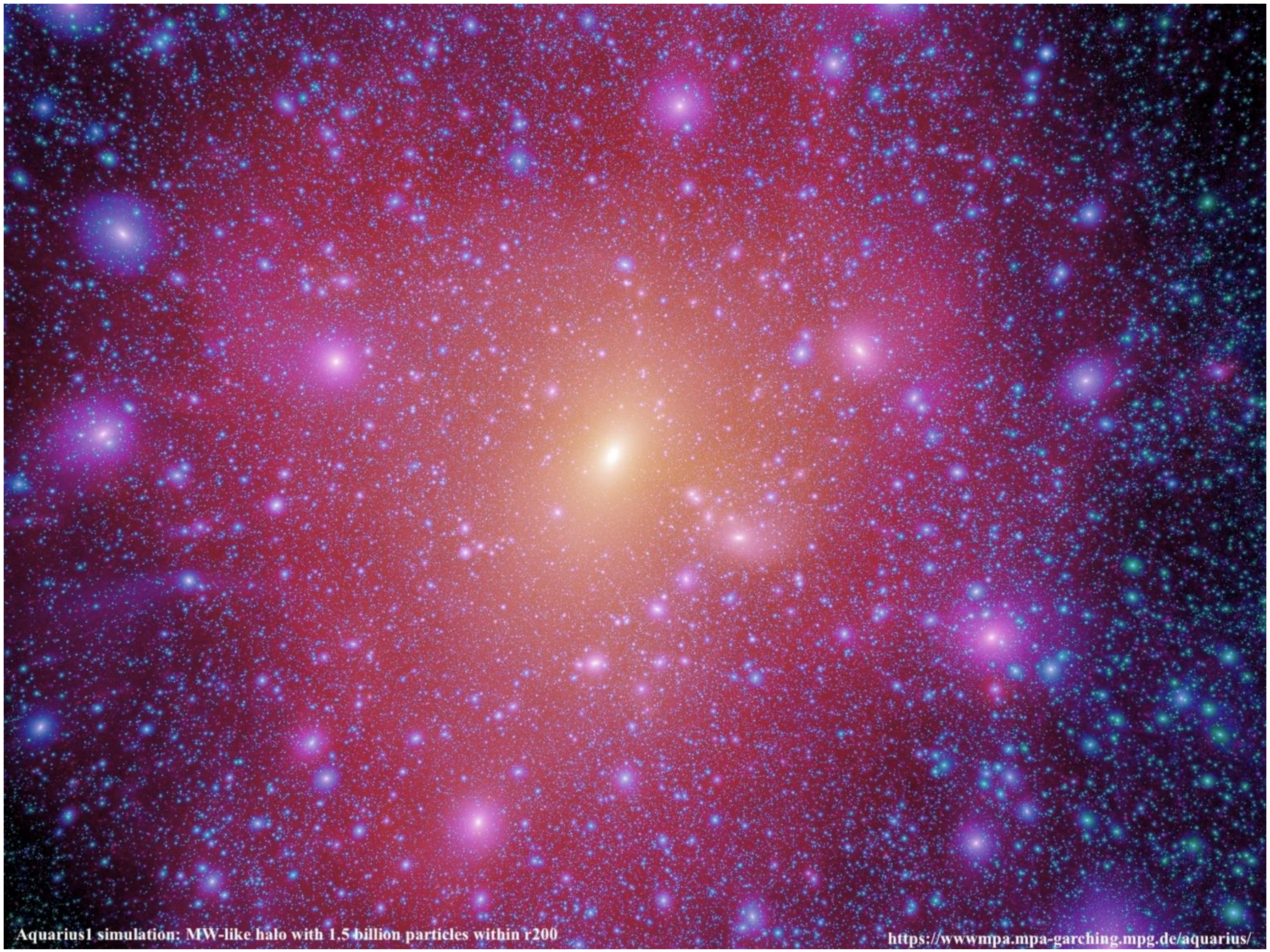
Gaia & the Galactic Halo: a voyage into Galaxy formation from inside

Michele Bellazzini
INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna



Theory 2004

82 *Bullock and Johnston* 2004, ASP CS, 327, 80

Cosmology and the stellar halo

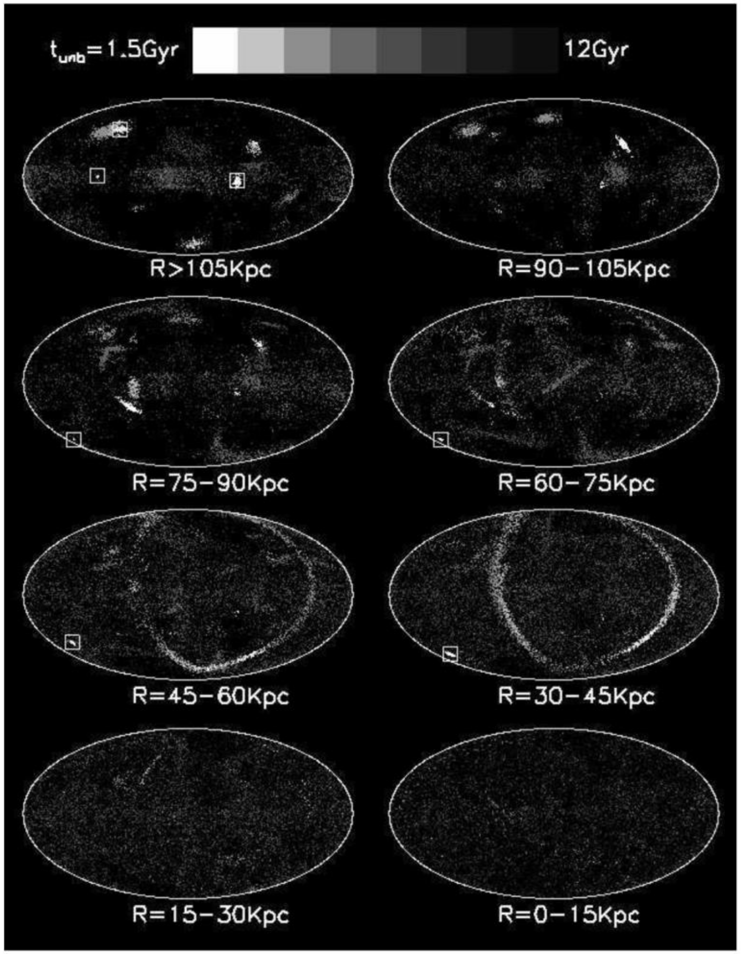


Figure 2. One of our model stellar halos shown in all-sky projection within bins of 15 kpc stepping out in galactocentric radius. Each point represents a tracer star of one per 500 $L_{\odot}$ in total V-band luminosity. The gray-scale code (shown at the top) represents the time the particle became unbound from its original satellite. Bound particles and recent disruptions are white. The boxes signify bound systems at $z = 0$. Substructure is apparent in this color space, which may provide a reasonable tracer of how chemically evolved the stars should be.

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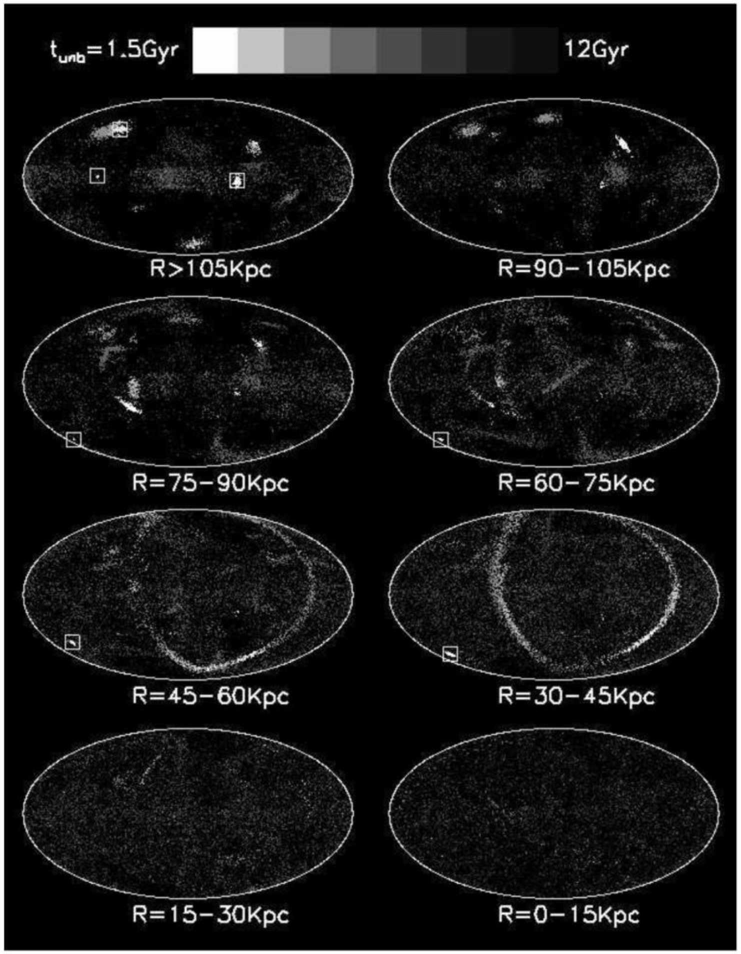

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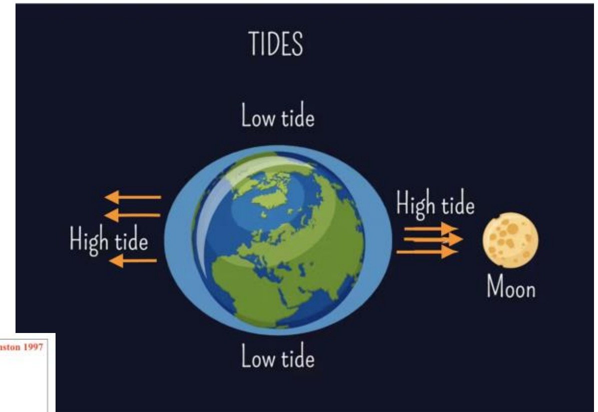
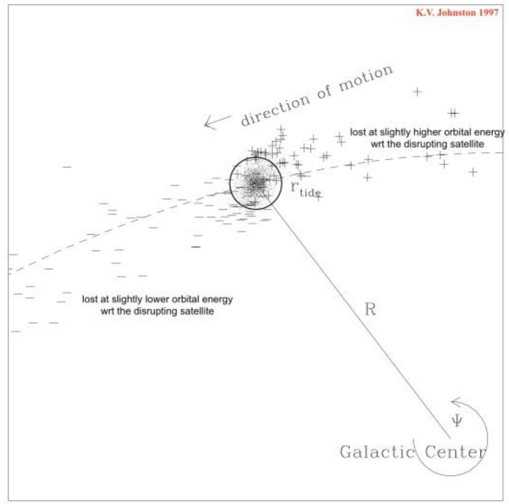




Actual extended tidal styreams known at this epoch: <5

A. Bonaca and A.M. Price-Whelan *New Astronomy Reviews 100 (2025) 101713*

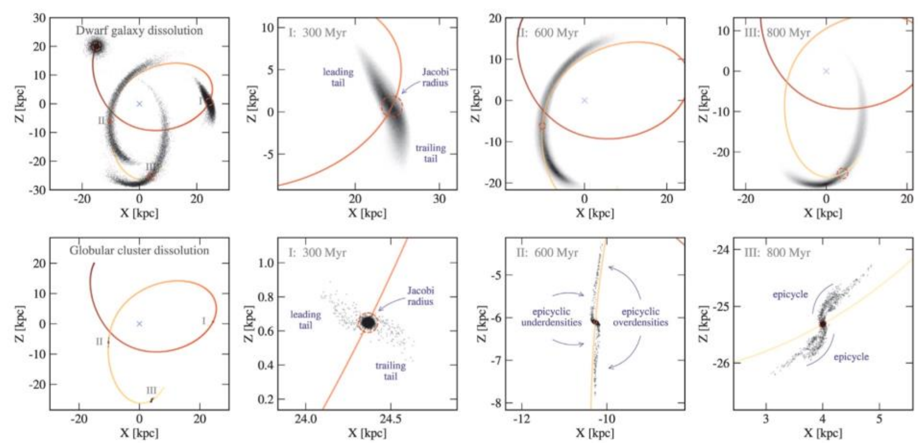


Fig. 1. Numerical models of a 10^8 $M_{\odot}$ dwarf galaxy (top) and a 10^4 $M_{\odot}$ globular cluster (bottom) tidally dissolving on the same orbit in a Milky Way-like gravitational potential

Theory 2004

Gaia measures 2021
Only spatially coherent structures

82 *Bullock and Johnston* 2004, ASP CS, 327, 80
Cosmology and the stellar halo

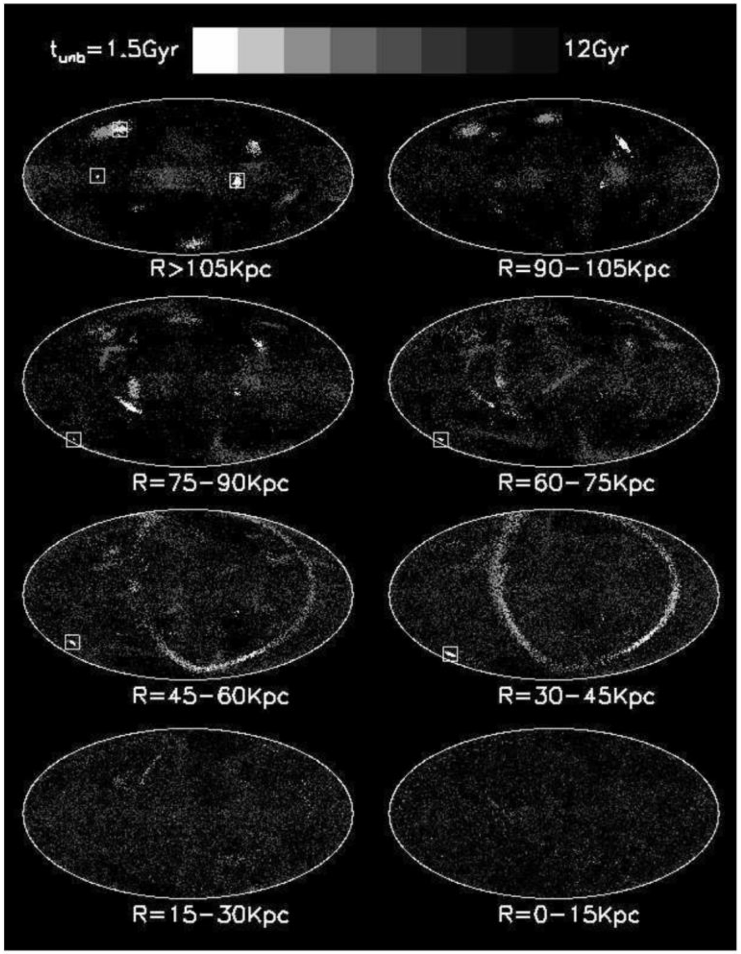
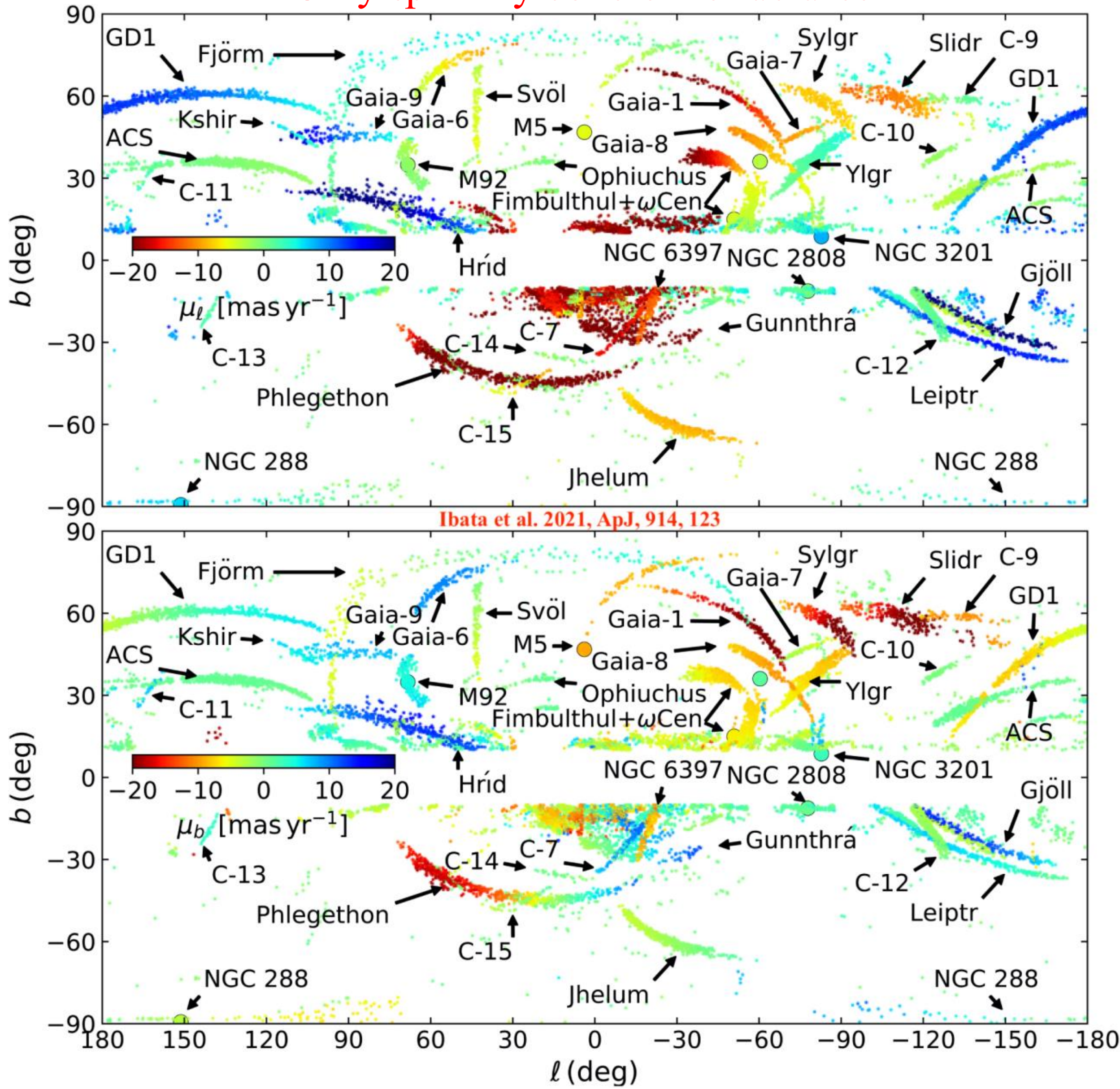


Figure 2. One of our model stellar halos shown in all-sky projection within bins of 15 kpc stepping out in galactocentric radius. Each point represents a tracer star of one per 500 $L_{\odot}$ in total V-band luminosity. The gray-scale code (shown at the top) represents the time the particle became unbound from its original satellite. Bound particles and recent disruptions are white. The boxes signify bound systems at $z = 0$. Substructure is apparent in this color space, which may provide a reasonable tracer of how chemically evolved the stars should be.



LXVI Congresso Nazionale della Società Astronomica Italiana (SAIt): Dal Sistema Solare all'Universo profondo
Firenze, 3-6 Giugno 2025

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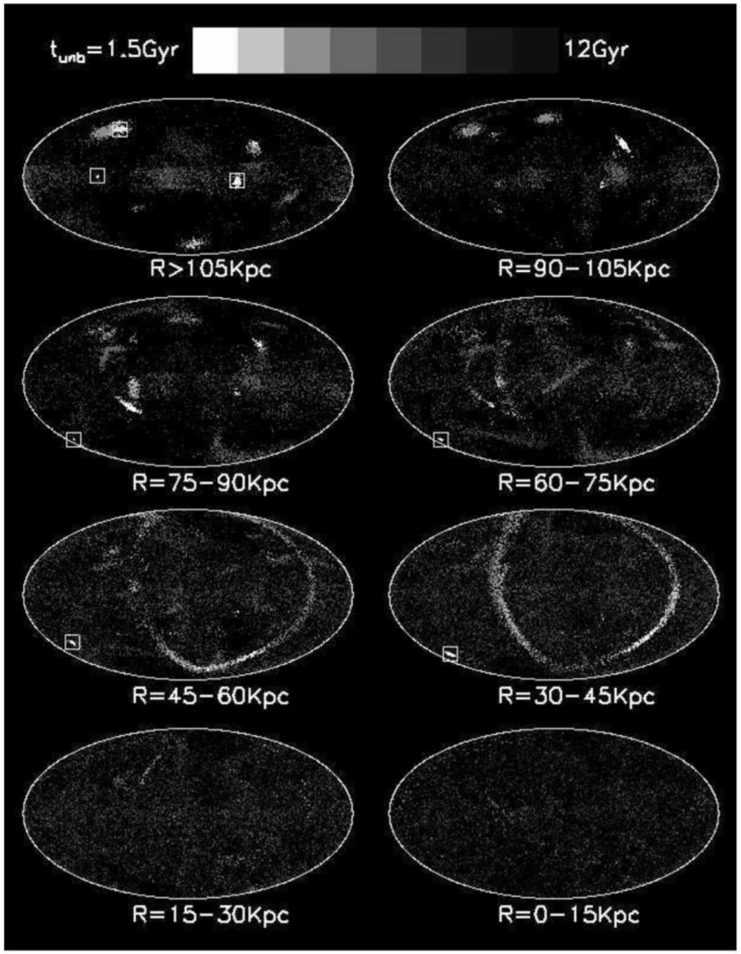
Cosmology and the stellar halo



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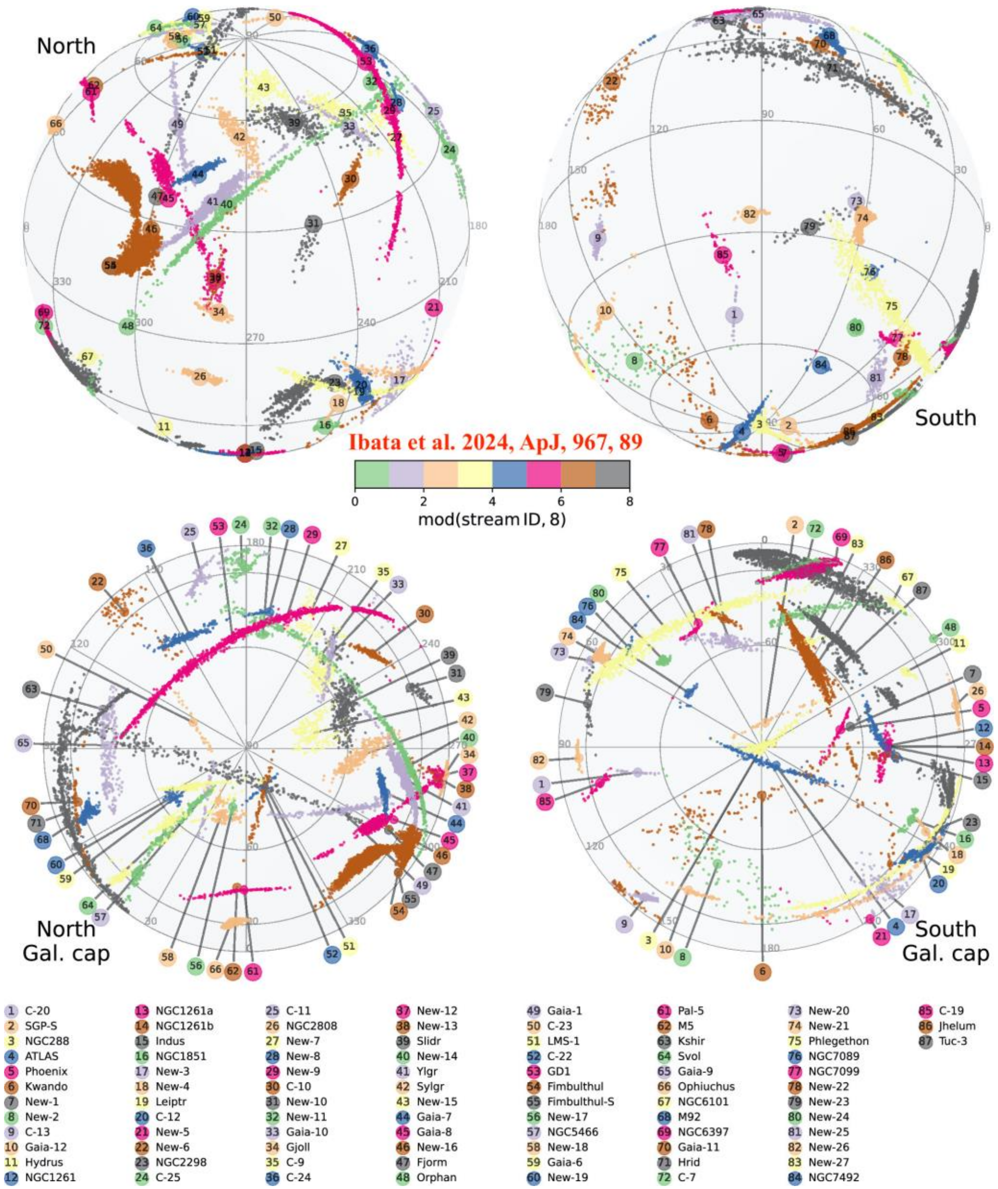
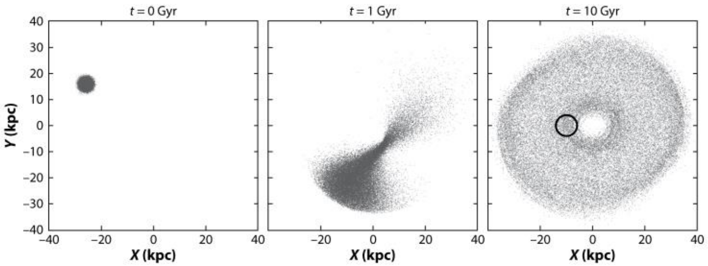
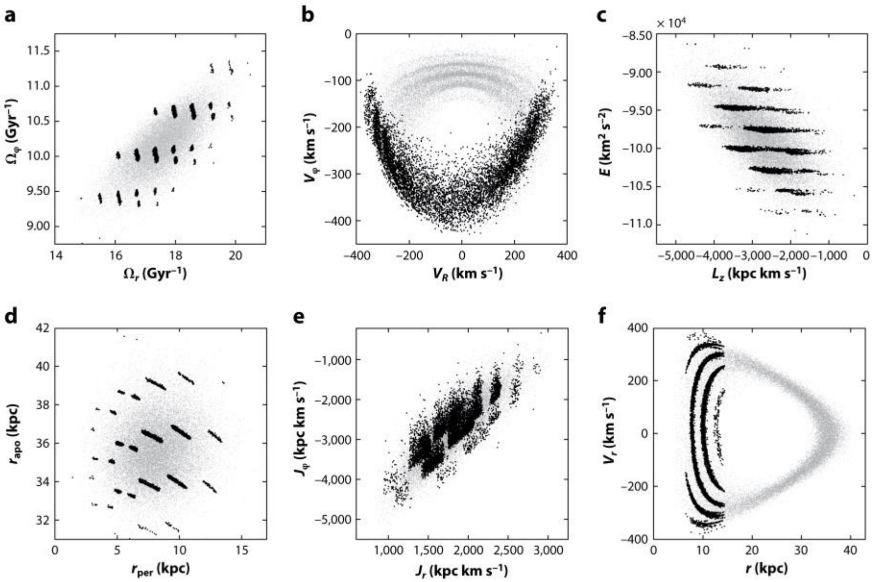
Gaia measures 2024
Only spatially coherent structures



Theory: completely disrupted satellites





Helmi A. 2020.
Annu. Rev. Astron. Astrophys. 58:205–56

Helmi 2025, ARA&A, 58, 205

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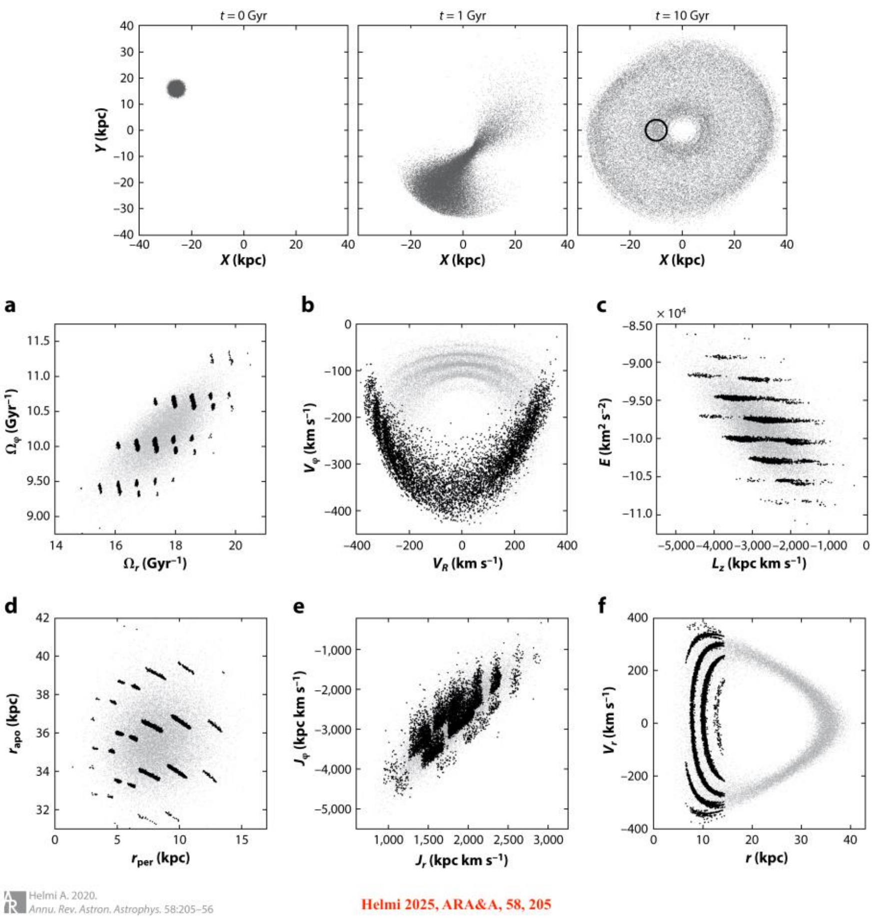
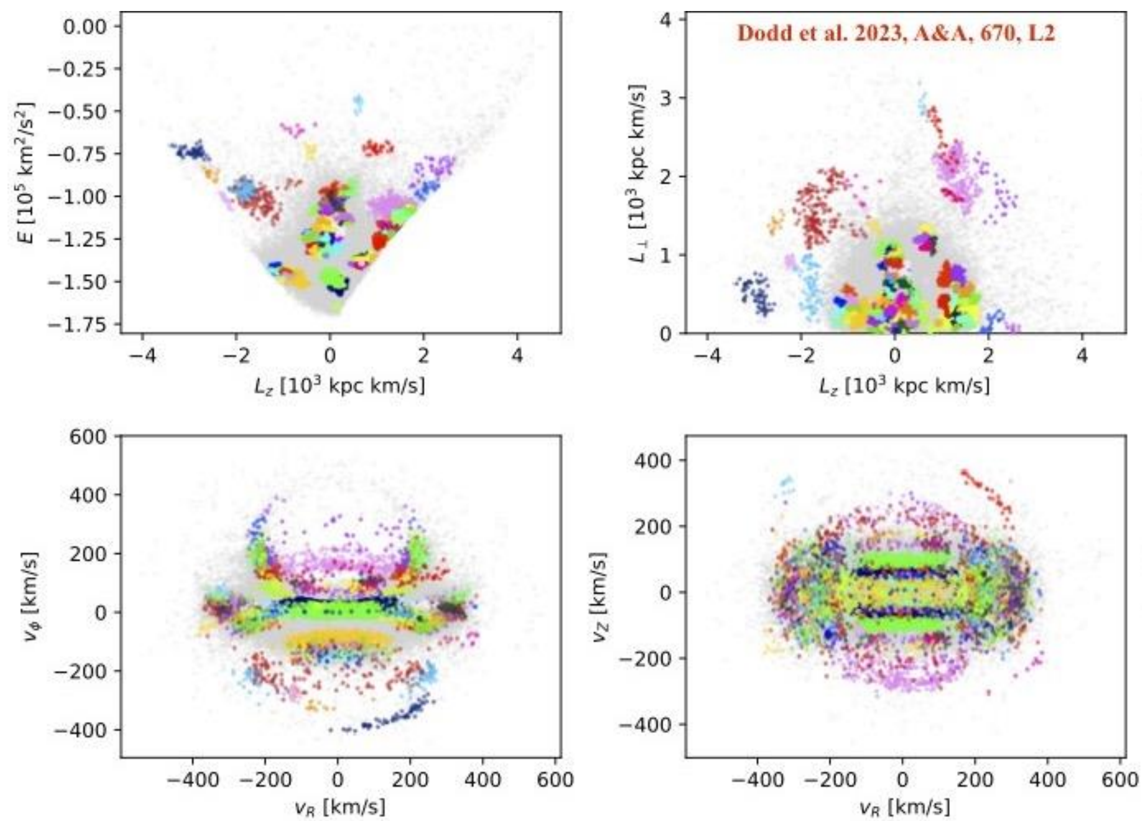
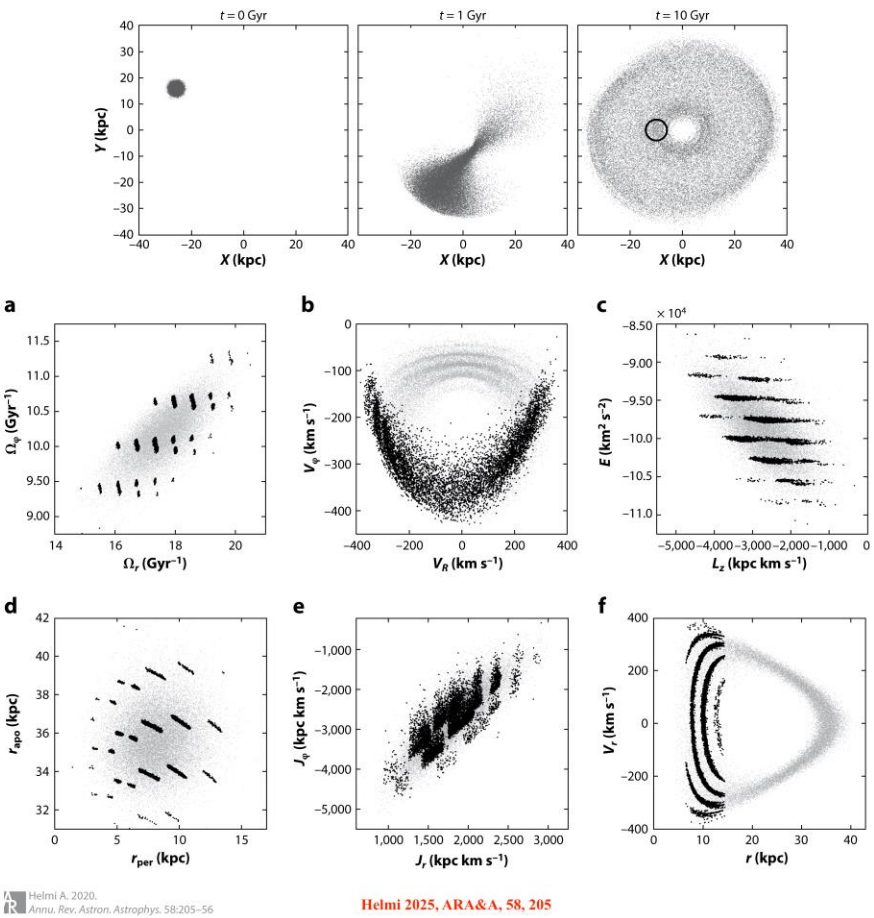


Helmi 2025, ARA&A, 58, 205

Gaia measurements 2023: candidate completely disrupted satellites



Theory: completely disrupted satellites



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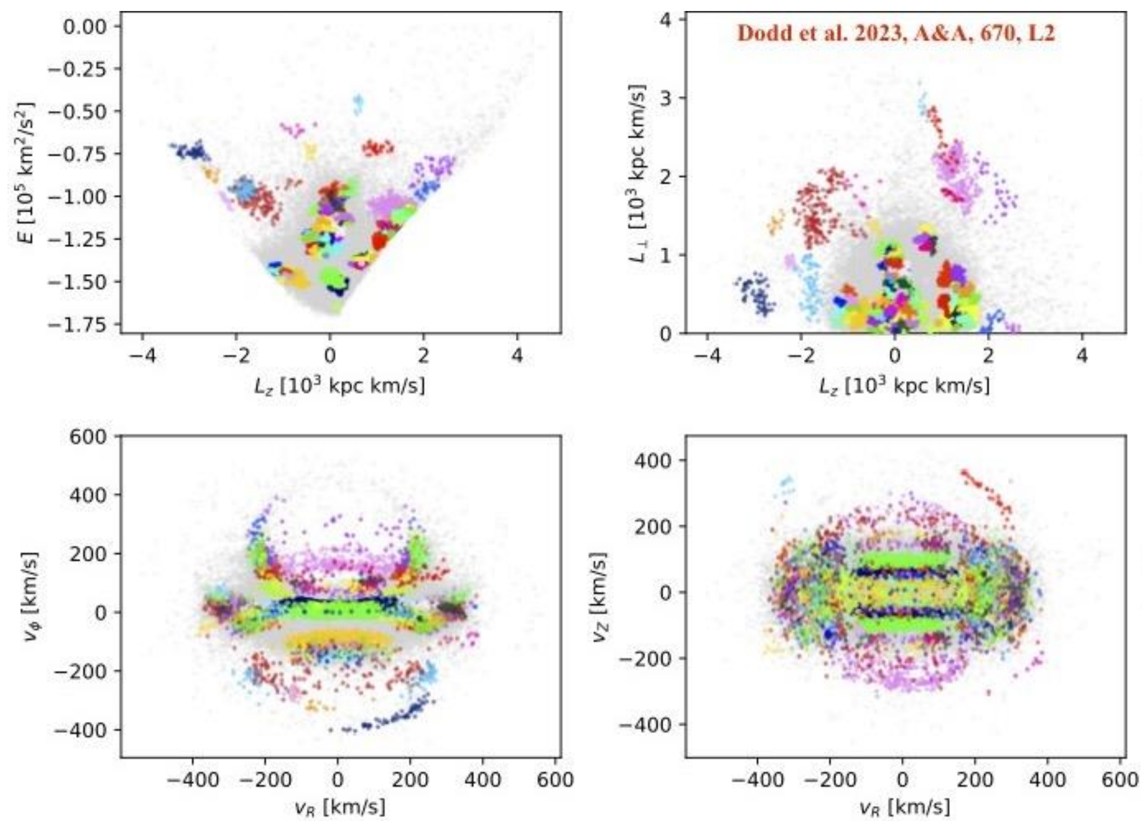

Contamination! Different portions of the same relic identified as two separate entities (Thomas et al. 2025 arXiv:2504.10398).
Much work to be done to get a clear map.

Letter | Published: 31 October 2018

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

Amina Helmi, Carine Babusiaux, Helmer H. Koppelman, Davide Massari, Jovan Veljanoski & Anthony G. A. Brown

Nature 563, 85–88 (2018) | Cite this article

Abstract

The assembly of our Galaxy can be reconstructed using the motions and chemistry of individual stars[1,2]. Chemo-dynamical studies of the stellar halo near the Sun have indicated the presence of multiple components[3], such as streams[4] and clumps[5], as well as correlations between the stars' chemical abundances and orbital parameters[6–8]. Recently, analyses of two large stellar surveys[9,10] revealed the presence of a well populated elemental abundance sequence[7,11], two distinct sequences in the colour–magnitude diagram[12] and a prominent, slightly retrograde kinematic structure[13,14] in the halo near the Sun, which may trace an important accretion event experienced by the Galaxy[15]. However, the link between these observations and their implications for Galactic history is not well understood. Here we report an analysis of the kinematics, chemistry, age and spatial distribution of stars that are mainly linked to two major Galactic components: the thick disk and the stellar halo. We demonstrate that the inner halo is dominated by debris from an object that at infall was slightly more massive than the Small Magellanic Cloud, and which we refer to as Gaia–Enceladus. The stars that originate in Gaia–Enceladus cover nearly the full sky, and their

Co-formation of the disc and the stellar halo★

V. Belokurov,[1,2]† D. Erkal,[1,3] N. W. Evans,[1] S. E. Koposov[1,4] and A. J. Deason[5]
[1]Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
[2]Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA
[3]Department of Physics, University of Surrey, Guildford GU2 7XH
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[5]Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK

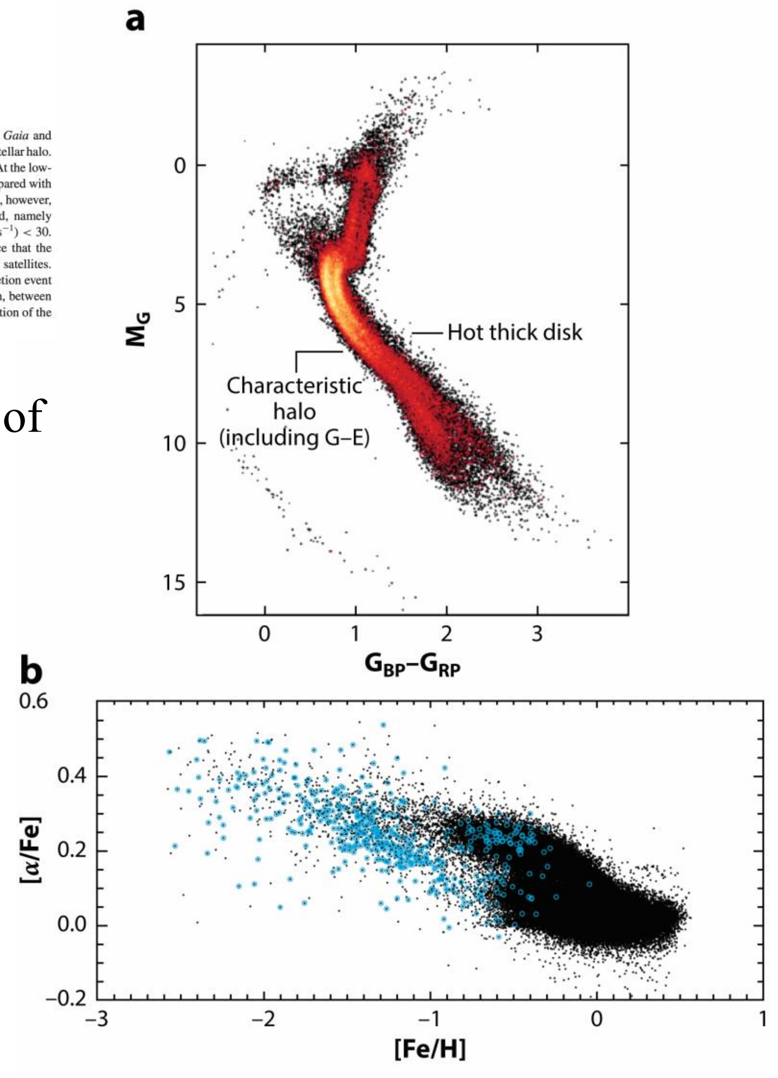
Accepted 2018 April 17. Received 2018 April 16; in original form 2018 February 9

ABSTRACT

Using a large sample of main sequence stars with 7D measurements supplied by *Gaia* and SDSS, we study the kinematic properties of the local (within ~10 kpc from the Sun) stellar halo. We demonstrate that the halo's velocity ellipsoid evolves strongly with metallicity. At the low-[Fe/H] end, the orbital anisotropy (the amount of motion in the radial direction compared with the tangential one) is mildly radial, with $0.2 < \beta < 0.4$. For stars with [Fe/H] > -1.7, however, we measure extreme values of $\beta \sim 0.9$. Across the metallicity range considered, namely $-3 <$ [Fe/H] < -1, the stellar halo's spin is minimal, at the level of $20 < \bar{v}_\theta(\mathrm{km\,s^{-1}}) < 30$. Using a suite of cosmological zoom-in simulations of halo formation, we deduce that the observed acute anisotropy is inconsistent with the continuous accretion of dwarf satellites. Instead, we argue, the stellar debris in the inner halo was deposited in a major accretion event by a satellite with $M_{vir} > 10^{10} M_\odot$ around the epoch of the Galactic disc formation, between 8 and 11 Gyr ago. The radical halo anisotropy is the result of the dramatic radialization of the massive progenitor's orbit, amplified by the action of the growing disc.

Discovery that the local halo is dominated by the remnant of a significant merger occurred ≈10 Gyr ago: GSE

Measurable effects on thick & thin disc properties



Helmi A. 2020.
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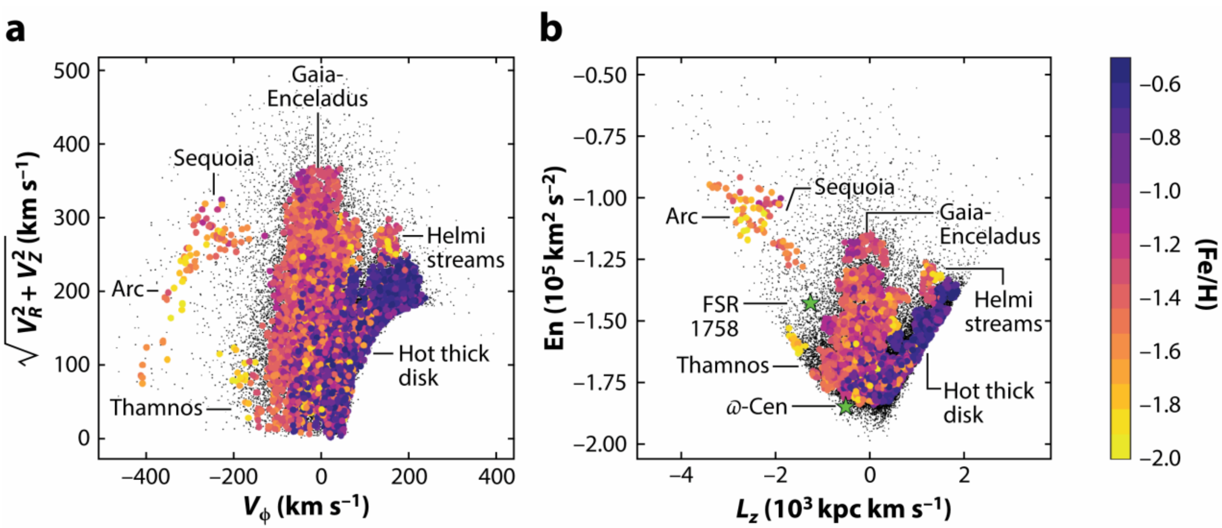

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[3]Department of Physics, University of Surrey, [...]
[4]Department of Physics, M[...]
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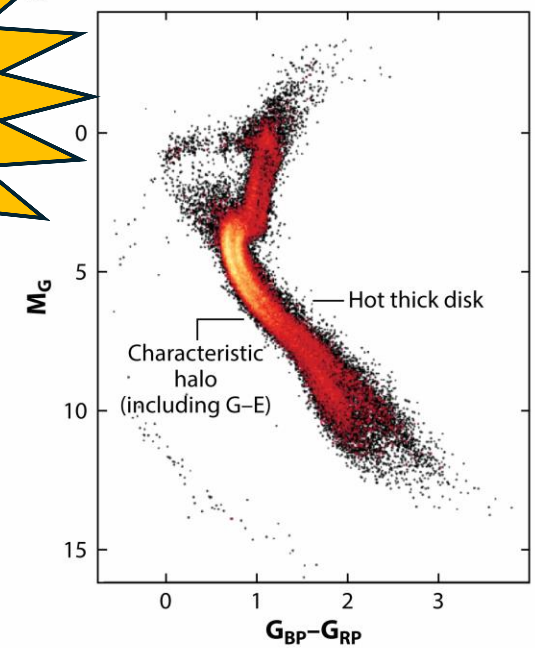
Accepted 2018 Apri[...]

Using [...] obs[...] In [...] a satellite wi[...], between 8 and 11 Gyr a[...] on of the massive proge[...] s orbit, an[...] the [...] c.

Not only astrometry.
High-precision all-sky photometry is a key feature

a



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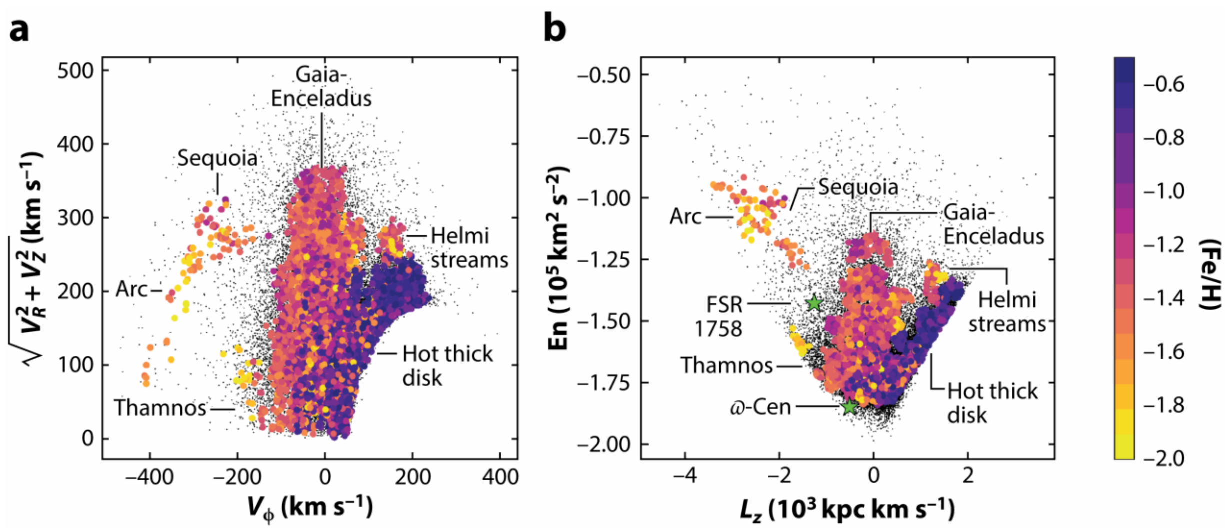

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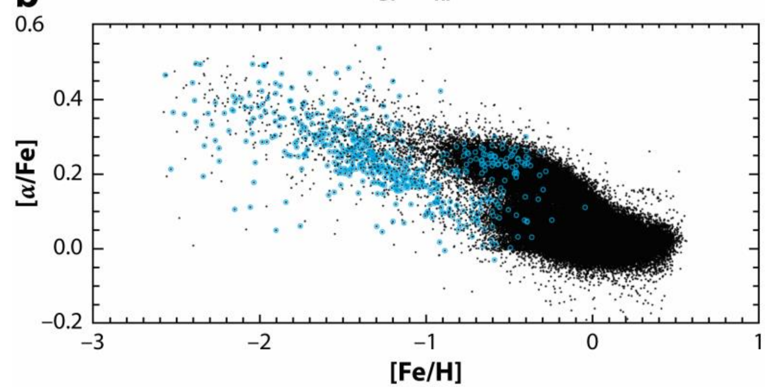

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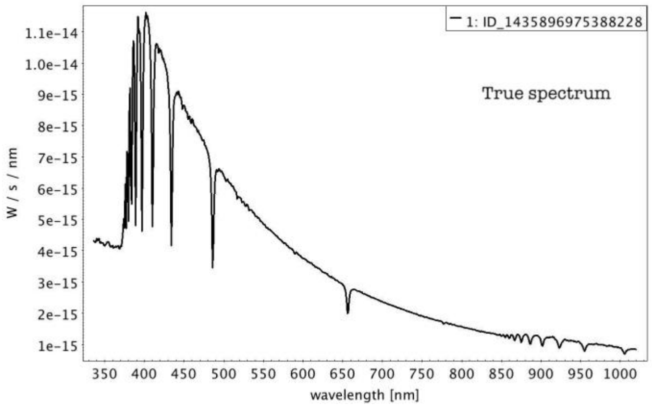
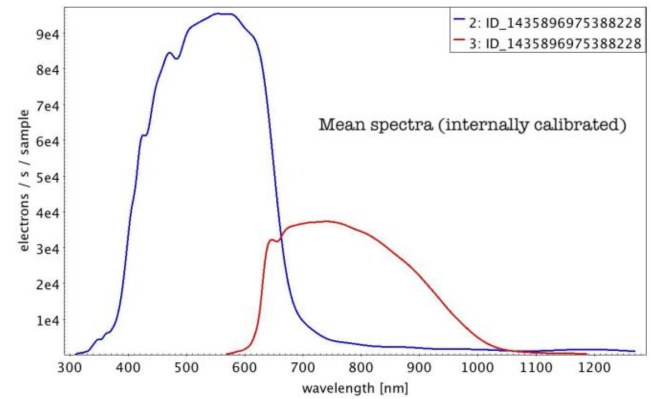
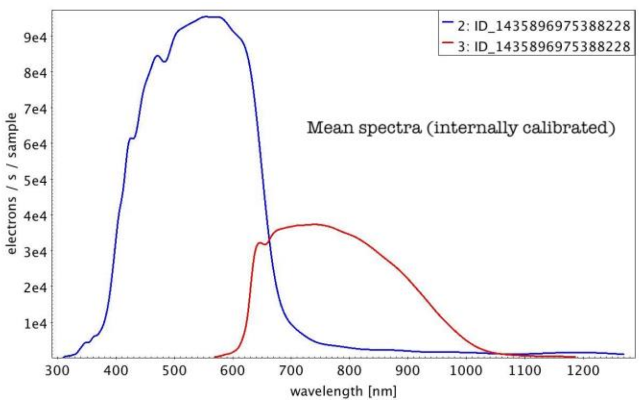
Gaia DR3: not only astrometry and photometry in three broad bands (2 bn stars) and RV for 33 million stars, but also **spectrophotometry in the range 330 nm ≲ λ ≲ 1100 nm with spectral resolution 25 ≲ λ/Δλ ≲ 80 for 220 million stars**

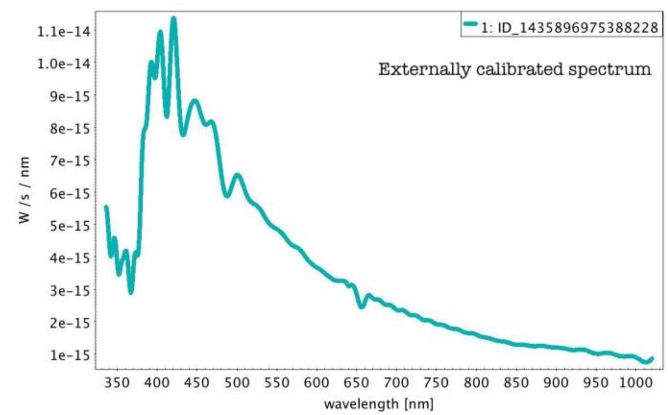


Observation by Gaia telescope + BP/RP spectrographs + internal calibration





Instrument model
External calibration process



Do these spectra carry any info in addition to a broad spectral classification?

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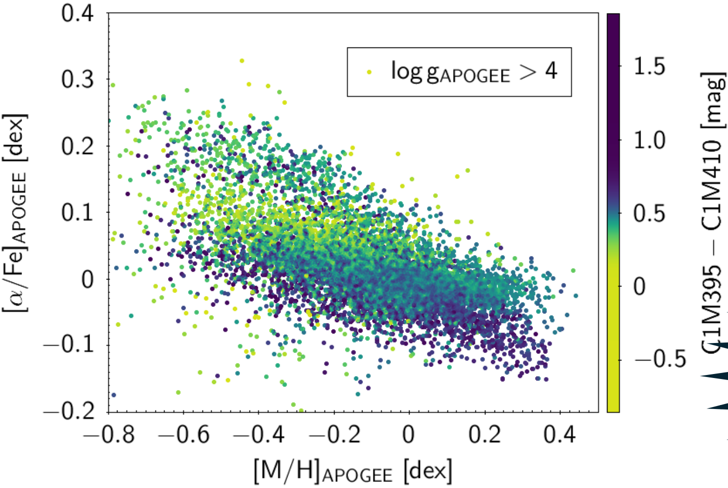
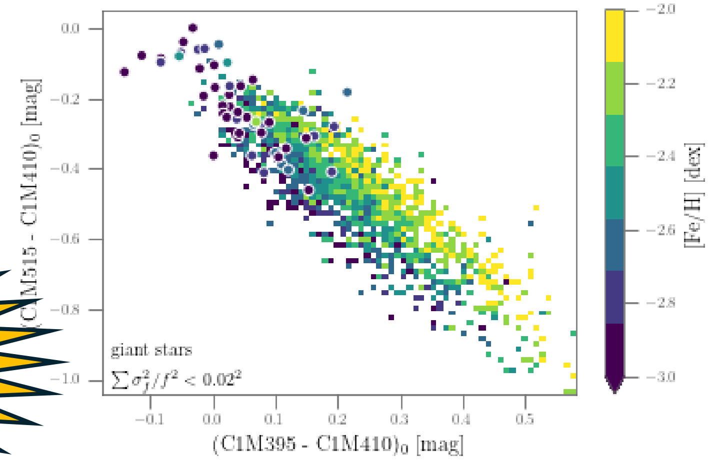
Yes, they do!



Metallicity!
[α/Fe] ratios!



Many groups around the world have extracted astrophysical parameters and/or metallicity and/or [α/Fe] ratios from these spectra using a variety of machine learning or classical approaches:

Andrae et al. 2023, Bellazzini et al. 2023, Hattori et al. 2024, Martin et l. 2024, Huson et al 2025, Yang et al. 2025

Do these spectra carry any info in addition to a broad spectral classification?

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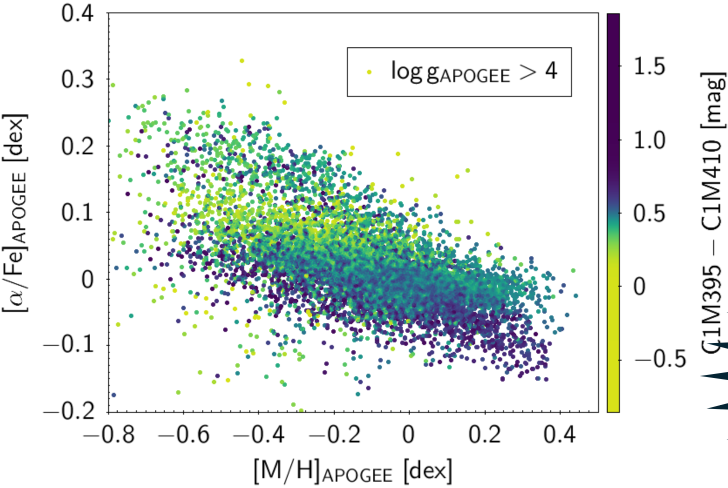

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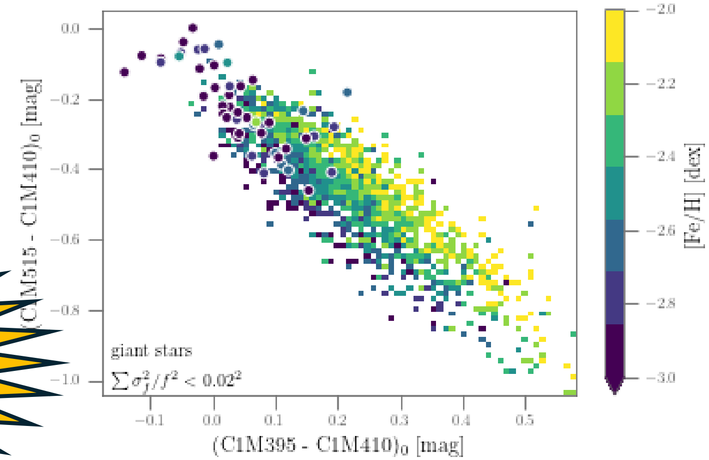
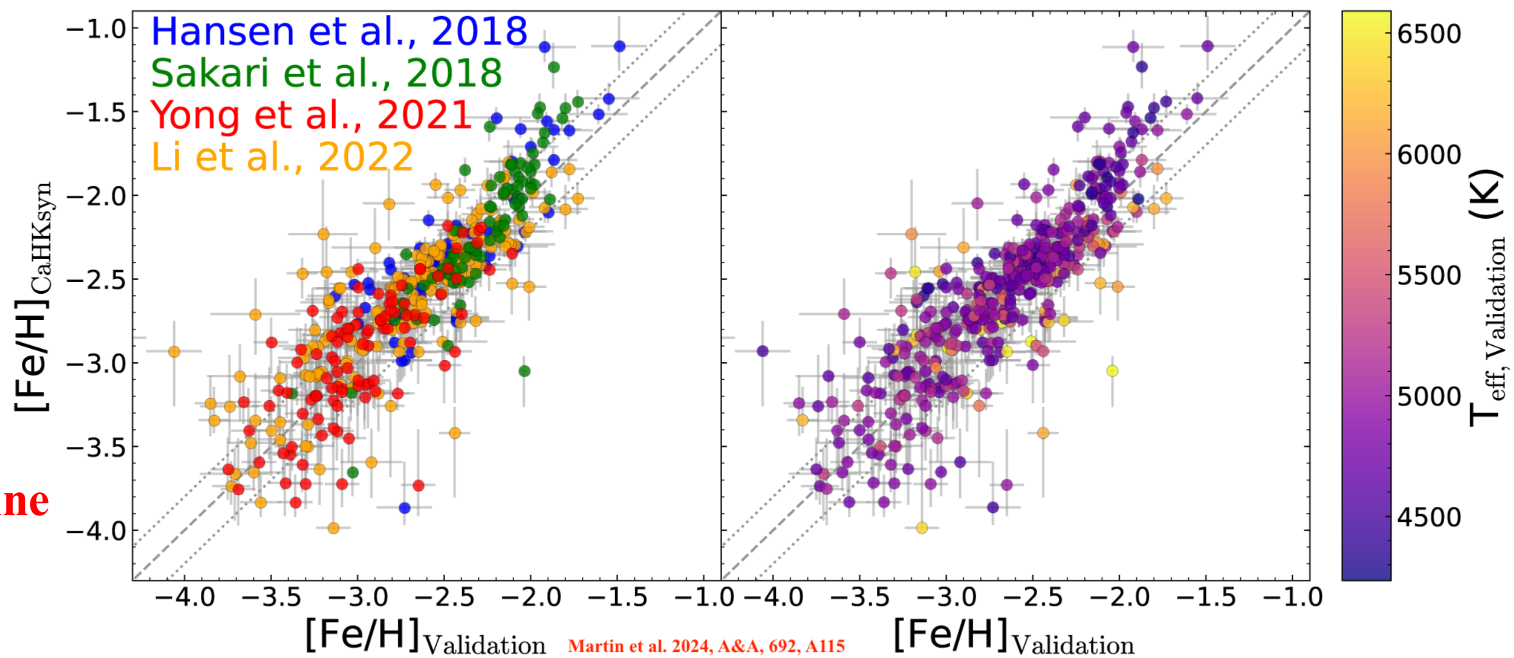




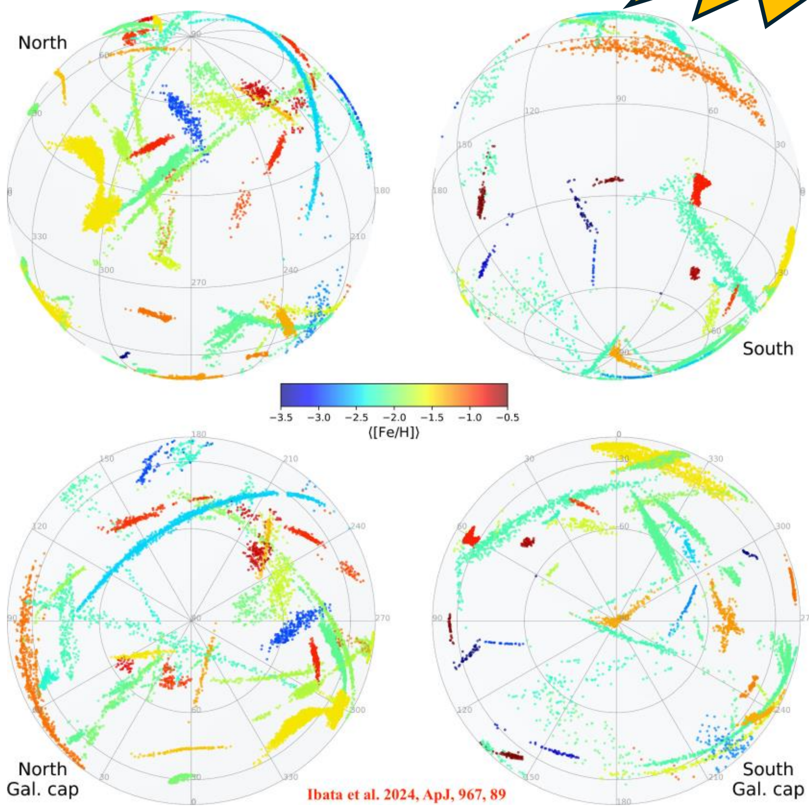
Martin et al. 2024, A&A, 692, A115

Making Pristine all-sky with Gaia

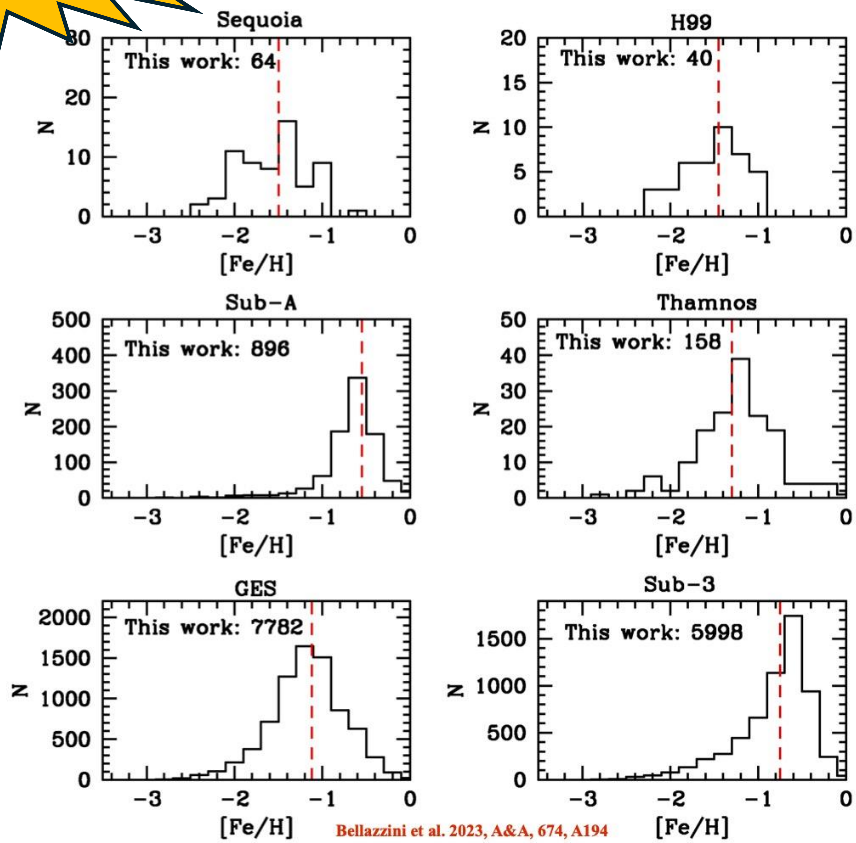
Then what we can do with the metallicity of million stars?

Look into the chemical composition of the relics of the MW hierarchical build-up!

Opening completely new dimensions!



Ibata et al. 2024, ApJ, 967, 89



Bellazzini et al. 2023, A&A, 674, A194

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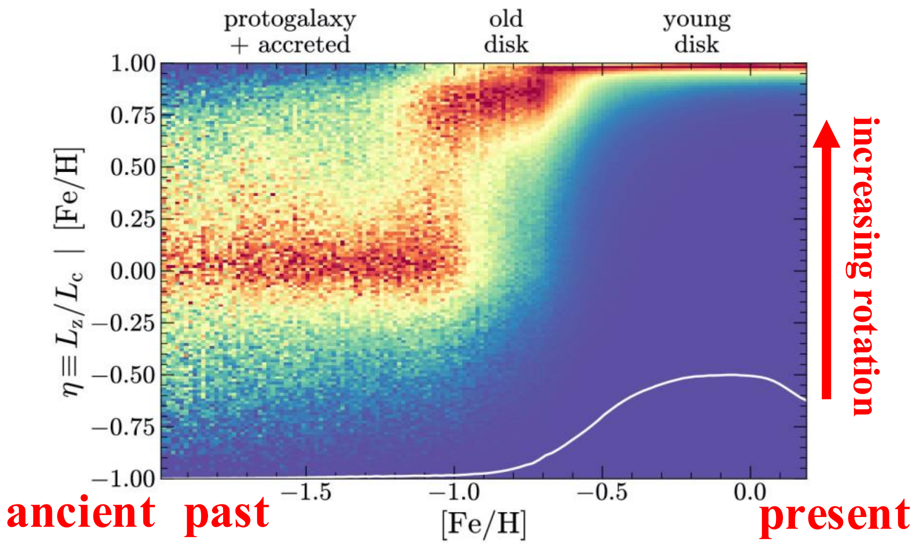
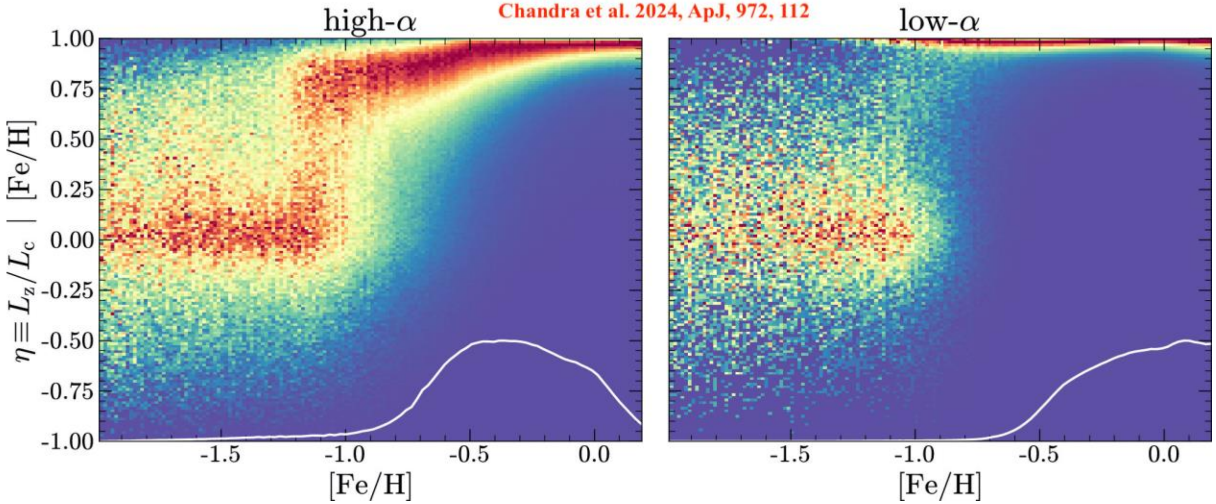
Trace the evolution of the MW as a disc galaxy using metallicity as a marker of time!



Chandra et al. 2024, ApJ, 972, 112



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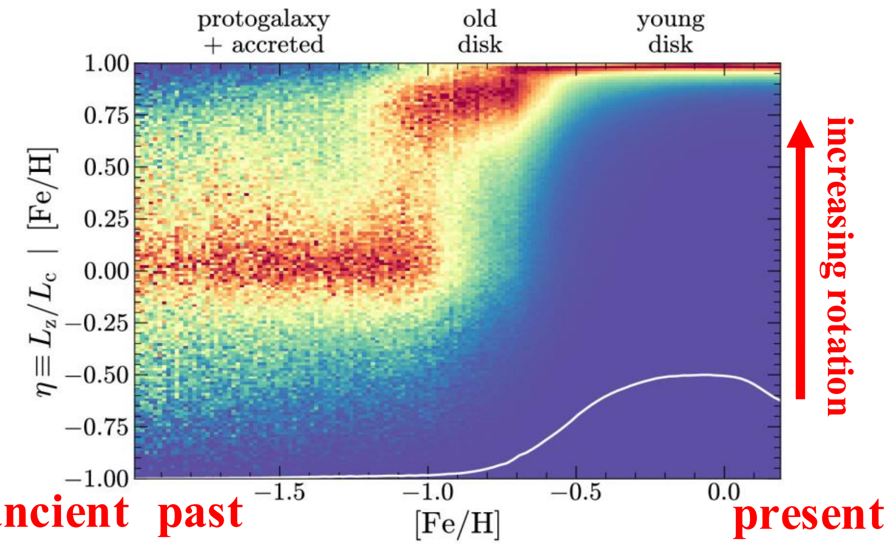
Unprecedented view of the evolution of our Galaxy!



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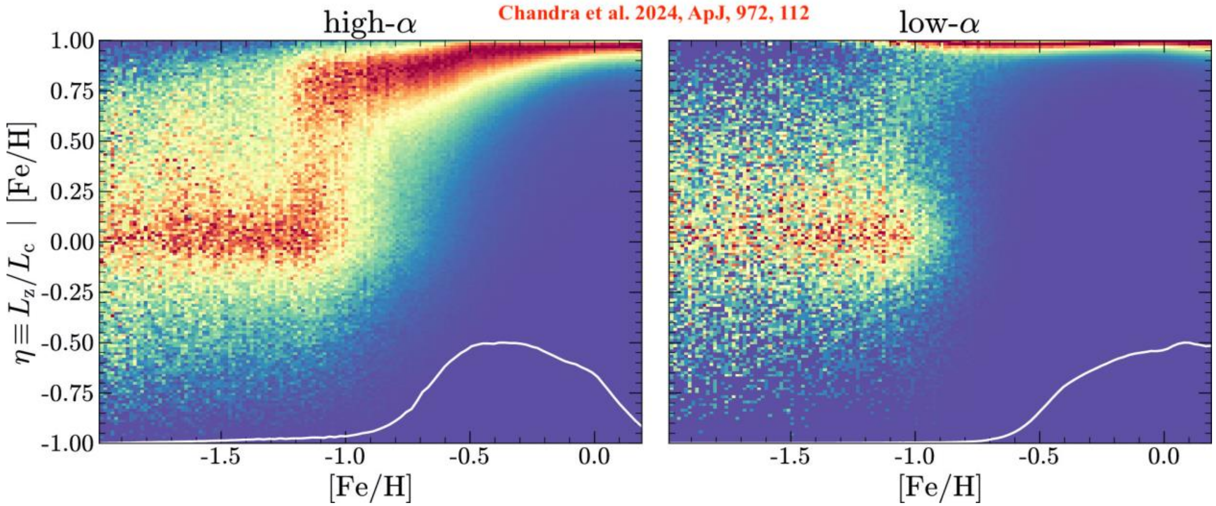
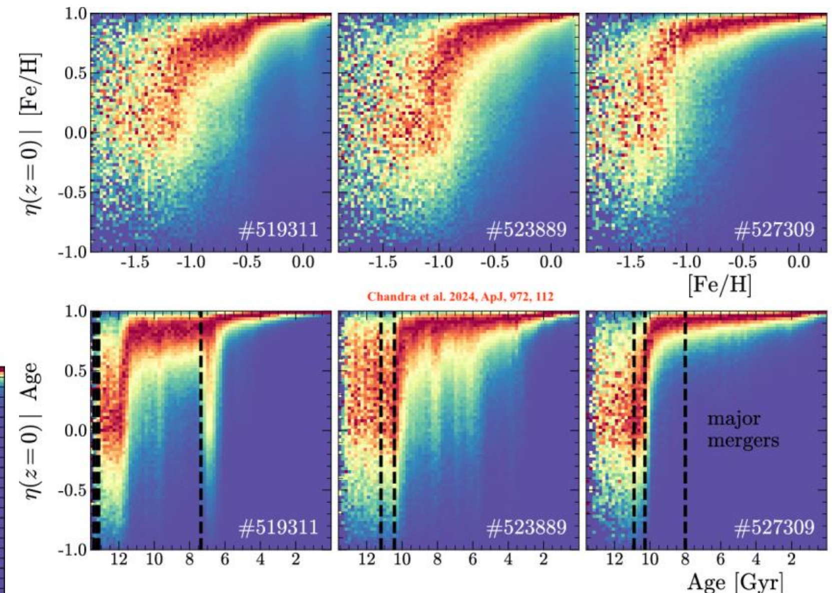
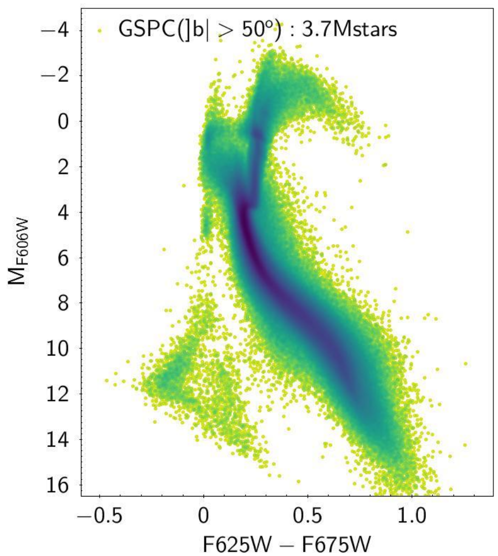


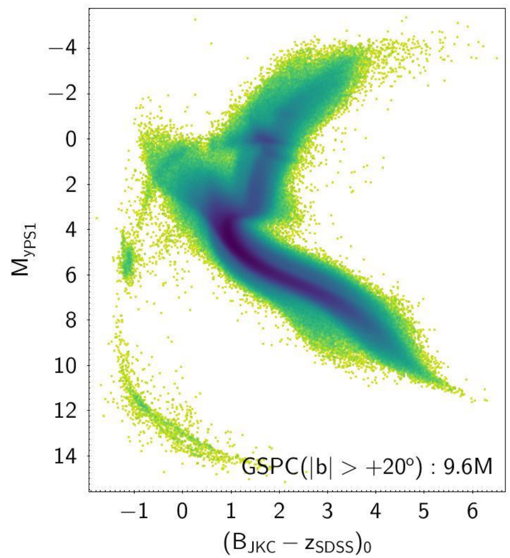


Counterparts in numerical Simulations: observations matches Theoretical expectations

Then what we can do with very low R spectrophotometry of million stars?

All-sky flux-calibrated synthetic photometry :
calibrate your own survey / photometric system





The worldwide reference dataset for photometric calibration and validation

A&A, 691, A42 (2024)
https://doi.org/10.1051/0004-6361/202449575

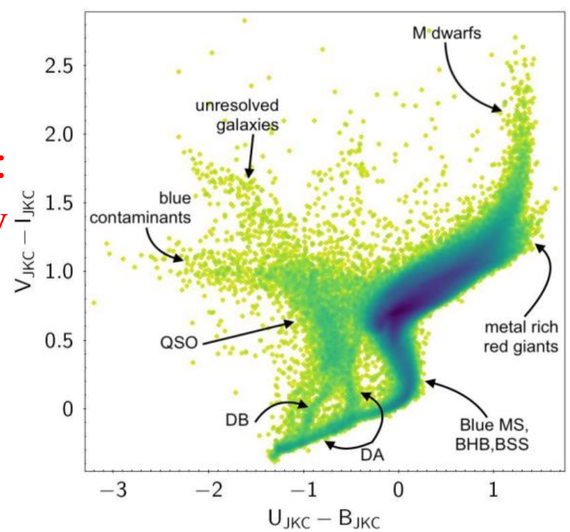
Astronomy & Astrophysics

The red giant branch tip in the SDSS, PS1, JWST, NGRST, and *Euclid* photometric systems

Calibration in optical passbands using *Gaia* DR3 synthetic photometry

M. Bellazzini* and R. Pascale

Only Gaia data here:
Synthetic photometry
from XP spectra



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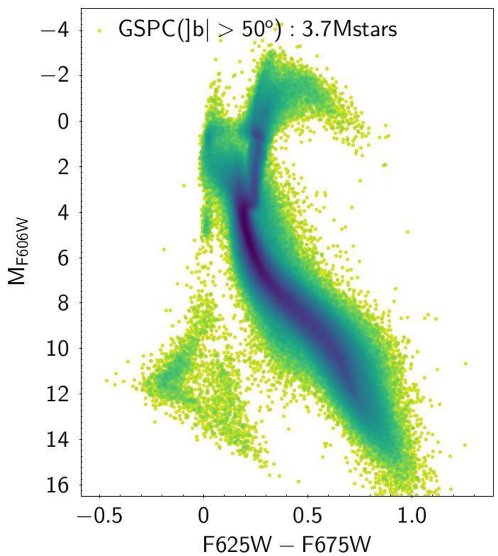
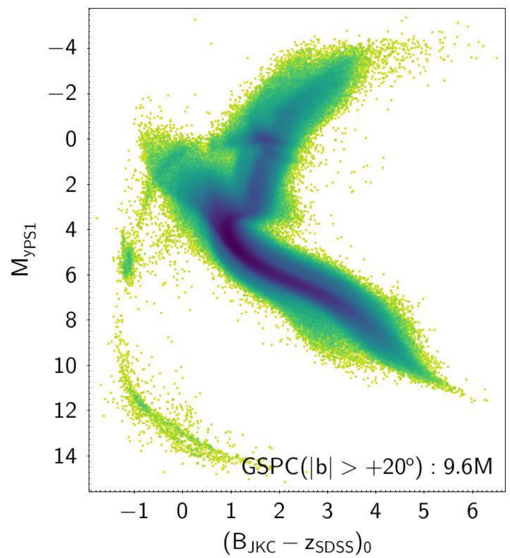




The worldwide reference dataset for photometric calibration and validation

Flying toward Mercury since October 2018 will reach its destination November 2026

A&A, 693, A115 (2025)
https://doi.org/10.1051/0004-6361/202451632

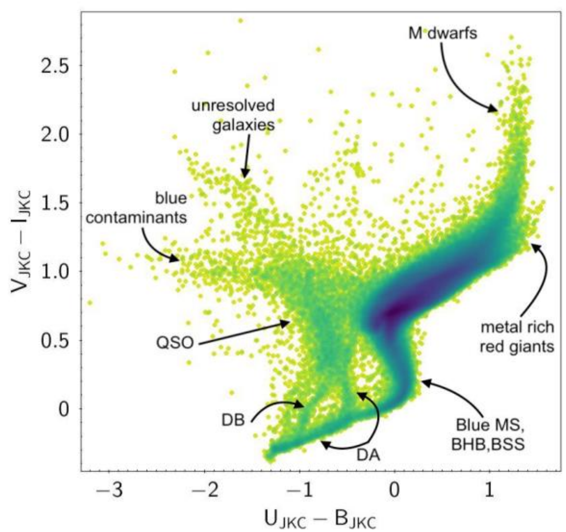
Astronomy & Astrophysics

Using *Gaia* and synthetic photometry for the absolute flux calibration of planetary cameras: The case of BepiColombo/SIMBIO-SYS

G. Munaretto[1,*], G. Cremonese[1], M. Bellazzini[2], P. Montegriffo[2], R. Sordo[1], R. La Grassa[1], C. Re[1], A. Tullo[1], and M. Messineo[3,2]

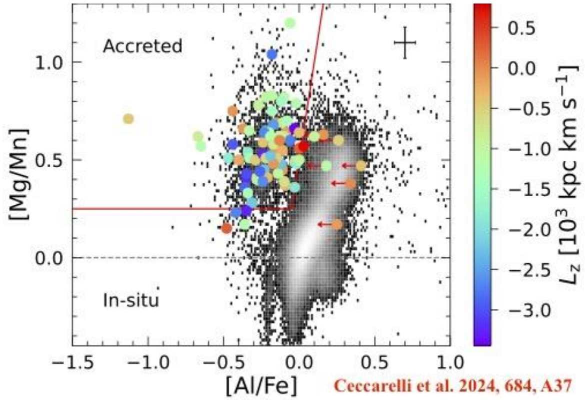
[1] INAF Astronomical Observatory of Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
[2] INAF Osservatorio di Astrofisica e Scienza dello Spazio, via Gobetti 93/3, 40129 Bologna, Italy
[3] Dipartimento di Fisica e Astronomia "Augusto Righi", Alma Mater Studiorum, Università di Bologna, via Gobetti 93/2, 40129 Bologna, Italy

Only Gaia data here: Synthetic photometry from XP spectra



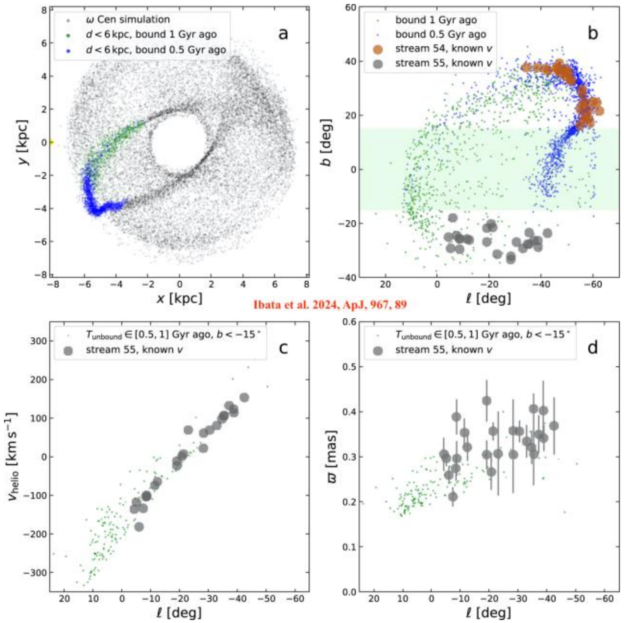
DR3: XP spectra for 220 million stars
DR4: XP spectra for >2 billion stars

There are tens of fascinating results, developments and follow-ups that would be worth reporting on…

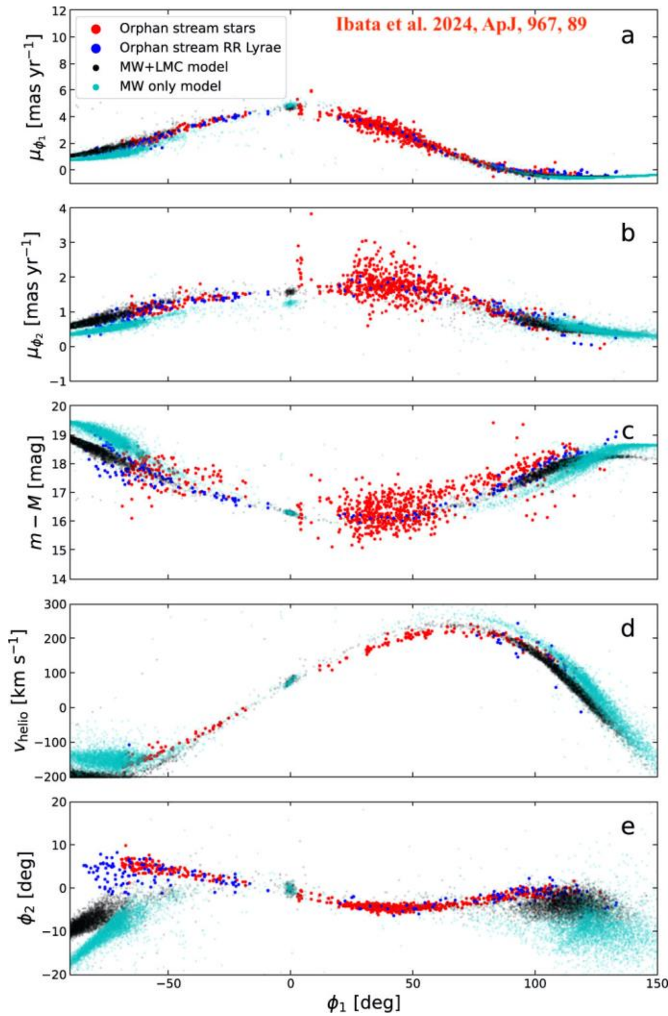


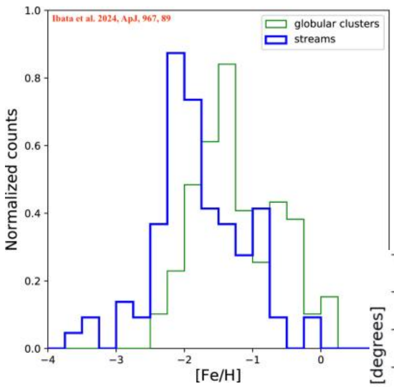
Elemental abundnces of stars in relics and tidal streams

The tidal stream of Omega Cen plays peekaboo across the MW disc: spotted out!



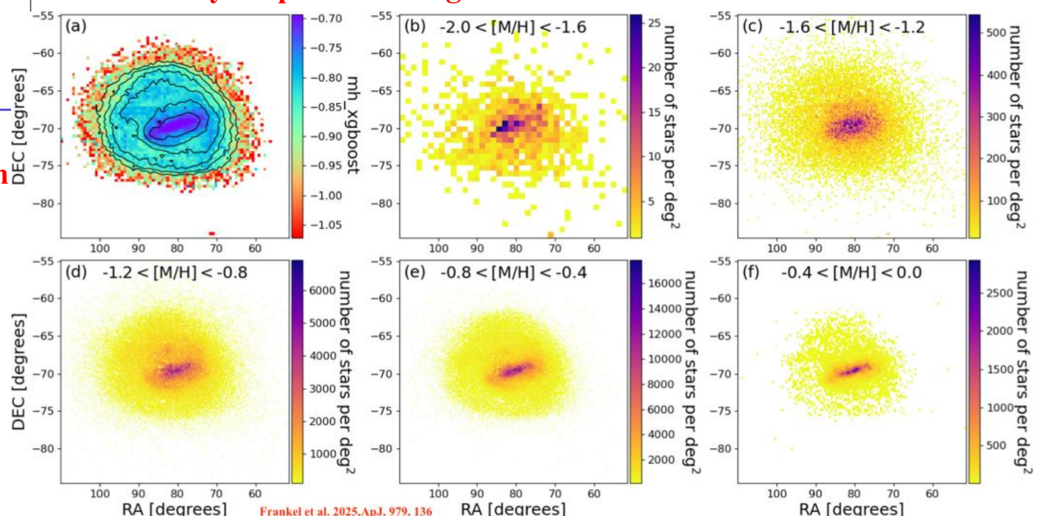
Gravitational effect of the LMC on the morphology and kinematics of thin tidal streams: detected!





MDF of disrupted GCs much more metal-poor than that of surviving ones

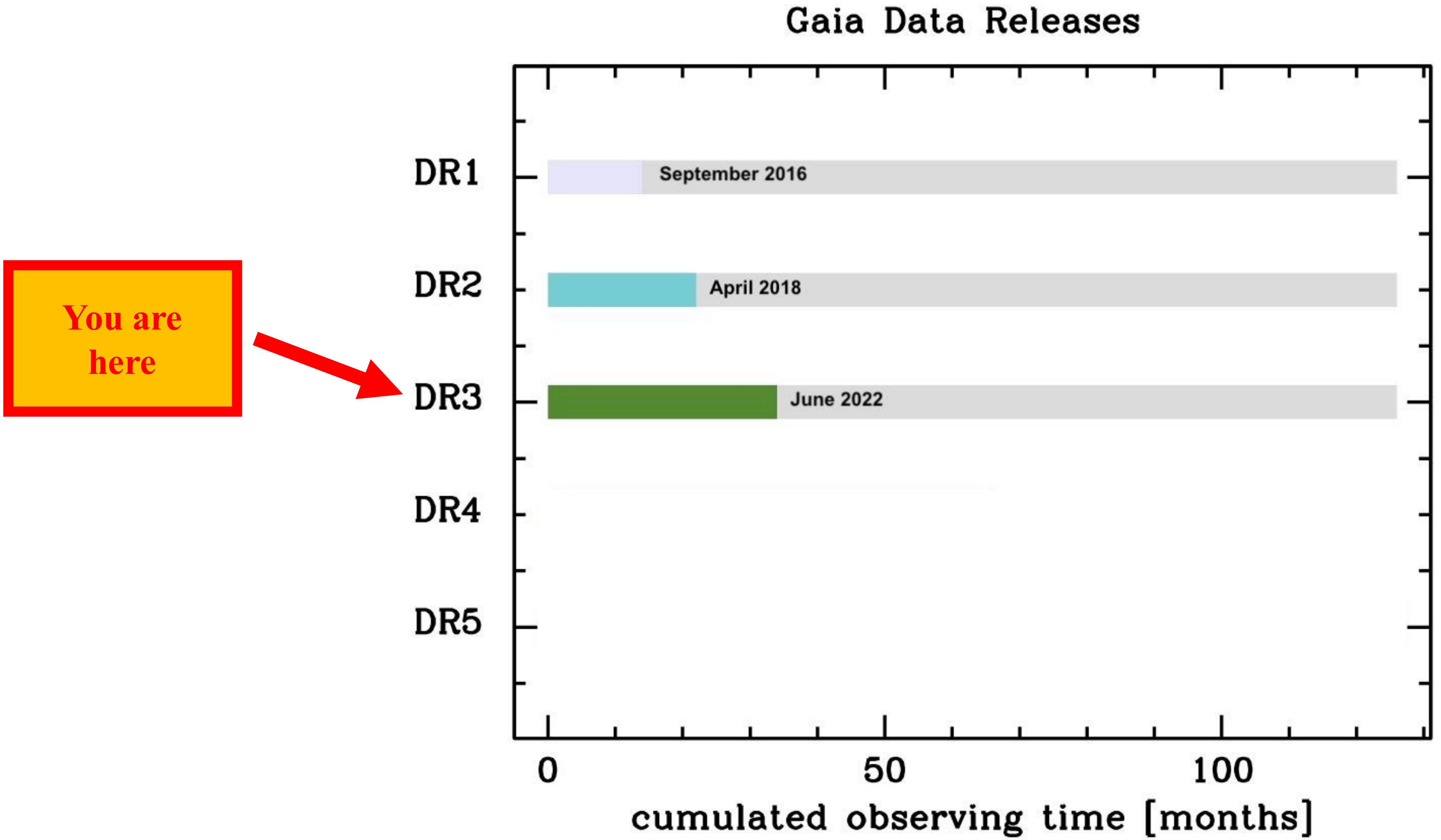
Metallicity maps of the Magellanic Clouds



See also Erkal et al. 2021, MNRAS, 506, 26: we see the halo response to the incoming LMC

… but it is very important to me to convey a specific message

Gaia: the best is still to come!



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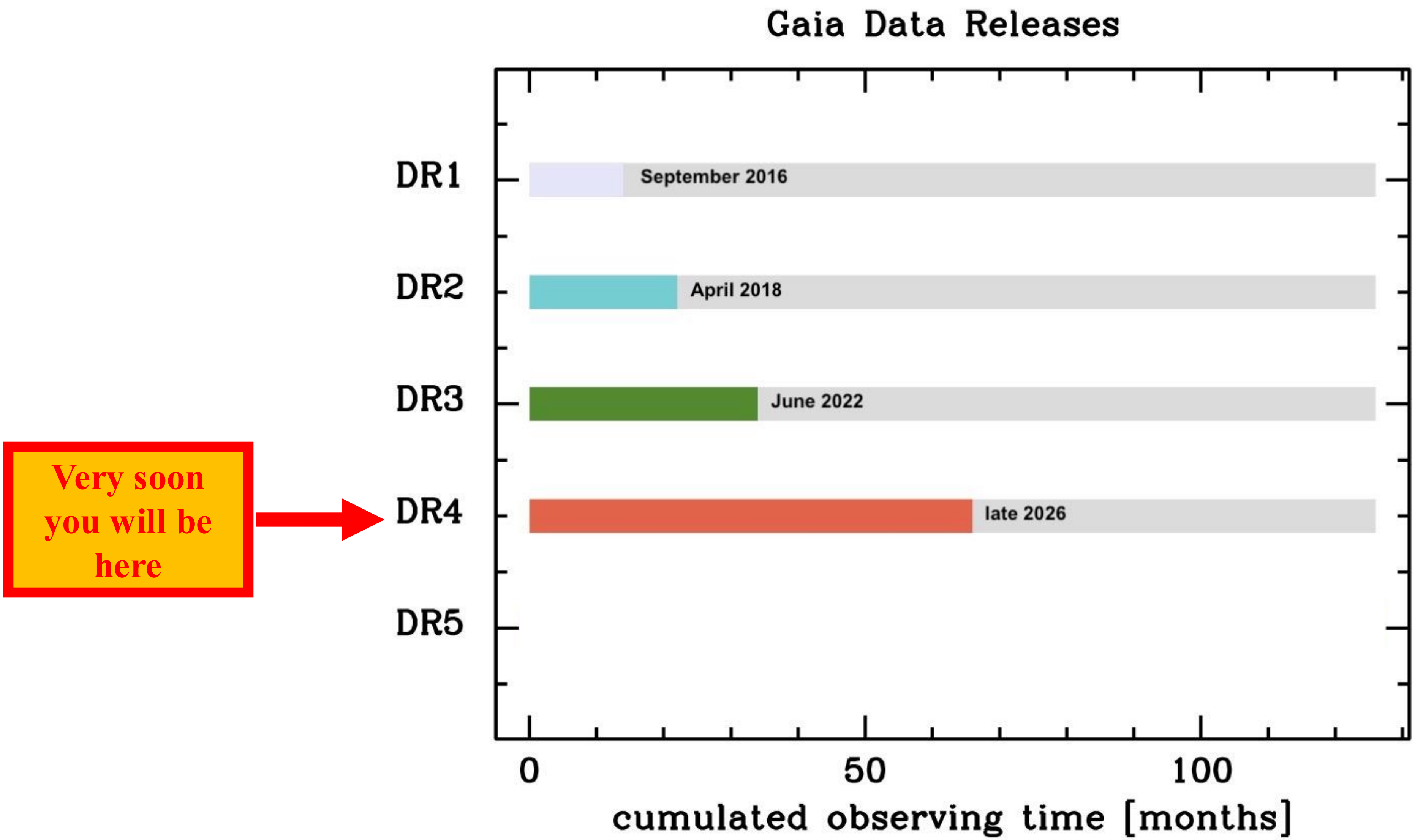
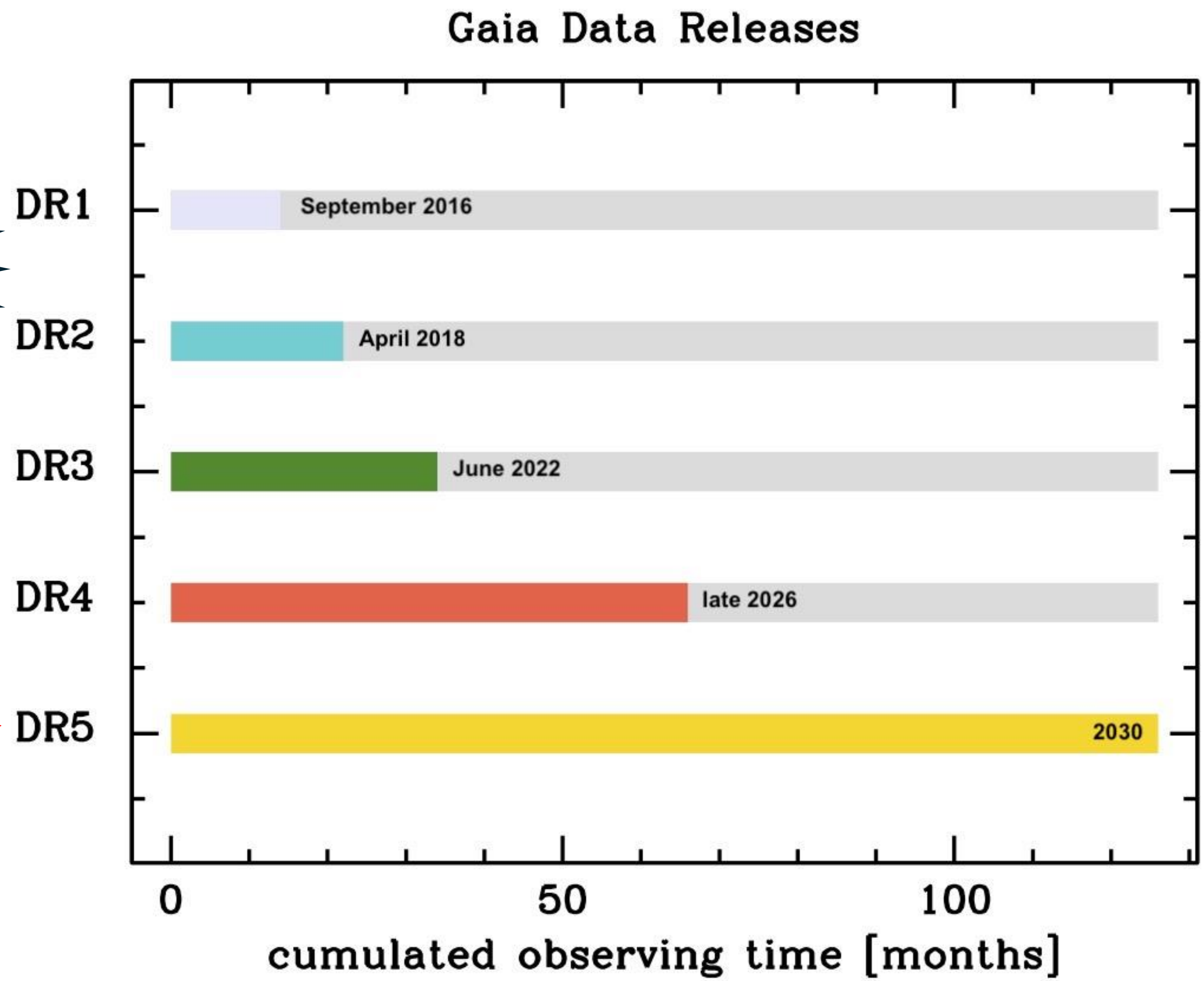


… but it is very important to me to convey a specific message

Gaia: the best is still to come!

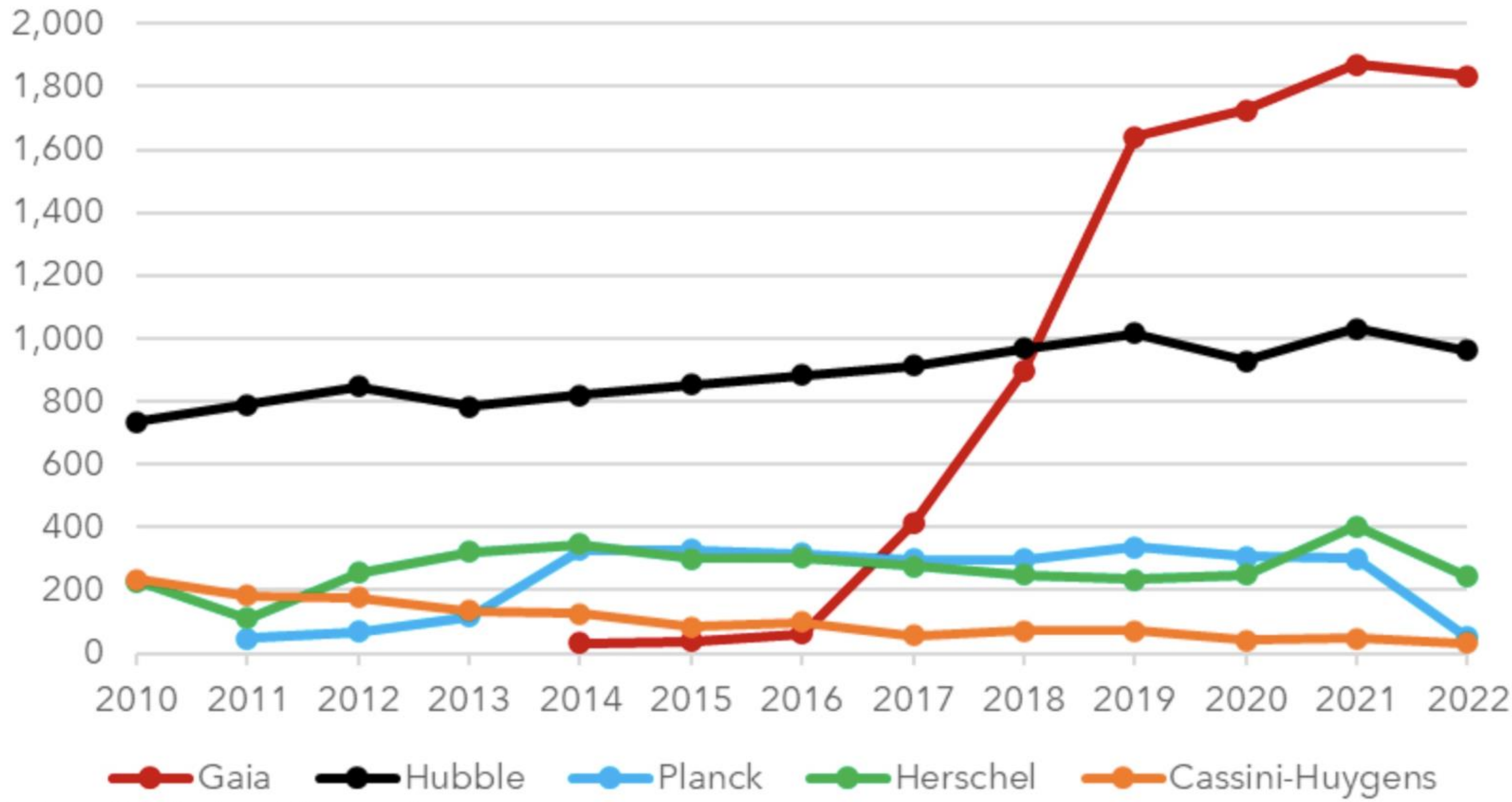
Doubling the amount of data at each release



And the full power of Gaia will become available only in 2030

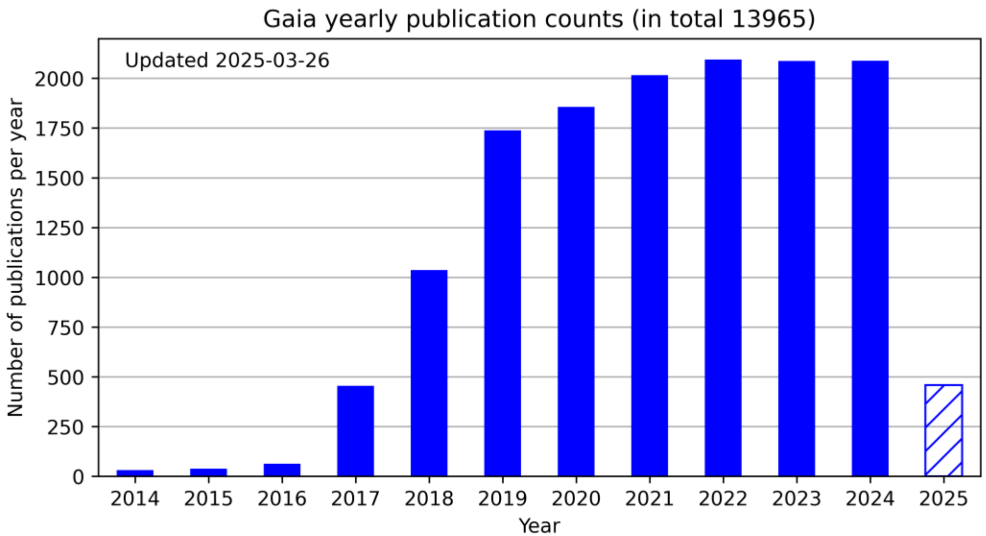
Gaia productivity overwhelmes any other mission

Figure 4 *Publications by year: selected space science missions*



Gaia Interim Impact Evaluation - UK Space Agency

Source: know.space analysis using NASA ADS and ESA-curated publication lists by mission



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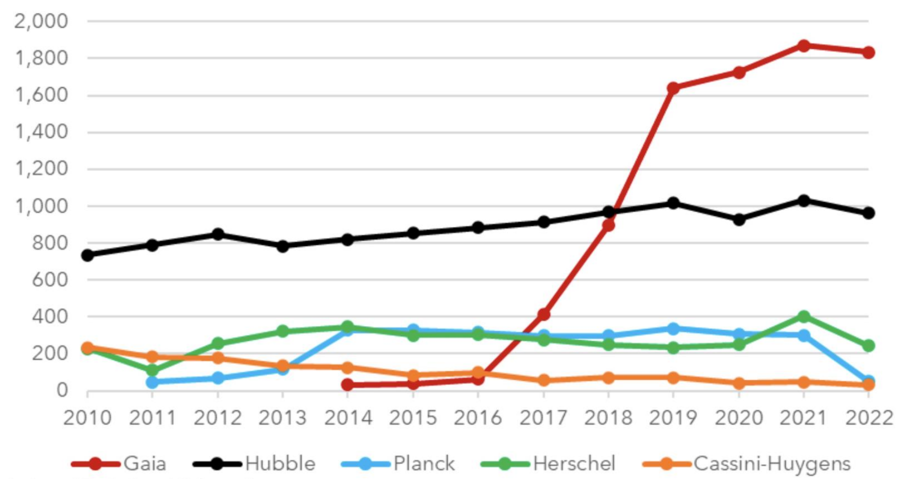
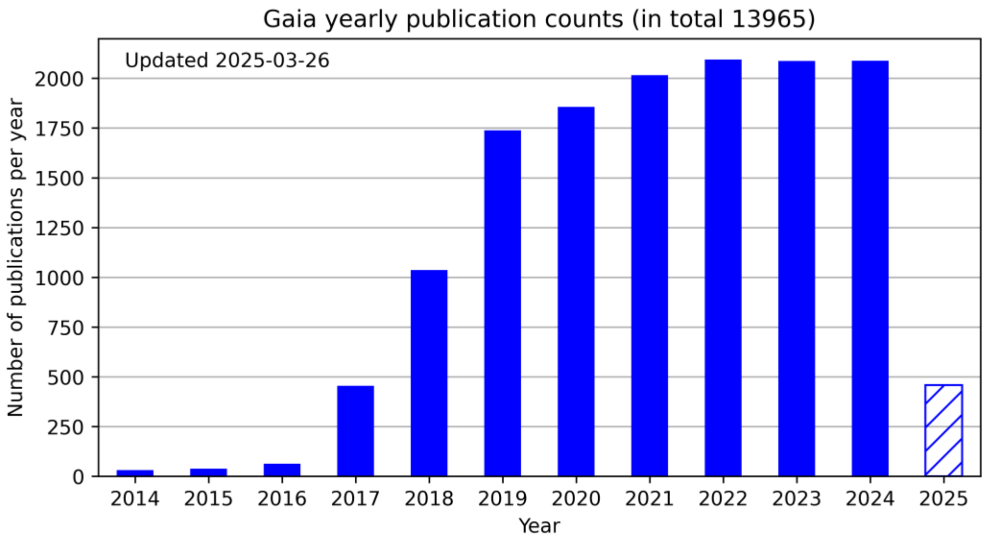


Gaia Interim Impact Evaluation - UK Space Agency

Source: know.space analysis using NASA ADS and ESA-curated publication lists by mission

And the best years are the forthcoming ones



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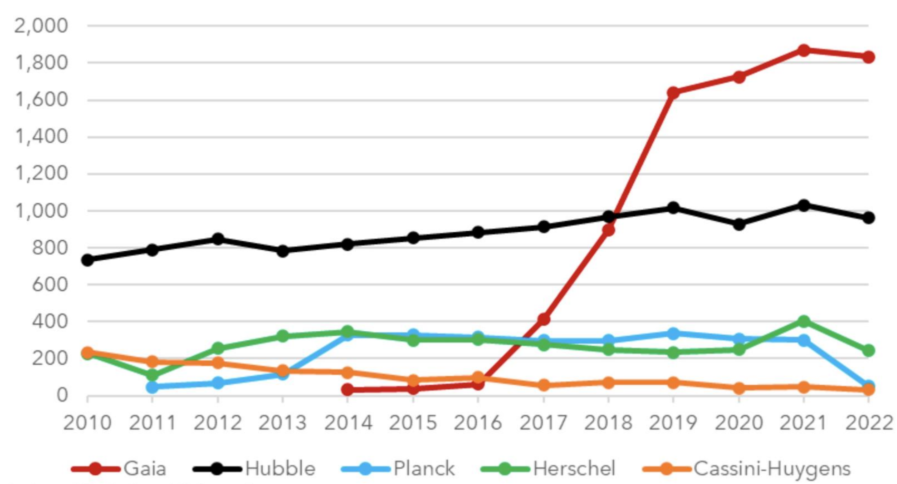

Gaia Interim Impact Evaluation - UK Space Agency

Source: know.space analysis using NASA ADS and ESA-curated publication lists by mission

Thank you