The turbulent youth of the Milky Way
and observable properties of the pre-disk in-situ stellar population

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the unsolved problem:

when and how Milky Way disk formed?
How typical is Milky Way disk formation?

solved problem:

how do we study the pre-disk stage of evolution?

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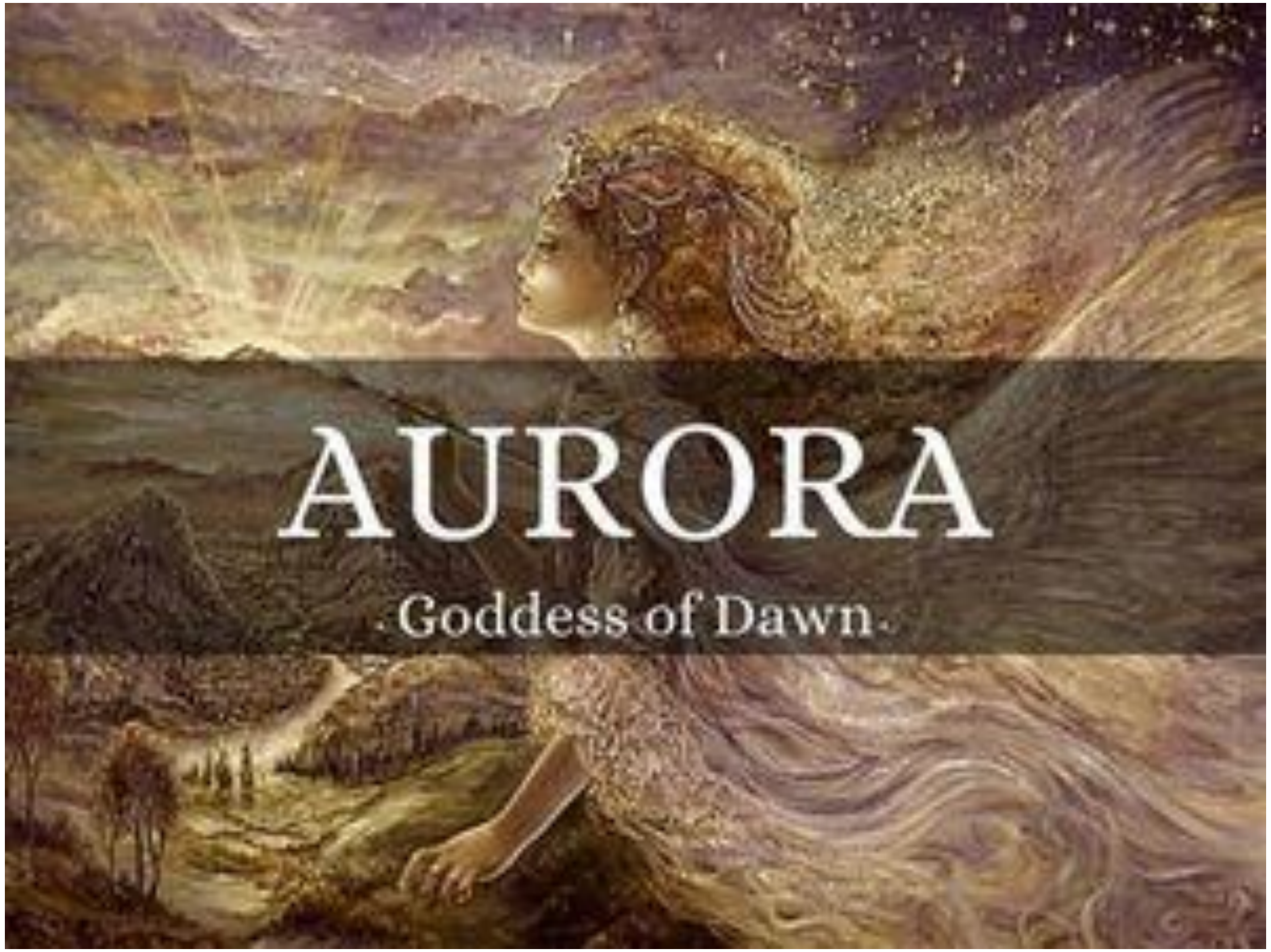
how do we study the pre-disk stage of evolution?



Expected early evolution of the Milky Way from models

The model predictions shown in the right panel below indicate that *in-situ* stars with [Fe/H] ≤ −1 formed more than 10 Gyr ago (cf. also Kruijssen et al. 2019; Agertz et al. 2021).

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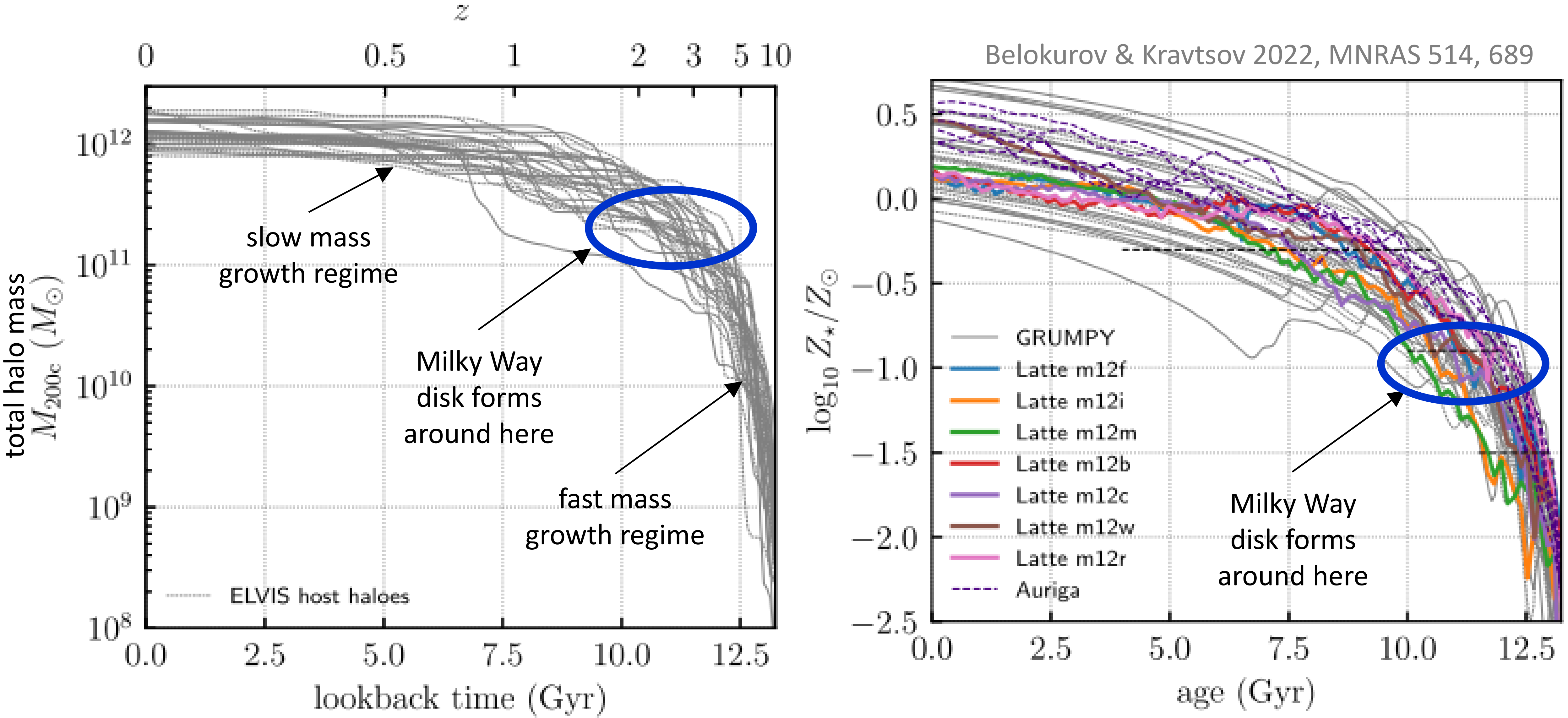

Cumulative distribution of mass fraction (in %) of in-situ stars in age and metallicity

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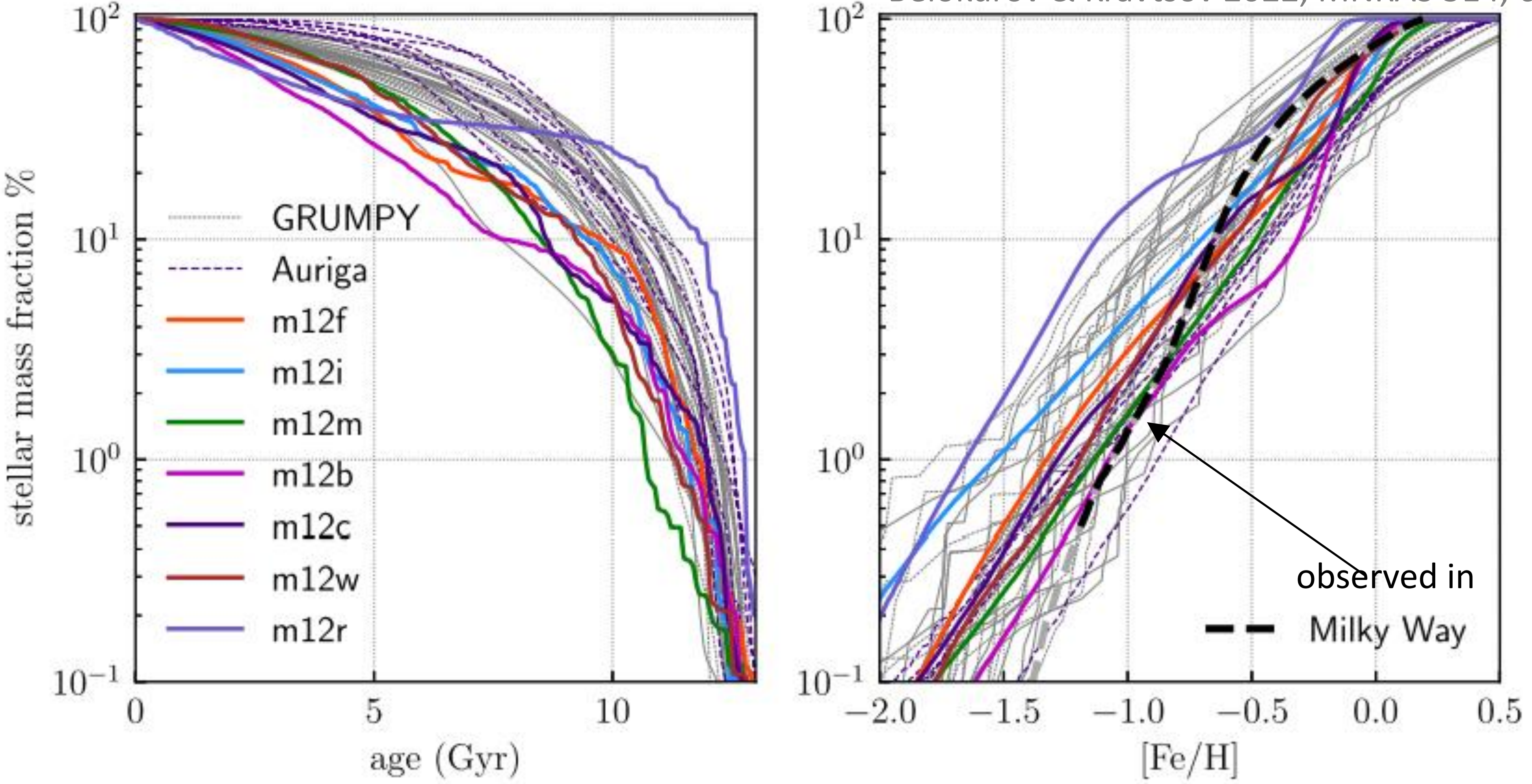

Chaotic pre-disk stage and disk "spin-up" 8-11 Gyrs ago are generic in galaxy formation simulations

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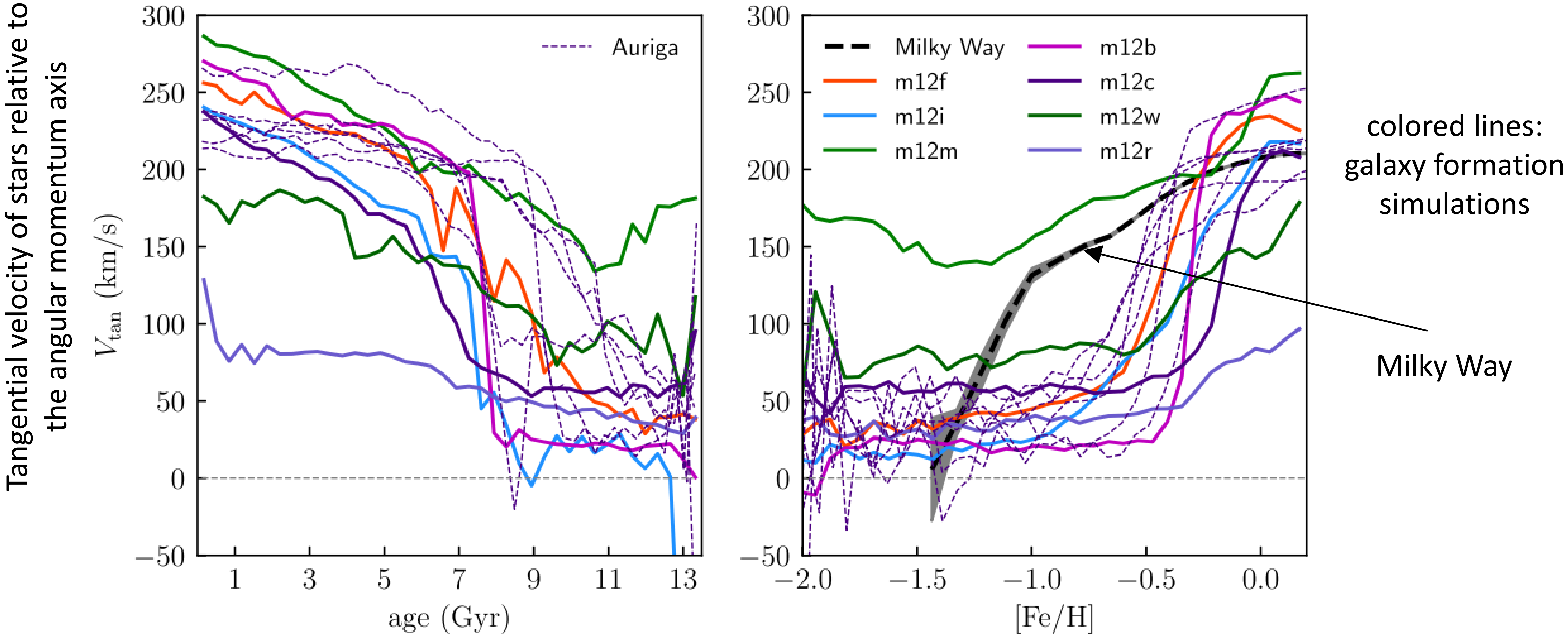
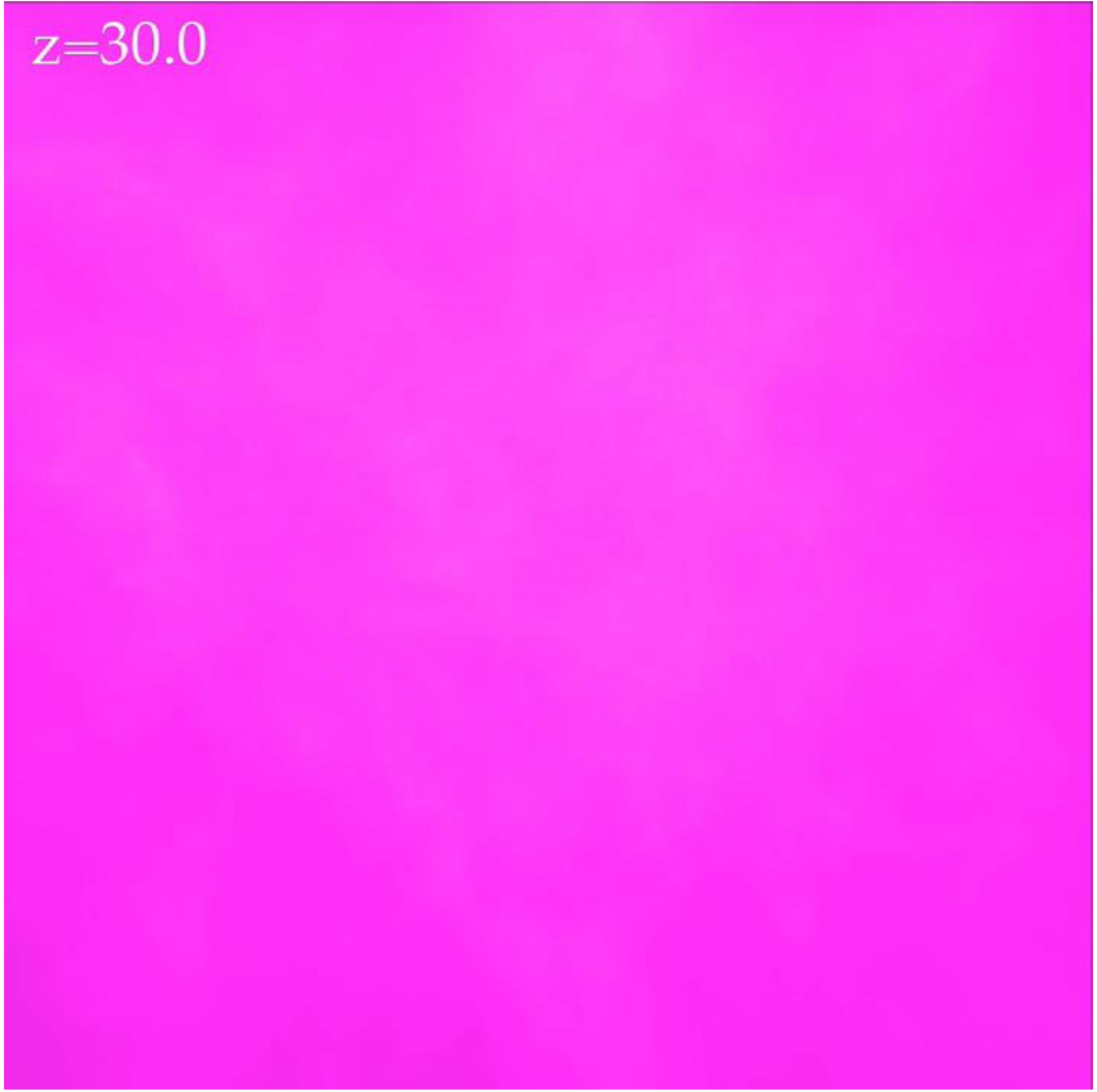


Figure 17. Median tangential velocity of stars in the Latte and Auriga simulations as a function of stellar age (left-hand panel) and metallicity (right-hand panel). The solid coloured lines show median curves for nine simulated Milky Way-sized galaxies, as indicated in the legend. The black dashed line shows the median measurement for the Milky Way obtained using the APOGEE DR17 data with shaded grey area representing 68 per cent uncertainty.



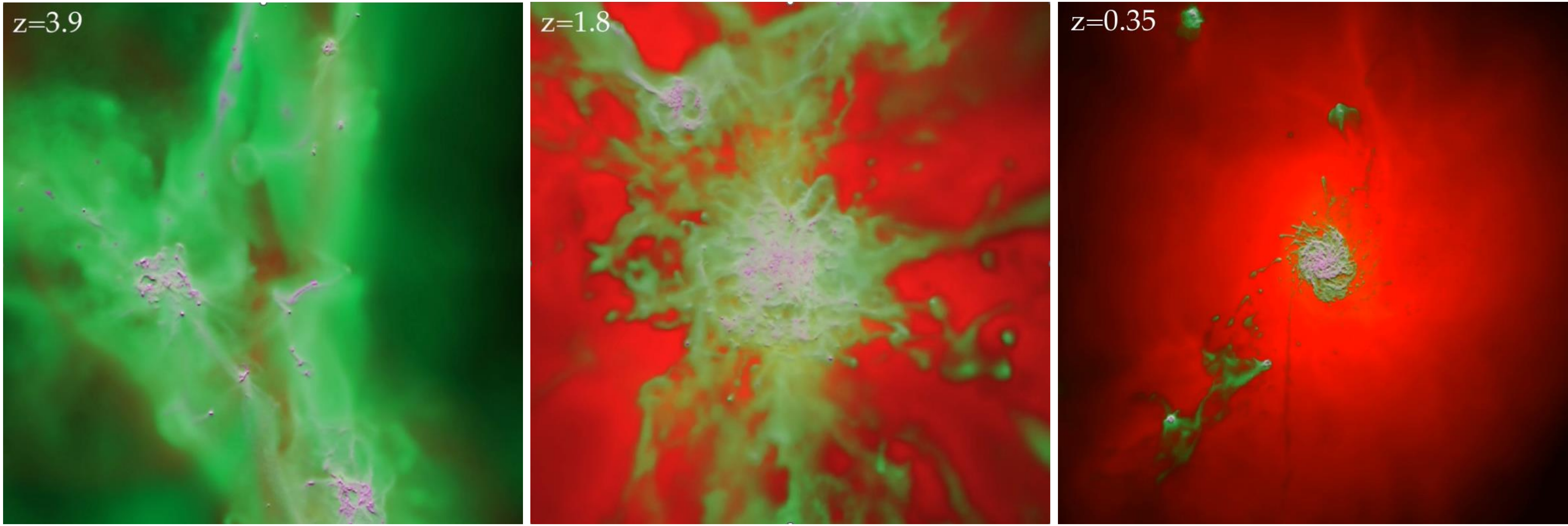
distribution of gas density and temperature
at different stages of evolution,
magenta green color T~10^4-10^5 K;
red: T~10^6 K

Credit:
FIRE collaboration

http://www.tapir.caltech.edu/~phopkins/Site/Movies_cosmo.html

What is the physics of the transition from the turbulent pre-disk stage to disk formation?

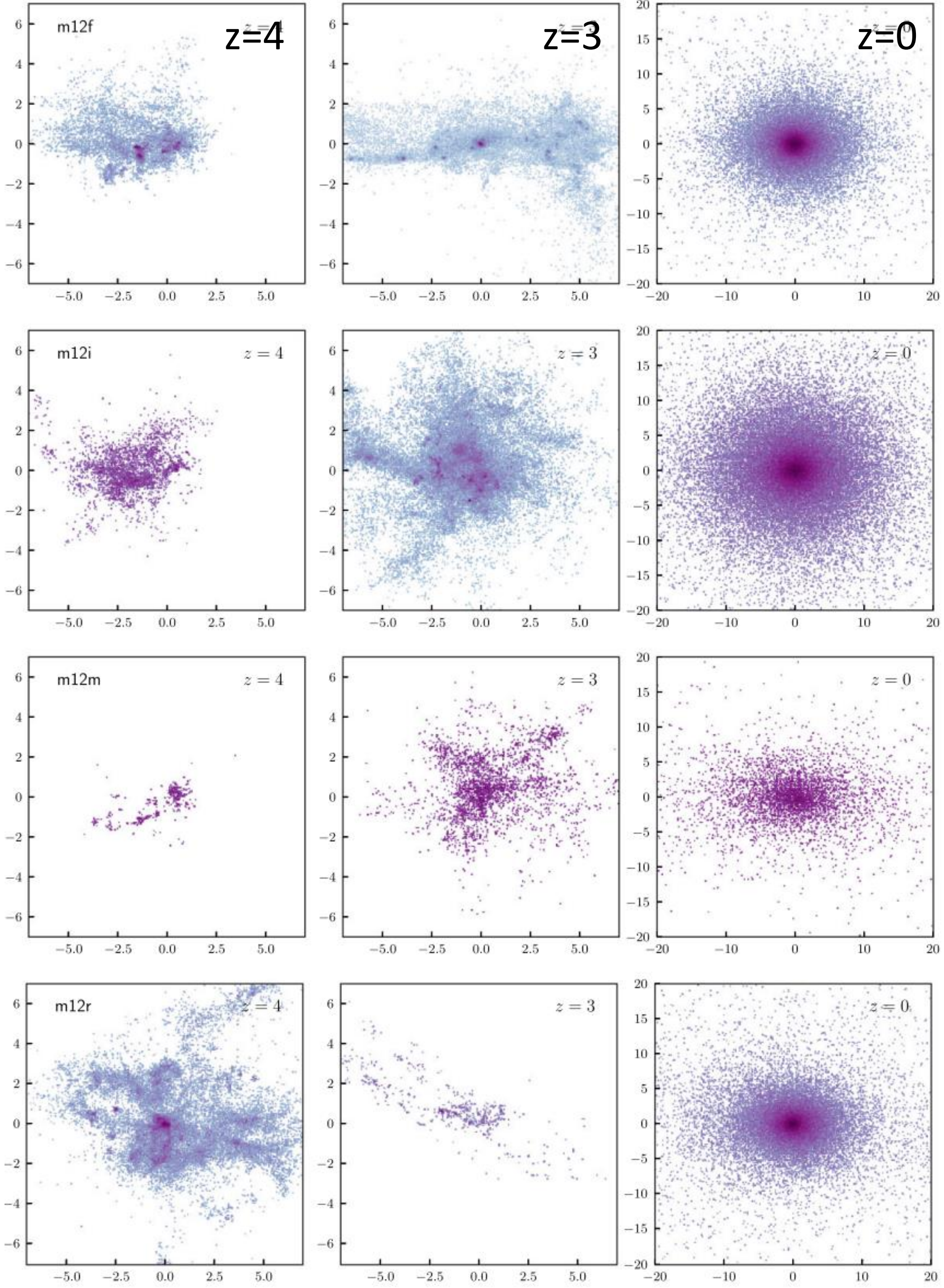
Still debated, but disk formation appears to coincide with halo mass reaching ~2×10^{11} Msun and development of hot gaseous halo. Large mass confines the outflows and limits their disruptive effects, while hot halo mediates accretion of gas that creates conditions conducive to formation and survival of coherent disk (e.g., Dekel et al. 2020; Stern et al. 2021; Gurvich et al. 2022; Hafen et al. 2022)



Distribution of gas density and temperature at different stages of evolution, magenta green color T~10^4-10^5 K; red: T~10^6 K

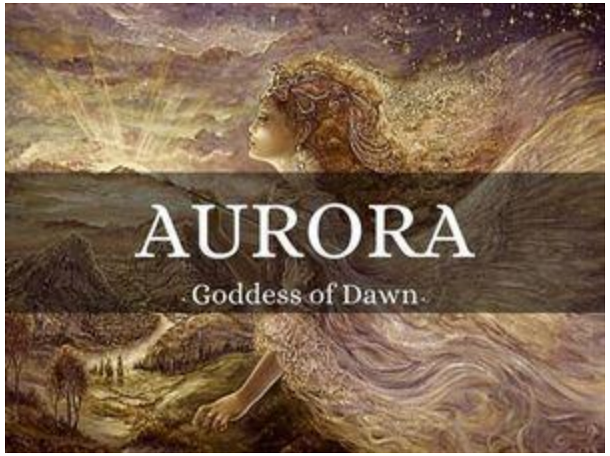
Different simulations of Milky Way-sized galaxy

Young in-situ stars are shown at z=4 and 3



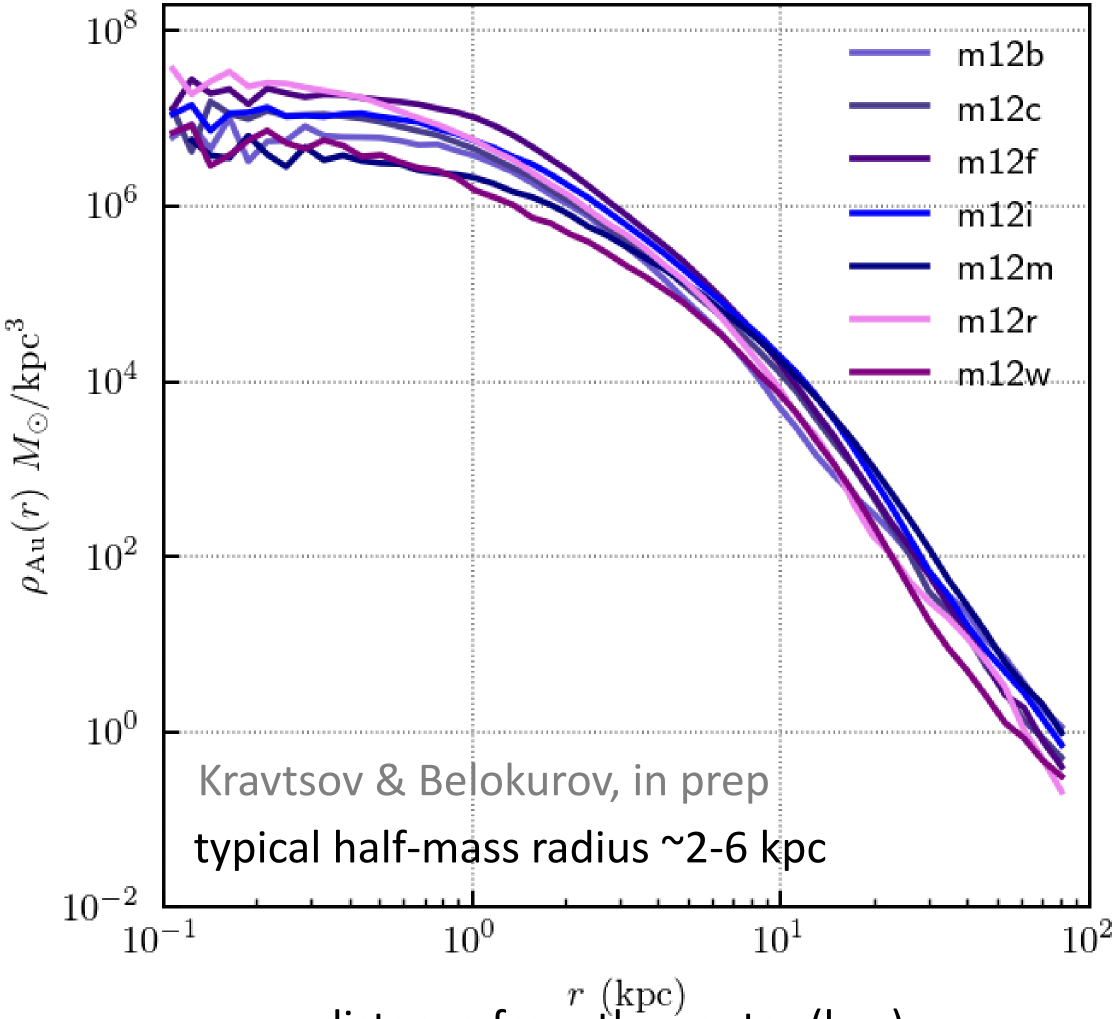
z=0 panels show today's distribution of the in-situ stars shown at z=3 and 4

The Aurora stellar population



Radial density profile of the low-metallicity in-situ stars

Is similar in different Milky Way-sized galaxies and is well described by the "lowered isothermal profile" (e.g., King 1966; Gomez-Leyton & Velazquez 2014; Gieles & Zocchi 2015 MN 454, 576)



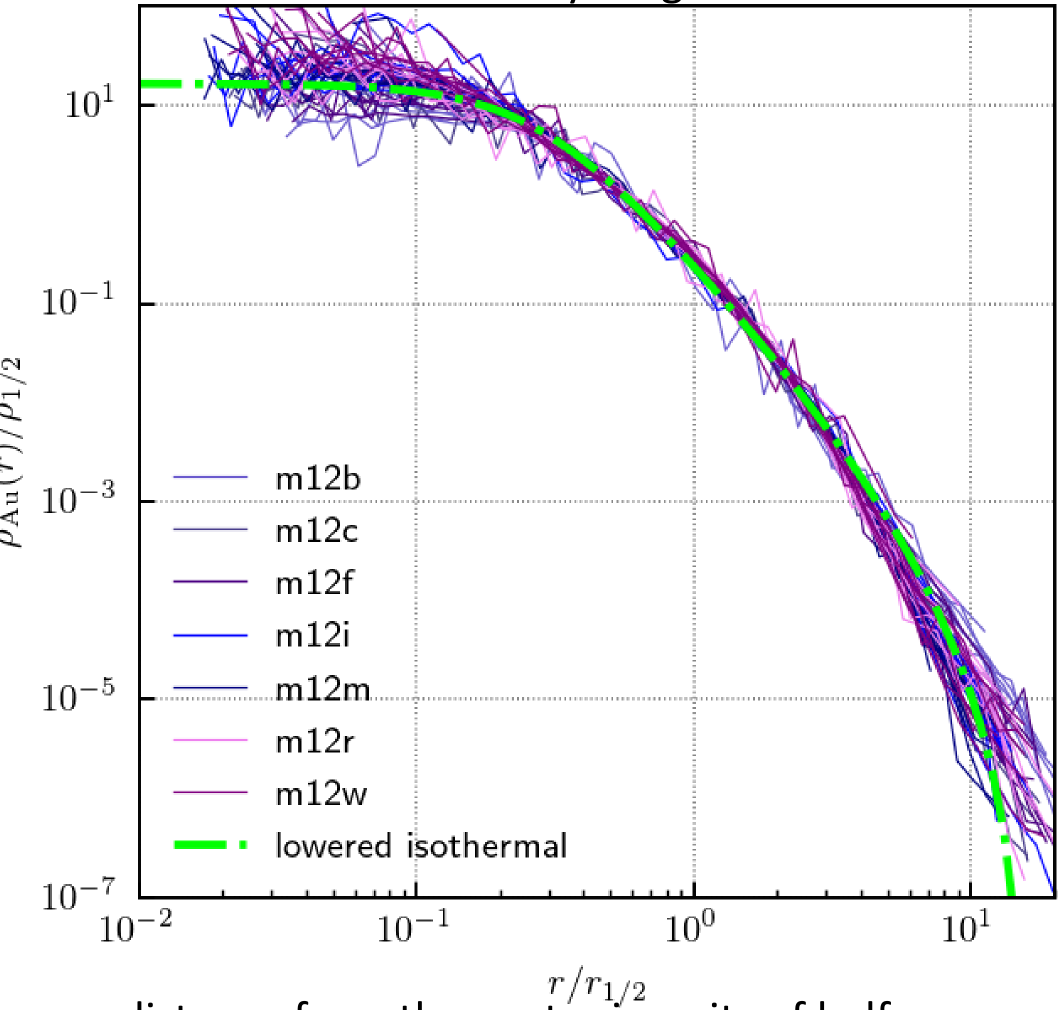
density of stars

Kravtsov & Belokurov, in prep

typical half-mass radius ~2-6 kpc

distance from the center (kpc)

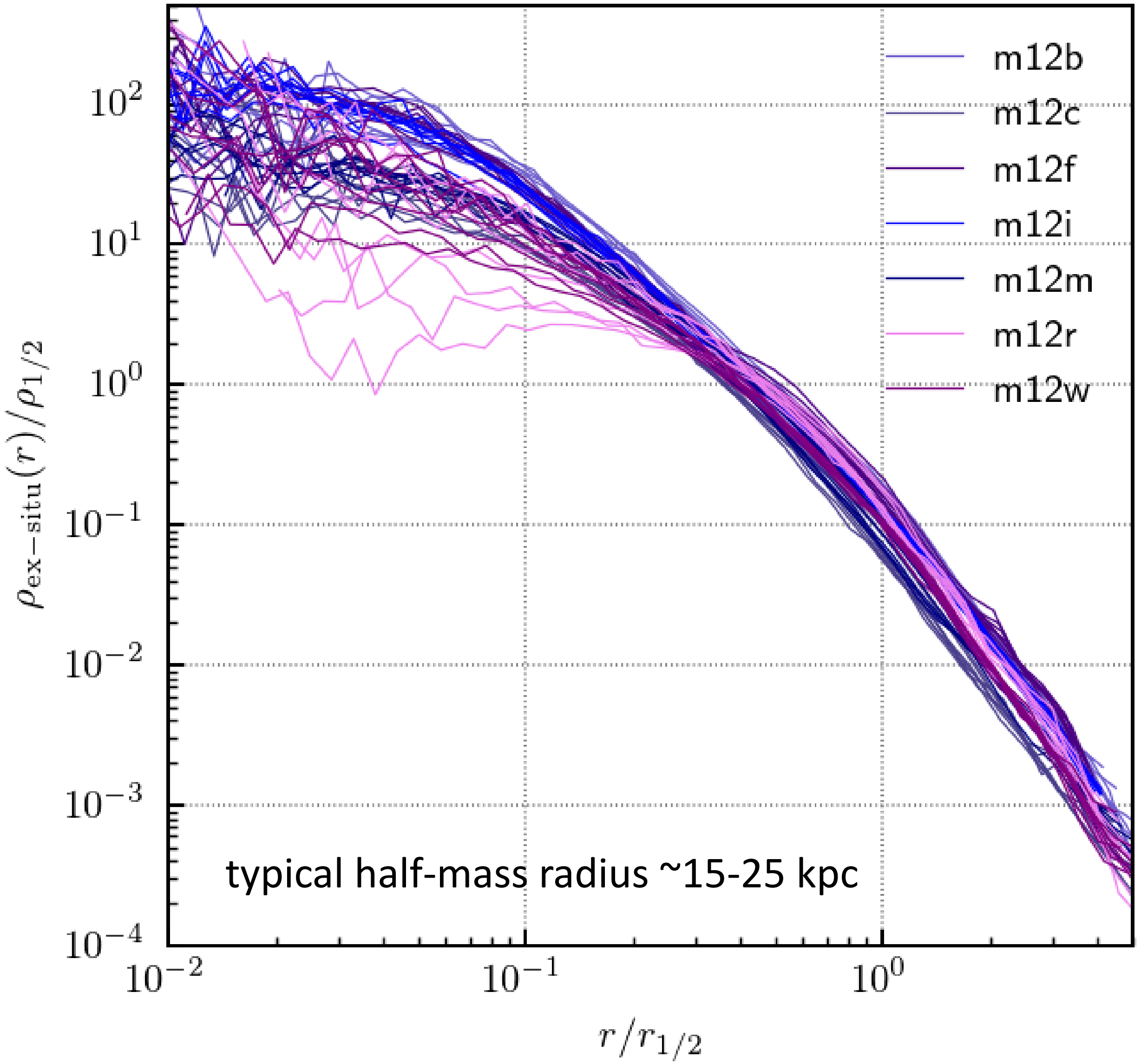
density profile of in-situ stars indifferent objects and different metallicity ranges



density of stars normalized to rho(<$r_{1/2}$)

distance from the center in units of half-mass radius

Radial density profile of the accreted stars exhibits considerably more variation for different MW-sized galaxies

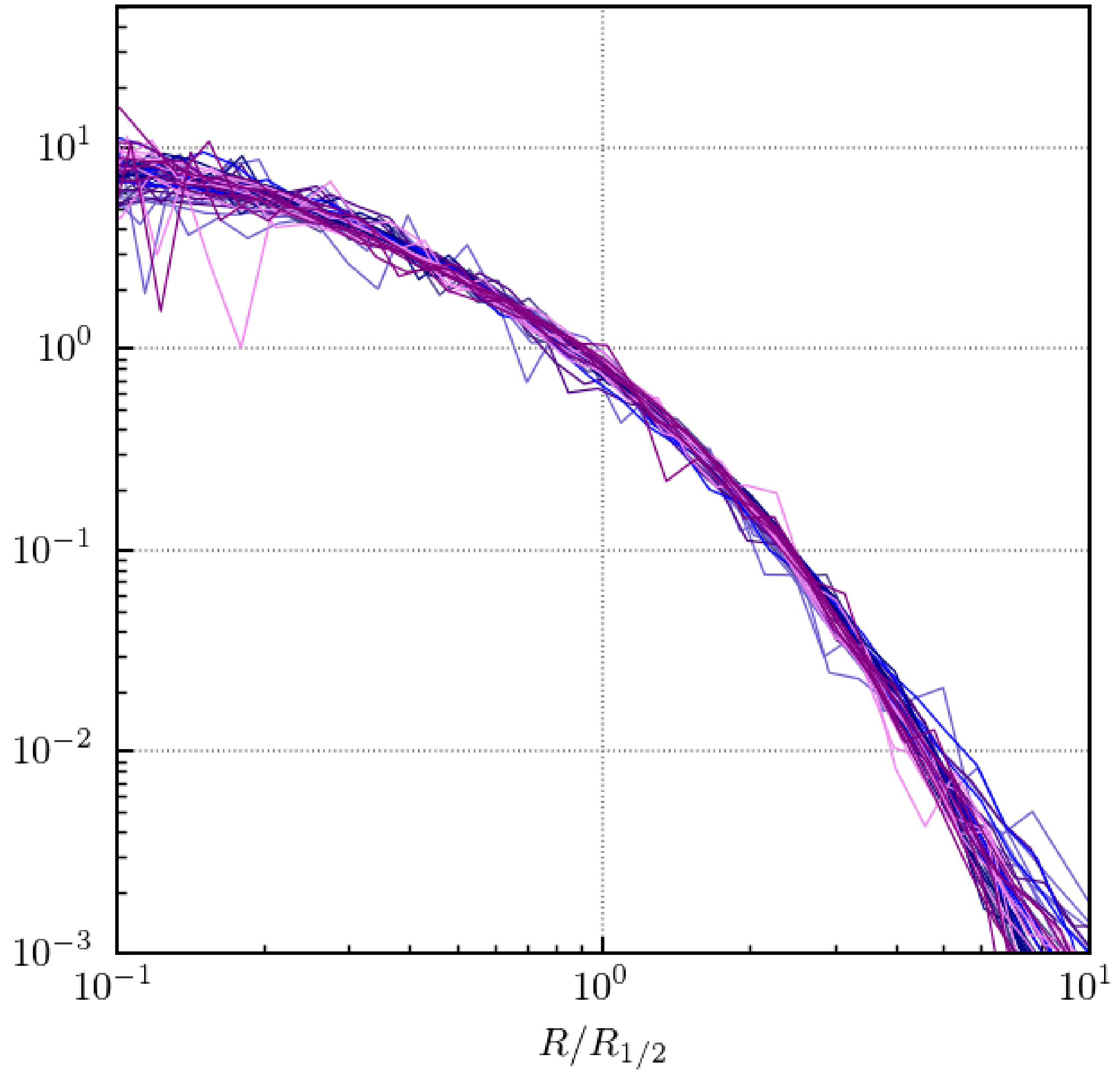


Projected radial density profile of the low-metallicity in-situ stars (the Aurora component)

is predicted to be nearly the same for different objects and different metallicity ranges

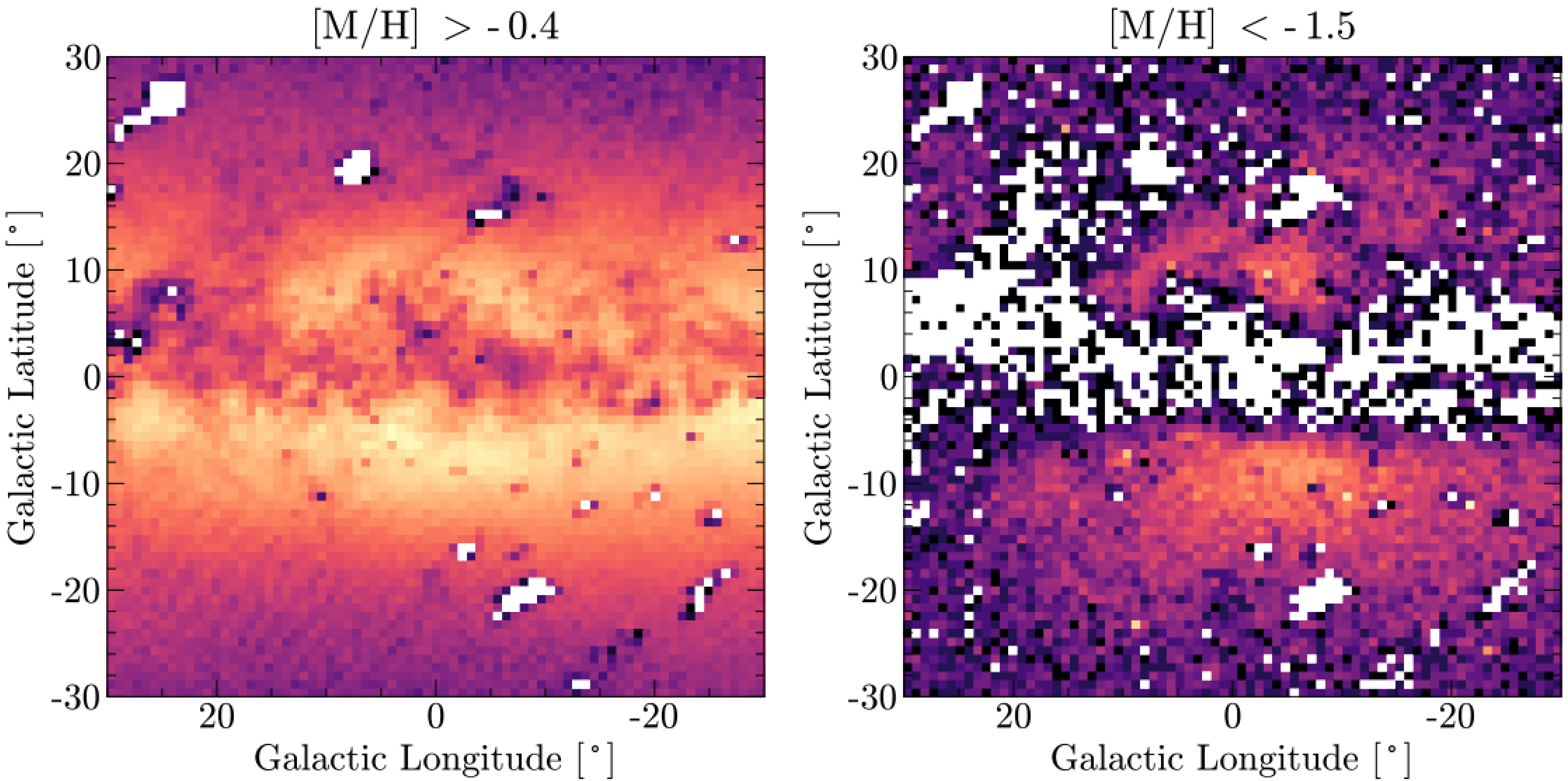
Kravtsov & Belokurov, in prep

Projected density of stars normalized to $\Sigma(<R_{1/2})$



projected distance from the center in units of half-mass radius

Approximately spheroidal distribution of low-Z in-situ stars was recently observed



Rix et al. 2022 (arXiv/2209.02722)

Summary:

- Observations show that Milky Way disk forms when metallicity of stars reaches ~0.1 solar (Vasily Belokurov's talk)

- Lower metallicity in-situ stars are a new stellar component of the Milky Way (the Aurora) and probe chaotic pre-disk stages of Milky Way evolution

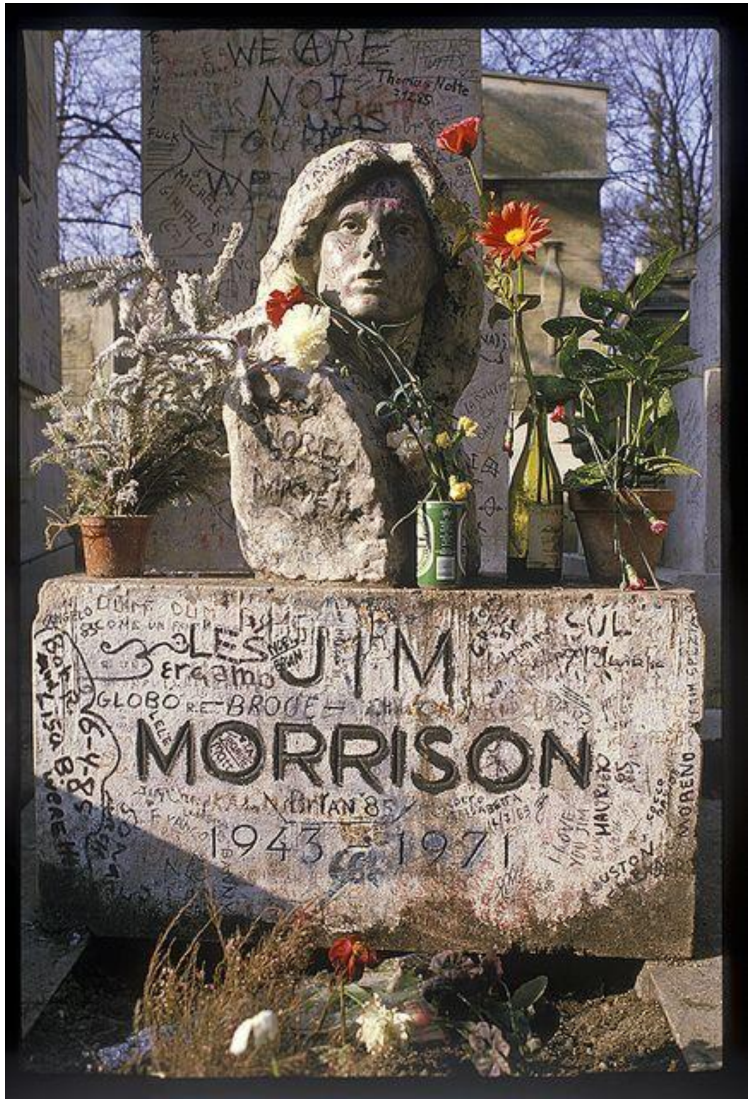
- In models disk forms at lookback times of 10-12.5 Gyrs ago (or z~2-5)

- Current galaxy formation simulations seem to predict disk formation at higher metallicities and later times: either Milky Way is unusual or simulations are systematically getting disk formation wrong. Need to check with larger samples.

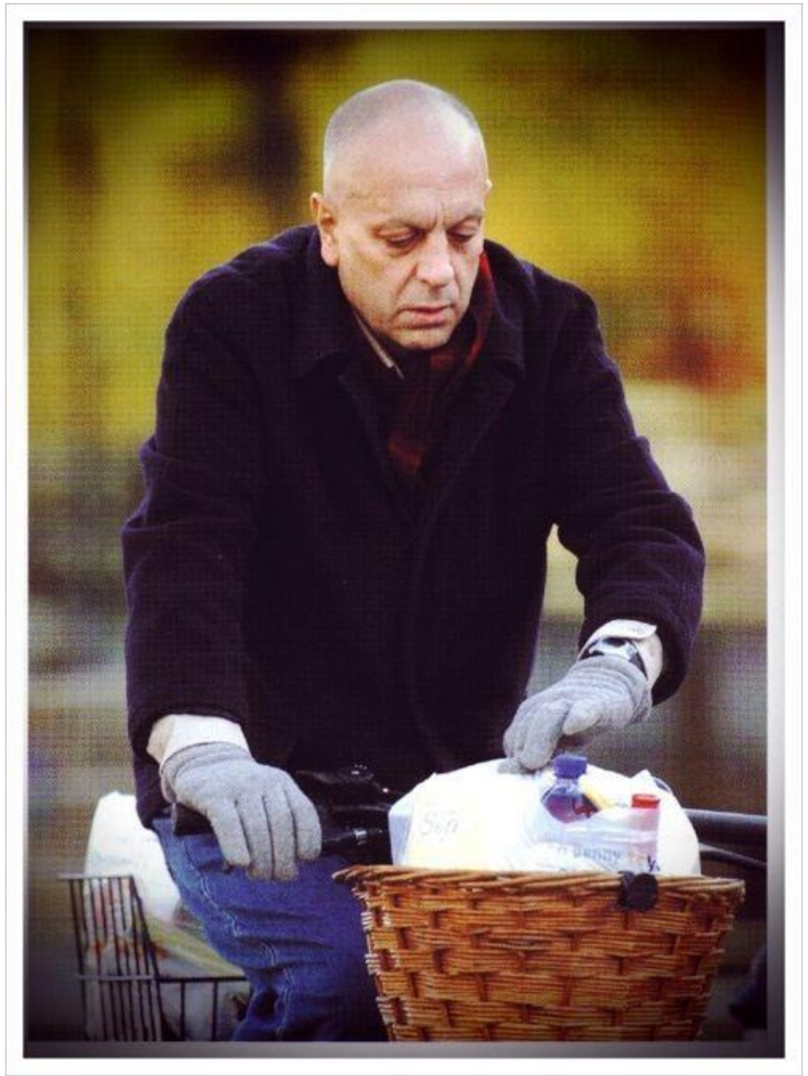
- The low-metallicity in-situ stars are predicted to have spheroidal morphology with a "lowered isothermal" density profile. Spheroidal morphology has been confirmed in observations, predicted density profile is yet to be tested by observations.

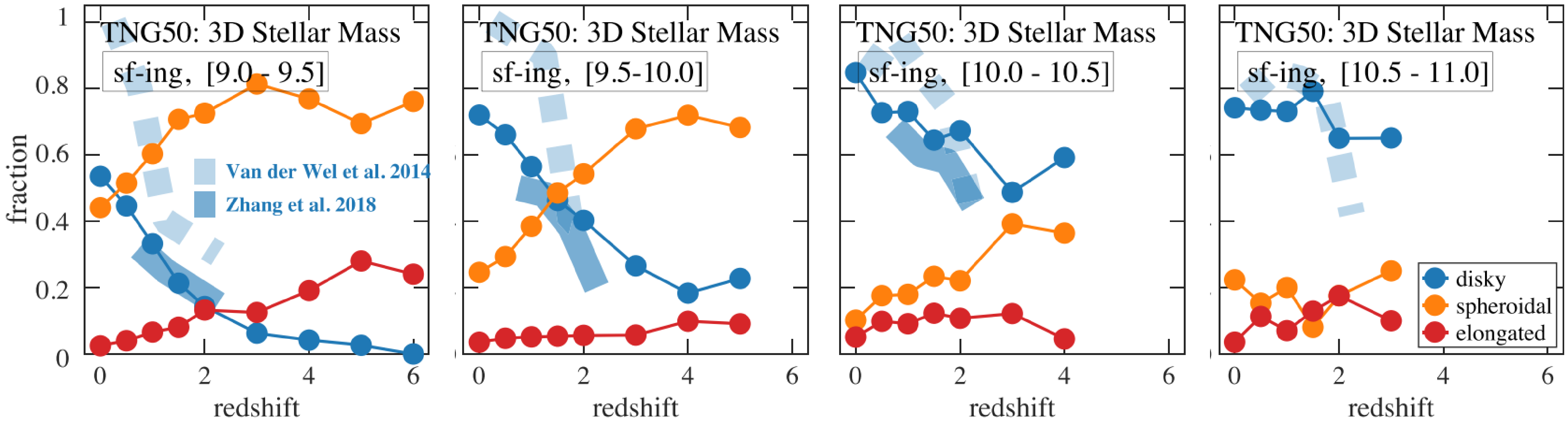
Belokurov & Kravtsov 2022, MNRAS 514, 689   Kravtsov & Belokurov, in prep

Elliptical galaxies



disk galaxies





Pillepich et al. 2019 MN 490, 3196

Age distribution of stars in different metallicity slices forming in galaxy formation simulations

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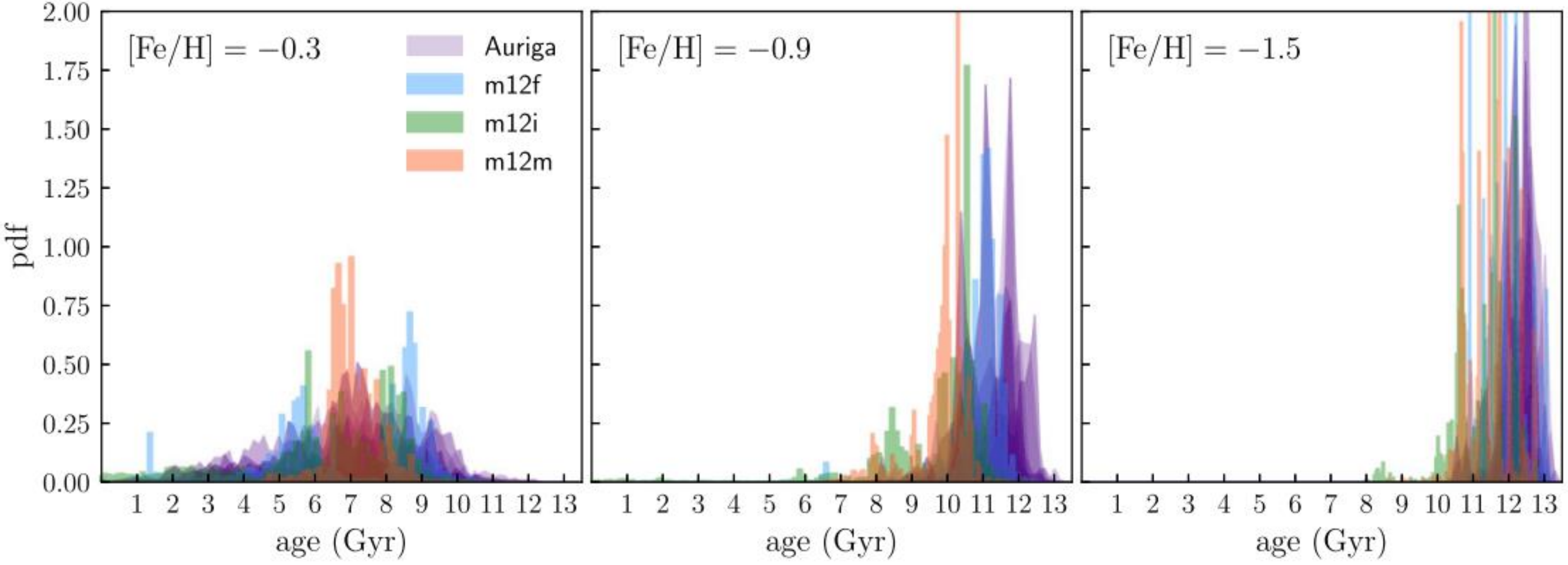
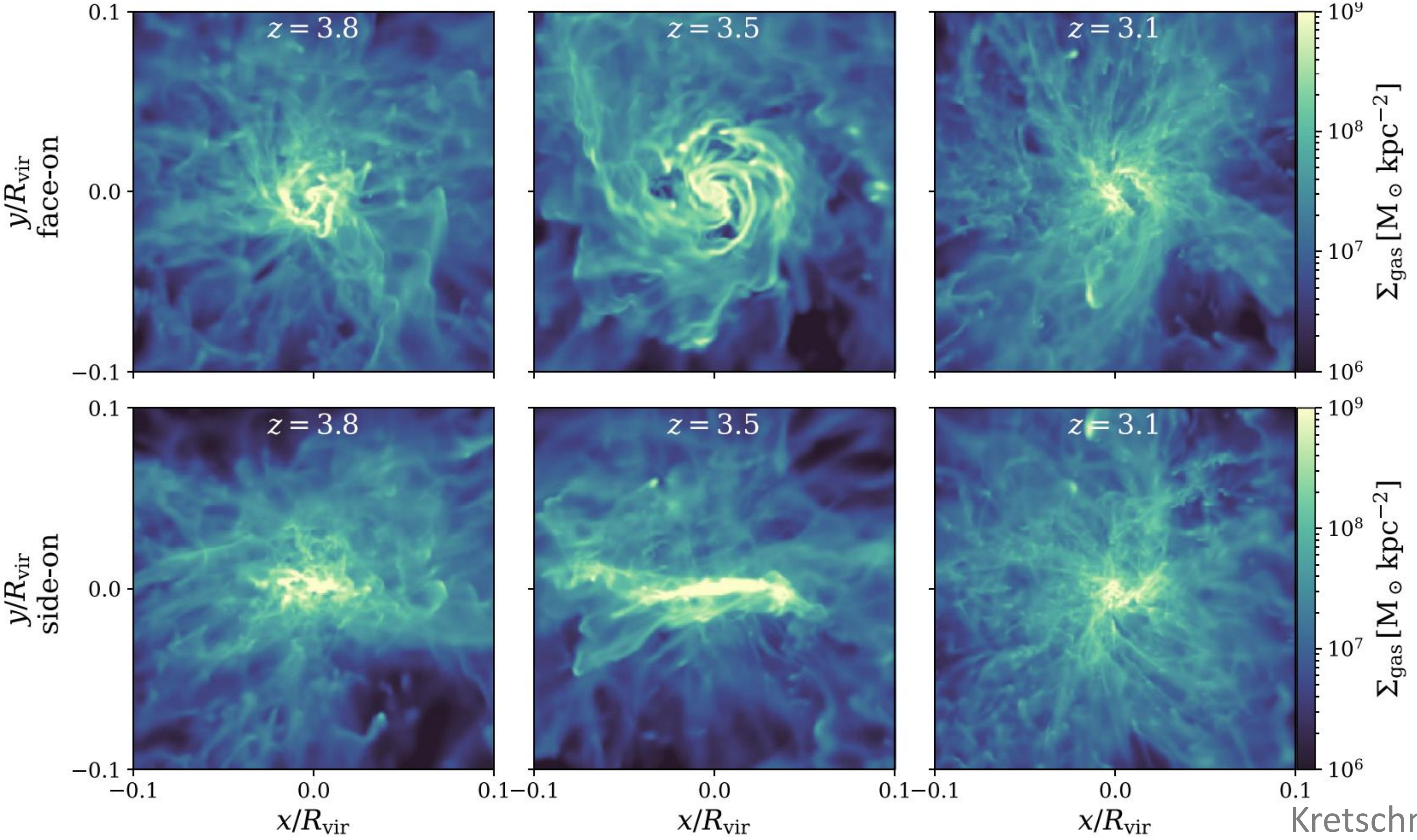


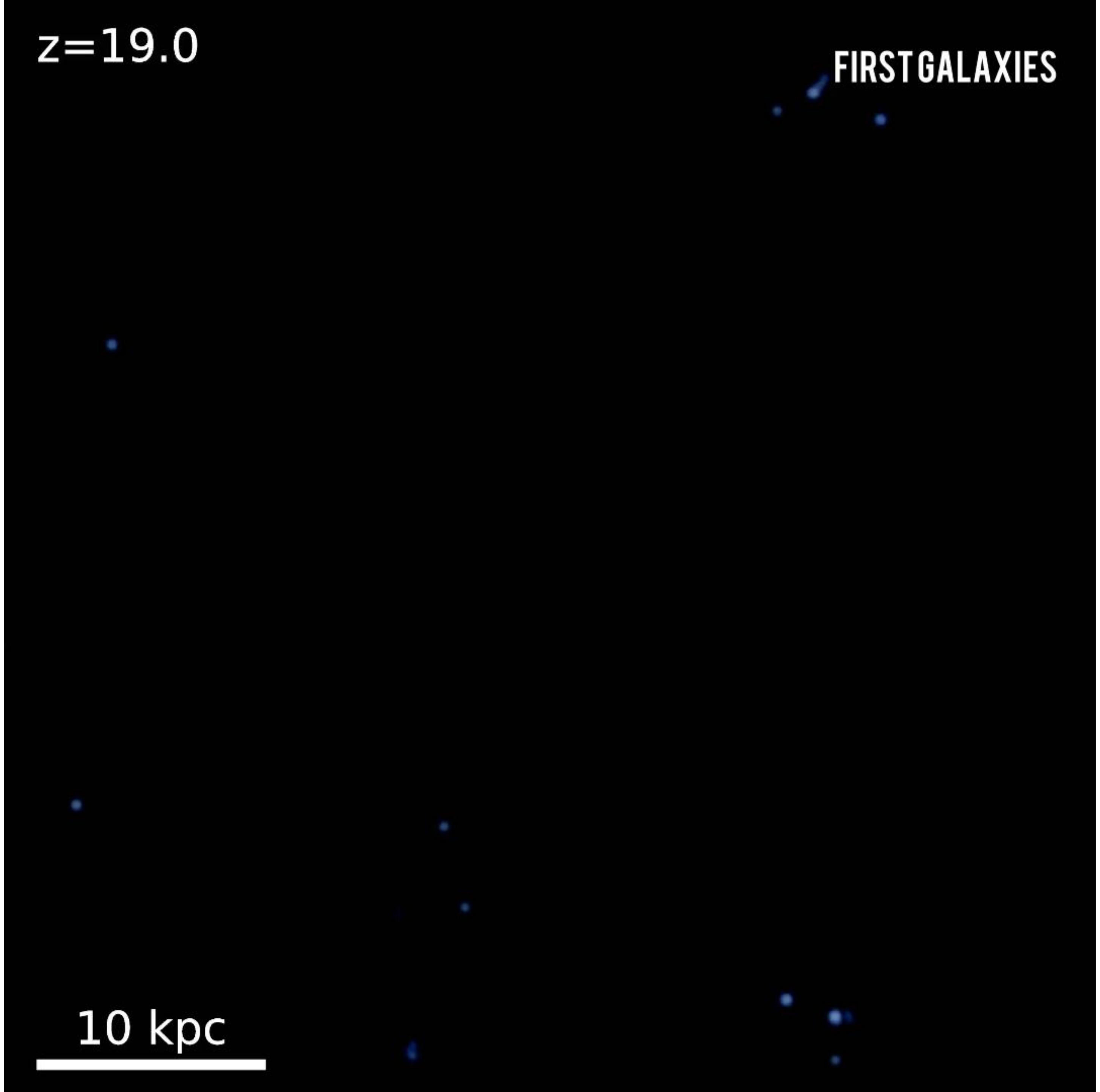
Figure 15. Age distributions of stars with metallicities $[Fe/H] = -0.3 \pm 0.025$, -0.9 ± 0.025, -1.5 ± 0.025 in the nine simulated MW-mass galaxies from the Latte and Auriga simulations. In both simulation suites stars are selected within $5 < R/\mathrm{kpc} < 11$ and $|Z| < 3$ kpc.

Gas and young stars distribution in high-z Milky Way progenitors tends to be chaotic and turbulent in different galaxy formation simulations

e.g., McCarthy et al. 2012; Tillson et al. 2015; Pillepich et al. 2019
Meng & Gnedin 2021; Kretschmer et al. 2022



Kretschmer, Dekel & Teyssier 2022
MNRAS 510, 3266



Credit:
Xuejian Shen
and Latte
collaboration

https://xuejianshen.github.io/personal-website/