The age of globular clusters as the missing piece to solve the puzzle of their origin

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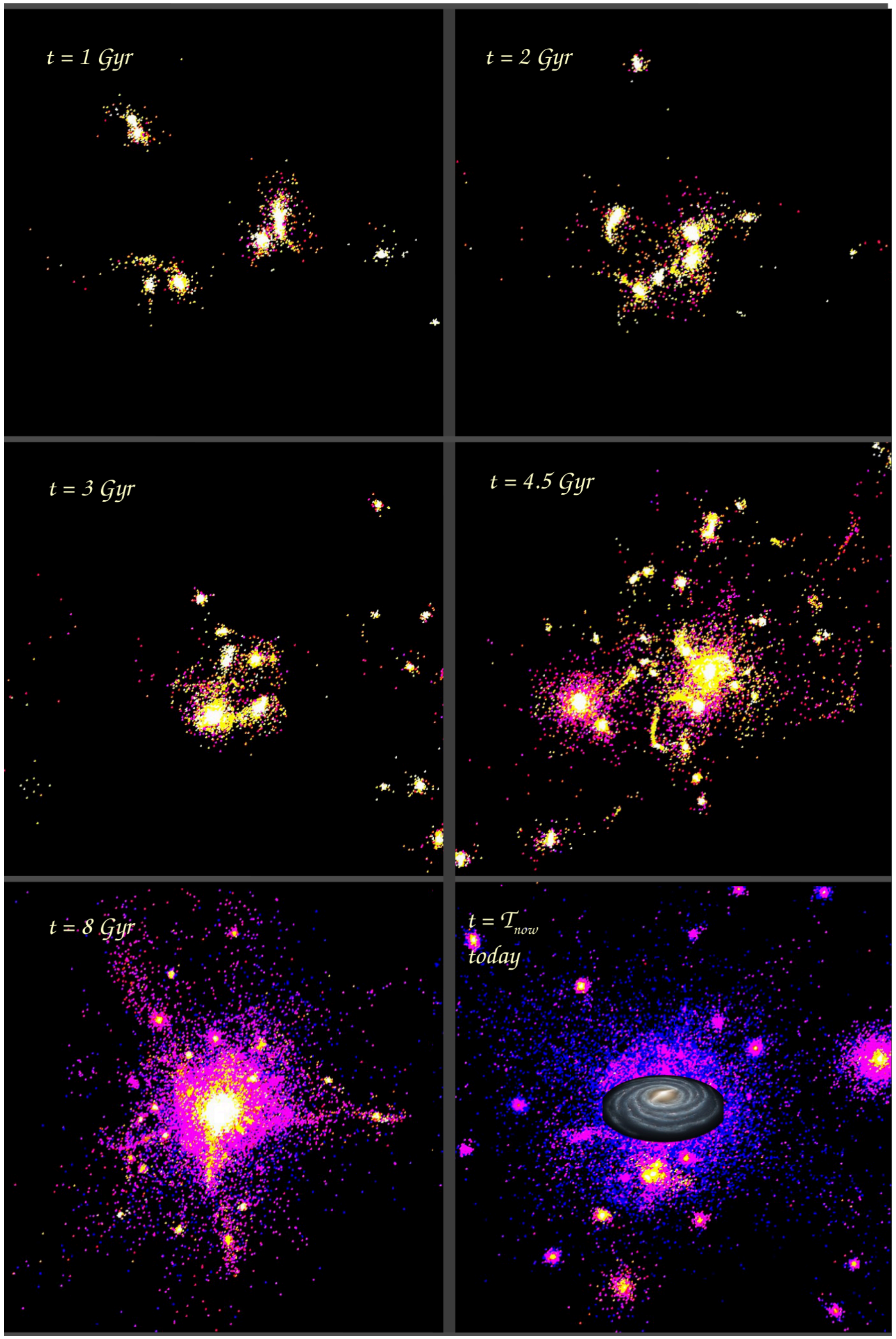
Main collaborators: M. Monelli, F. Aguado-Agelet, S. Cassisi, E. Ceccarelli, E. Pancino and the CARMA and MGCS collaborations

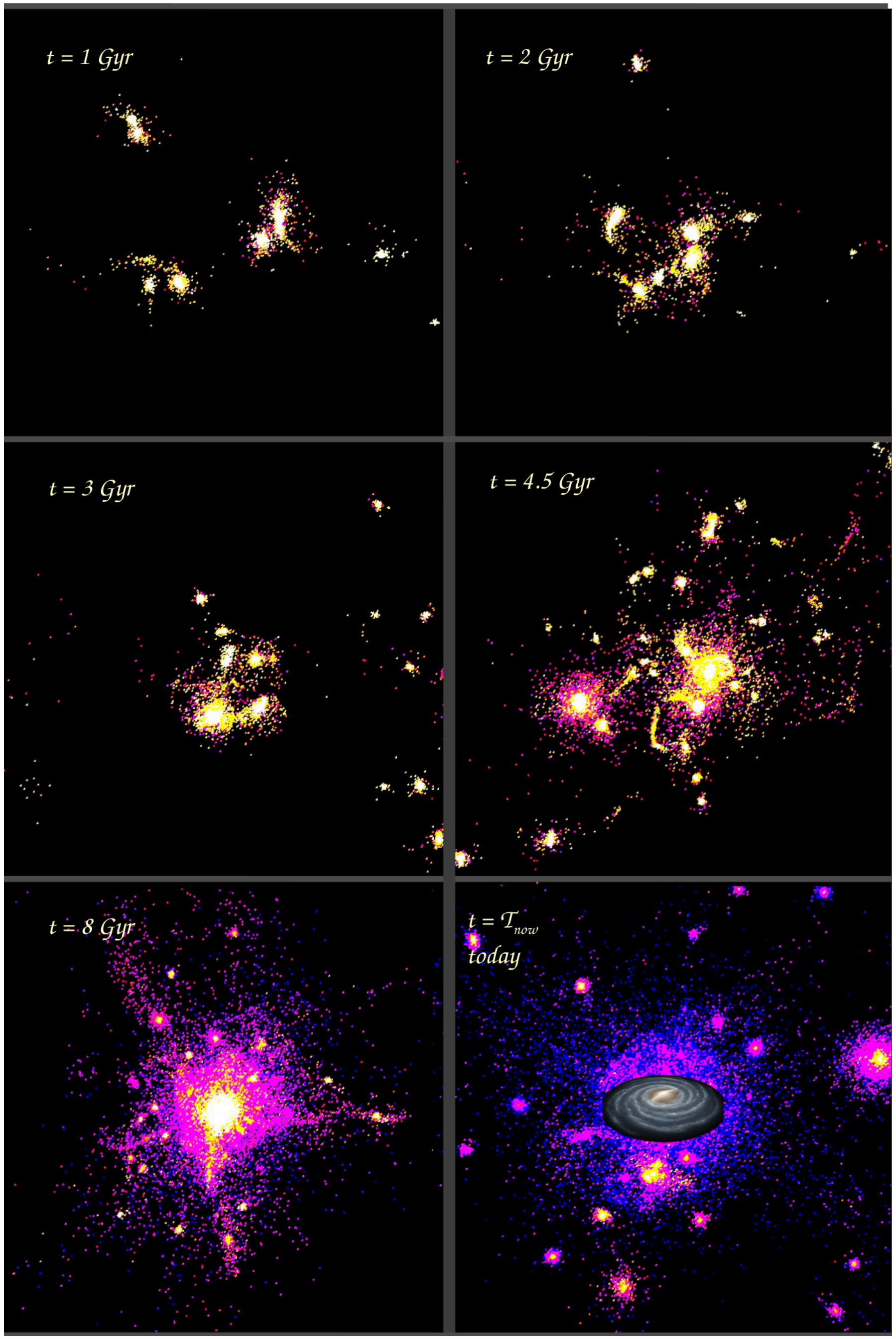
IAU Symposium 395 – November 18, 2024 – Paraty (Brazil)

Galactic archaeology with GCs: dynamics



Snapshots credits to J. Gardner

Galactic archaeology with GCs: dynamics



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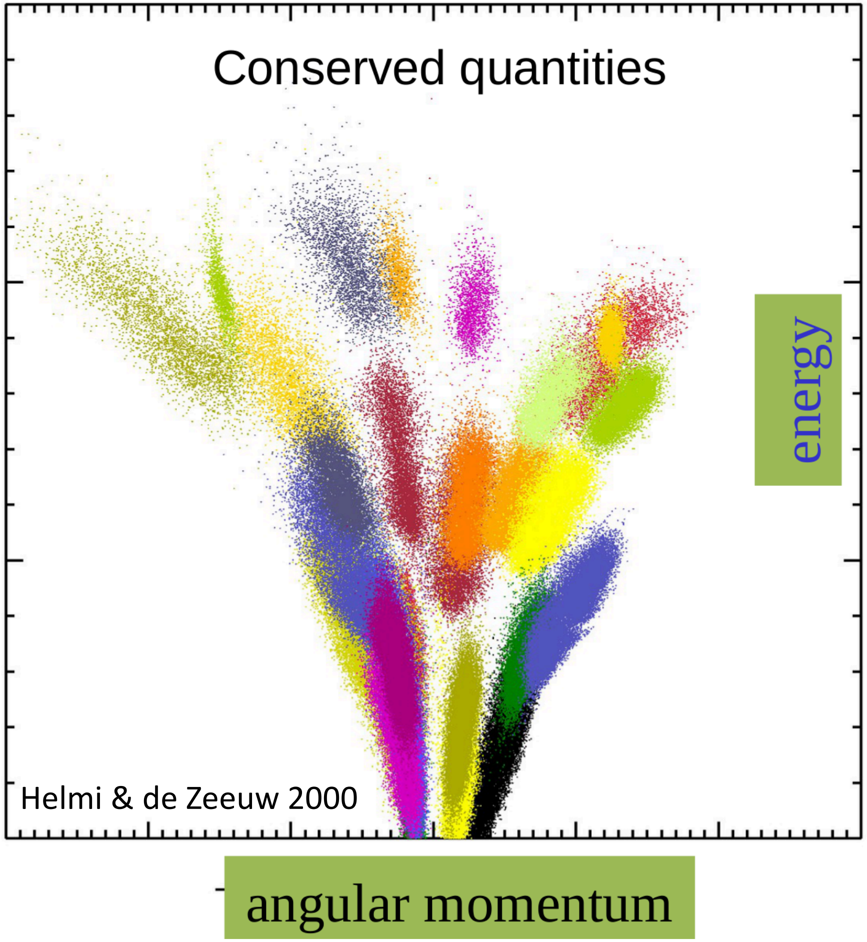
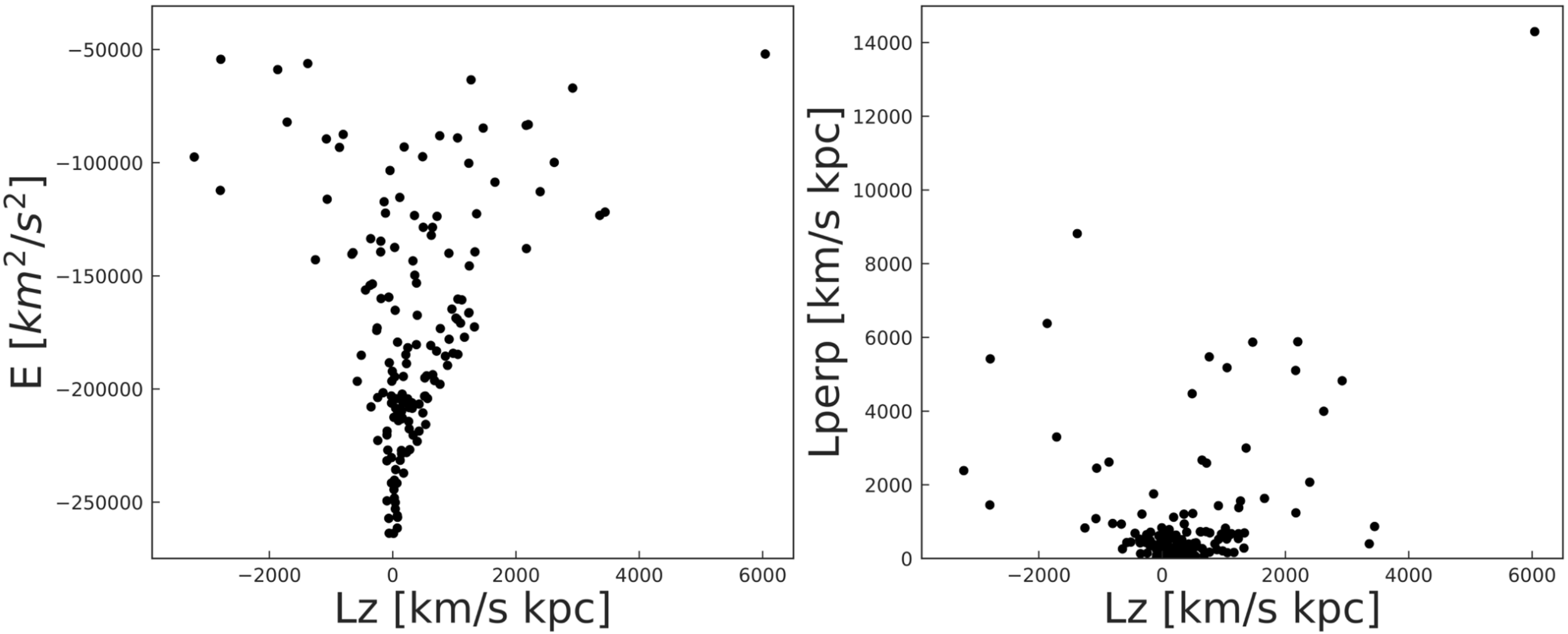
Integrals of motion



Six parameters of the phase space
+
MW gravitational potential

Dynamics of the MW GCs system

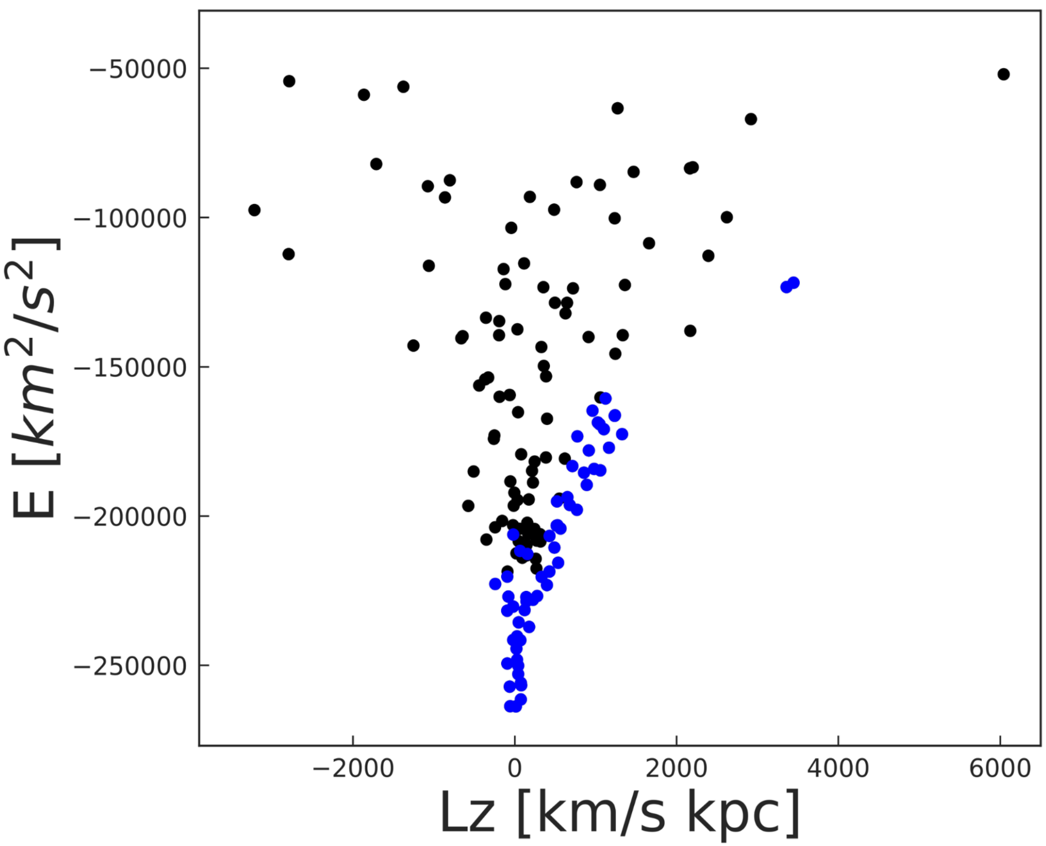
Integrals of motion



Massari et al. 2019

GCs and progenitor galaxies

Integrals of motion



In-situ GCs

Bulge = apo<3.6 kpc

Disk = zmax<5 kpc
Circ > 0.5

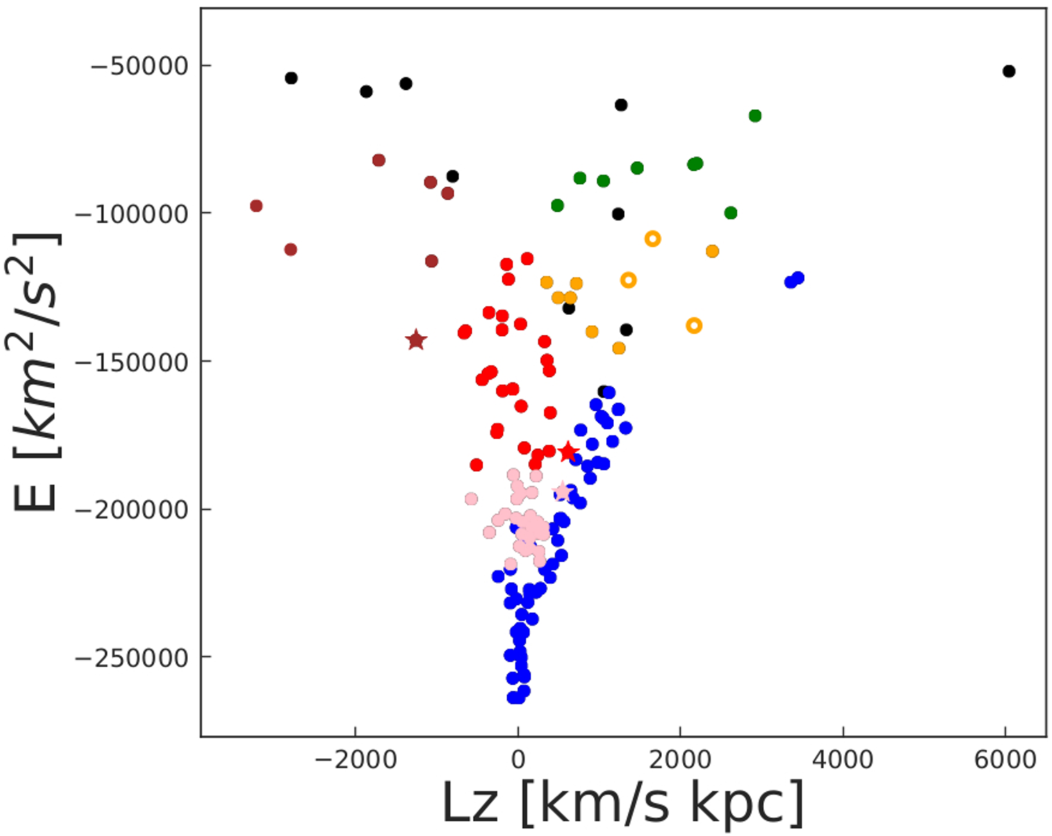
<u>About 50% of the MWGC system</u>

Consistent with simulations
(Qu+2017, Keller+20, Davison+20)

Massari et al. 2019

GCs and progenitor galaxies

Integrals of motion

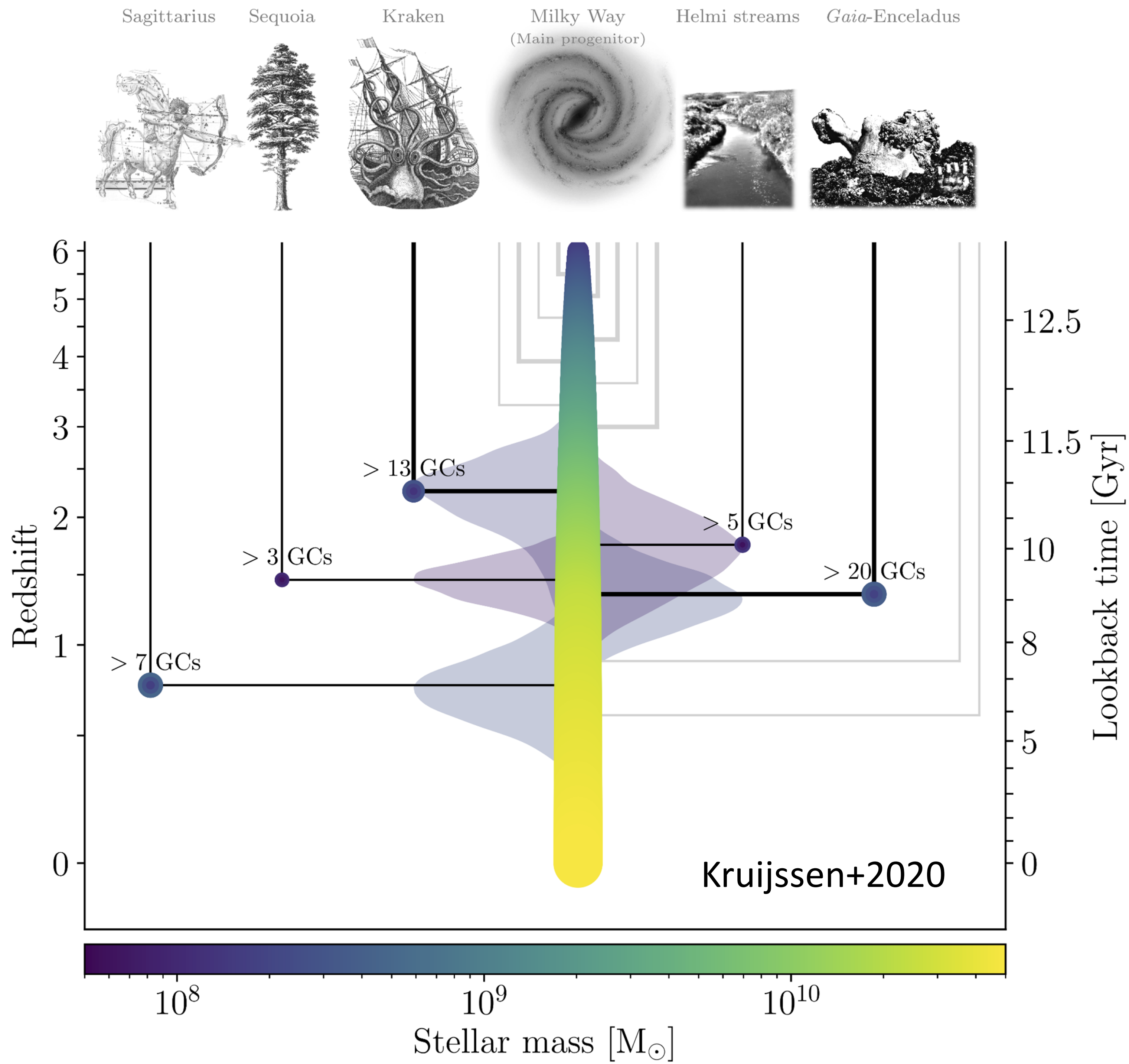


Associations to:

- Sagittarius
- Gaia-Sausage-Enceladus
- Helmi streams
- Sequoia
- Low-energy group – Kraken
- Smaller, unknown mergers

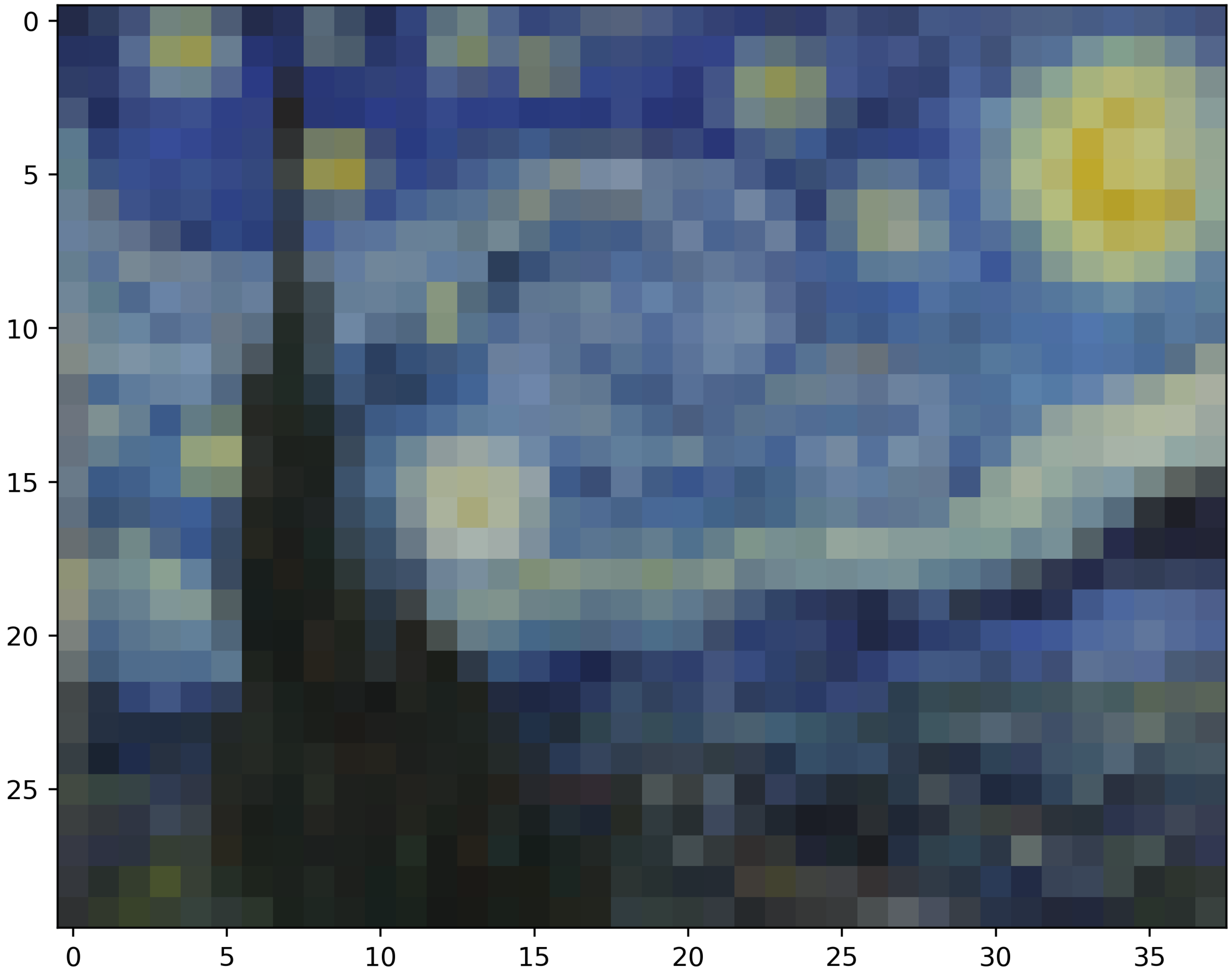
Massari et al. 2019

GCs based MW assembly history



Kruijssen+2020

GCs based MW assembly history



GCs based MW assembly history

GCs and progenitor galaxies

GC	Progenitor	GC	Progenitor	GC	Progenitor	GC	Progenitor
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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
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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 are uncertain

- Uncertainties in the measured kinematics

Improvements with Gaia DR3 (Callingham+22, Malhan+22)

GCs and progenitor galaxies

GC	Progenitor	GC	Progenitor	GC	Progenitor	GC	Progenitor
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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
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NGC 5904	H99	Terzan 4	M-B	BH 261	M-D	FSR1758	Seq

Associations are uncertain

- Uncertainties in the measured kinematics
- Overlapping dynamical properties (Koppelman+2020)
- High-order dynamical effects (e.g., Belokurov+2022, Chen & Gnedin 2023)

GCs and progenitor galaxies

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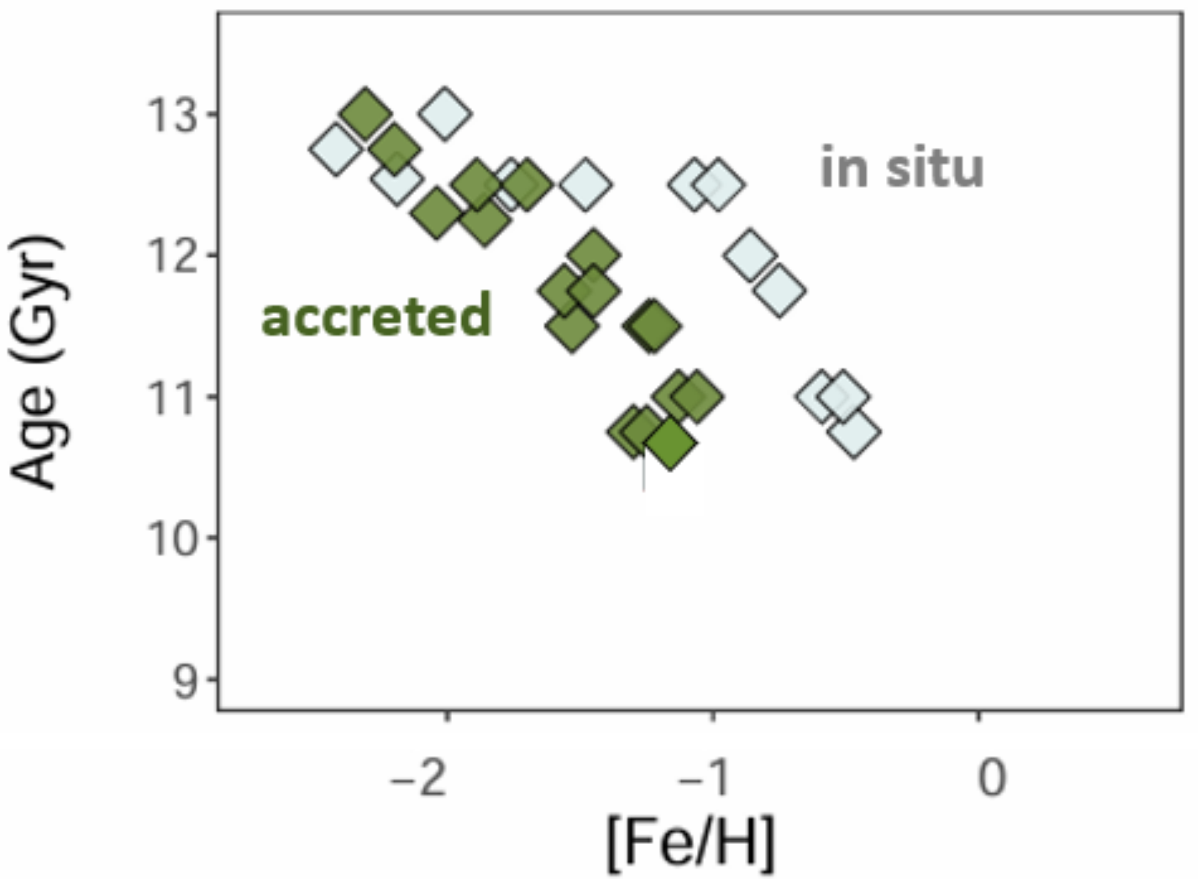
Associations to be refined based on conserved quantities:

Age-metallicity relation

Galactic archaeology with GCs: AMR

Marin-Franch+09, Forbes&Bridges2010, Leaman+13

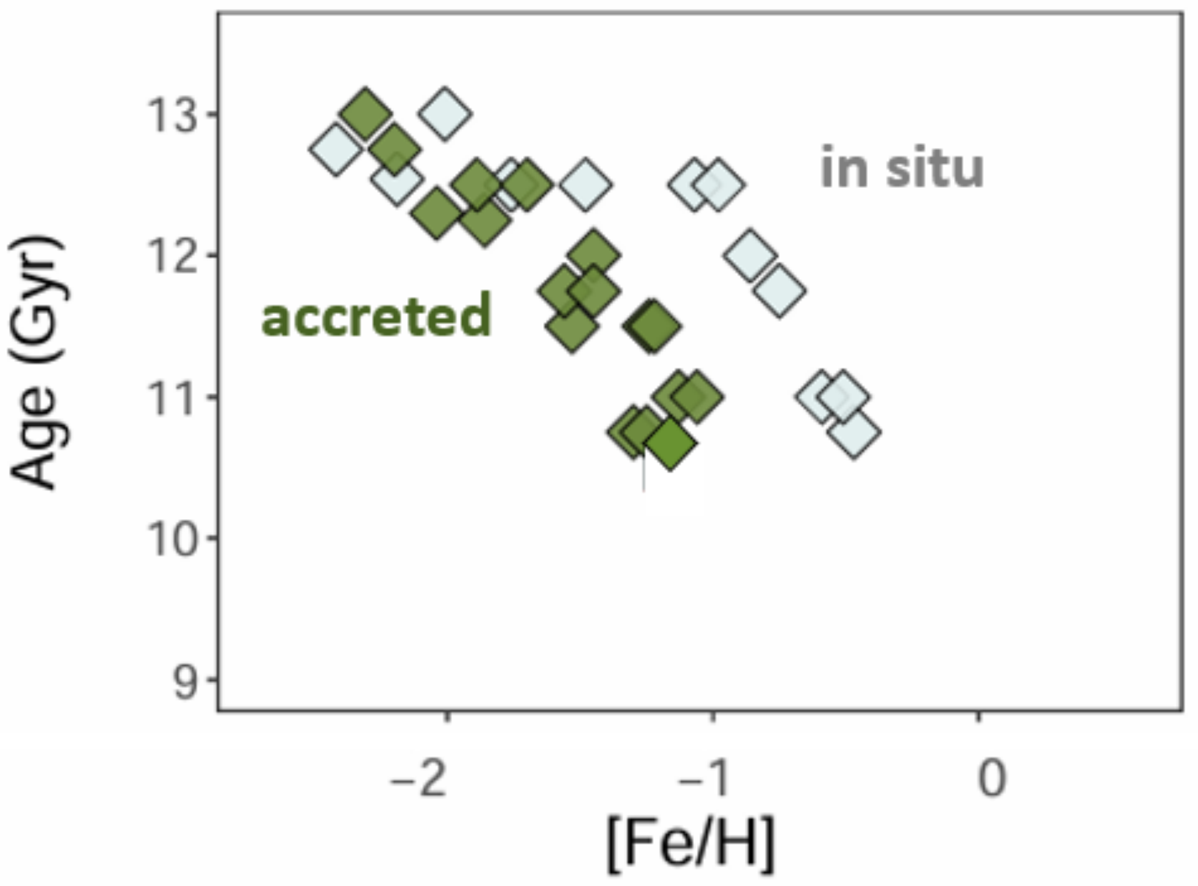


Current age estimates:

✔ Separating in-situ from accreted at [Fe/H]>-1.5

Galactic archaeology with GCs: AMR

Marin-Franch+09, Forbes&Bridges2010, Leaman+13



Current age estimates:

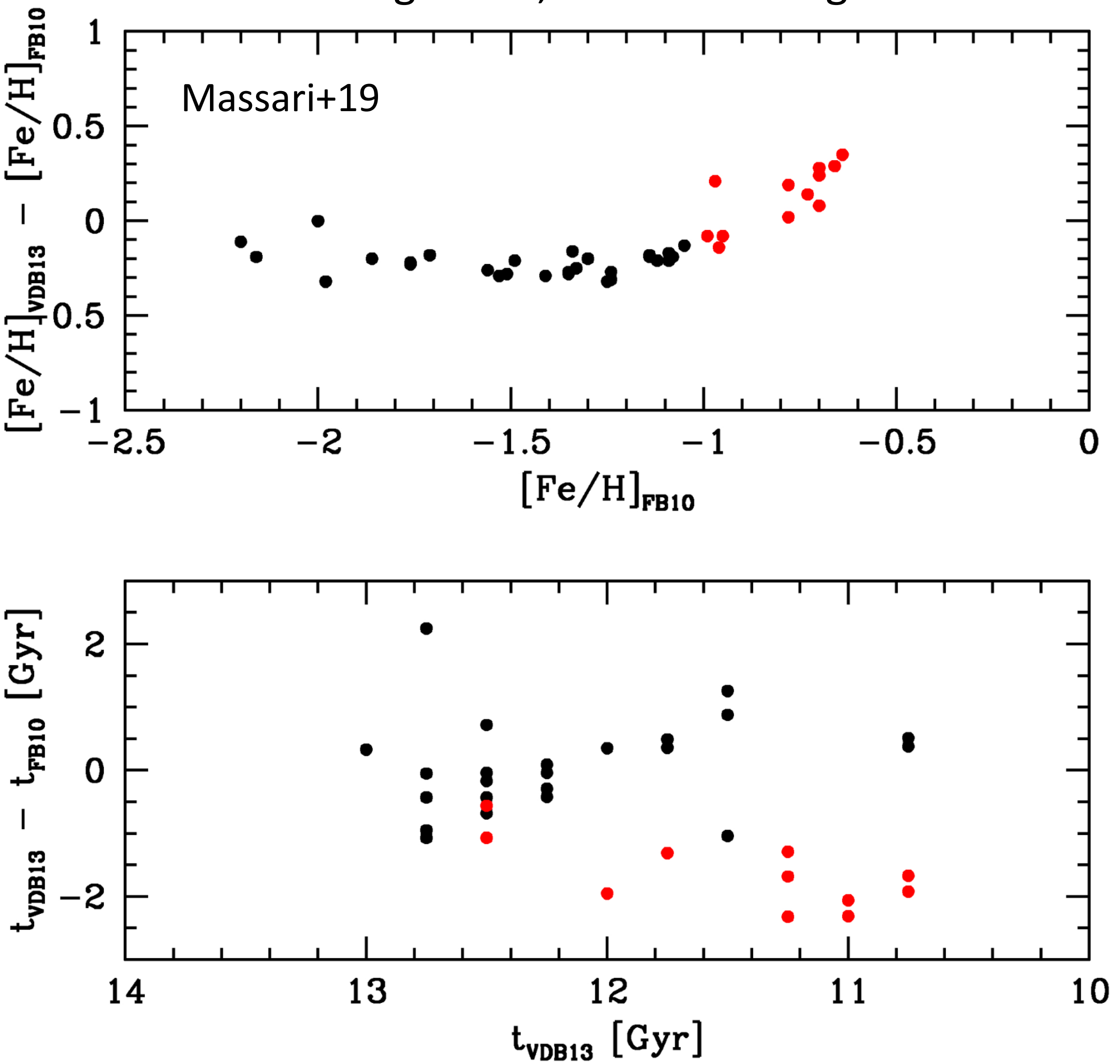
Separating in-situ from accreted at [Fe/H]>-1.5

Separating in-situ from accreted at [Fe/H]<-1.5

Separating different progenitors

Current limitations on age measurements

Vandenberg+2013, Forbes & Bridges 2010

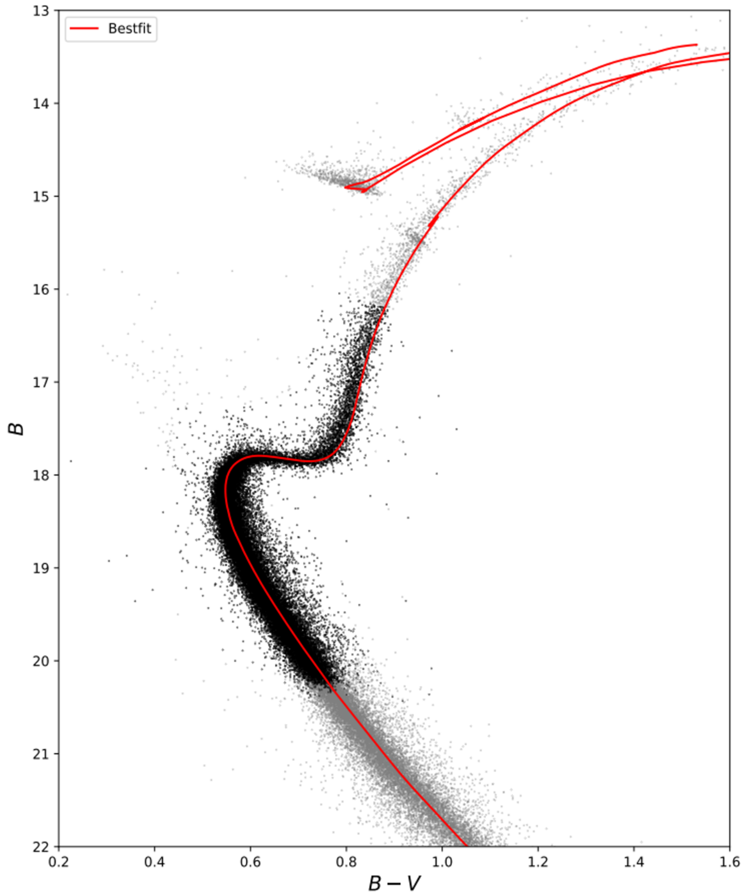


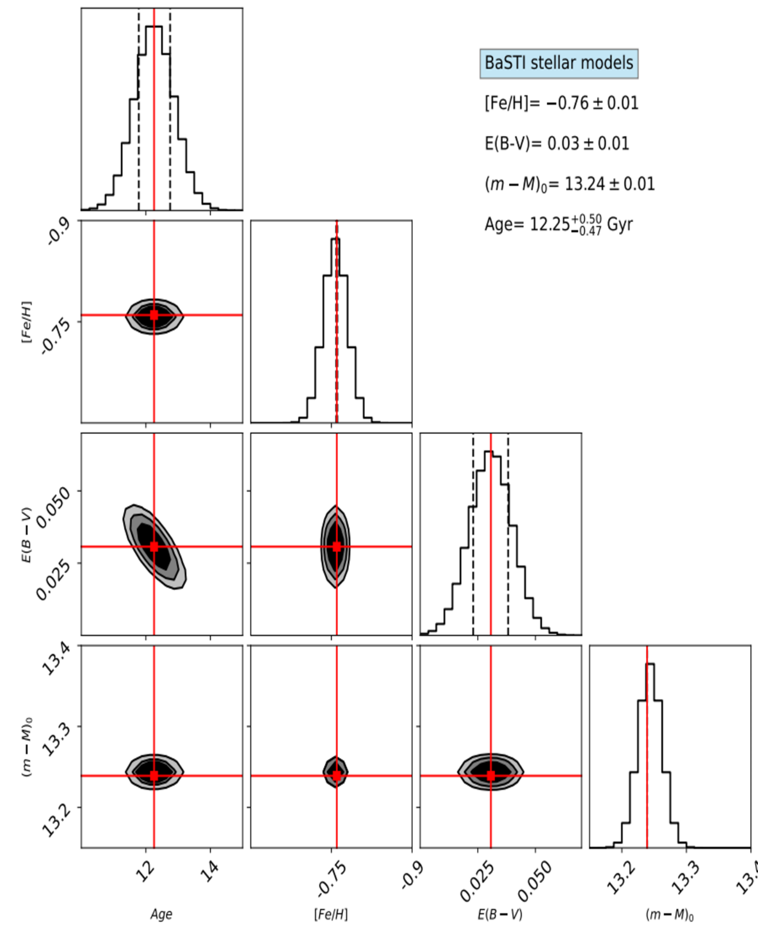
Different methods,
theoretical models
photometric systems

Can lead to systematics
as large as 2 Gyr

CARMA project

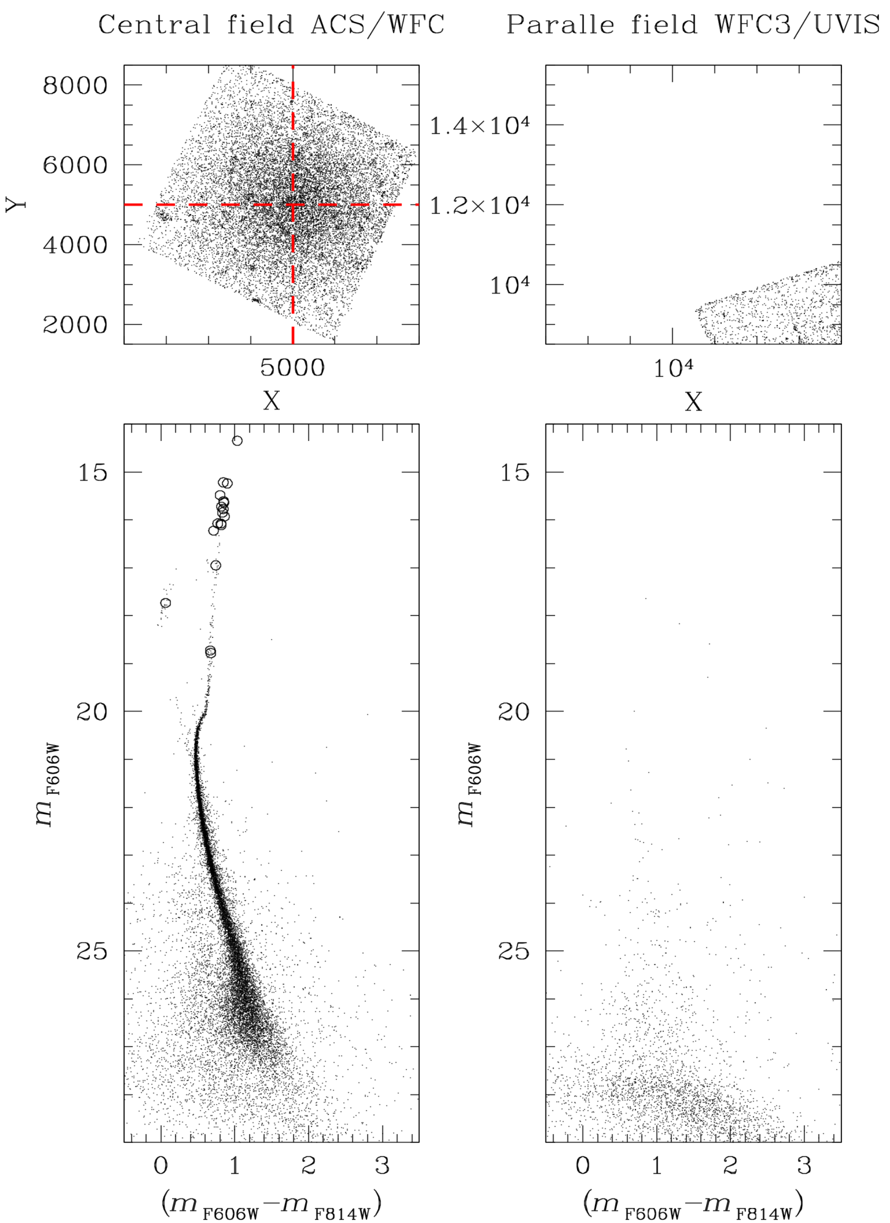
(Clusters Ages to Reconstruct the Milky way Assembly)





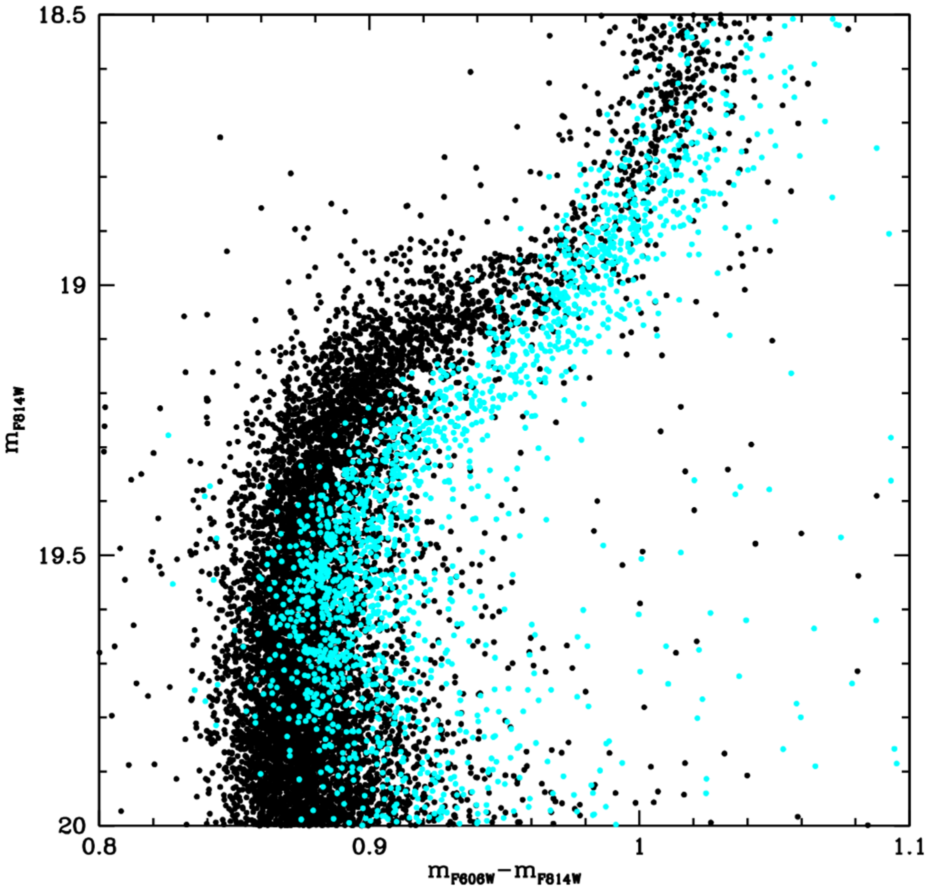
State-of-the-art BaSTI isochrones, homogeneous photometry, complete sample of MWGCs

CARMA project: homogeneous photometry



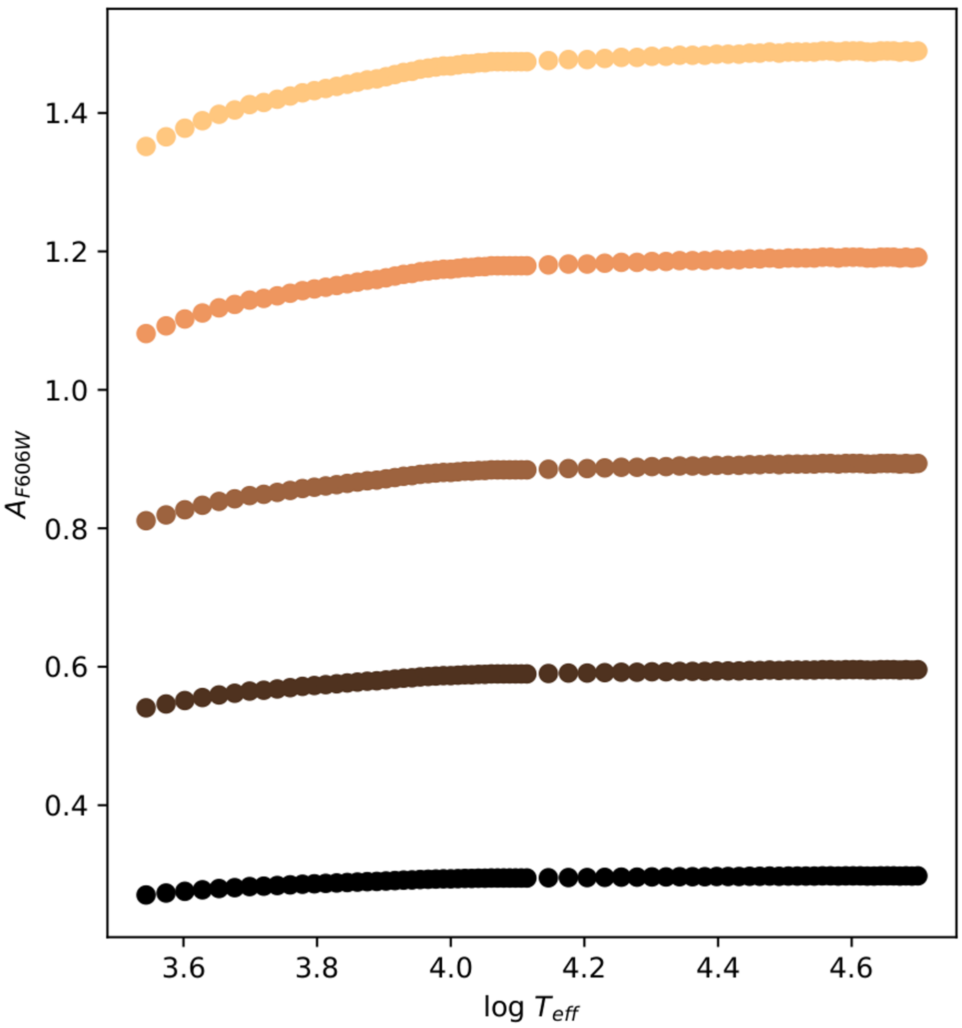
- Hubble Space Telescope
- F606W and F814W (no multi-pops issue)
- **Missing GC Survey**: HST Treasury Programme (PI: Massari) to add all the 34 GCs never observed with HST

CARMA project: homogeneous photometry



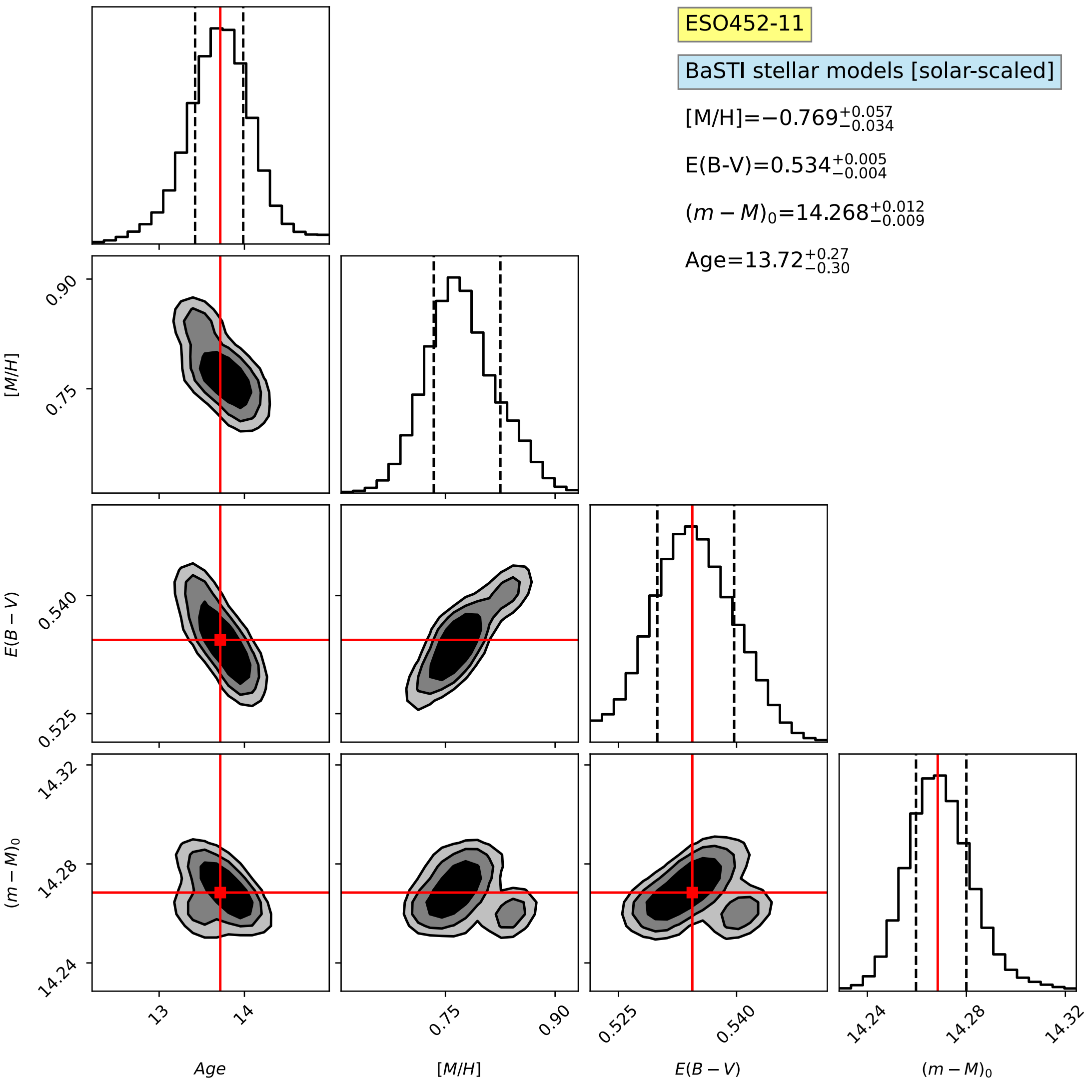
- Hubble Space Telescope
- F606W and F814W
- **Missing GC Survey**: HST Treasury Programme (PI: Massari) to add all the 34 GCs never observed with HST
- Proper motion based membership selection
- Differential reddening correction
- Exclusion of chemically peculiar stars (either spatially or with additional UV bands)

CARMA project: homogeneous models



- Isochrones from the BaSTI database
- State-of-the-art models including diffusion (Hidalgo+2018)
- Grid: 6 < age < 14 Gyr (0.1 Gyr step)
  -2.5 < [M/H] < 0 (0.01 dex step)
- Temperature-dependent reddening correction E(B-V) > 0.1 mag

CARMA project: homogeneous method



- Isochrone fitting code based on Saracino+19
- Parallelised
- MCMC approach to derive
  Age
  Distance
  E(B-V)
  [M/H]

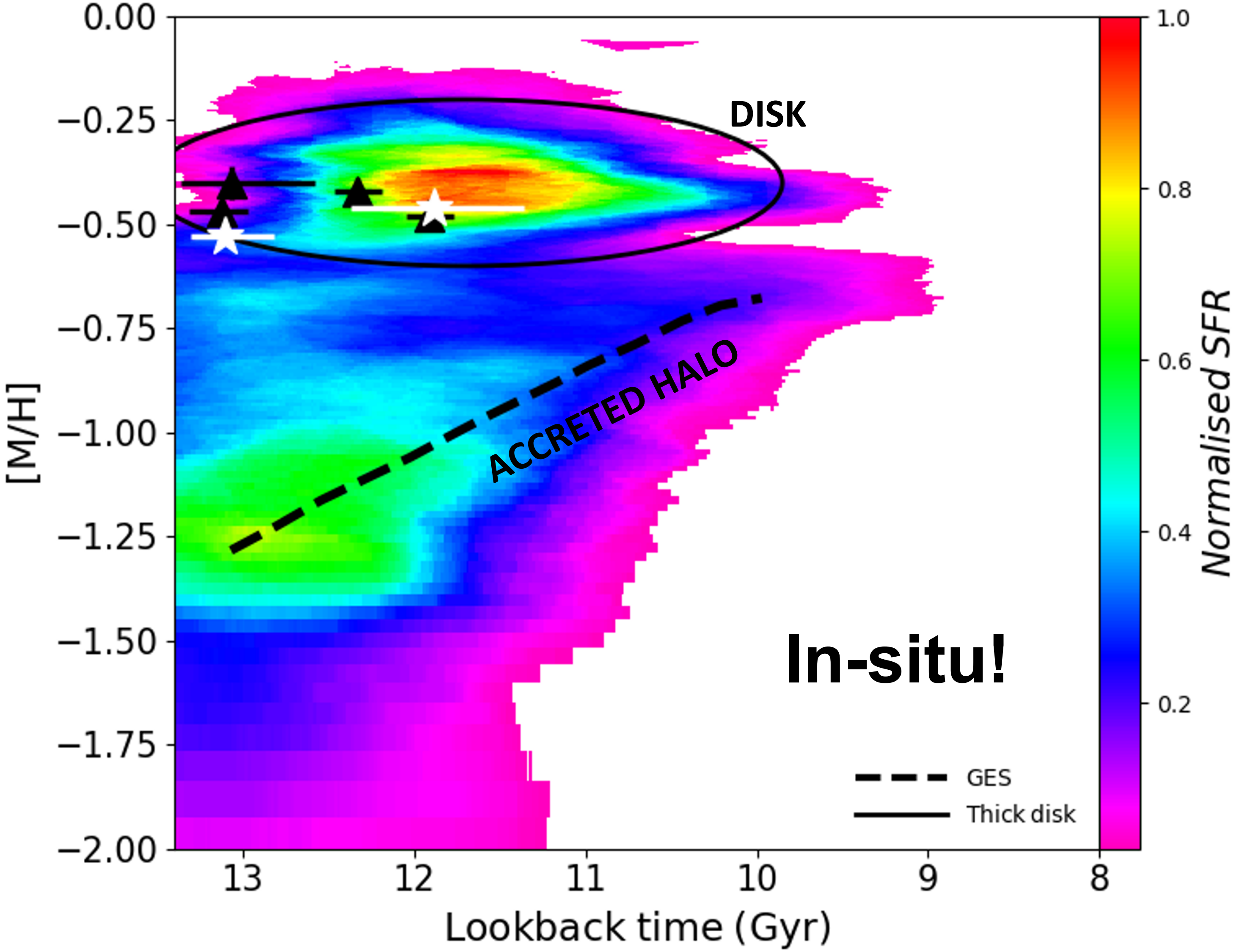
CARMA I: NGC6388 and NGC6441
(Massari et al. 2023)

	Dynamics		Chemistry	
	in situ	accreted	in situ	accreted
NGC6388	Massari+19* Forbes 2020 Callingham+21		Carretta & Bragaglia 2022	Minelli+21, Horta+20
NGC6441	Forbes 2020 Callingham+21	Massari+19*	Carretta & Bragaglia 2022	Minelli+21

Control sample at [Fe/H]=-0.5: NGC5927, NGC6304, NGC6352, NGC6496

If accreted → 2 Gyr younger than control sample

CARMA I: NGC6388 and NGC6441
(Massari et al. 2023)



Field star selection:

R < 1 kpc,
|Z| < 3.5 kpc
v_t > 200 km/s

Gallart+24

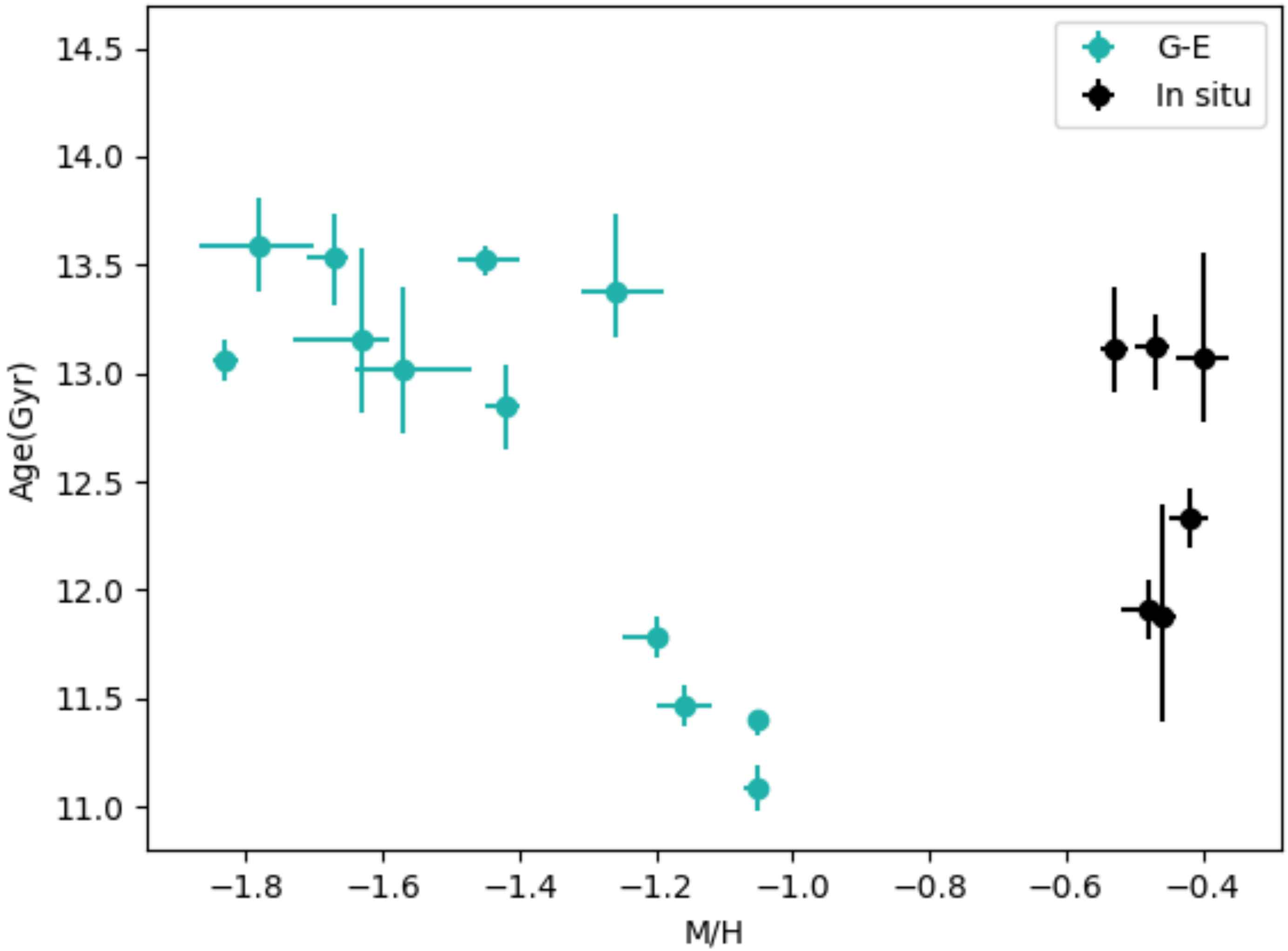
CARMA II: GSE GCs
(Aguado-Agelet et al. in prep.)

13 GC with photometry in F606W and F814W

Differential reddening corrected

Chromosome maps to get rid of SG stars

CARMA II: GSE GCs
(Aguado-Agelet et al. in prep.)

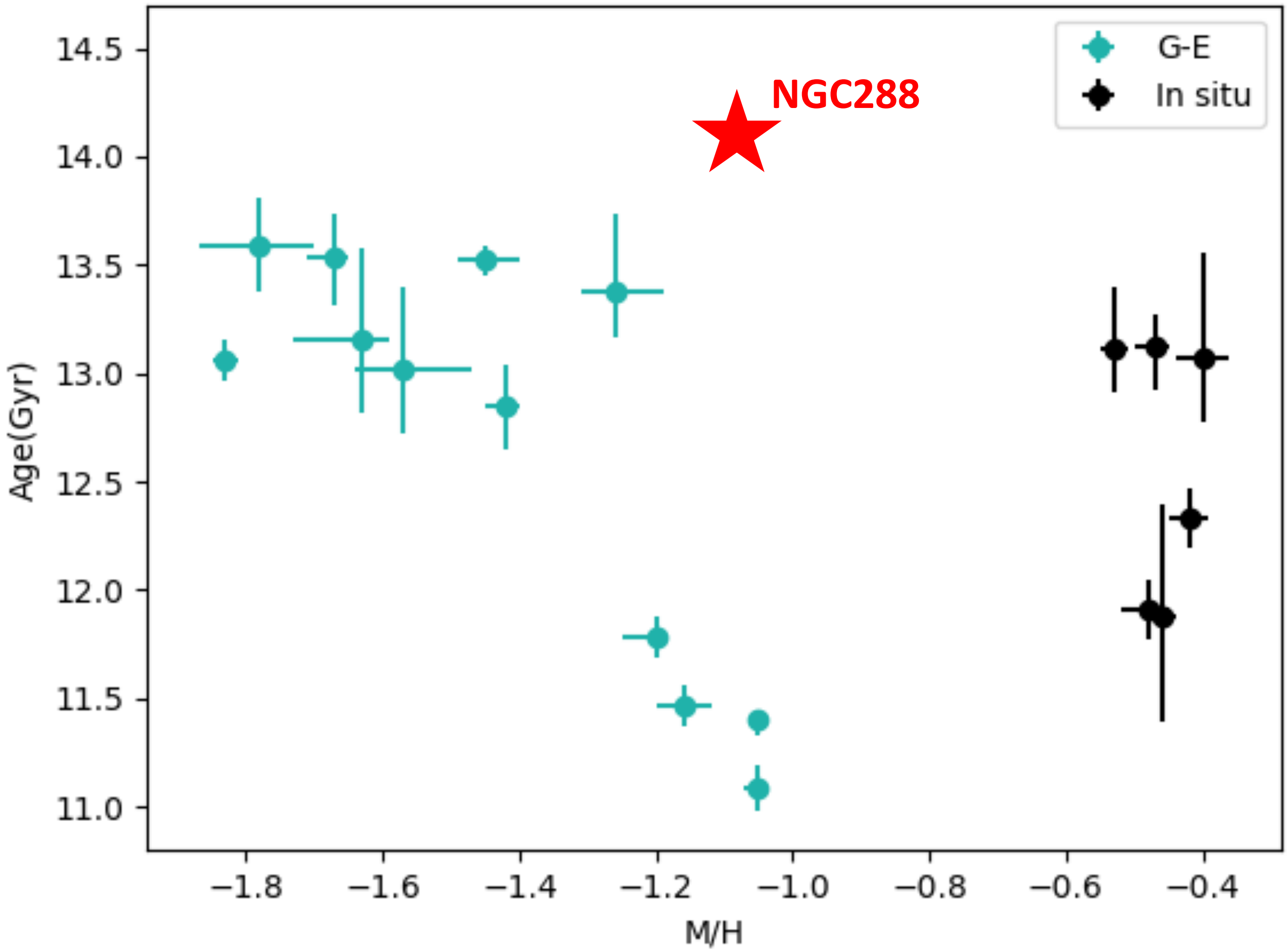


Clear difference wrt in-situ

Very tight AMR

Evidence for two bursts
Of GC formation?

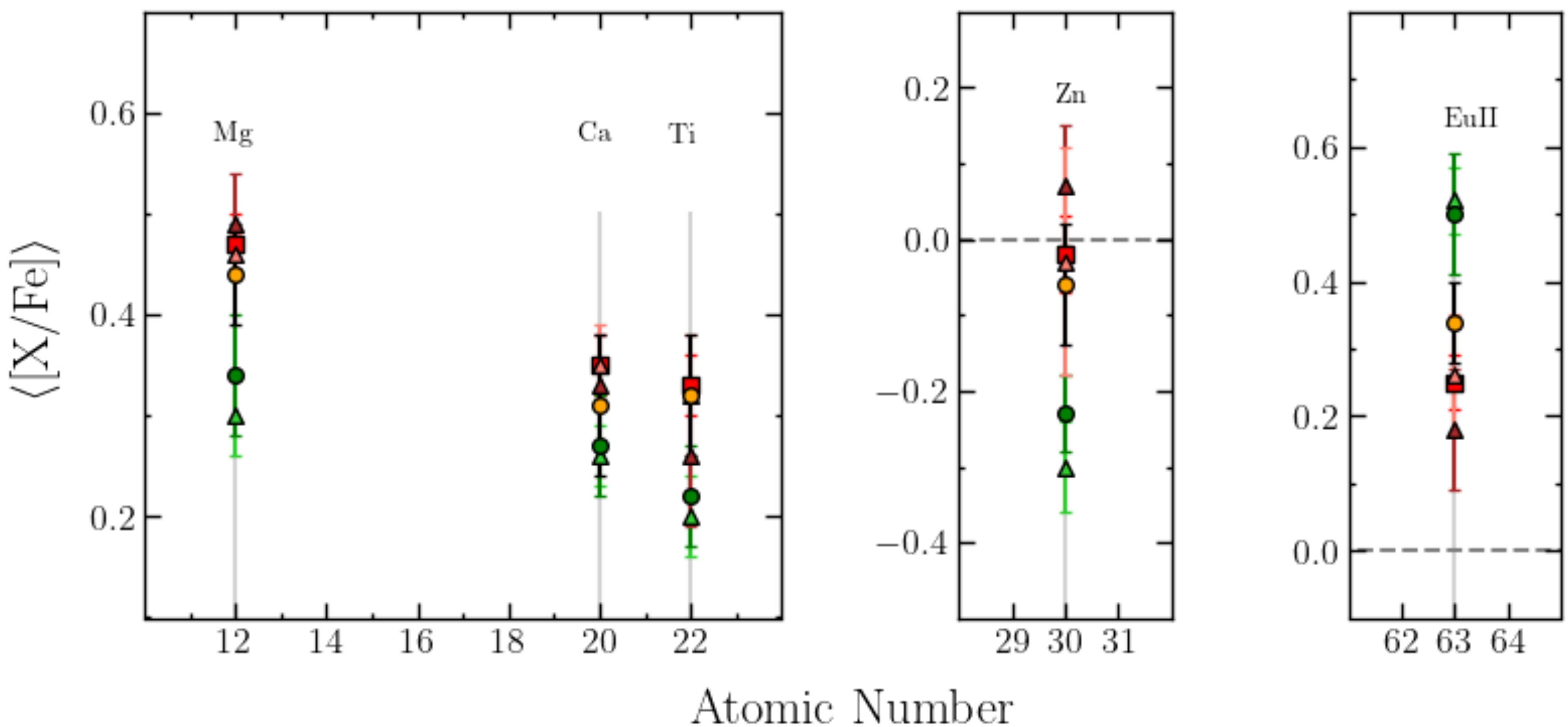
CARMA III: the first Splashed GC



>2.5 Gyr older than
Other GSE GCS
at [Fe/H]=-1.1

See also Green & Norris 1990
Bellazzini+2001
Gratton+2010

CARMA III: the first Splashed GC
(Ceccarelli et al. 2024b)



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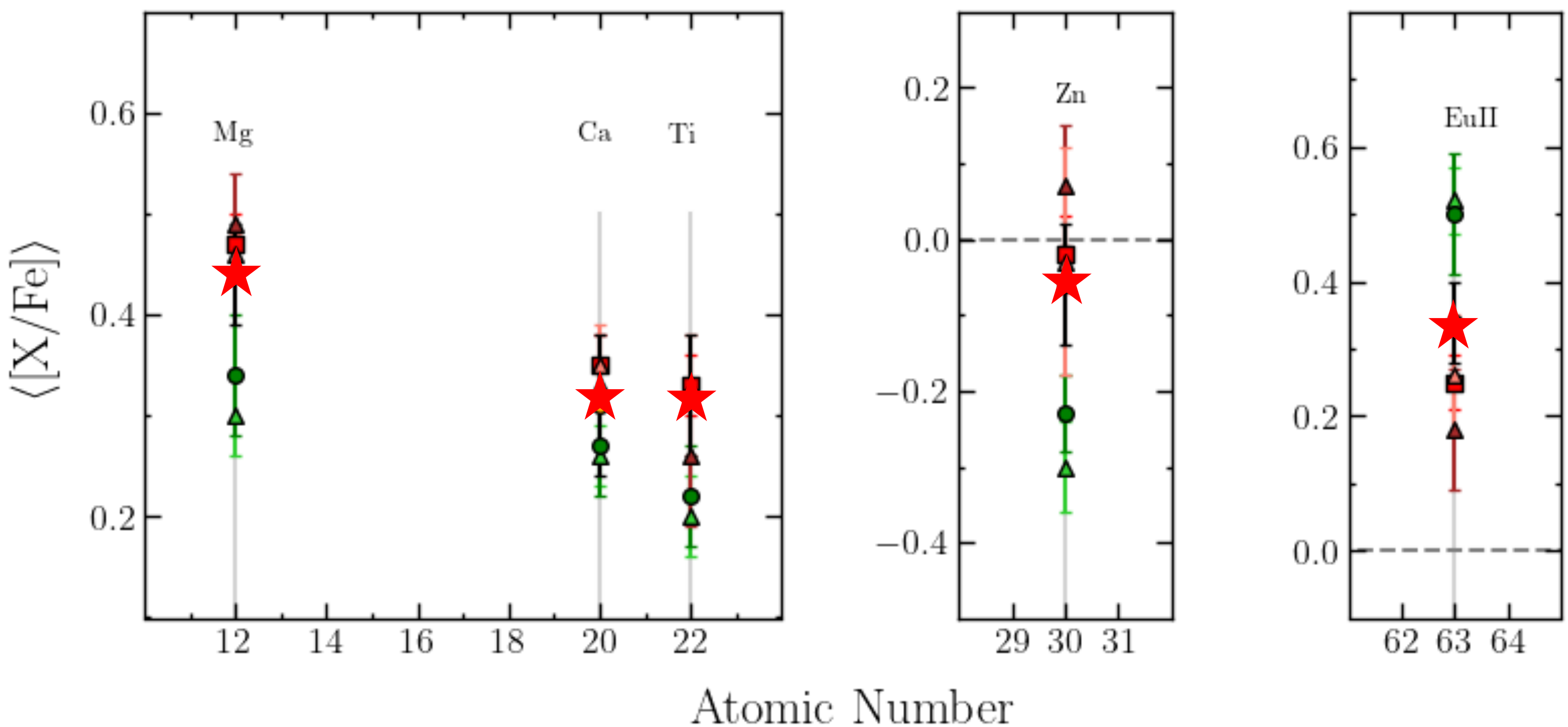


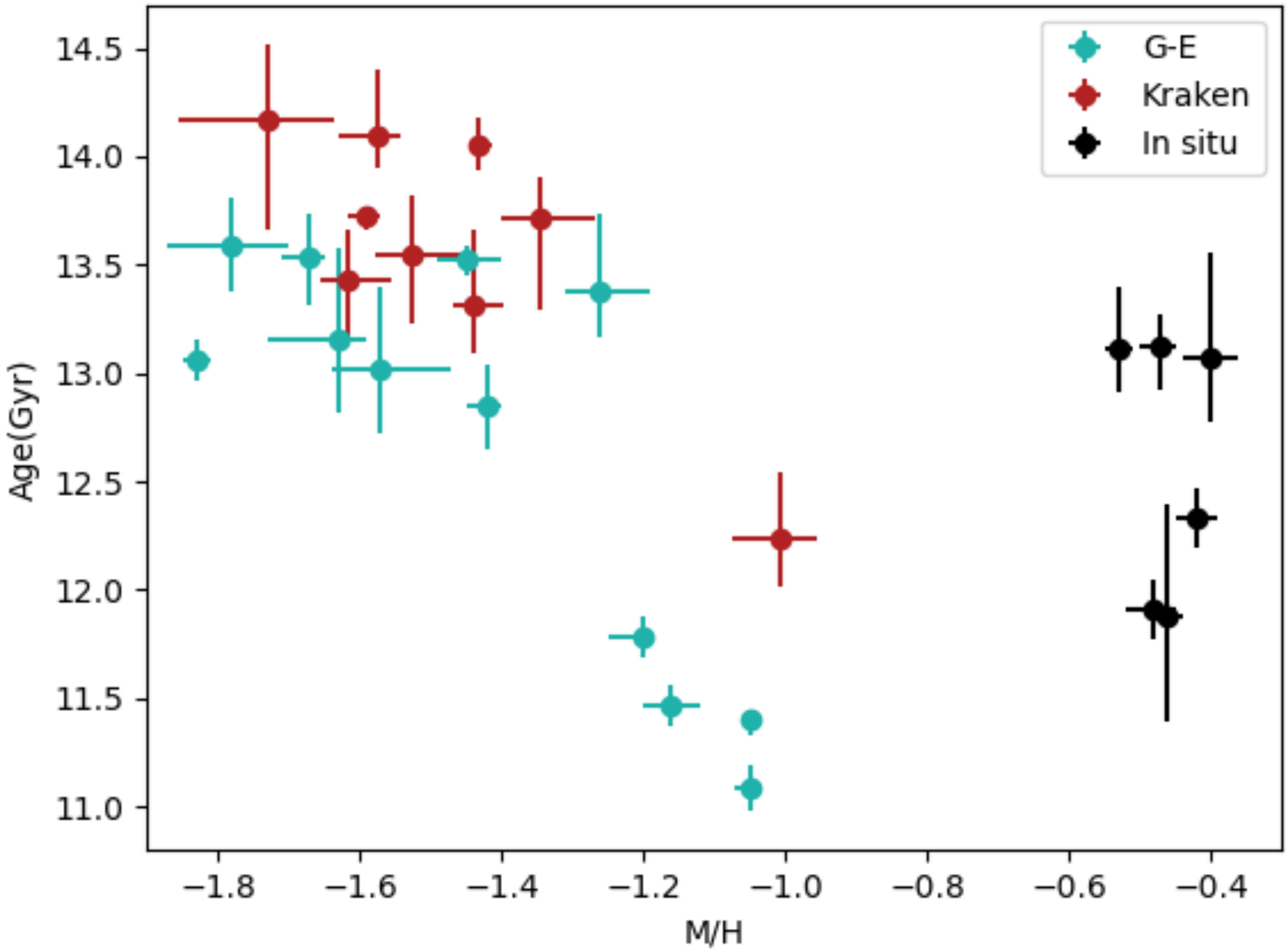
CARMA IV: Kraken GC
(Zerbinati et al. in prep.)

Can we tell apart AMRs from different progenitors?

The second most numerous AMR is Kraken's

11 GCs – analysis ongoing

CARMA IV: Kraken GC
(Zerbinati et al. in prep.)



Clearly different AMR compared to GSE

- Add more metal-rich Kraken GCs
- Compare with metal-poor in-situ

Conclusions

- GCs are powerful tracers of the Milky Way assembly

- GCs dynamics is not enough - **Age** is an efficient dimension to add

- **CARMA** aims at providing very precise relative ages for the complete sample of MW GCs

- Prelimiary results: precision high enough to **separate AMR from different progenitors**, even at low [Fe/H]

Gaia DR2, Gaia Collaboration+2018