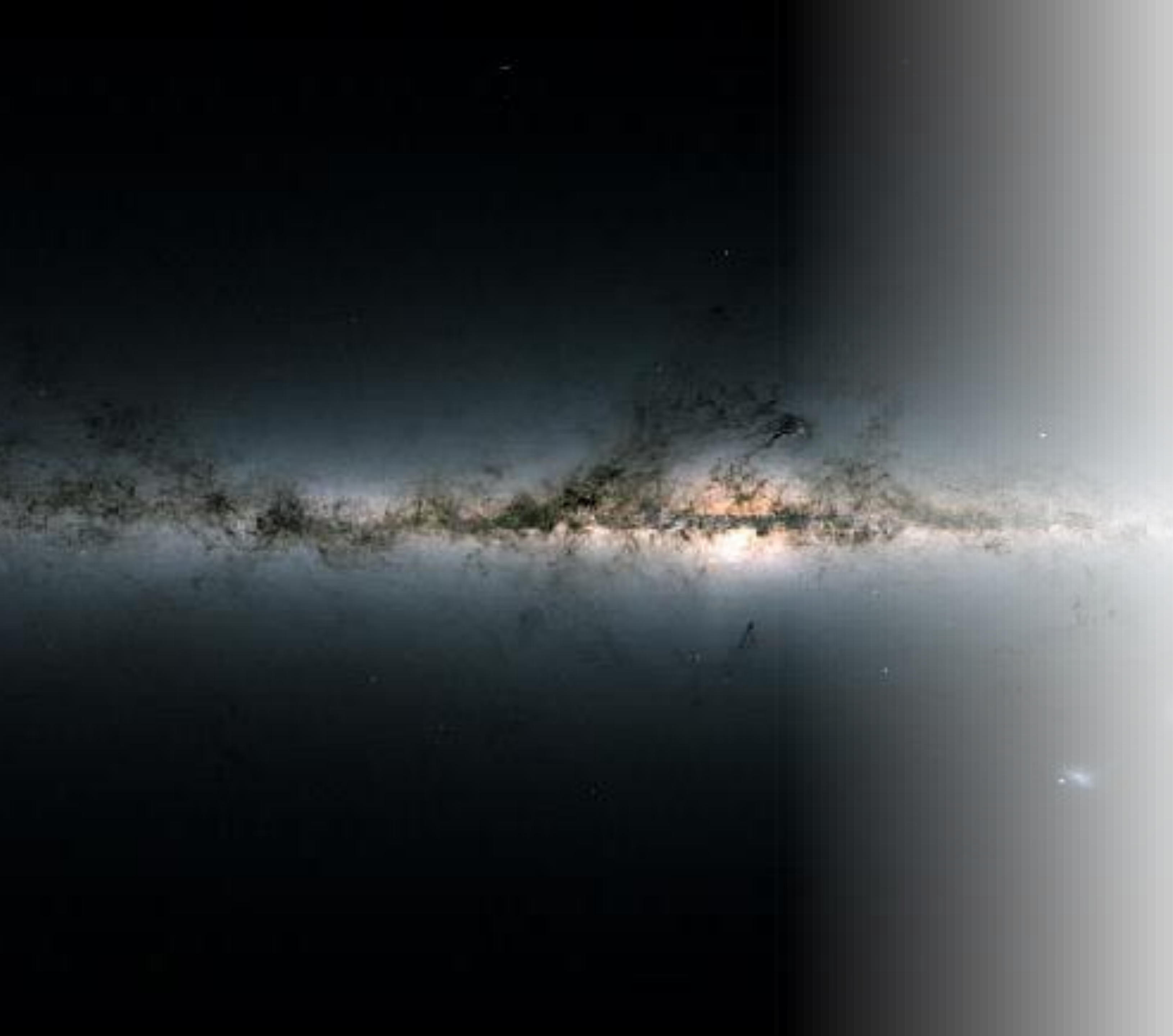
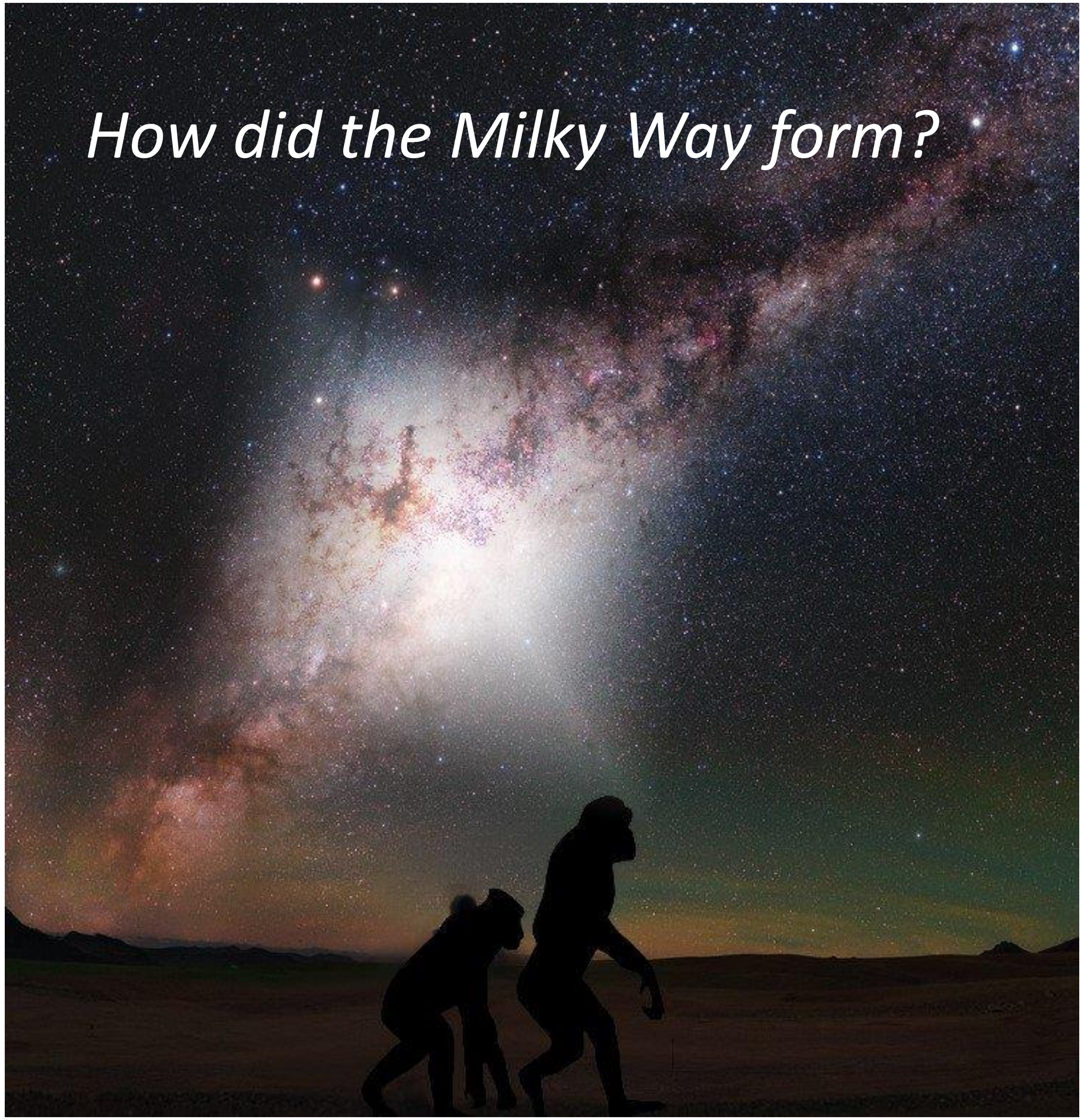
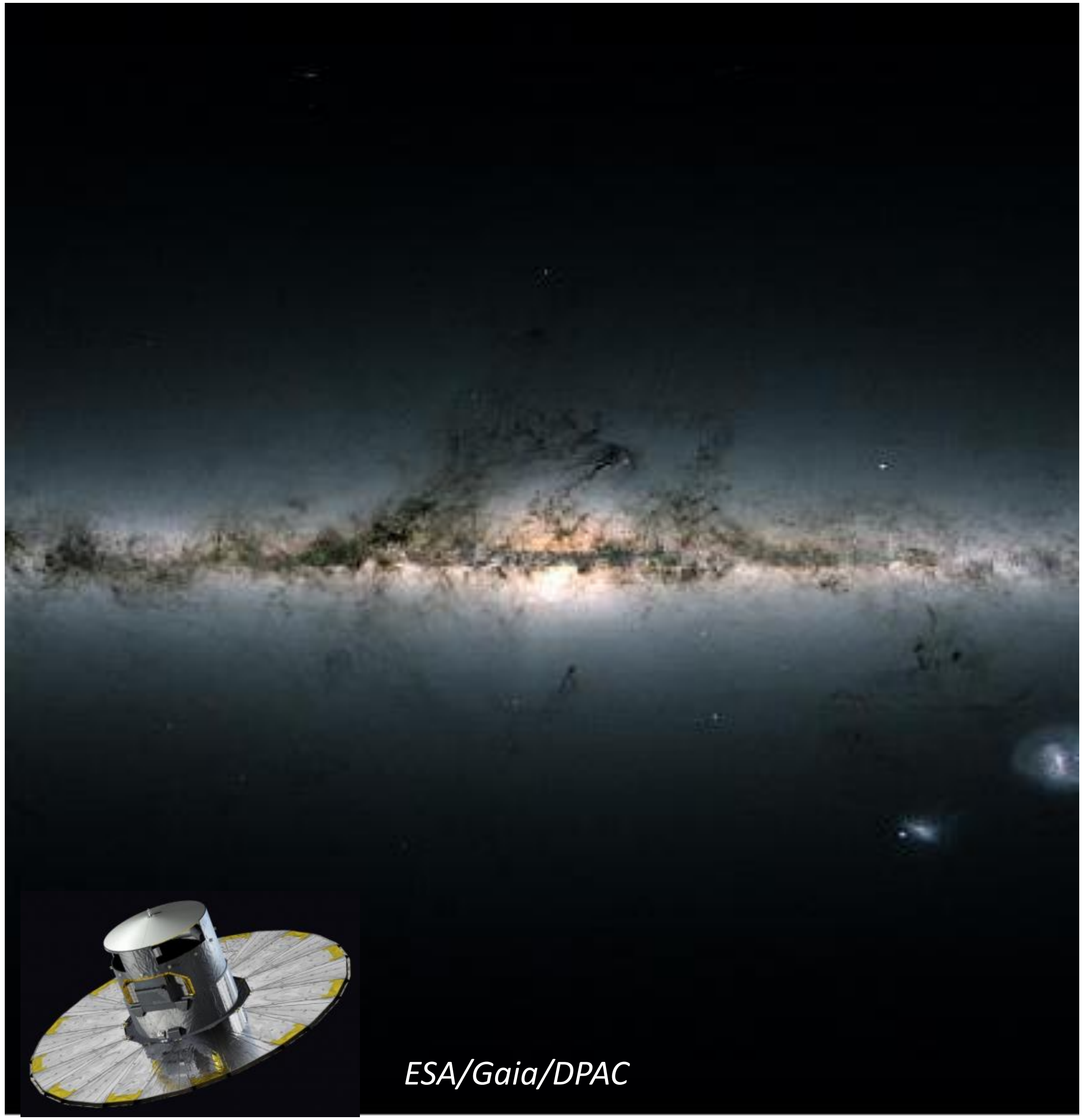
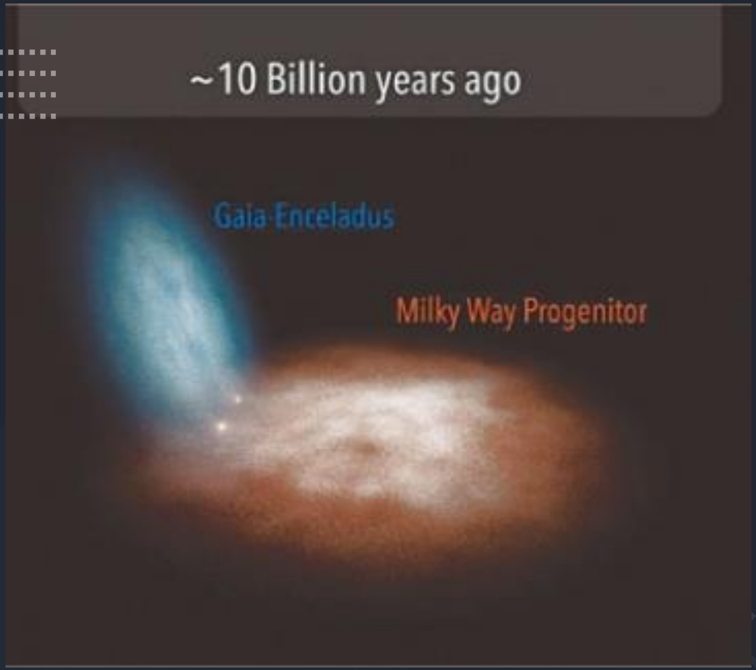


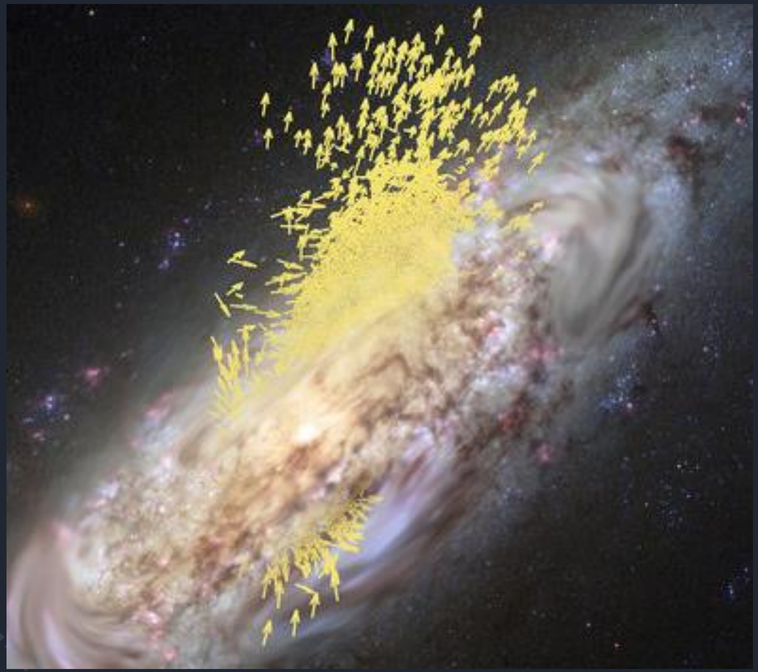
Understanding the formation of the Milky Way in a cosmological context

How unique is our Galaxy?


How did the Milky Way form?


ESA/Gaia/DPAC





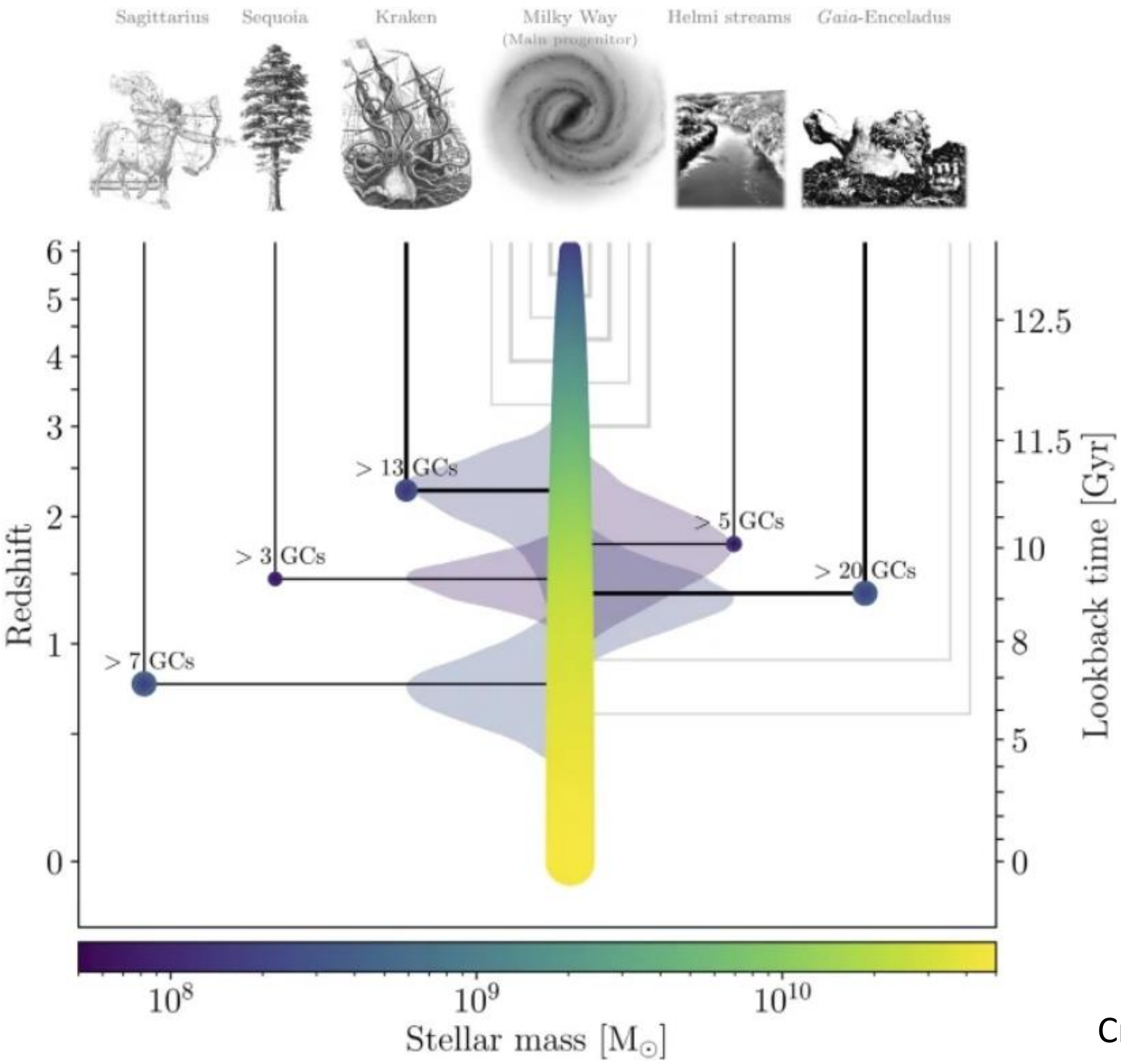
"Gaia-Enceladus"/"Sausage"

- **an ancient merger with another galaxy of LMC-mass, ~ 9 Gyr ago.**

Helmi et al (2018); Belokurov et al (2018).

Milky Way's 'family tree'

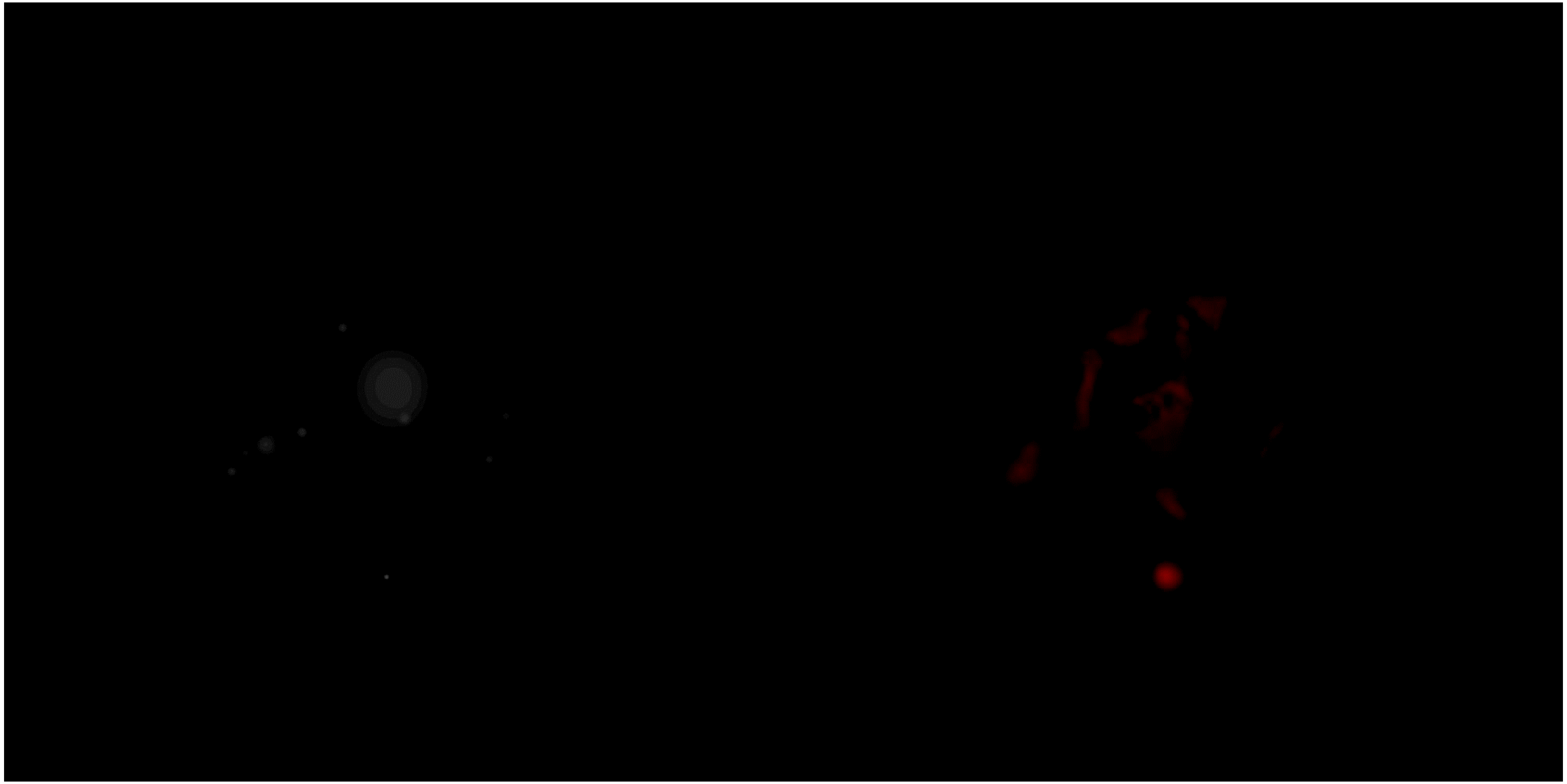
(i.e., the **merger tree**)



Credit: D. Kruijssen

Formation of a Milky Way-like galaxy in a ΛCDM cosmology

stars



gas

ARTEMIS simulations
(Font et al 2020)

(https://www.youtube.com/watch?v=OZmED2ix9w4)

Milky Way's family portrait

(pieced together from observations and cosmological simulations)

- *Is Milky Way a 'typical' galaxy for its mass?*

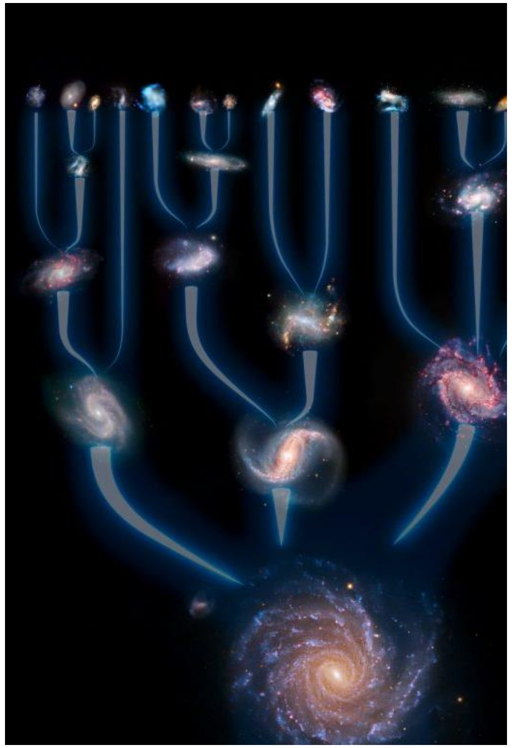
- How does the **MW's merger history** compare with those of other massive (M_{vir} ~10^{12} M_{Sun}) spiral galaxies?

i.e., the 'Milky Way analogues'.

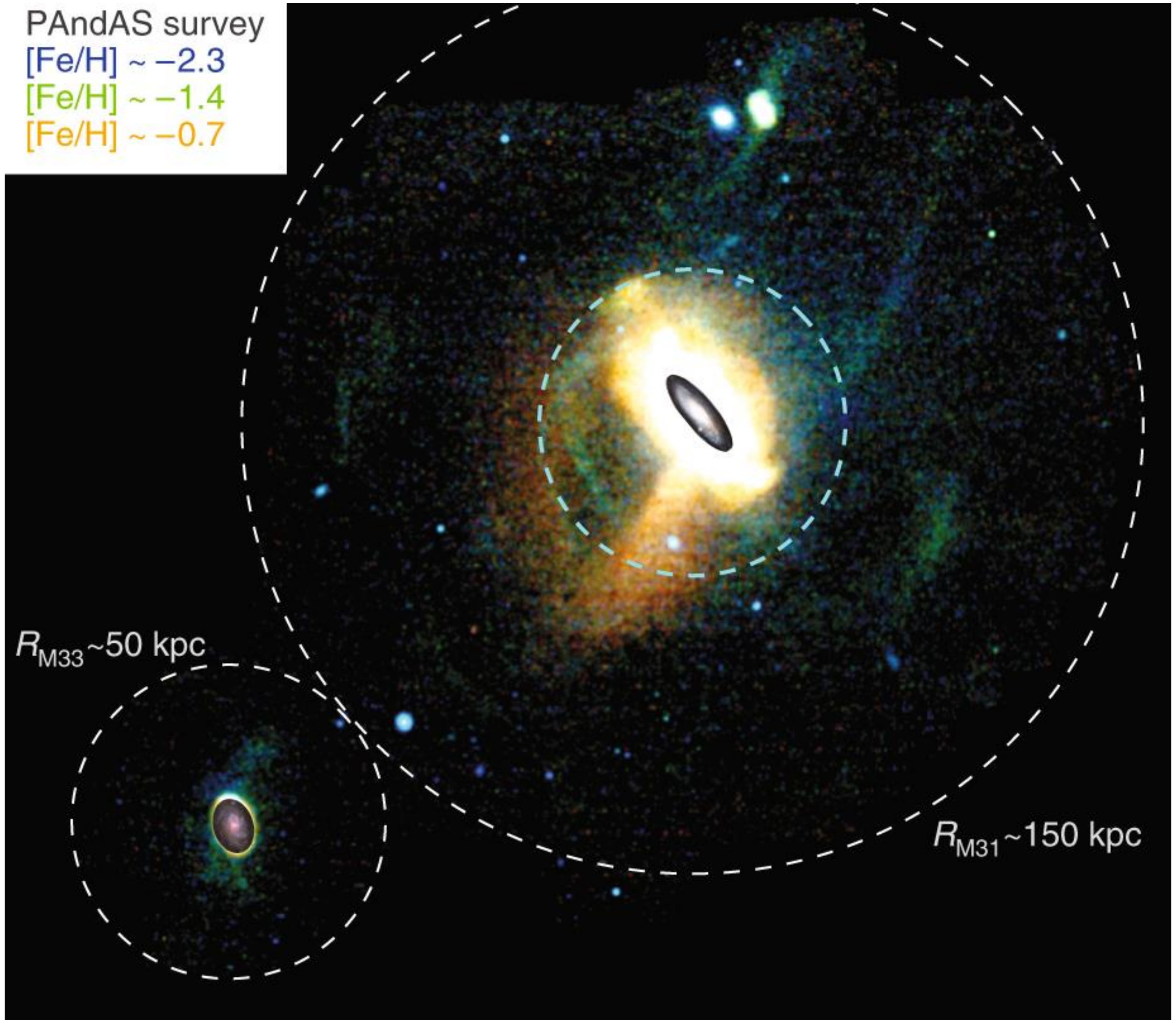
Stellar haloes are repositories of debris from past accretion events
-> constraints on **merger history**.

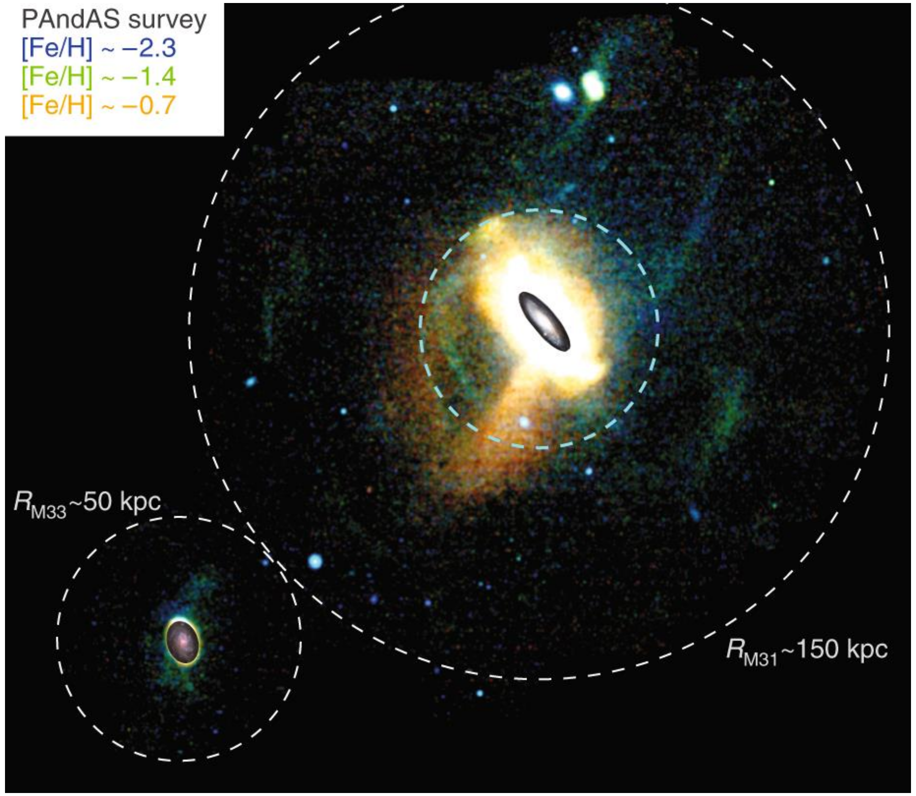
low-mass progenitors / accreted long-time ago ->

high-mass progenitors / accreted more recently ->



Andromeda (M31)
PAndAS survey
(Martin et al 2013)



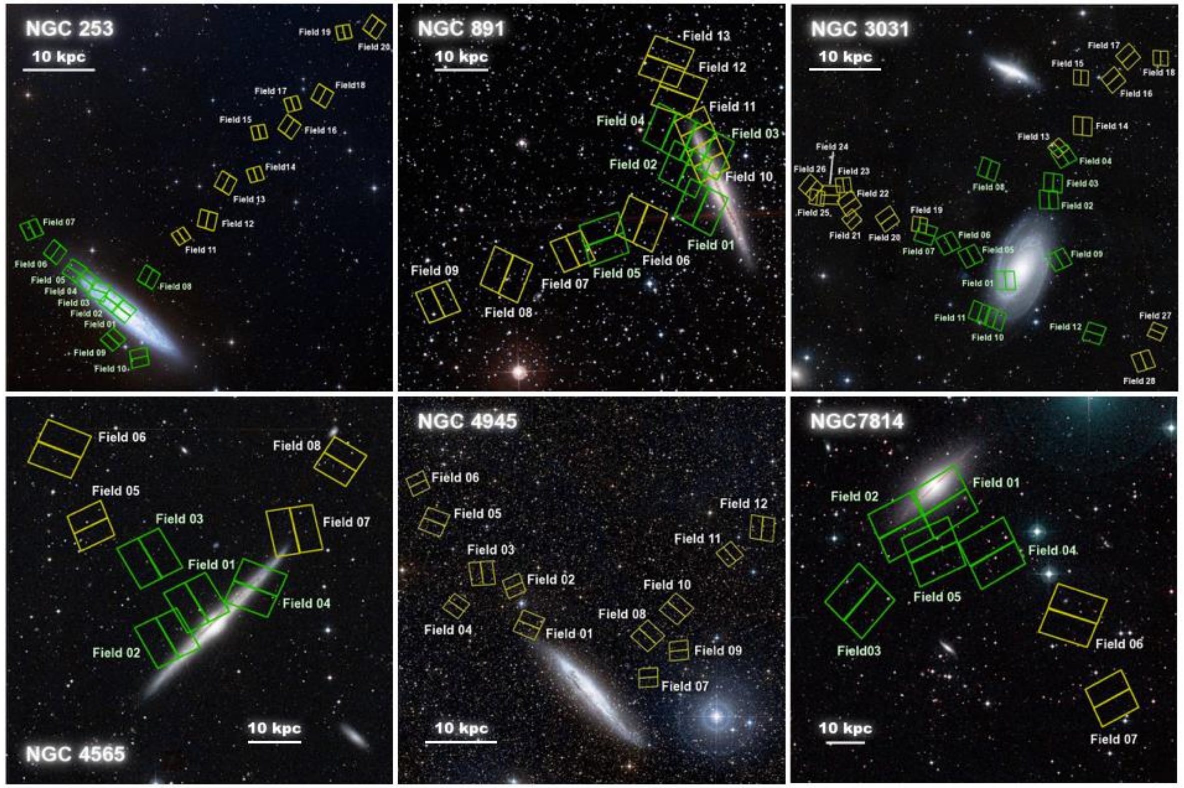


MW vs 'MW analogues':

How similar are their **stellar haloes?**

Stellar haloes are repositories of debris from past mergers -> constraints on merger history.

M31, PAndAS survey
(Martin et al 2013)



GHOSTS survey
(Monachesi et al 2016)

MW vs 'MW analogues':

How similar are their **satellite populations**?

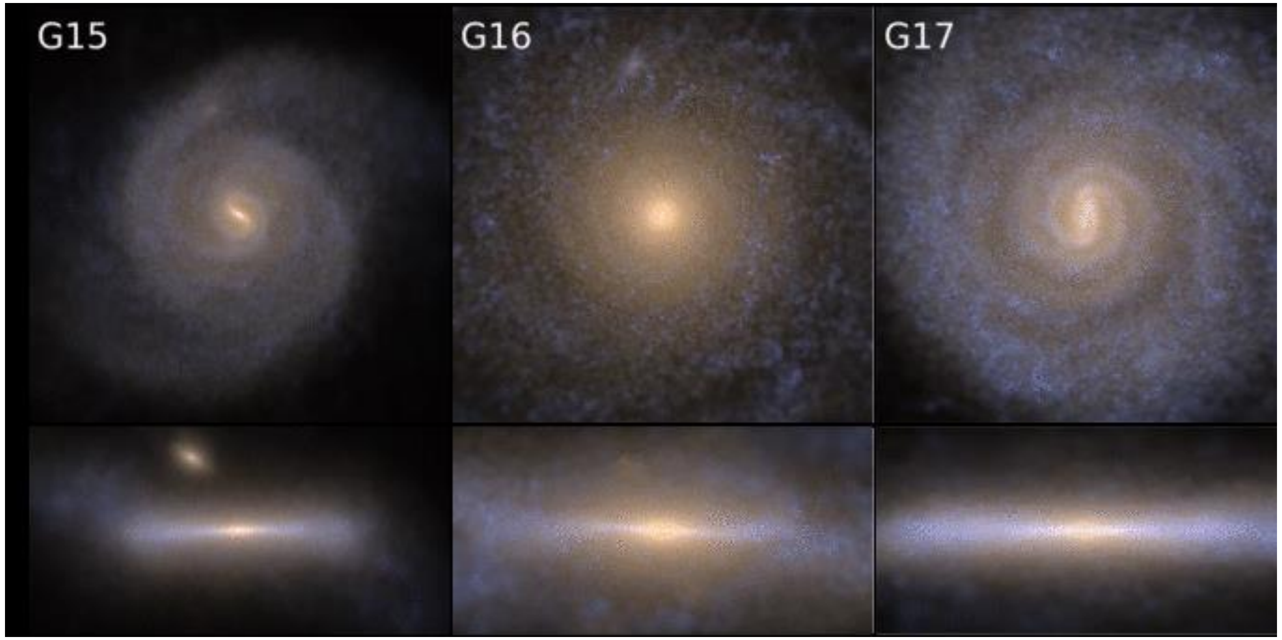
Present-day satellite galaxies keep a record of the **more recent accretion history**.

SAGA survey:
MW analogues, between 20 - 40 Mpc.

(Geha et al 2017, Mao et al 2020)

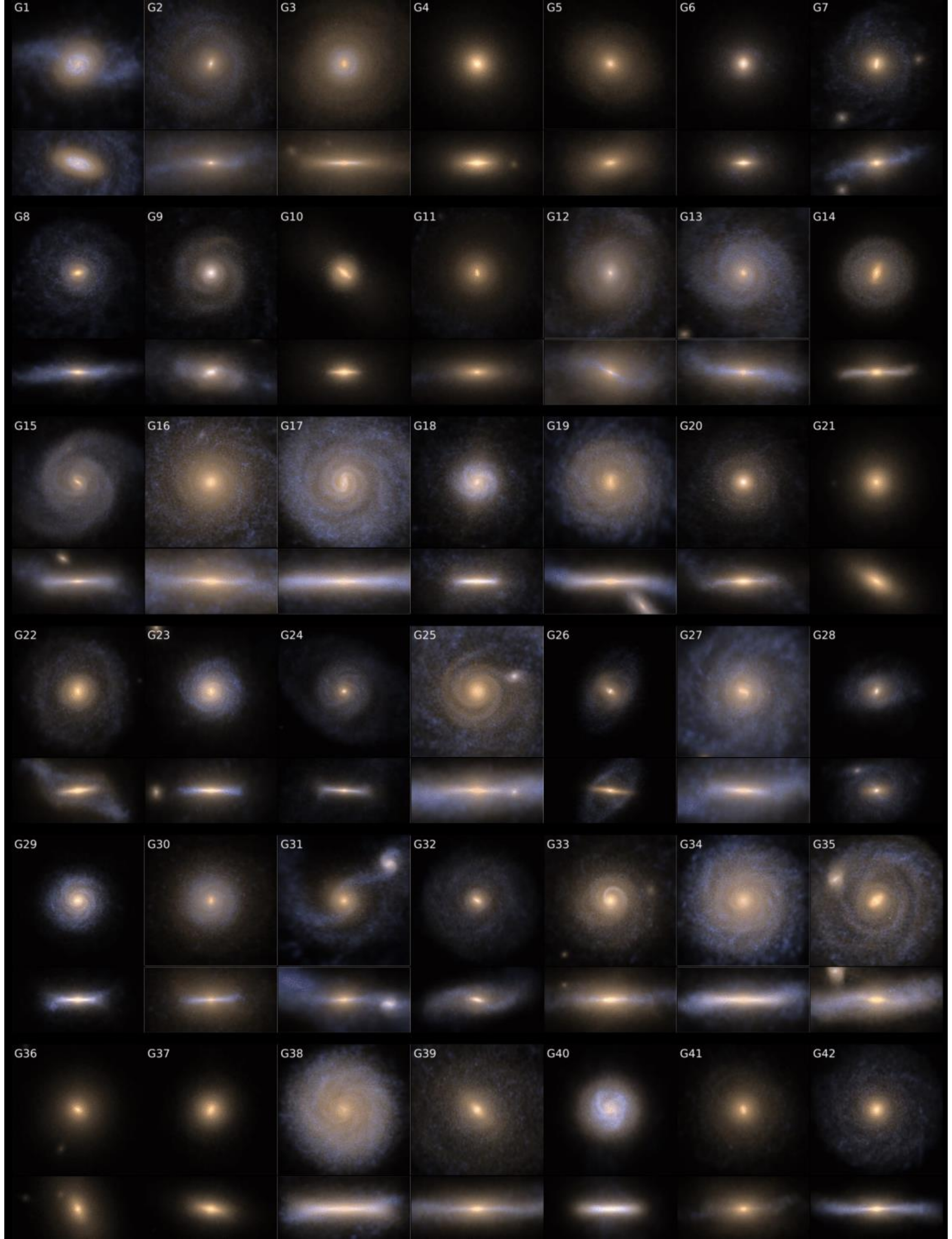
ARTEMIS simulations
(Assembly of high-ResoluTion Eagle-simulations of MIlky Way-type galaxieS)

- 45 MW analogues simulated in a ΛCDM cosmology
- Milky Way mass range: $M_{200} = 7 \times 10^{11} – 2 \times 10^{12}\ M_{sun}$
- High resolution: $m_{star} \sim 10^4\ M_{Sun}$, $m_{dm} \sim 10^5\ M_{Sun}$



- run with the a hydrodynamical code (EAGLE simulations, Schaye et al 2015)

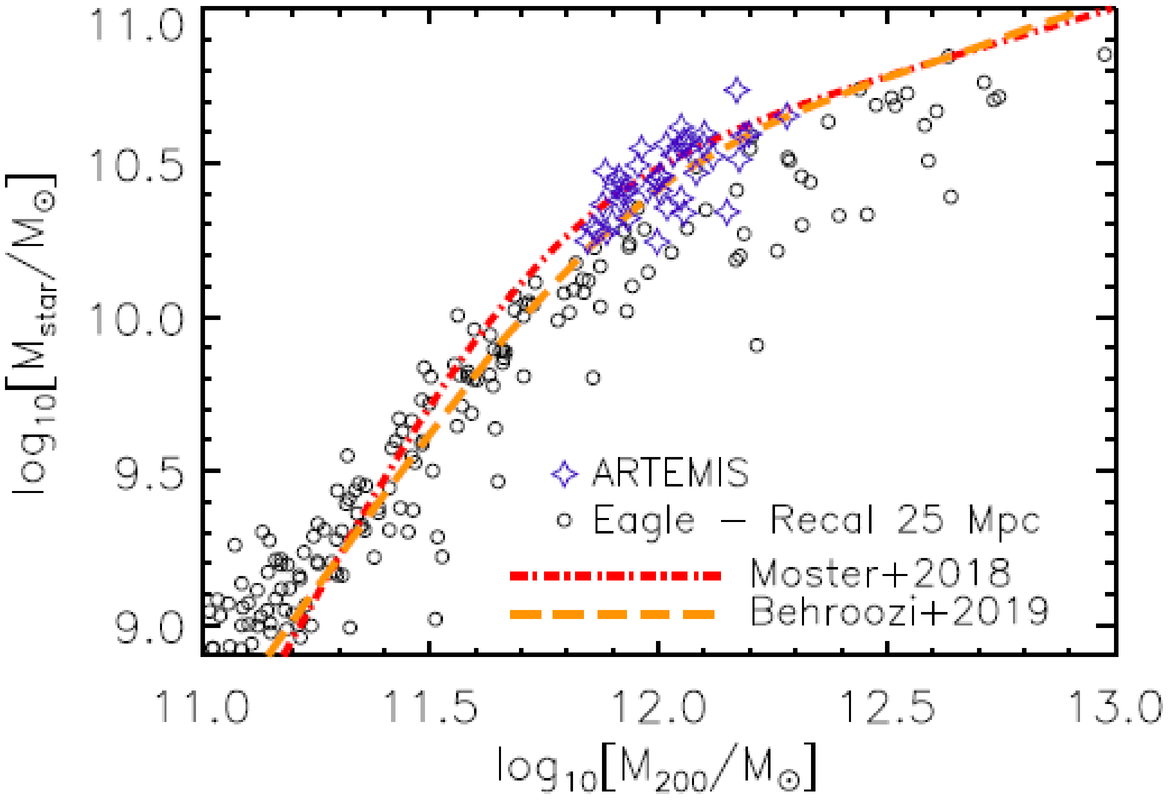
Include prescriptions for star formation, supernova feedback, stellar winds, reionization, AGN feedback, black hole growth.



Font et al. 2020
MNRAS, 498, 1765

ARTEMIS matches the global scaling relations of galaxies

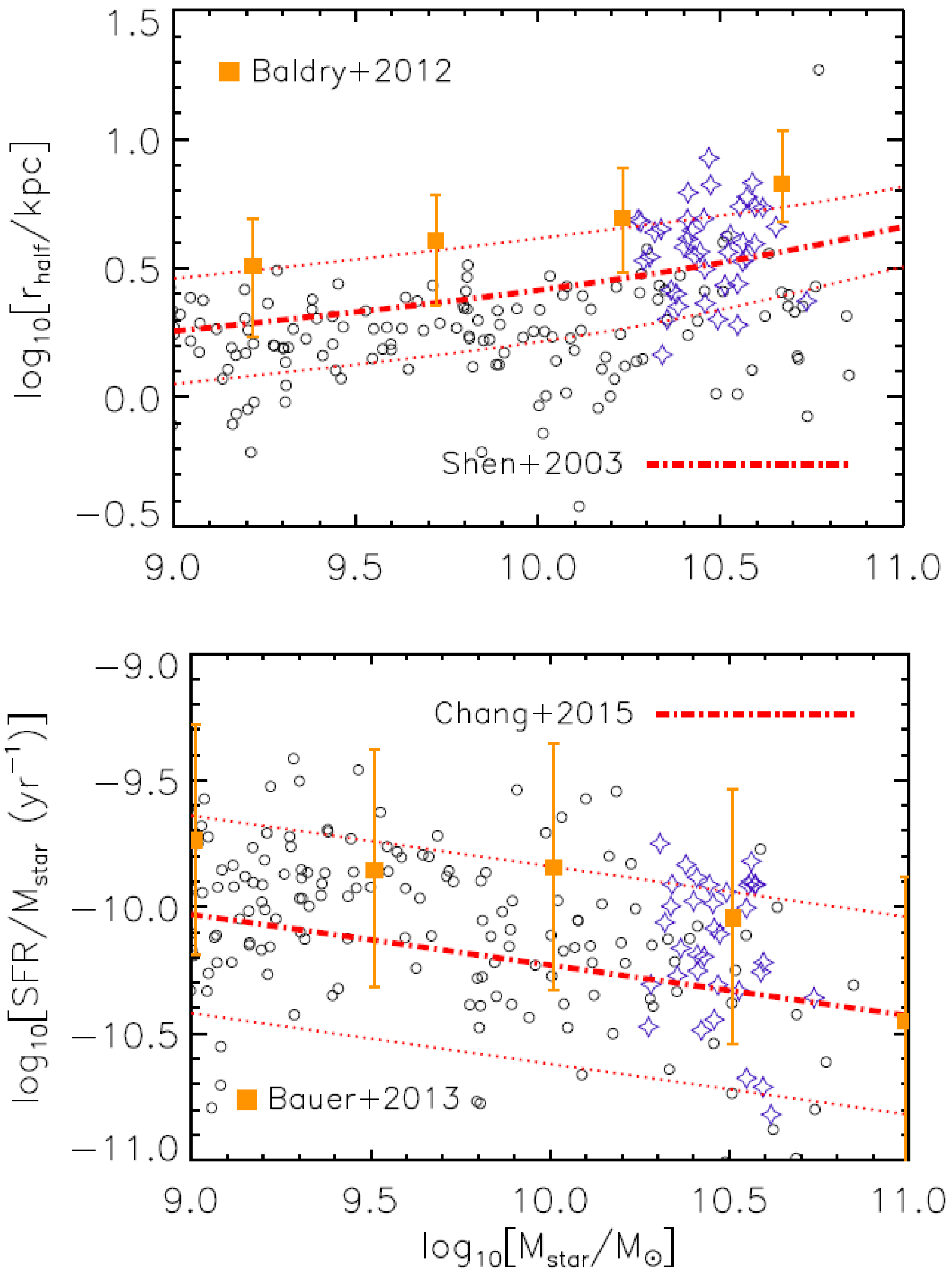
- the $M_{halo} - M_{star}$ relation:



Eagle simulation data from Schaye et al 2015.

- The size – stellar mass relation
  $r_{half} - M_{star}$

- The star formation rates – stellar mass relation
  $sSFR - M_{star}$



What are stellar haloes made of?

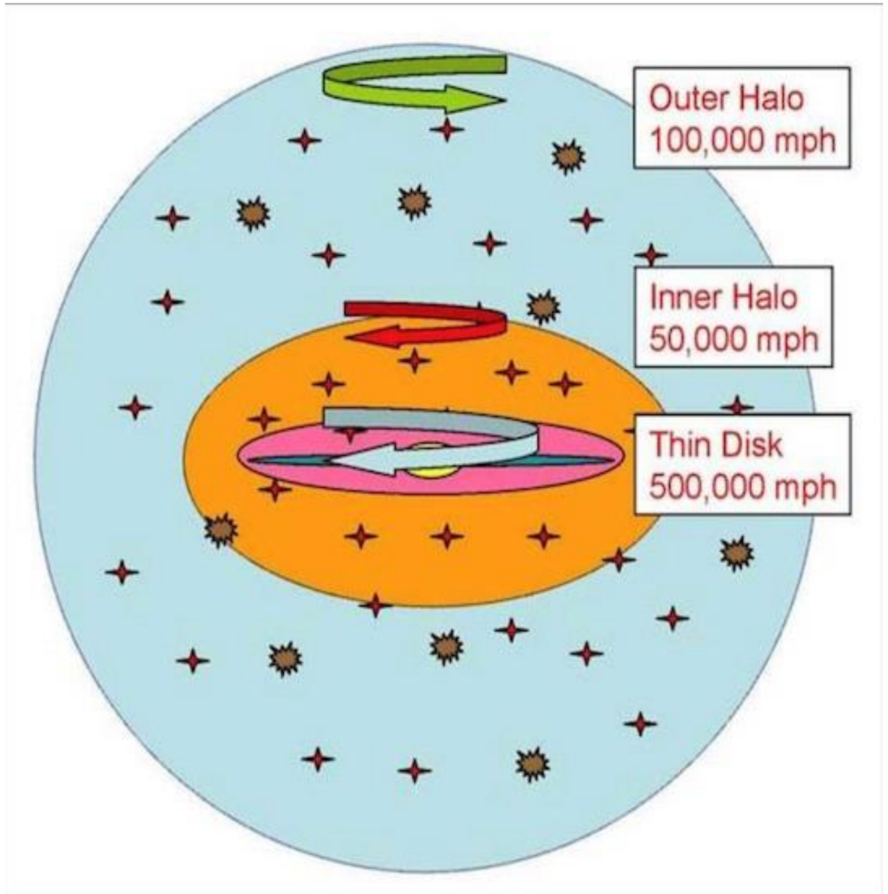
- accreted stars only

OR

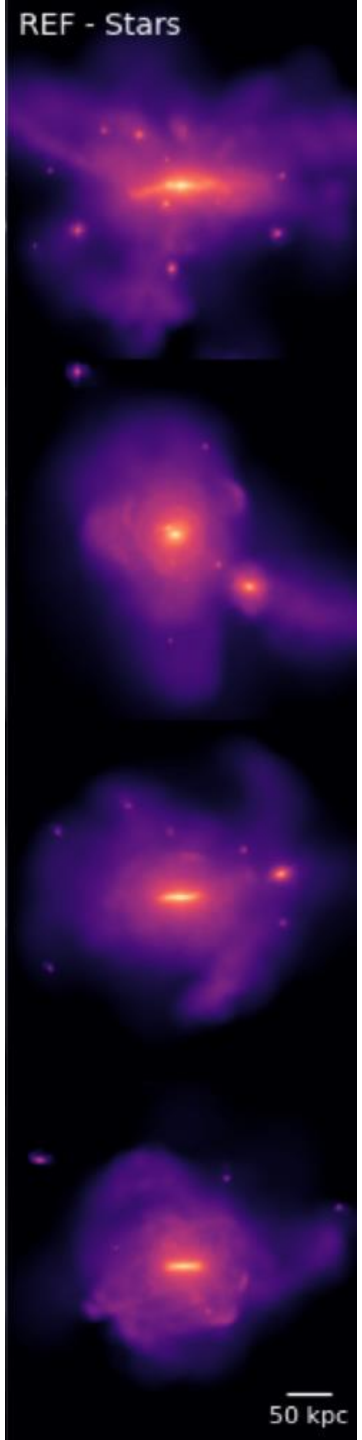
- accreted + in situ ('dual nature')

Possible **origin of in situ stars:**

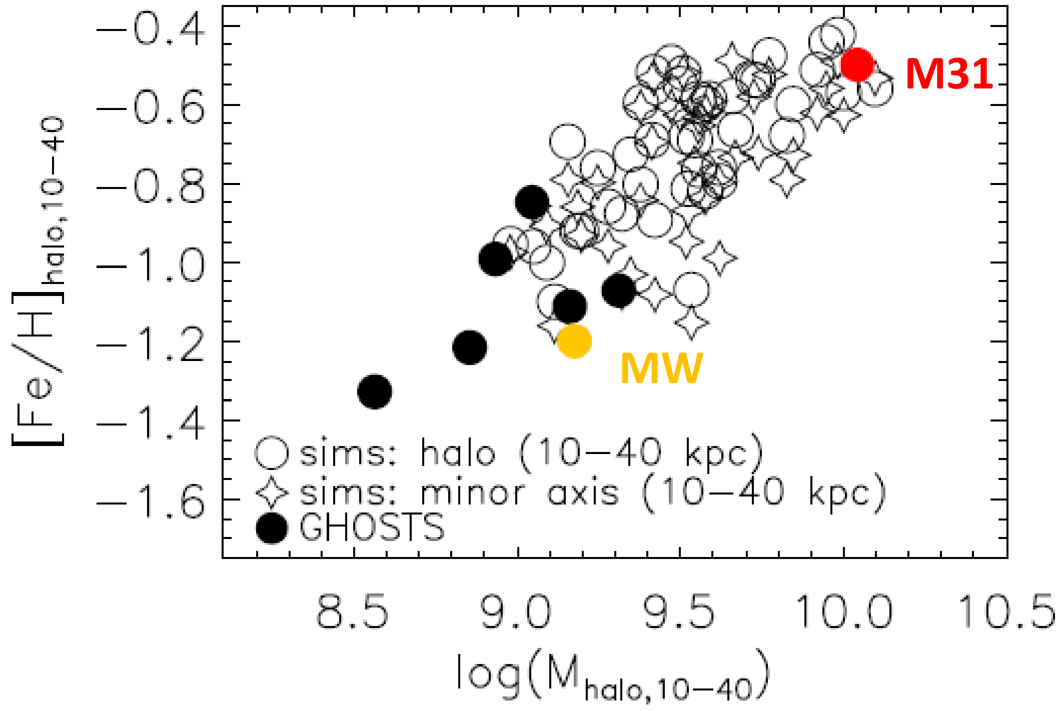
- stars ejected from the galaxy disc, 'heated discs'
- gas tidally stripped from satellite galaxies & forming stars
- stars formed inside filaments of cold gas that permeate the galaxy



Credit: C. Carollo.

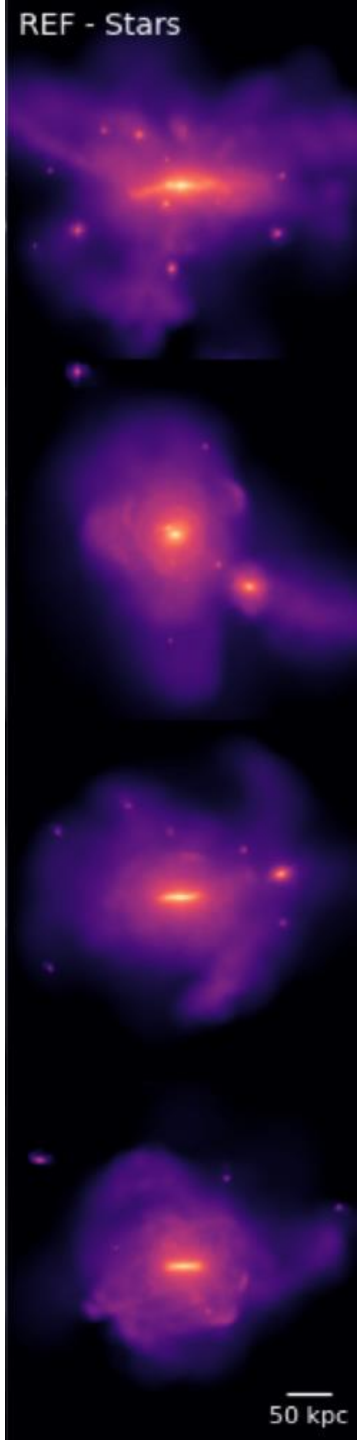


What are stellar haloes made of?



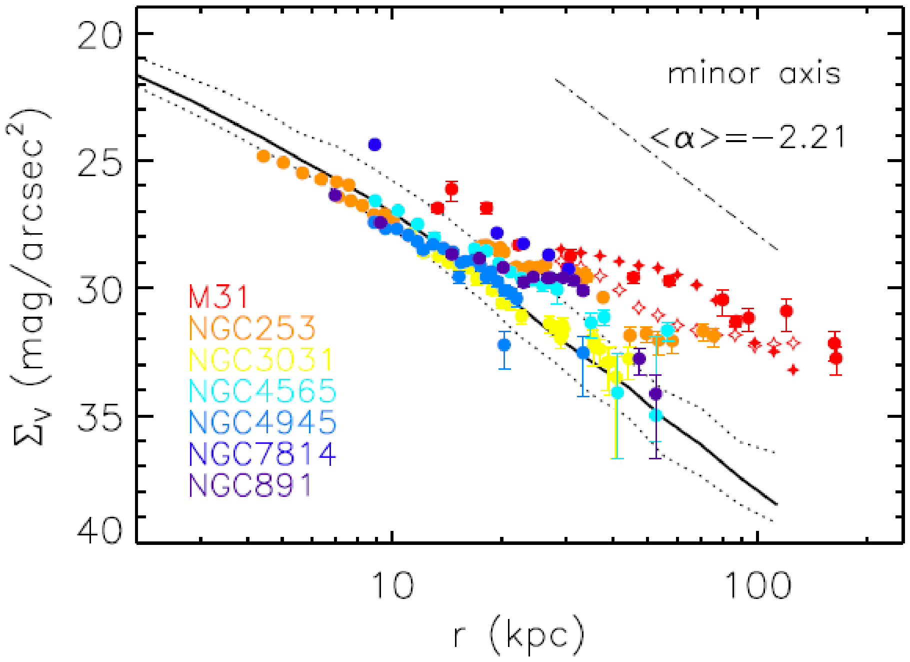
The stellar halo mass – metallicity relation is consistent with stellar haloes having a 'dual nature' = accreted + in situ.

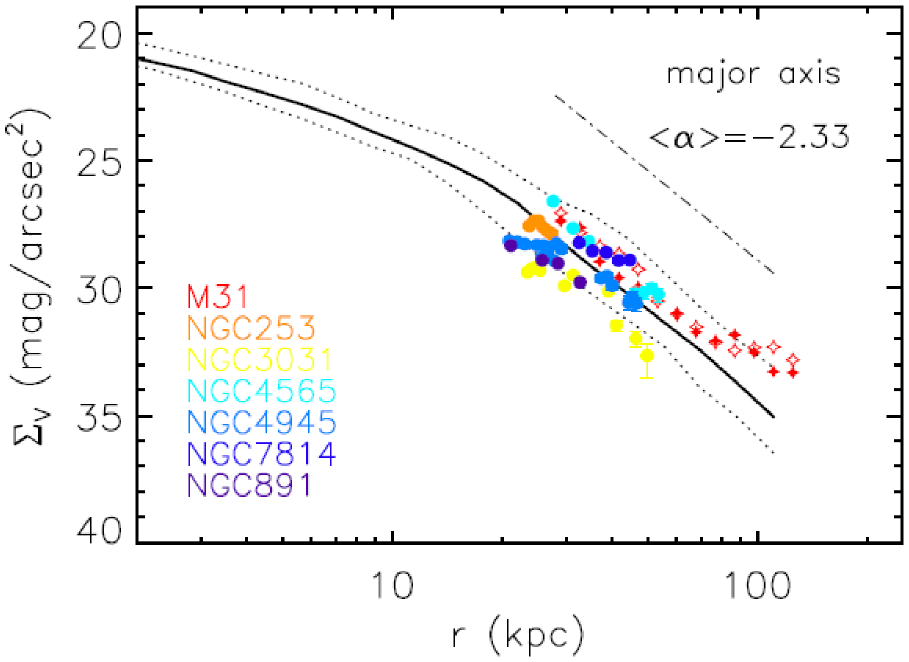
MW's stellar halo is within the range of observed/ simulated haloes, although on the more metal-poor side.



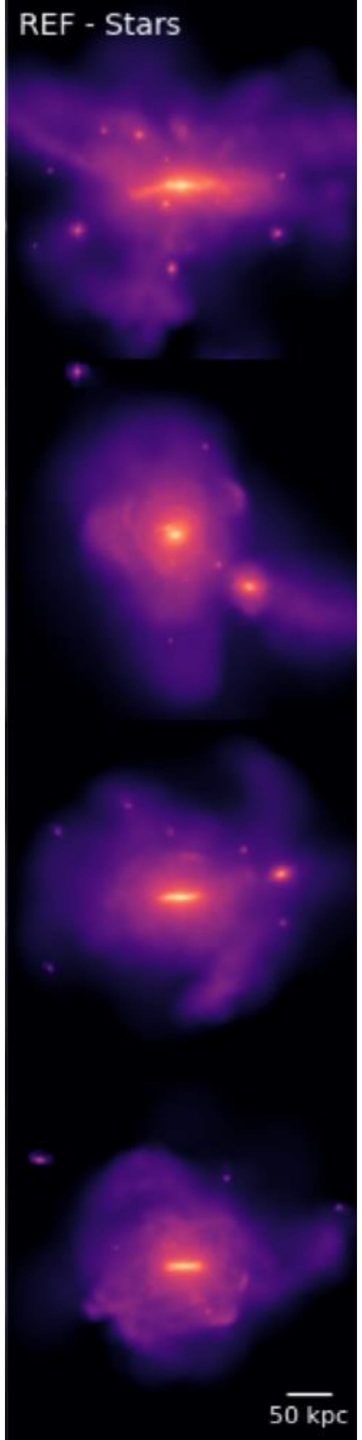
ARTEMIS: Match to surface brightness profiles of MW analogues

– along both the major and minor axes of galaxies



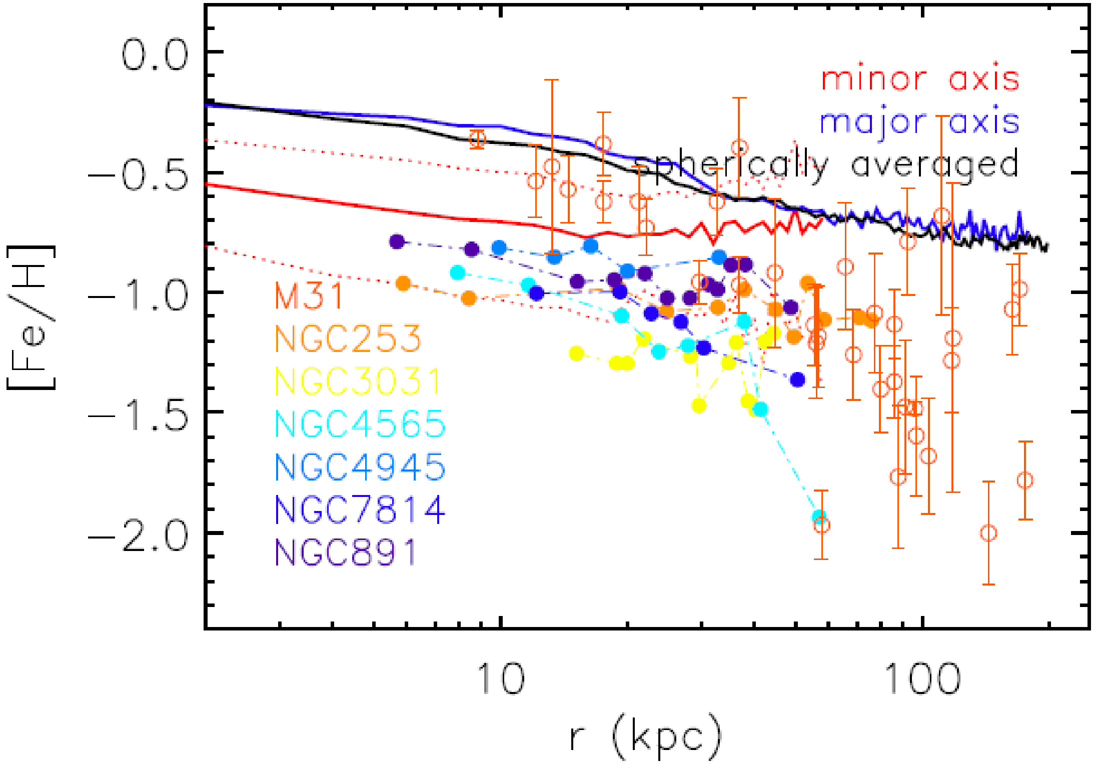


Observations: GHOSTS survey (Harmsen et al 2017) + M31 (Guhathakurta et al 2012; Ibata et al.2014).



ARTEMIS: Match to the [Fe/H] profiles of MW analogues

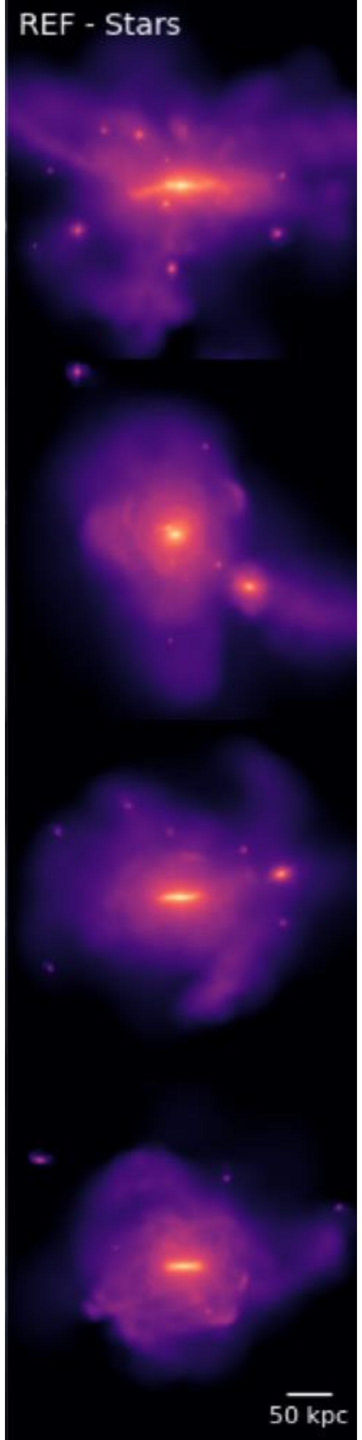
[Fe/H] gradients? If ‘universal’, [Fe/H] gradients may indicate the presence of in situ stars.



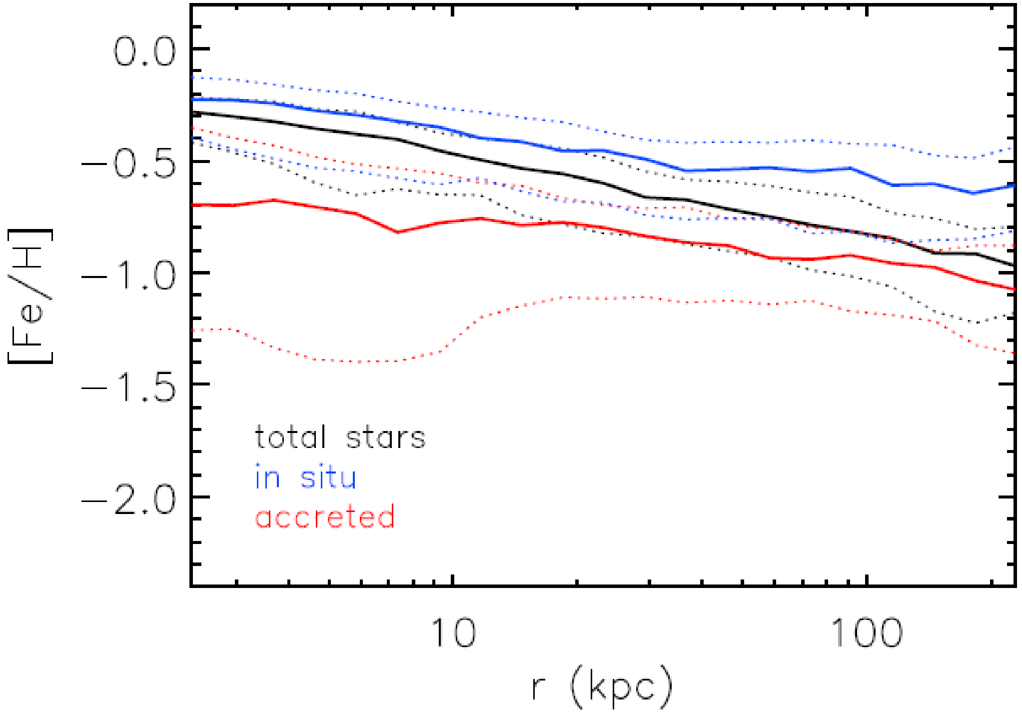
Observations: M31 (Gilbert et al 2014), GHOSTS survey (Harmsen et al 2016)

ARTEMIS sims predict:

- stronger gradients along the major axes (**~0.75 dex**) – mostly of in situ origin
- weaker (or no) gradients along the minor axes **(<~ 0.2 dex)** – accreted origin.



Distinctive [Fe/H] gradients along the major vs minor axes of galaxies:



Major axes-> dominated by metal-rich stars, formed in situ.

Minor axes-> dominated by metal-poor stars, of accreted origin.

Observations need to target more the major axes to constrain fraction of in situ stars.

Surviving satellite galaxies

I. Can cosmological simulations match the **diversity of satellite populations** of MW analogues?

Observations show:

- large scatter in luminosity functions. Too large for ΛCDM models?

- radial distributions that are either too concentrated (e.g. MW) or too sparse (e.g. galaxies in the SAGA survey) compared with ΛCDM. Tension with theory?

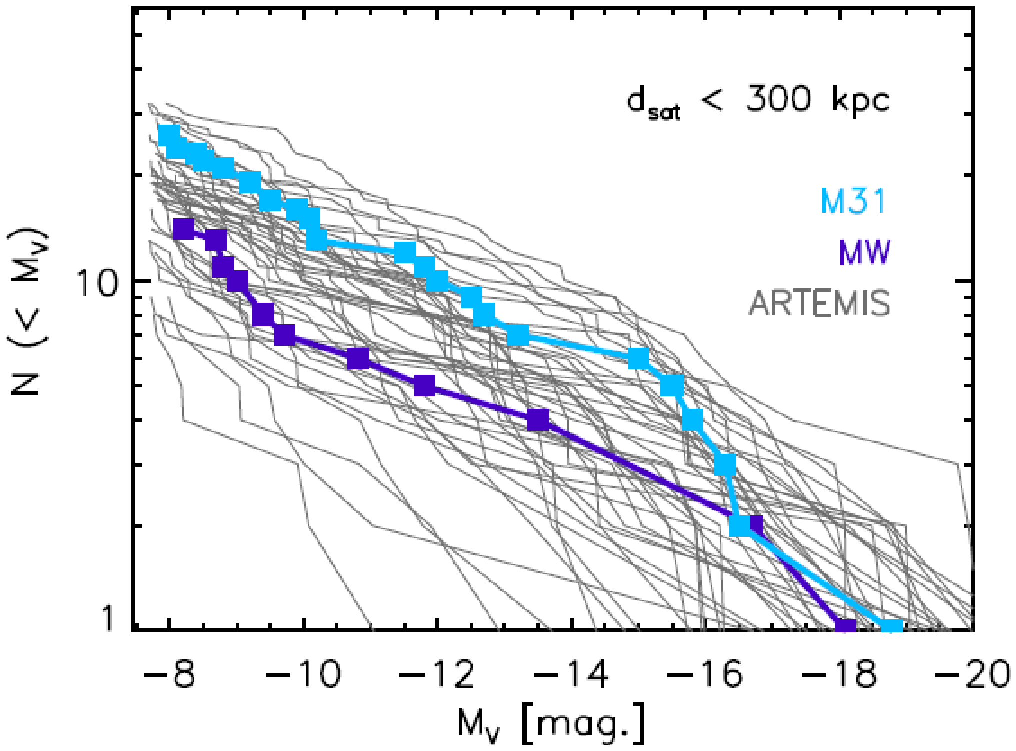
II. Satellite galaxies may act as **proxies** for the **host galaxy formation history**.

- how does Nsat correlate with host galaxy properties (e.g. total mass, stellar mass, luminosity, morphology)?

- does the radial distribution of satellites 'know' about the host properties?

Luminosity functions (LFs) of satellite galaxies

ARTEMIS (->ΛCDM model) predicts large scatter in LFs at fixed host galaxy mass.



The Milky Way has ~ a dozen 'classical' dwarf galaxies orbiting around it today.

This is **within the range** of LF predictions in a ΛCDM model.

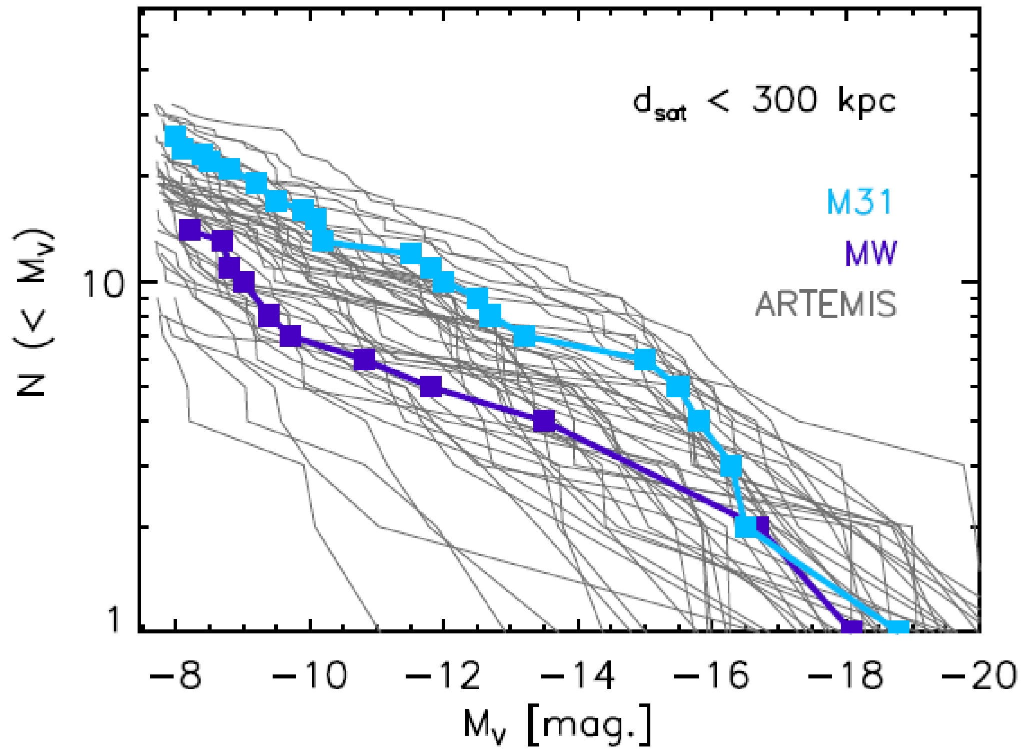
Somewhat on the lower side.

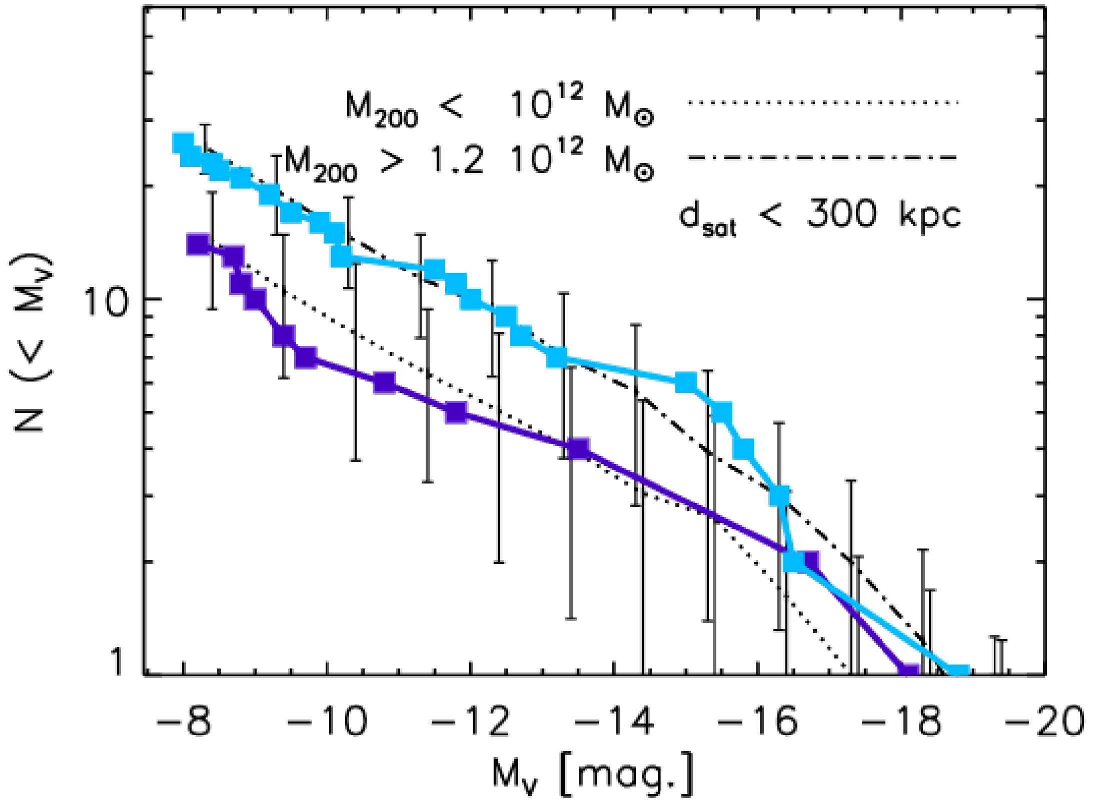
Observations:
McConnachie 2012 + PAndAS survey.

Font, McCarthy & Belokurov (2021)

As N_{sat} increases ~ mass of host galaxy,

it implies that MW has a lower mass than M31:

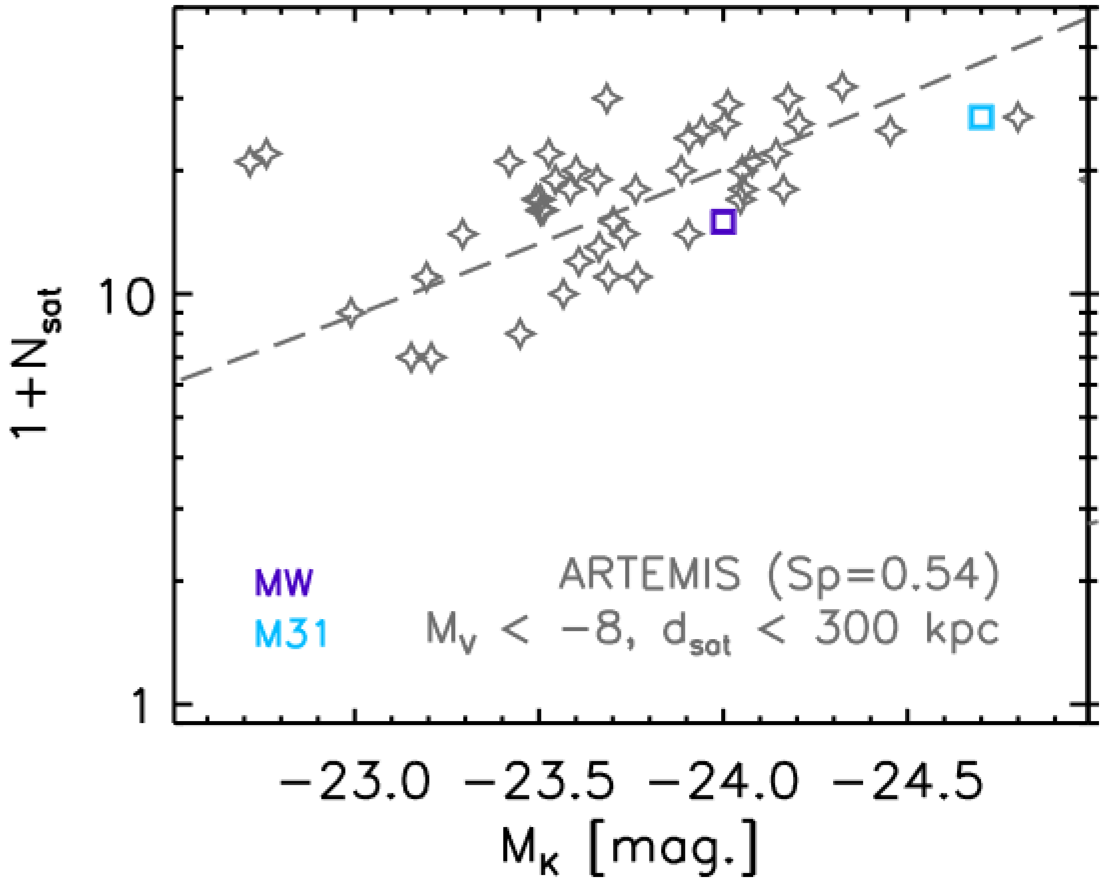




Observations:
McConnachie 2012 + PAndAS survey.

Font, McCarthy & Belokurov (2021)

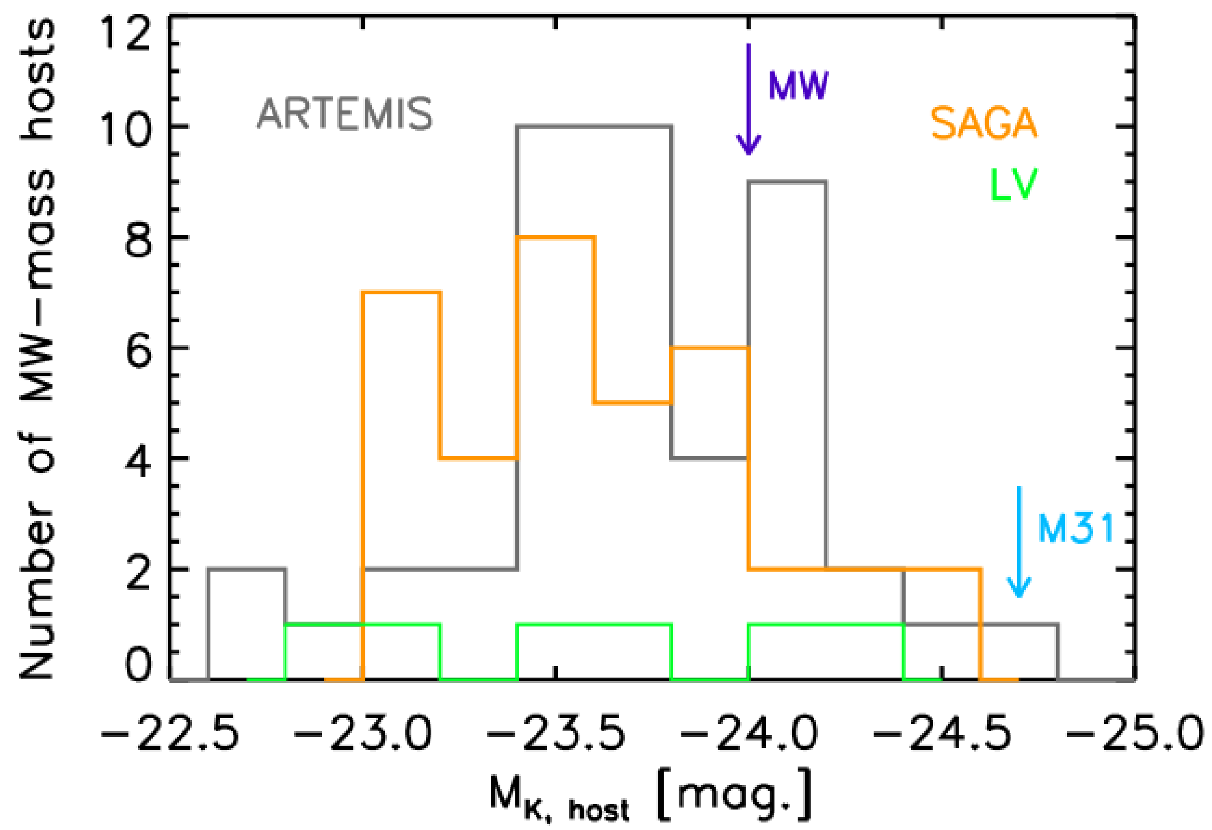
N_{sat} ~ stellar mass of host (M_K acts as proxy).



MW's satellite population is again within the range predicted by ΛCDM models.

Font, McCarthy & Belokurov (2021)

ARTEMIS vs. observed MW analogues in the Local Volume & in SAGA survey



Font, McCarthy & Belokurov (2021)

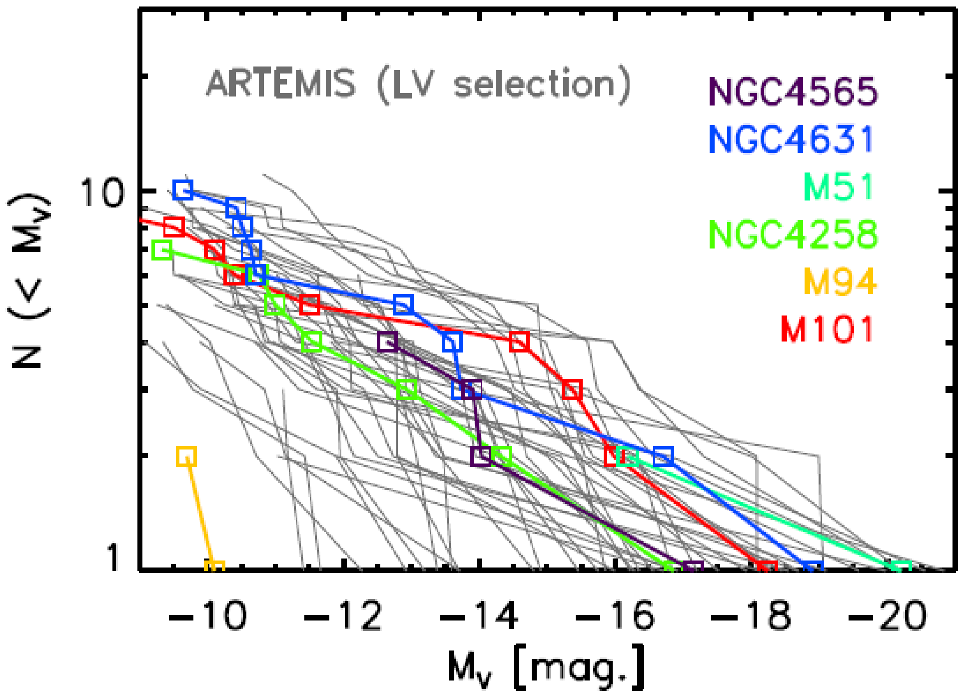
Local Volume (Carlsten et al 2020)
SAGA (Geha et al 2017, Mao et al 2020)

Luminosity functions of MW analogues:

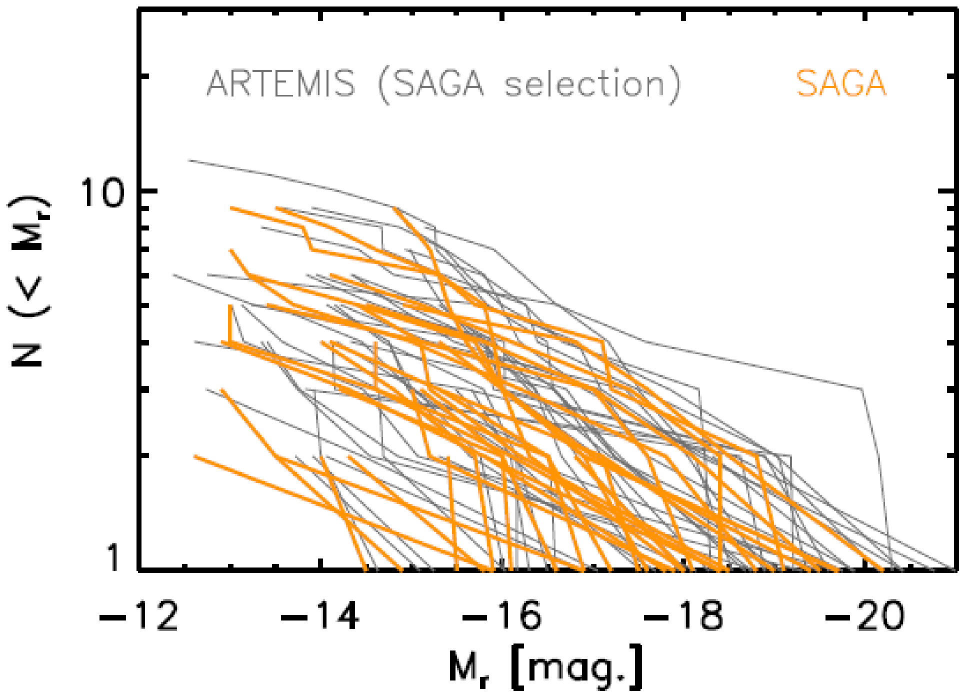
ARTEMIS simulations vs.

observations

in the Local Volume (< 10 Mpc):

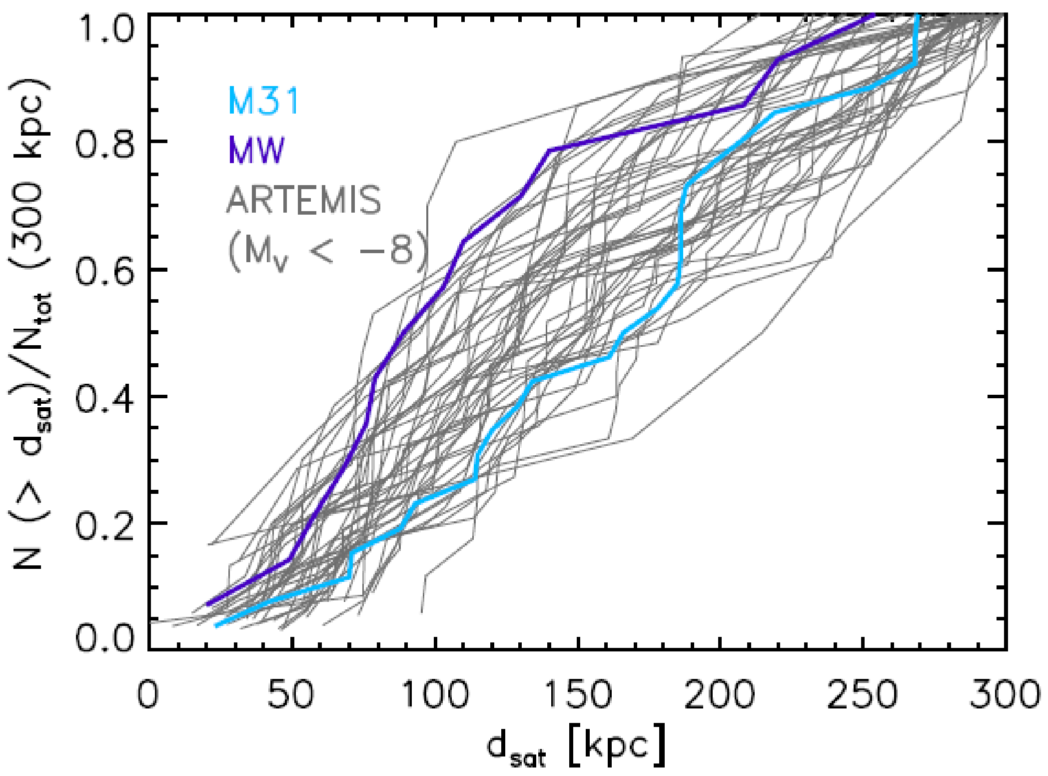


in the SAGA survey (20 - 40 Mpc):



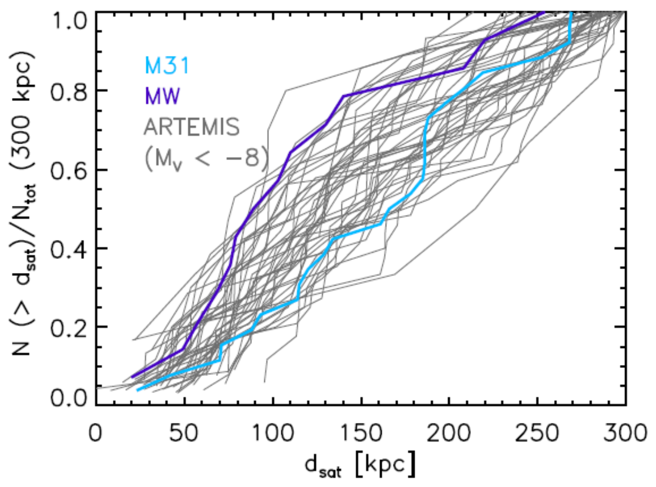
Radial distributions of satellite galaxies in MW analogues

ARTEMIS vs MW and M31:

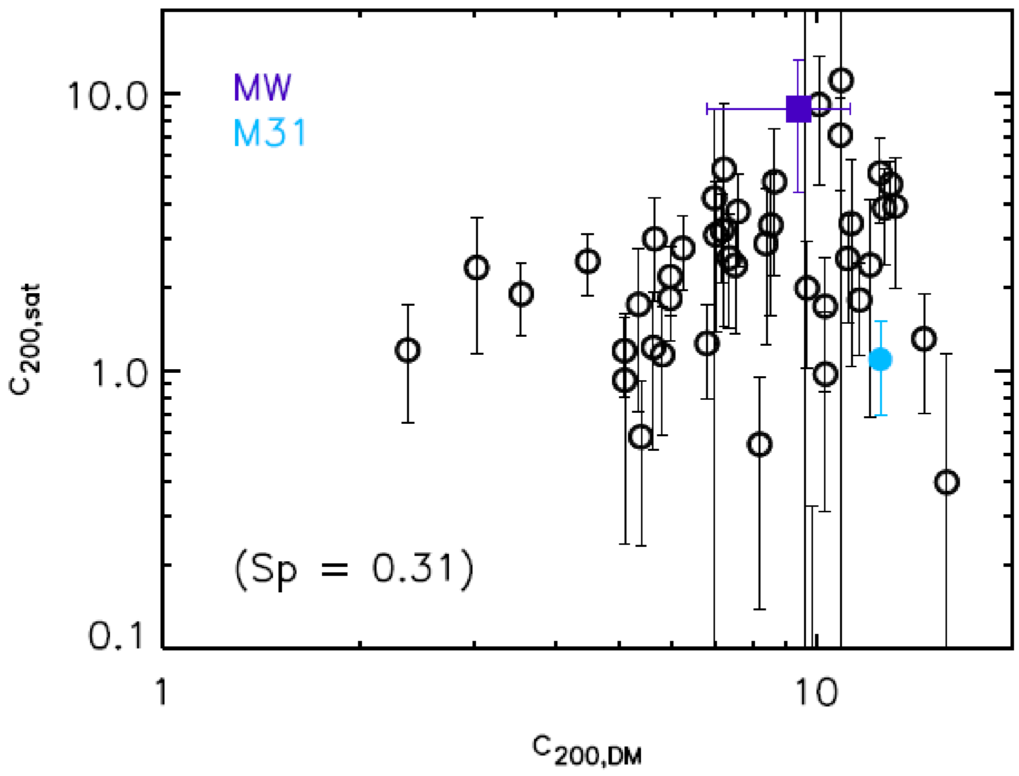


Milky Way's distribution is **within the scatter**.

Radial distributions



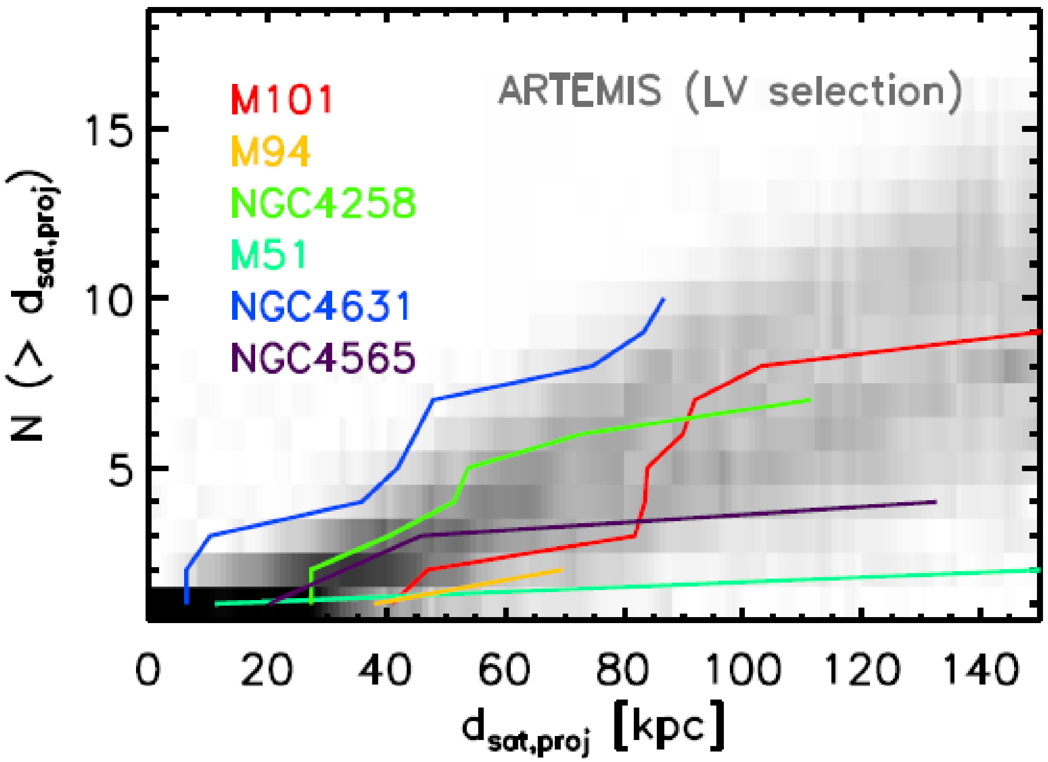
The **concentration** of satellites seems to 'know about' the host's dark matter halo (albeit weakly):



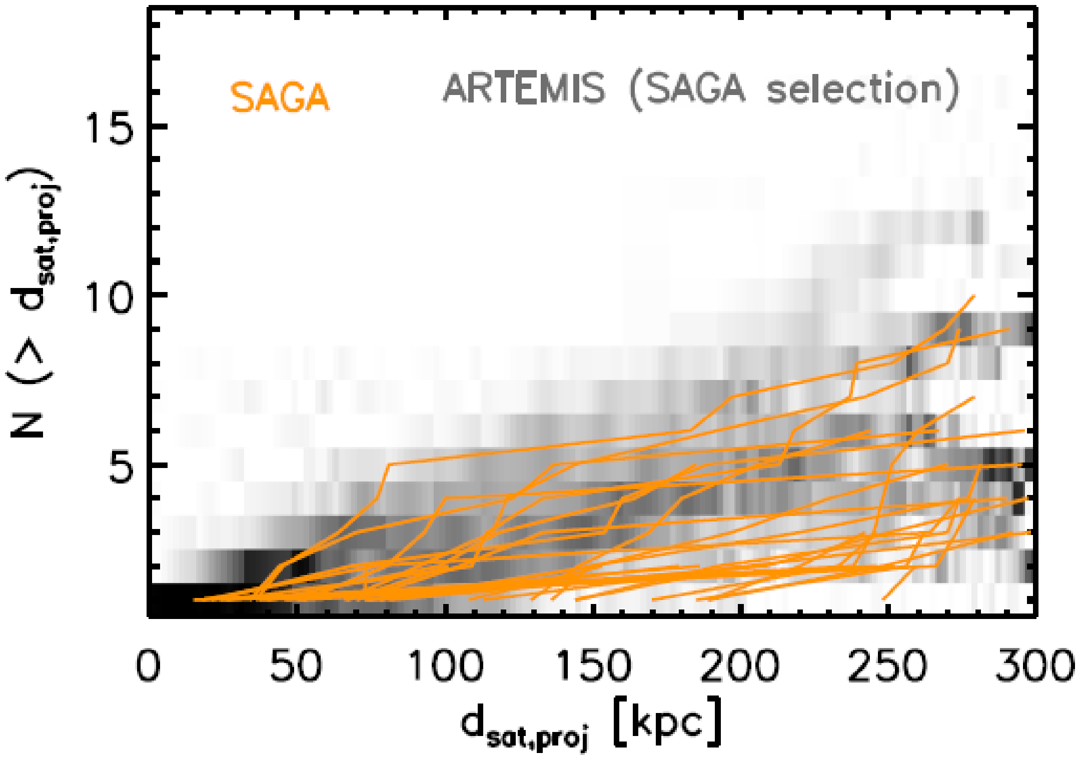
Radial distributions

ARTEMIS vs observed MW analogues

I. in the Local Volume (<10 Mpc):



II. in the SAGA survey (20 – 40 Mpc):



Good agreement once the various **survey selection effects** are taken into account!

Conclusions

- ΛCDM models predictions agree well with observations

i.e., properties of observed galaxies (MW & MW analogues): stellar halo distributions, LFs and radial distributions of satellite galaxies.

- Milky Way's properties are **within the range** of properties predicted by ΛCDM.

However, it's **not quite typical** for a galaxy for its mass. Indications that it may have had a **less active merging history:** has a metal-poor stellar halo, a low number of satellites, which are more radially concentrated.

<u>*Future directions:*</u>

- *Can we find further clues to confirm/infirm that MW had a more subdued merger history? Understanding the formation of MW's thin & thick discs may help.*
- *How many other past merger events remain still to be discovered inside the MW? Gaia DR3 and Vera Rubin Observatory are ideal for discovery of more ultra-faint dwarf galaxies and faint tidal streams.*