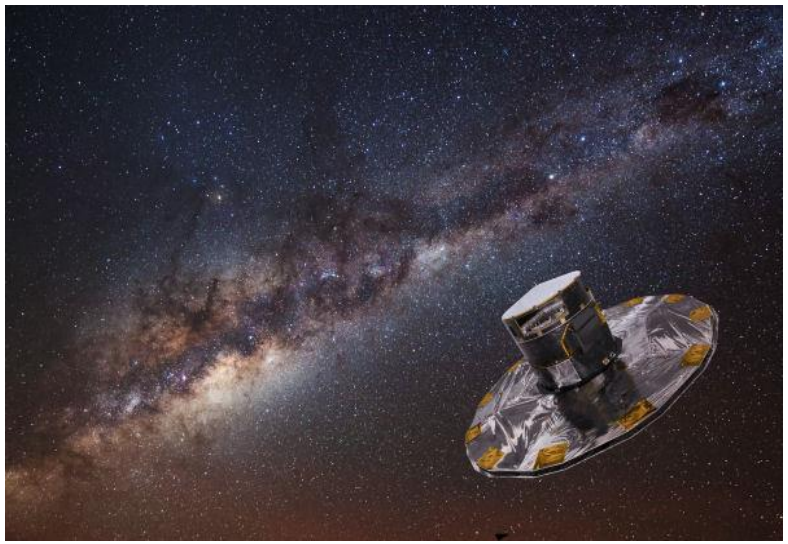
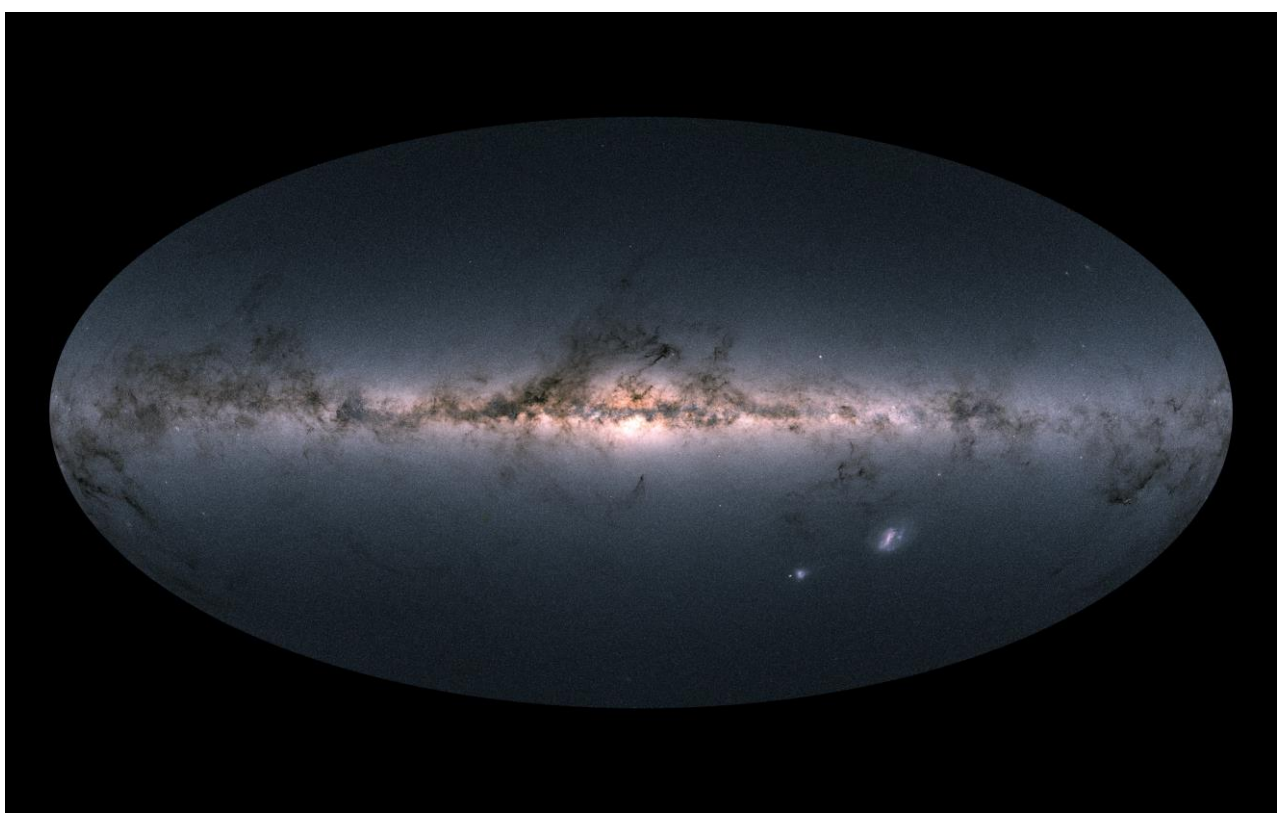


Gaia
Second Data Release

D. Katz,

on behalf of the Gaia DPAC



Gaia's 25th birthday

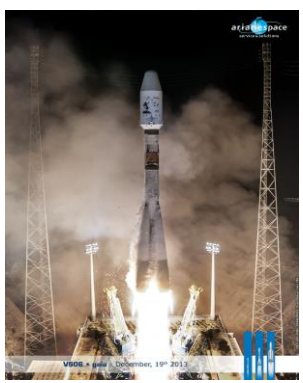
1990 2000 2010 2020

1993
1st concepts

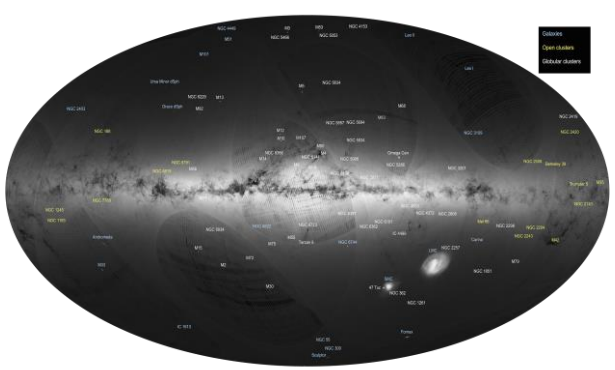
2000
Selected as ESA cornerstone mission

2006
DPAC

19 Dec 2013
Launch



14 Sep 2016
1st data release

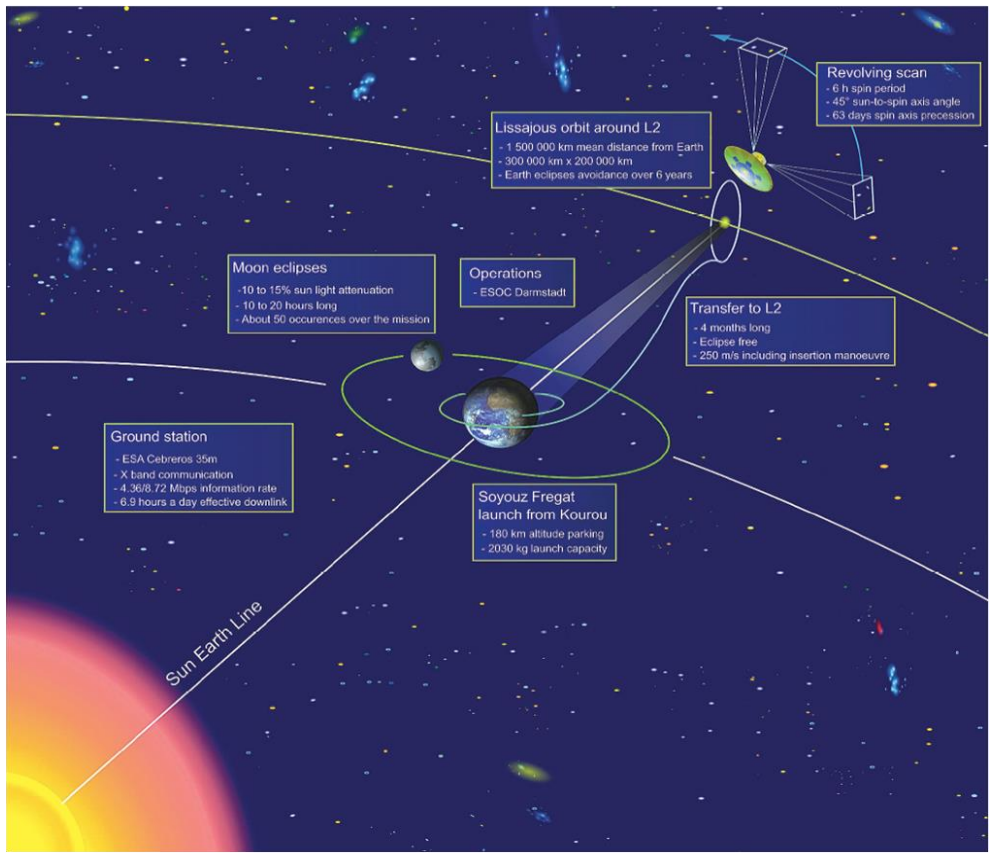


25 April 2018
2nd data release

Launch and operations

19 December 2013

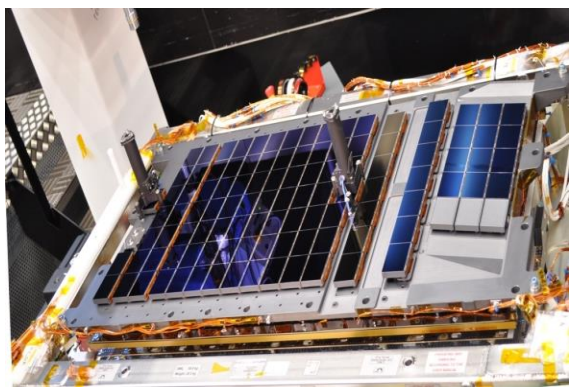
9:12:19 UTC

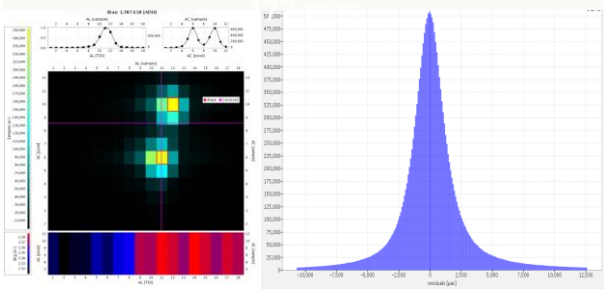


- Operated at L2
- Continuously scans the sky
- Nominal mission: 25th July 2014 (5 years)
- 1st extension → 2020
- Fuel → 2024

Payload

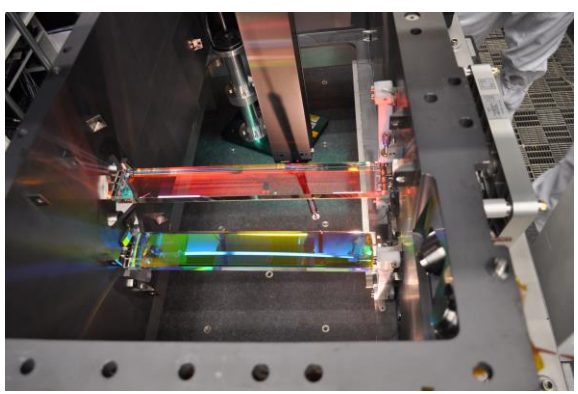
- 2 Telescopes
- 3 Instruments

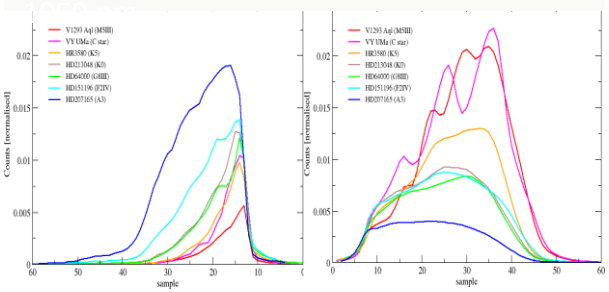




Astrometric instrument

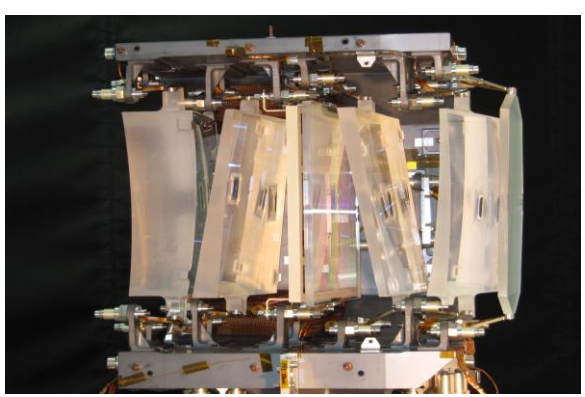
- G < 21
- α, δ, ϖ, μ_α, μ_δ
- 70 transits (in 5 years)

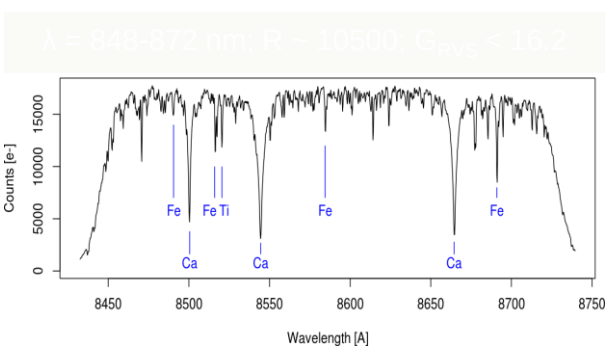




Spectro-photometer : Bp / Rp

- Bp : [330, 680] nm
- Rp : [640, 1050] nm
- Teff, log, [Fe/H], Av, ...



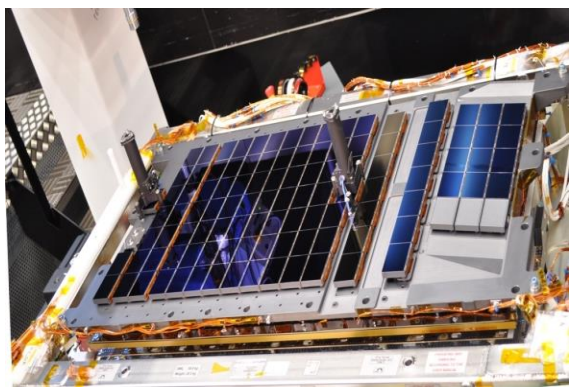


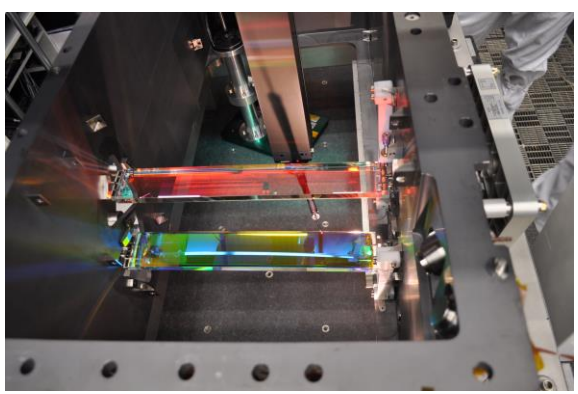
Spectrograph : RVS

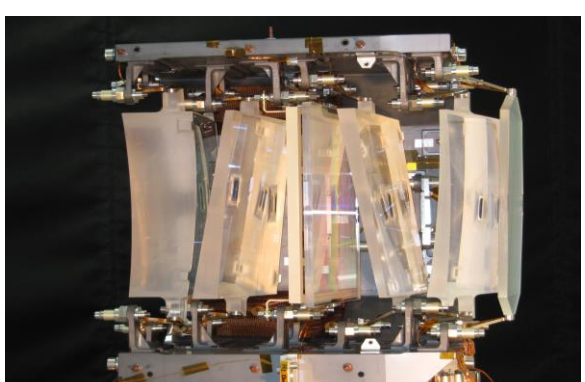
- $G_{RVS} \leq 16.2$
- R ~ 11 000 λ [845,872] nm
- Vr, v sin i, APs, [X/Fe], ...

DR2: a broader variety of data

- Information from **all 3 instruments**: astrometry, spectro-photometry, RVS spectrograph
- Information from **all DPAC coordination units**



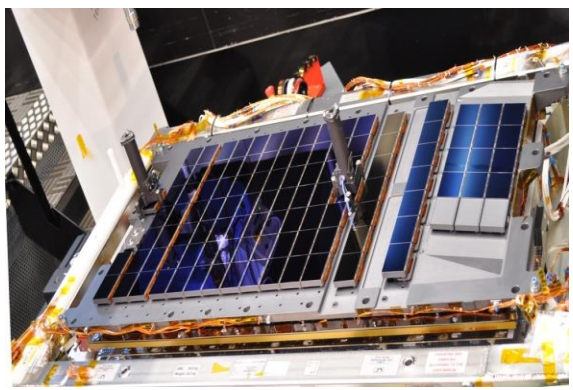


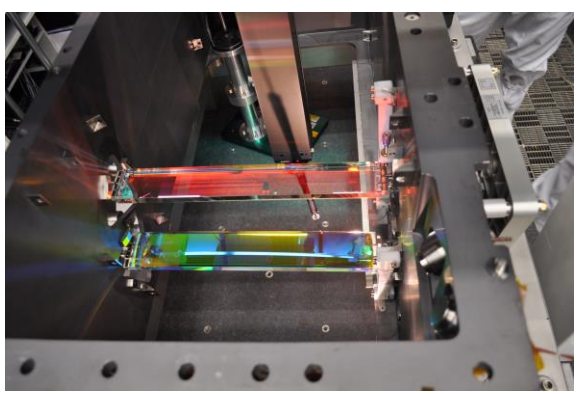


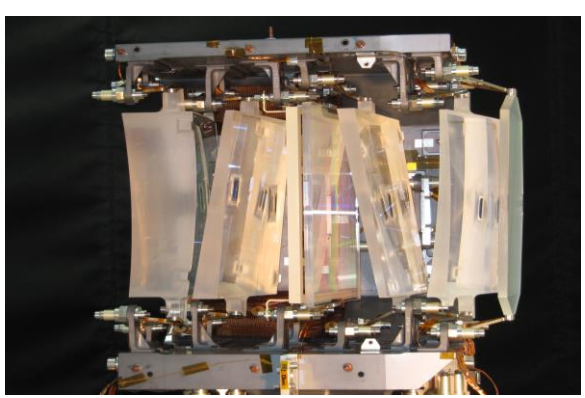
DR1	DR2
• Positions • Parallaxes • Proper-motions	• Positions • Parallaxes • Proper-motions • **Solar system objects**
• G mag • Variable stars	• G mag • **Bp, Rp mag** • Variable stars • **Astrophysical parameters**
	• **Radial velocities**

DR2: 1.3 billion parallaxes and ...

DR2: **25 July 2014 – 23 May 2016 (22 months)**



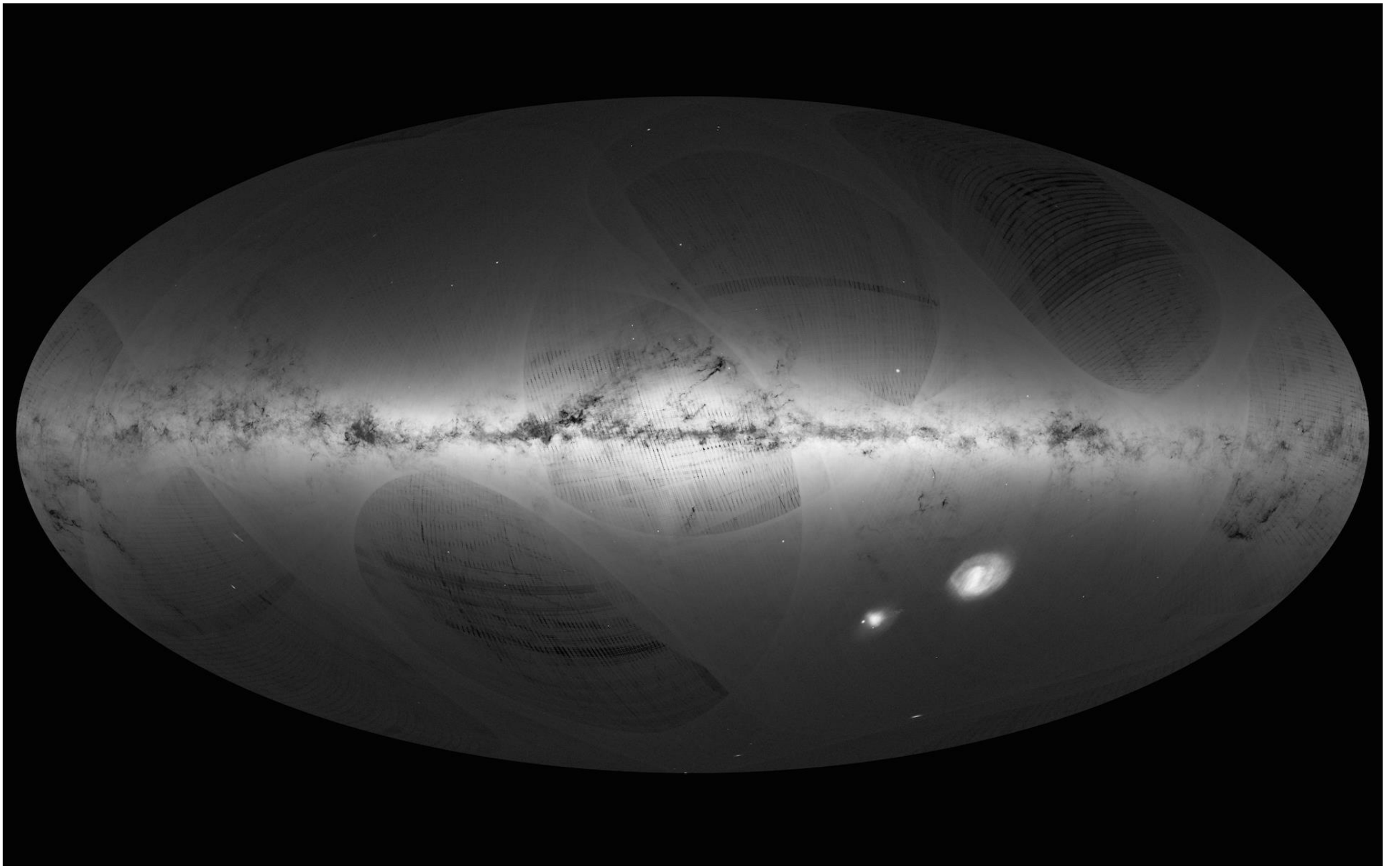




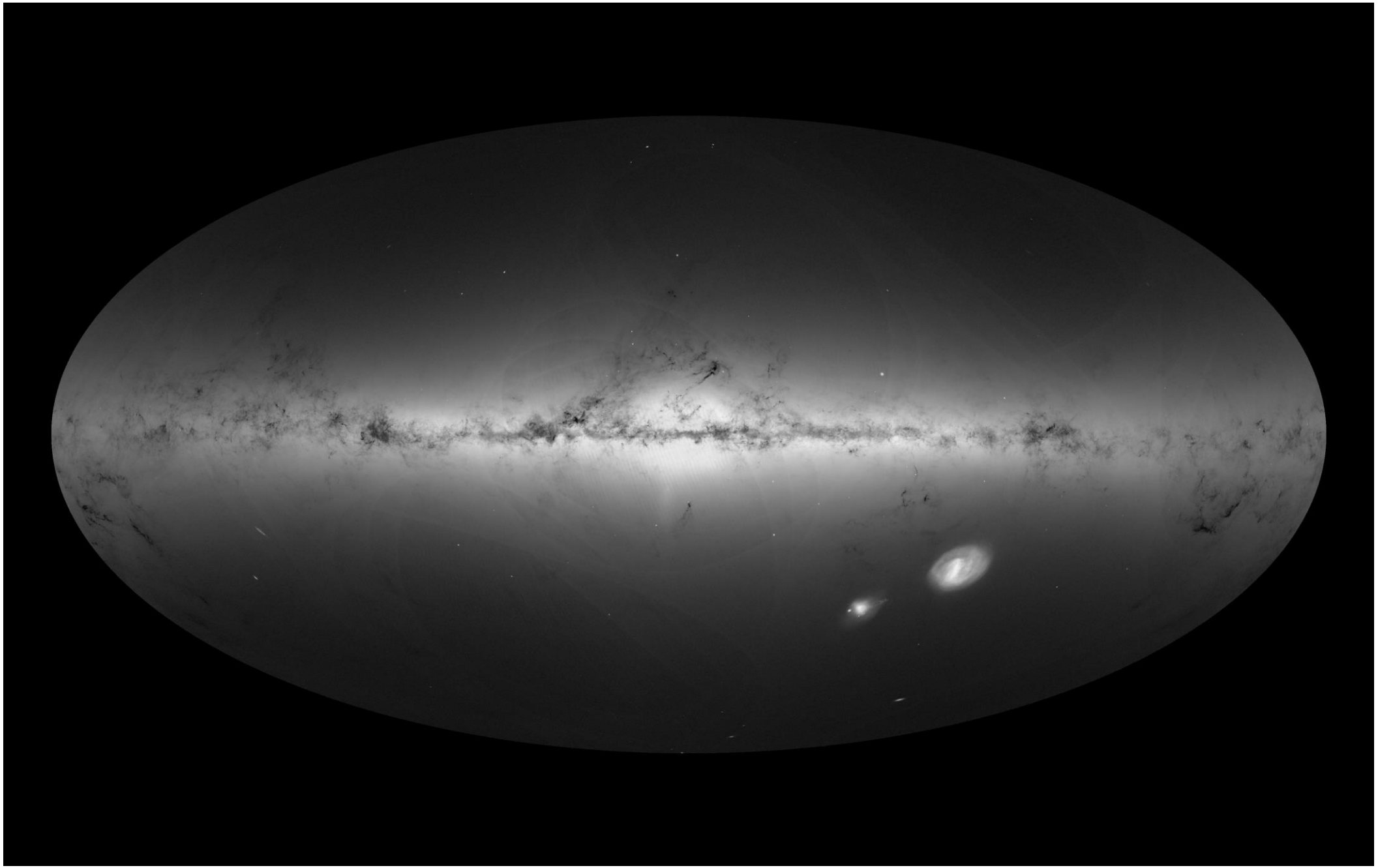
	DR1	DR2
• Data processed	14 months	22 months
• Positions	$1.1\ 10^9$	$1.7\ 10^9$
• Parallaxes	$2\ 10^6$	**$1.3\ 10^9$**
• Proper-motions	$2\ 10^6$	**$1.3\ 10^9$**
• Solar system objects	- -	14 000
• G mag	$1.1\ 10^9$	$1.7\ 10^9$
• Bp, Rp mag	- -	**$1.4\ 10^9$**
• Variable stars	$3\ 10^3$	**$551\ 10^3$**
• Astrophysical parameters	- -	**$77 - 161\ 10^6$**
• Radial velocities	- -	**$7.2\ 10^6$**

Documentation:
- DR2 Overview: Gaia collaboration, Brown et al., 2018

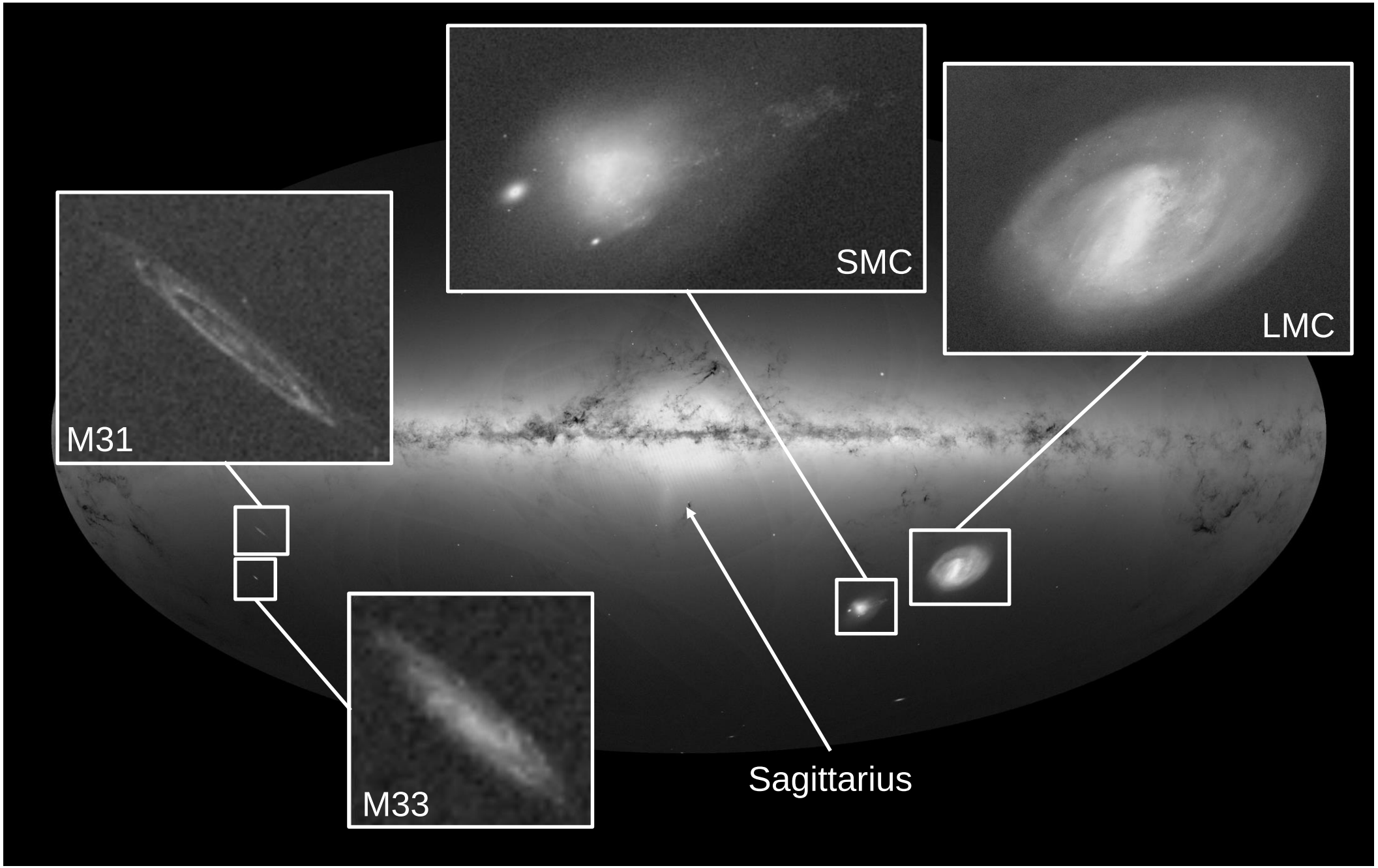
DR1 sky



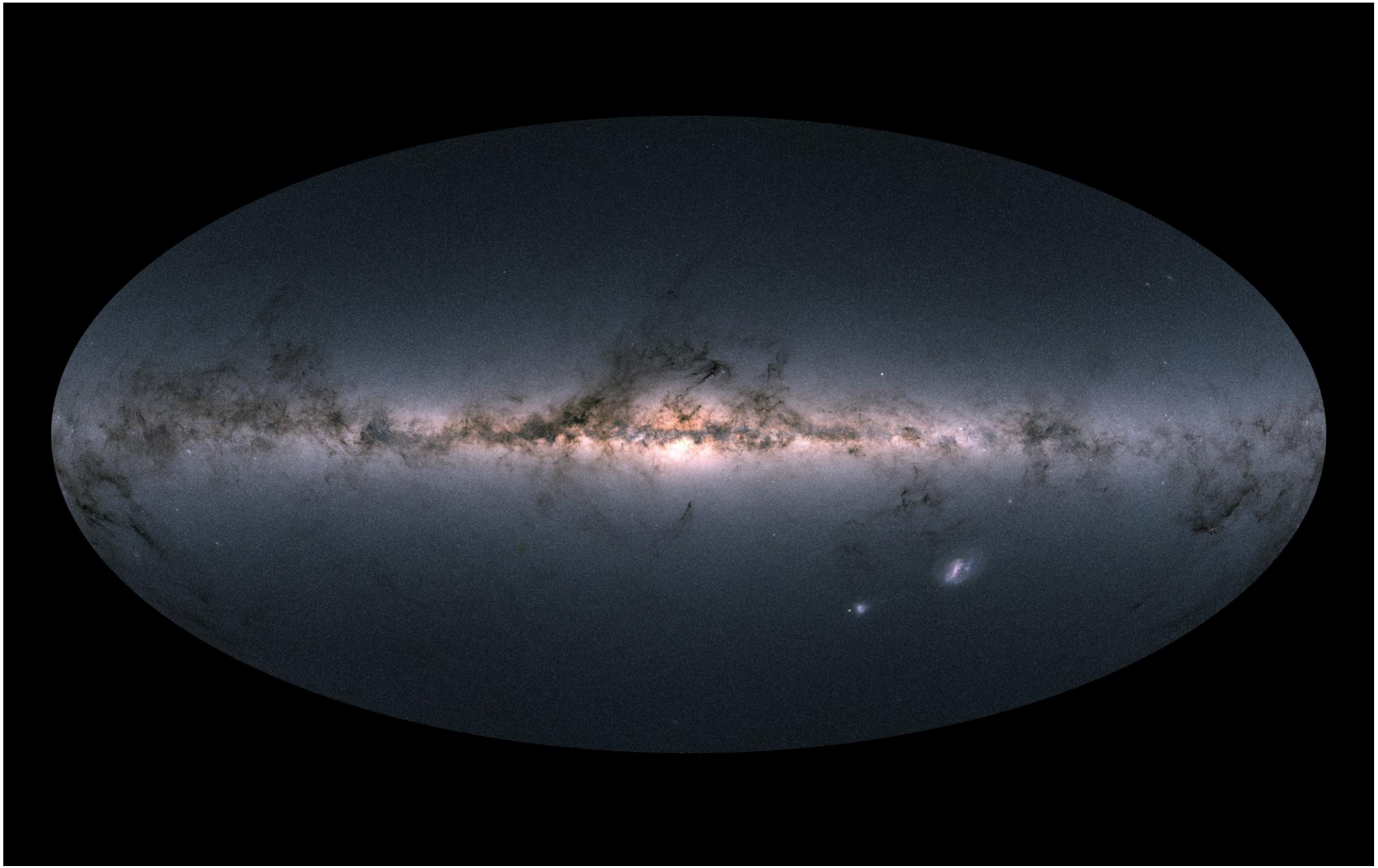
DR2 sky



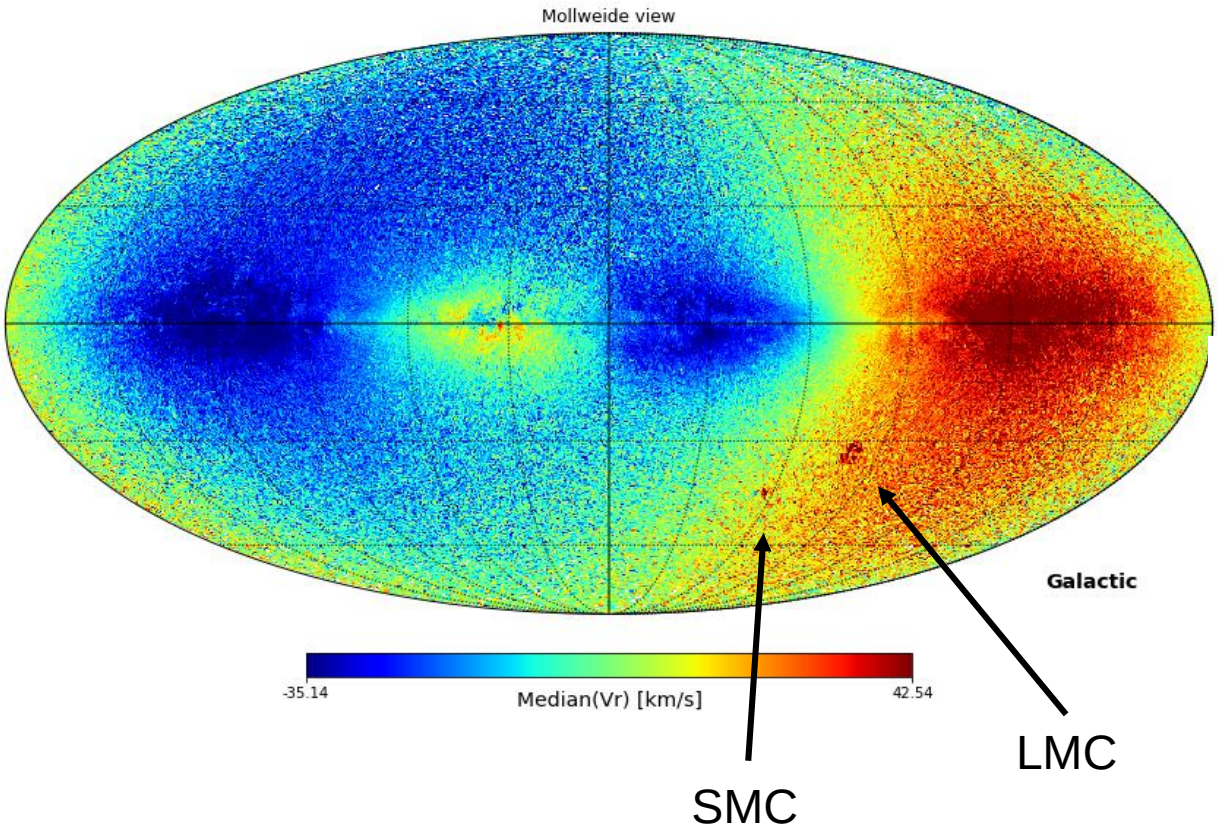
DR2 sky

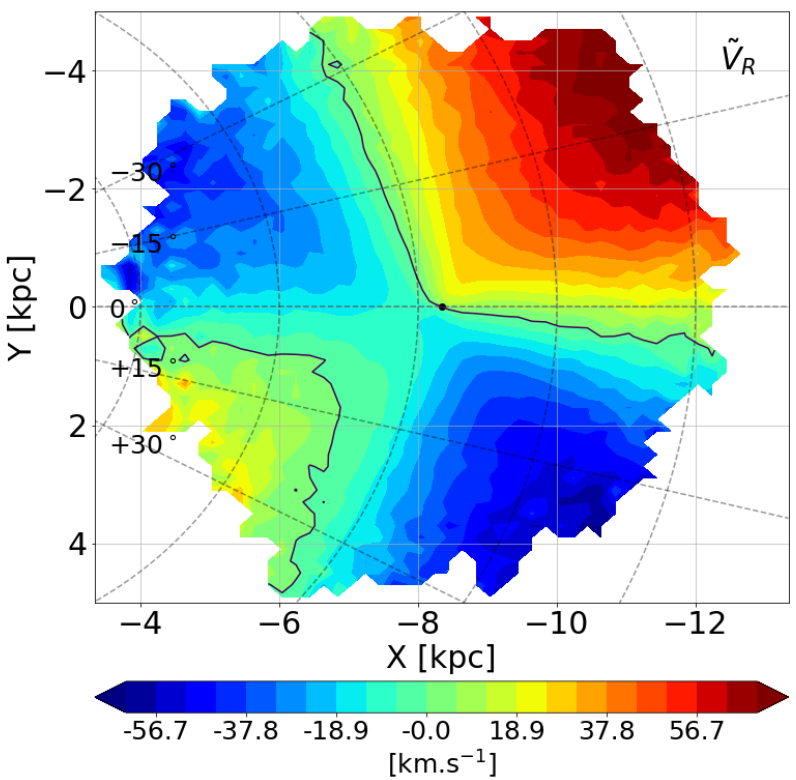


DR2 sky



DR2 sky



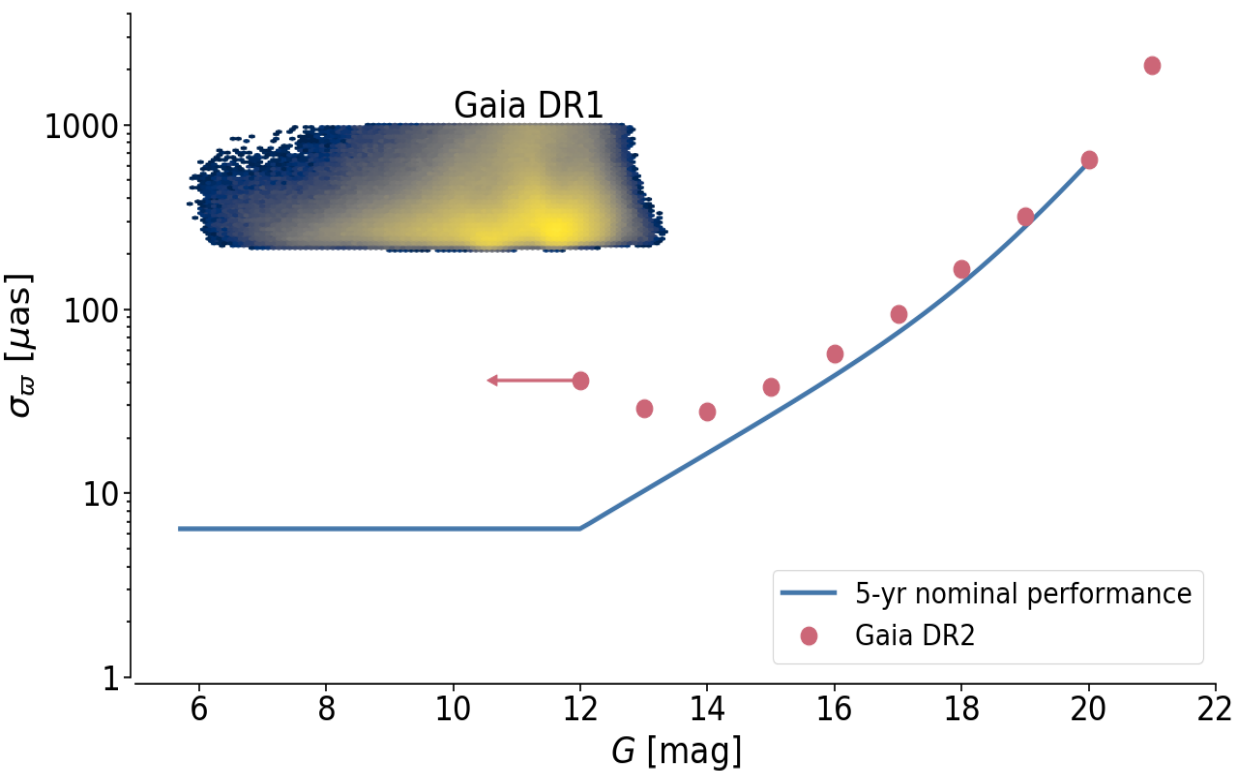


- Median(median line-of-sight velocity)
- Milky Way differential rotation as observed from the Sun, projected on the line-of-sight

Parallax

Improvements wrt DR1

- More/better input data
- **Gaia-only solution**
- Improved calibration
- Improved removal of attitude disturbance

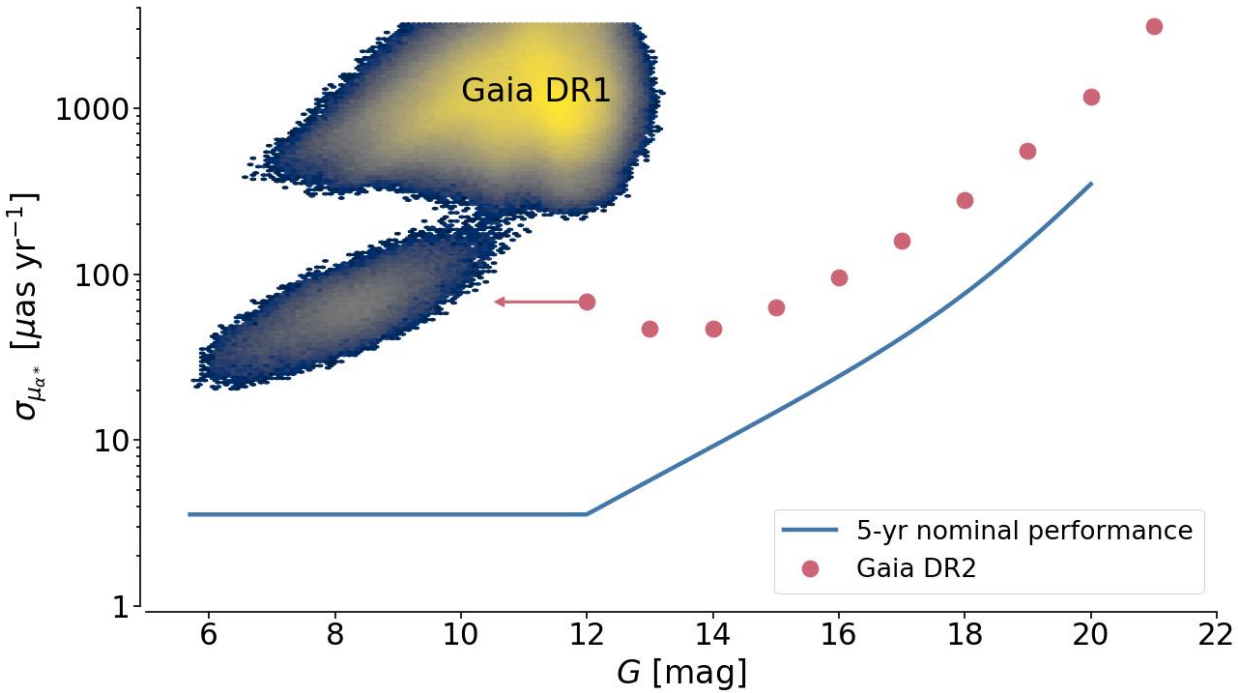


- Typical **parallax precision**
  - **G = 15 20 - 40 µas**
  - G = 17 100 µas
  - G = 20 700 µas
  - G = 21 2 mas

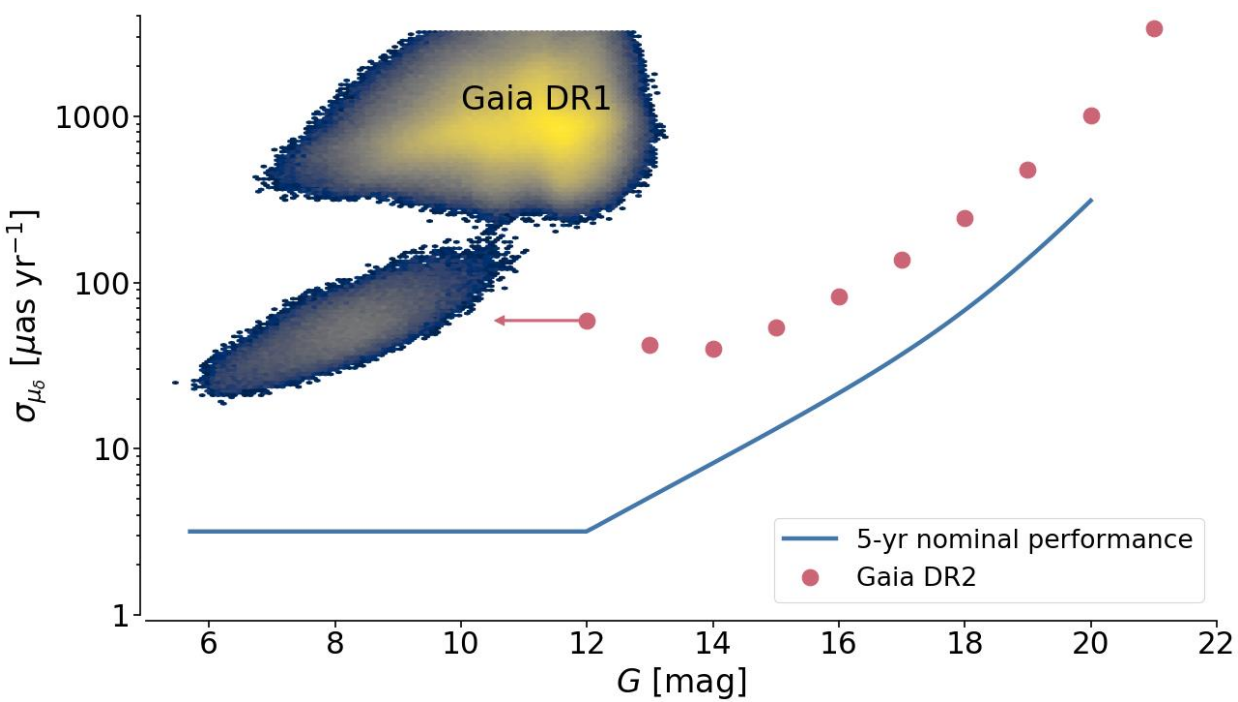
- Systematic errors **< 100 µas**
- E.g. wrt ICRF2: -31 +/- 3 µas
- Spatial correlations at different scales: e.g. (G ≥ 16):
  - 14 – 20 deg: +/- 17 µas
  - < 1 deg : +/- 1 µas
- Bright star performance: calibration limited

Documentation:
- Astrometry: Lindegren et al., 2018
- Validation: Arenou et al., 2018
- Usage: Luri et al., 2018

Proper motions



- Typical precision:
  - G = 15 50 – 60 µas/yr
  - G = 17 200 µas/yr
  - G = 20 1.2 mas/yr
- Systematics and spatial correlations



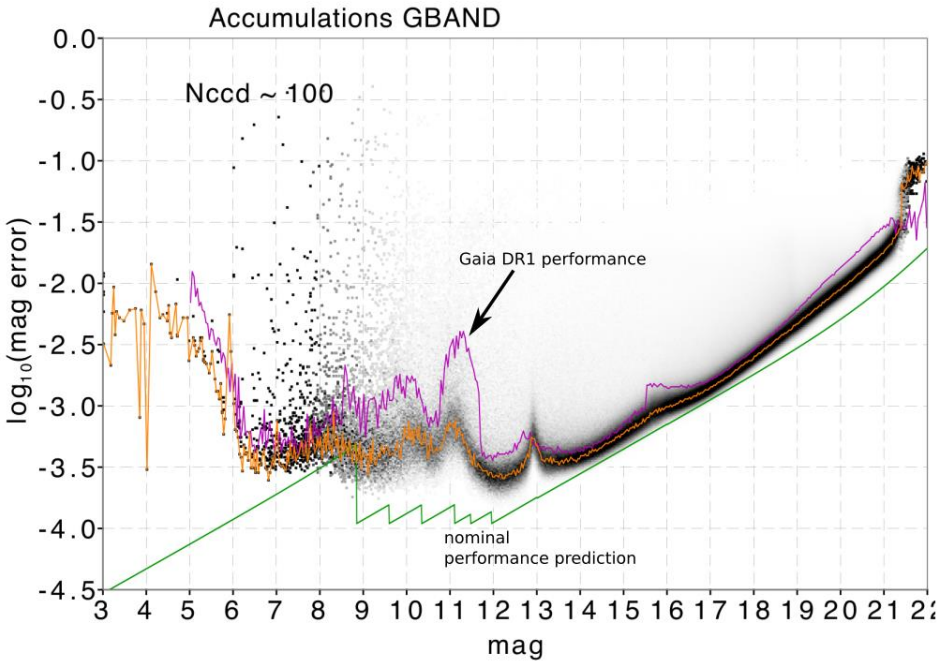
- Typical precision:
  - G = 15 40 – 60 µas/yr
  - G = 17 100 µas/yr
  - G = 20 1 mas/yr
- Systematics and spatial correlations

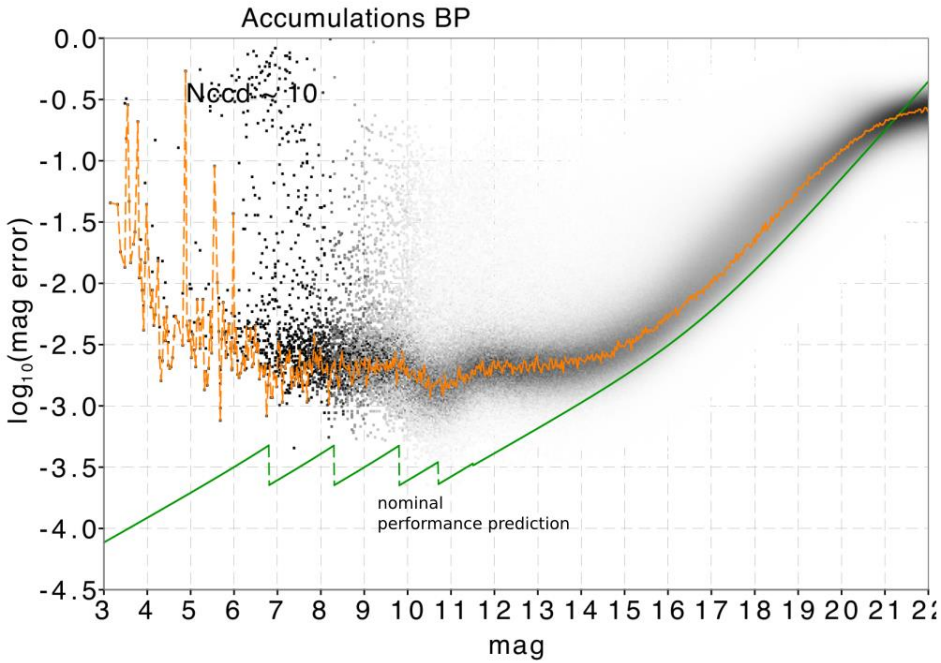
Documentation:
- Astrometry: Lindegren et al., 2018
- Validation: Arenou et al., 2018

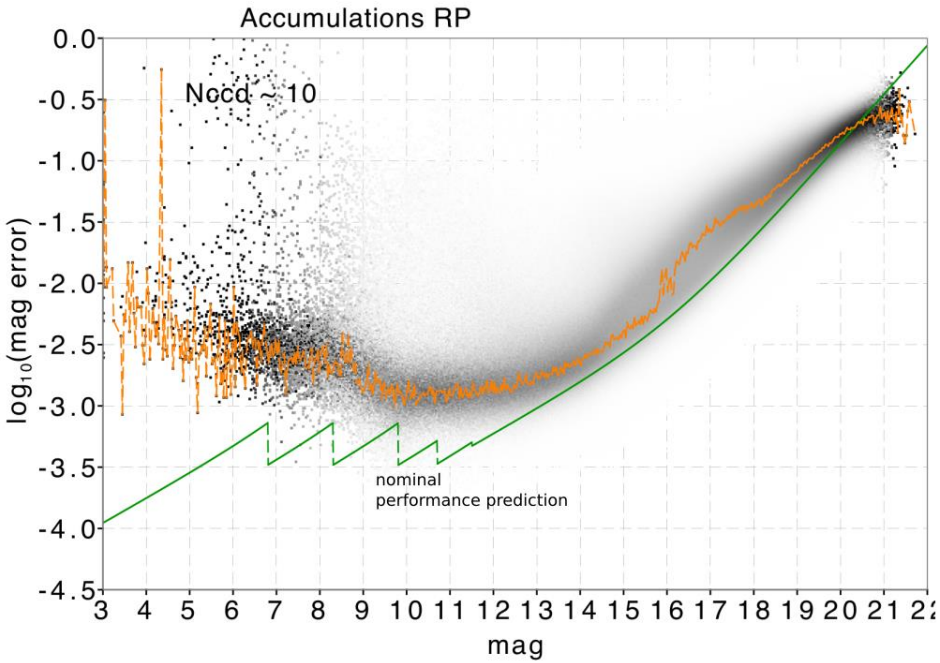
Photometry: G, Bp, Rp

- Typical precision: G, G_{BP}/G_{RP}:
  - G < 13 0.3 mmag 2 mmag
  - G = 17 2 mmag 10 mmag
  - G = 20 10 mmag 200 mmag
- G_{BP}/G_{RP} longer windows → suffer more from crowding and contamination

Documentation:
- Processing: Riello et al., 2018
- Validation: Evans et al., 2018



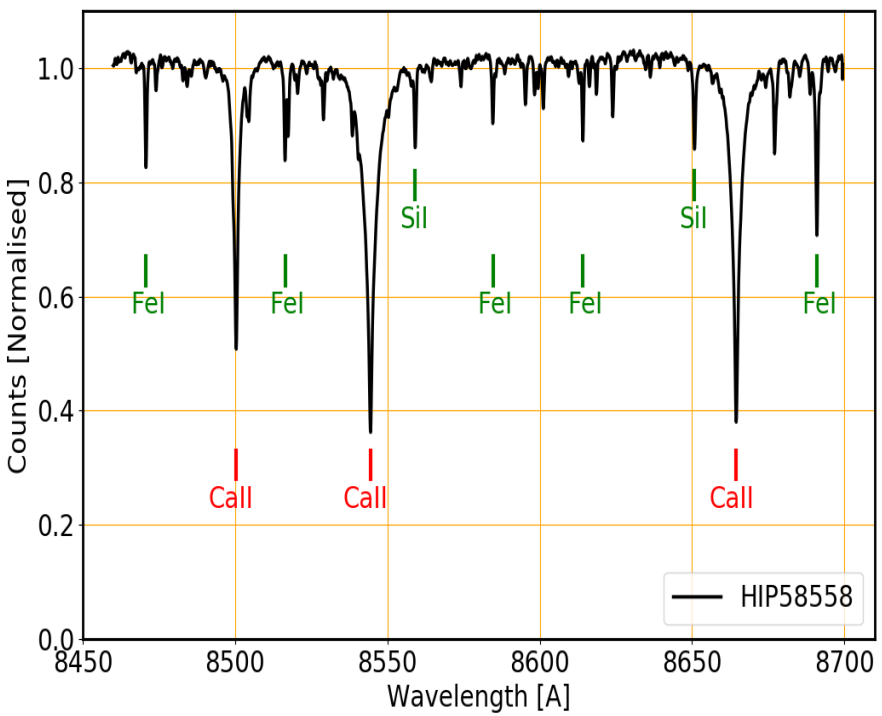


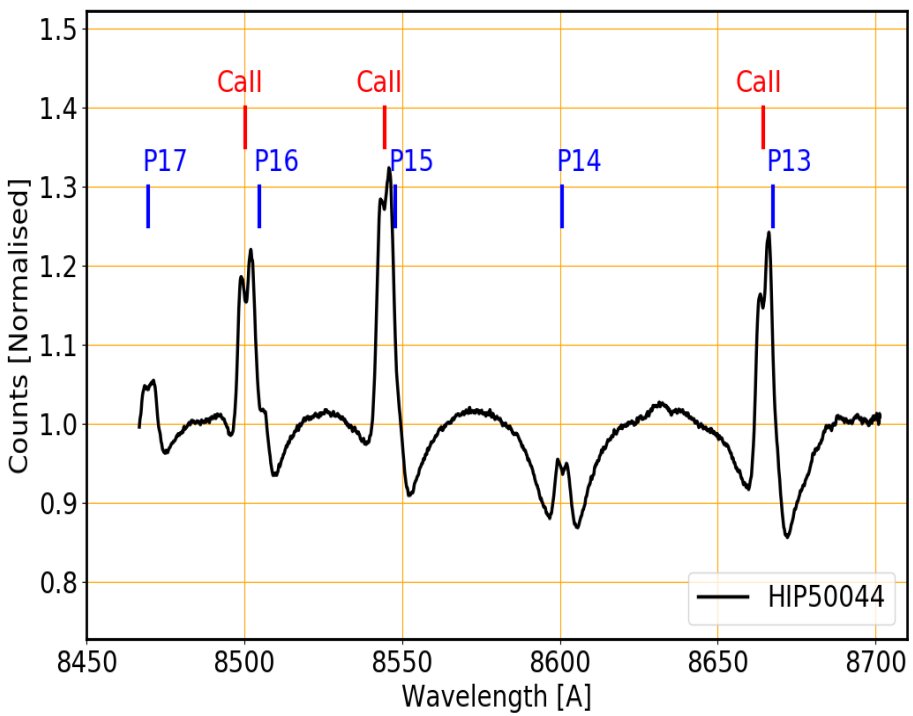


Line-of-sight velocities

- Grvs ≤ 12 mag
- Vr in [-1000, +1000] km/s
- Teff in [3550, 6900] K

- No binaries (when detected)
- No emission-lines (when detected)
- No large amplitude variables (when detected)
- No non-rectangular windows processed

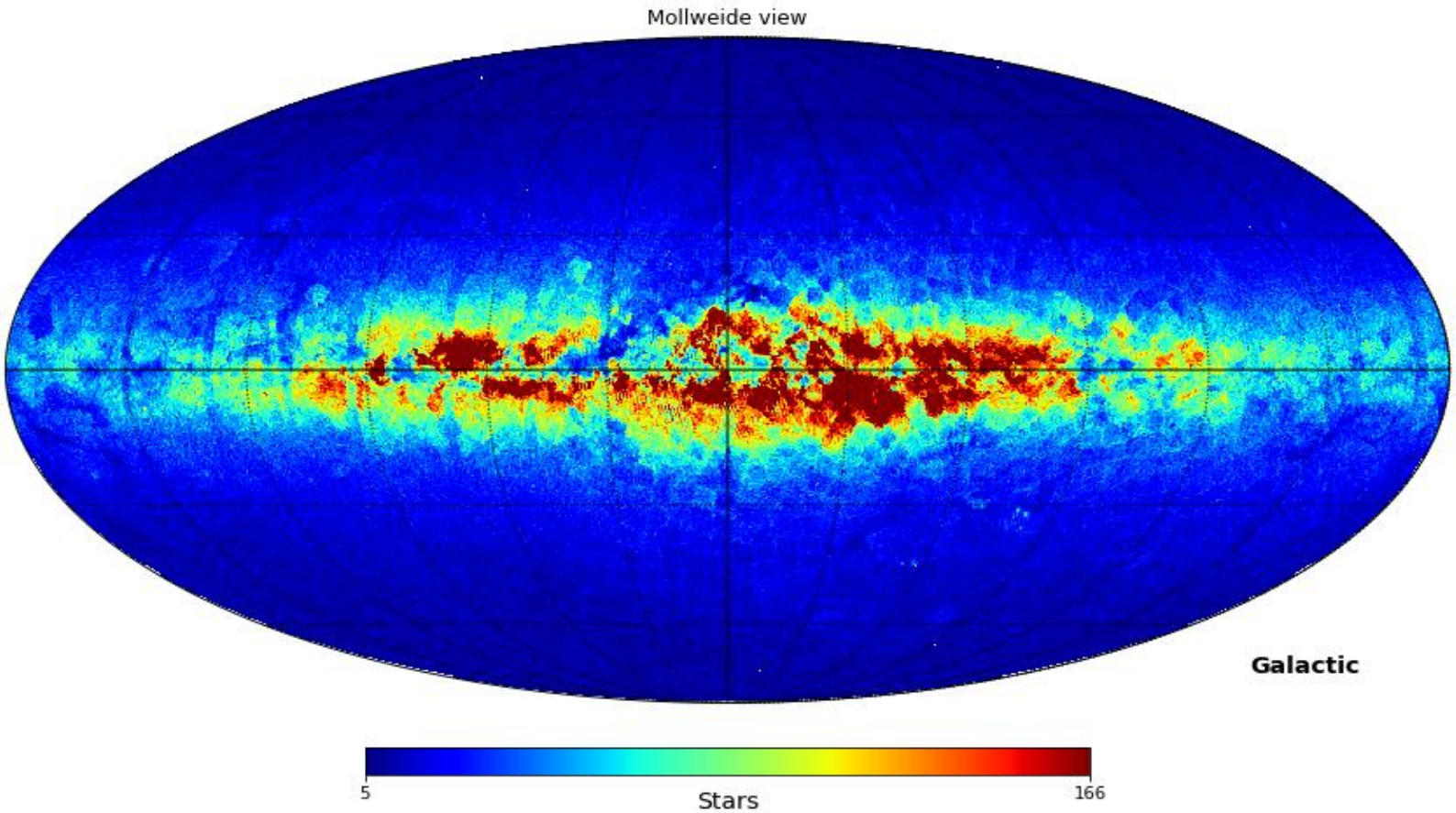




Documentation:
- RVS instrument: Cropper et al., 2018
- Processing: Sartoretti et al., 2018
- GB standards: Soubiran et al., 2018
- Validation and performance: Katz et al., 2018

Line-of-sight velocities: DB content

7 224 631 stars

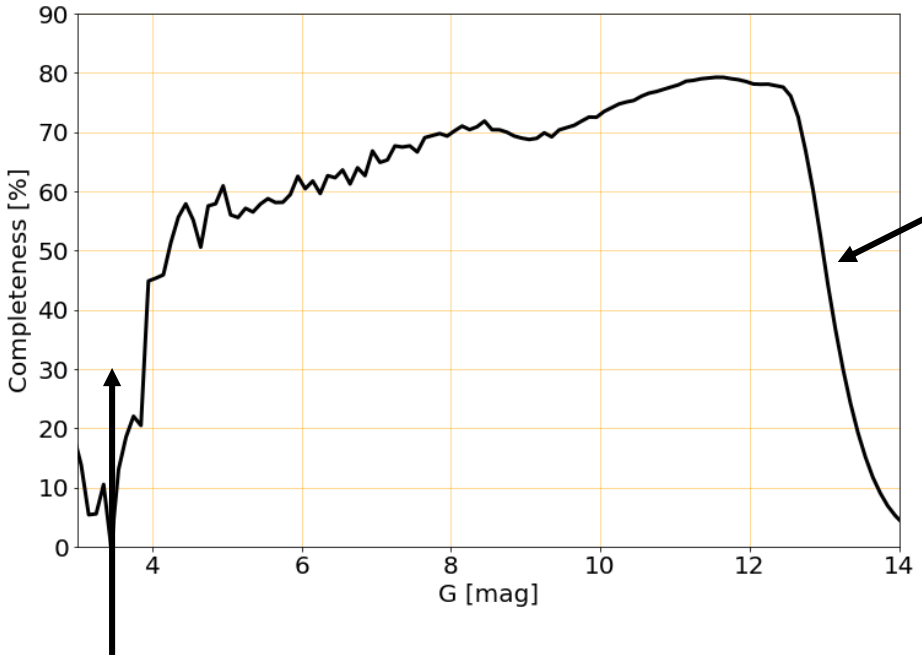


Products

- Median line-of-sight velocity
- Line-of-sight velocity uncertainty
- Number of transits

- Template : Teff, logg, [Fe/H]
- Do not use as estimate of atmospheric parameters

Completeness

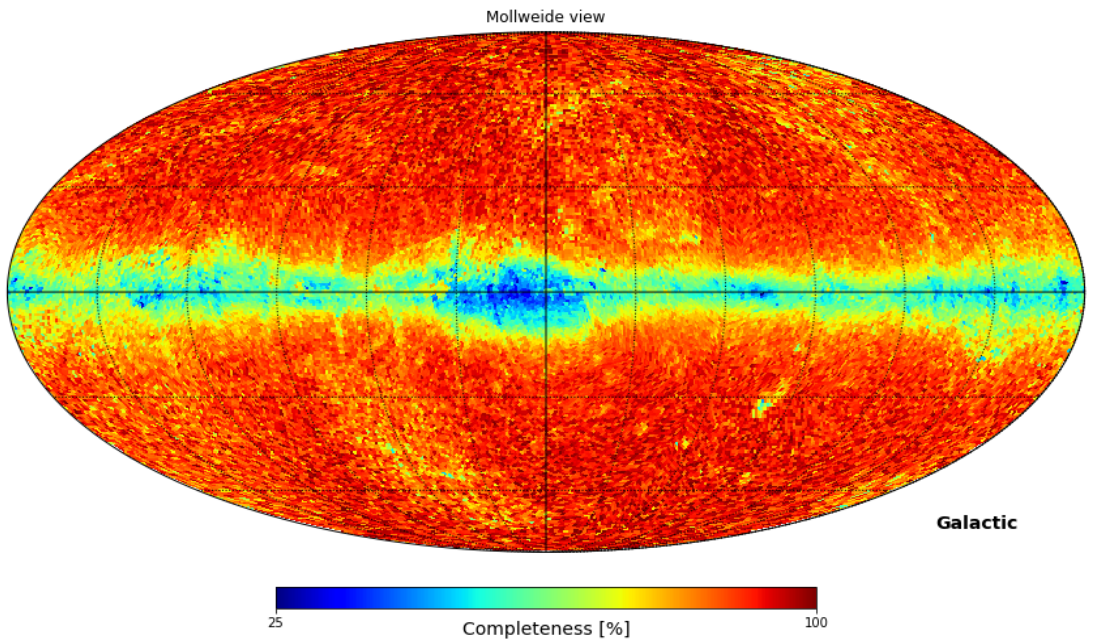


Processing limit:
Grvs = 12

Median completeness for
G ≤ 12.5 : 77 %

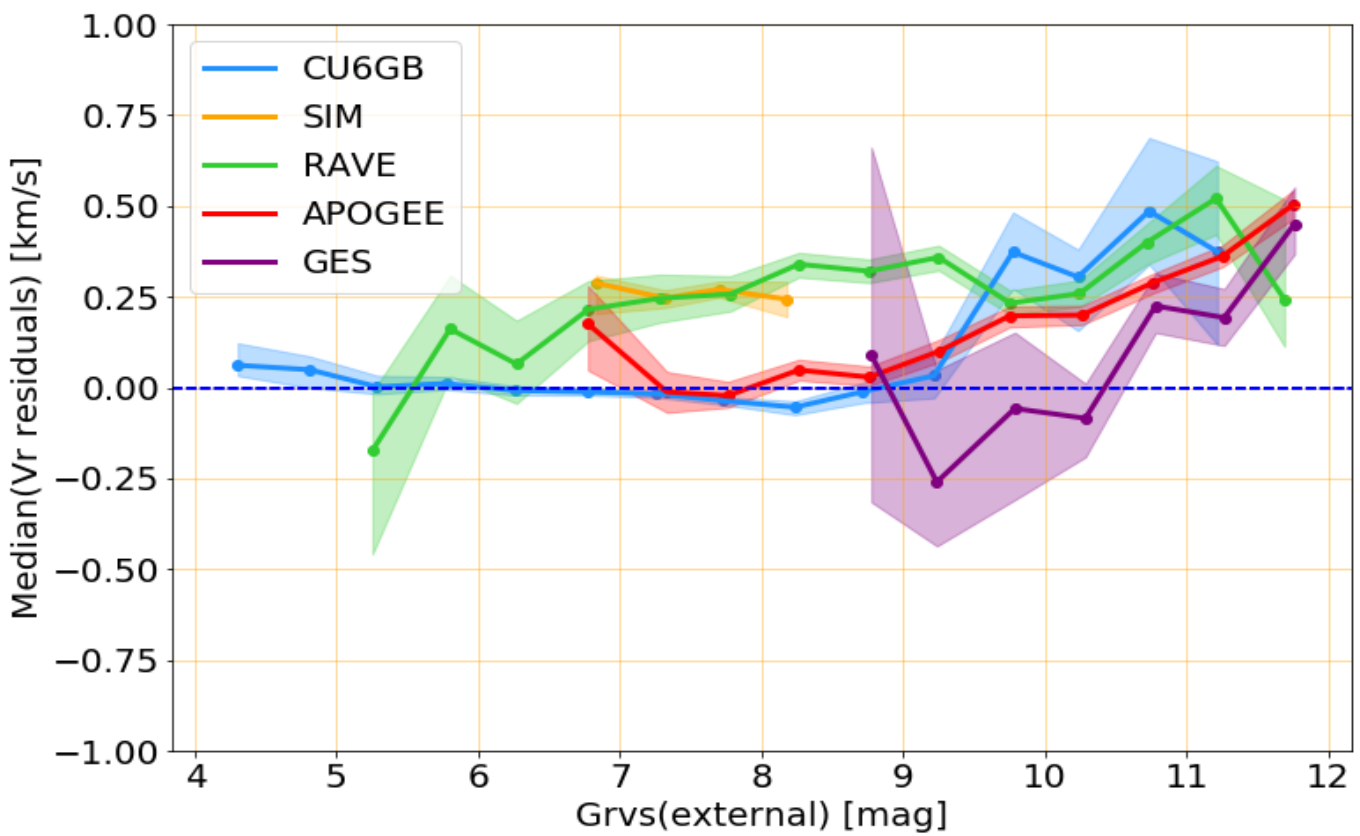
Saturation:
G ~ 4 mag

Completeness lower in high density areas → windows conflicts



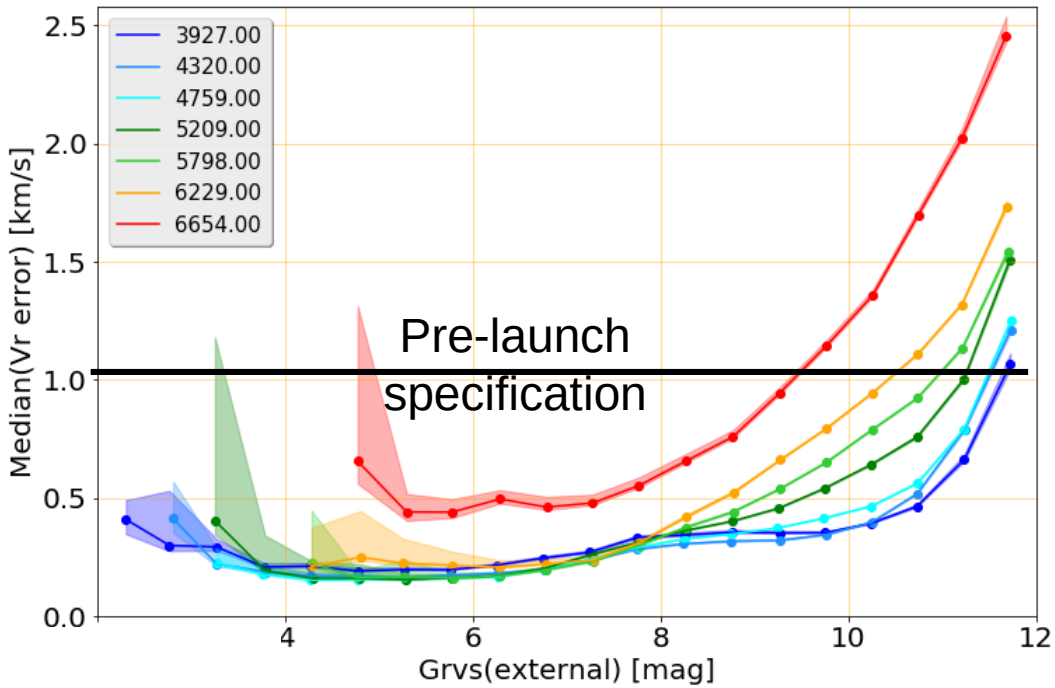
Accuracy

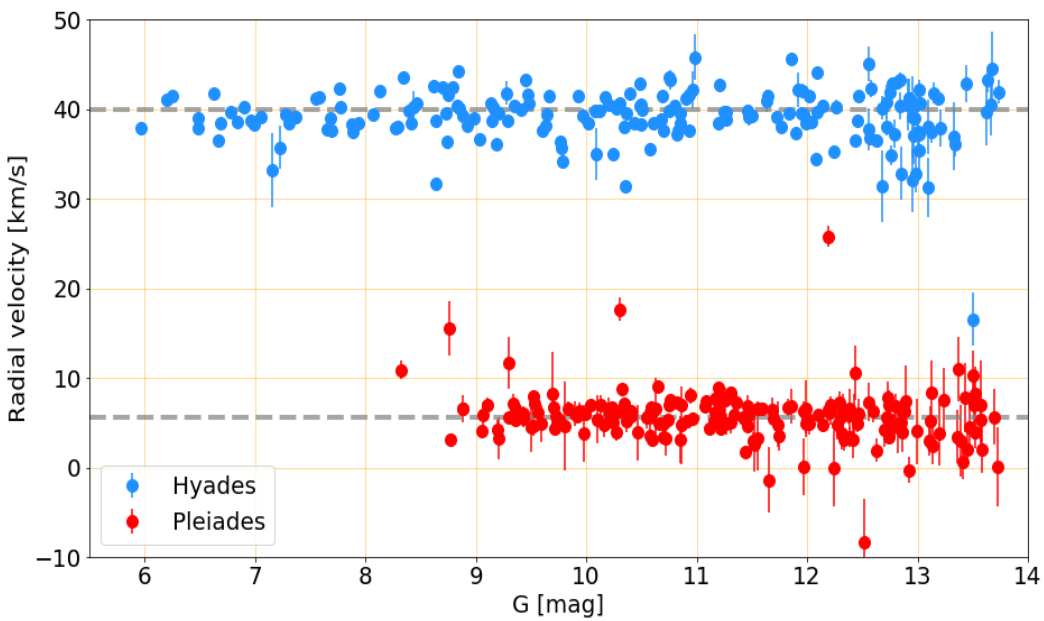
- Median offset calculated with respect to ground-based catalogues : CU6GB, SIM, RAVE, APOGEE, GES
- Varies from catalogue to catalogue : **a few 100 m/s**
- Trend with magnitude : start at Grvs ~ 9 mag → ~ 500 m/s at Grvs = 12 (calibrated and corrected in DR3)



Precision

- Multi-parametric question: mag., nb of transits, APs, coordinates, etc…
- Bight stars: **~200 m/s**
- Grvs = 11.75 mag:
  - Solar: **~ 1.5 km/s**
  - 6700 K: **~ 2.5 km/s**





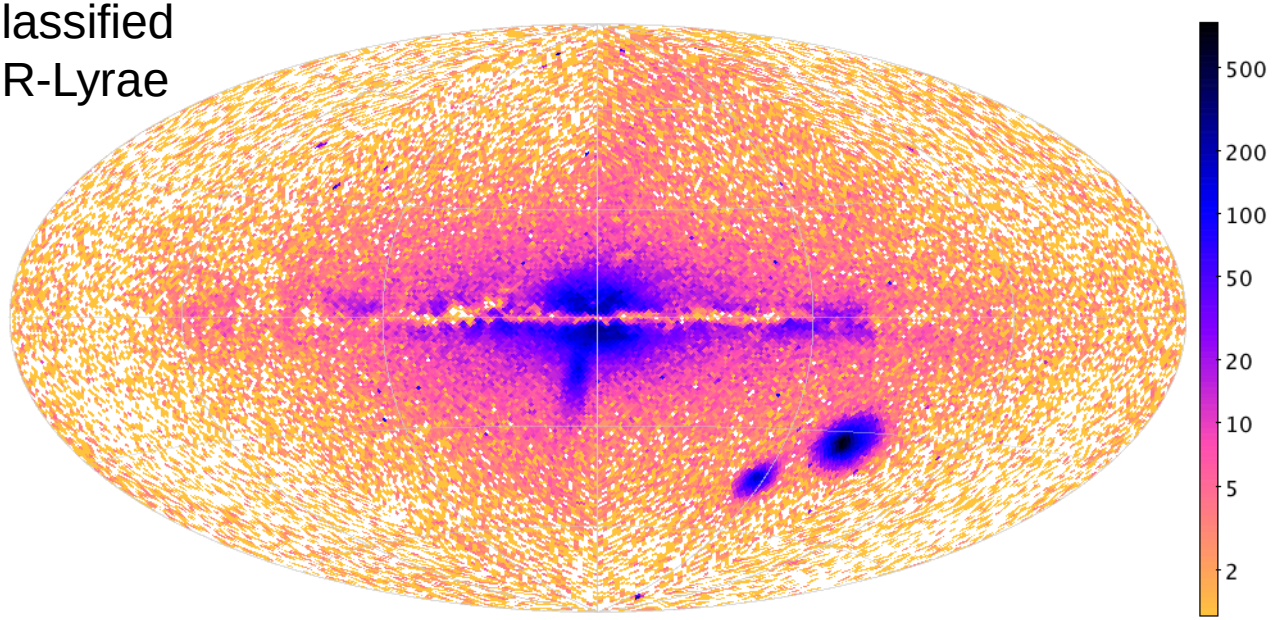
Hyades (blue) / Pleiades (red):

- Standard deviation ~ 2 km/s (includes clusters intrinsic scatter)

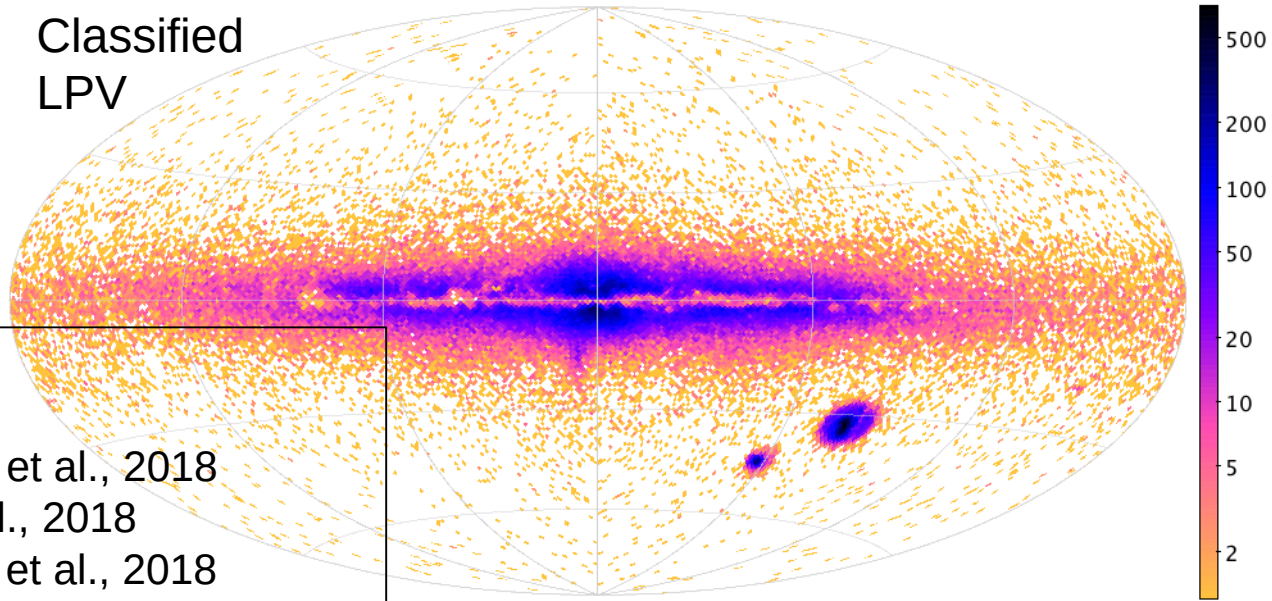
Variable stars

- 551 thousand variables identified → many more in future release
- Subset classified by variability type:
  - based on ≥ 2 transits
- Overlapping subset studied in detail:
  - based on ≥ 12 transits

Classified RR-Lyrae

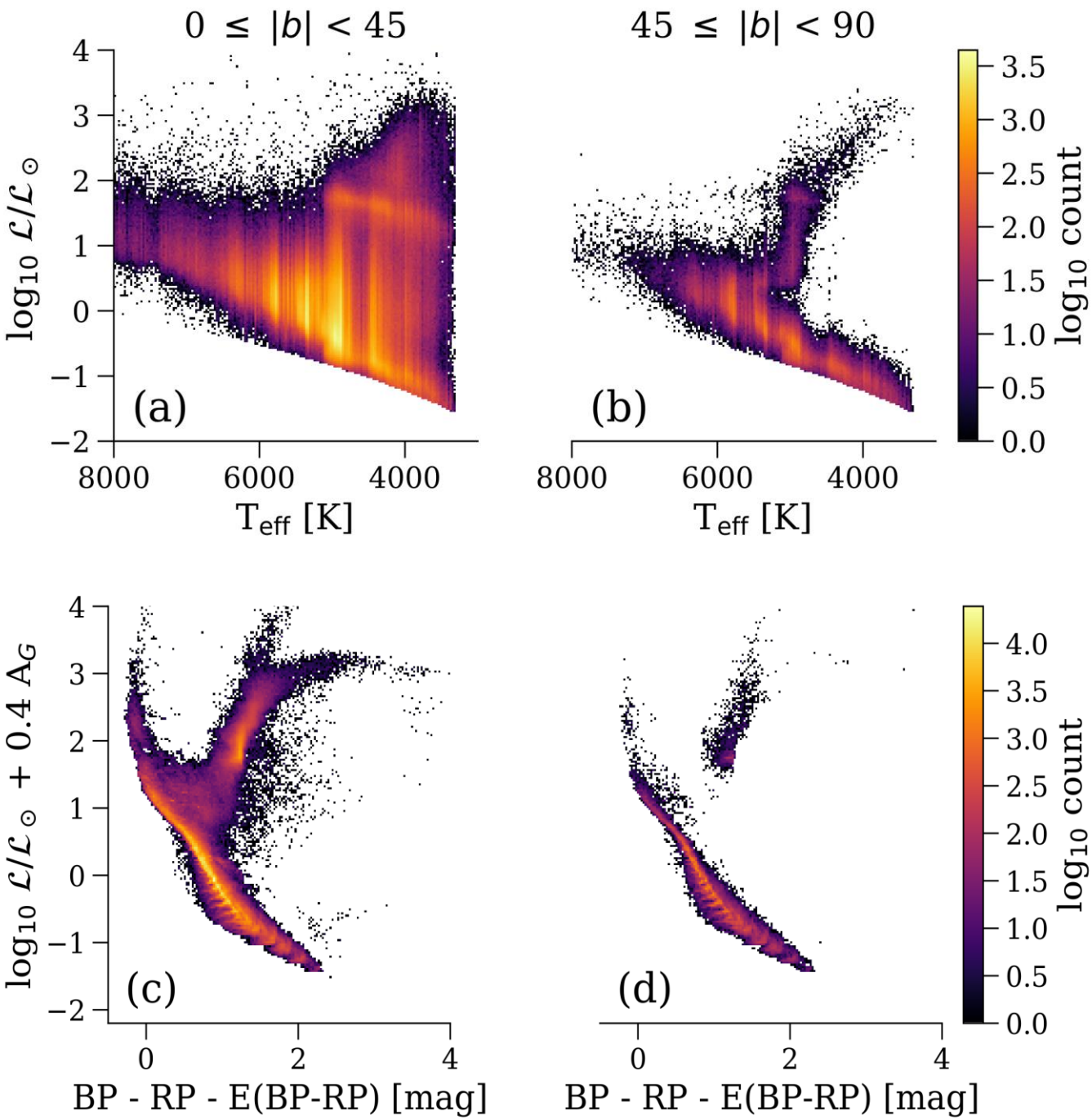


Classified LPV



Documentation:
- Processing: Holl et al., 2018
- Cepheids and RR Lyrae: Clementini et al., 2018
- Long period variables : Mowlavi et al., 2018
- Short time-scale variability: Roelens et al., 2018
- Variables in CMD: Gaia collaboration, Eyer et al., 2018

Astrophysical parameters



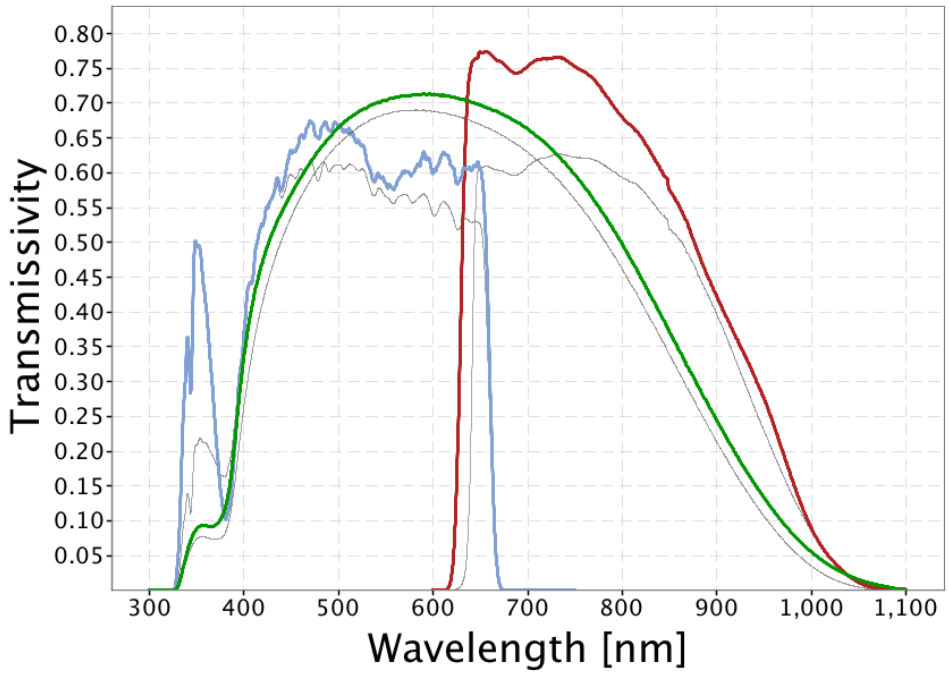
- Teff, A_G, E(B-V), L, R:
  - from G, G_{BP}, G_{RP} and parallaxes
- Teff / A_G degeneracy at low galactic latitude → use preferentially Teff in low extinction directions
- Teff flags (Appendix B) → recommended to use sources with PRIAM flags: 0100001, 0100002, 0110001, 0110002, 0120001 or 0120002

Documentation:
- APs: Andrae et al., 2018

DR2 is independent from DR1

- Astrometry is based on Gaia data alone

- Photometric system is different
  - Colour dependent difference in G (mean of -0.1 for $\Delta G = G_{DR1} - G_{DR2}$)
  - Passband differences: do not use nominal or DR1 passbands



- Source list changed substantially:
  - At G ≤ 16 some 80–90% of sources changed identifier
  - Redo your cross-matches (or use the pre-computed ones provided for Gaia DR2)
  - Always qualify a source identifier with data release number (Gaia DRn xxx...xxx)
  - DR2 ↔ DR1 match table is provided
    - > 99% cases are one-to-one matches

Features and recommendations

- Complex selection function:
  - Scanning law, on-board data prioritisation, filtering during processing, filtering before publication
- Calibration limitations, in particular at bright end.
- Photometric (color) systematics related to crowded fields and background subtraction.
- Uncertainties vary as a function of magnitude, position, source properties, ...
  - uncertainties may be asymmetric
  - uncertainties may be correlated: take covariance matrix into account
- Systematics, etc...
  - Rather include in forward modelling than correct the data

Recommendation: read the documentation

Features and recommendations

- Small fraction of spurious astrometric solutions: e.g.
  - 113 393 sources with $\varpi < -10$ mas concentrate in dense areas: disk, LMC, SMC
  - 59 sources "are closer" than Proxima
  - Several filters could be applied: see Sect. 4.1 of Arenou et al, 2018
  - Filters could also reject good astrometric solutions → assess the merits and drawbacks of the filters depending on the specificities of the sample/question considered.

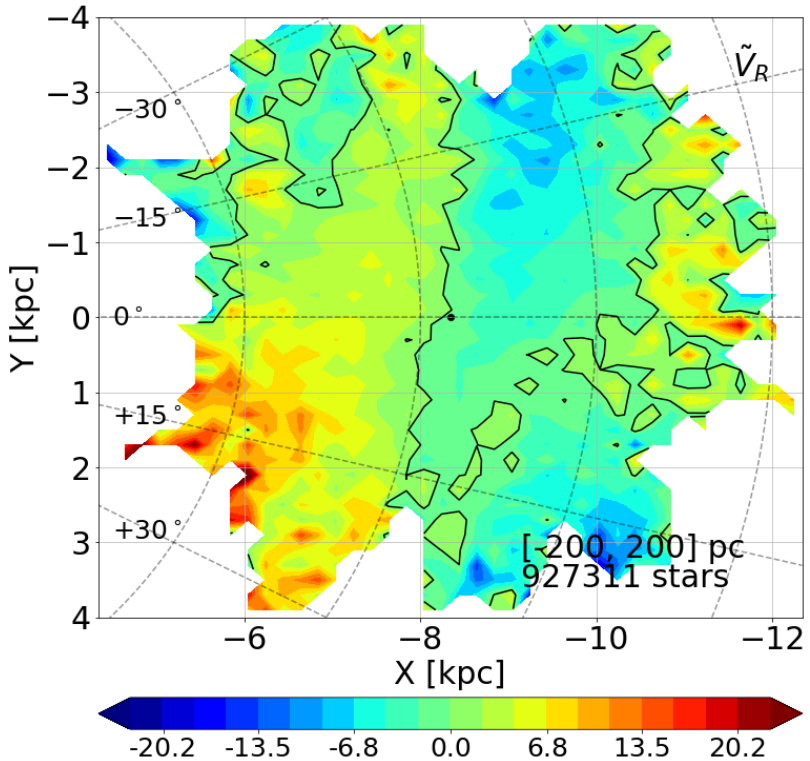
- Processing limitations (single-star model, sub-optimal calibration models) → some lower quality solutions. Indicators of the quality of the astrometric solution:
  - astrometric_excess_noise, astrometric_gof_al, astrometric_n_bad_obs_al

- Parallax uncertainties underestimated for $13 \leq G \leq 15$ and astrometric_nobs_ac = 0
  - Reweighting: see Eq. A6 of Lindegren et al., 2018

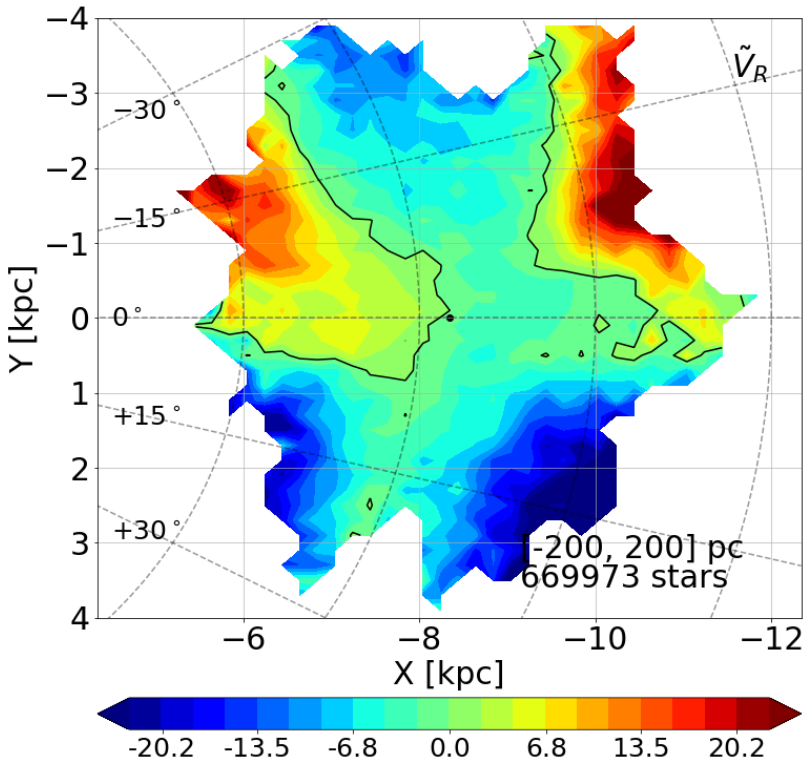
Recommendation: read the documentation

Features and recommendations

- Some correlations values/uncertainties → filtering on uncertainties modifies the distribution of values : e.g. Vr, Vphi, Vz



All stars



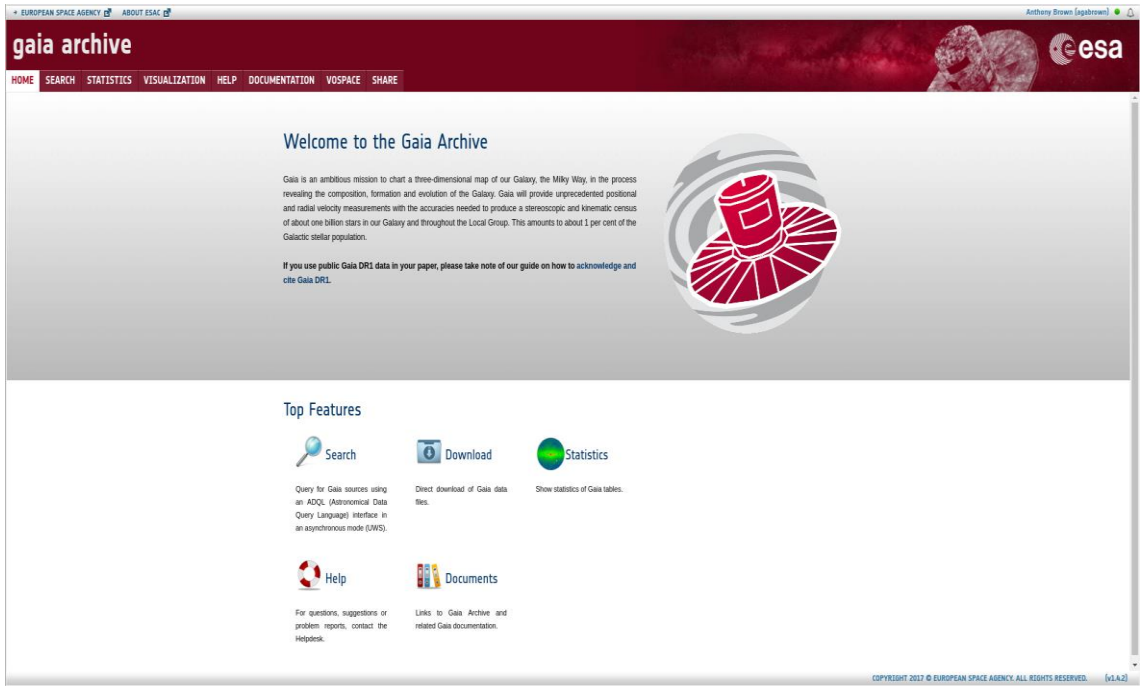
$\varepsilon_{Vr} \leq 2$ km/s

Recommendation: read the documentation

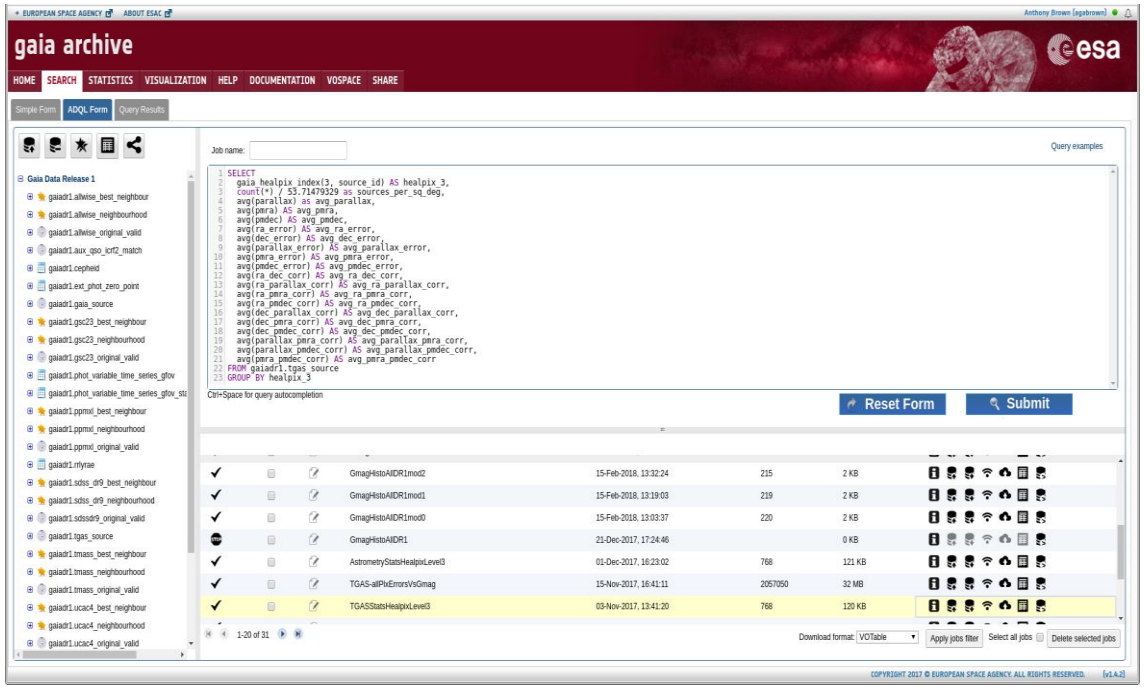
Data Access

- **archives.esac.esa.int/gaia**

- http://cds.u-strasbg.fr/gaia
- http://gaia.ari.uni-Heidelberg.de/
- https://gaia.aip.de/
- http://gaiaportal.asdc.asi.it/



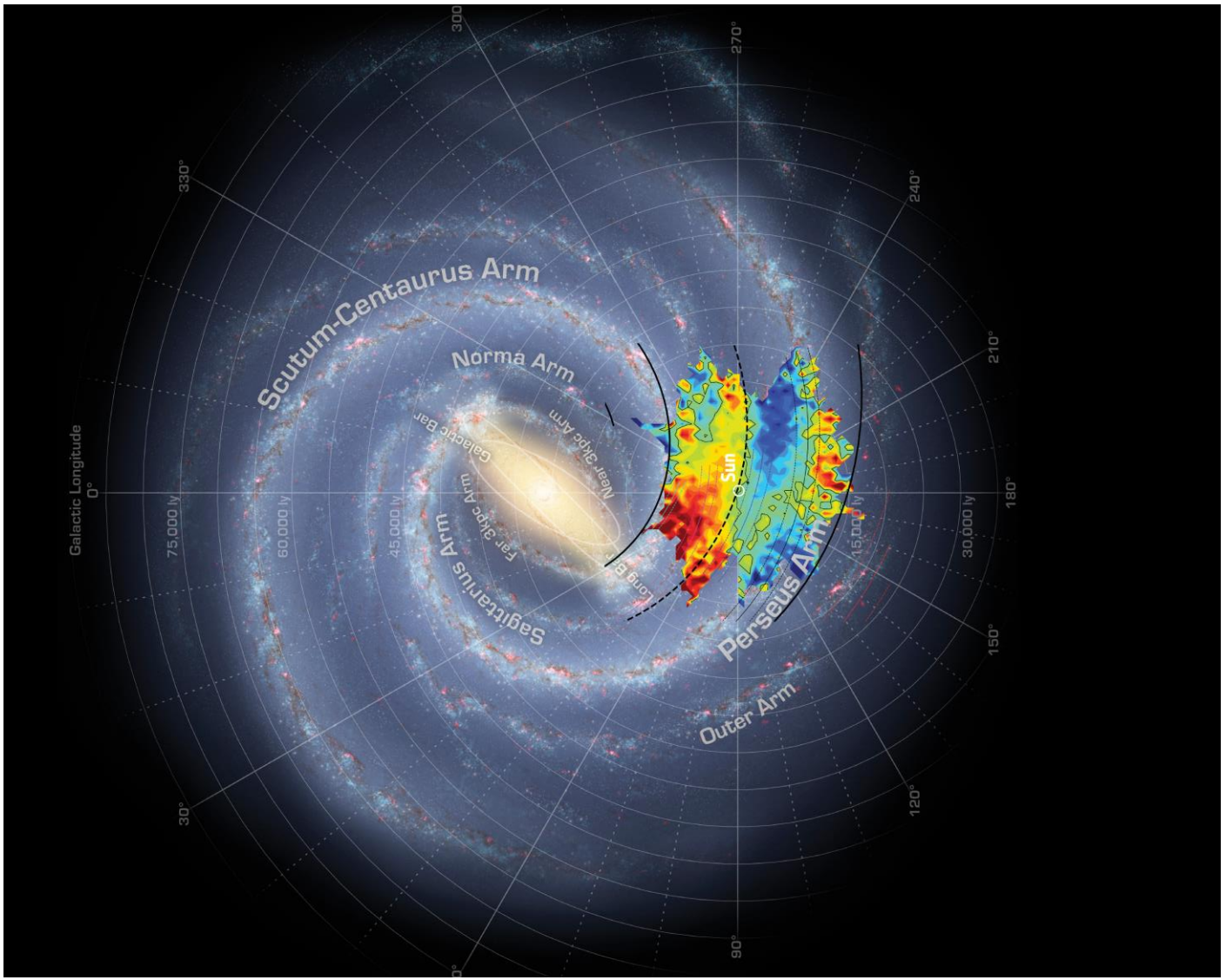
- Pre-computed X-matches to other large surveys.
- Space to upload users data.



Performance verification papers

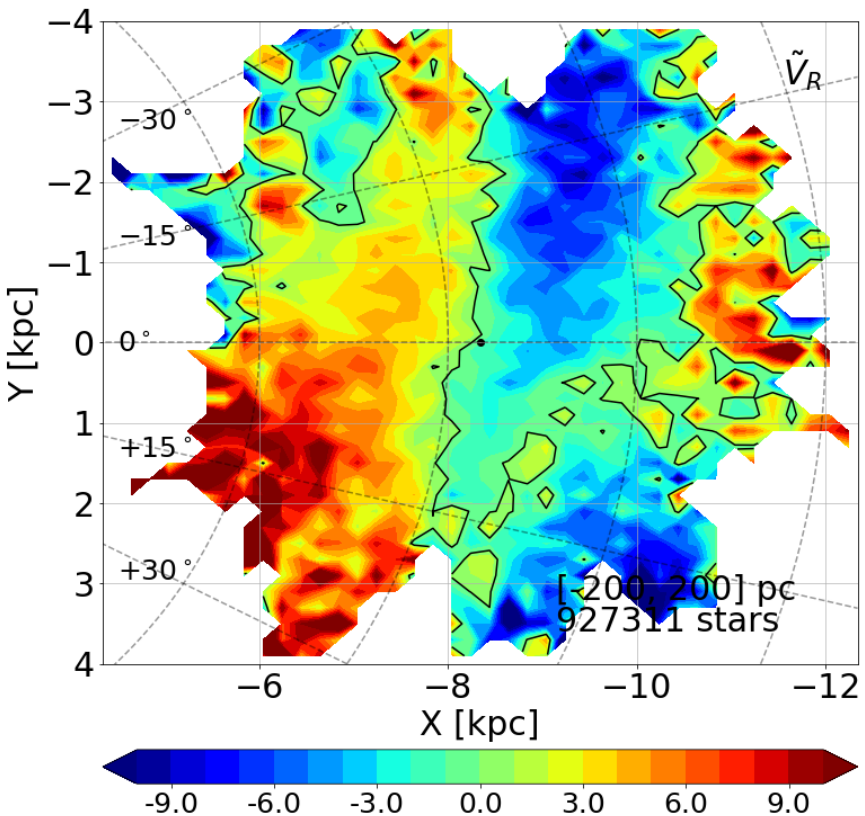
- The Celestial reference frame (Gaia-CRF2), Gaia Collaboration, F. Mignard, S.A. Klioner, L. Lindegren et al., 2018, arXiv 1804.09377
- *Kinematics of globular clusters and dwarf galaxies around the Milky Way, Gaia collaboration*, Helmi, van Leeuwen, P.J. McMillan et al., 2018, arXiv 1804.09381
- *Mapping the Milky Way disc kinematics*, Gaia Collaboration, D. Katz, T. Antoja, M. Romero-Gómez et al., 2018, arXiv 1804.09380
- *Observational Hertzsprung-Russell diagrams*, Gaia Collaboration, C. Babusiaux, F. van Leeuwen, M.A. Barstow et al., 2018, arXiv 1804.09378
- *Variable stars in the colour-absolute magnitude diagram*, Gaia Collaboration, L. Eyer, L. Rimoldini, M. Audard et al., 2018, arXiv 1804.09382
- *Observations of solar system objects*, Gaia Collaboration, F. Spoto, P. Tanga, F. Mignard et al., 2018, arXiv 1804.09379

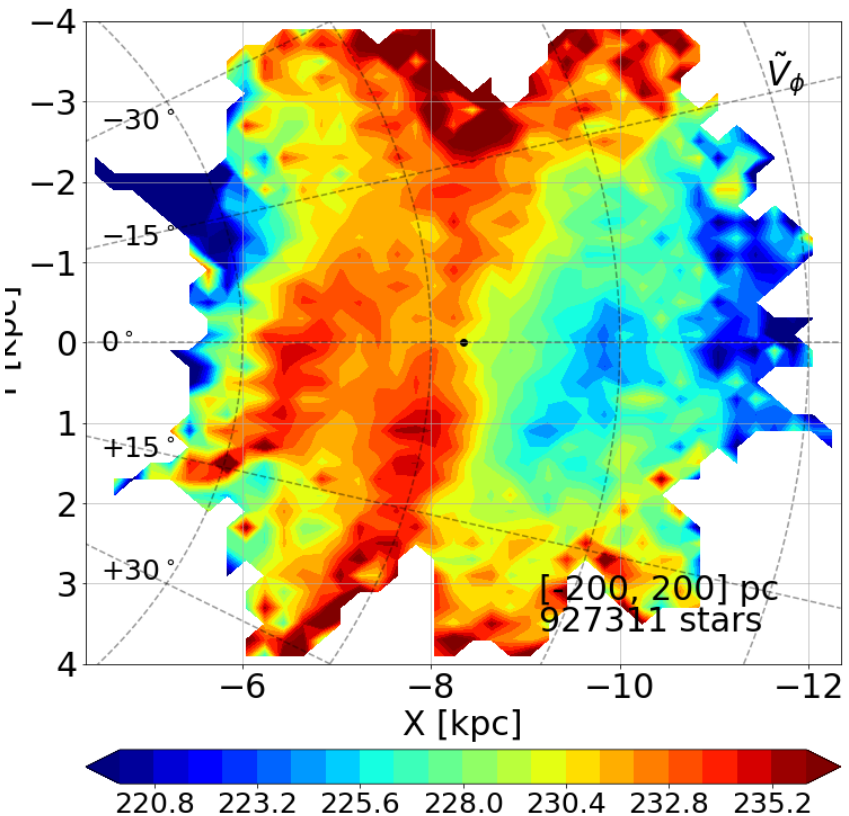
Mapping the disc kinematics



- 6.4 million F-G-K stars with full 6D phase-space coordinates and $\sigma_{\varpi} / \varpi \leq 20\%$
- Maps: $5 < R < 13$ kpc

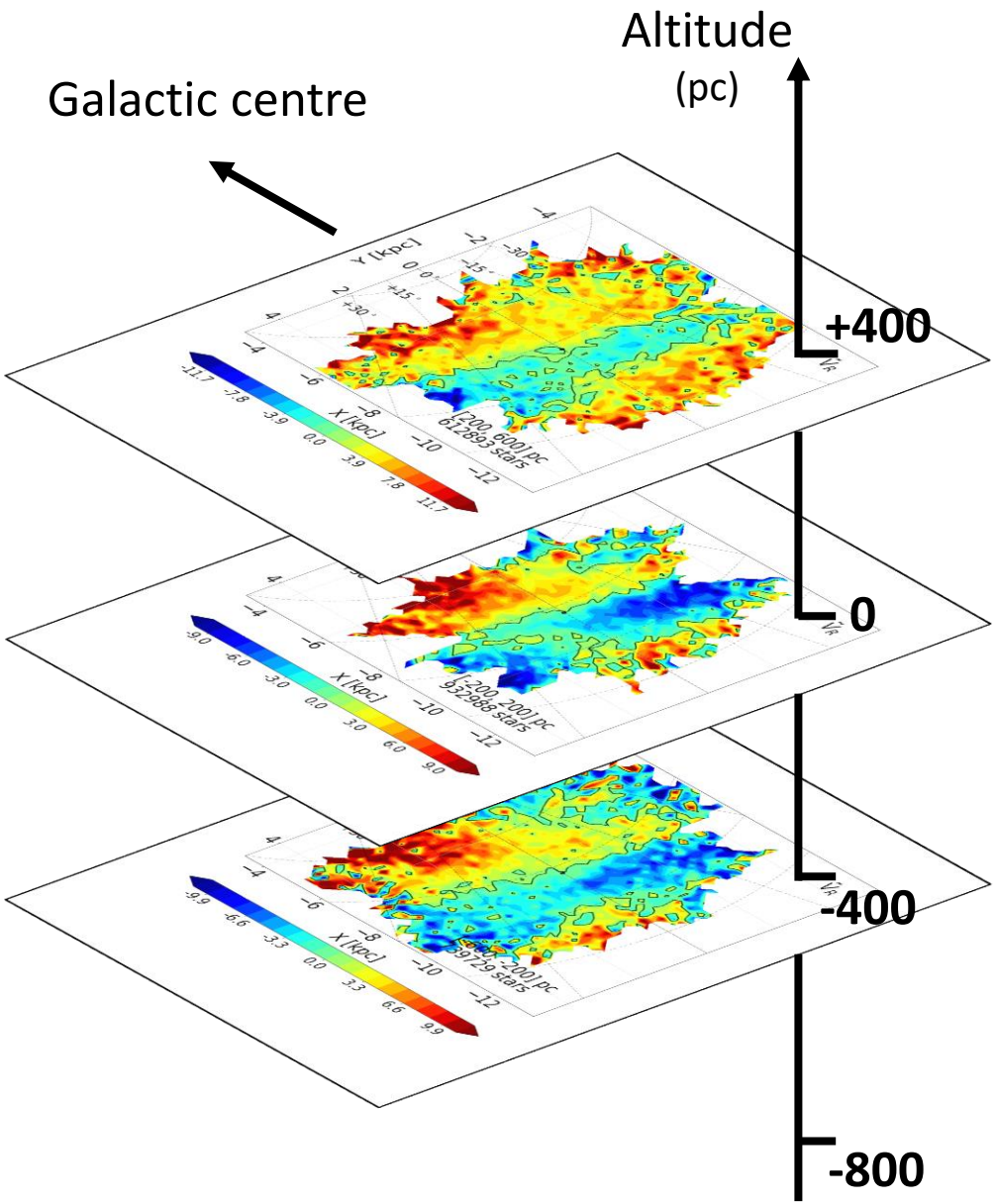
Mapping the disc kinematics





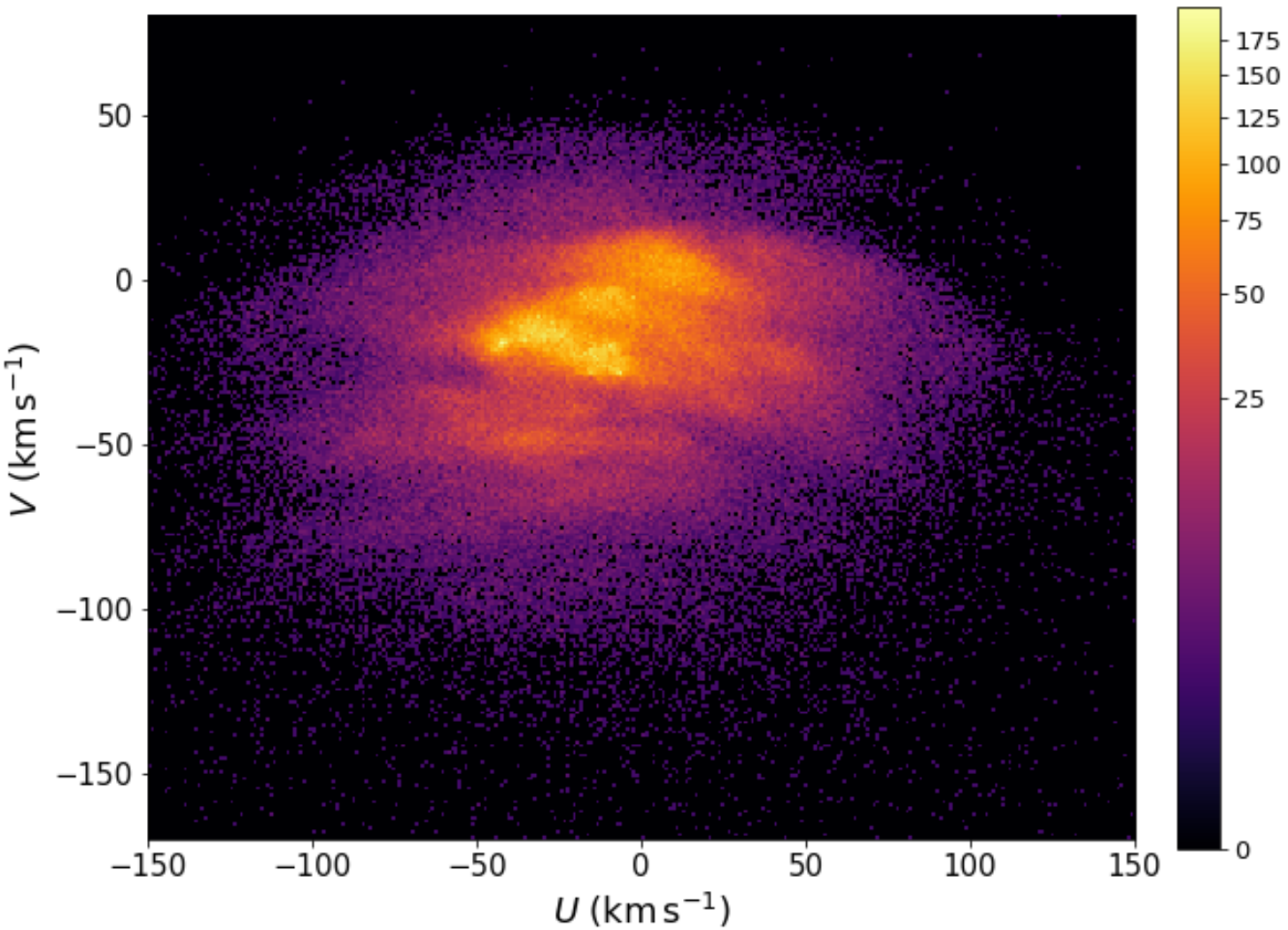
- Streaming motions in all velocity components + patterns in velocity dispersions.
- Some already known: e.g. Siebert et al. 2011, Widrow et al. 2012, Williams et al. 2013; Carlin et al. 2013; Sun et al. 2015; Carrillo et al. 2017; Pearl et al. 2017; Tian et al. 2017; Liu et al. 2017; Baba et al. 2017, ...
- New features
- Detailed 2D maps ...

3D maps



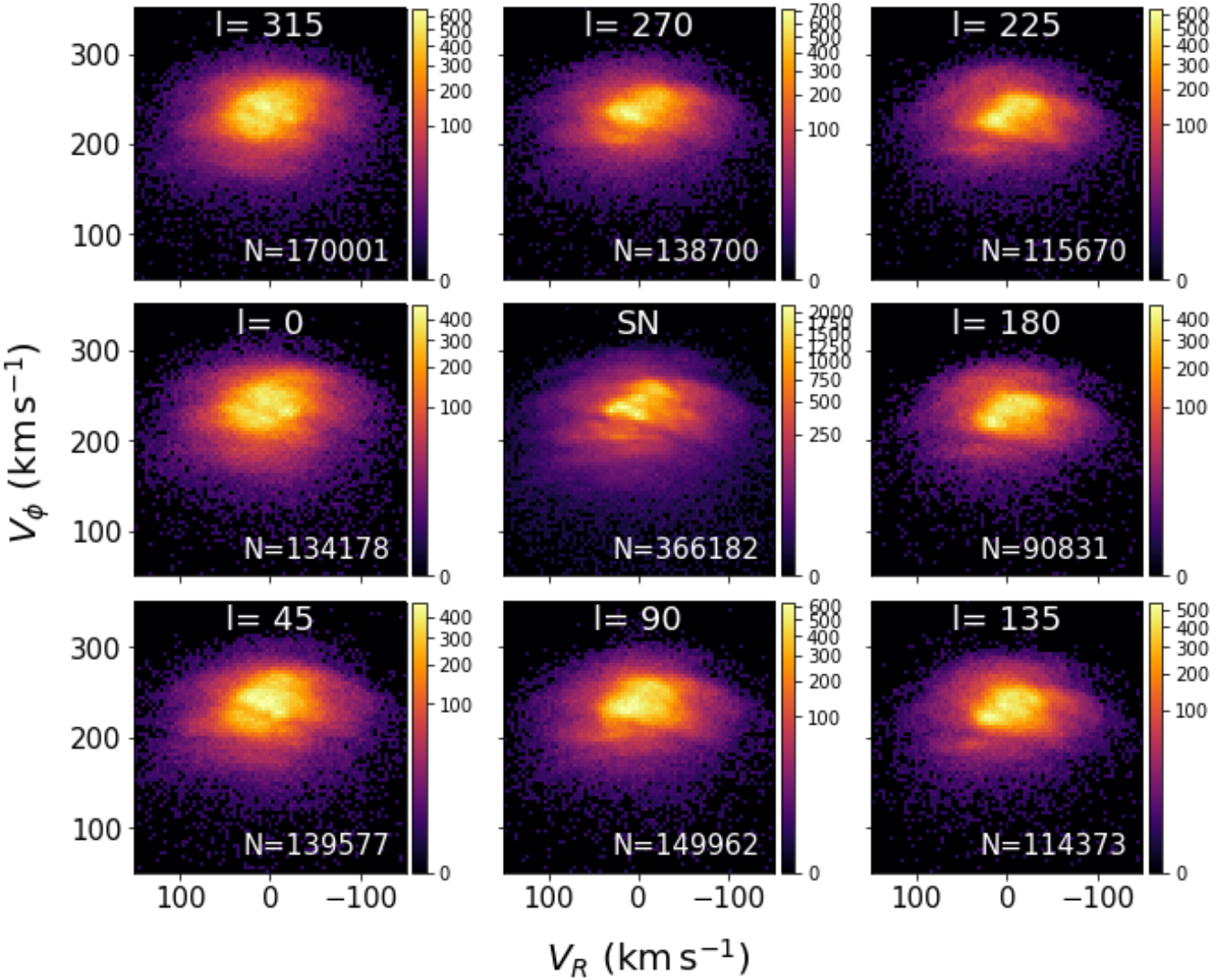
- ... 3D maps
- Disentangle influences and constrains characteristics of:
  - the bar
  - the spiral arms
  - Sagittarius, LMC, SMC
  - ....

Velocity space



- Solar neighbourhood: d < 200 pc
- 366 182 stars
- ε_U and ε_V < 1 km/s for 80% stars
- Nearly horizontal arch-like structures
- Hercules split in 2 or 3 branches

Velocity space



Galactic centre

- 500 < d < 1000 pc
- Velocity structures change from region to region, with greater changes in Galactic radius than in azimuth

Science with DR2

- *Radial Distribution of Stellar Motions in Gaia DR2*, Daisuke Kawata, Junichi Baba, Ioana Ciuca et al., 2018, arXiv 1804.10175
- *Wrinkles in the Gaia data unveil a dynamically young and perturbed Milky Way disk*, T. Antoja, A. Helmi2, M. Romero-Gomez et al., 2018, arXiv 1804.10196
- *Warped kinematics of the Milky Way revealed by Gaia*, E. Poggio, R. Drimmel, M. G. Lattanzi et al., 2018, arXiv 1805.03171
- *Coma Berenices: first evidence for incomplete vertical phase-mixing in local velocity space with RAVE ... confirmed with Gaia DR2*, G. Monari, B. Famaey, I. Minchev et al. 2018, arXiv 1804.07767
- *The Galactic Disc in Action Space as seen by Gaia DR2*, Wilma H. Trick, Johanna Coronado and Hans-Walter Rix, 2018, arXiv 1805.03653
- *Mass and shape of the Milky Way's dark matter halo with globular clusters from Gaia and Hubble*, Lorenzo Posti and Amina Helmi, 2018, arXiv 1805.01408
- .... > 70 science paper in 1 month

And beyond DR2 ...

Data Release 3

- Targeted **mid/late 2020**

Examples of possible new products:

- Source classification
- Source APs from Bp/Rp/RVS spectra
- Bp/Rp/RVS spectra (sources with APs)

- Radial velocities: $G_{RVS} < 14$
- Non-single stars
- Extended variable stars catalogue
- Extended solar system objects catalogue

Data Release 4

- Targeted **end 2022**

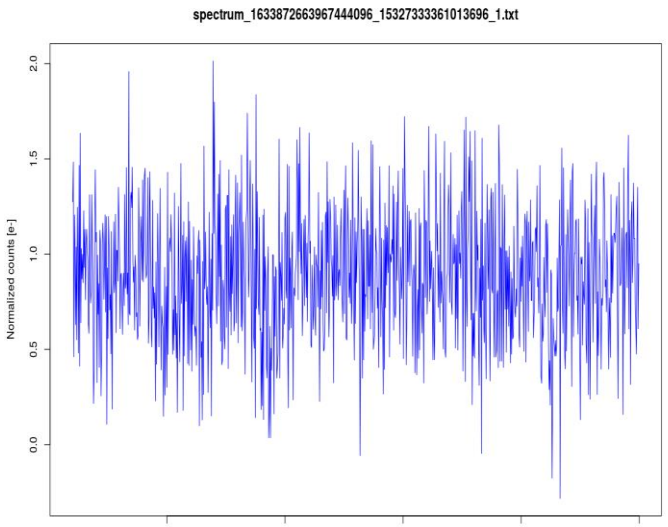
Final release for the nominal mission

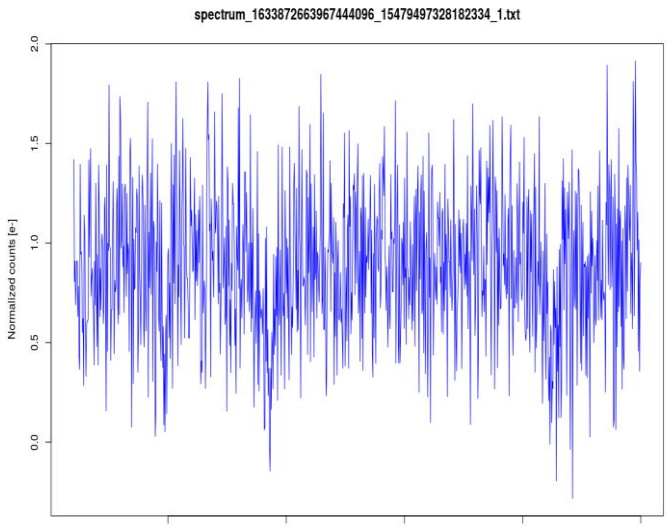
Foreseen products

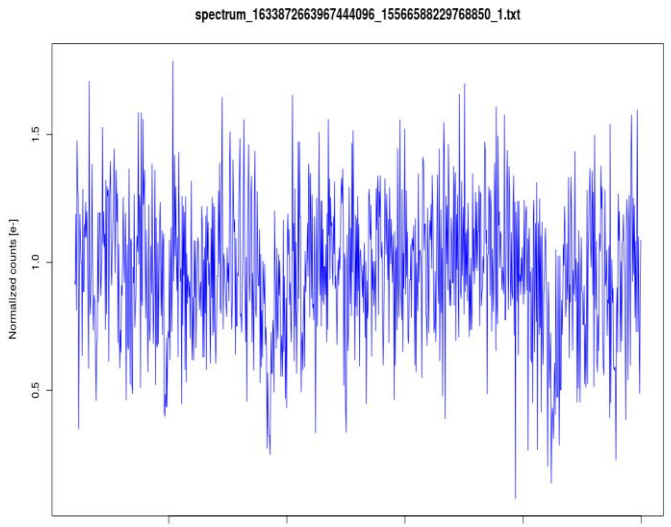
- **Full catalogues**: astrometry, photometry, radial velocities
- **All available variable and non-single stars** solutions
- **Classification/APs from X-instruments** information: AF, BP/RP/ RVS
- **Exo-planet** list
- **All epochs/transit** data

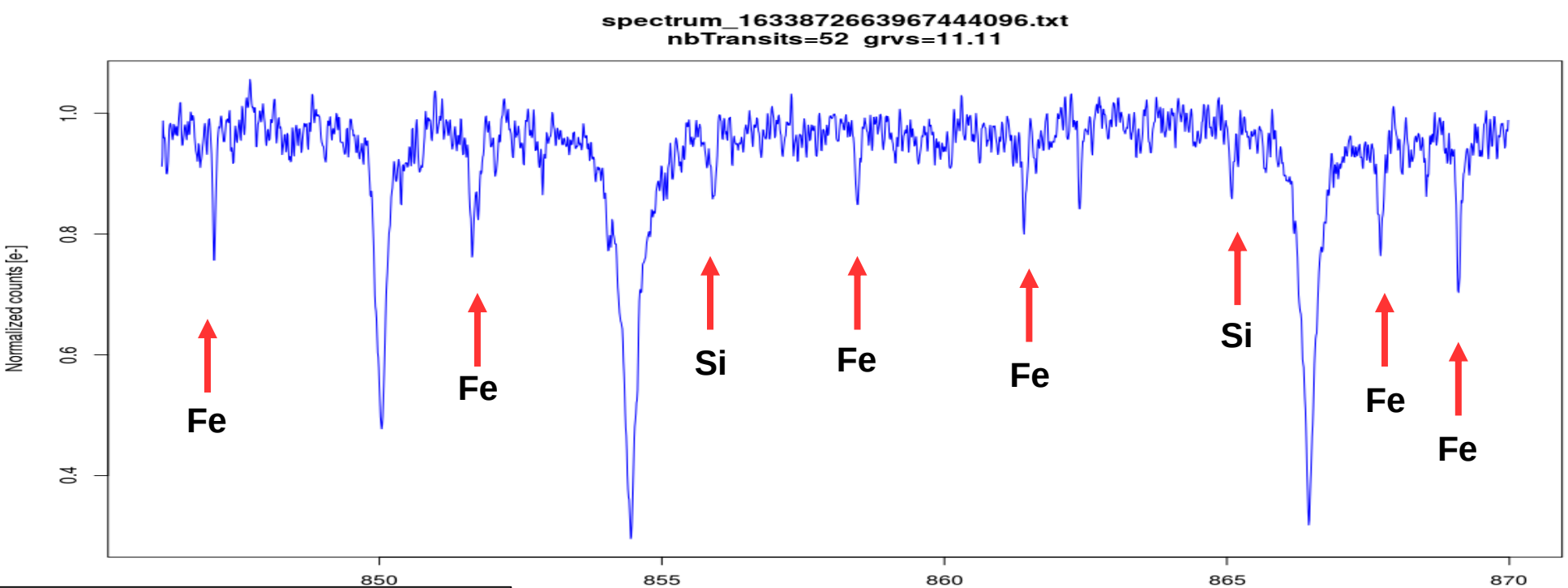
DR > 2 : Combined spectra

- G_{RVS} = 11.11 mag
- 52 transits combined
- To be used by **CU8 to derive APs**





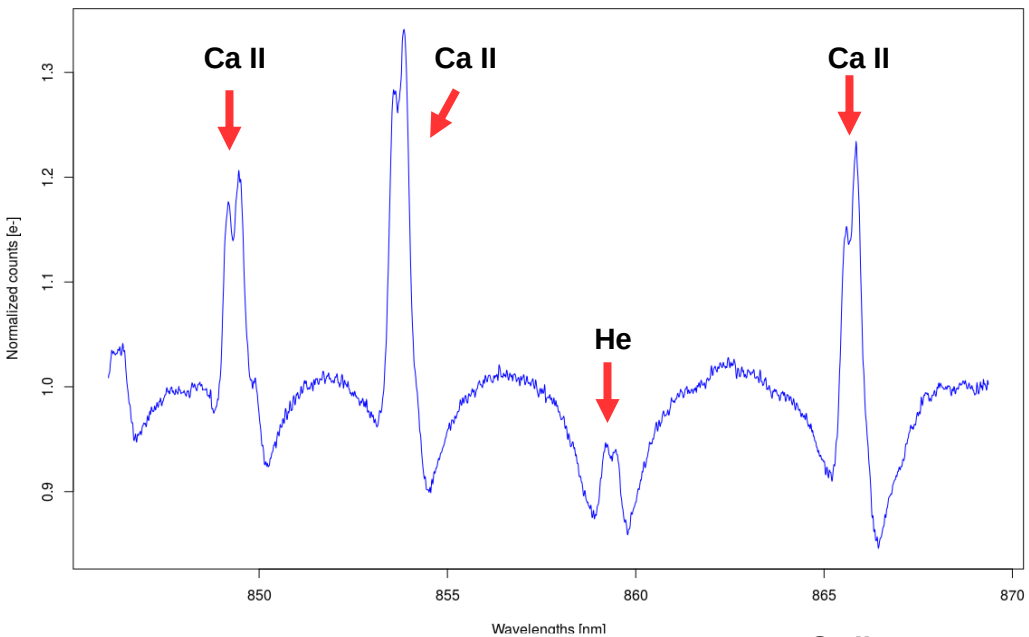




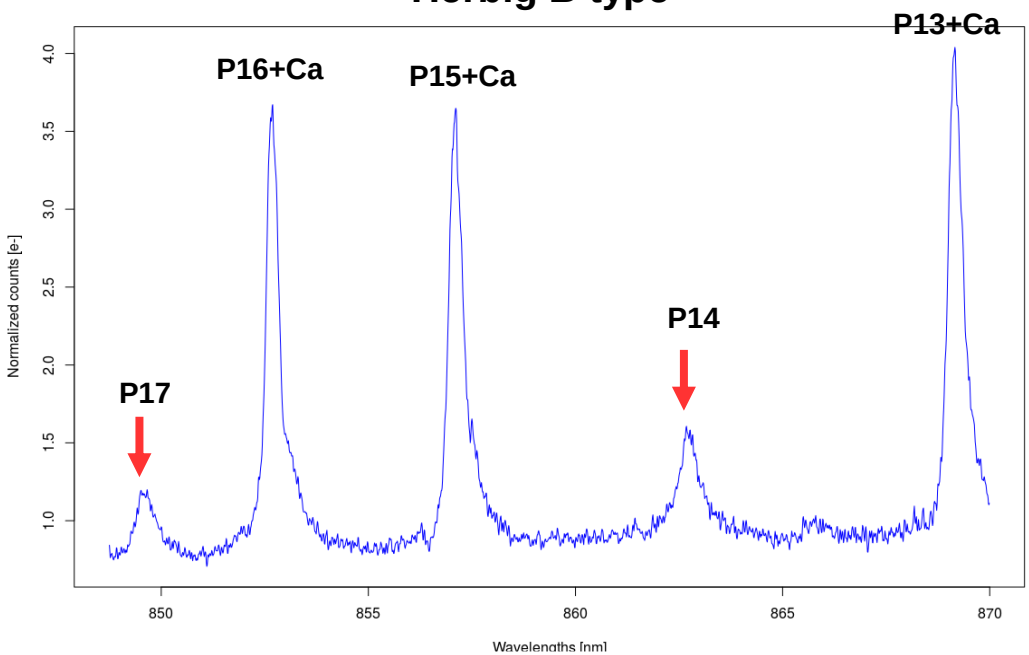
Module: K. Benson, G. Seabroke, Images: O. Marchal

DR > 2 : Emission line stars

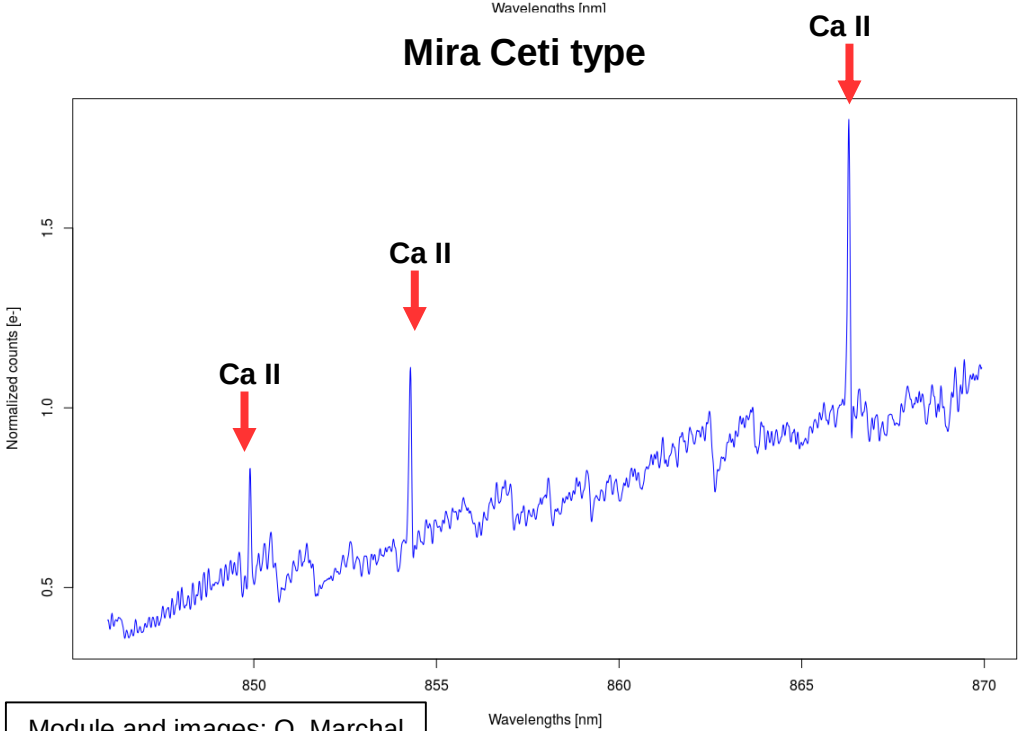
Be type



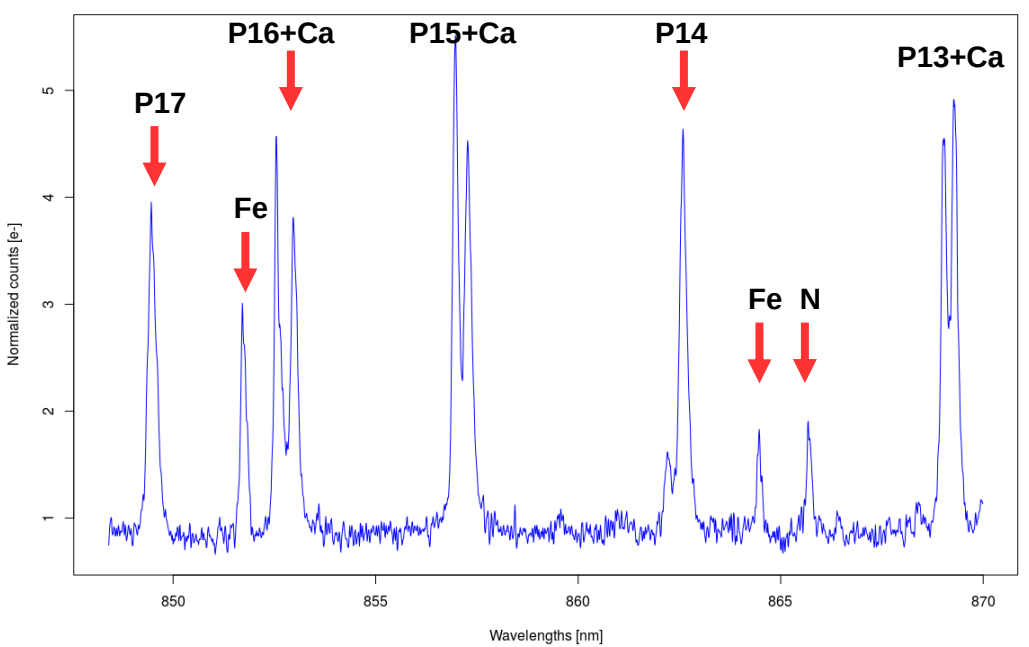
Herbig B type



Mira Ceti type

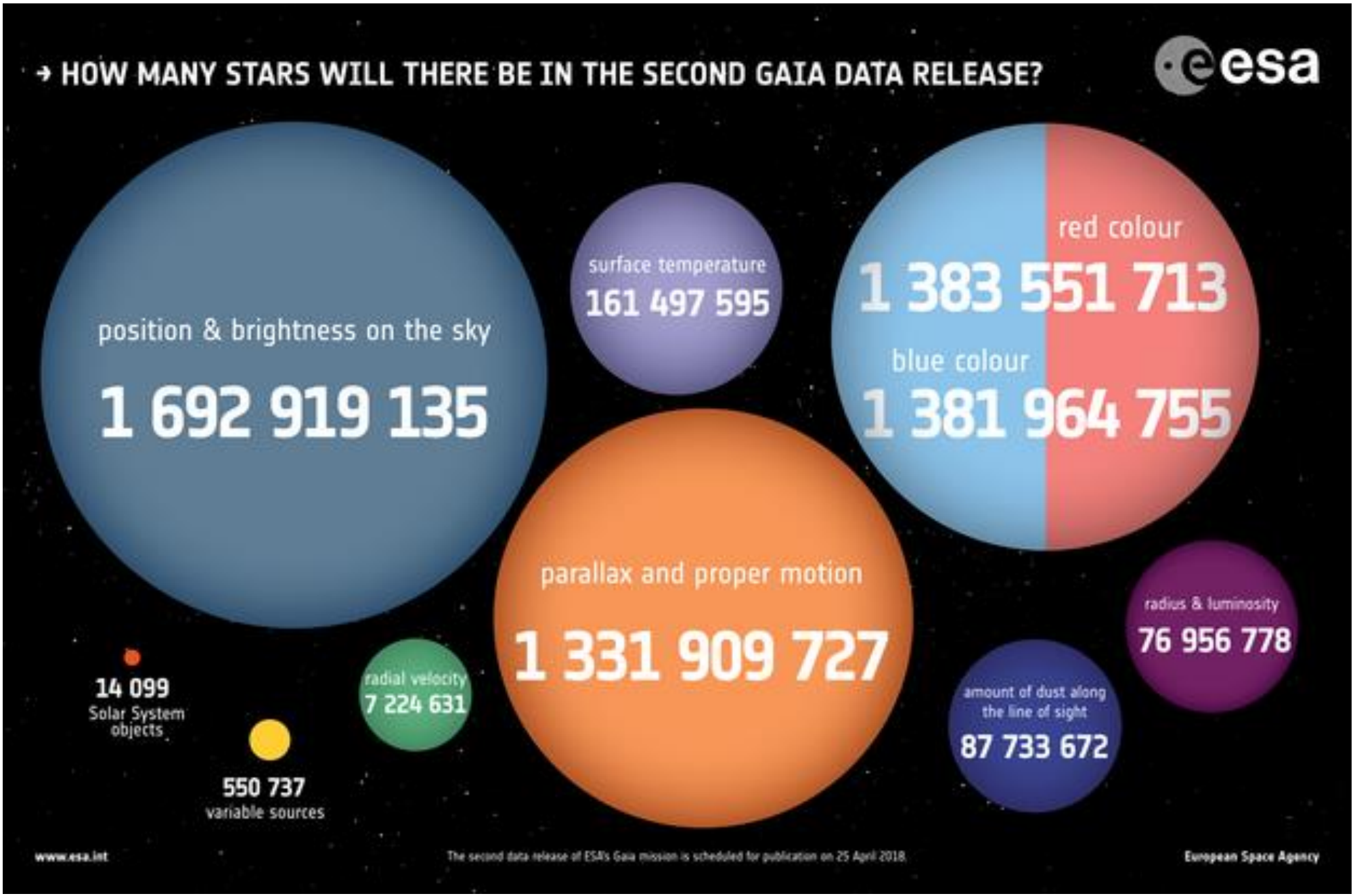


Post AGB type



Module and images: O. Marchal

Second Gaia Data Release



Bending & breathing modes