

Studying the stellar disc and halo of the Milky Way with the GASTRO Simulations and Blue Horizontal Branch Stars

João A. S. Amarante – ICCUB
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Via Lactea project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (G.A. no 852839).

VIA LACTEA project
PI: Chervin Laporte - ICCUB

In collaboration with UCLan's
Galaxy Dynamics group led
by Victor Debattista



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Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA



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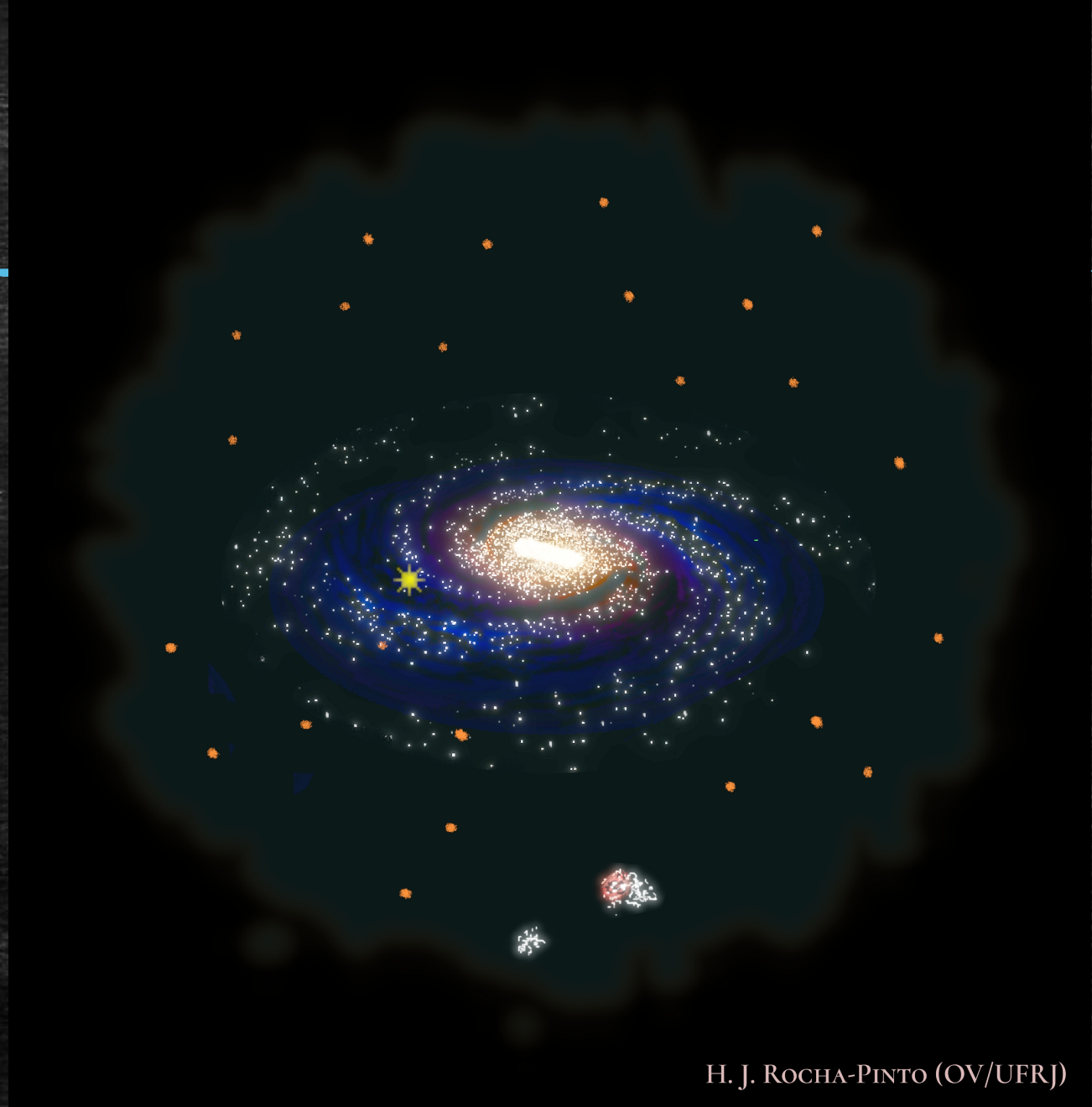
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The Milky Way

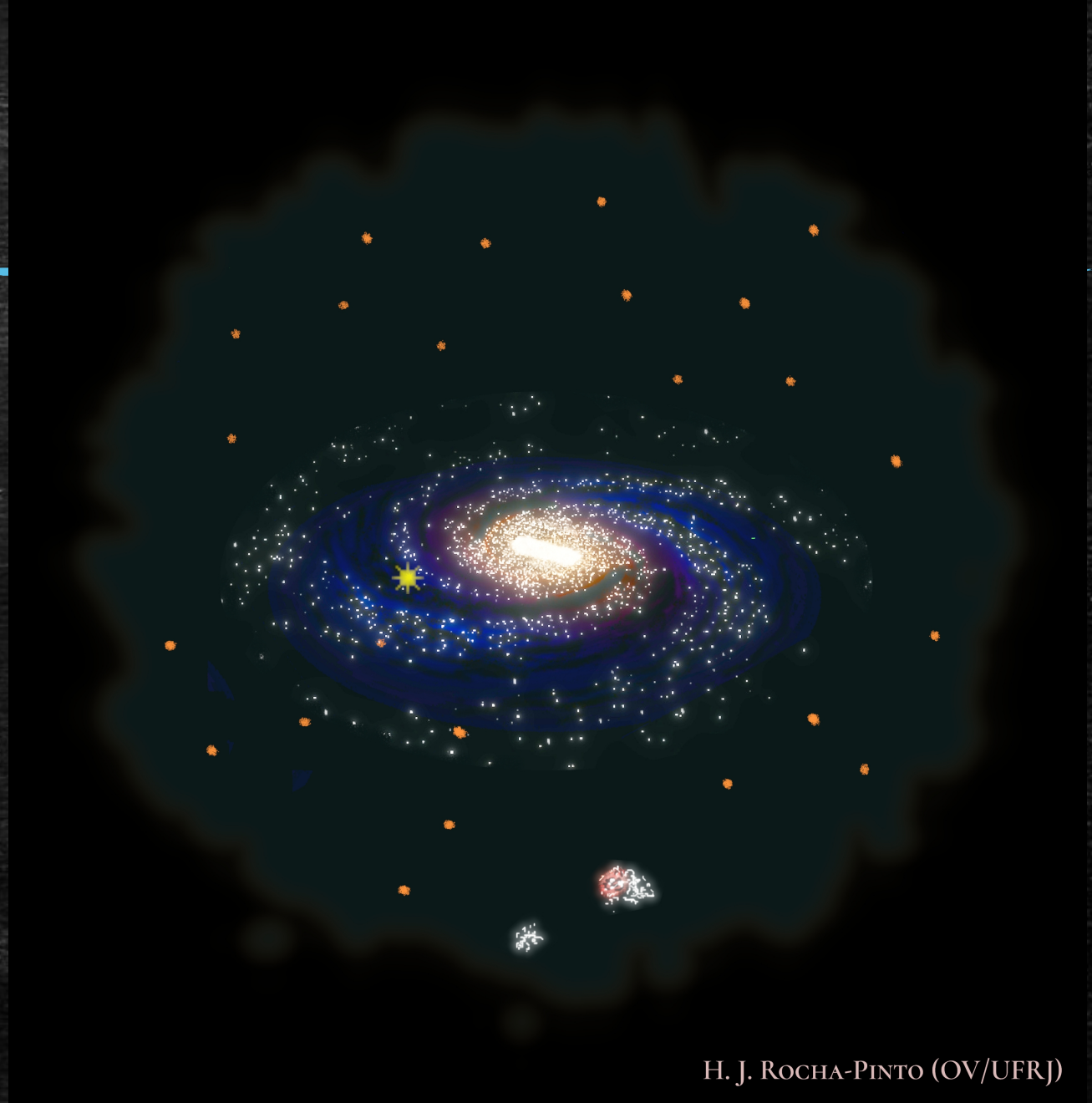


H. J. ROCHA-PINTO (OV/UFRJ)

The Milky Way

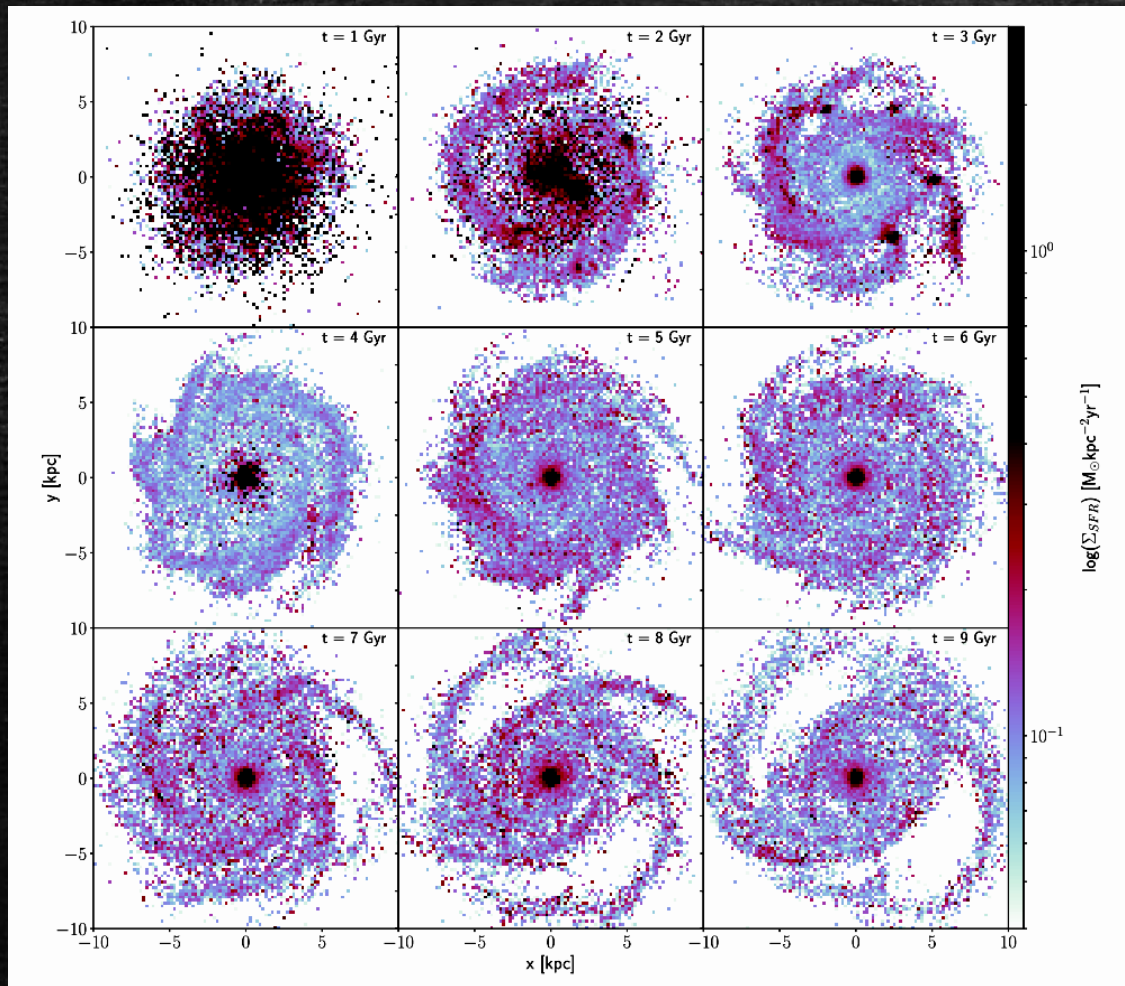
How and when the alpha-rich (thick-) and alpha-poor (thin-) discs form? (e.g. talks by Belokurov, Chiappini, Queiroz, Nepal...)

Do we need the GSE to trigger the alpha-poor disc formation? (e.g. talks by Buder, Fernandez-Alvar...)



H. J. ROCHA-PINTO (OV/UFRJ)

Clumpy formation scenario



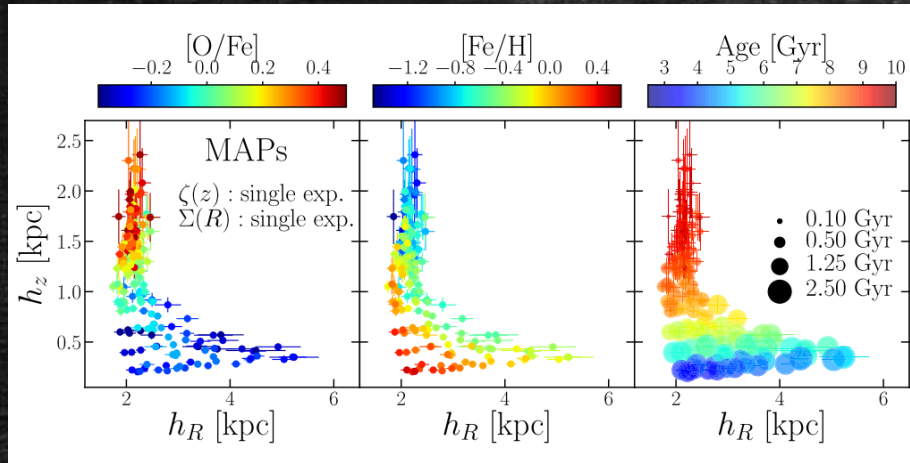
N-body + SPH model ran
with GASOLINE

IC - NFW DM halo + hot gas
corona;

Star formation from the gas
cooling \rightarrow self-consistent
chemical evolution;

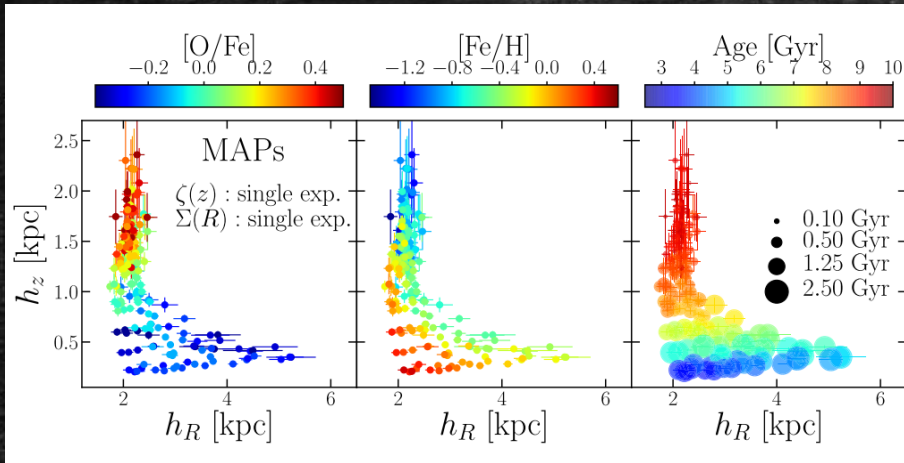
Clarke+2019

Clumpy formation scenario

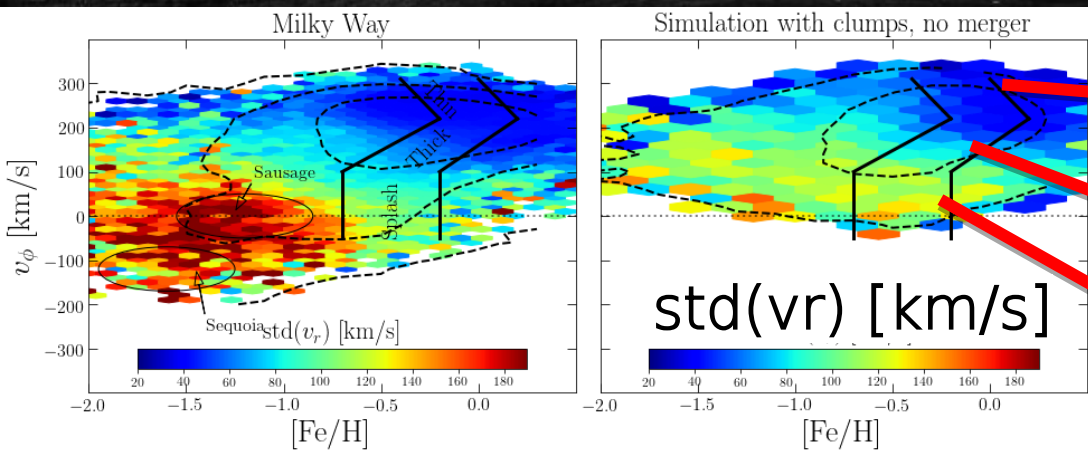


Beraldo e
Silva+20 -
Chemo-
geometric
dichotomy as in
the MW

Clumpy formation scenario



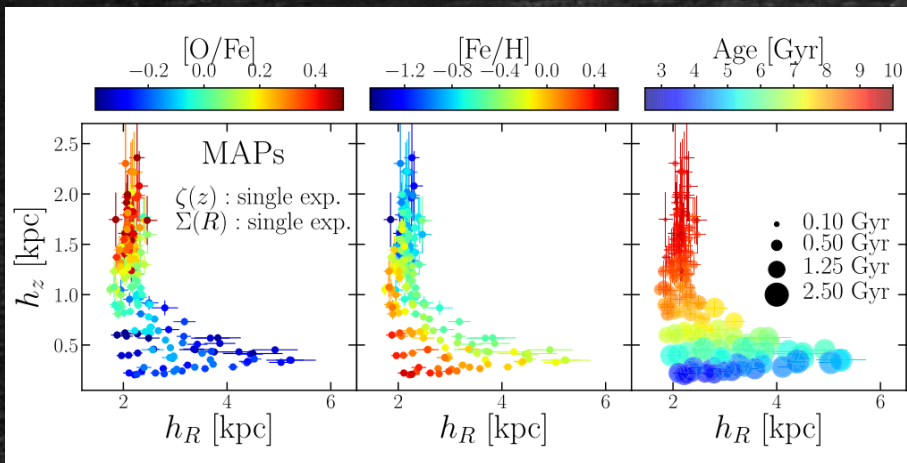
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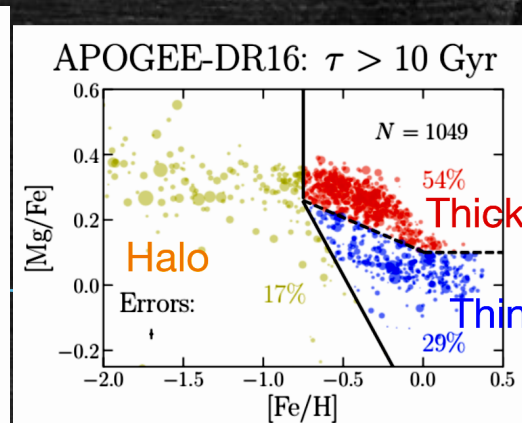
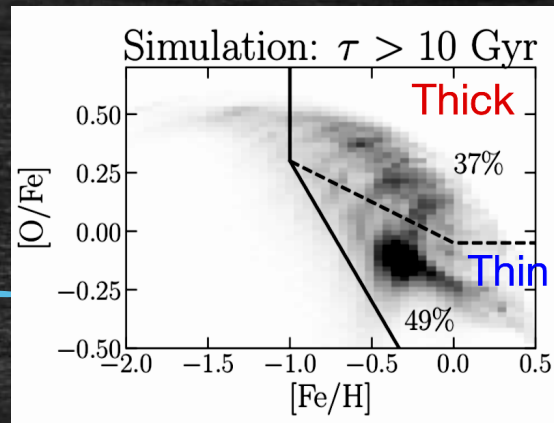
Thin disc
Thick disc
Splash

Amarante+20a – The Splash without a merger (see also Di Matteo+19, Belokurov+20, Liao+24)

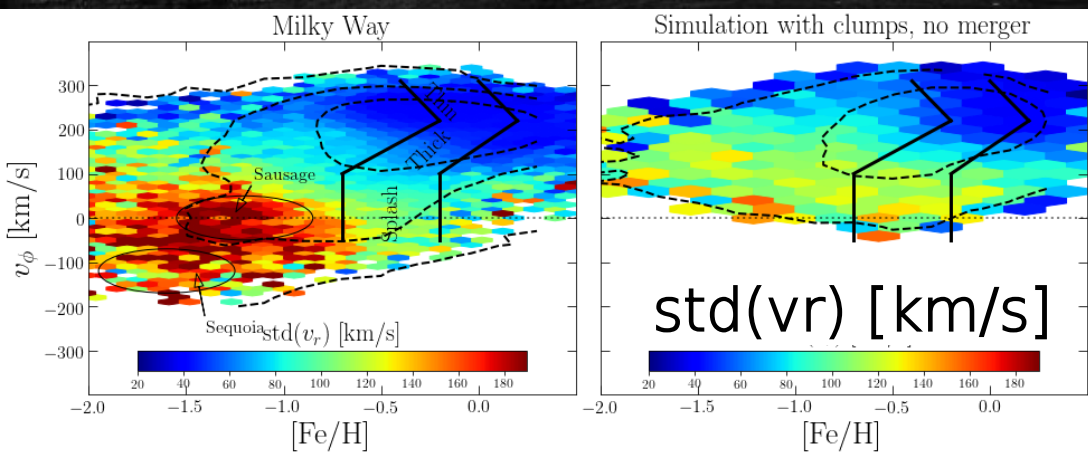
Clumpy formation scenario



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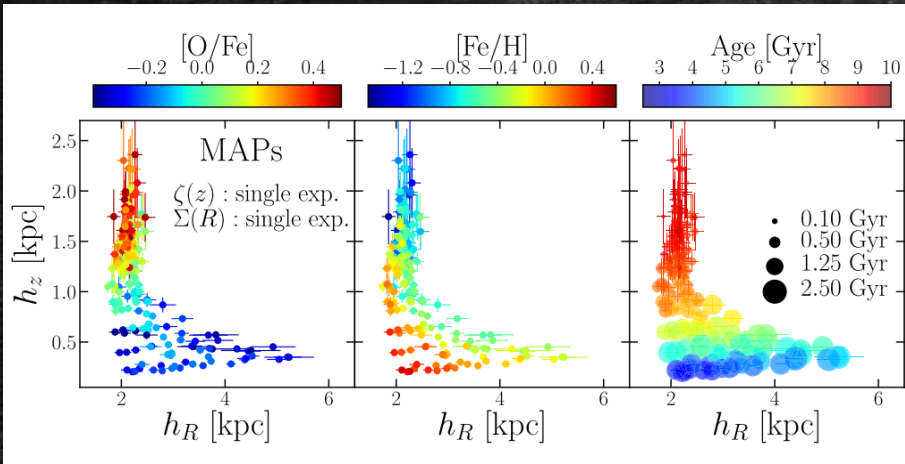


Beraldo e Silva+2021 – Co-formation of the alpha-poor; alpha-rich disc (e.g. Laporte+20, Nepal+24,)

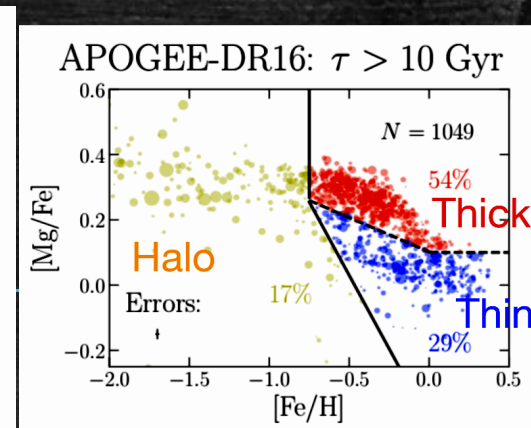
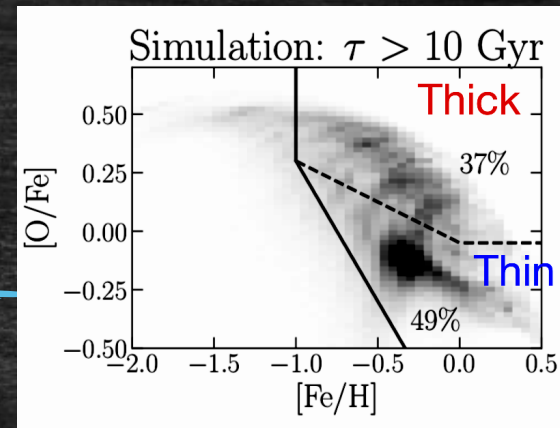


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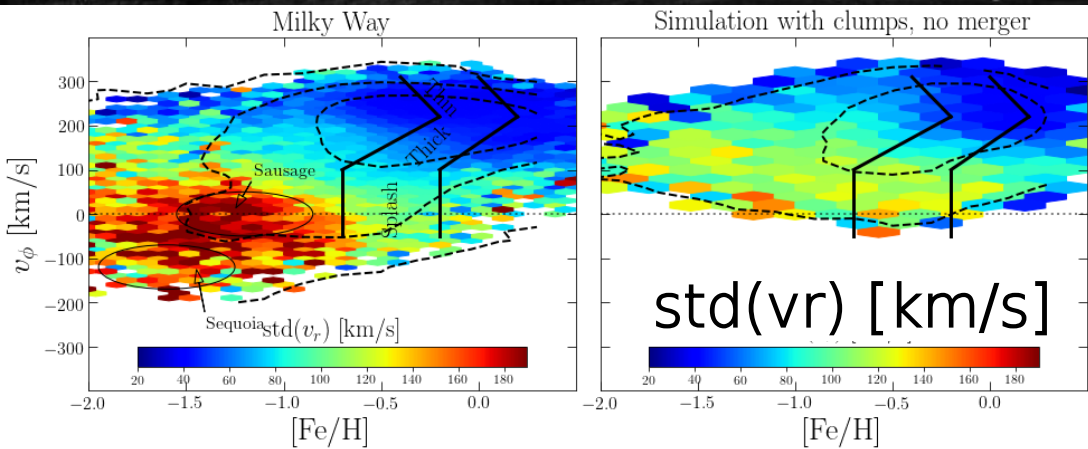
Clumpy formation scenario



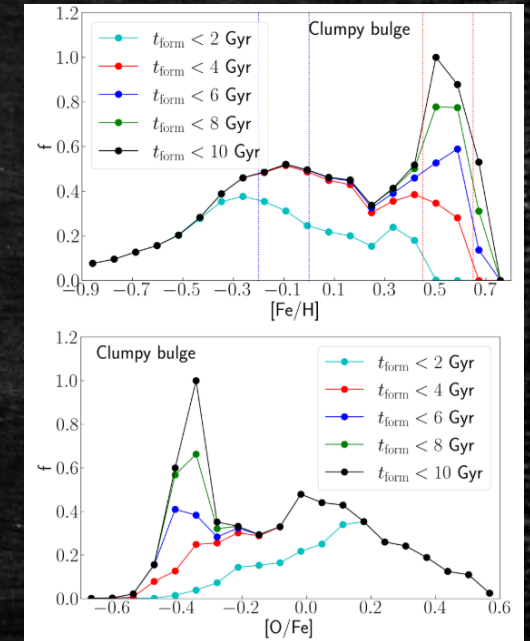
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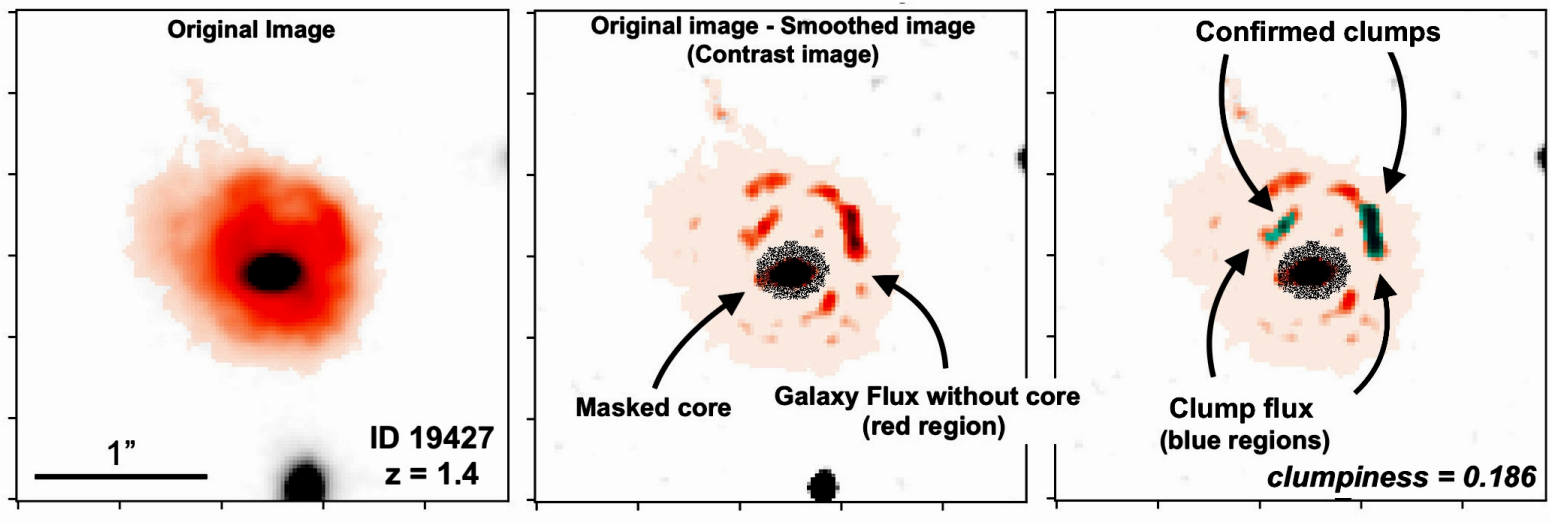


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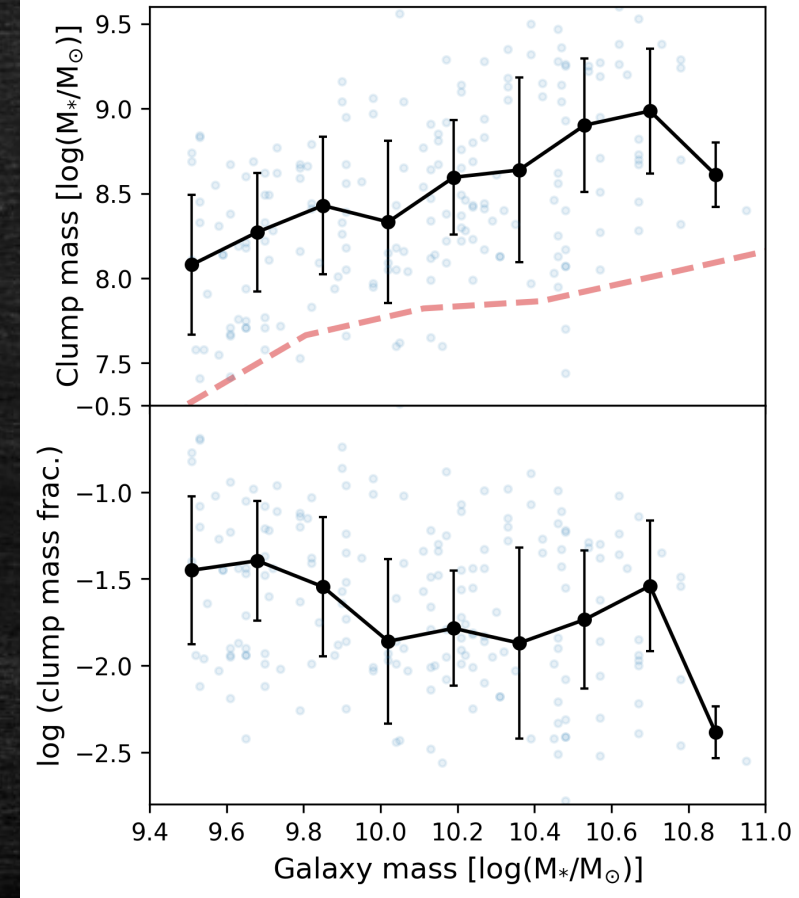


Debattista+2023 – The chemistry of the bulge

Clumpy formation scenario



Kalita+2024a: Clumps at $1 < z < 2$ with JWST; NIR overlap with clumps observed at UV/optical (see e.g. Guo+2018) \rightarrow features in the stellar-mass distribution



Kalita+2024b

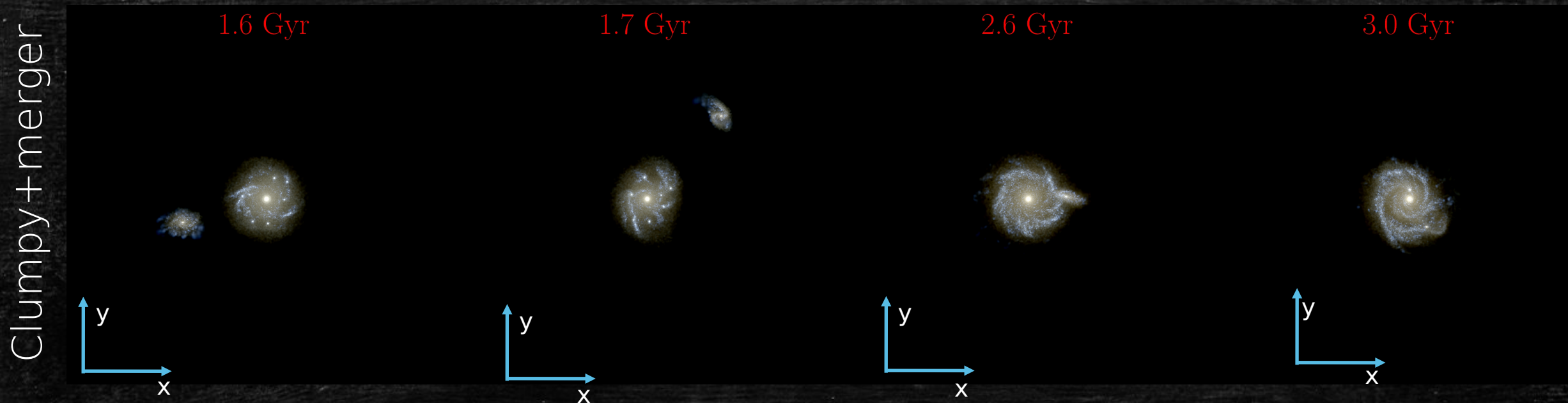
Open Questions

Open Questions

- What are the real effects of a merger in an existing disc?
- Did the Milky Way experience a clumpy formation in its first Gyrs?
- Is it possible to disentangle the effects of the merger from an early clumpy phase?

Gaia-EncelAdus-Sausage Timing, chemistRy and Orbit library

GASTRO library: a N-body + Smoothed-particle hydrodynamics (SPH) suite of simulations to be publicly available



Gaia-EncelAdus-Sausage Timing, chemistRy and Orbit library

What do we want to match?

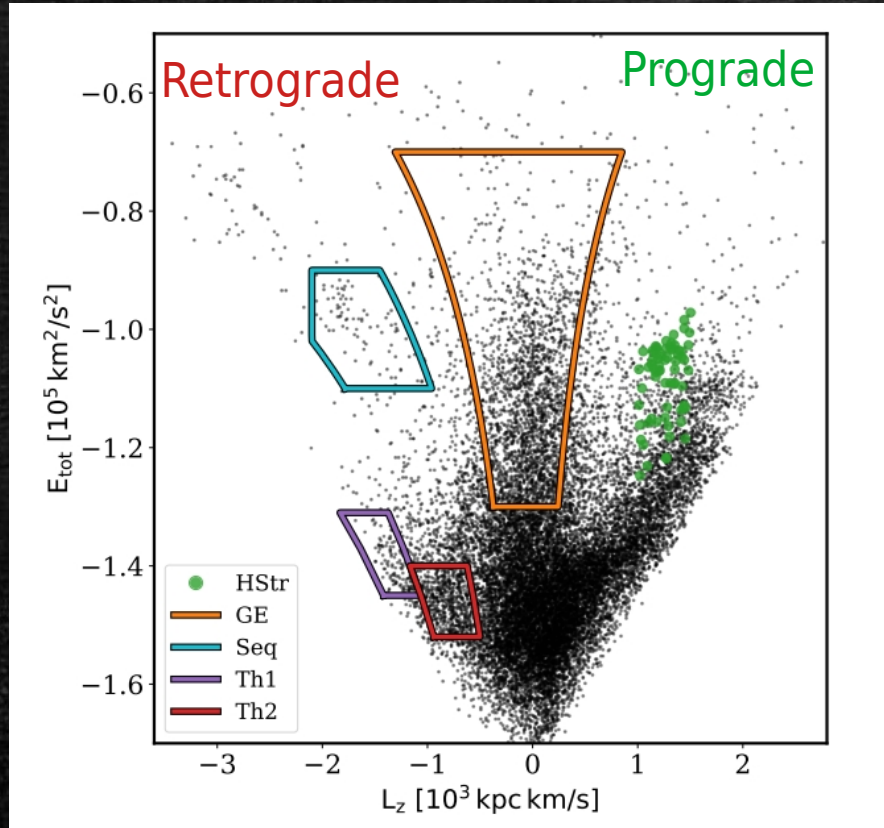
- Milky Way features:
 - Geometrical and chemical thin and thick disc;
 - Chemo-kinematics interface between Splash and inner stellar halo;
 - Chemodynamical substructures in the inner stellar halo;

Gaia-EncelAdus-Sausage Timing, chemistRy and Orbit library

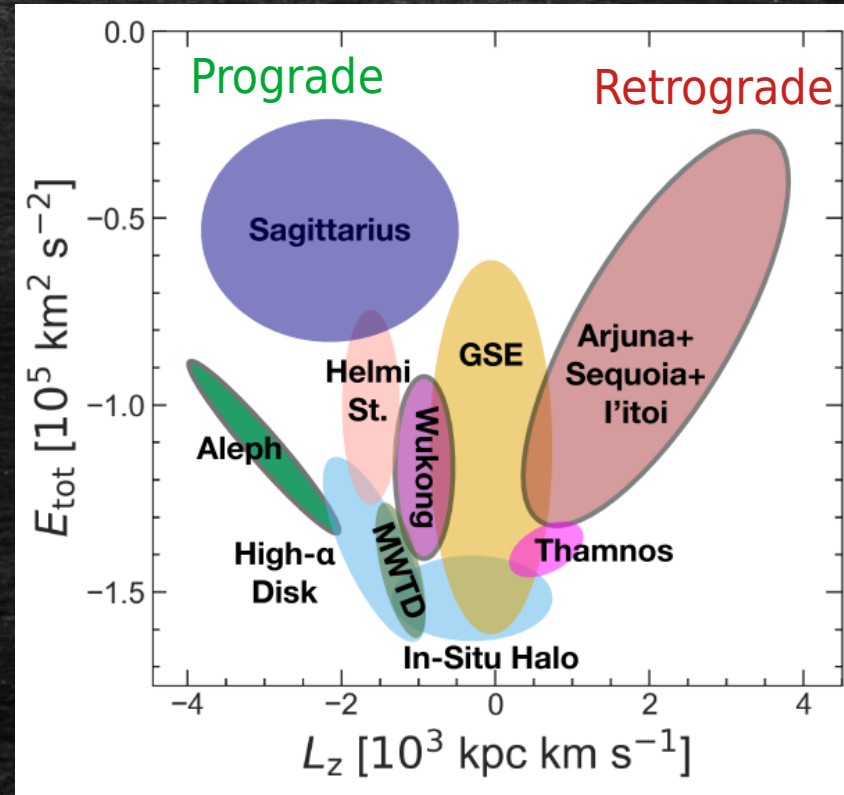
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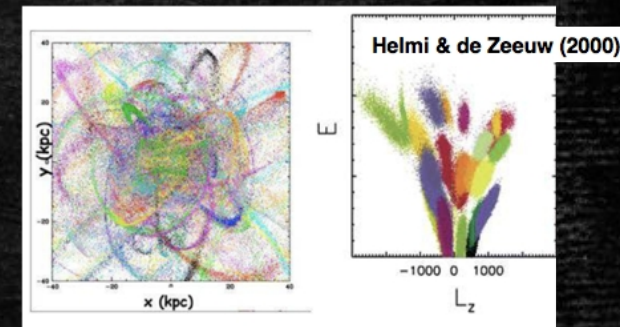
MW's stellar halo chemodynamical substructures



Balbinot+2021, nearby halo, $r_{\text{gal}} < 2.5 \text{ kpc}$ in *Gaia*EDR3

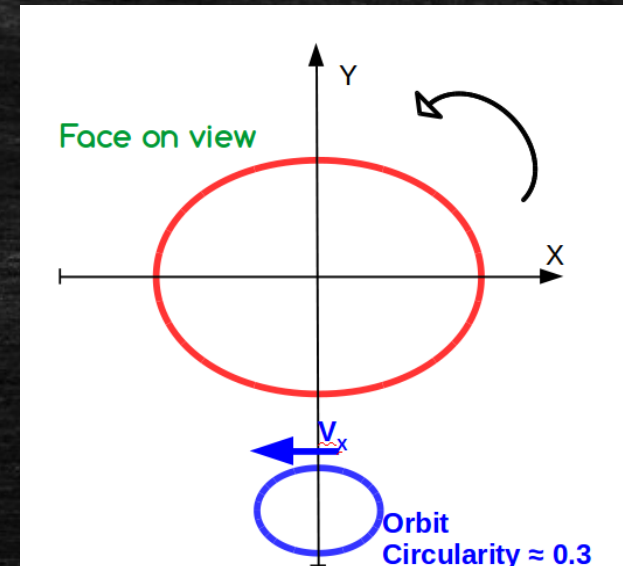
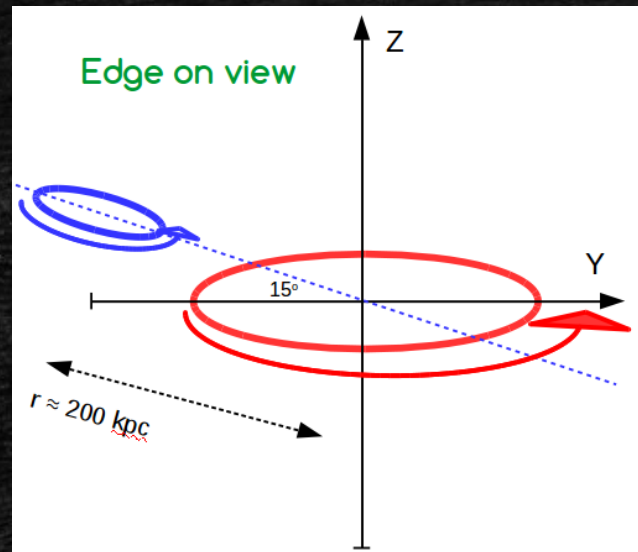


Naidu+2020, $r_{\text{gal}} \sim 25 \text{ kpc}$, H3 survey



GASTRO I: Initial set up

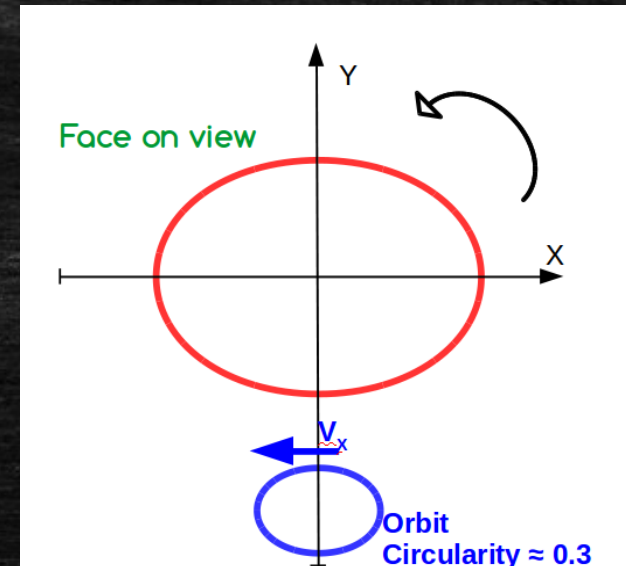
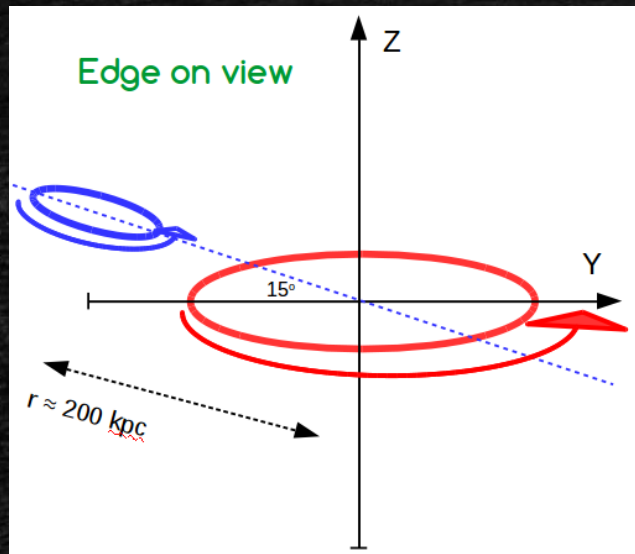
Sims are set up with a NFW DM halo and a hot gas corona. Stars form directly from the gas \rightarrow self-consistent chemical evolution



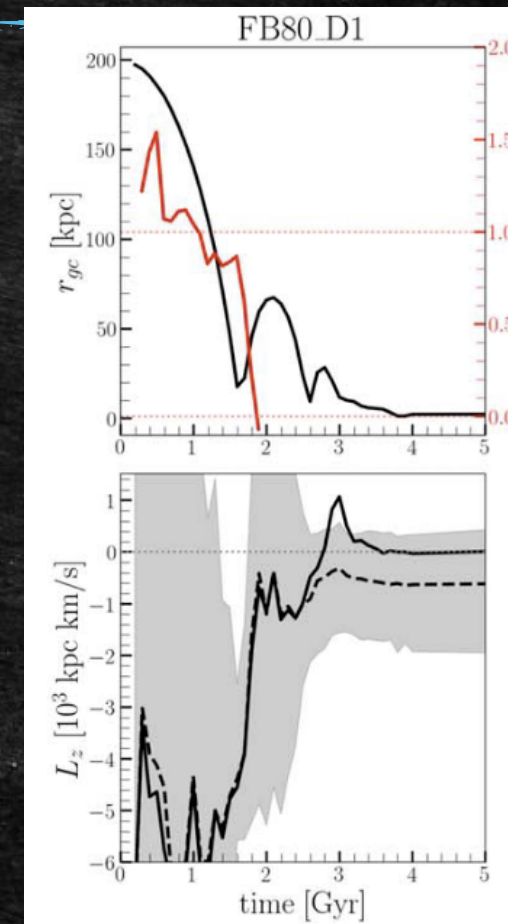
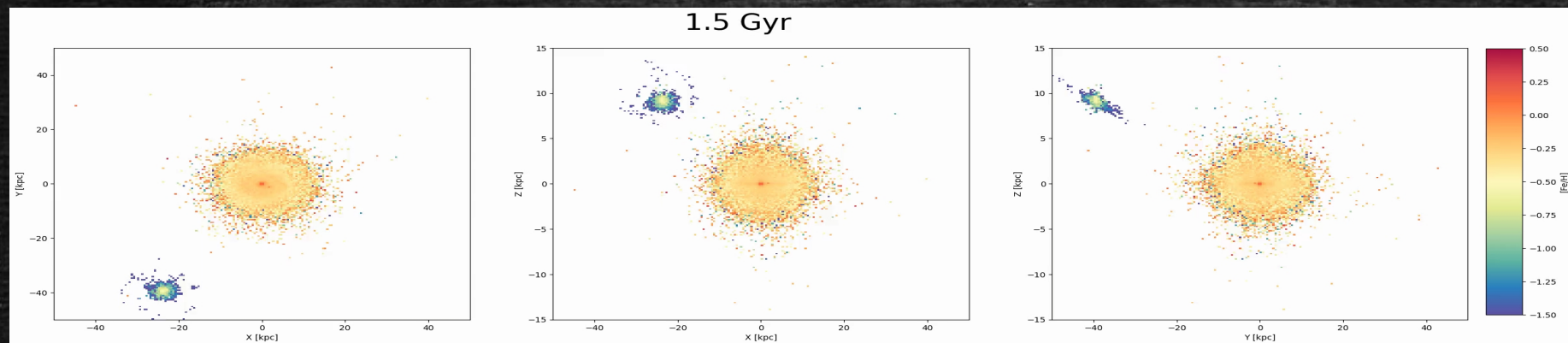
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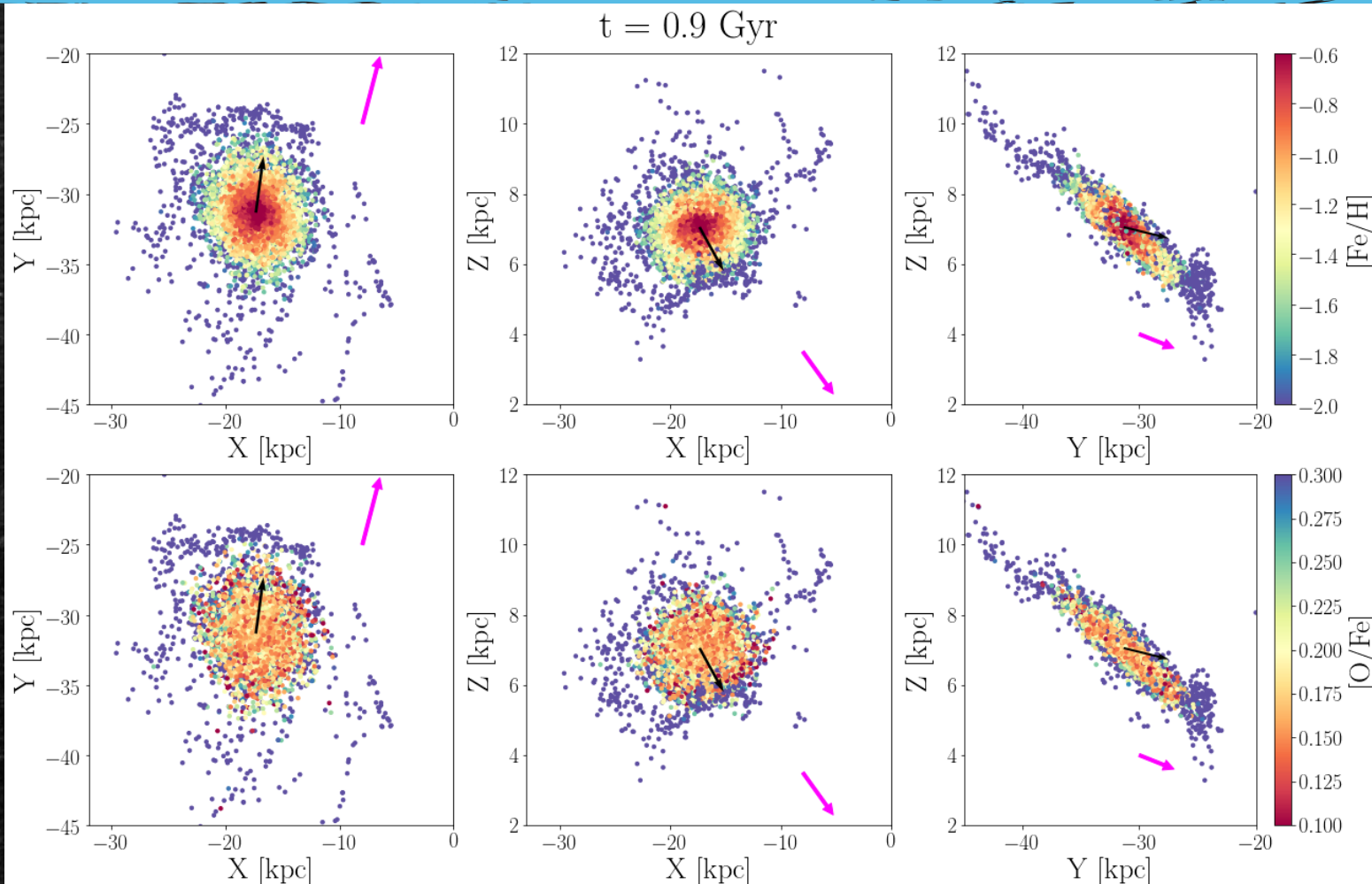
Merger completes at $\sim 3\text{Gyrs}$; with $M_* \sim 6 \times 10^8 M_{\text{sun}}$



GASTRO I: dwarf evolution



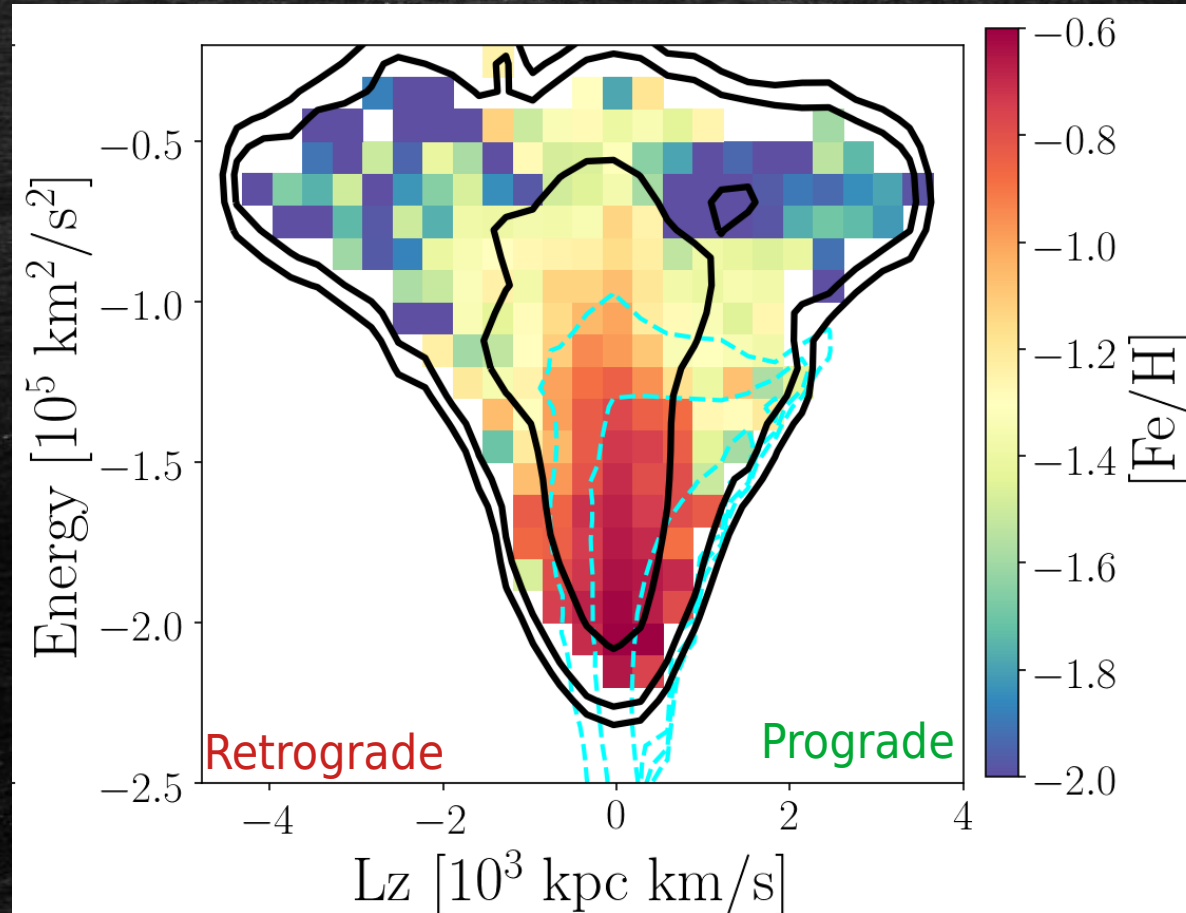
GASTRO I: dwarf evolution



$t=0.9$ Gyr

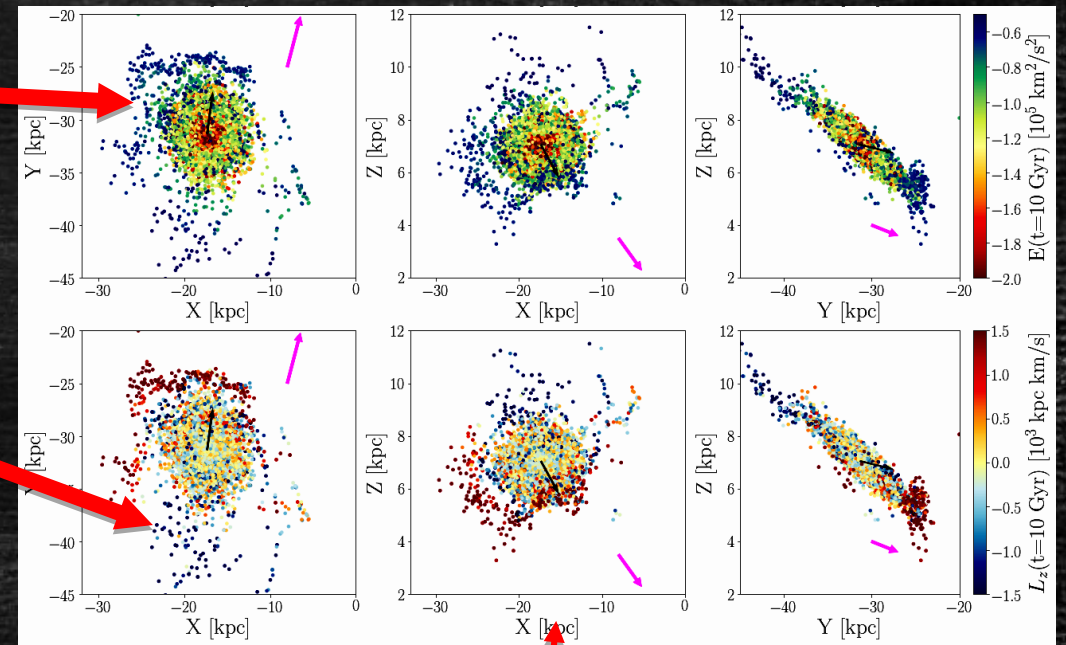
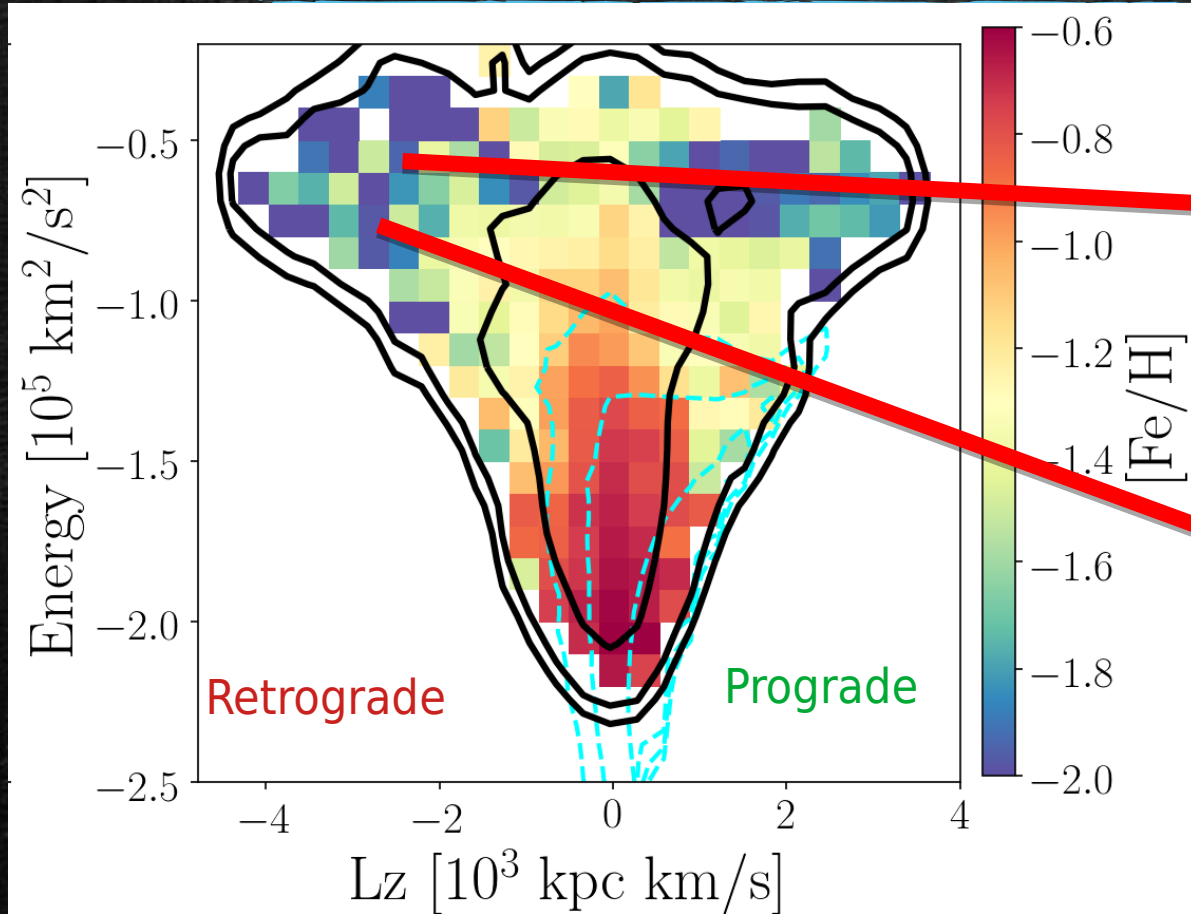
Amarante+22

GASTRO I: Lz-Energy - t=10 Gyr



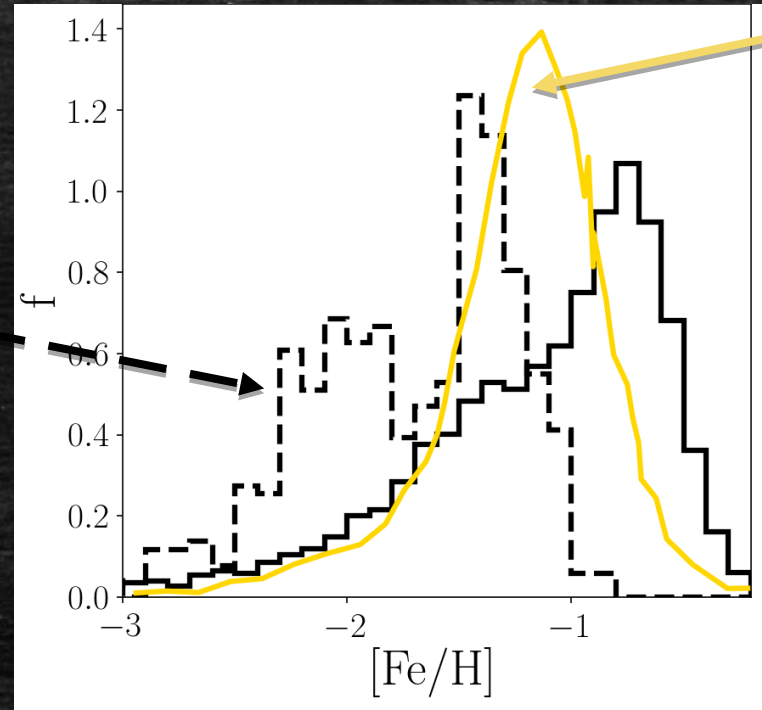
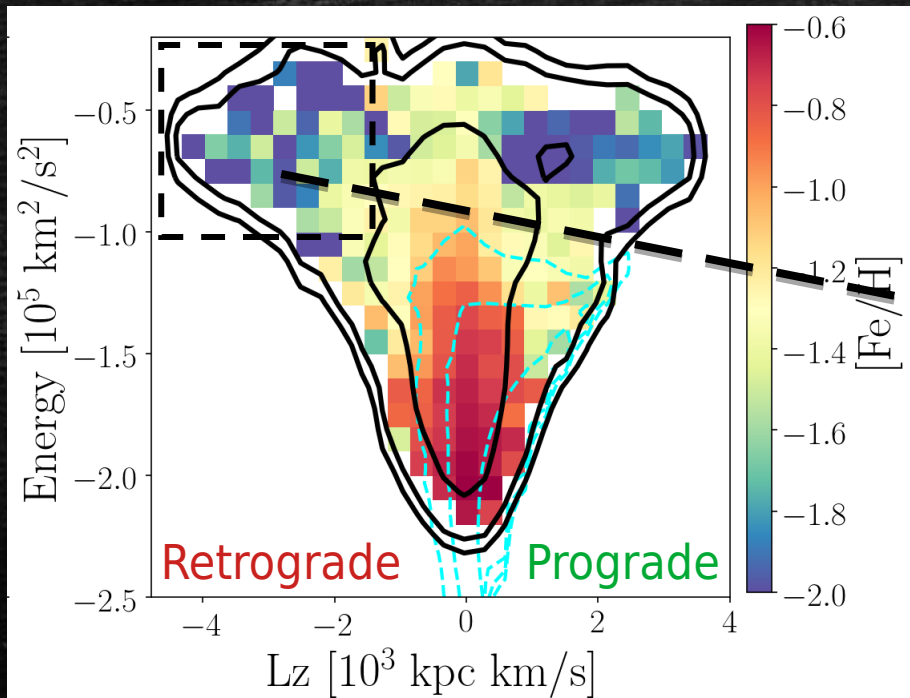
Amarante+22

GASTRO I: Lz-Energy - t=10 Gyr



Amarante+22

GASTRO I: Lz-Energy - t=10 Gyr

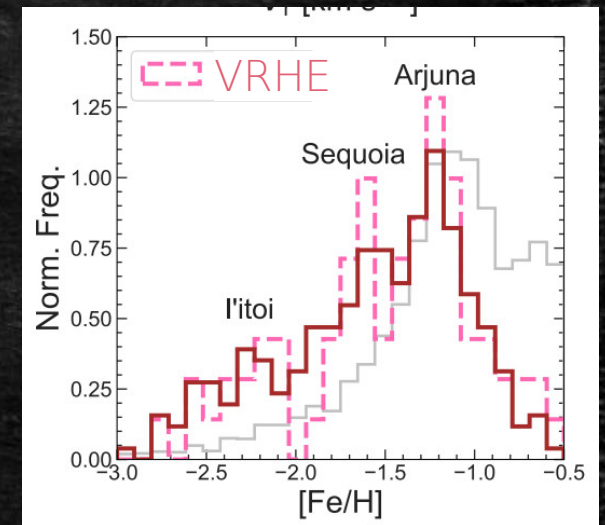
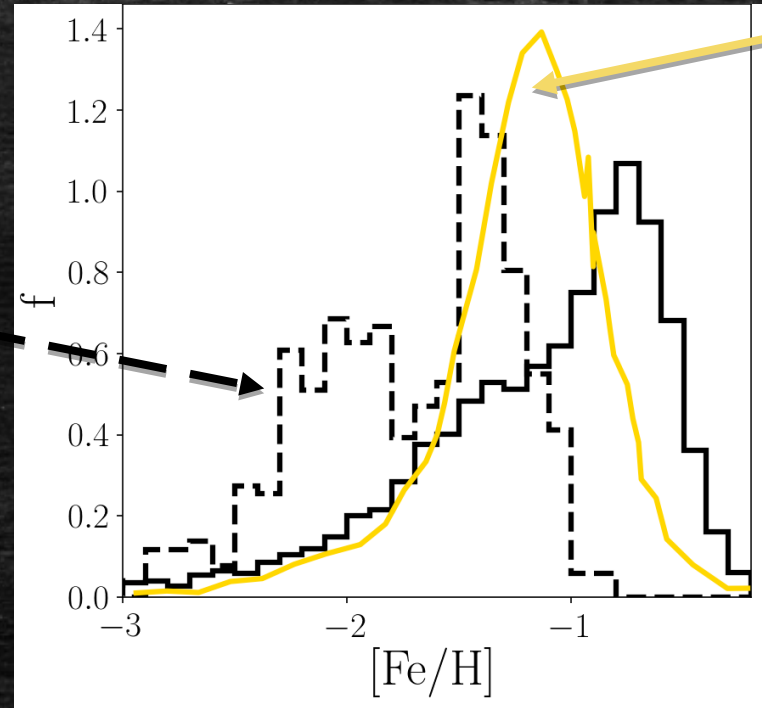
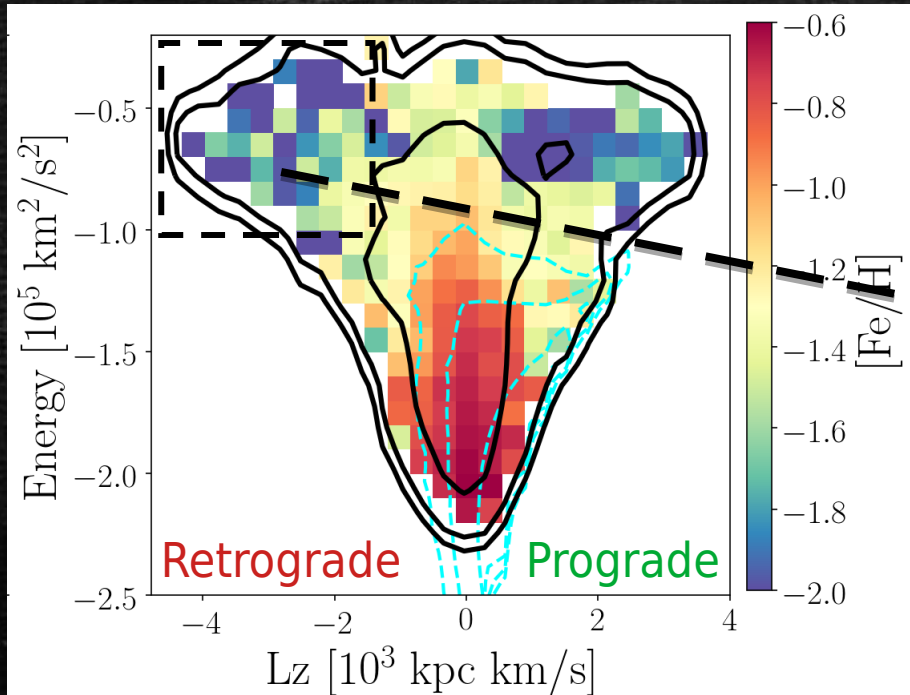


H3 Survey,
Naidu+2020

Amarante+22

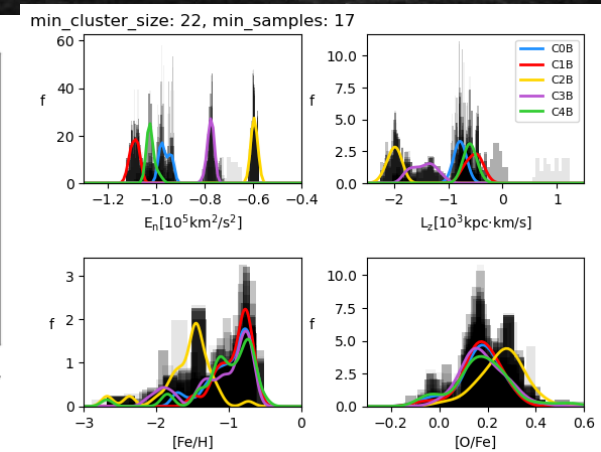
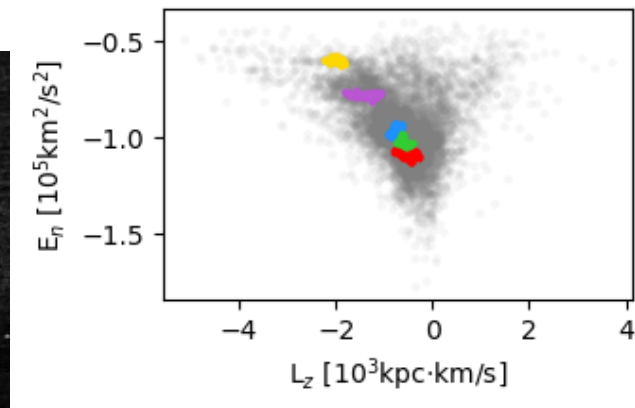
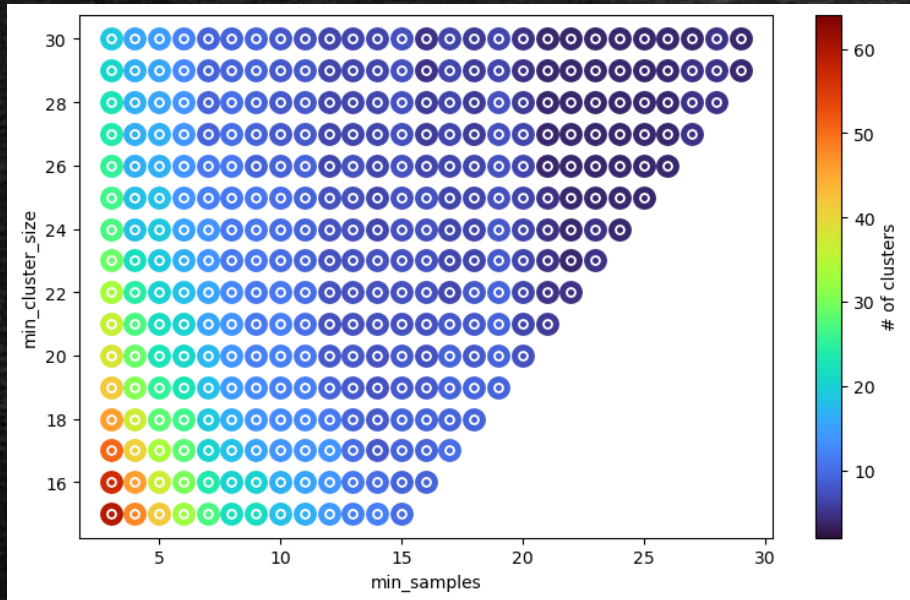
GASTRO I: Lz-Energy - t=10 Gyr

H3 Survey,
Naidu+2020



Naidu+2020, H3 survey

GASTRO with HDBSCAN - by Mónica Arroyo Argenté

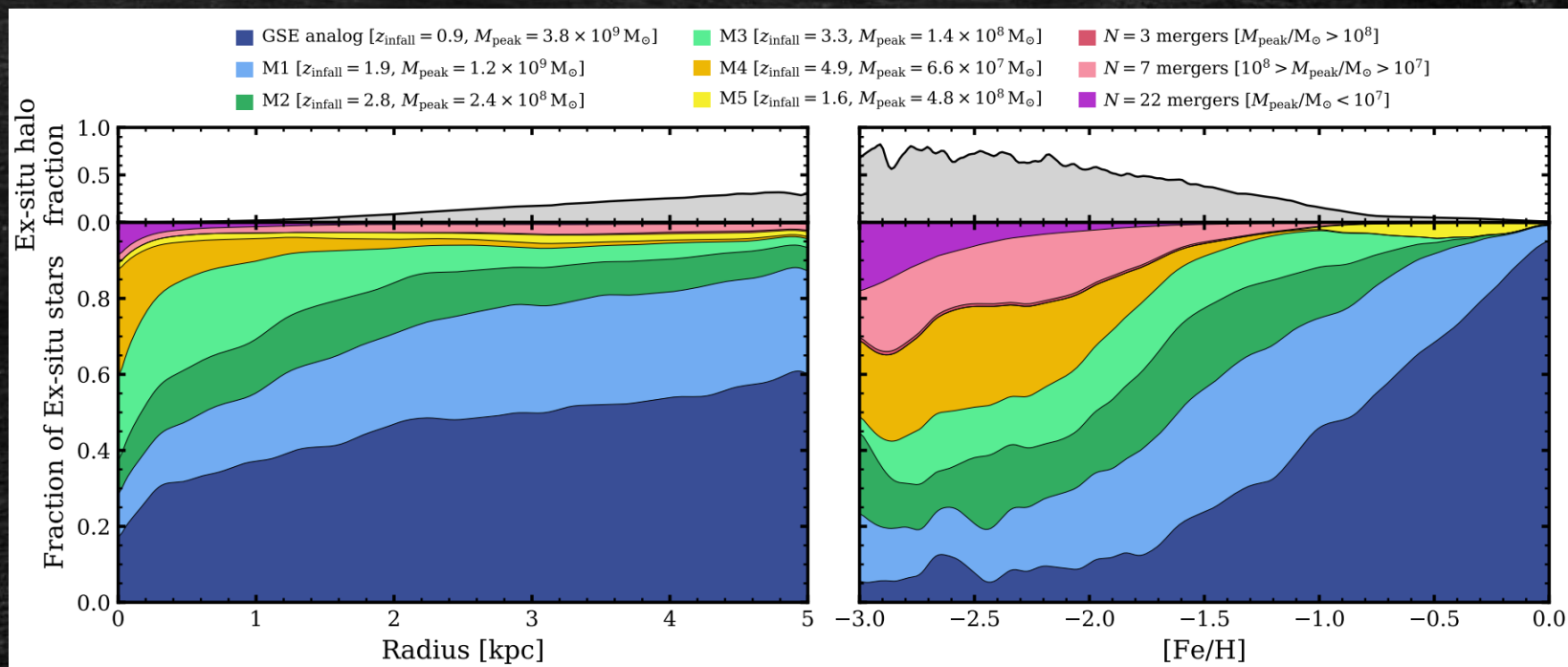


How do we find the earliest and small accreted satellites?

Cosmological simulations suggest that the inner stellar halo is dominated by on average three mergers (Fattahi+2020)

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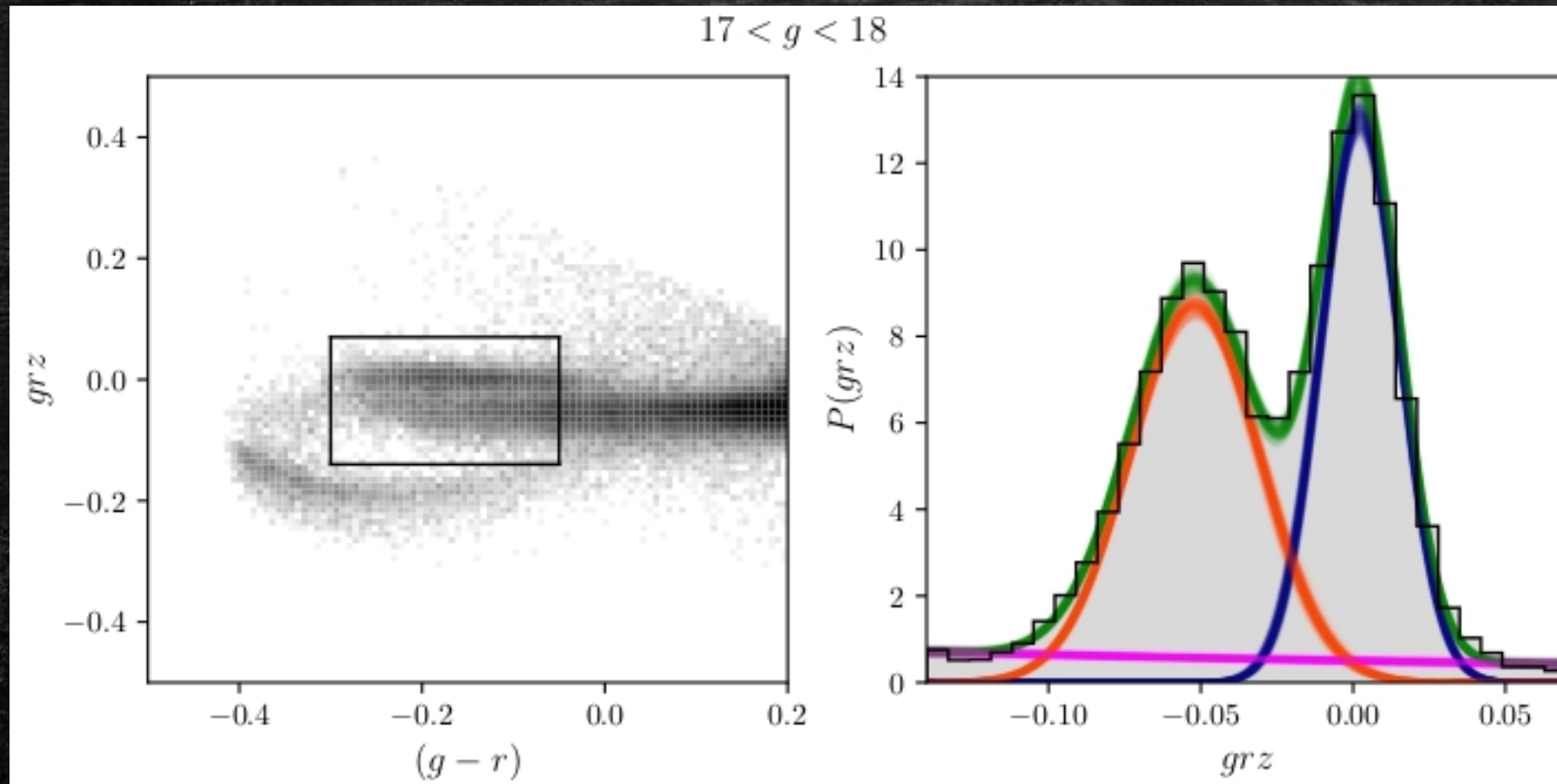
Orkney+2023

Mapping the anisotropic Galactic stellar halo with Blue Horizontal Branch stars

Amarante, Koposov & Laporte (2024) - arxiv: 2404.09825

Mapping the anisotropic Galactic stellar halo with Blue Horizontal Branch stars

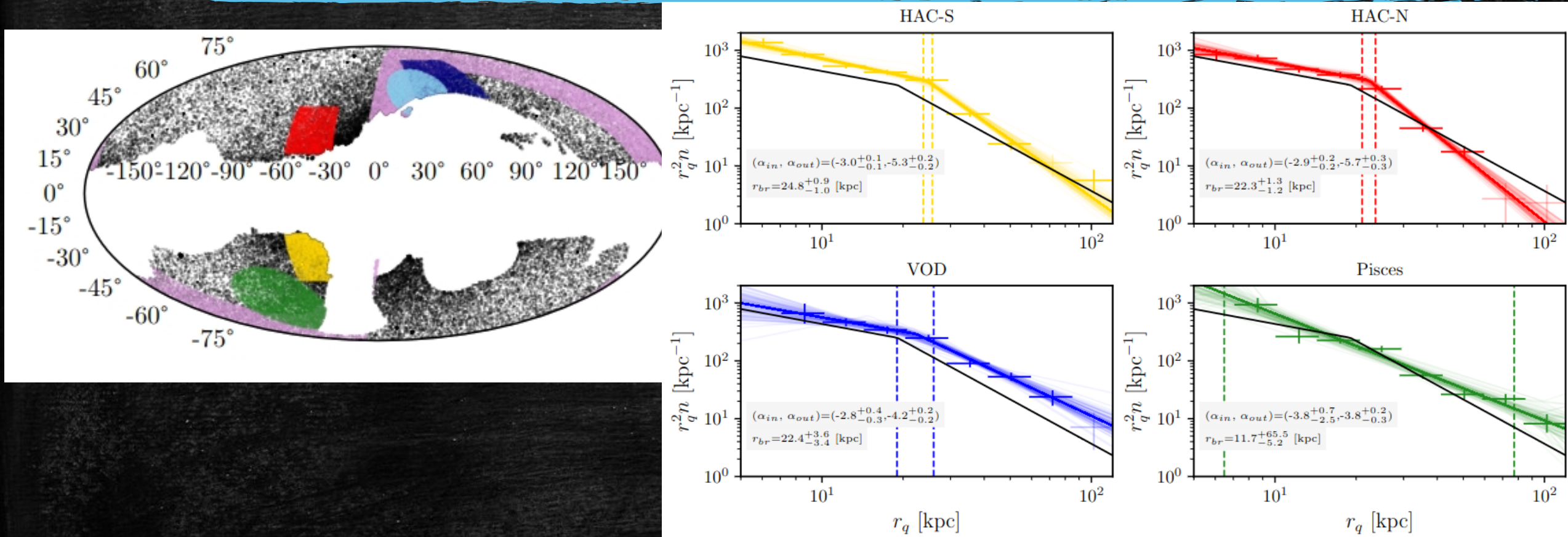
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See Li+19

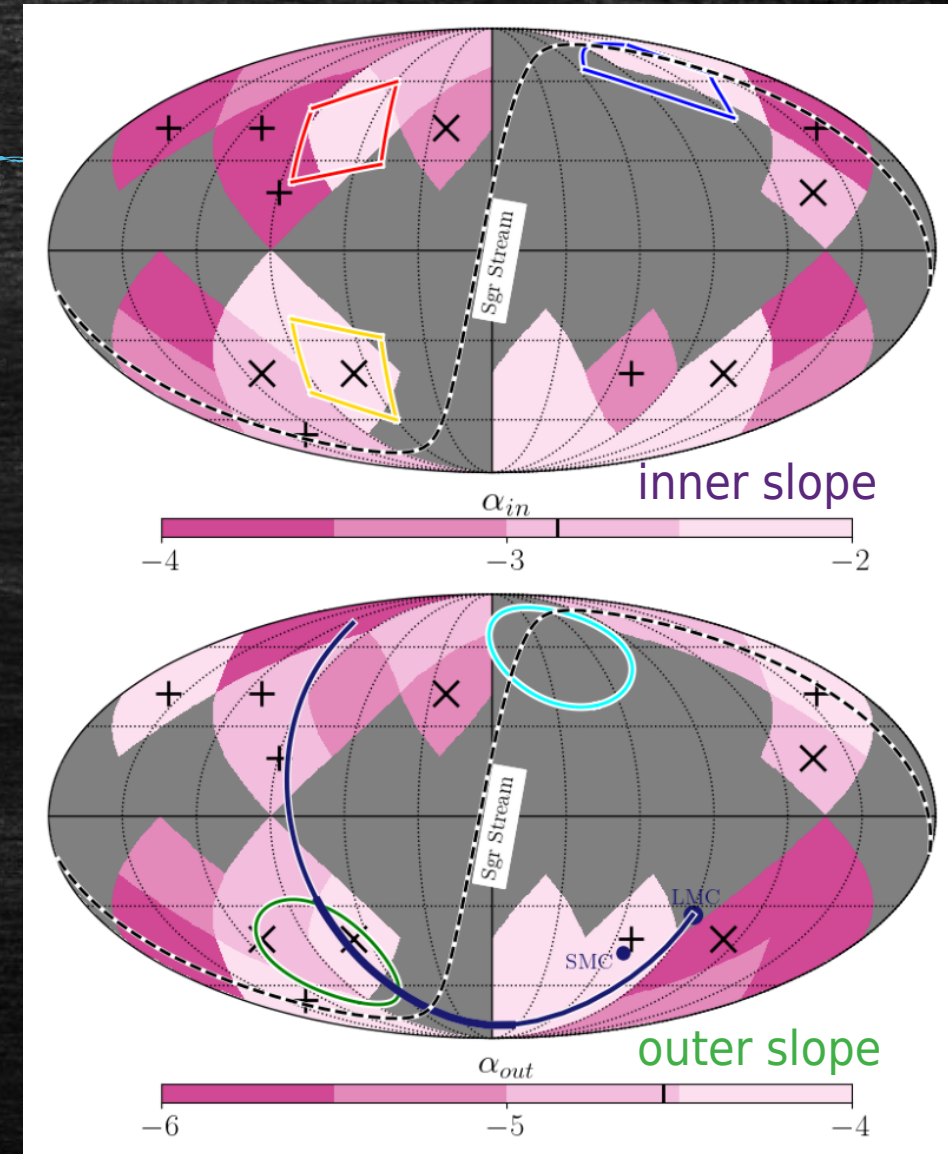
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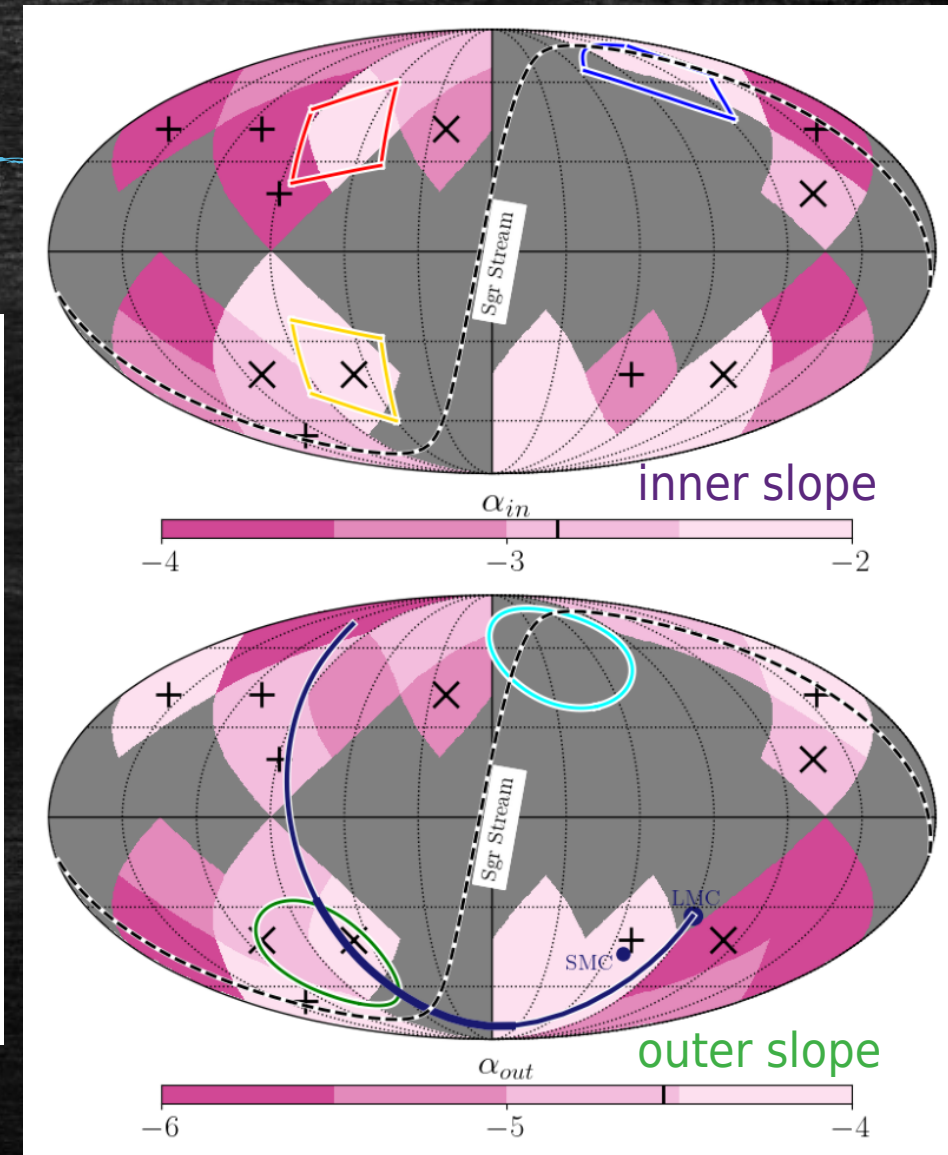
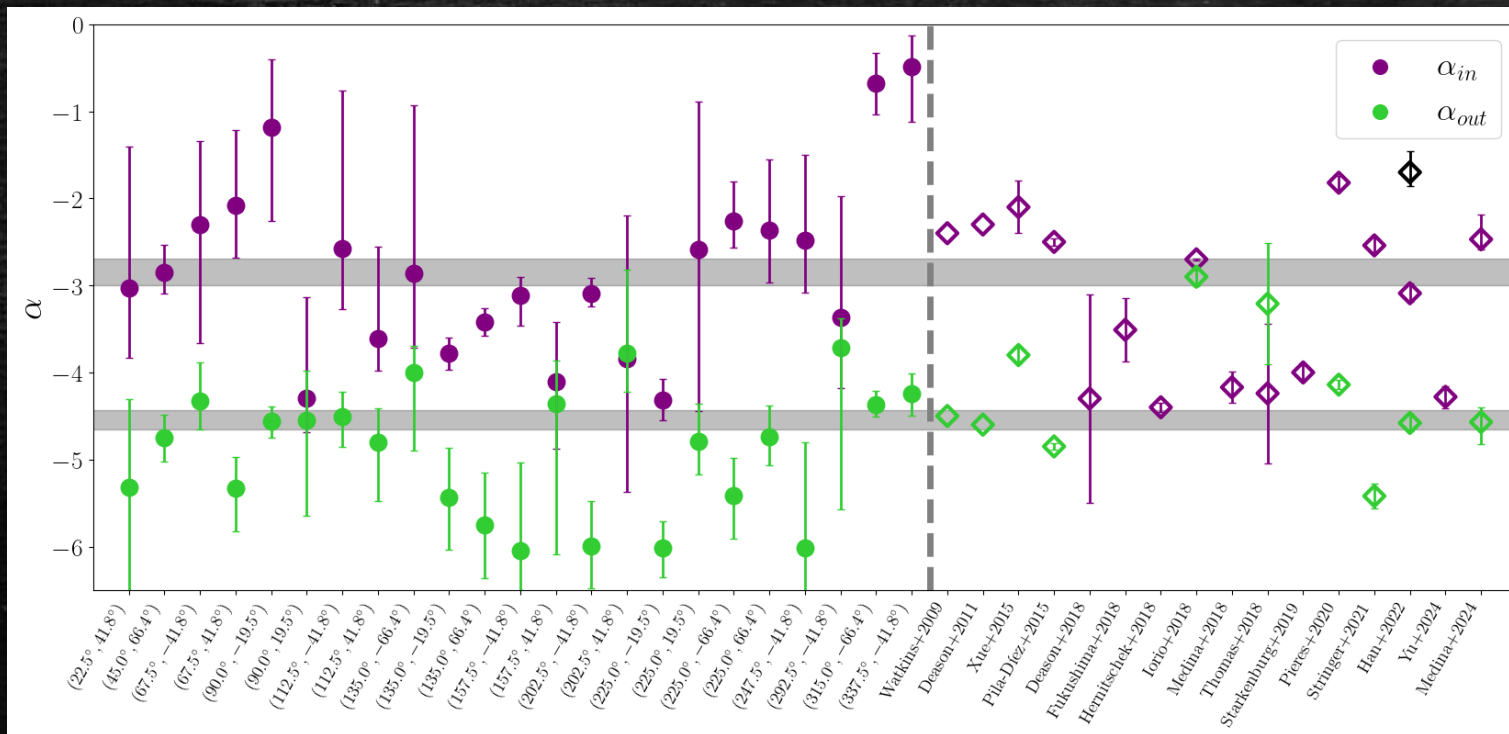
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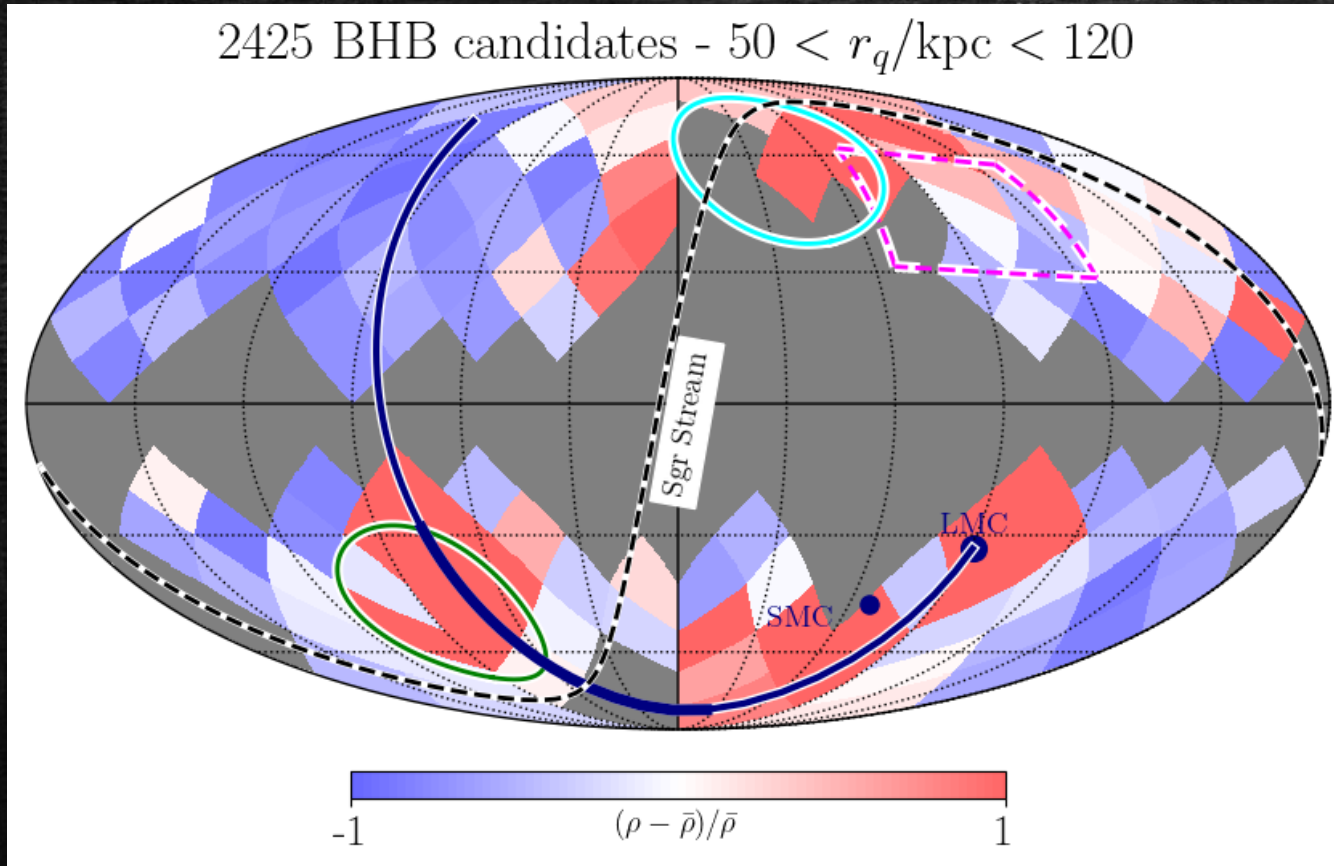
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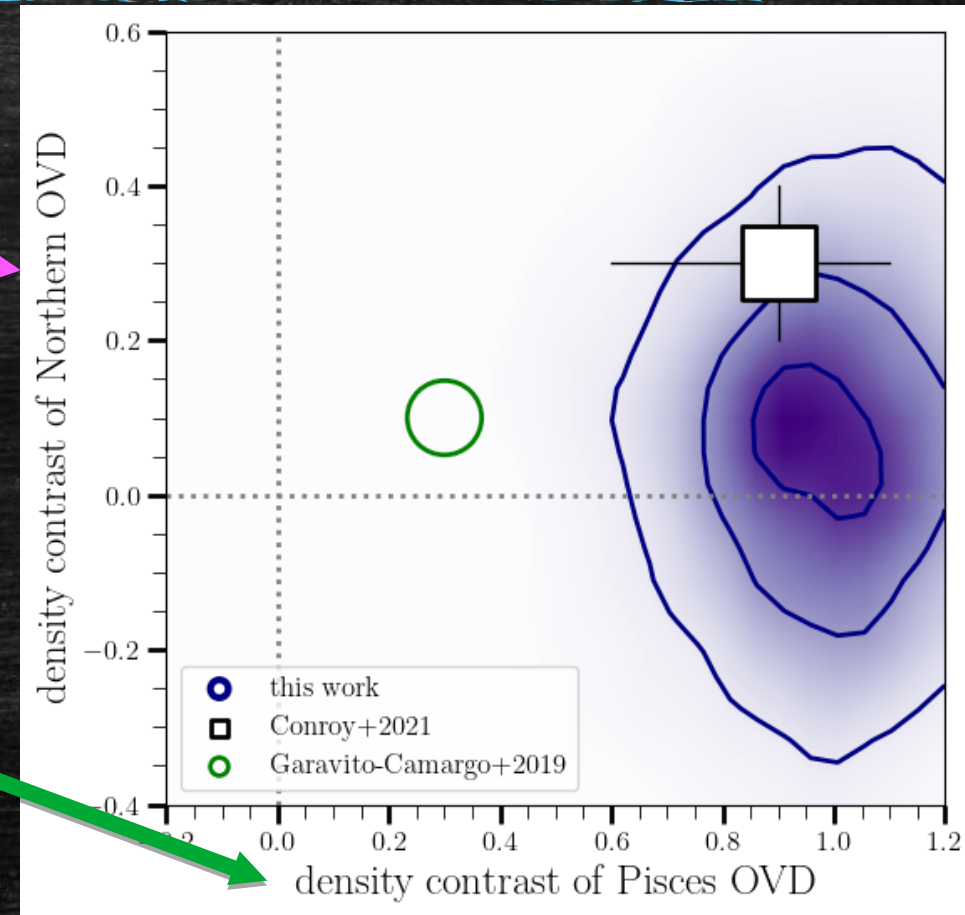
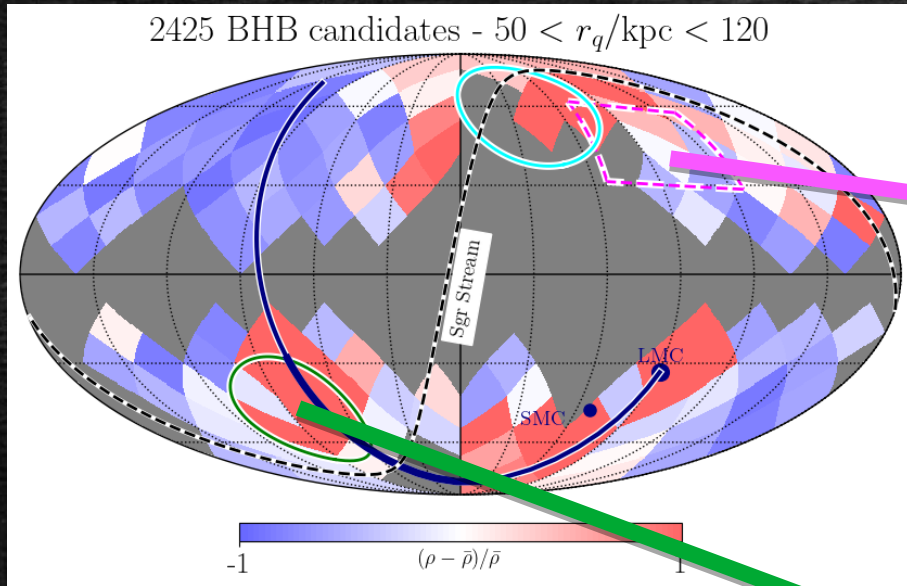
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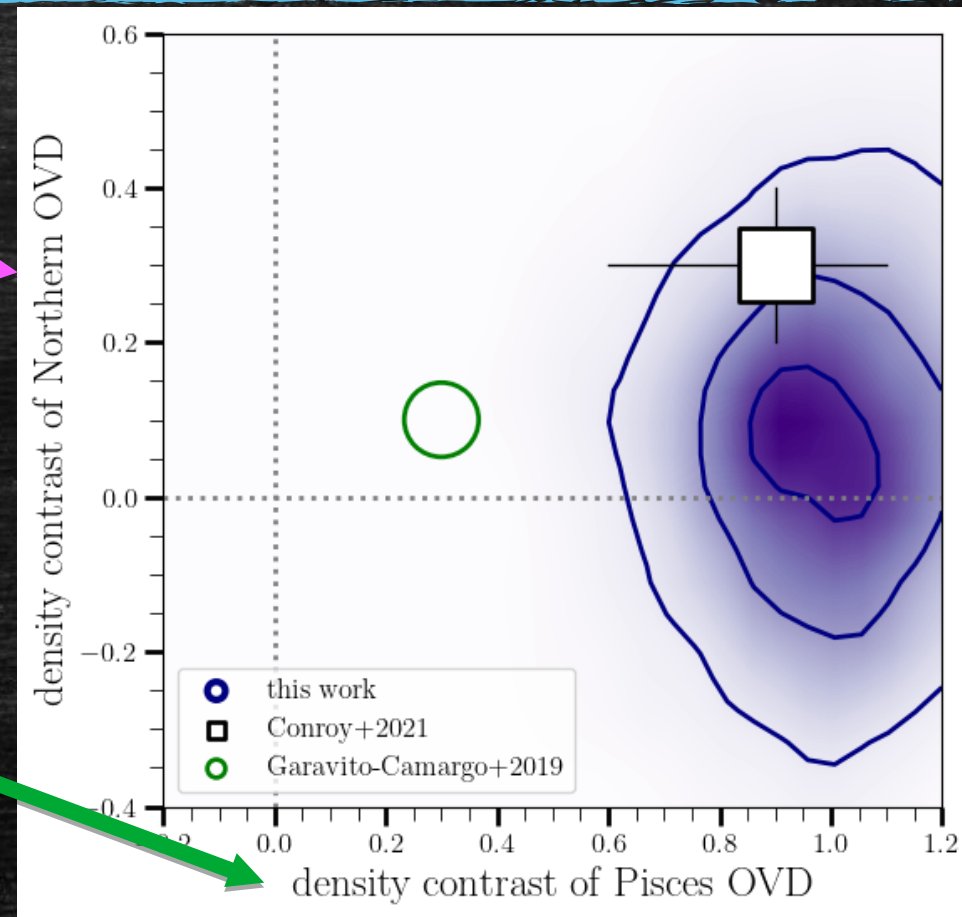
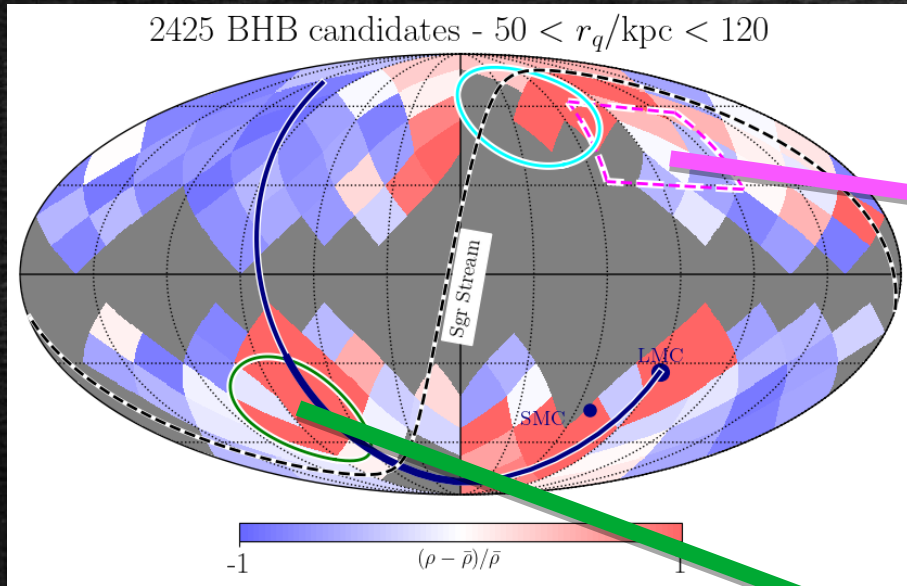
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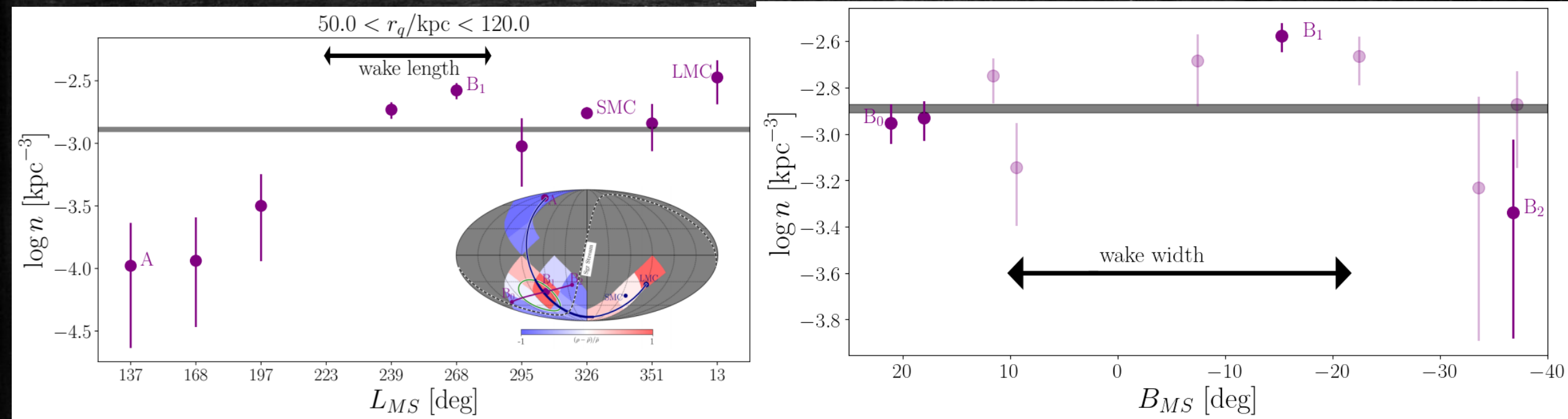
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Chandra's talk and the detection of the global wake on the velocity space (Chandra+24)

Mapping the anisotropic Galactic stellar halo with Blue Horizontal Branch stars

Amarante, Koposov & Laporte (2024) - arxiv: 2404.09825



Important constraints for simulations (e.g. Garavito-Camargo+19, Vasiliev+23)

Conclusions

Simulations → observations

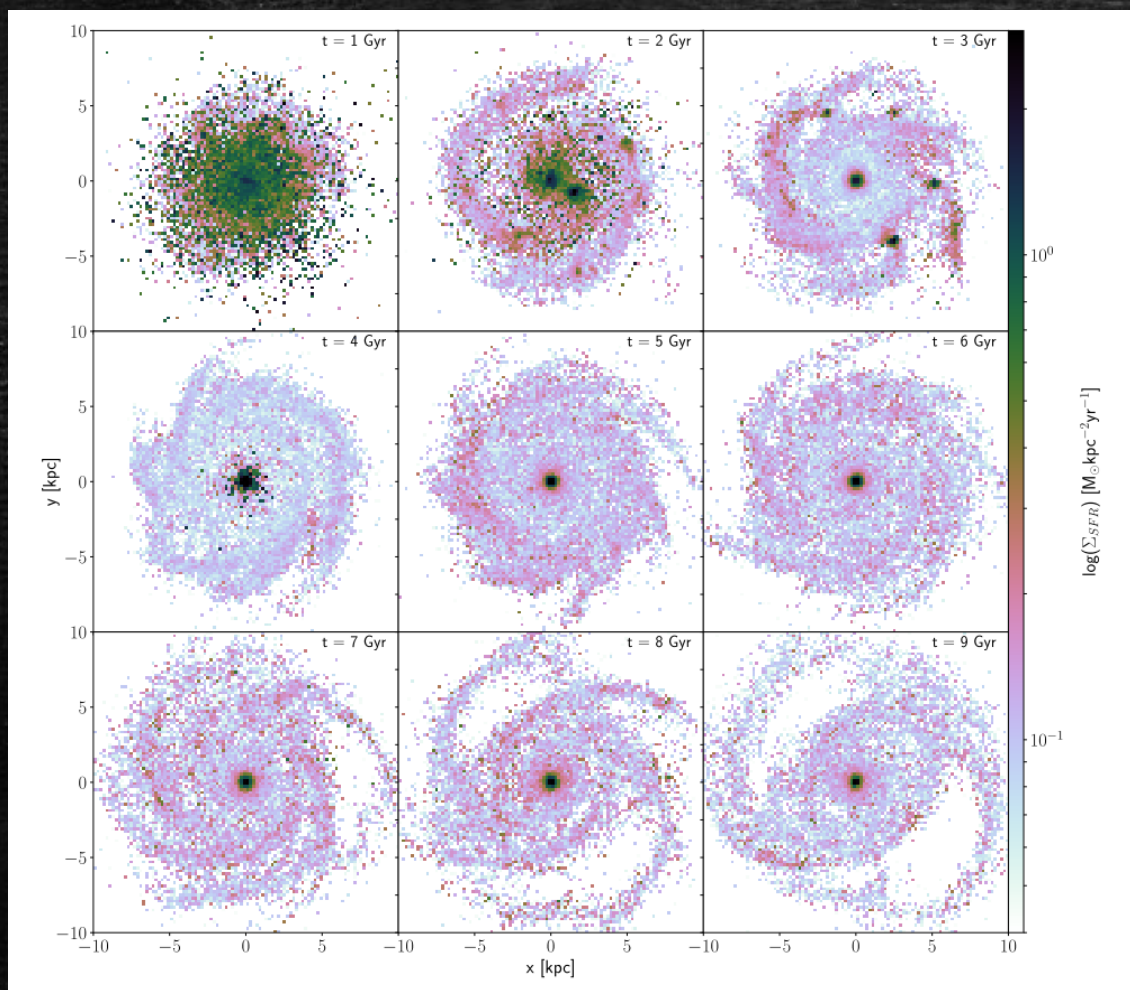
- Clumpy formation scenario can account for the geometrical and chemical thin and thick disc (Clarke+19, Beraldo e Silva+20), Splash-like population (Amarante+20), the presence of old thin disc stars in the SN (Beraldo e Silva+21) and the chemistry of the MW's bulge (Debattista+23);
- GSE-like merger produces a rich chemodynamical space and can conceal other substructures found in the MW (e.g. Khoperskov+23, Mori+24):
- For instance, Arjuna, Sequoia and I'tói, the very retrograde high energy accreted stars, are a natural consequence of a GSE-like merger; (high-res spectroscopic data as a path to disentangle this, e.g. Matsuno's talk)

Observations → simulations

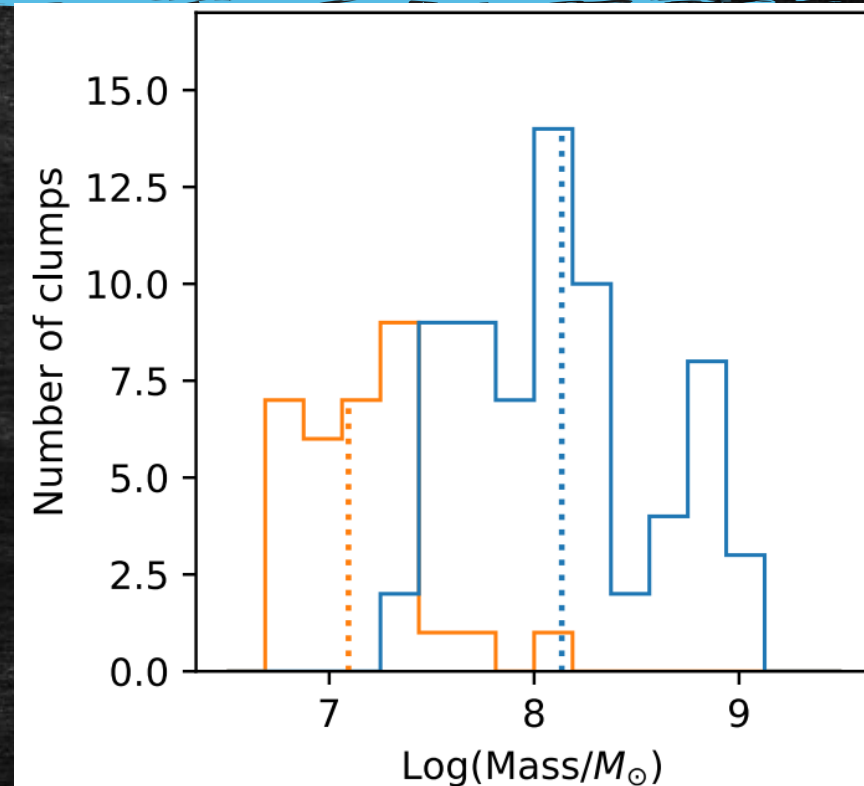
- Strong evidence for an anisotropic stellar halo, indicated by different steepness of the density profile and by $\sim 20\%$ of the sky containing $\sim 55\%$ of BHB stars at $r > 50$ kpc (how can this potentially affect the stellar OVDs caused by the MW-LMC interaction?)
- Pisces OVD extension would correspond to a wake width of ~ 32 kpc at a distance of ~ 70 kpc (possible constraint to the MW-LMC models);
- We confirm the overdensity in the Pisces region (local wake), but our results do not show a statistically significant signature of the collective response; (looking forward to V. Chandra's forthcoming paper on the kinematic signature!)

Thank you!

Clumpy formation scenario

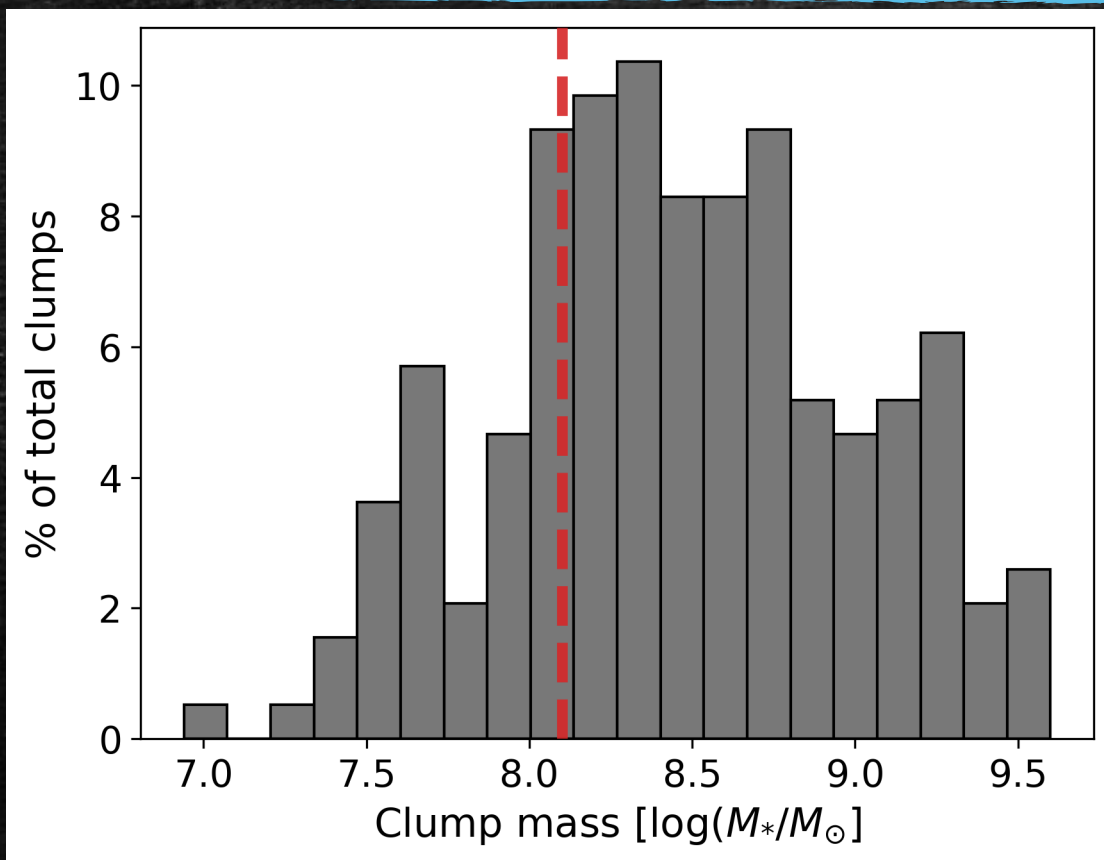


Clarke+2019



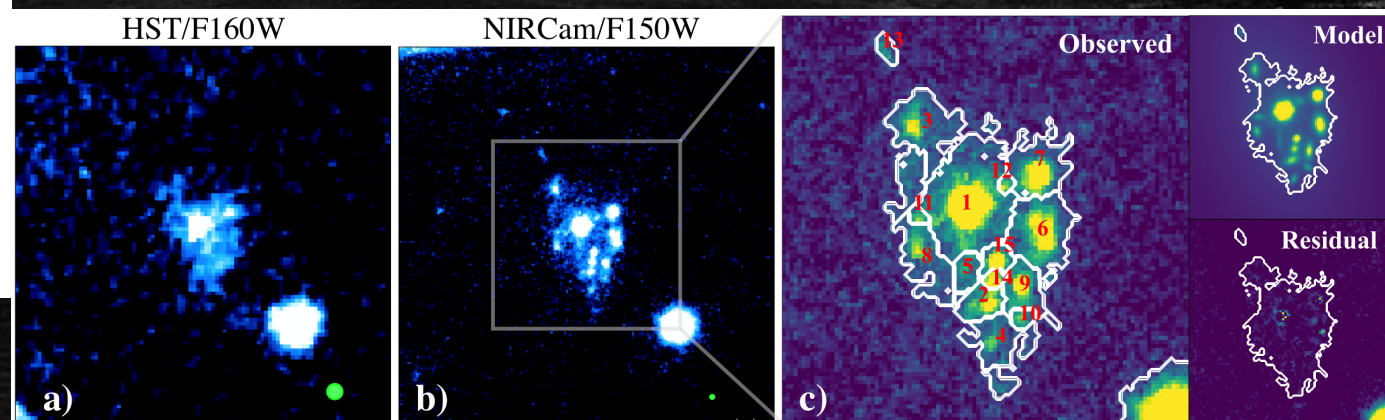
Garver+2023;

Clumpy formation scenario

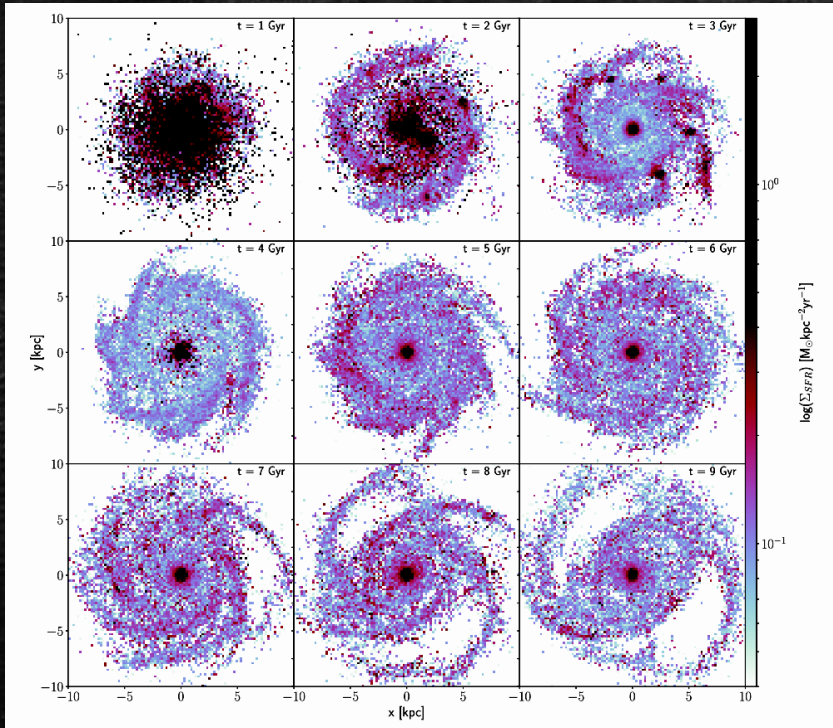


Kalita+2024b

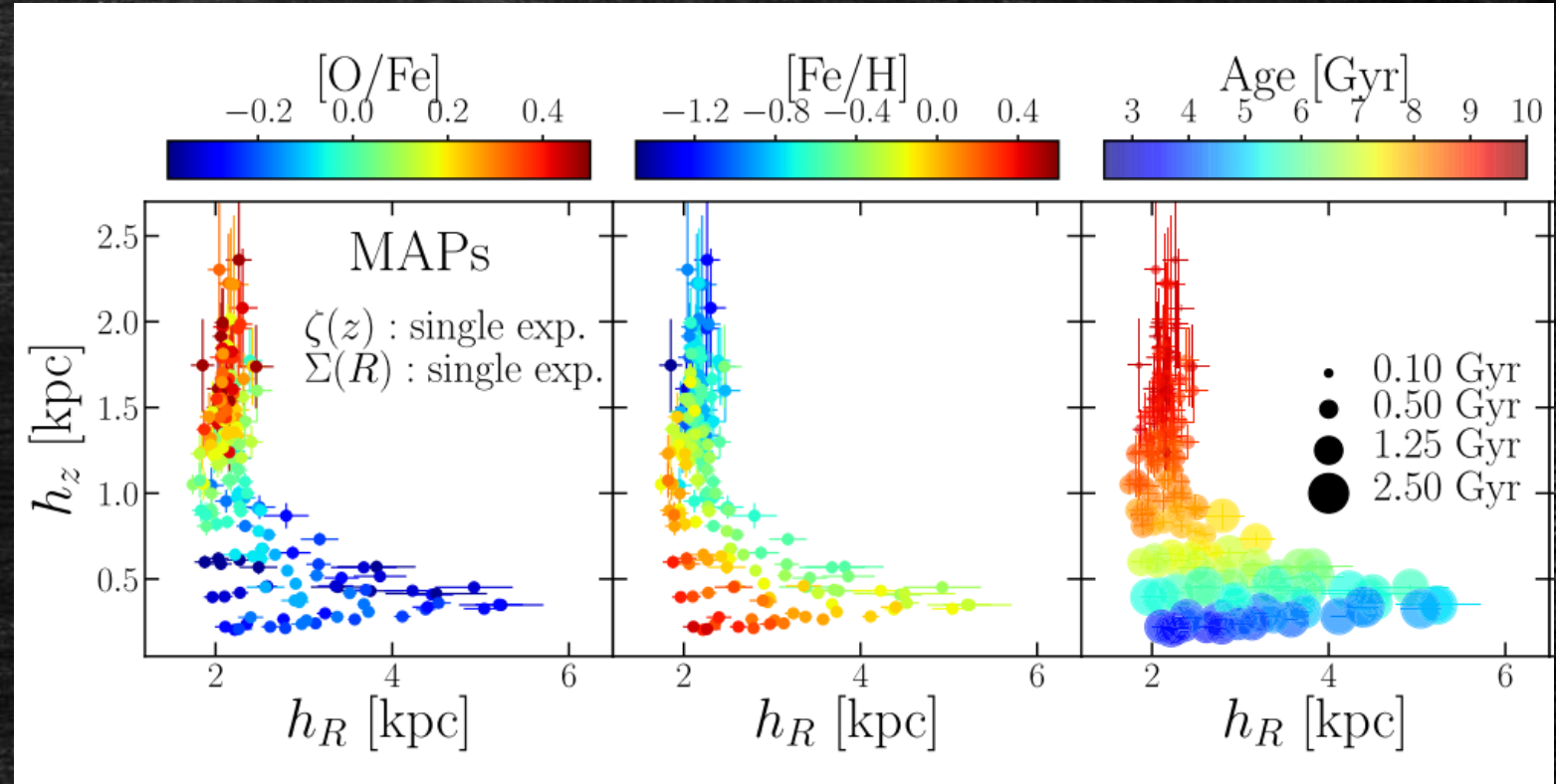
Fujimoto+2024



Clumpy formation scenario



Clarke+2019



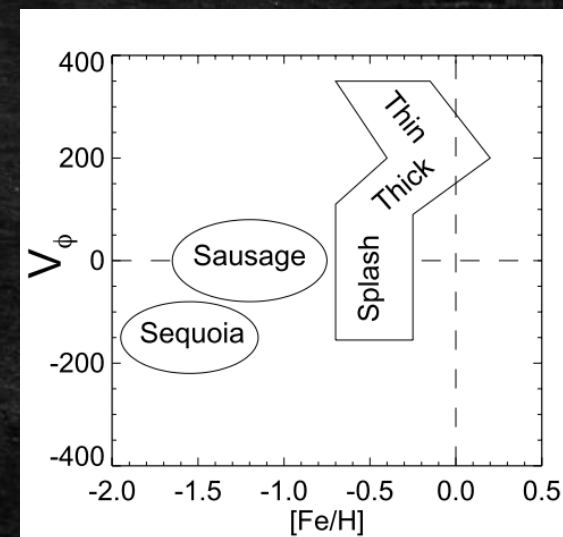
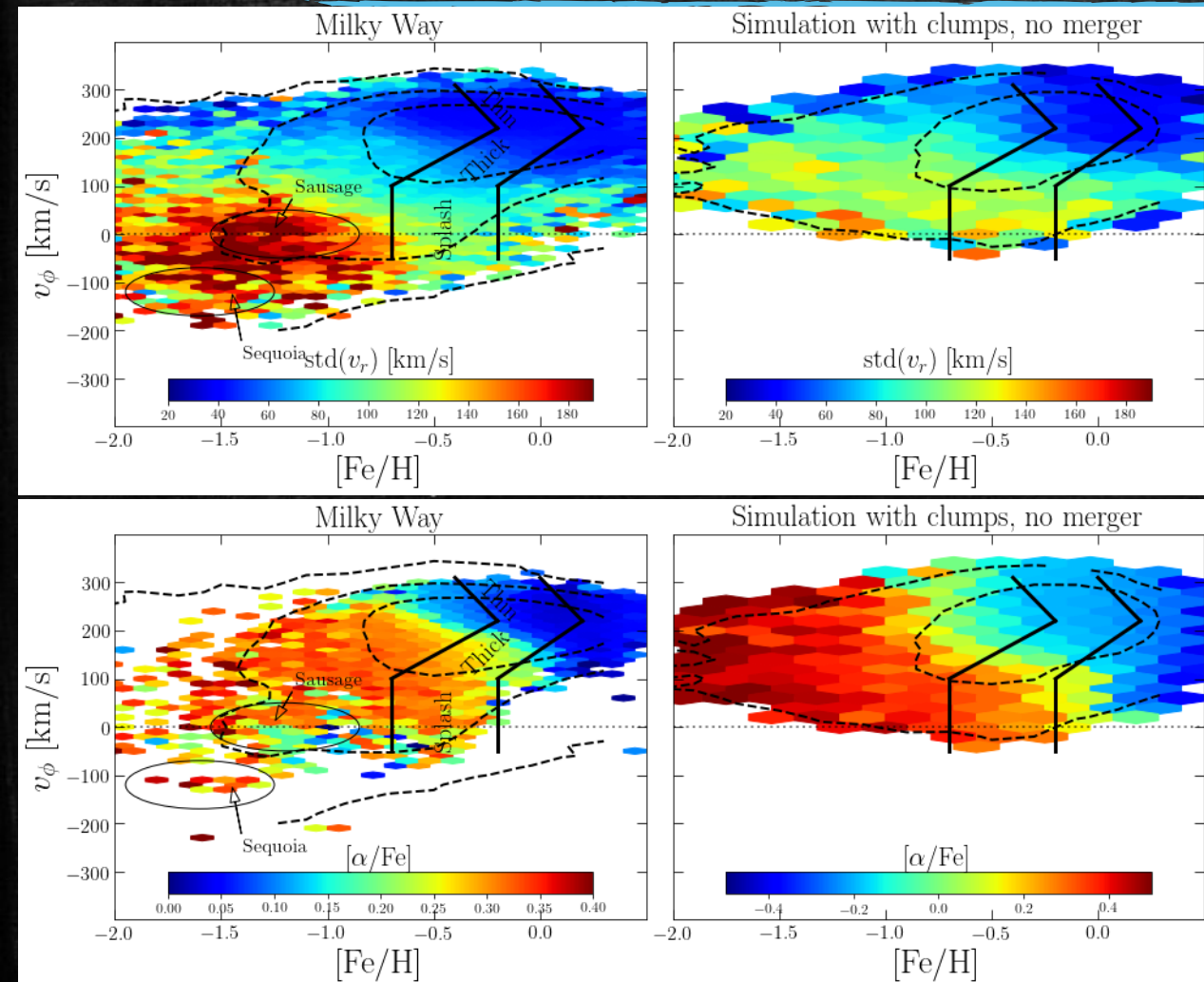
Beraldo e Silva+2020 – similar chemo-geometric dichotomy as in the MW

Clumpy formation scenario: The Splash without a merger

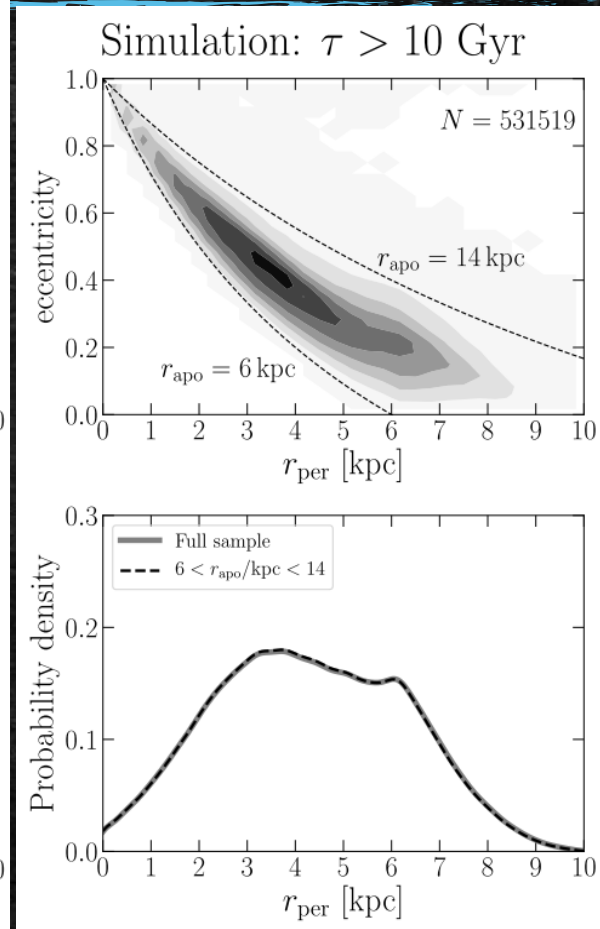
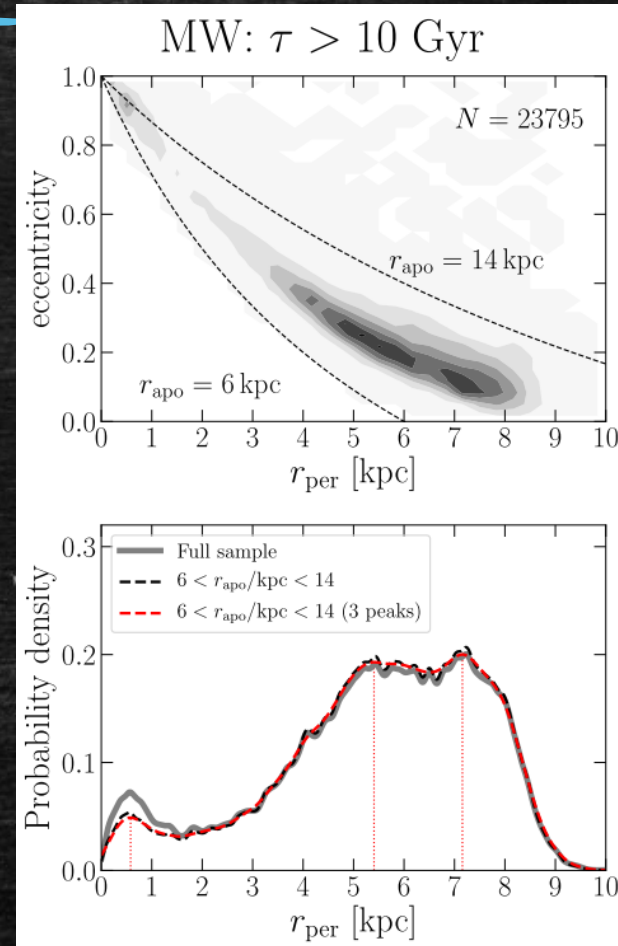
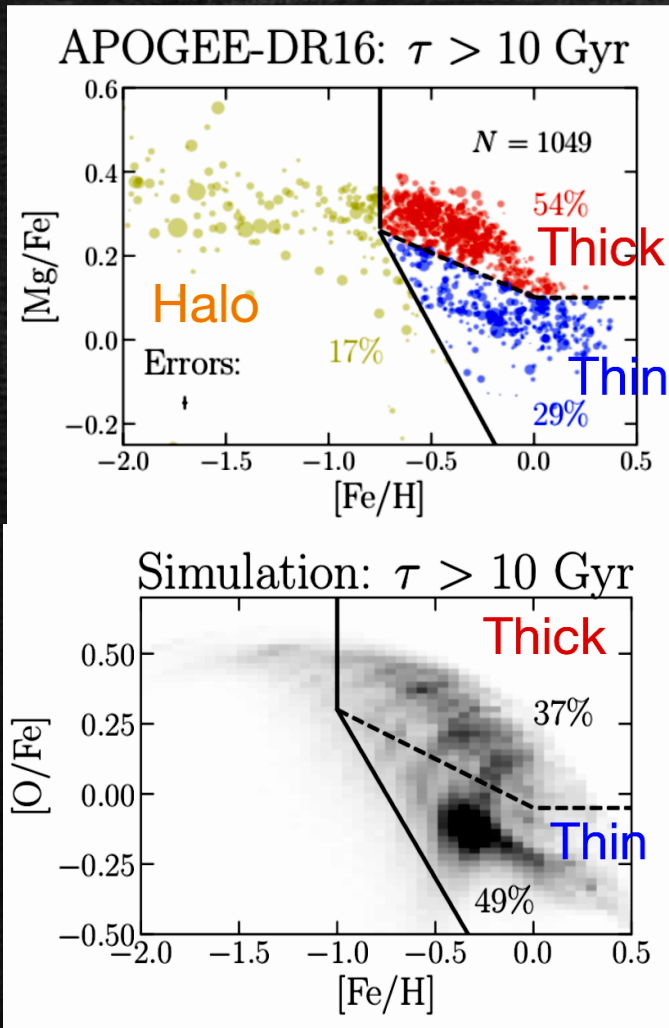
Amarante+2020a

Belokurov+2020

See also Di Matteo+2019

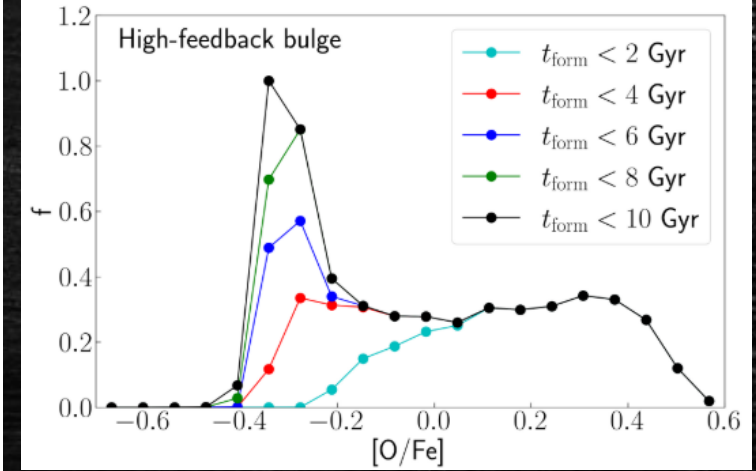
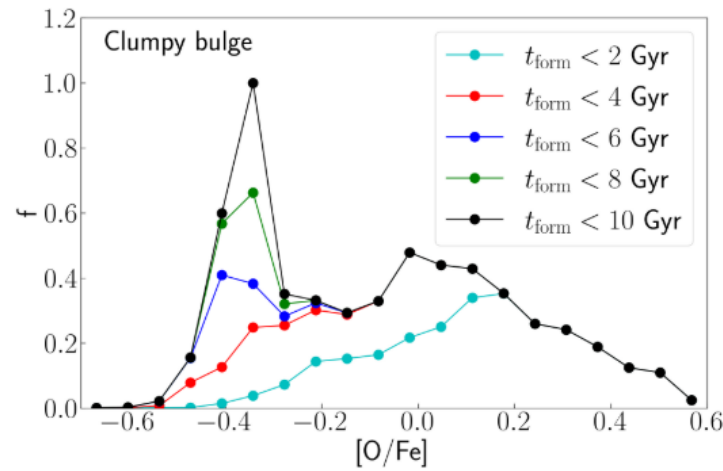
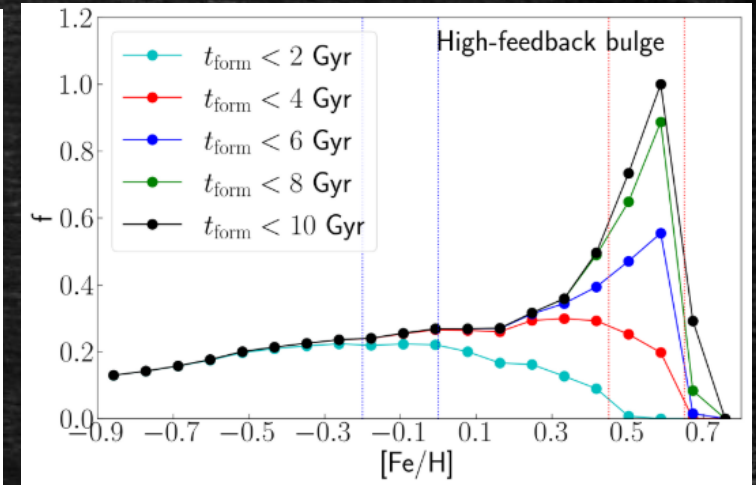
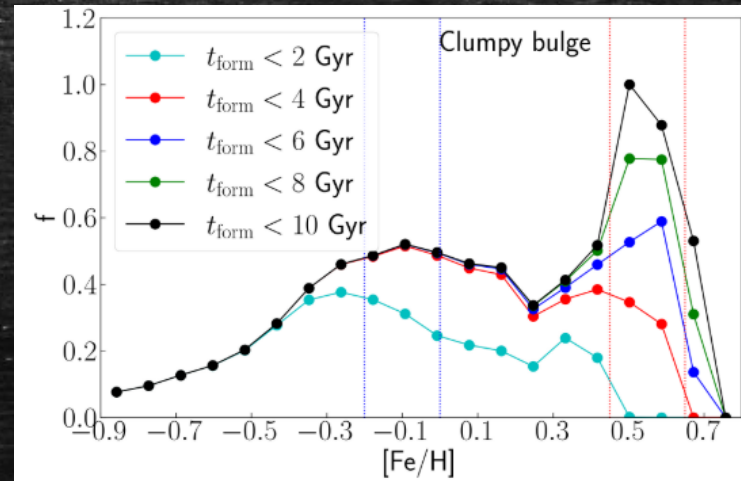
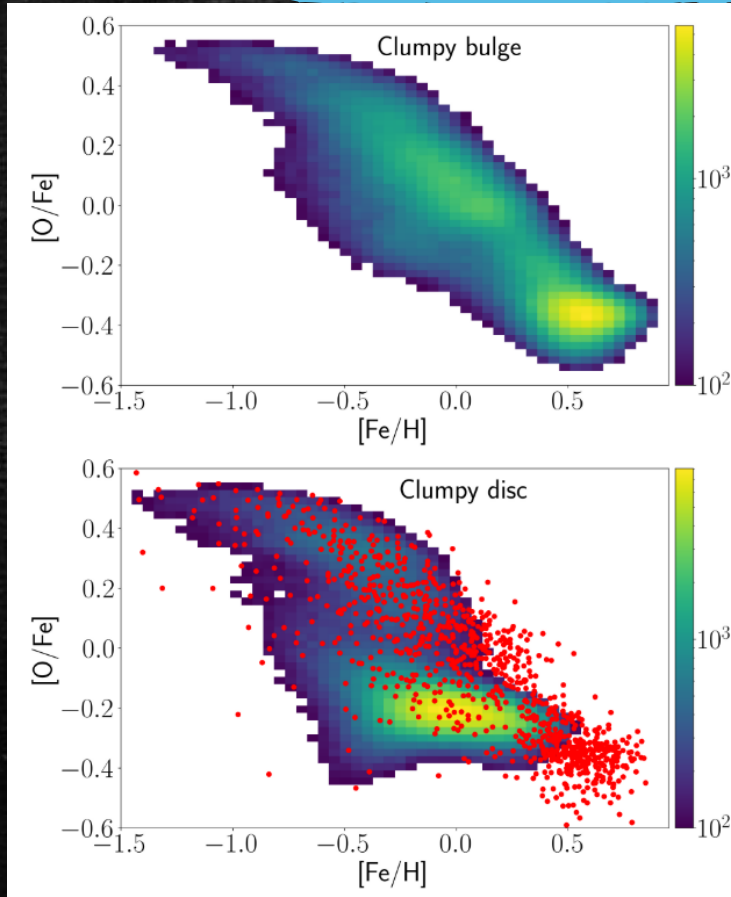


Clumpy formation scenario: co-formation of the alpha-poor and alpha-rich discs



Beraldo e Silva+2021

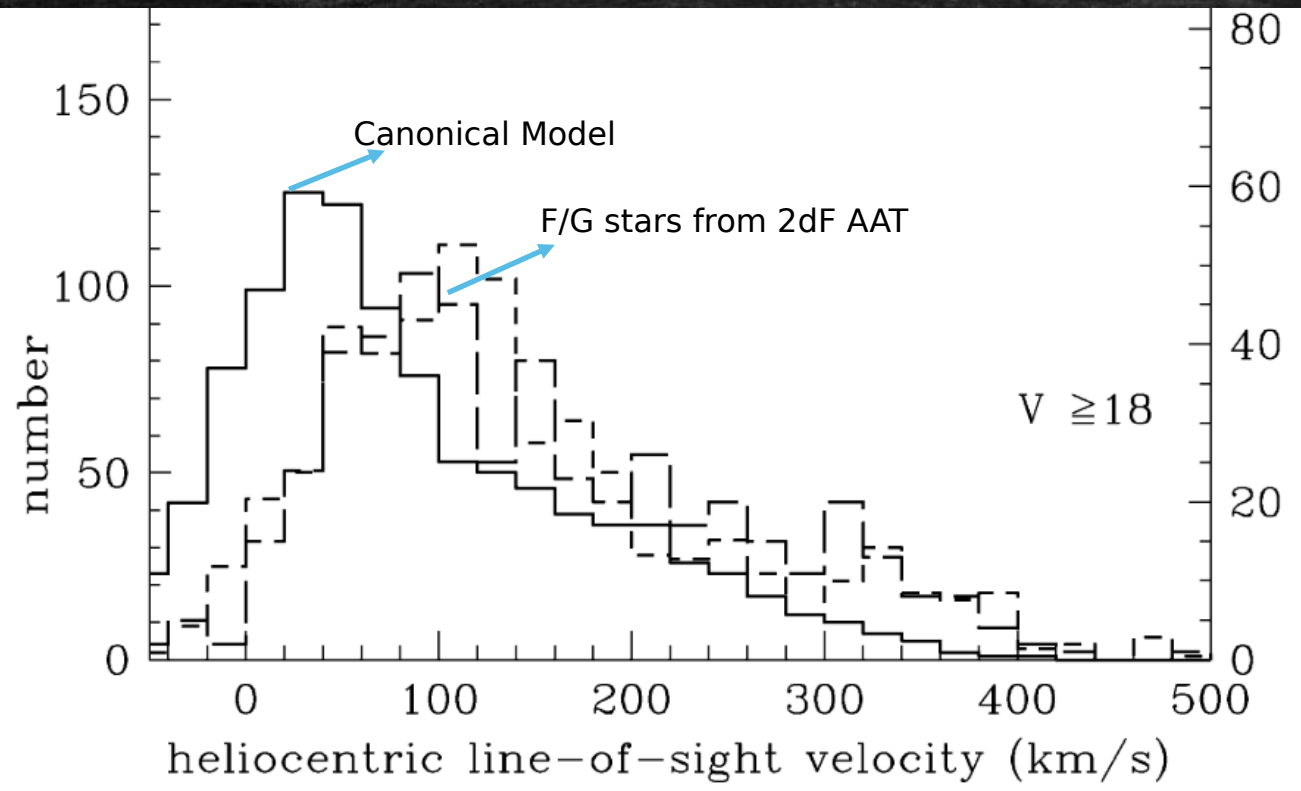
Clumpy formation scenario: The chemistry of the bulge



Debattista+2023

The *Gaia*-Enceladus-Sausage

Gilmore+2002: $\sim 2\text{k}$ stars, $v_{\text{err}} \sim 15\text{ km/s}$

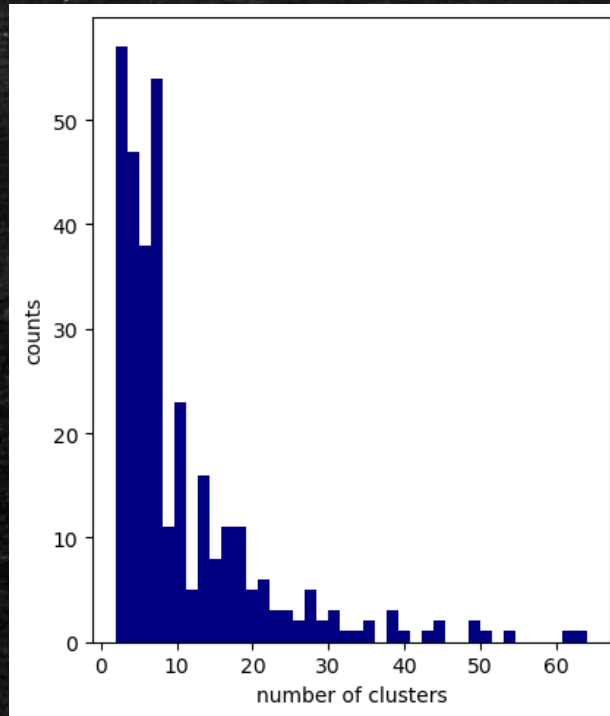


~ 20 years, some *hints* for a main merger event in our Galaxy (see also e.g. Chiba & Beers+2000, Meza+2005, Deason+2013)

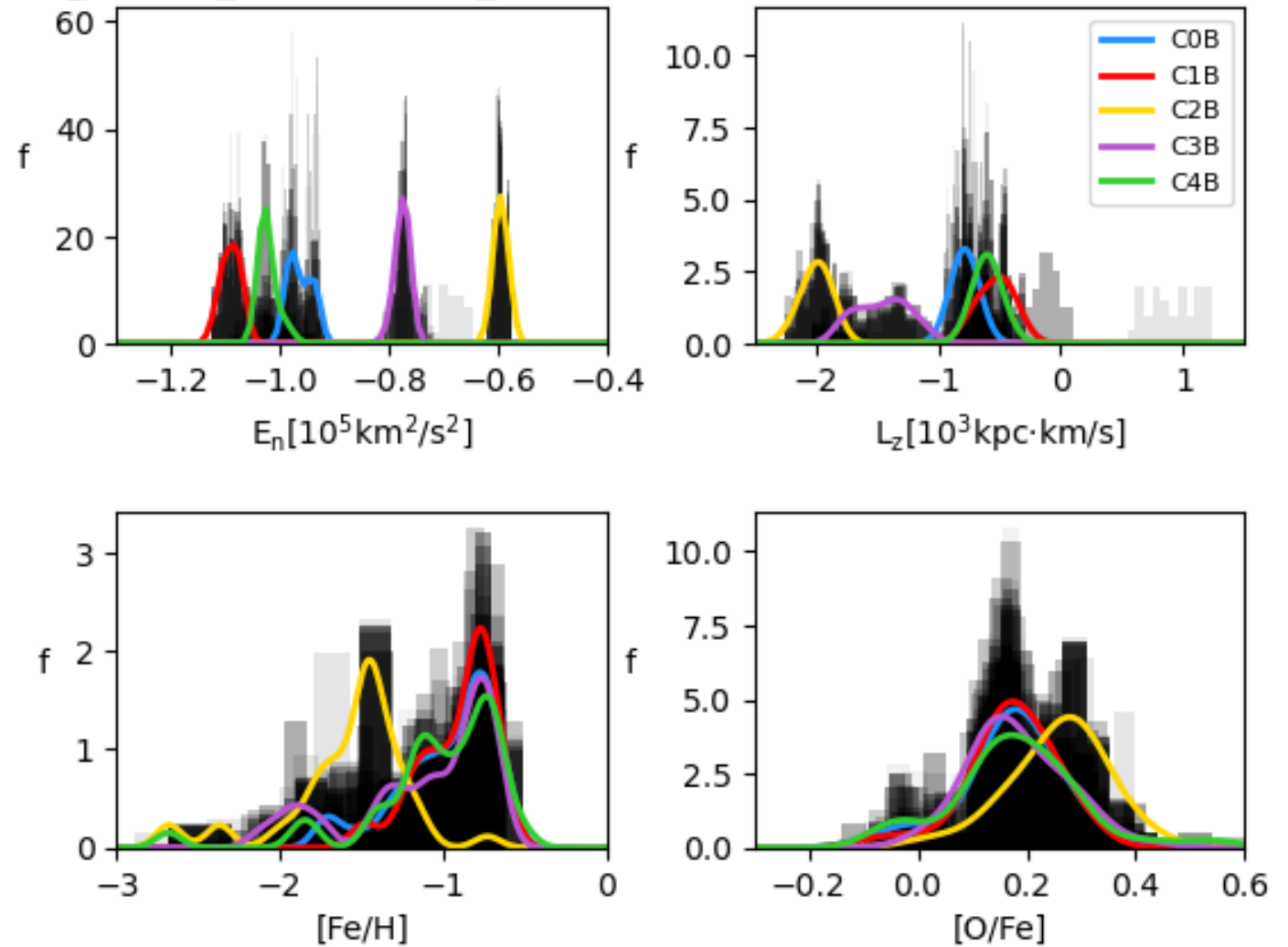
The *Gaia*-Enceladus-Sausage

- $T_{\text{merger}} \sim 10\text{-}11$ Gyr (e.g. Gallart+2019)
- $[\text{Fe}/\text{H}] \sim -1.45$ to -1.17 (e.g. Feuillet+2020, Bird+2021, Liu+2022)
- Stellar mass $\sim 7 \times 10^8 M_{\text{sun}}$ (e.g. Naidu+2020)
- Constitutes up to $\sim 74\%$ of the inner halo, $r_{\text{gc}} < \sim 30$ kpc, (e.g. Wu+2022)
- Likely progenitor of the HACs and VOD (e.g. Simion+2019, Wang+2022, Perottoni w/ Amarante+2022)
- 1/3 of MW-like galaxies in Auriga have a GSE-like halo (Fattahi+2019)

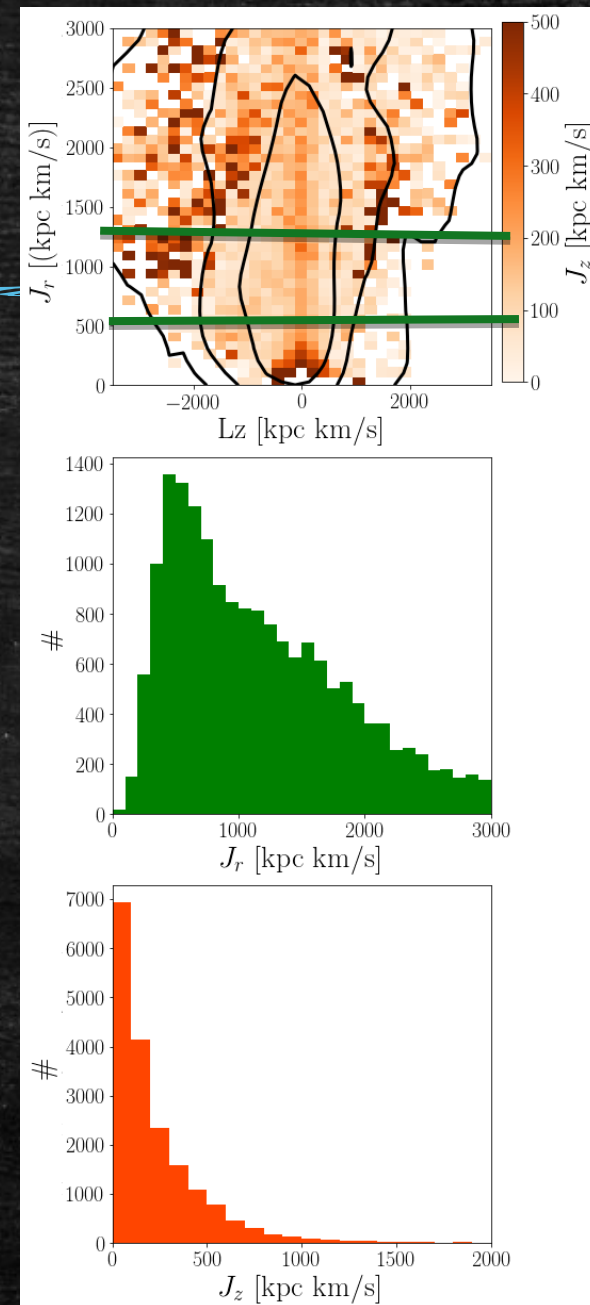
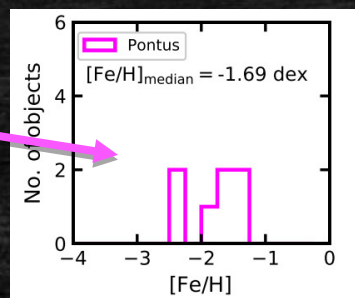
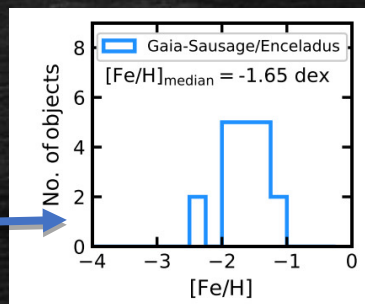
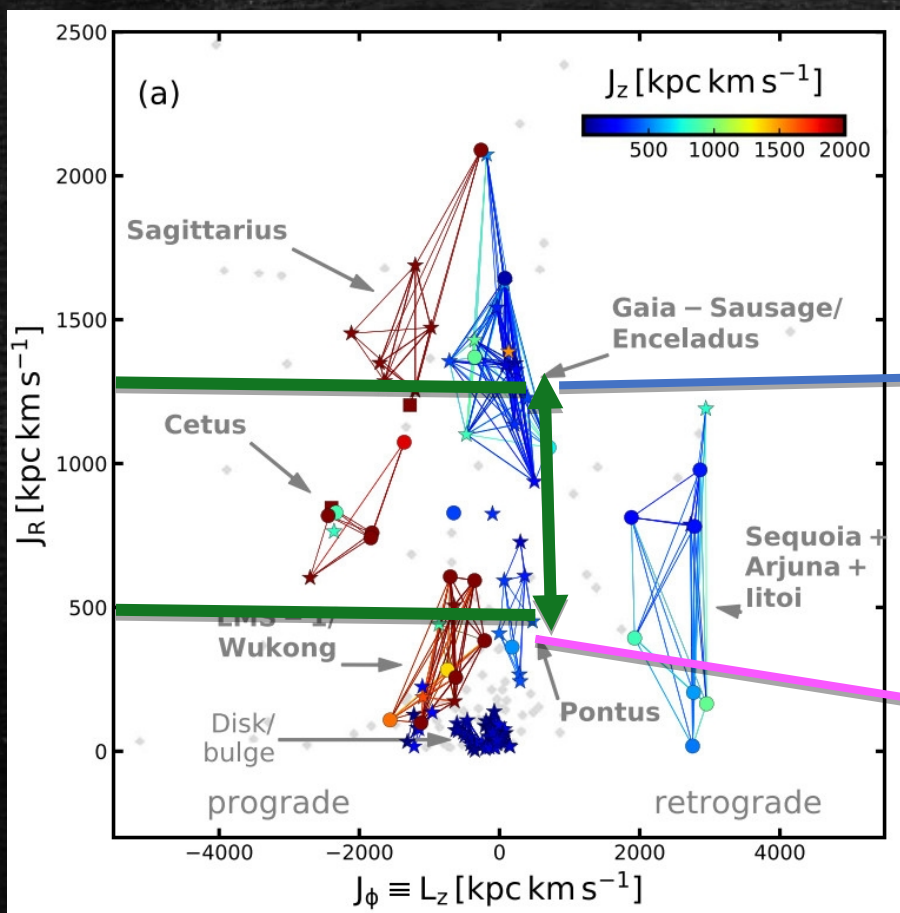
HDSBSCAN



min_cluster_size: 22, min_samples: 17

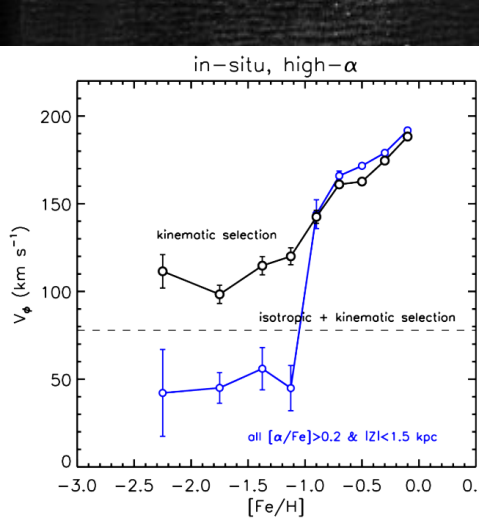


GASTRO I: Action space – 10 Gyr

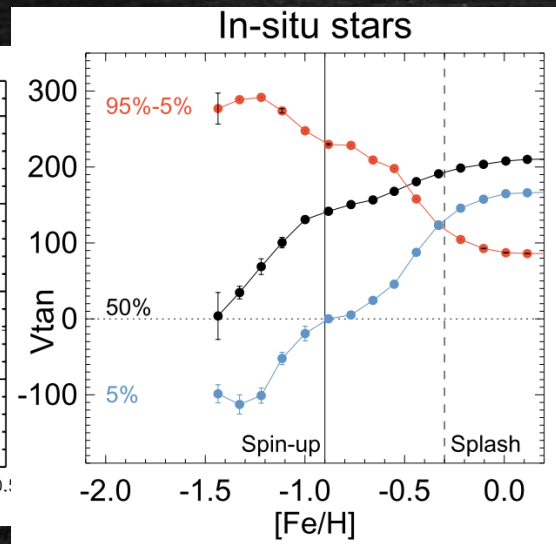


Malhan+2022 w/ ENLINK group finder

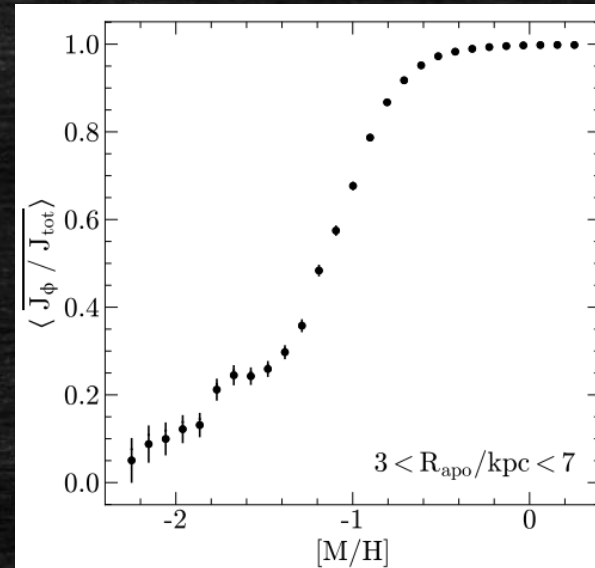
The young Milky Way



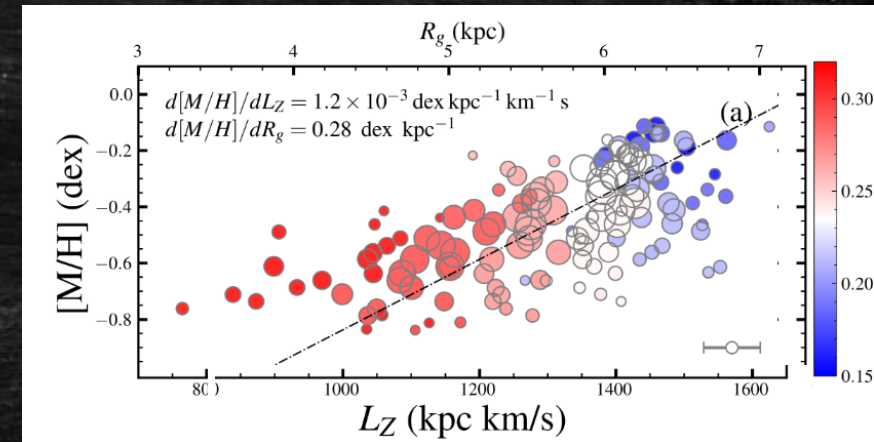
Conroy+22
H3 survey



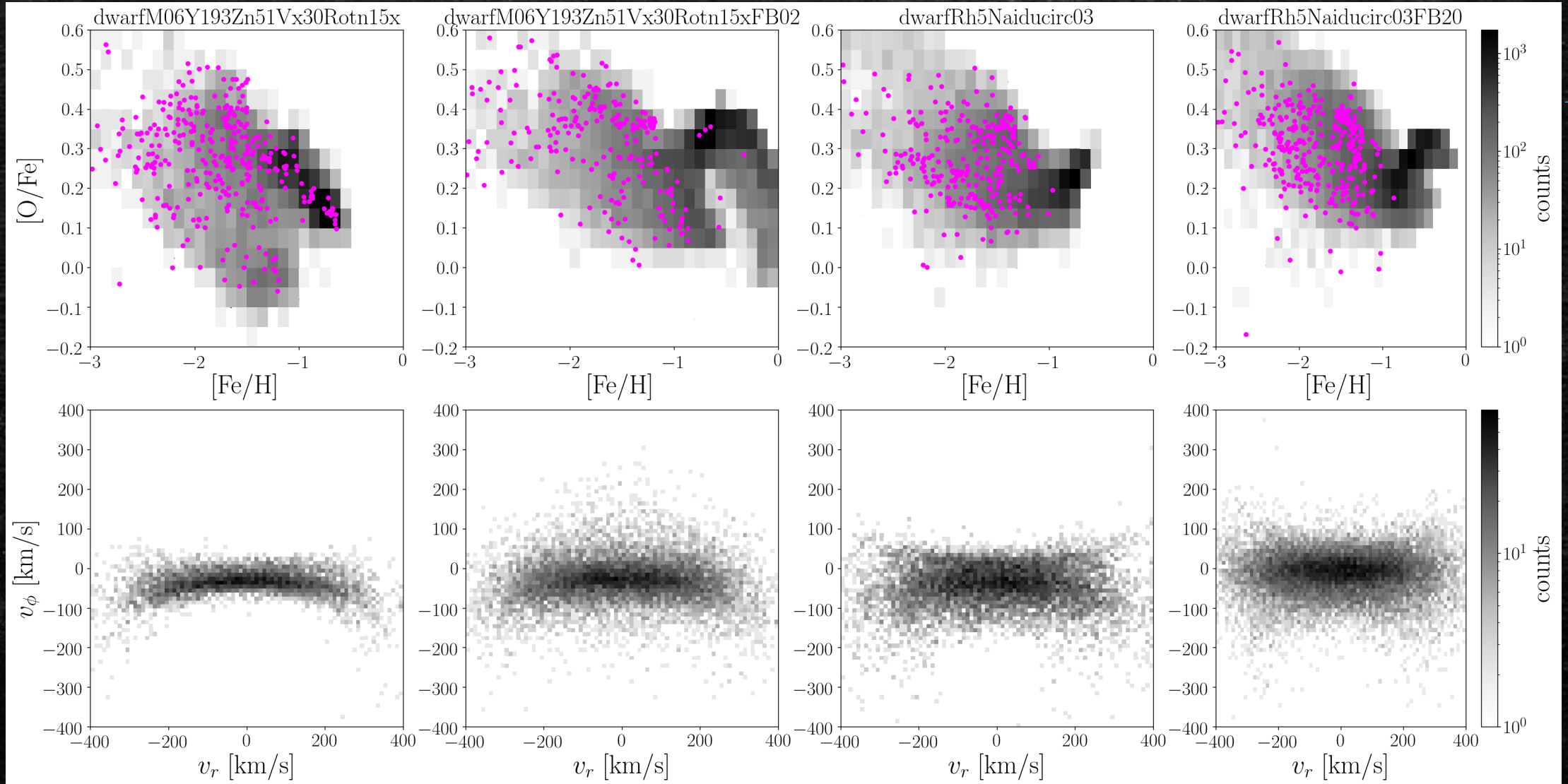
Belokurov+22 -
APOGEE



Rix+22 - GaiaXP



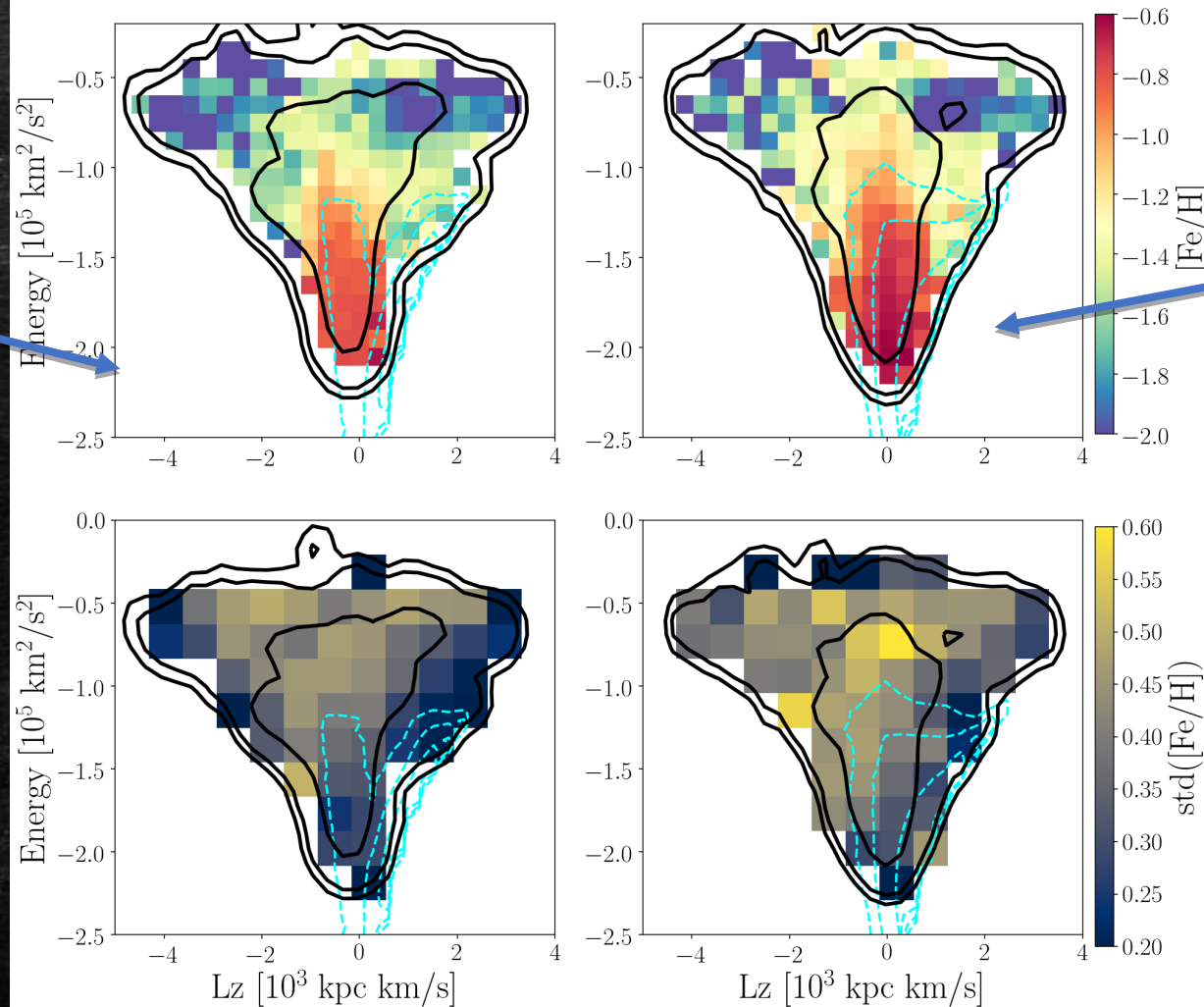
Hu+22 - APOGEE



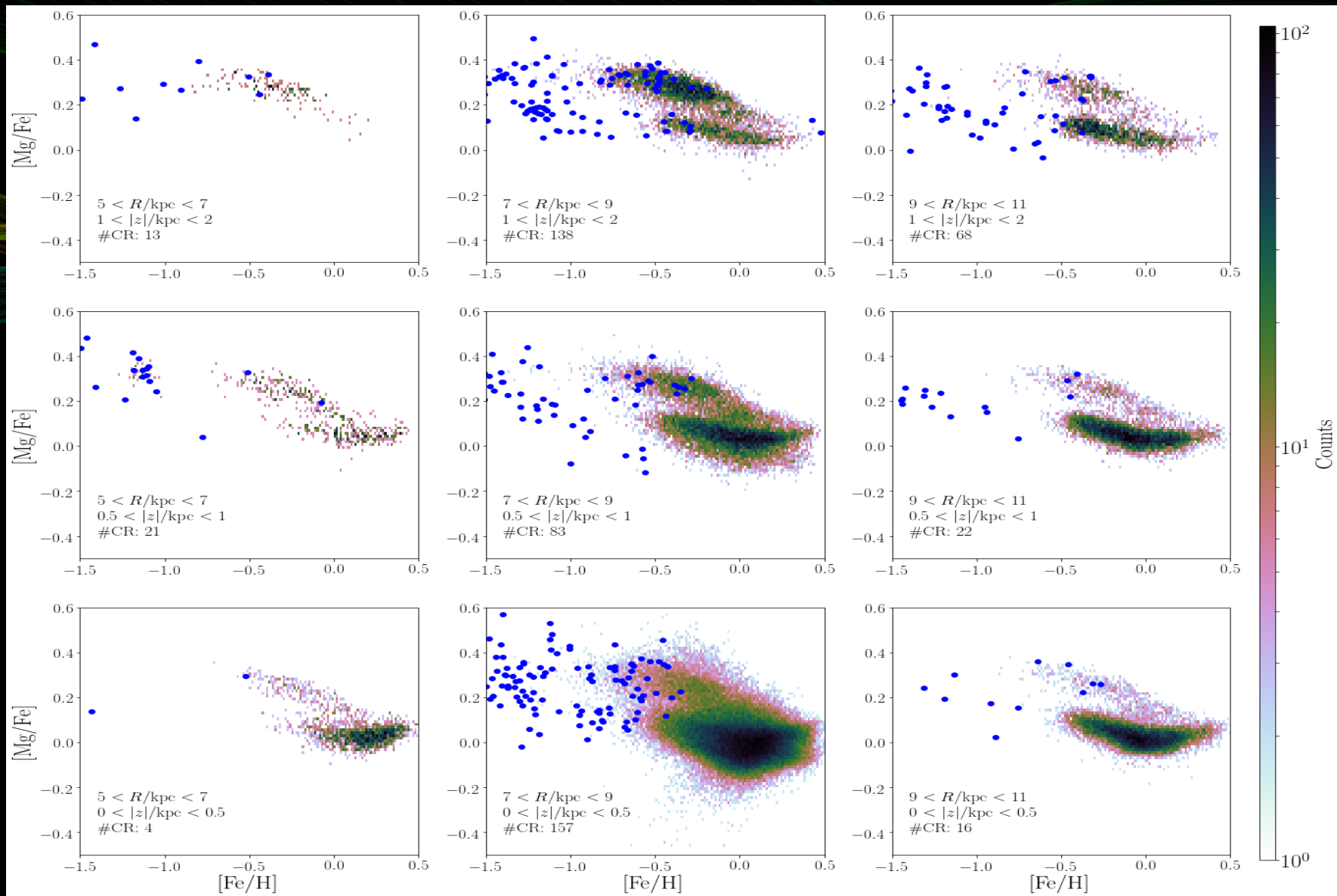
GASTRO I: Lz-Energy - t=10 Gyr

High fb

Low fb



Milky Way thick disk



Gaia DR2-
APOGEE DR15

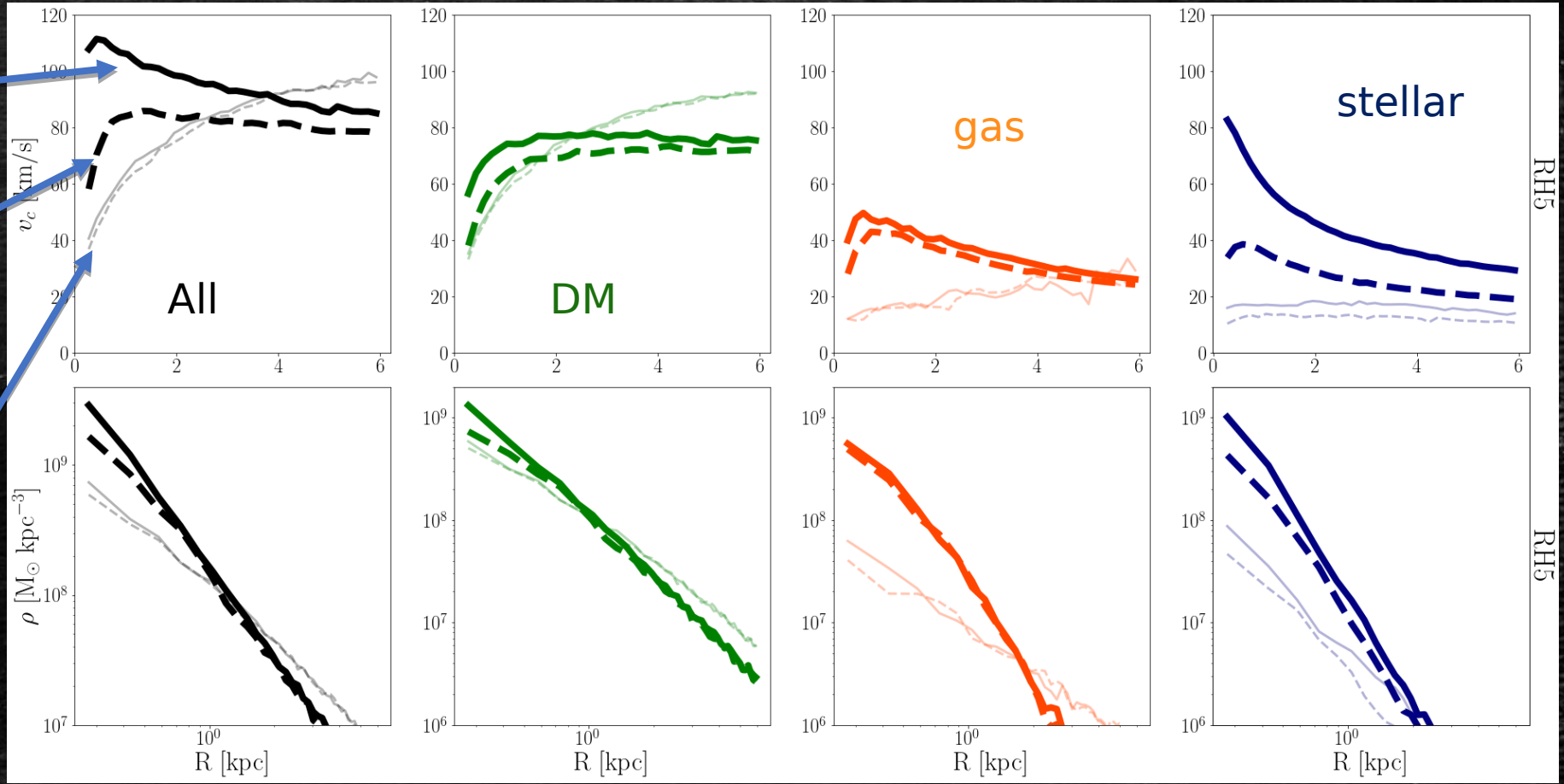
Gastro I: dwarf evolution

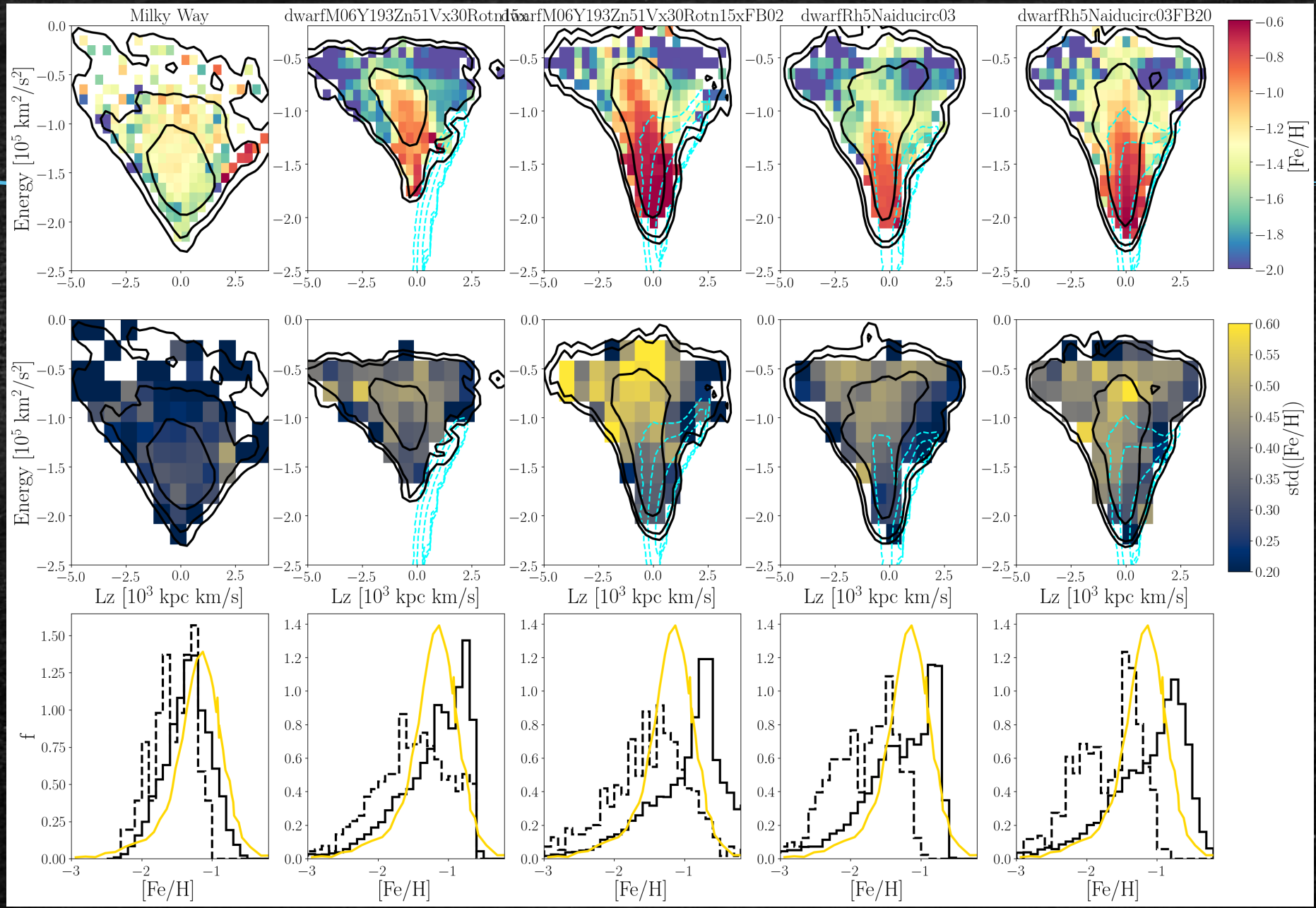
Amarante et al. (2022)

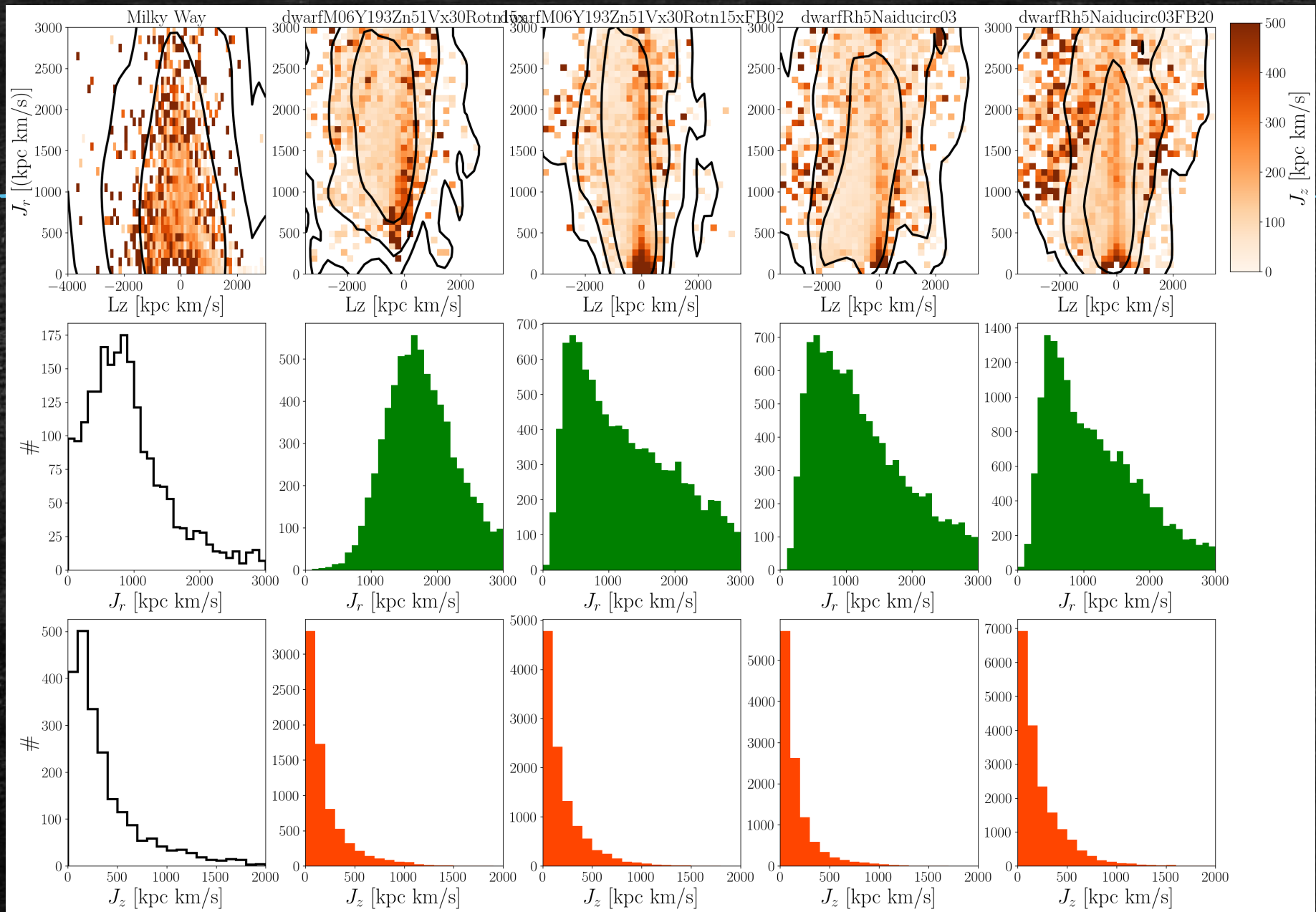
Low fb, after pericenter

High fb, after pericenter

Before pericenter



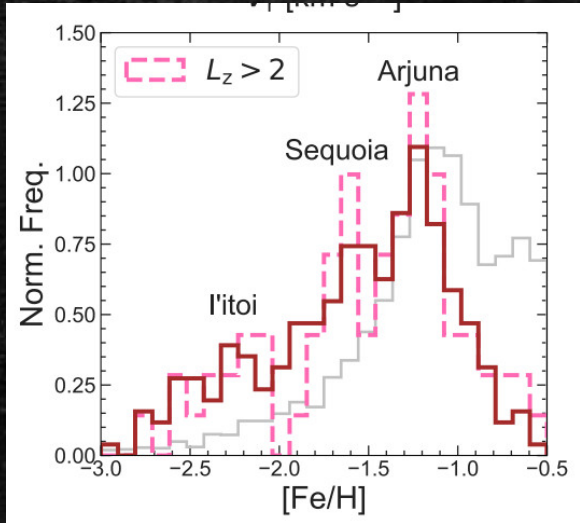
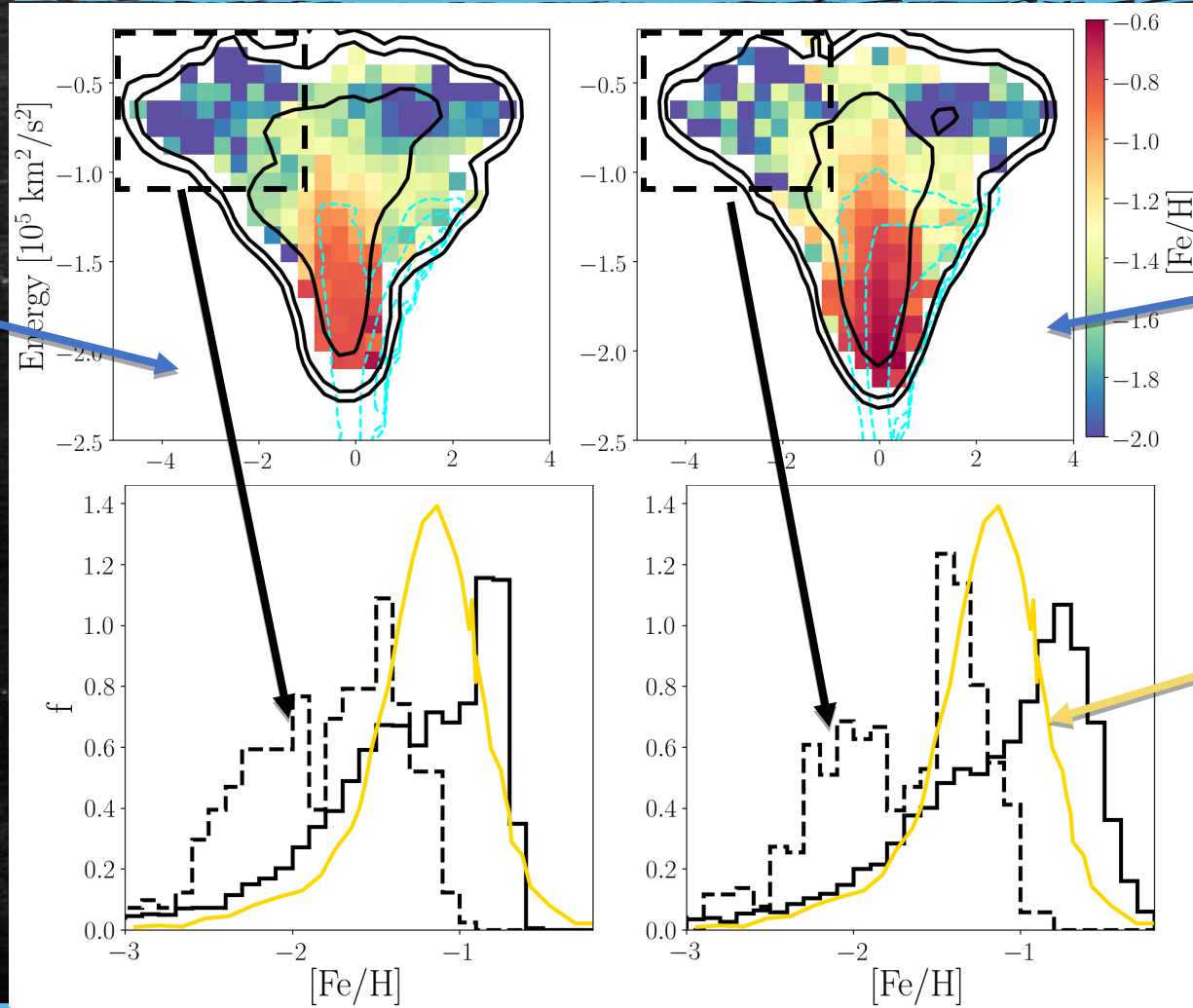




GASTRO I: Lz-Energy - t=10 Gyr

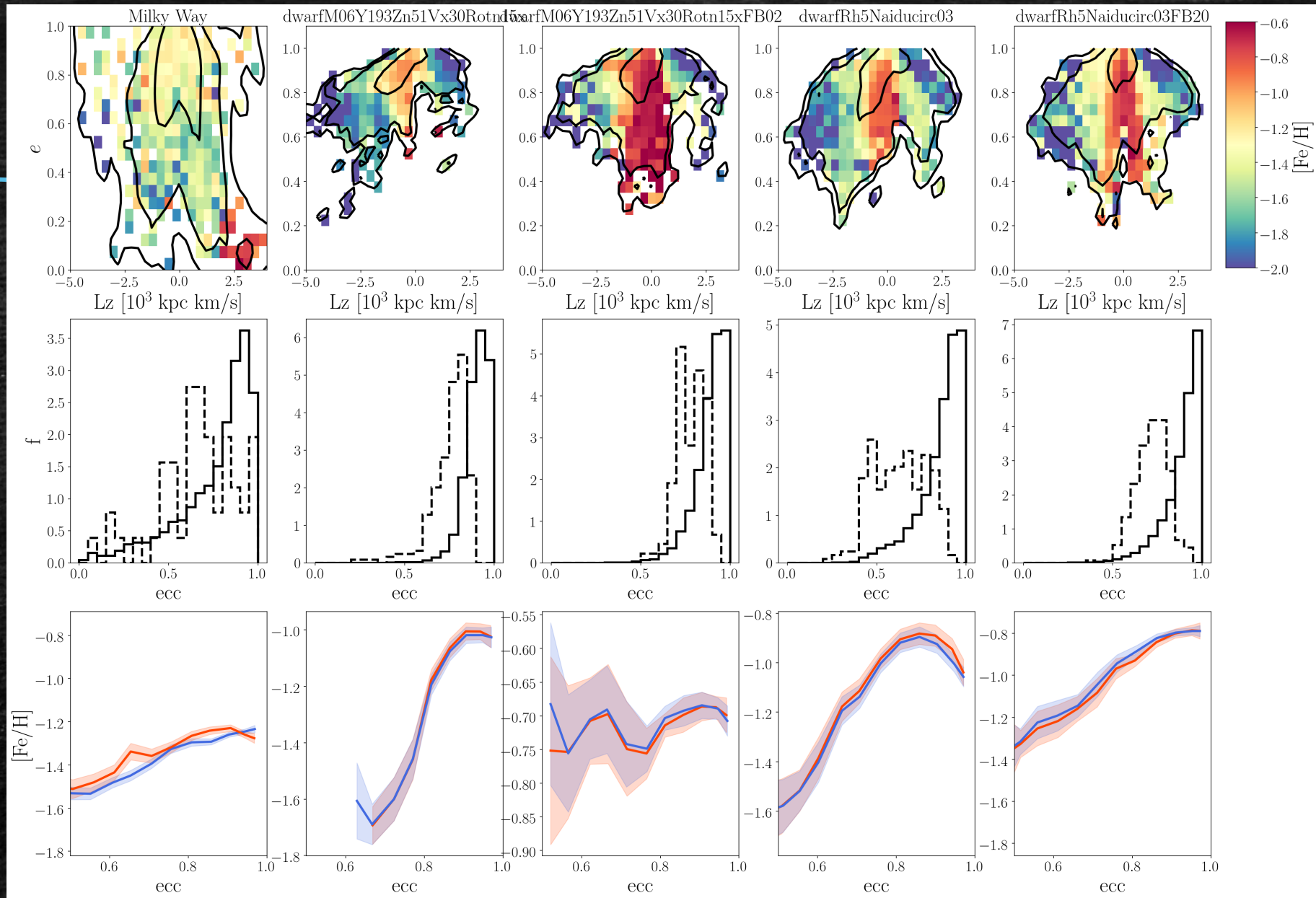
High fb

Low fb



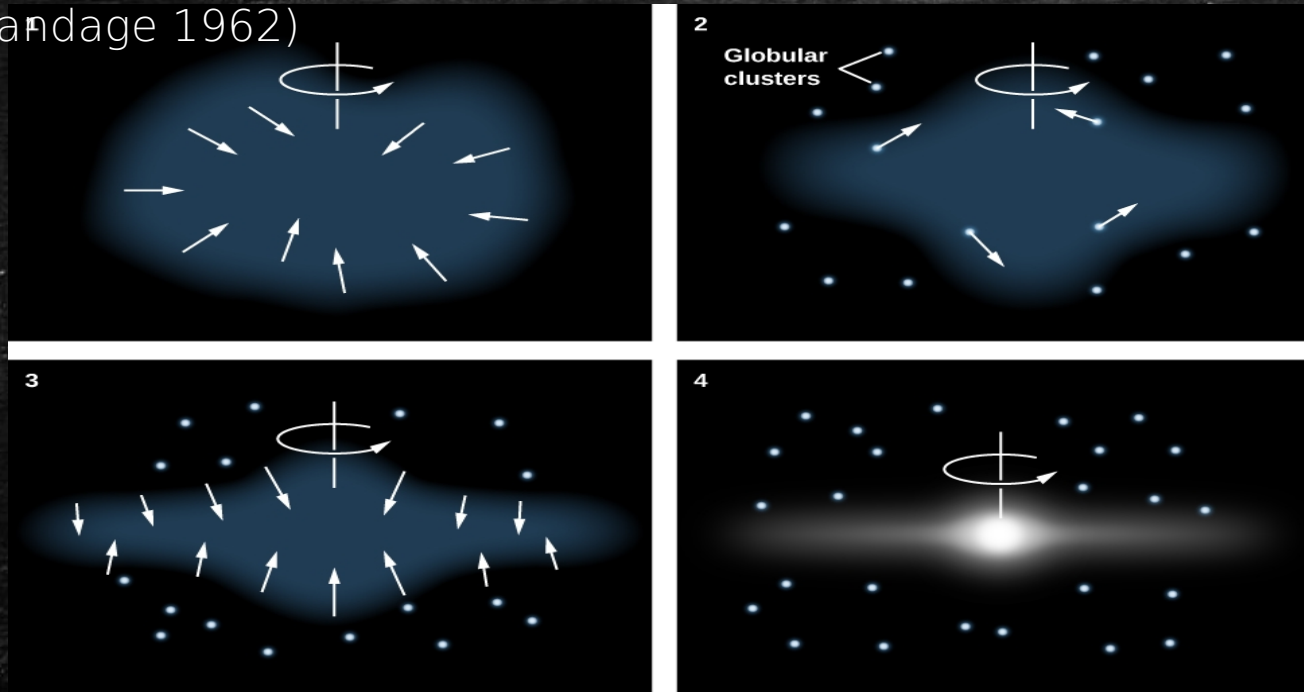
Naidu+2020, H3 survey

H3 Survey,
Naidu+2020

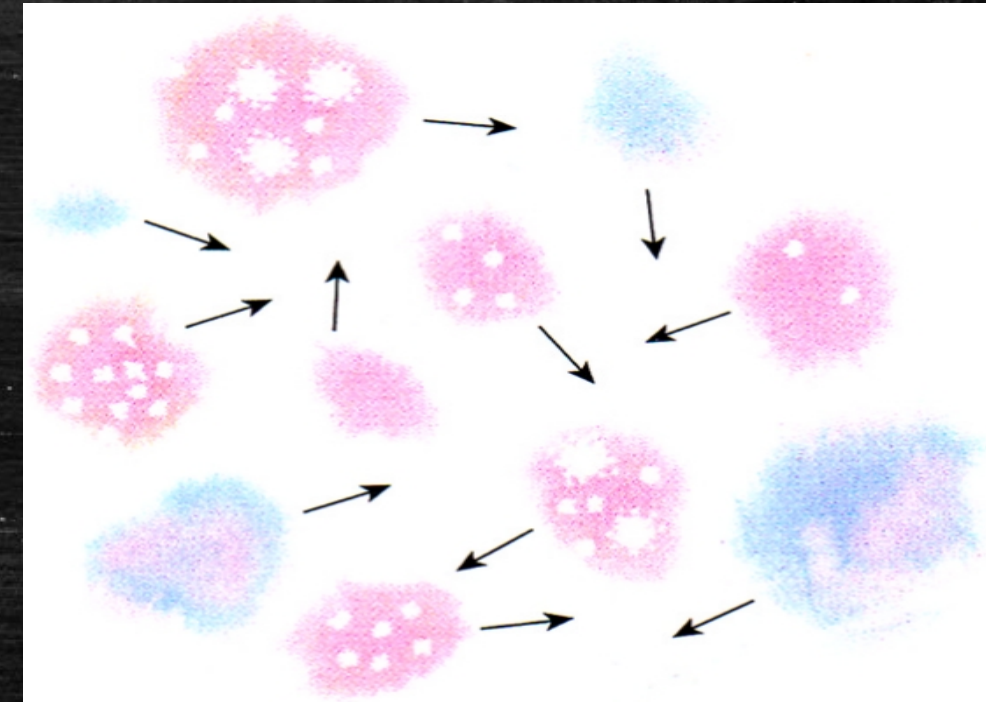


The Milky Way

Monolithic-collapse scenario
(Eggen, Lynden-Bell &
Sandage 1962)



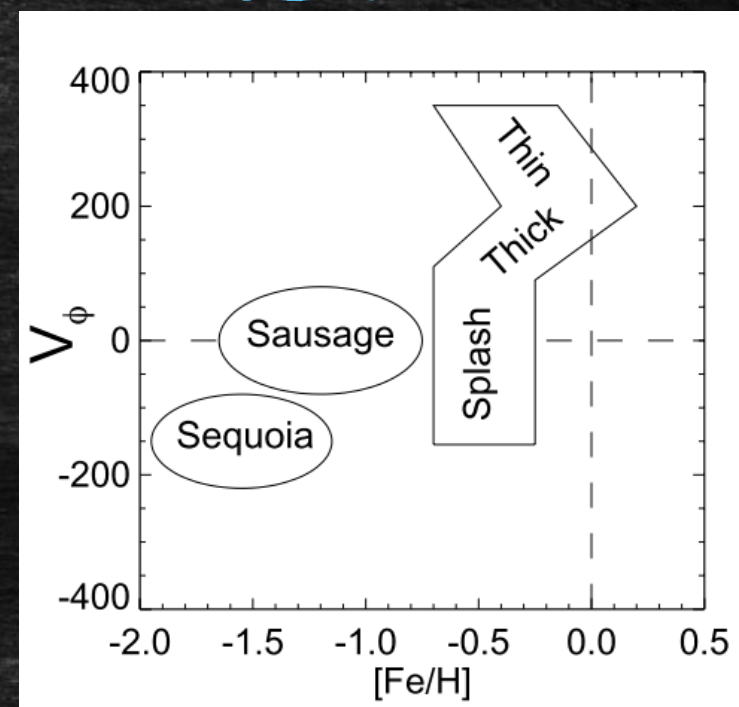
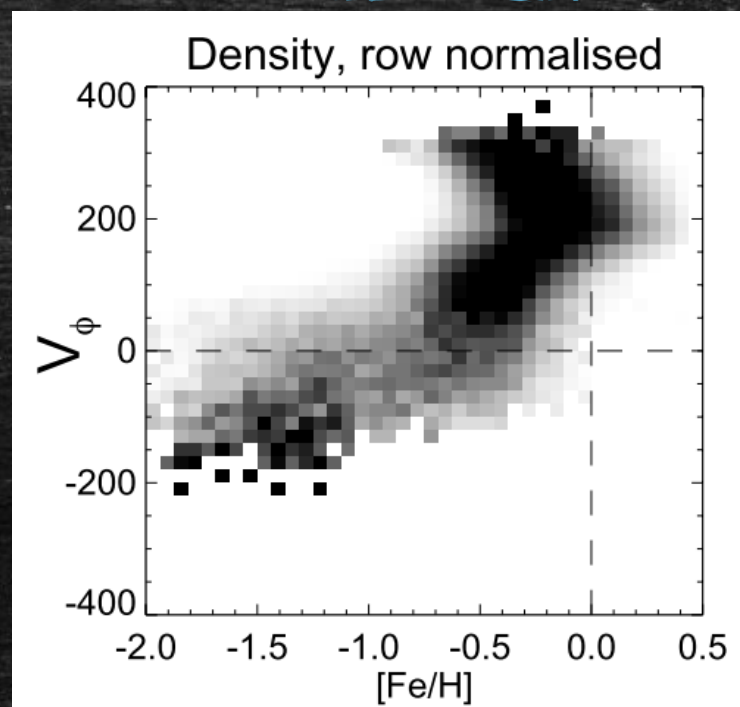
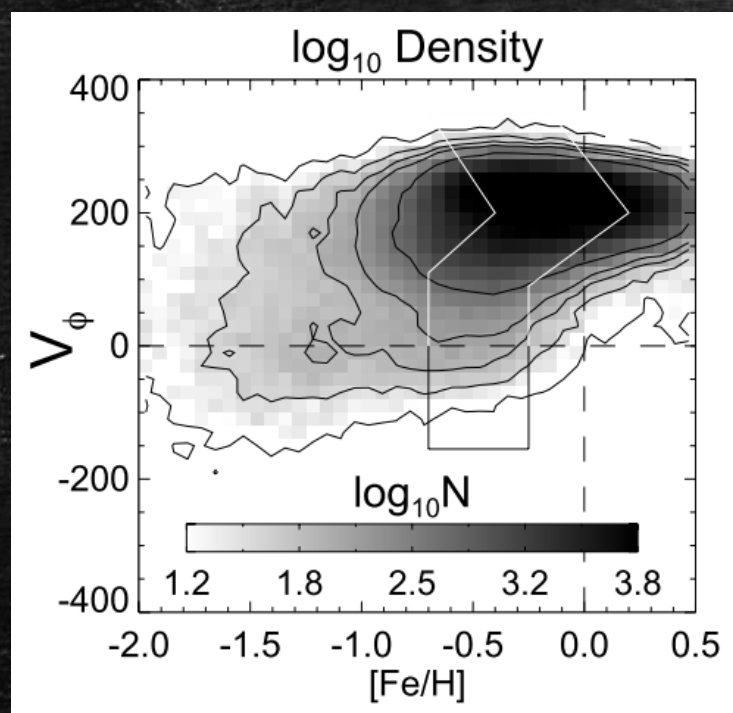
Hierarchical/fragmented formation
scenario (Searle & Zinn 1978)



Credit: [https://phys.libretexts.org/TextMaps/Astronomy_and_Cosmology_TextMaps/Map%3A_Astronomy_\(OpenStax\)/25%3A_The_Milky_Way_Galaxy/25.6_The_Formation_of_the_Galaxy](https://phys.libretexts.org/TextMaps/Astronomy_and_Cosmology_TextMaps/Map%3A_Astronomy_(OpenStax)/25%3A_The_Milky_Way_Galaxy/25.6_The_Formation_of_the_Galaxy)

Chiappini, C. (2002). *The Formation and Evolution of the Milky Way* The distribution of the chemical elements in our galaxy serves as a "fossil record" of its evolutionary history.

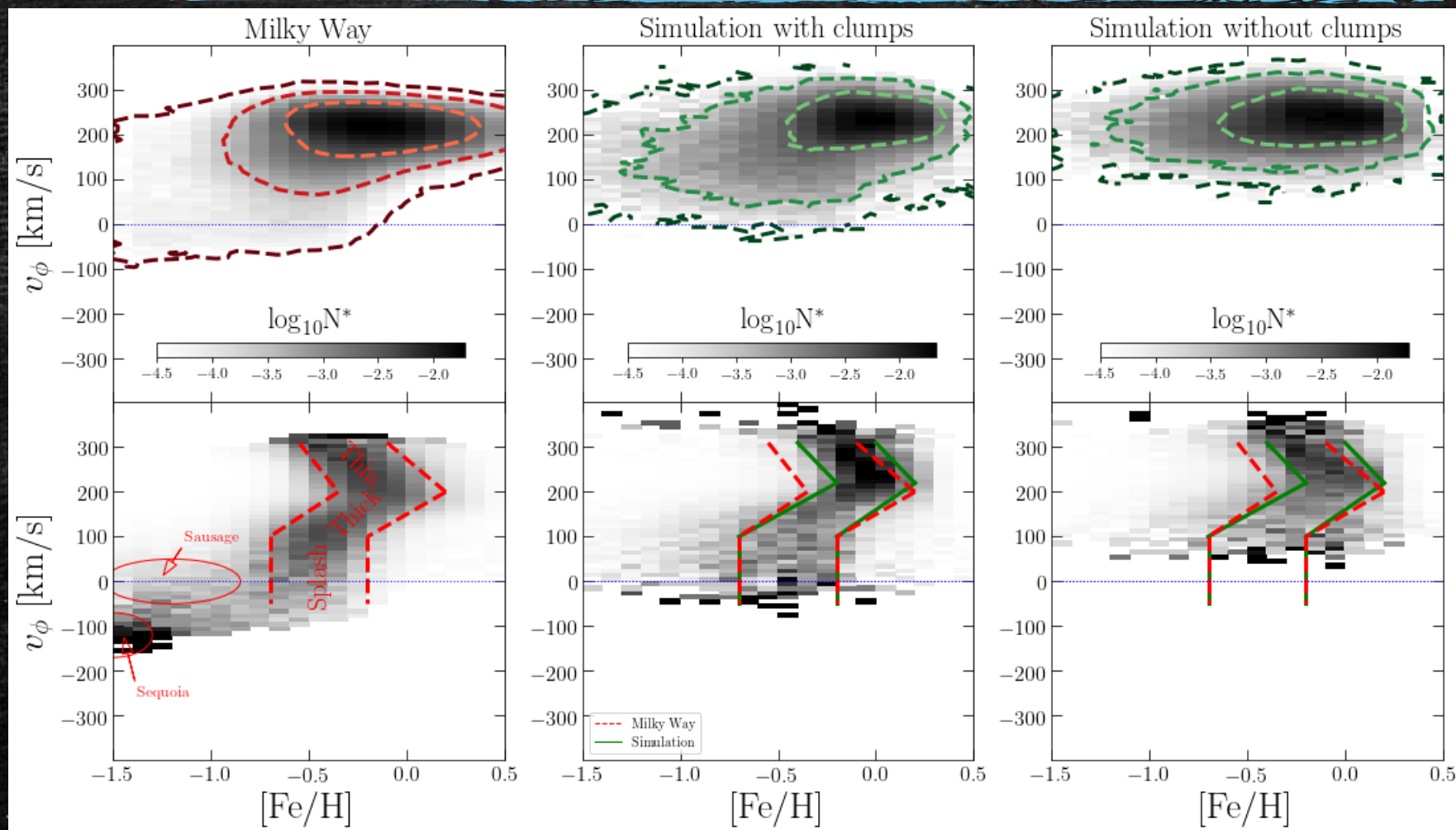
The heated thick disc



Belokurov+2020; also shown in DiMatteo+2019, *Gaia*+APOGEE DR14 ("The Plume")

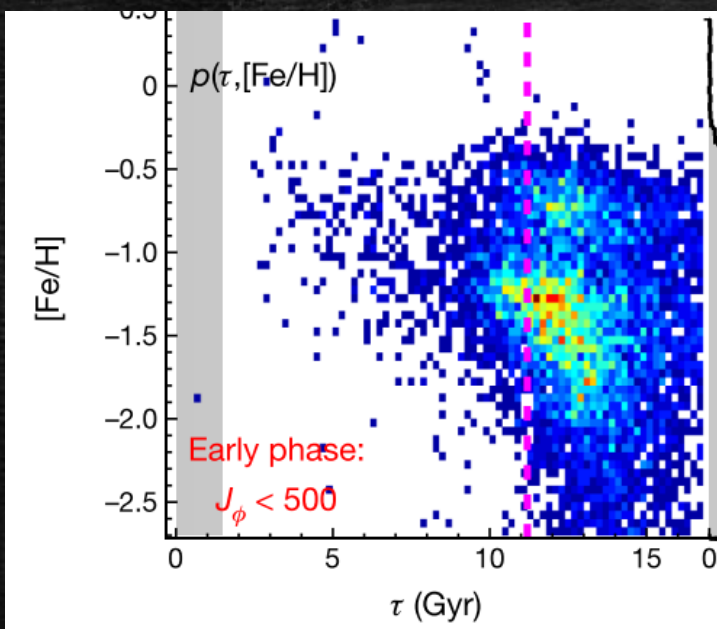
The Splash without a merger

Amarante et al. (2020)b

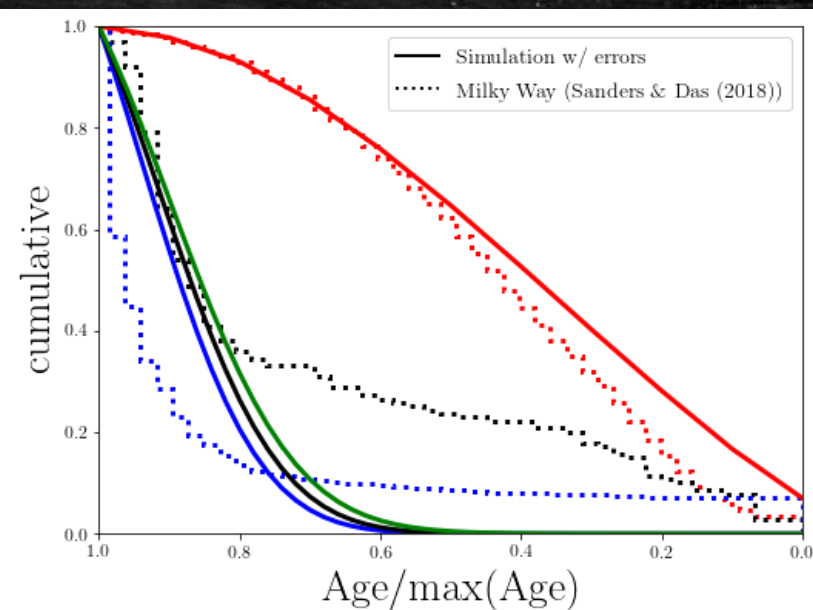
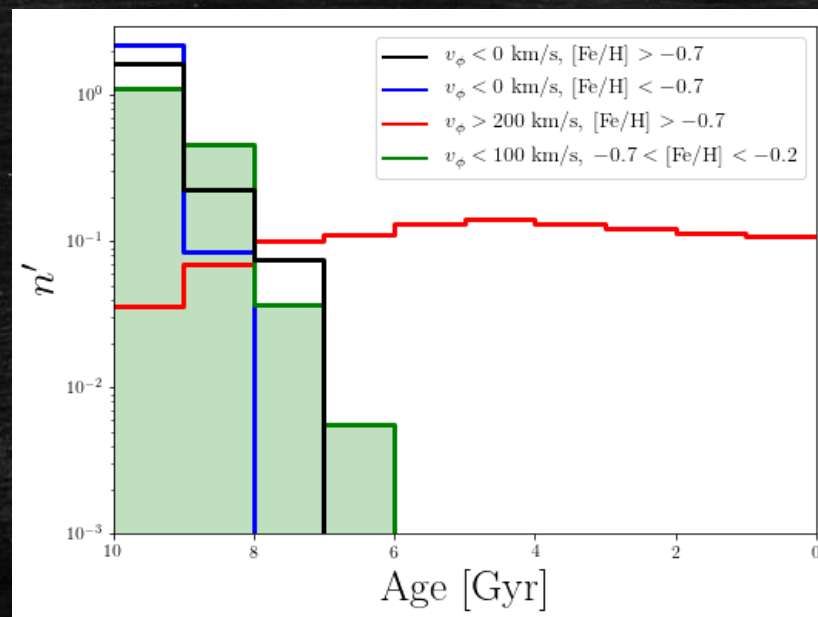


The Splash without a merger

Amarante et al. (2020)b

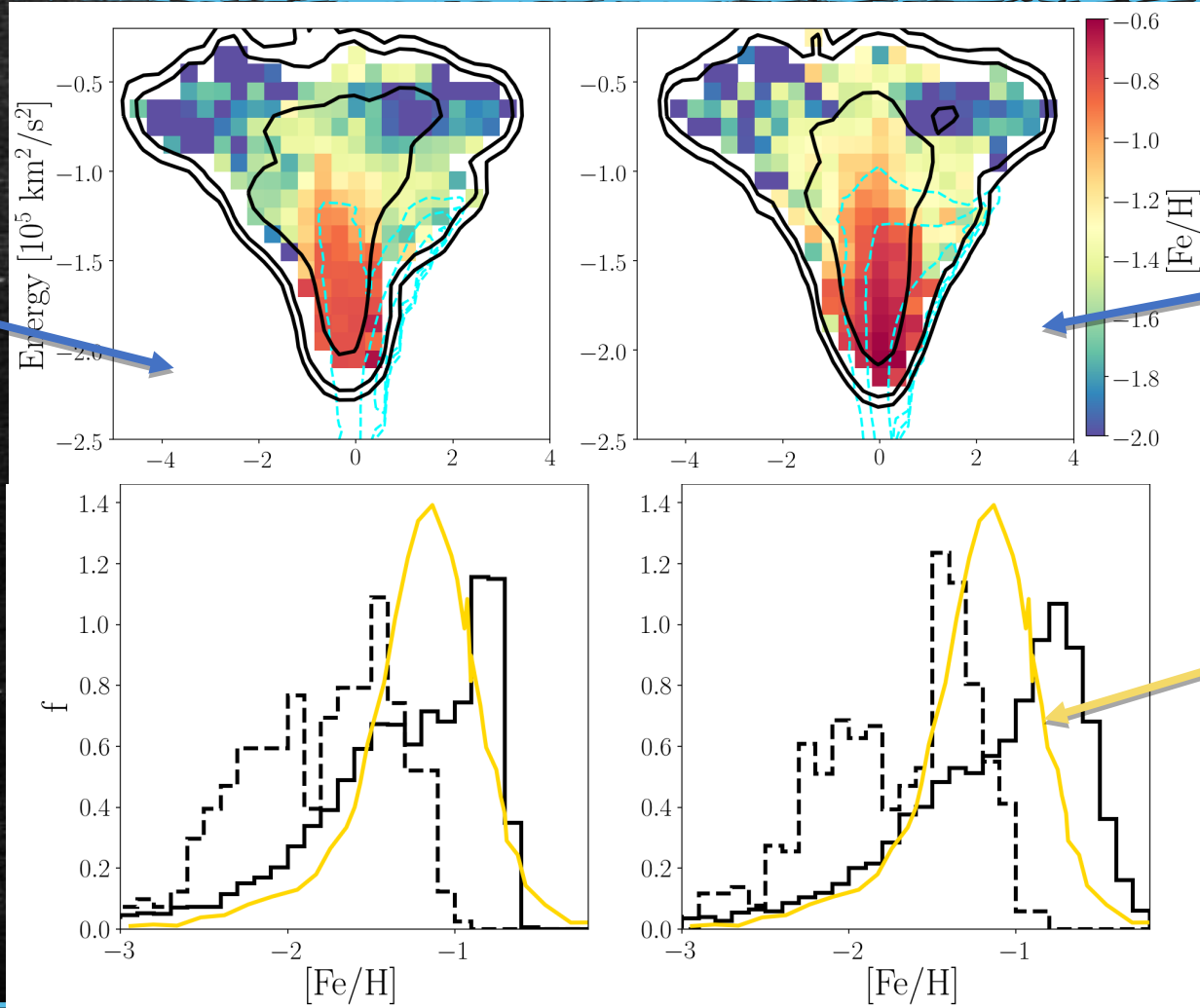


Xiang & Rix (2022), LAMOST subgiants

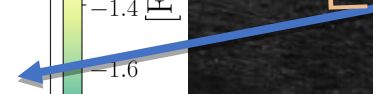


GASTRO I: Lz-Energy - t=10 Gyr

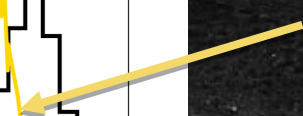
High fb



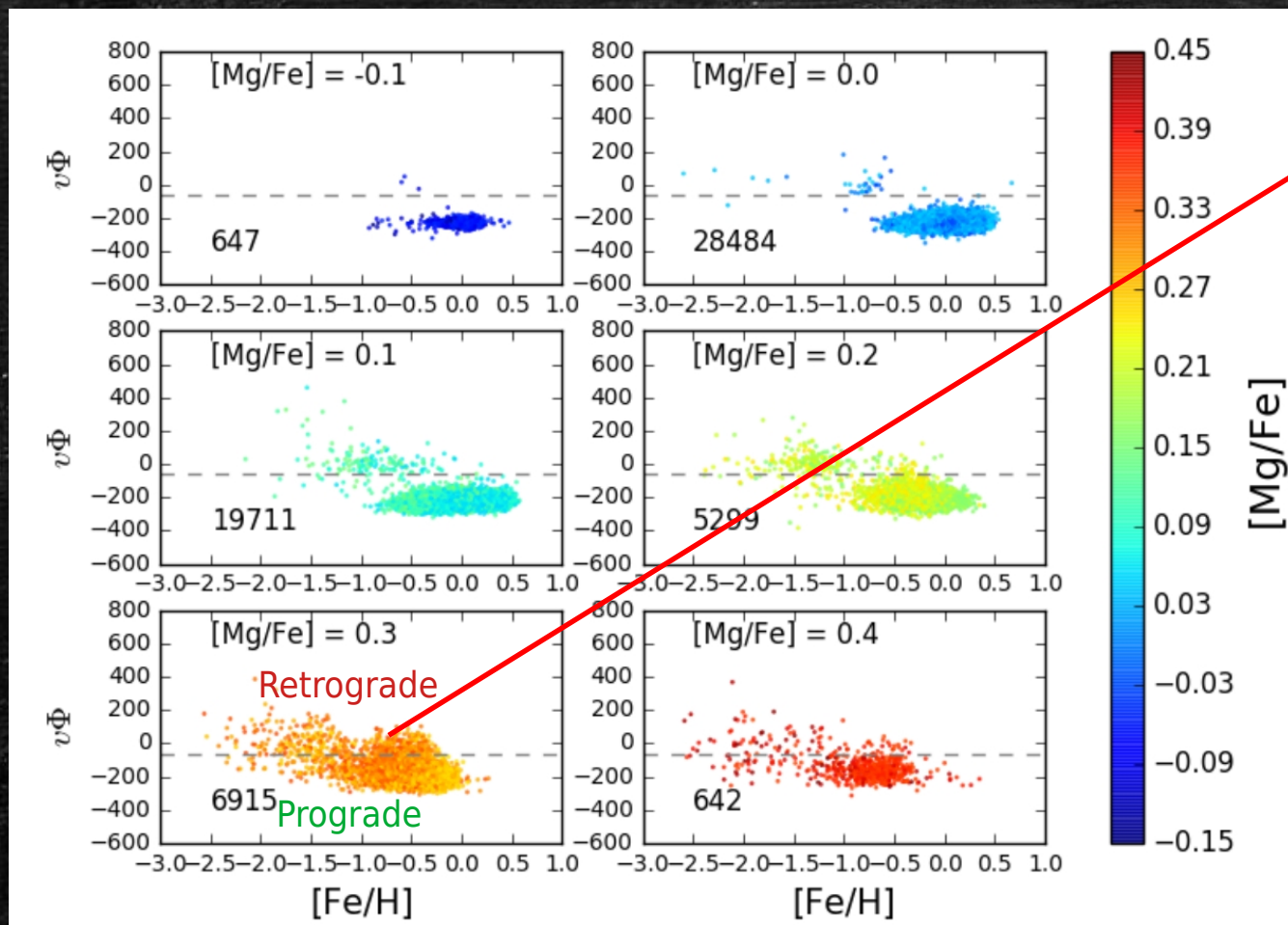
Low fb



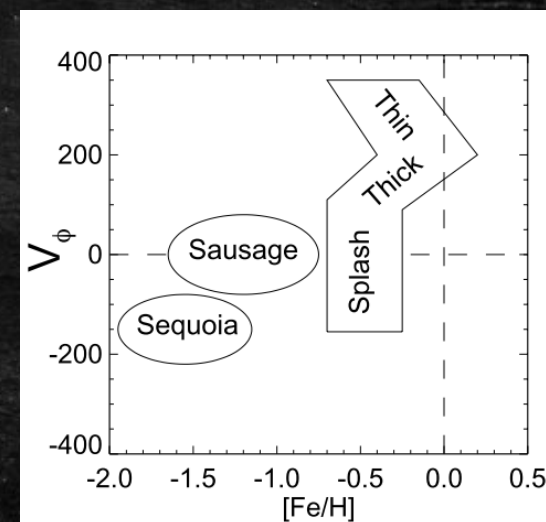
H3 Survey,
Naidu+2020



The heated thick disc



"The Plume"
A heated thick disc as
the "in-situ halo"



See also: "The Splash"
(Belokurov+2020)