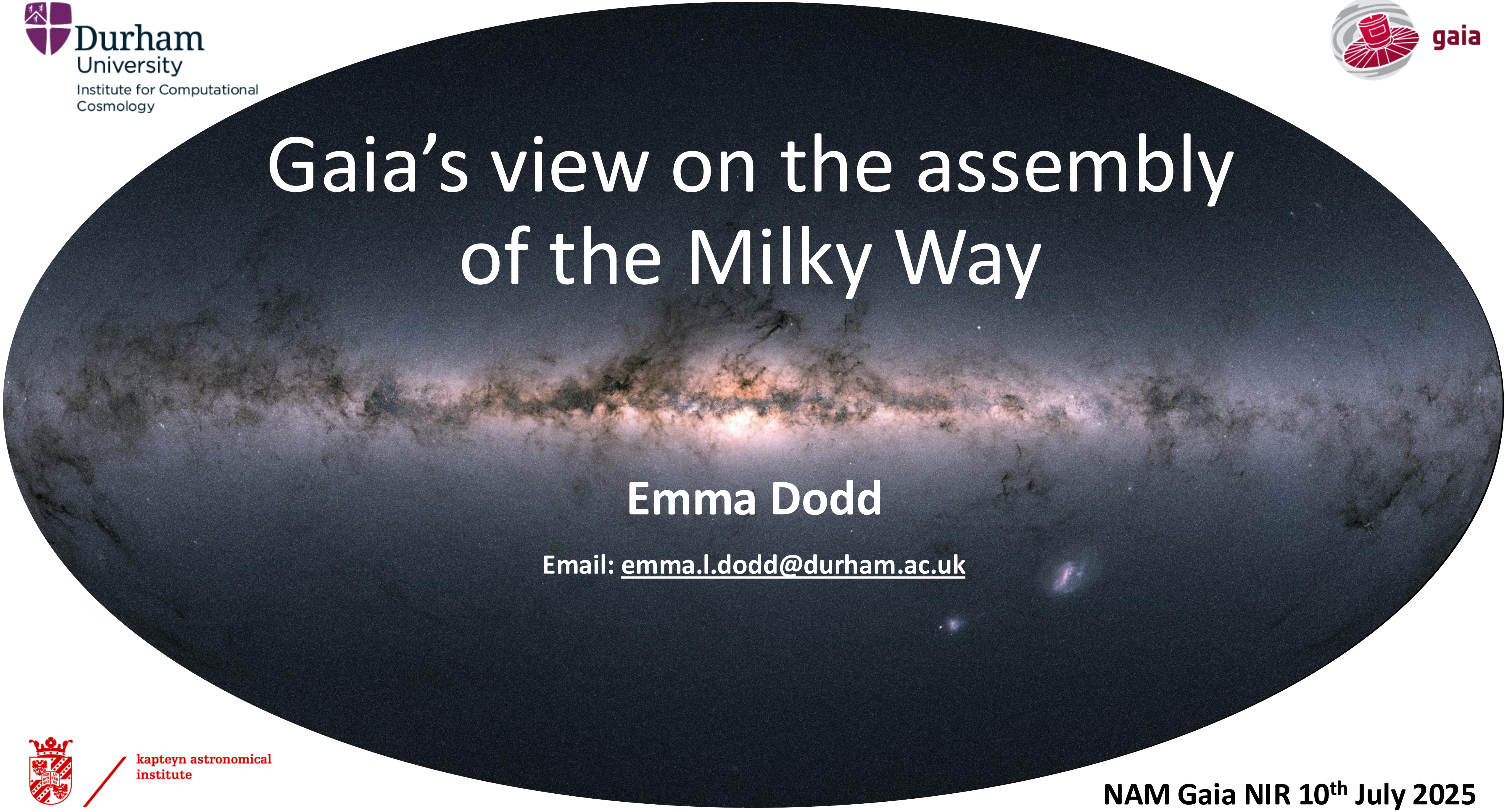
Durham University
Institute for Computational Cosmology

gaia



Gaia's view on the assembly of the Milky Way

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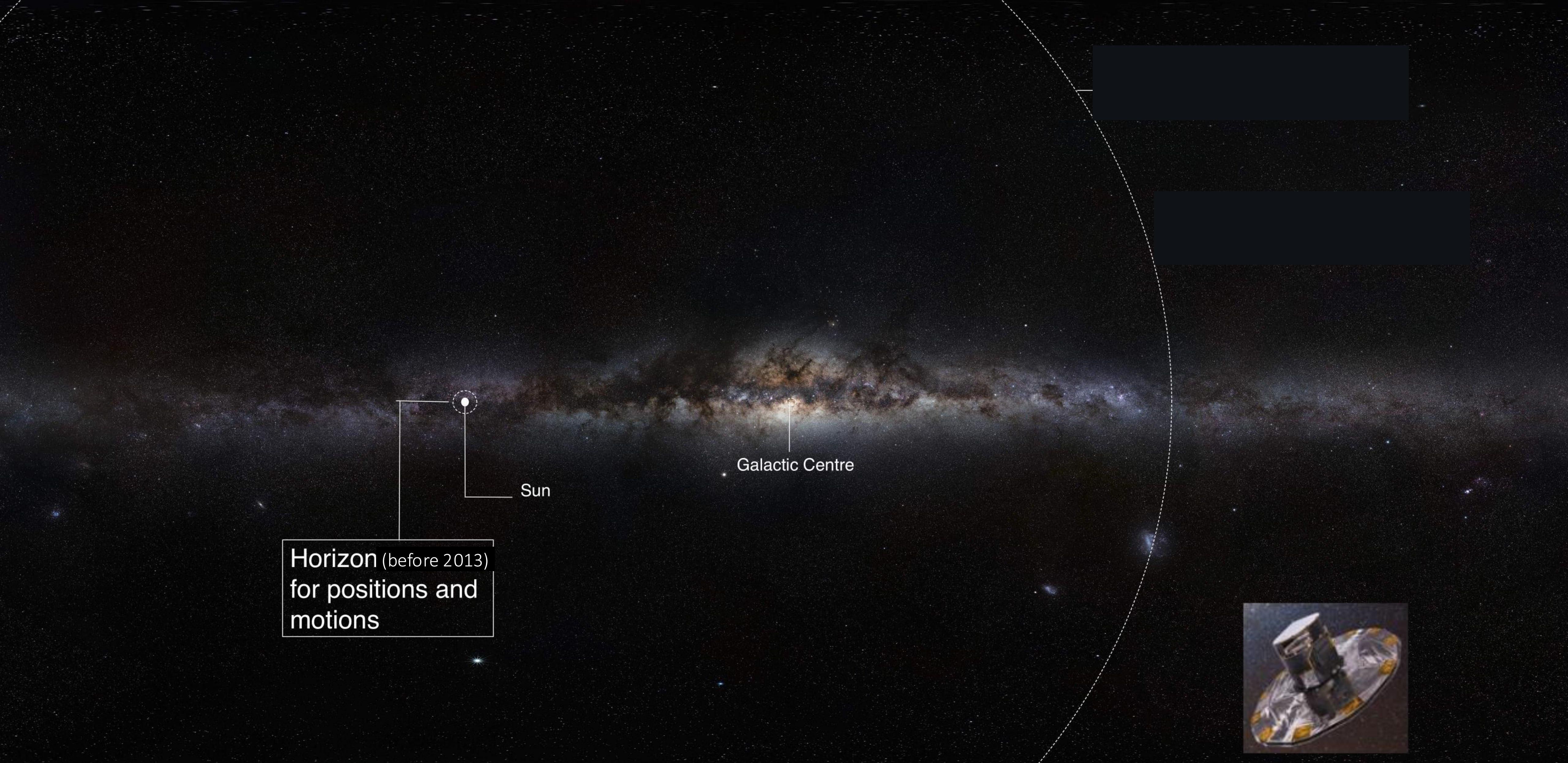
kapteyn astronomical institute

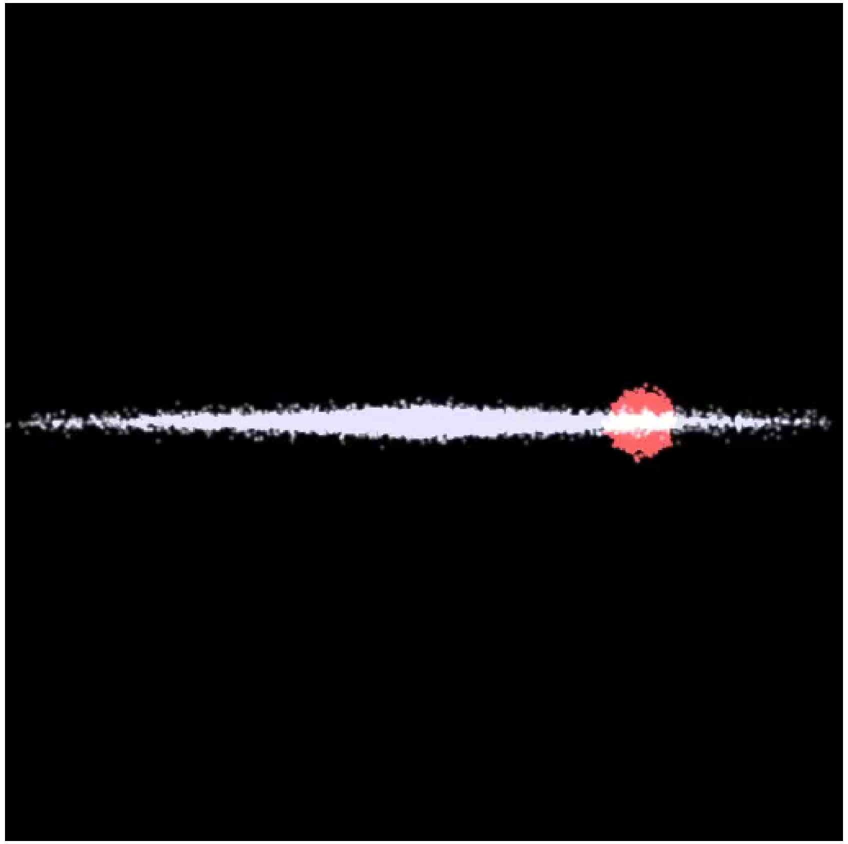
NAM Gaia NIR 10th July 2025



Gaia (10,000x more objects than predecessor); 100,000x bigger volume; 100x more precise

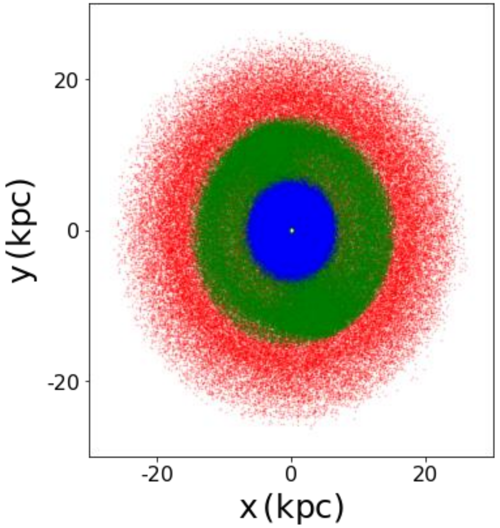
Gaia fully public data releases of nearly **2 billion stars – revolutionary!**

How do we find merger debris?

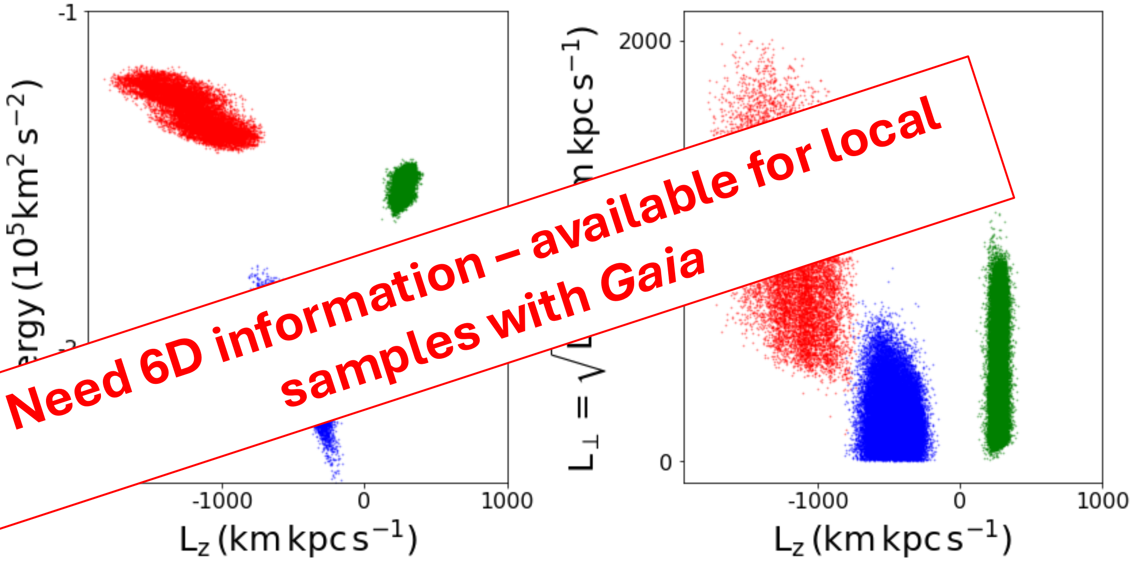


Phase mixed merger debris. Credit: Maarten Breddels & Amina Helmi, Kapteyn Astronomical Institute.

Sattellite galaxies debris after 10 Gyr disrupting in a static Milky Way like potential:



Integrals of Motion space:



Need 6D information – available for local samples with Gaia

Adapted from Helmi et al. (2000)

How do we characterise merger debris?

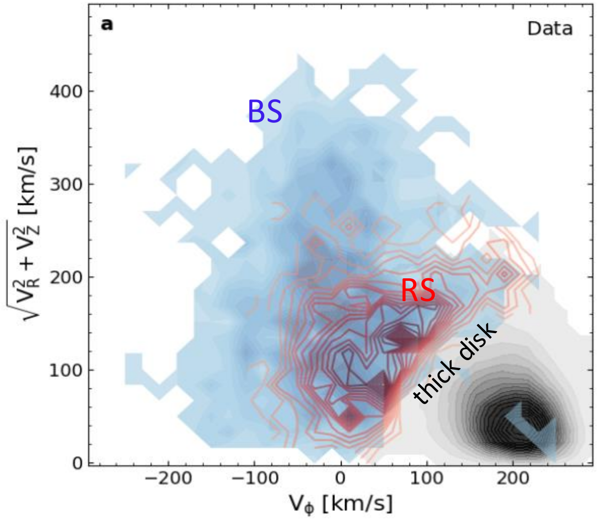
Tools of Galactic archaeology

motions → reveal site of origin

chemical composition → birth environment

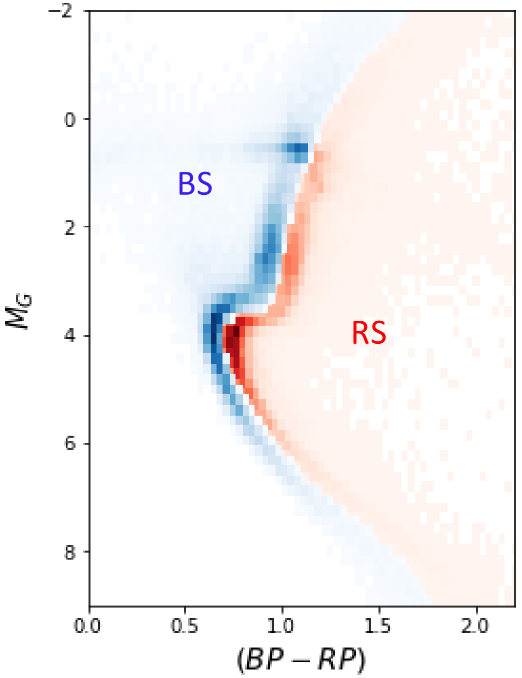
ages → time of birth

Dynamics



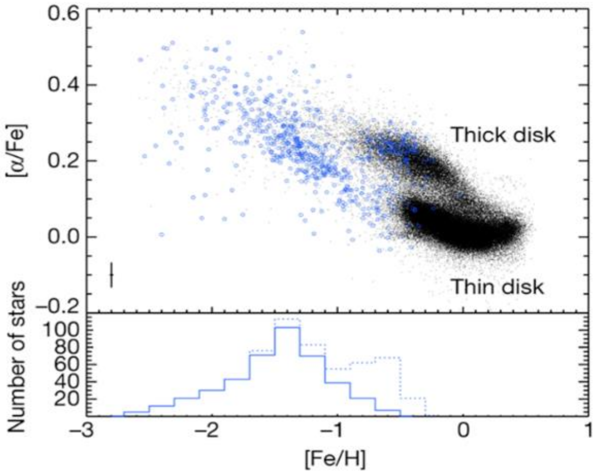
Gallart et al. (2019)

Stellar populations



Colour-magnitude diagram of local halo stars (right), two sequences which also differ in their motions (left)

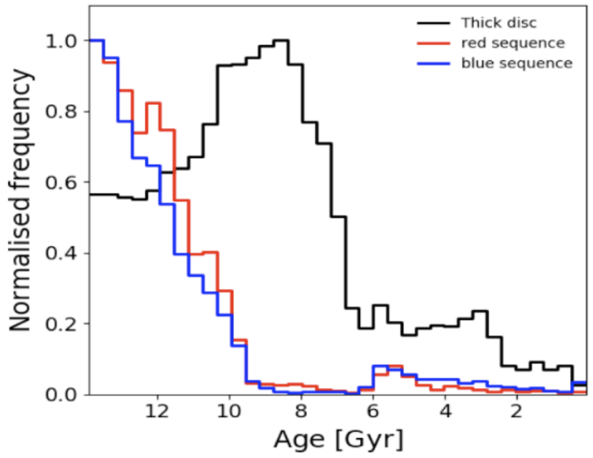
Chemistry



Distinct chemical abundance track of blue sequence stars

Helmi et al. (2018)

Ages



Gallart et al. (2019)

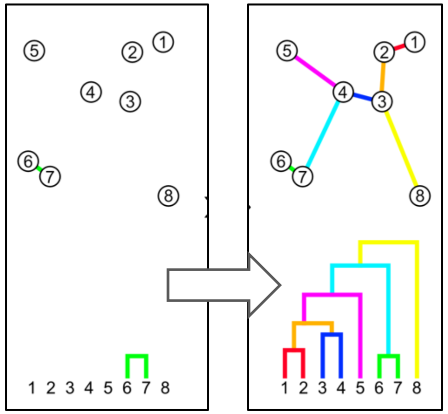
***Gaia* Enceladus –**
the last major merger
Belokurov et al. 2018,
Helmi et al. 2018

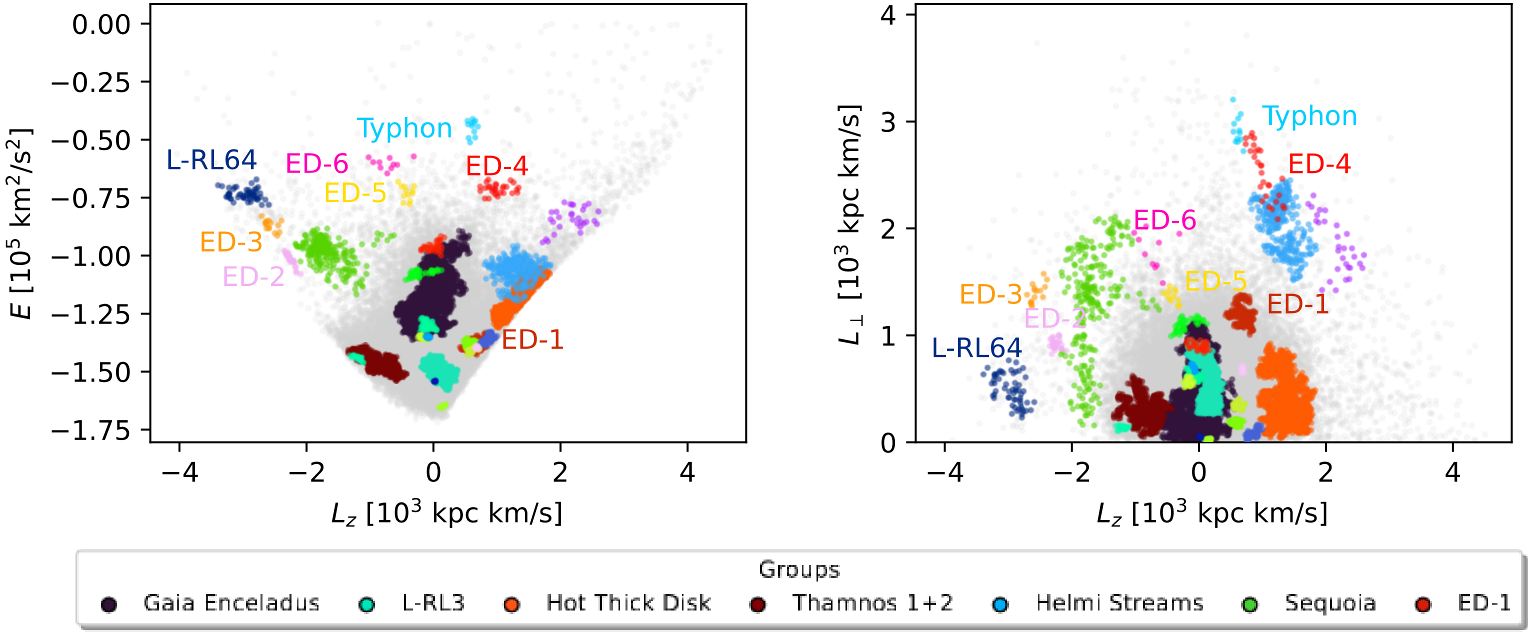
Local halo substructure with Gaia DR3

Clustering in IoM space (Lövdal et al. 2022, Ruiz-Lara et al. 2022, Dodd et al. 2023)

- Local halo where we have 6D information
- Select halo stars kinematically
- 70,000 stars after quality cuts

Dodd et al. 2023





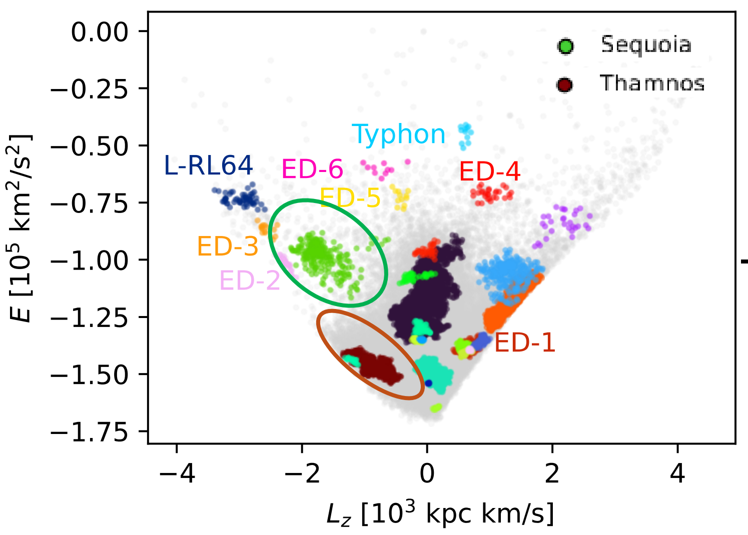
Single-linkage algorithm, clusters are built hierarchically using distances between stars

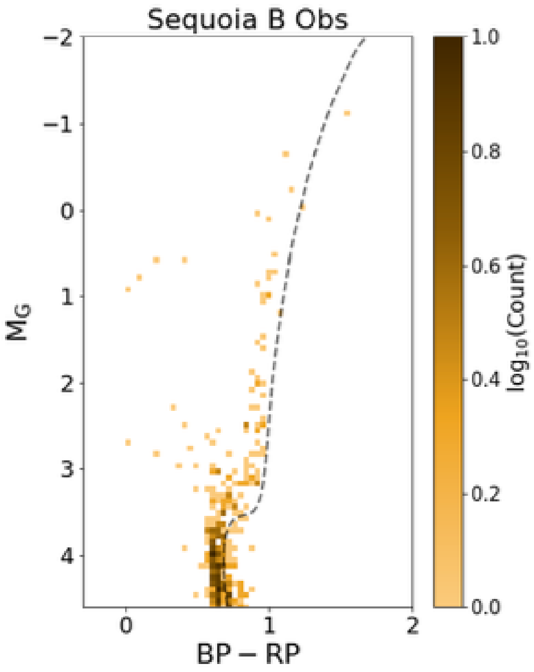
- every star is in a cluster
- use significance to determine where to stop linkage

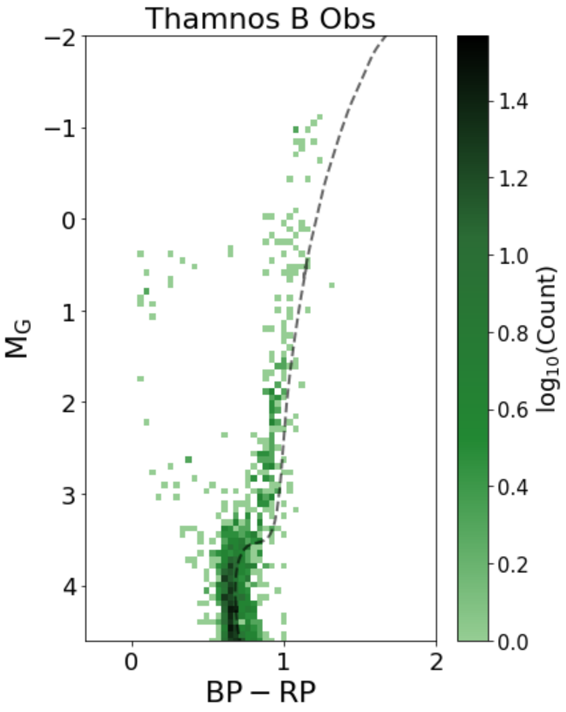
Typhon (Tenachi et al. 2022), L-RL64 (Lövdal et al. 2022, Ruiz-Lara et al. 2022)

Characterising building blocks

Sequoia & Thamnos







Smaller objects (Sequoia), too few bright stars with 6D info → 5D dataset (no v_{los})

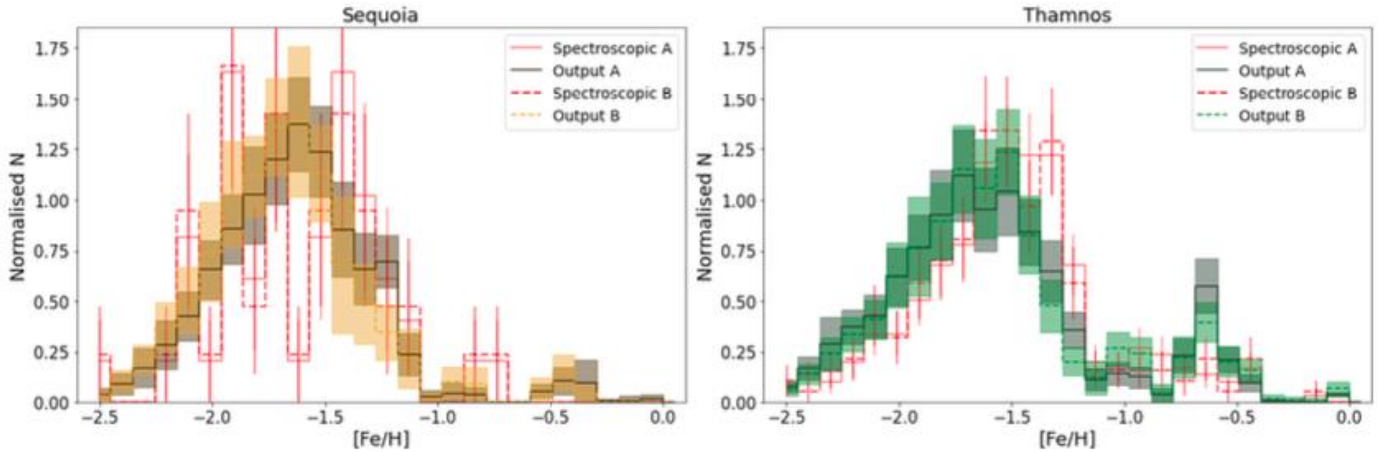
- Select in pseudo-velocity space (assuming $v_{los} = 0$) and then clean samples
- Increase in number of stars by > factor of 2

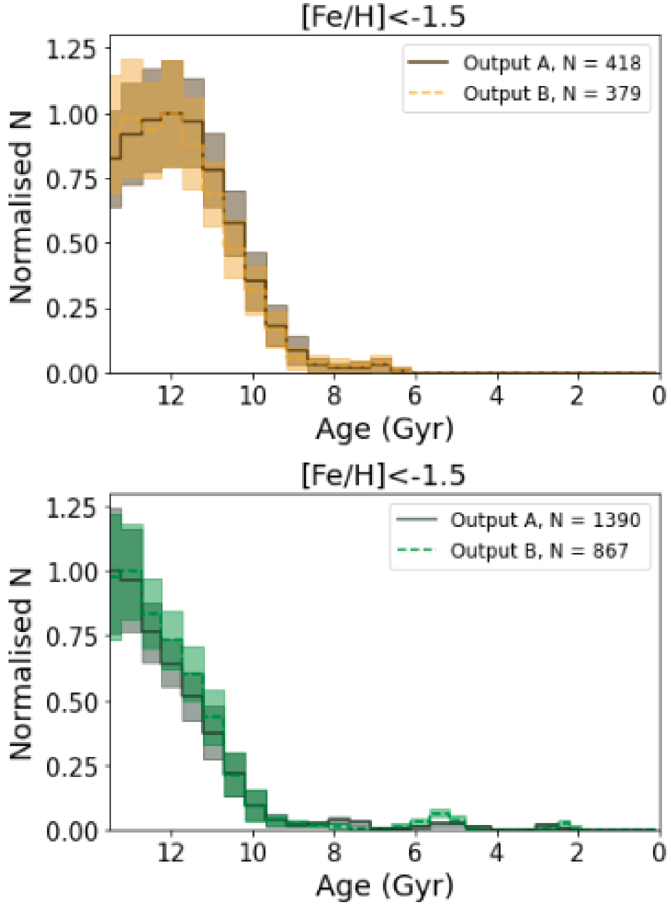
6D possible for larger objects (e.g. GE see Yllari et al. 2025) and will become possible for smaller ones with Gaia DR4

Dodd et al. (2025)

For Sequoia; an accreted galaxy + ~20% Gaia-Enceladus at [Fe/H] >-1.5 dex, Matsuno et al. (2022)
For Thamnos an excess of metal poor stars + dominanted by contamination from in-situ and Gaia-Enceladus

Age distributions





- Metallicity distributions consistent with spectroscopic (with small offset)
- Age distributions allow us to estimate infall times

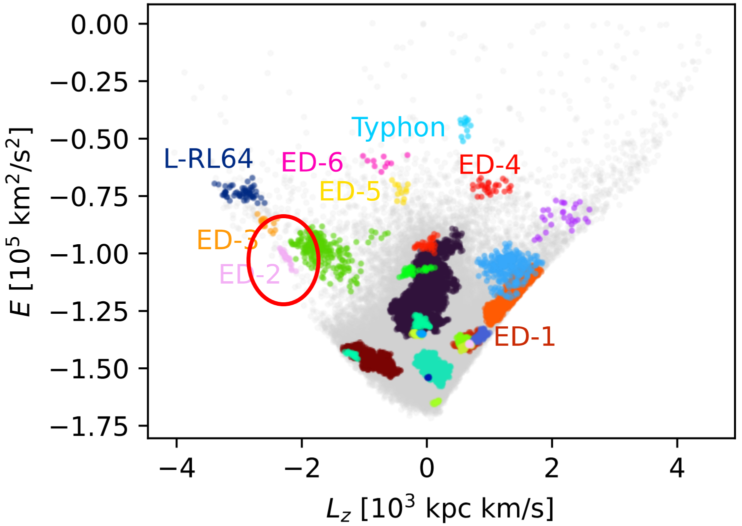
Sequoia T_{50}~ 12±0.3 Gyr z ~ 4
Thamnos T_{50} ~ 12.3±0.3 Gyr z ~ 5

Thamnos → Sequoia

GE T_{50} ~ 12.1±0.1 Gyr z ~ 4.4
Helmi streams T_{50}~ 10.5±0.2Gyr z ~ 2.2 (Ruiz-Lara et al. 2022)

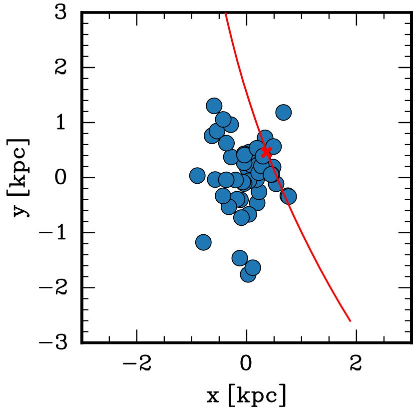
Dodd et al. (2025)

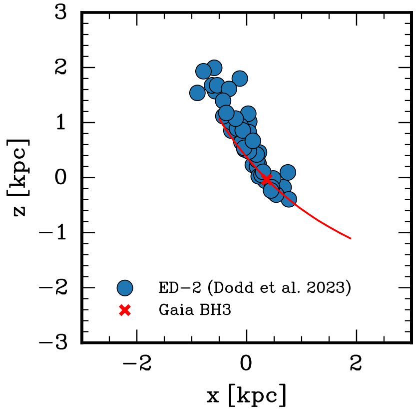
Characterising the small clumps



5 new and interesting small clusters ED-2 to -6 (Dodd et al. 2023)

- High energy indicative of accreted origin
- Very tight dynamically
- HR follow-up (PI: Dodd, UVES)





BH3 is part of ED-2!

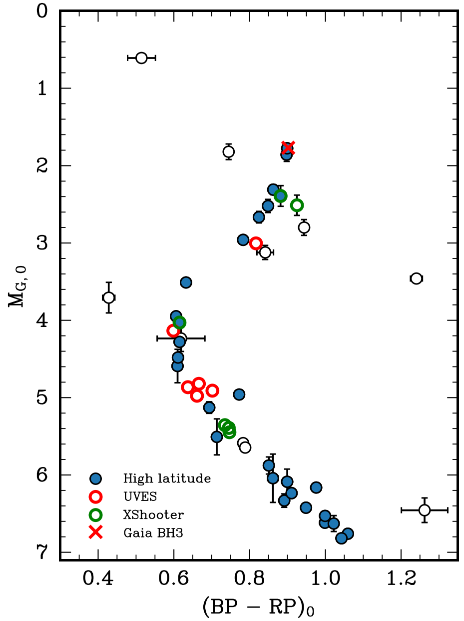
Hosts the 33 Msun Gaia BH3!

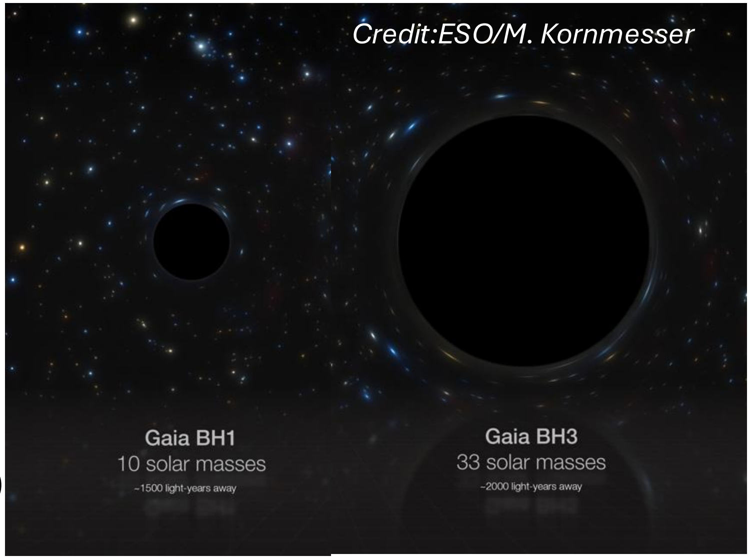
ED-2 stream: a disrupted ancient star cluster at low metallicity, [Fe/H] = -2.5 with negligble spread

Compared to Fnx-1

(similar Fe/H, larger spread in other elements):

→ $M_{ED-2} < (4.2 \pm 0.1) \times 10^4\ M_{sun}$





Balbinot et al (inc Dodd, 2024): Dodd et al (2025)

ED2 and M92, 13.8 Gyr ([Fe/H] ~ -2.3)

Timeline of the Milky Way pre Gaia

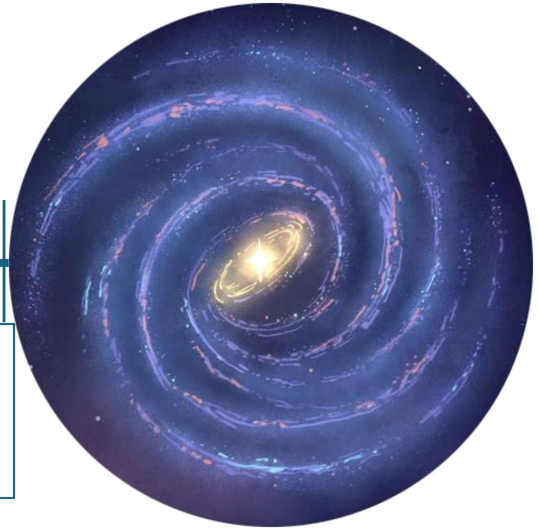
Big Bang

t= -13.8 Gyr

disk formation

?

Ongoing mergers: Sagittarius (Ibata et al. 1994)



Helmi streams – merger debris in solar neighbourhood identified in Hipparcos data (Helmi et al. 1999)

LMC, SMC known satellittes but infall and orbital history unclear

Timeline of the Milky Way since Gaia

with Gaia Enceladus

Big Bang

t= -13.8 Gyr

disk formation

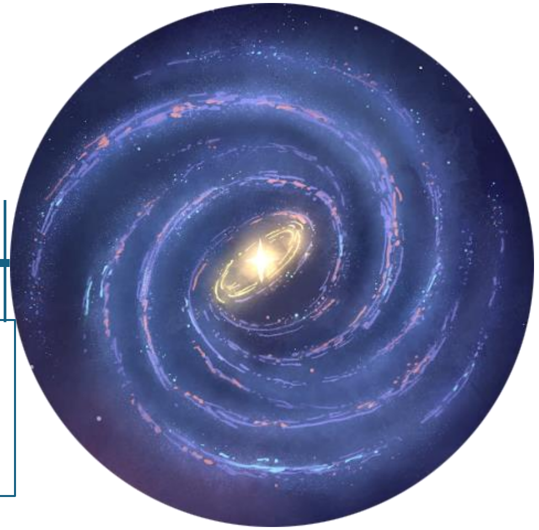
Pre existing disk splashed onto halo like orbits by the merger

Starburst inducded formation of the present day thick disk

thin disk formation

Gaia **Enceladus:**
the last major merger
Belokurov et al. 2018,
Helmi et al. 2018

Ongoing mergers: Sagittarius



Timeline of the Milky Way since Gaia

Non exhaustive!

In-situ proto Milky Way Belokurov & Kravstov (2022)

Big Bang

t= -13.8 Gyr

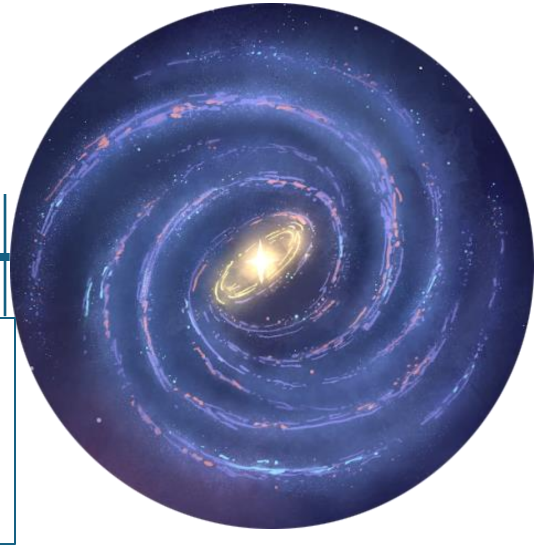
Pre existing disk splashed onto halo like orbits by the merger

t= -10 Gyr

Starburst inducded formation of the present day thick disk

disk formation

thin disk formation



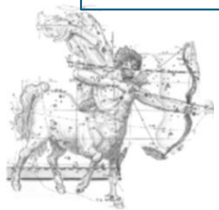
ED-2

Early major merger?
Kraken/Heracules
Kruissjen et al. 2020, Horta et al. 2021

***Gaia* Enceladus:** the last major merger
Belokurov et al. 2018, Helmi et al. 2018

Helmi streams
~7-9 Gyr ago
Helmi et al. 1999, Koppelman et al. 2019, Ruiz-Lara et al. 2022

Ongoing mergers: Sagittarius, LMC, SMC



And many more streams and substructures

Other mergers Sequoia, Thamnos
Myeong et al. 2019, Koppelman et al. 2019

Images adapted from Kruijssen et al. 2020

Summary

- Gaia has revolutionised our understanding of the assembly of our galaxy
- We know the main characters in the story but are unravelling also the smaller building blocks
- Gaia NIR will allow us to push this type of work to larger volumes and to the inner galaxy → hosts the most ancient merger debris

Big thanks to all the hard work of the

Gaia DPAC