Digging for the Relics of Ancient Mergers at the Heart of the Milky Way

Thomas Tomlinson

with Francesca Fragkoudi, Andreia Carrillo, and Azadeh Fattahi

Durham University

ICC Institute for Computational Cosmology

UKRI Science and Technology Facilities Council

thomas.j.tomlinson@durham.ac.uk

Image: NASA/JPL-Caltech/S. Stolovy

Unraveling the Miky Way's history using galactic archaeology

- Stars preserve information about the environment they formed through their chemical composition and their dynamics
- We are living in a golden age of Milky Way archaeology, with the advent of Gaia and positions and velocities of over a billion stars (Gaia Collaboration+ 2021), as well as spectroscopic measurements reaching deeper and deeper into the galaxy
- Simulations can provide predictions and interpretations for observations

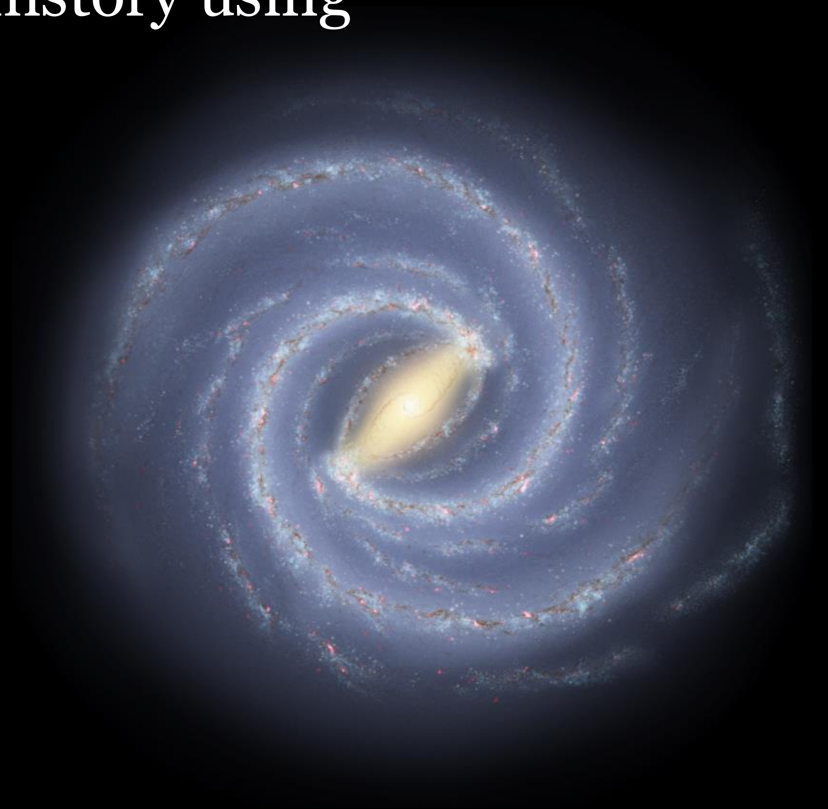
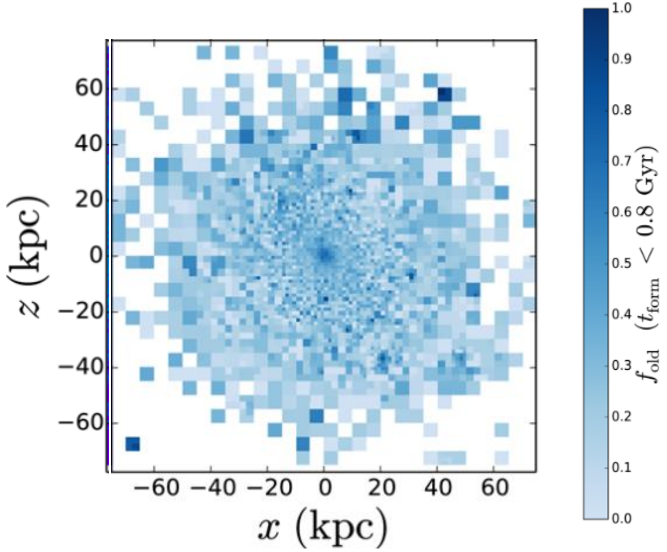


Image: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Why the centre?

- According to our galaxy formation models, they grow "inside-out", with the centre containing the oldest stars in the galaxy (Starkenburg+ 2017)
- Further, remnants of the oldest mergers are found here (Barbuy+ 2018)
- However, probing the centre of the galaxy comes with challenges such as: extremely high density of stars, small dynamical timescales, overlapping features (such as disc, bar, stellar halo)

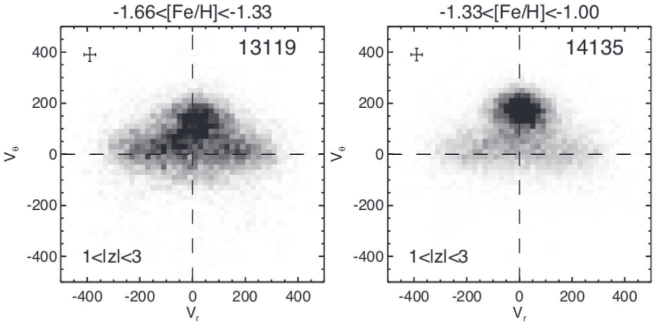


Starkenburg+ 2017

Unraveling our merger history: Tools at our disposal

Belokurov+ 2018

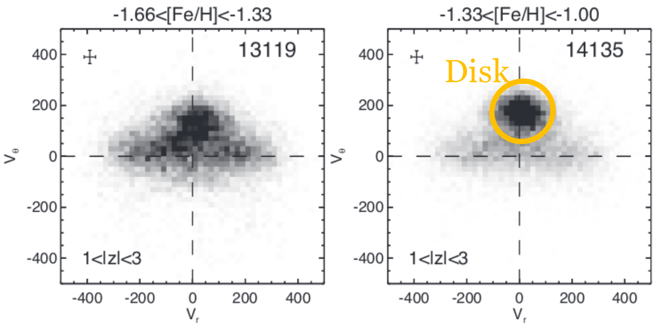
Phase space



Unraveling our merger history: Tools at our disposal

Belokurov+ 2018

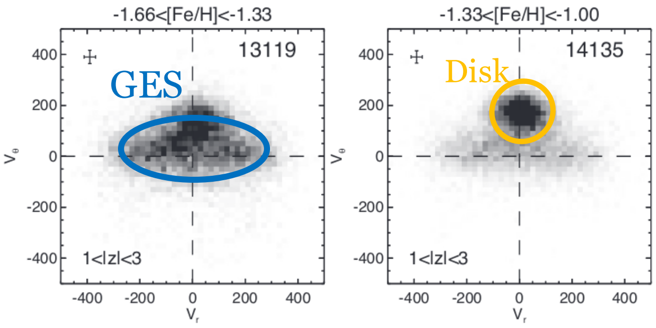
Phase space



Unraveling our merger history: Tools at our disposal

Belokurov+ 2018

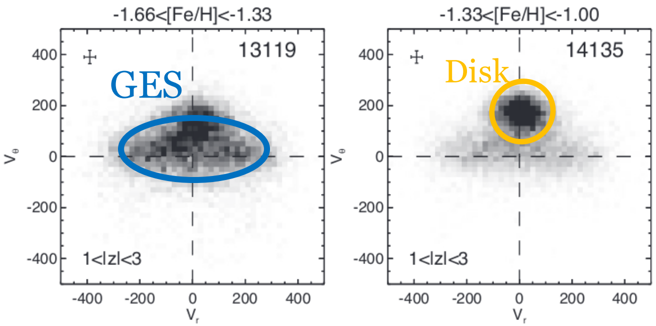
Phase space



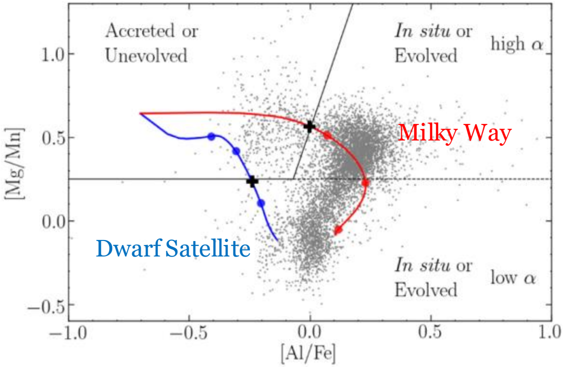
Unraveling our merger history: Tools at our disposal

Belokurov+ 2018

Phase space



Chemical composition

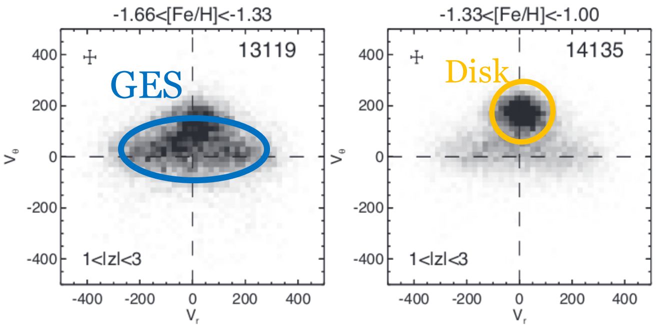


Horta+ 2020

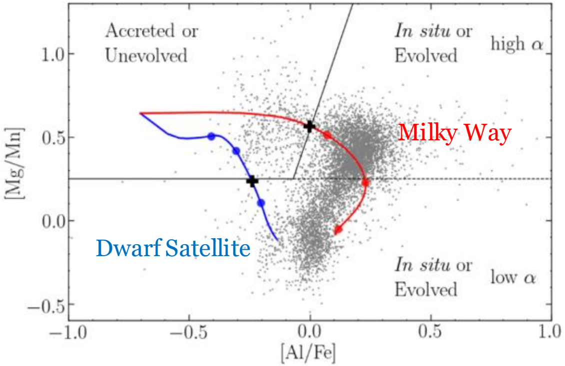
Unraveling our merger history: Tools at our disposal

Belokurov+ 2018

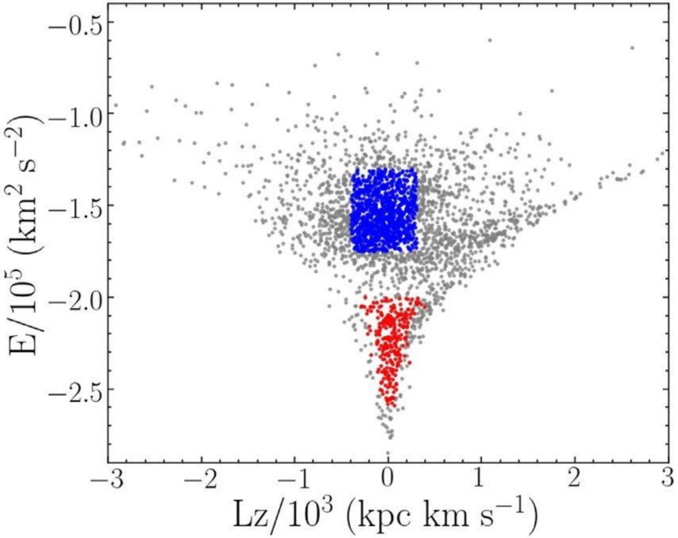
Phase space



Chemical composition



Horta+ 2020

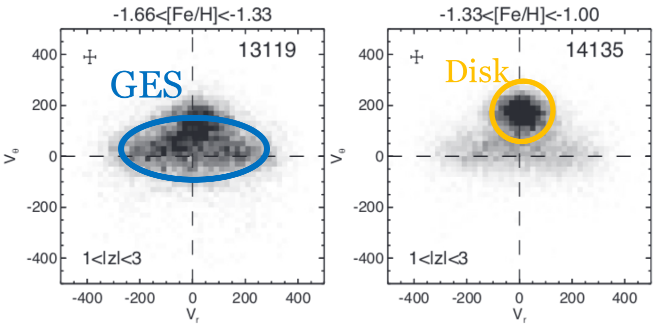


Horta+ 2020

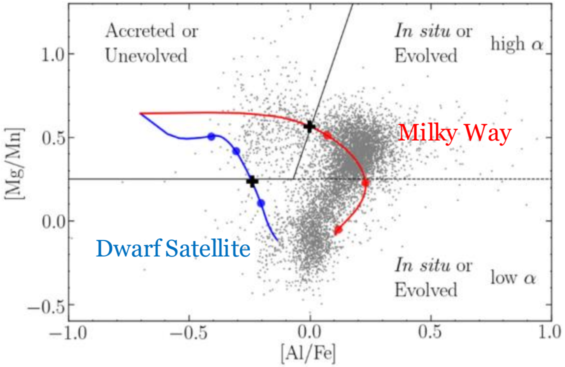
Unraveling our merger history: Tools at our disposal

Belokurov+ 2018

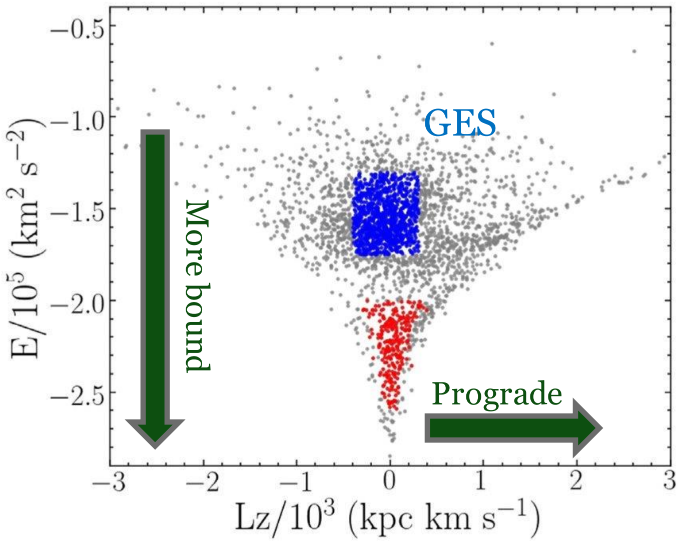
Phase space



Chemical composition



Horta+ 2020

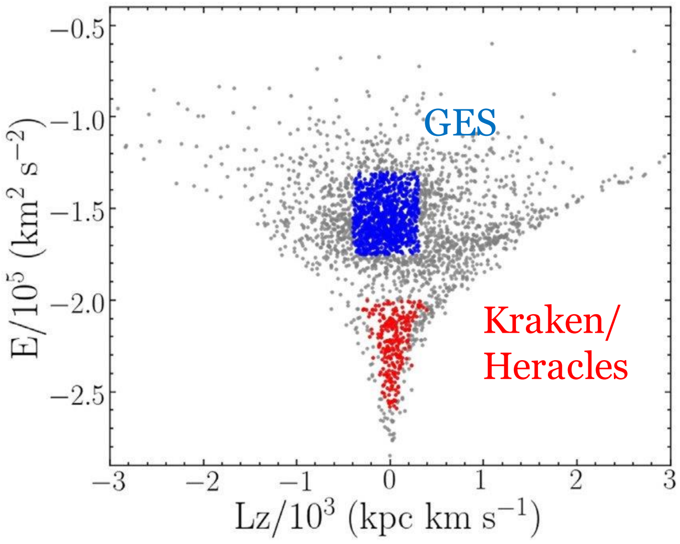


Horta+ 2020

Probing the early assembly of the Milky Way

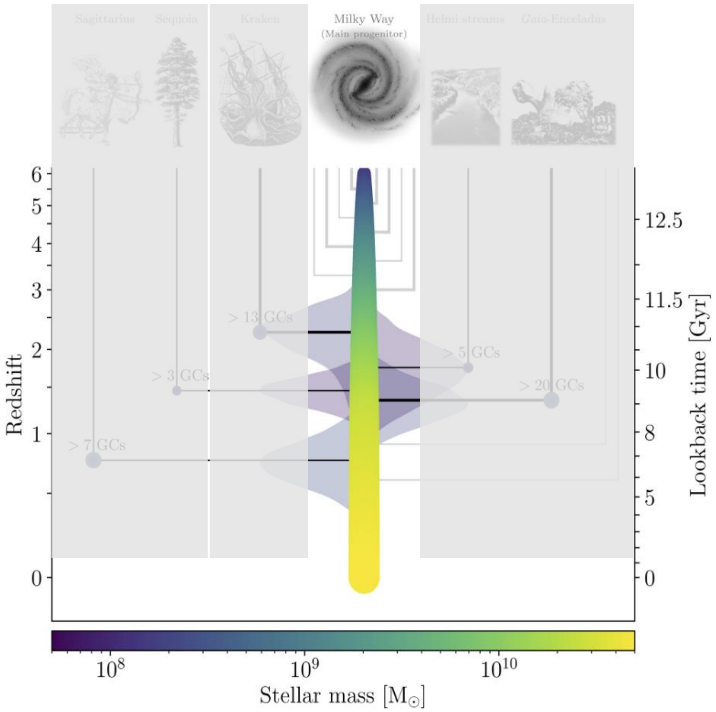
Examples of early mergers:
Kraken and Heracles

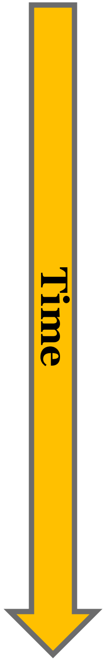
- Discovered through dynamical and chemical properties which suggest an accreted origin (Kruijssen+ 2020, Horta+ 2020)
- However not yet clear if Kraken and Heracles describe the same accretion event (Horta+ 2024)
- Possibly the largest merger in the Milky Way's history with a merger mass ratio of around 1:7 (Kruijssen+ 2020)
- An accretion event that is buried in the inner regions of the galaxy (Kruijssen+ 2020)



Horta+ 2020

The big picture

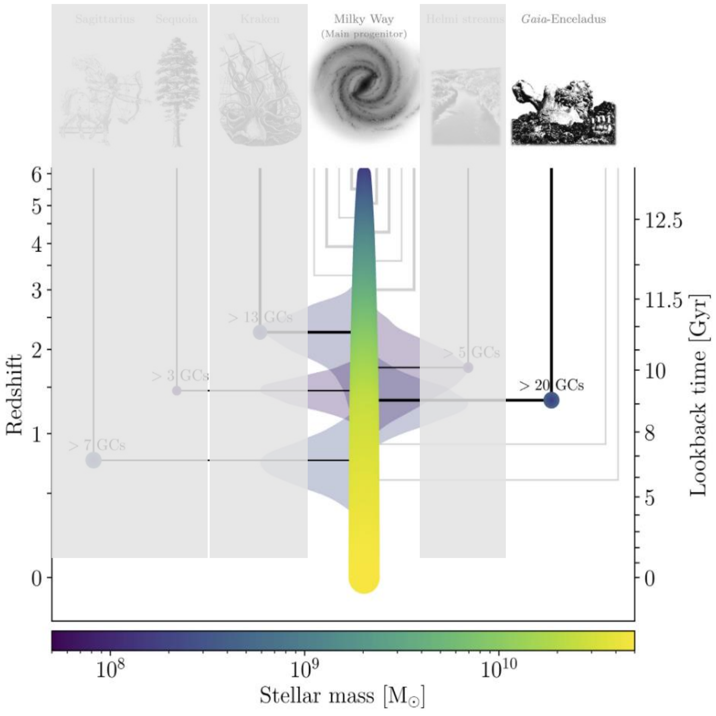


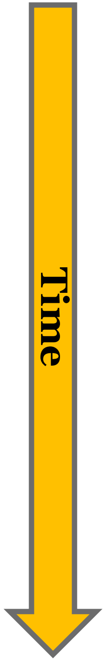


Kruijssen+ 2020

The big picture

GES

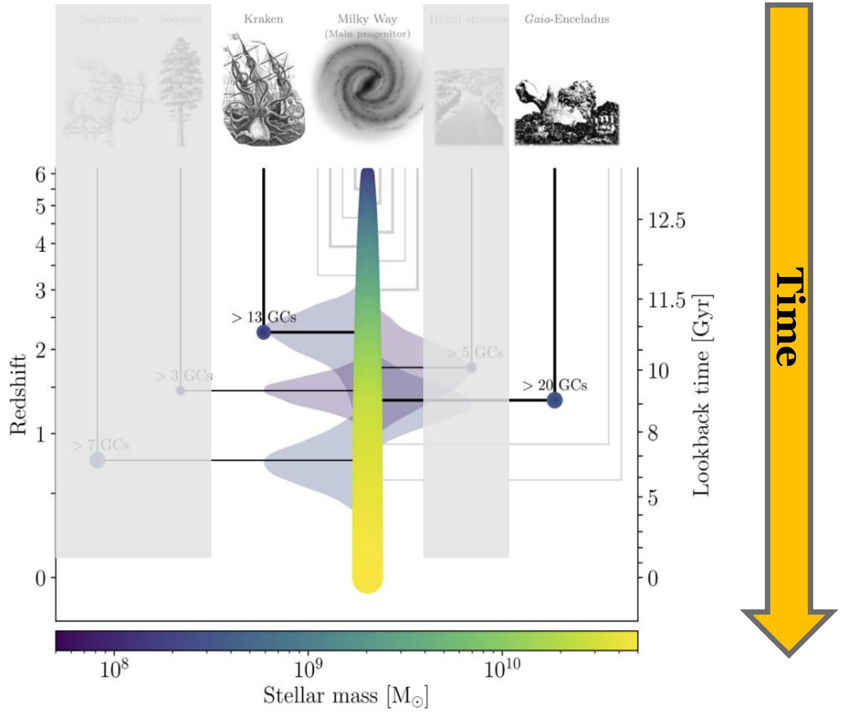




Kruijssen+ 2020

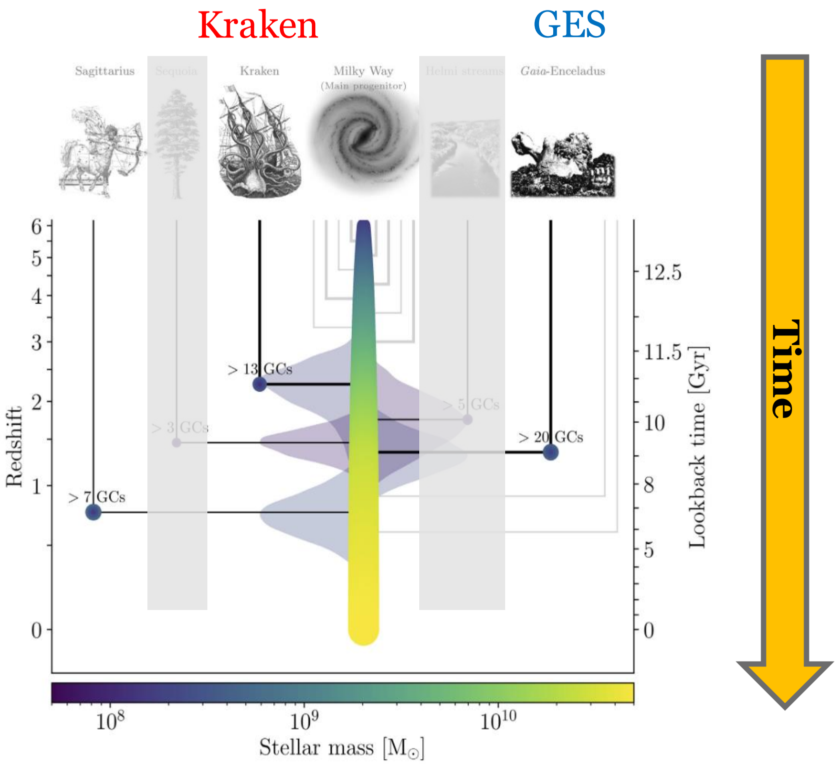
The big picture

Kraken GES



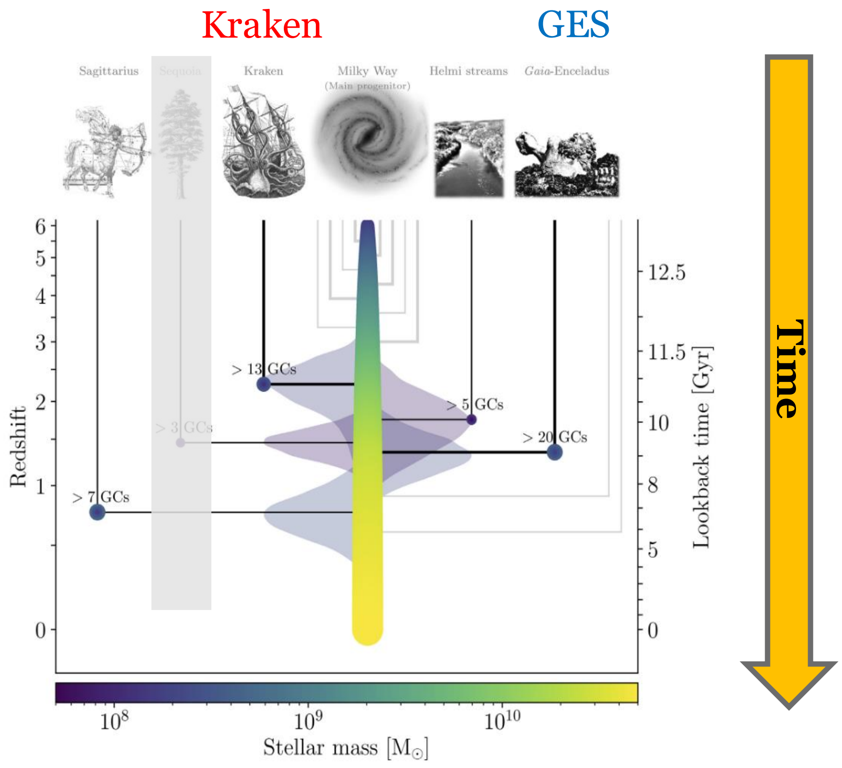
Kruijssen+ 2020

The big picture



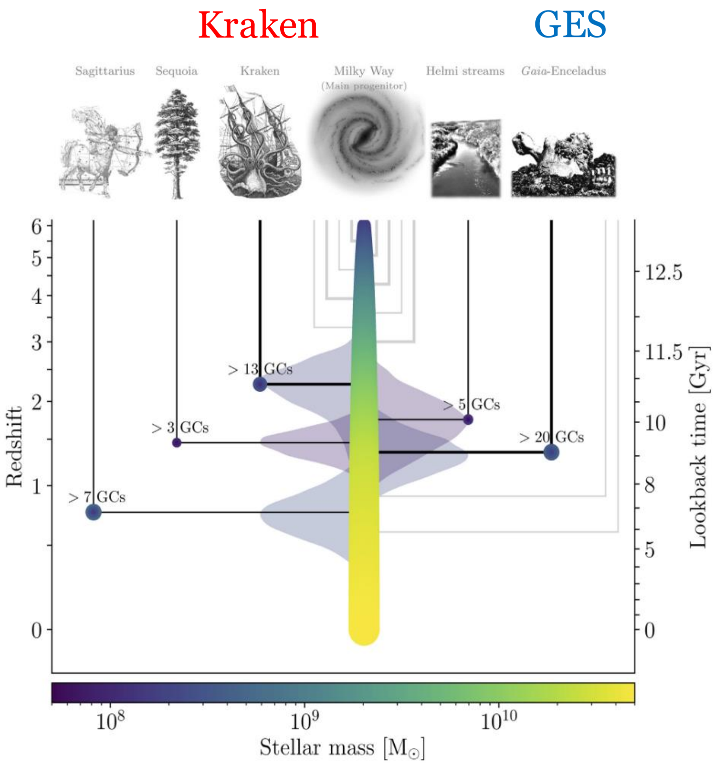
Kruijssen+ 2020

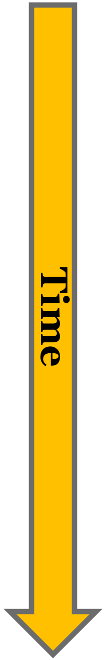
The big picture



Kruijssen+ 2020

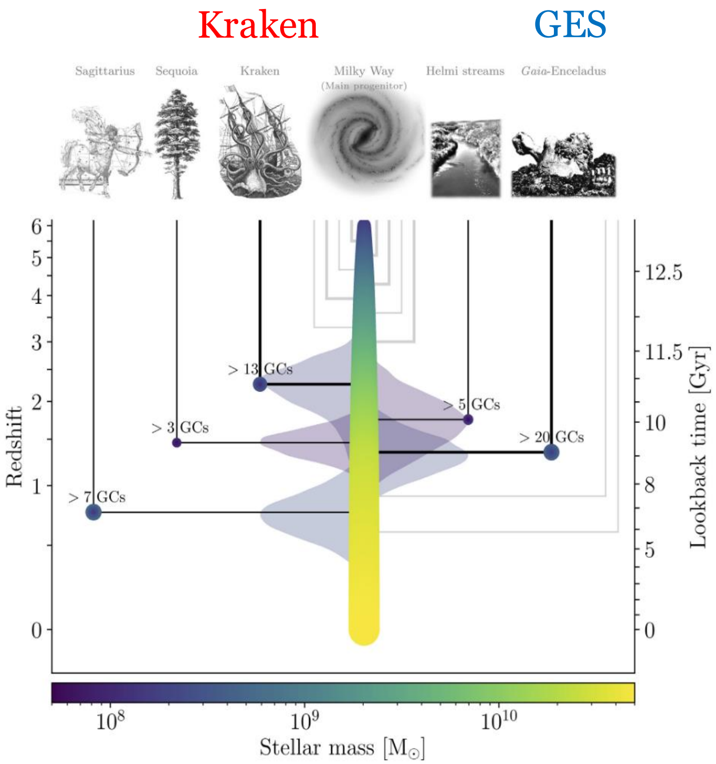
The big picture

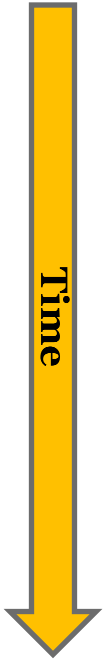


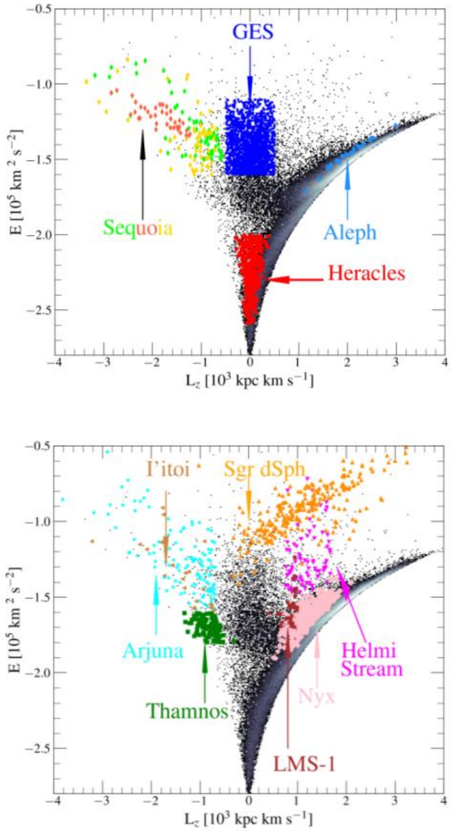


Kruijssen+ 2020

The big picture





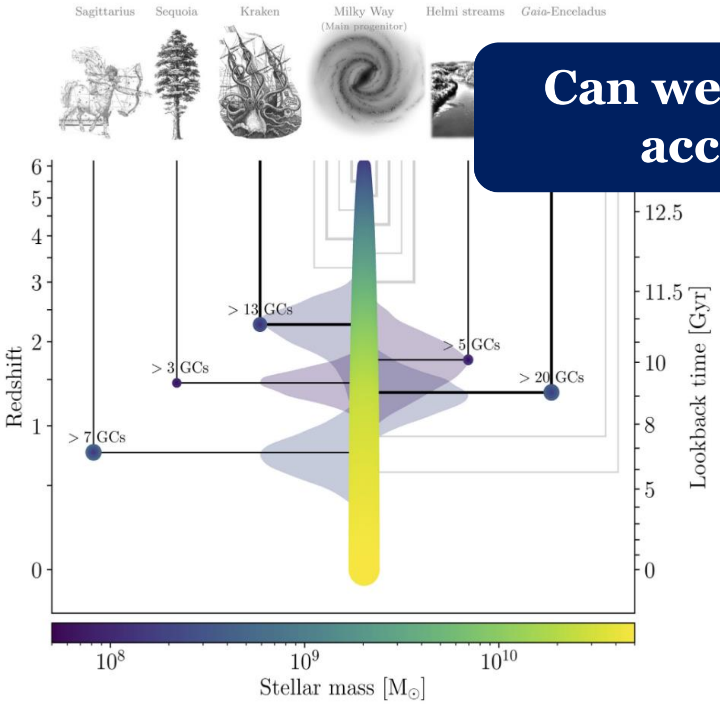


Kruijssen+ 2020

Horta+ 2024

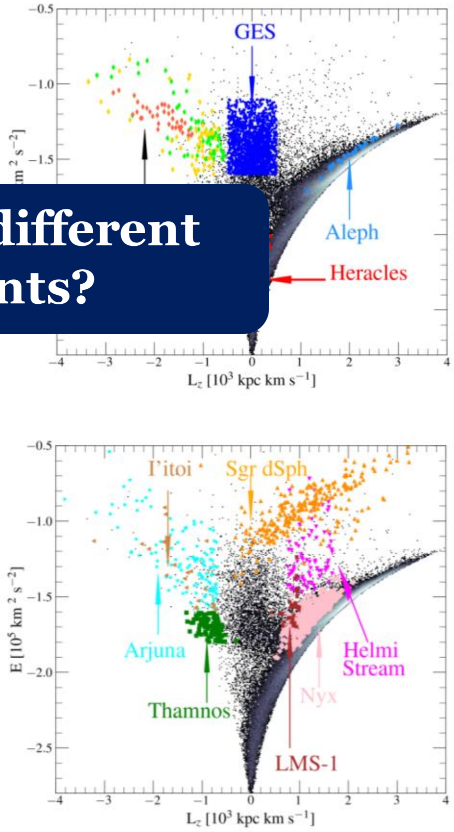
The big picture

Kraken GES



Time

Can we separate different accretion events?



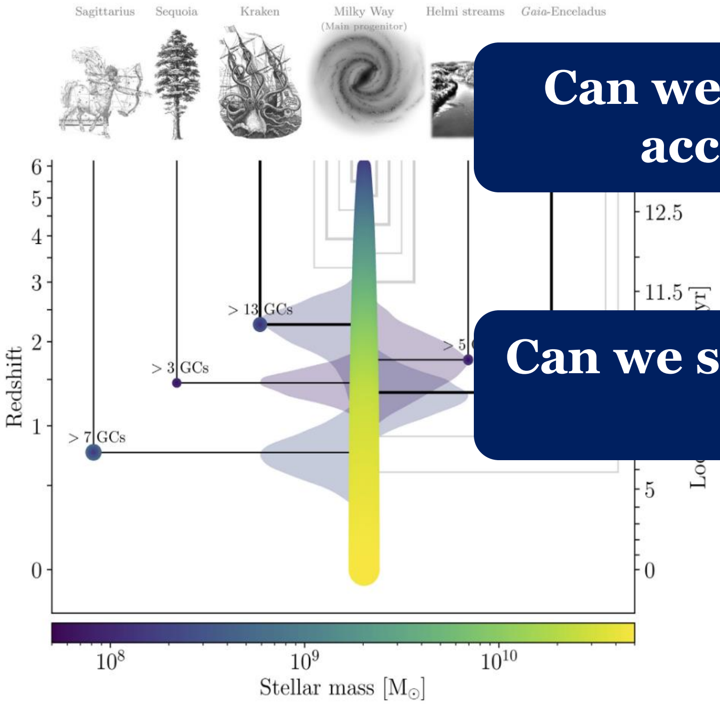
Kruijssen+ 2020

Horta+ 2024

The big picture

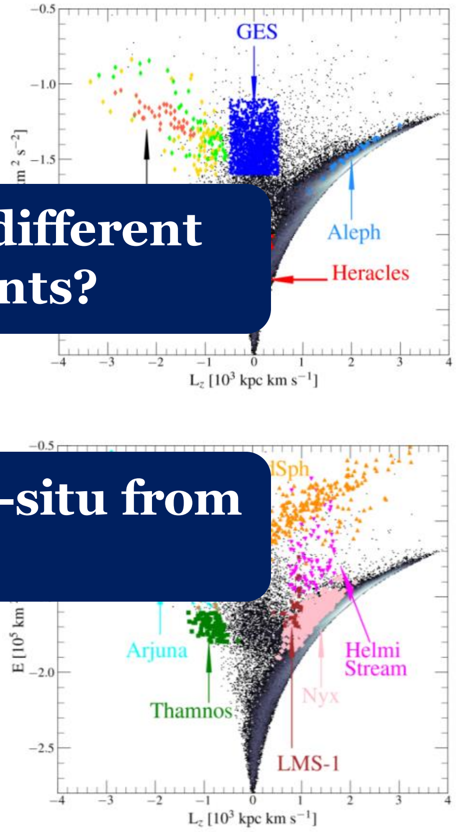
Kraken

GES



Can we separate different accretion events?

Can we separate in-situ from accreted?



Kruijssen+ 2020

Horta+ 2024

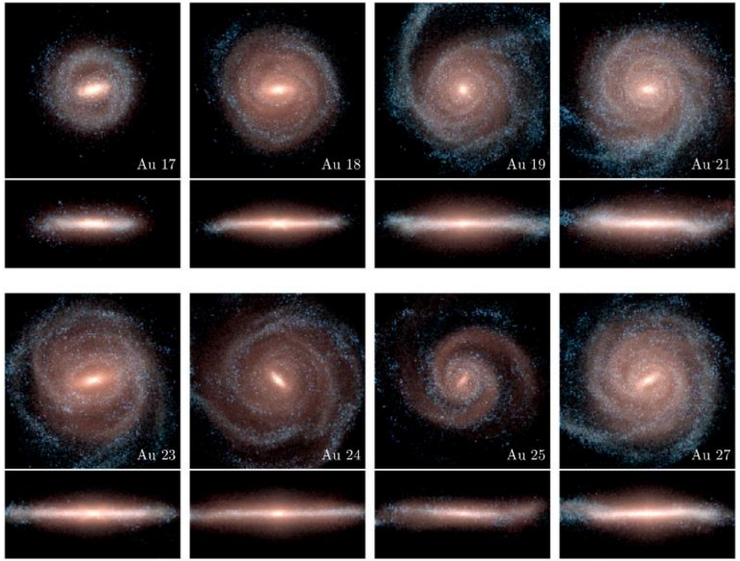
Auriga Superstars: Using ultra-high resolution to study the metal-poor population

Cosmological zoom-in simulation
using AREPO (Springel+ 2010)

High resolution re-simulations of halos from the Auriga suite of 30 Milky Way mass halos (Grand+ 2016)

Simulation parameters:

- Dark matter mass resolution of 6 x 10^3 $M_\odot$
- Gas resolution of 5 x 10^4 $M_\odot$
- Stellar particle resolution of 800 $M_\odot$



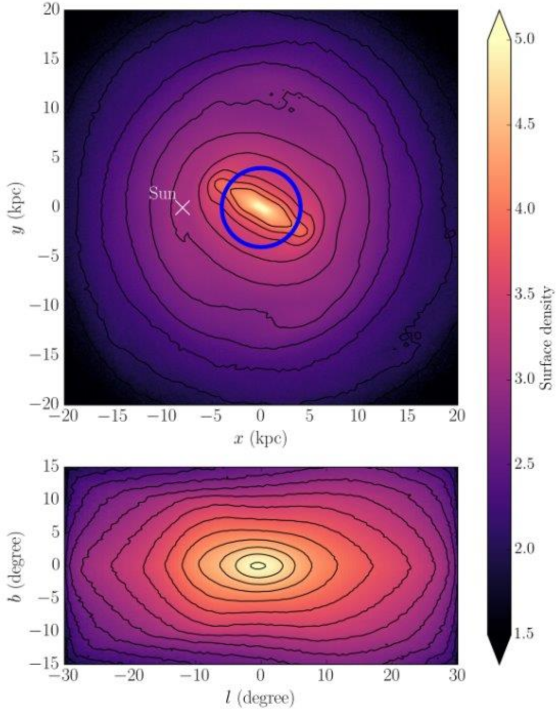
Grand+ 2016

Auriga 18 – A Milky Way "analogue"

Halo 18

- Virial mass of ~$1.2 \times 10^{12}\ M_\odot$
- Boxy/peanut bulge with a bar
- Bulge is chemo-dynamically similar to the Milky Way (Fragkoudi+ 2020)
- Merger history with analogues to Milky Way (Fattahi+ 2019)

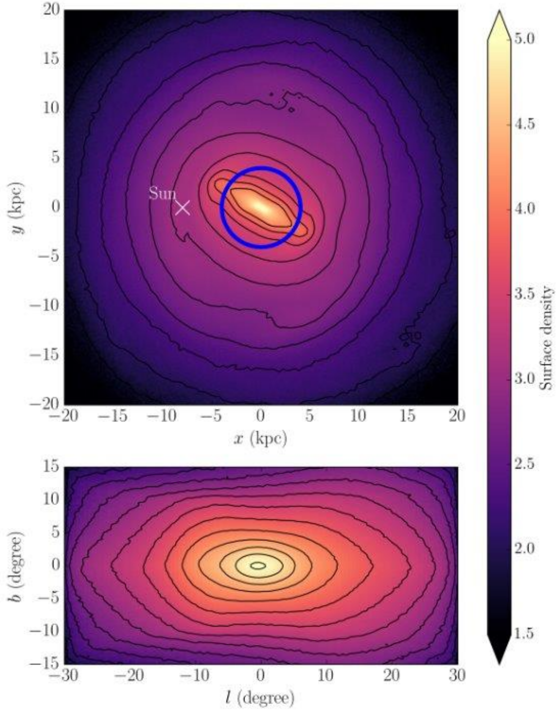
	Merger time (Gyrs)	Peak halo mass ($M_\odot$)	Peak stellar mass ($M_\odot$)	Merger mass ratio
Merger 1	1.91	3.0×10^9	1.5×10^8	1:14
Merger 2	2.26	9.6×10^9	1.9×10^8	1:17
Merger 3	5.34	1.6×10^{10}	5.6×10^8	1:40
Merger 4	5.52	3.6×10^{10}	1.5×10^9	1:17



Auriga 18 – A Milky Way "analogue"

Halo 18

- Virial mass of ~$1.2 \times 10^{12}\ M_\odot$
- Boxy/peanut bulge with a bar
- Bulge is chemo-dynamically similar to the Milky Way (Fragkoudi+ 2020)
- Merger history with analogues to Milky Way (Fattahi+ 2019)



Kraken/ Heracles

	Merger time [illegible]	Peak [illegible]	Peak stellar mass ($M_\odot$)	Merger mass ratio
Merger 1	[illegible]	3.0×10^{9}	1.5×10^8	1:14
Merger 2	2.26	9.6×10^9	1.9×10^8	1:17
Merger 3	5.34	1.6×10^{10}	5.6×10^8	1:40
Merger 4	5.52	3.6×10^{10}	1.5×10^9	1:17

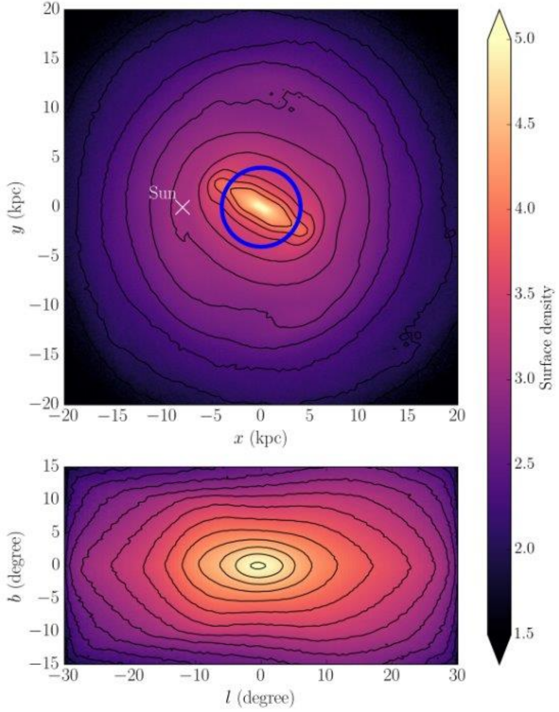
Auriga 18 – A Milky Way "analogue"

Halo 18
- Virial mass of ~$1.2 \times 10^{12}\ M_{\odot}$
- Boxy/peanut bulge with a bar
- Bulge is chemo-dynamically similar to the Milky Way (Fragkoudi+ 2020)
- Merger history with analogues to Milky Way (Fattahi+ 2019)

	Merger time ([illegible])	[illegible]	Peak stellar mass ($M_{\odot}$)	Merger mass ratio
Merger 1	[illegible]	3.0×10^9	1.5×10^8	1:14
Merger 2	2.26	9.6×10^9	1.9×10^8	1:17
Merger 3	[illegible]	1.6×10^{10}	5.6×10^8	1:40
Merger 4	[illegible]	[illegible]	1.5×10^9	1:17

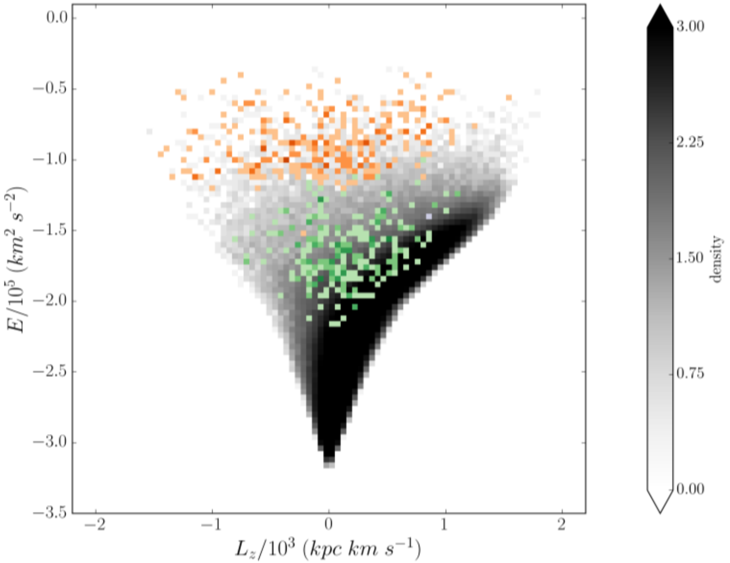
Kraken/ Heracles

GES



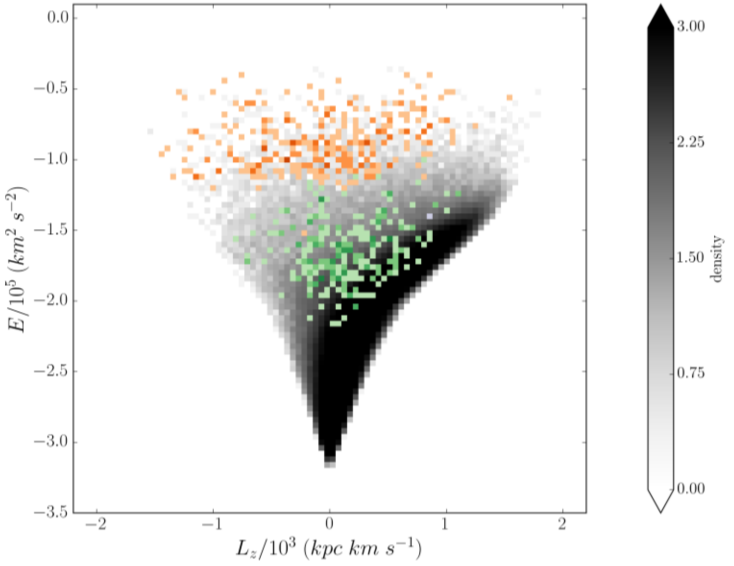
Is this higher resolution useful?

Level 4 - 5 x 10^4 $M_{\odot}$

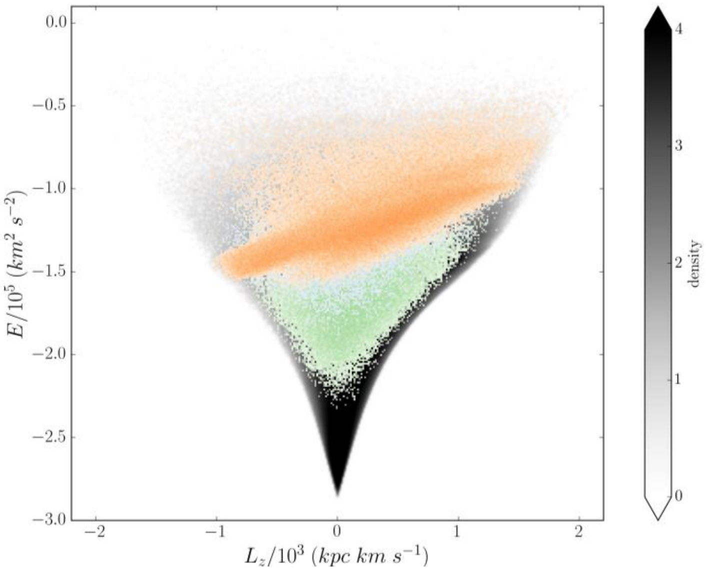


Is this higher resolution useful?

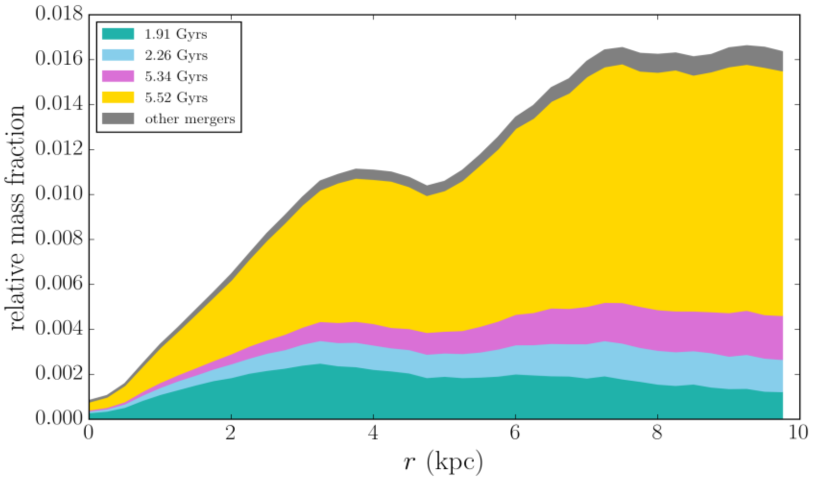
Level 4 - 5 x 10^4 $M_\odot$



Superstars - 800 $M_\odot$

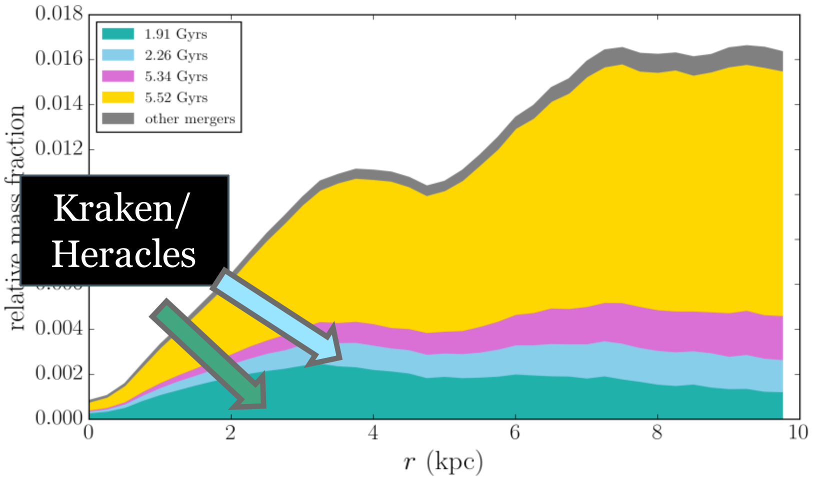


Understanding the accreted population in Au-18



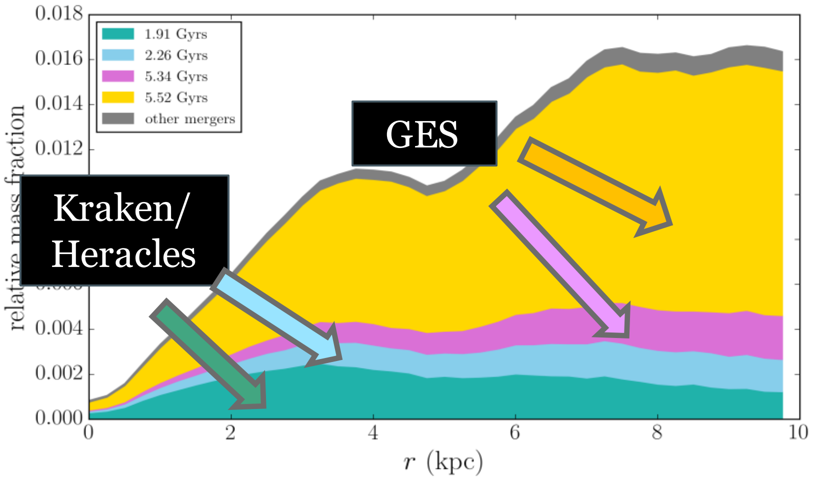
- Accreted population dominated by in-situ stars at the centre
- Butt earliest merger peaks within 4 kpc region

Understanding the accreted population in Au-18



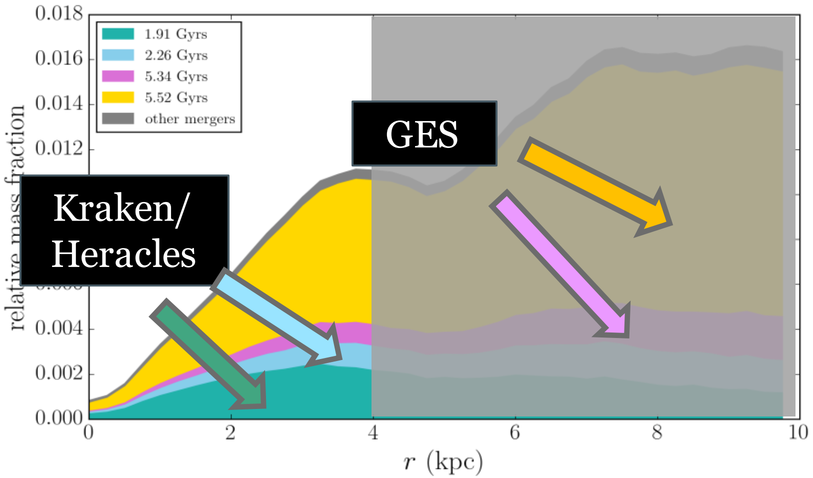
- Accreted population dominated by in-situ stars at the centre
- But earliest merger peaks within 4 kpc region

Understanding the accreted population in Au-18



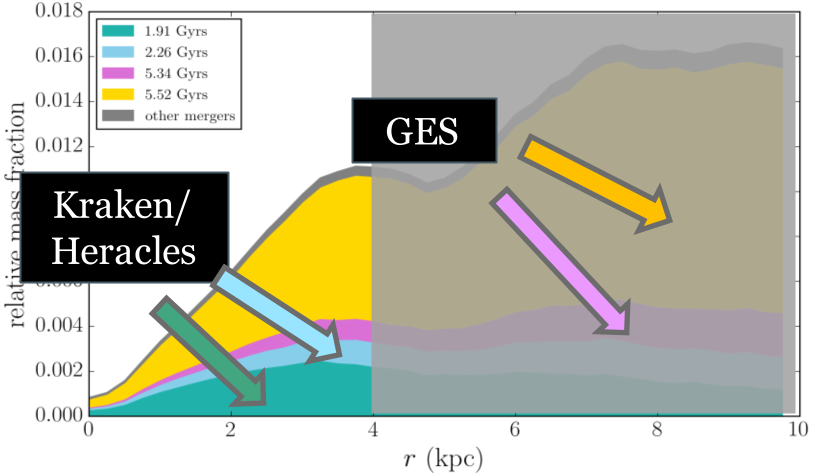
- Accreted population dominated by in-situ stars at the centre
- But earliest merger peaks within 4 kpc region

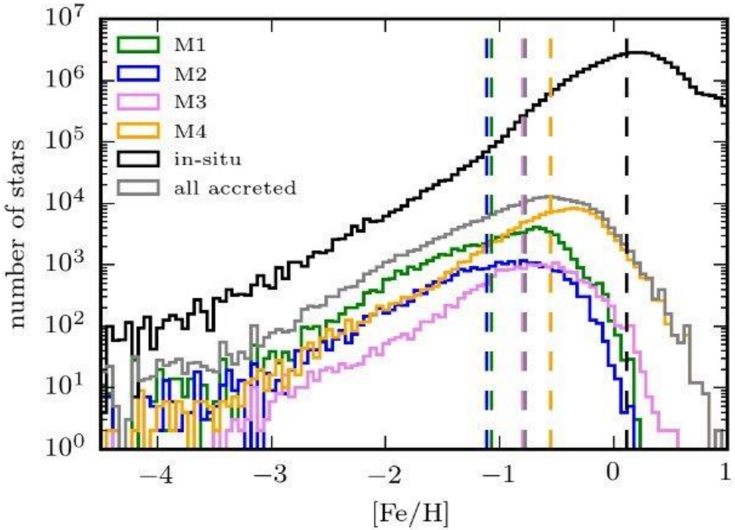
Understanding the accreted population in Au-18



- Accreted population dominated by in-situ stars at the centre
- But earliest merger peaks within 4 kpc region

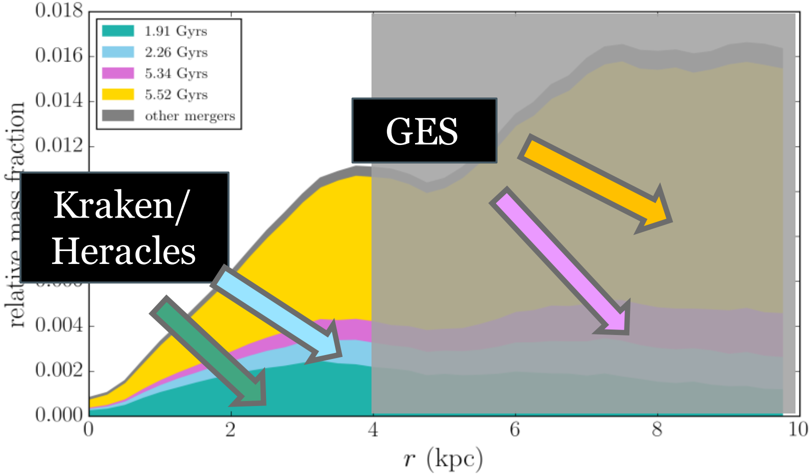
Understanding the accreted population in Au-18

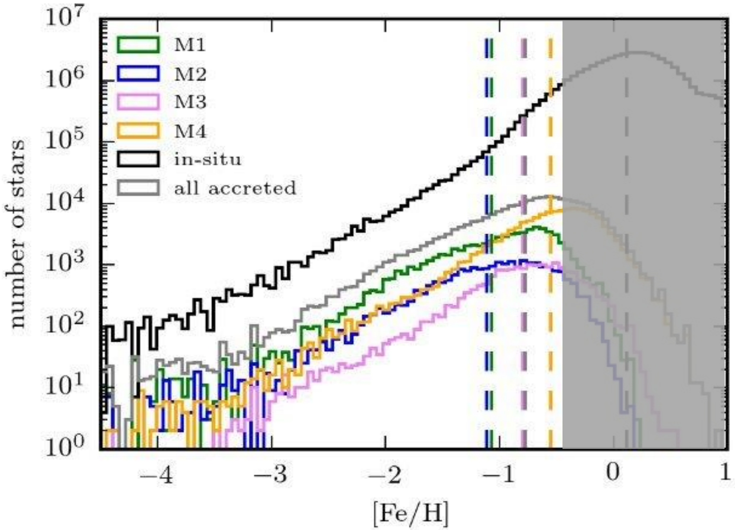




- Accreted population dominated by in-situ stars at the centre
- But earliest merger peaks within 4 kpc region

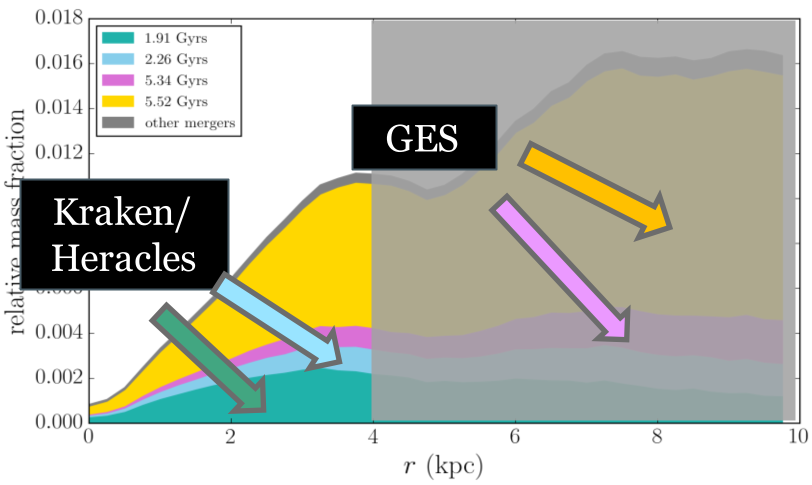
Understanding the accreted population in Au-18

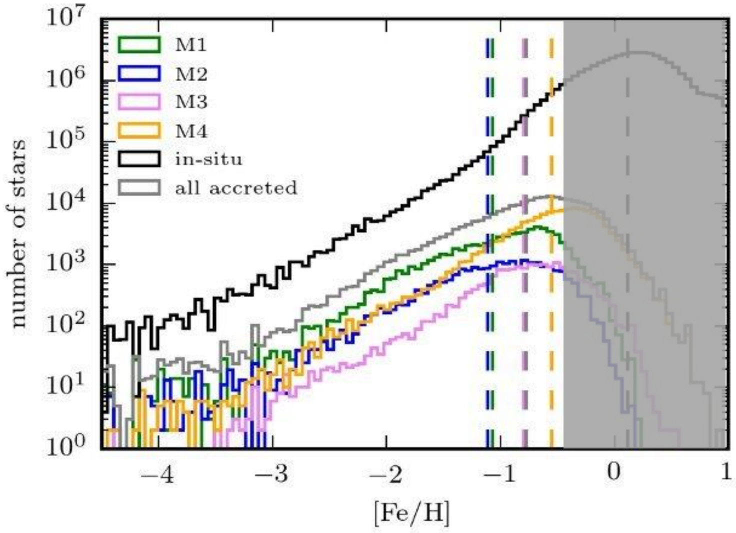




- Accreted population dominated by in-situ stars at the centre
- But earliest merger peaks within 4 kpc region

Understanding the accreted population in Au-18



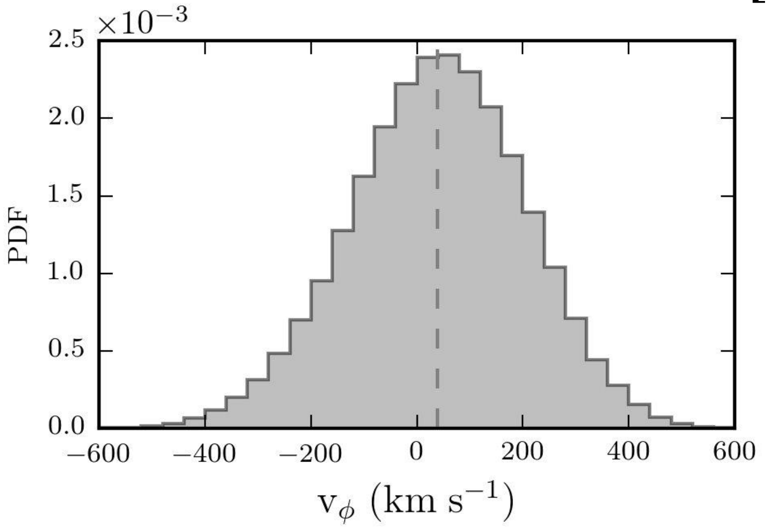


- Accreted population dominated by in-situ stars at the centre
- But earliest merger peaks within 4 kpc region

Going to lower metallicities alleviates in-situ contamination – but doesn't get rid of it

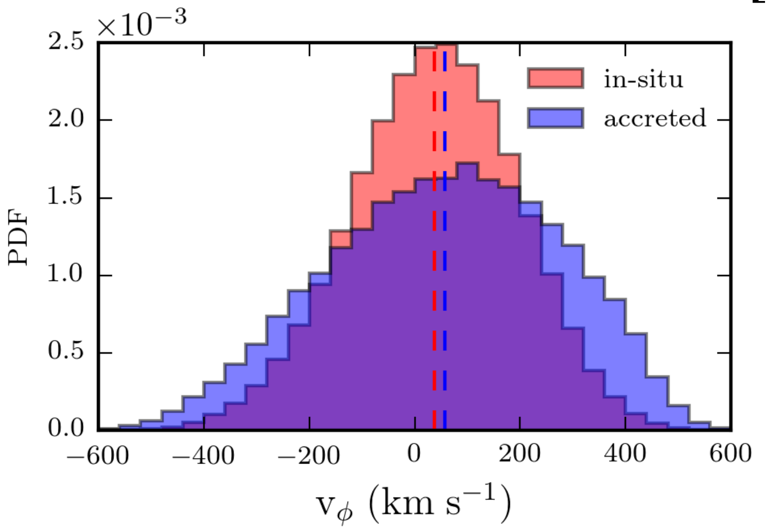
Understanding the accreted population in Au-18

-2 < [Fe/H] < -1



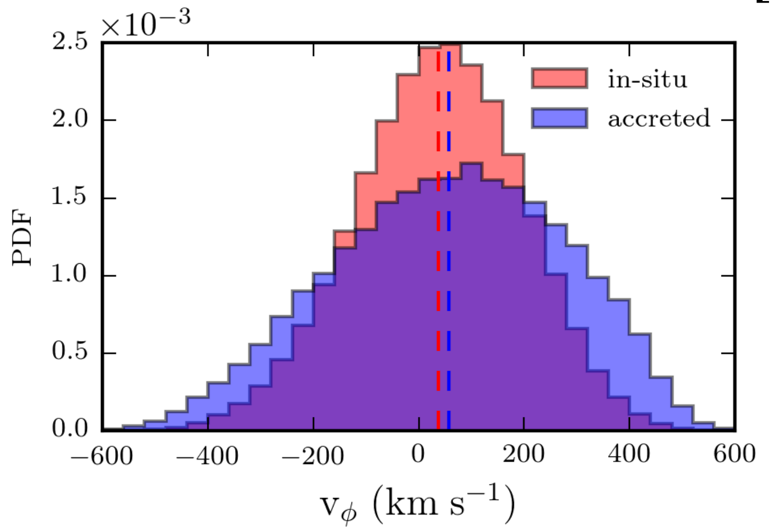
Understanding the accreted population in Au-18

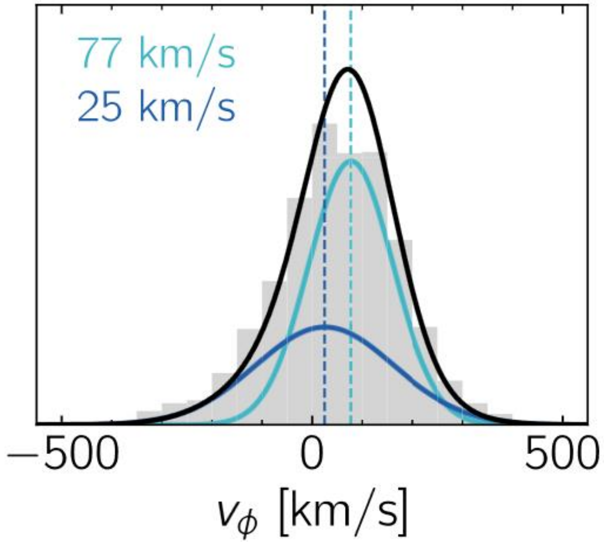
-2 < [Fe/H] < -1



Understanding the accreted population in Au-18

-2 < [Fe/H] < -1





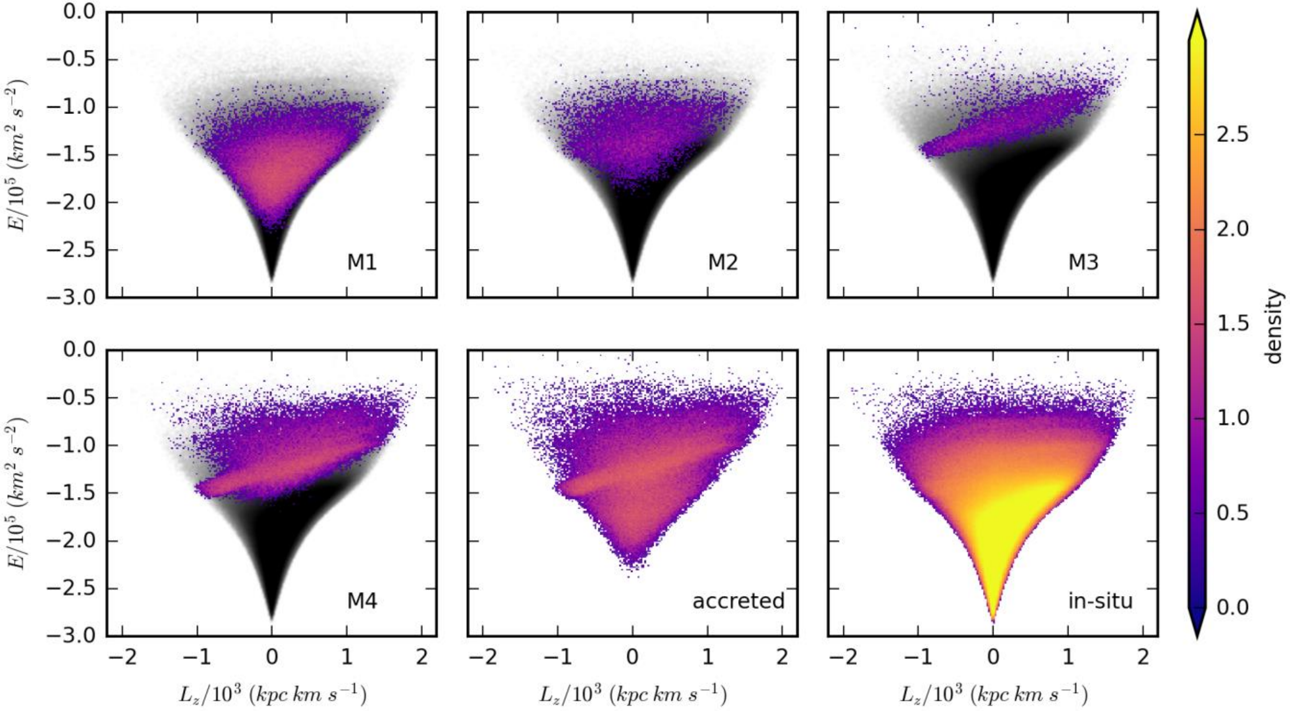
Rotation in the accreted population! - Also not Gaussian

Ardern-Arentsen+ 2023

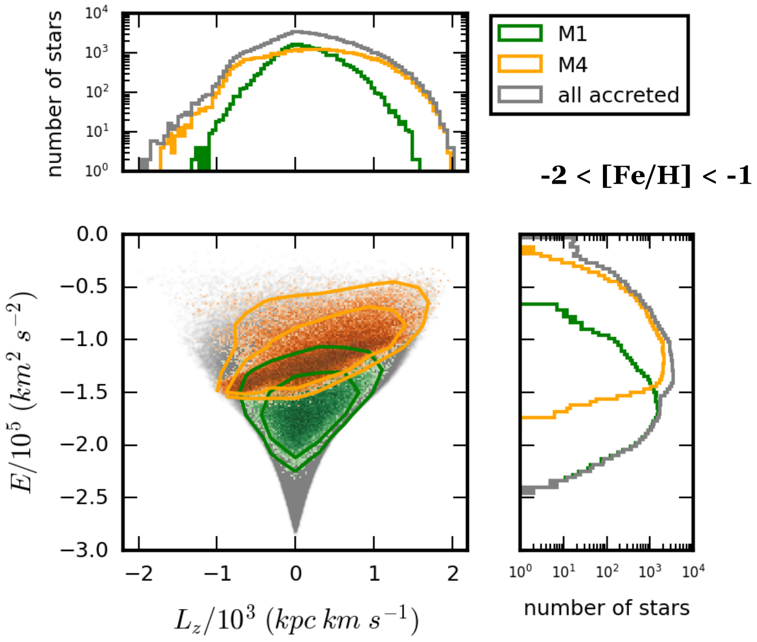
See also talk by Hanyuan Zhang

The mergers in E-L_z space

[Fe/H] < -0.5

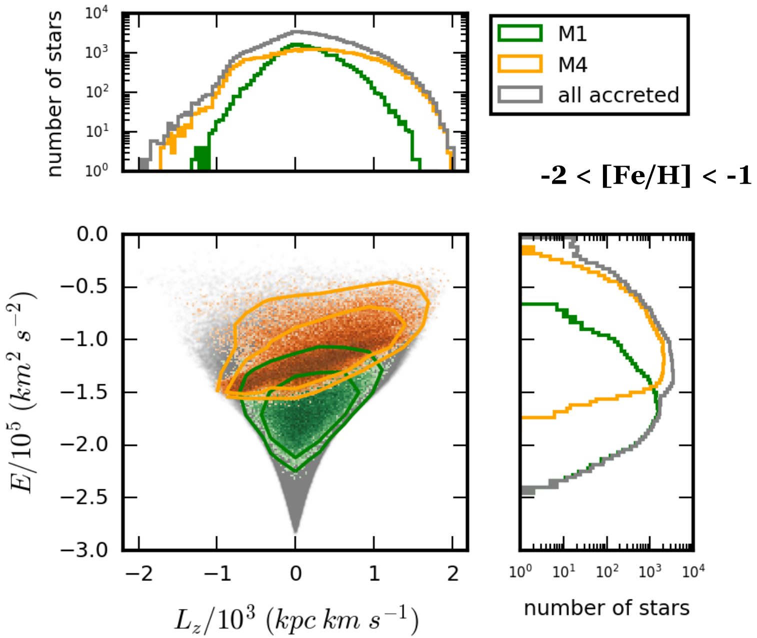


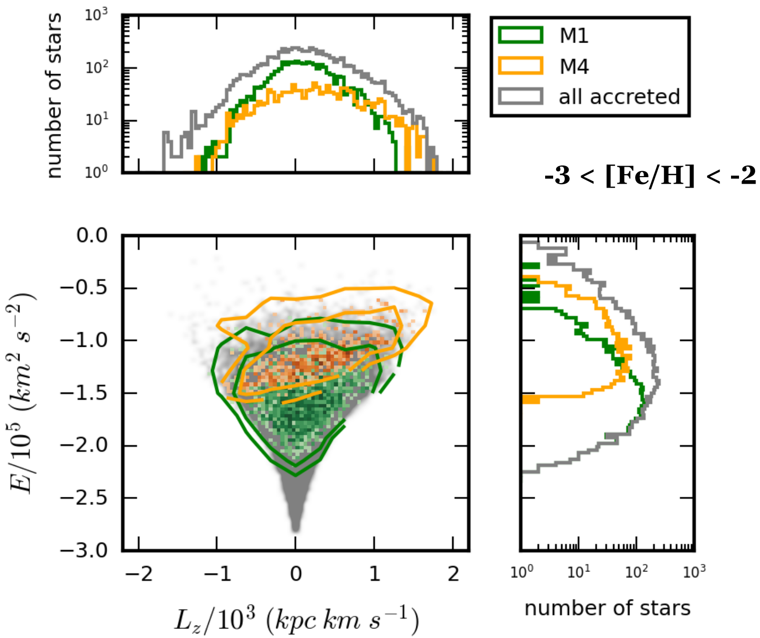
Separating Merger 1 and Merger 4



- Distribution of these two mergers is quite different in E-L_z space, in addition to their differences in metallicity
- However, large overlaps will complicate assigning stars in the overlapping regions

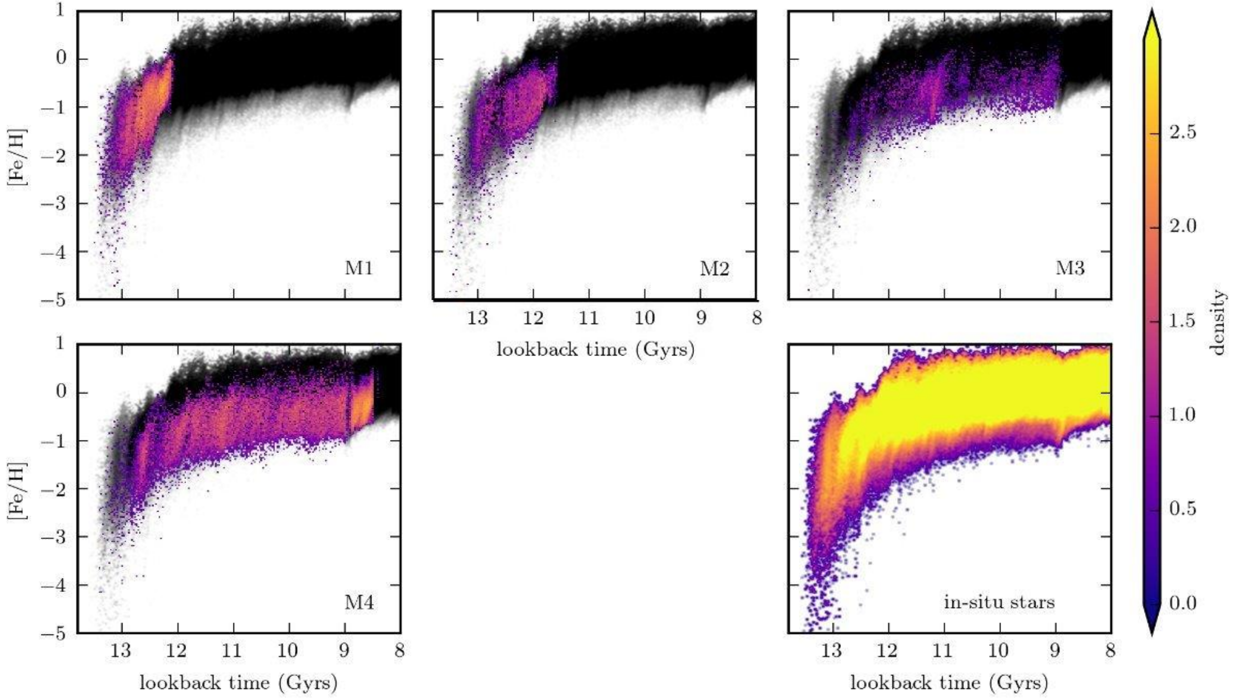
Separating Merger 1 and Merger 4





- Distribution of these two mergers is quite different in E-L_z space, in addition to their differences in metallicity
- However, large overlaps will complicate assigning stars in the overlapping regions

Age-metallicity relations



Differences between the accreted and in-situ population

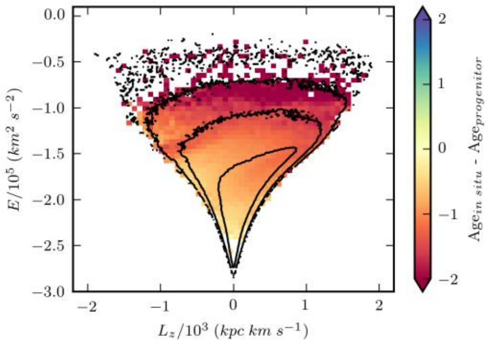
Accreted older than in-situ

Accreted same age as in-situ

Accreted younger than in-situ

Differences between the accreted and in-situ population

Merger 1



Accreted older than in-situ

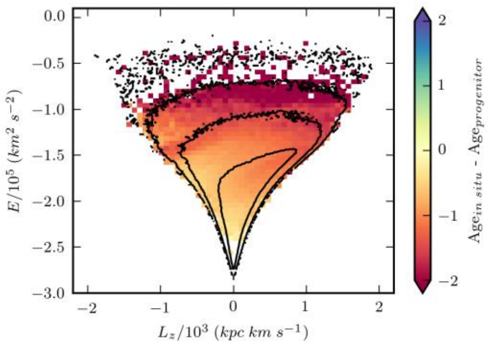
Accreted same age as in-situ

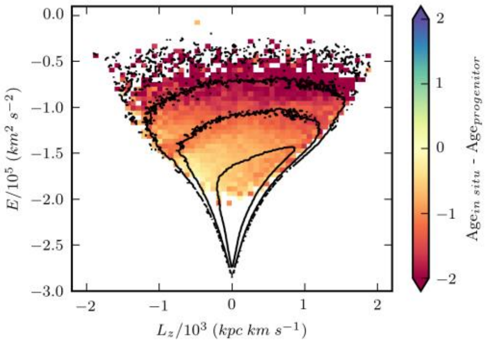
Accreted younger than in-situ

[Fe/H] < -0.5

Differences between the accreted and in-situ population

Merger 1





Merger 2

Accreted older than in-situ

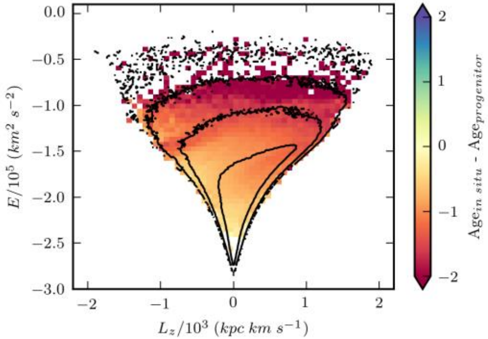
Accreted same age as in-situ

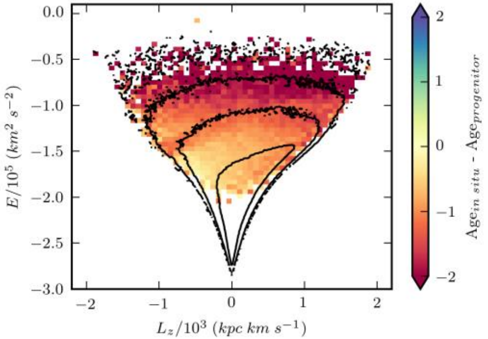
Accreted younger than in-situ

[Fe/H] < -0.5

Differences between the accreted and in-situ population

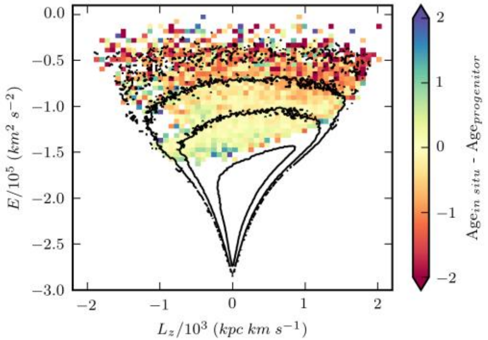
Merger 1





Merger 2

Merger 3



Accreted older than in-situ

Accreted same age as in-situ

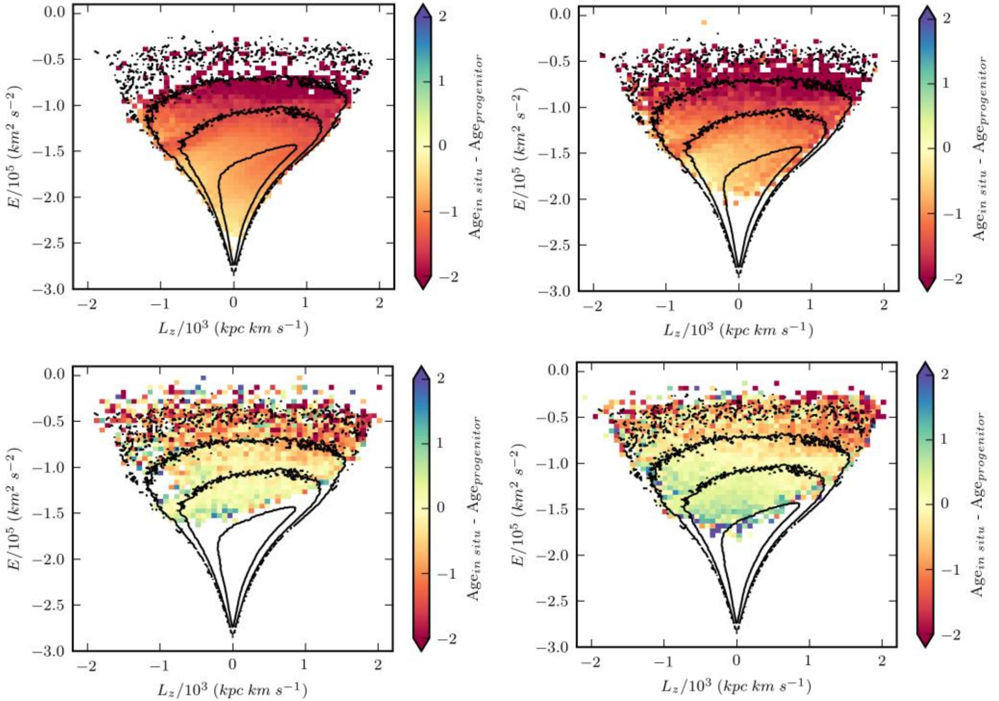
Accreted younger than in-situ

[Fe/H] < -0.5

Differences between the accreted and in-situ population

Merger 1

Merger 2



Merger 3

Merger 4

Accreted older than in-situ

Accreted same age as in-situ

Accreted younger than in-situ

[Fe/H] < -0.5

Conclusions

Can we separate the different accretion events?

- The distribution of stars from different mergers is different, however with significant overlaps
- The different mergers have different prevalences in various metallicity ranges
- At least separating the earlier (Kraken-like) from the later mergers (GES-like) seems feasible
- Further separating these into individual mergers appears challenging

Can we further separate in-situ from accreted?

- In-situ population dominant even in low metallicity regime
- It may be possible to separate in-situ from accreted with accurate measurements and the inclusion of more chemical abundances
- However, the old, metal-poor in-situ and early accreted populations are very similar

Conclusions

Can we separate the different accretion events?

- The distribution of stars from different mergers is different, however with significant overlaps
- The different mergers have different prevalences in various metallicity ranges
- At least separating the earlier (Kraken-like) from the later mergers (GES-like) seems feasible
- Further separating these into individual mergers appears challenging

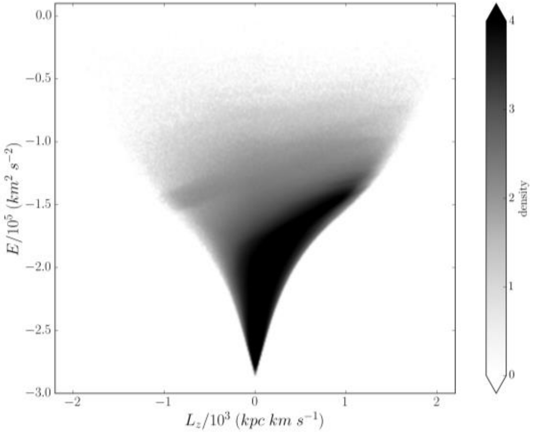
Thank You!!

Can we further separate in-situ from accreted?

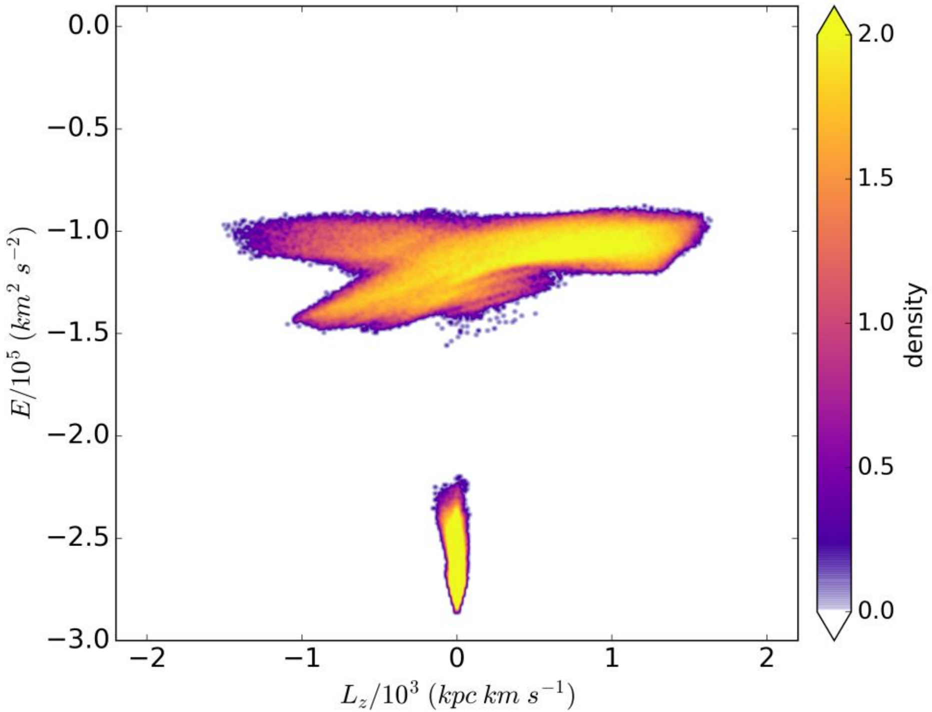
- In-situ population dominant even in low metallicity regime

  It may be possible to separate in-situ from accreted with accurate measurements in a multi-dimensional space with more chemical abundances
- However, the old, metal-poor in-situ and early accreted populations are very similar

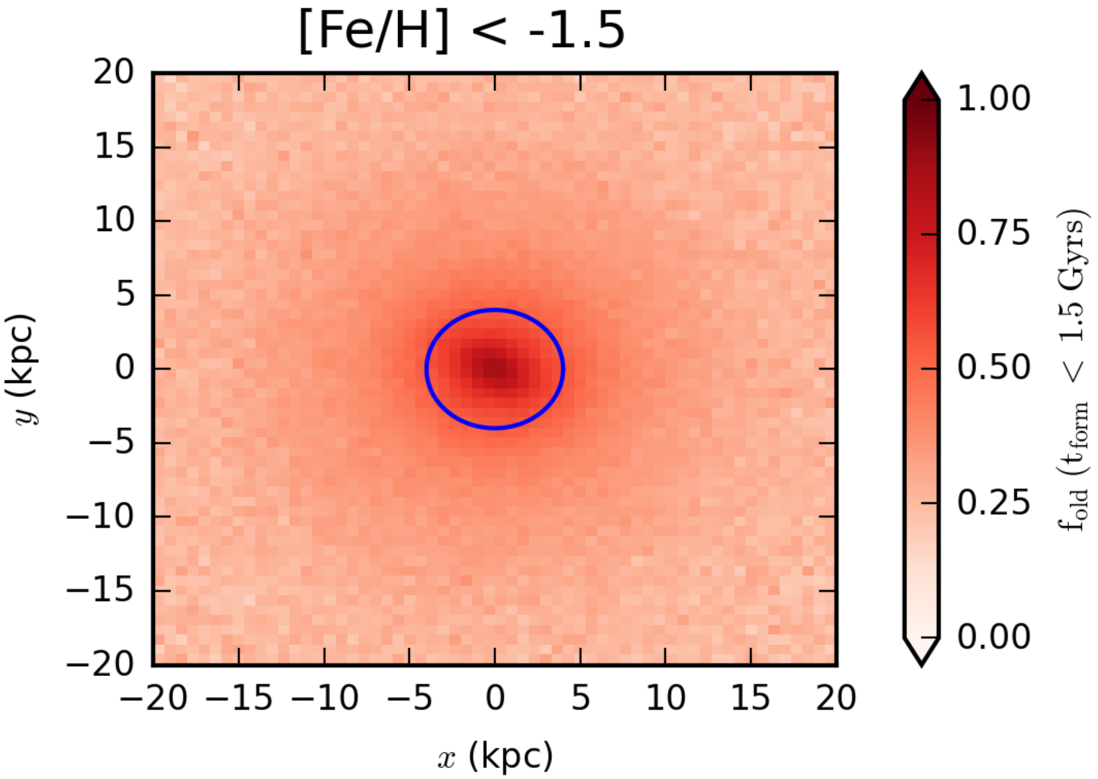
Additional Slides



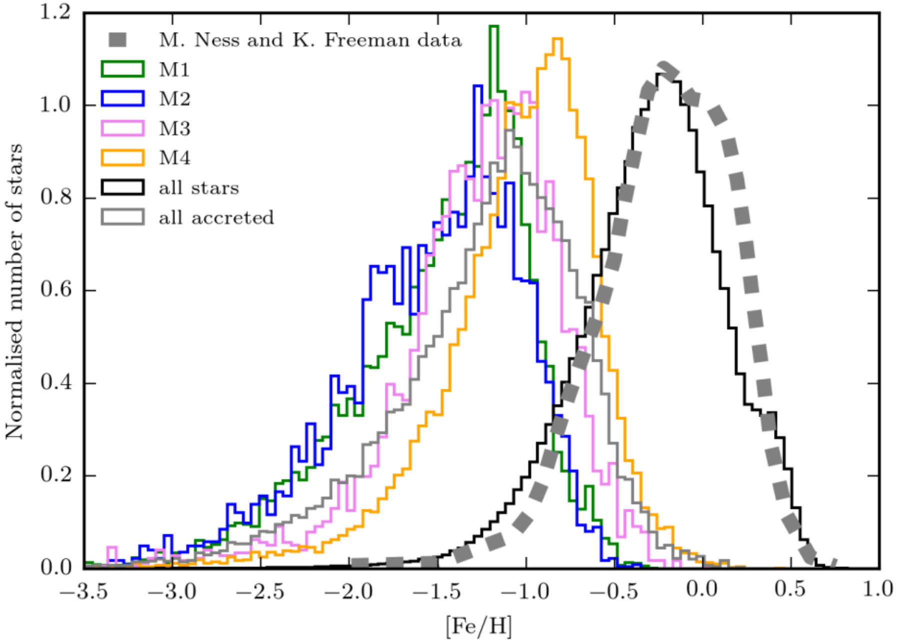
Stars with co-rotation orbits



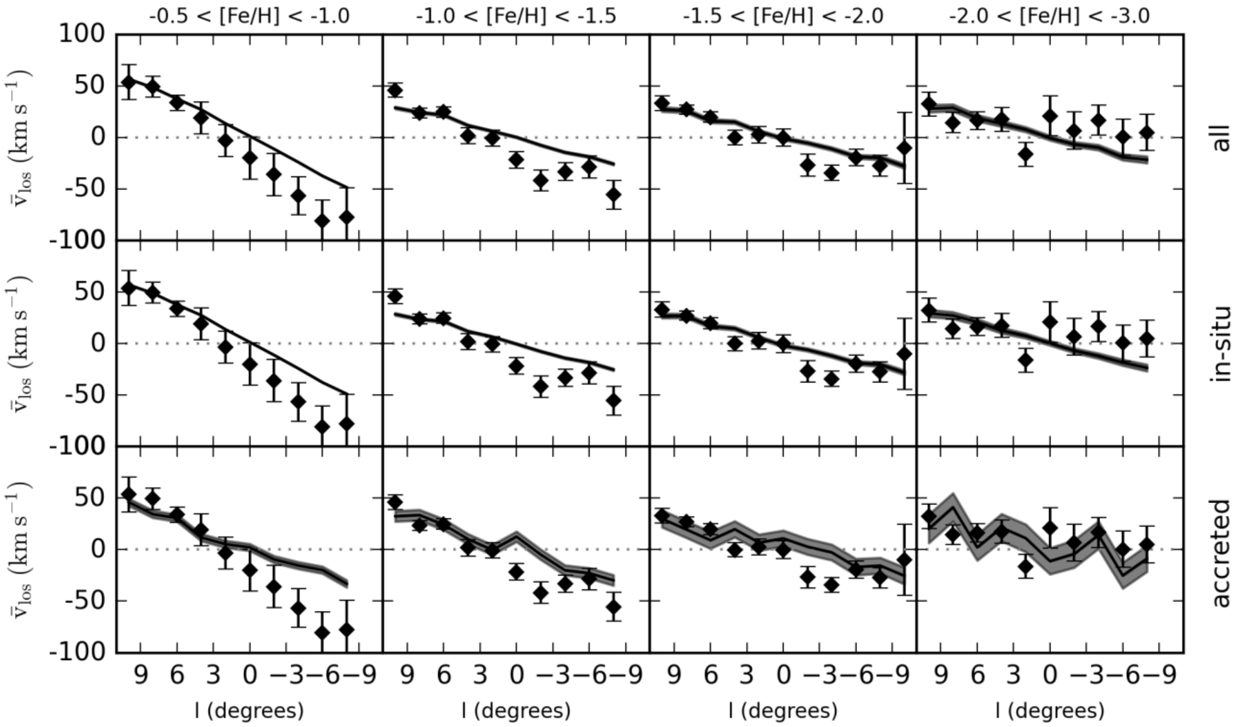
Starkenburg plot for Au18



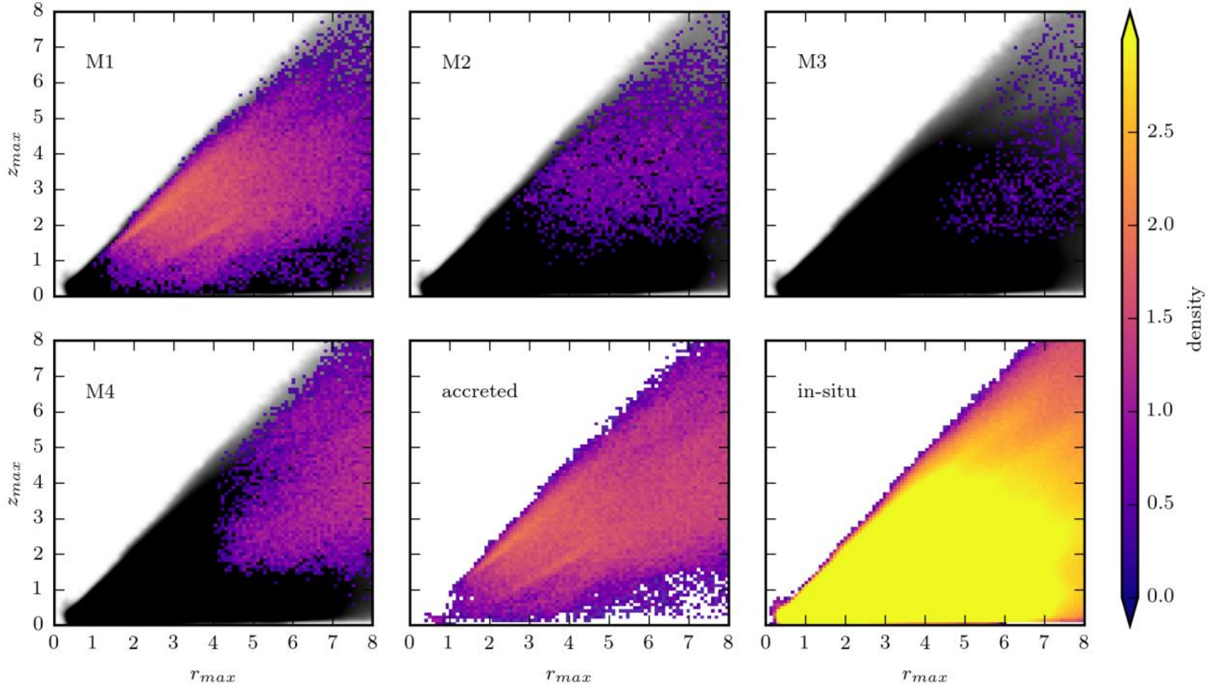
Normalised MDFs



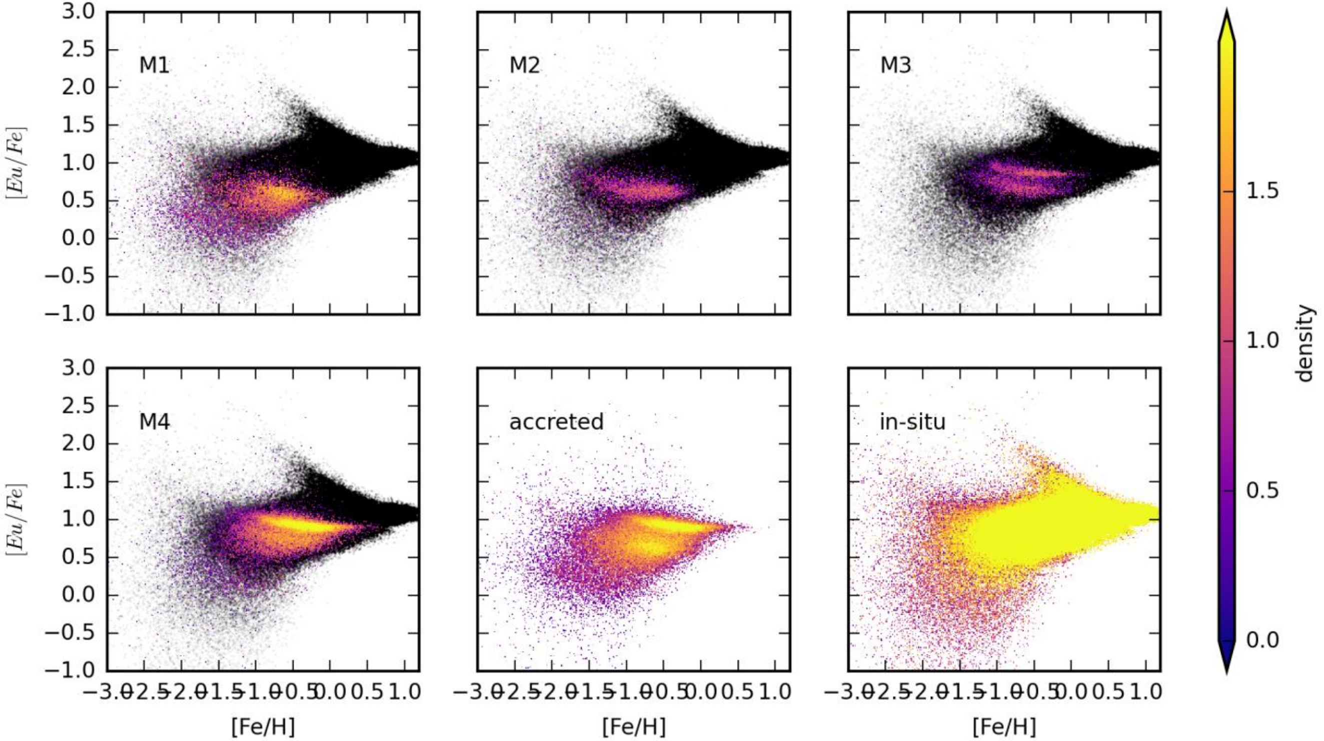
Kinematics of all, in-situ, and accreted stars in different metallicity bins compared to data from Arentsen+ 2020



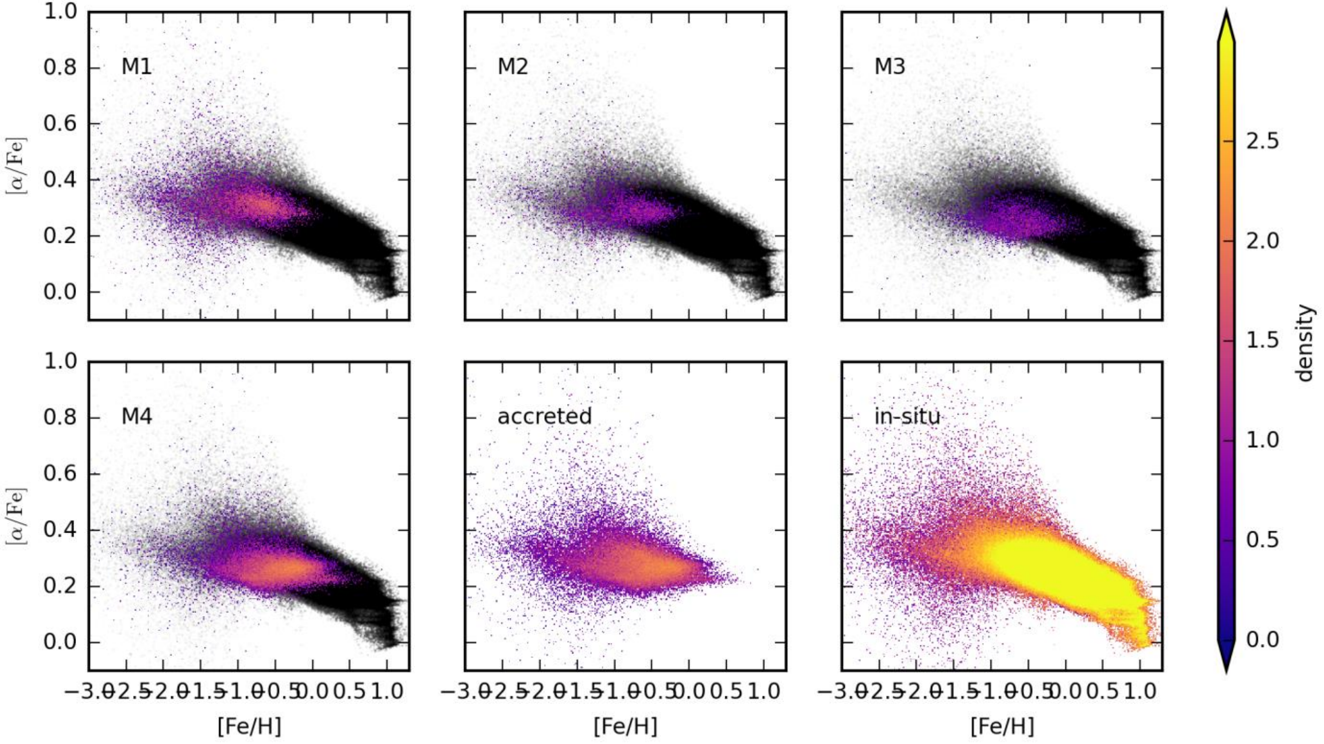
Apocentre distribution



[Fe/H] vs [Eu/Fe]


M1
M2
M3
M4
accreted
in-situ
[Eu/Fe]
[Fe/H]
density
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−3.0 −2.5 −2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0
1.5
1.0
0.5
0.0

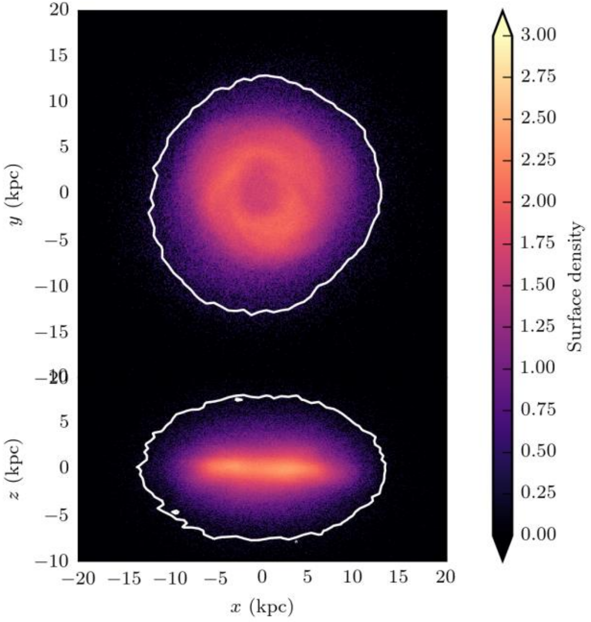
[Fe/H] vs [α/Fe]



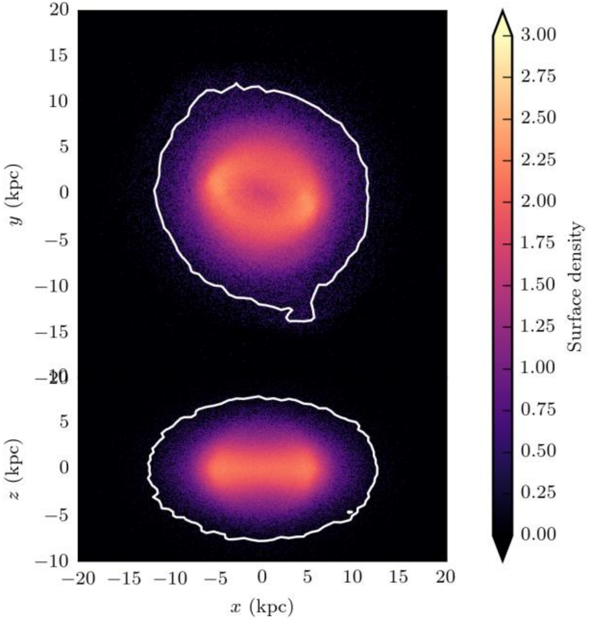
M1
M2
M3
M4
accreted
in-situ
[α/Fe]
[Fe/H]
density
1.0
0.8
0.6
0.4
0.2
0.0
−3.0 −2.5 −2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0
0.0 0.5 1.0 1.5 2.0 2.5

High energy in-situ population before GES-like merger and at almost present day

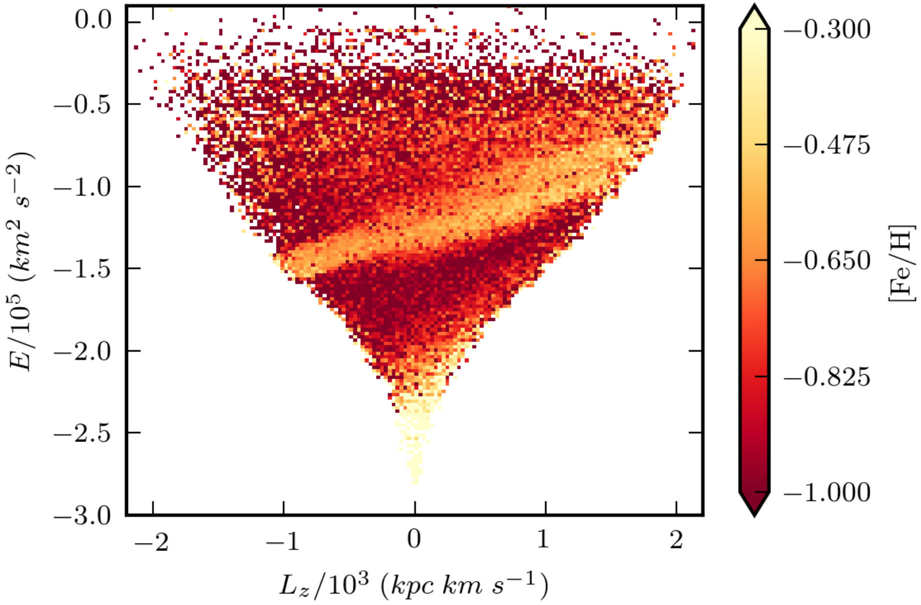
Before GES-like merger



Almost present day

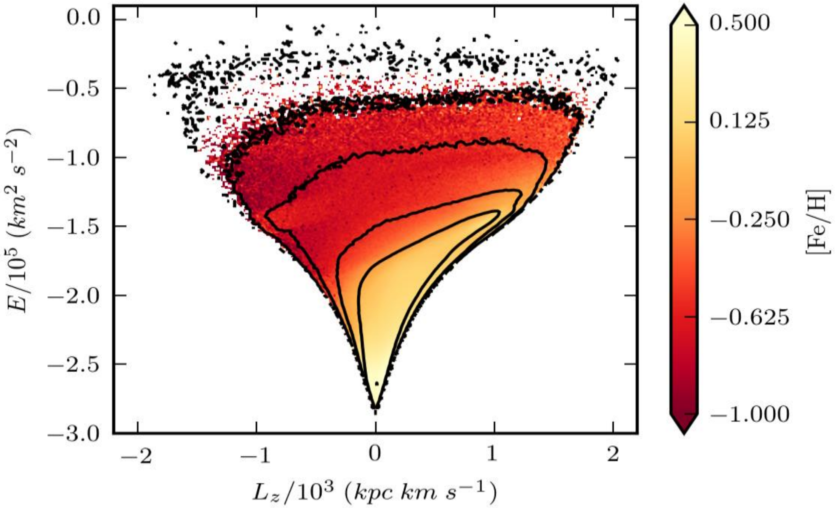


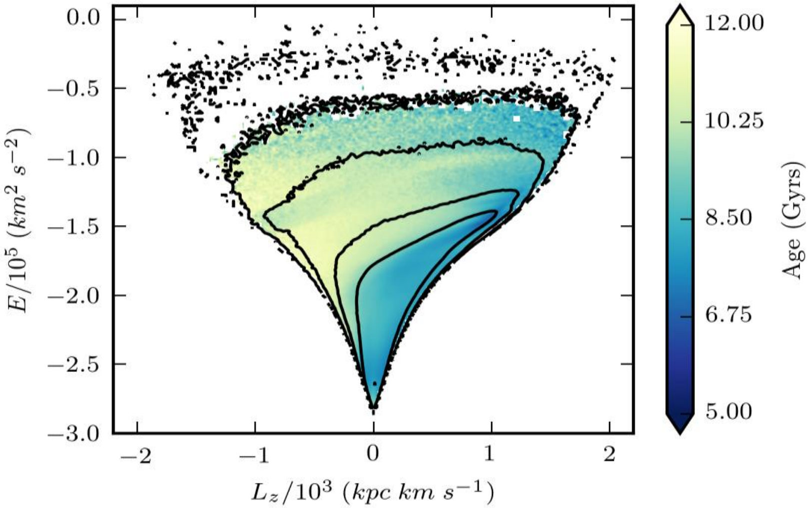
[Fe/H] distribution in accreted population



Exploring the distribution in ages and [Fe/H]

Distribution in only the in-situ population





[Eu/Mg] vs Energy