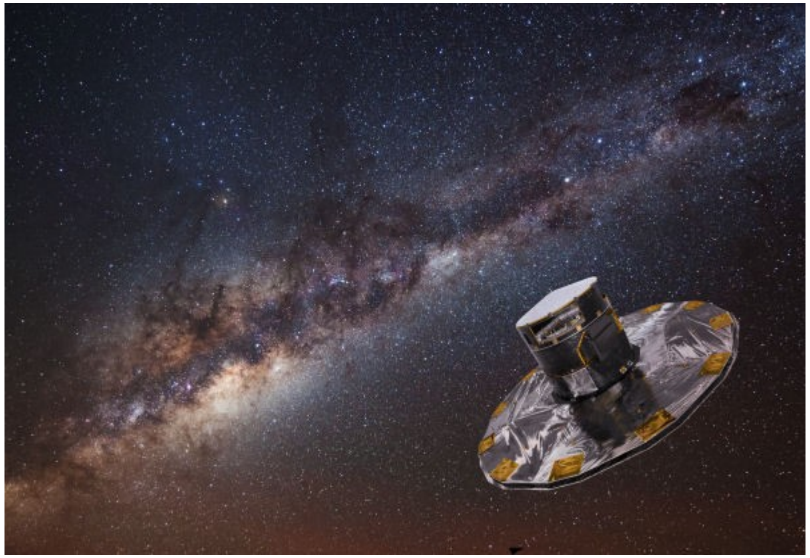
Gaia DR3

a pinch of satellite,
a teaspoon of catalogue
a cup of Milky-Way

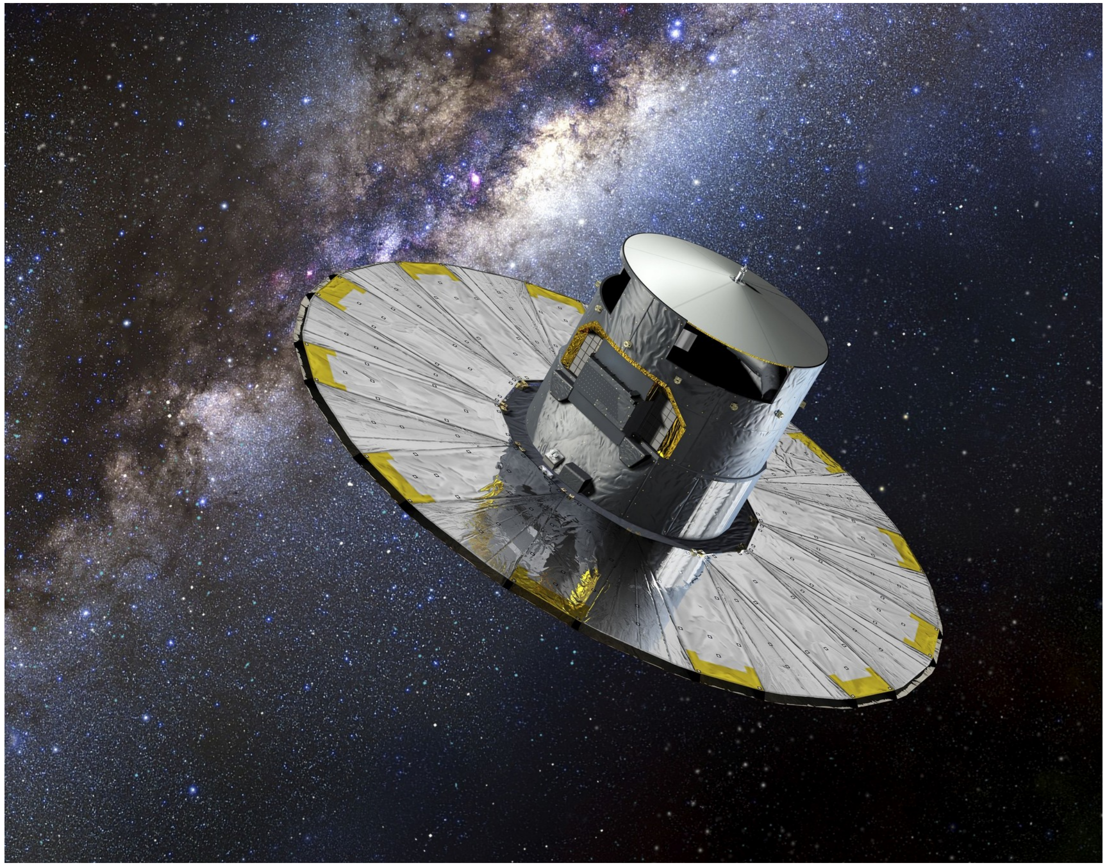


D. Katz

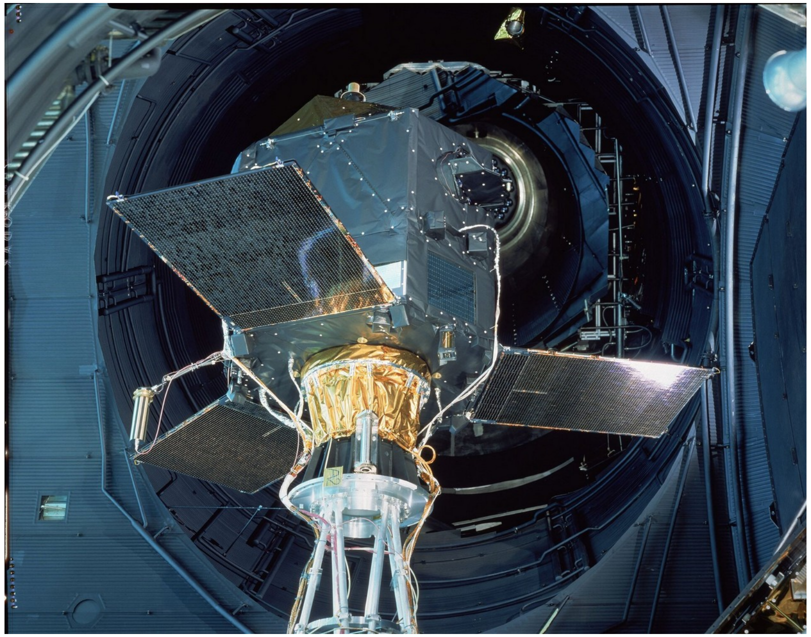
Observatoire de Paris

Gaia spectroscopic processing group

A pinch of satellite



Space astrometry

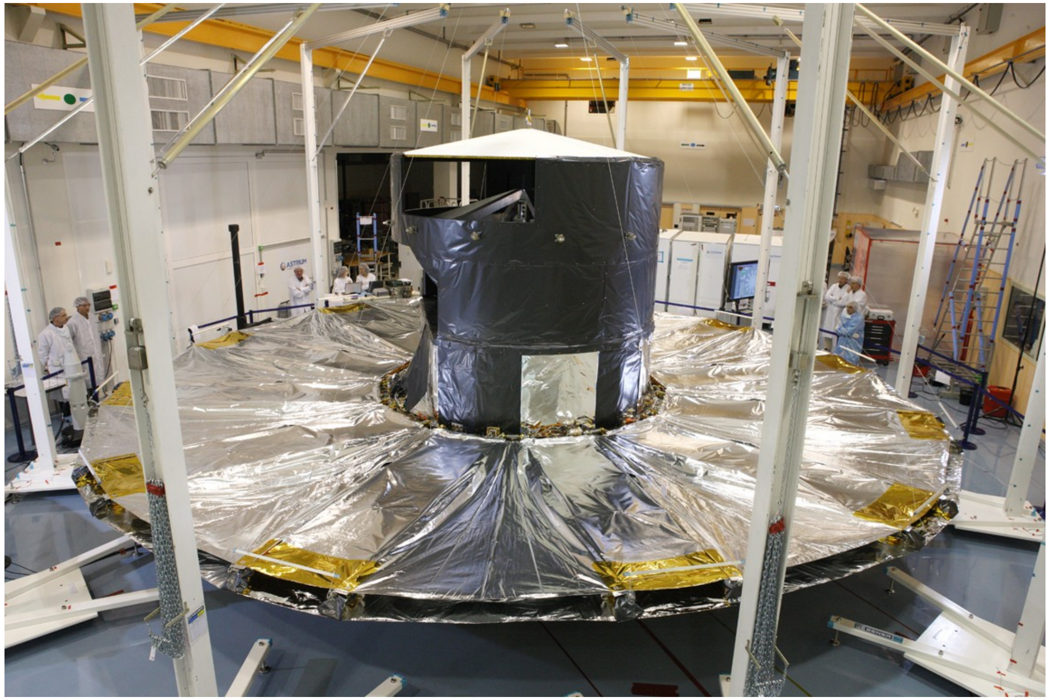


Hipparcos

- Operations: 1989 - 1993
- Parallaxes: ~ 118 000 stars

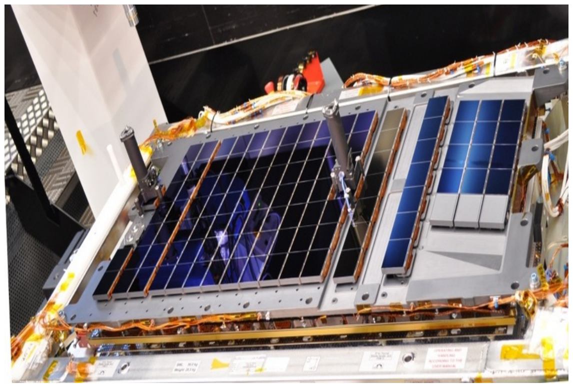
Gaia

- Operations: 2014 - (2025 TBC)
- Full sky survey: G ≤ 21 mag
- Parallaxes: ~ 1.5 billion stars

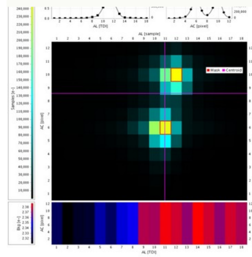


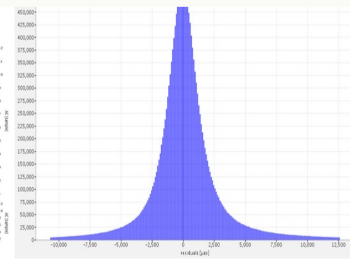
Instruments

- 2 Telescopes
- 3 Instruments



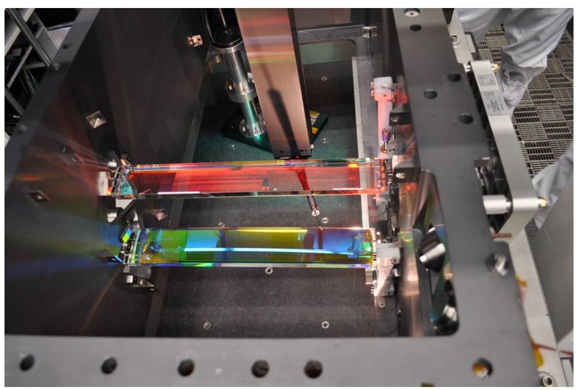
62 AF CCD of 4500 x 1966 pixels of 59 x 177 mas



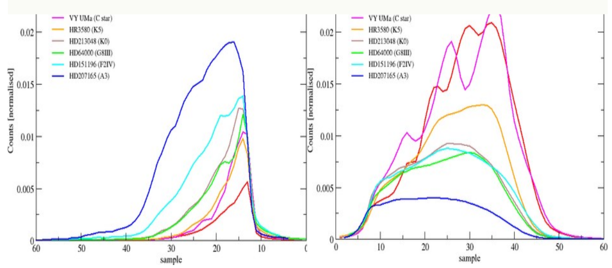


Astrometric instrument

- G < 21
- α, δ, ϖ, μ_{α}, μ_{δ}
- 70 transits (5 ans)

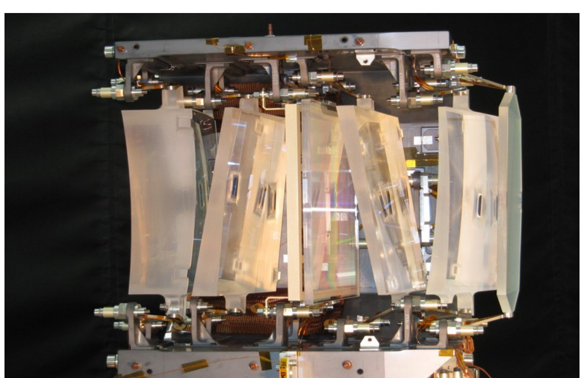


Blue 330–680 nm Red 640–1050 nm

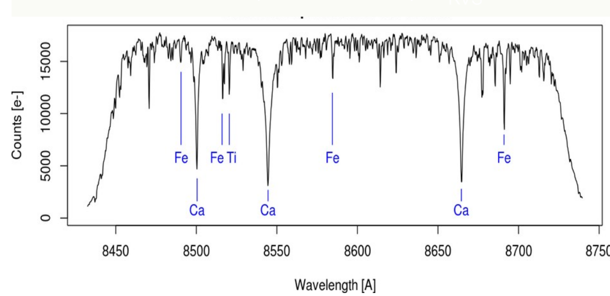


Spectro-photometer : Bp / Rp

- Bp : [330, 680] nm
- Rp : [640, 1050] nm
- Astroph. param., redshifts...



λ = 848-872 nm; R ~ 10500; G_{RVS} < 16.2



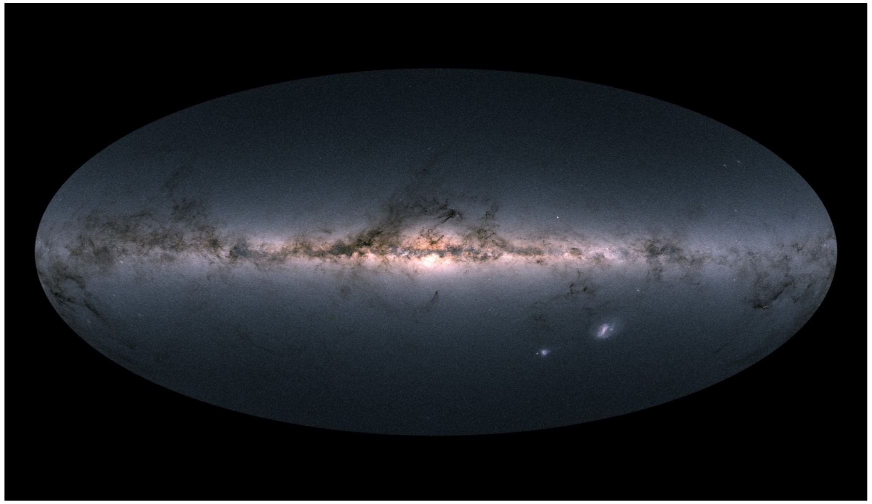
Spectrograph : RVS

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

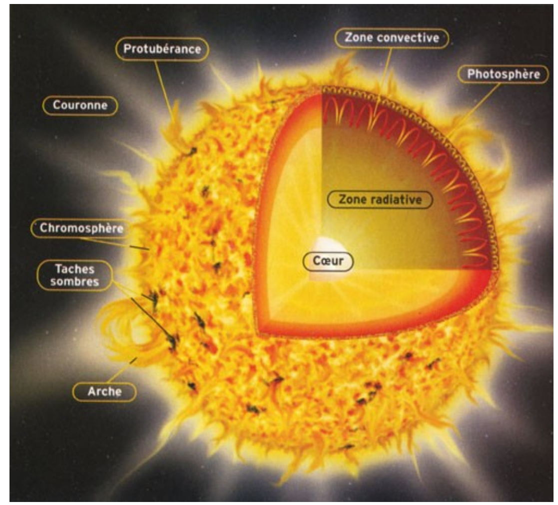
Scientific objectives

The Galaxy, ISM and local group

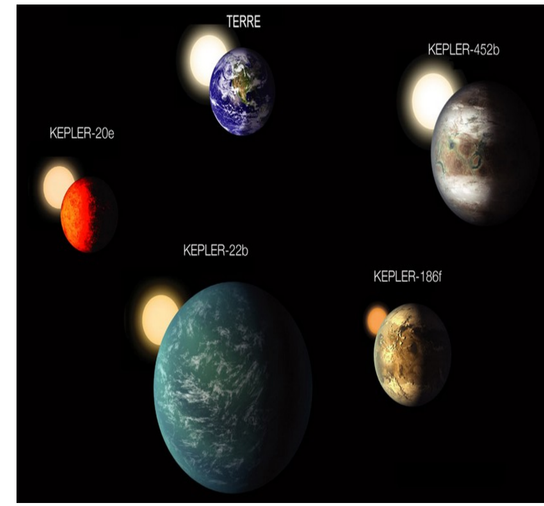
Structure, physics, formation, history



Stellar physics

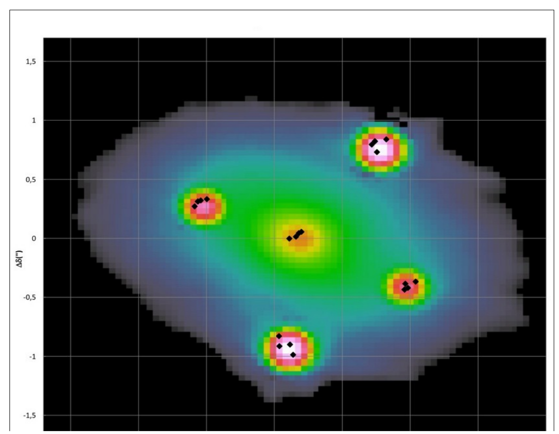


Extra-solar planets



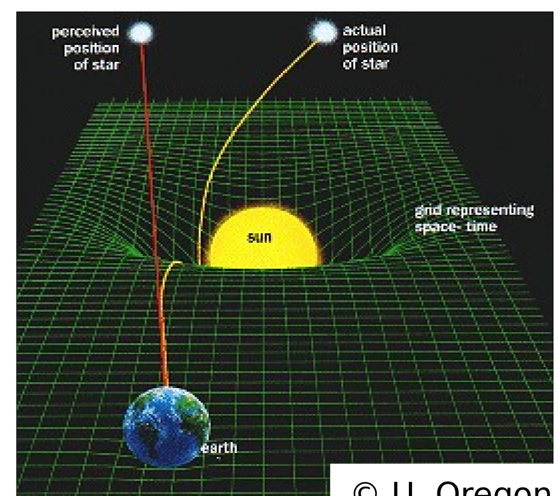
Solar system

Galaxies and quasars, science alerts



Einstein Cross (Q2237+030)

Reference frame / fondamental physics

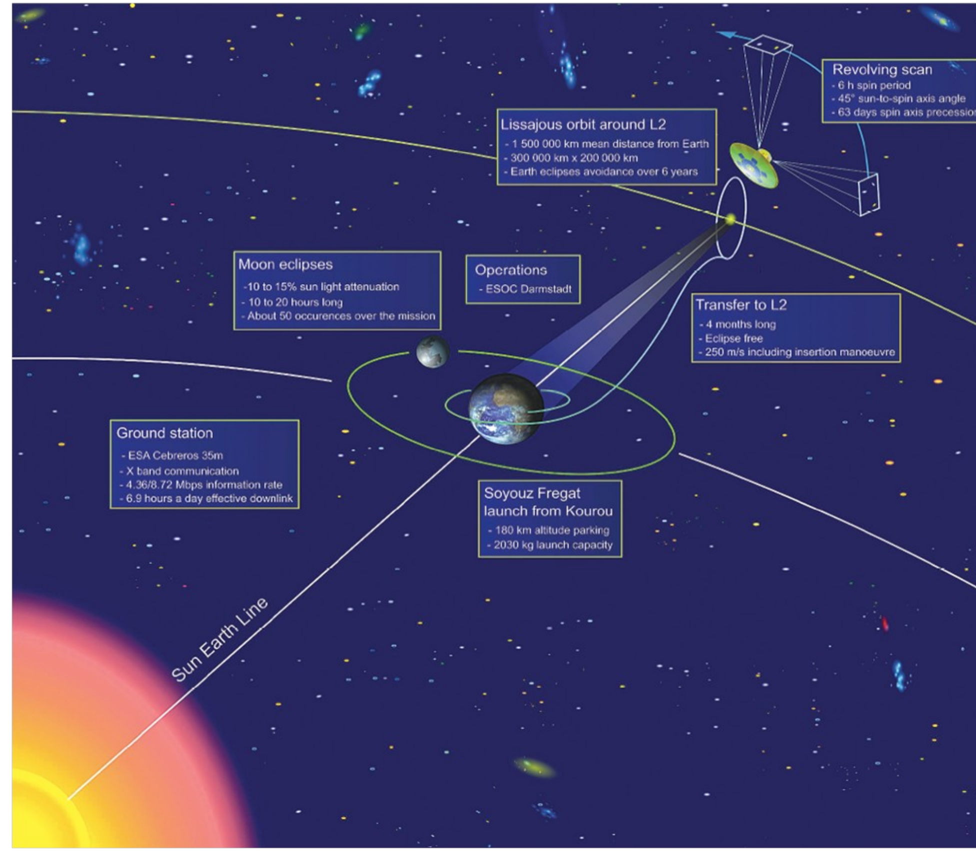


© U. Oregon

Launch and operations

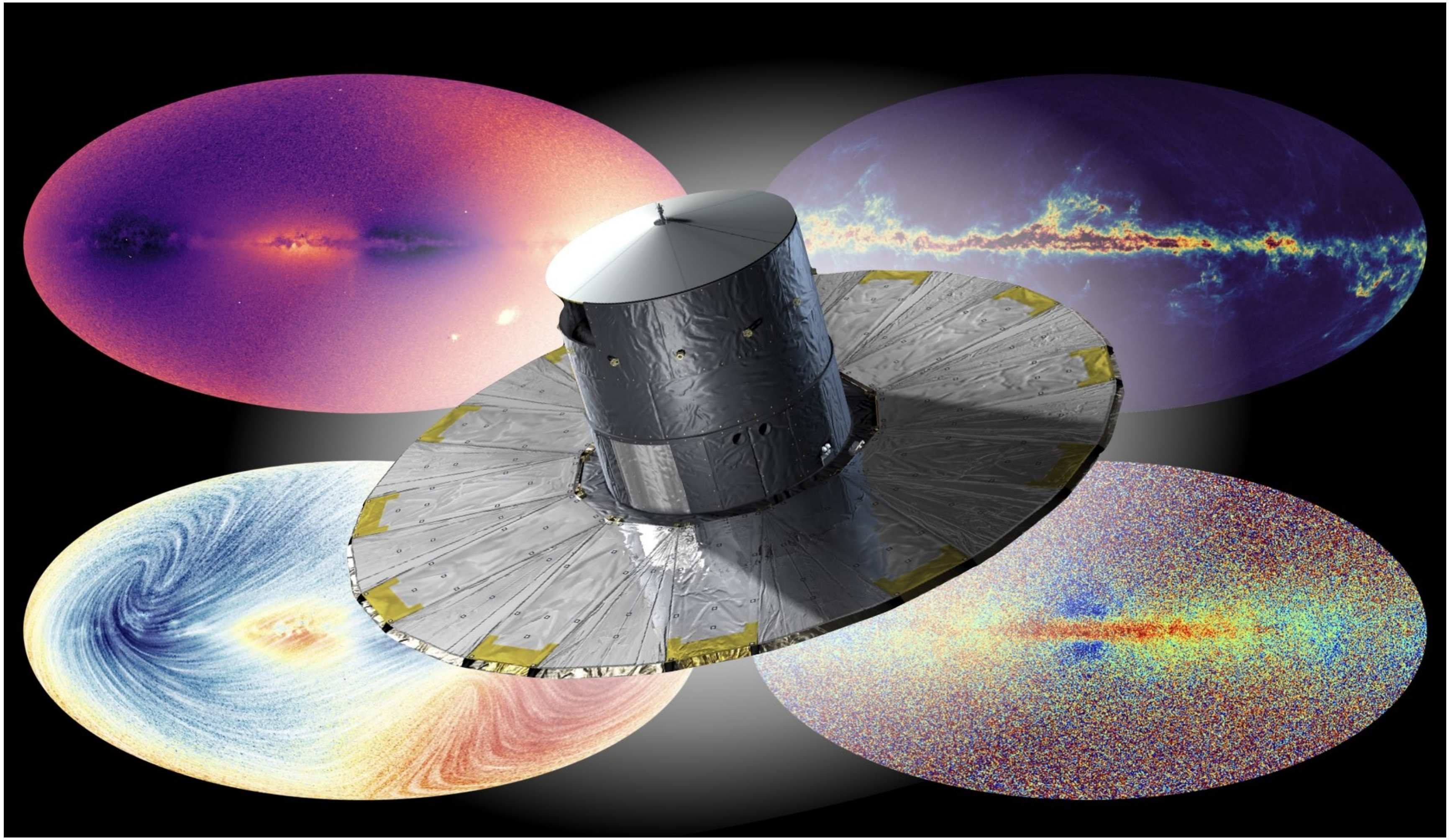
19 Décembre 2013

9:12:19 UTC



- Operated at Lagrange point L2
- 2978 days in science operations
- ~ 200 billions FoV crossing recorded
- ~ 110 TB science data gathered

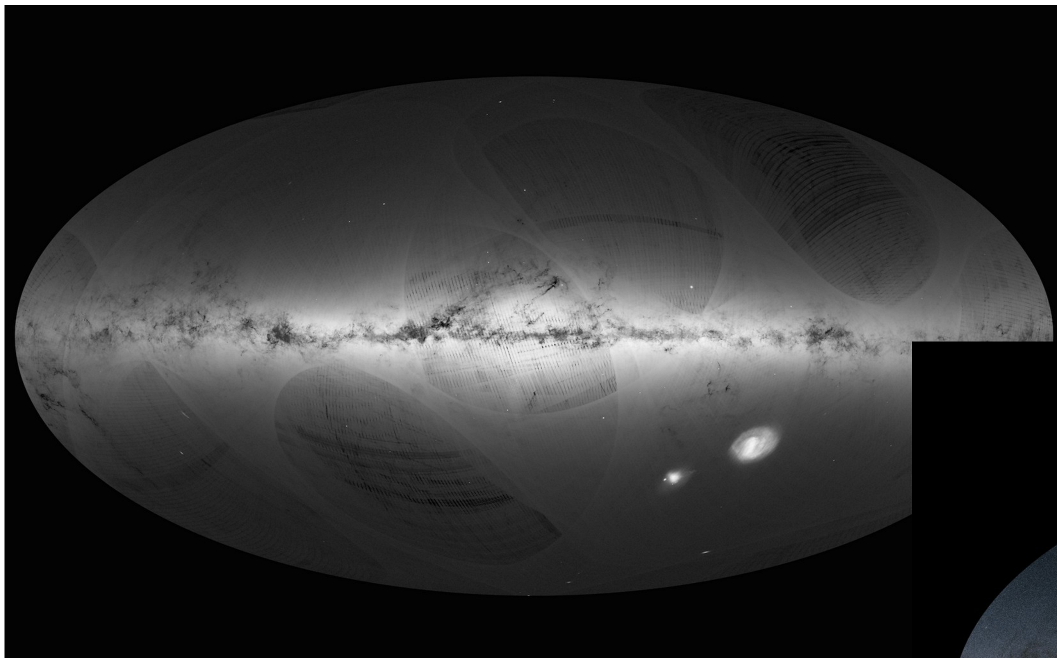
A teaspoon of catalogue



Data releases

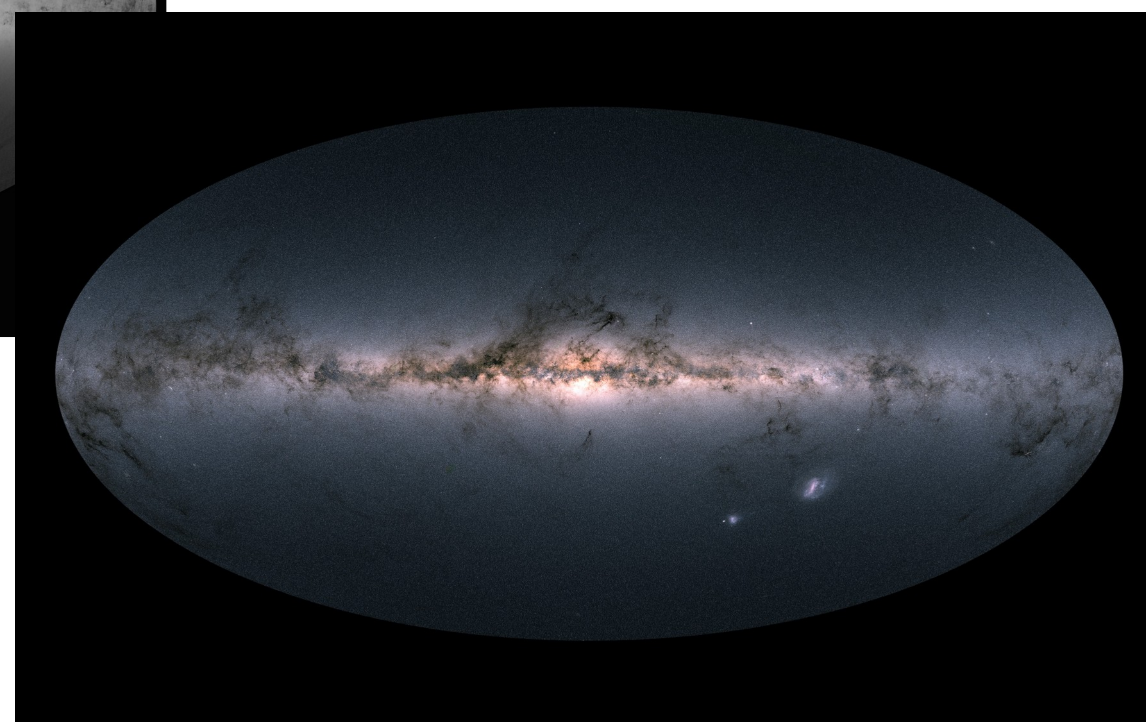
Regular data releases

- Improved accuracy / precision
- New products



Gaia DR1

14 September 2016



Gaia DR2

25 April 2018

Gaia EDR3 / DR3

Gaia Early-DR3 (3 December 2020)

- Full astrometric solution → 1.5 x 10^9 sources
- Photometry: G, G_{BP}, G_{RP} → 1.8 x 10^9 / 1.5 x 10^9 sources

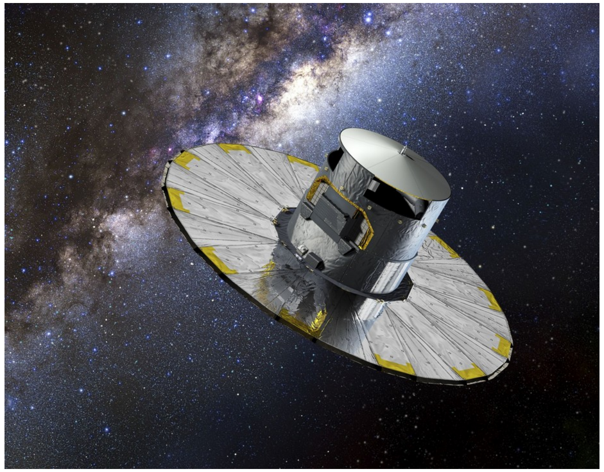
Gaia DR3

13 June 2022

Classification
- 1.6 x 10^9 sources

Asteroids
- 154 000 orbital solutions
- 60 000 reflectance spectra
- ...

Stars
- 34 x 10^6 radial velocities
- 3.5 x 10^6 broadening velocities
- 10^6 spectra
- 470 x 10^6 parameters
- 2.5 x 10^6 chemical abundances
- …



Galaxies and Quasars
- 6.4 x 10^6 QSO redshifts
- 4.8 x 10^6 galaxy candidates
- 1.4 x 10^6 galaxy redshifts
- ...

Interstellar medium
- 472 000 DIBs

Variable stars
- 10 x 10^6 classified variables
- 15 000 Cepheids
- 272 000 RR Lyrae
- ...

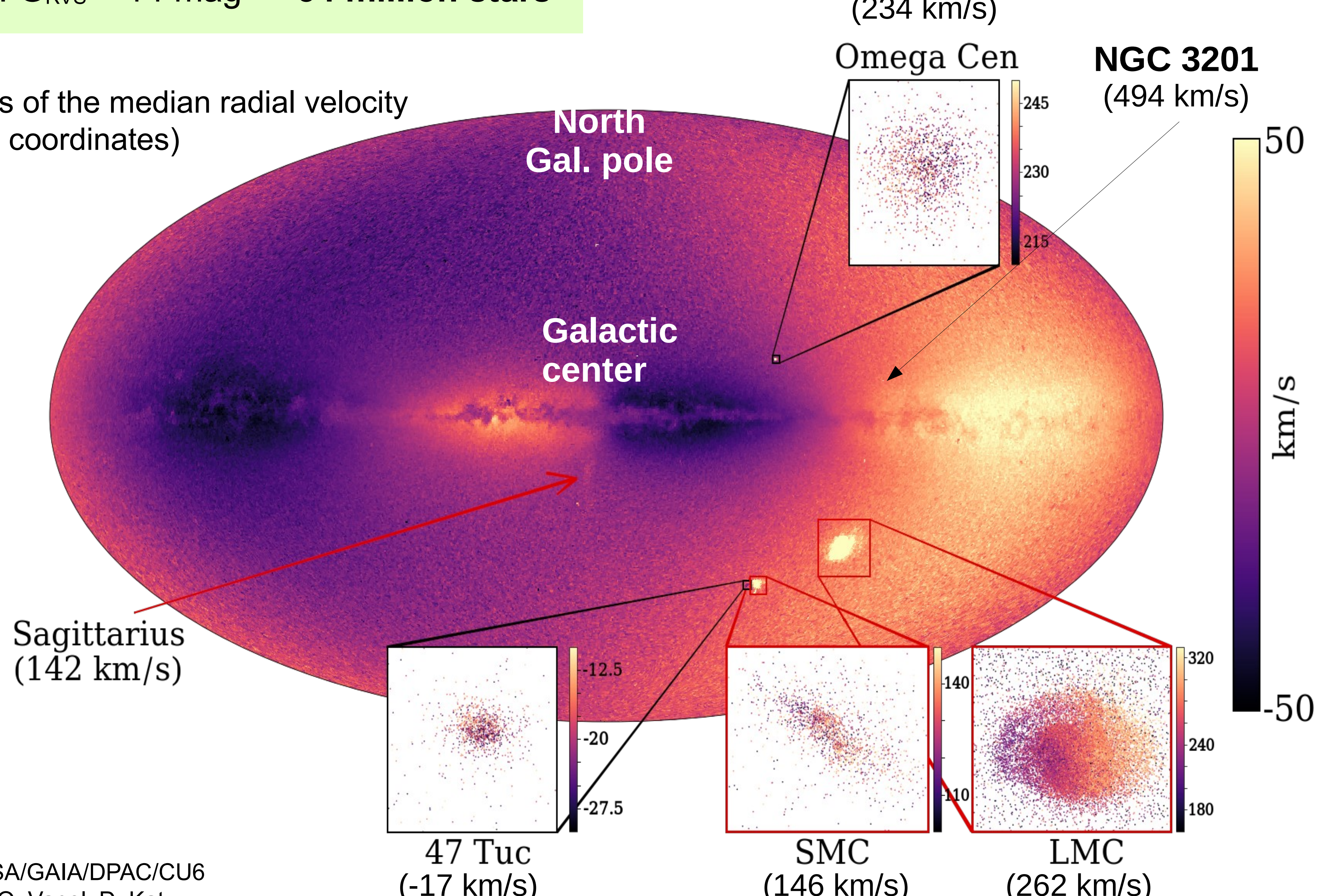
Binary stars
- 814 000 binaries
- 169 000 astrometric orbits
- 187 000 spectroscopic orbits
- …

Milky Way and local group

Radial velocities: panorama

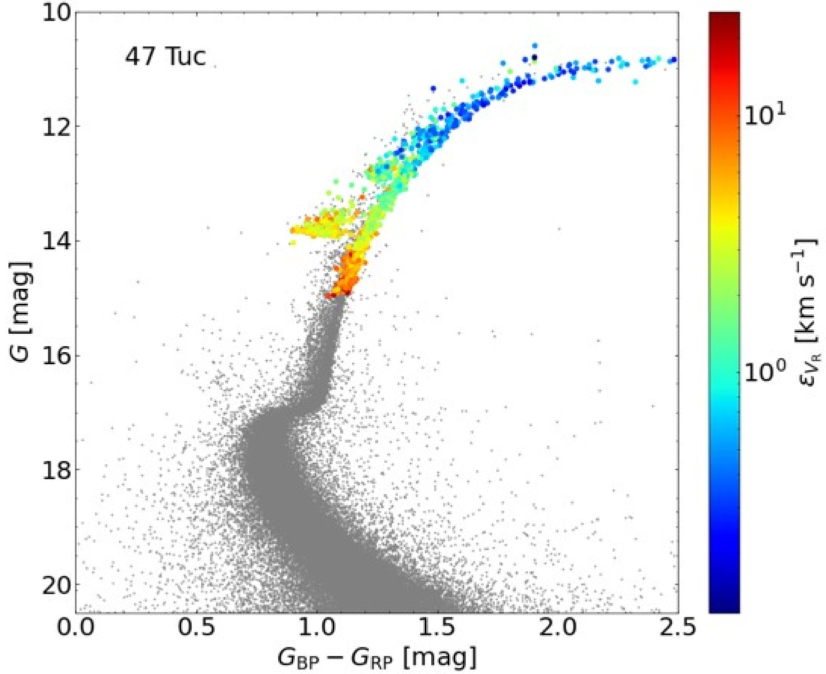
- DR2: G_{RVS} ≤ 12 mag → 7 million stars
- DR3: G_{RVS} ≤ 14 mag → **34 million stars**

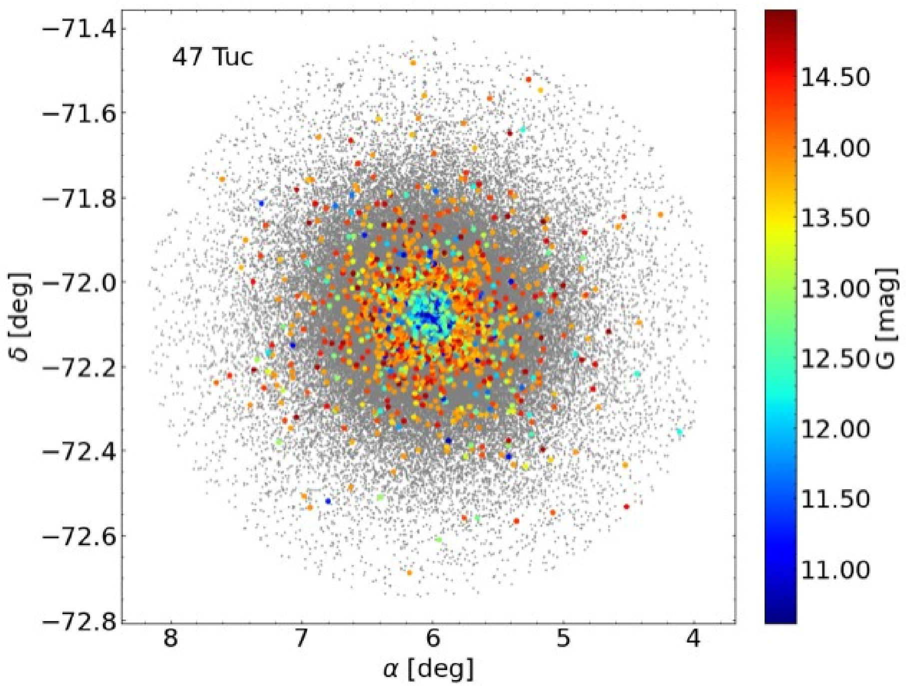
Sky maps of the median radial velocity (Galactic coordinates)



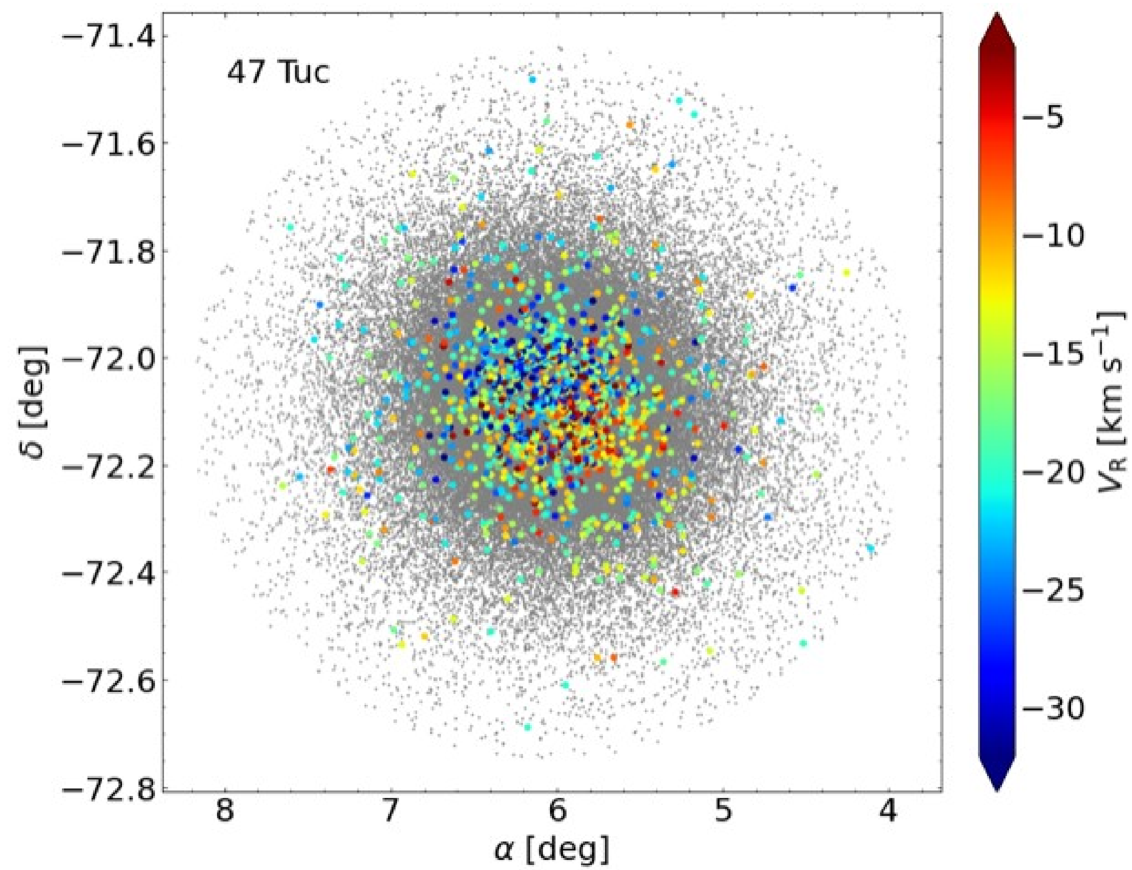
Credits: ESA/GAIA/DPAC/CU6
C. Hottier, O. Vanel, D. Katz

Radial velocities: globular clusters





- 111 Globular clusters in GDR3
- 1000 measures (47 Tuc, Omega Cen)
  → 5 measures (Terzan 5, NGC6522)



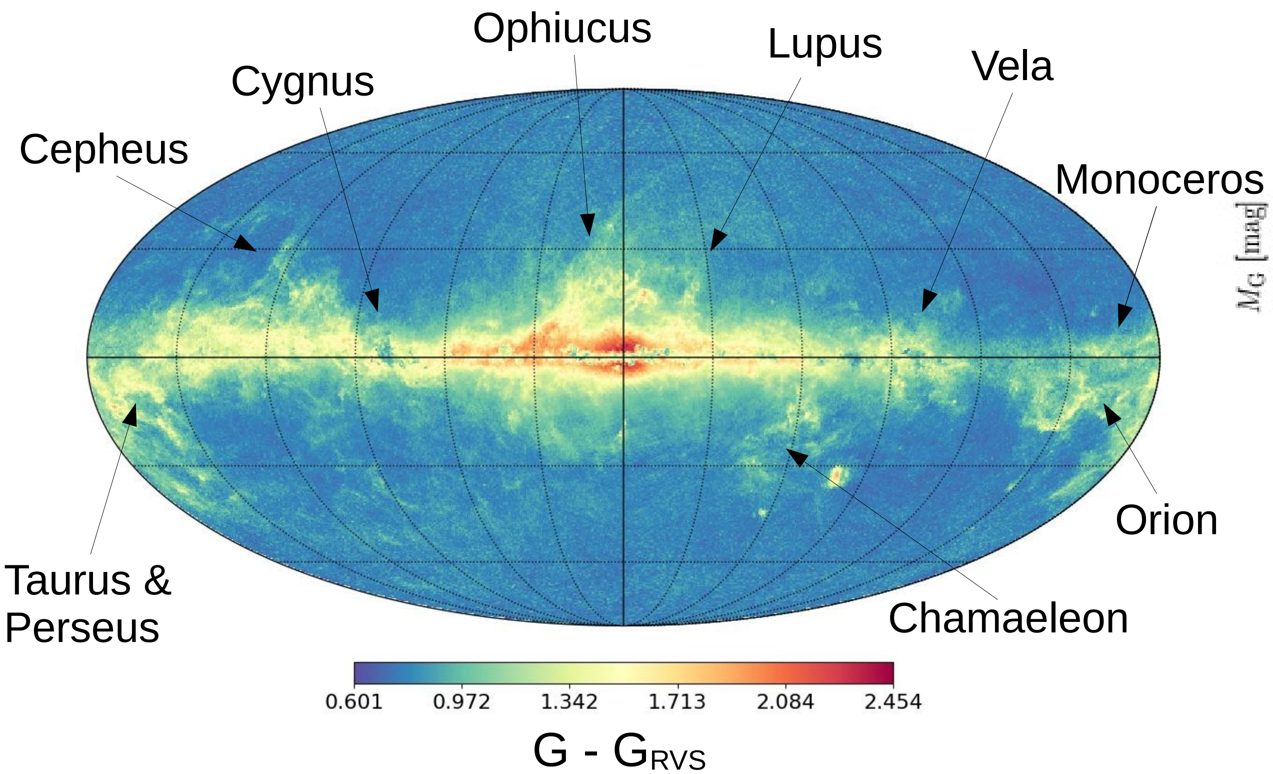
47 Tuc → line-of-sight rotational velocity

Katz, Sartoretti, Guerrier et al., 2022,
A&A, arXiv:2206.05902

32.2 million G_{RVS} magnitudes

- Narrow band: [846, 870] nm

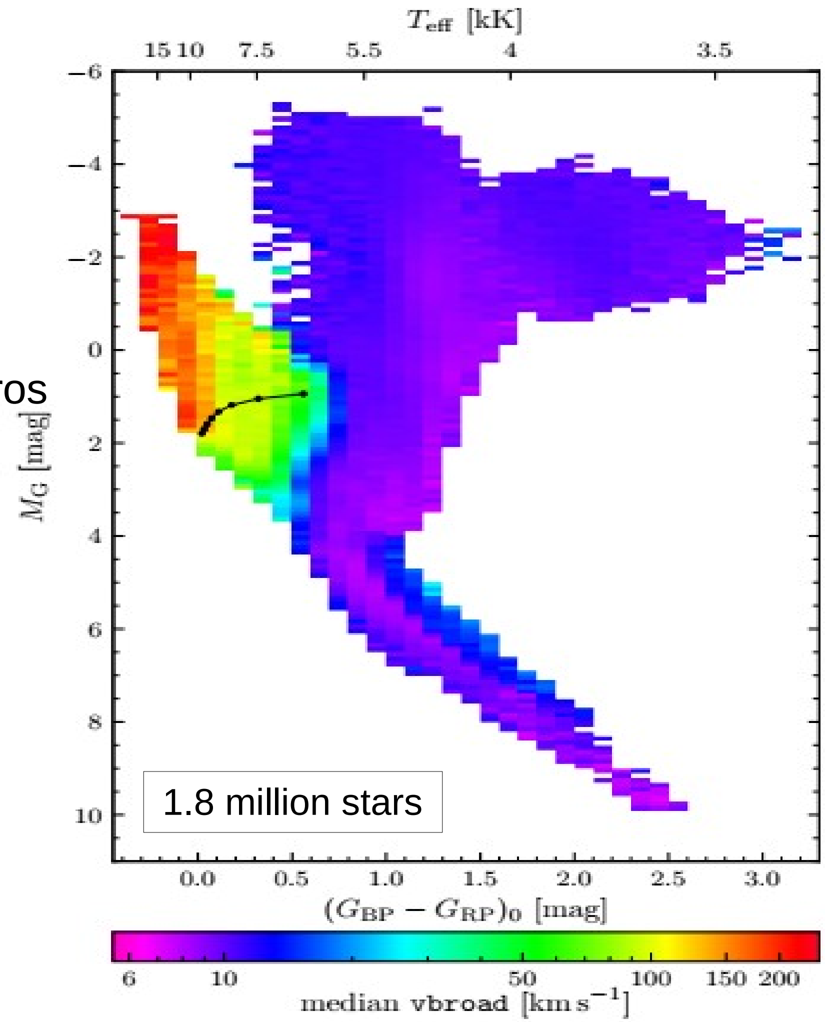
Sartoretti, Marchal, Babusiaux et al., 2022, A&A, arXiv:2206.05725



$G - G_{RVS}$ → interstellar dust

3.5 million broadening velocities

Frémat, Royer, Marchal et al., 2022, A&A, arXiv:2206.10986



Vbroad across HR diagram

Astrophysical parameters

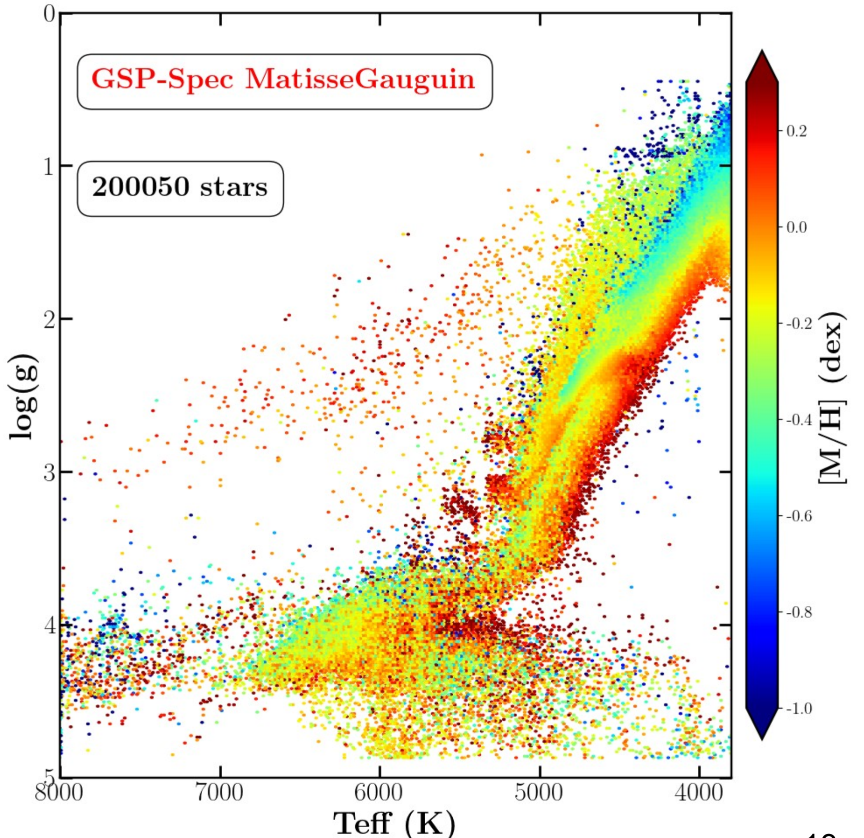
Spectro-photometer

- **Source classification**: **1.6 billions sources** → quasar, galaxy, stars, white dwarfs, binary stars
- **Atmospheric parameters**: **470 millions stars** → temperature, gravity, metallicity
- Stellar mass, radius, ages …
- Specific sources: ultra-cool dwarfs, hot stars, ...

Spectrograph (RVS)

- **Atmospheric parameters**: **5.6 million stars**
- **Individual abundances**: **12 elements** → N, Mg, Si, S, Ca, Ti, Cr, Fe, Ni, Zr, Ce and Nd
- Numerous quality flags → selection of more precise sub-sample

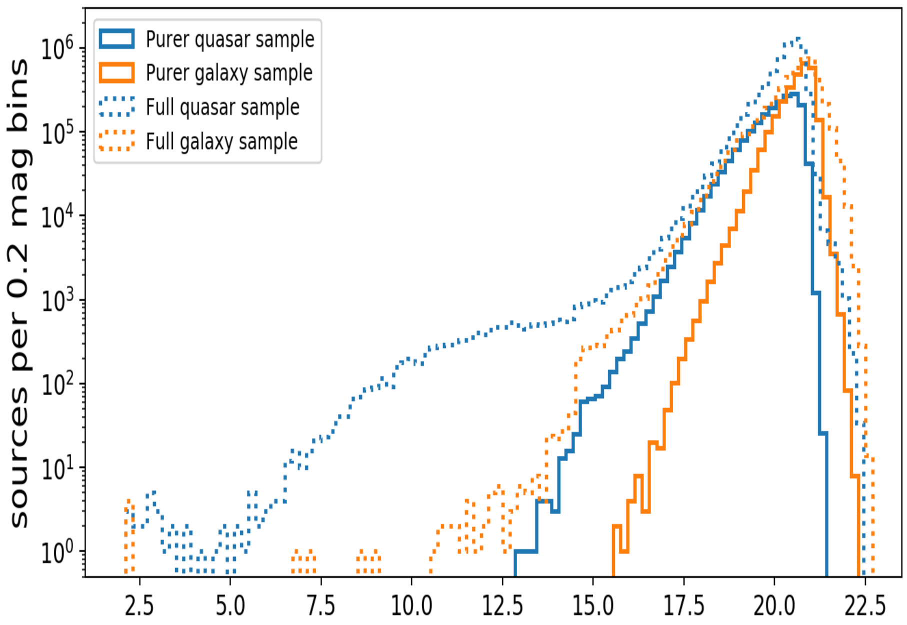
Recio-Blanco, Laverny, Palicio et al., 2022, A&A, arXiv:2206.05541



Documentation:
- Creevey, Sordo, Pailler, 2022, A&A, arXiv:2206.05864
- Fouesneau, Frémat, Andrae, A&A, arXiv: 2206.05992
- Delchambre, Bailer_Jones, Bellas-Velidis, 2022, A&A, arXiv:2206.06710
- Andrae, Fouesneau, Sordo, 2022, A&A, arXiv:2206.06138
- Lanzafame, Brugaletta, Frémat, 2022, A&A, arXiv:2206.05766
- Recio-Blanco, Laverny, Palicio et al., 2022, A&A, arXiv:2206.05541

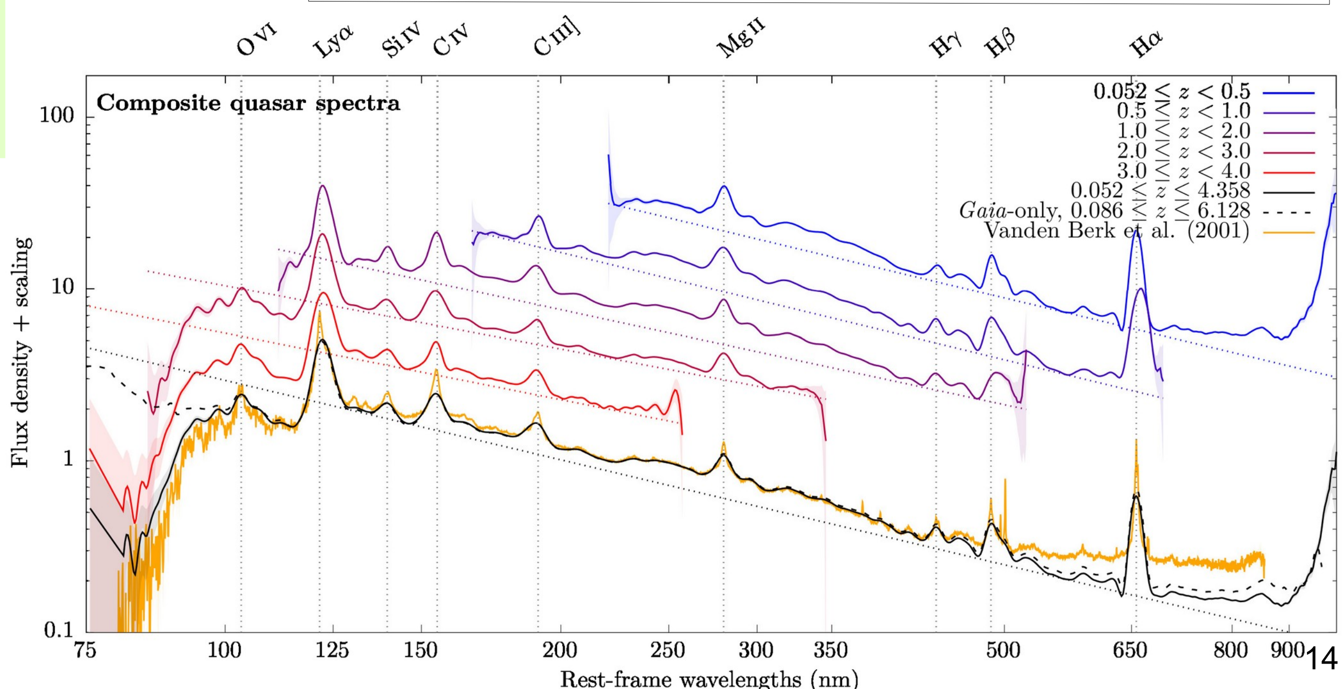
Galaxies and Quasars

- **Galaxy candidates: 4.8 millions**
- **QSO candidates: 6.6 millions**
- **Flags** → balance purity vs completeness → 2.9 millions galaxies / 1.9 millions quasars (95% purity)
- **Redshifts**: 1.4 millions (galaxies), 6.4 millions (QSO)



- **QSO host galaxy: 65 000**
- **Morphology** (Sersic index): 1 million (galaxies), 15 000 (QSO)

Gaia collaboration, Bailer-Jones et al., 2022, A&A, arXiv:2206.05681

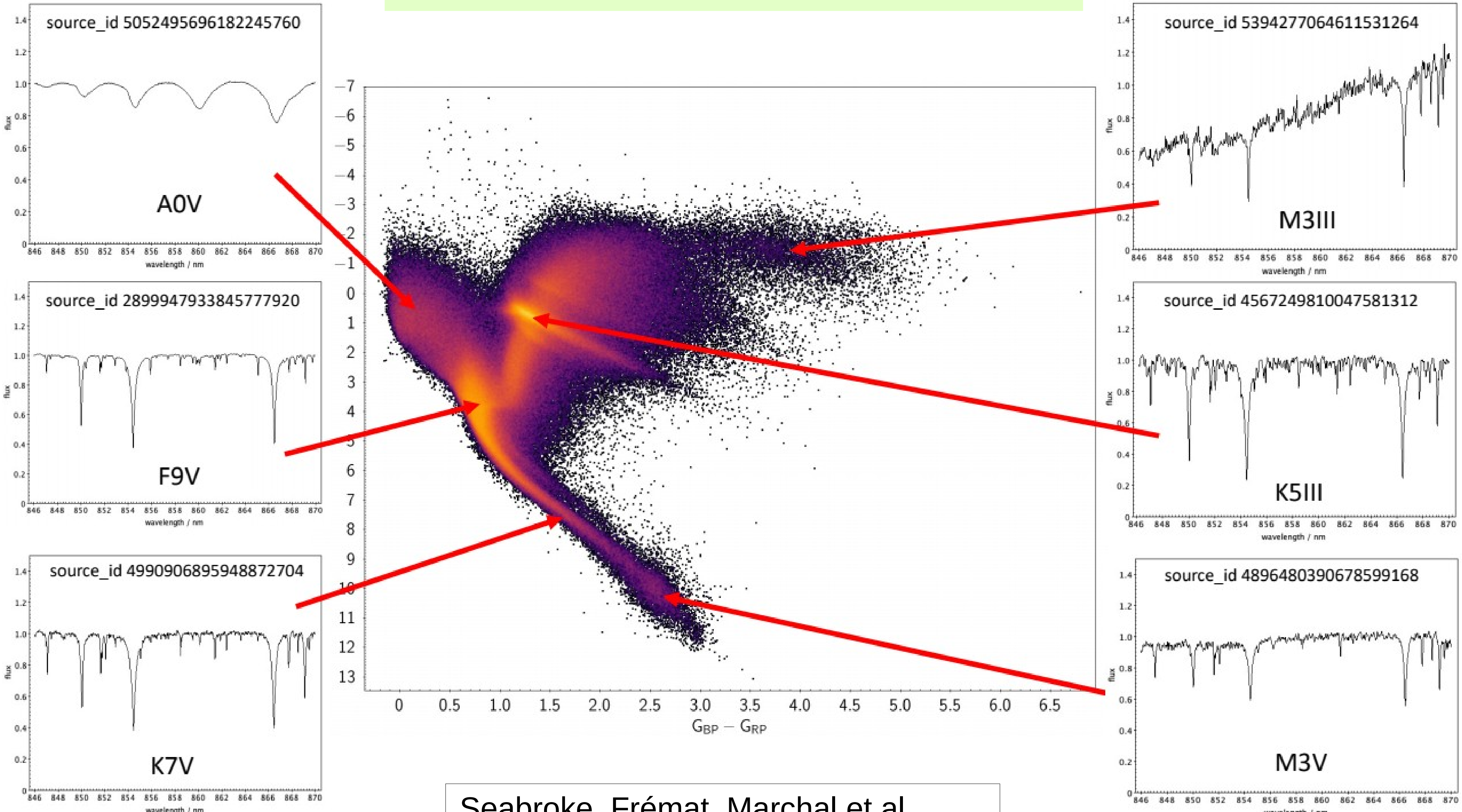


Documentation:

- Delchambre, Bailer_Jones, Bellas-Velidis, 2022, A&A, arXiv:2206.06710
- Ducourant, Krone-Martins, Gallucio, 2022, A&A, arXiv:2206.14491
- Gaia collaboration, Bailer-Jones et al., 2022, A&A, arXiv:2206.05681

Spectra

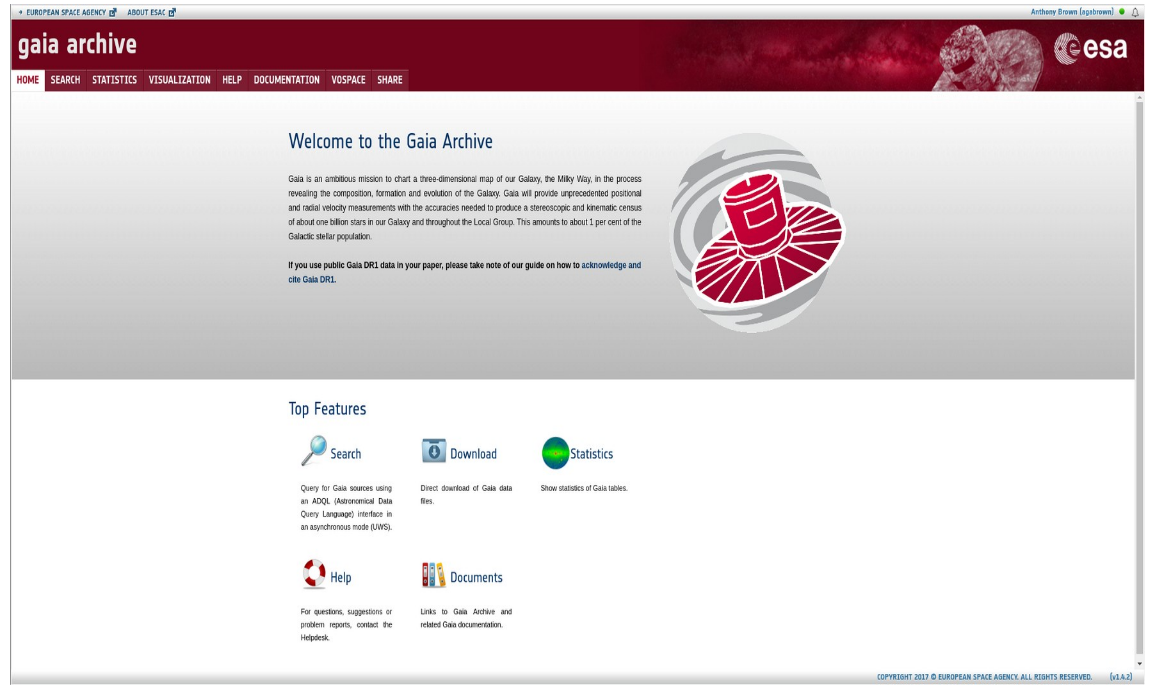
- Spectro-photometer: 220 millions spectra
- Spectrograph: 1 million spectra

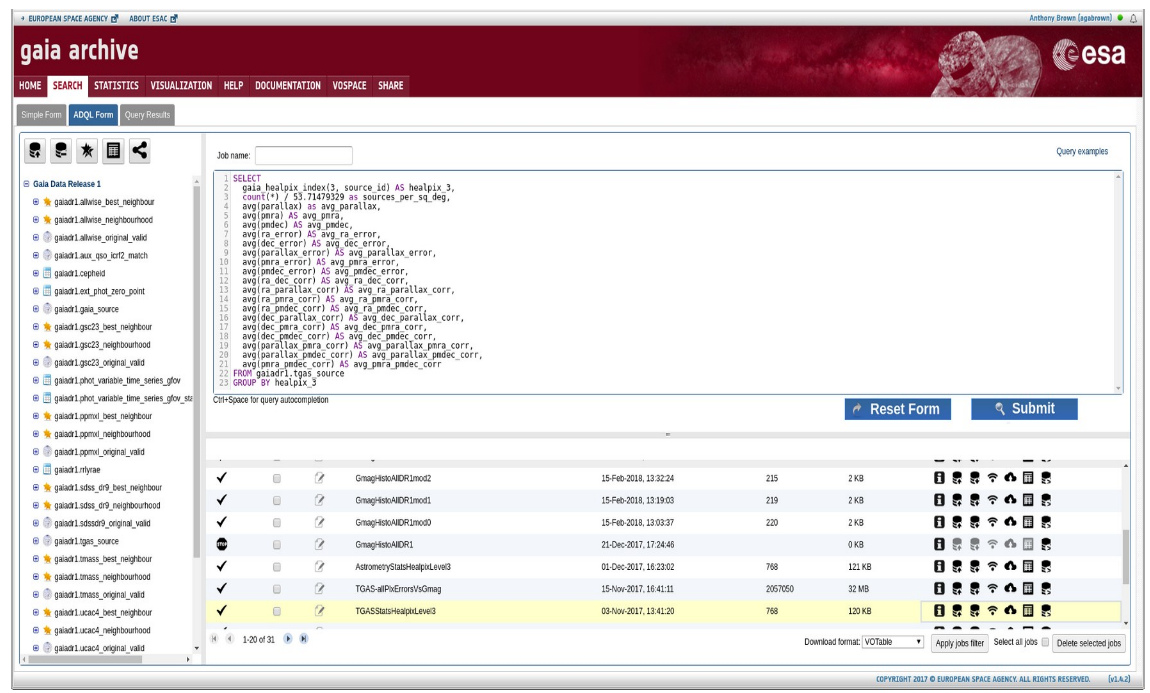


Seabroke, Frémat, Marchal et al., 2022, A&A, in prep

Data Access

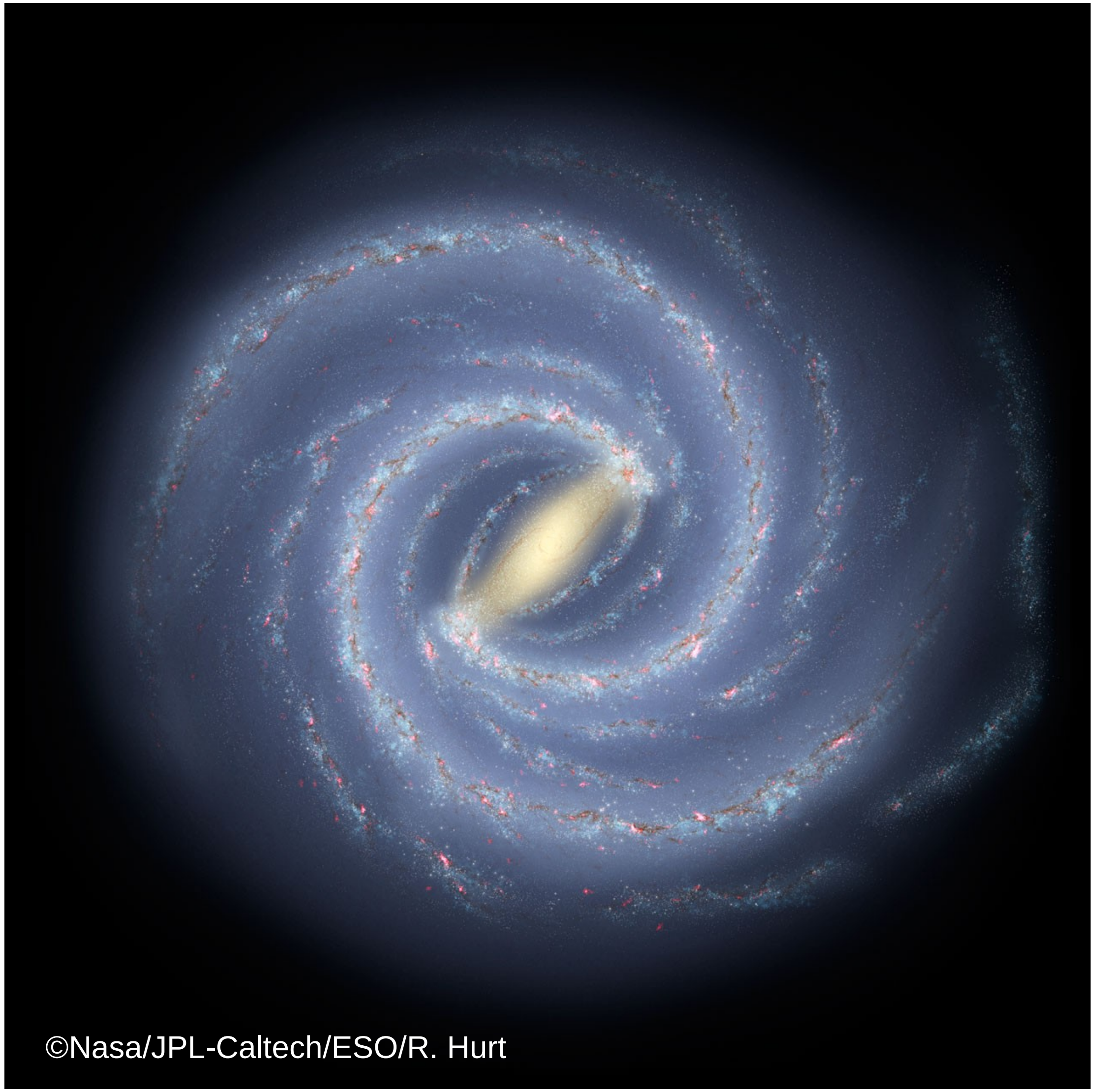
- **archives.esac.esa.int/gaia**
- https://gaia.obspm.fr/tap-server/tap
- http://cds.u-strasbg.fr/gaia
- http://gaia.ari.uni-Heidelberg.de/
- https://gaia.aip.de/
- http://gaiaportal.asdc.asi.it/



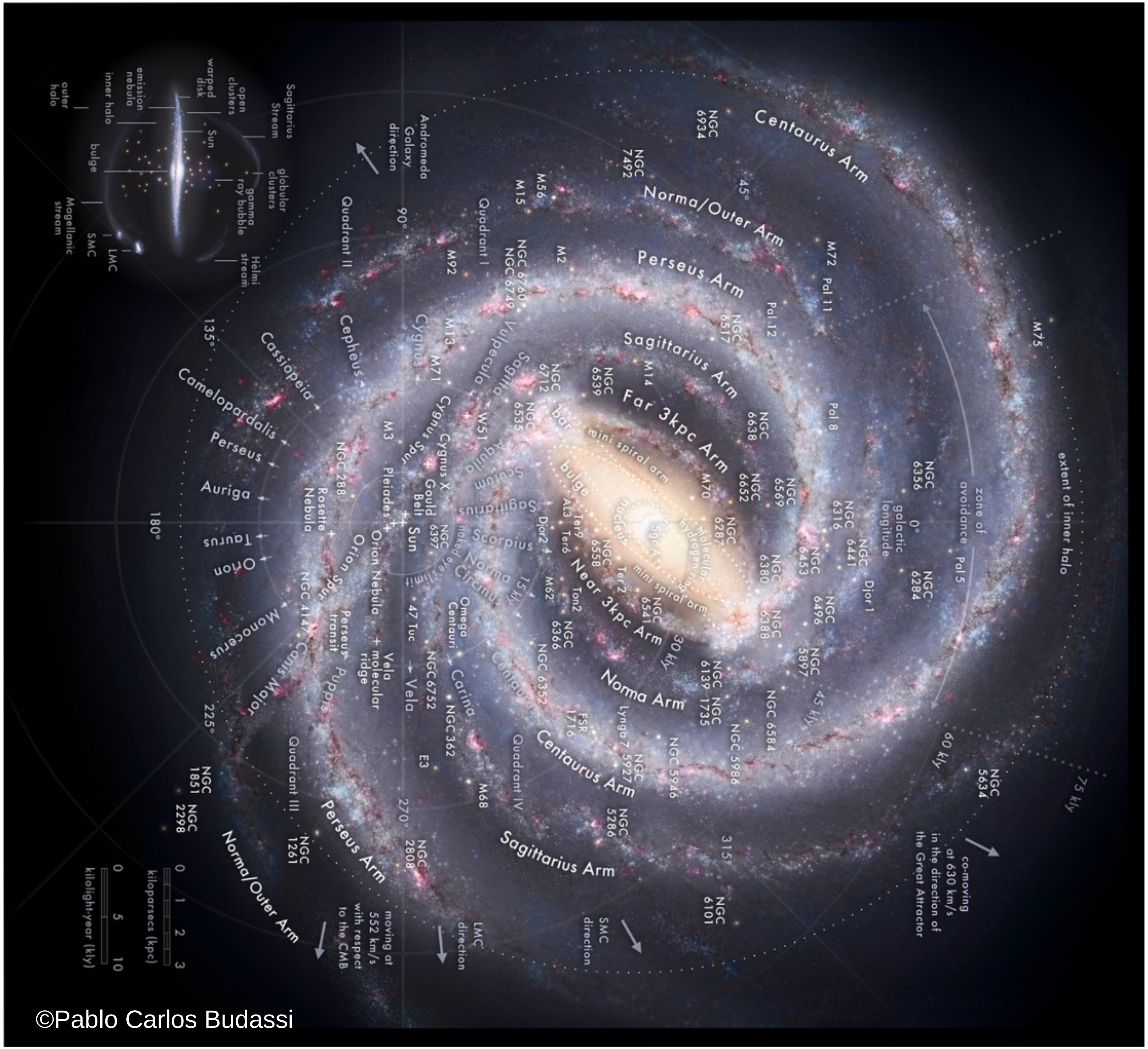


- Pre-computed X-matches to other large surveys.
- Space to upload users data.

A cup of Milky-Way



The Milky Way

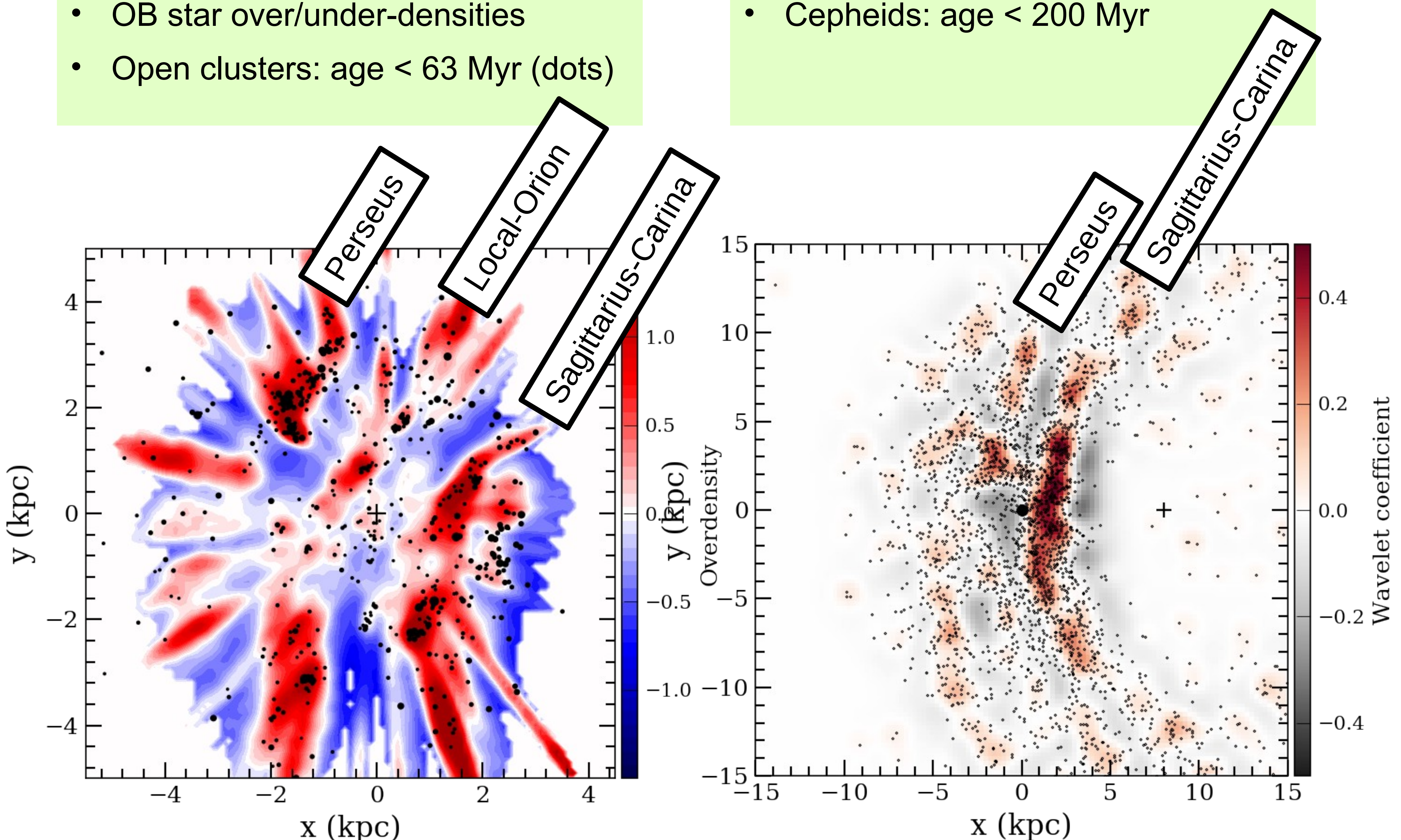


©Pablo Carlos Budassi

Spiral arms: stars

- OB star over/under-densities
- Open clusters: age < 63 Myr (dots)

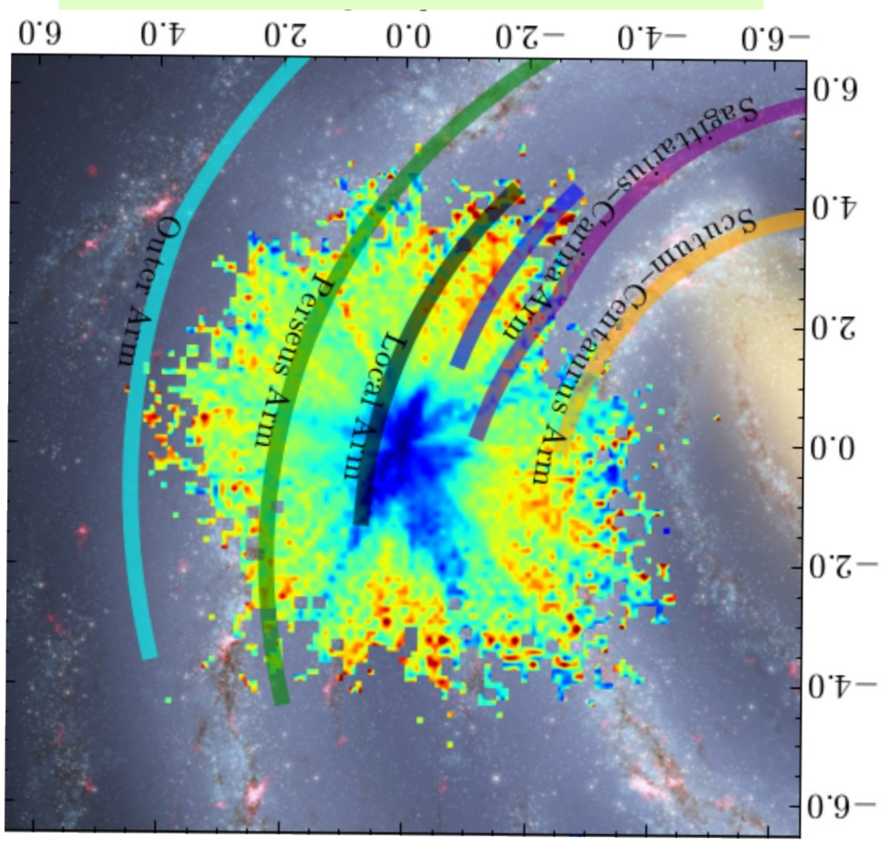
- Cepheids: age < 200 Myr



Gaia collaboration, Drimmel et al., 2022, A&A, arXiv:2206.06207

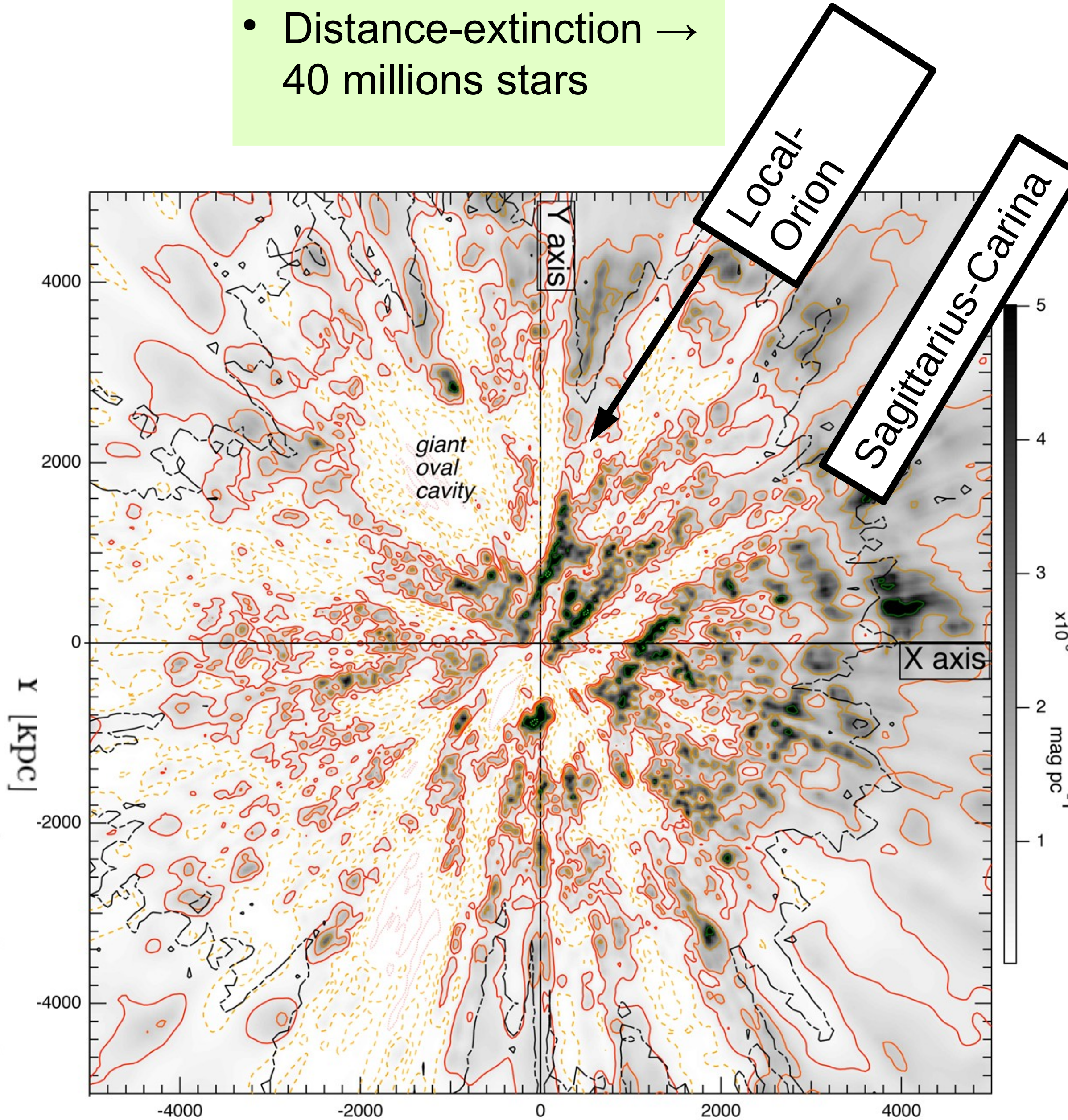
Spiral arms: gas and dust

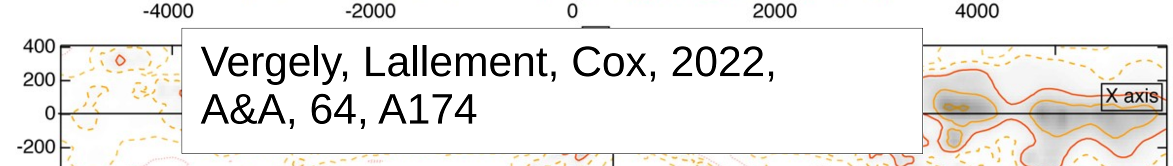
- RVS wavelength range → **Diffuse Interstellar Band** (DIB): 862 nm
- EW correlates with reddening → interstellar medium
- **472 000 stars**



Gaia collaboration, Schultheis, Zhao et al., 2022, A&A, arXiv:2206.05536

- Distance-extinction → 40 millions stars

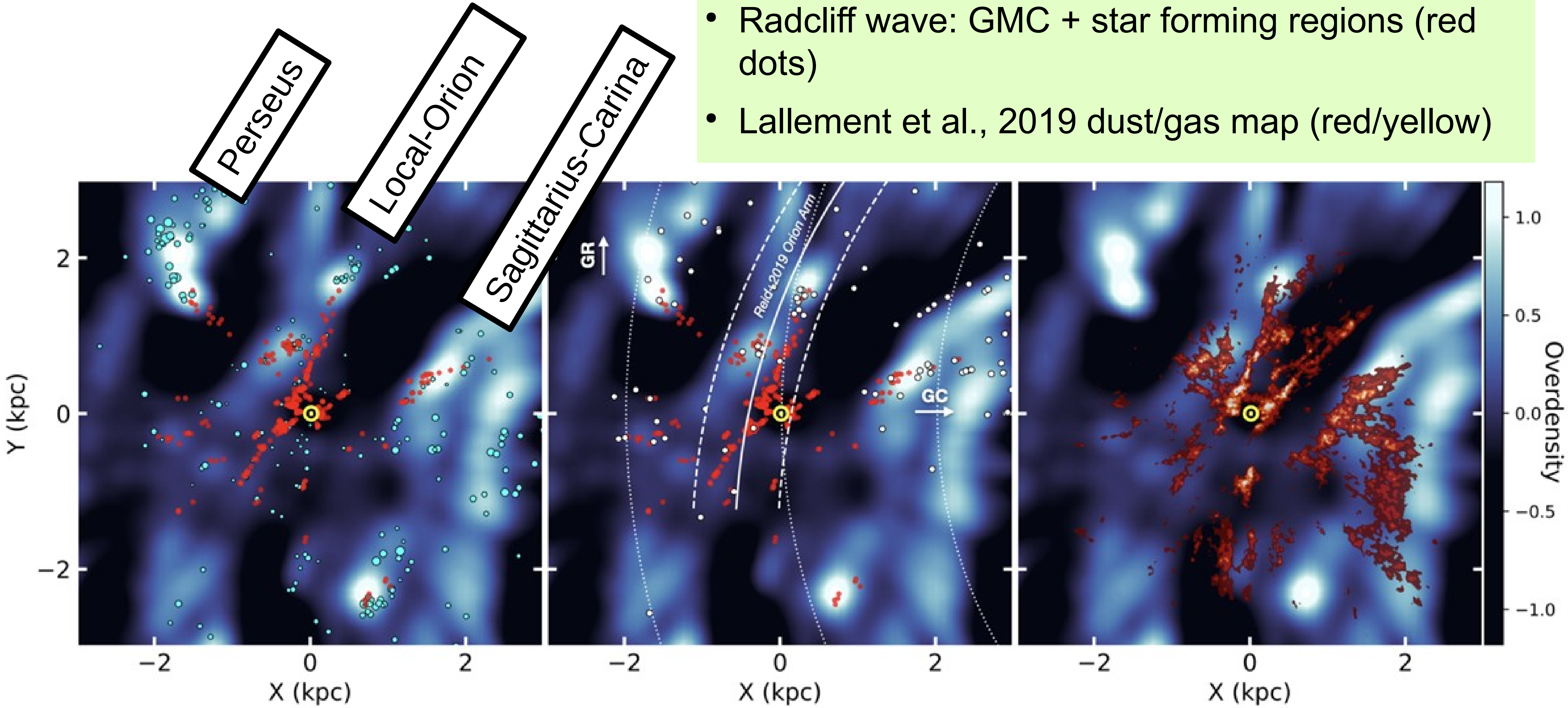




Vergely, Lallement, Cox, 2022, A&A, 64, A174

Spiral arms: physics

- OBA stars (black/blue/white)
- Open clusters: age < 30 Myr (cyan dots)
- Radcliff wave: GMC + star forming regions (red dots)
- Lallement et al., 2019 dust/gas map (red/yellow)



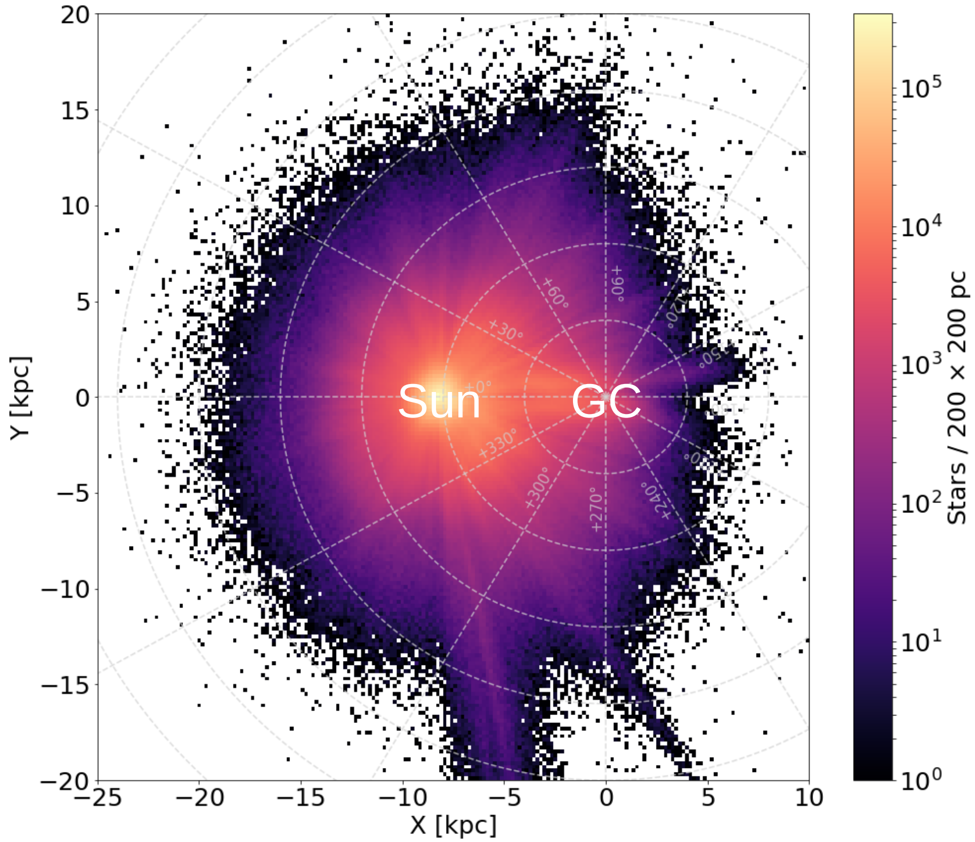
Swiggum, Alves, D'Onghia et al. 2022, A&A, 664, L13

- Gas/dust/star forming regions
  - → front of the Local-Orion arm
  - → offset between stellar generations

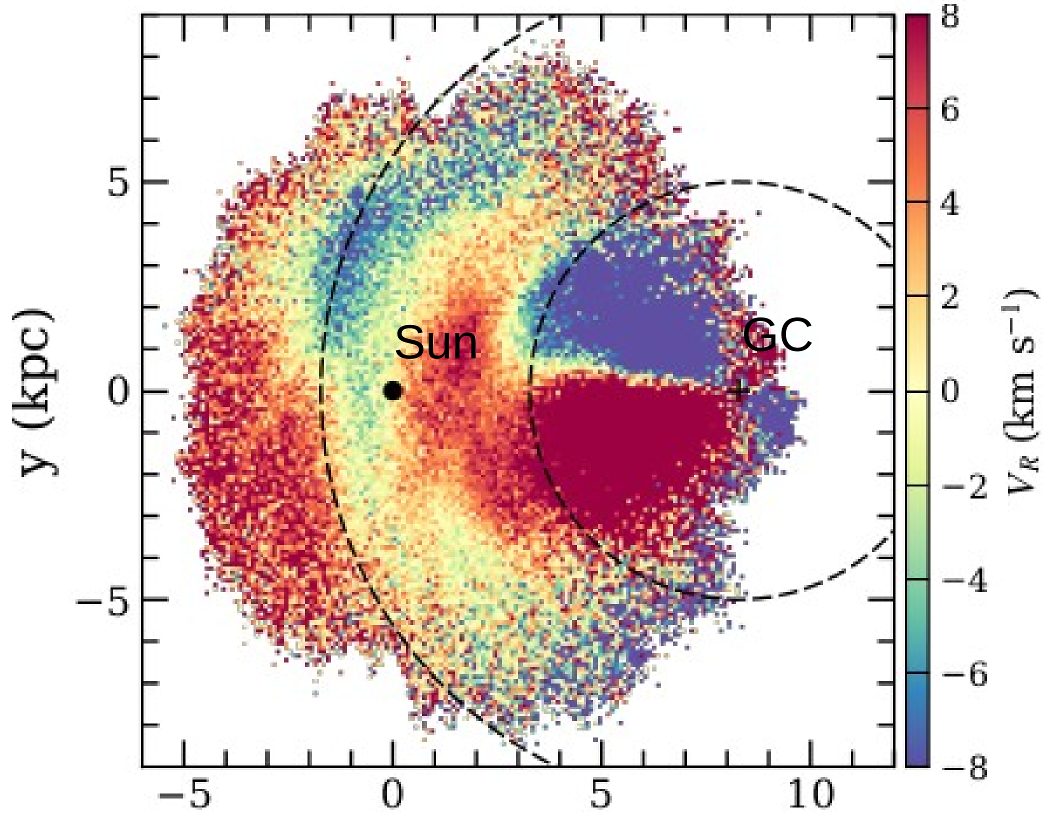
Disc and bar kinematic

- 6D parameters → 29 million stars
- 1/3 to 1/2 of the MW disc

- MW "seen" from the Galactic north pole
- Milky Way rotates clockwise



Katz, Sartoretti, Guerrier et al., 2022, A&A, arXiv:2206.05902



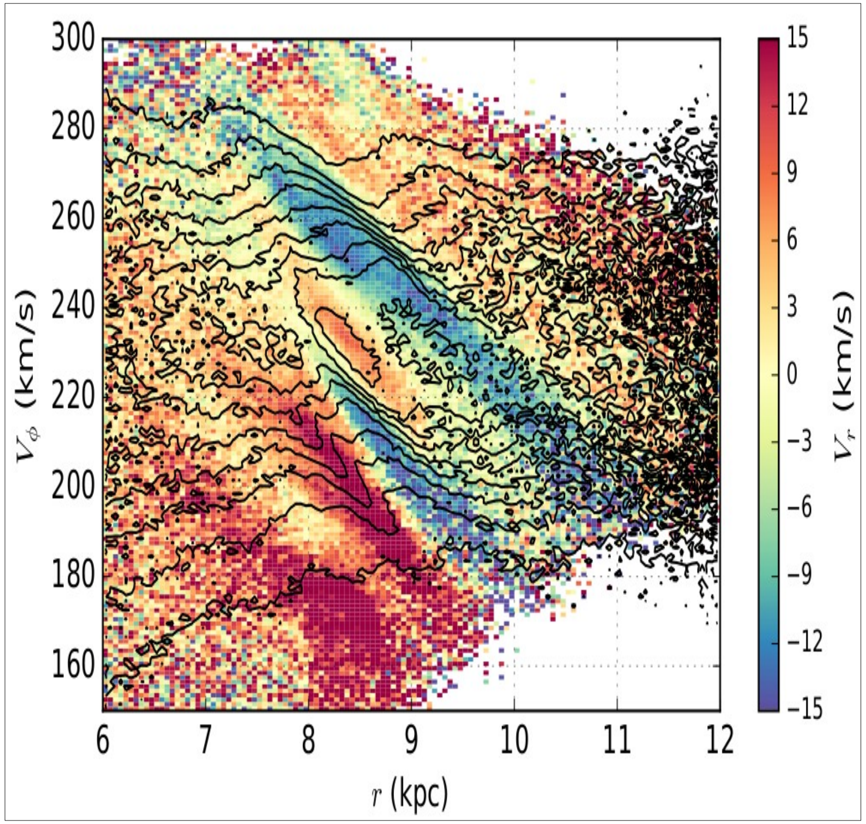
- Radial motion wrt. Galactic centre → red outward / blue inward
- Disc velocity field → perturbations
- Kinematic signature of the bar

Gaia collaboration, Drimmel, et al., 2022, A&A, arXiv:2206.06207

Disc phase space

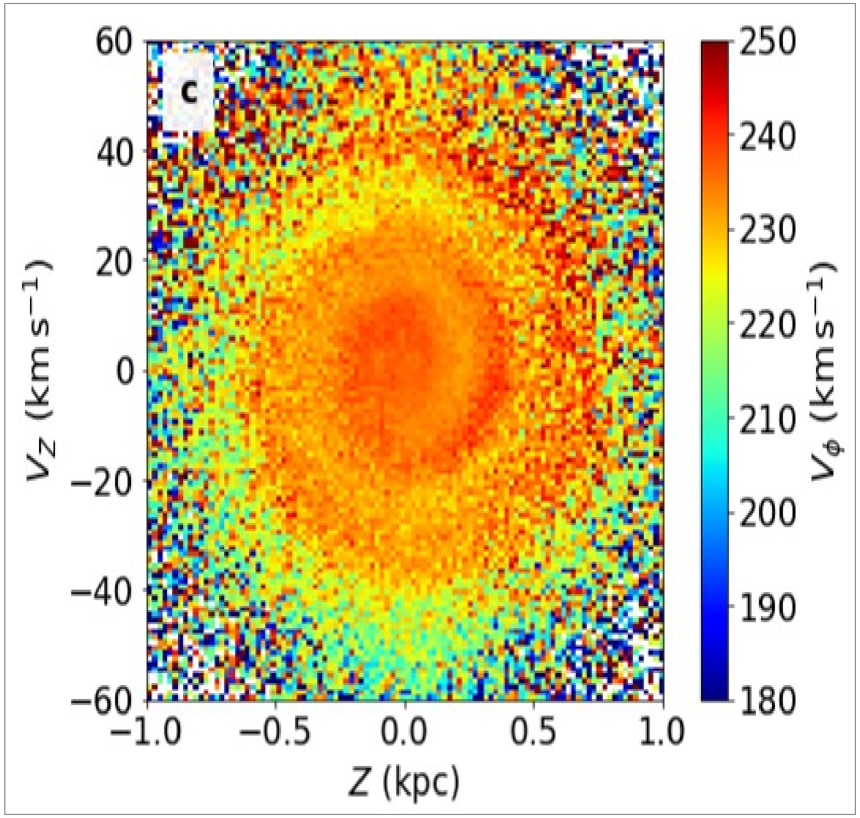
- GDR2 has revealed many perturbation/correlation in phase-space

- Ridges in (R, Vphi) space
- Correlation with R, Vr, Vphi



Fragkoudi, Katz, Trick et al., 2019, MNRAS, 488, 3324

- Spiral in (Z, Vz) space
- Correlation Z, Vz, Vphi



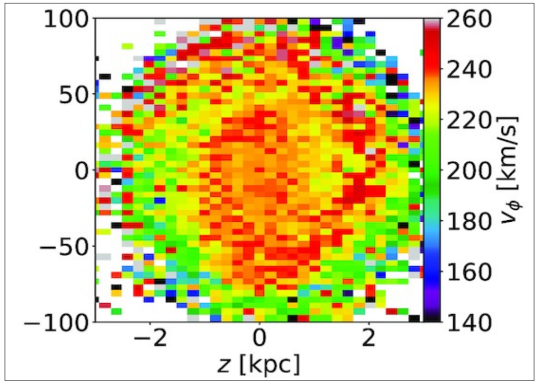
Antoja, Helmi, Romero-Gomez et al., 2018, Nature, 561, 360

Dynamics of the disc

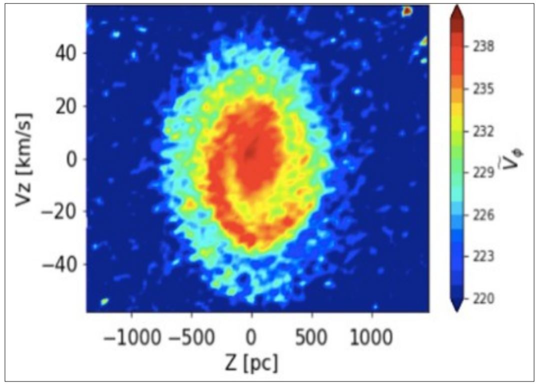
- **Bar and spiral arms** → many features of the velocity field and phase/actions spaces
  - ➢ **Spiral arms**: Quillen et al., 2018 ; Hunt et al., 2018 ; Khana et al., 2019 ; Sellwood et al., 2019 ; ...
  - ➢ **Bar**: Fragkoudi et al., 2019; Monari et al., 2019 ; Trick et al., 2019 ; ...
  - ➢ **Bar + spiral arms**: Hunt et al., 2019 ; ...
  - ➢ Bar length and pattern speed ?
  - ➢ Spiral arms: Transient ? Material ? Quasi-steady density waves ?

- **Satellite → Sagittarius**
  - **Arch-like structures in (Vr, Vphi)**: Minchev et al., ; ...
  - **(Z, Vz) spiral**: Antoja et al., 2018 ; Binney & Schönrich, 2018 ; Laporte et al., 2019 ; Bland-Hawthorn et al., 2018 ; ...

- **Bar buckling**:
  - **(Z, Vz) spiral**: Khoperskov et al., 2019



N-body simu
Sagittarius
Laporte et al., 2019

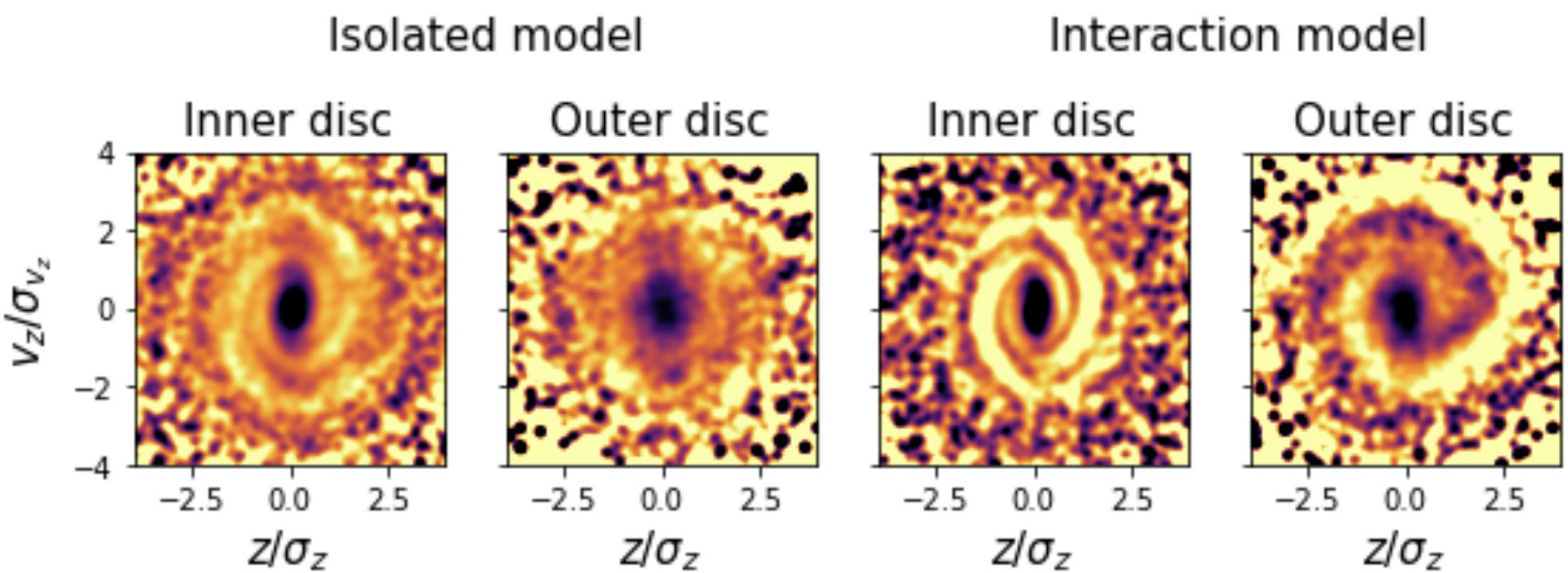


N-body simu
Bar buckling
Khoperskov et al., 2019

Recent development

- Inner disk → 2 arms spiral
- Outer disk → 1 arm spiral

- Bar / spiral arms → 2 arms
- + satellite → 1 arm (outer disc)

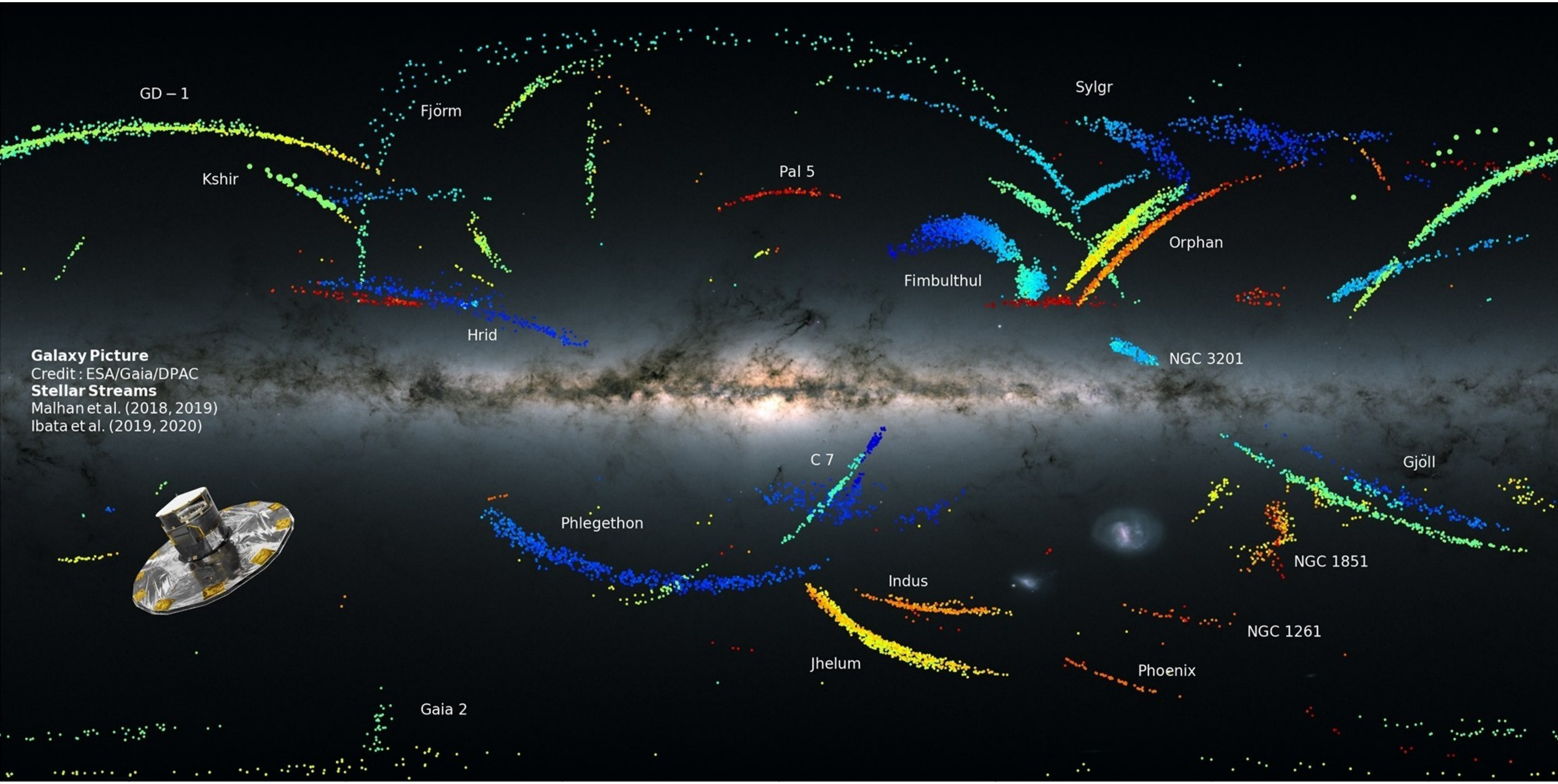


Hunt, Price-Whelan, Johnston, Darragh-Ford, 2022, MNRAS, arXiv:2206.06125

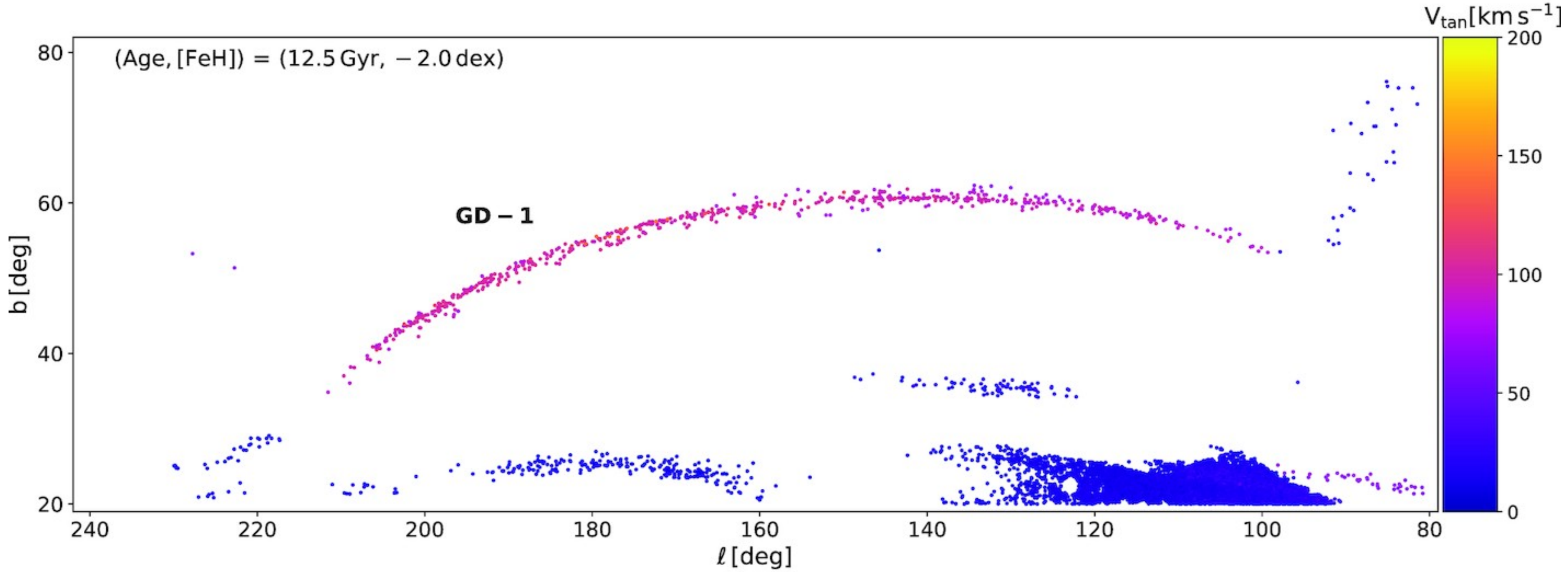
Halo streams

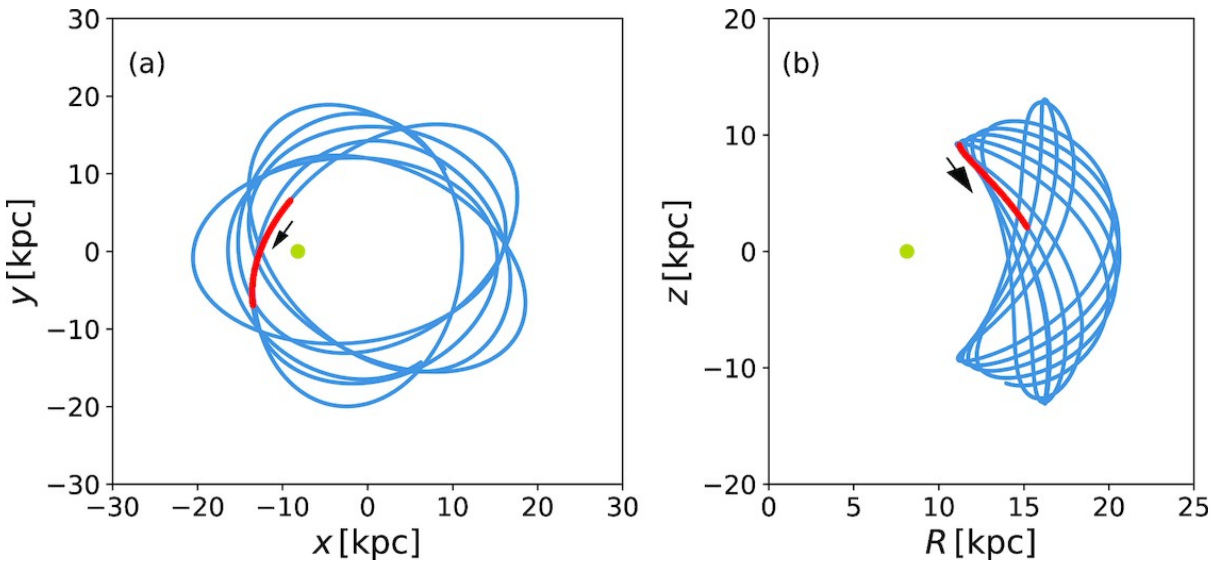
- Discovery and/or caracterisation of many (cold) streams

→ coherent spatial/kinematical structure over wide portions of the sky



Halo streams





- Probes of the gravitational potential, dark matter content, halo axis ratio

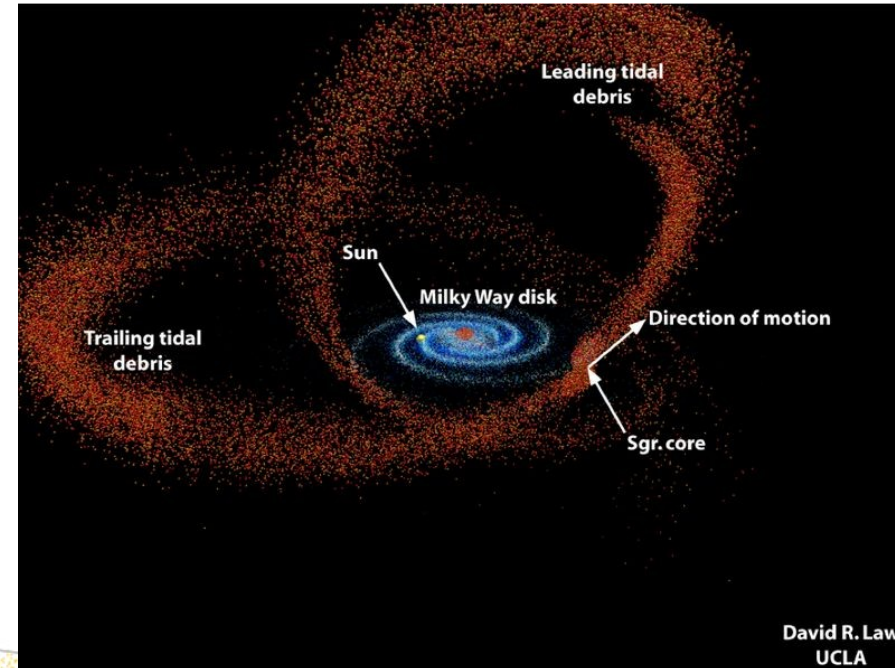
- Malhan, Ibata, 2019, MNRAS,486, 2995
  M_{MW}(R<20kpc) = 2.5 10^{11} Msun

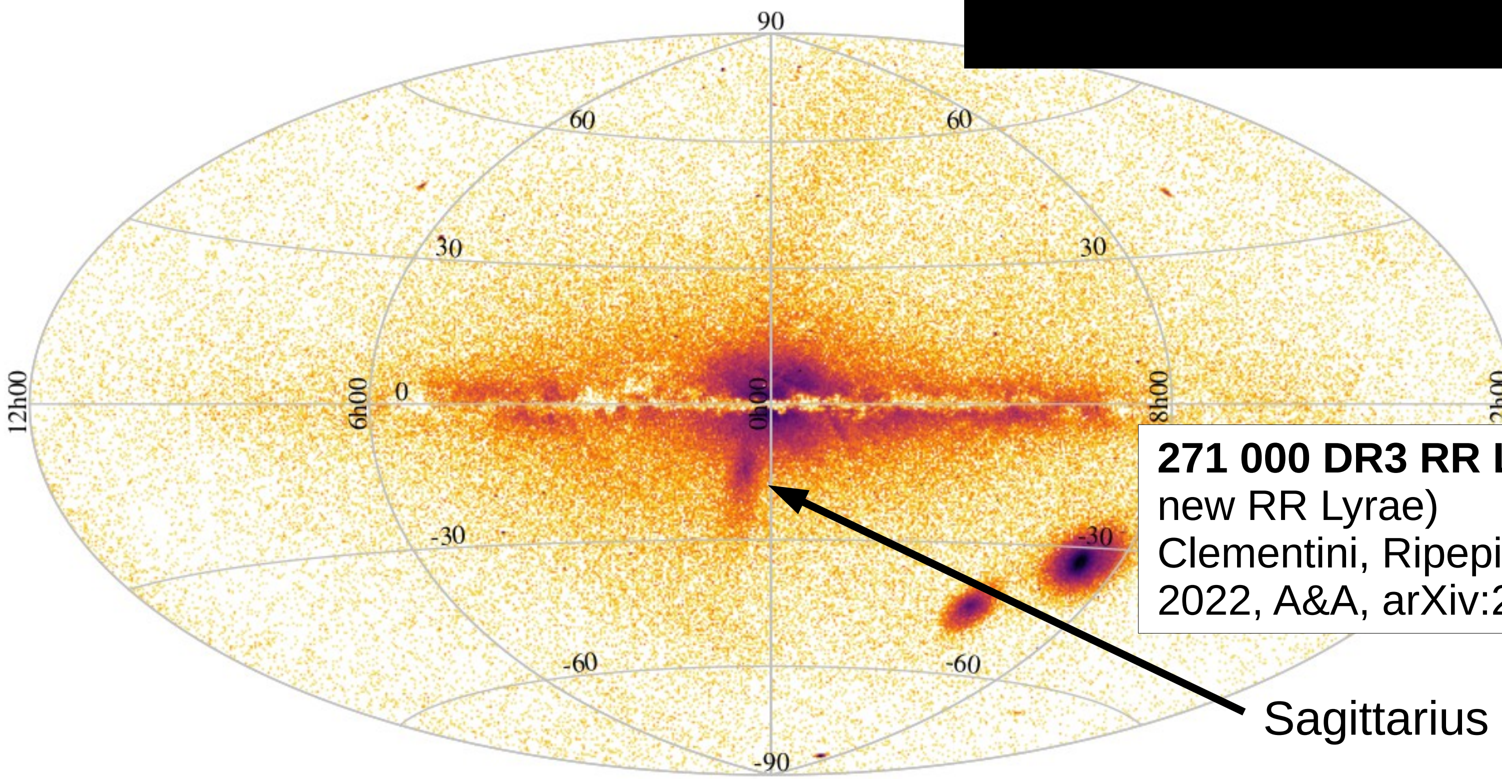
- Probes of the halo clumpiness → presence of dark matter sub-halo

Halo assembly

- Cosmological simulations → hierarchical structure formation
- MW/halo assembly → mergers

- Sagittarius galaxy → accretion in progress
- Many past accretion → disolved into the halo





271 000 DR3 RR Lyrae (incl 71 000 new RR Lyrae)
Clementini, Ripepi, Garofalo et al., 2022, A&A, arXiv:2206.06278

The pre-Gaia halo ... in 1 slide

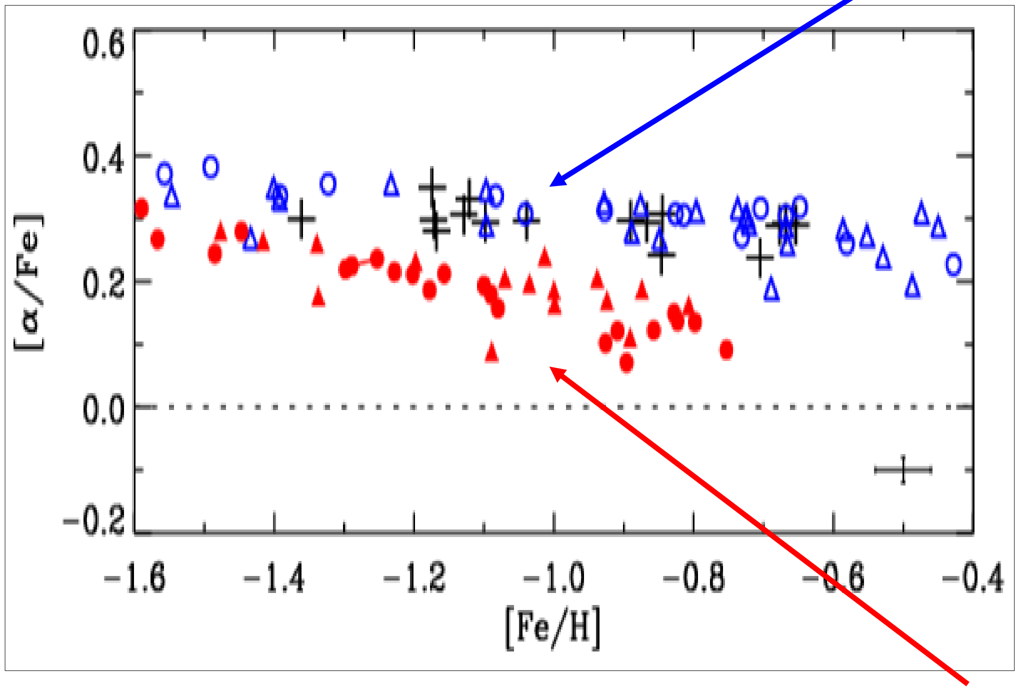
Last decade

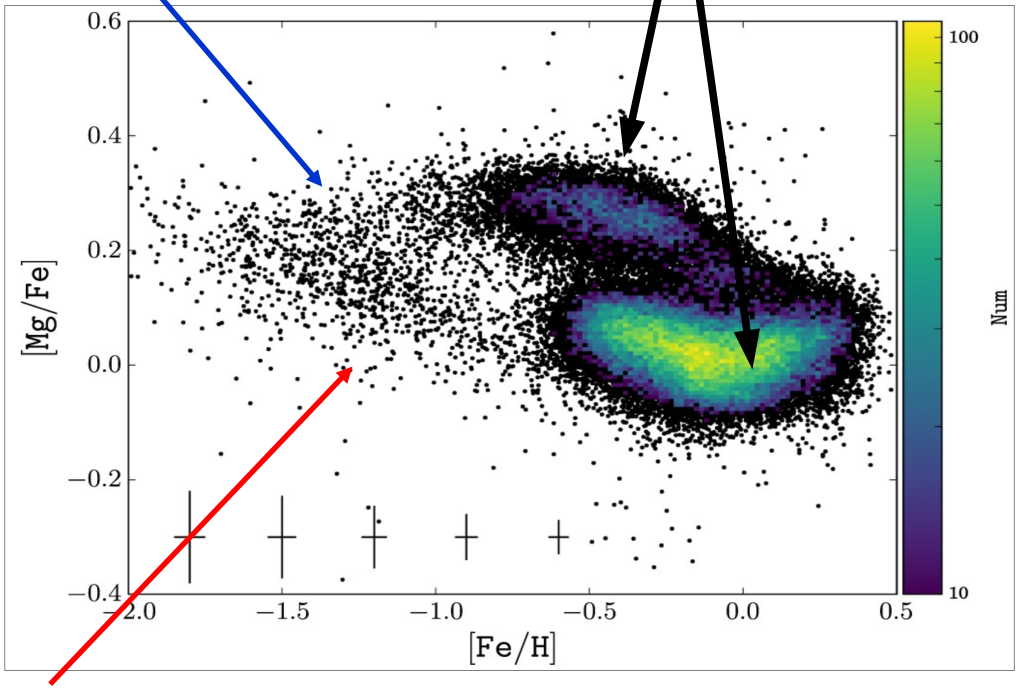
- Chemical abundances → evidence of two distinct halo populations: in-situ / accreted

Halo

in-situ

Disc





Nissen & Schuster, 2010, A&A, 511, 10

accreted

Hayes, Majewski, Shetrone et al., 2018, ApJ, 852, 49

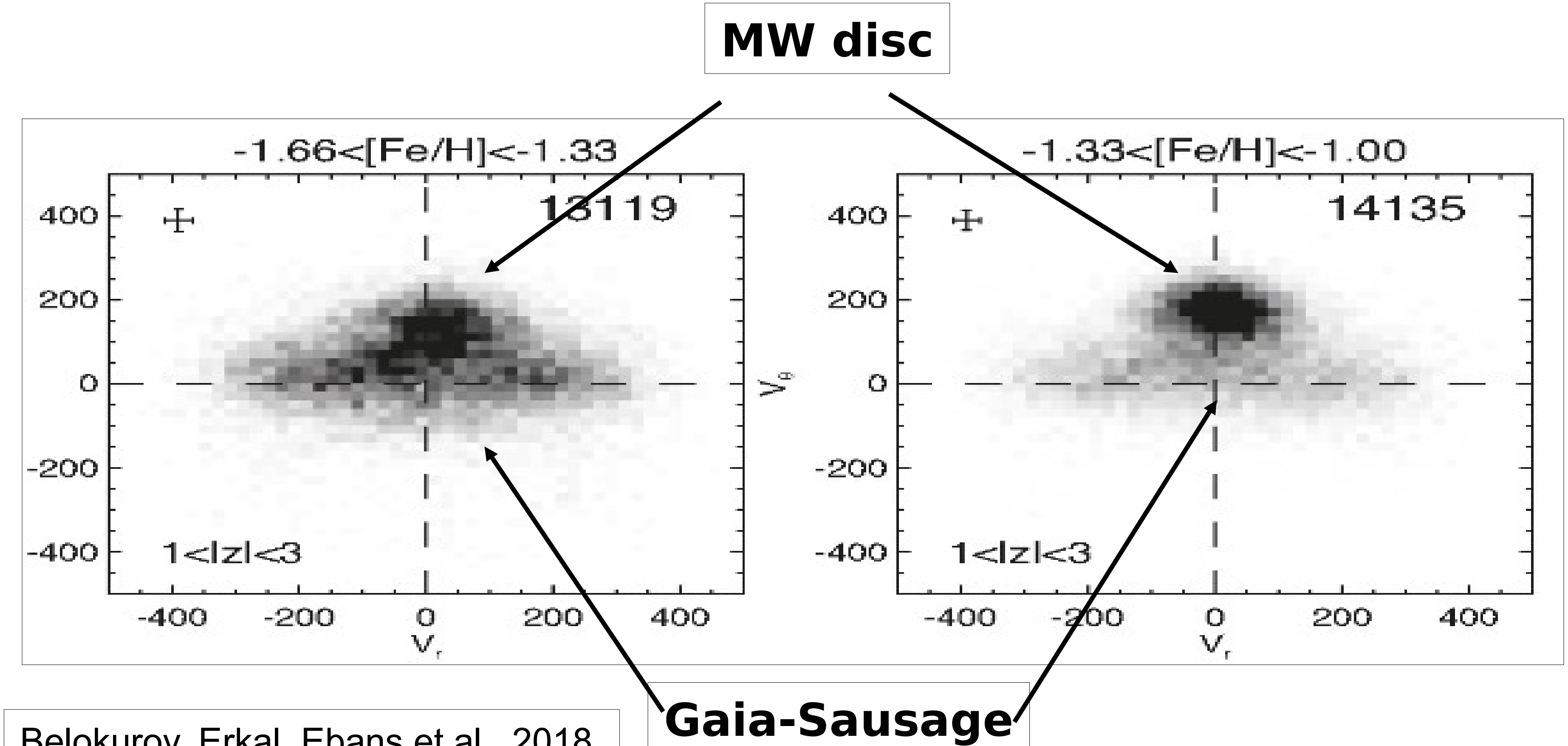
The Gaia-DR1 halo ... in 1 slide

Gaia DR1: Belokurov et al., 2018

- From (V_R, V_Φ) anisotropy vs [Fe/H]

→ **1 major accretion event**: **Gaia-Sausage**

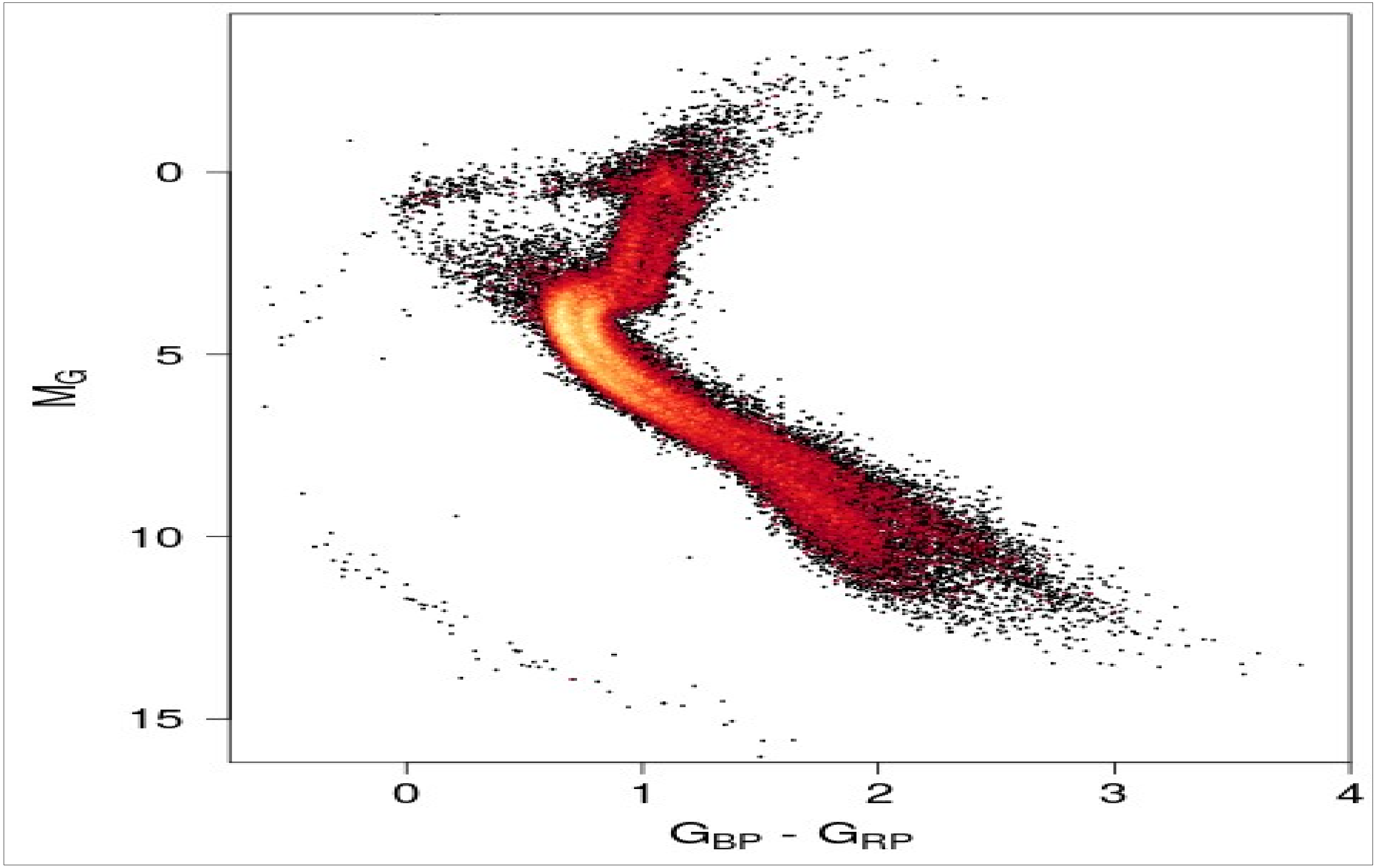
- Mvir > 10^{10} Msun
- 8 – 11 Gyr ago



Belokurov, Erkal, Ebans et al., 2018, MNRAS, 477, 1472

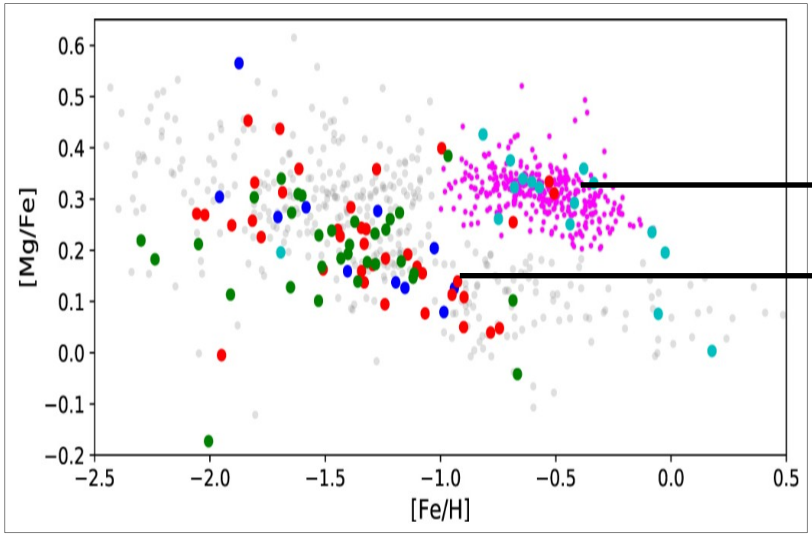
Major accretion event in Gaia-DR2

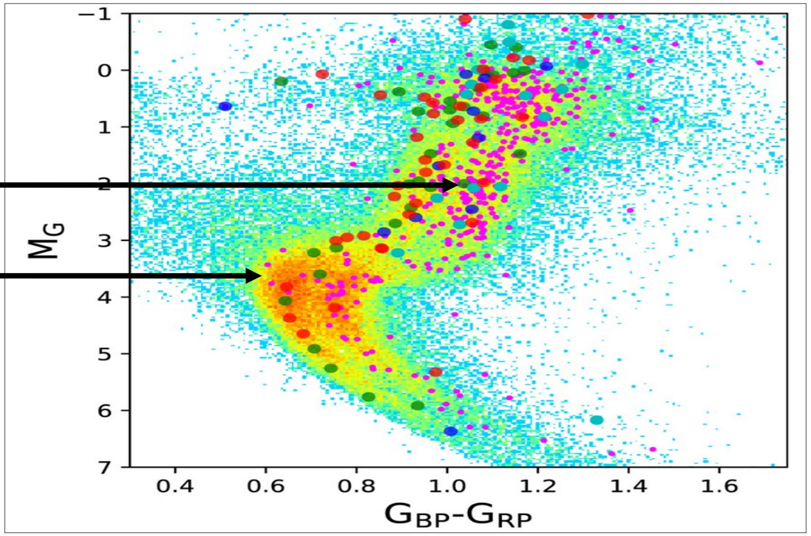
- Double sequence in HRD of high transverse velocity stars



Gaia collaboration, Babusiaux et al., 2018, 616, 10

Major accretion event in Gaia-DR2





Haywood, Di Matteo, Lehnert et al., 2018, ApJ, 863, 113

Haywood et al., 2018

- Bluest sequence → accreted stars: 1 main accretion event
- Reddest sequence → thick disk partially "heated" dur. merger
- Halo in-situ component elusive

Helmi et al., 2018

- Similar conclusions → accreted satellite: **Gaia-Enceladus**

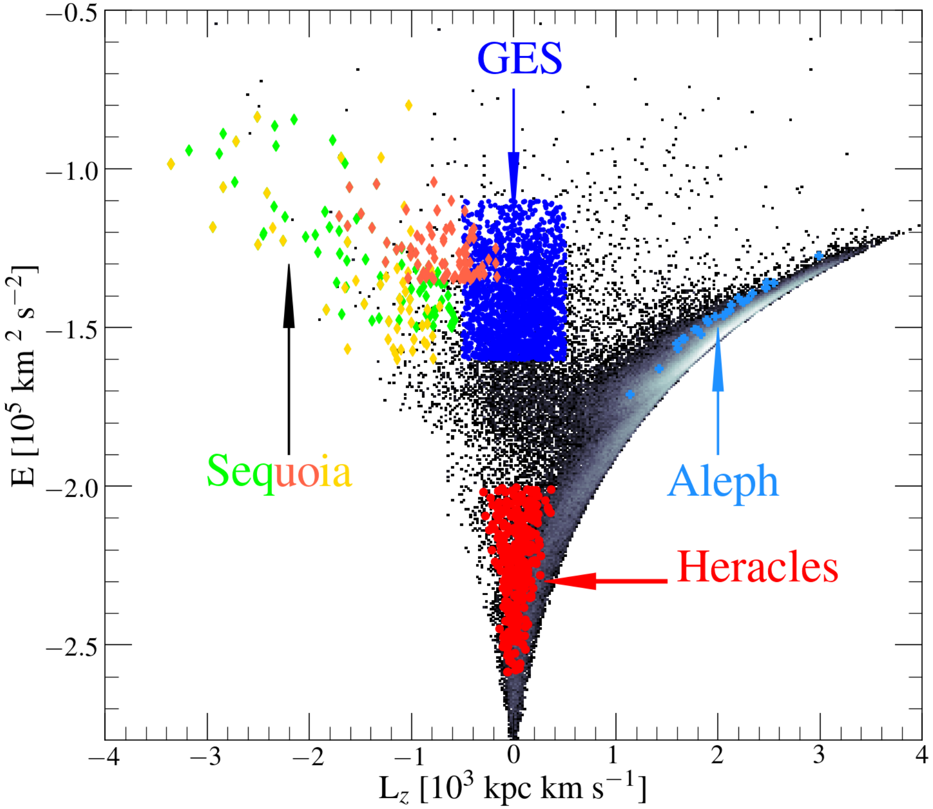
(See also: Gallart et al., 2019)

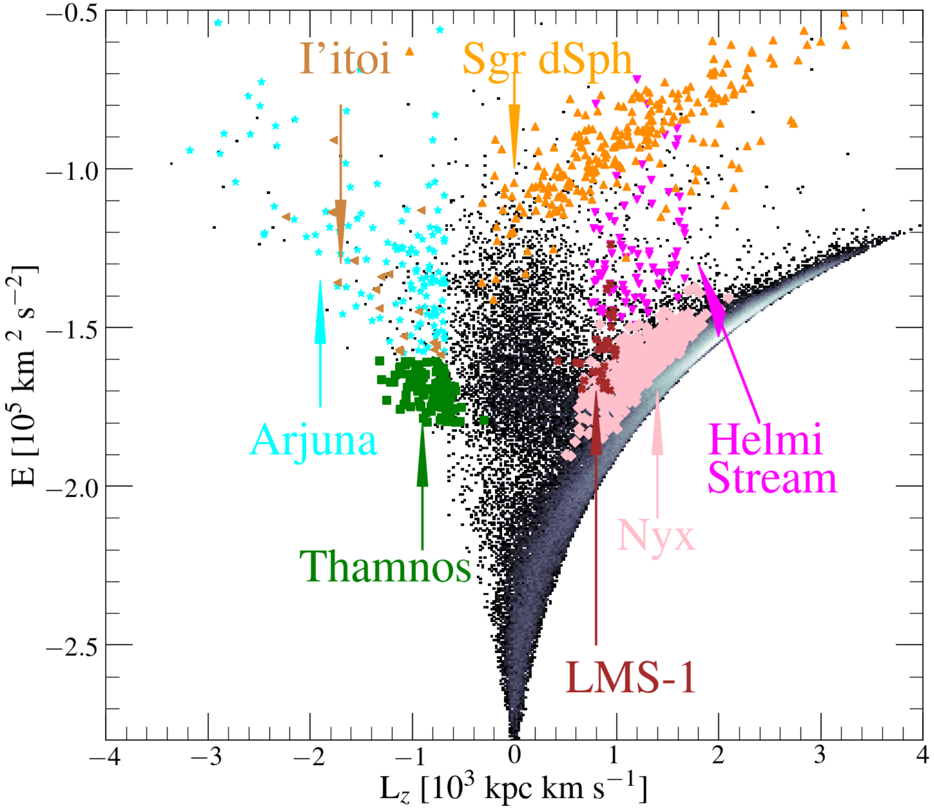
- Further studies

Mackereth et al., 2018 ; Deason et al., 2018 ; Myeong et al., 2018 ; Ioro & Belokurov, 2019 ; Myeong et al., 2019 ; Lancaster, Belokurov & Evans, 2019 ; Fattahi et al., 2019 ; Lancaster et al., 2019

Numerous accretion events

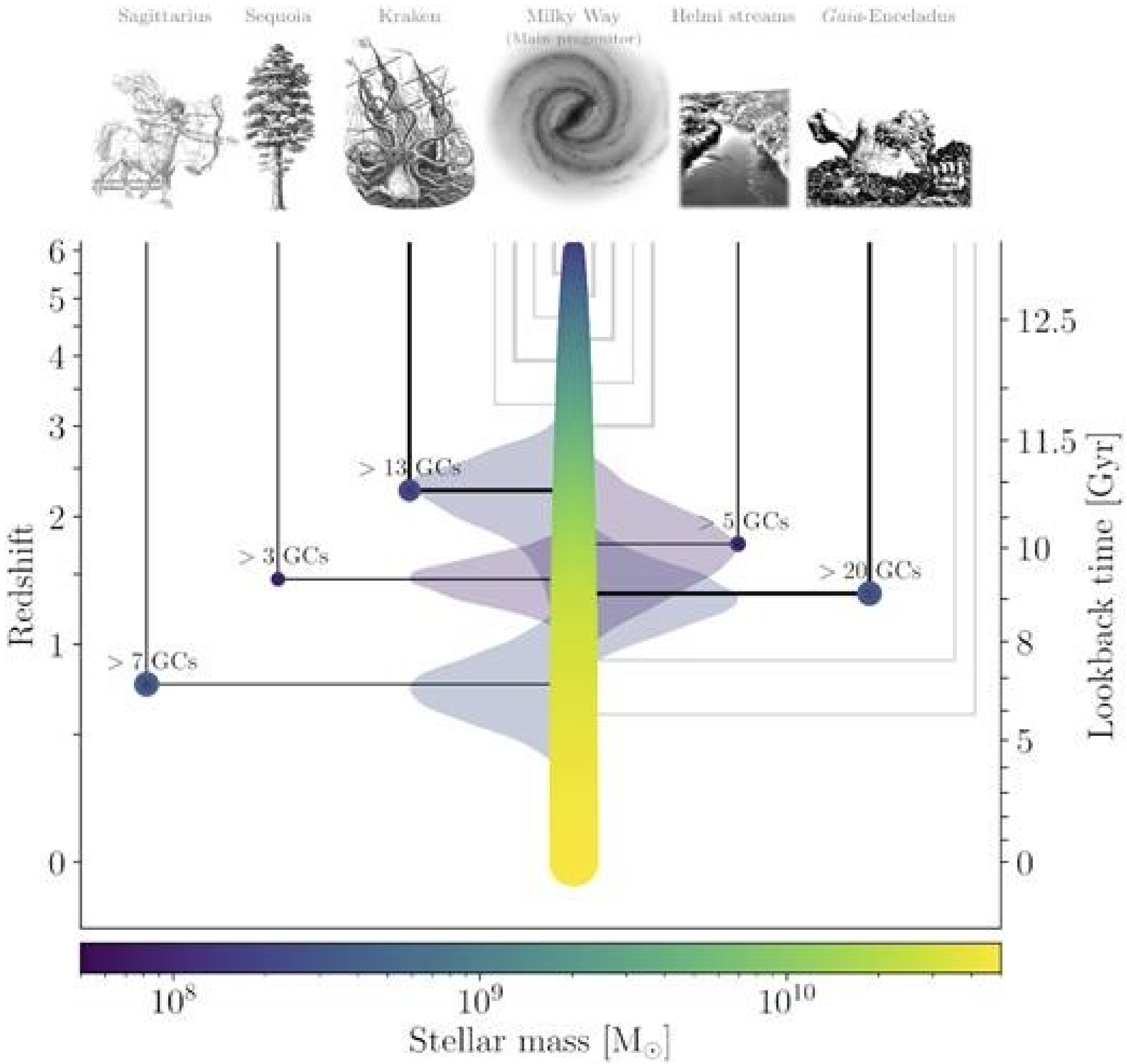
- Disolved satellite → stars grouped in E, Lz space
- Numerous detections





Horta, Schiavon, Mackereth et al., 2022, arXiv:2204.04233

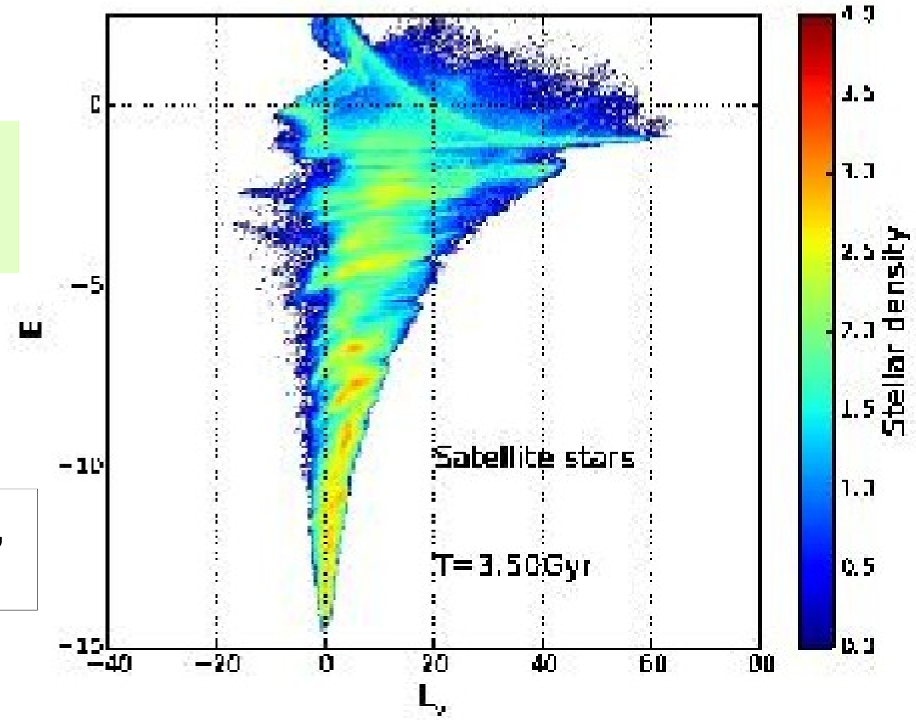
Accretion history



Kruijssen, Diederik, Pfeffer et al., 2020, MNRAS, 498, 2472

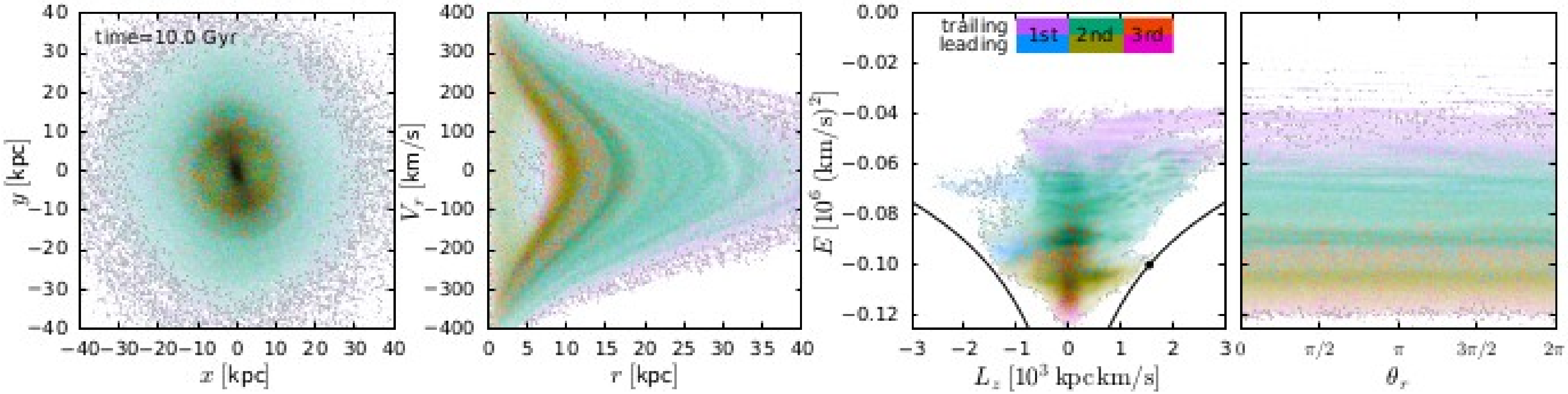
A more complex picture ...

- An accreted satellite produces several clumps in E, Lz space

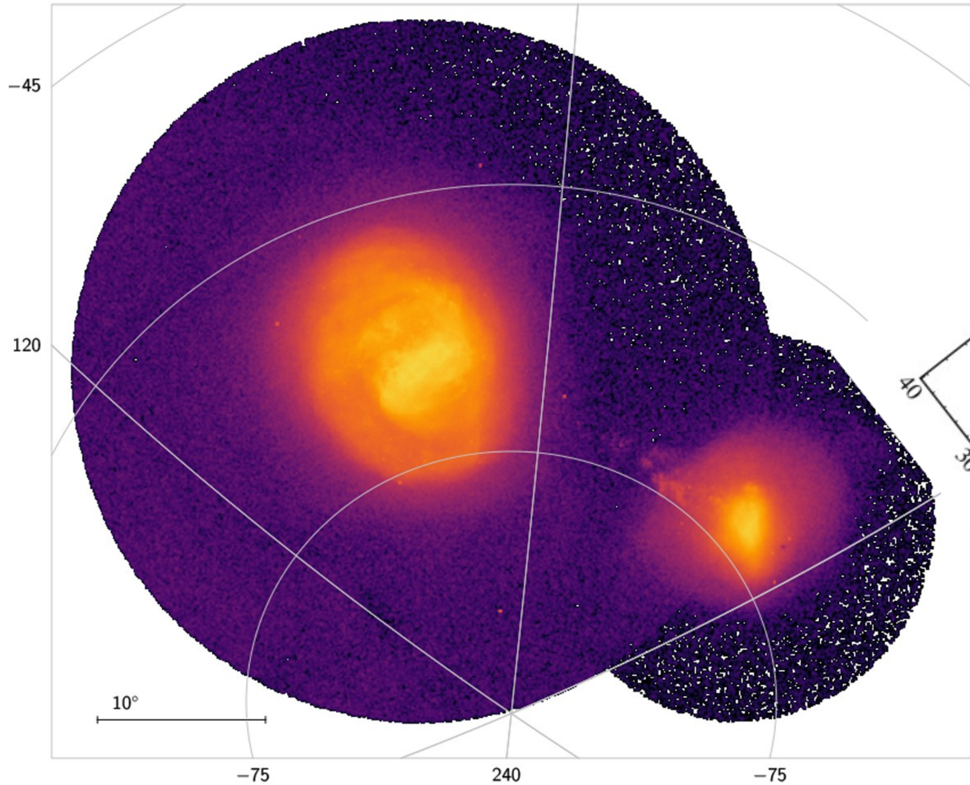


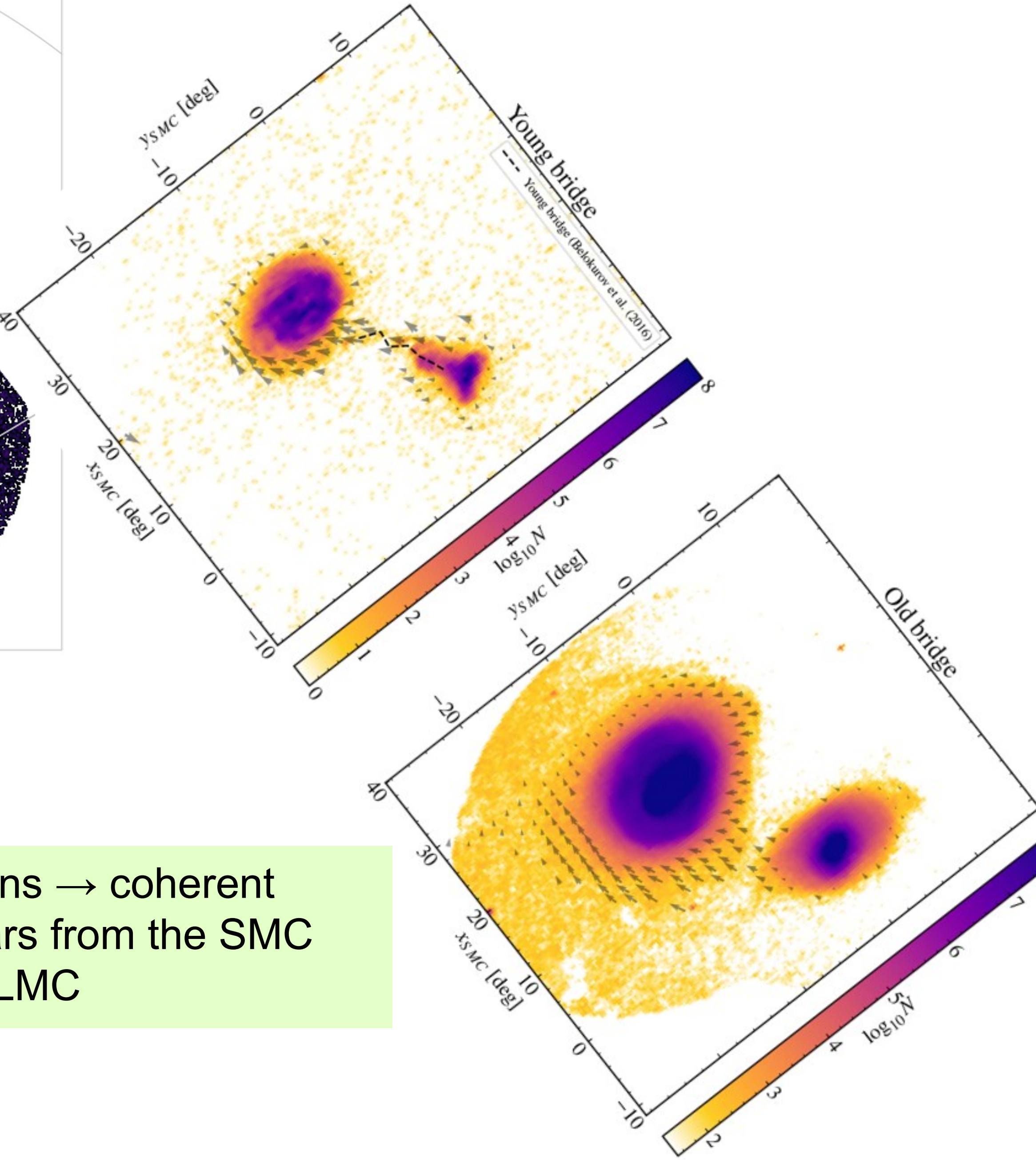
Jean-Baptiste, Di Matteo, Haywood et al., 2017, A&A, 604, 106

Belokurov, Vasiliev, Deason et al., 2022, MNRAS, arXiv:2208.11135



Large Magellanic Cloud in EDR3



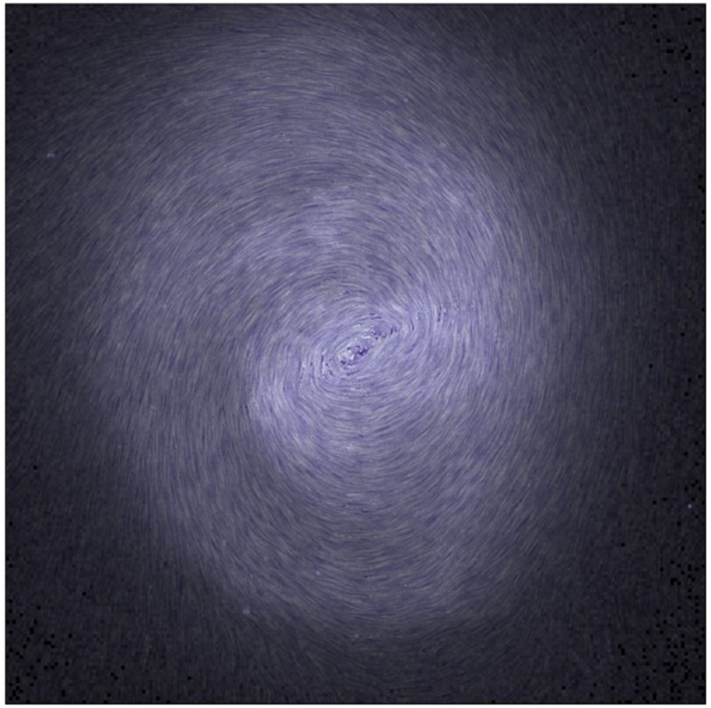


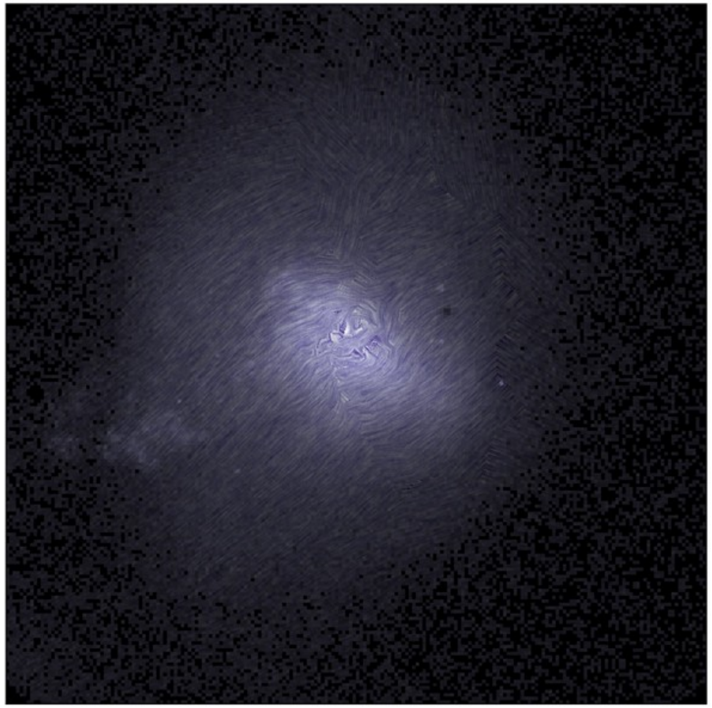
12.4 millions LMC + SMC stars

proper motions → coherent motion of stars from the SMC towards the LMC

Gaia collaboration, Luri et al., 2021, A&A, 649, 7

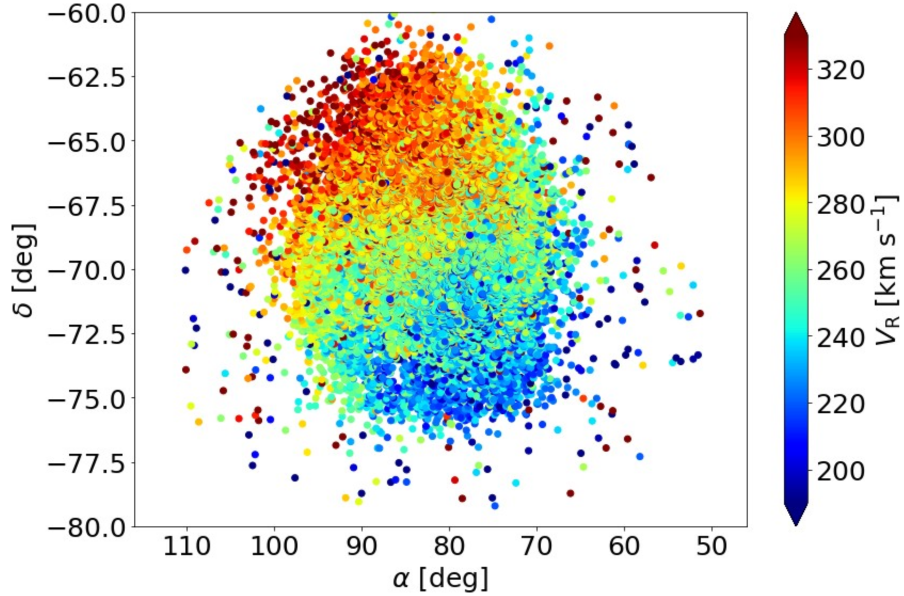
Large Magellanic Cloud in EDR3/DR3





proper motions → tangential velocity

Gaia collaboration, Luri et al., 2021, A&A, 649, 7



- 10 degree radius
- $\omega / \sigma_\omega < 5$
- $V_R > 150$ km/s

→ 29 600 stars

LMC → line-of-sight rotational velocity

Katz, Sartoretti, Guerrier et al., 2022, A&A, arXiv:2206.05902

Beyond GDR3 ...

GDR4 (2025)

- Work started about two years ago
- New products, such as:
  - astrometric, photometric and radial velocity **time series**
  - **150 million radial velocities** down to Grvs = 16
  - Challenge: very low signal-to-noise → machine learning / deep learning

GDR5 (2030)

- Final catalogue → processing of **10 years of data** (2014 - 2025)
- Final accuracy / precision / number of epochs / products