The Biggest Splash

Vasily Belokurov (University of Cambridge)

Jason Sanders, A. Fattahi, M. Smith, A. Deason, W. Evans, R. Grand

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The biggest splash

Vasily Belokurov,[1★] Jason L. Sanders,[1] Azadeh Fattahi,[2] Martin C. Smith,[3] Alis J. Deason,[2] N. Wyn Evans[1] and Robert J. J. Grand[4,5,6]

[1] *Institute of Astronomy, Madingley Rd, Cambridge CB3 0HA, UK*
[2] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[3] *Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China*
[4] *Heidelberger Institut für Theoretische Studien, Schloß-Wolfsbrunnenweg 35, D-69118 Heidelberg, Germany*
[5] *Zentrum für Astronomie der Universität Heidelberg, Astronomisches Recheninstitut, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany*
[6] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany*

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ABSTRACT

Using a large sample of bright nearby stars with accurate *Gaia* Data Release 2 astrometry and auxiliary spectroscopy we map out the properties of the principle Galactic components such as the 'thin' and 'thick' discs and the halo. We confirm previous claims that in the Solar neighbourhood, there exists a large population of metal-rich ([Fe/H] > -0.7) stars on highly eccentric orbits. By studying the evolution of elemental abundances, kinematics, and stellar ages in the plane of azimuthal velocity v_ϕ and metallicity [Fe/H], we demonstrate that this metal-rich halo-like component, which we dub the *Splash*, is linked to the α-rich (or 'thick') disc. Splash stars have little to no angular momentum and many are on retrograde orbits. They are predominantly old, but not as old as the stars deposited into the Milky Way (MW) in the last major merger. We argue, in agreement with several recent studies, that the Splash stars may have been born in the MW's protodisc prior to the massive ancient accretion event which drastically altered their orbits. We cannot, however, rule out other (alternative) formation channels. Taking advantage of the causal connection between the merger and the Splash, we put constraints of the epoch of the last massive accretion event to have finished 9.5 Gyr ago. The link between the local metal-rich and metal-poor retrograde stars is confirmed using a large suite of cutting-edge numerical simulations of the MW's formation.

Key words: Galaxy: formation – Galaxy: halo – galaxies: dwarf – Local Group.

What is this talk about?

- The **early epochs** of the Milky Way formation
- In fact, this is about **the one accretion event** that mattered the most in the life of our Galaxy
- How the Milky Way was transformed, i.e. its **shape** and its **star formation**

What are the tools?

- We will look at the **Galactic stellar halo**, i.e. the stars moving at large distances from the disc plane with little net angular momentum
- We will use data from the ***Gaia*** space observatory and **large spectroscopic surveys**
- We will compare observation to **numerical simulations** of galaxy formation

Stellar halo formation in ΛCDM

Accreted: small number of massive mergers dominate the mass budget

Bullock & Johnston 2005, Robertson et al. 2005, Font et al. 2006, De Lucia & Helmi 2008

In-situ: early spheroid, proto-disc heating, satellite gas borrowing, outflows

Zolotov et al. 2009, McCarthy et al. 2012, Tissera et al. 2012, Cooper et al. 2015, Ishibashi & Fabian 2012, Zubovas et al 2013, Maiolino et al 2017

pre-Gaia Era

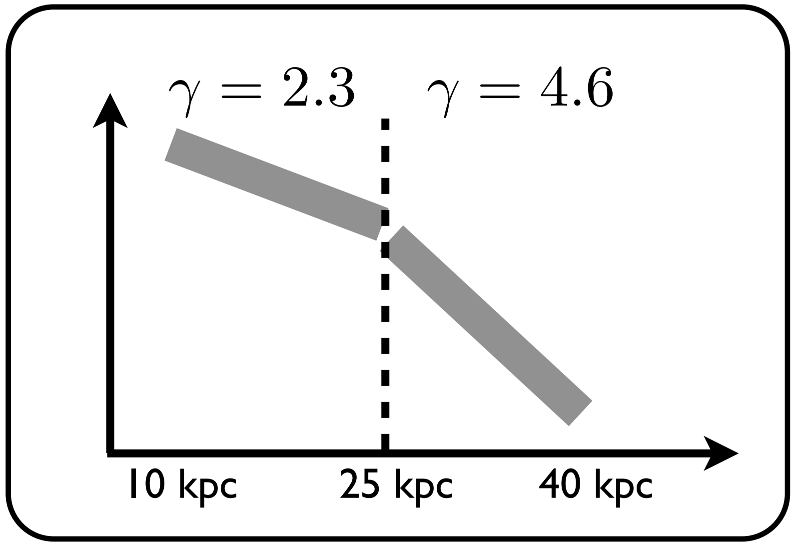
The Deason Break Hypothesis

"Broken and Unbroken. The Milky Way and M31 stellar halos"

"The presence or absence of a break in the stellar halo profile can be related to the accretion history of the galaxy. We find that a break radius is strongly related to the buildup of stars at apocenters. We relate these findings to observations, and find that the "break" in the Milky Way density profile is likely associated with a **relatively early (~6–9 Gyr ago) and massive accretion event.**"

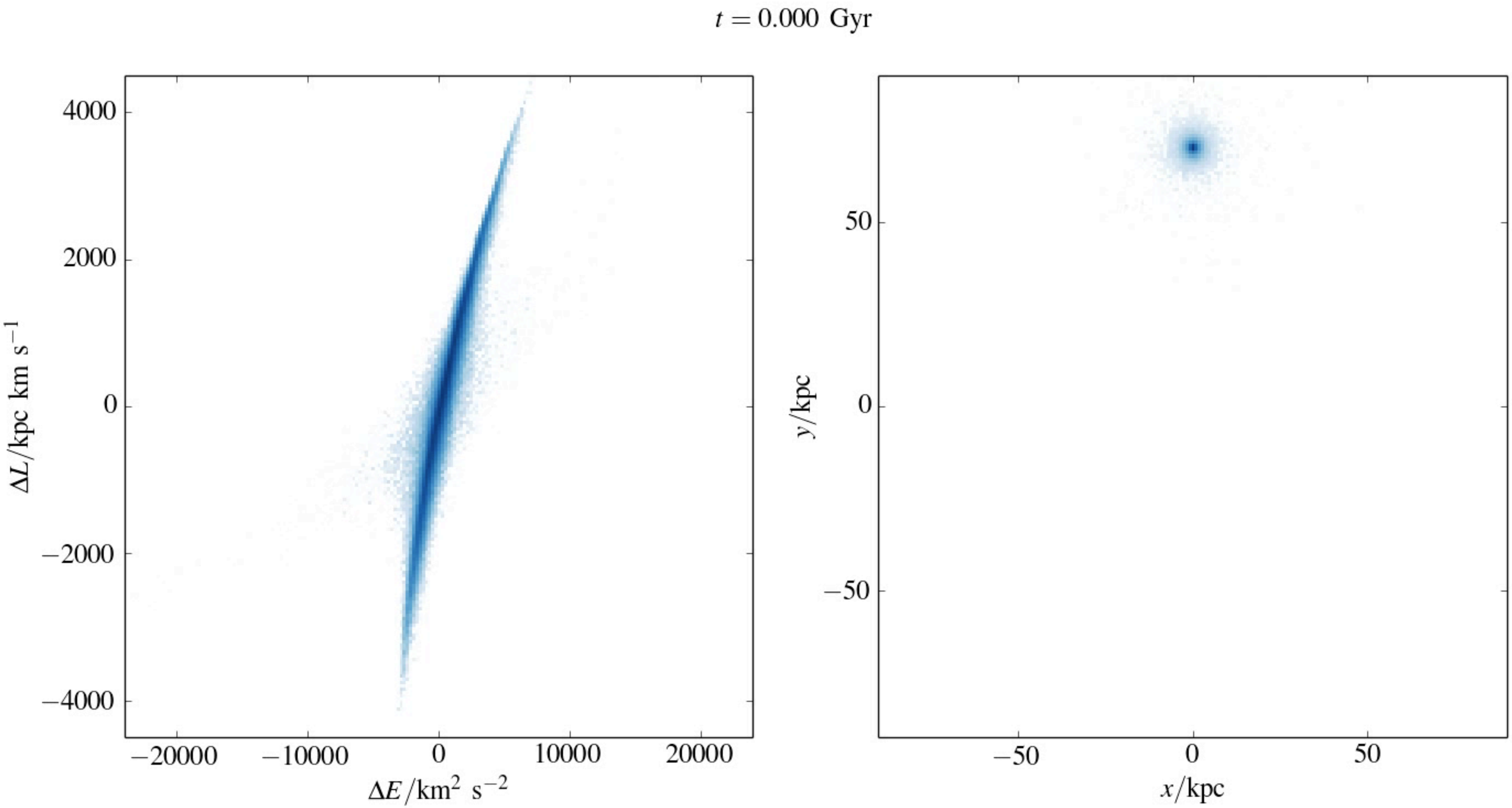
Alis Deason et al, 2013

break in the stellar halo density



Satellite disruption

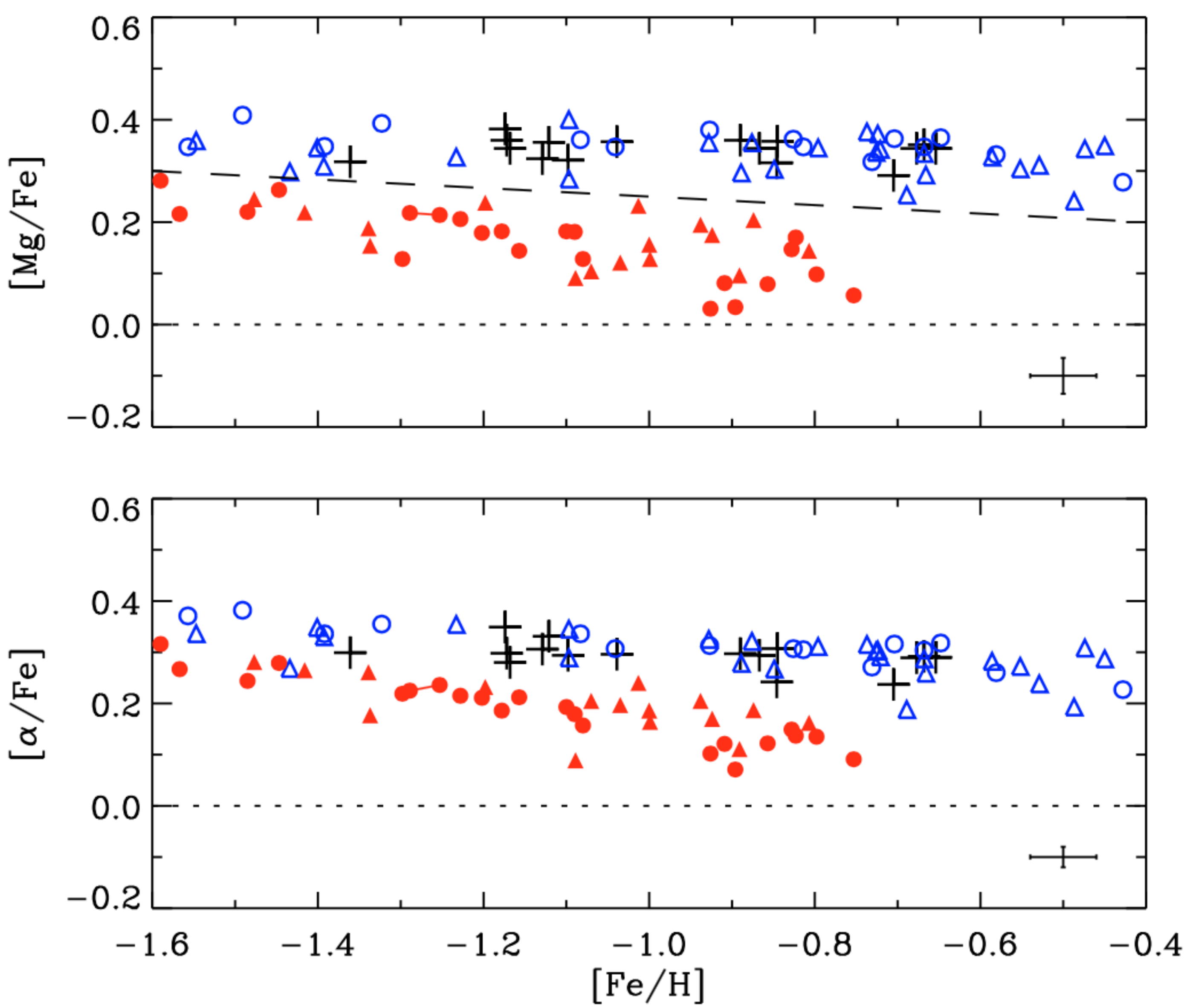
Energy and Angular Momentum

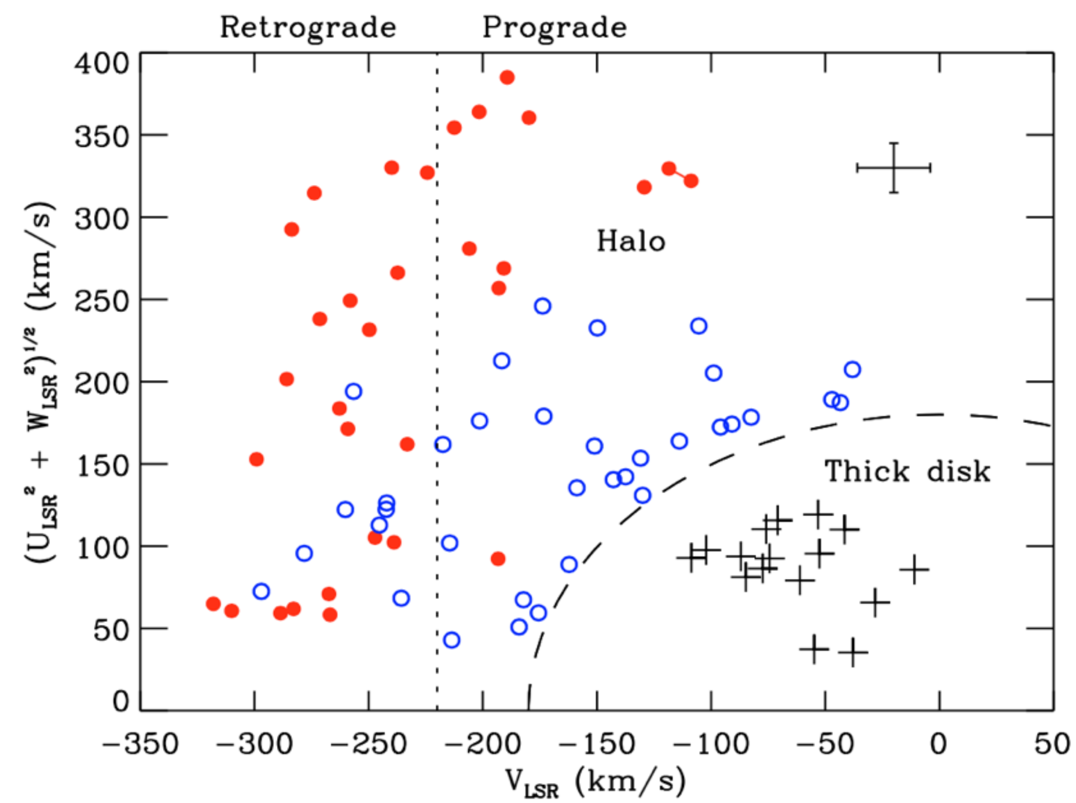


relative momentum

relative energy

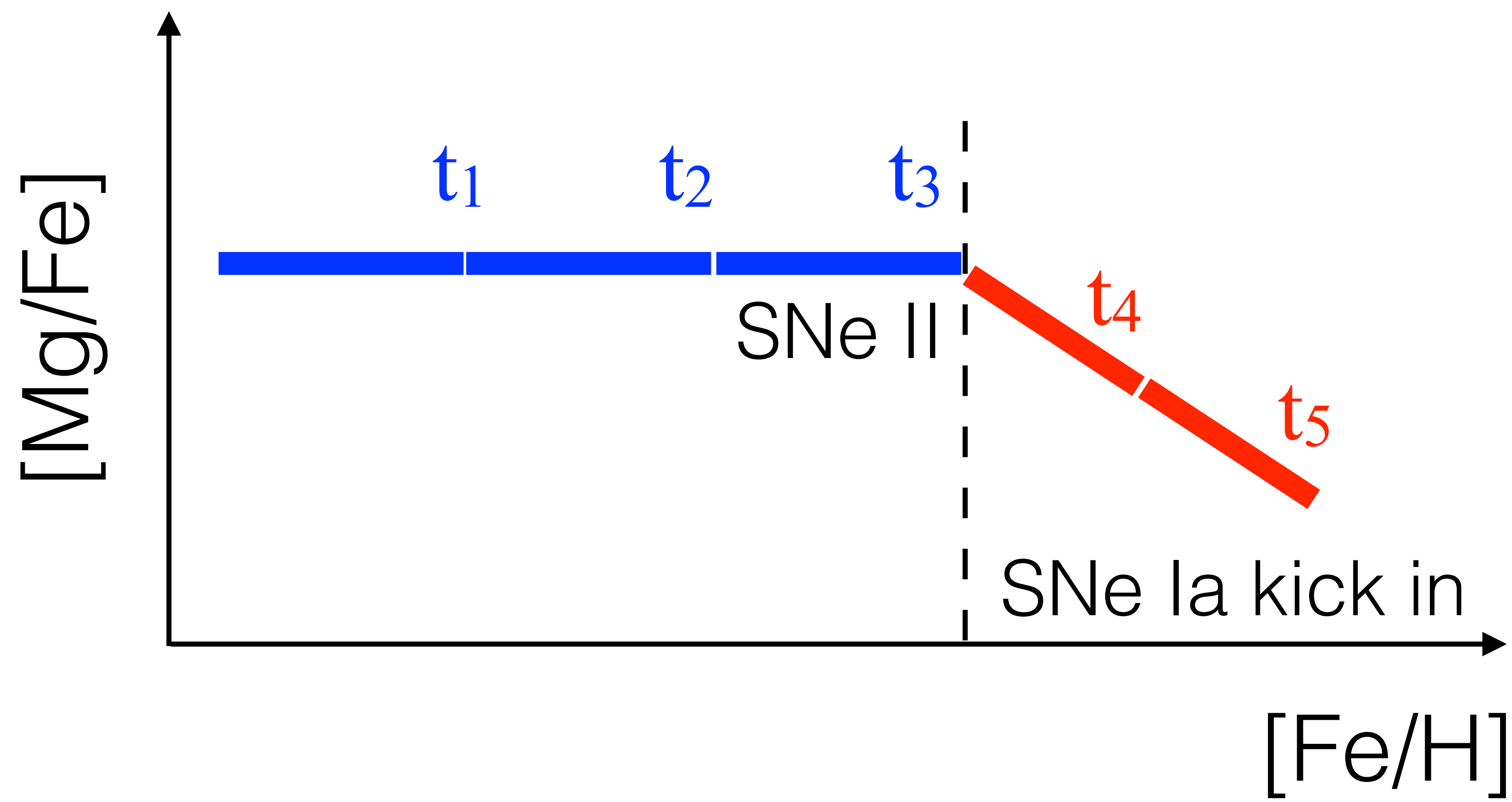
Dual MW stellar halo of Nissen and Schuster

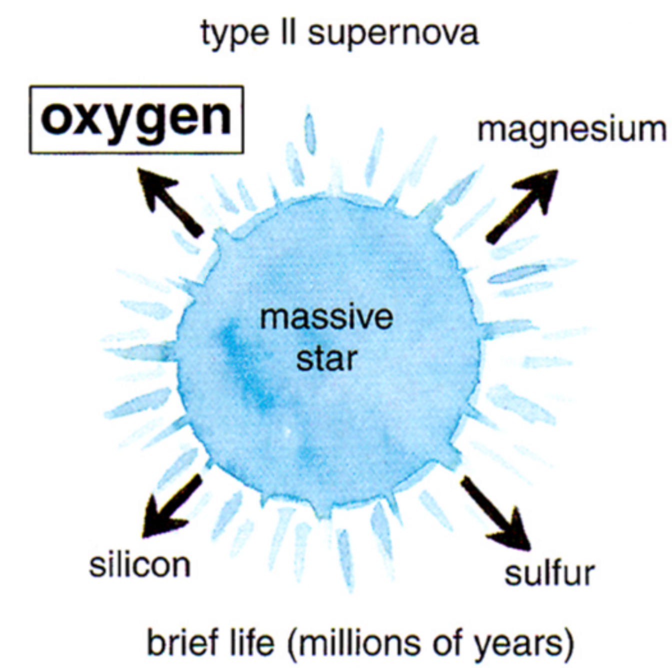


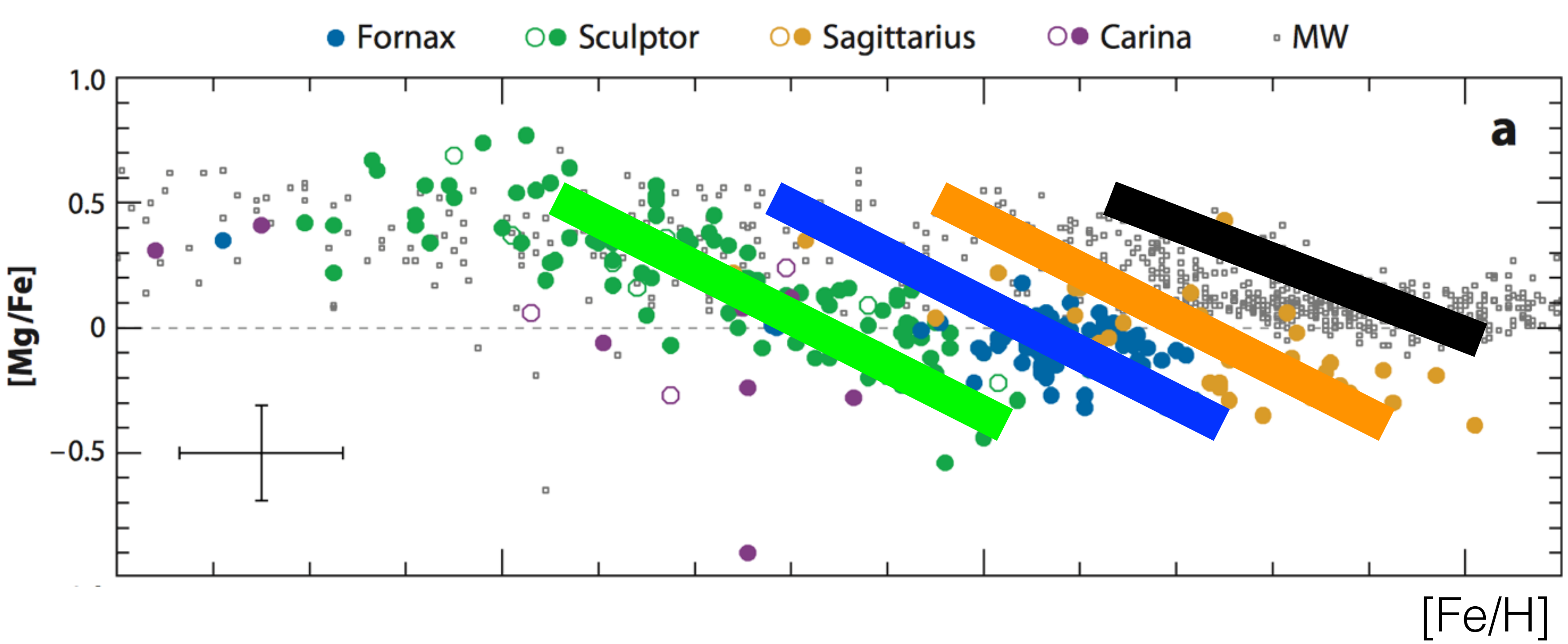


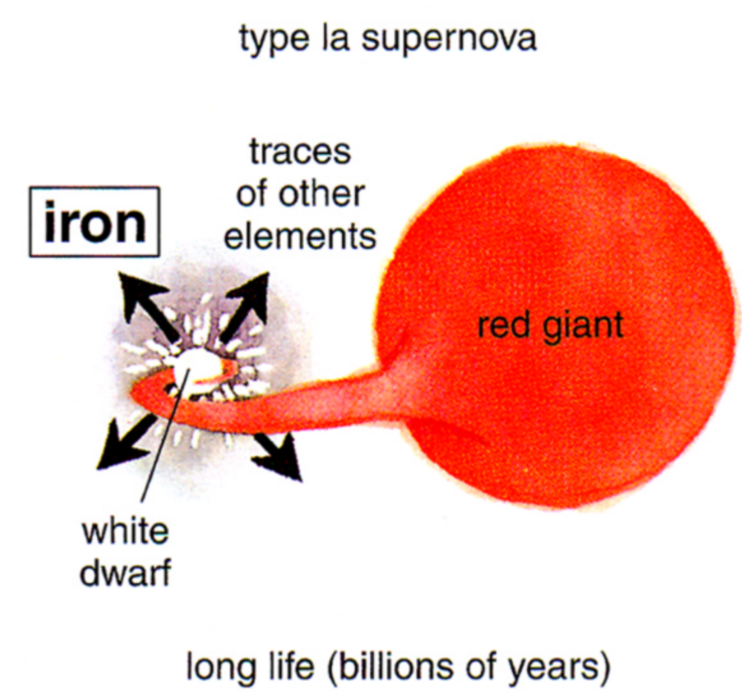
Nissen & Schuster 2010

SFH from chemical signatures









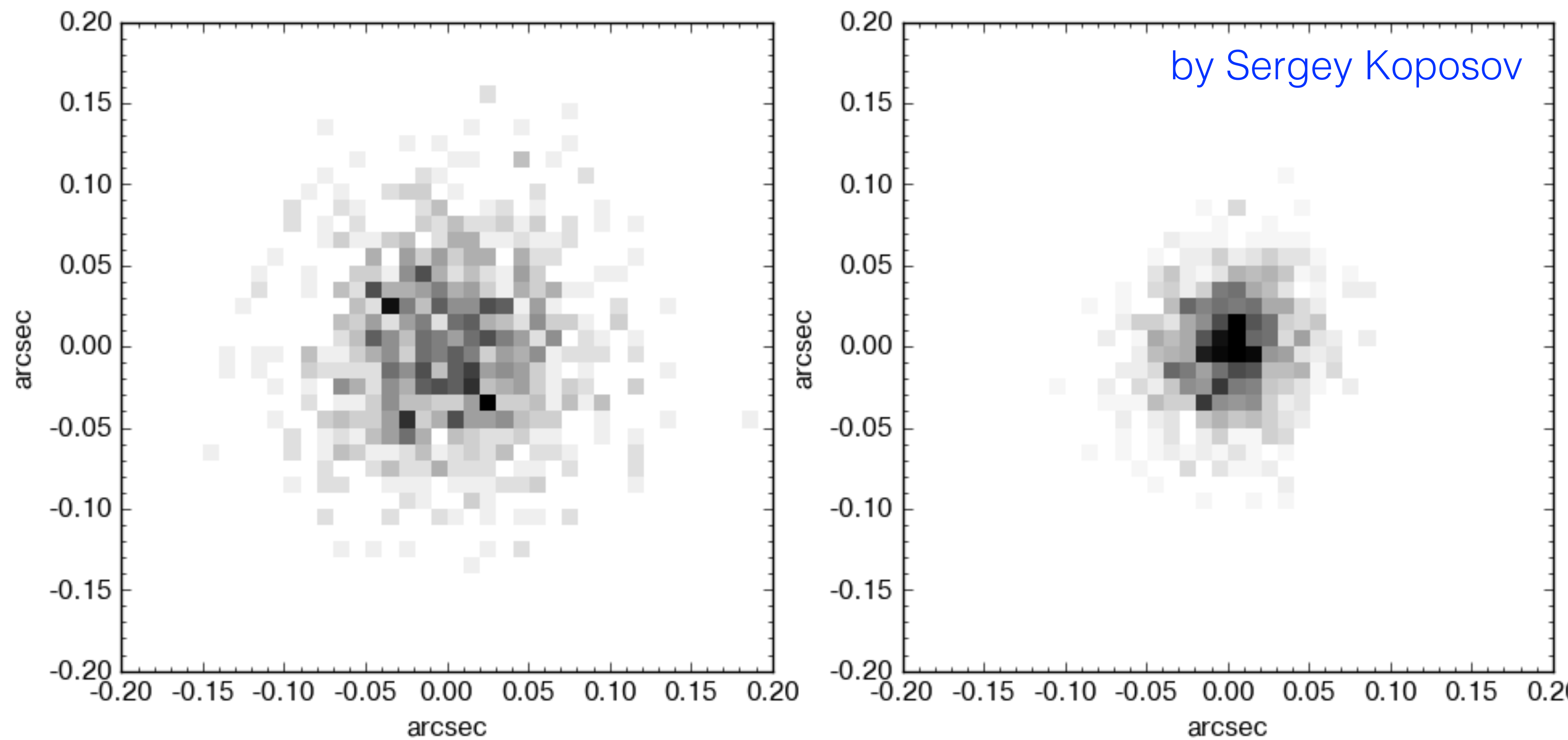
C. Chiappini

Gaia Era

Gaia DR1+SDSS

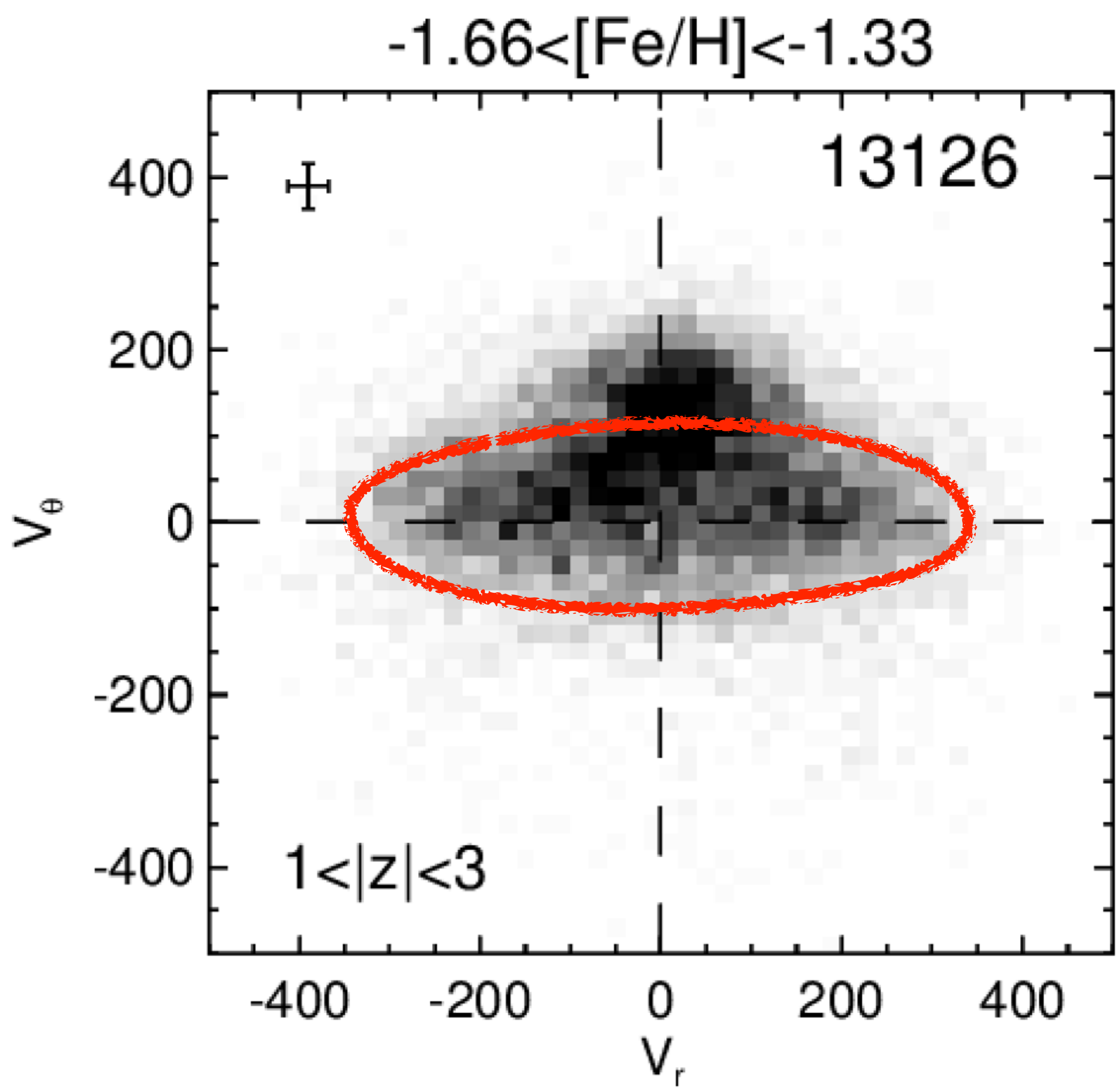
QSO proper motions in SDSS+Gaia DR1

QSO proper motions in recalibrated SDSS+Gaia DR1



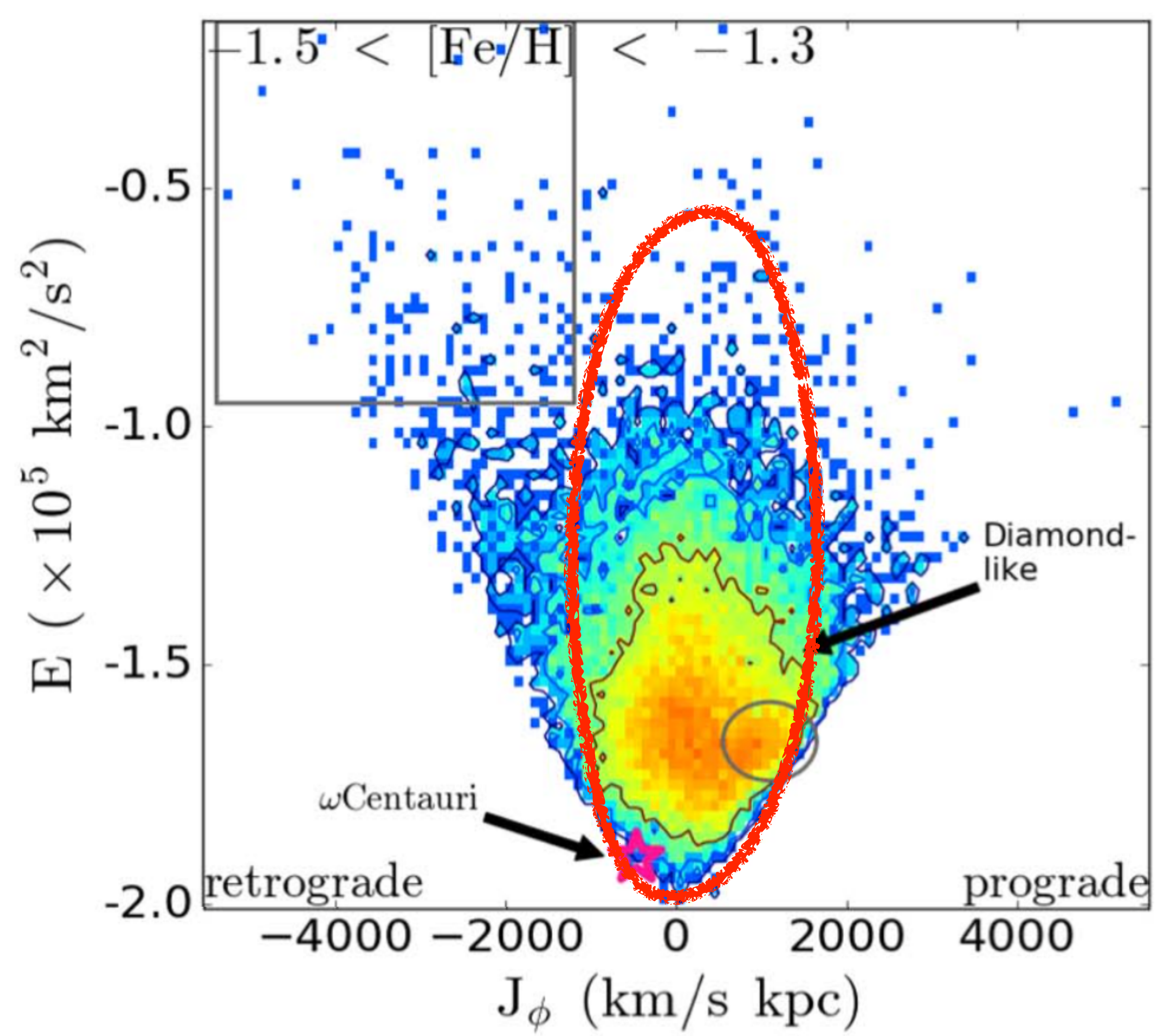
Local stellar halo in Gaia DR1-SDSS has a Sausage shape in velocity space

in velocity space



VB et al 2018

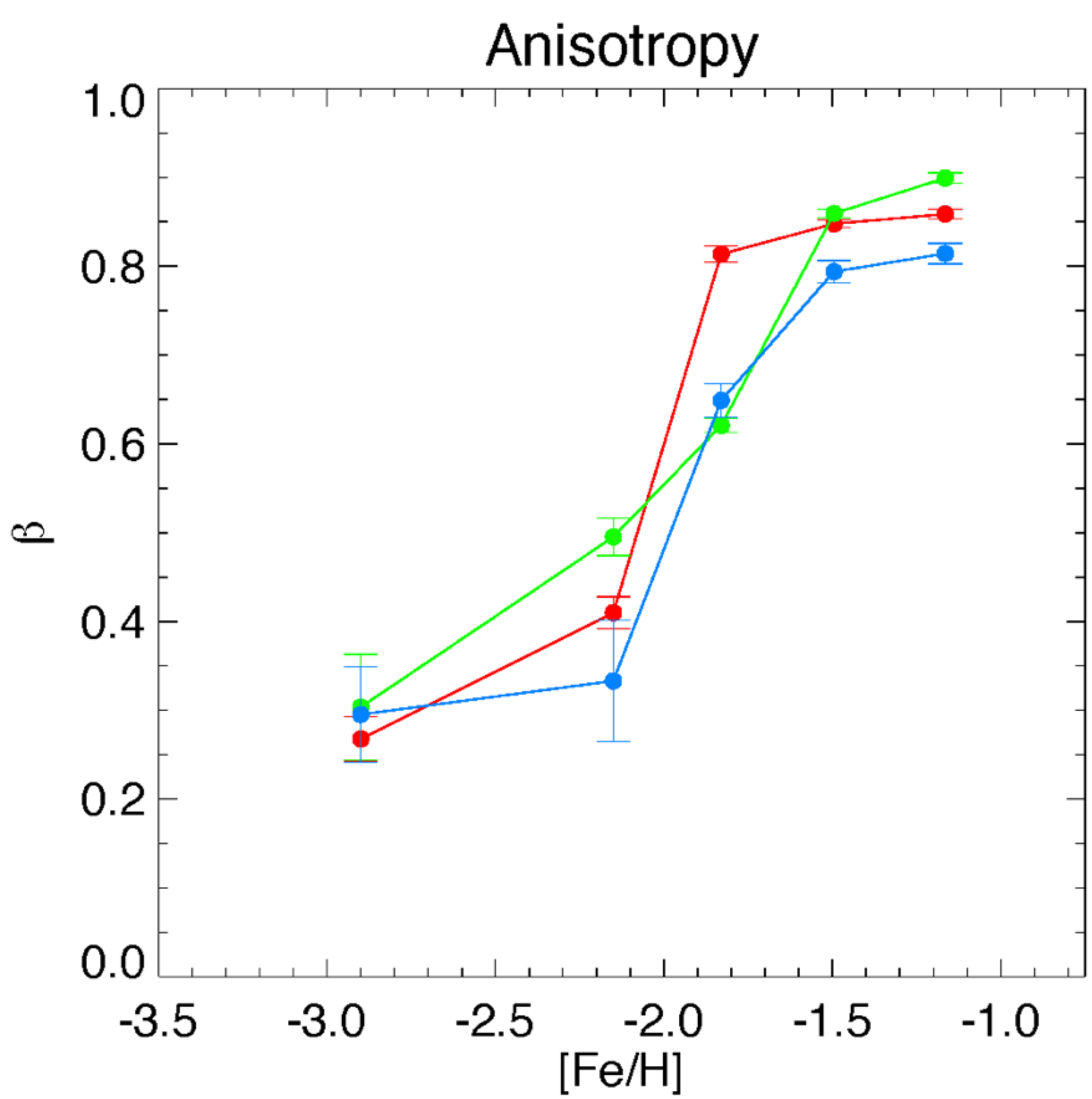
in action space



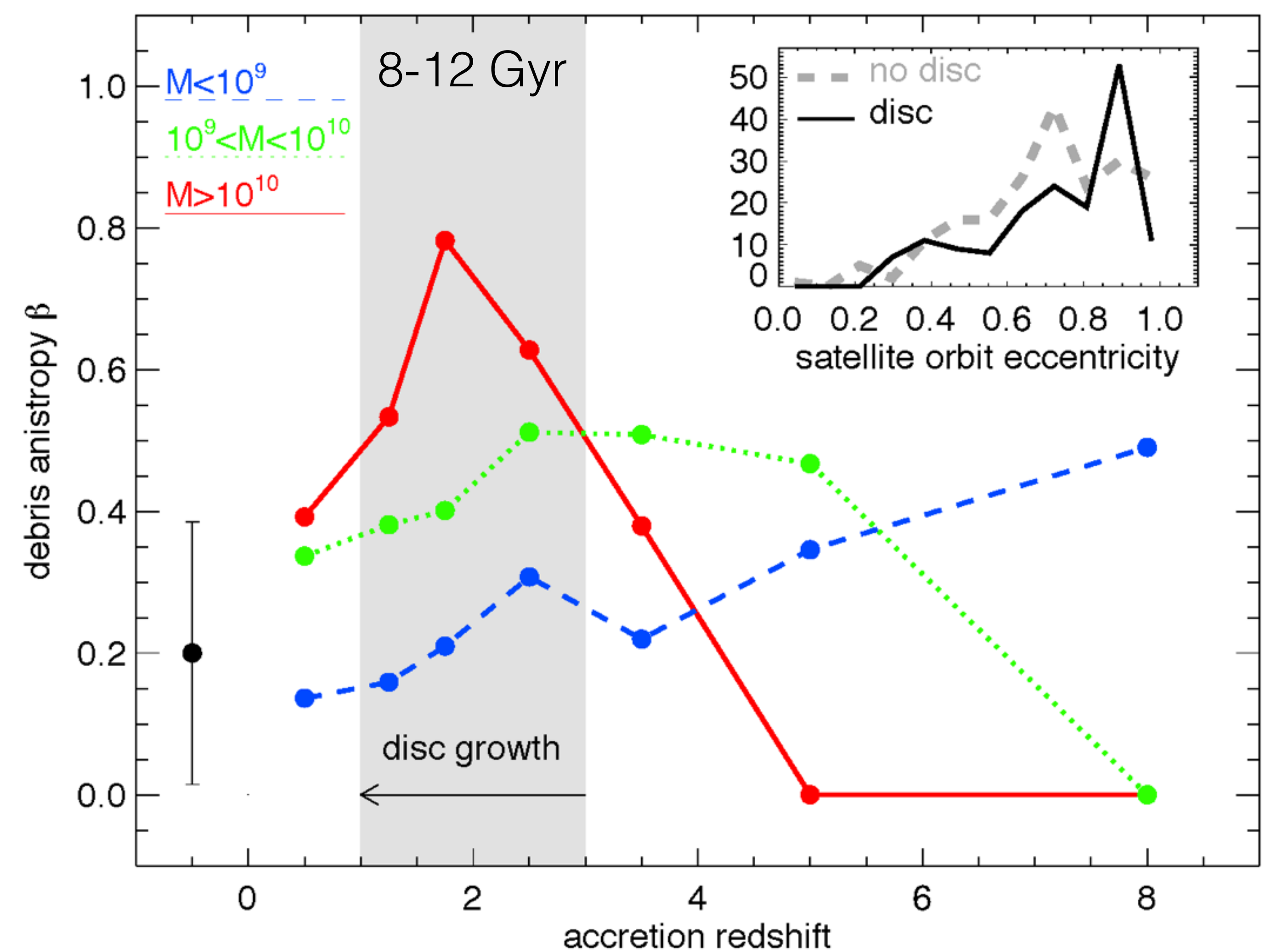
Myeong et al 2018

Genesis of (relatively) metal-rich & radially anisotropic halo component

Gaia DR1-SDSS

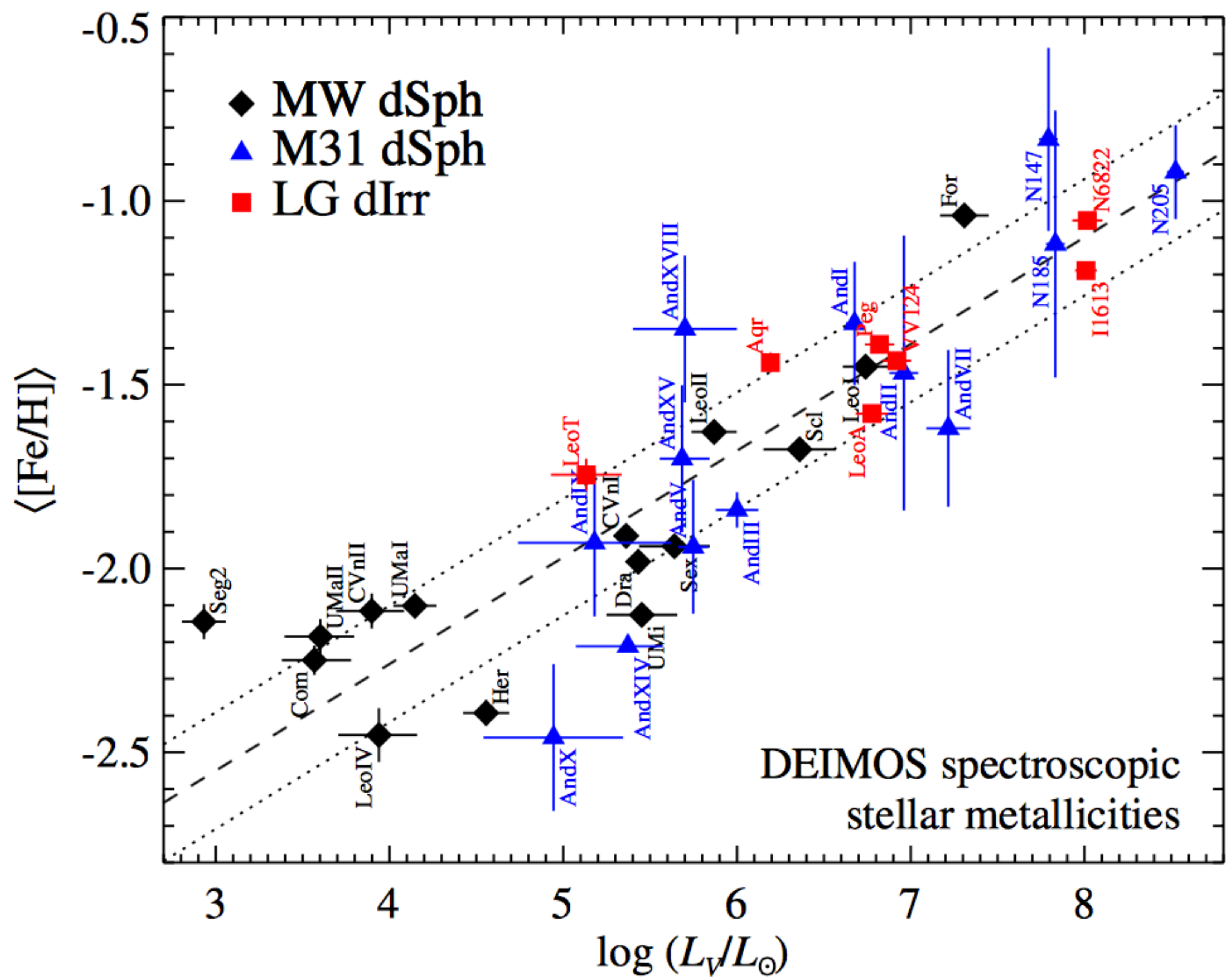


Cosmological zoom-in



VB et al 2018

Sausage progenitor stellar mass



Kirby et al 2013

Evidence for a single ancient massive merger

- **Single**: 2/3 of the local stellar (with [Fe/H]<-1) halo share the sense of motion (strongly radial)

- **Massive**: high metallicity (up to [Fe/H]=-0.7, use mass-metallicity relation)

- **Ancient**: ages of the stellar debris >10 Gyr

- **Ancient**: quite smooth, little remaining sub-structure (although see Simion et al 2019)

- **Single**: massive (see above) so no room for many events like this (total stellar halo mass is $<10^9$)

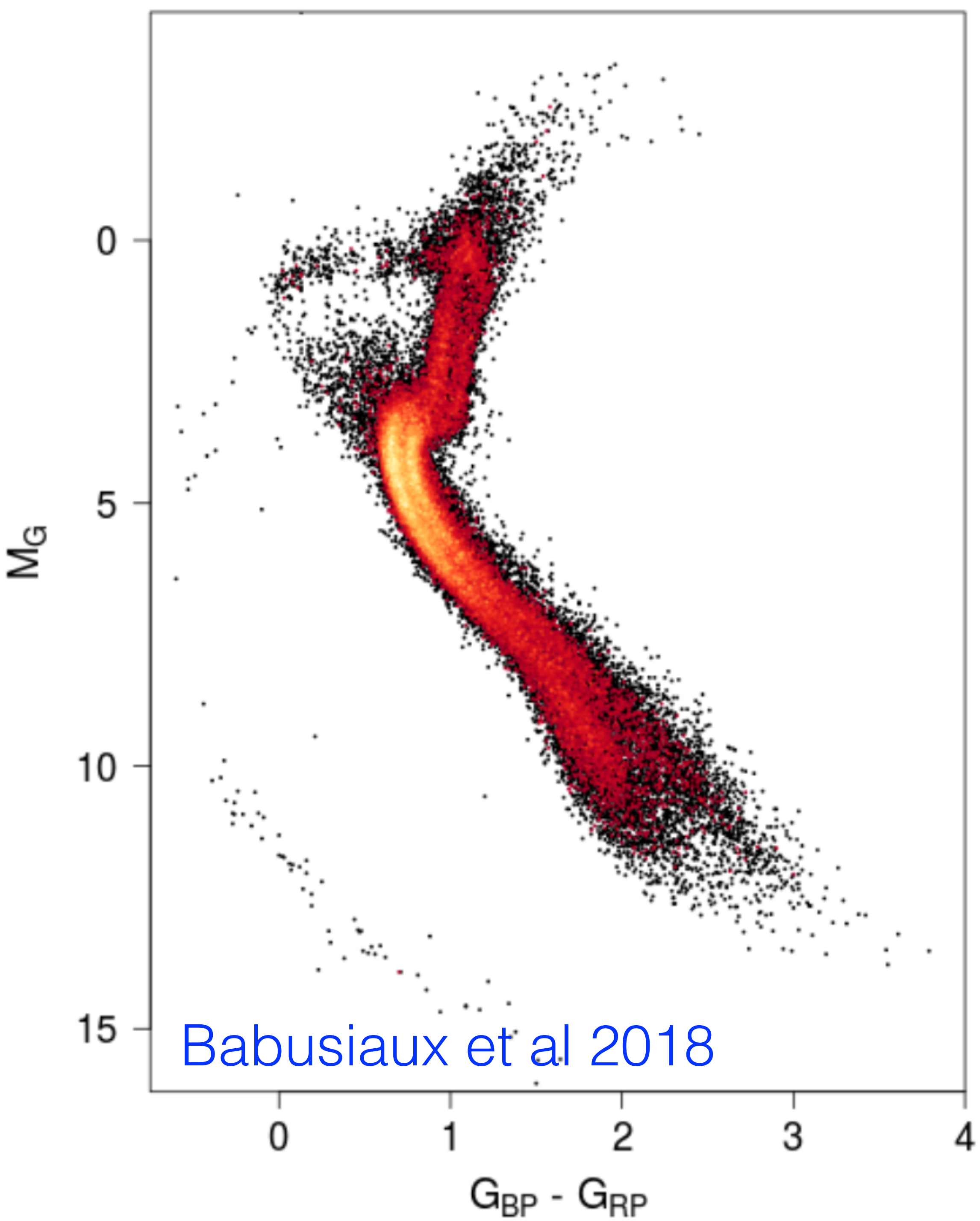
- **Single, Massive, Ancient**: comparison with simulations

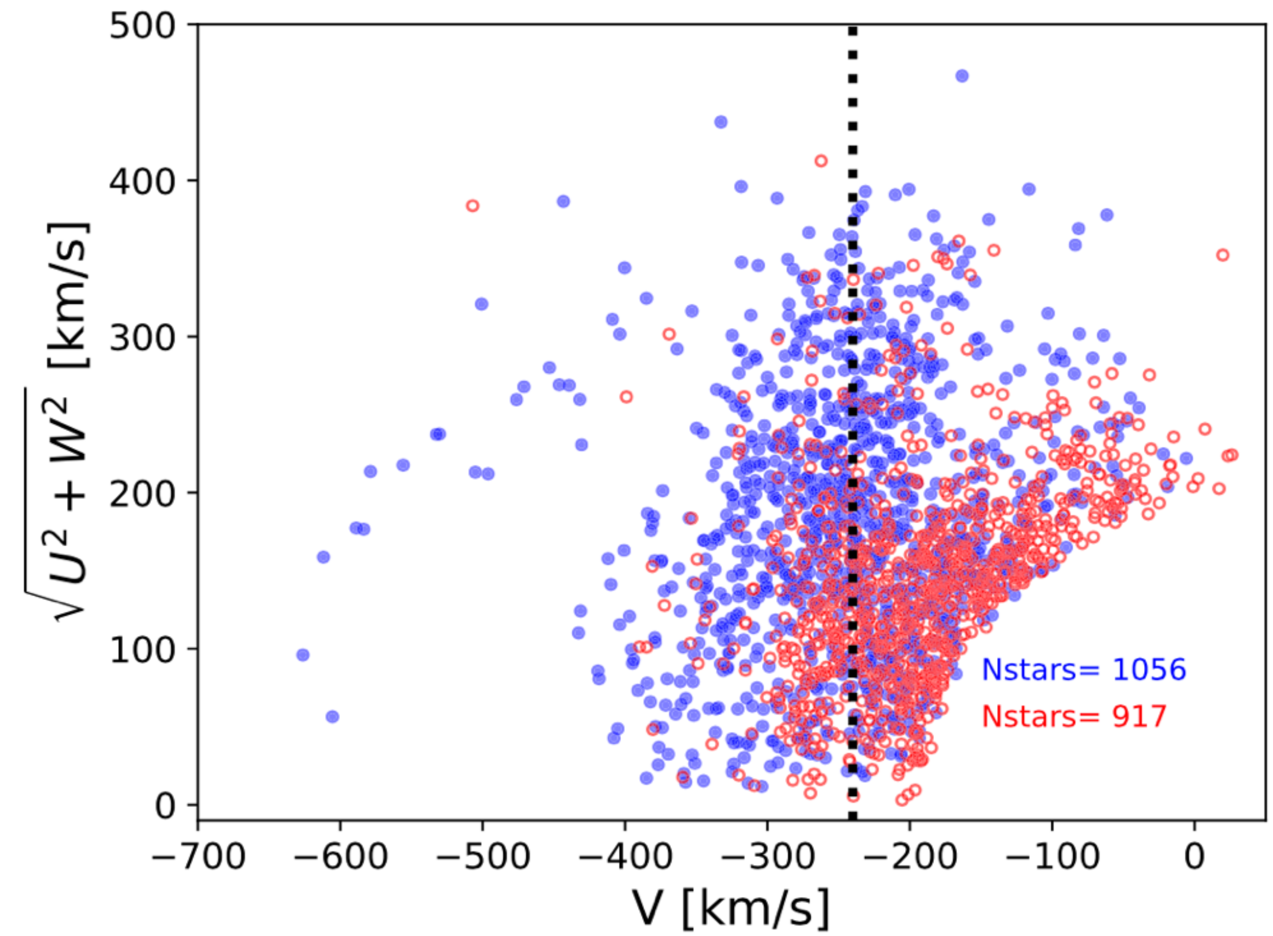
Gaia DR2 follow-up

Insights from the Gaia DR2

The nature of the double sequence in GDR2 CMD

Stars with halo-like motion



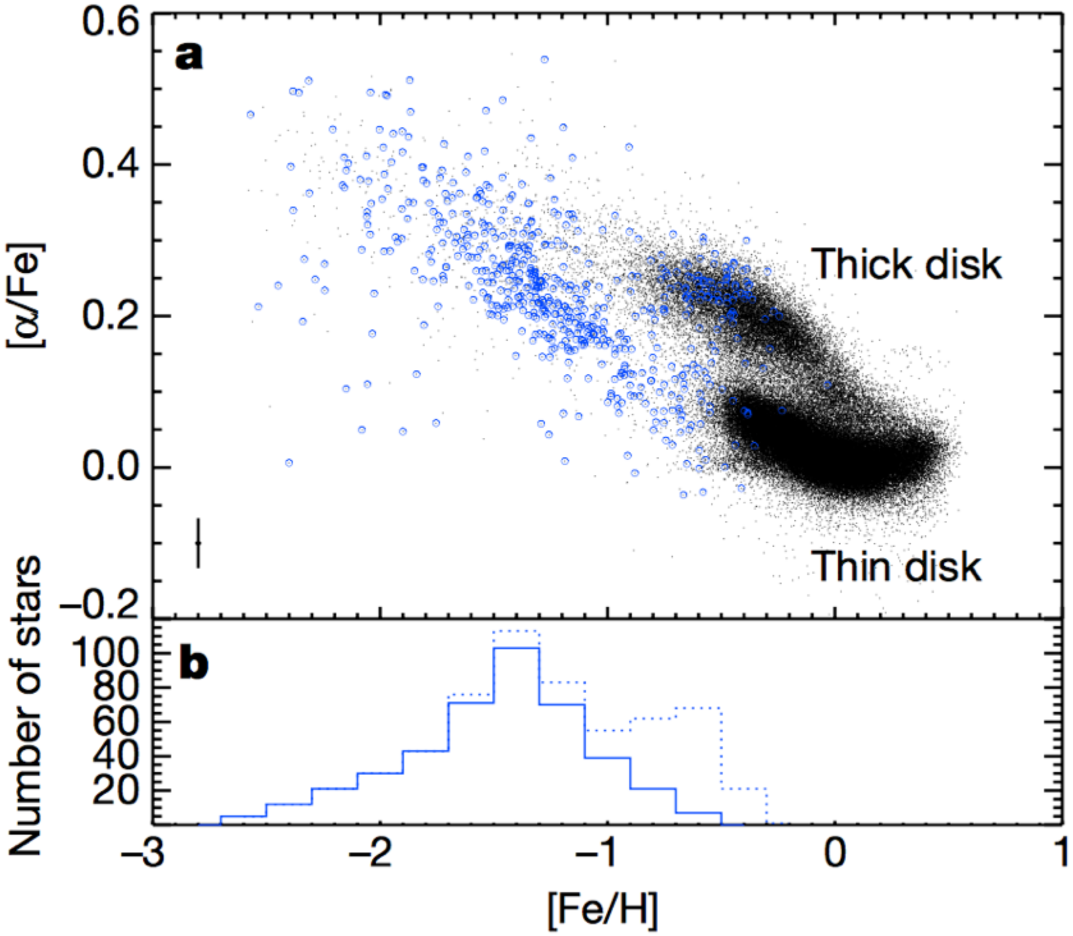


Haywood et al 2018: blue - last major merger, red - in-situ (thick disc+)

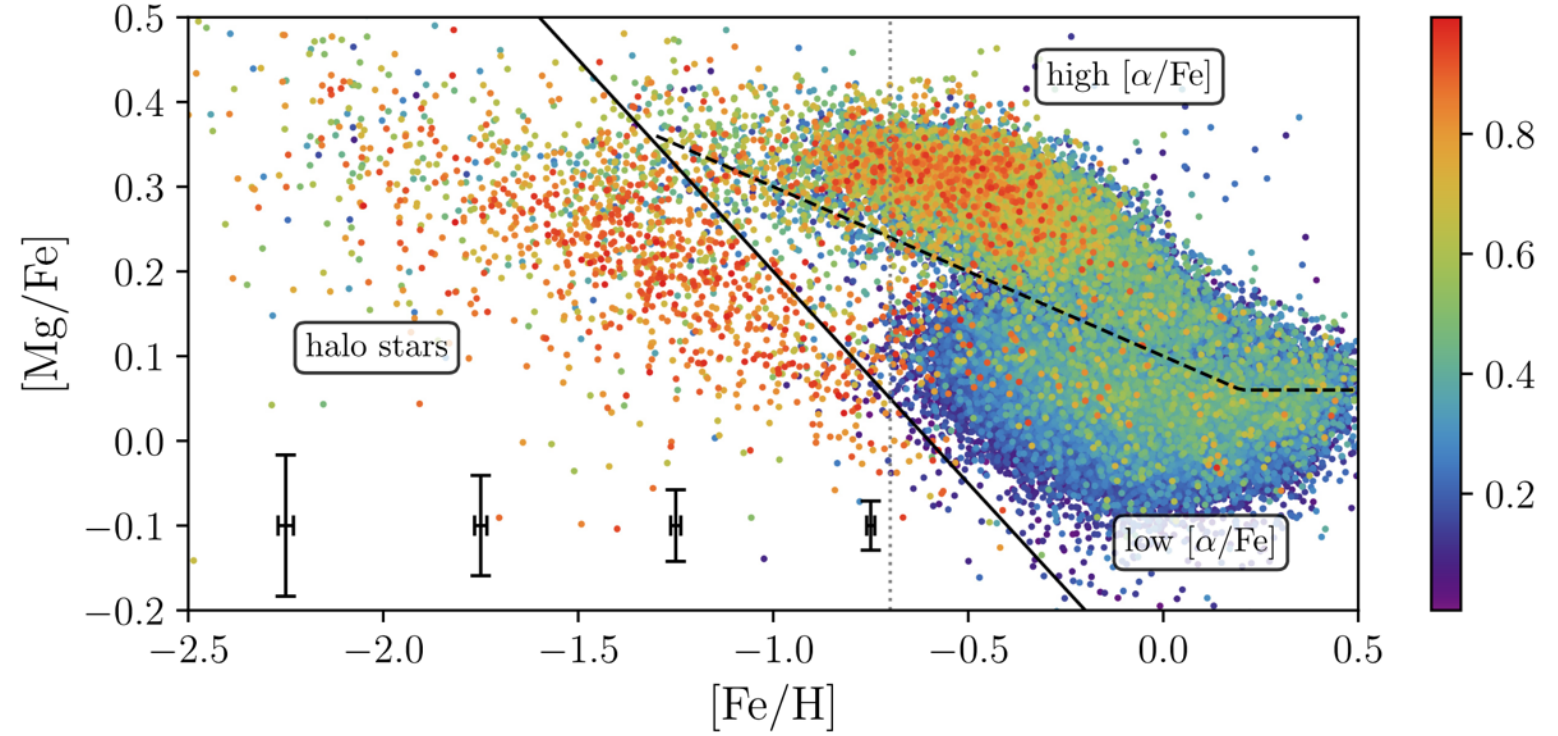
Gallart et al 2019: part of the red sequence - prehistoric in-situ halo

Linking orbits and chemistry

Helmi et al 2018

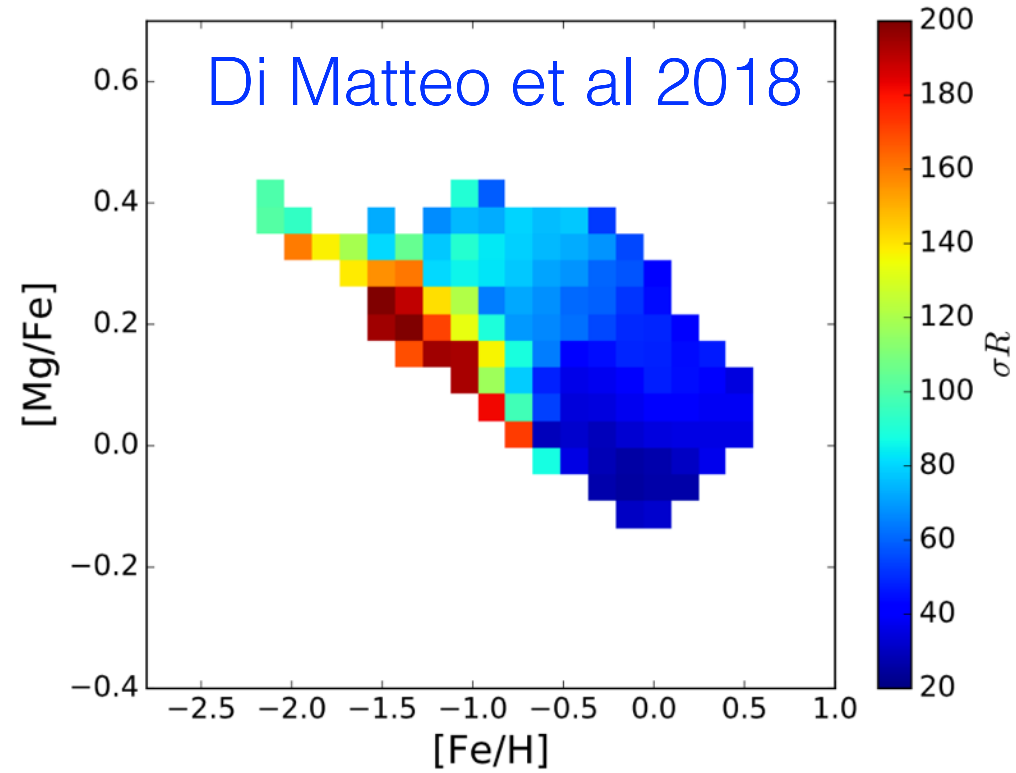


Mackereth et al 2018



1. A clear alpha-[Fe/H] sequence for the major merger debris selected kinematically
2. Two halo sequences with distinct alpha abundances

Di Matteo et al 2018



What happened
to the Milky Way
as a result of the
Gaia Sausage accretion?

Questions

- Epoch of the last massive merger
- Geometry of the interaction
- Masses involved
- Response of the Milky Way

Isochrone ages for ~3 million stars with the second Gaia data release

Pangaea by Sanders & Das 2018

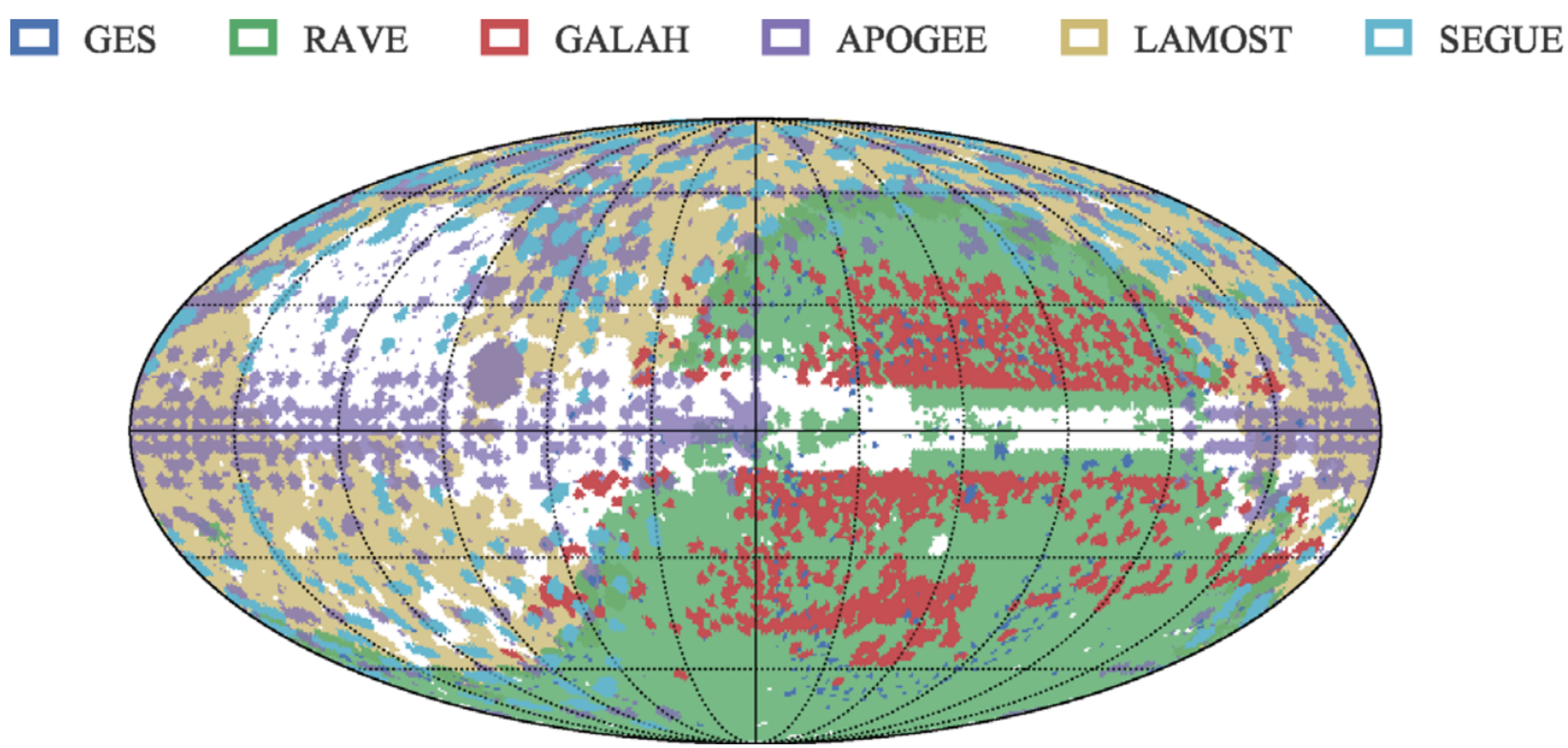
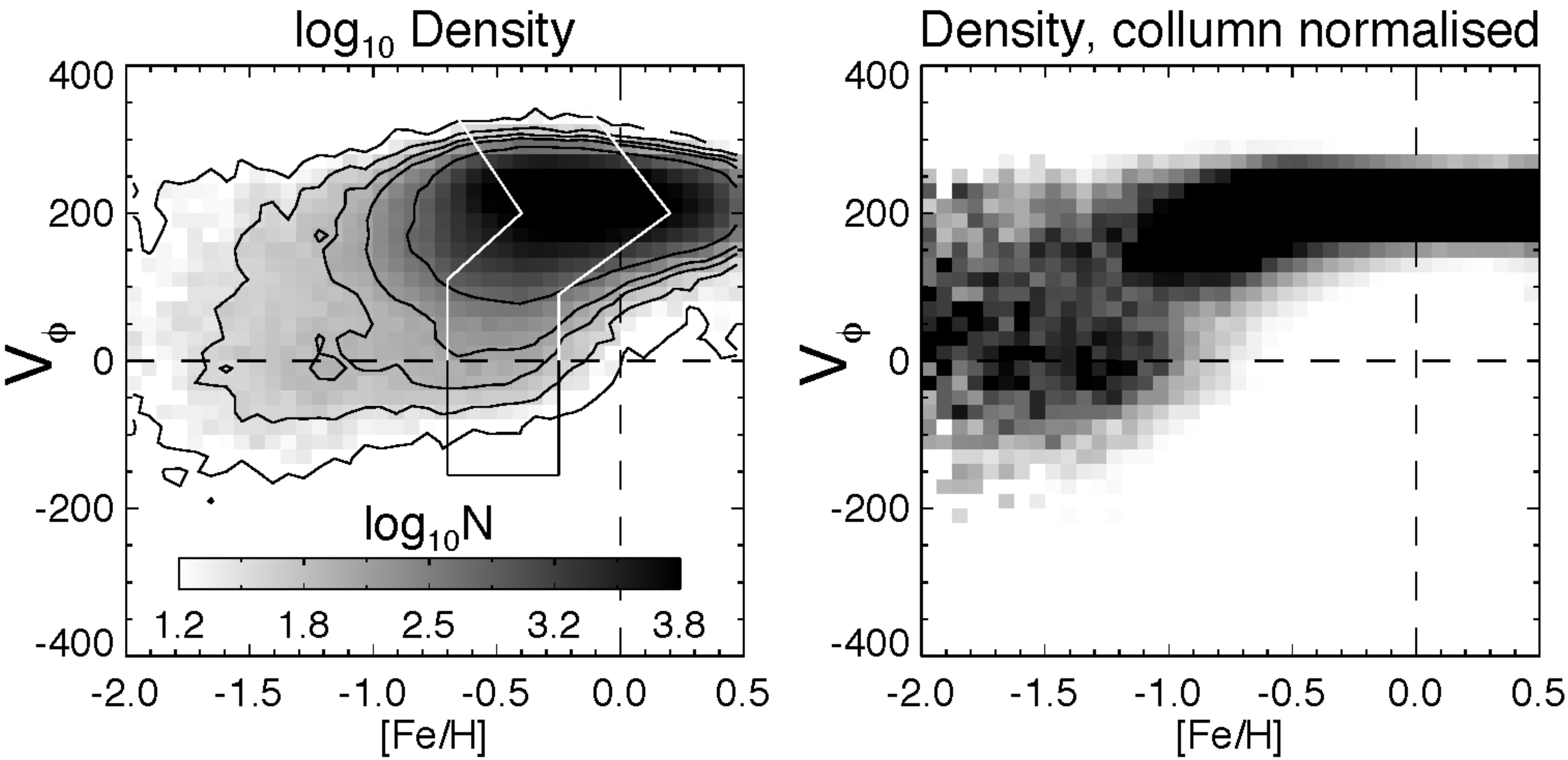


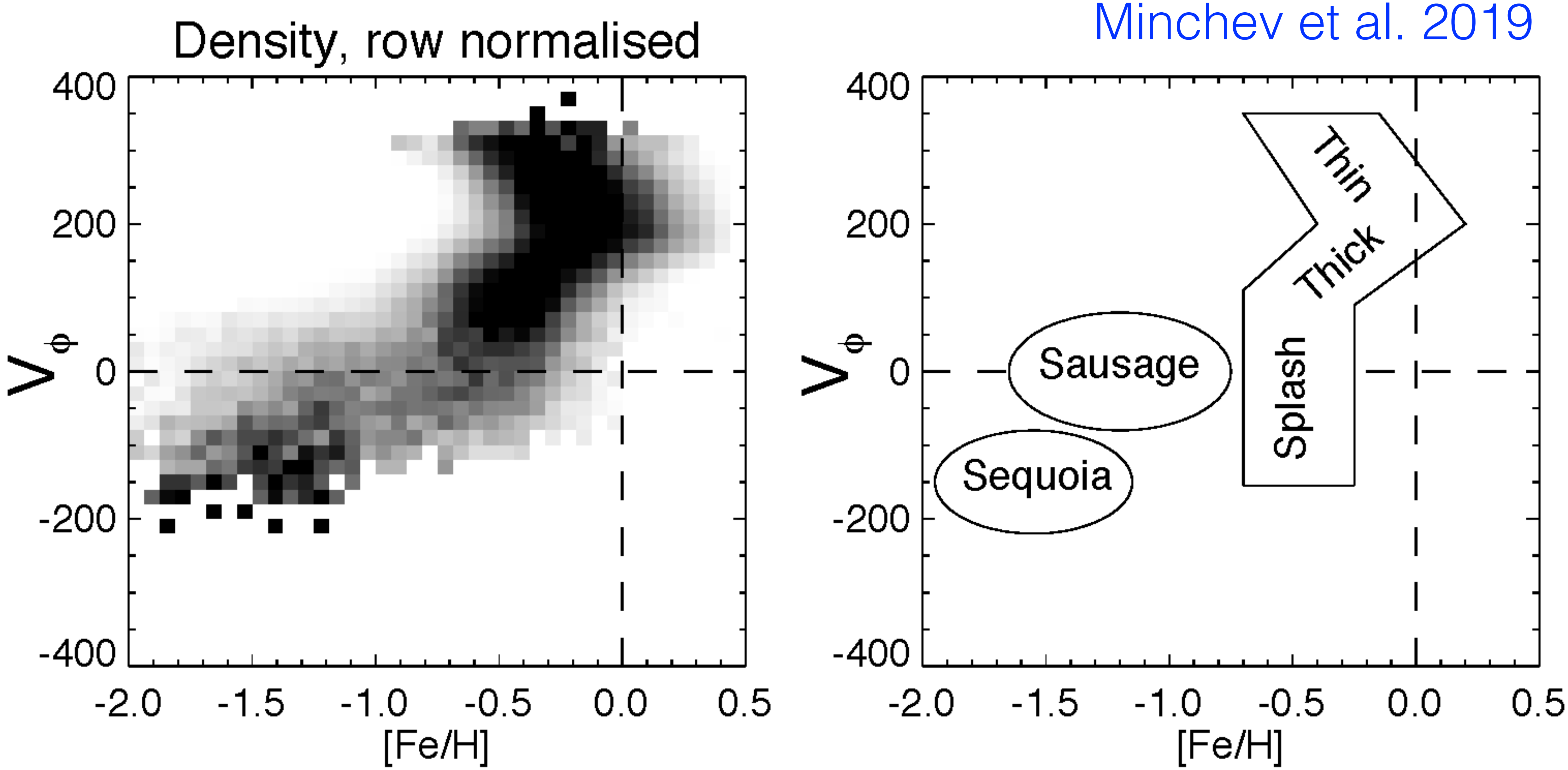
Figure 1. On-sky galactic distribution of the stars processed by our pipeline coloured by survey.

Galactic chemo-kinematics



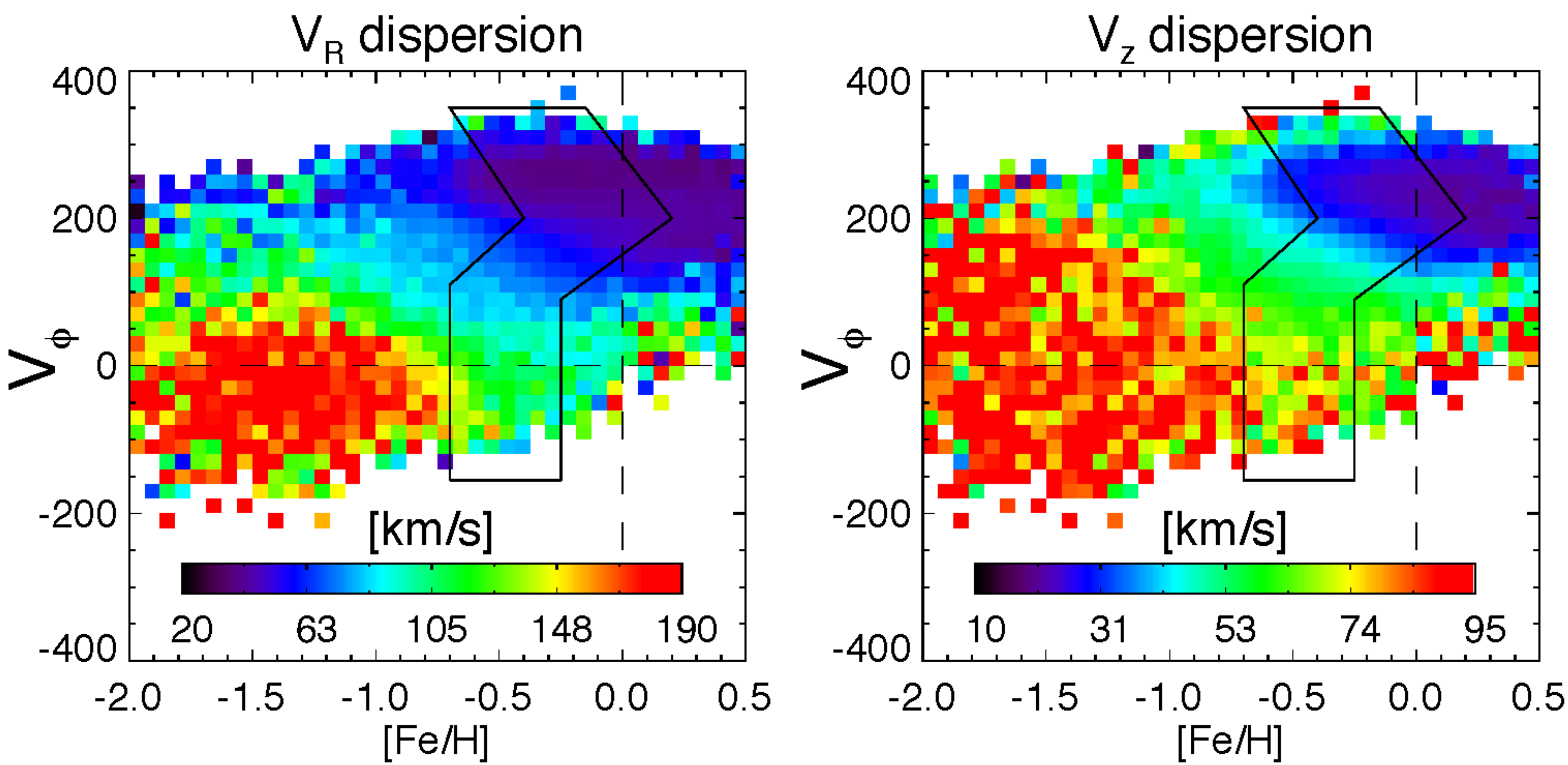
Galactic chemo-kinematics

Schönrich & Mcmillan 2017
Minchev et al. 2019



If you want to know what <u>Sequoia</u> is read **Myeong et al (2019)**

Galactic chemo-kinematics



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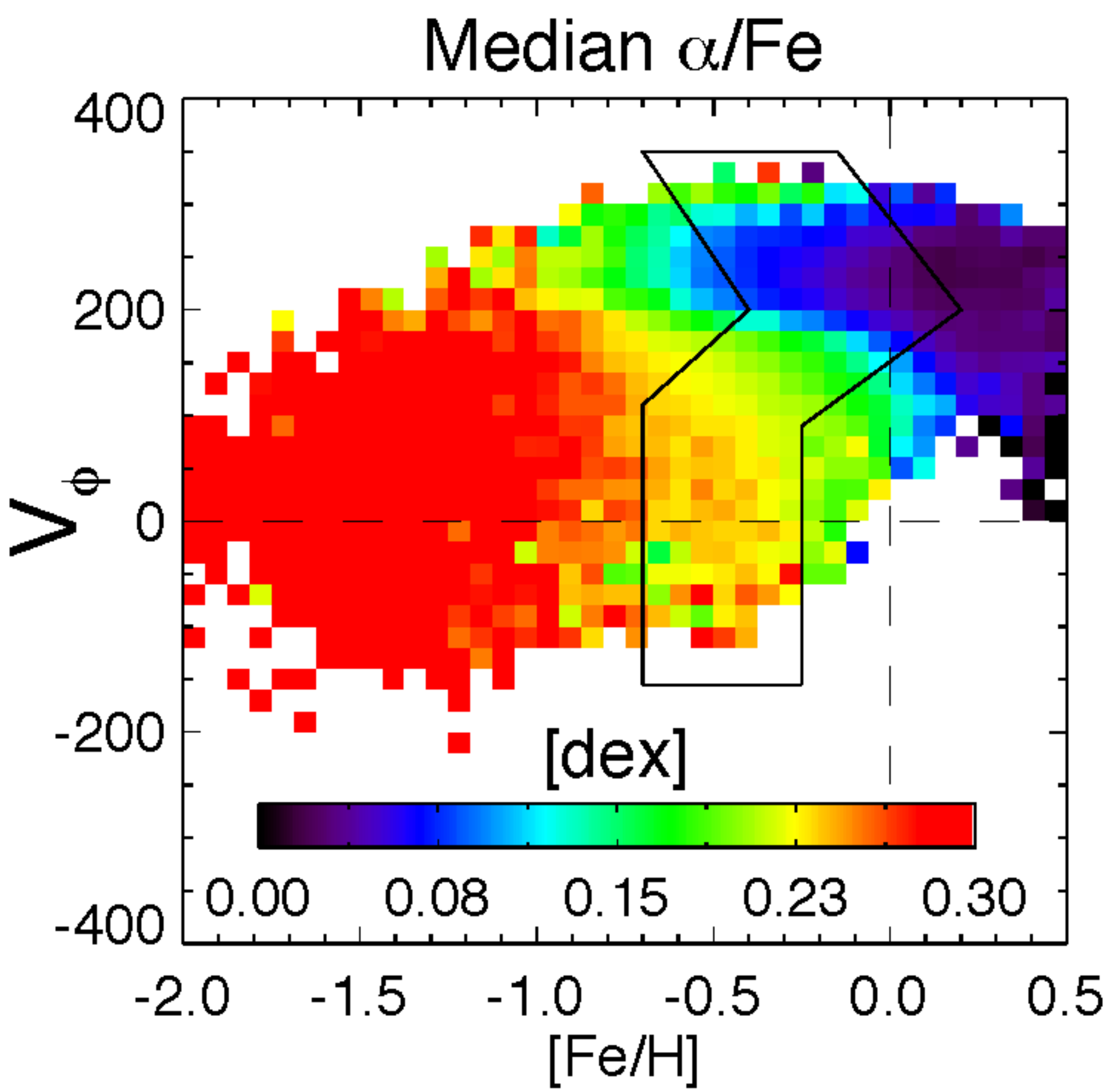
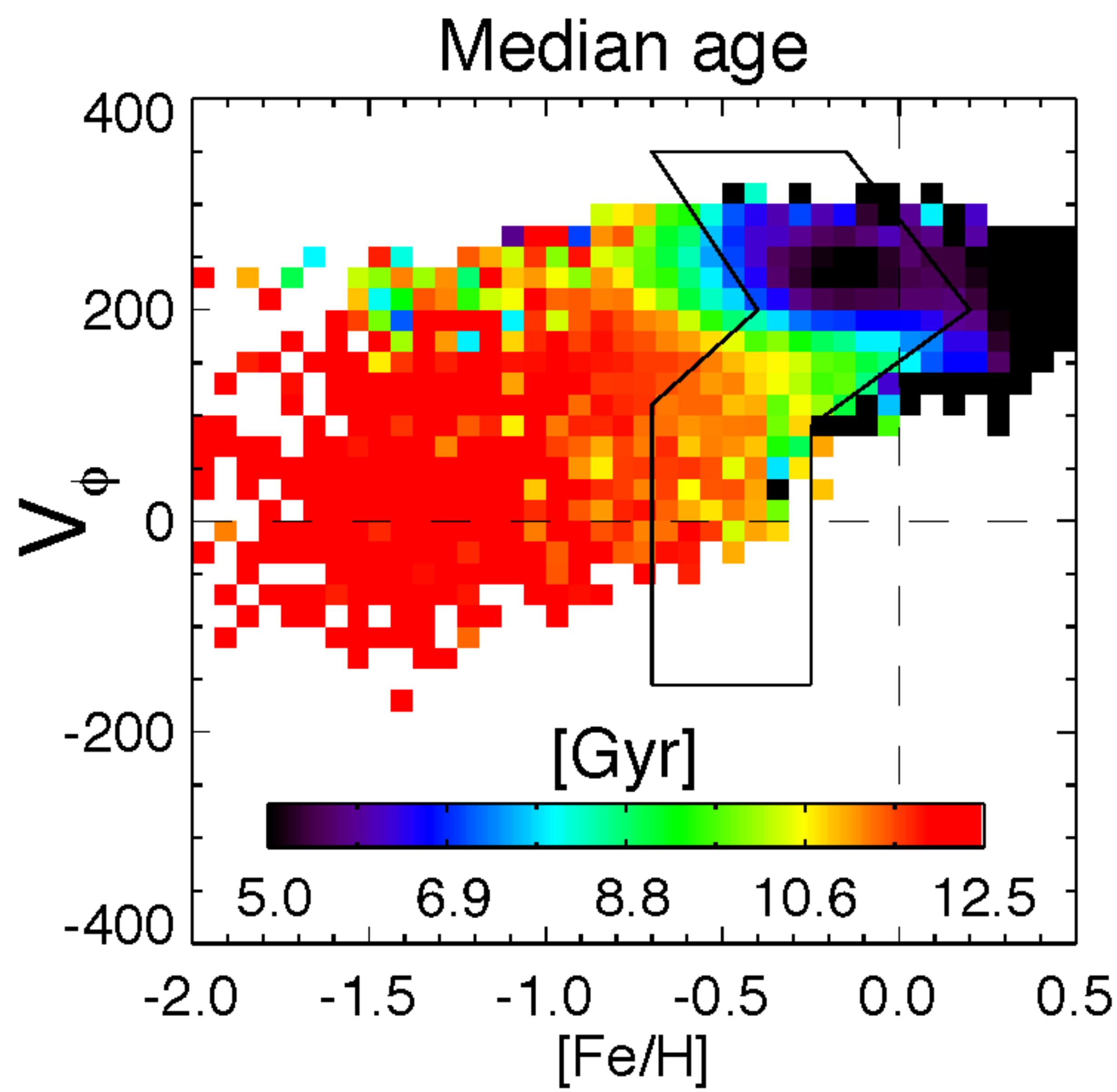




The “Splash”

- ~50% of the stars on halo-like orbits locally are metal-rich with -0.7<[Fe/H]<-0.2
  consistent with many previous studies, in particular
  Bonaca et al 2017, Haywood et al 2018, Di Matteo et al 2019

- Distinct kinematics

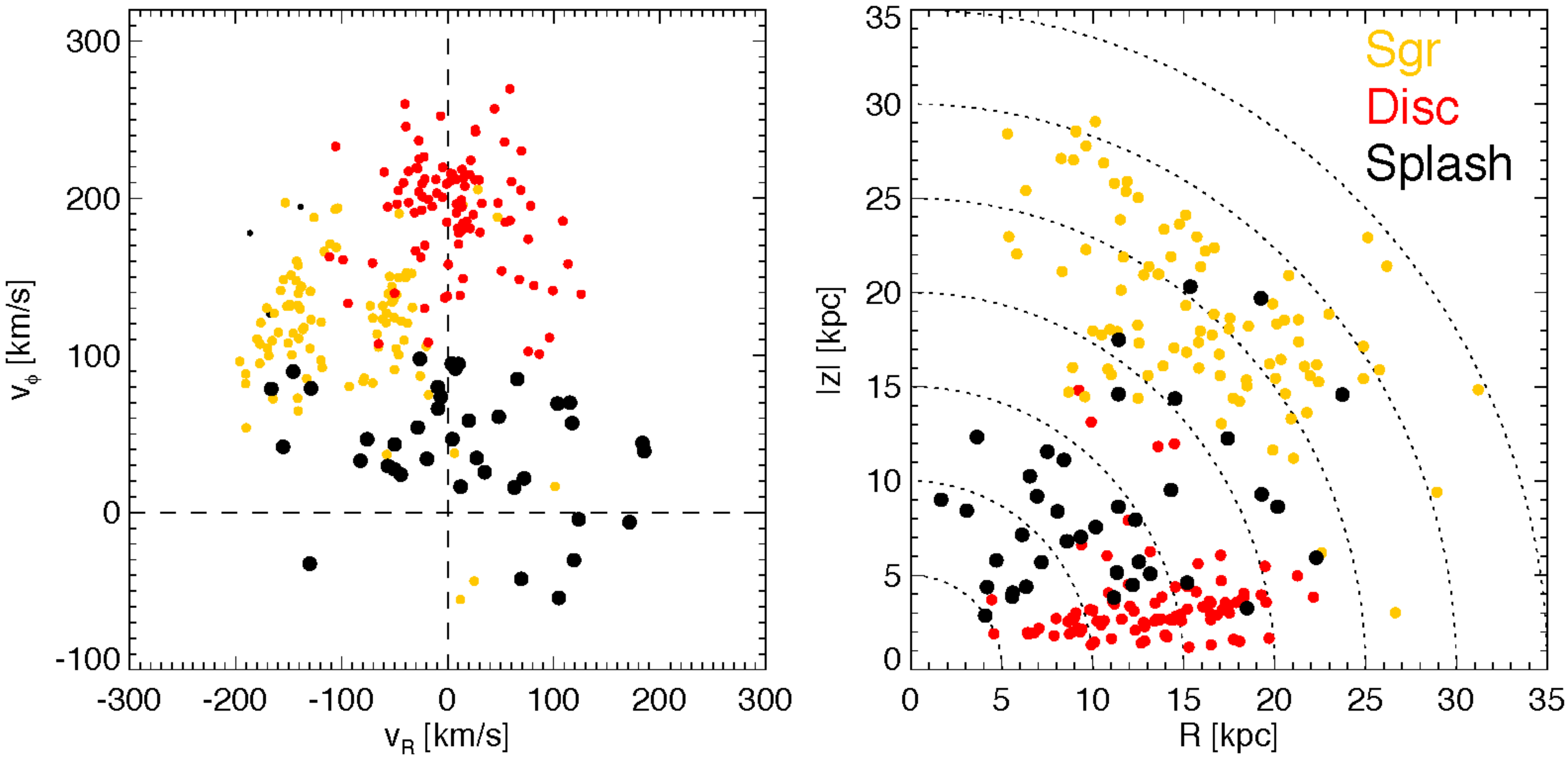
- Distinct alpha-abundances

- Distinct ages

VB et al 2020

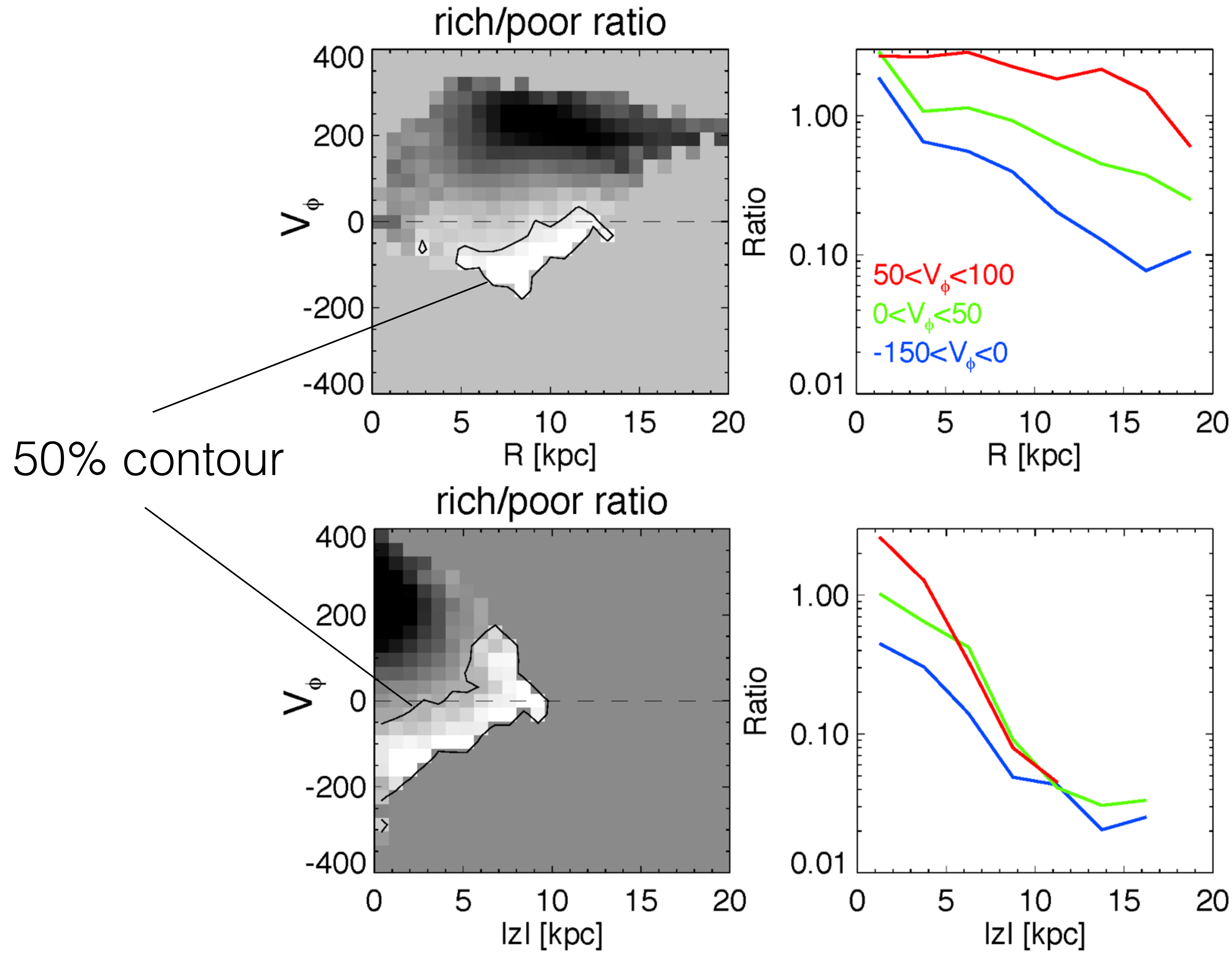
Splash beyond the Solar Neighbourhood

Metal-rich SDSS K-giants



Xue et al 2014 sample

Metal-rich vs poor “halo”



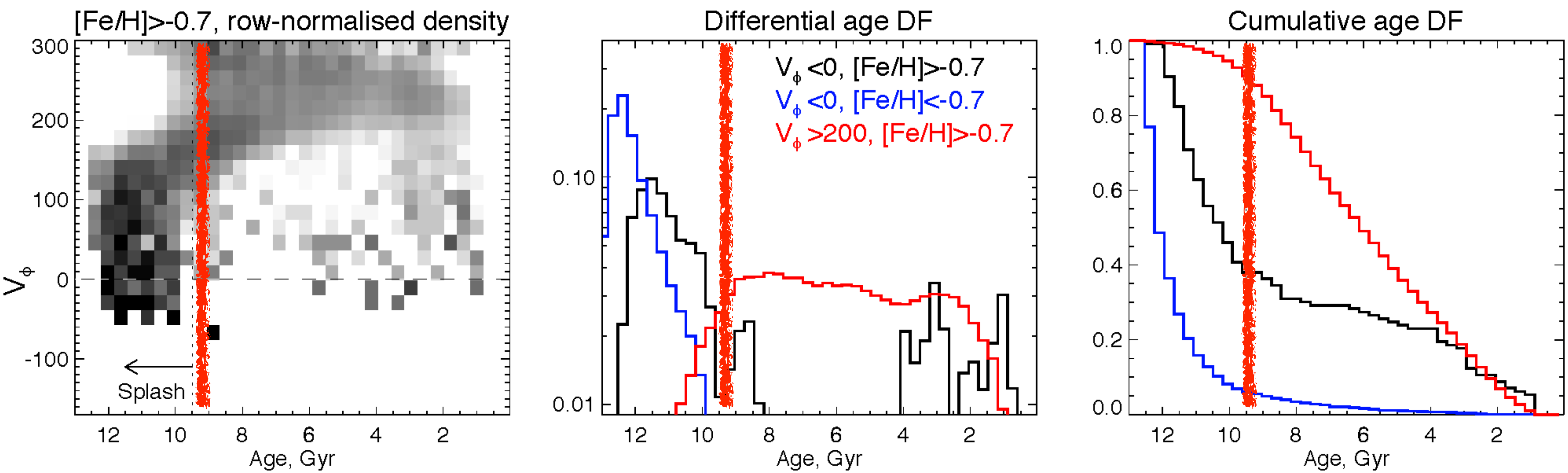
The extent of Splash

- Starts at 50% of the halo locally but quickly drops to ~few% at $|z|=10$ kpc
- Much puffier and rounder than the thick disc, much smaller than the accreted halo (e.g. the Sausage)

Making a Splash

Dating the last major merger

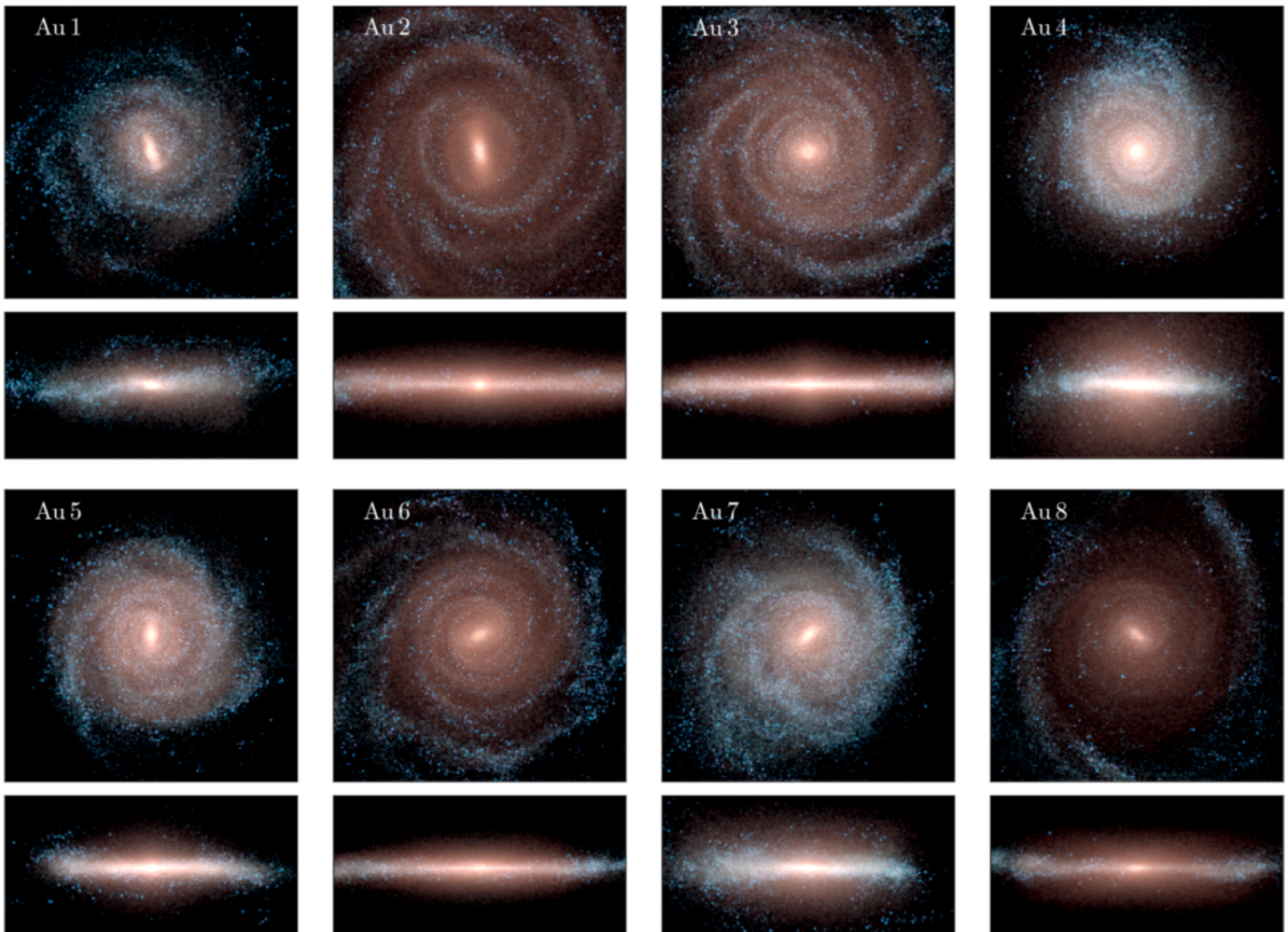
VB et al 2020



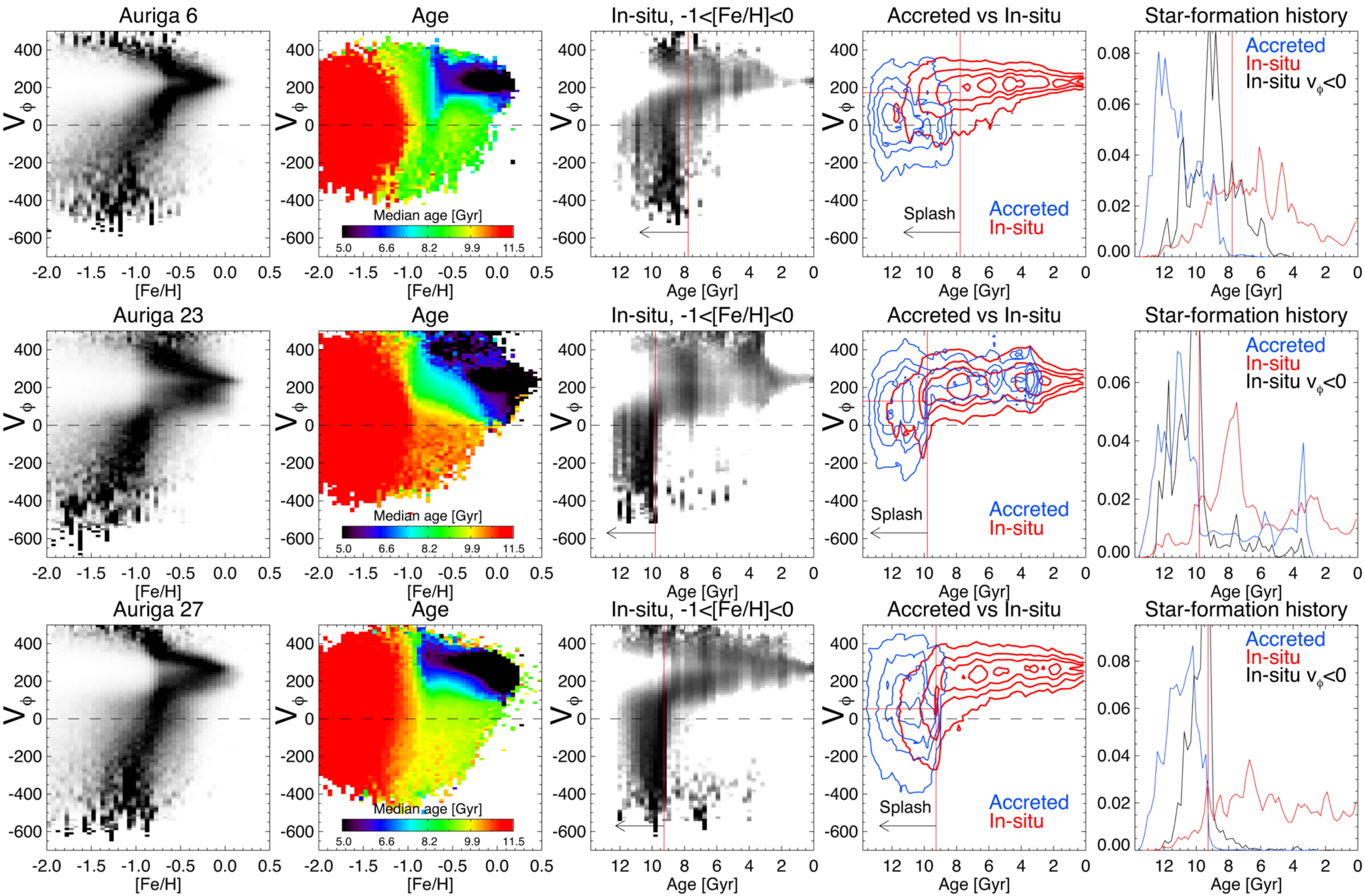
Similar to but not totally in agreement with Gallart et al 2019

Cosmological simulations

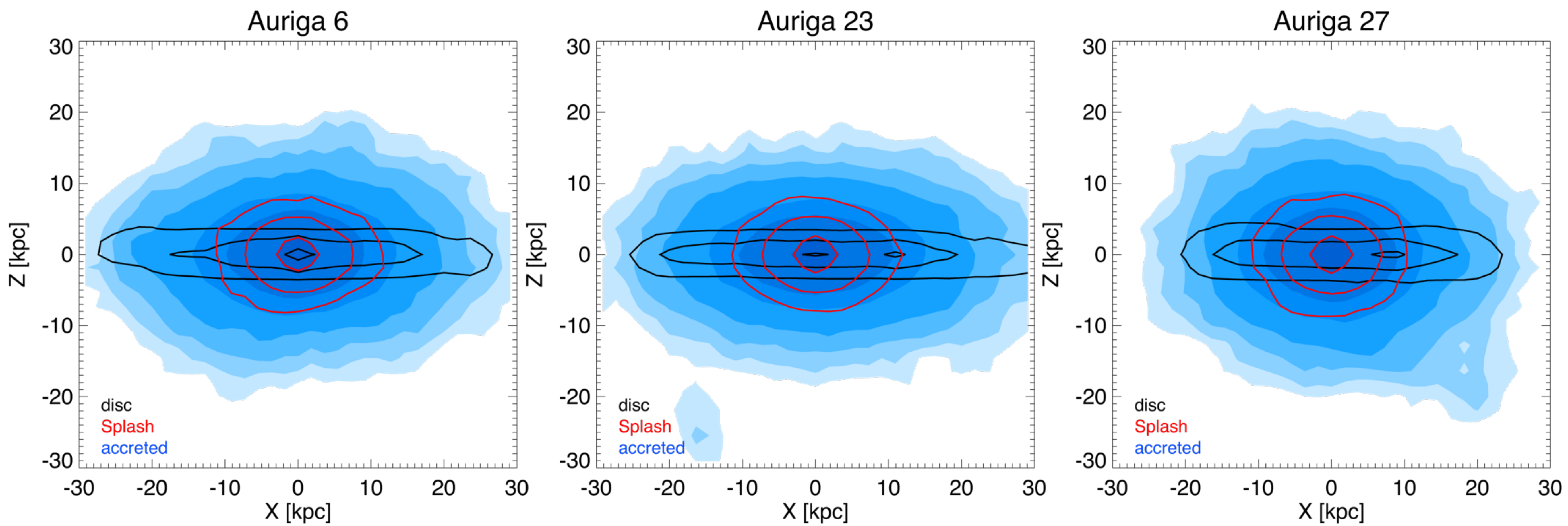
The Auriga suite (Grand et al 2017) - 30 Milky Ways



Splash examples in Auriga



Structure today

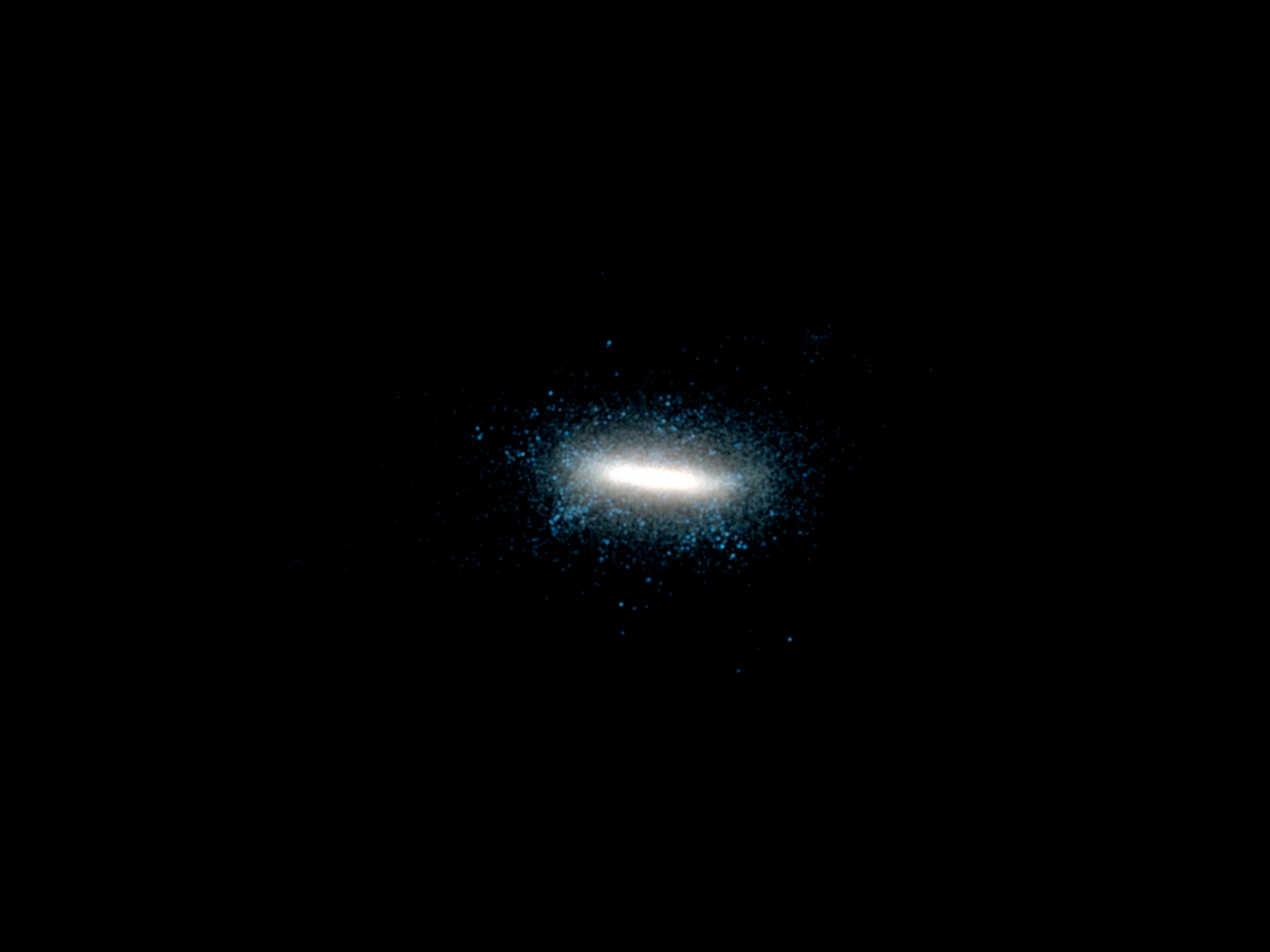


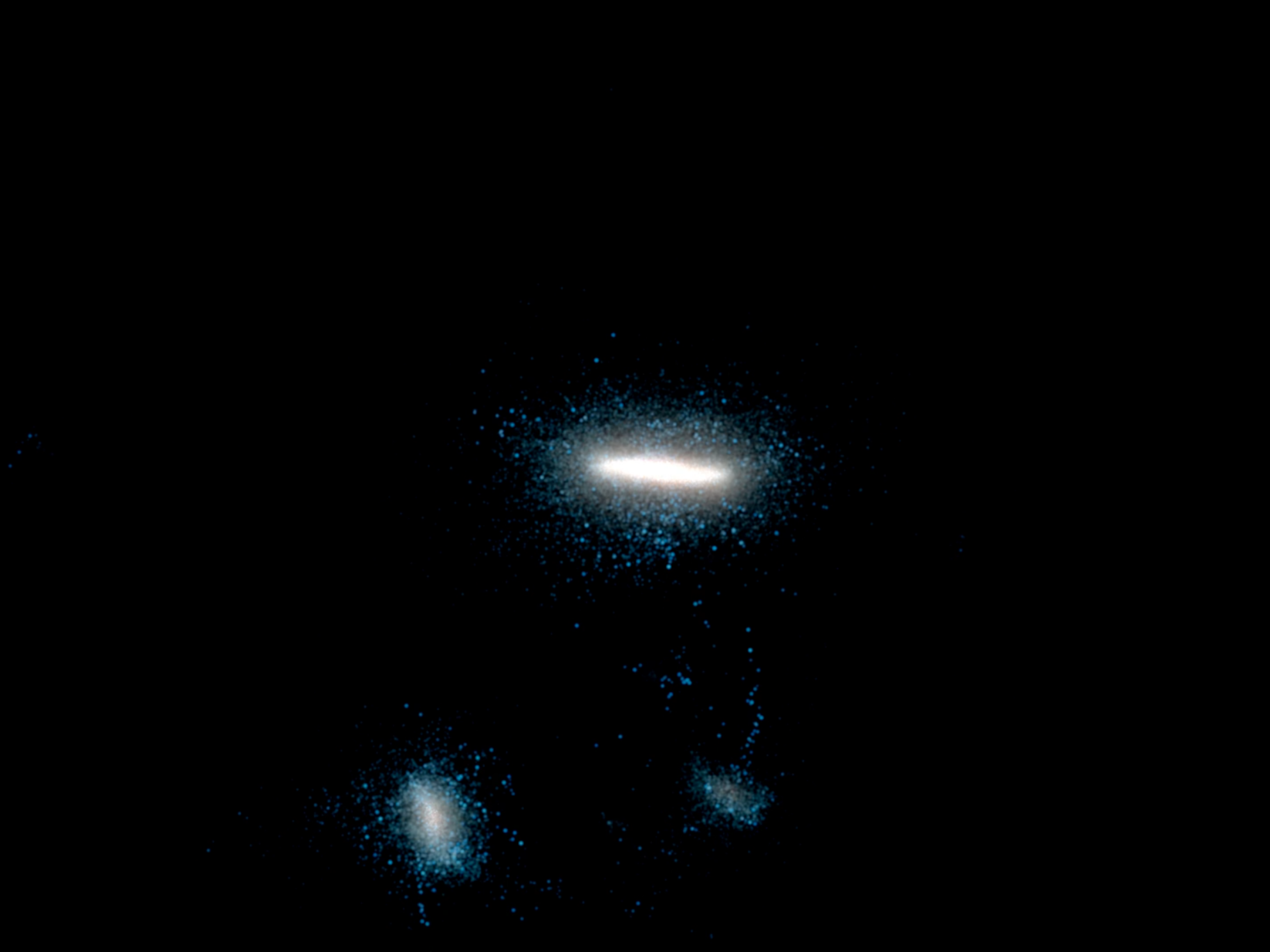
Does not the Splash look like a fluffy version of a classical bulge?

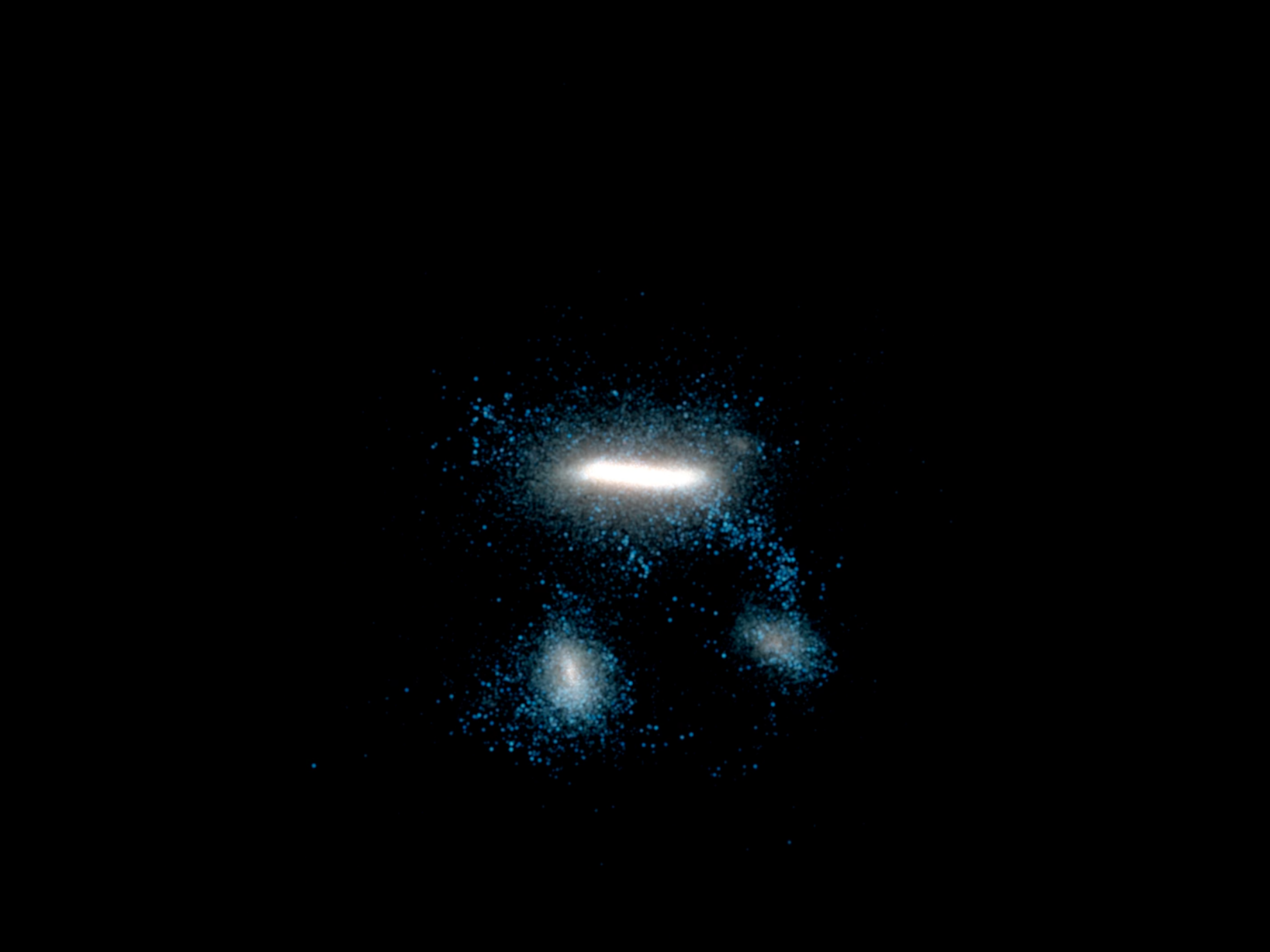
What might have happened to the young Milky Way

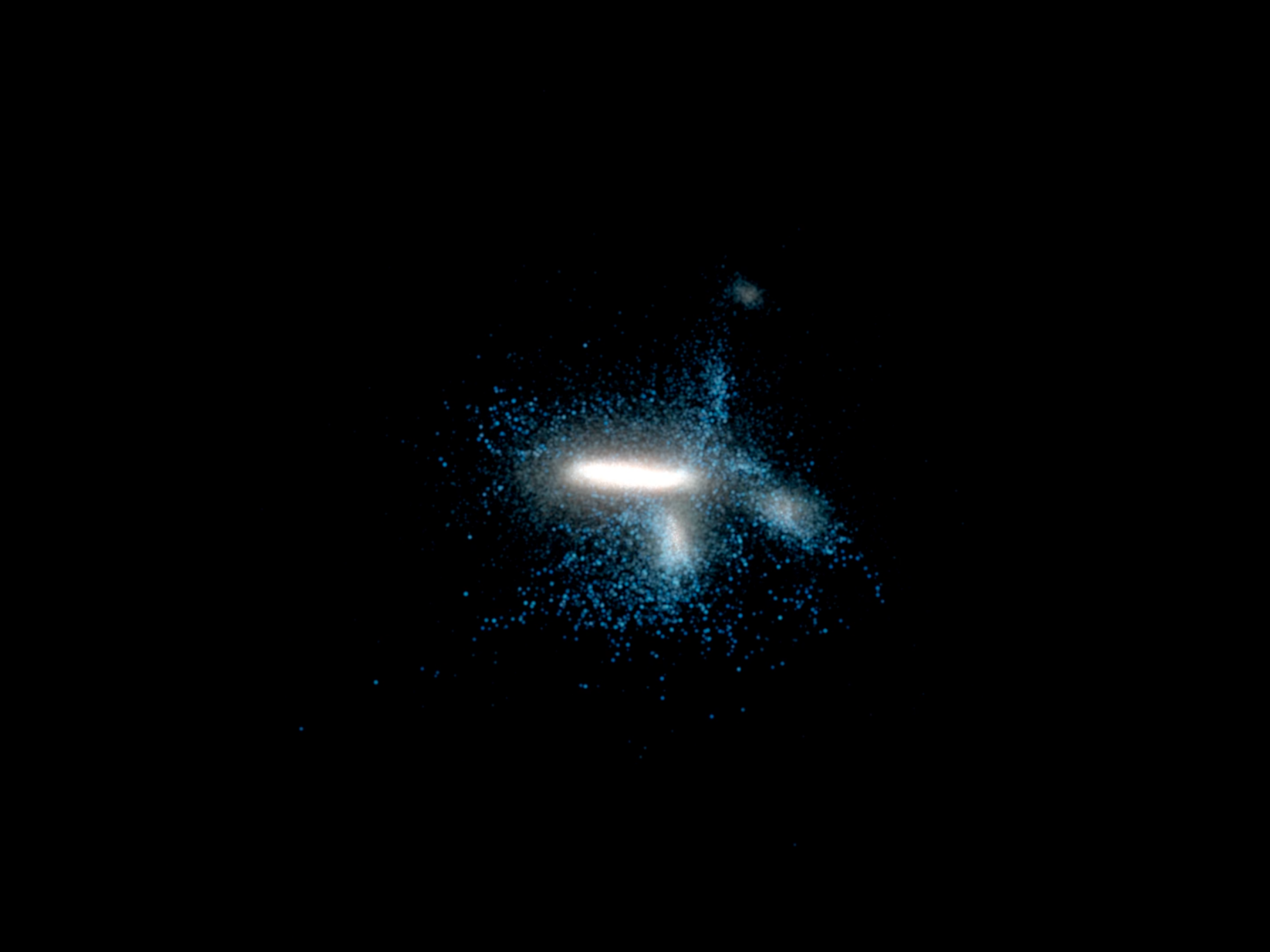
Auriga 18 movie snapshots courtesy of

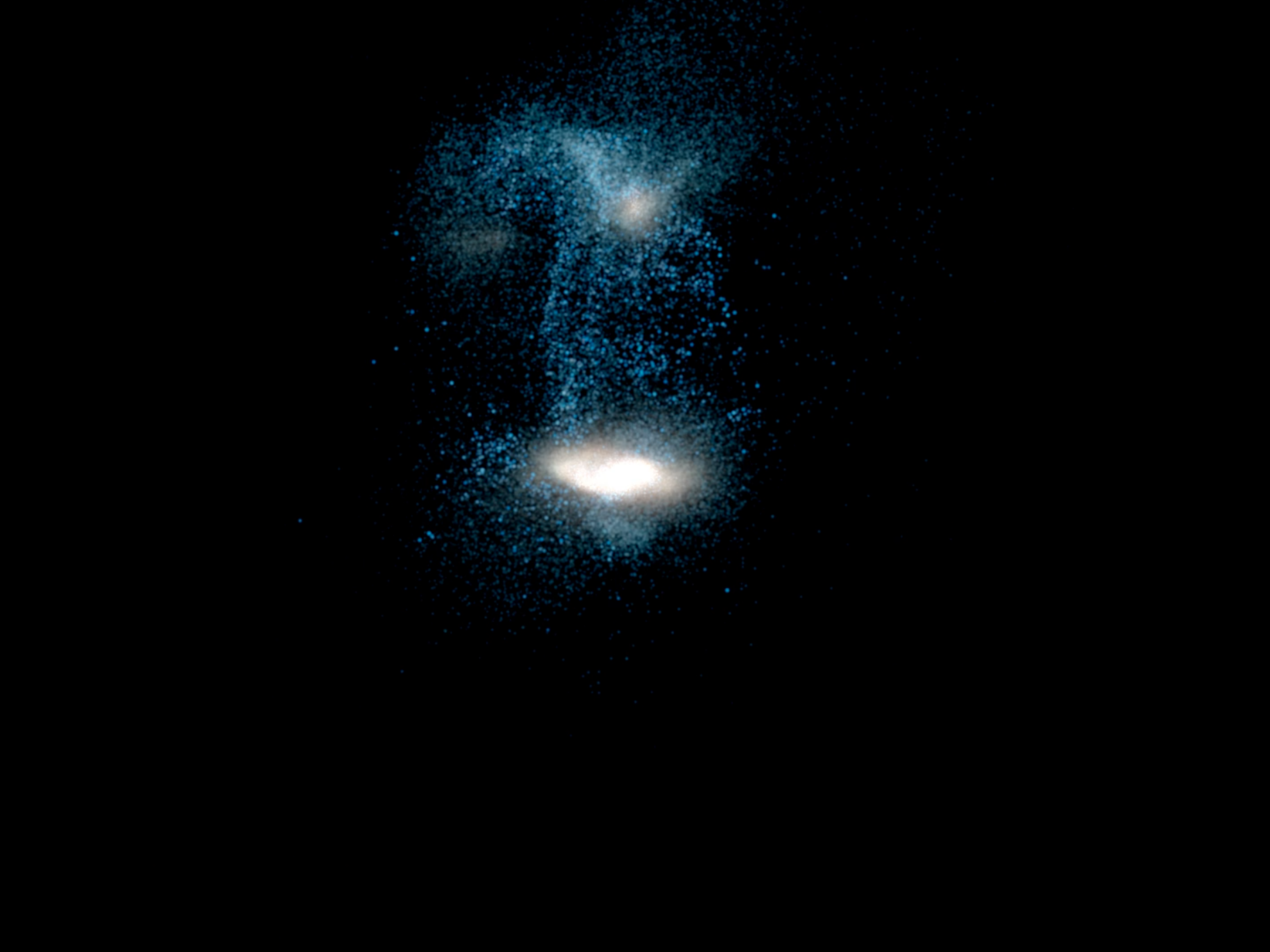
Auriga Collaboration
and Rüdiger Pakmor

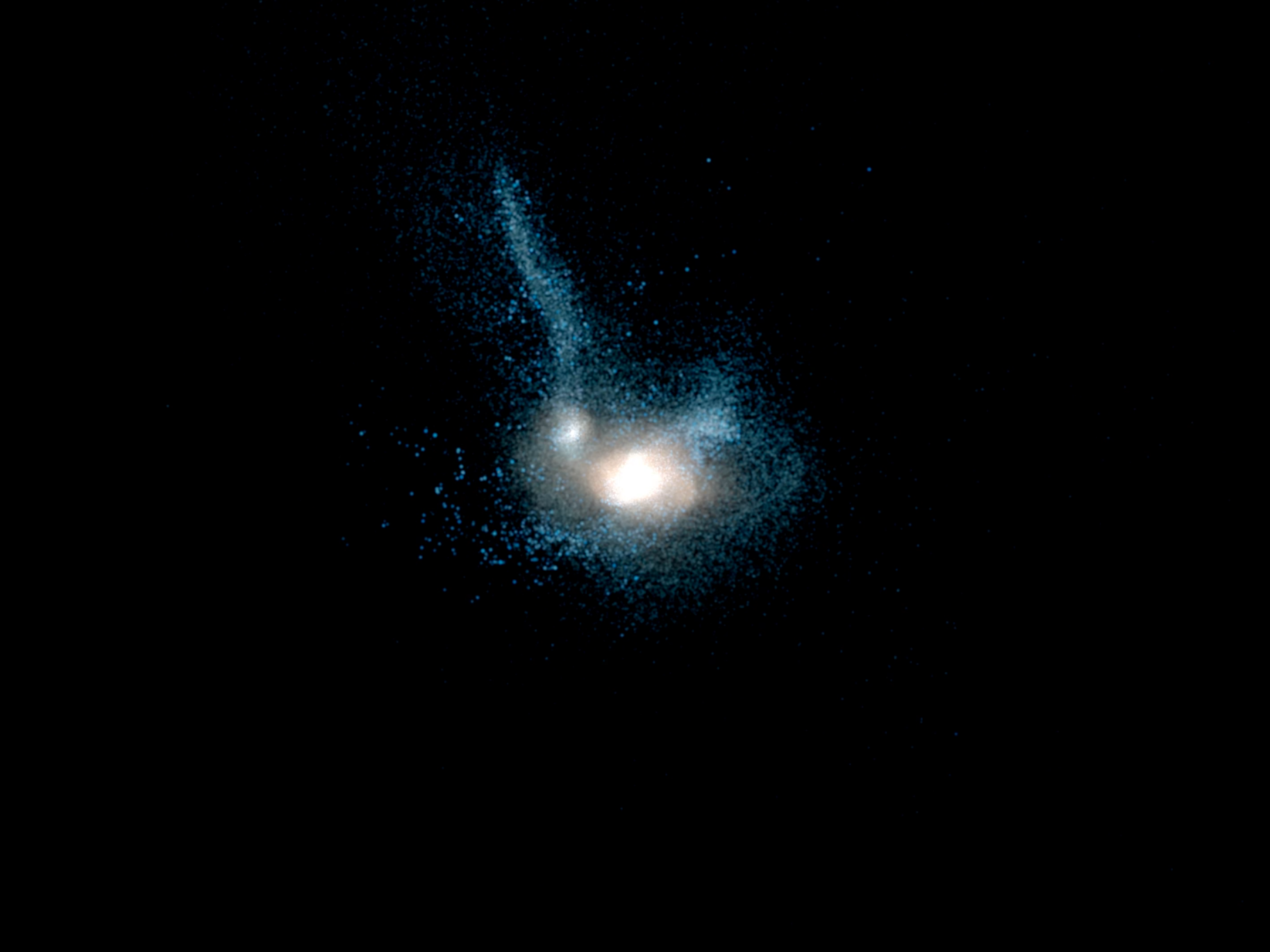


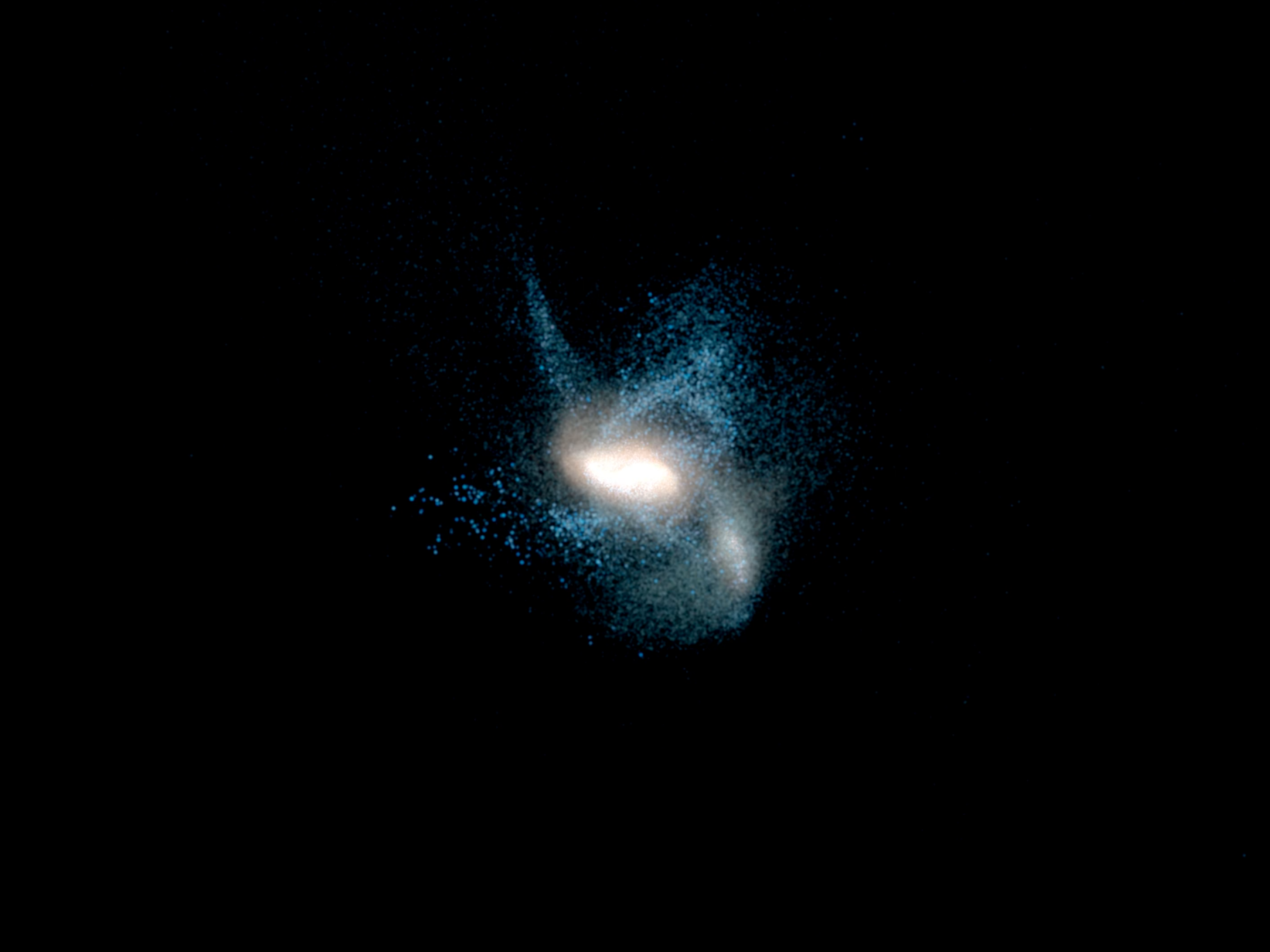


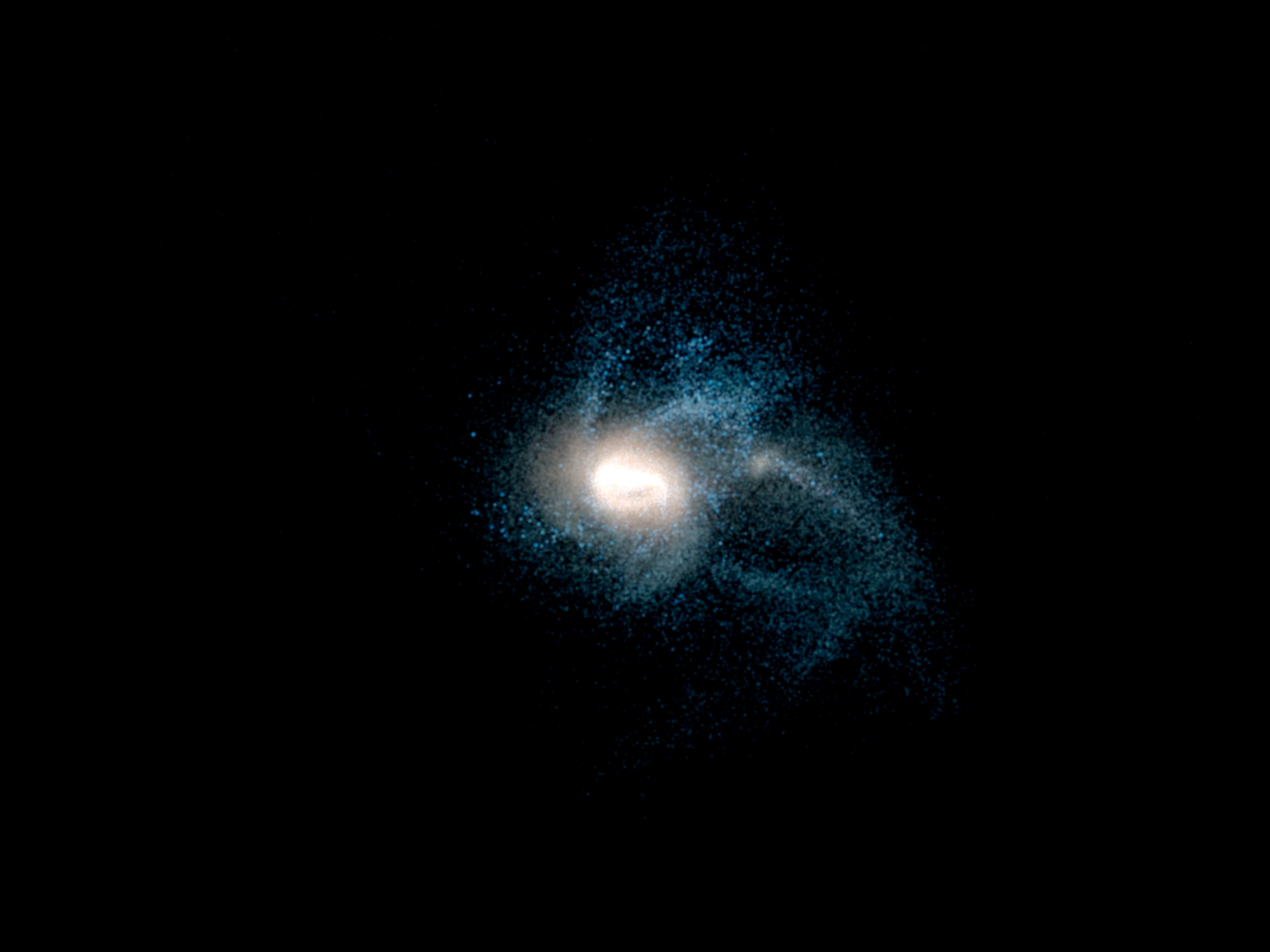


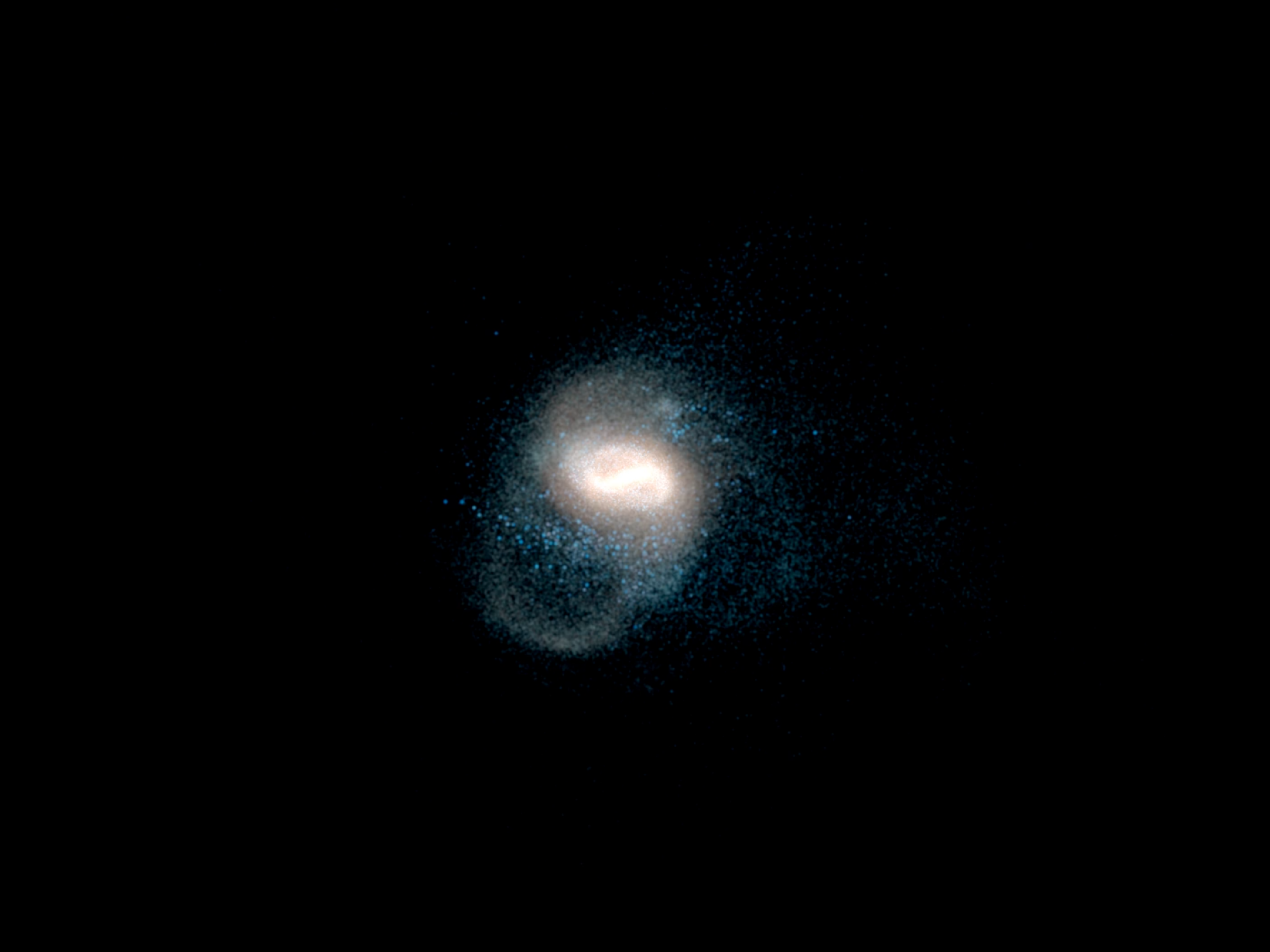


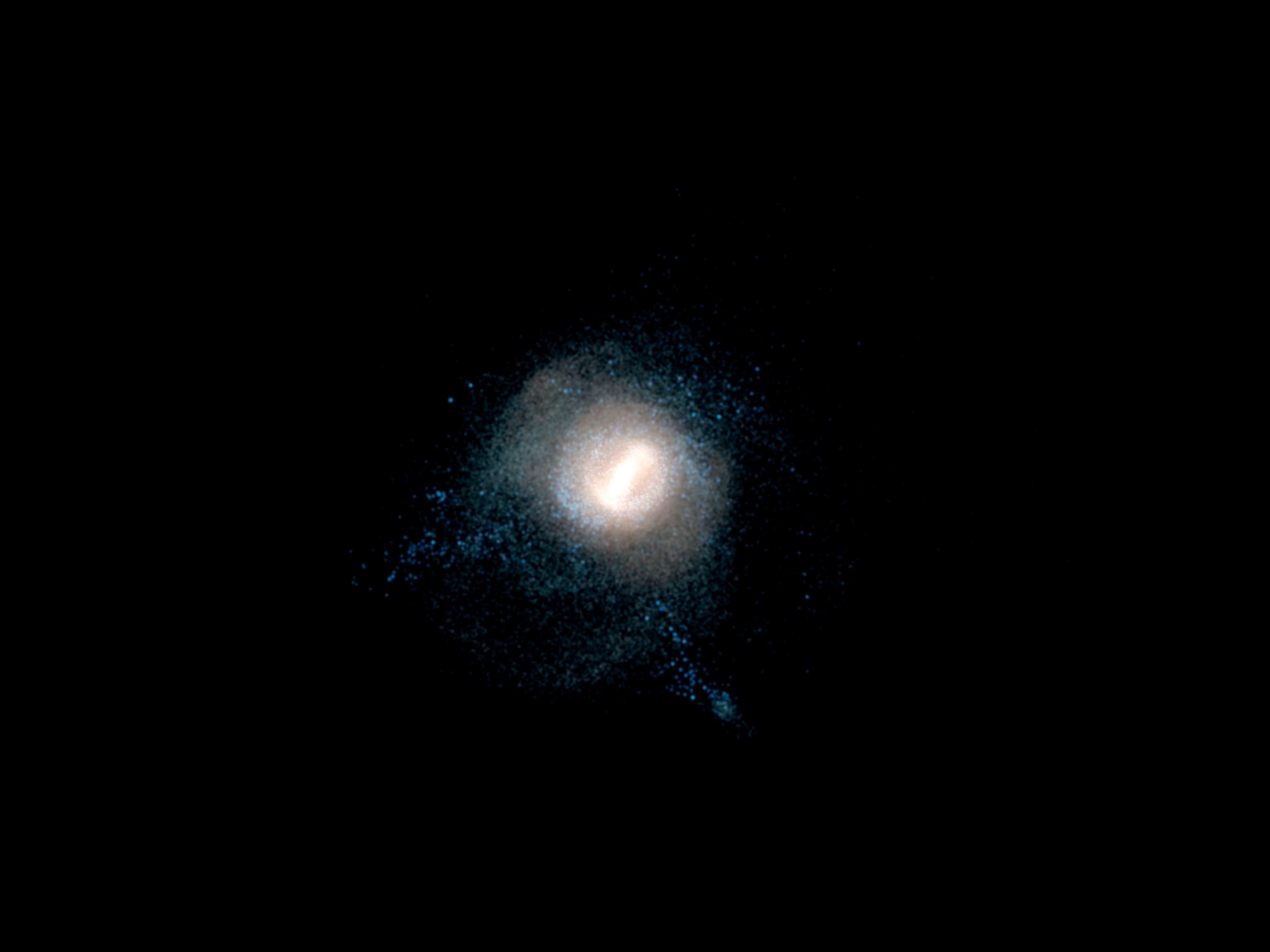












What might have happened to the young Milky Way

MNRAS **000**, 1–15 (2019) Preprint 22 May 2020 Compiled using MNRAS LaTeX style file v3.0

Sausage & Mash: the dual origin of the Galactic thick disc and halo from the gas-rich Gaia-Enceladus-Sausage merger

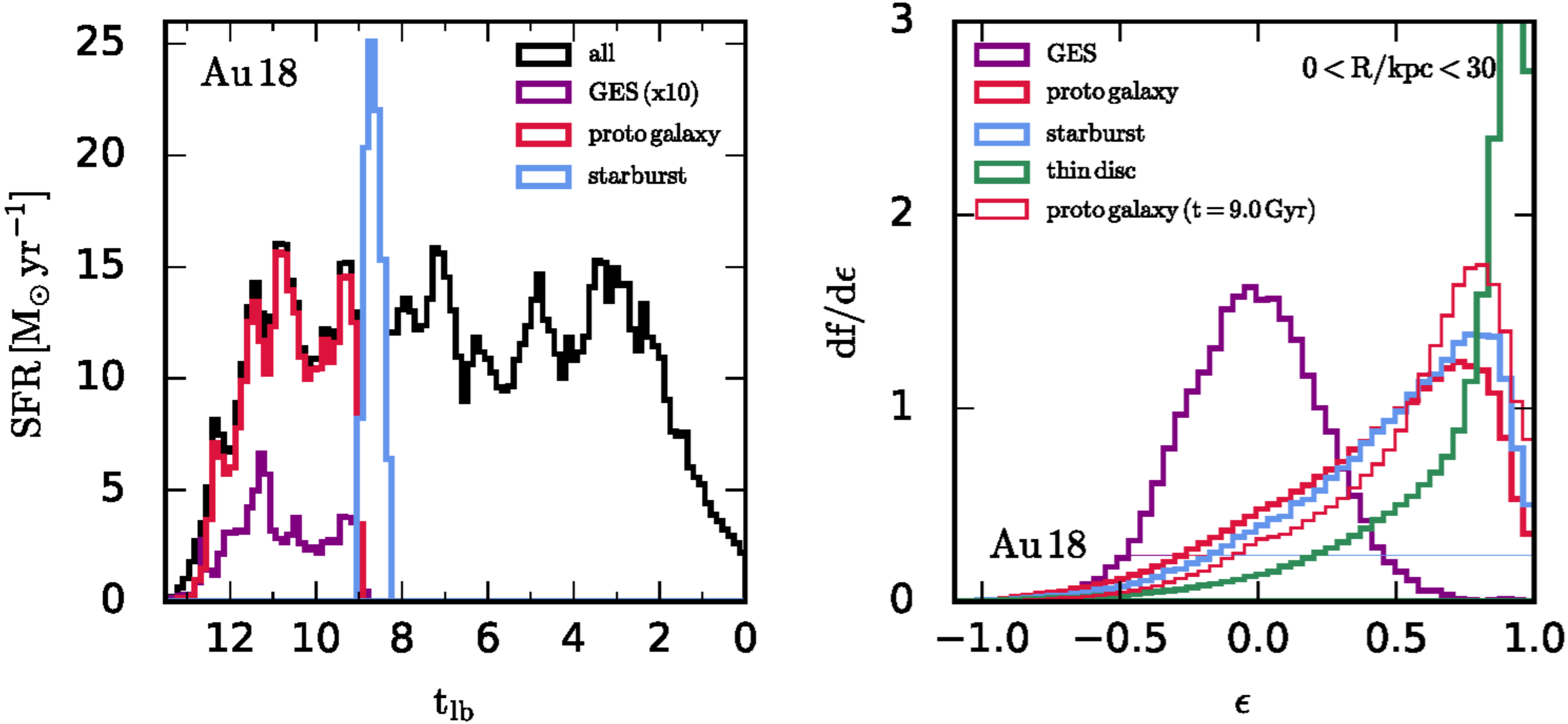
Robert J. J. Grand,[1★] Daisuke Kawata[2], Vasily Belokurov[3], Alis J. Deason[4], Azadeh Fattahi[4], Francesca Fragkoudi[1], Facundo A. Gómez[5,6], Federico Marinacci[7], Rüdiger Pakmor[1]

[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany*
[2] *Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK*
[3] *Institute of Astronomy, Madingley Rd, Cambridge, CB3 0HA*
[4] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[5] *Instituto de Investigación Multidisciplinar en Ciencia y Tecnología, Universidad de La Serena, Raúl Bitrán 1305, La Serena, Chile*
[6] *Departamento de Astronomía, Universidad de La Serena, Av. Juan Cisternas 1200 Norte, La Serena, Chile*
[7] *Department of Physics & Astronomy, University of Bologna, via Gobetti 93/2, 40129 Bologna, Italy*

Gaia-Sausage event was gas-rich merger

- $\log_{10}$ **stellar** mass of order of 9 $M_\odot$
- $\log_{10}$ **gas** mass of order of 10 $M_\odot$

Milky Way star-burst at the end of accretion - simulation

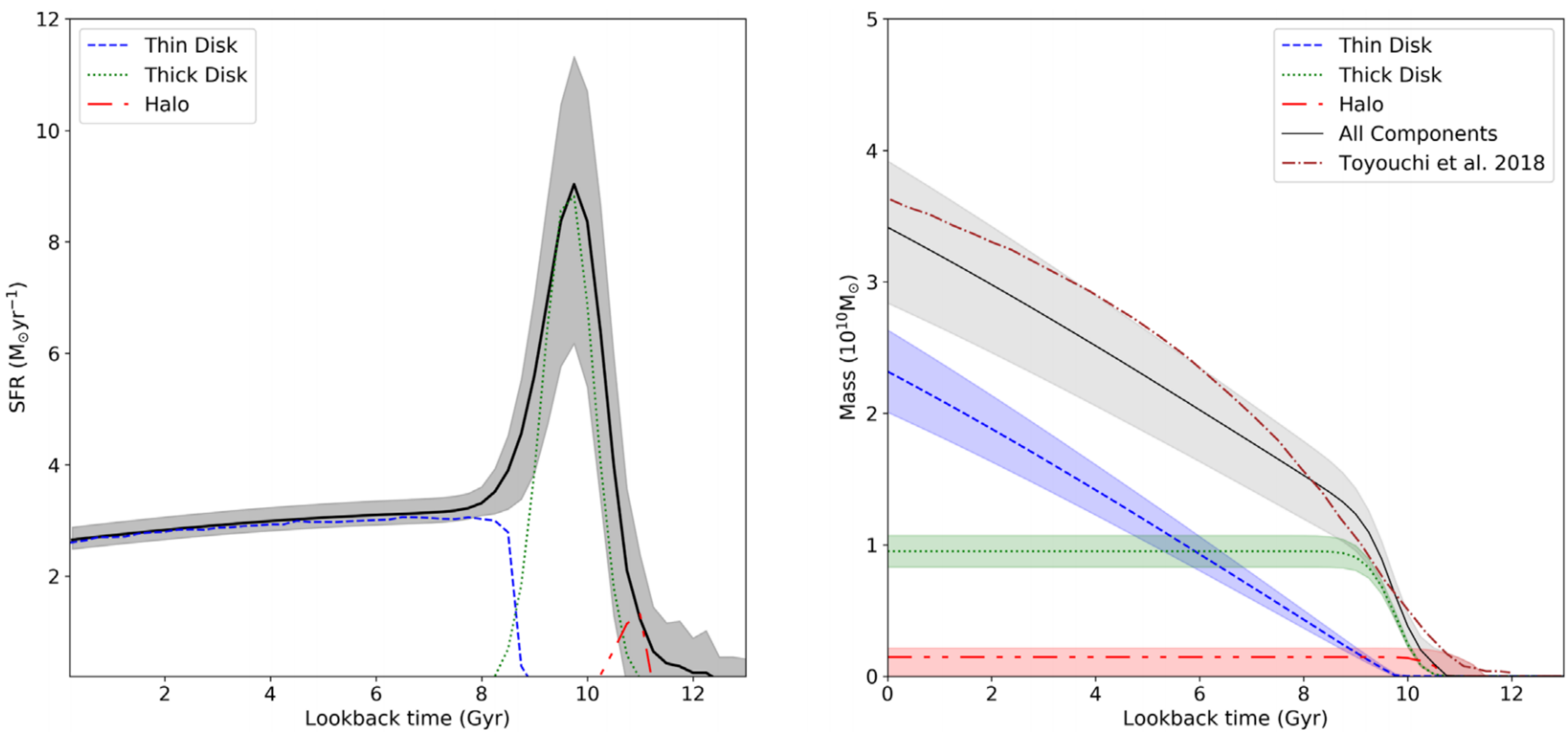


look-back time

orbital circularity

Grand et al 2020

Star-formation history of the Milky Way - observations



based on the modelling of white dwarfs cooling, Fantin et al 2020

Take Home Message

- **Splash** is the new component of the Milky Way
- **Splash** contains the oldest stars in the Galaxy
- **Splash** was most likely formed at the time and as a result of (in response to) the **Gaia-Sausage** merger

Conclusions 1 (of 3)

- Half of the stars on halo like orbits <u>locally</u> is in a Splash, i.e. old metal-rich in-situ population
- Splash is kinematically distinct from the accreted halo (e.g. Gaia Sausage)
- Splash appears to be the extension of the thick disc into zero angular momentum and retrograde orbits
- Splash is limited to $|z| < 10$ kpc, $R < 15$ kpc

Conclusions 2 (of 3)

- Characteristic (truncated) age distribution - strong constraint on the time of the last major merger

- Overall plenty of angular momentum - suggesting that young MW was a proto-disc

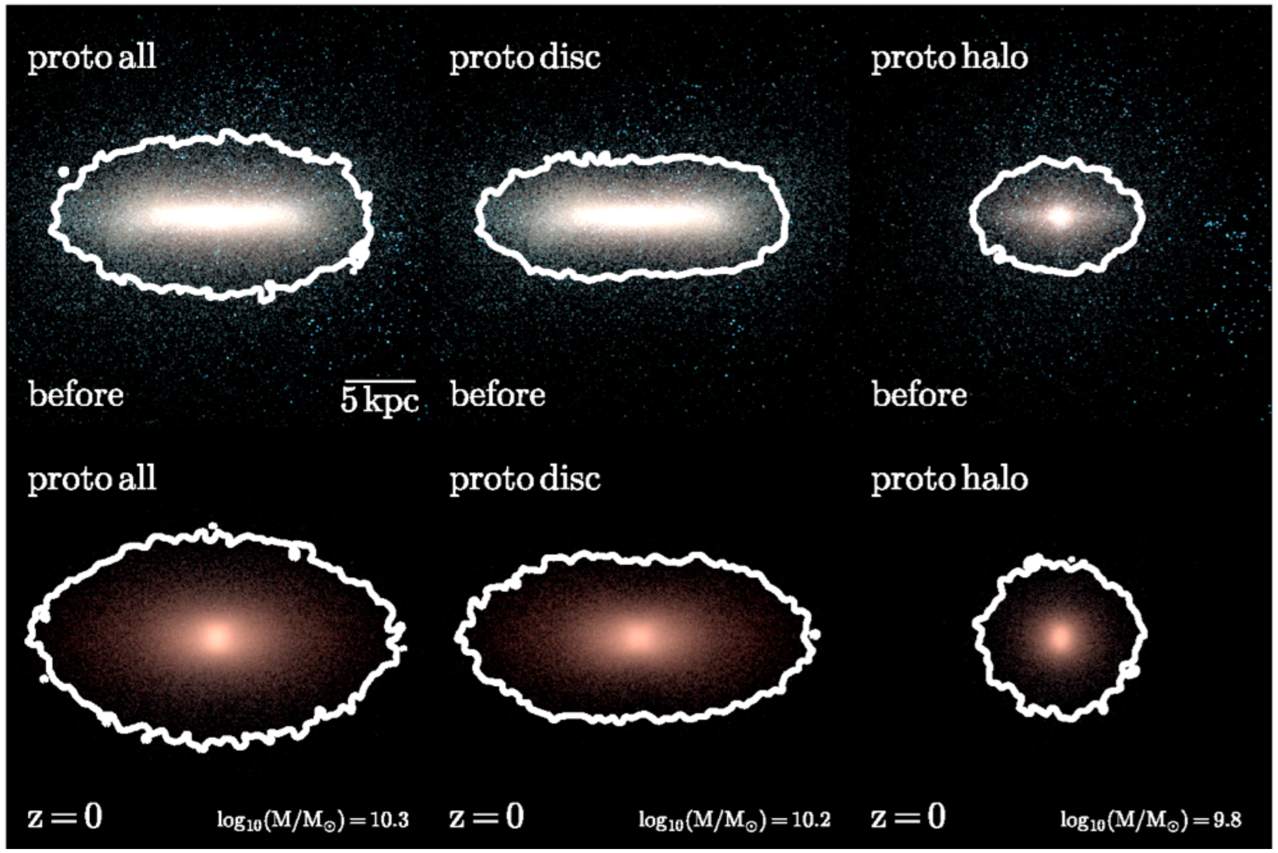
- If Splash=in-situ halo, then McCarthy et al 2012 mechanism is preferred (disc heating) and the fraction of splashed stars can be used to constrain the total mass of the Sausage progenitor

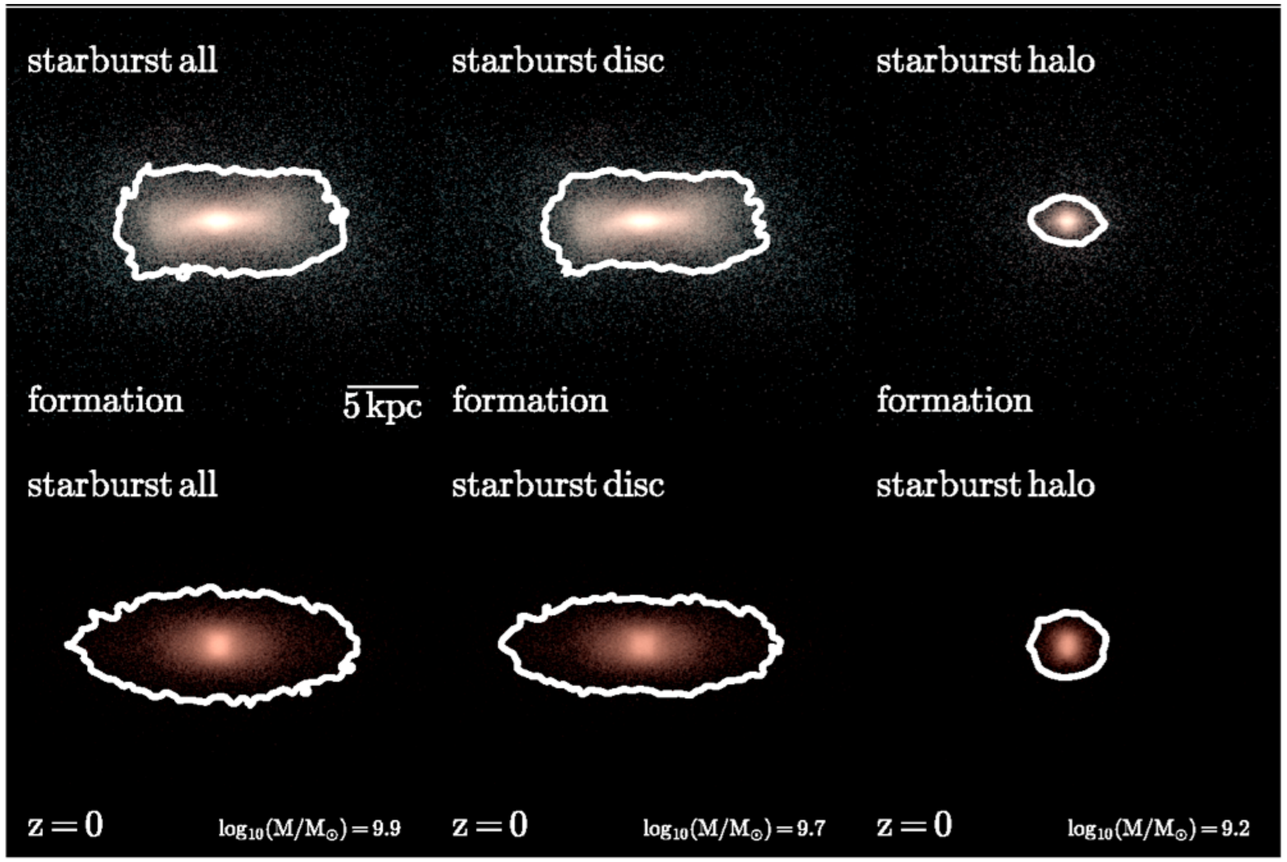
Conclusions 3 (of 3)

- The Sausage merger was likely gas-rich
- Milky Way underwent a star-burst event as a result of the merger
- The starburst contributes to both the thick disk and the halo populations of the Milky Way
- Sausage progenitor provides between 10% and 50% of the gas used in the star-burst

Extra Slides

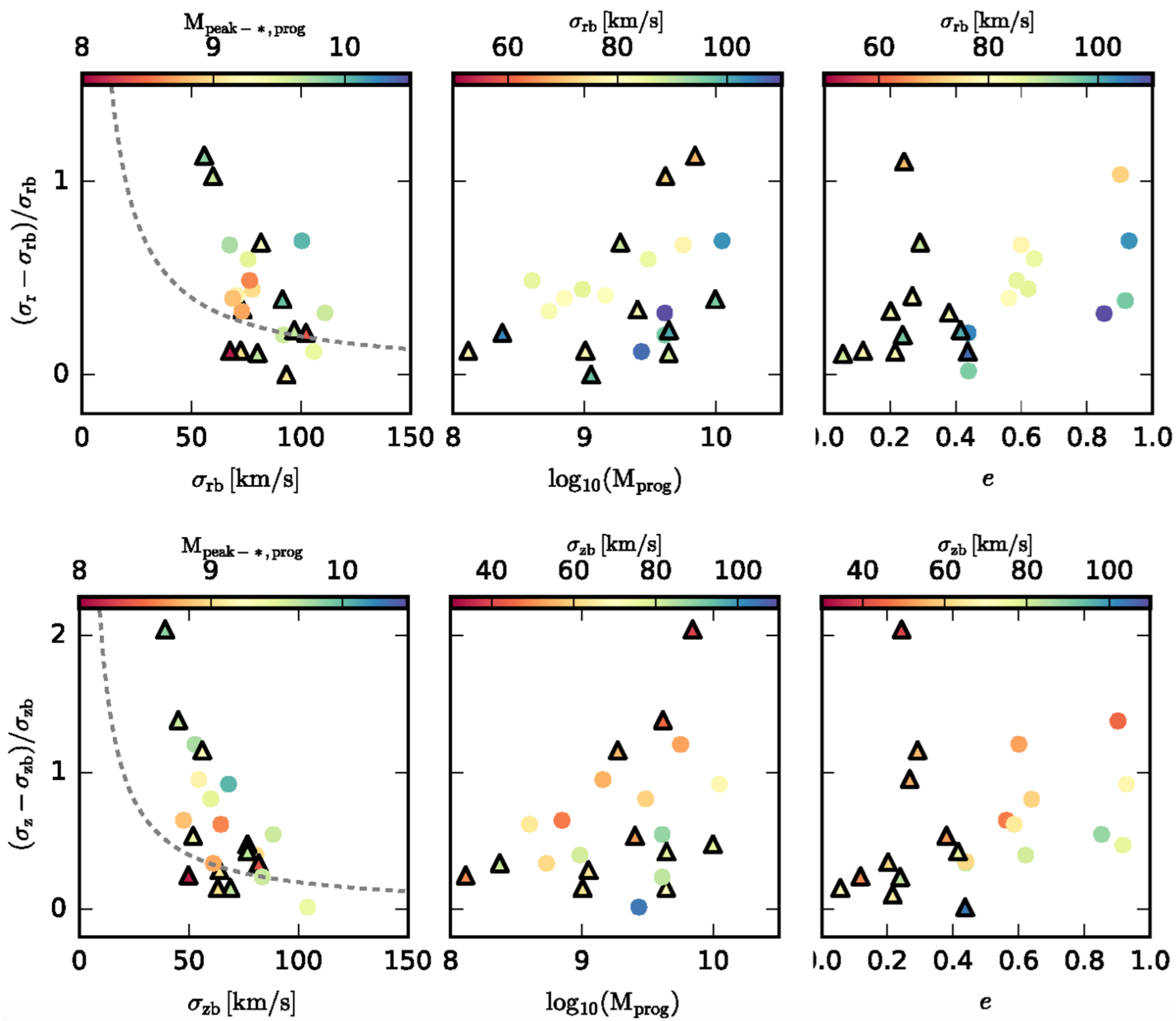
In-situ components: before and after





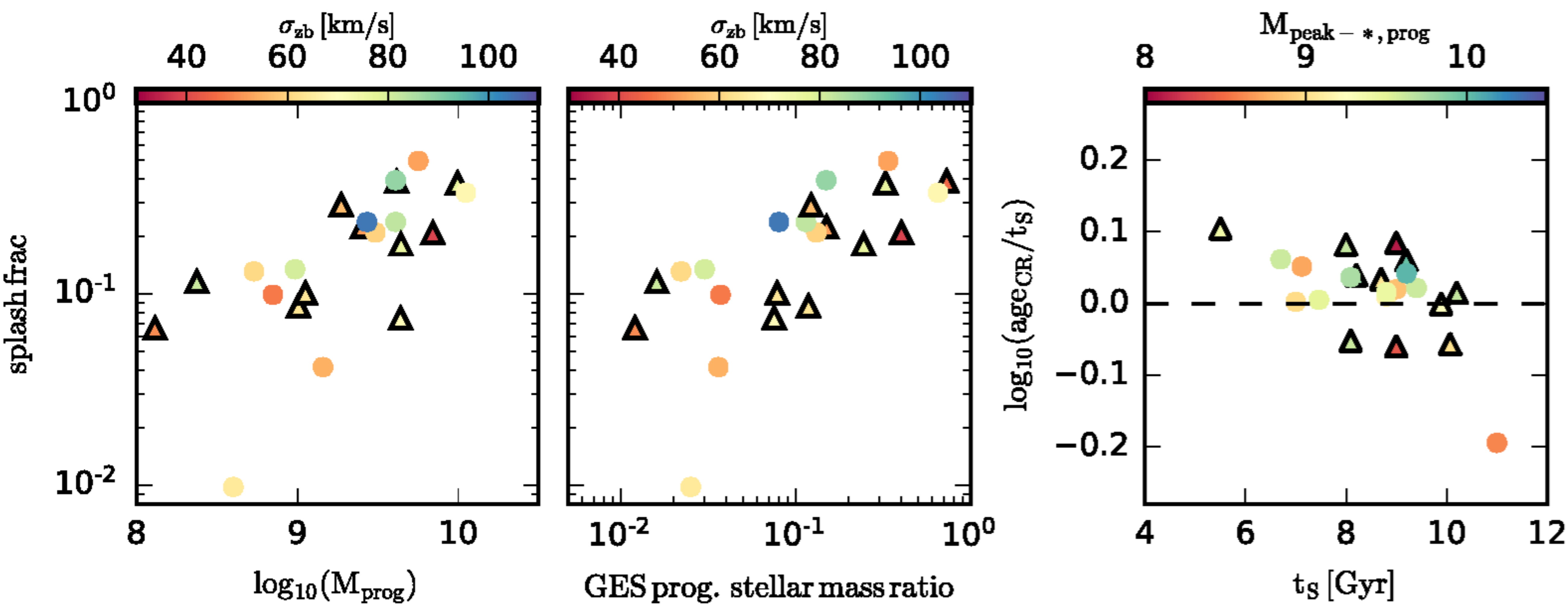
Grand et al 2020

Heating of the Galaxy



Grand et al 2020

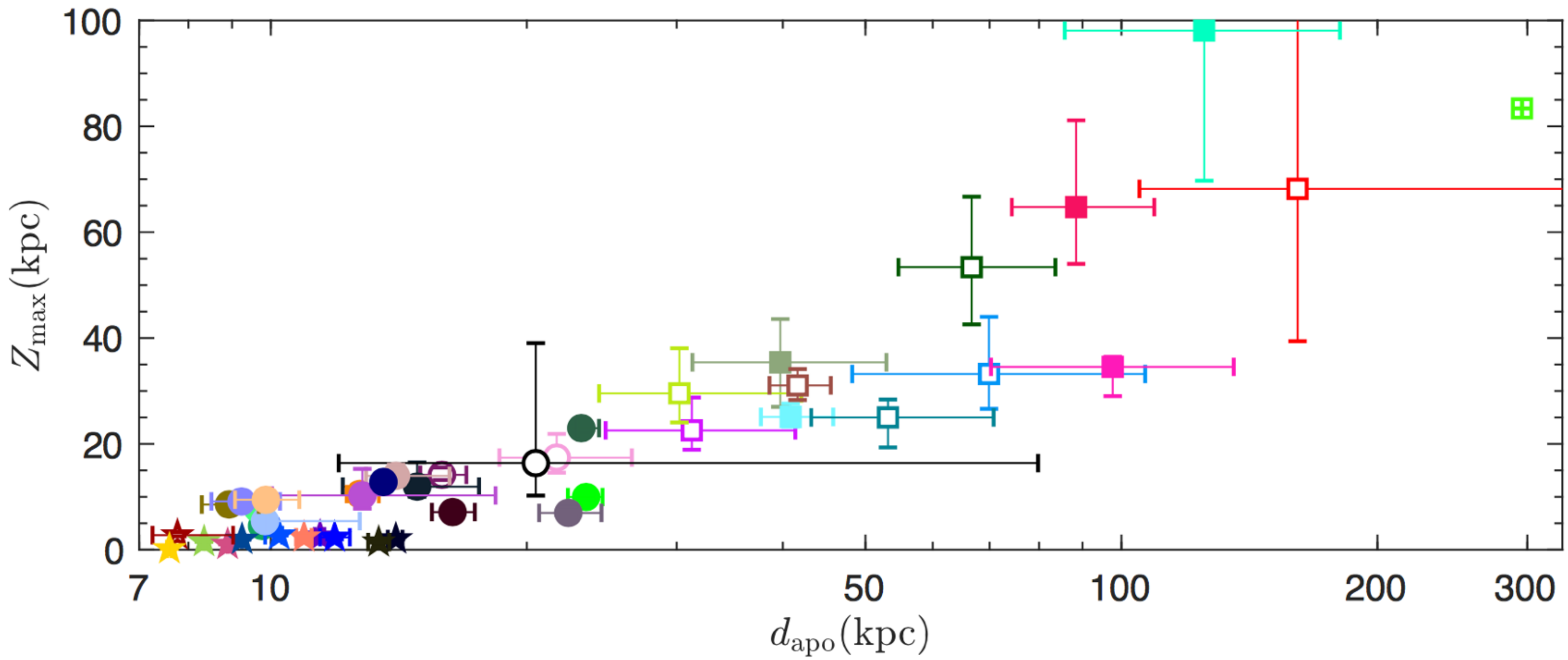
Link between Splash and the Sausage event



Grand et al 2020

Unexpected piece of the puzzle: very metal-poor stars in the disc

stars with [Fe/H] < −4.0



Sestito et al 2020

Evidence that not all prehistoric disc was destroyed
Could indicate a different mechanism for Splash creation which does not require disc heating/destruction