The Milky Way assembly tale told by its stars and globular clusters

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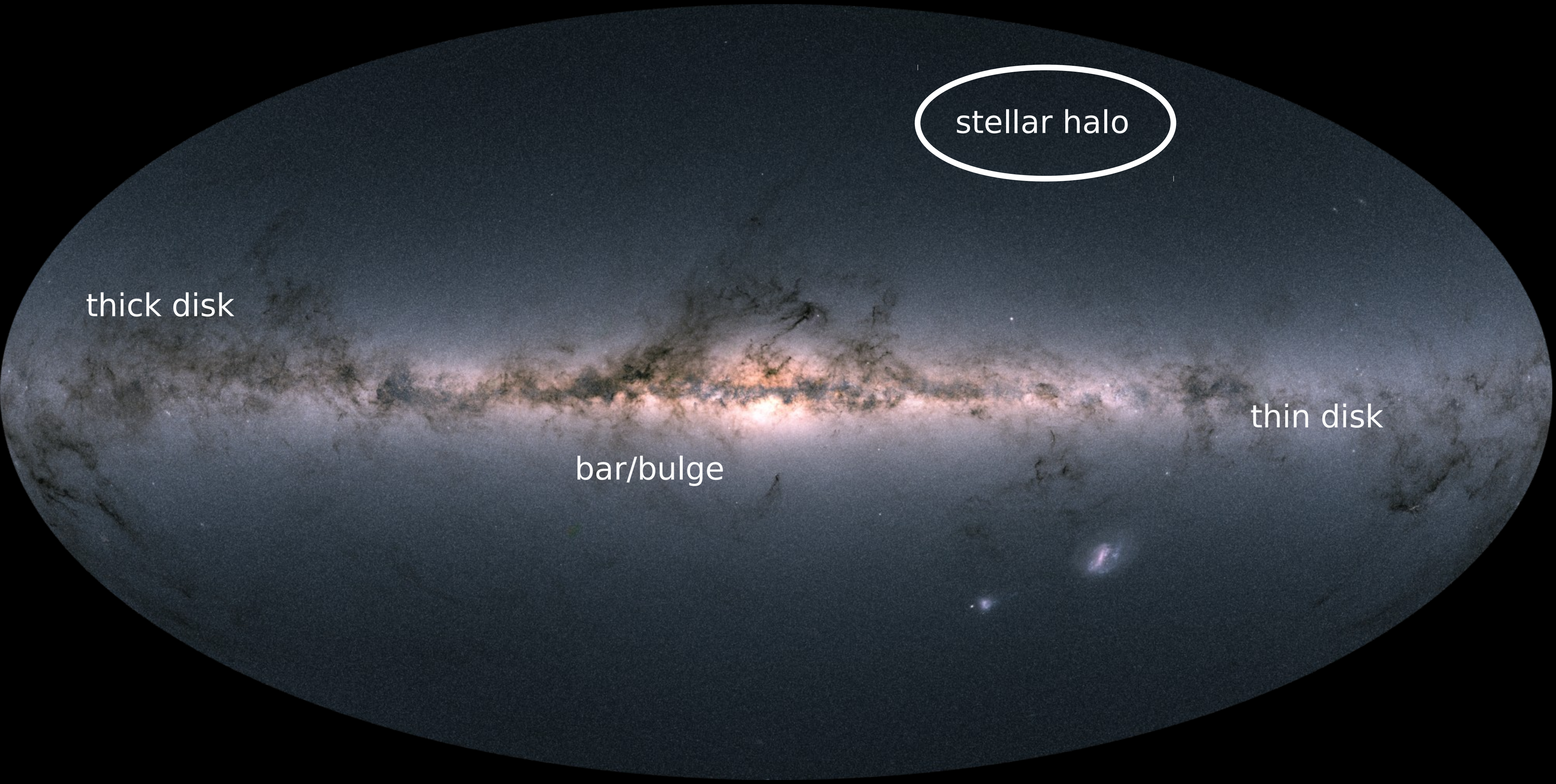
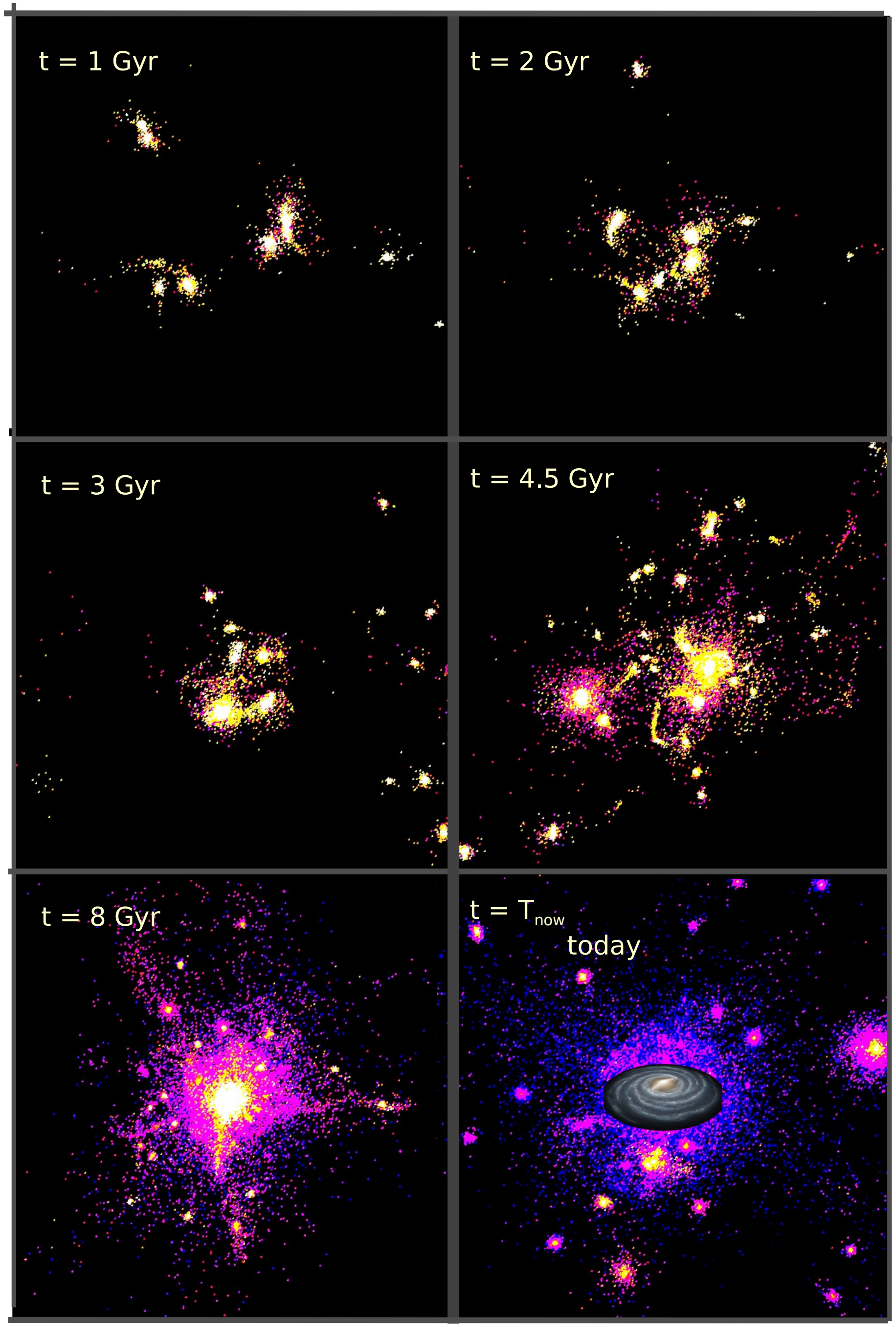
Main collaborators: A. Helmi, H.H. Koppelman, A. Mucciarelli and the Gaia consortium

Gaia DR2, Gaia Collaboration+2018

How did the Galaxy come to be like this?

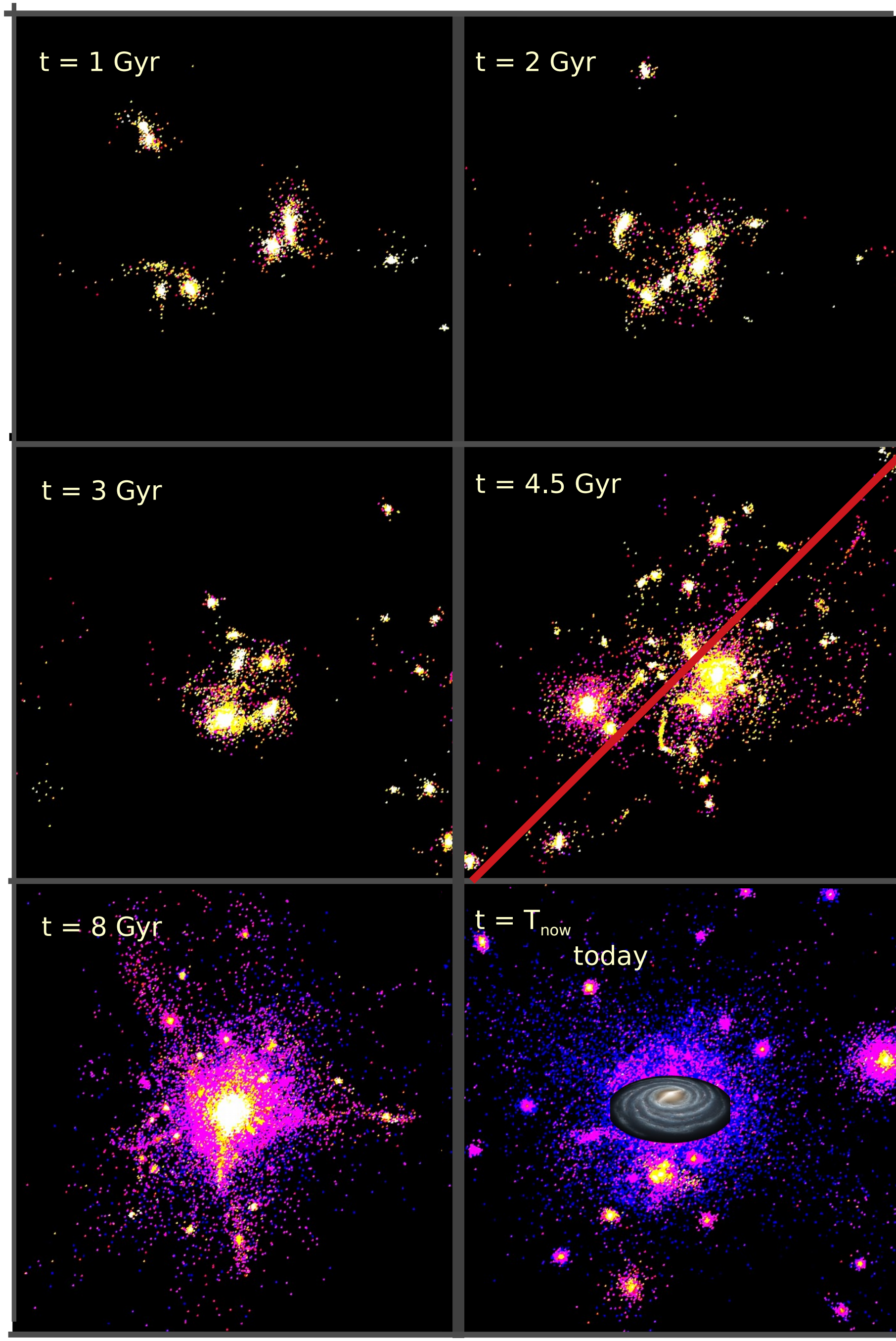


Milky Way assembly history



snapshots: J. Gardner

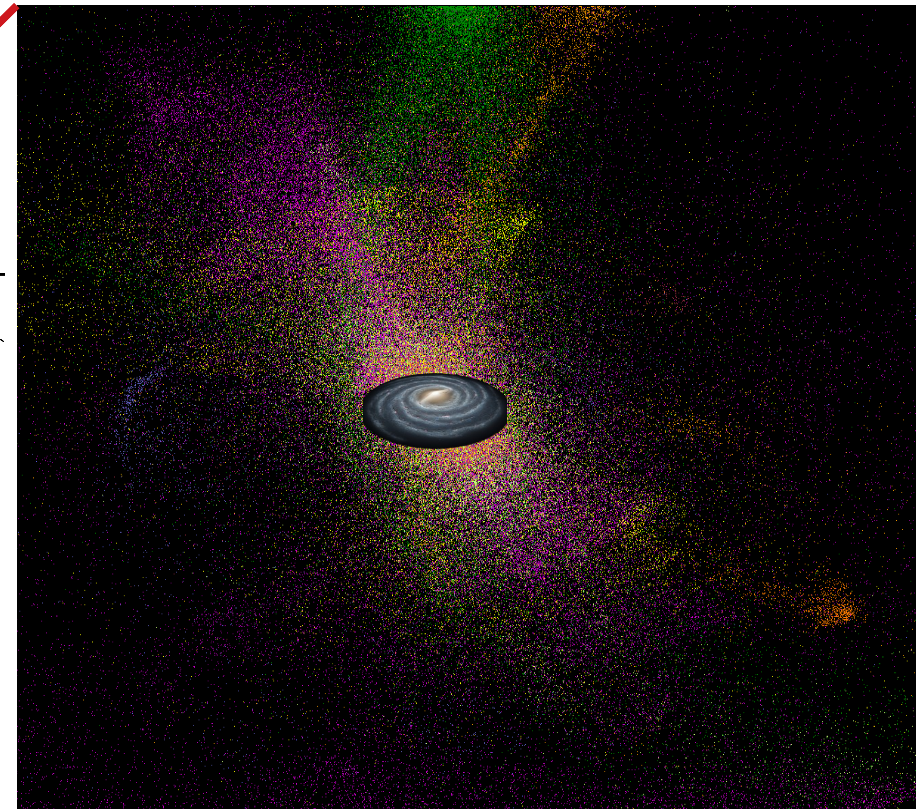
Milky Way assembly history



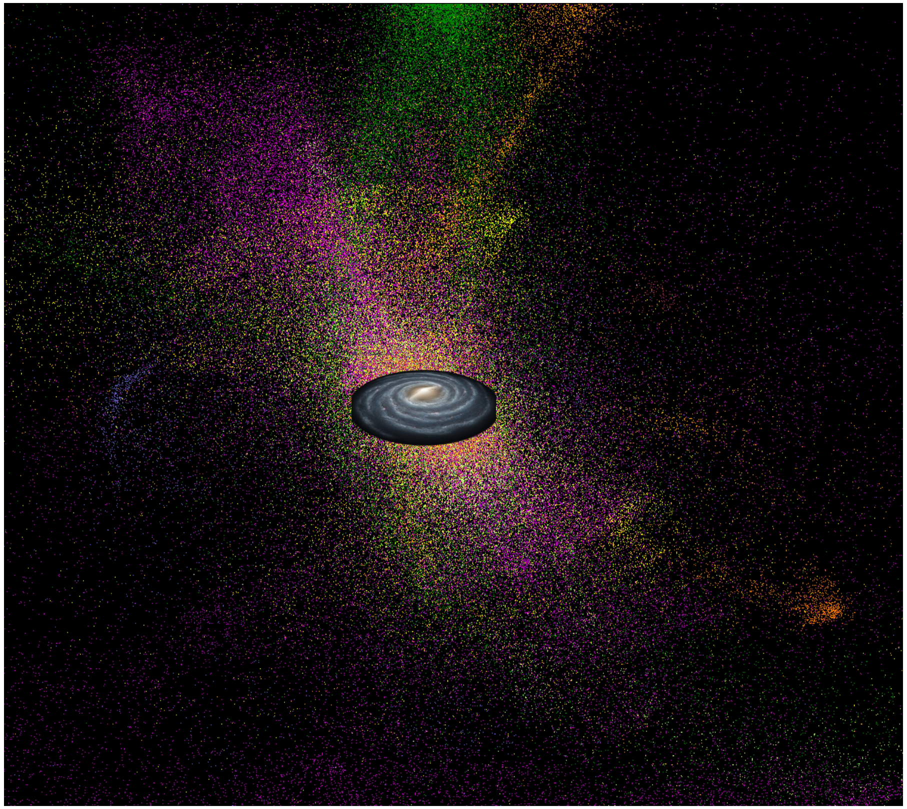
snapshots: J. Gardner

Very hard to trace the debris back to the original progenitor based on **spatial** info

Bullock & Johnston 2005, Cooper et al. 2010



Milky Way assembly history



Bullock & Johnston 2005, Cooper et al. 2010

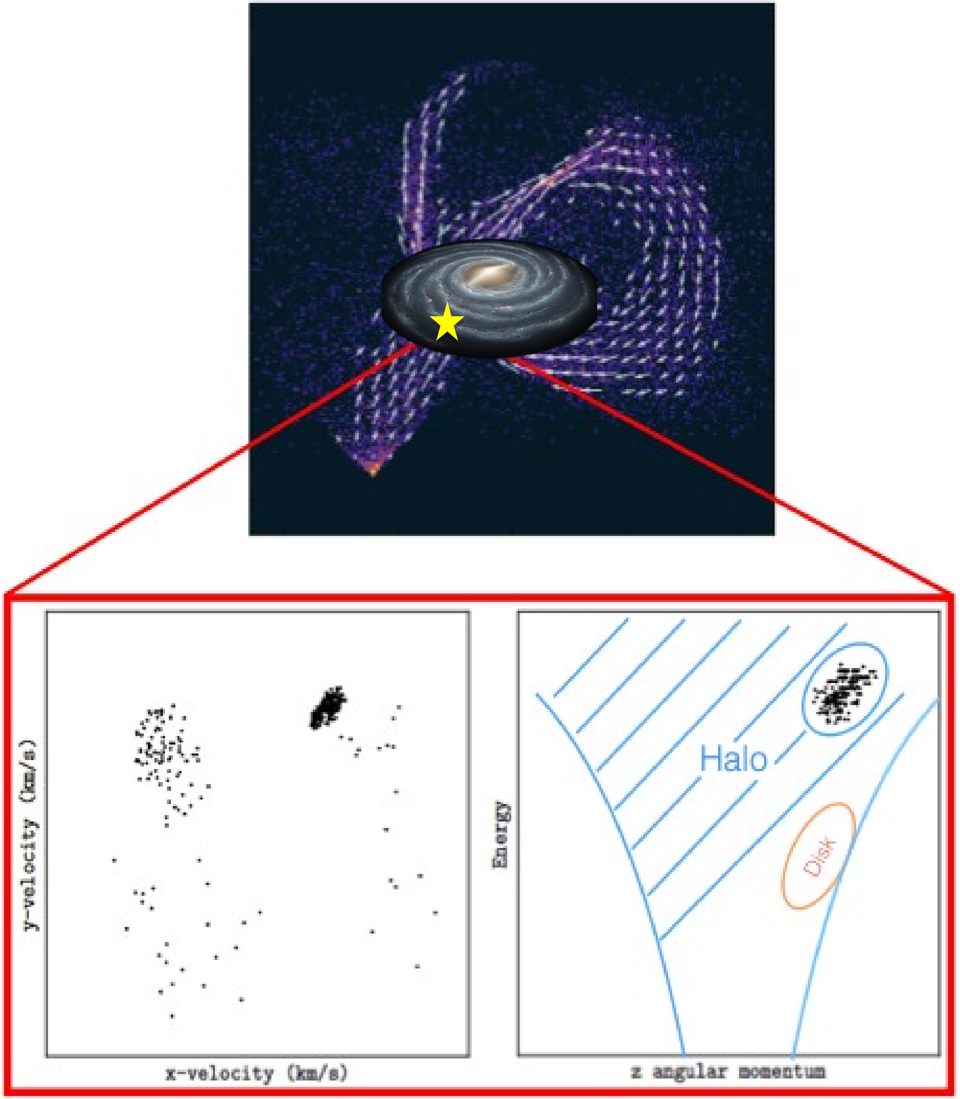
1) Focus on suitable tracers:

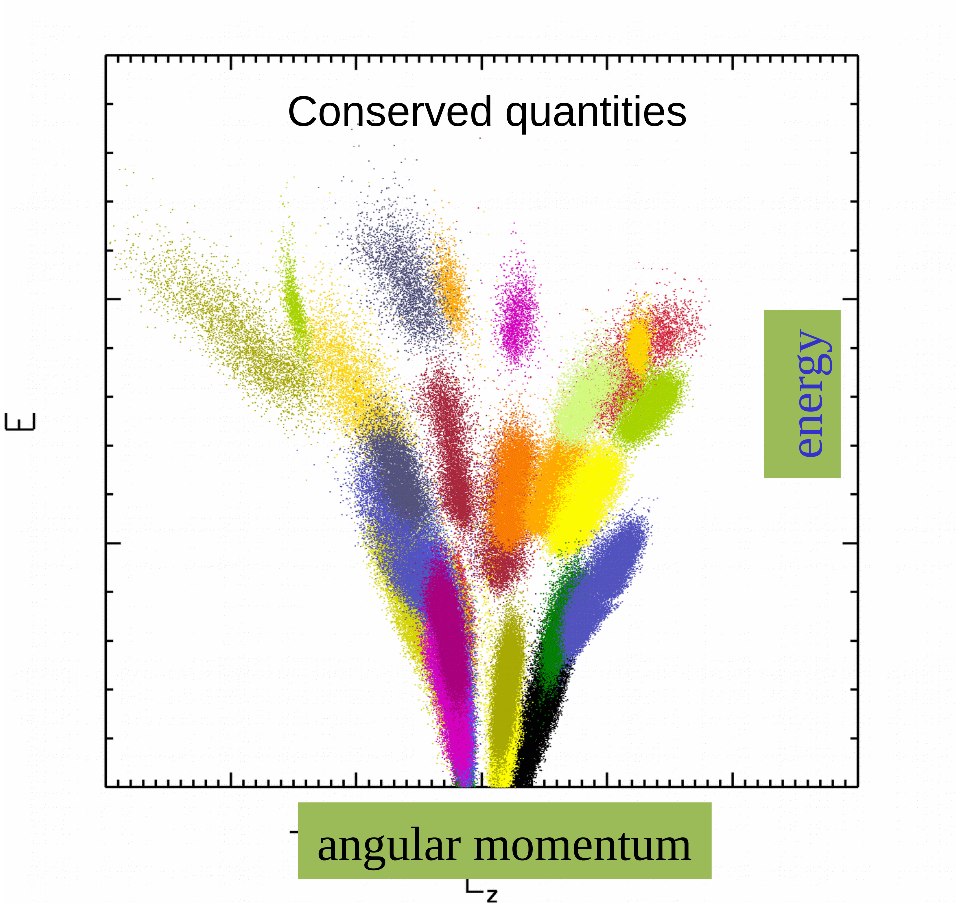
- stars (nearby)
- globular clusters (farther away)

2) Focus on their properties that have not changed after their accretion:

- age distribution
- chemistry
- dynamics

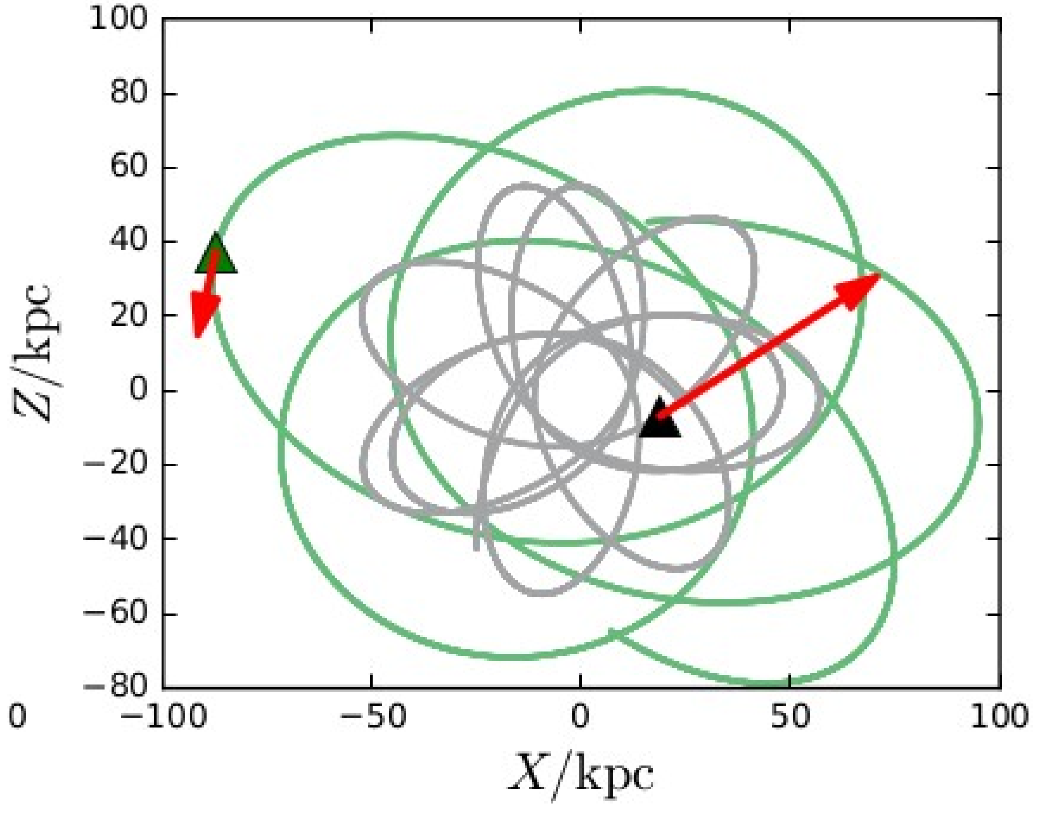
Dynamics to find merger debris





Helmi & de Zeeuw (2000)

How to determine dynamical quantities?

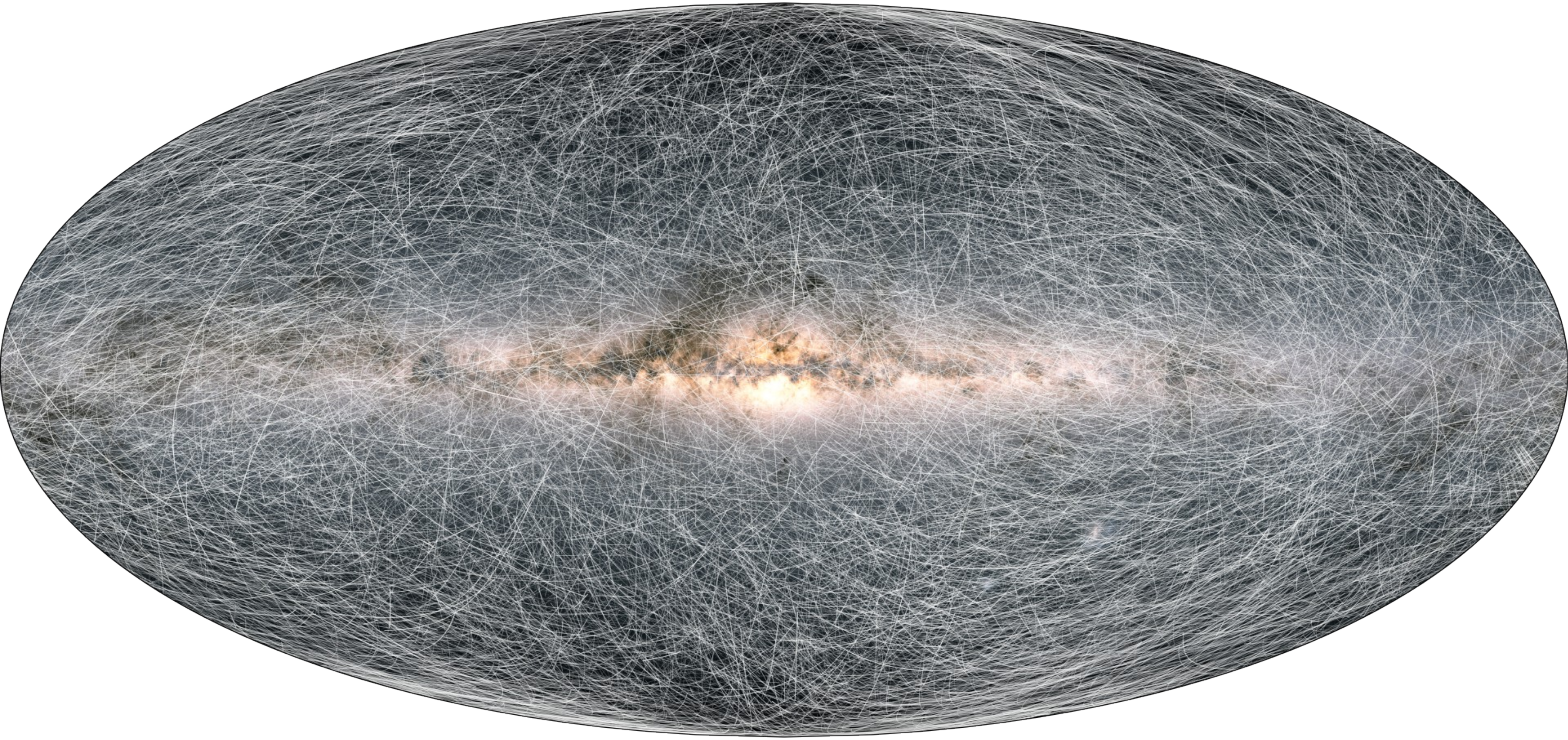


Positions
+
Radial velocity
+
Proper motions
+
Gravitational Potential
=

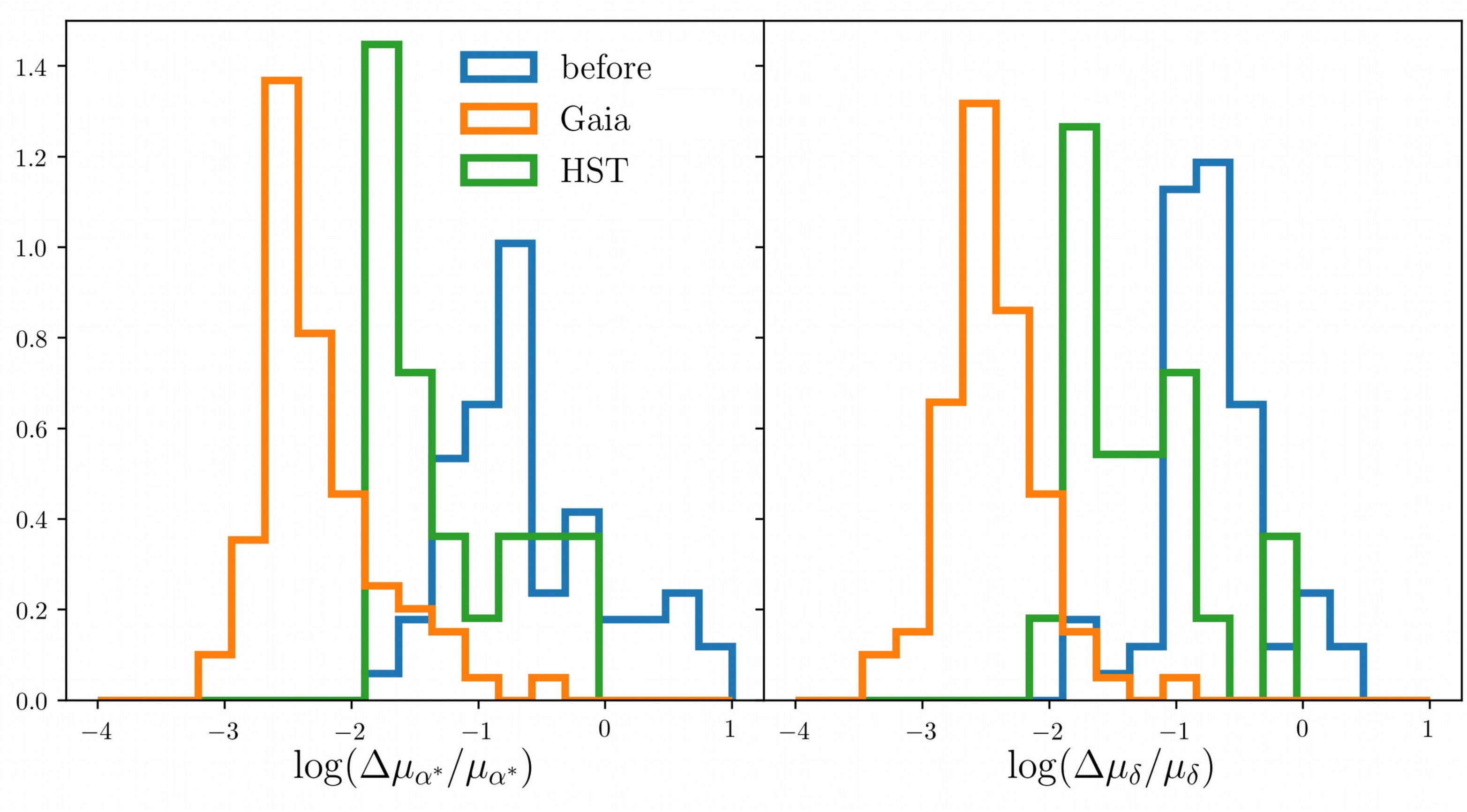
Orbits!

Golden era of Astrometry: *Gaia e*DR3

Positions + Proper motions for 1.5 billion stars



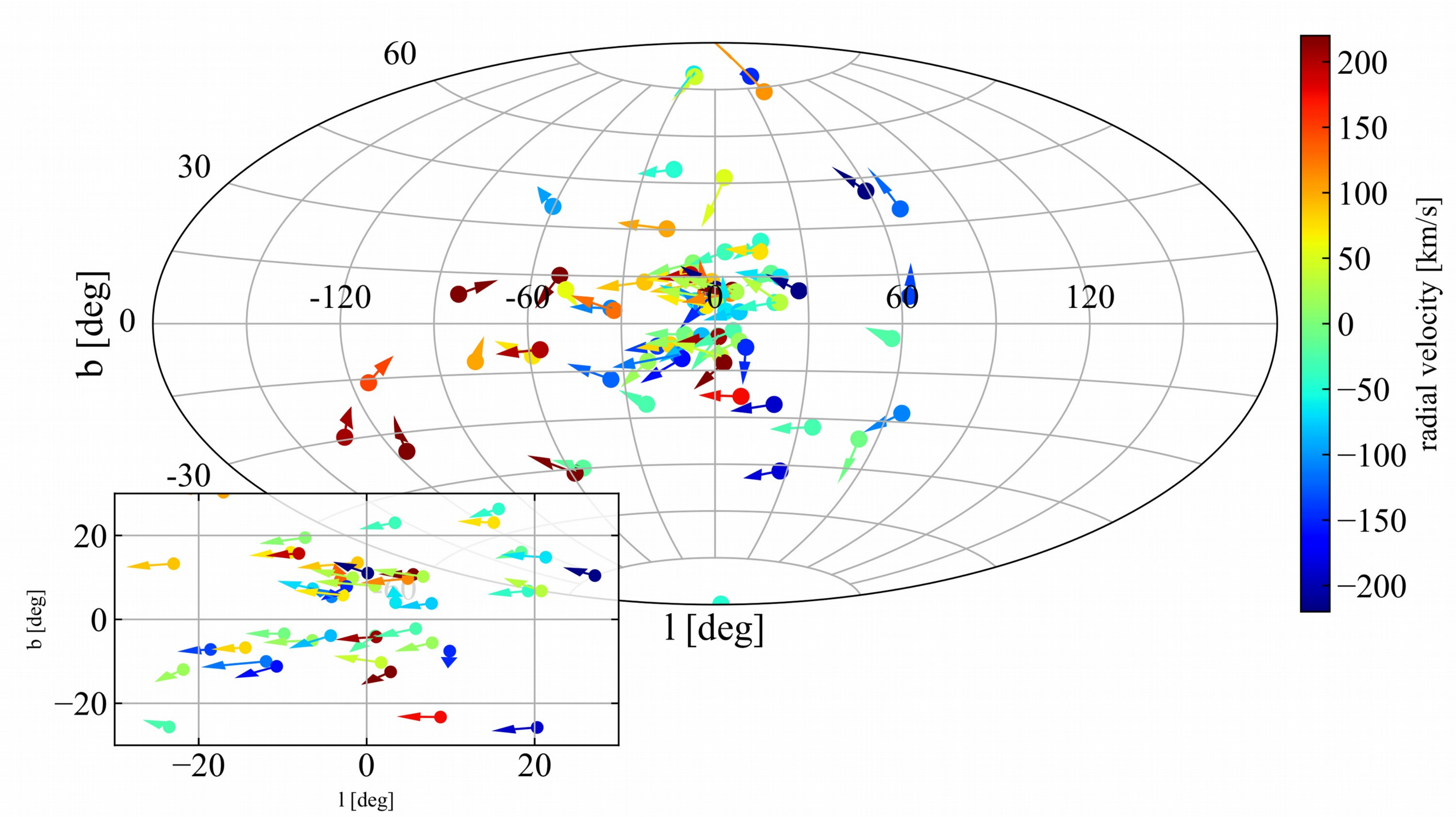
Gaia Revolution: proper motions



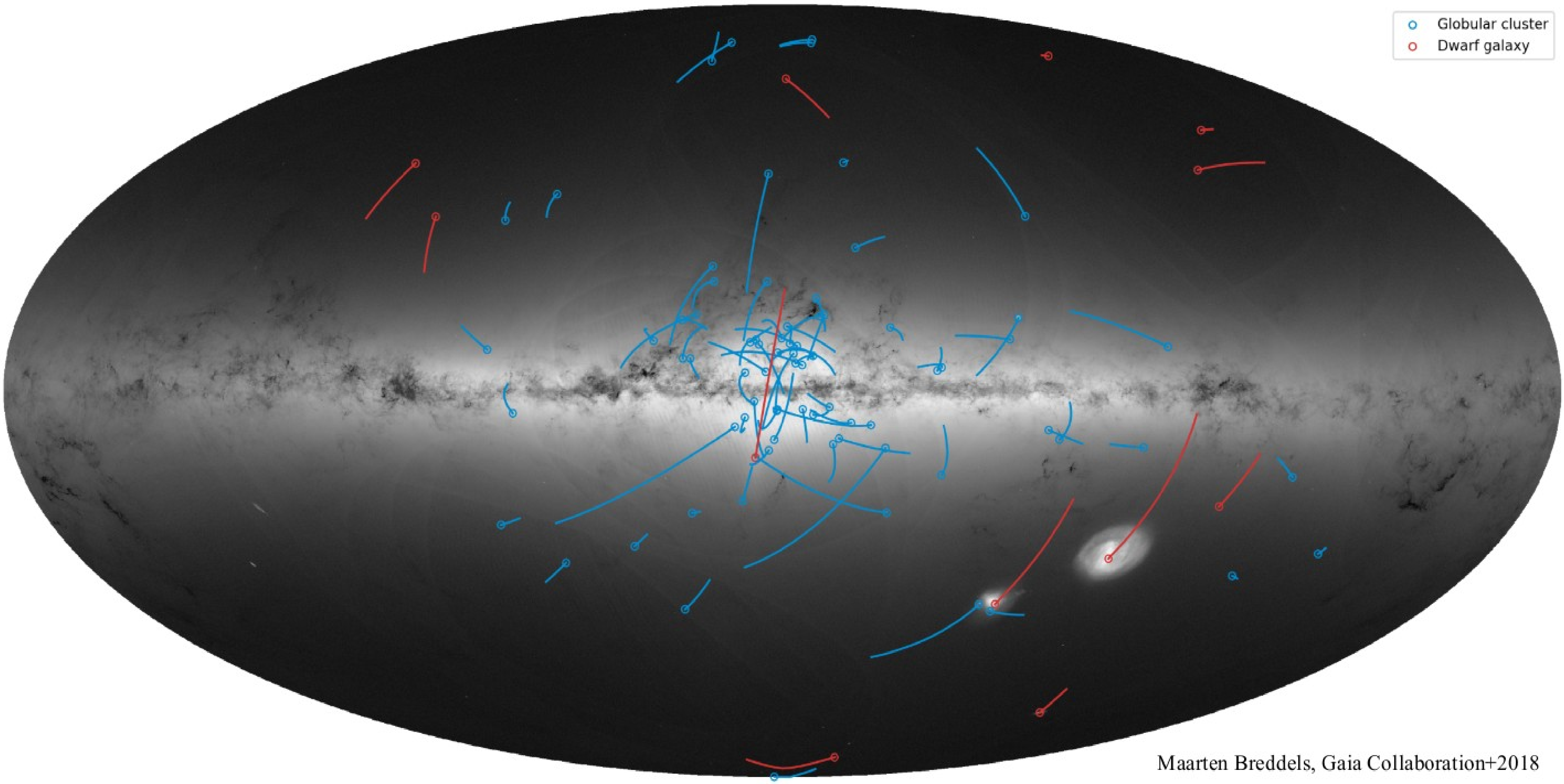
HST needs background galaxies / Gaia needs stellar members

Globular clusters

Gaia collaboration, Helmi, van Leeuwen, McMillan, **DM** et al.2018

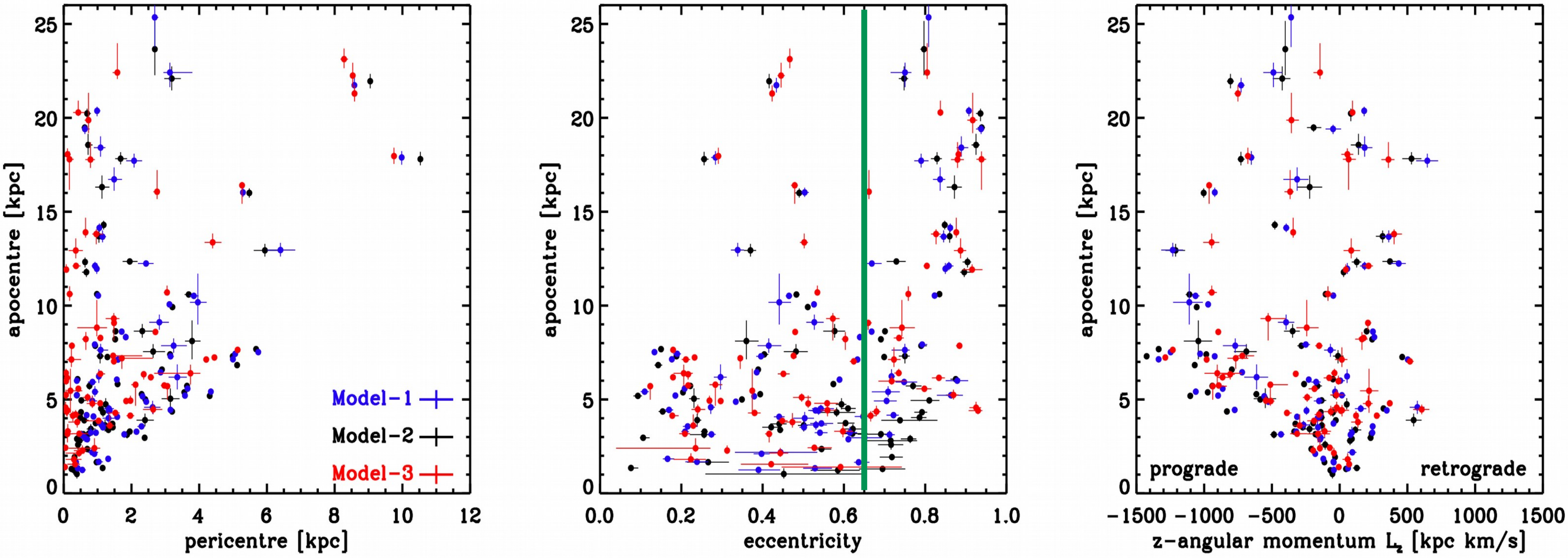


Orbits


Globular cluster
Dwarf galaxy
Maarten Breddels, Gaia Collaboration+2018

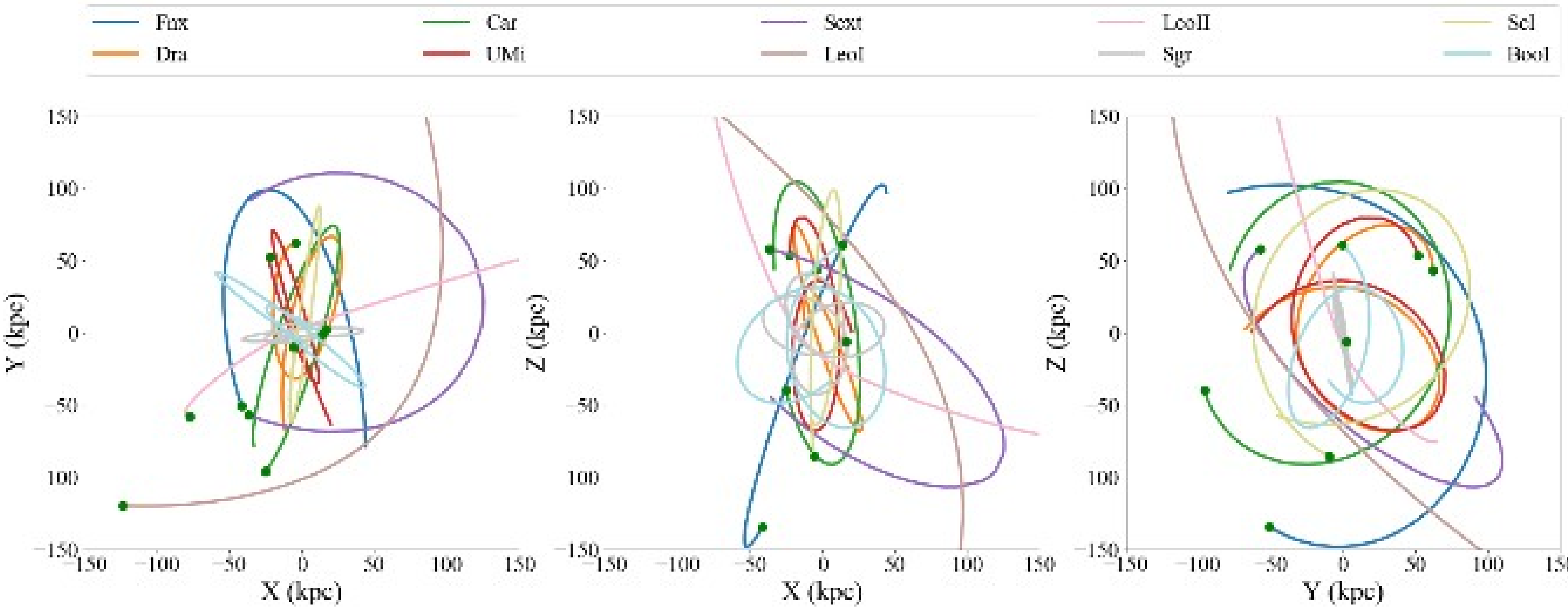
Globular clusters

Gaia collaboration, Helmi, van Leeuwen, McMillan, **DM** et al.2018



Classical dwarf spheroidals

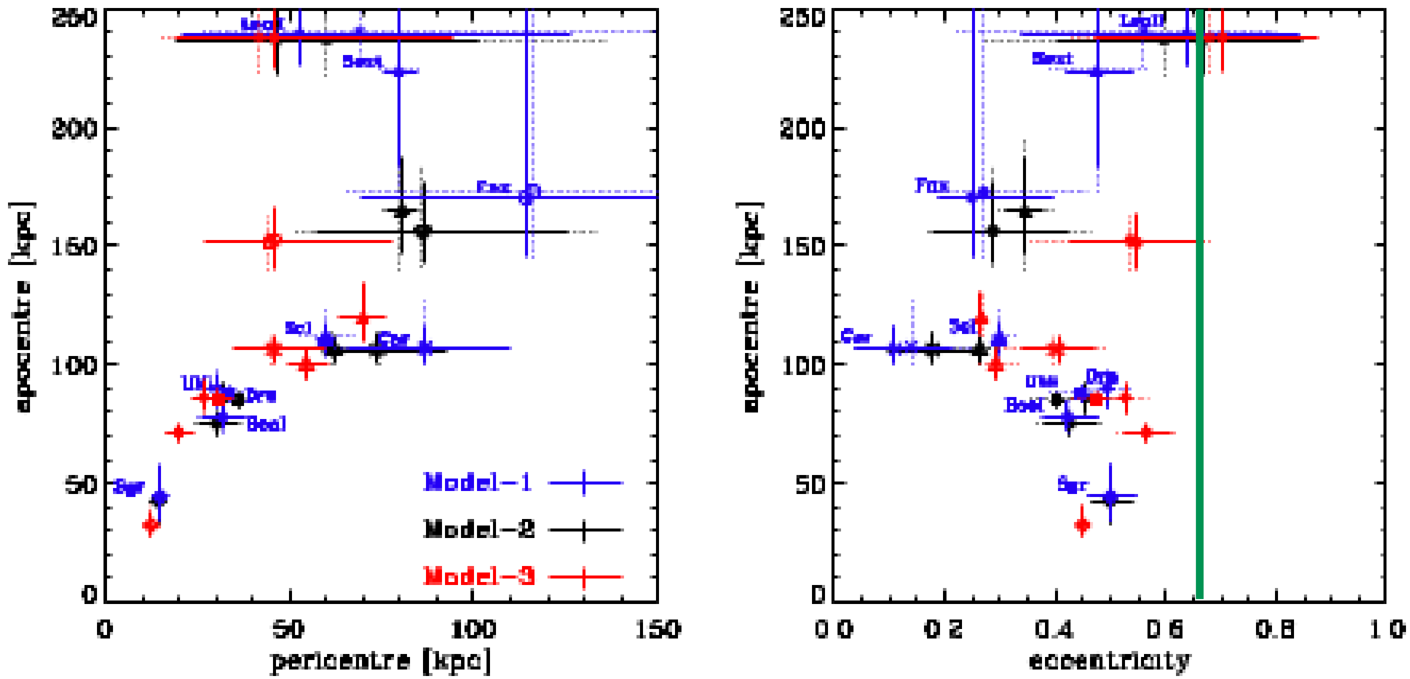
Gaia collaboration, Helmi, van Leeuwen, McMillan, **DM** et al.2018



Likely associations! Group infall?

Classical dwarf spheroidals

Gaia collaboration, Helmi, van Leeuwen, McMillan, **DM** et al.2018



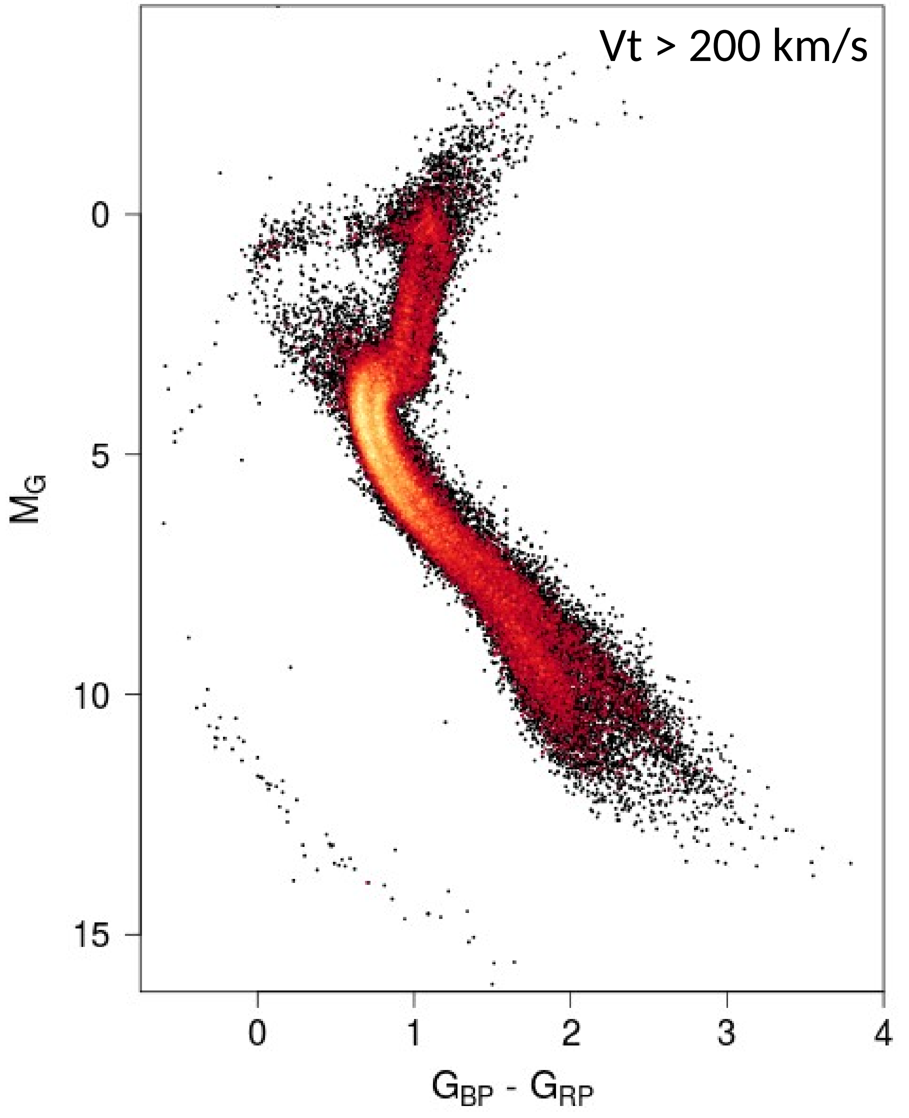
1- Low-ecc: dSph and GCs are different populations?

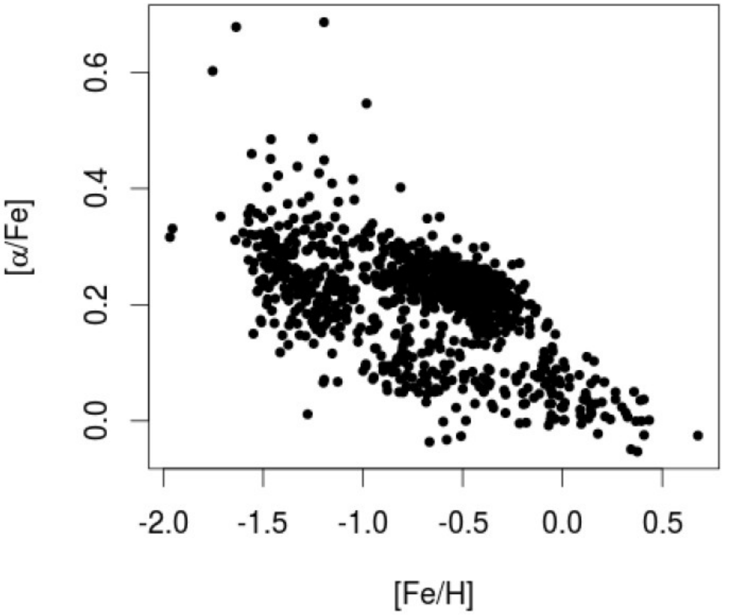
BIASED SAMPLE: WHAT ABOUT DISRUPTED DWARFS?

Disrupted dwarfs: Gaia-Enceladus

(Helmi, Babusiaux, Koppelman, DM et al. 2018, Nature, 563, 85)

Gaia-Enceladus: 1) Halo HR diagram

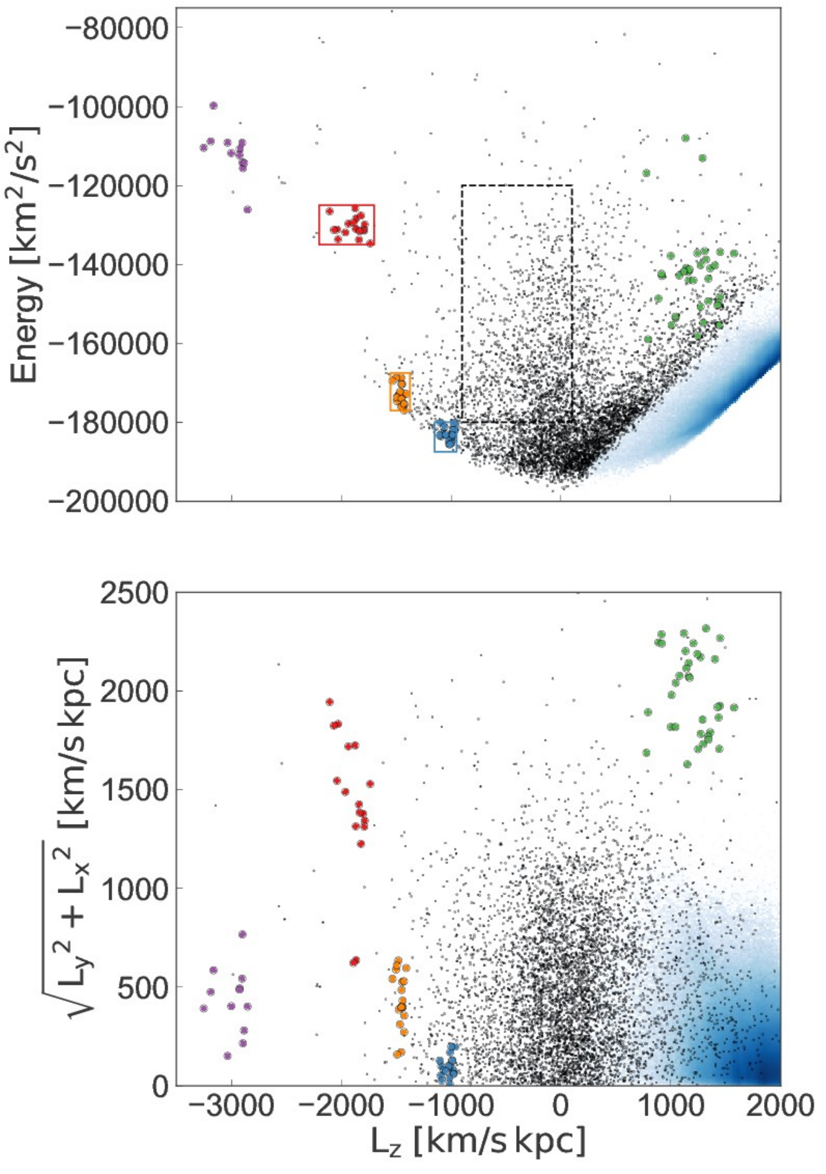




The nearby halo is dominated by two components of different ages/chemistry

Gaia Collaboration, Babusiaux et al. 2018

Gaia-Enceladus: 2) Halo kinematics



1- Still a prominent thick disk

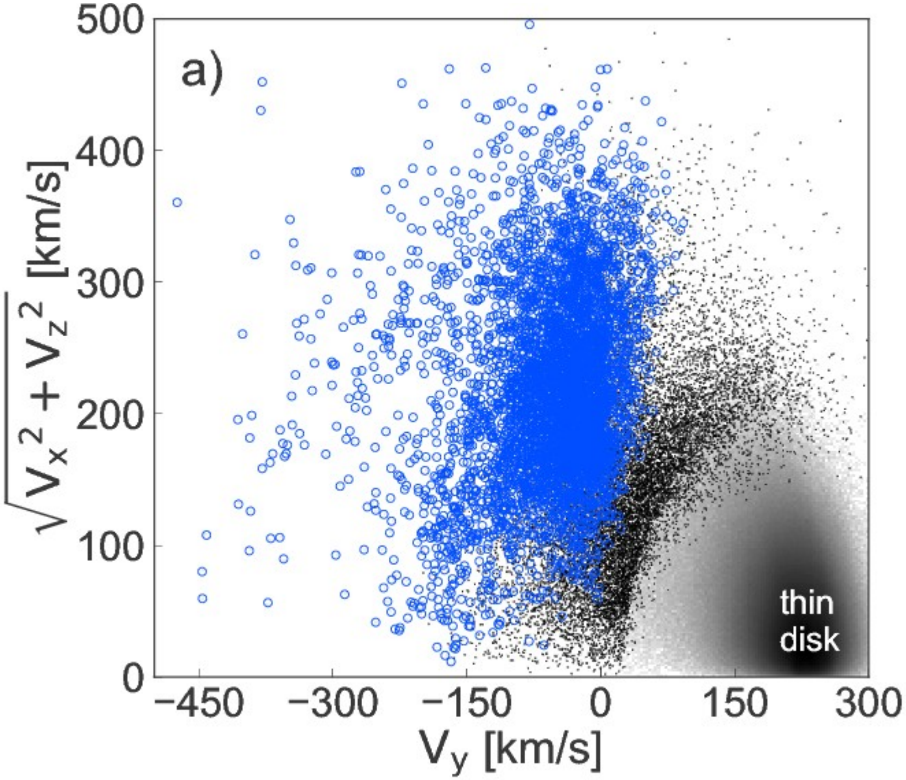
2- Small clumps
(predicted for haloes built via mergers)

3- Large, slightly retrograde feature

(Koppelman et al. 2018)

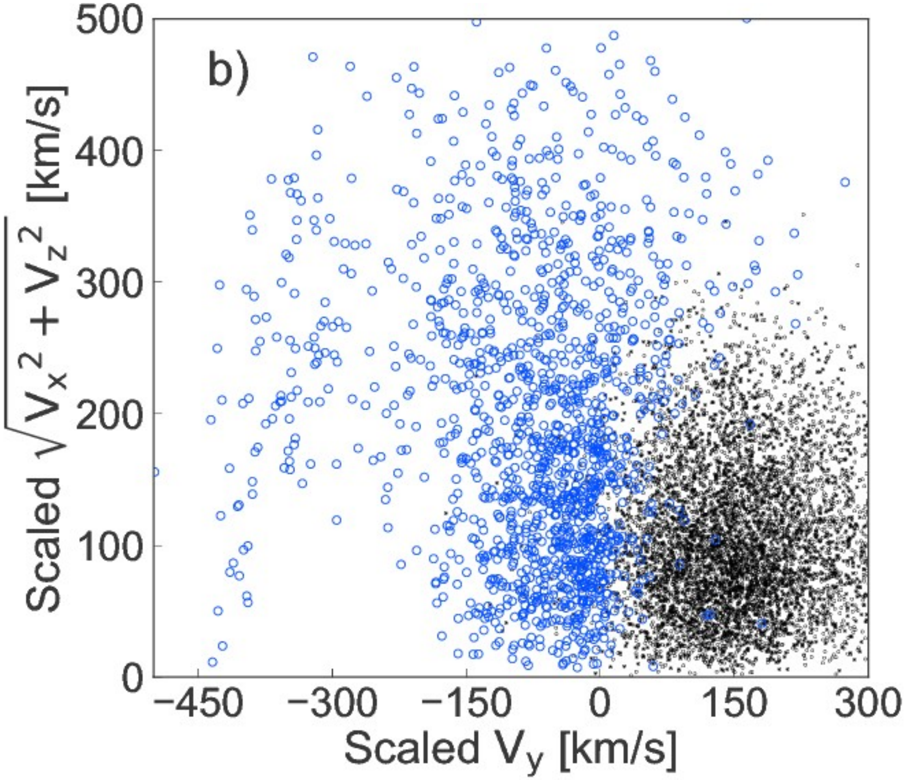
Gaia-Enceladus: 3) the retrograde blob

DATA



Helmi et al.2018

SIMULATION of 5:1 mass ratio merger

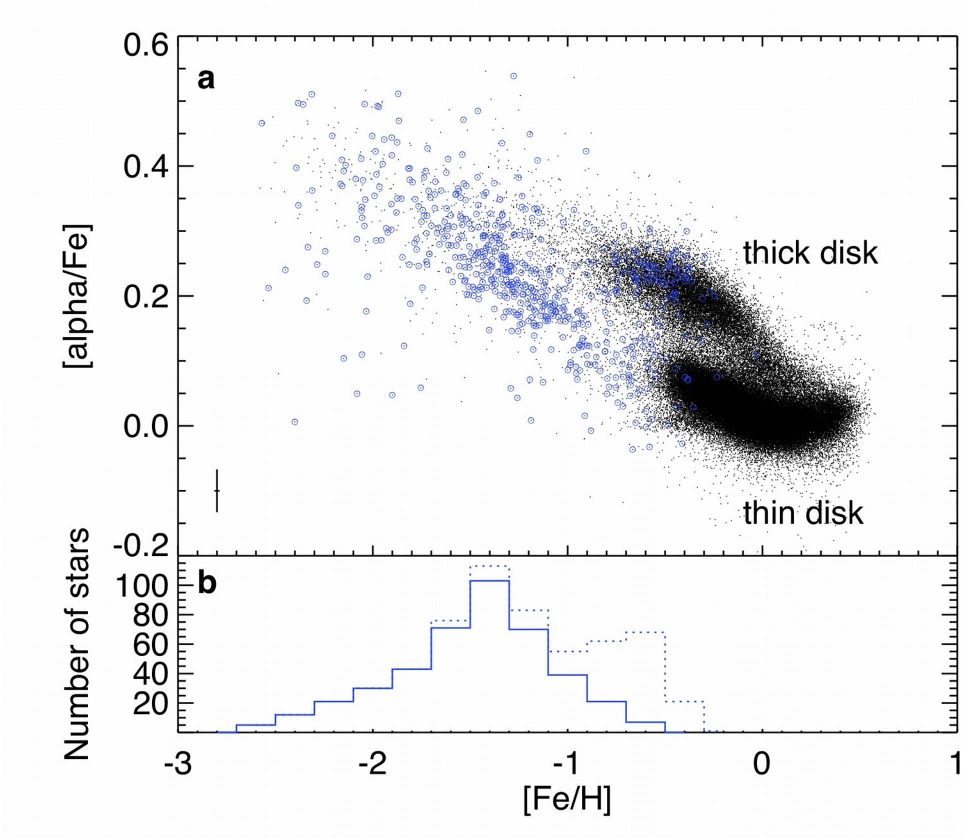


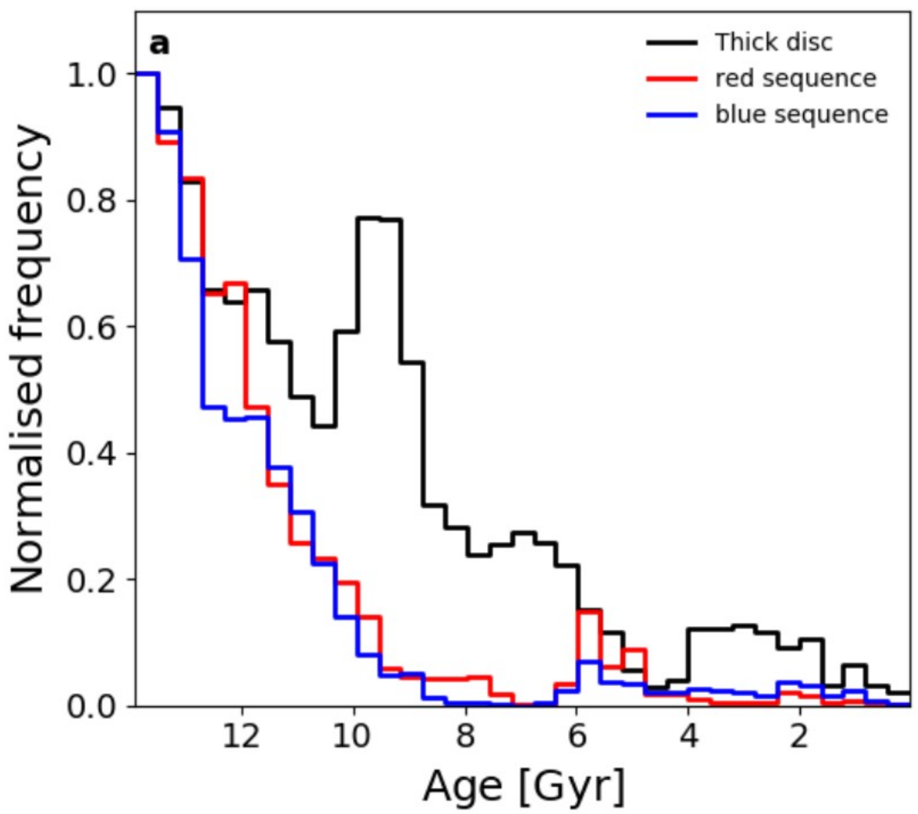
Villalobos & Helmi (2008)

Same feature recognised by Belokurov et al. (2018)/the Sausage

Gaia-Enceladus: 4) final picture

See also Nissen & Schuster 2010, Hayes et al. 2018, Haywood et al. 2018





- [alpha/Fe] decreases with [Fe/H] in galaxies

  → blob stars formed elsewhere
  → lower SFR; massive: $M_* \sim 6 \times 10^8 M_{sun}$
  (Fernandez-Alvar et al. 2018, Mackereth et al.2019)

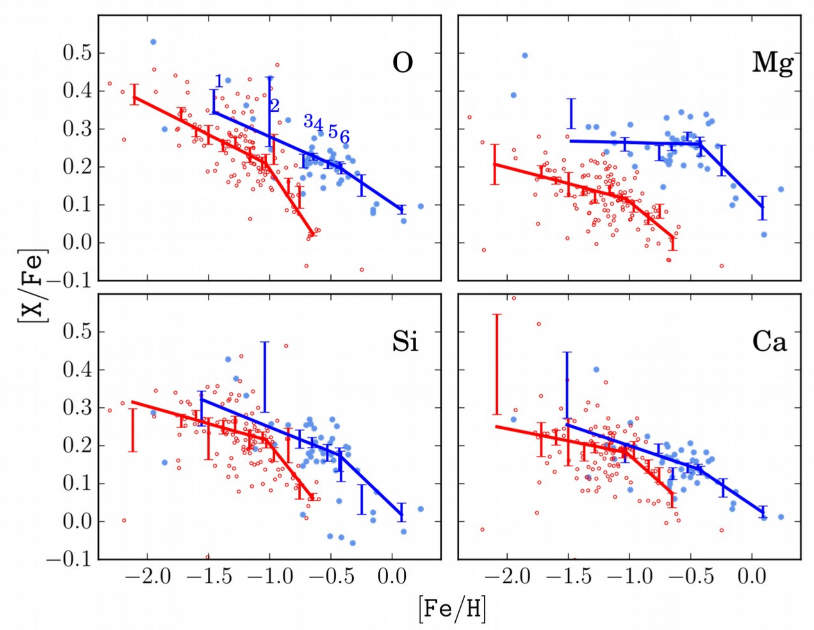
- Two sequences coheval (Gallart et al.2019)

- Accretion caused thick-disc like stars to move on eccentric orbits with little Lz

Gaia-Enceladus: 4) final picture

Stellar Mass

$M_* \sim 2\text{-}8 \times 10^8 M_{sun}$



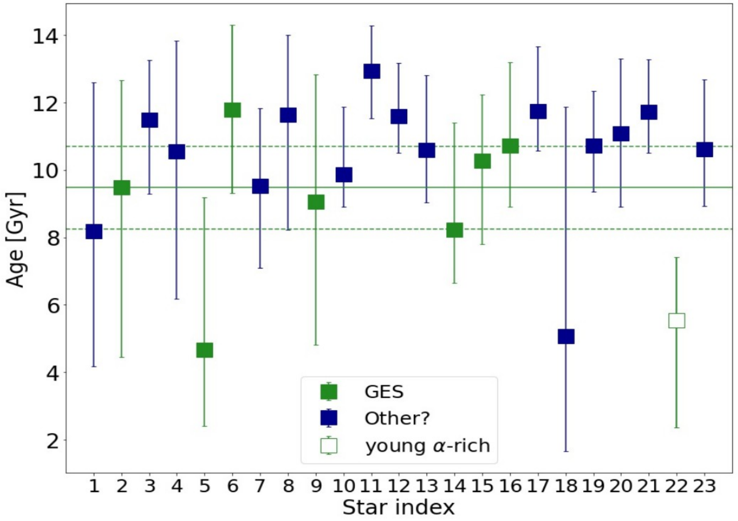
Fernadnez-Alvar+18

Kruijssen+20

Naidu+20

Accretion Time

t ~ 8-10 Gyr



Kruijssen+20

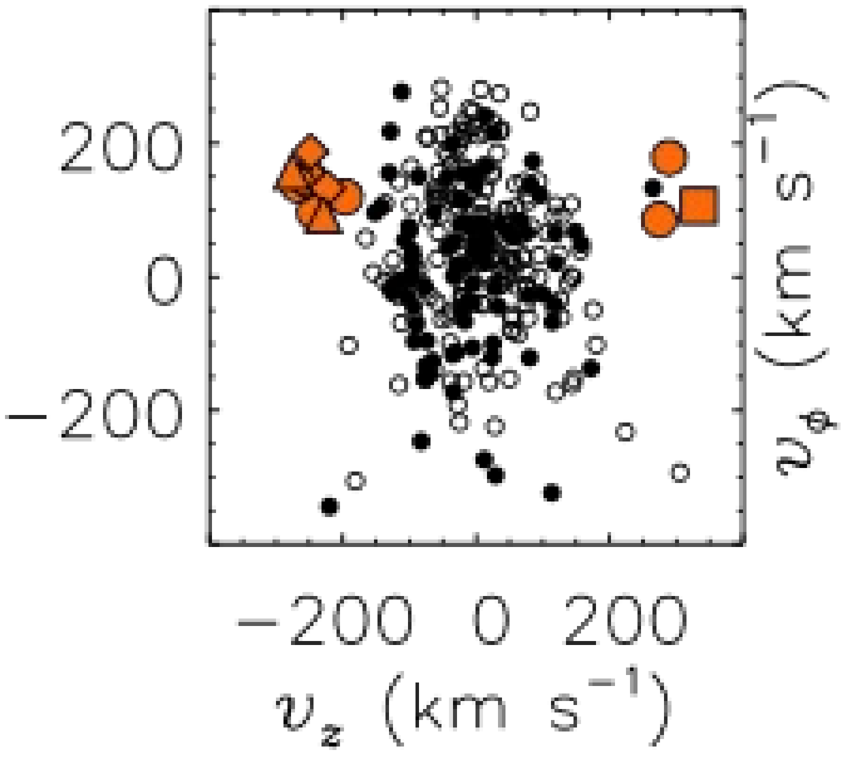
Montalban+21

Borre+21

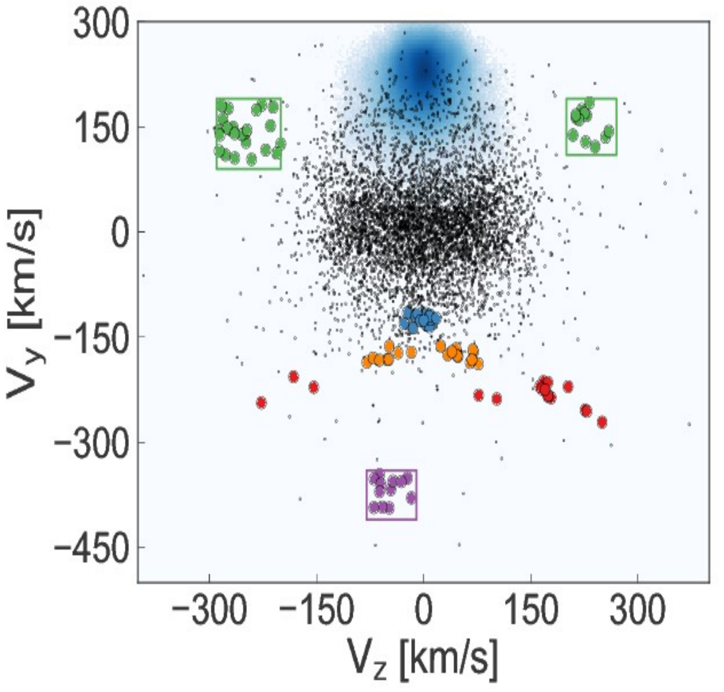
Progenitor of the Helmi streams

Helmi et al (1999)

Hipparcos

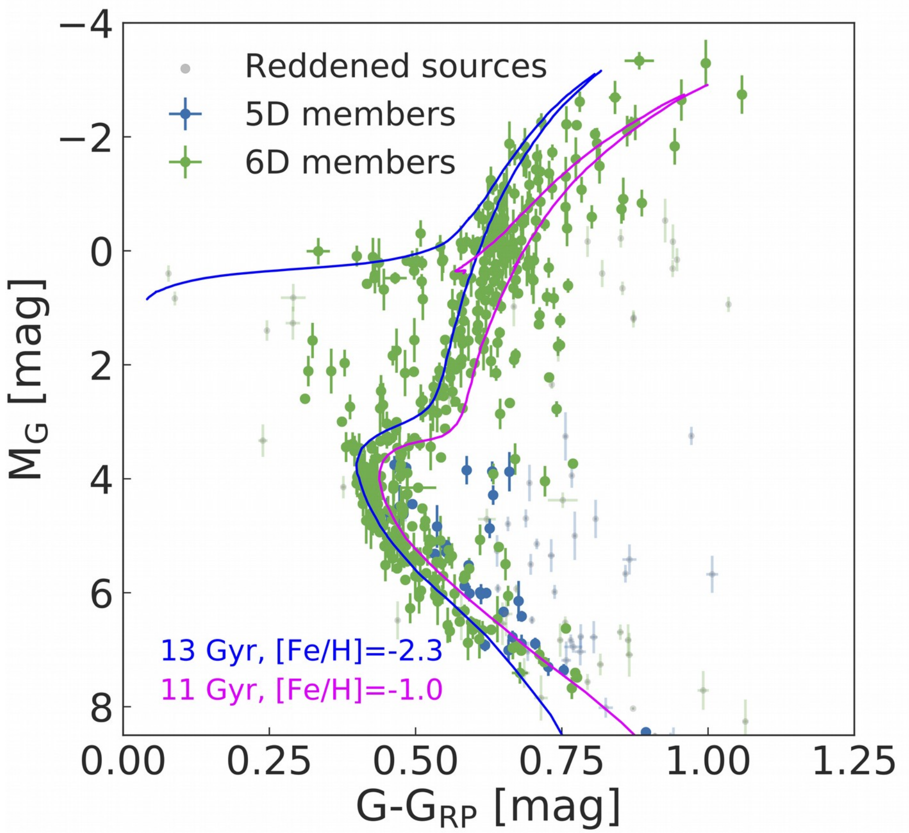


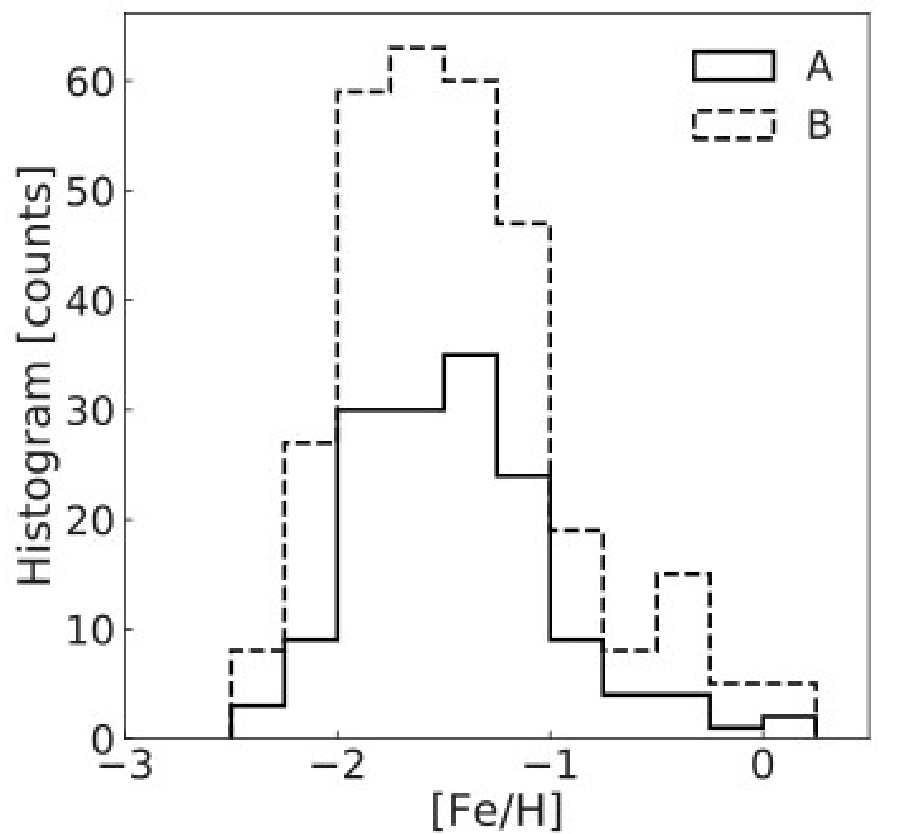
Gaia DR2



Progenitor of the Helmi streams

Koppelman, Helmi, DM et al. 2019a



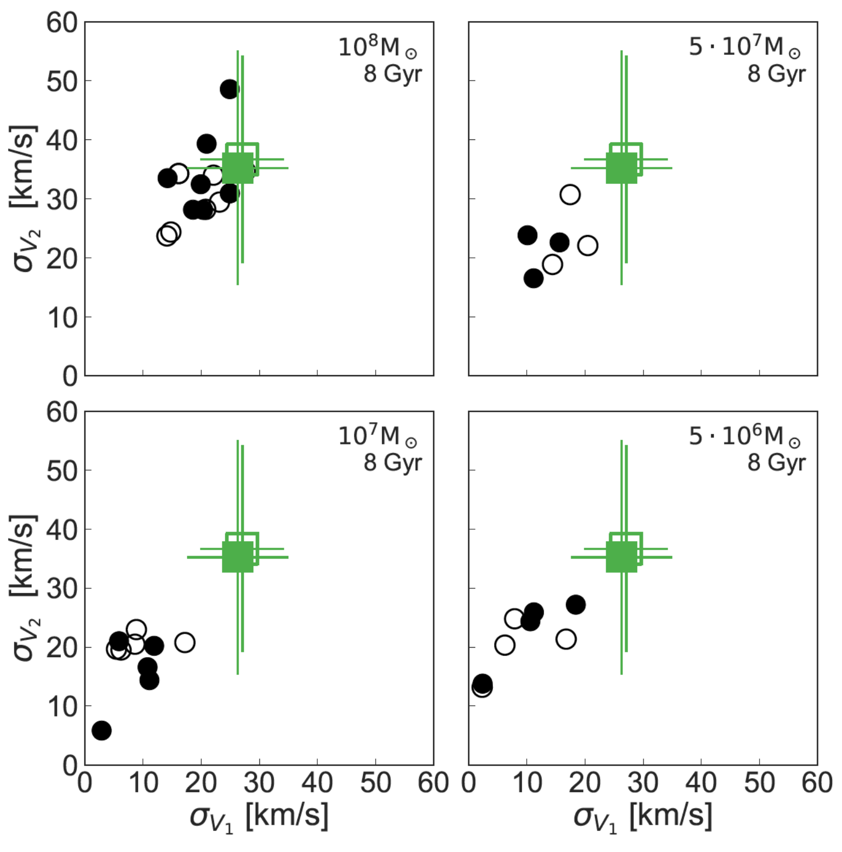


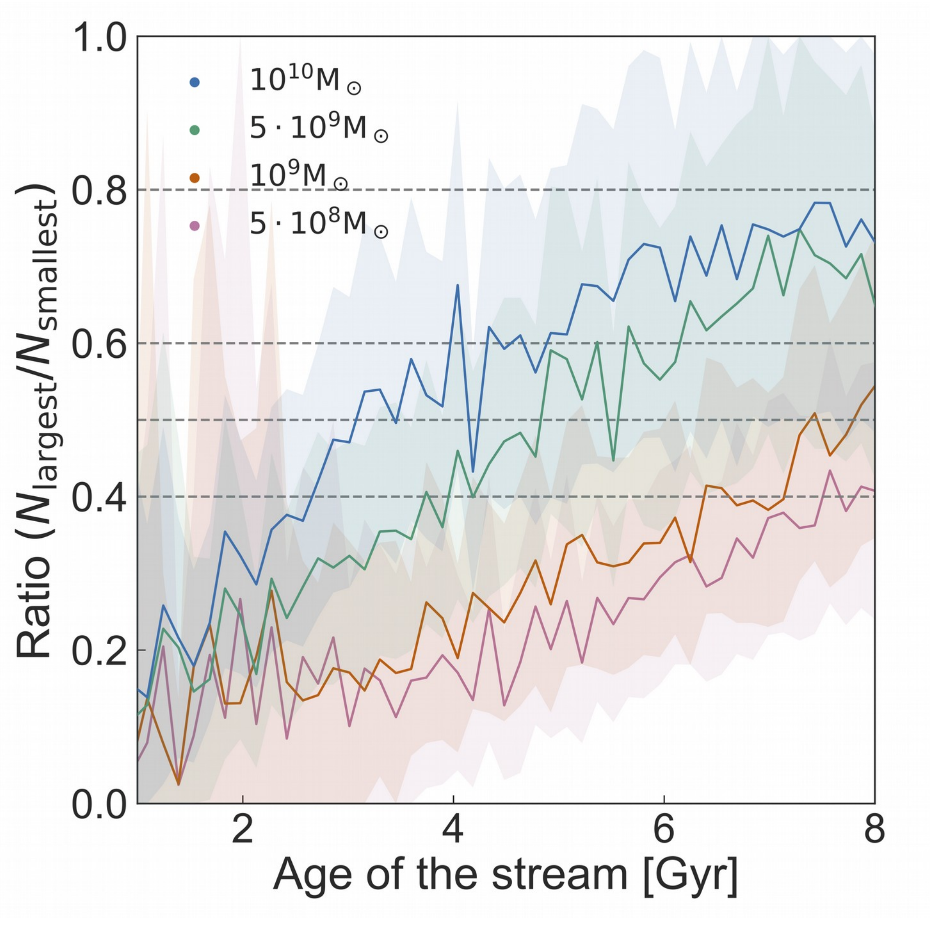
- HR diagram broad MSTO and RGB: not a single stellar population
- Extended star formation history (+/- 2 Gyr)
- Broad metallicity distribution, w/ peak at [Fe/H] ~ -1.8

= dwarf galaxy

Progenitor of the Helmi streams

Koppelman, Helmi, DM et al. 2019a

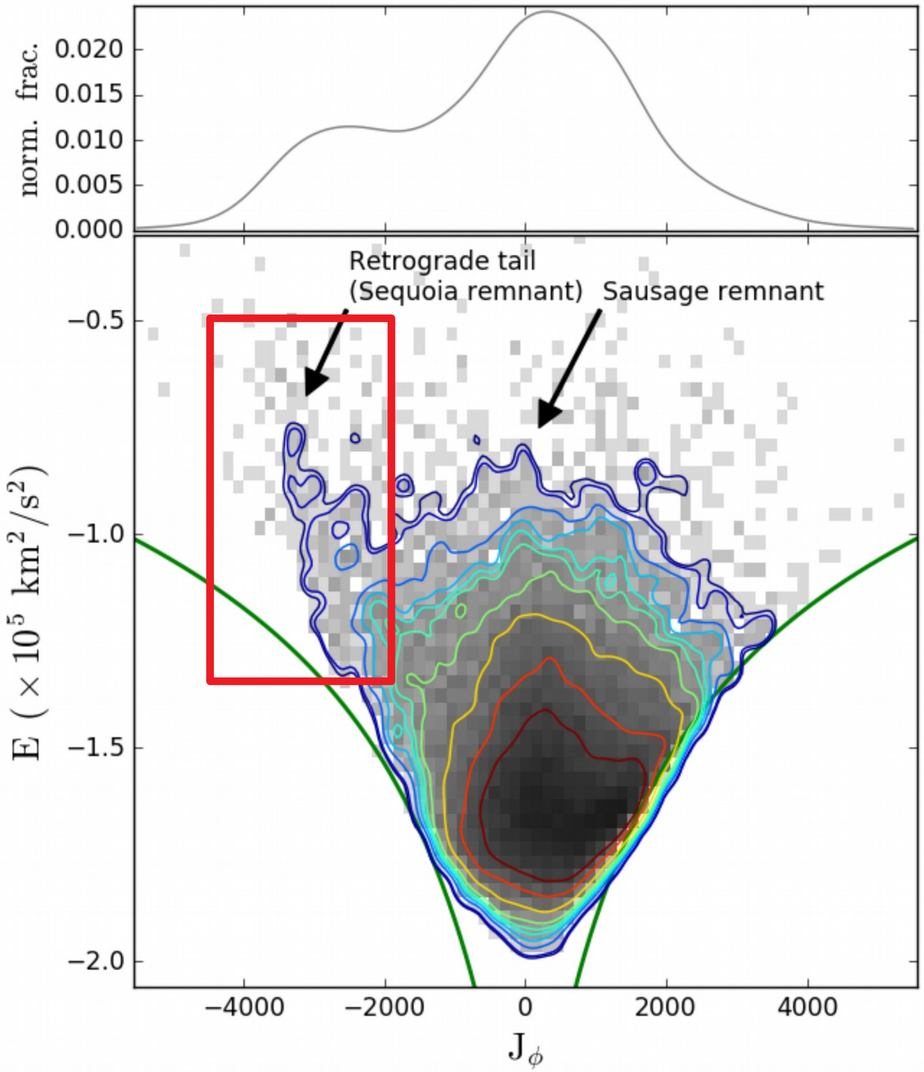


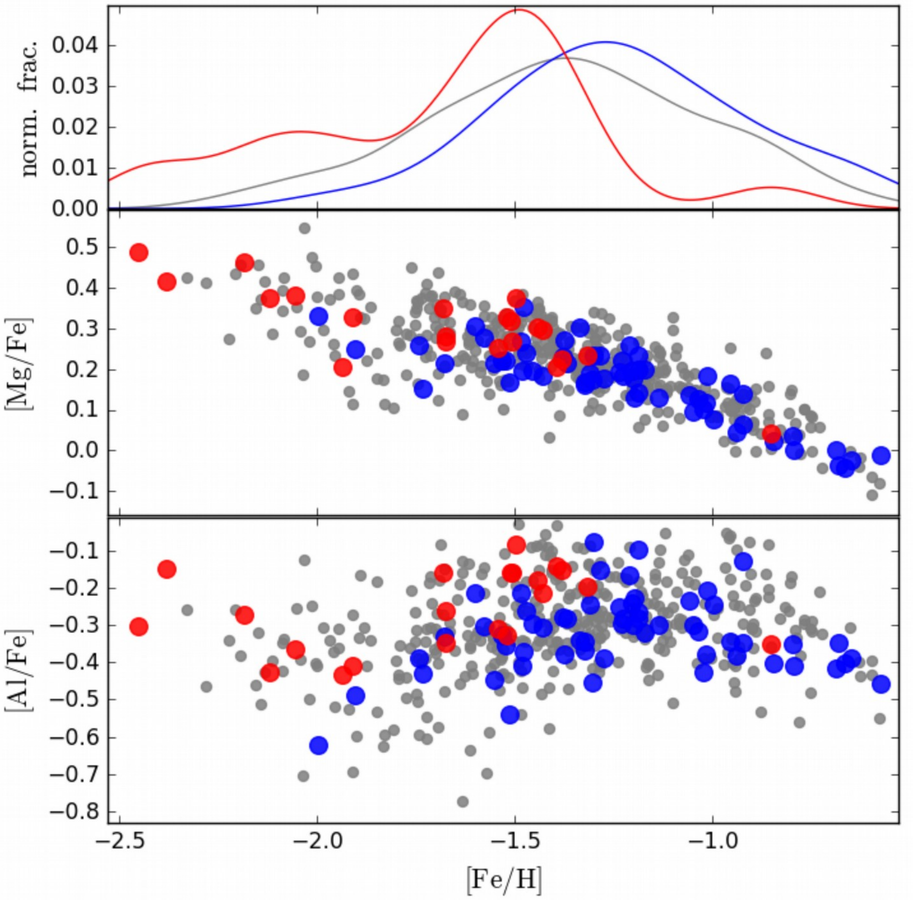


Velocity dispersion stellar mass log(M*)=8

Asymmetry in counts = accretion 5/8 Gyr ago

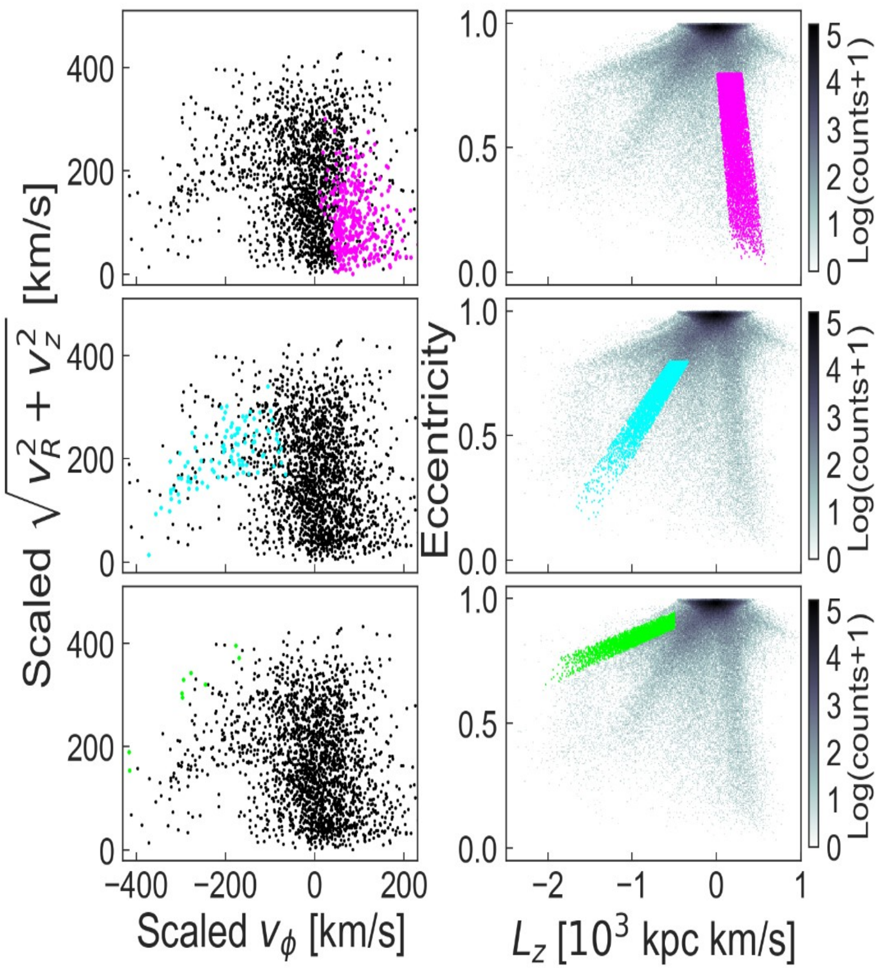
The Sequoia dwarf galaxy

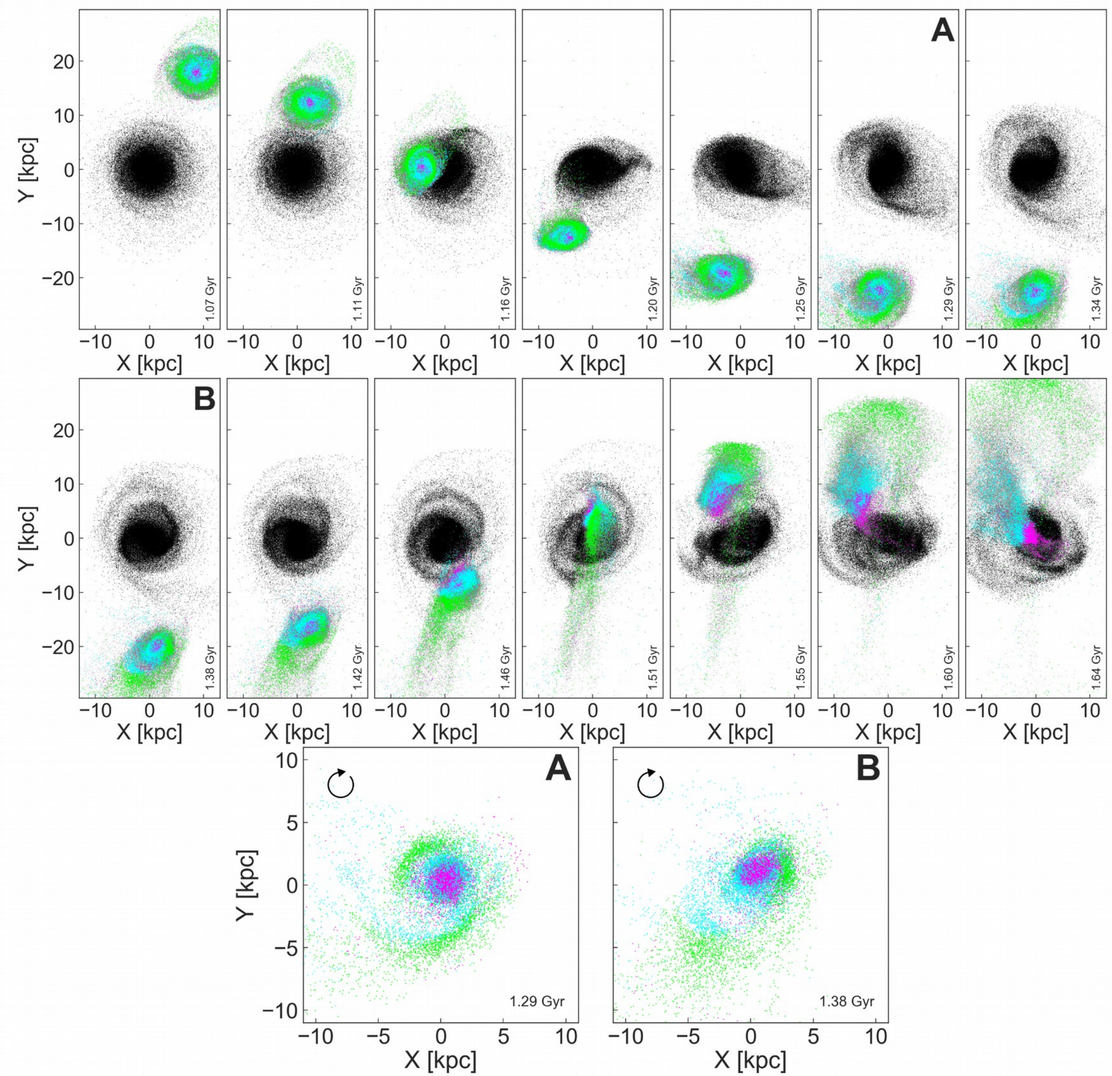




Myeong et al.2019

The Sequoia dwarf galaxy



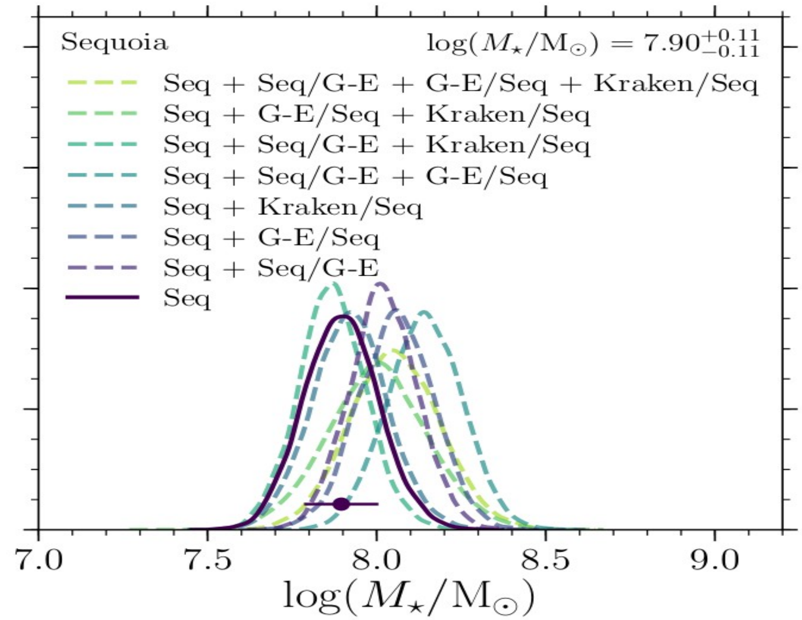


Koppelman et al.2021

The Sequoia dwarf galaxy

Stellar Mass

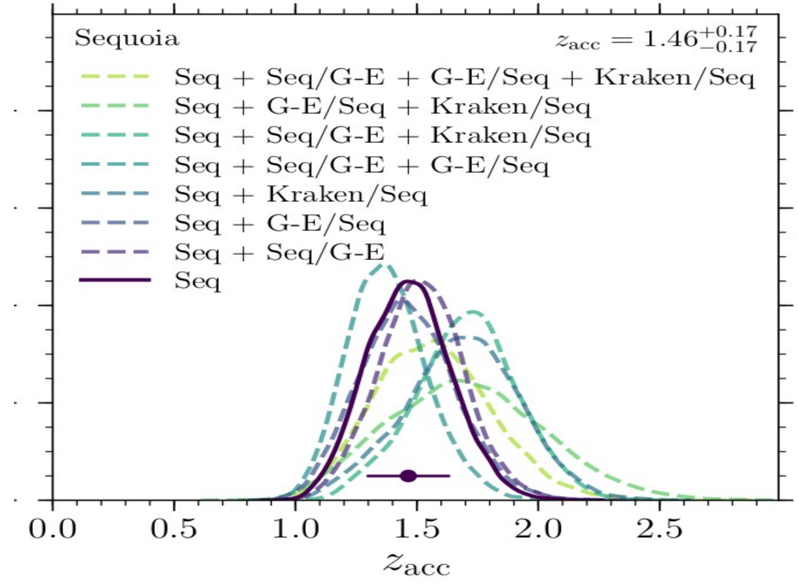
$M_* \sim 5\text{-}9 \times 10^7 M_{sun}$



Kruijssen+20

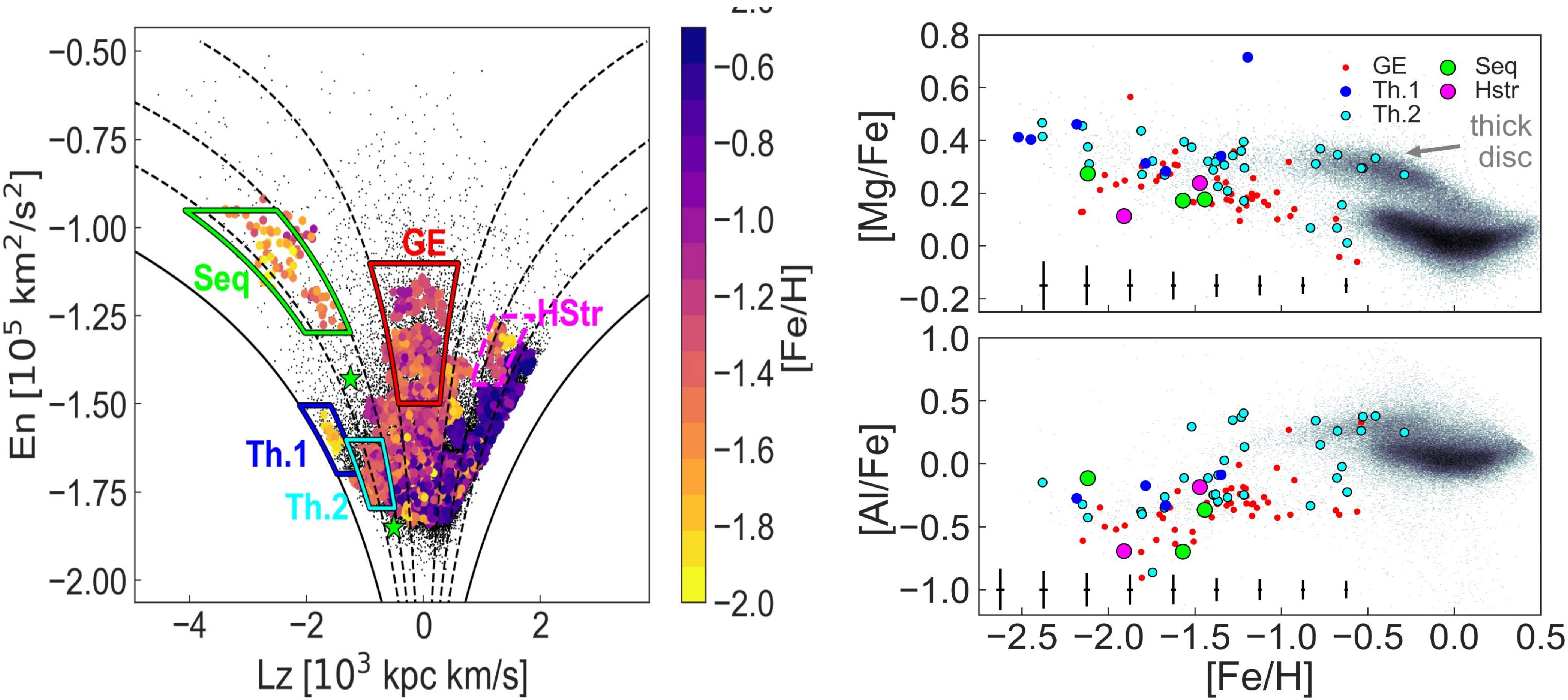
Accretion Time

t ~ 9-11 Gyr



Kruijssen+20

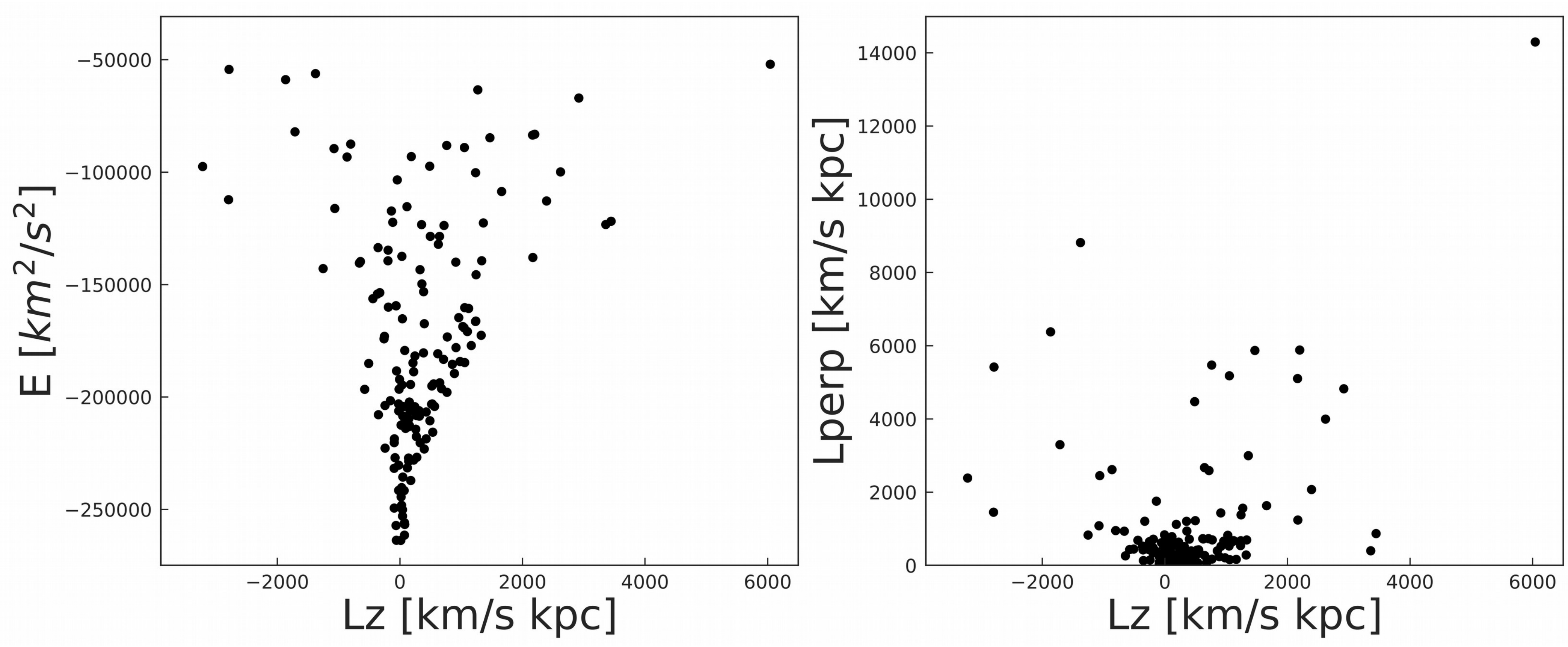
Thamnos



Koppelman, Helmi, DM et al. 2019b

Disrupted dwarfs – GCs link

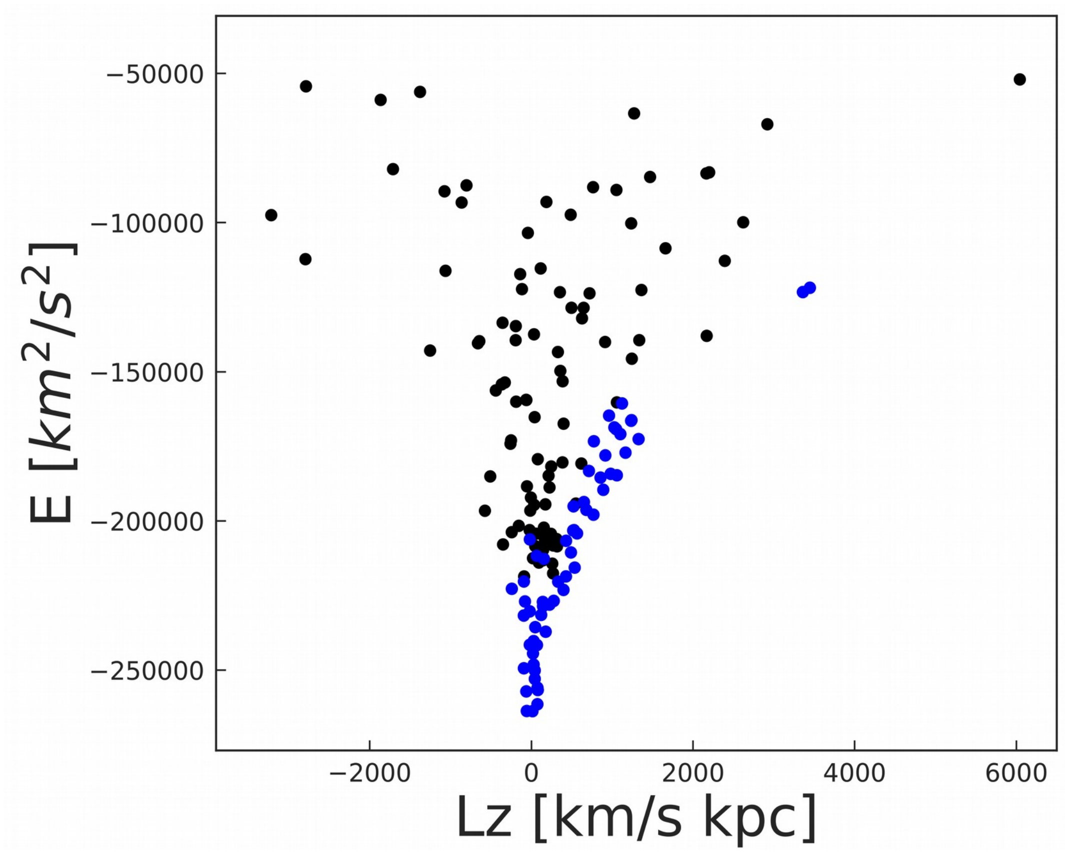
Integrals of motion



Massari et al. 2019

Disrupted dwarfs – GCs link

Integrals of motion



MAIN PROGENITOR – Milky Way

Bulge = E< -2.2e5 km2/s2

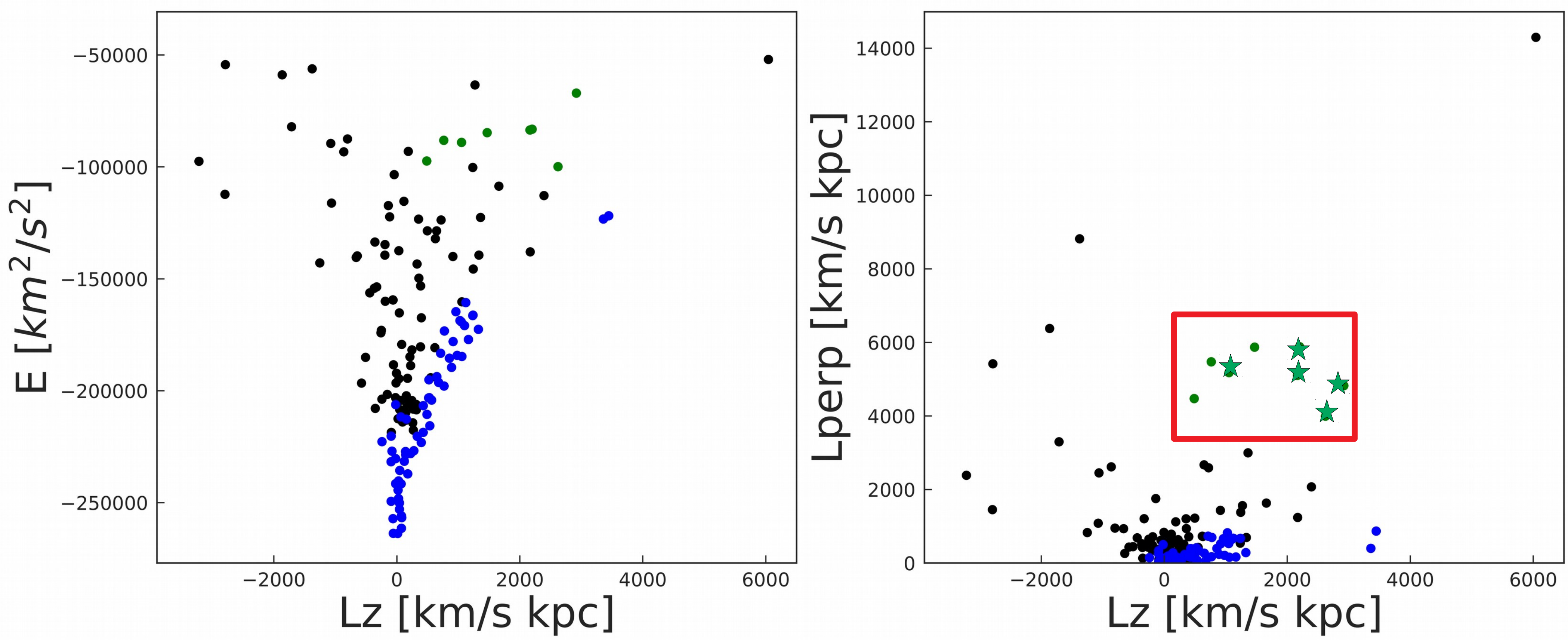
Disk = zmax<5 kpc
Circ > 0.5

Massari et al. 2019

Disrupted dwarfs – GCs link

Integrals of motion

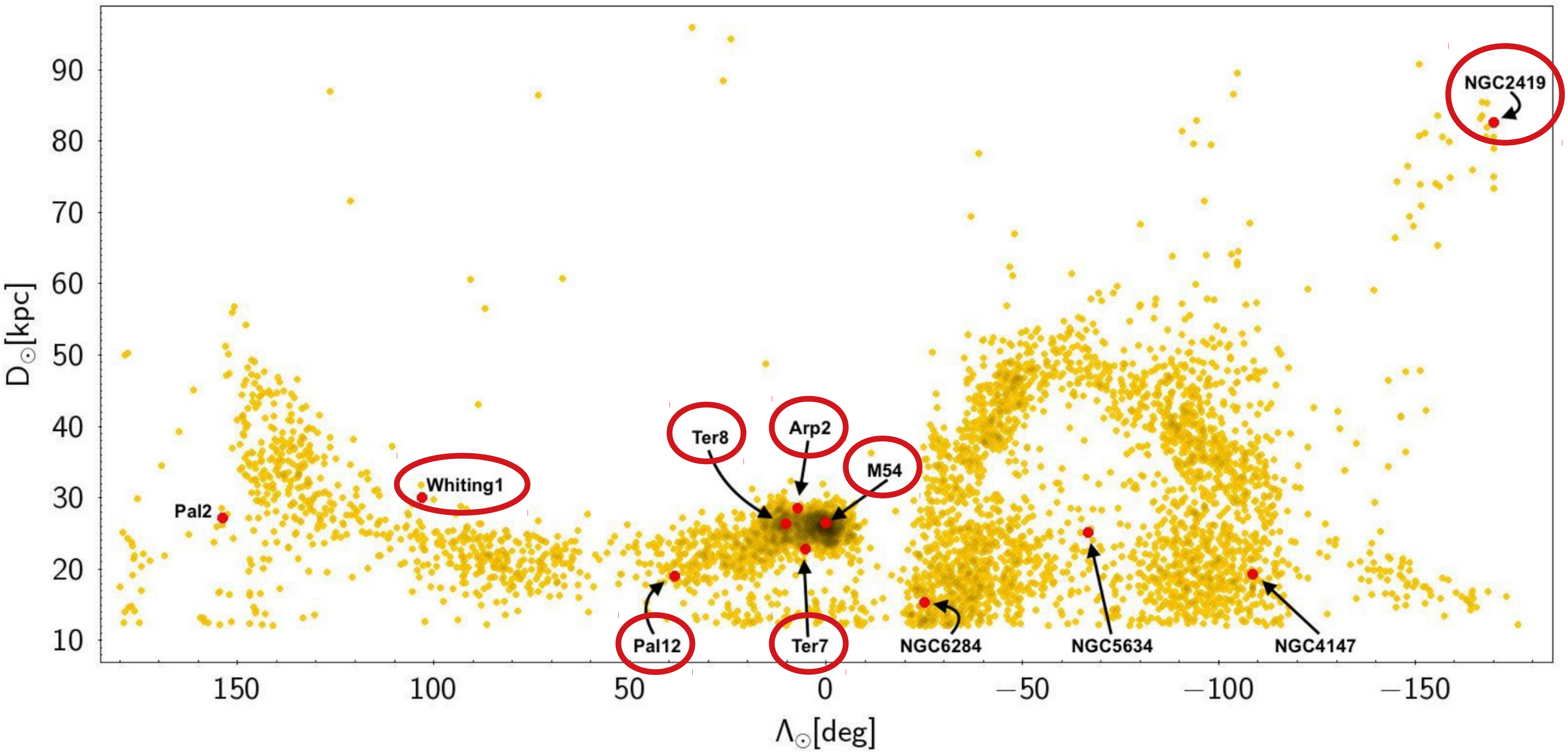
Sagittarius dSph
(Sohn et al.2018)



Massari et al. 2019

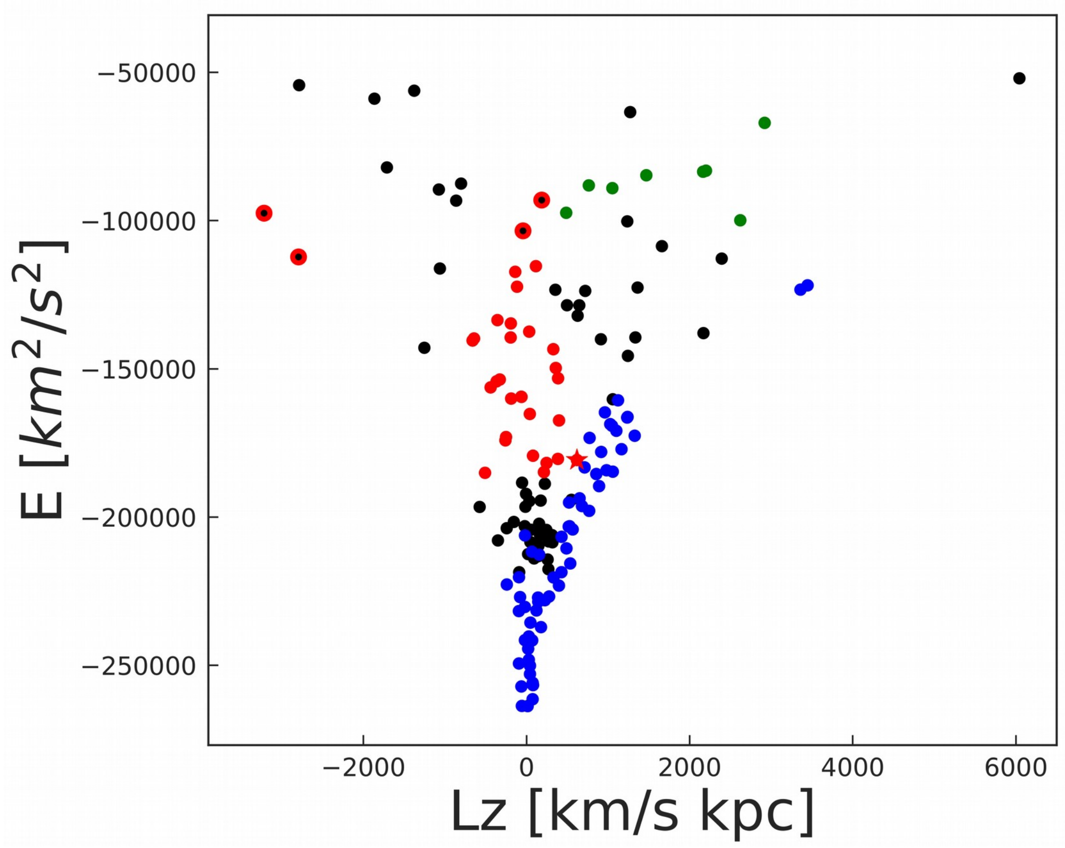
Disrupted dwarfs – GCs link

Bellazzini et al.2020 – associations confirmed

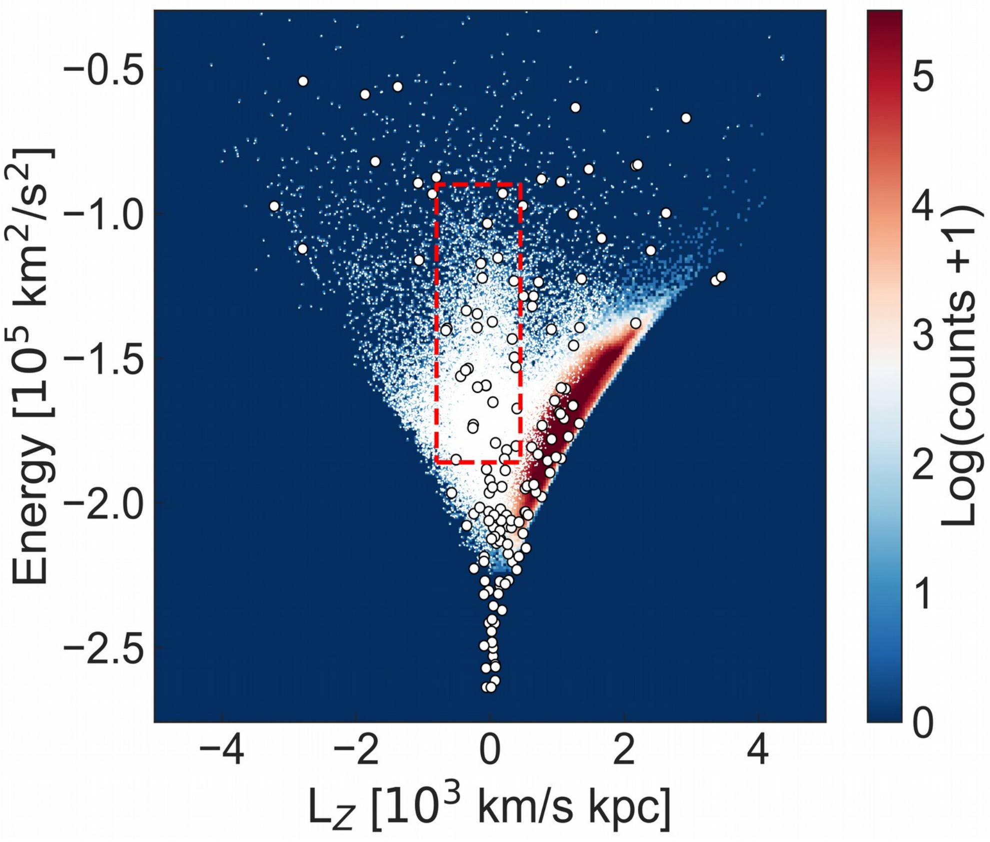


Disrupted dwarfs – GCs link

Integrals of motion



Gaia-Enceladus



Massari et al. 2019

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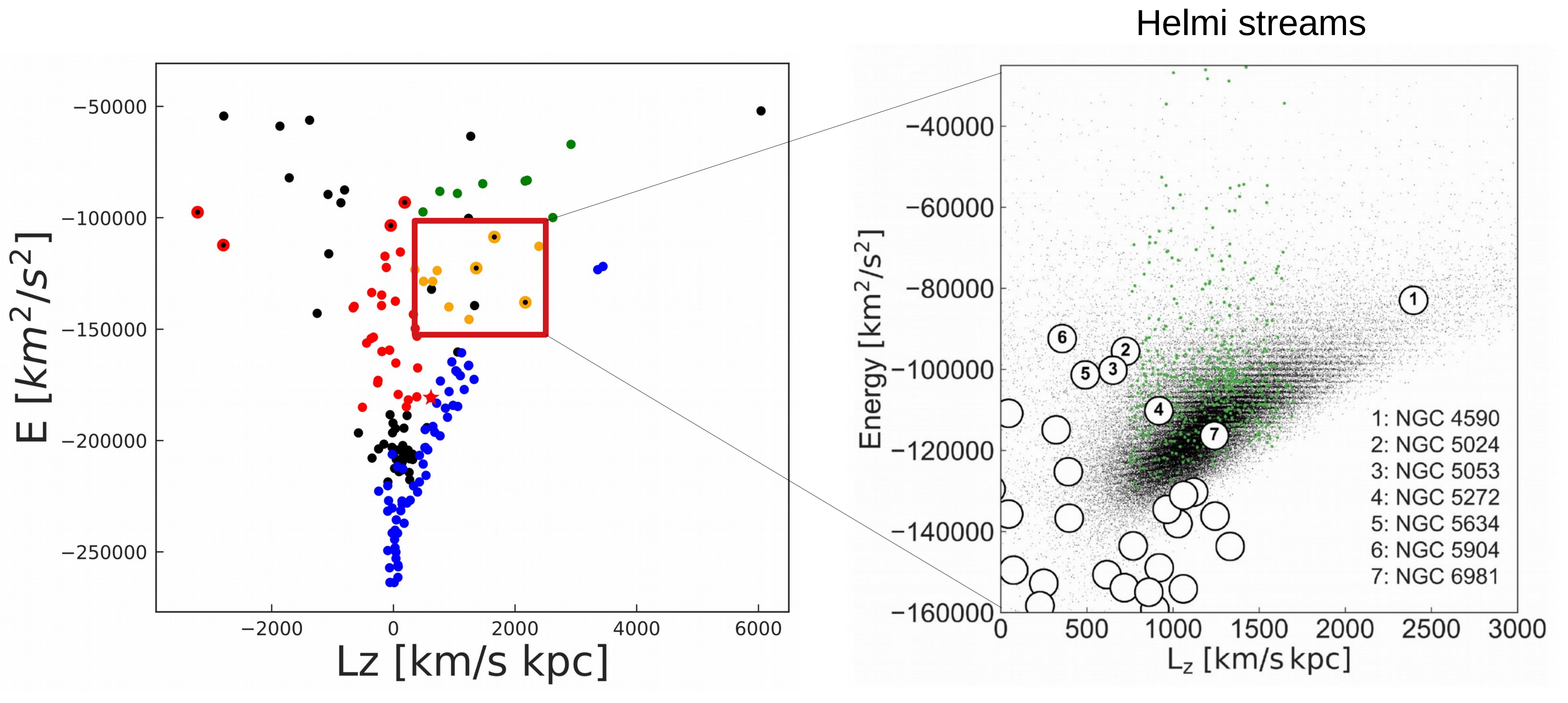
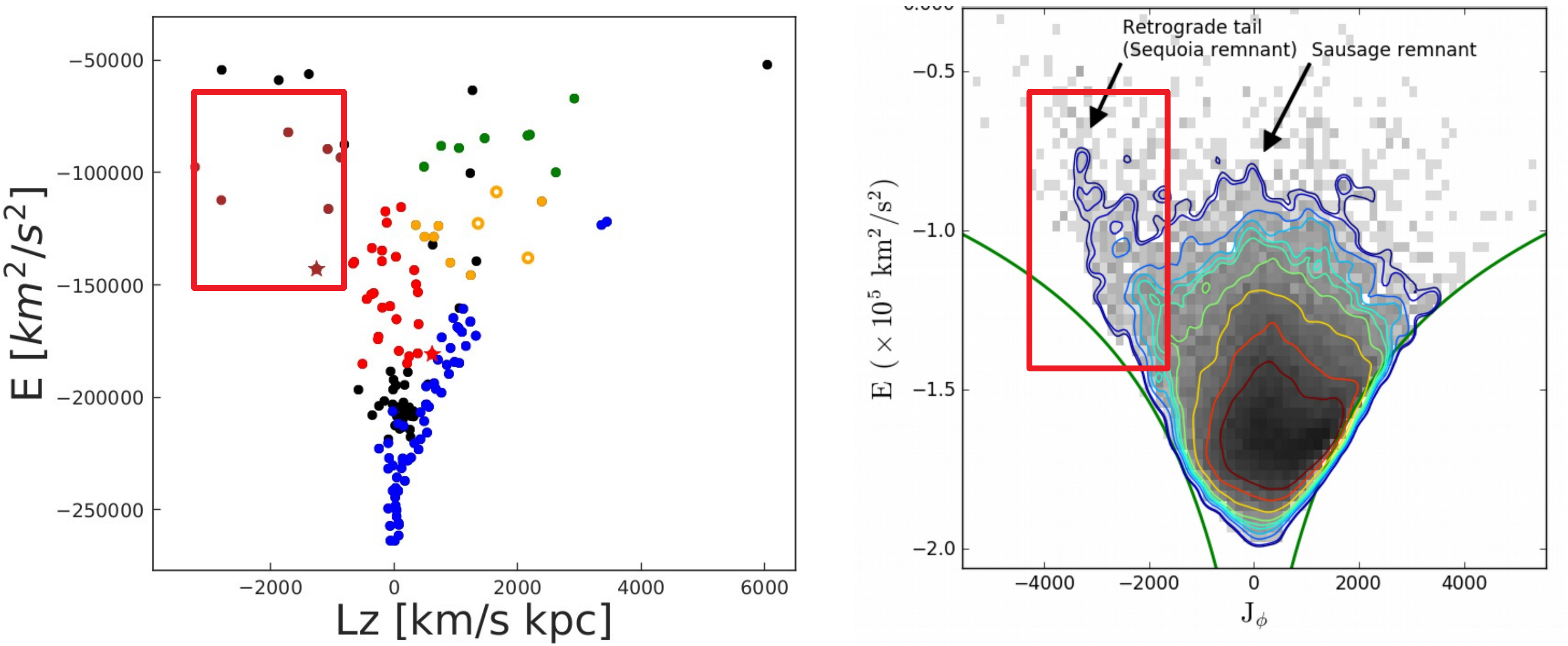


Massari et al. 2019

Disrupted dwarfs – GCs link

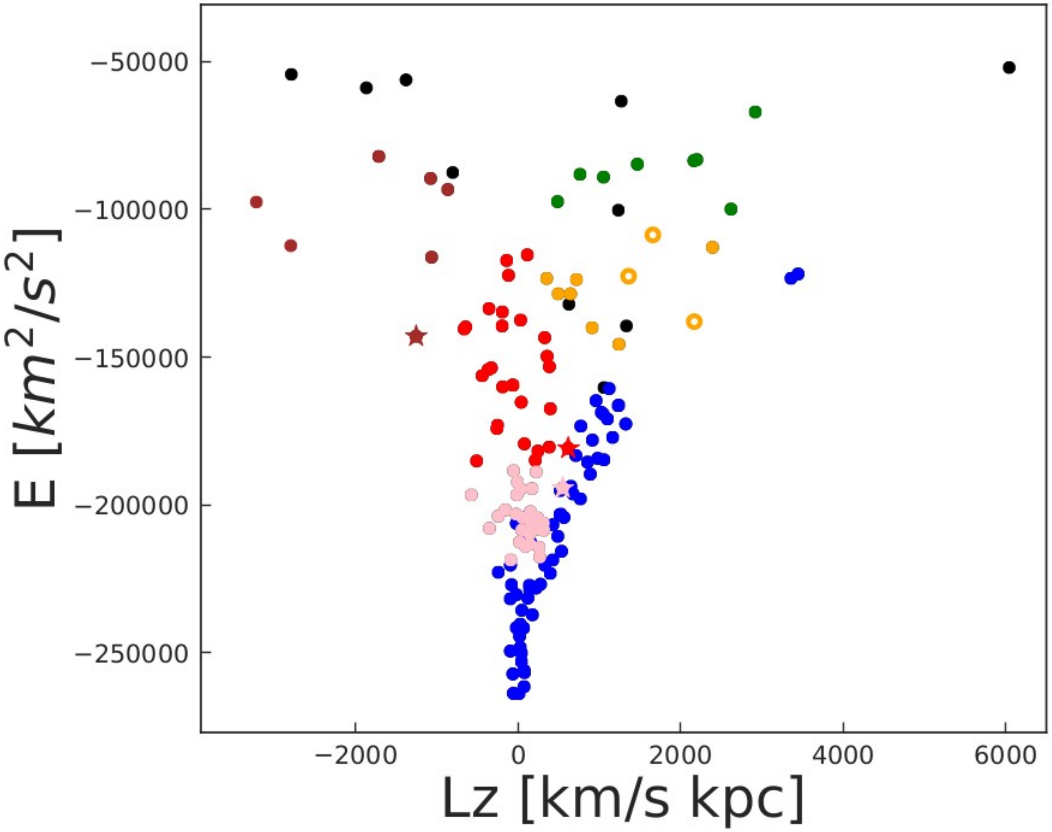
Integrals of motion



Massari et al. 2019

Disrupted dwarfs – GCs link

Integrals of motion



Low-energy group

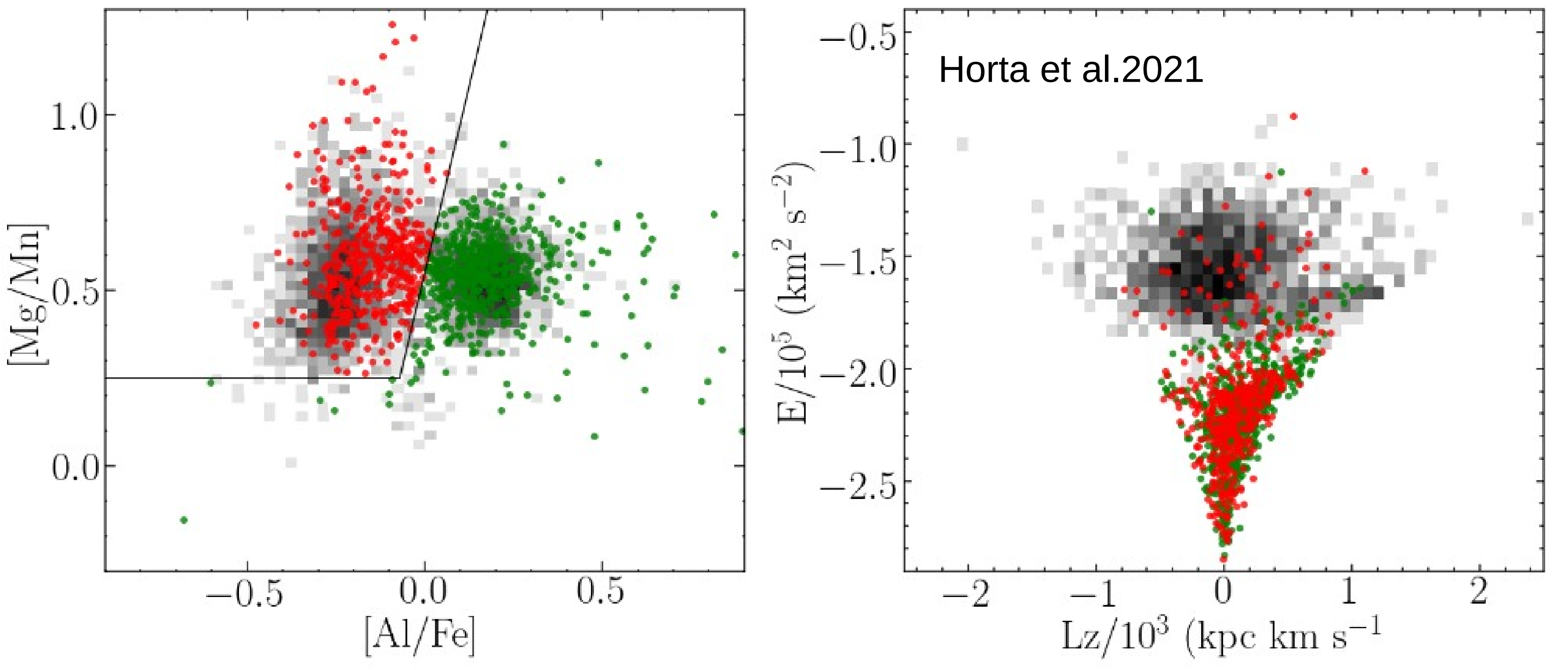
25 GCs

Coherent structure

Same progenitor! **Kraken**
(see e.g. Kruijssen et al. 2019)

Massari et al. 2019

Kraken

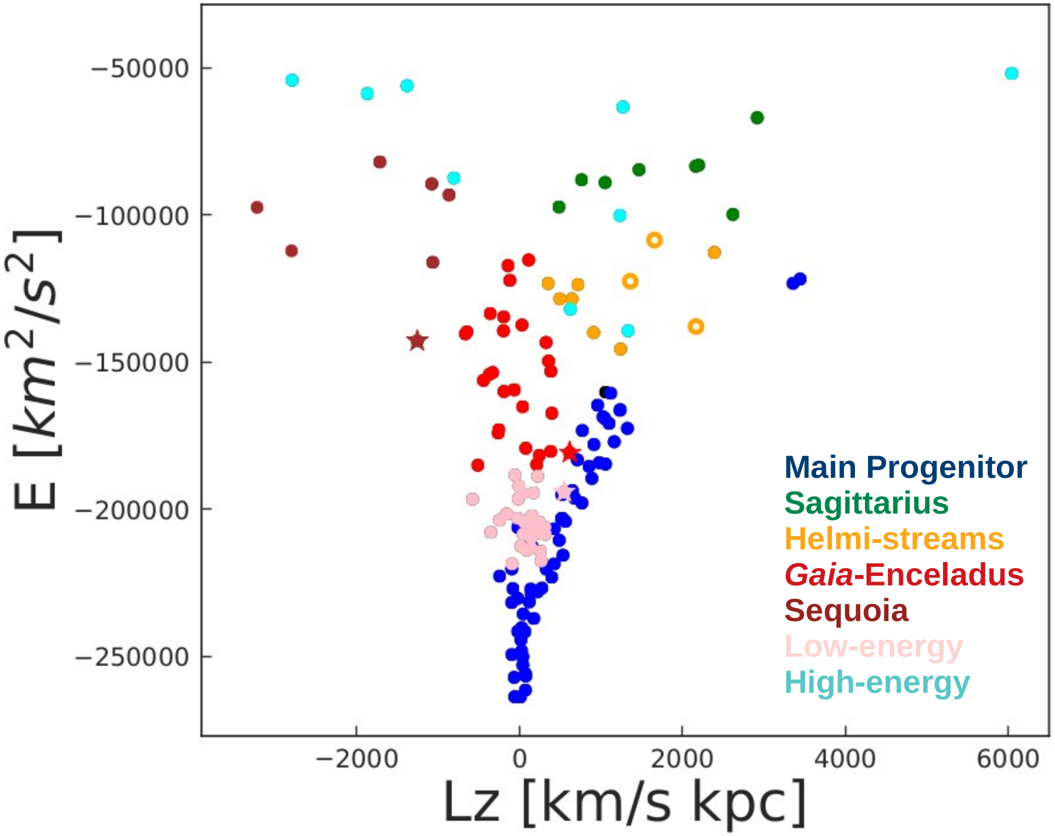


Low-energy = early accretion

N. GCs = stellar mass ~ M_{GES}

Disrupted dwarfs – GCs link

Integrals of motion



High-energy group

11 GCs

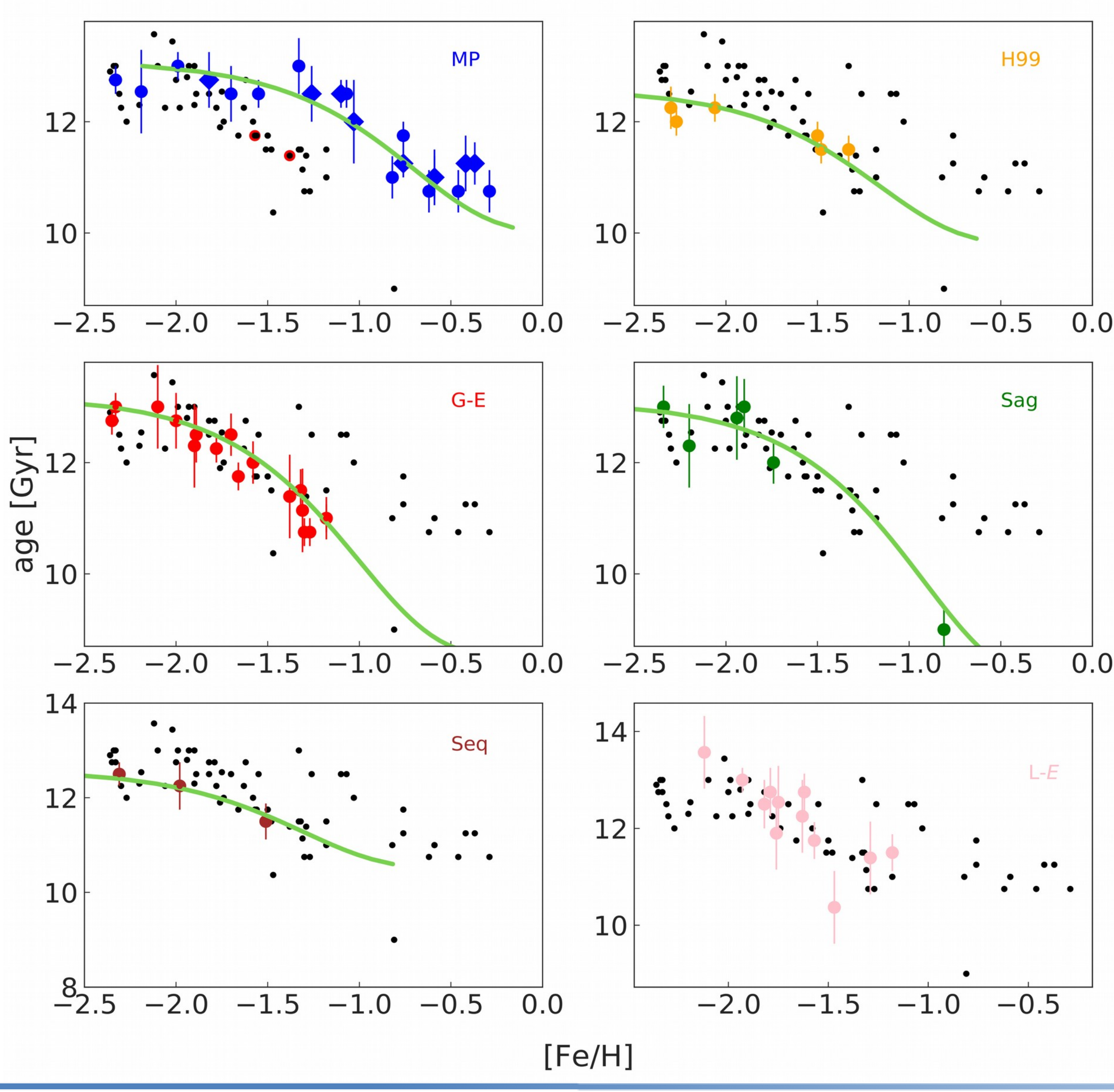
Not coherent structure

Several (uknown) progenitors

Massari et al. 2019

Disrupted dwarfs – GCs link

Age-metallicity relation



Massari et al. 2019

Conclusions (part 1)

GC	Progenitor	GC	Progenitor	GC	Progenitor	GC	Progenitor
NGC 104	M-D	NGC 5927	M-D	HP 1	M-B	GLIMPSE2	XXX
NGC 288	G-E	NGC 5946	L-E	NGC 6362	M-D	NGC 6584	H-E
NGC 362	G-E	BH 176	M-D	Liller 1	XXX	NGC 6624	M-B
Whiting 1	Sag	NGC 5986	L-E	NGC 6380	M-B	NGC 6626	M-B
NGC 1261	G-E	Lynga 7	M-D	Terzan 1	M-B	NGC 6638	M-B
Pal 1	M-D	Pal 14	H-E	Ton 2	L-E	NGC 6637	M-B
AM 1	H-E	NGC 6093	L-E	NGC 6388	M-B	NGC 6642	M-B
Eridanus	H-E	NGC 6121	L-E	NGC 6402	L-E	NGC 6652	M-B
Pal 2	G-E?	NGC 6101	G-E/Seq	NGC 6401	L-E	NGC 6656	M-D
NGC 1851	G-E	NGC 6144	L-E	NGC 6397	M-D	Pal 8	M-D
NGC 1904	G-E	NGC 6139	L-E	Pal 6	L-E	NGC 6681	L-E
NGC 2298	G-E	Terzan 3	M-D	NGC 6426	H-E	GLIMPSE1	XXX
NGC 2419	Sag	NGC 6171	M-B	Djorg 1	G-E	NGC 6712	L-E
Ko 2	XXX	1636-283	M-B	Terzan 5	M-B	NGC 6715	Sag
Pyxis	H-E	NGC 6205	G-E	NGC 6440	M-B	NGC 6717	M-D
NGC 2808	G-E	NGC 6229	G-E	NGC 6441	L-E	NGC 6723	M-B
E 3	H99?	NGC 6218	M-D	Terzan 6	M-B	NGC 6749	M-D
Pal 3	H-E	FSR 1735	L-E	NGC 6453	L-E	NGC 6752	M-D
NGC 3201	G-E/Seq	NGC 6235	G-E	UKS 1	XXX	NGC 6760	M-D
Pal 4	H-E	NGC 6254	L-E	NGC 6496	M-D	NGC 6779	G-E
Ko 1	XXX	NGC 6256	L-E	Terzan 9	M-B	Terzan 7	Sag
NGC 4147	G-E	Pal 15	G-E?	Djorg 2	M-D	Pal 10	M-D
NGC 4372	M-D	NGC 6266	M-D	NGC 6517	L-E	Arp 2	Sag
Rup 106	H99?	NGC 6273	L-E	Terzan10	G-E	NGC 6809	L-E
NGC 4590	H99	NGC 6284	G-E	NGC 6522	M-B	Terzan 8	Sag
NGC 4833	G-E	NGC 6287	L-E	NGC 6535	L-E	Pal 11	M-D
NGC 5024	H99	NGC 6293	L-E	NGC 6528	M-B	NGC 6838	M-D
NGC 5053	H99	NGC 6304	M-D	NGC 6539	L-E	NGC 6864	G-E
NGC 5139	G-E/Seq	NGC 6316	M-B	NGC 6540	M-D	NGC 6934	H-E
NGC 5272	H99	NGC 6341	G-E	NGC 6544	L-E	NGC 6981	H99
NGC 5286	G-E	NGC 6325	M-B	NGC 6541	L-E	NGC 7006	H-E
AM 4	XXX	NGC 6333	L-E	2MS-GC01	XXX	NGC 7078	M-D
NGC 5466	H-E	NGC 6342	M-B	ESO-SC06	G-E	NGC 7089	G-E
NGC 5634	H99	NGC 6356	M-D	NGC 6553	M-D	NGC 7099	G-E
NGC 5694	H-E	NGC 6355	M-B	2MS-GC02	XXX	Pal 12	Sag
IC 4499	H-E	NGC 6352	M-D	NGC 6558	M-B	Pal 13	H-E
NGC 5824	Sag	IC 1257	G-E	IC 1276	M-D	NGC 7492	G-E
Pal 5	H99?	Terzan 2	M-B	Terzan12	M-D	Crater	H-E
NGC 5897	G-E	NGC 6366	M-D	NGC 6569	M-D	FSR 1716	M-D
NGC 5904	H99	Terzan 4	M-B	BH 261	M-D	FSR1758	Seq

Associations to be refined based on:

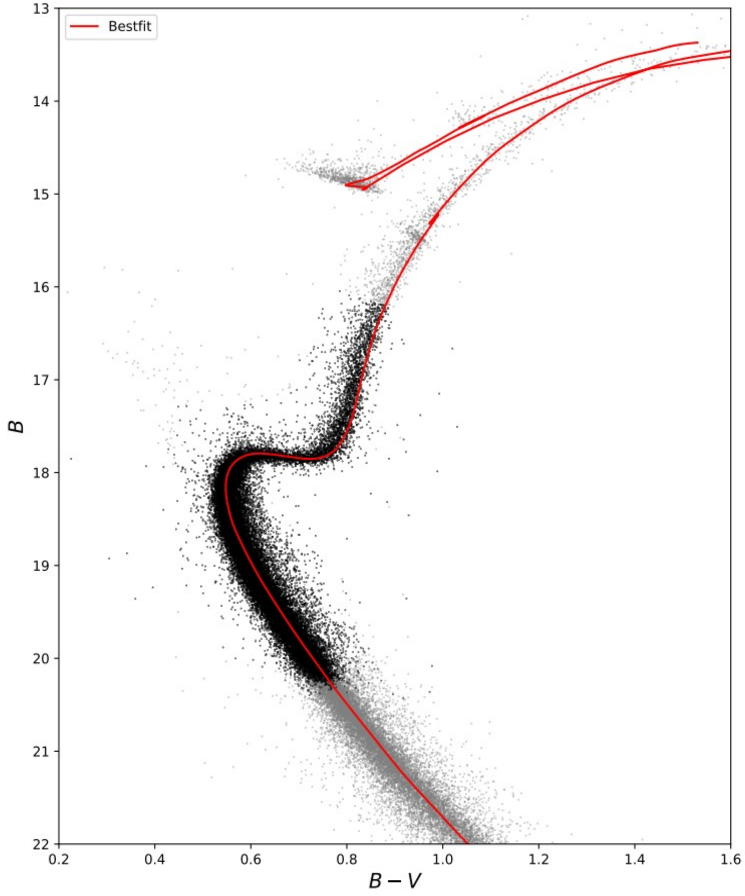
- Chemistry

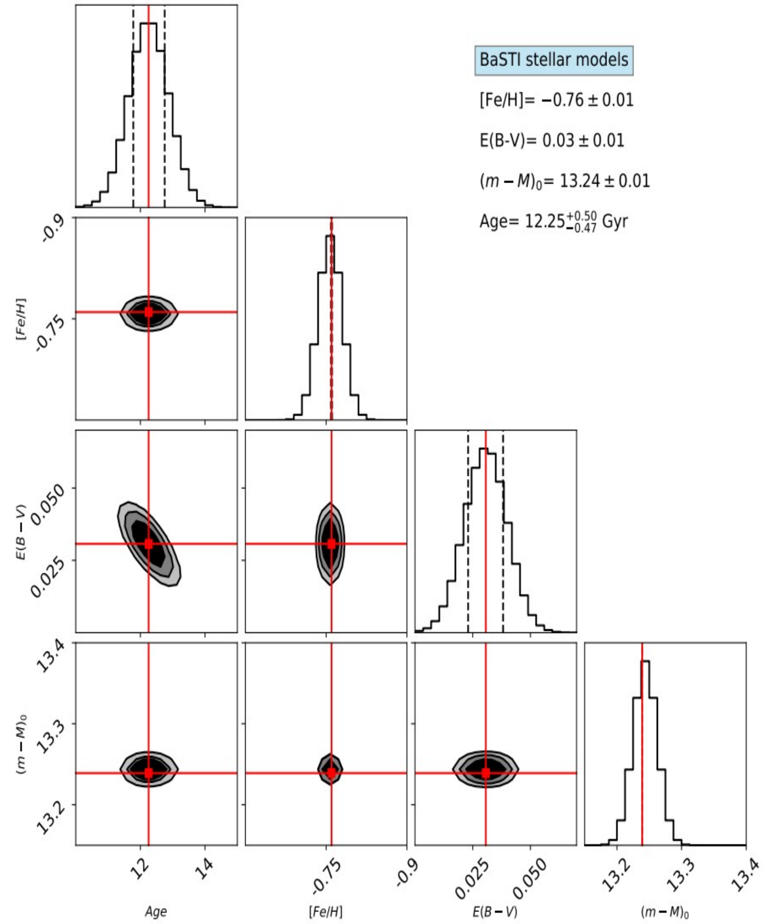
- Complete (and accurate) age information

- Improved kinematics (*Gaia* systematic errors correction)

- Mass function

CARMA project
(Clusters Ages to Reconstruct the Milky way Assembly)





CARMA team: DM, E. Pancino, S. Cassisi, M. Salaris, S. Saracino, A. Pietrinferni + collaborators

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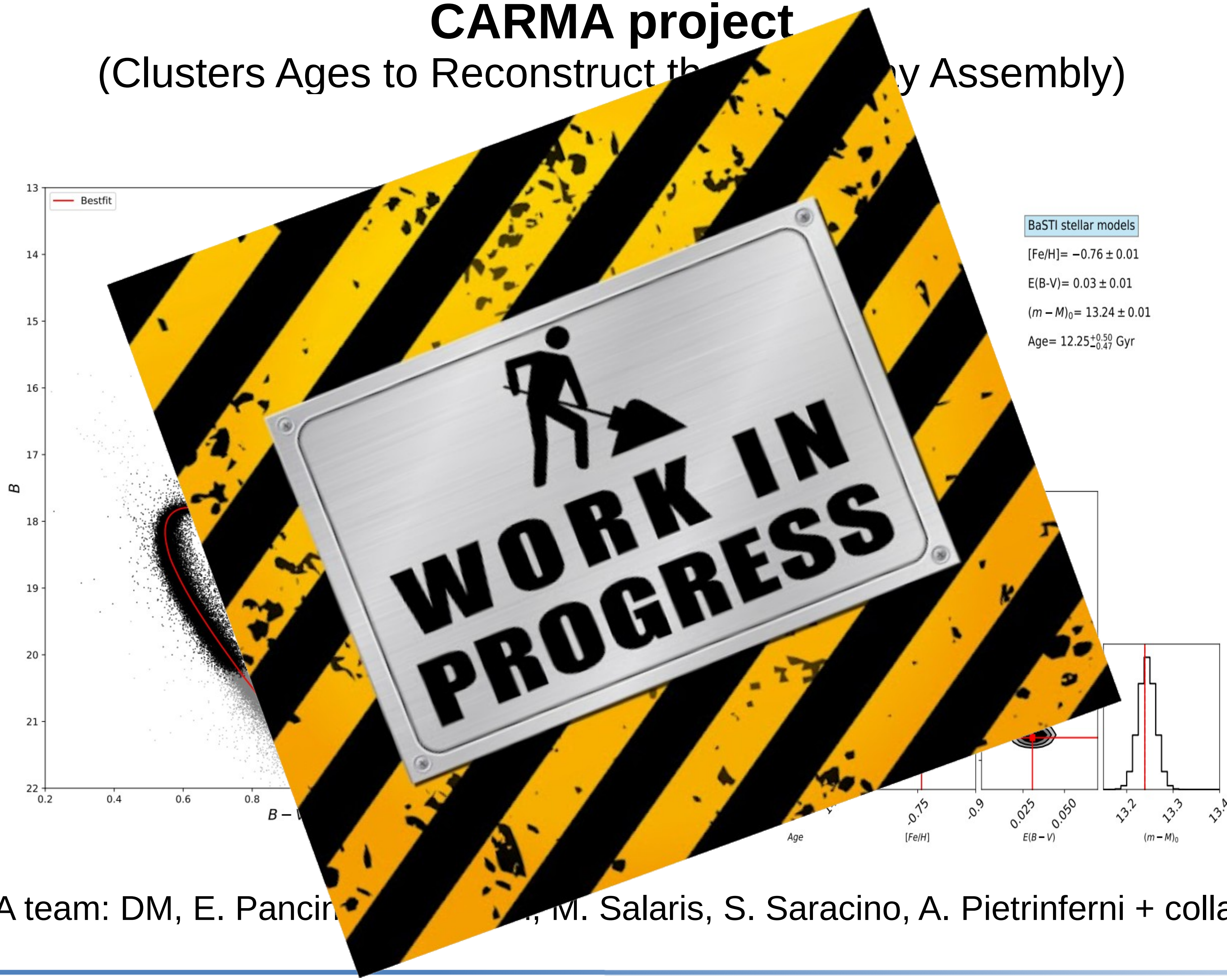

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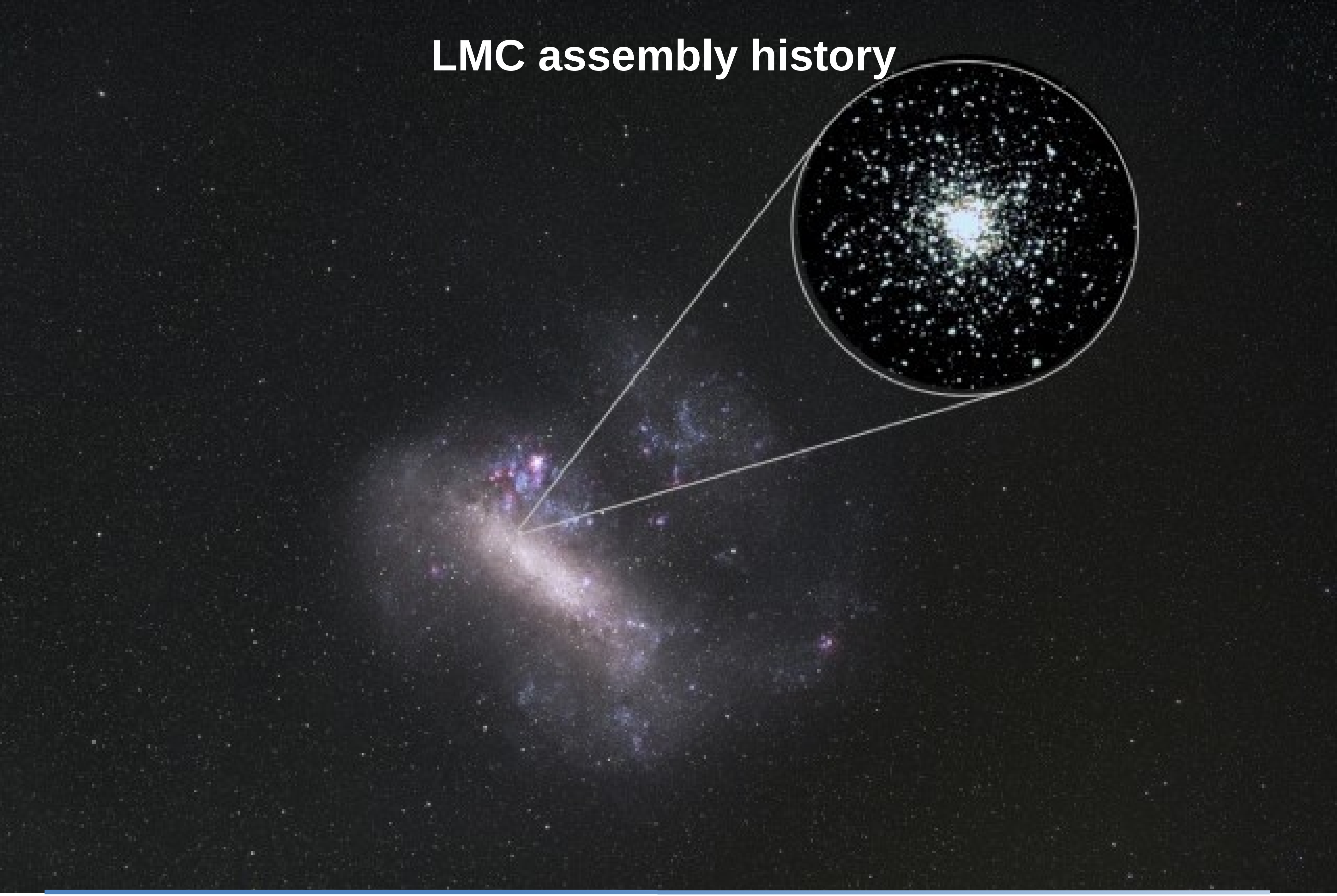
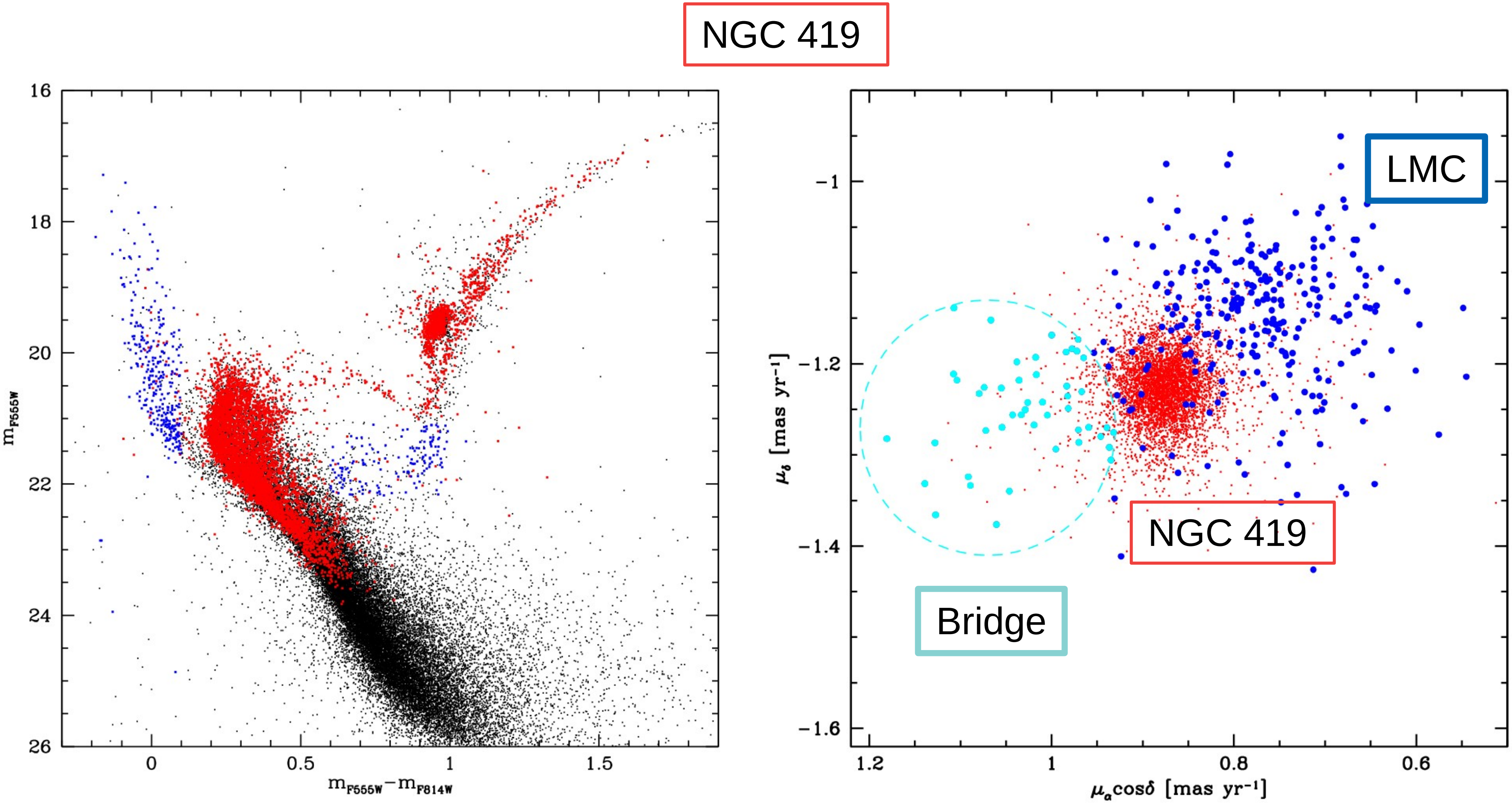
LMC assembly history



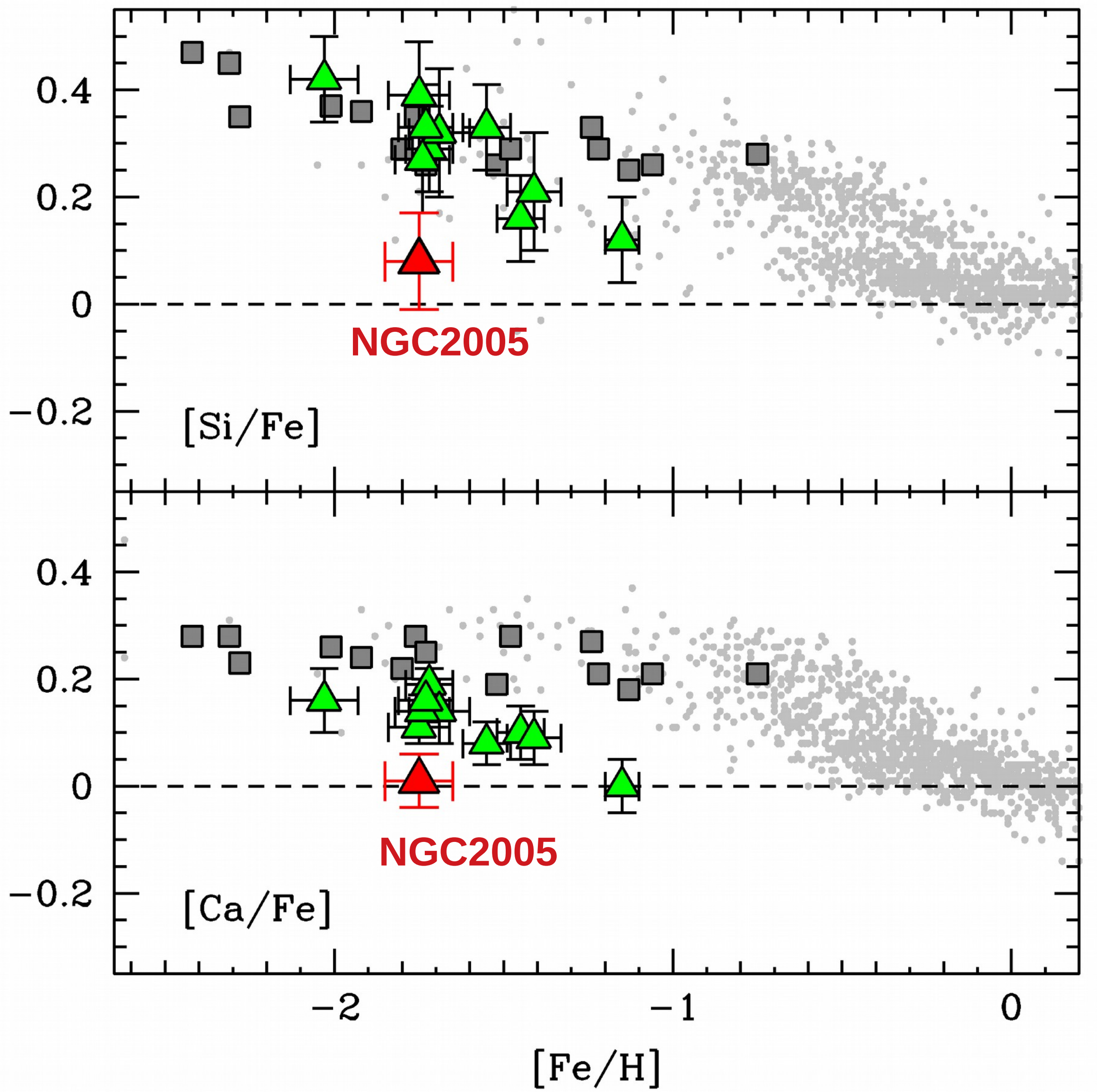
Dynamics out of reach



Massari et al. 2021

Chemistry

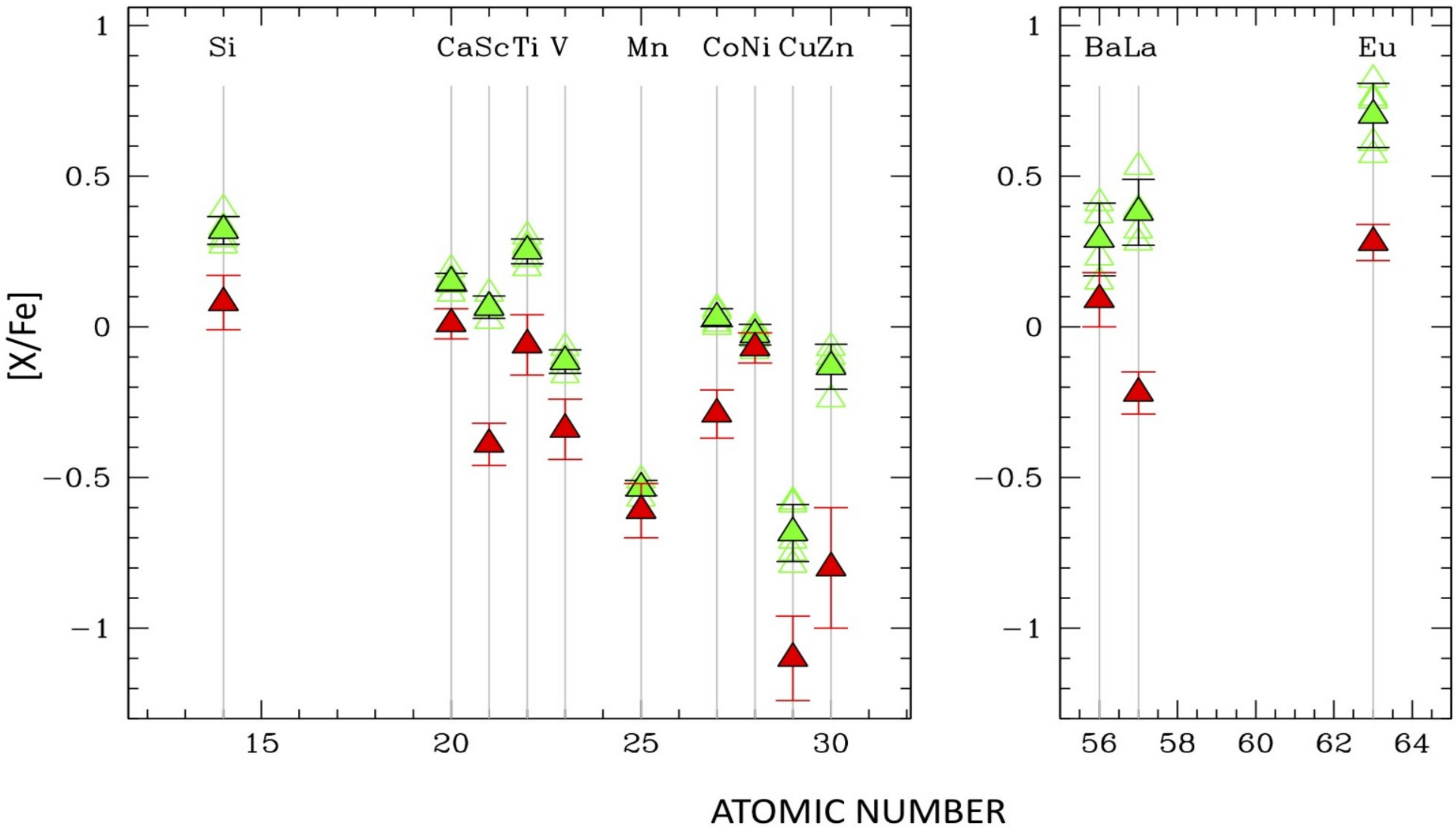
(Mucciarelli A., Massari D., et al. 2021, Nature Astronomy)



- 11 old LMC clusters
- 13 species
- high accuracy

Chemistry

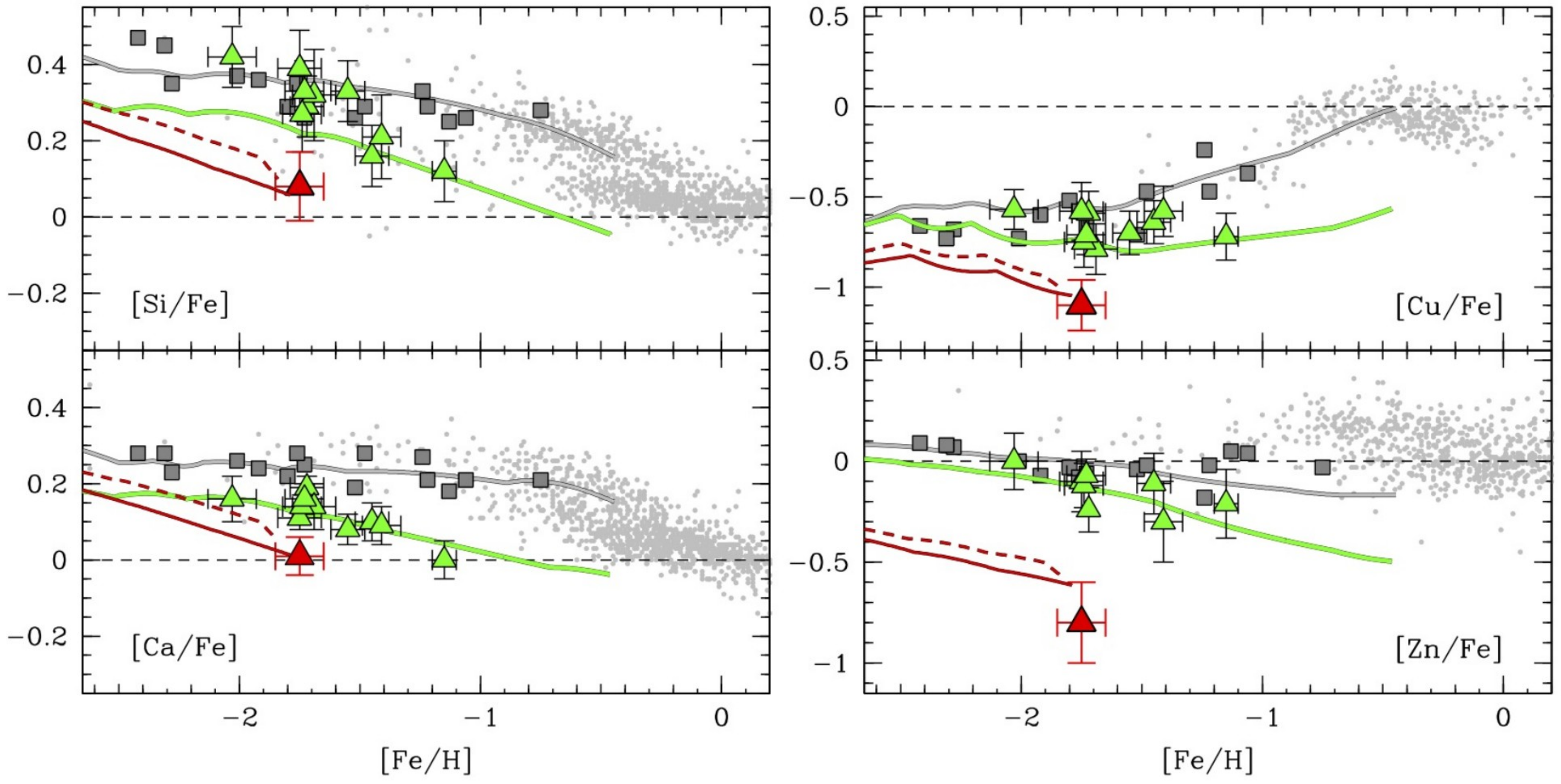
(Mucciarelli A., Massari D., et al. 2021, Nature Astronomy)



NGC2005 systematically lower abundances for all elements

Chemistry

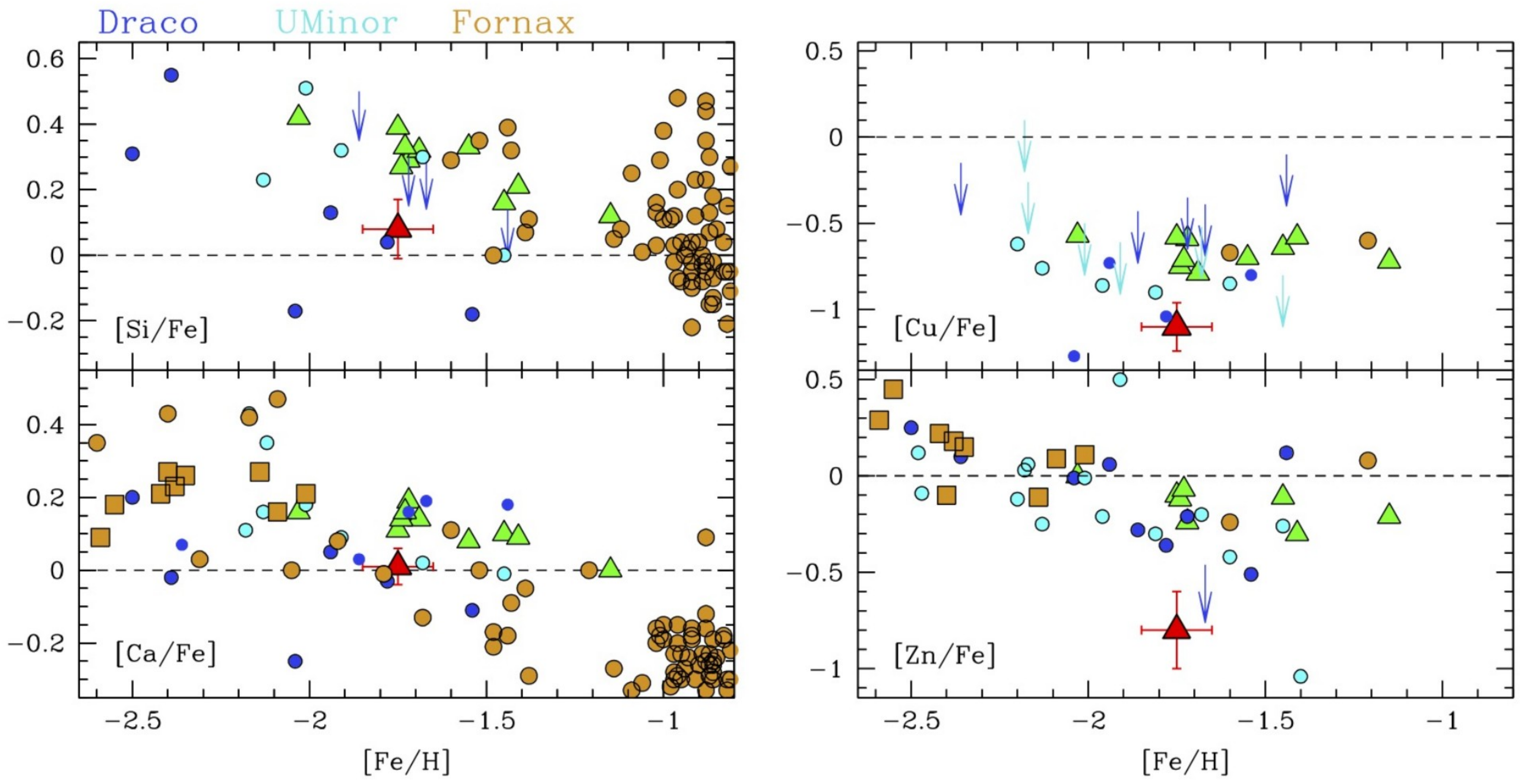
(Mucciarelli A., Massari D., et al. 2021, Nature Astronomy)



Best fit chemical evolutionary models: low SFR environment (<5x10^{-4} Msol/yr)

Chemistry

(Mucciarelli A., Massari D., et al. 2021, Nature Astronomy)



NGC2005 born in small dwarf galaxy accreted by LMC

Conclusions

- *Gaia* opened the path towards the complete reconstruction of the Milky Way assembly

- GCs are the ideal tracers to investigate regions that are too far away or too extincted for *Gaia*

- Urged to exploit their complete and accurate dynamics, age, chemistry, to characterise the complete Galactic assembly

- As a demonstration of GC effectiveness, discovery of past LMC accretion event

Gaia DR2, Gaia Collaboration+2018