The Gaia mission
Overview and data releases

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Outline

1. Introduction
2. The mission
3. Data Release 2 (25 Apr 2018)
4. DR2 DPAC papers (some results)
5. Gaia papers (selection)
6. Data Release 3 and beyond

1. Introduction

Gaia mission status

Gaia spacecraft is fine and operating nominally

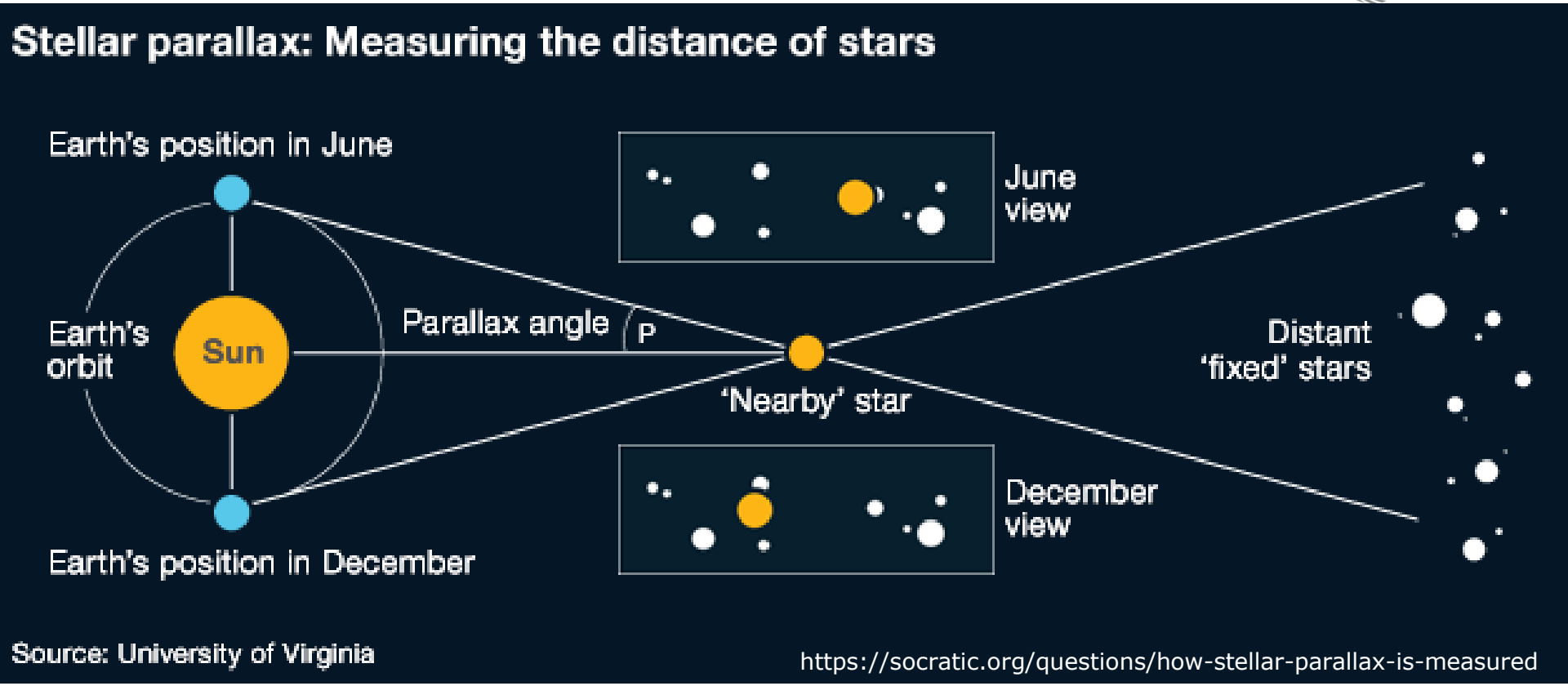
End of nominal 5 year mission in summer 2019

Gaia DR2 22 months of data, Gaia DR3 34 months of data, collected so far 58 months

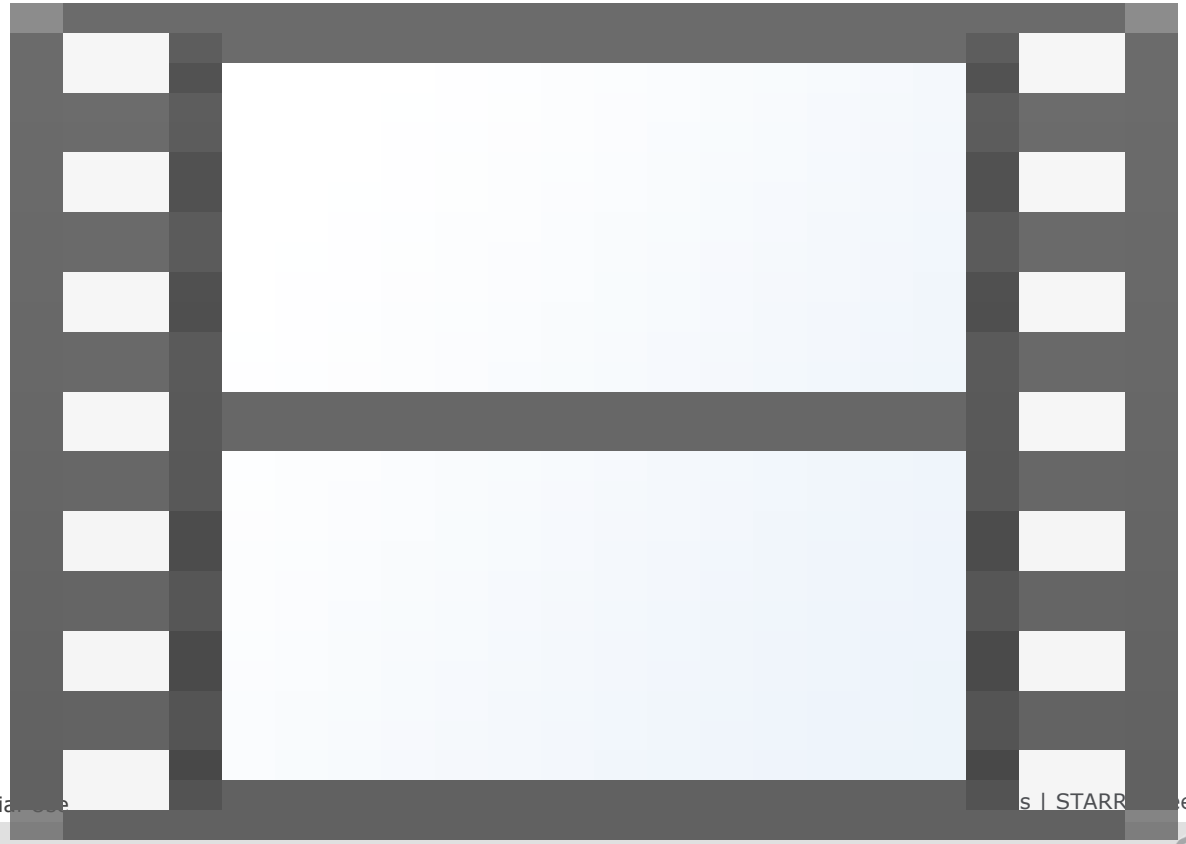
MISSION STATUS NUMBERS

CURRENT DATE AND TIME	2019-06-16T07:05:16 (TCB)
MISSION STATUS	
Satellite distance from Earth (in km)	1,603,316
Number of days having passed since 25 July 2014	1787
OPERATIONS DATA (collected since 2014/07/25)	
Volume of science data collected (in GB)	67,116
Number of object transits through the focal plane	127,944,547,836
Number of astrometric CCD measurements	1,261,167,685,808
Number of photometric CCD measurements	255,259,065,886
Number of spectroscopic CCD measurements	24,726,346,215
Number of object transits through the RVS instrument	8,258,125,095

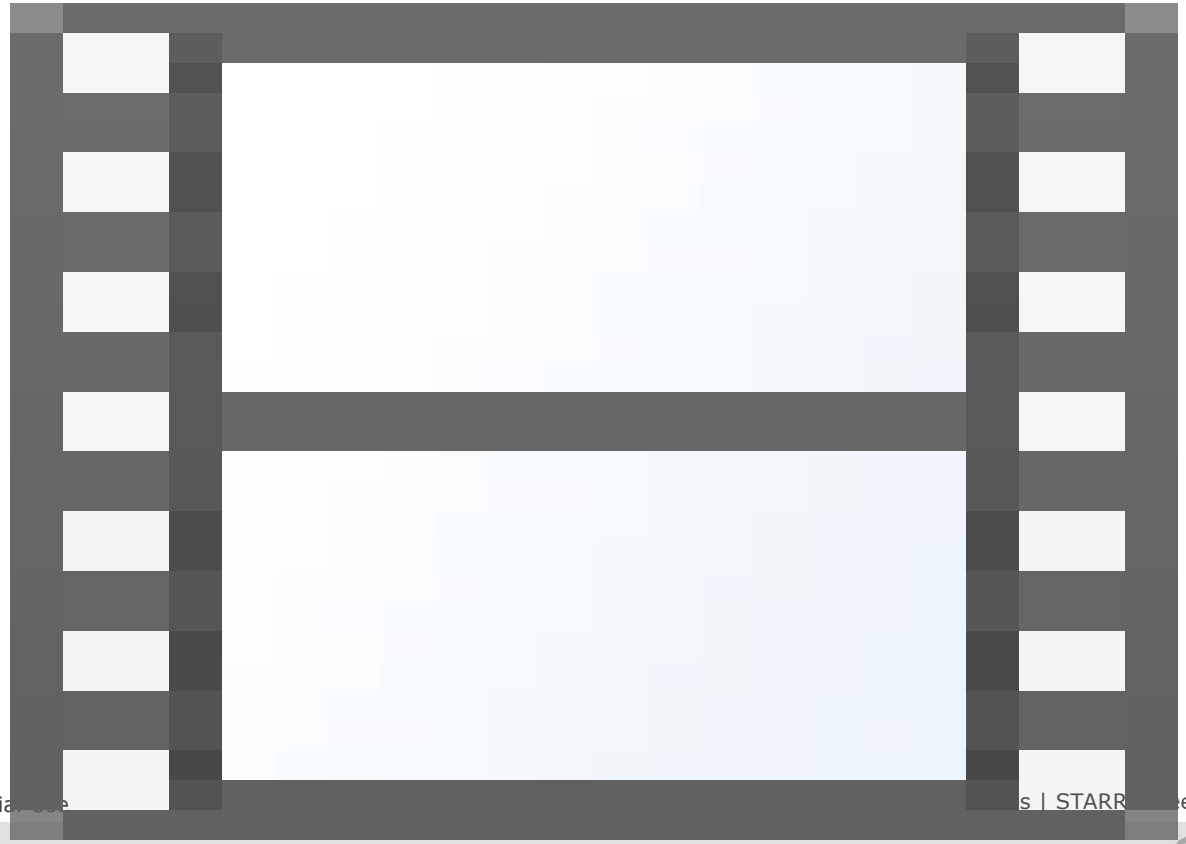
2. Gaia: parallaxes ➔ distances



2. Parallax + proper motion



2. The Hyades open cluster



2. The mission

Scientific Mission Goals

Astrometry (G < 20 mag)

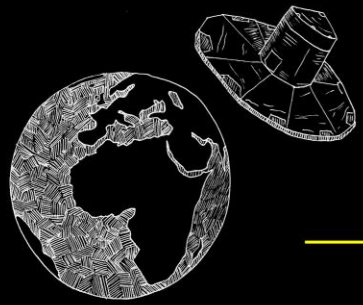
completeness to 20 mag (on-board detection) ⇒ 10^9 stars
accuracy: 26 μarcsec at G=15 mag (Hipparcos: 1 milliarcsec at 9 mag)
scanning satellite, two viewing directions
⇒ global accuracy, with optimal use of observing time
principle: global astrometric reduction (as for Hipparcos)

Photometry (G < 20 mag)

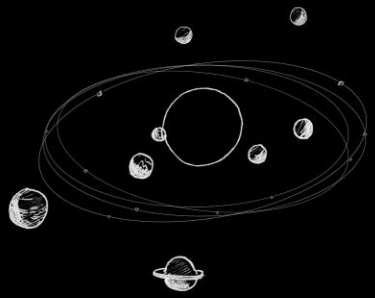
astrophysical diagnostics (low-dispersion photometry) + chromaticity
⇒ΔT_{eff} ~ 100 K, log g, [Fe/H] to 0.2 dex, extinction (at G=15 mag)

Radial velocity (G_{RVS} < 16 mag)

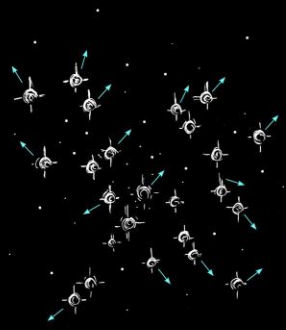
accuracy: 15 km s^{-1} at G_{RVS}=16 mag
application:
third component of space motion, perspective acceleration
dynamics, population studies, binaries
spectra for G_{RVS} < 12 mag: chemistry, rotation
principle: slitless spectroscopy in Ca triplet (845-872 nm) at R = ~10,800



Earth & Gaia

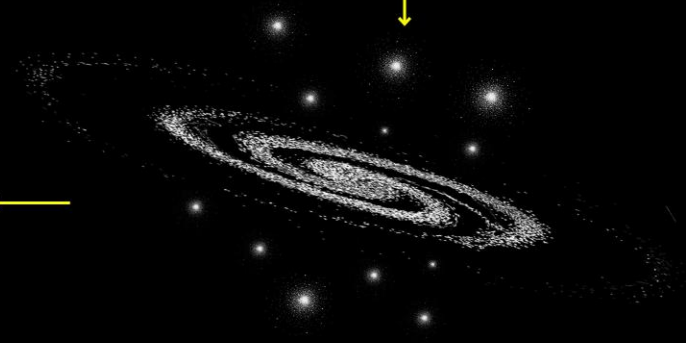


Solar System objects



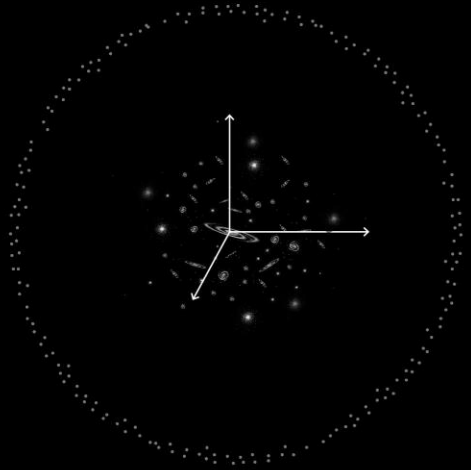
Stars near the Sun

Milky Way: disc and bulge



Milky Way: halo and globular clusters

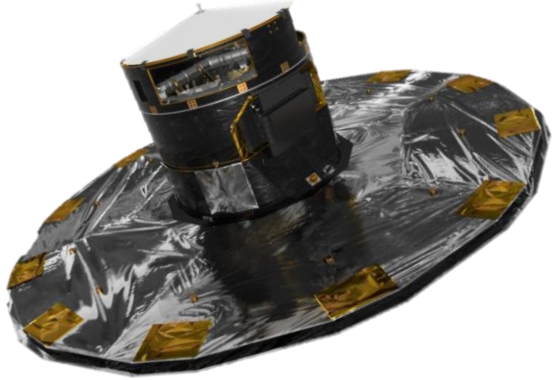
Nearby galaxies



Celestial reference frame: distant quasars

Satellite and System

- ESA-only mission
- Launch: 19 December 2013
- Launcher: Soyuz–Fregat from French Guiana
- Orbit: L2 Lissajous orbit
- Ground stations: Cebreros, New Norcia + Malargüe
- Lifetime: nominal mission 5 years
- Downlink rate: 8 Mbps



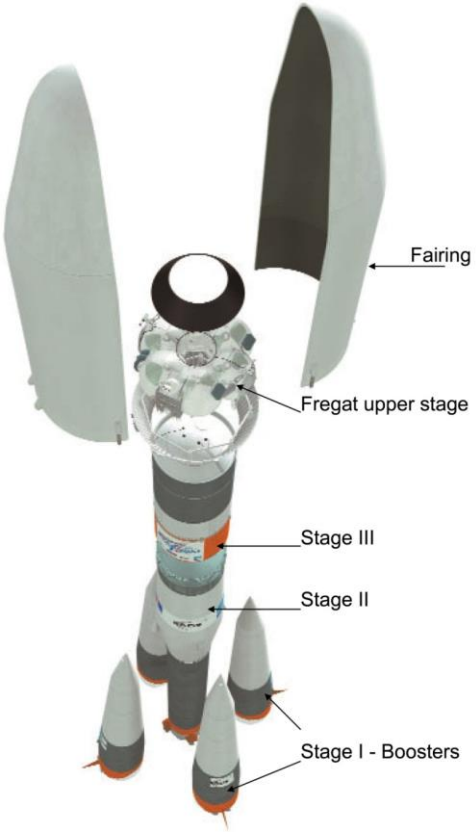
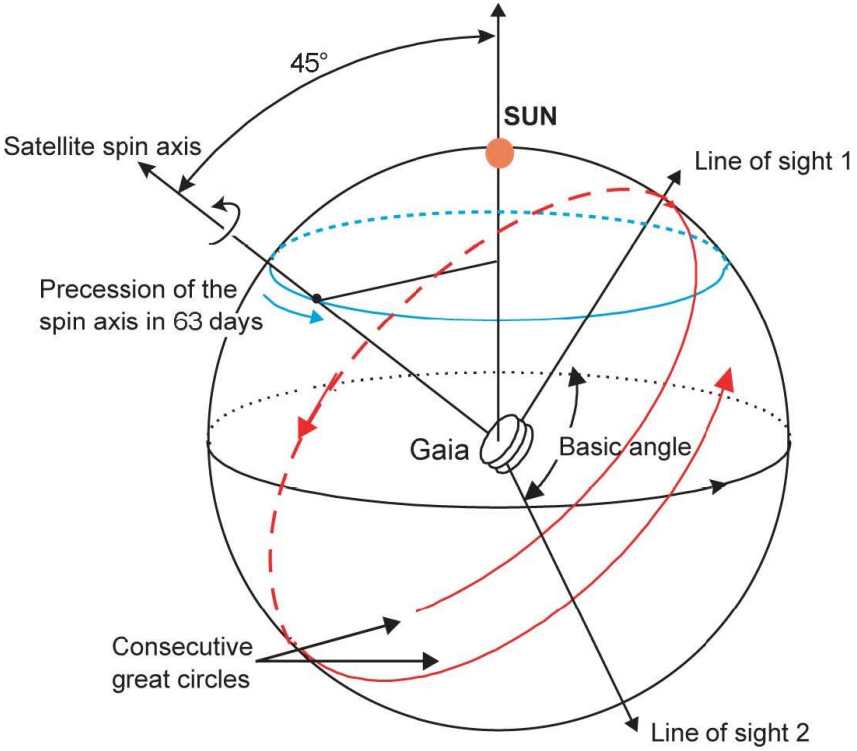
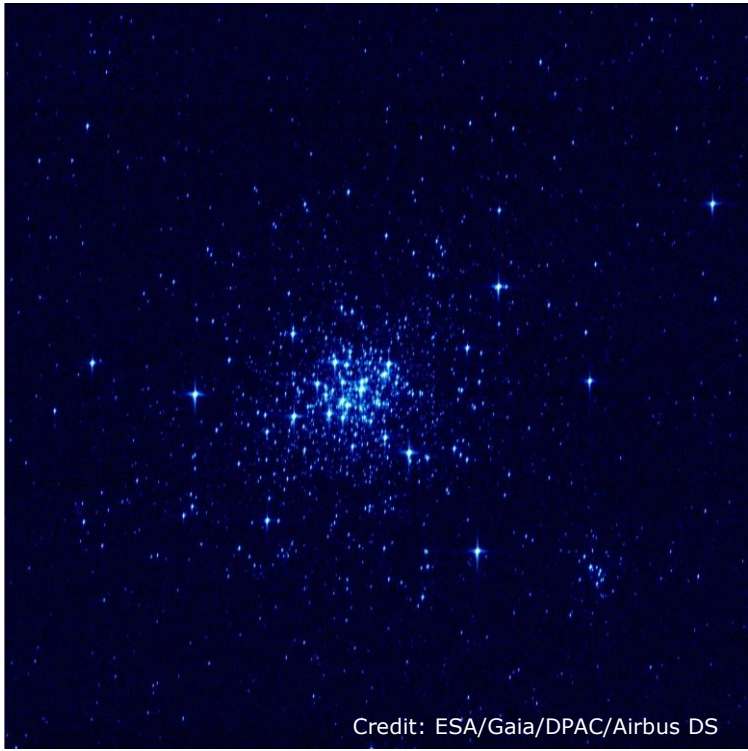


Figure Soyuz: Arianespace; figure Gaia: ESA - C. Carreau

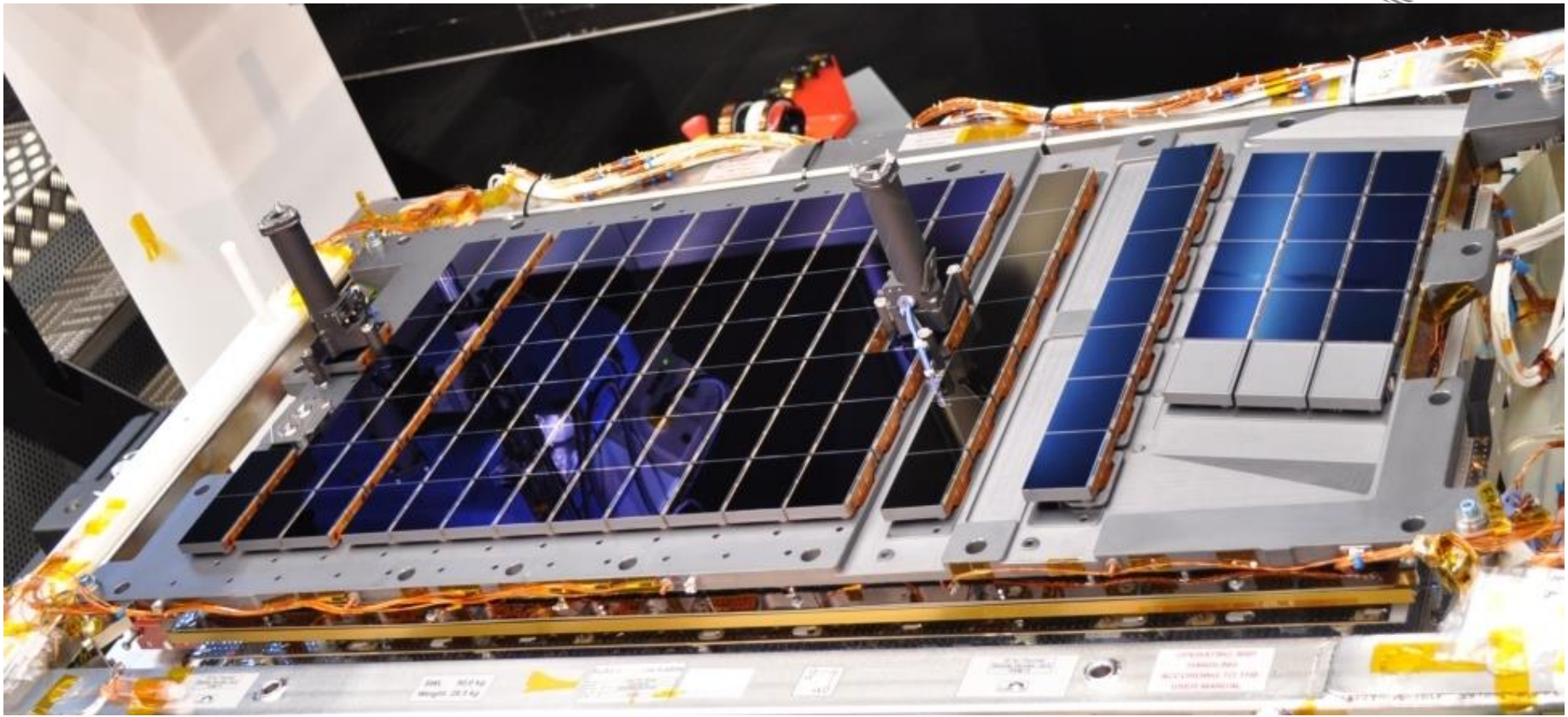
Measurement principle

Two telescopes (absolute astrometry) + large optics (sharpness) + CCDs (SNR)



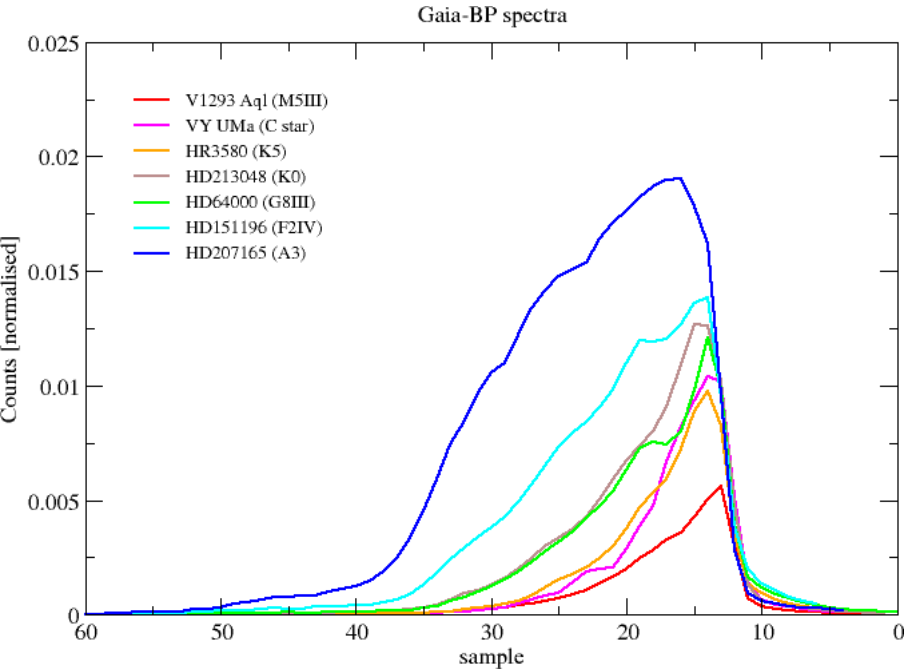


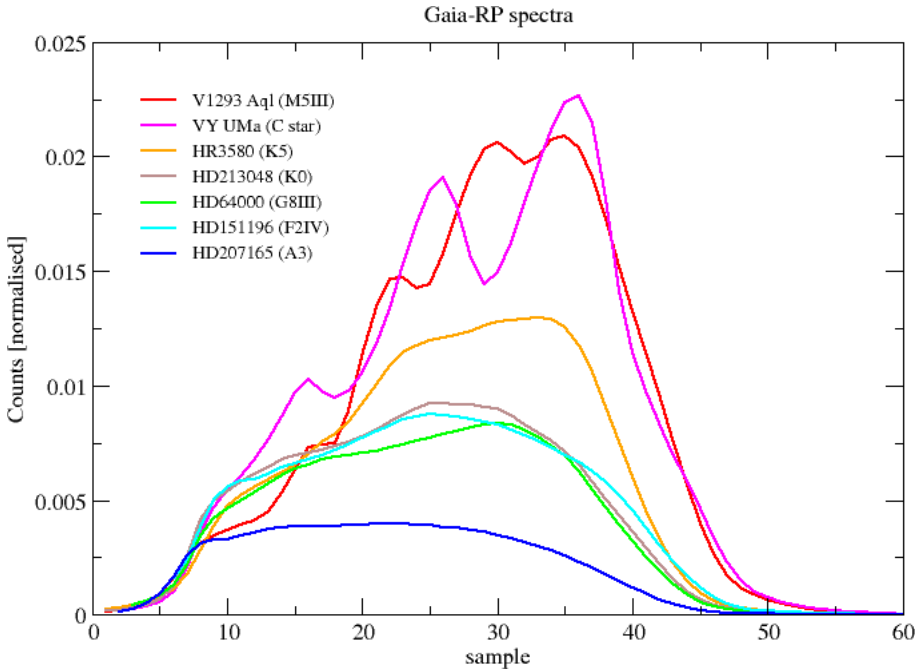
Gigapixel focal plane



Photometry

Low resolution spectrophotometry ➔ ≲1 billion stars x ~100 epochs visible SEDs





Diagrams courtesy C. Jordi and J.-M. Carrasco

Spectroscopy

Intermediate resolution CaII IR triplet ➔ tens of millions, largest spectroscopic survey!

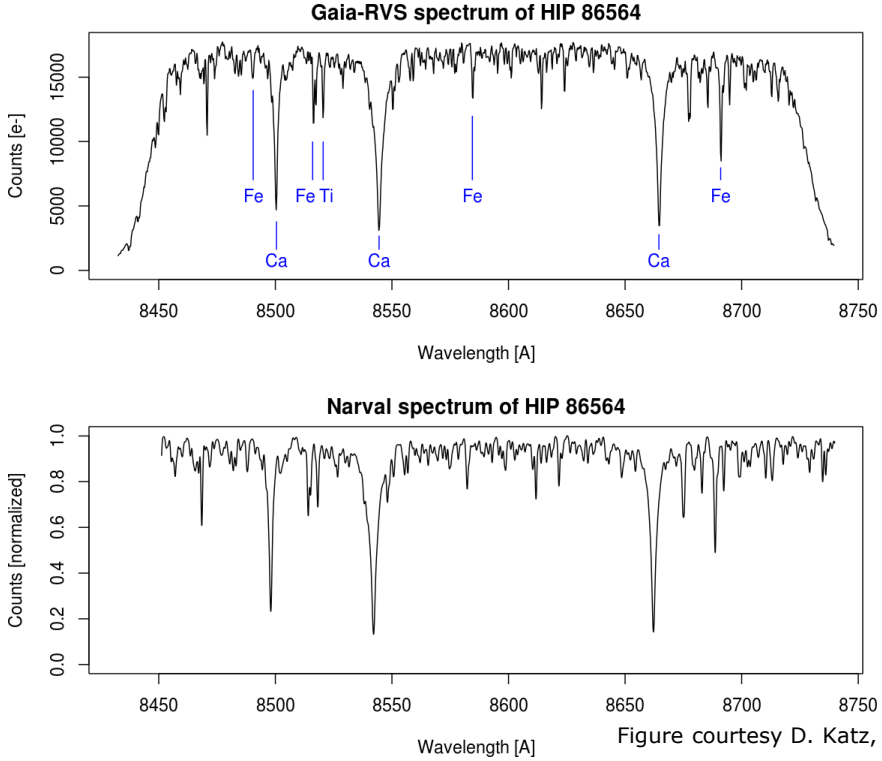


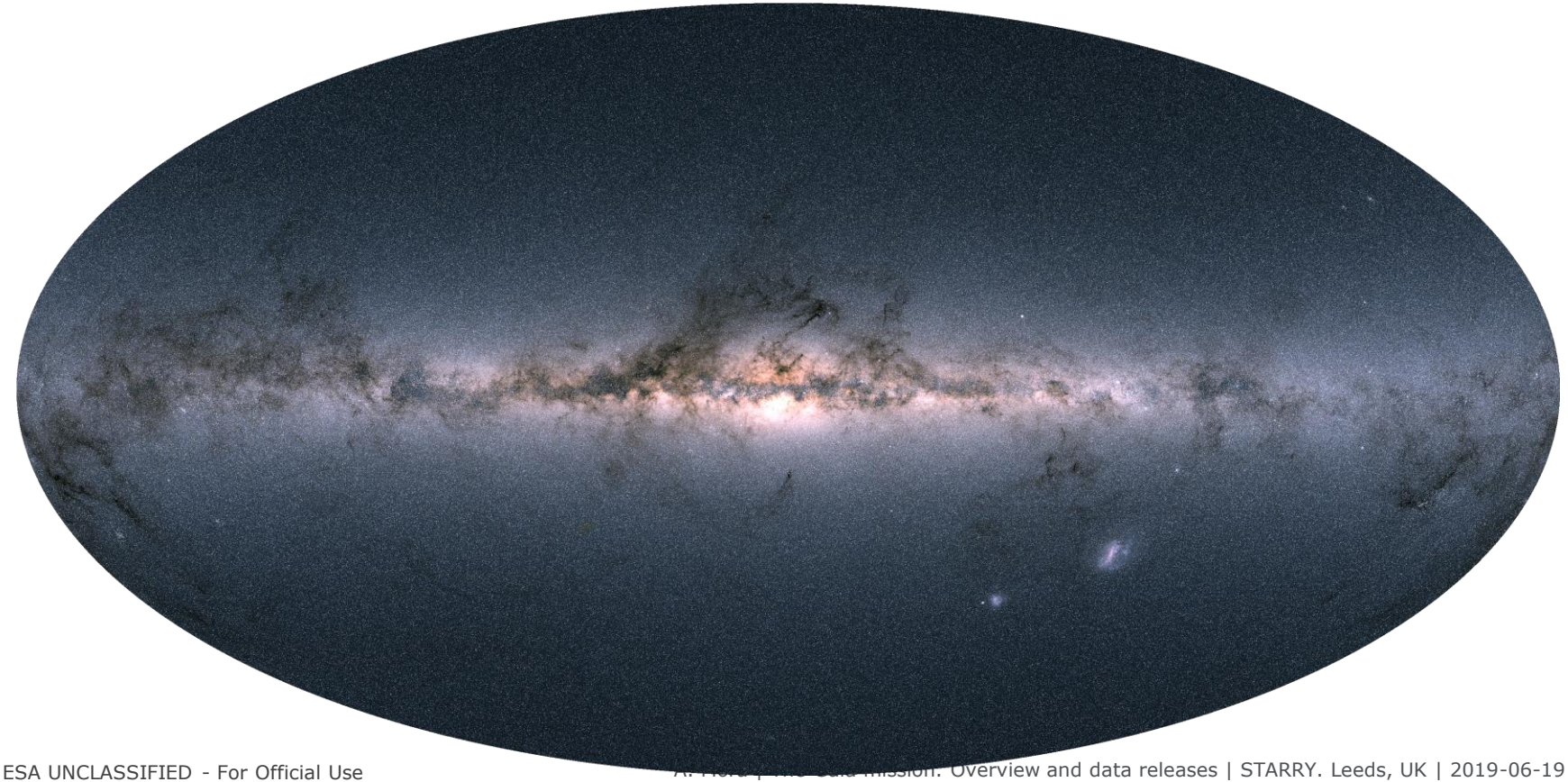
Figure courtesy D. Katz, O. Marchal, C. Soubiran

3. Data Release 2 (25 Apr 2018)

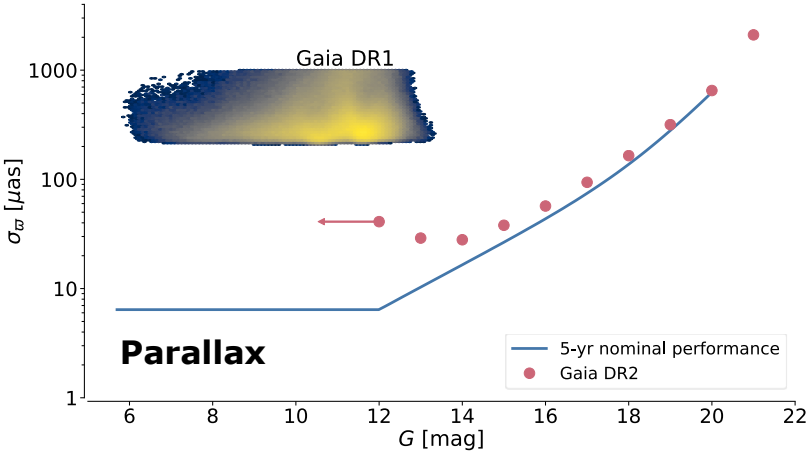
Gaia Data Release 2 in numbers

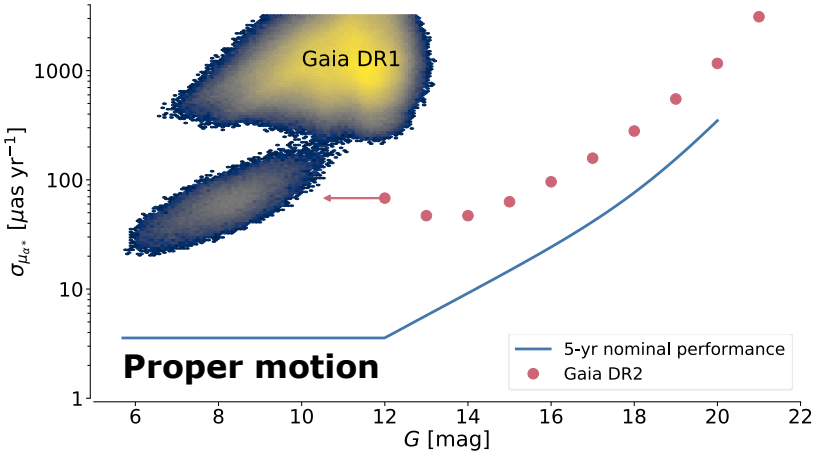
Data Products	Gaia DR2	Gaia DR1
Total number of sources (G, α, δ)	1.69 billion	1.14 billion
Position, parallax proper motion	1.33 billion	0.002 billion
Position only (α, δ)	0.36 billion	1.14 billion
Colours (BP/RP)	1.38 billion	-
Radial velocity at G_{RVS} < 12 (~ G < 13)	7.2 million	-
Stellar Parameters	77-161 million	-
Variable star light curves	551 thousand	3 thousand
Asteroid epoch astrometry/photometry	14 thousand	-

The Gaia Sky in Colour



Astrometry performance





Precision	Parallax	Prop. motion
G=15	0.03 mas	0.06 mas/yr
G=17	0.1 mas	0.2 mas/yr
G=20	0.7 mas	1.2 mas/yr
G=21	2.0 mas	3.1 mas/yr

Systematics below 0.1 mas/0.1 mas/yr

Bright star performance calibration limited

Spatial Correlations at ~1 deg and ~20 deg scales

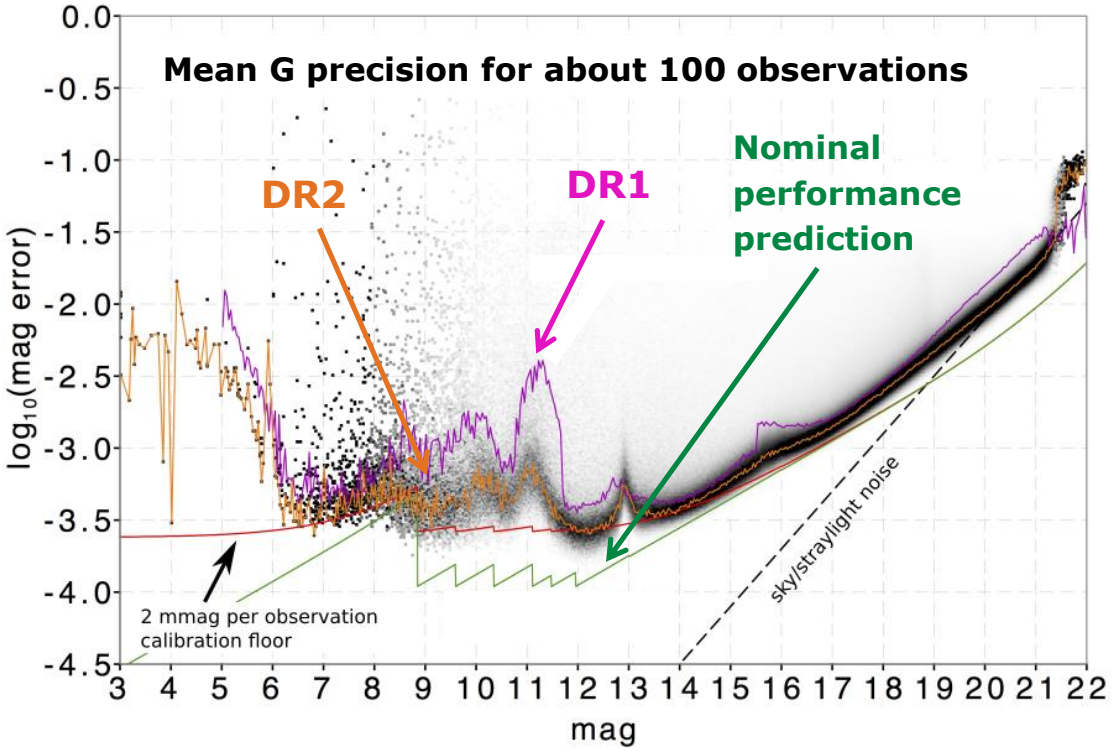
Photometric performance

Significant calibration improvements w.r.t. DR1

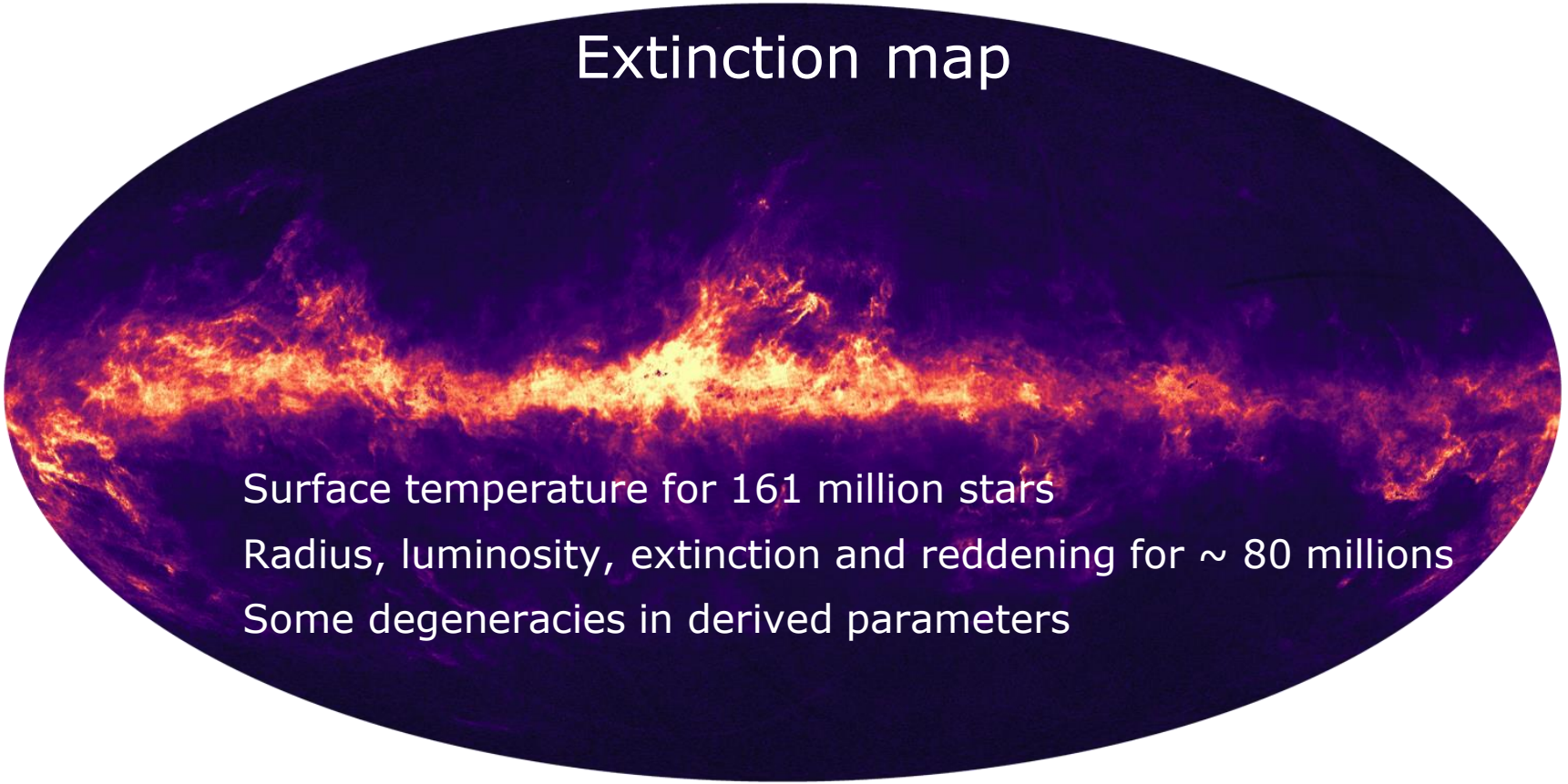
Systematics $\lesssim$ 10 mmag

Remaining caveats

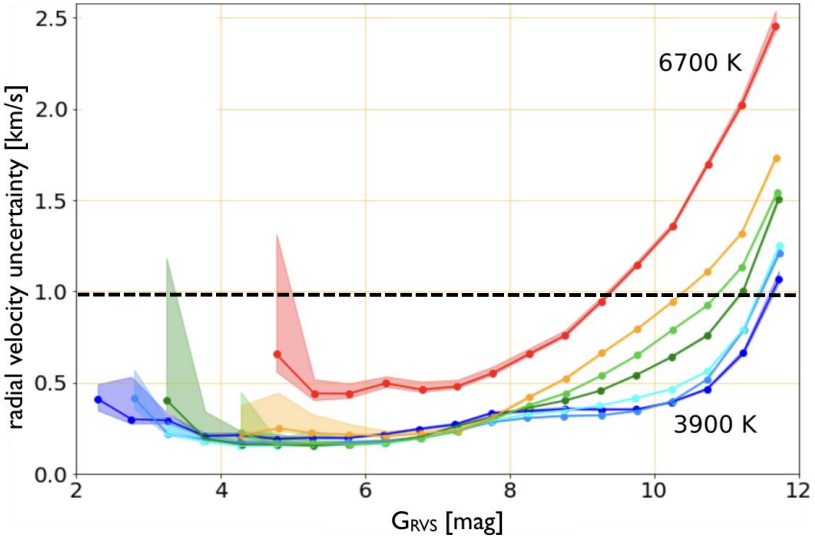
- Faint end dominated by stray-light
- Bright end affected by saturation effects
- Calibration issues at window class regime transitions

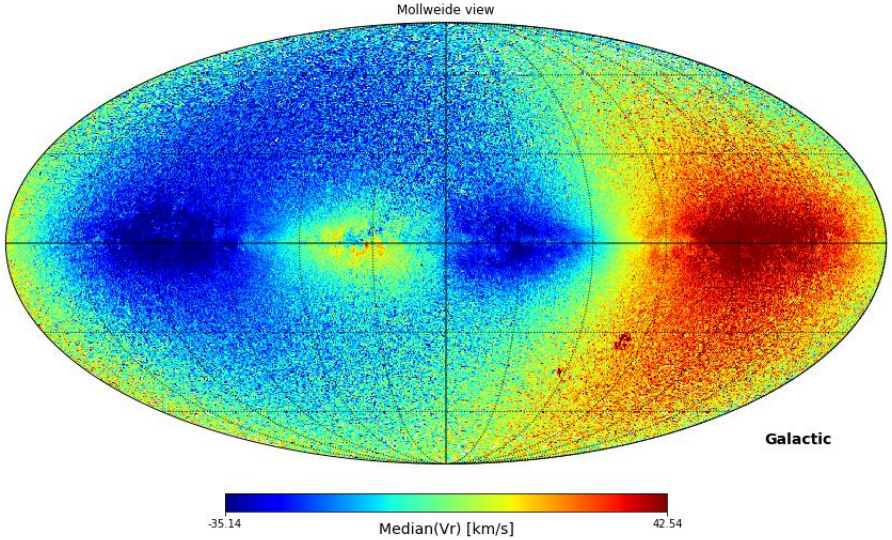


Stellar Parameters



Radial velocities in DR2





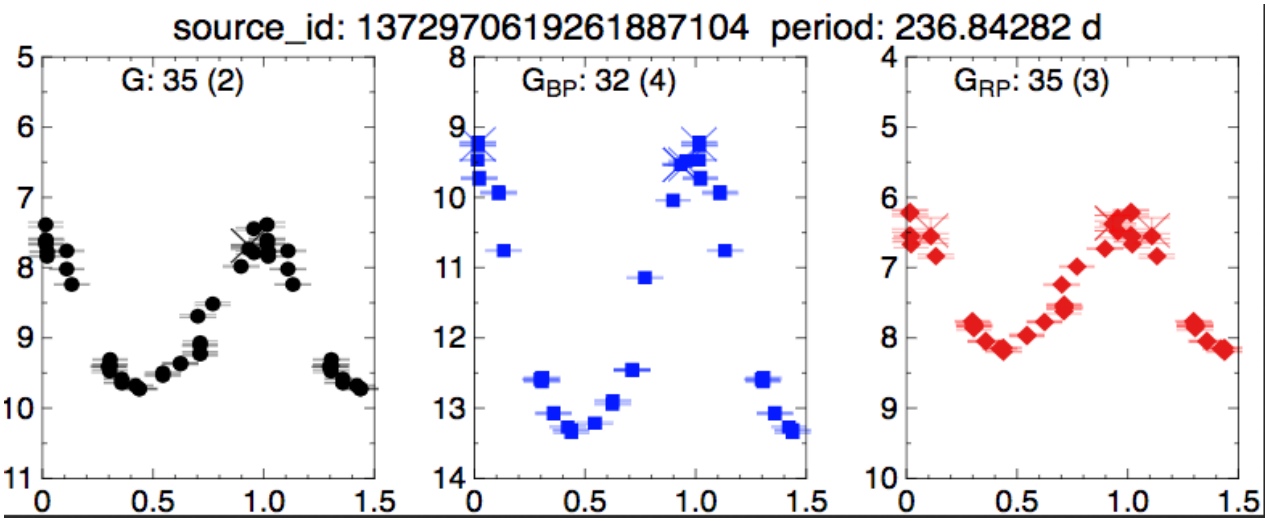
Accuracy around a few 100 m/s, worse at higher magnitude

End of mission requirement on precision (1 km/s) already met at bright end

Only provided for sources at ~ $3550<T_{eff}<6900$ K

Variable stars: light curves

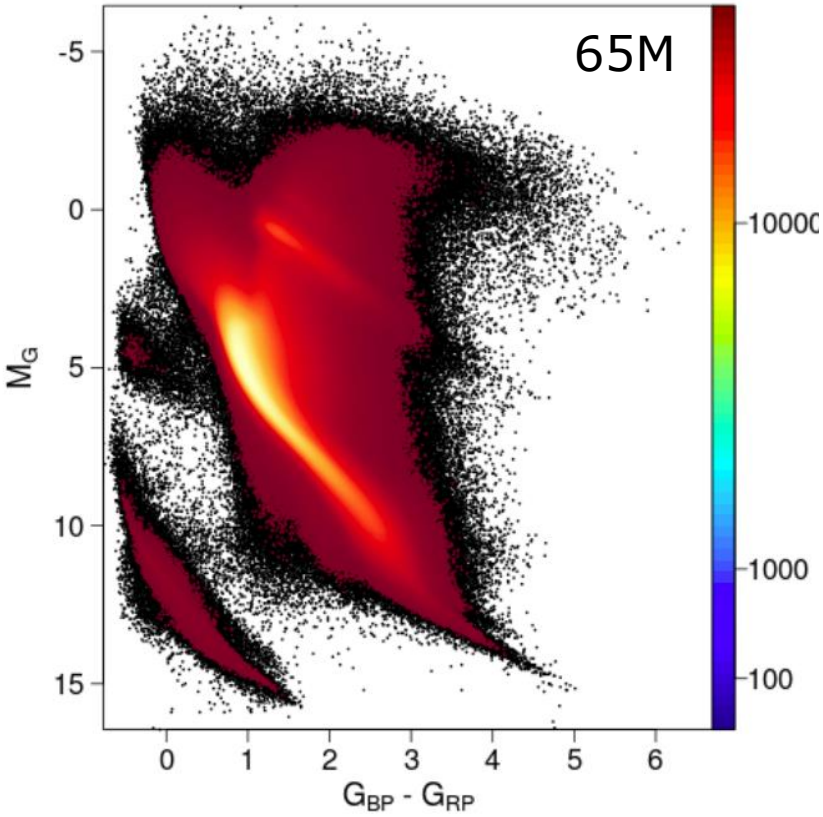
- 550,000+ variable stars identified. 7 Vioque+ (2018) HAeBe
  - 3-band light curves for all
- Variability classes (RR Lyrae, Cepheids, Mira, etc) and detailed parameters (e.g. period) for sub-sets

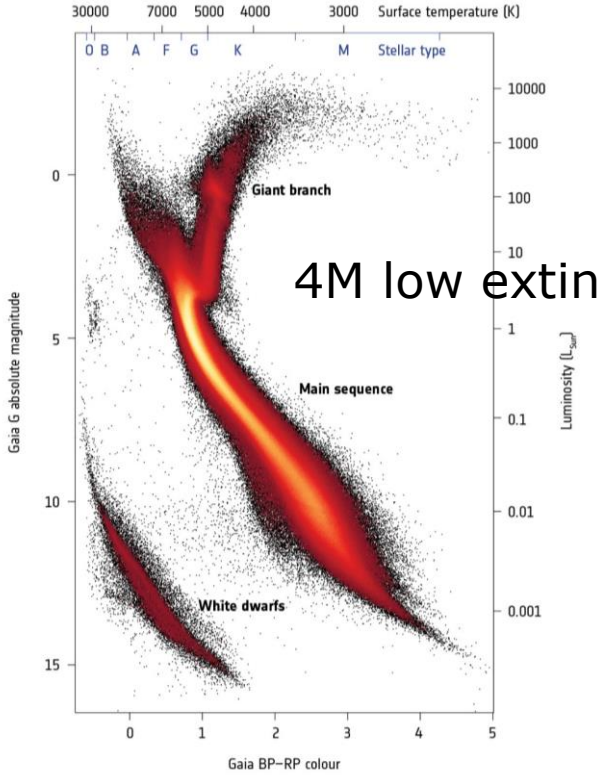


Folded 3-band light-curve for one long period variable

4. DR2 DPAC papers (some results)

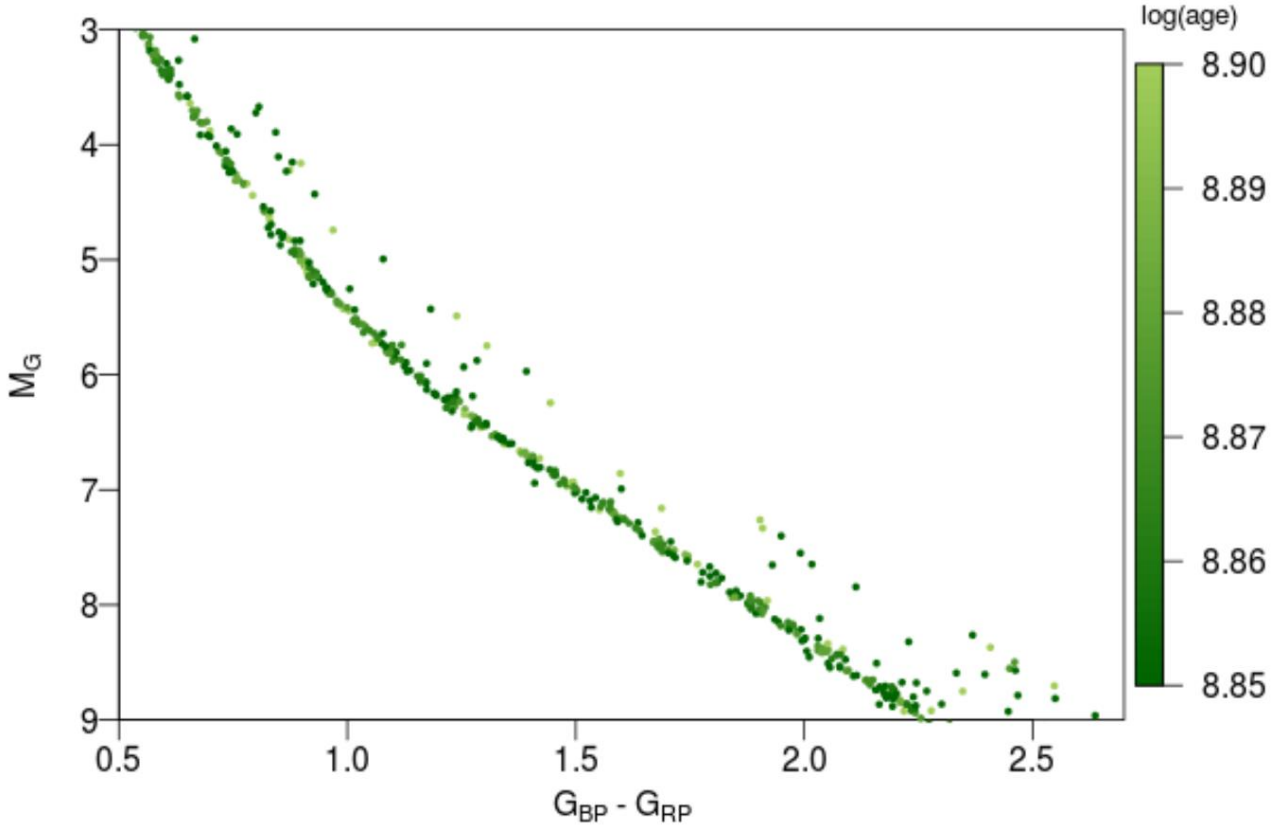
Babusiaux+ HR diagram



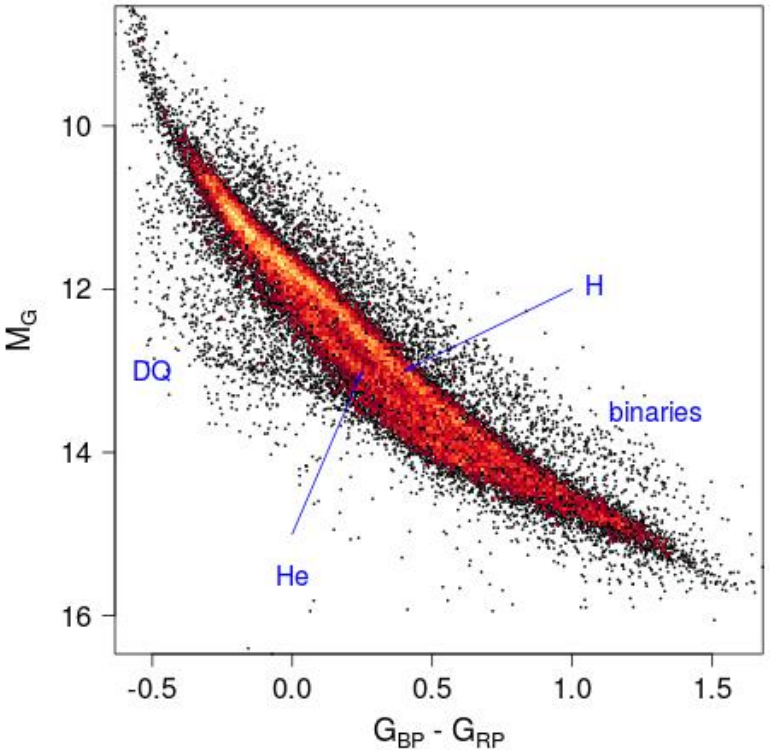


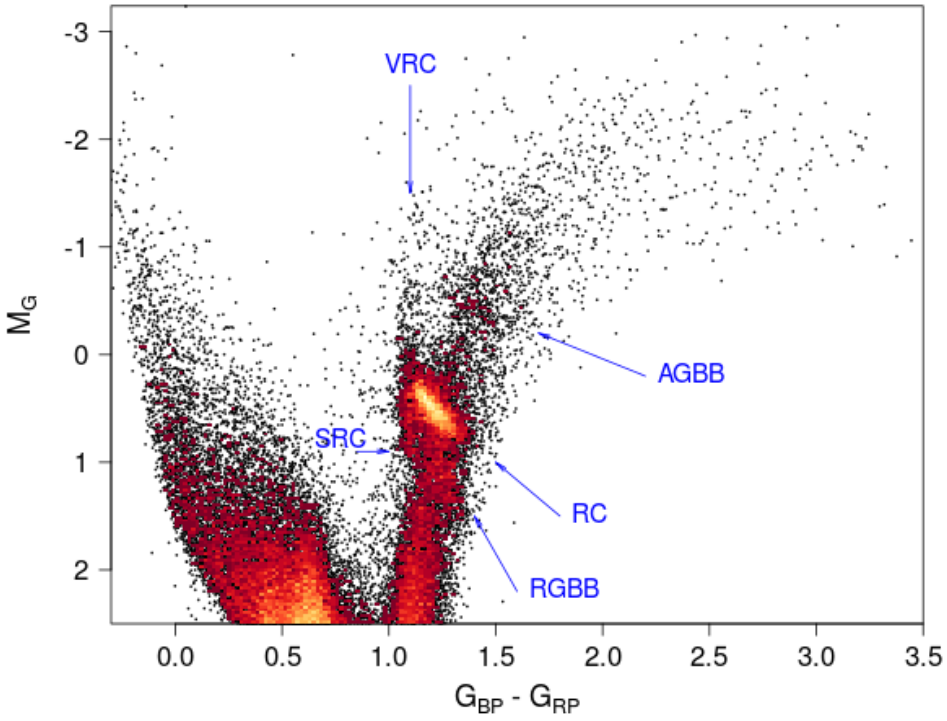
4M low extinction

Babusiaux+ MS Hyades, Praesepe

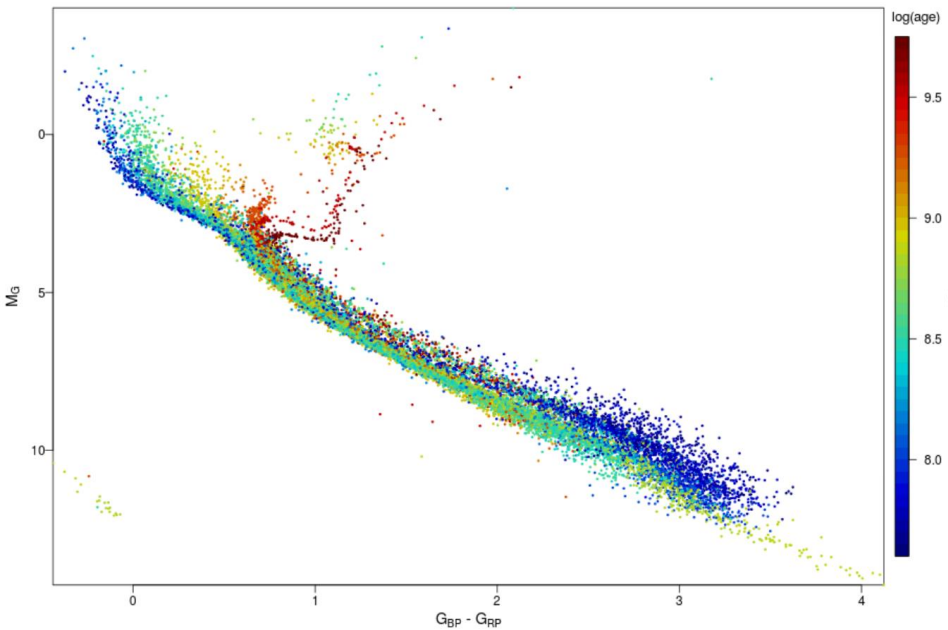


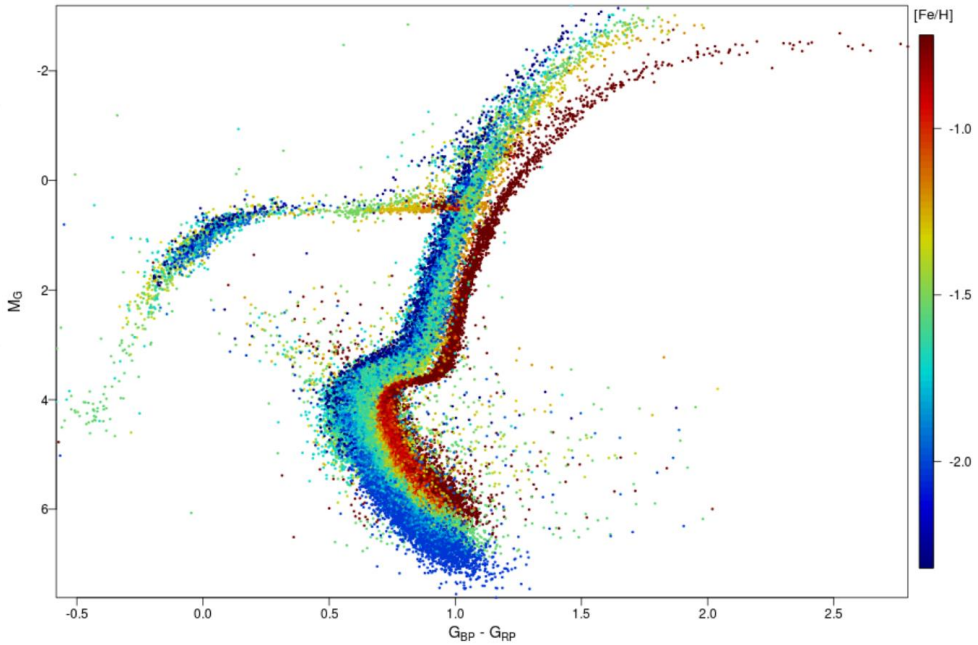
Babusiaux+ WDs and red clump





Babusiaux+ stellar clusters

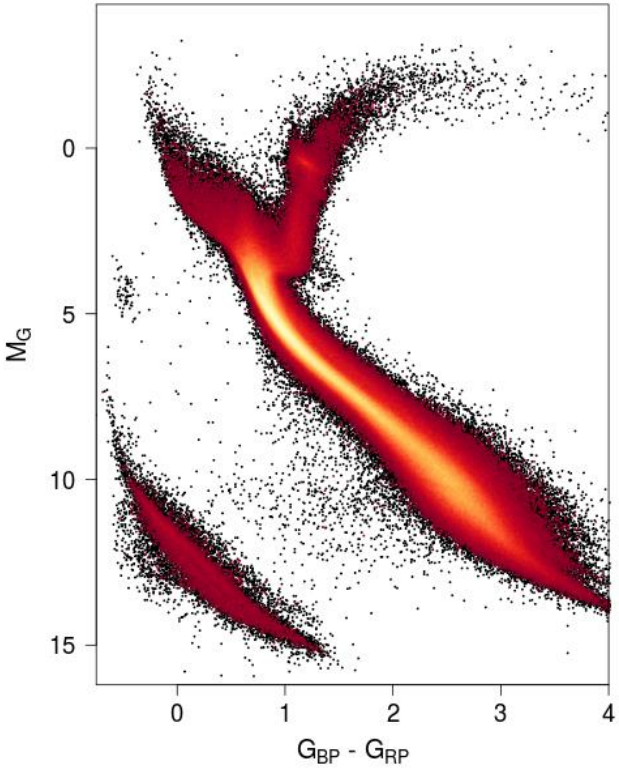




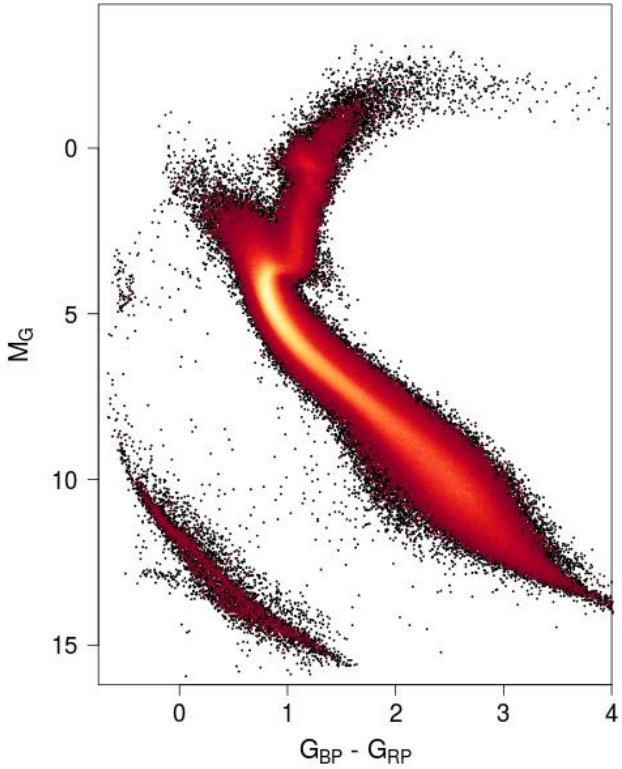
Open clusters: age

Globular clusters: metallicity

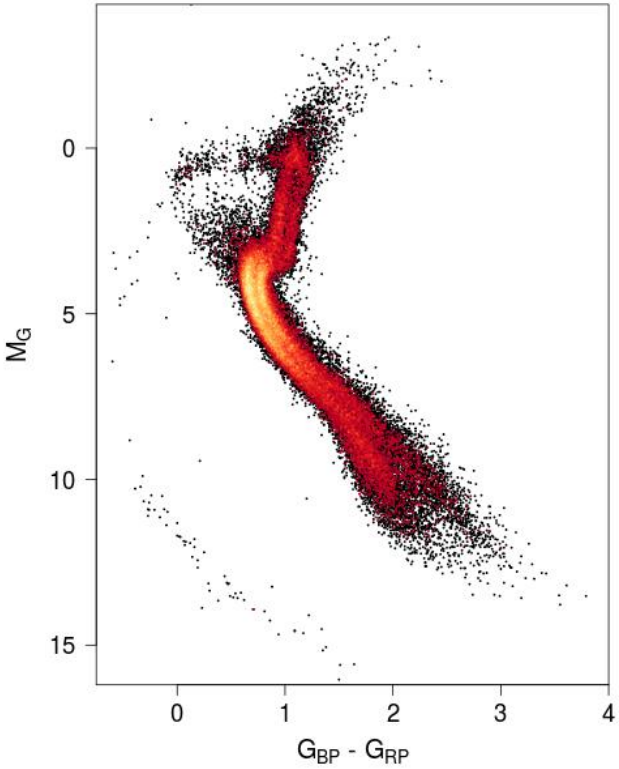
Babusiaux+ stellar populations



V_{tan}< 40 km/s

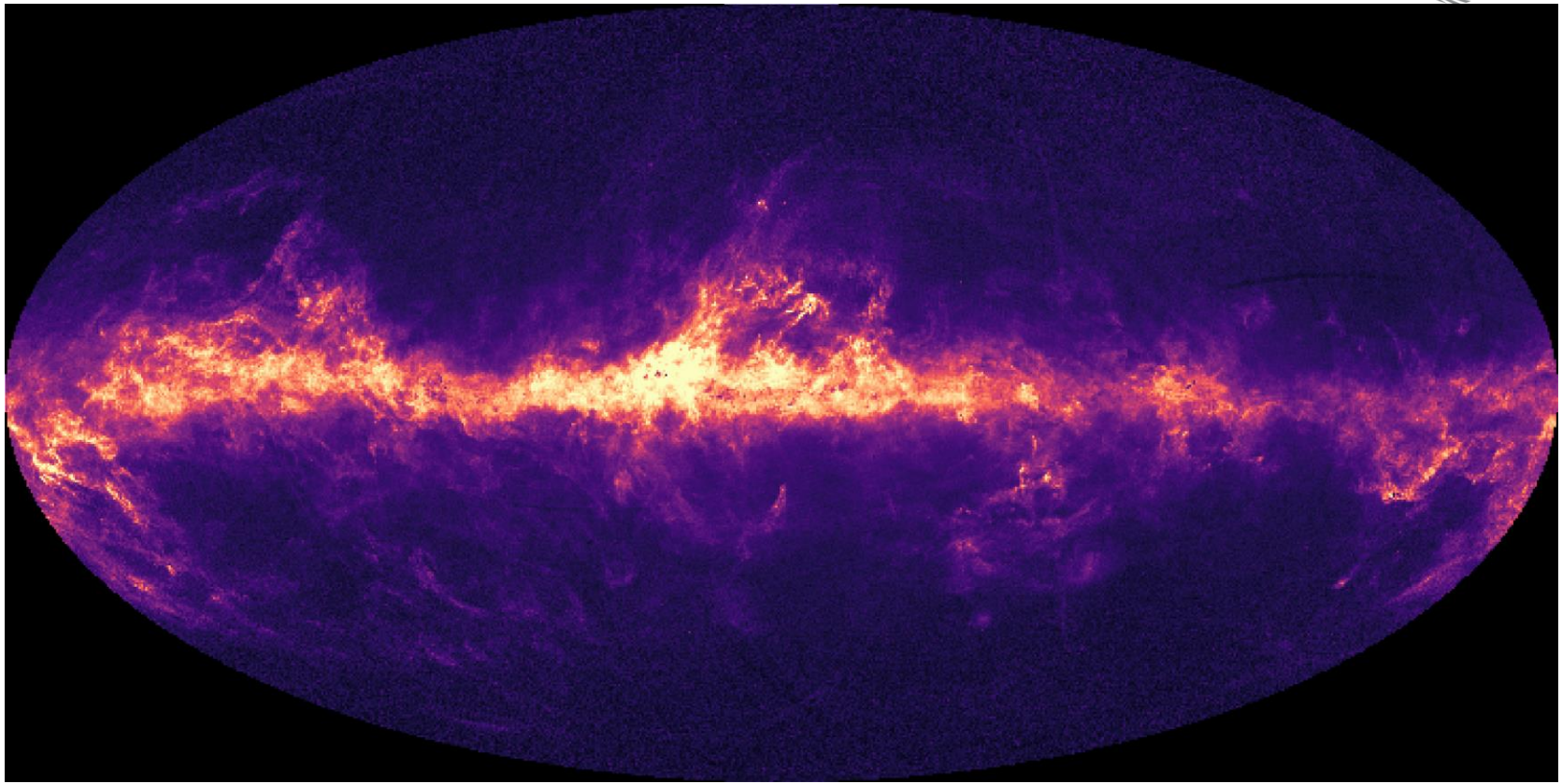


60 km/s < V_{tan}< 150 km/s

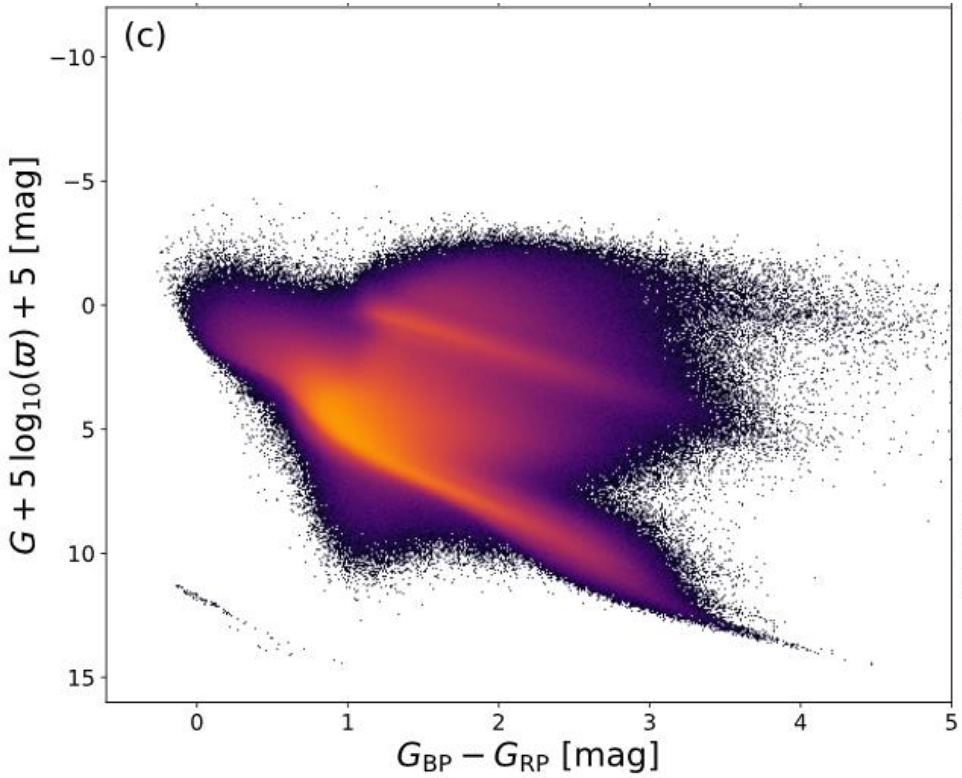


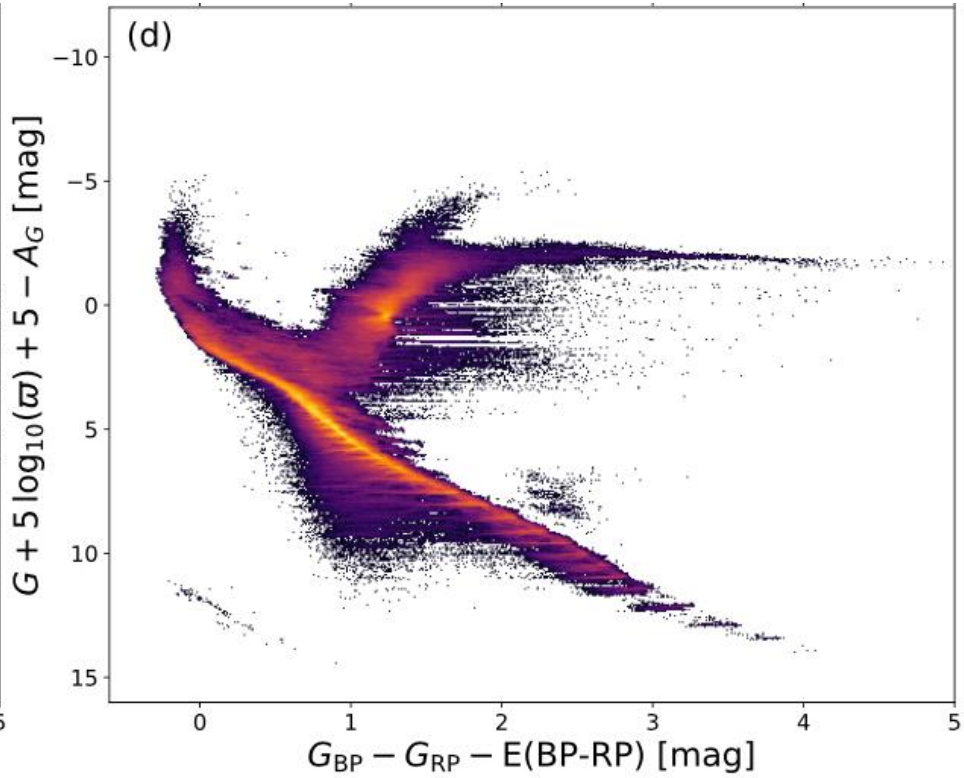
V_{tan} > 200 km/s

Andrae+ 88M extinctions

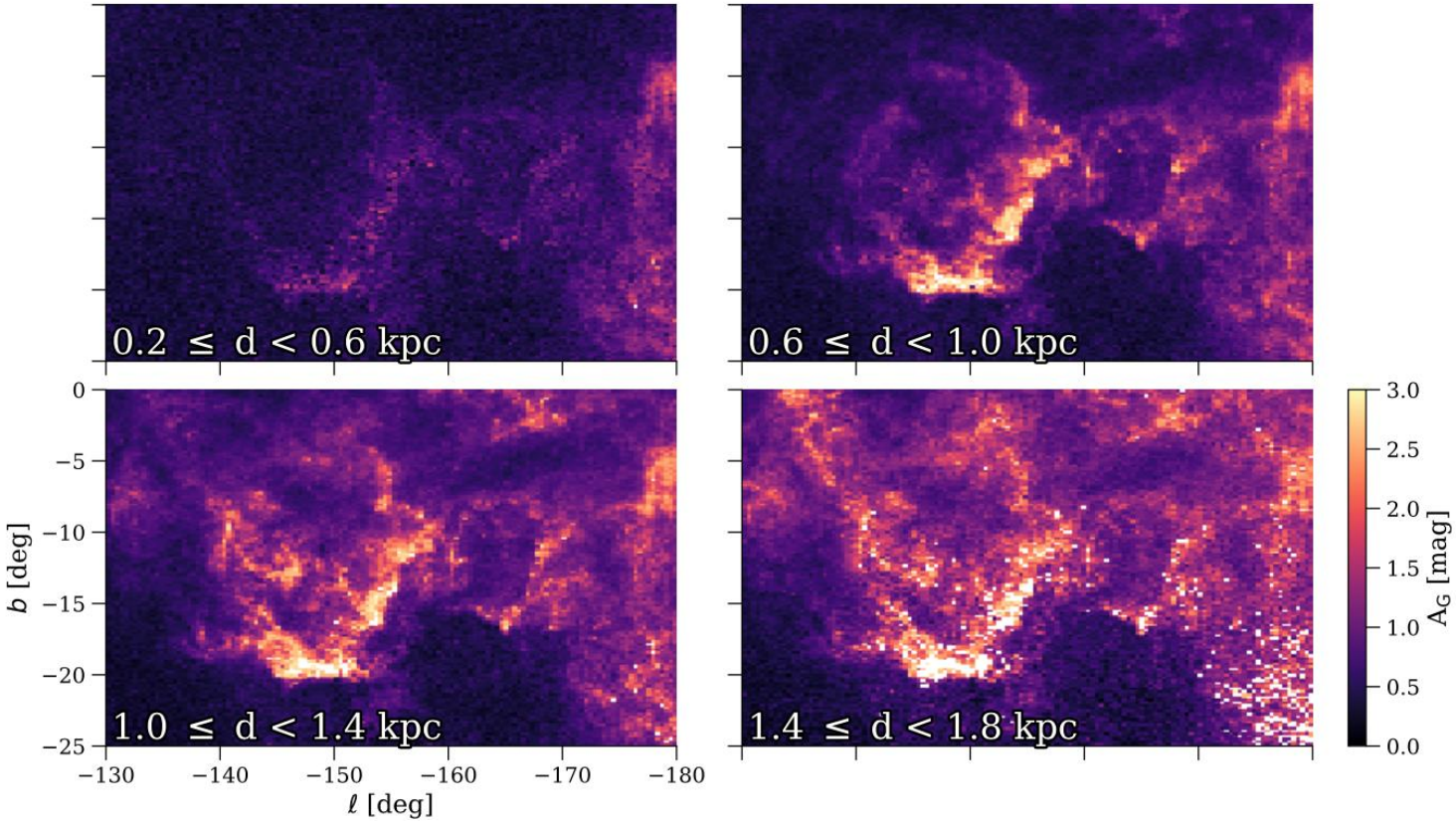


Andrae+ dereddened HR diagram

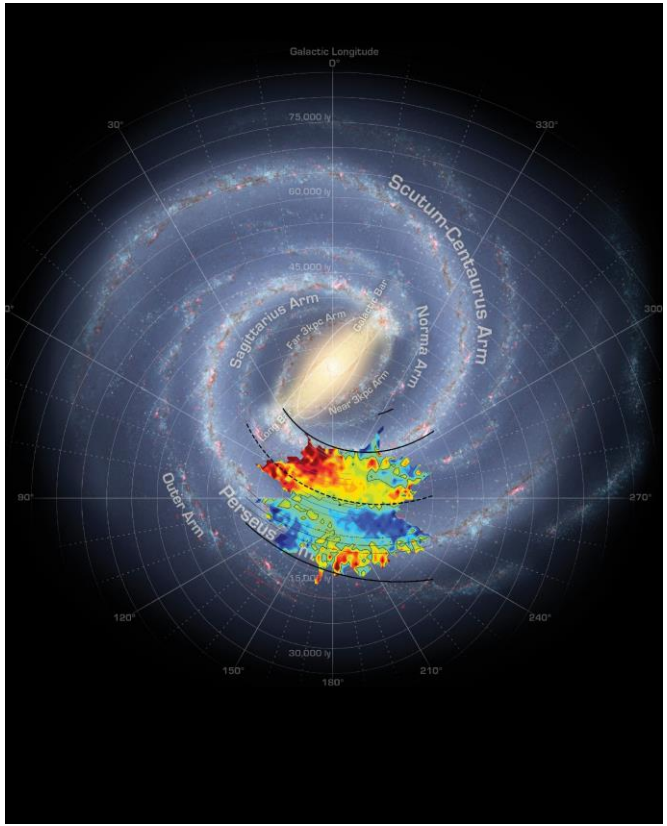


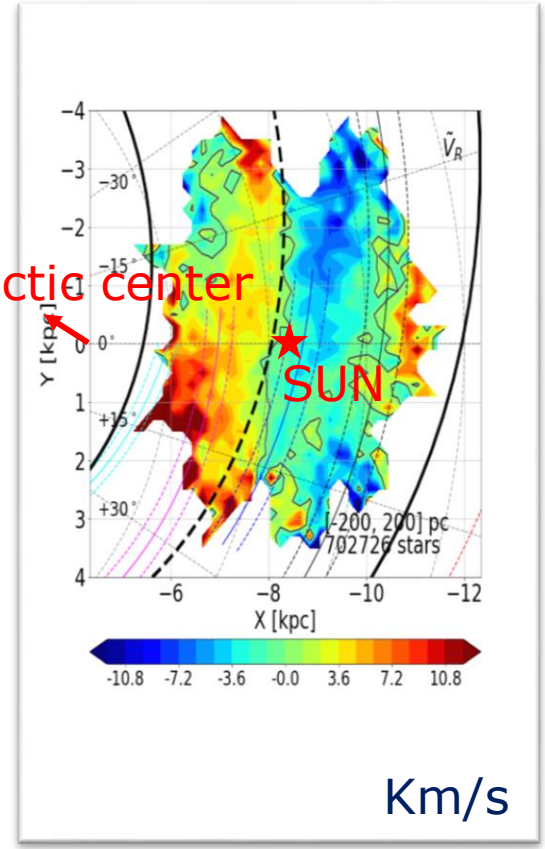


Andrae+ Orion dust tomography



Katz+ Milky Way disc kinematics

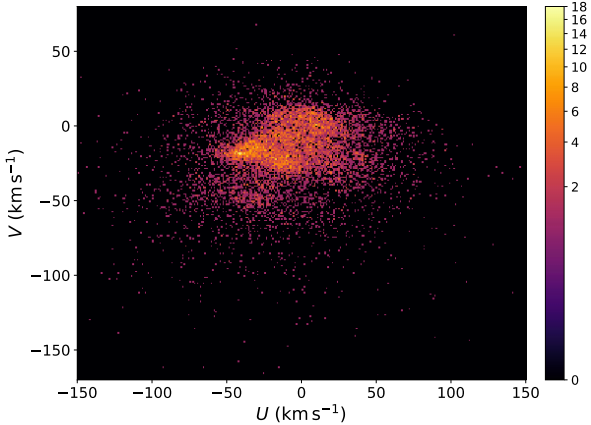




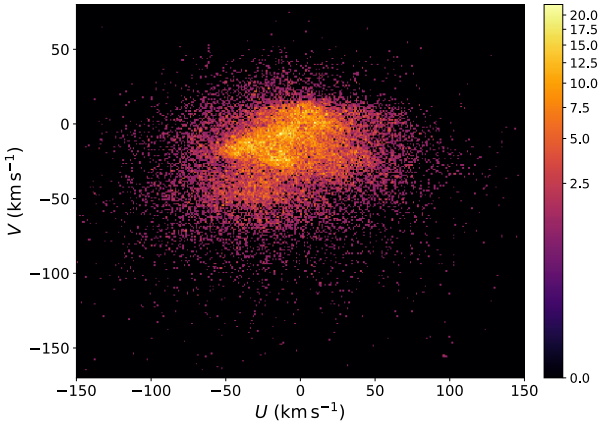
Katz+ Milky Way disc kinematics

Lots of structure in velocity plane: equilibrium?

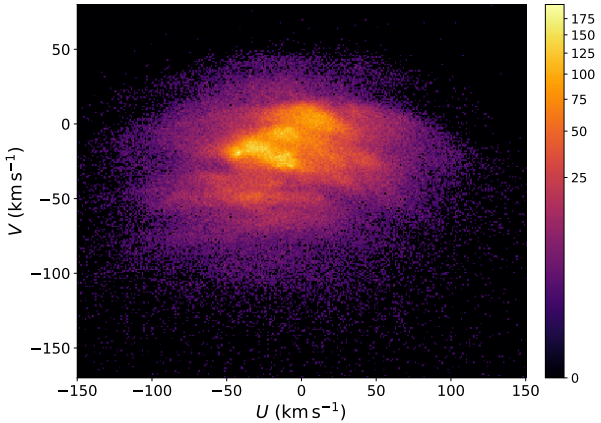
2009
11939 stars



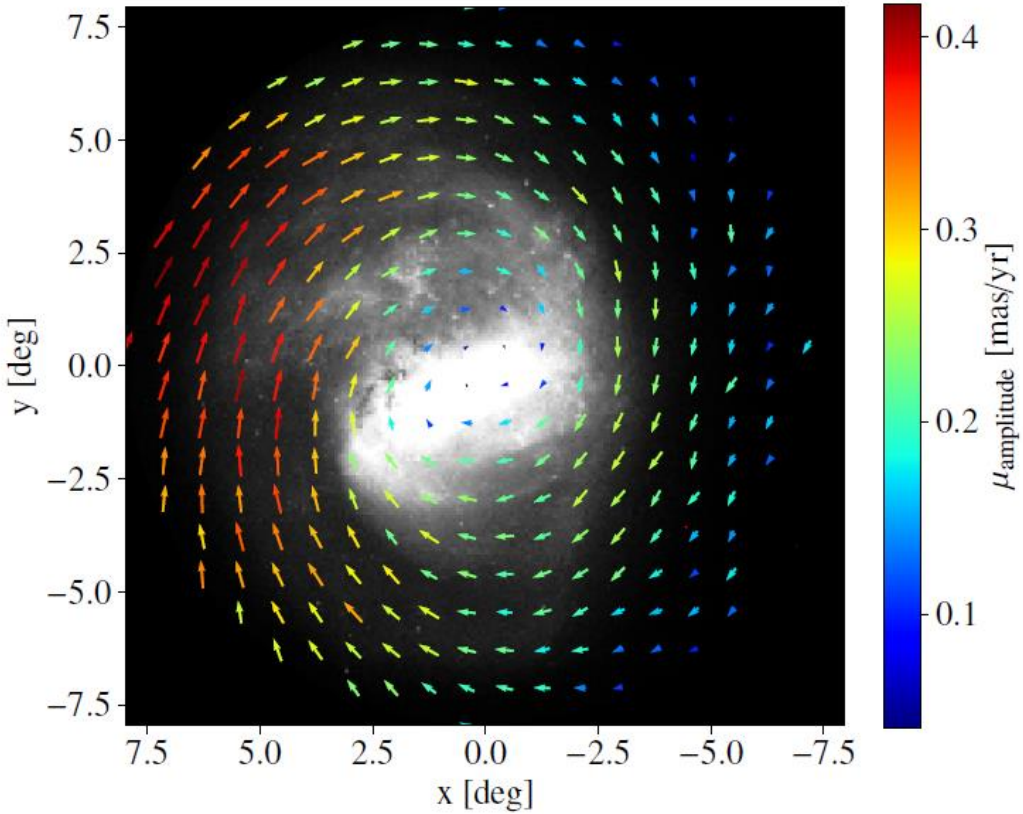
2017
37419 stars



Gaia DR2
2018
366182 stars



Helmi+ LMC rotation



5. Gaia papers (selection)

ADS statistics

Gaia all refereed papers: 1755

All citations: 25482

DR2 refereed papers: 1264 ~3/day

Refereed citations: 7308

Most cited paper (1528):

Gaia Collaboration; Brown+ 2018A&A...616A...1G

Gaia Data Release 2. Summary of the contents and survey properties

Most cited papers (non-DPAC)

Ivezić+ (978) 2019ApJ...873..111I

LSST: From Science Drivers to Reference Design and Anticipated Data Products

Bailer-Jones+ (313) 2018AJ....156...58B

Estimating Distance from Parallaxes. IV. Distances to 1.33 Billion Stars in Gaia Data Release 2

Most cited: DPAC

Gaia Collaboration; Brown+ (1528) 2018A&A...616A...1G

Gaia Data Release 2. Summary of the contents and survey properties

Gaia Collaboration; Prusti+ (1340) 2016A&A...595A...1G

The Gaia mission

Gaia Collaboration; Brown+ (1086) 2016A&A...595A...2G

Gaia Data Release 1. Summary of the astrometric, photometric, and survey properties

Lindegren+ (491) 2016A&A...595A...4L

Gaia Data Release 1. Astrometry: one billion positions, two million proper motions and parallaxes

Lindegren+ (465) 2018A&A...616A...2L

Gaia Data Release 2. The astrometric solution

Most cited: the Galaxy

Gaia Collaboration; Katz+ (92) 2018A&A...616A..11G

Gaia Data Release 2. Mapping the Milky Way disc kinematics

Helmi+ (81) 2018Natur.563...85H

The merger that led to the formation of the Milky Way's inner stellar halo and thick disk

Antoja+ (76) 2018Natur.561..360A

A dynamically young and perturbed Milky Way disk

Belokurov+ (67) 2018MNRAS.478..611B

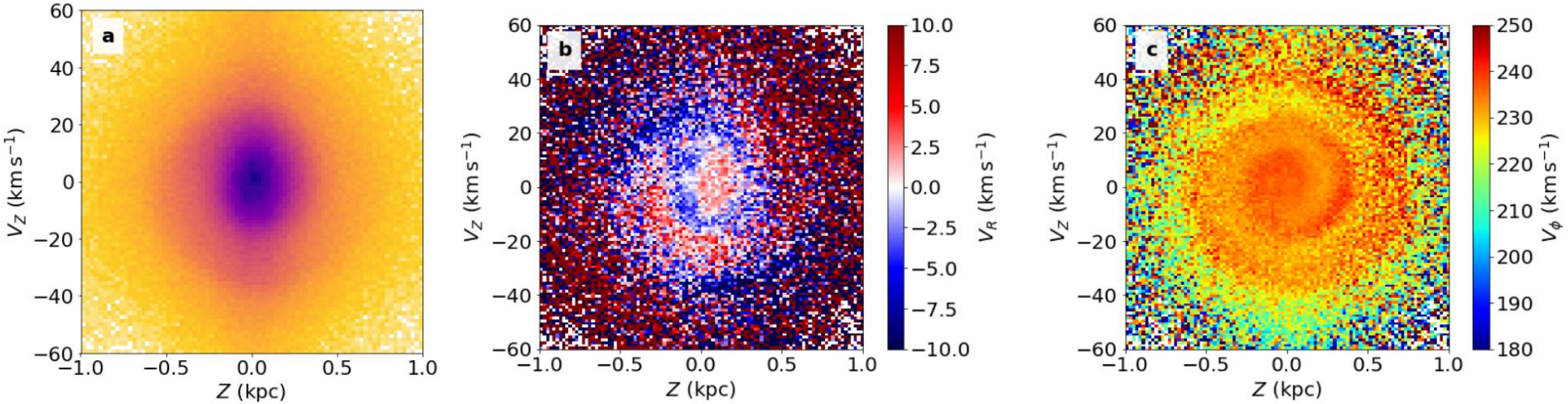
Co-formation of the disc and the stellar halo

Bovy+ (55) 2016ApJ...833...31B

The Shape of the Inner Milky Way Halo from Observations of the Pal 5 and GD--1 Stellar Streams

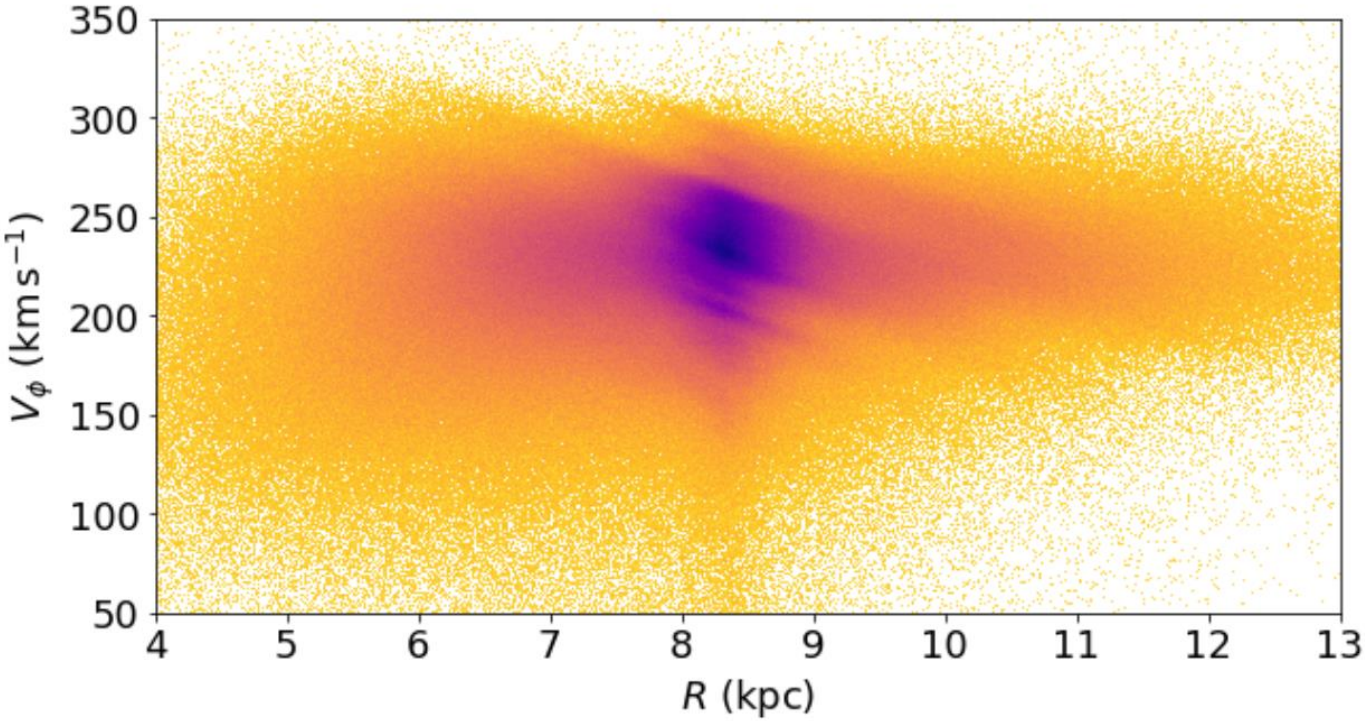
Most cited: the Galaxy

Antoja+ (2018): spiral patterns in phase space projections



Most cited: the Galaxy

Antoja+ (2018): ridges in phase space ➔ mixing. Perturbation by Sagittarius passage?



Most cited: astrometric bias

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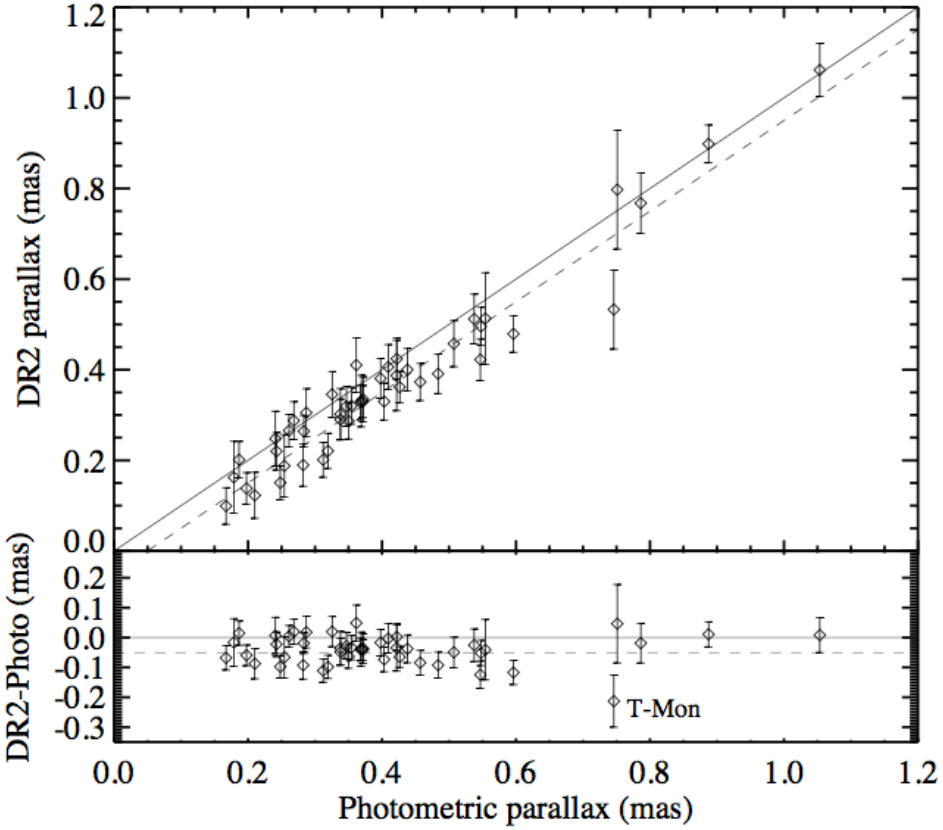
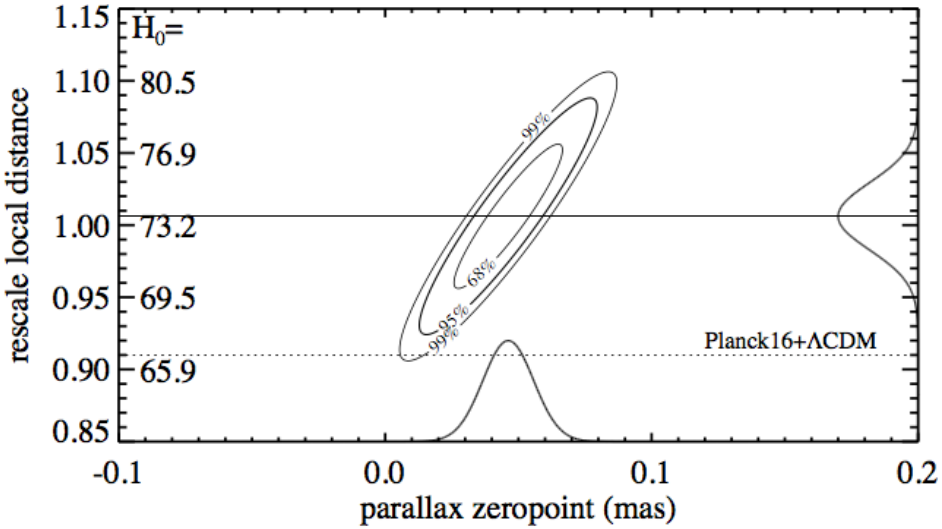
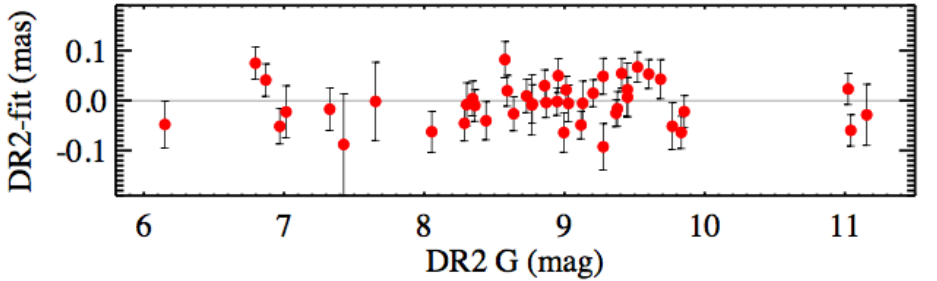
Asteroseismology and Gaia: Testing Scaling Relations Using 2200 Kepler Stars with TGAS Parallaxes

Most cited: astrometric bias







Most cited: other surveys

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LSST: From Science Drivers to Reference Design and Anticipated Data Products

Albareti+ (269) 2017ApJS..233...25A

The 13th Data Release of the Sloan Digital Sky Survey: First Spectroscopic Data from the SDSS-IV Survey Mapping Nearby Galaxies at Apache Point Observatory

Kunder+ (223) 2017AJ....153...75K

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Luo+ (117) 2017ApJS..228....2L

The Chandra Deep Field-South Survey: 7 Ms Source Catalogs

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UCAC5: New Proper Motions Using Gaia DR1

Most cited: other surveys

Ivezić+ (2019): Gaia reference ➔ superb astrometry and photometry

Table 3. The expected proper motion, parallax and accuracy for a 10-year long baseline survey.

r	σ_{xy} [a]	σ_π [b]	σ_μ [c]	σ_1 [d]	σ_C [e]
mag	mas	mas	mas/yr	mag	mag
21	11	0.6	0.2	0.01	0.005
22	15	0.8	0.3	0.02	0.005
23	31	1.3	0.5	0.04	0.006
24	74	2.9	1.0	0.10	0.009

[a] Typical astrometric accuracy (rms per coordinate per visit).

[b] Parallax accuracy for 10-year long survey.

[c] Proper motion accuracy for 10-year long survey.

[d] Photometric error for a single visit (two 15-second exposures).

[e] Photometric error for coadded observations (see Table 1).

Most cited: exoplanets

Mathur+ (107) 2017ApJS..229...30M

Revised Stellar Properties of Kepler Targets for the Q1-17 (DR25) Transit Detection Run

Perryman+ (99) 2014ApJ...797...14P

Astrometric Exoplanet Detection with Gaia

Stassun+ (86) 2018AJ....156..102S

The TESS Input Catalog and Candidate Target List

Thompson+ (79) 2018ApJS..235...38T

Planetary Candidates Observed by Kepler. VIII. A Fully Automated Catalog with Measured Completeness and Reliability Based on Data Release 25

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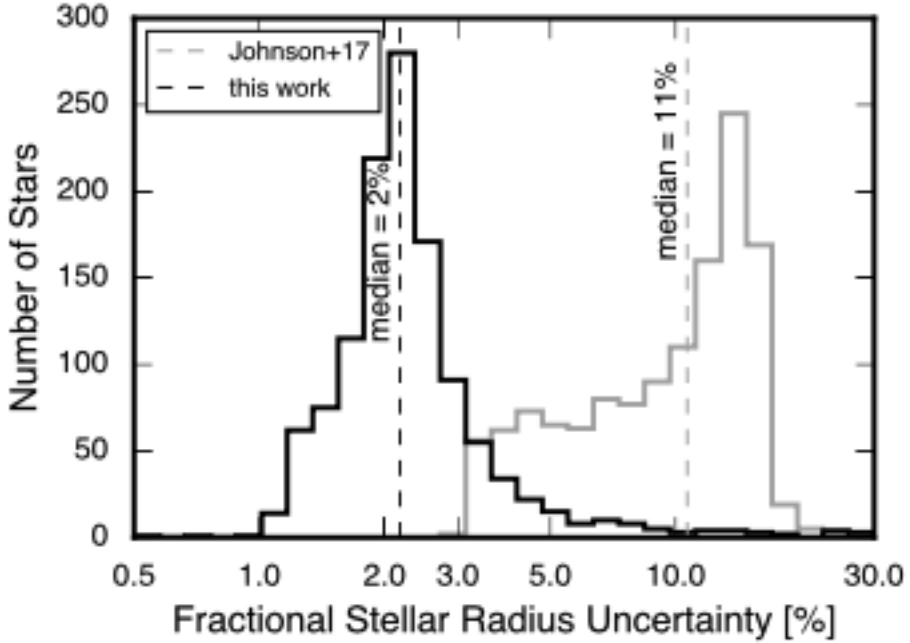
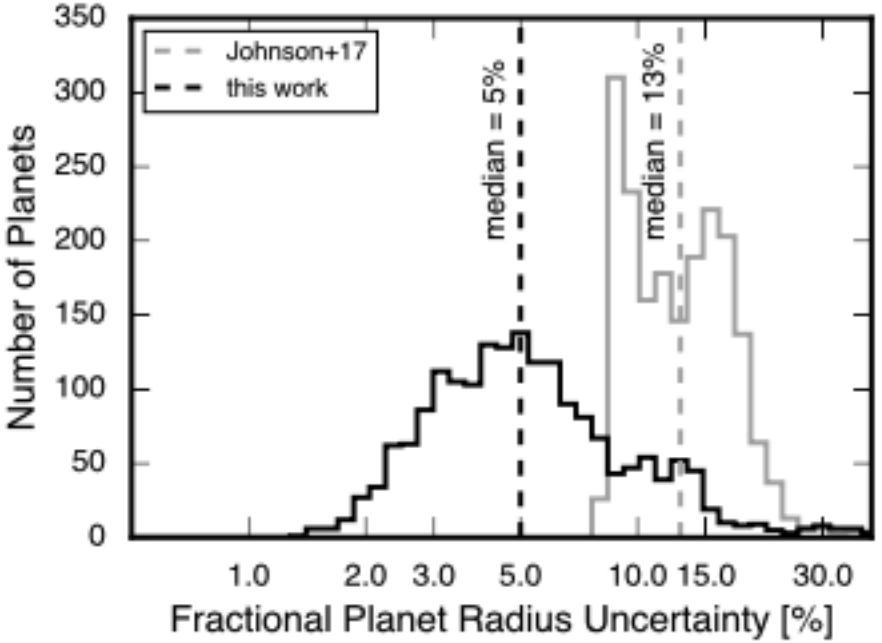
The California-Kepler Survey. VII. Precise Planet Radii Leveraging Gaia DR2 Reveal the Stellar Mass Dependence of the Planet Radius Gap

Most cited: exoplanets

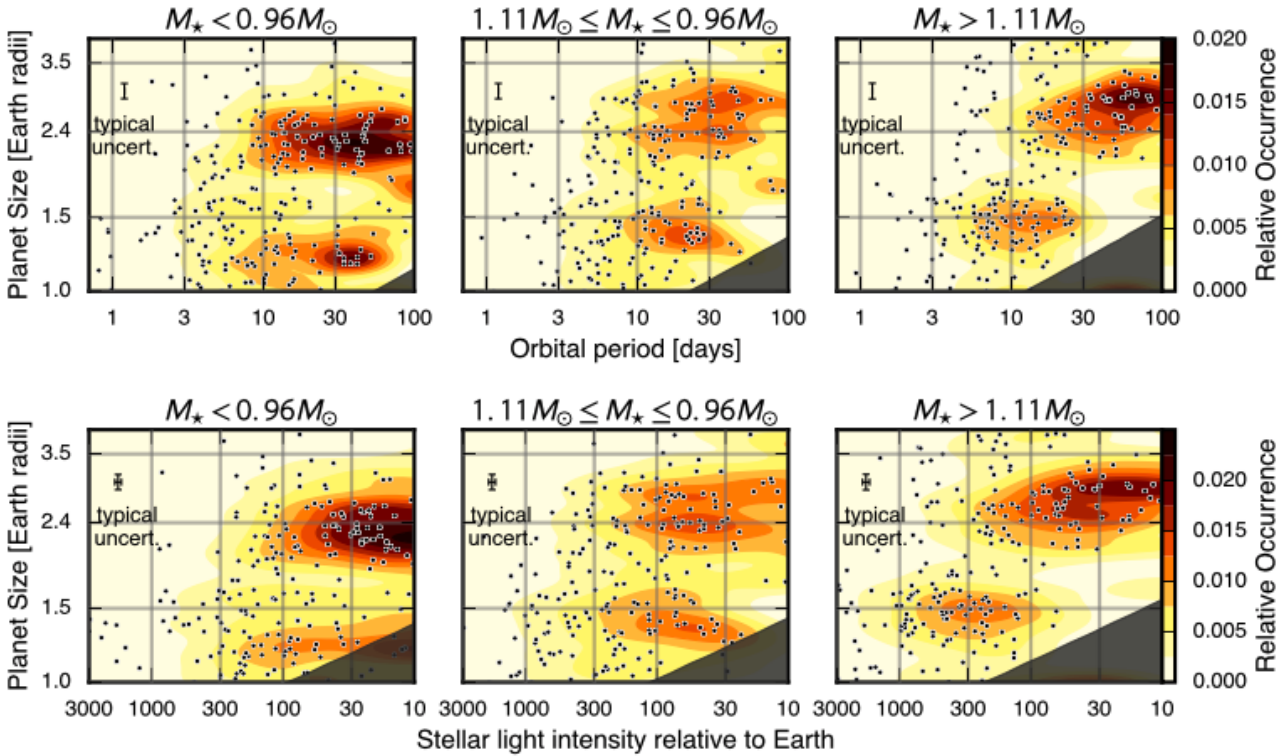
Fulton & Petigura (2018). Much better transiting planet radii uncertainties





Most cited: exoplanets

Fulton & Petigura (2018). Distinction between sub-Neptunes and super-Earths



Most cited: young stars and discs

Fedele+ (87) 2017A&A...600A..72F

ALMA unveils rings and gaps in the protoplanetary system HD 169142: signatures of two giant protoplanets

van Boekel+ (78) 2017ApJ...837..132V

Three Radial Gaps in the Disk of TW Hydrae Imaged with SPHERE

Gagné+ (73) 2018ApJ...856...23G

BANYAN. XI. The BANYAN Σ Multivariate Bayesian Algorithm to Identify Members of Young Associations with 150 pc

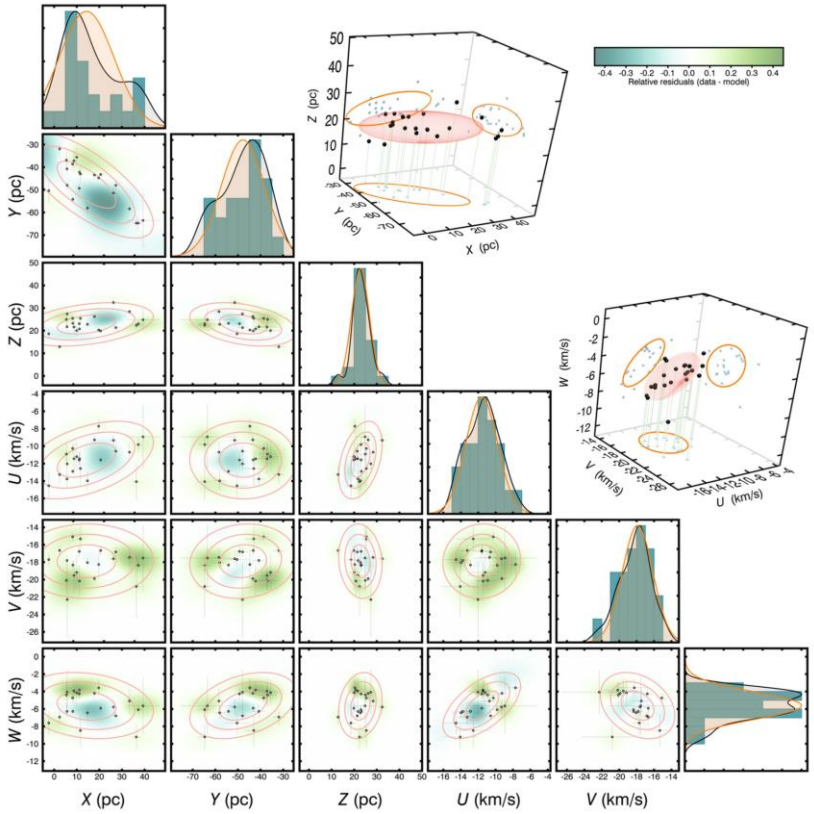
Keppler+ (56) 2018A&A...617A..44K

Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70

Cleeves+ (56) 2016ApJ...832..110C

The Coupled Physical Structure of Gas and Dust in the IM Lup Protoplanetary Disk

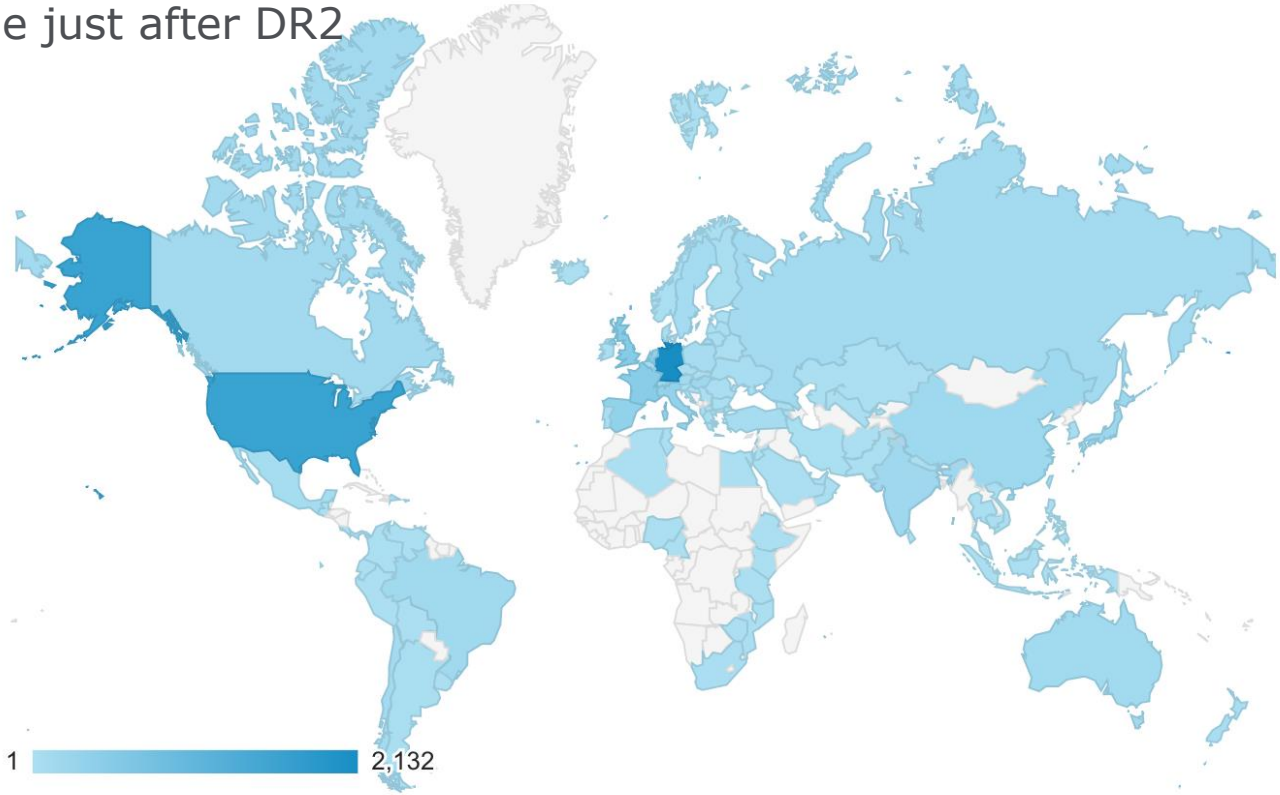
Most cited: young stars and discs



- Gagné+ (2018) 2018ApJ...856...23G
- Young association automatic detection
- 6D input (positions + velocities)
- Very active field (contributions in this conference)

Global science

Archive usage just after DR2



Nature's 10 2018

ANTHONY BROWN: Star mapper

Working behind the scenes, an astronomer coordinated the release of Gaia's long-awaited bounty of Milky Way data.

BY RACHEL COURTLAND

6. Data Release 3 and beyond

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		

New in Gaia EDR3: extended sources

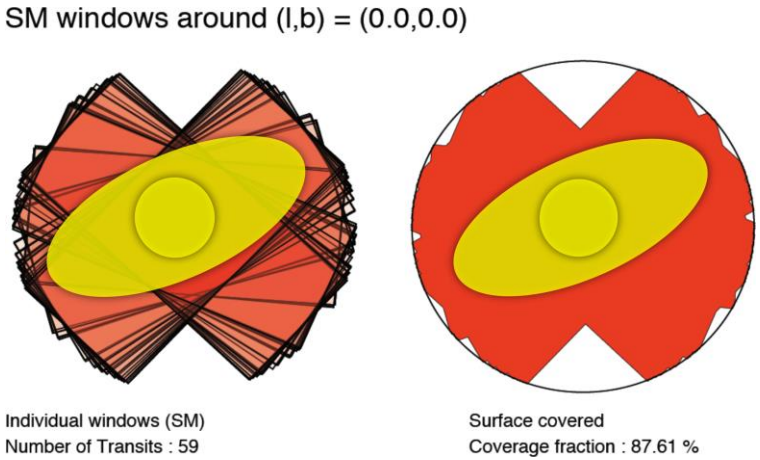


Figure credits: DPAC-CU4/C. Ducourant

- 'Stacking' of multiple transits across extended source
  - detection of extended components
- Galaxy morphology, bulge/disk ratio, basic disk parameters
- QSO host galaxy morphology, ratio QSO to host intensity, offsets between the two
- Based on input list of ~ 1.9 million galaxies and ~ 1.6 million QSOs
- NOTE: Stacked images are not released

Contents of Gaia DR3

Data Product	No. of sources	Comments
Repeat of EDR3 contents		
Source Classification and astrophysical parameters	>~ 300 million	based on the BP/RP spectra, magnitude limit TBD
Radial velocities	~ 30 million	*G*RVS <~ 14
Mean BP/RP/RVS spectra	TBD subset of sources	
Photometric variability characterization, classification, light curves	~ 7 million	eclipsing, (MS) pulsating, transients, spotted, flaring, evolved pulsators, and quasars
Solar system objects epoch astrometry/photometry	~ 100 000	including orbit solutions
Solar system objects mean BP/RP reflectance spectra	~ 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_{eff}, A_G, $E(G_{\mathrm{BP}} - G_{\mathrm{RP}})$, 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
- Sourceclassification(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

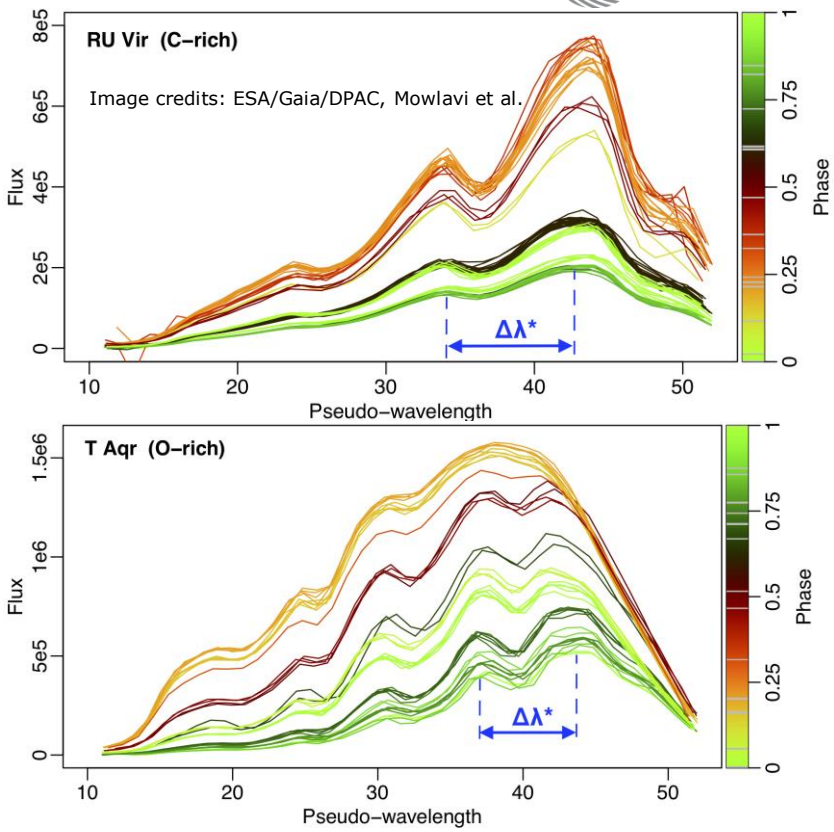
- Orbits
- Reflectance spectra

Gaia DR4

- Final release for the nominal misión
  - 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

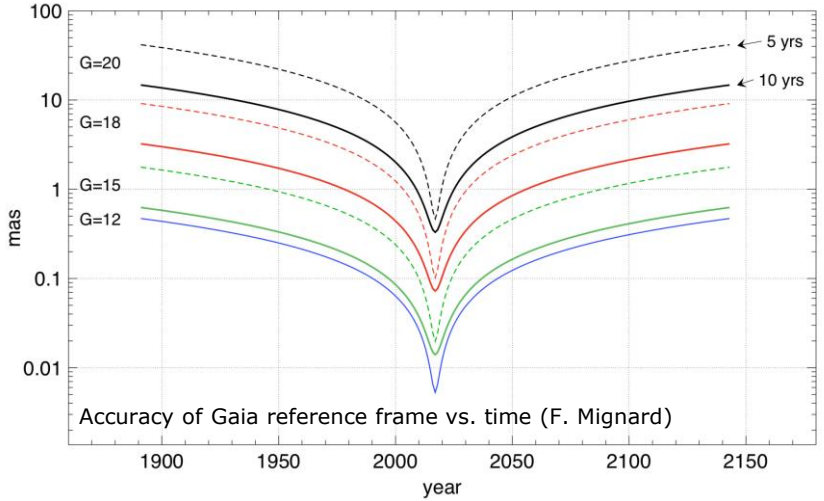


Gaia extension

- Nominal Gaia mission ends 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 extensión
- approved to end 2020, preliminary approval to end 2022, submit proposal for 2023–2024 in 2020

10 year mission

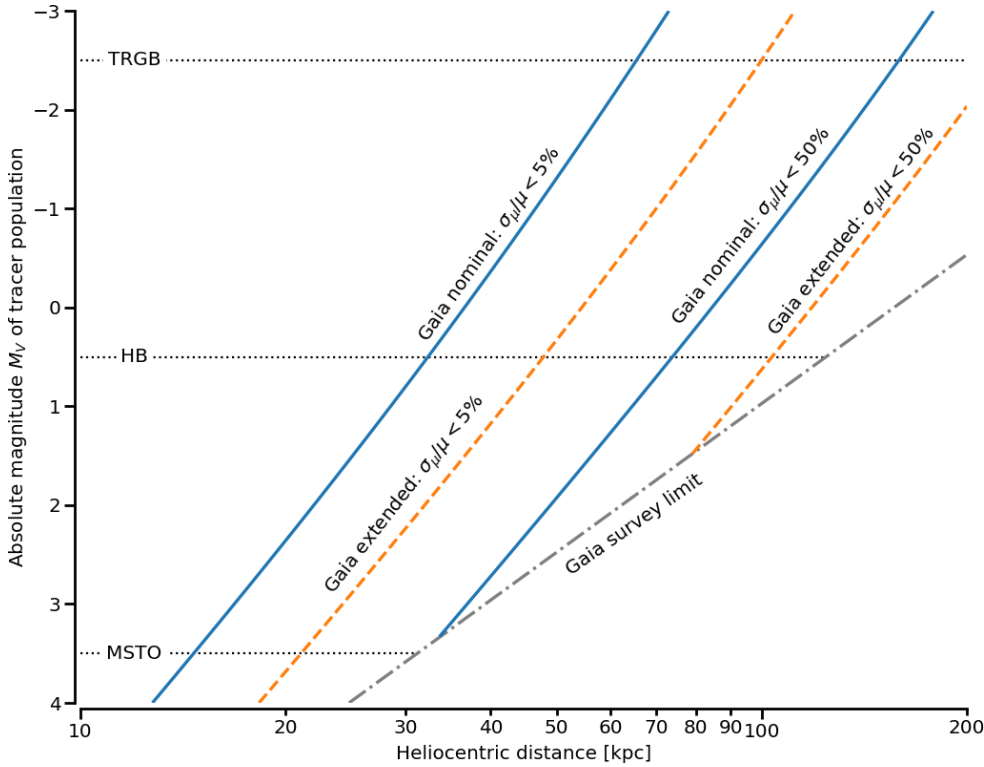
- Parallaxes, photometry, radial velocities improve by factor 1.4 with respect to DR4
- Proper motions improve by factor of 2.8 wrt DR4
  - Improvement of more complex motions (e.g., planets) up to factors of 20
- Accurate tangential motions over 22.6× larger volume



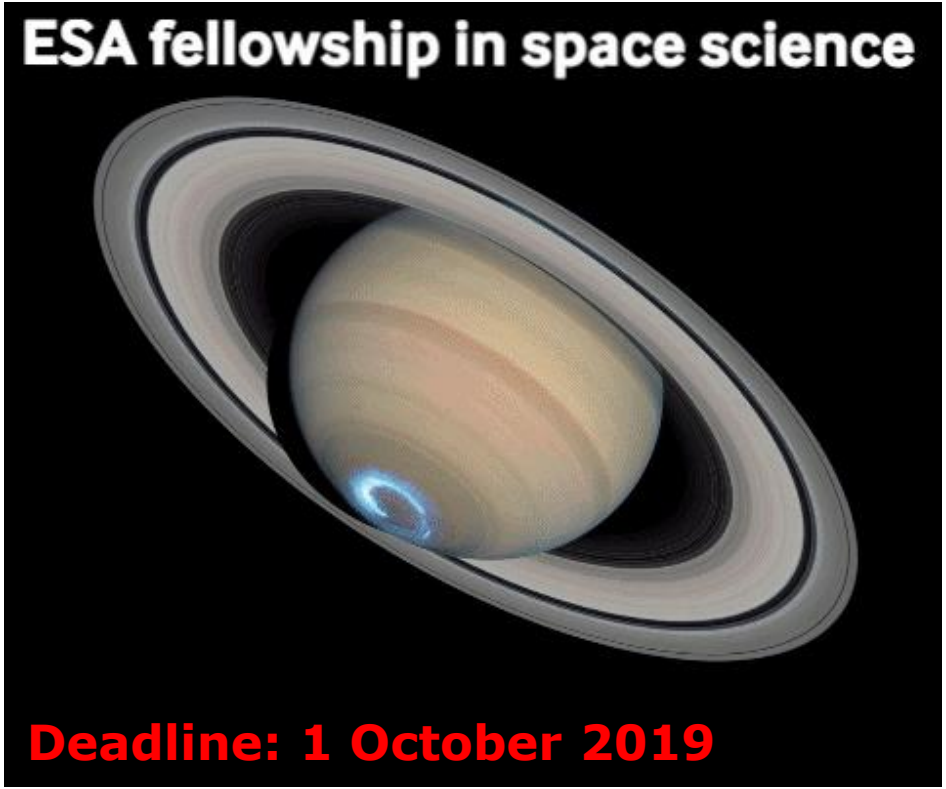
Accuracy of Gaia reference frame vs. time (F. Mignard)

Gaia extension

- Larger volume reached throughout the halo at given proper motion accuracy
- Uncover more streams
- Probe young and unmixed debris located beyond 20–30 kpc
- Calibration of spectrophotometric distance indicators on nearby samples ➔ full gain in tangential motion performance



ESA postdoctoral fellowships



https://www.cosmos.esa.int/web/science-faculty/research-fellowship

Your papers are the best argument for an extended Gaia mission

- 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

Additional slides

2. Gaia: spacecraft, launch and orbit

Photometry and spectroscopy

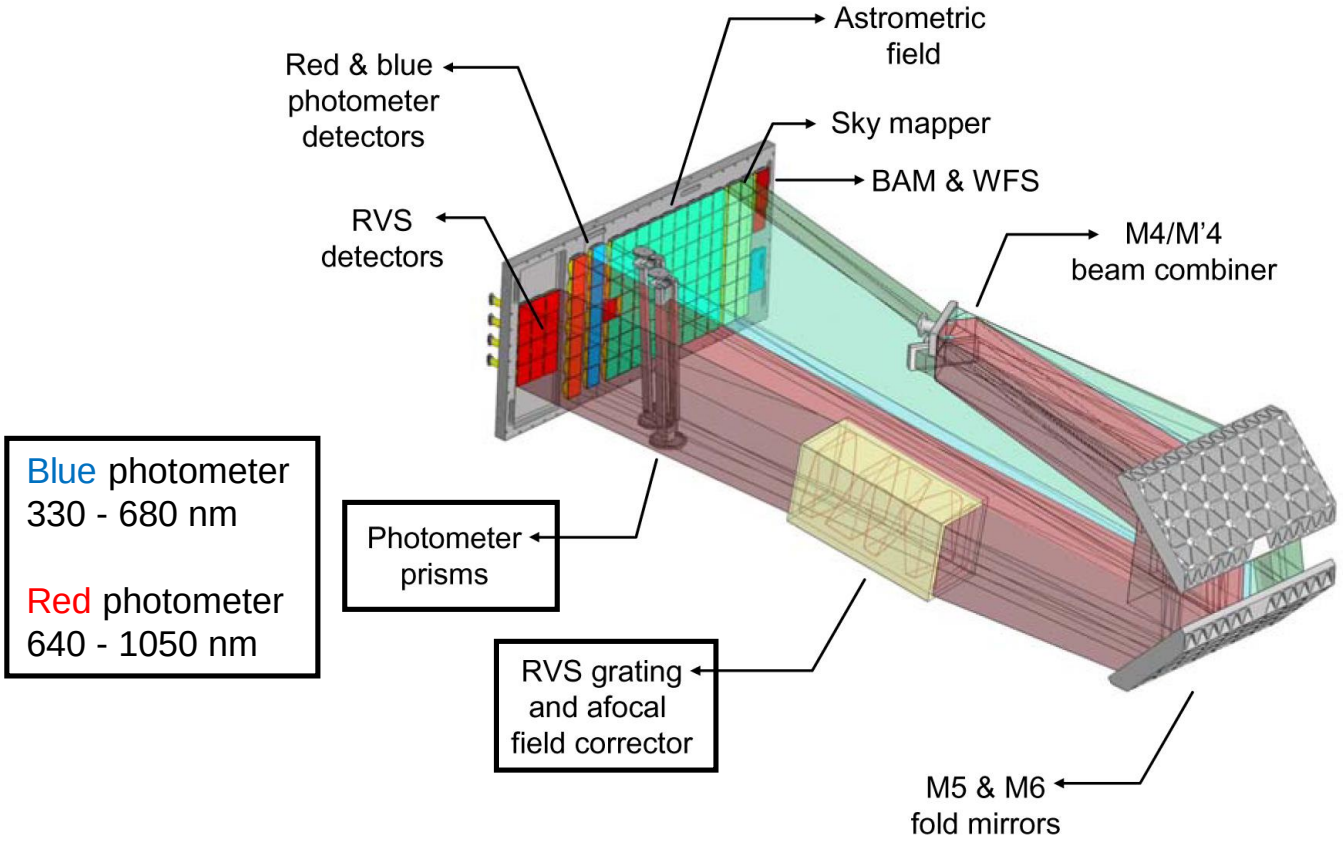


Figure courtesy EADS-Astrium