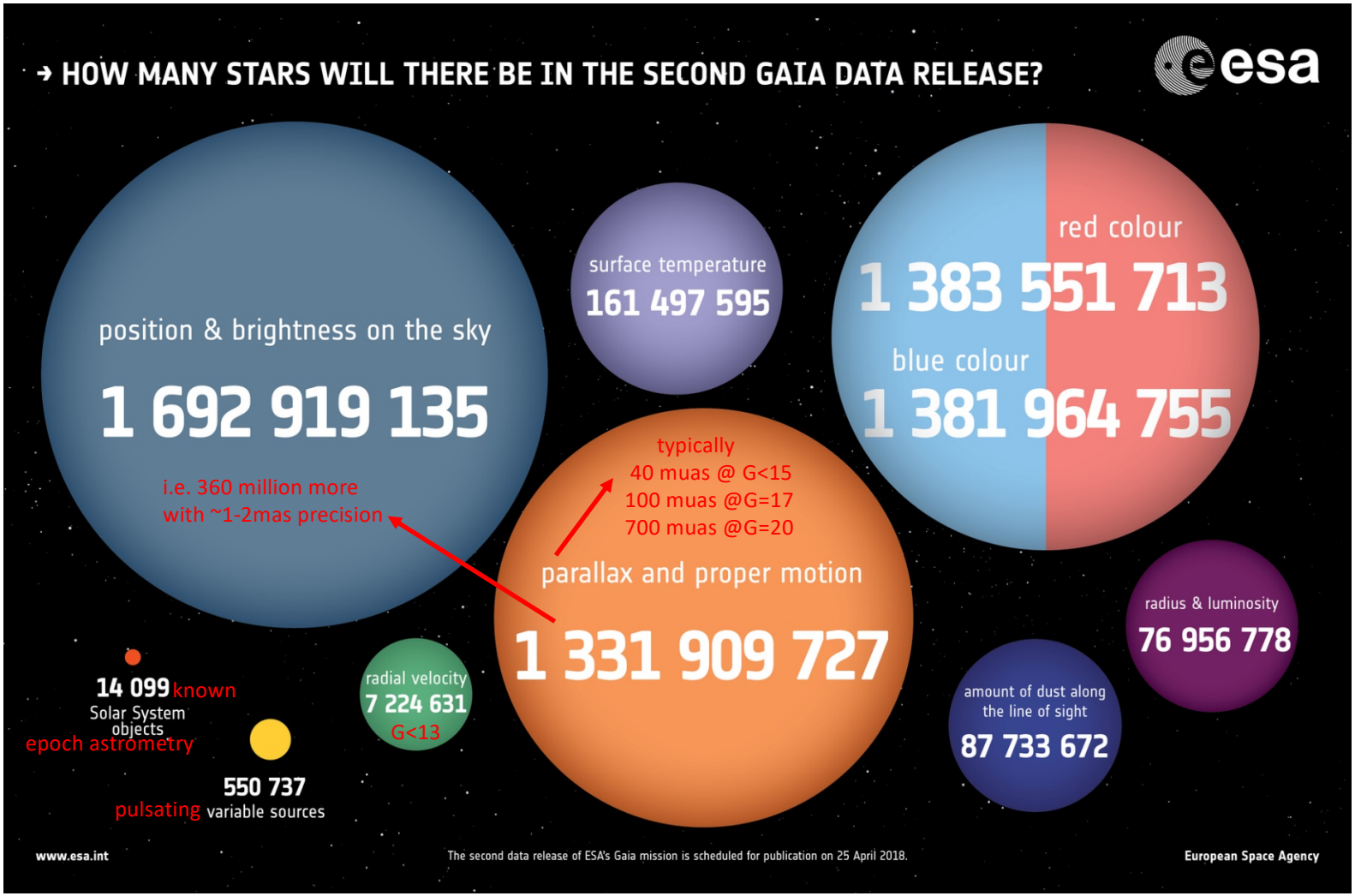
ϖ = Parallax in arcsec

v_T= velocity in km/s

Gaia DR2 contents



Gaia DR2 contents



Twenty microarcseconds (final goal at G=15)

- Astrometry means measuring angles
- Goal: 20 microarcseconds = 10^{-10} radians
- To avoid systematic errors: 10^{-11} radians needed
- Relative precision of 10^{-10} needed
- Calibration to 10^{-10} needed
- At a size of 2 m this corresponds to 0.2 nm
- 0.2 nm for instrument geometry AND orientation
- At a CTE of 10^{-6}/K this corresponds to 10^{-4} K
- 20 μas = 333 ns; 10^{-10} relative timing precision

After U. Bastian

Topics of first Gaia DR2 papers

- Asteroids
- White Dwarfs
- Cepheids
- Cataclysmic variables
- Magnetic stars
- AGB stars
- RR Lyrae stars
- Red giant stars
- Luminous blue variables
- Red clump stars
- Runaway and hypervelocity stars:
- Microlensing events
- Exoplanet radii
- Stellar kinematics
- Structure of the Milky Way
- Bolometric corrections
- Star forming regions
- Distances and kinematics of pulsars
- Binaries for gravitational wave detections (LISA)
- Luminosities of exoplanet stars
- Finding open clusters, finding cluster members
- Isochrone ages of stars
- Gaia photometry
- Stellar distances
- Determining open and globular cluster properties (kinematics, age, metallicities)
- Finding and analysing tidal streams
- Galactic disk
- Investigation of the Milky Way halo
- Proper motion of Milky Way satellites and galaxies in the Local Group
- Quasars
- Strongly lensed quasars
- Hubble constant
- Reference system
- Dark Matter
- Planetary Nebula

Stefan Jordan, August 26, 2019

Stars on the Run 2, Potsdam, August 25-30, 2019

Topics of first Gaia DR2 papers

- Asteroids

A total of 2114 papers using Gaia DR2

More than 4 papers per day since April 25, 2018!
https://ui.adsabs.harvard.edu/public-libraries/TMaUkmOYRYWxkdJxl619sw

- RR Lyrae stars
- Red giant stars
- Luminous blue variables
- Red clump stars
- Runaway and hypervelocity stars:
- Microlensing events
- Exoplanet radii
- Stellar kinematics
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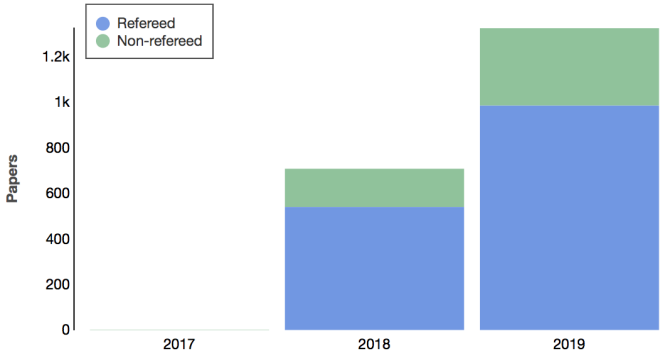
- Binaries for gravitational wave detections (LISA)



- Determining open and globular cluster properties metallicities)
- Finding and analysing tidal streams

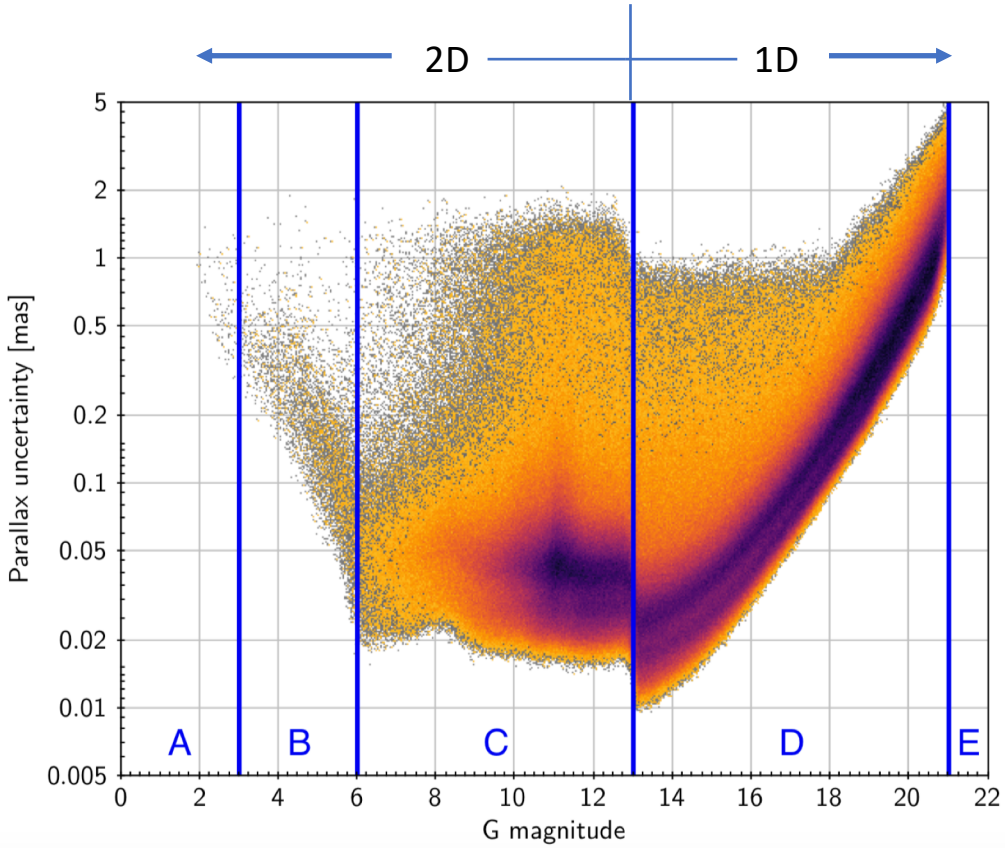
Runaway and hypervelocity stars:
40 Gaia DR2 papers with this topic in the title
https://ui.adsabs.harvard.edu/public-libraries/O4HWDcO3RJaa66cf3SOOMg

- Strongly lensed quasars
- Hubble constant
- Reference system
- Dark Matter
- Planetary Nebula

Stefan Jordan, August 26, 2019

Stars on the Run 2, Potsdam, August 25-30, 2019

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

Main quality indicators for proper motion and parallax

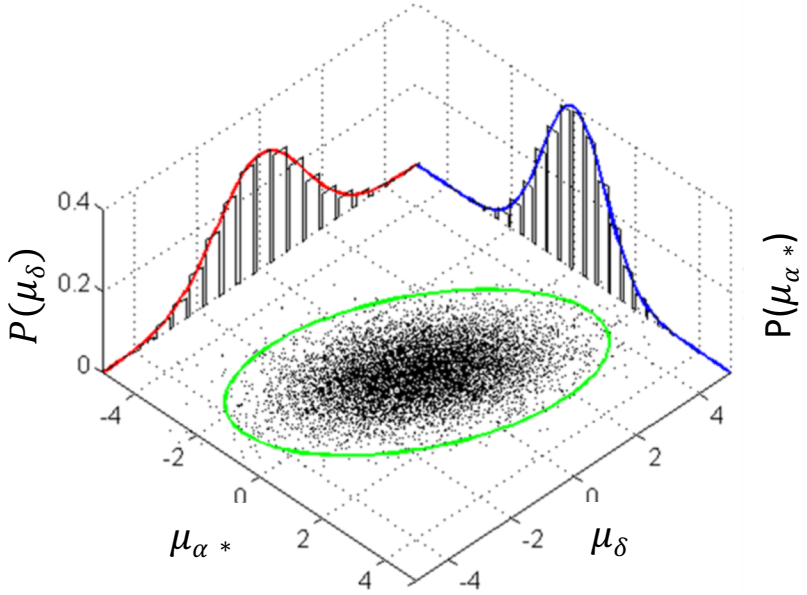
- parallax_error = standard uncertainty in parallax σ_{ϖ}
- pmra_error = standard uncertainty of proper motion in right ascension $\sigma_{\mu_{\alpha^*}} = \sigma_{\mu_\alpha} \cos \delta$,
- pmdec_error = standard uncertainty of proper motion in declination σ_{μ_δ}
- semi-major axis of error ellipse in proper motion $\sigma_{pm,max}$
- astrometric_excess_noise = excess source noise ε_i (=0)
- astrometric_excess_noise_sig = significance of excess source noise (significant if >2)
- visibility_periods_used=number of visibility periods of the source i.e. groups of observations separated by at least four days (>5)
- RUWE (<1.4)

Semi-major axes of the error ellipse in pm

- The semi-major axes of the error ellipses in proper motion are not given in the *Gaia* Archive:

$$\sigma_{\mathrm{pm,\,max}} = \sqrt{\frac{1}{2}(C_{33} + C_{44}) + \frac{1}{2}\sqrt{(C_{44} - C_{33})^2 + 4C_{34}^2}}$$

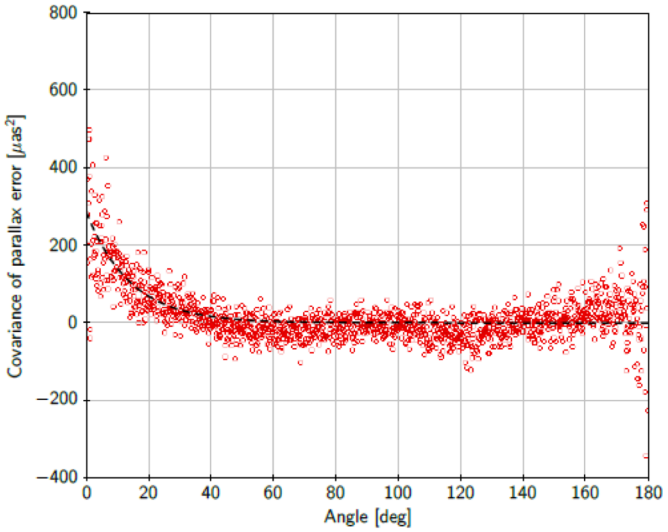
$$C_{33} = \texttt{pmra\_error} \times \texttt{pmra\_error}$$
$$C_{34} = \texttt{pmra\_error} \times \texttt{pmdec\_error} \times \texttt{pmra\_pmdec\_corr}$$
$$C_{44} = \texttt{pmdec\_error} \times \texttt{pmdec\_error}$$

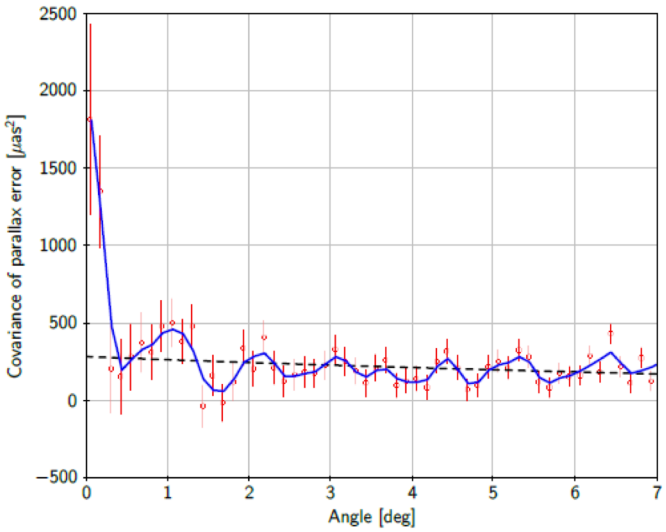


After https://commons.wikimedia.org/w/index.php?curid=25235145

Systematic errors in Gaia DR2

- The global (QSO-derived) parallax zeropoint error
- The small-scale systematics (~1 degree)
- The large-scale systematics (20 degrees)





generally below 100 μas, typically ~30-50 μas

After U. Bastian

Systematic errors in astrometry

- DR1:
  - „generally below 300 muas“
  - typically ~100 μas
- DR2:
  - „generally below 100 μas“
  - typically ~30-50 μas
- DR3:
  - uncertain
  - hopefully another factor 2-3 at least
  - final mission goal still far away
  - bright stars still badly calibrated

After U. Bastian

Quality indicators for radial velocity

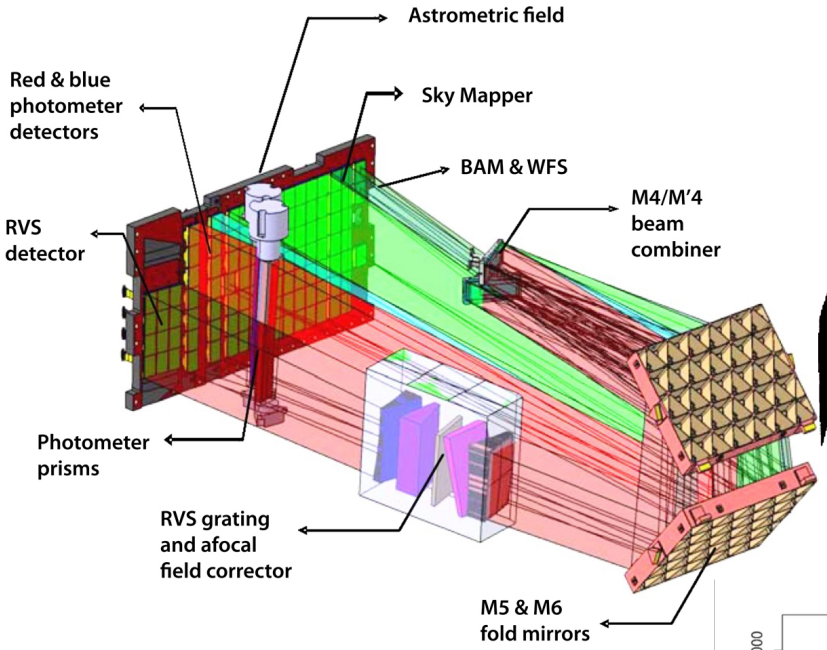
- radial_velocity_error σ_{V_r}
- distance to nearest star >6.4”

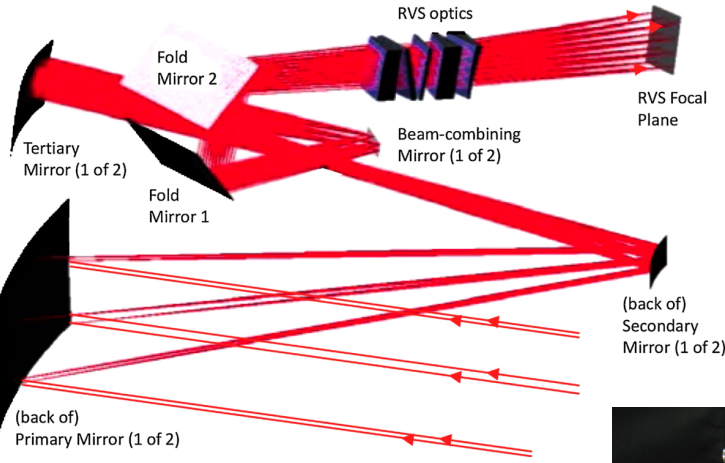
Gaia – Rave synergy

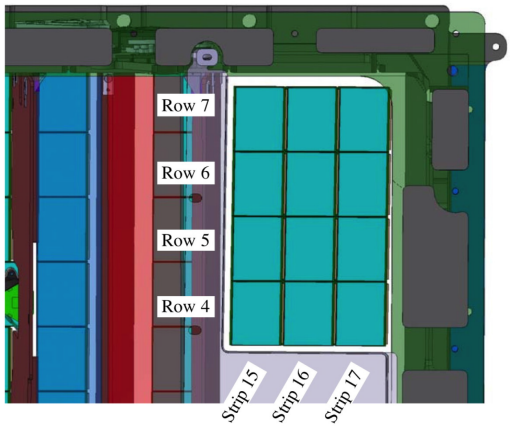
Steinmetz et al. (2018), RNAAS, 2, 194

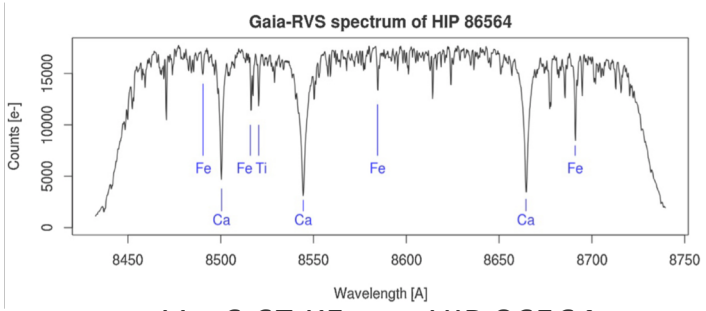
- RAVE DR5 and Gaia DR2 have 450587 stars in common
- Systematic offset of about -0.32 km/s
- 707 stars that exhibit a constant velocity offset of +105 km/s or -76 km/s, respectively
- Problem of the reduction pipeline in propagating the wavelength calibration between neighboring fibres near the edges of the field plate, in particular for observations done just before fibre repairs

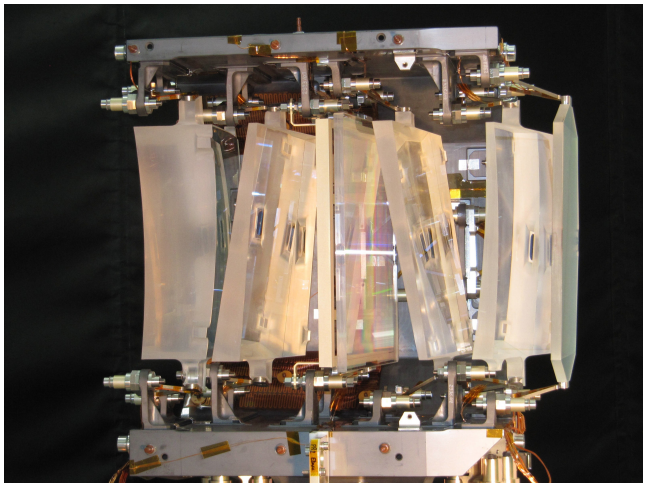
Gaia's Radial-Velocity Spectrometer (RVS)











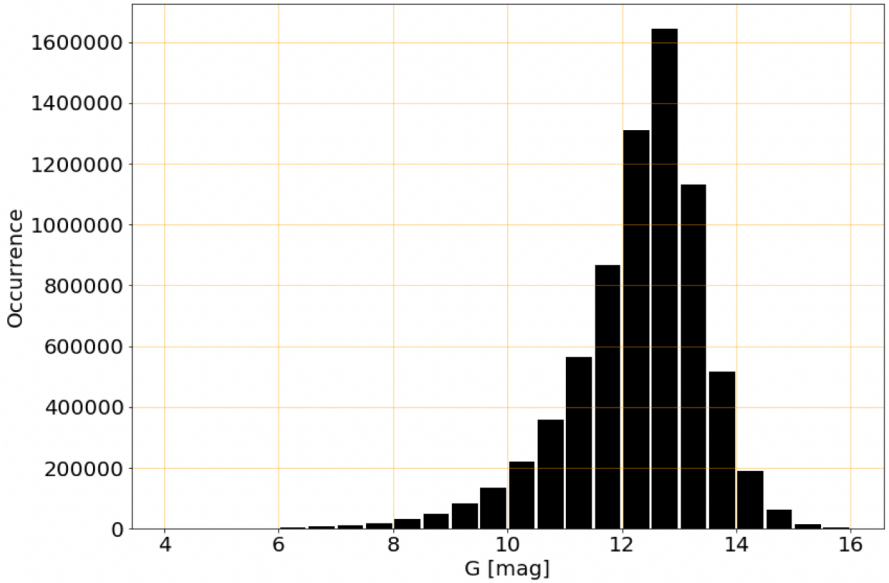
8470–8740 Å bandpass

median resolving power: 11500

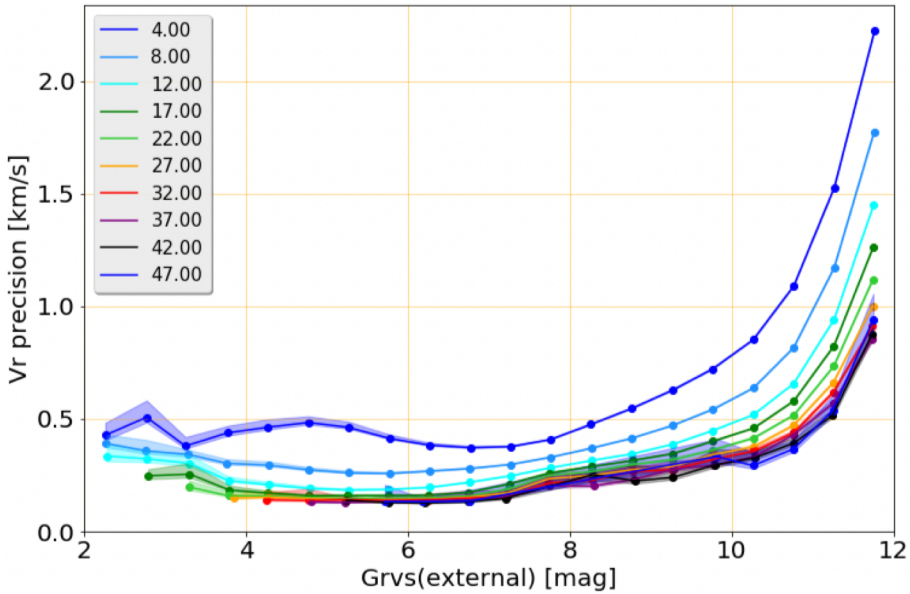
V = 6.67 K5 star HIP 86564

RVS in Gaia DR2

Katz et al.: *Gaia* Data Release 2, A&A 622, A205 (2019)



G-magnitude distribution of the stars with a radial velocity published in *Gaia* DR2

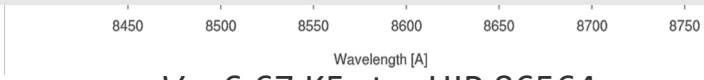


Radial velocity precision as a function of $G_{\text{ext RVS}}$ magnitude and number of transits. The mean number of transits of each interval is given in the legend.

Gaia's Radial-Velocity Spectrometer (RVS)

D. Katz et al.: *Gaia* Data Release 2, 2019, A&A, 622, A205

- 613 were higher than or equal to 500 km s^{-1}
- sample of high-velocity stars is very small com- pared to the full sample
- easily be significantly contaminated by outliers
- one undetected outlier in 10 000 stars would produce about 350 false high-velocity stars
- Of the 613 stars, 216 were considered as valid high-velocity stars



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Contamination of Gaia RVS spectra in crowded fields

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **486,** 2618–2630 (2019) doi:10.1093/mnras/stz253
Advance Access publication 2019 January 29

Lessons from the curious case of the 'fastest' star in *Gaia* DR2

D. Boubert,[1★] J. Strader,[2] D. Aguado,[3] G. Seabroke,[4] S. E. Koposov,[3,5] J. L. Sanders,[3] S. Swihart,[2] L. Chomiuk[2] and N. W. Evans[3]
[1]*Magdalen College, University of Oxford, High Street, Oxford OX1 4AU, UK*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
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[4]*Mullard Space Science Laboratory, University College London, Dorking, Surrey RH5 6NT, UK*
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Accepted 2019 January 22. Received 2019 January 21; in original form 2018 December 18

ABSTRACT

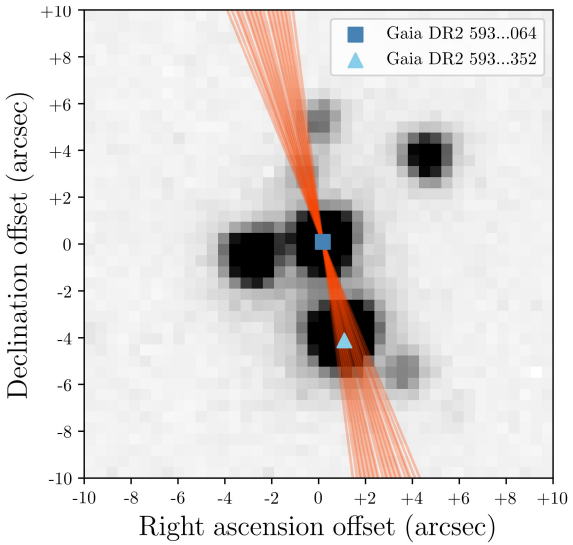
Gaia DR2 5932173855446728064 was recently proposed to be unbound from the Milky Way based on the $-614.3 \pm 2.5\,\mathrm{km\,s^{-1}}$ median radial velocity given in *Gaia* DR2. We obtained eight epochs of spectroscopic follow-up and find a very different median radial velocity of $-56.5 \pm 5.3\,\mathrm{km\,s^{-1}}$. If this difference were to be explained by binarity, then the unseen companion would be an intermediate-mass black hole; we therefore argue that the *Gaia* DR2 radial velocity must be in error. We find it likely that the spectra obtained by *Gaia* were dominated by the light from a star 4.3 arcsec away, and that, due to the slitless, time

Douglas Boubert
@neuronomer

This paper started with a mystery. Marchetti et al. (2018) published a list of fast stars they found in Gaia DR2 and one of them caught my eye. It has a Gaia radial velocity of -614.3 +/- 2.5 km/s, i.e. this star is so fast that it is escaping the galaxy!

- RVS windows only start or end on multiples of 105 pixels (before June 2015) or 108 pixels (after June 2015), called macrosample boundaries.
- 105 and 108 pixels corresponds to approximately 6.2 and 6.4 arcseconds respectively.
- Two sources with angular separations in the along scan (AL) direction smaller than these values will have RVS windows starting on the same macrosample boundary.

This plot shows the scan angles over that 4 day period. Gaia looked at a brighter star immediately before looking at our star. Imagine adding the spectra of a bright and faint star and then trying to measure a RV. You only detect the lines of the brighter star!



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Listen to the following talk by Douglas Boubert

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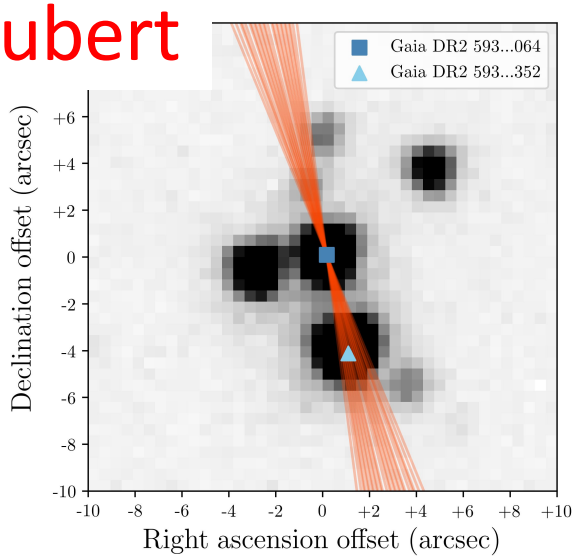


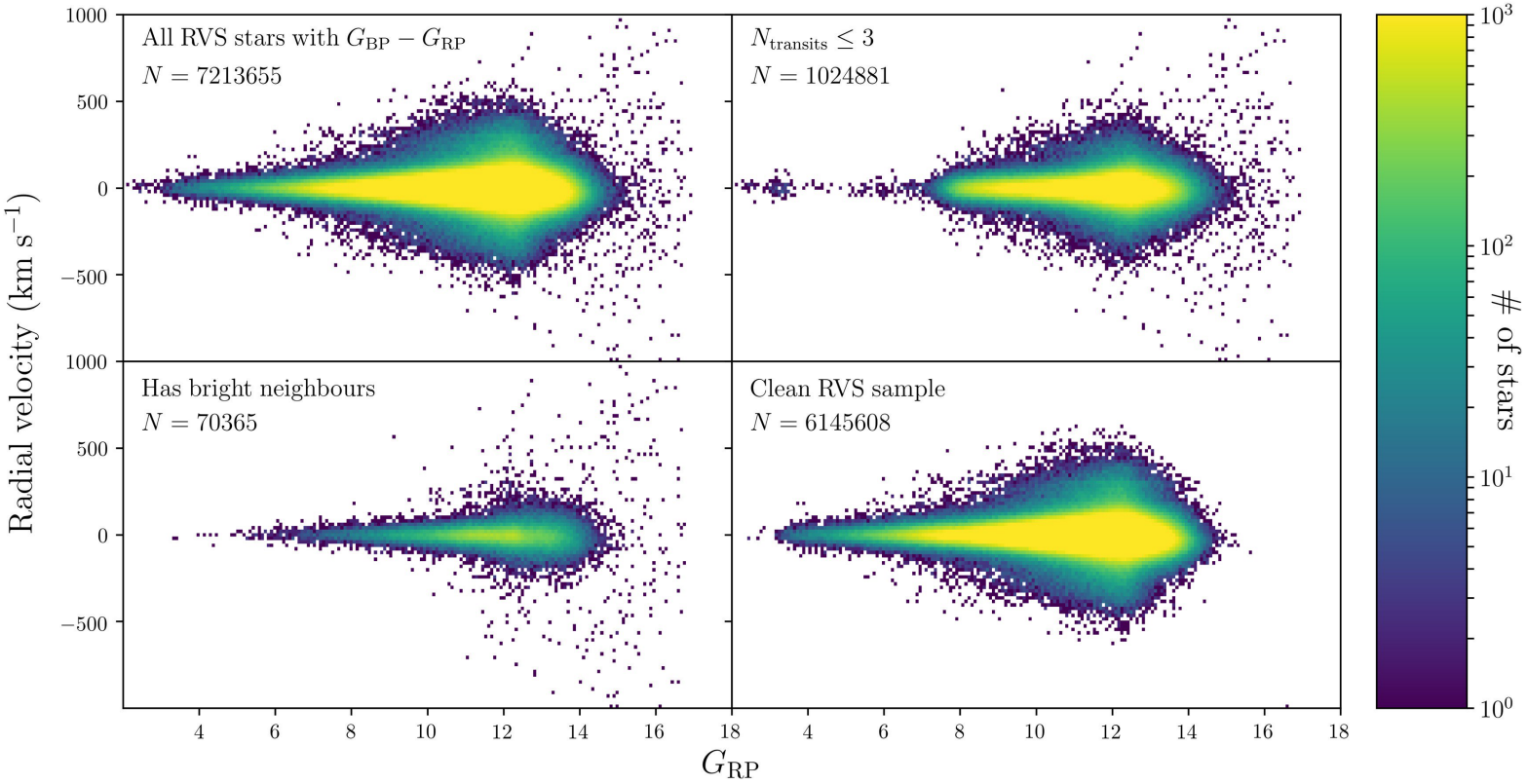
Contamination of Gaia RVS spectra in crowded fields

along-scan shift <105/108 pixel=6.4“

Stefan Jordan, August 26, 2019

Stars on the Run 2, Potsdam, August 25-30, 2019

Contamination of Gaia RVS spectra in crowded fields



Boubert et al. (2019)

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, Gaia DR1**
- **25. April 2018: Second (first "real") Gaia Catalogue, Gaia DR2**
- **July 16, 2019: End of the nominal mission (5 years time)**
- **July 16, 2019-December 31, 2020: Approved extended mission (1.5 years)**
- **Third quarter 2020: Early Third Gaia catalogue, Gaia EDR3**
- **Second half of 2021: Third Gaia catalogue, Gaia DR3**
- **2020-2024: Expected extended mission (3.5 years)**
- **TBD: Fourth catalogue due to the nominal mission**
- **TBD: Fifth catalogue due to extended mission**

Splitting of Gaia DR3:

- Early Gaia Data Release 3 (EDR3), third quarter 2020
  - improved astrometry (positions, parallaxes, proper motions)
  - improved photometry (integrated G, G_{BP}, G_{RP})
  - “Extended Objects”: full quasars and some galaxies results?

- Gaia Data Release 3 (DR3), second half 2021:
  - e.g. epoch photometry, epoch radial velocities, spectra, binary-star astrometry, multi-band colours (low-res B_P and R_P spectra)
    - EDR3 contents (see above) unchanged
    - More
- Gaia Data Release 4: three years (?) after nominal mission
  - Full variety of data items; full nominal mission as input data
- Gaia Data Release 5: three years after extended mission

Gaia EDR3/DR3 schedule

- Gaia EDR3 in third quarter of 2020
- Gaia DR3 second half 2021
- Both releases based on same input data and same source list
  - 34 months of input data

(E)DR3 contents on following slides are subject to successful processing and validation. Source numbers are preliminary estimates!

Contents of Gaia EDR3

Data Product	No. of sources	Comments
Astrometry	~ 1.8 billion	including new quality indicators: RUWE, source image descriptors
Integrated G, G_{BP}, G_{RP} photometry	~ 1.8 billion	with corresponding passbands
QSO host and galaxy morphological characterization	~ 3 million	based on input list
Cross-match with external catalogues		
Gaia-CRF		
DR2-to-DR3 match table		

A. Brown, ESLAB-53

Contents of Gaia DR3

Data Product	No. of sources	Comments
Repeat of EDR3 contents		
Source Classification and astrophysical parameters	$\gtrsim$ 300 million	based on the BP/RP spectra, magnitude limit TBD
Radial velocities	$\sim$ 30 million	$G_{\rm RVS} \lesssim 14$
Mean BP/RP/RVS spectra	TBD subset of sources	
Photometric variability characterization, classification, light curves	$\sim$ 7 million	eclipsing, (MS) pulsating, transients, spotted, flaring, evolved pulsators, and quasars
Solar system objects epoch astrometry/photometry	$\sim$ 100 000	including orbit solutions
Solar system objects mean BP/RP reflectance spectra	$\sim$ 5000	
Catalogue of astrometric, spectroscopic, eclipsing non-single stars	TBD	Combined solutions where possible

New items in Gaia DR3

Astrometric non-single star solution types

- acceleration, 7 and 9 parameters
- orbital solutions, 12 parameters
- stochastic solutions
  - ➢ single star source model or basic binary star model does not fit
- **NOTE:** no epoch astrometry or epoch radial velocities will be released as part of Gaia DR3

Astrophysical parameters based on BP/RP/RVS spectra

- $T_{\rm eff}$, $A_{\rm G}$, $E(G_{\rm BP} - G_{\rm RP})$, log g, metallicity, abundances, distances, radii, masses, activity index
  - ➢ solutions from multiple algorithms will be provided rotational velocity for bright subset of stars (TBC)
- Extinction map
  Source classification(star, binary, galaxy,...)

Mean BP/RP/RVS spectra

- For subset of sources only
- Tool to handle BP/RP spectra will be provided

Solar system objects

- Orbits
- Reflectance spectra

after A. Brown, ESLAB-53

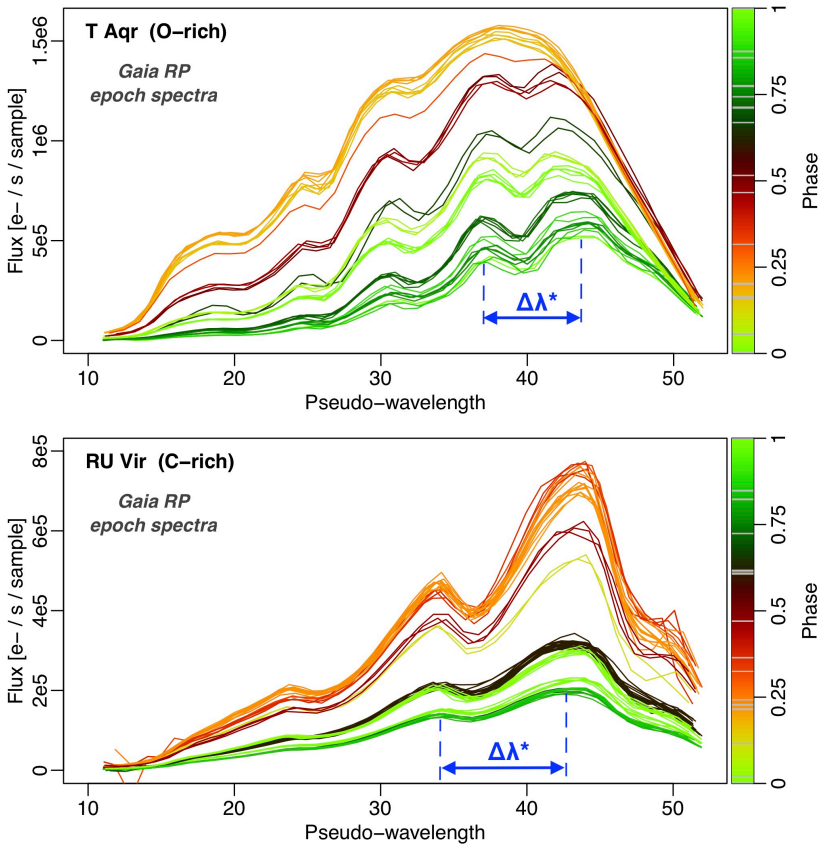
after A. Brown, ESLAB-53

Gaia DR4

- Final release for the nominal mission
  - 60 months input data; schedule TBD
- Foreseen data products
  - Full astrometric, photometric, and radial-velocity catalogues
  - All variable-star and non-single-star solutions
  - Source classifications (probabilities) plus multiple astrophysical parameters (derived from BP/RP, RVS, and astrometry) for stars, unresolved binaries, galaxies, and quasars
  - Catalogue of binaries and exo-planets
  - Image reconstruction results
  - All epoch and transit data for all sources, including all BP/RP/RVS spectra

Overall gain in precision for DR3 and DR4: factors 1.2 and 1.7 with respect to DR2

- proper motions improve by factors 1.9 and 4.5



Epoch RP spectra of the O-rich Mira star T Aqr (top panel, pulsation period of 203 days) and the C-rich Mira star RU Vir (bottom panel, pulsation period of 425 days) at various phases of their pulsation cycle, colour-coded according to the colour scale on the right of the figures. The horizontal axis represents an arbitrary, dimensionless pseudo-wavelength. The flux on the Y-axis is given in units of photo-electrons per second per sample. The displayed spectra approximately cover the wavelength range from 640 to 1100 nm. Image credit: ESA/Gaia/DPAC, Mowlavi et al.

Gaia extension

- Nominal Gaia mission ended mid-2019 after 5 years of measurements
- Hardware in good shape, only limiting factor is micro-propulsion fuel
- mission can continue to end-2024 (±0.5 yr)
- Proposal submitted to ESA for 5 year extension
  - approved to end 2020, preliminary approval to end 2022, submit proposal for 2023–2024 in 2020

10 year mission comparted to nominal 5 years:

- Parallaxes, photometry, radial velocities improve by factor 1.4 ($2^{1/2}$) with respect to DR4
- Proper motions improve by factor of 2.8 ($2^{3/2}$) with respect to DR4
  - Improvement of more complex motions (e.g., planets) up to factors of 20 ($2^{5/2}$)

- Accurate proper motions over 22.6 ($2^{9/2}$) times larger volume

A. Brown, ESLAB-53

Gaia is European Teamwork

- Please acknowledge the work by DPAC and ESA in your papers!
  - helps us argue the case for continued funding of the data processing
  - https://gea.esac.esa.int/archive/documentation/credits.html
- Communicate your Gaia results
  - https://www.cosmos.esa.int/web/gaia/communicating-your-results