Streams and the accretion history of the Milky Way

Amina Helmi

FOGGIE
Figuring Out Gas & Galaxies In Enzo
Peeples et al

Stellar halo:
a treasure trove

Mergers: characteristic of cosmological model

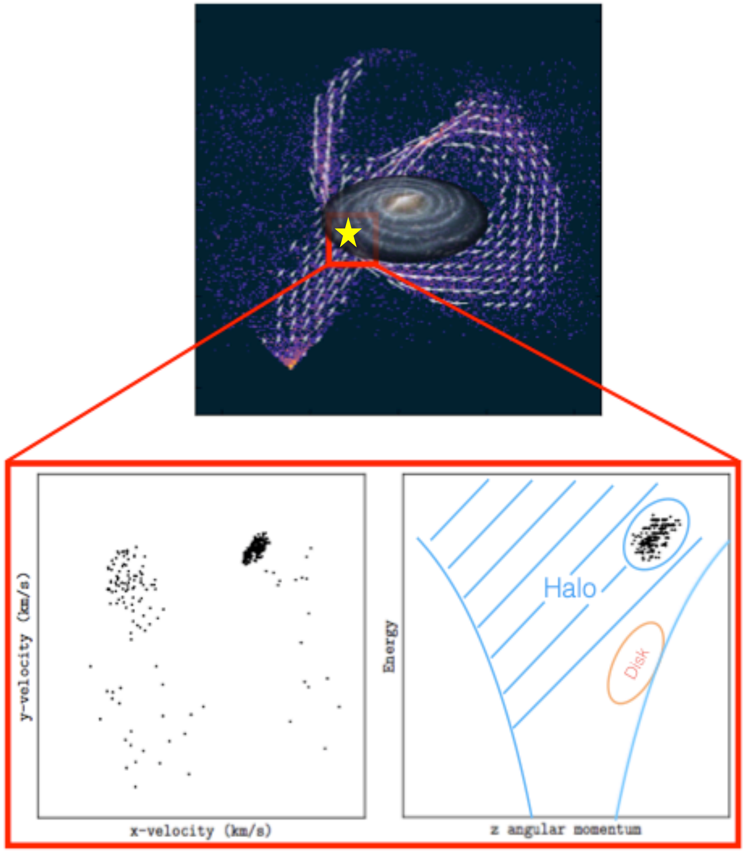
Stars’ motions, chemistry and ages trace origin

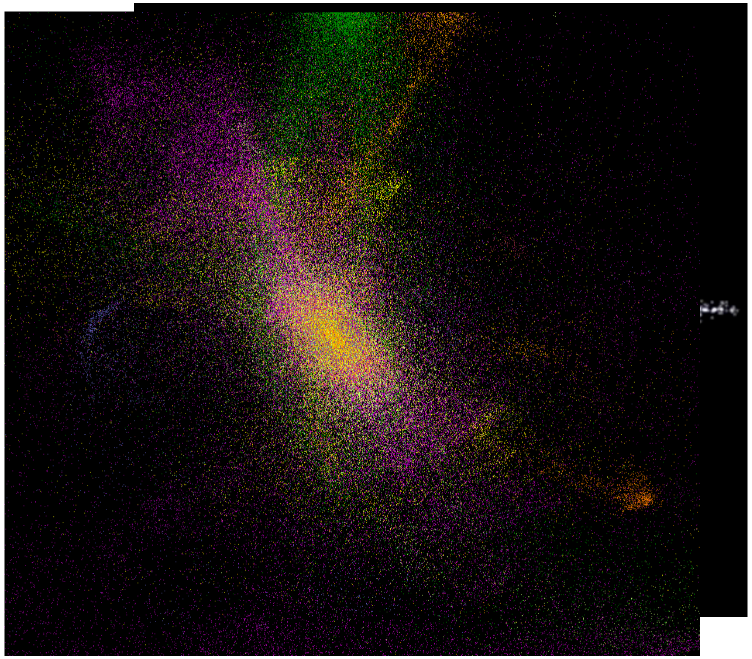
t = 1.1 Gyr
z = 5.28

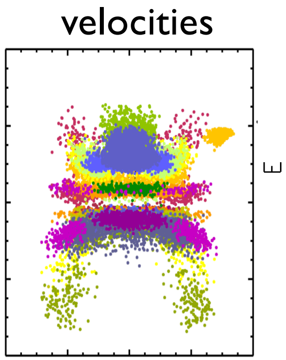
How many mergers? When?
What were the building blocks like?

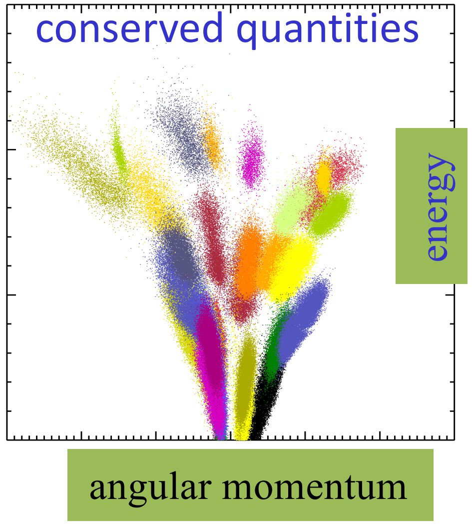
How do we find (old) merger debris?

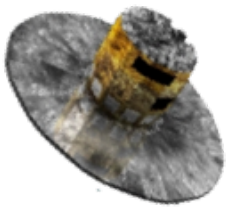
Helmi & de Zeeuw (2000)

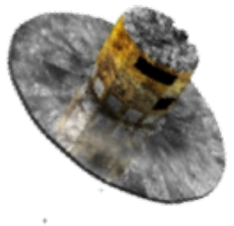






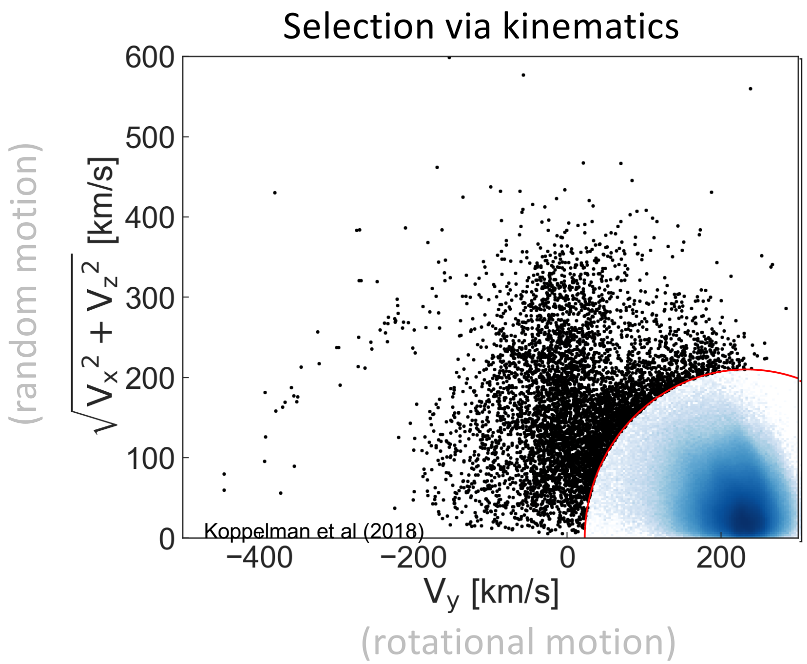






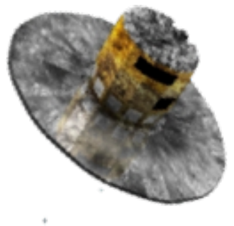
Substructure in the halo near the Sun

A story with two main characters



- Thick disk still apparent at very low velocities (~50% of stars): “in-situ”

- One large *slightly retrograde* “blob” (sausage) and an arc



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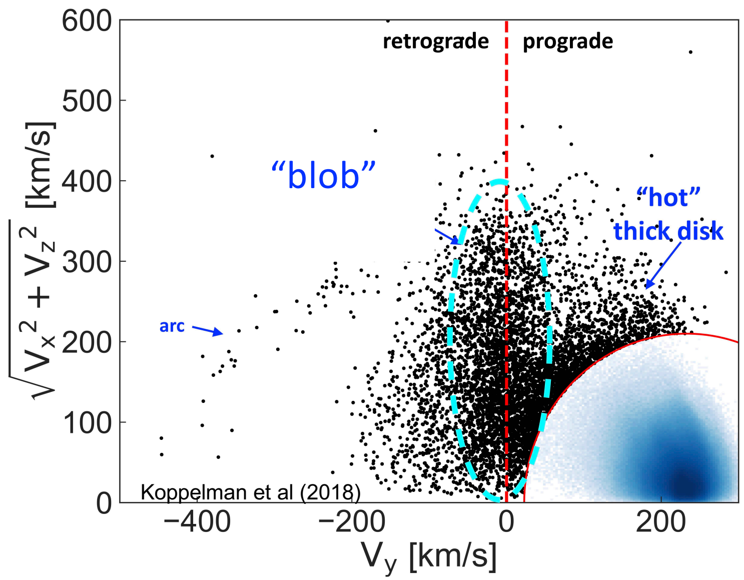

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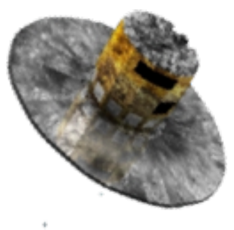

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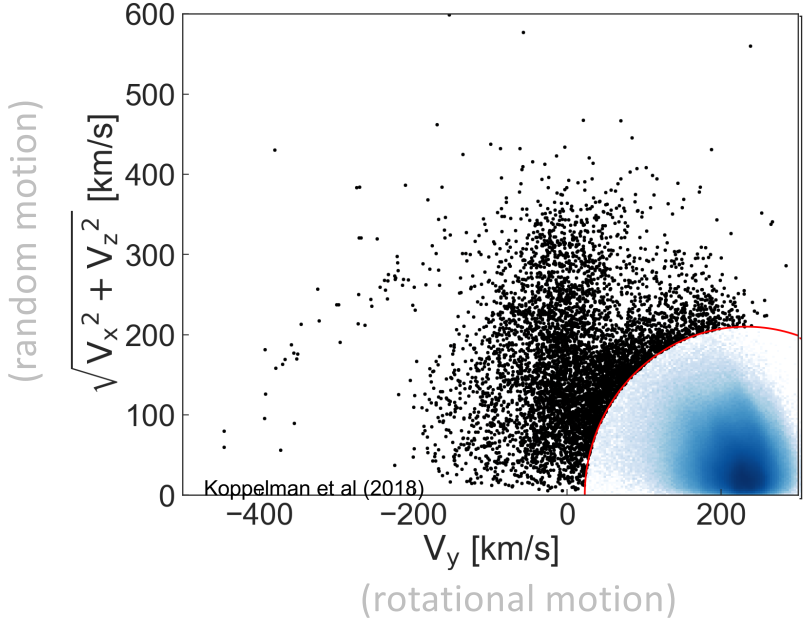
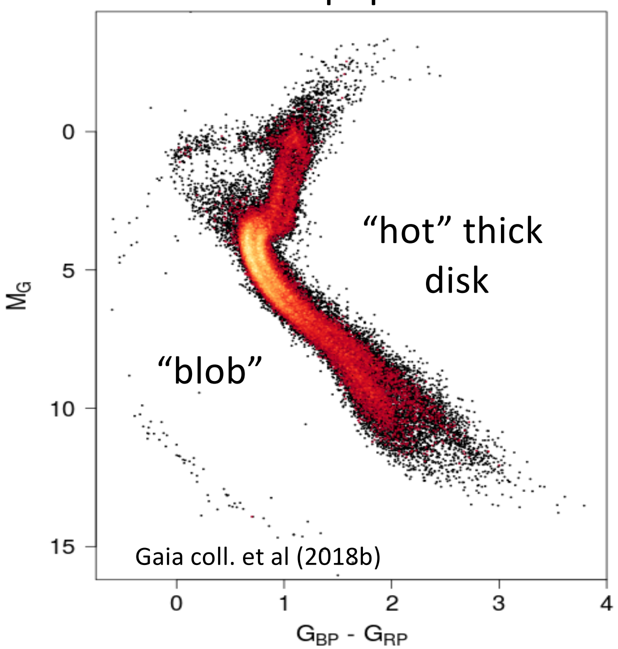
Selection via kinematics



Stellar populations



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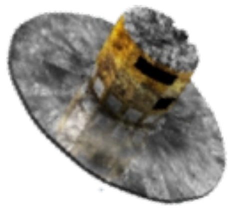

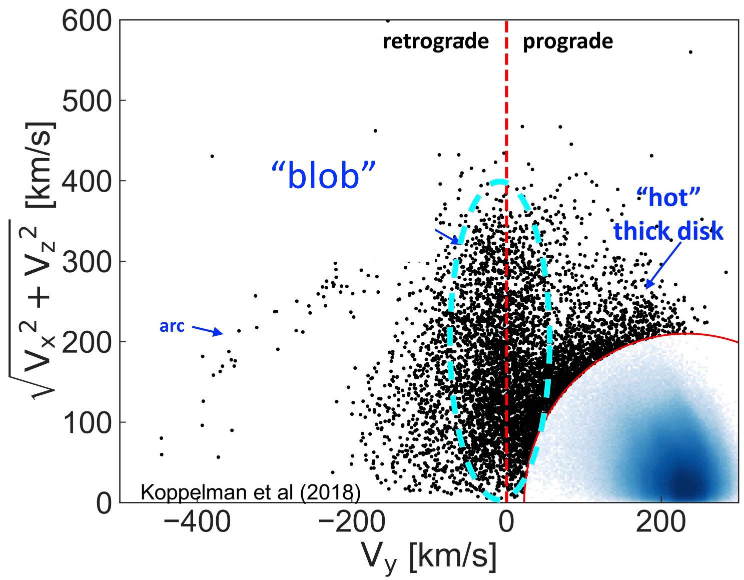

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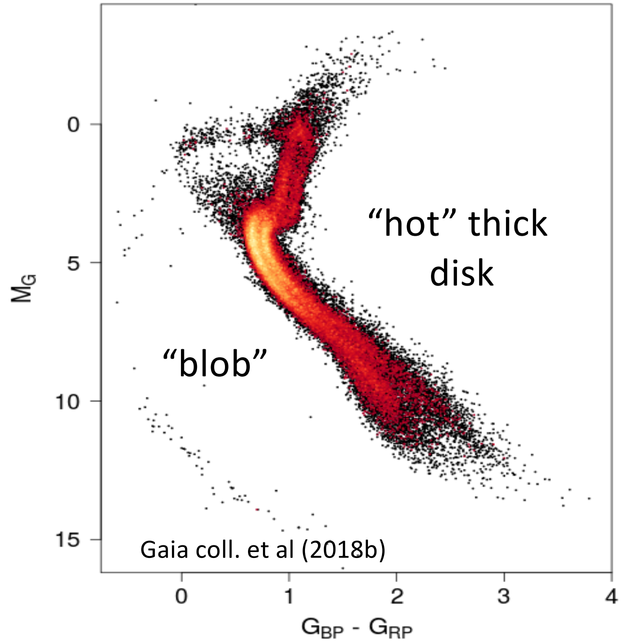
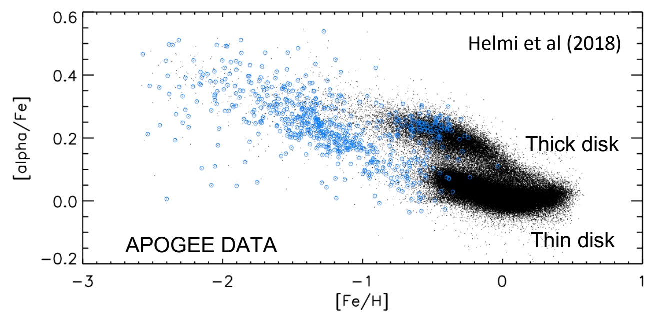


Chemical sequence



- Thick disk still apparent at very low velocities (~50% of stars): "in-situ"
- One large *slightly retrograde* "blob" (sausage) and an arc

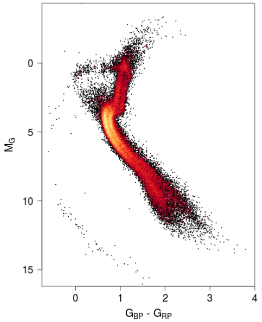
Ch. sequence → blob stars formed elsewhere; low SFR and massive object: $M_* \sim 6 \times 10^8 M_{sun}$

(Fernandez-Alvar et al. 2018)

Age comparison: Disk present @ accretion, mass-ratio of merger ~ 0.24

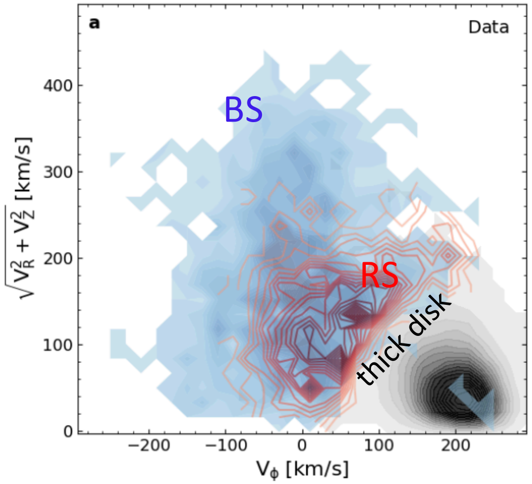
→ "formation" of thick disk at z ~ 1.8

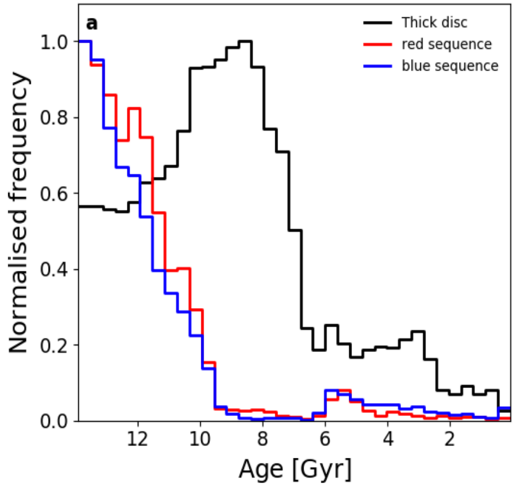
see also Bonaca et al (2017); Belokurov et al (2018); Haywood et al (2018)



Gaia-Enceladus and formation of the thick disk

- Age distribution of these stars is similar (but different [Fe/H])
- “Traditional” thick-disk has higher [Fe/H] and is younger





<u>Sequence of events</u>

- G-E fell in there was a disk → heating led to (in-situ disk) stars more halo-like motions (Jean-Baptiste et al 2017; Belokurov et al. 2020)
- Early MW was likely gas-rich → event (possibly) triggered formation of traditional thick disk

Gallart et al. (2019),
Xiang & Rix (2022)

→ multiple roles played by a single (massive) dwarf galaxy

Impact of GE not restricted to the halo

gas evolution, chemical bimodality and metallicity gradients with time

MNRAS **491,** 5435–5446 (2020)
Advance Access publication 2019 November 26
doi:10.1093/mnras/stz3289

On the origin of the chemical bimodality of disc stars: a tale of merger and migration

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Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany

The Astrophysical Journal, 972:112 (16pp), 2024 September 1
https://doi.org/10.3847/1538-4357/ad5b60

The Three-phase Evolution of the Milky Way

Vedant Chandra[1,2], Vadim A. Semenov[1], Hans-Walter Rix[2], Charlie Conroy[1], Ana Bonaca[3], Rohan P. Naidu[4,5], René Andrae[2], Jiadong Li (李佳东)[2], and Lars Hernquist[1]
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Chasing the impact of the Gaia-Sausage-Enceladus merger on the formation of the Milky Way thick disc

Ioana Ciucă[1,2,3,★] Daisuke Kawata[4], Yuan-Sen Ting[1,2], Robert J. J. Grand[5,6], Andrea Miglio[7,8], Michael Hayden[3,9], Junichi Baba[10,11], Francesca Fragkoudi[12], Stephanie Monty[13], Sven Buder[1,3], Ken Freeman[1]

JOURNAL ARTICLE

The impact of early massive mergers on the chemical evolution of Milky Way-like galaxies: insights from NIHAO-UHD simulations FREE

Tobias Buck, Aura Obreja, Bridget Ratcliffe, Yuxi(Lucy) Lu, Ivan Minchev, Andrea V Macciò

Monthly Notices of the Royal Astronomical Society, Volume 523, Issue 1, July 2023, Pages 1565–1576, https://doi.org/10.1093/mnras/stad1503
Published: 19 May 2023 **Article history** ▾

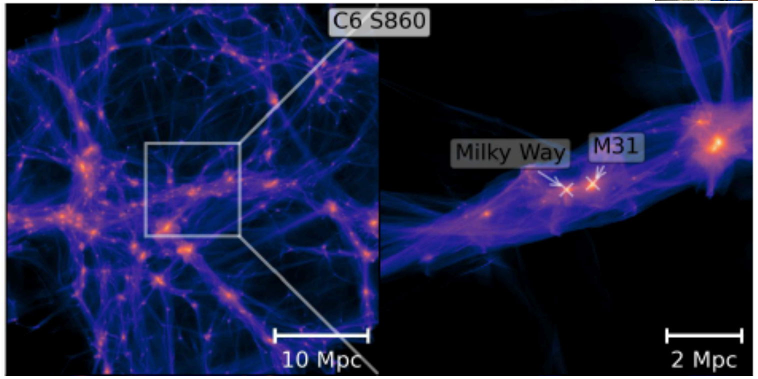
Monthly Notices of the Royal Astronomical Society
MNRAS **503,** 5846–5867 (2021)
doi:10.1093/mnras/stab250

VINTERGATAN – II. The history of the Milky Way told by its mergers

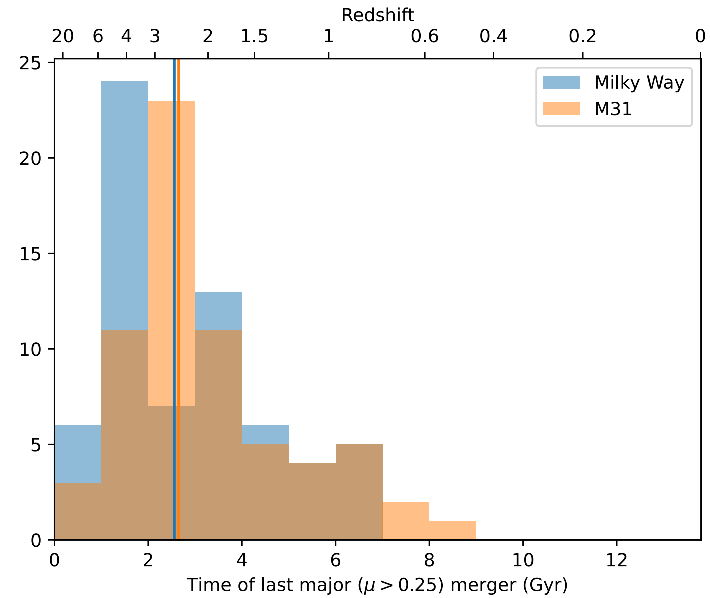
Florent Renaud[1★] Oscar Agertz[1] Justin I. Read[2] Nils Ryde,[1] Eric P. Andersson[1] Thomas Bensby,[1] Martin P. Rey[1] and Diane K. Feuillet[1]
[1] *Department of Astronomy and Theoretical Physics, Lund Observatory, Box 43, SE-221 00 Lund, Sweden*
[2] *Department of Physics, University of Surrey, Guildford, GU2 7XH, UK*

MWs in constrained cosmological simulations

- Suite of cosmological sims reproducing MW/M31 props (masses, kinematics, distance)
- MW's last major merger infall likely 1-2 Gyr after BB



Wempe et al. (2024a)

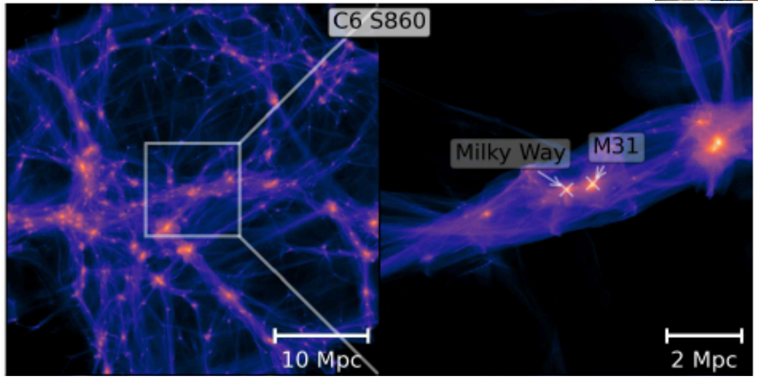


Wempe et al. (2024b, subm)

MWs in constrained cosmological simulations

- Suite of cosmological sims reproducing MW/M31 props (masses, kinematics, distance)
- MW's last major merger infall likely 1-2 Gyr after BB
- MW's dark halo formation biased early
  - T_{half} ~ 9 Gyr ago, 0.9 Gyr earlier than M31

→ older stellar halo (+thin disk) for MW than M31



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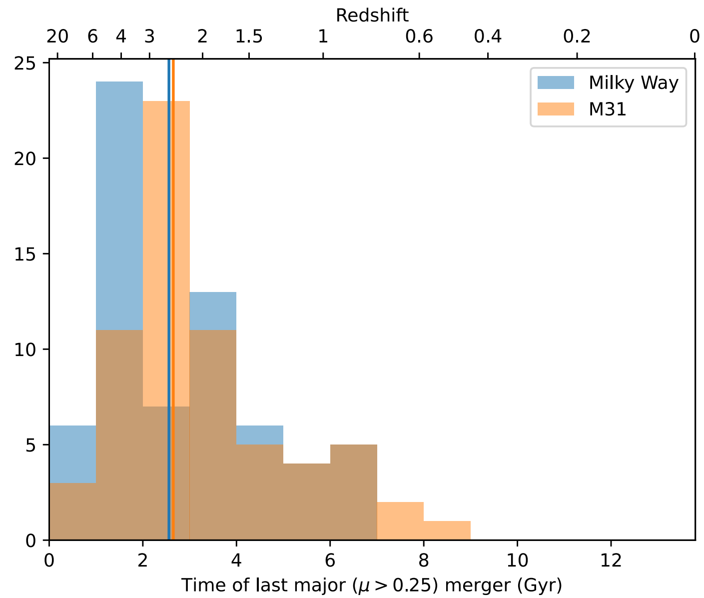

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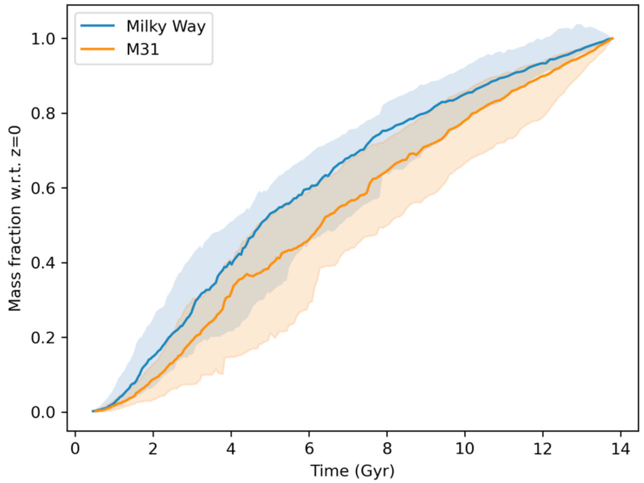
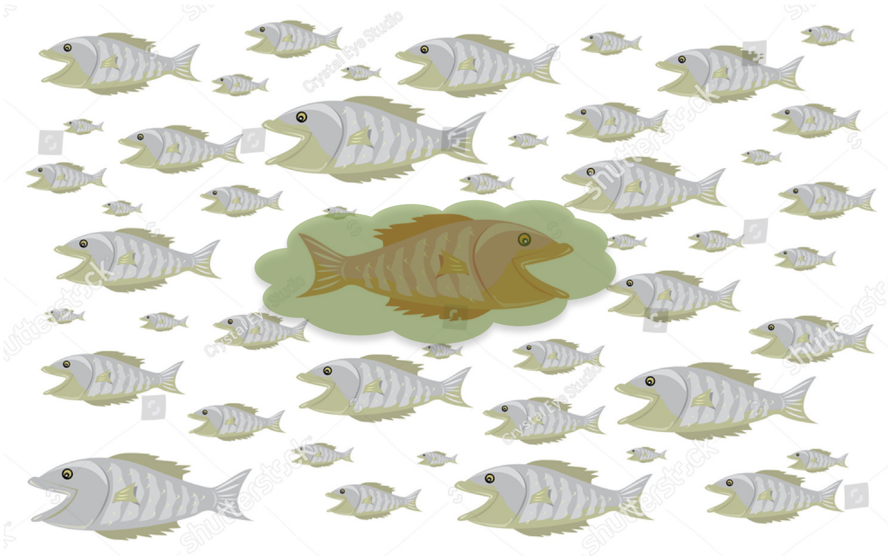
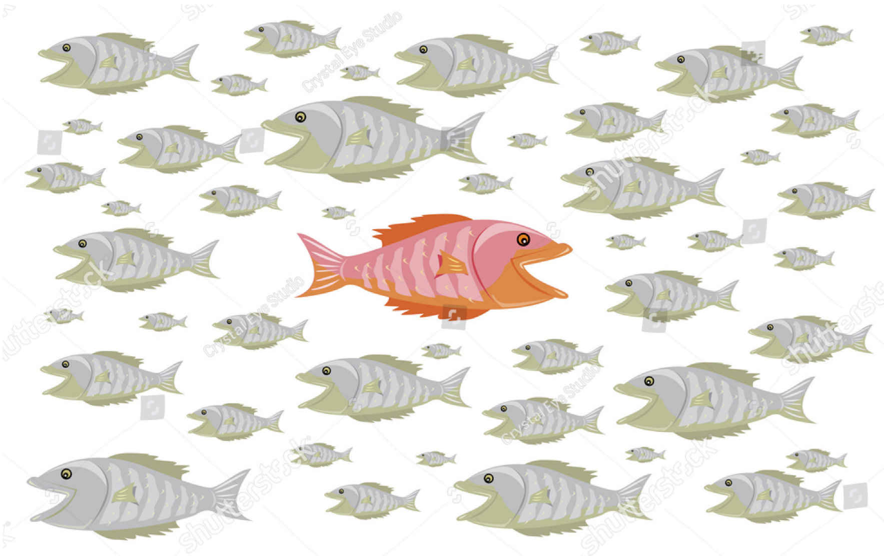


also Santistevan et al. (2020) biased formation in LG in FIRE-2



Other merger debris?



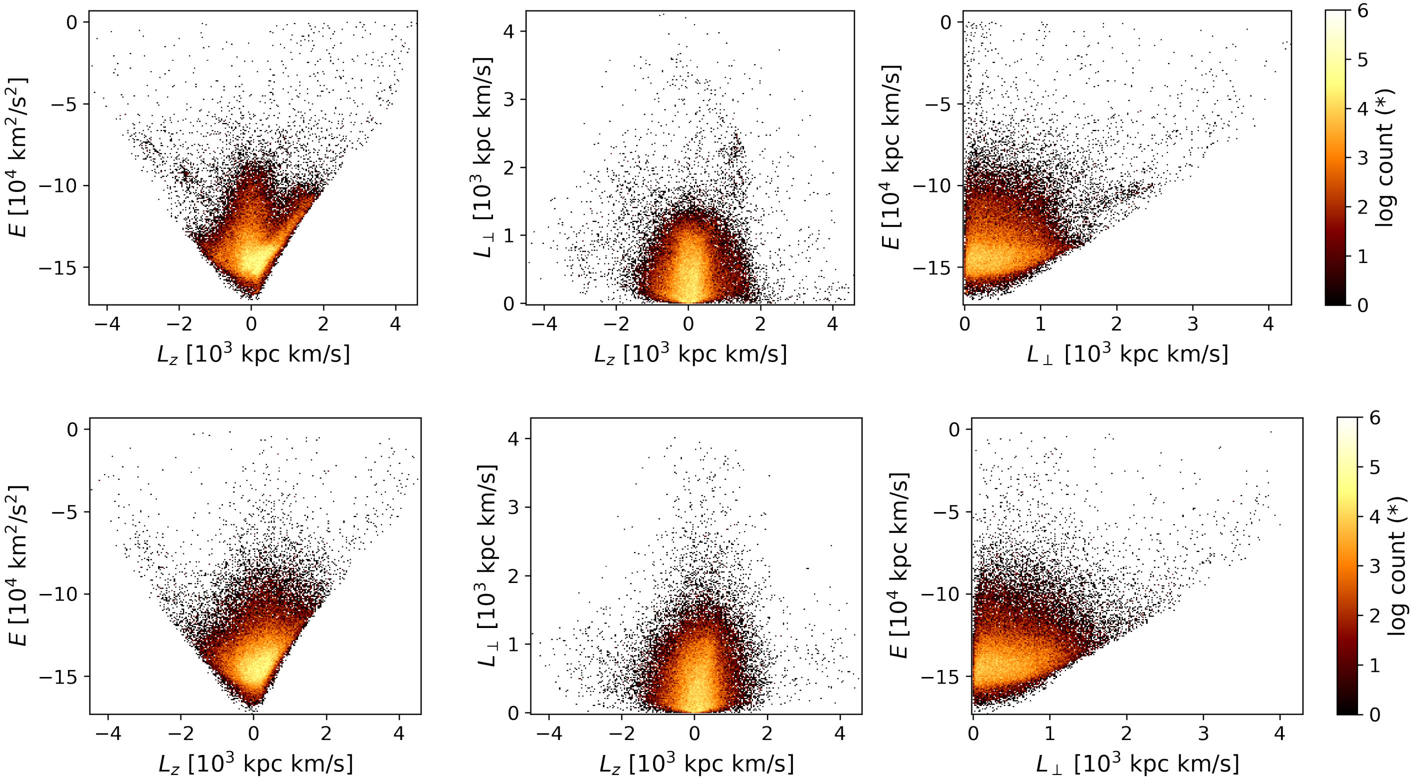
Other merger debris?

Identification of substructures through a data-driven clustering algorithm

Lövdal et al 2022, Ruiz-Lara et al (2022); Dodd et al (2023)

Single-linkage algorithm applied to 3D space defined by Integrals of Motion

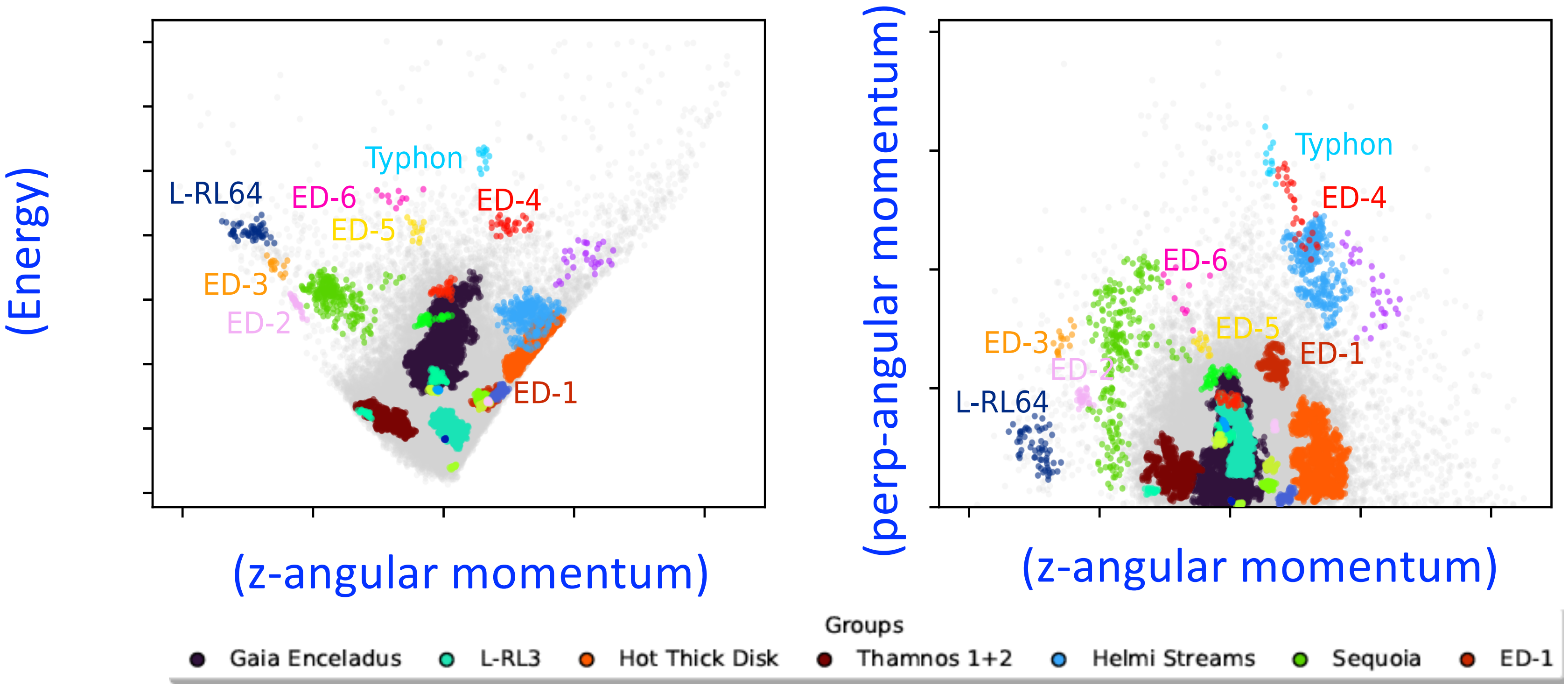
RANDOM SET



Significance determined by compare extent in 3D to randomized datasets

Large substructures and small clusters

The stars from the systems that built the early Milky Way



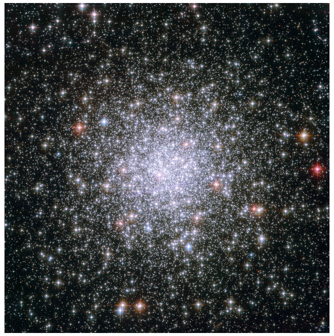
Dodd et al (2023)

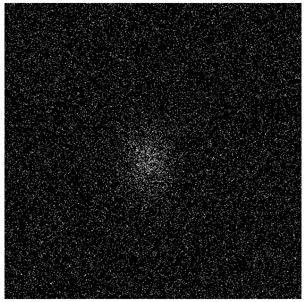
→ True "archaeology"

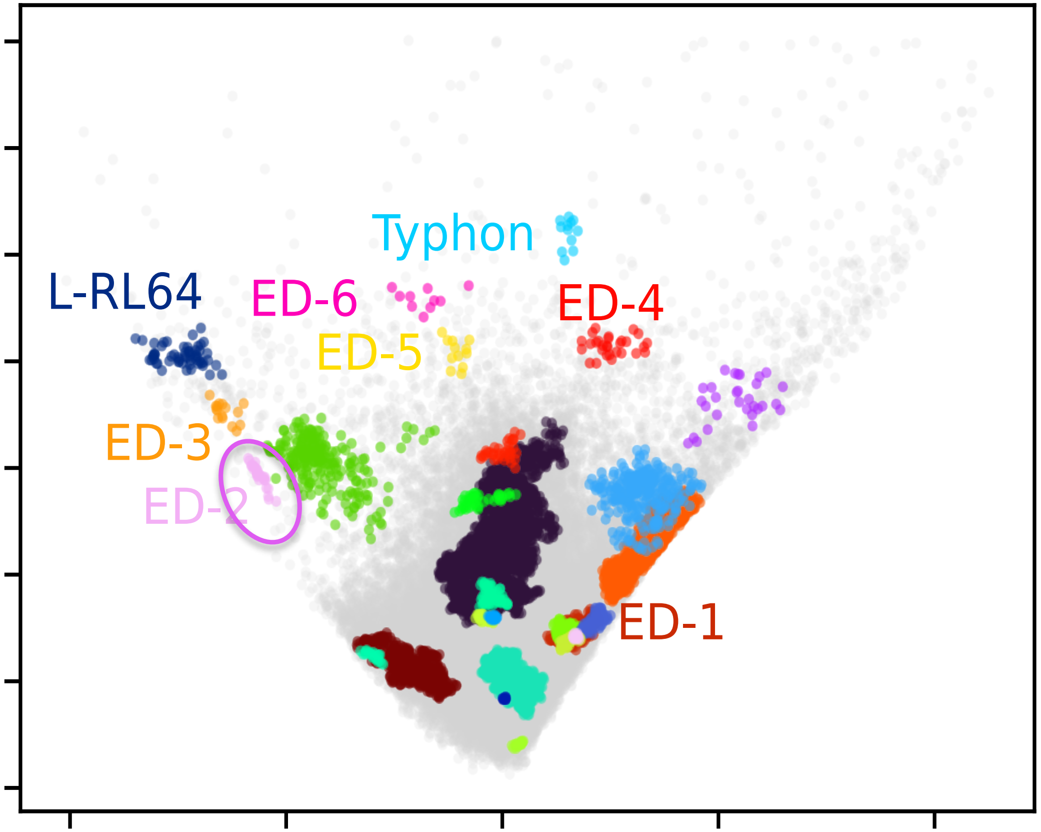
Stars IDs and characteristics of the structures publicly available

Characterizing the building blocks. I

The tight substructure ED-2







Dodd et al (2023); Balbinot et al (2023, 2024)

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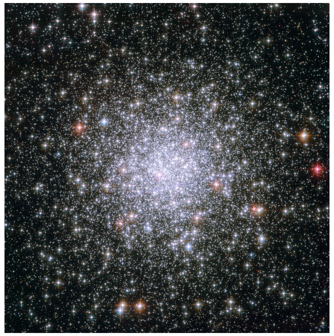
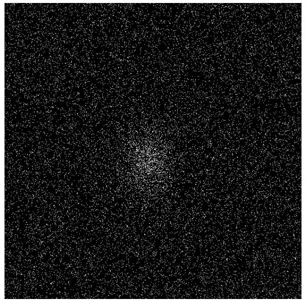
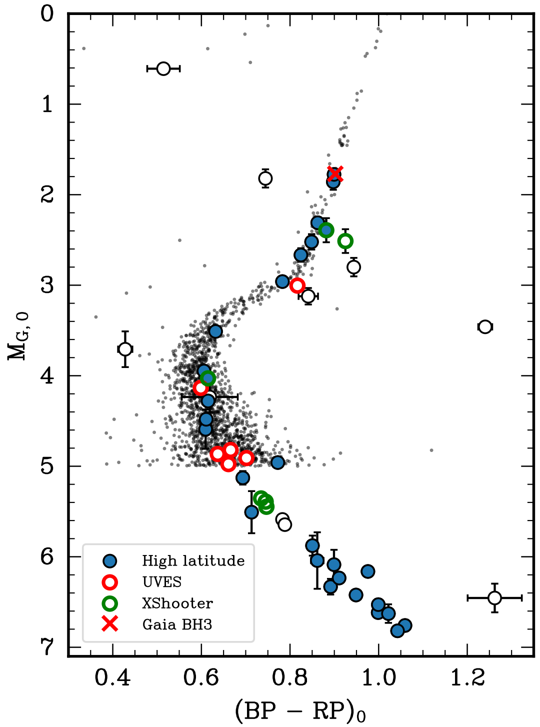






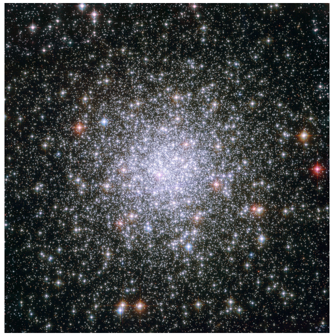
Narrow sequence

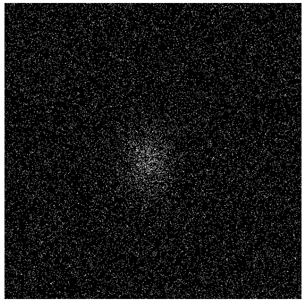
→ Stars born at approx. same time w/similar chemical composition (also from their spectra)

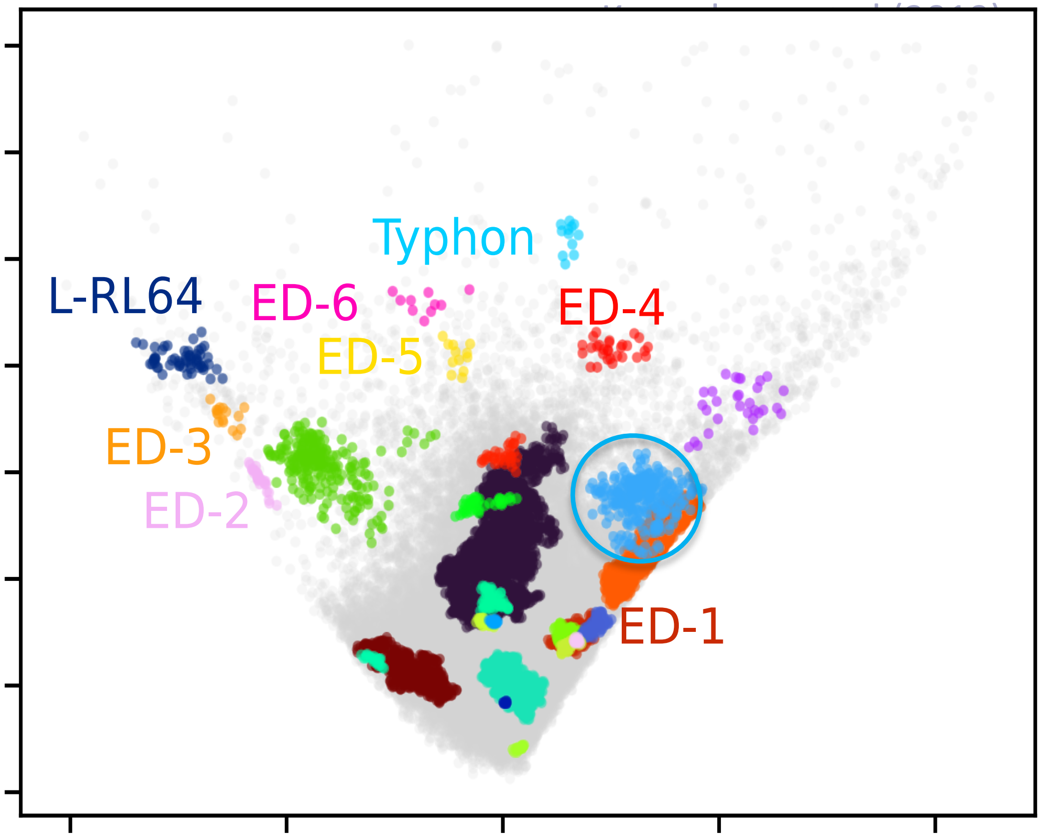
Dodd et al (2023); Balbinot et al (2023, 2024)

Characterizing the building blocks. II

The Helmi streams: a dwarf galaxy







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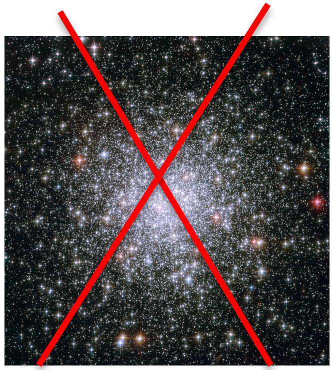
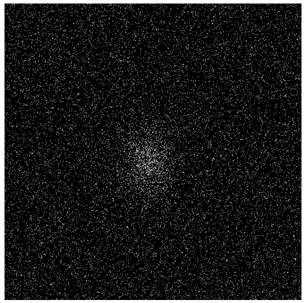
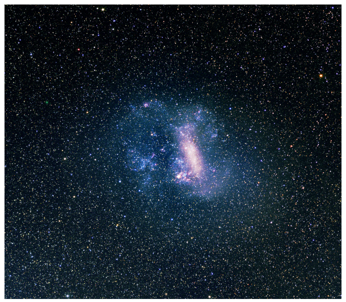
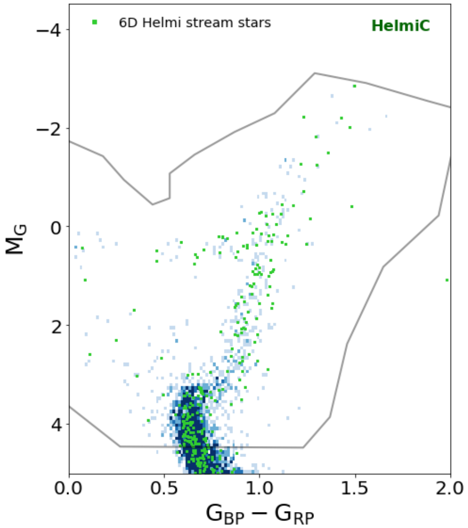
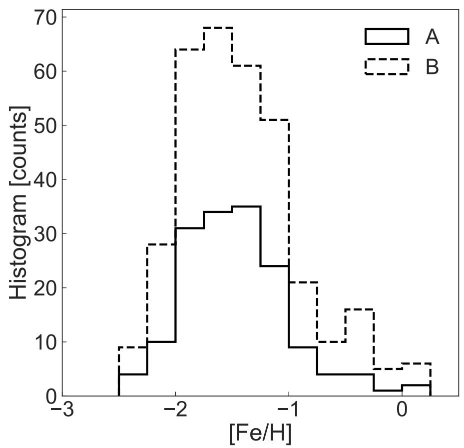




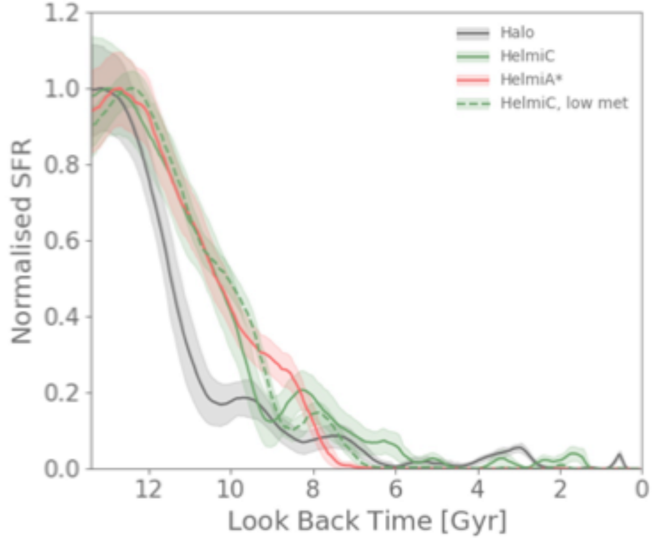




Koppelman et al (2019)



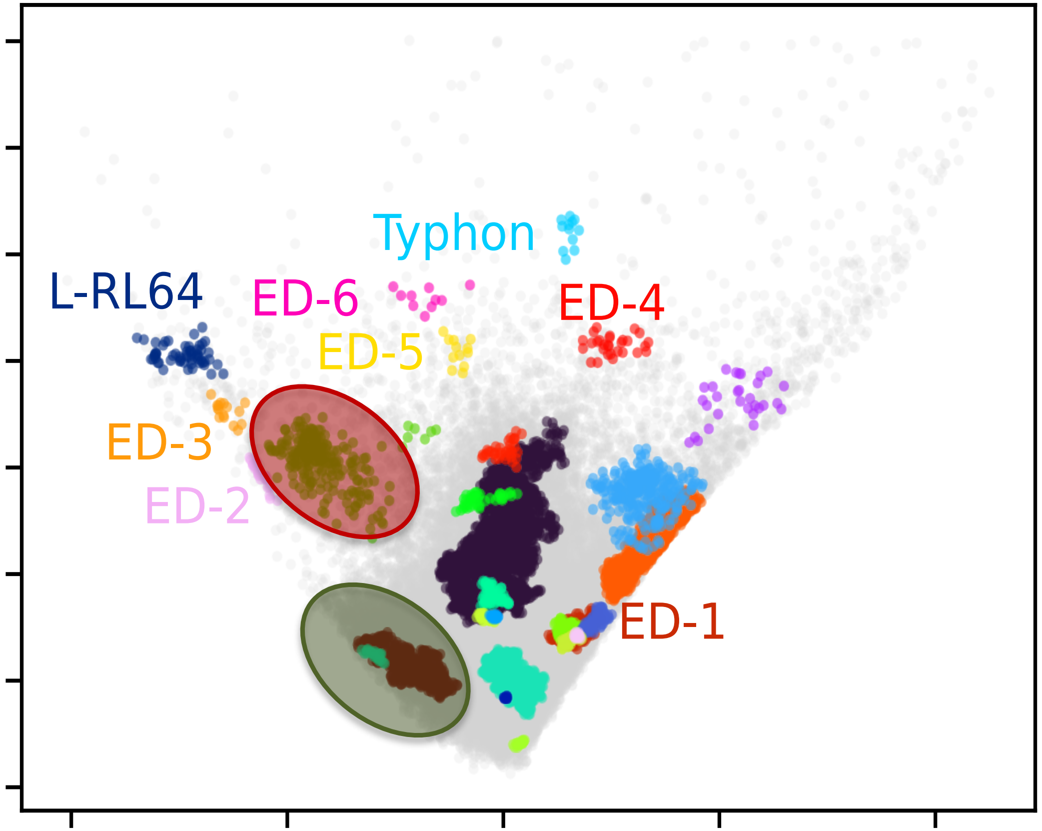
Ruiz-Lara et al (2023)



- Massive object (from dynamics and large metallicity spread)
- Extended star formation history (slower)
- τ_{50} = 10.5 $\pm$ 0.2 Gyr (z_{half} ~ 2)

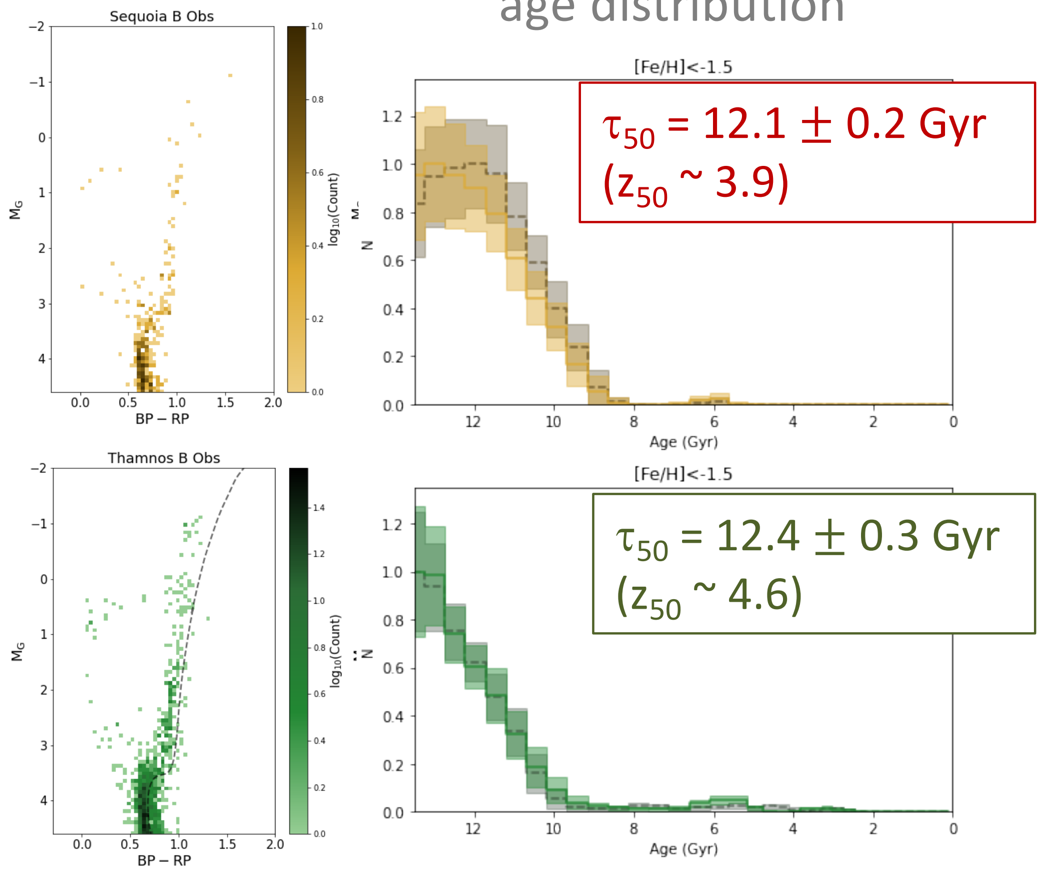
Characterizing the building blocks. II

Sequoia & Thamnos



Dodd et al 2024 (subm)

age distribution



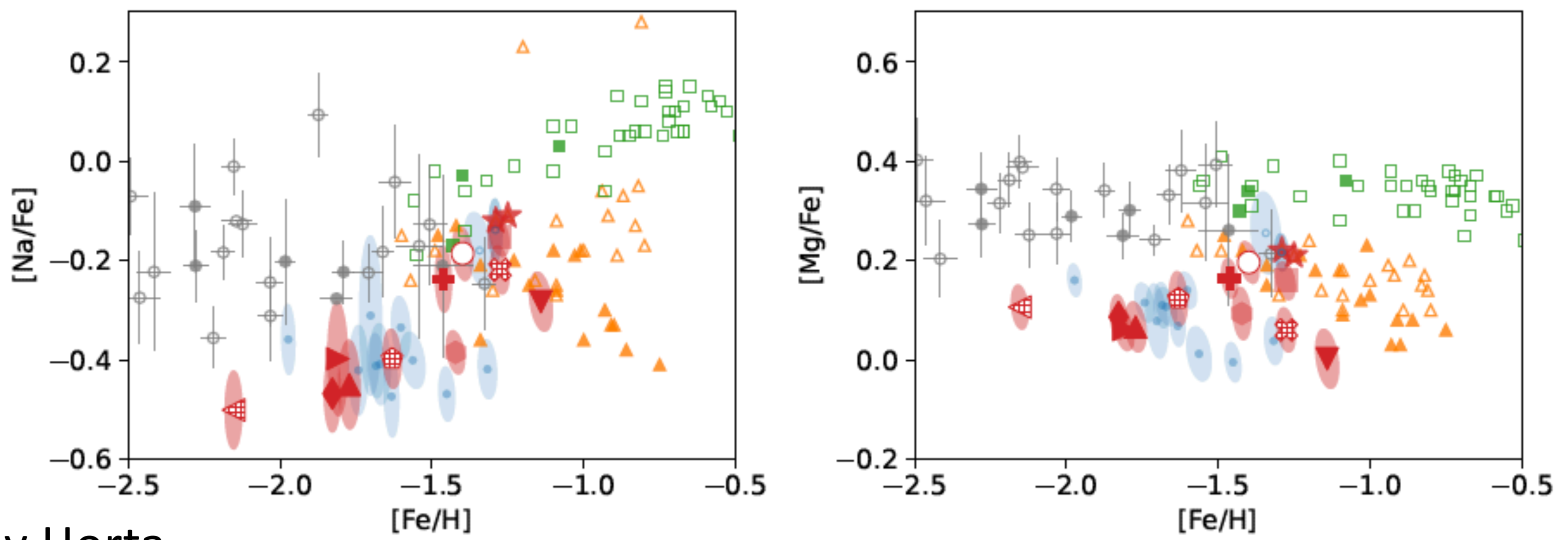
Characterization of the building blocks. III.
Chemical abundances: precision measurements

- Slower enrichment for smaller building blocks such as Sequoia and Helmi streams
  - Depict lower [X/Fe] in Na, Mg, Ca, Ti, Zn, and Y, compared to other halo stars, including GE

- Low alpha abundances (already at Fe=H] ~ -2)

  →star formation proceeded with low efficiency at early times

Matsuno et al (2021, 2022)



* Sequoia

* Helmi streams

See talk by Horta

Chemical abundances are crucial

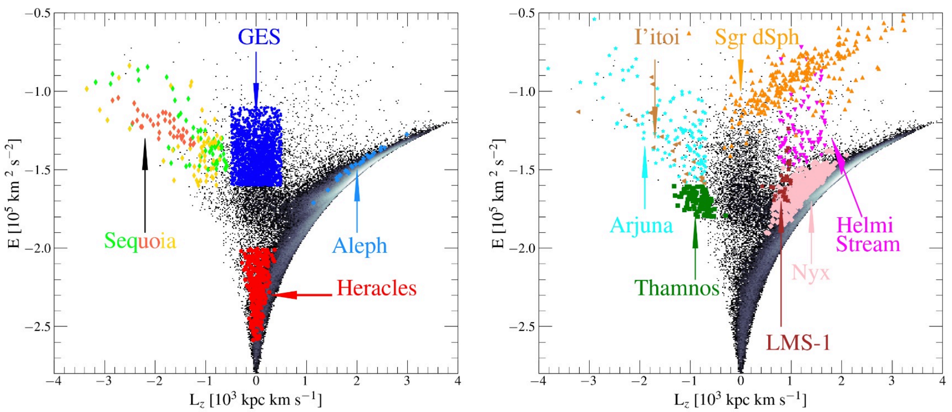
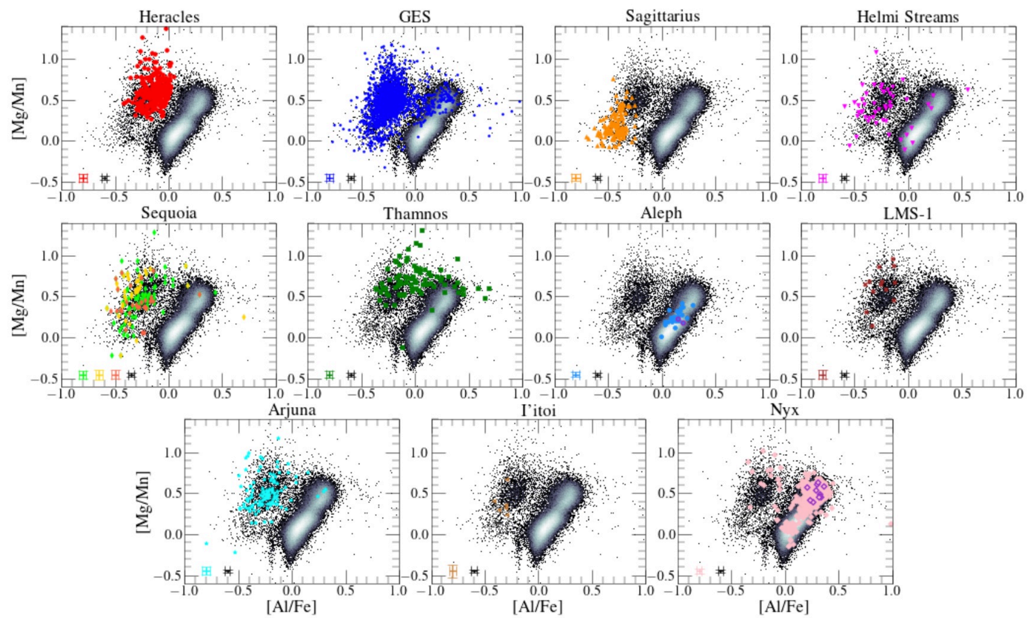


Figure 4. Distribution of the identified halo substructures in the orbital energy (E) versus angular momentum w.r.t. the Galactic disc (L_z) plane. The parent sample is plotted as a 2D histogram, where white/black signifies high/low density regions. The coloured markers illustrate the different structures studied in this work, as denoted by the arrows (we do not display Pontus(Icarus) as we only identify 2(1) stars, respectively). The figure is split into two panels for clarity.



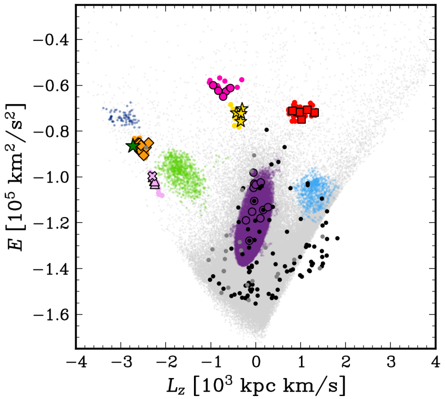
- [Mg/Mn] vs [Al/Fe] good indicator of (accreted) origin
- Most objects identified associated to merger debris

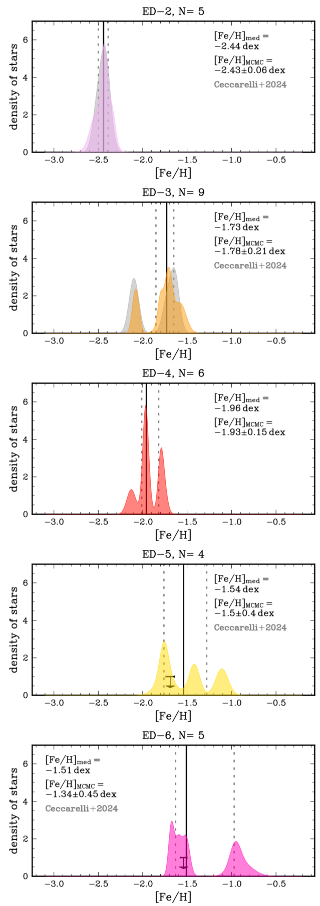
See also Gaia collaboration (2022): Recio-Blanco et al

Horta et al (2023) based on APOGEE

Chemical characterization of smaller substructures

Follow up with UVES



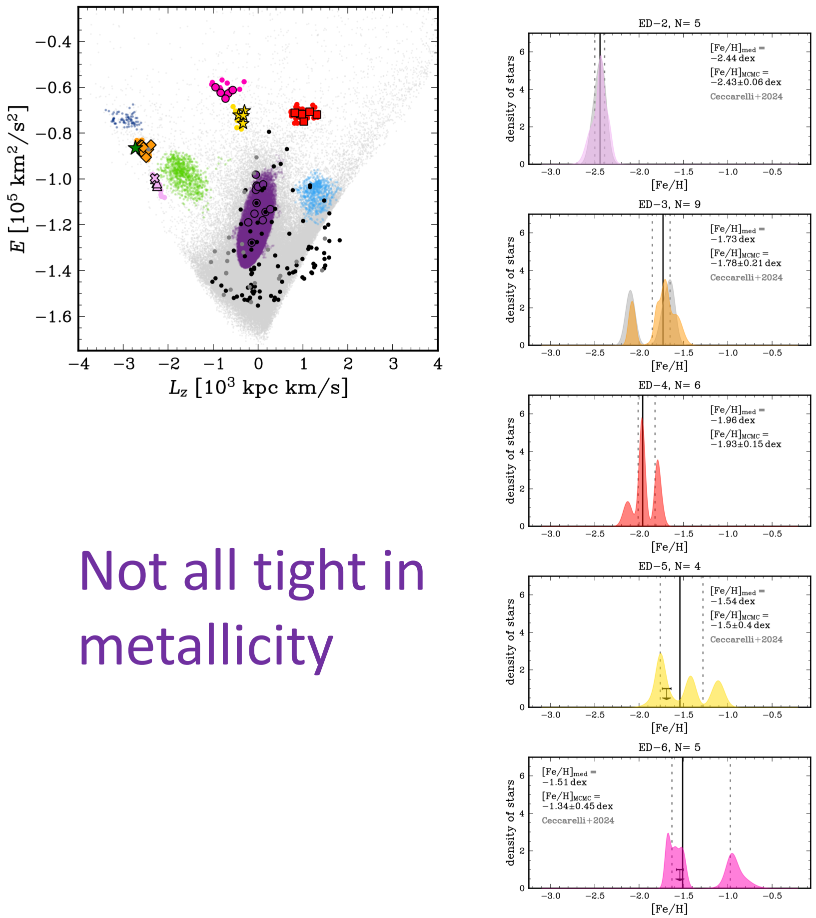


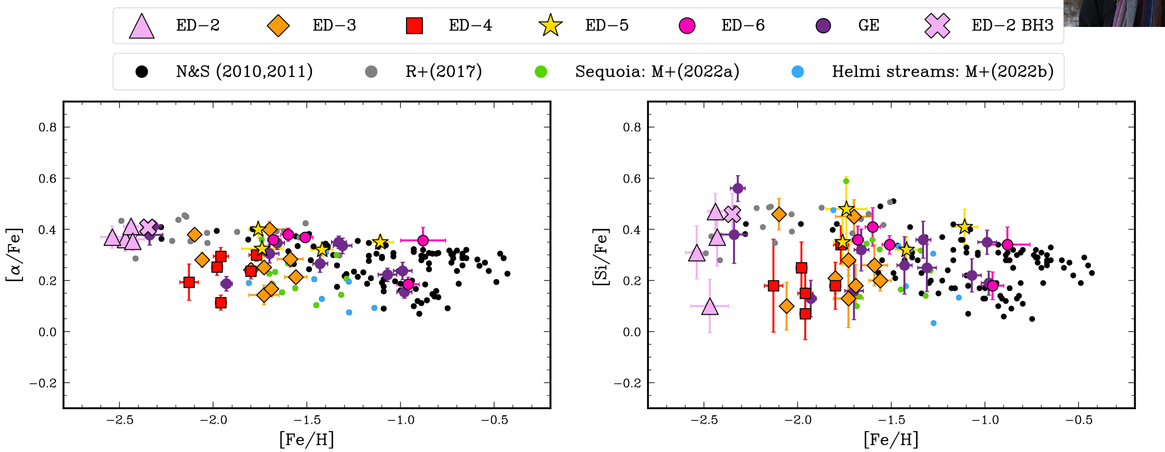
Not all tight in metallicity

Dodd, Matsuno et al 2024b (in prep)

Chemical characterization of smaller substructures

Follow up with UVES





Not all tight in metallicity

- Wide variety of origins
  - GE, glob. cluster, small dwarf
  - ED-3 possibly related to NGC3201
- Size of structure while proxy, not perfect
  - some streams close to resonances
  - GE left debris over large region in IoM

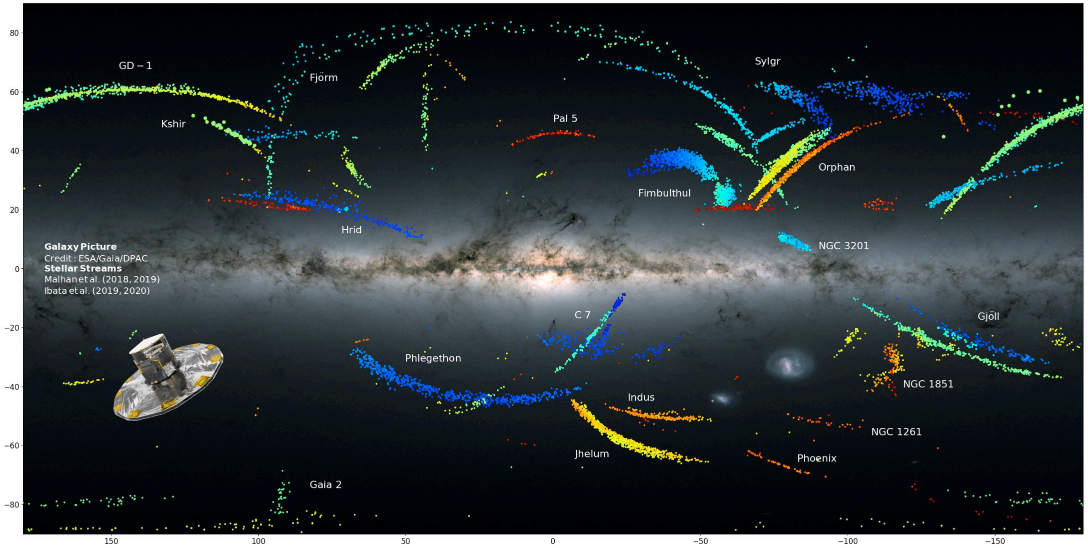
Koppelman+2019; Di Matteo+ 2020; Khopersov+2023; Mori+2024

Dodd, Matsuno et al 2024b (in prep)

Associations to globular clusters and cold streams

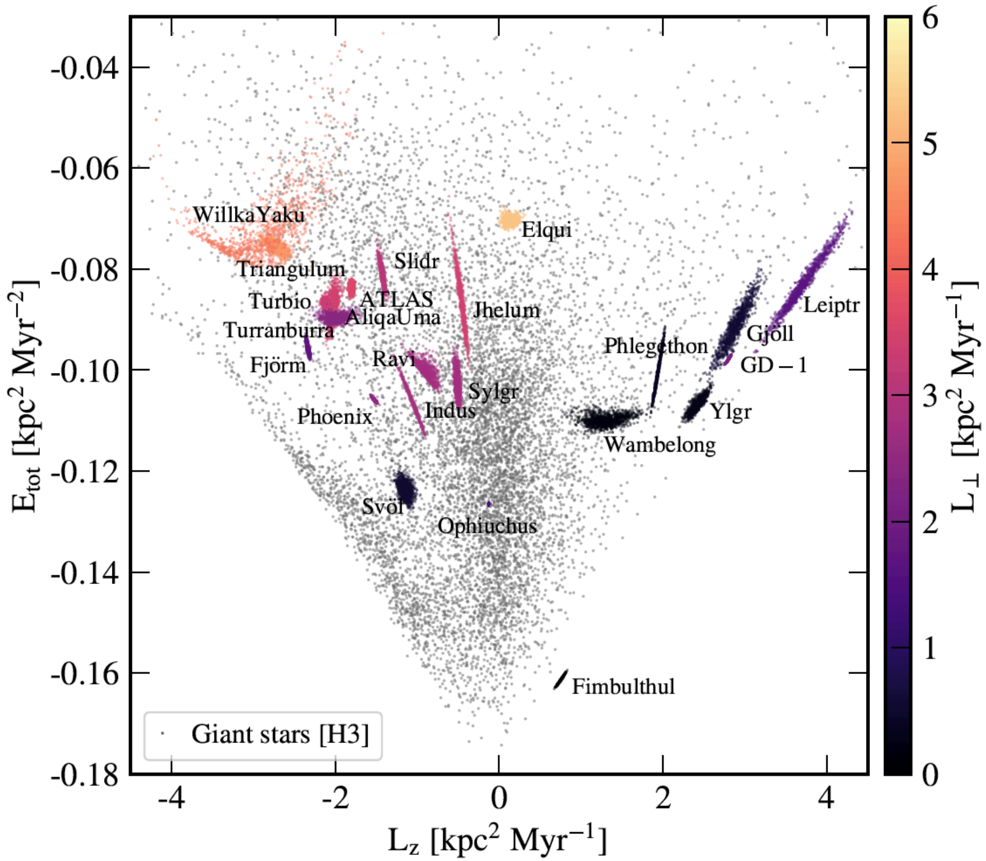
Talks by Massari, Horta; Session 2

Malhan et al (2021)



Many narrow streams have similar orbits as large building blocks

- Could have fallen-in together

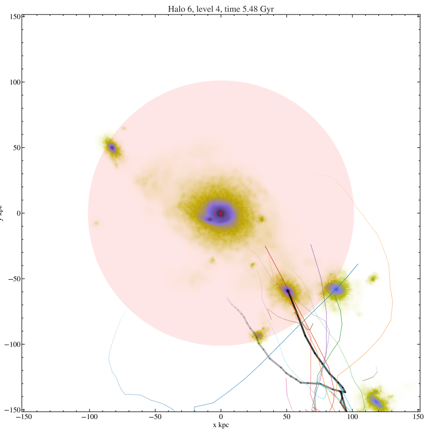


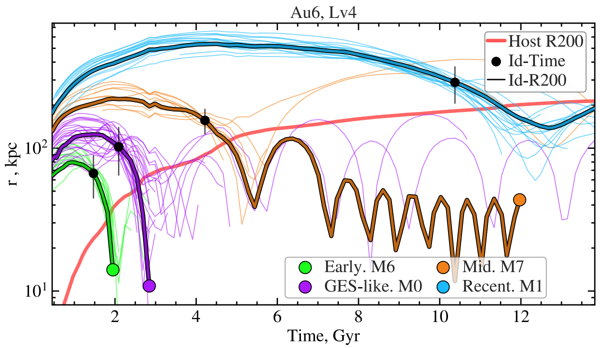
Bonaca et al (2021)

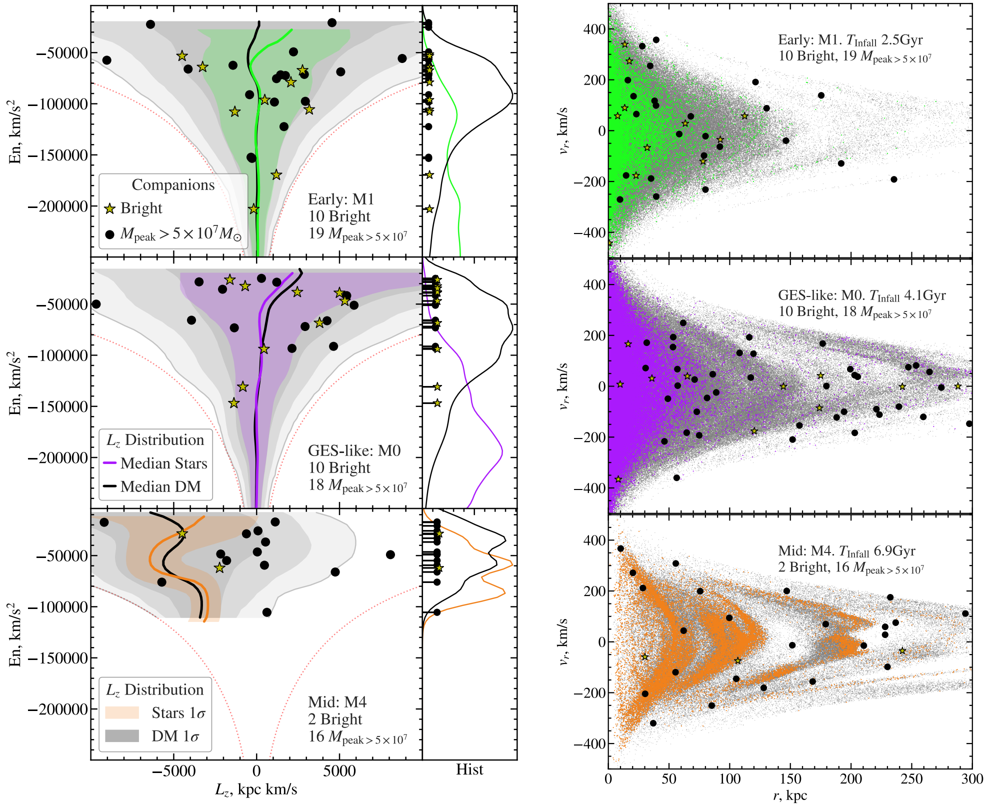
Group accretion likely happened

- LMC/SMC and UFDs clear example of recent group accretion
- Auriga simulations reveal group accretion

Callingham & AH (2024, in prep)



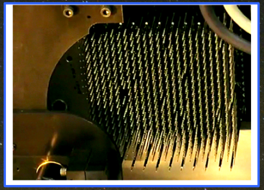


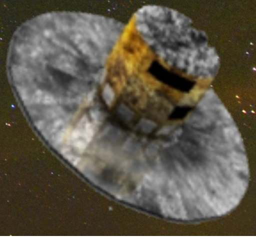


- Most companions on less bound orbits (larger distances)
- Depending on when group was accreted dynamical coherence may remain

Summary: we have come a long way
Where do we go from here?

- Identification of merger debris and characterization
- Identification in IoM obviously has limitations:
  - bar potential and triaxiality (no integrals – time dependence)
  - structures may have multiple origins
    - accretion and massive mergers are messy
    - response to mergers from in-situ populations
    - resonances





- Chemistry is critical
- Dynamics beyond the Solar vicinity
  - Complete samples important! selection functions leave imprints

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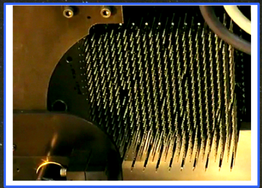
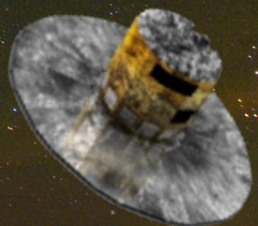
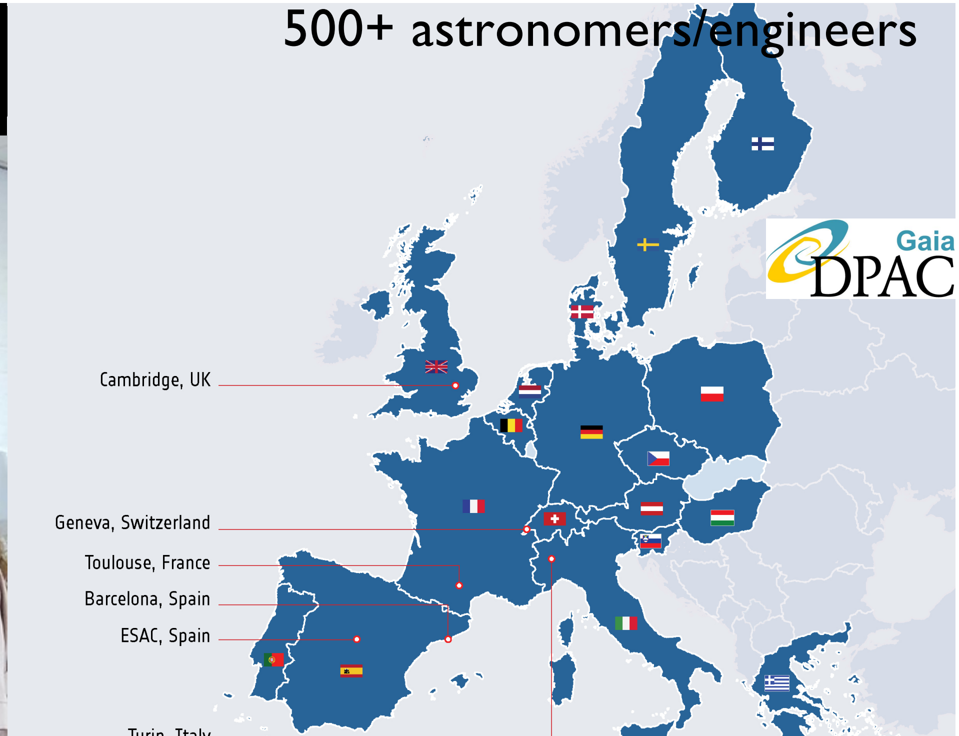
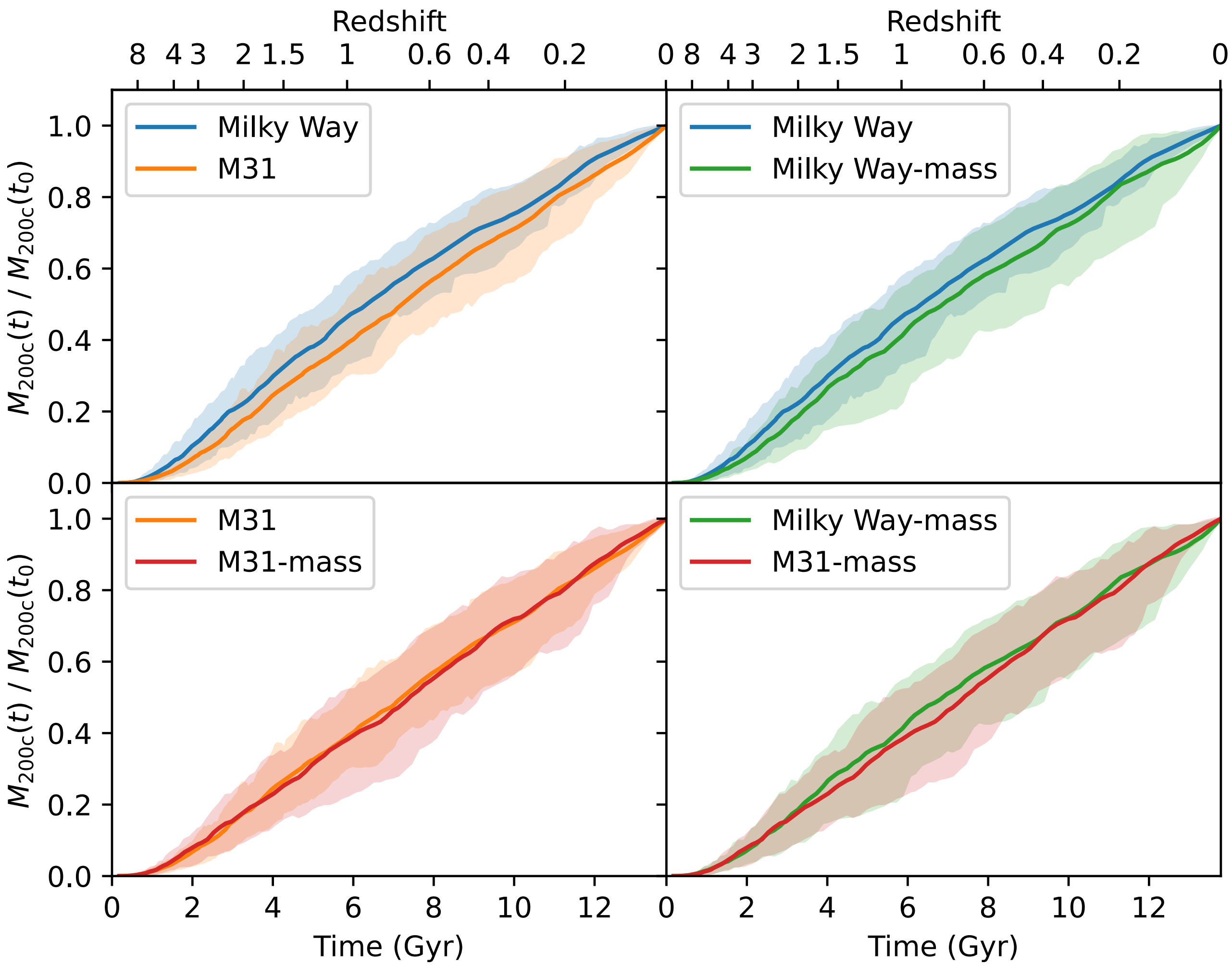
  - Complete samples important! selection functions leave imprints

Thank you for your attention
Parabéns para você Beatriz!

With big thanks to them!





Redshift
8 4 3 2 1.5 1 0.6 0.4 0.2 0
Milky Way
M31
Milky Way-mass
M31-mass
$M_{200c}(t)$ / $M_{200c}(t_0)$
0.0 0.2 0.4 0.6 0.8 1.0
0 2 4 6 8 10 12
Time (Gyr)