The Universe after Gaia Data Release 2

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University of Zürich
4 October 2019

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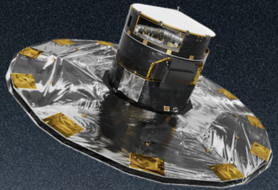
Alberto Giacometti, "Le Nez"

Synopsis



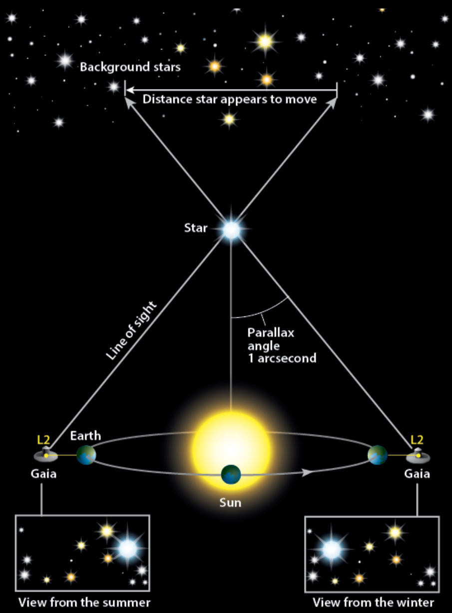
Overview of the Gaia mission and DR2:

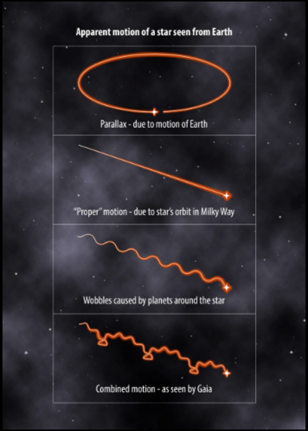
scientific instruments, catalogue contents,
measurement uncertainties, caveats and limitations.

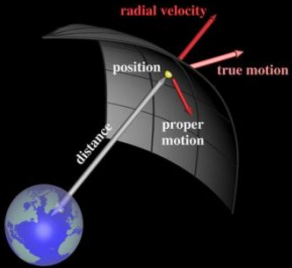
Scientific highlights:

Kinematic complexity of the disk
Accretion history of the halo
Search for new objects (streams, satellites)
Internal kinematics of stellar structures
Measurement of Milky Way gravitational potential

Astrometry 101

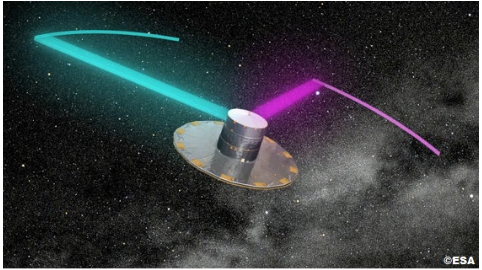


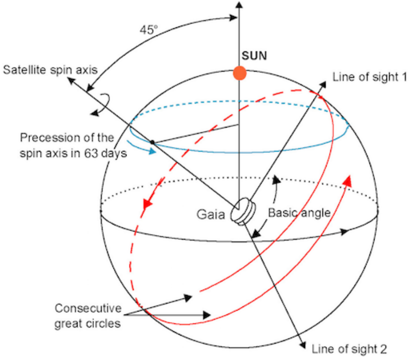


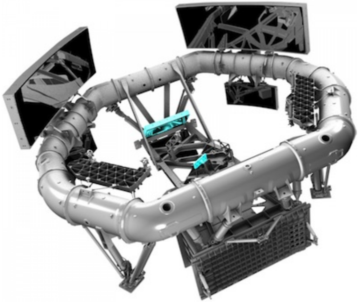


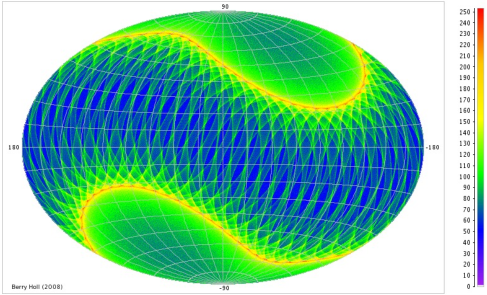
Position on the sky α, δ
Parallax $\varpi = 1/\text{distance}$
Proper motion μ_α, μ_δ
Line-of-sight velocity v_{los}
Binary orbit parameters

How Gaia astrometry works



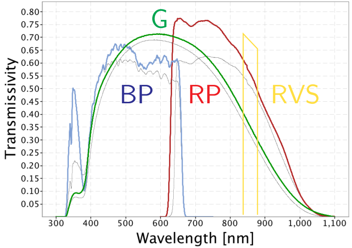


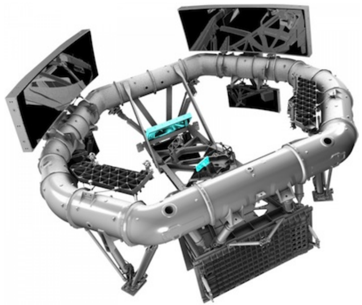


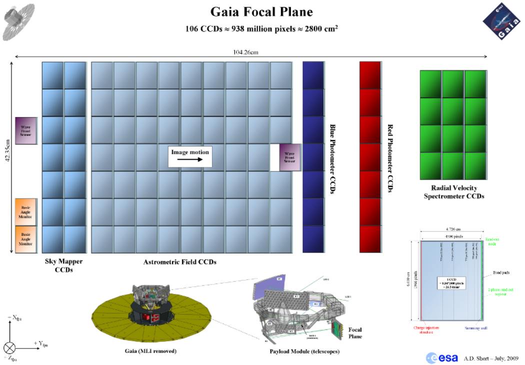


Overview of Gaia mission

- Scanning the entire sky every couple of weeks
- Astrometry for sources down to 21 mag
- Broad-band photometry/low-res spectra
- Line-of-sight velocity down to $\sim$ 15 mag (end-of-mission)



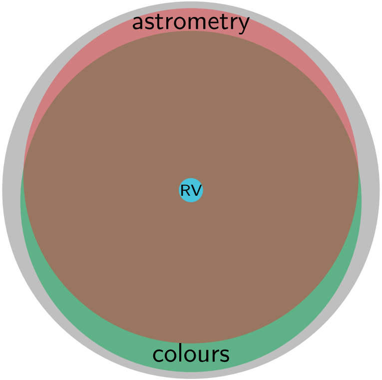


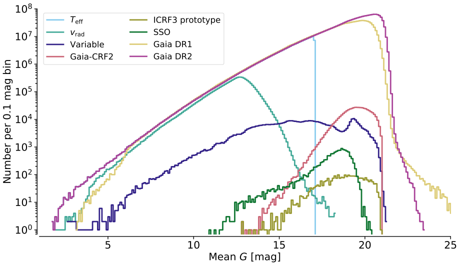


[Source: ESA]

Overview of Data Release 2

- Based on 22 months of data collection
- Total number of sources: 1.69×10^9
- Sources with full astrometry (parallax ϖ, proper motions $\mu_{\alpha*}, \mu_\delta$): 1.33×10^9
- Colours (G_{BP}, G_{RP}): 1.38×10^9
- Line-of-sight velocities: 7.2×10^6
- Effective temperature: 160×10^6
- Stellar parameters ($R_\odot, L_\odot$): 77×10^6
- Extinction and reddening: 88×10^6
- Variable sources: 0.55×10^6





[Brown+ 2018]

Measurement uncertainties

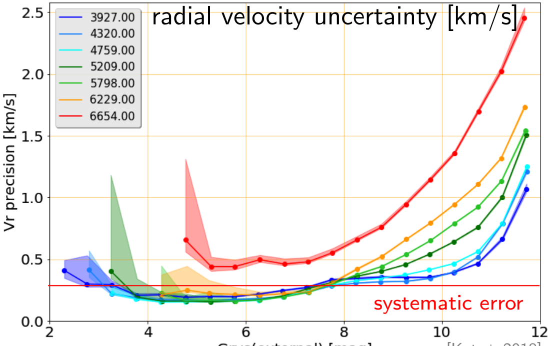
Parallax: $\epsilon_\varpi \gtrsim 0.05 - 0.1$ mas

Proper motion: $\epsilon_\mu \gtrsim 0.1 - 0.2$ mas/yr

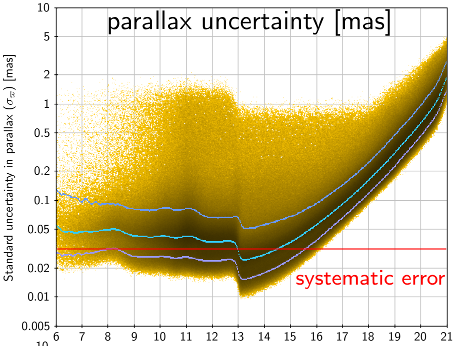
Line-of-sight velocity: $\epsilon_V \gtrsim 0.5$ km/s

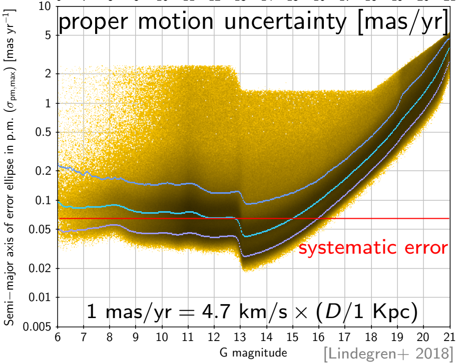
RV measurements only for stars with

$T_{\rm eff} \in [3500 \div 6900]$ K and $G_{\rm RVS} \leq 12$ ($G \lesssim 13$)



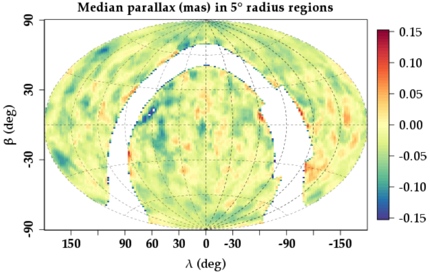
[Katz+ 2018]



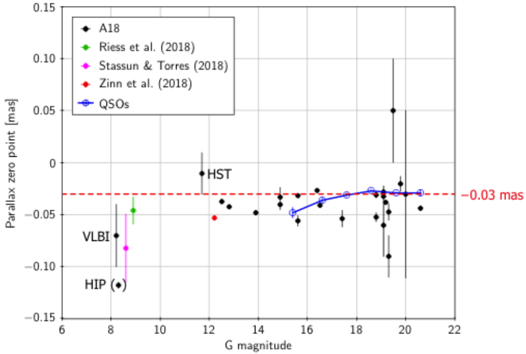


[Lindegren+ 2018]

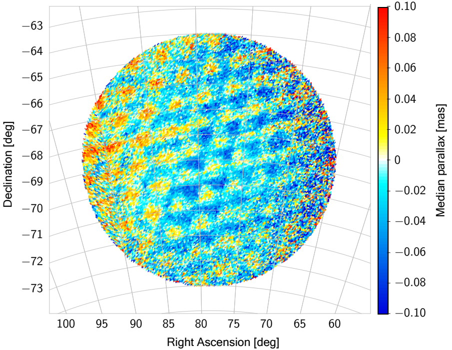
Gaia parallaxes and the absolute distance scale



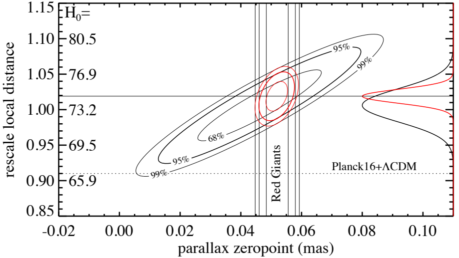
Mean parallax of 5×10^5 quasars [Arenou+2018]



Compilation of parallax offset measurements [Lindegren+2018b]



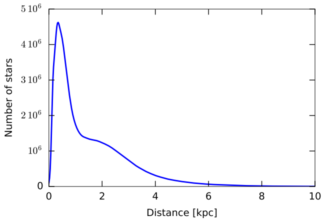
Mean parallax of LMC stars [Lindegren+2018a]

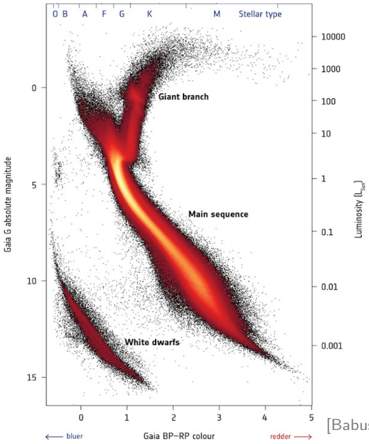


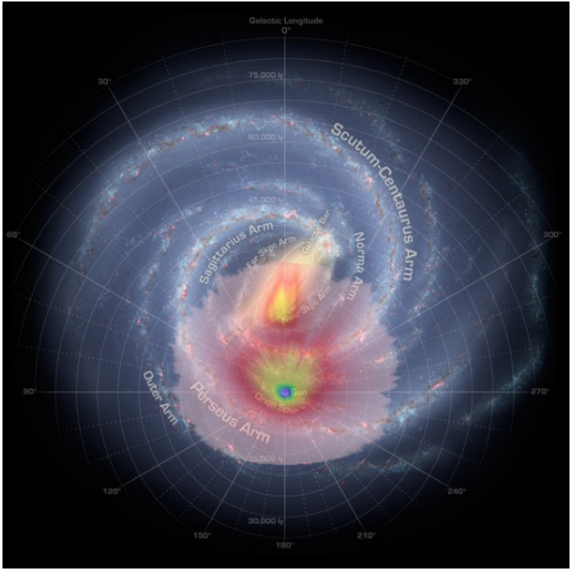
Cepheid distances and Planck constant [Riess+2018]

The “golden” 6D sample

$\sim 6 \times 10^6$ stars brighter than $G \sim 13$
with parallax uncertainty $\epsilon_\varpi/\varpi \leq 0.2$



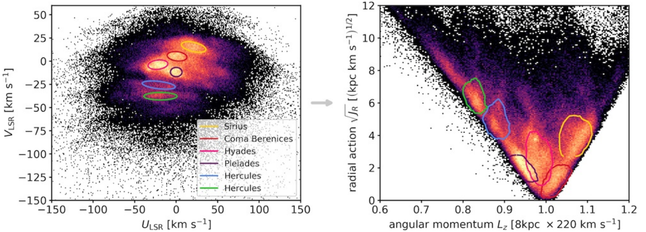




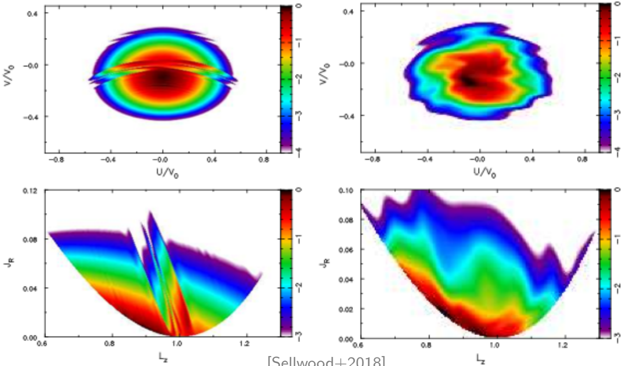
[Babusiaux+ 2018; Katz+ 2018]

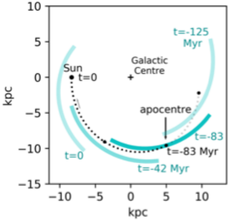
Kinematic complexity in the disk

- Moving groups in velocity space
  [Gaia Collaboration: Katz+2018] ⟹
  more clearly seen in action space.
- Bar pattern speed constraints
  [Monari+2018]
- Perturbations from spiral arms
  [Quillen+2018; Hunt+2018]
- Tests of spiral structure theories
  [Sellwood+2018]

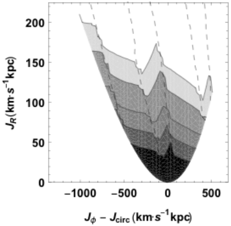


[Trick+2018]





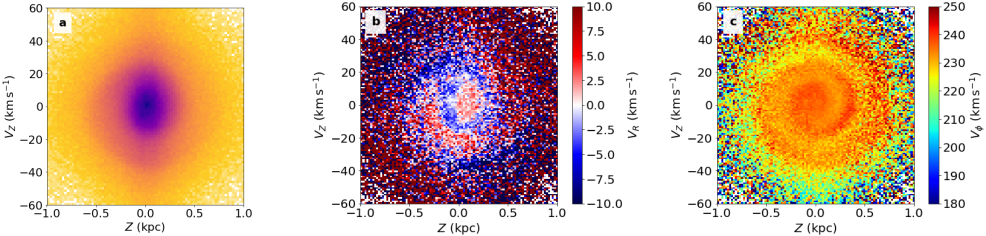
[Quillen+2018]



[Monari+2018]

[Sellwood+2018]

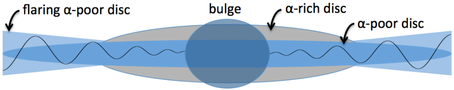
Vertical perturbations and the disk seismology



Phase-space spiral [Antoja+2018]

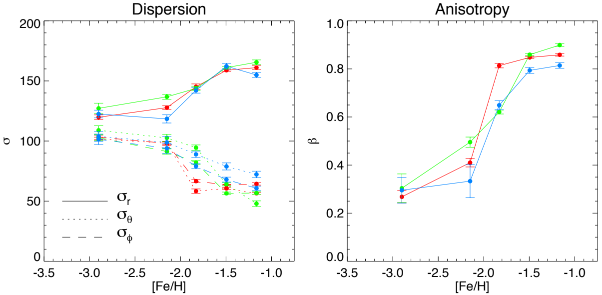
perturbation from a $(2-10)\times 10^{10}\,M_\odot$ satellite crossing the disk $200-400$ Myr ago (Sgr dSph?)

[Laporte+ 2018]
[Darling & Widrow 2018]
[Binney & Schönrich 2018]
[Bland-Hawthorn+ 2018]
[Li & Shen 2019]



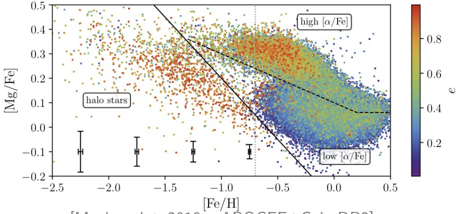
Radially-anisotropic population in the stellar halo

Evidence for a major merger with a $\gtrsim 10^9\ M_\odot$ satellite $\sim 8 - 10$ Gyr ago (kinematics + metallicity)

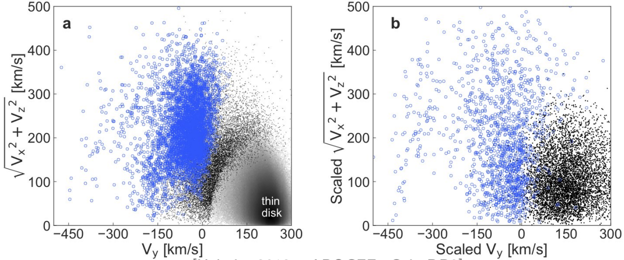


[Belokurov+ 2018 – SDSS+Gaia DR1]

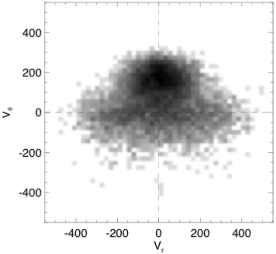
[see also Kruijssen+2018 for globular clusters]



[Mackereth+ 2019 – APOGEE+Gaia DR2]



[Helmi+ 2018 – APOGEE+Gaia DR2]



[Fattahi+ 2018 – Gaia DR2]

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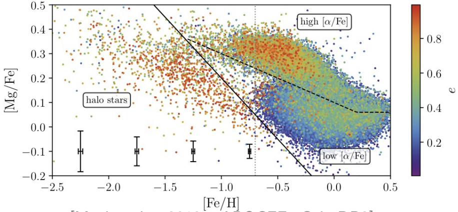
Helmi+ 2018



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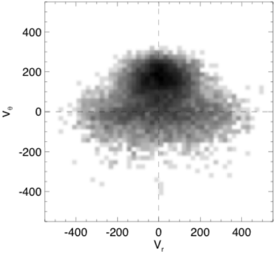

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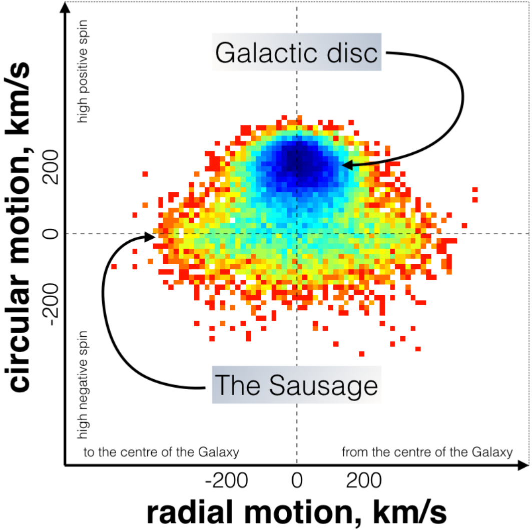
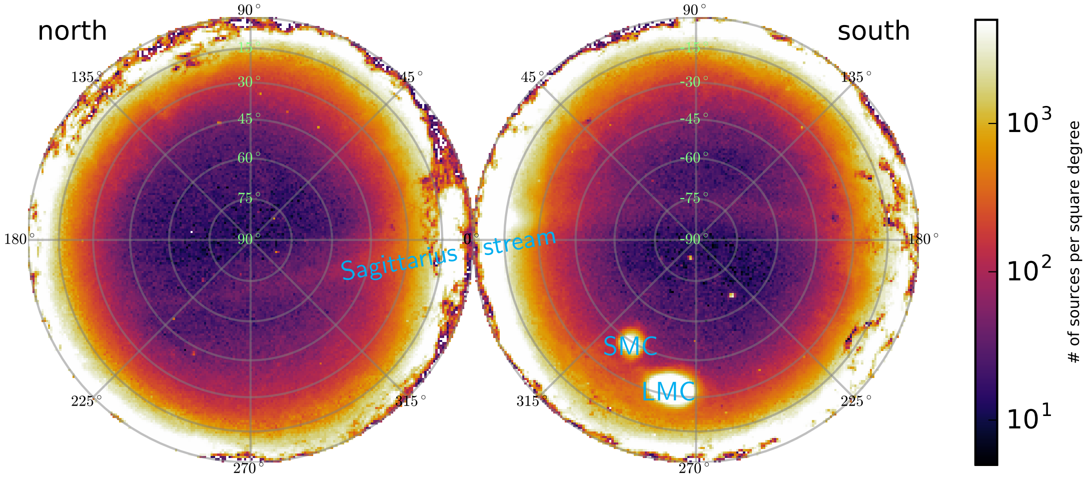
Helmi+ 2018



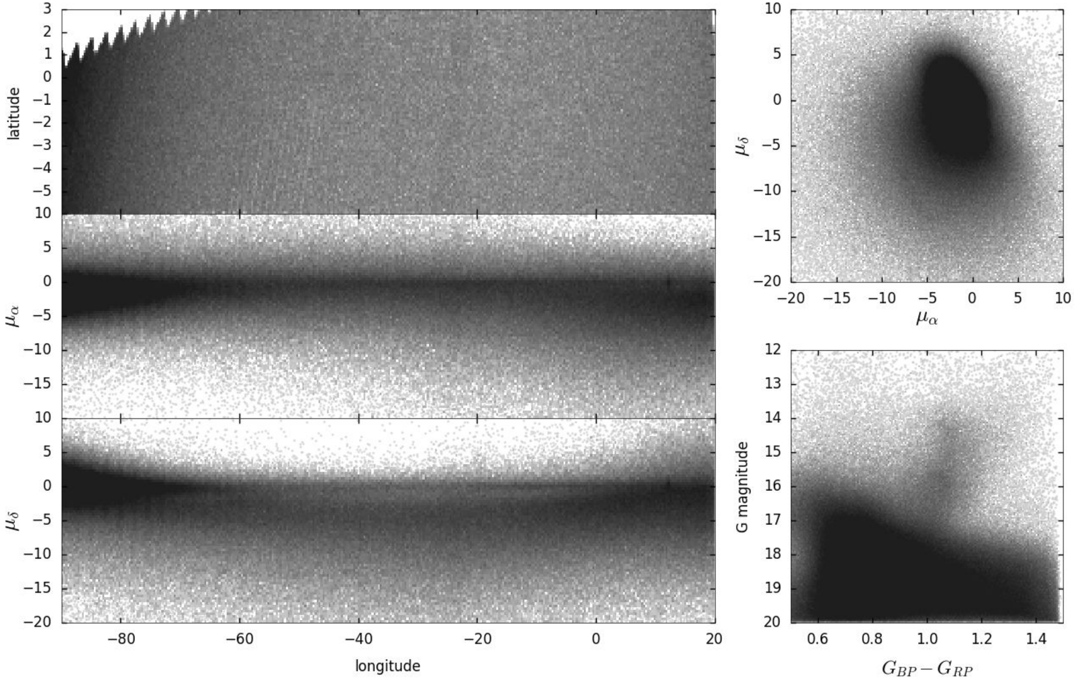
Belokurov+ 2018

Finding substructures with Gaia

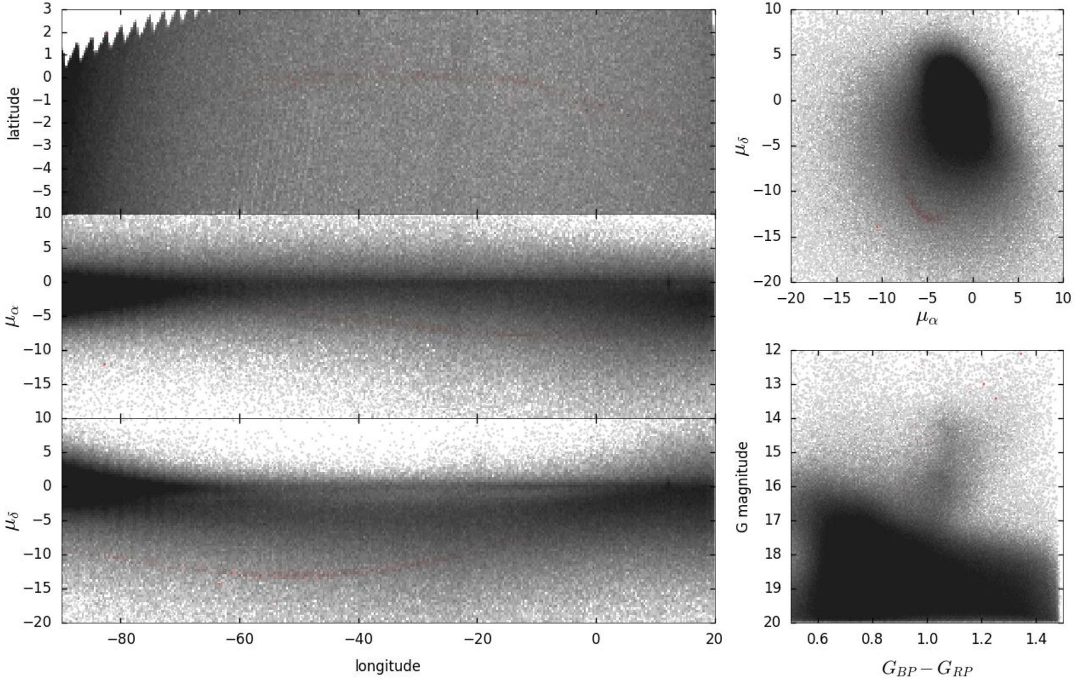


Stars with $\varpi < 0.3$, $1 < G_{\rm BP} - G_{\rm RP} < 1.5$, $|\mu_\alpha| < 3.5$, $|\mu_\delta| < 3.5$ (mainly distant halo)

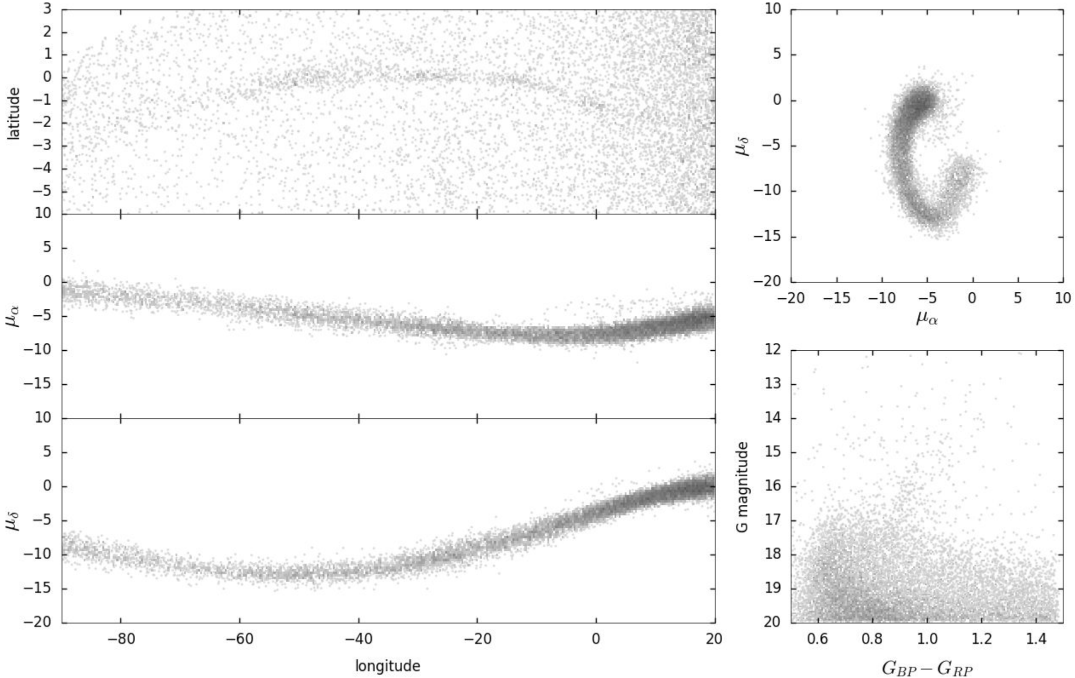
Finding streams with Gaia



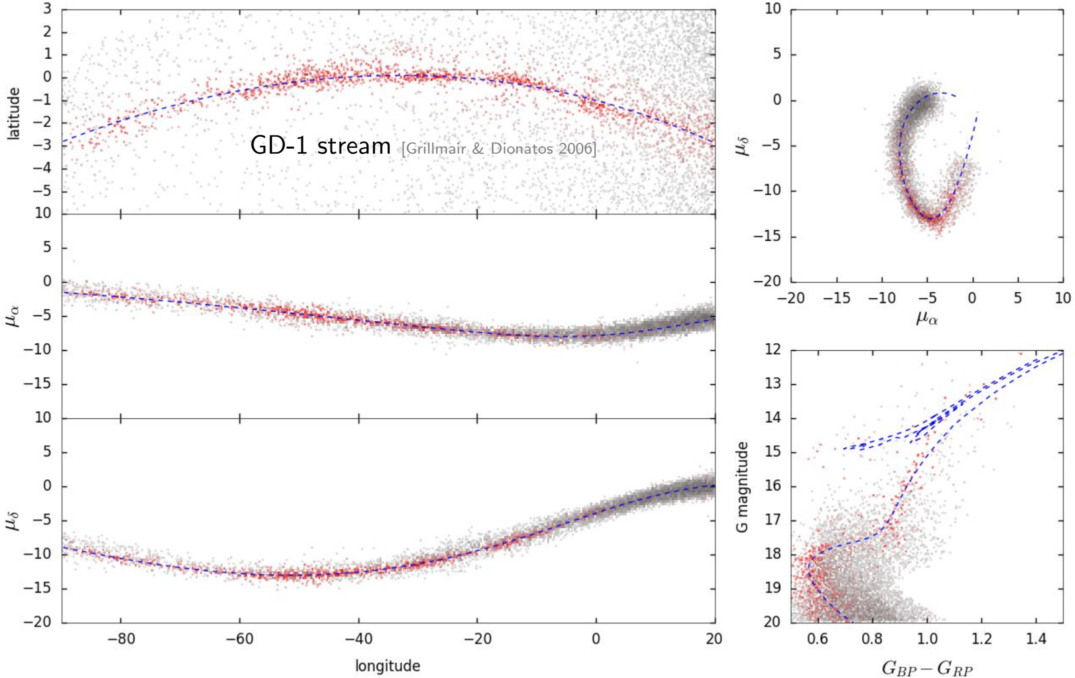
Finding streams with Gaia



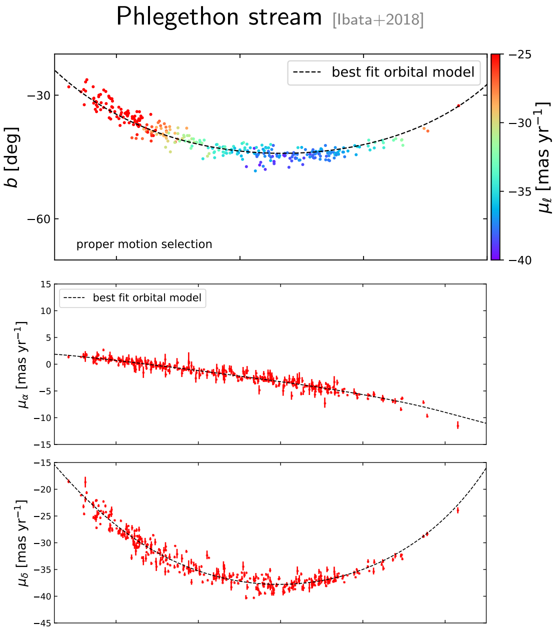
Finding streams with Gaia

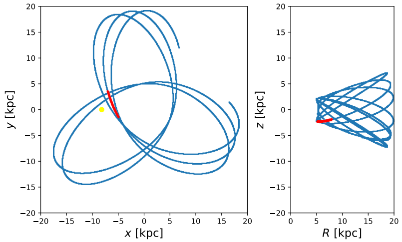


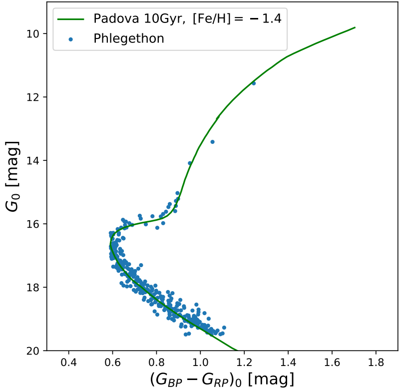
Finding streams with Gaia



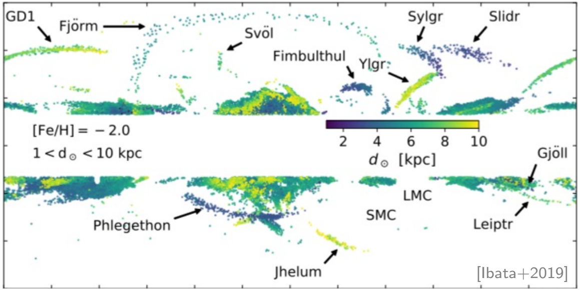
Finding new streams with Gaia

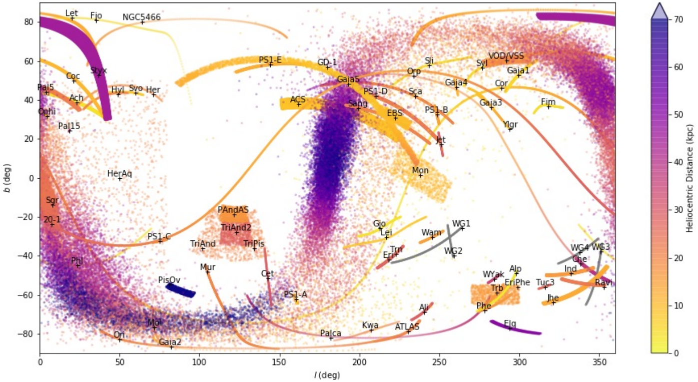






A census of stellar streams in the Milky Way





Stream name

Ylgr
Sylgr
Fjörm
Fimbulthul
Phlegethon
Styx
Kwando
Murrumbidgee
Chenab
Indus
Jhelum
Nix
Aliqa Uma
Willka Yaku
Turranburra
Orinoco
Wambelong
GD-1

[C.Mateu, GalStream database]

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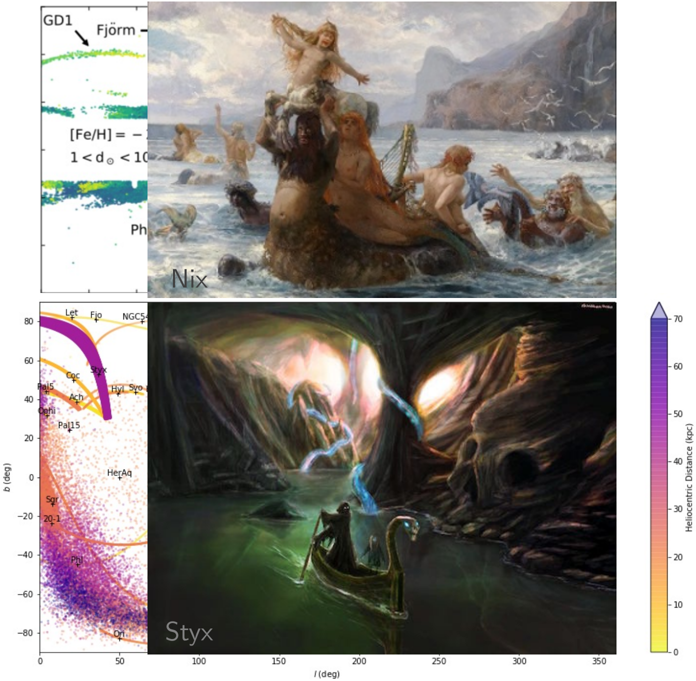

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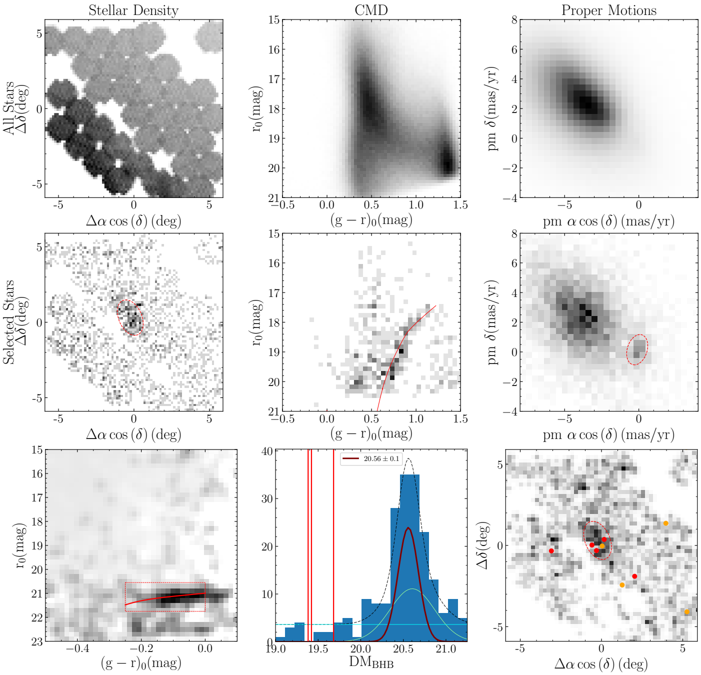
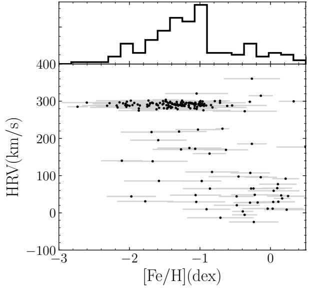
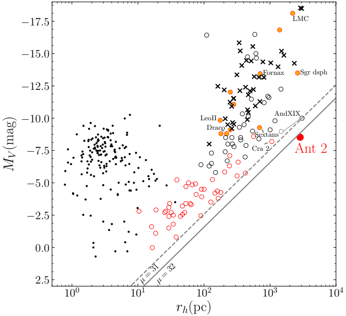
[C.Mateu, GalStream database]

Finding new satellite galaxies with Gaia: Antlia 2

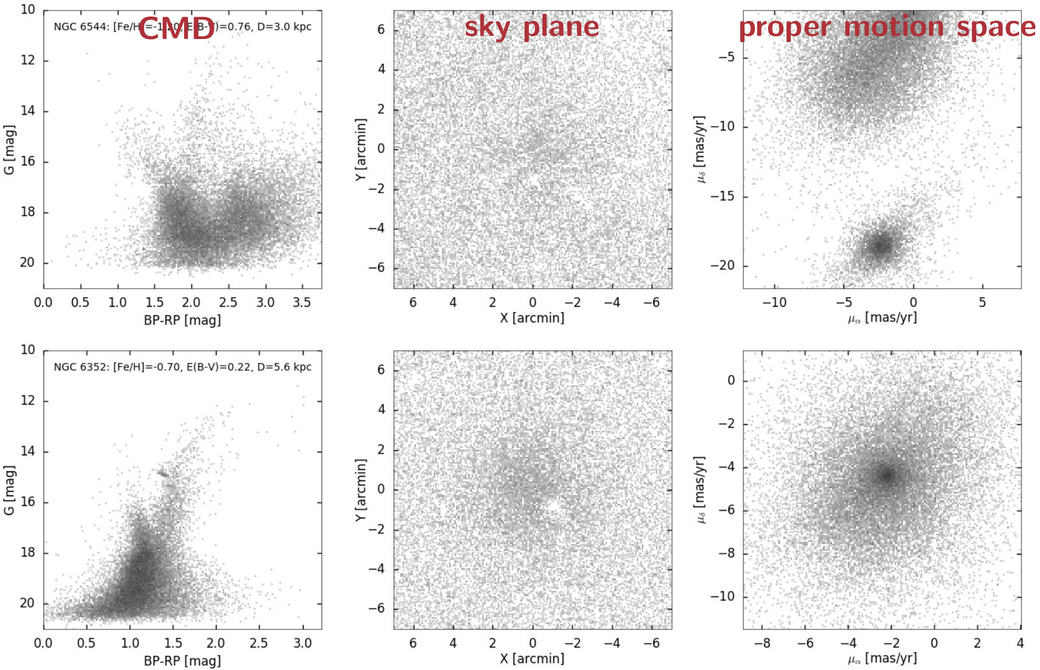




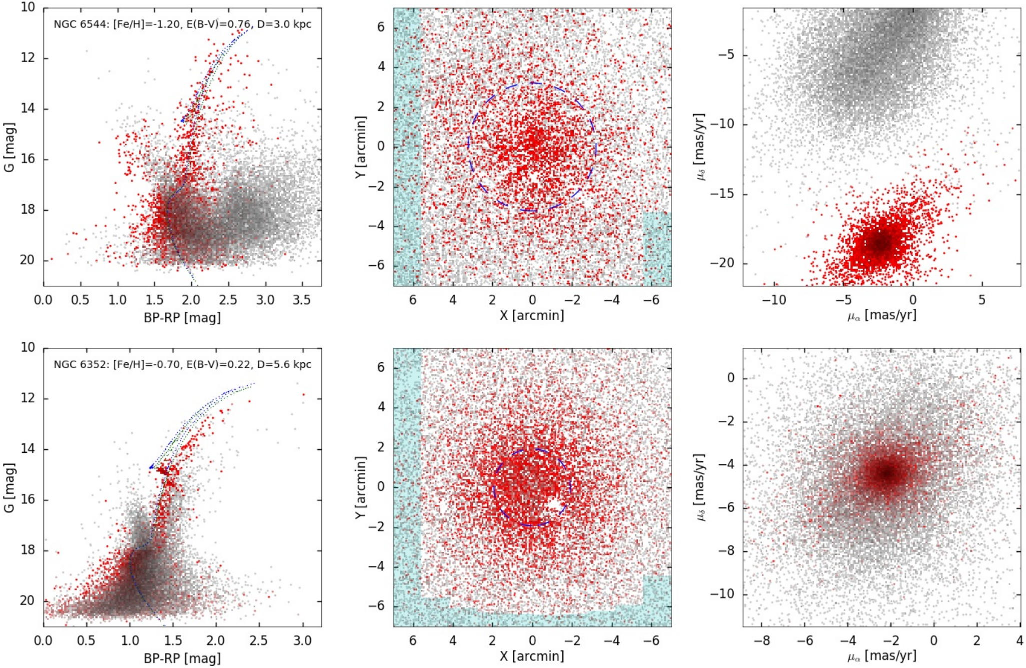


The most diffuse galaxy [Torrealba+2018]

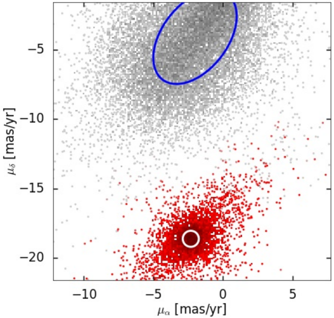
Determination of cluster membership



Determination of cluster membership



Probabilistic membership determination



A hard cutoff in PM space is not always possible and is conceptually unsatisfactory.

A more mathematically well-grounded alternative: gaussian mixture modelling.

$$f(\boldsymbol{\mu}_i) = q\,\mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\rm cl}}, \Sigma_{{\rm cl};i}) + (1-q)\,\mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\rm fg}}, \Sigma_{{\rm fg};i})$$

$$\mathcal{N}(\boldsymbol{\mu} \mid \overline{\boldsymbol{\mu}}, \Sigma) \equiv \frac{\exp\left[-\frac{1}{2}(\boldsymbol{\mu}-\overline{\boldsymbol{\mu}})^T\,\Sigma^{-1}\,(\boldsymbol{\mu}-\overline{\boldsymbol{\mu}})\right]}{2\pi\,\sqrt{\det\Sigma}},$$

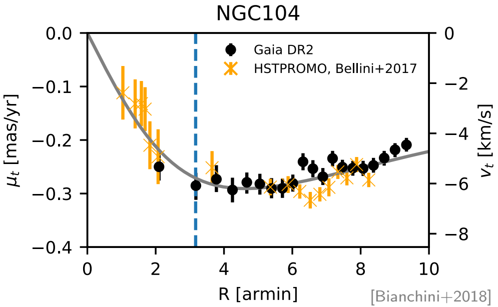
where the mean PMs $\overline{\boldsymbol{\mu}}$ and dispersions Σ of the cluster and foreground distributions, and the fraction of cluster members q, are all inferred by maximizing the likelihood of the observed stellar PMs $\ln\mathcal{L} \equiv \sum_{i=1}^{N_{\rm stars}} \ln f(\boldsymbol{\mu}_i)$.

Posterior membership probability for each star:

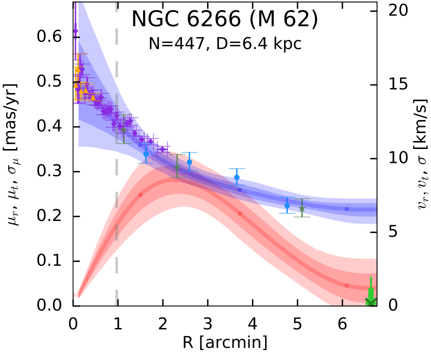
$$p_{{\rm cl};i} = \frac{q_{\rm cl}(\mathbf{r}_i)\,\mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\rm cl}}, \Sigma_{{\rm cl};i})}{q_{\rm cl}(\mathbf{r}_i)\,\mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\rm cl}}, \Sigma_{{\rm cl};i}) \;+\; [1-q_{\rm cl}(\mathbf{r}_i)]\,\mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\rm fg}}, \Sigma_{{\rm fg};i})}$$

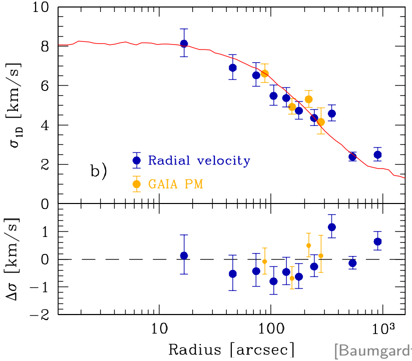
Internal kinematics of globular clusters

Rotation found in $\sim 10-20$ clusters, transverse velocity dispersion measured in $\sim 60-100$ clusters (outer regions)



[Bianchini+2018]

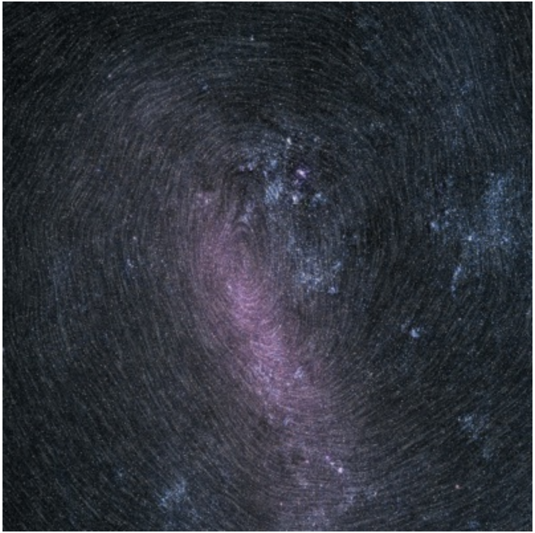




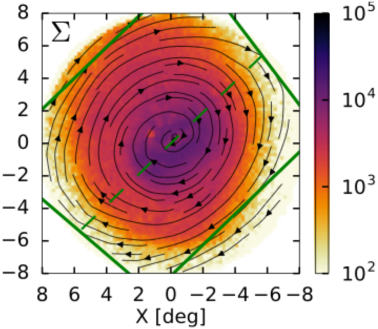
[Baumgardt+2019]

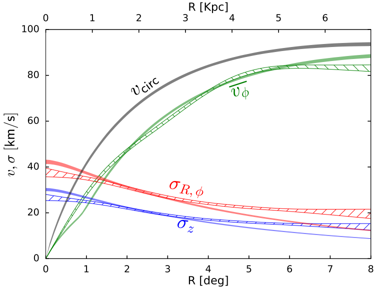
Internal kinematics of the Large Magellanic Cloud

rotation, velocity dispersion from $\sim 10^6$ stars at 50 kpc



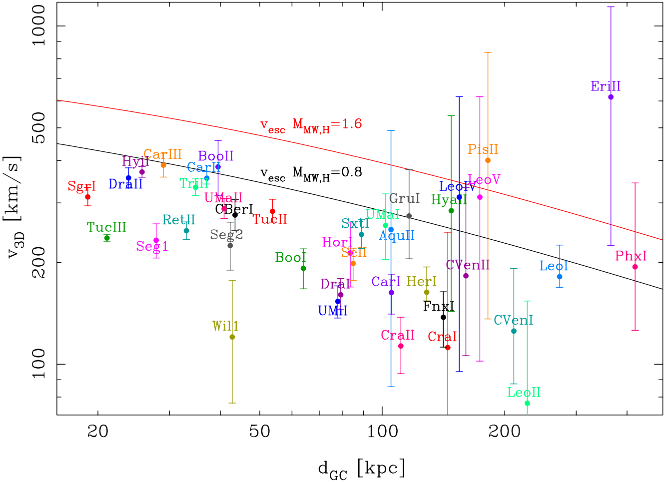
[credit: ESA/Gaia/DPAC]





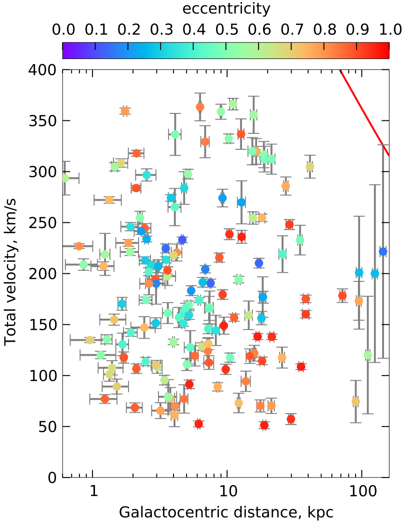
Measuring 6d phase-space coordinates and orbits of

Satellite galaxies

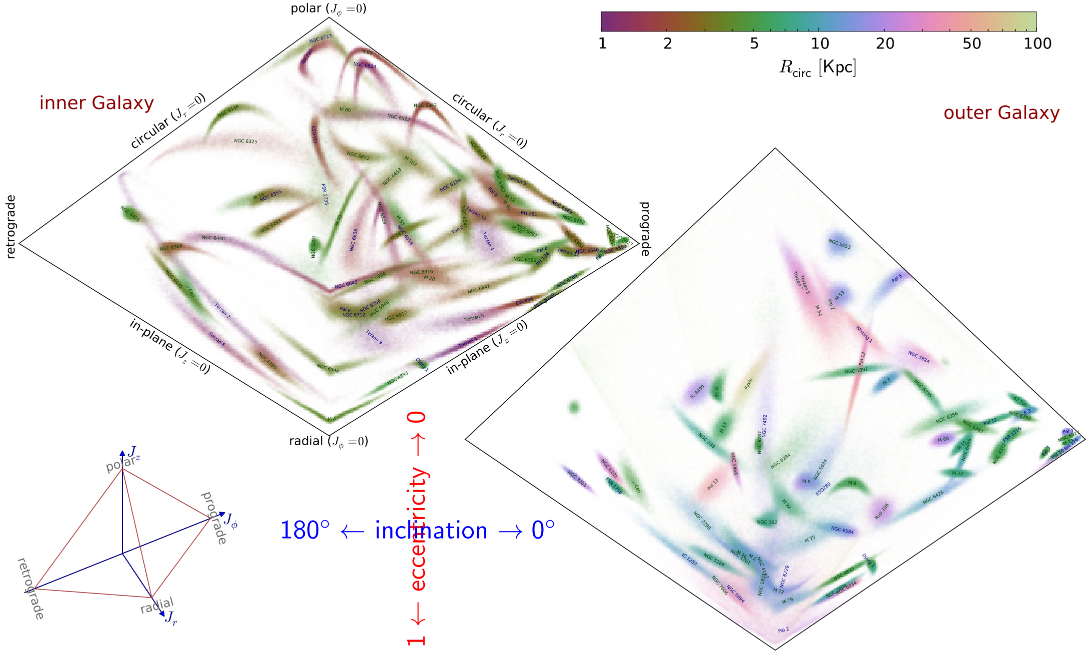


[Fritz+2018, see also Simon 2018; Pace & Li 2018; Massari & Helmi 2018]

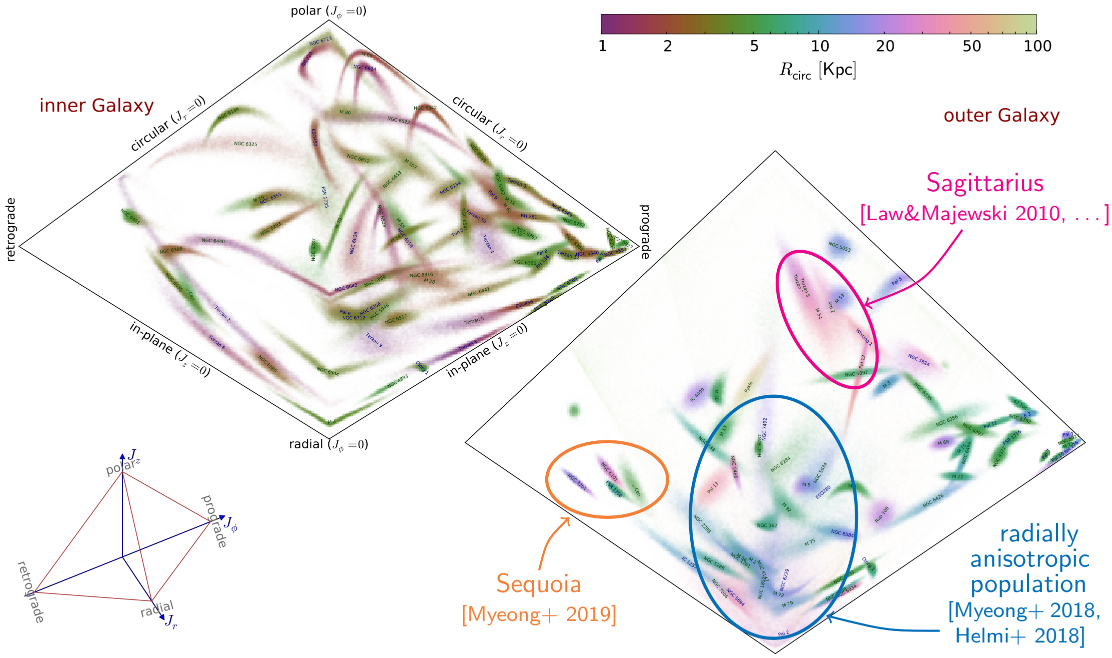
Globular clusters



Distribution of globular clusters in action space



Distribution of globular clusters in action space



Distribution of globular clusters in action space

Jackson Pollock, "Convergence"

Kliment Redko, "Uprising"

Swiss connection

https://www.zuerich.com/en/visit/lenin

Welcome,
Zürich, Switzerland. Things to Do Where to Stay City of the Locals Visitor Info

Lenin (1870 – 1924) – the Russian Revolutionary Leader in Zurich

Before the Russian Revolution, Lenin and his wife spent a year in exile in Zurich. They lived on the Spiegelgasse close to Cabaret Voltaire

During the First World War, Lenin lived with his wife Nadeshda Krupskaja at Spiegelgasse 14 in Zurich for about a year – a commemorative plaque on the house serves as a reminder. He finished his work "Imperialism as the Highest Stage of Capitalism" in Zurich. He spent a lot of his time in Zurich's libraries. However, in his free time, he and his wife are said to have loved driving up to the top of the Zürichberg hill, lying in the grass and eating Swiss chocolate. Whether Lenin visited the Cabaret Voltaire, the birthplace of Dadaism, is still unknown but has fuelled speculation as to whether Lenin was a secret Dadaist.

When the February revolution broke out in Russia in 1917, Lenin left his exile in Switzerland and returned to his homeland.

Address

Lenin Gedenktafel
Spiegelgasse 14
8001 Zürich

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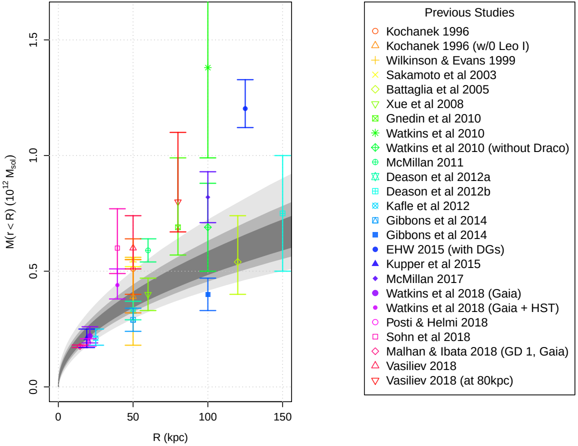
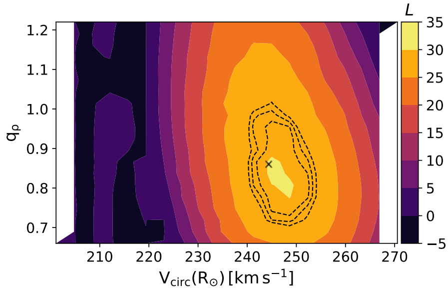
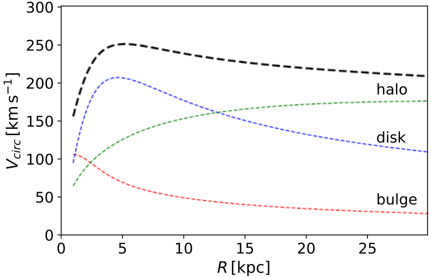
Constraining the Milky Way potential



Globular cluster dynamics

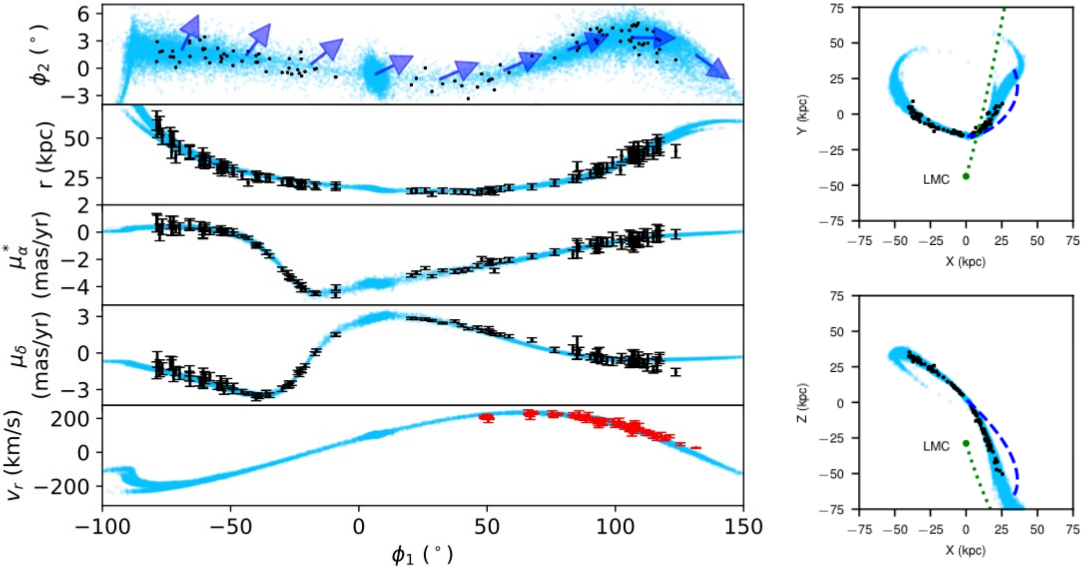
[Eadie & Juric 2018; see also Watkins+2018; Posti & Helmi 2018]





GD-1 stream [Malhan & Ibata 2018]

Constraining the mass of the Large Magellanic Cloud



5d kinematics of the Orphan stream deflected by LMC flyby [Erkal+2018]

Summary

The Universe is even more exciting after *Gaia* DR2!

Credit: Amanda Smith, IoA