Using simulations to explore the outside-in age gradients of dwarf galaxies of all types

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I. Introduction

The stellar age gradients of dwarf galaxies differ from those of better-understood Milky Way-mass galaxies. Milky Way-mass galaxies tend to form inside-out, forming stars further and further from the center with time, resulting in an age gradient with the youngest stars on the outskirts and the oldest stars in the inner regions. Dwarf galaxies display the opposite trend, with their oldest stars on the outskirts and their youngest stars closer to the center of the galaxy. ***We use the largest, most diverse sample to-date of 73 simulated field and satellite dwarf galaxies in order to investigate this trend.***

II. Methods

Our sample of 73 simulated dwarfs spans a stellar mass range of $10^{5.8} - 10^{9.4} M_{\odot}$. Our simulations also contain both field and satellite galaxies. The simulations we use are run with ChaNGa, a tree+SPH code [4]. We look at eight total simulations divided into two suites of simulations: the Marvel-ous dwarfs [5] and the near-mint DC Justice League (DCJL) [1, 2]. Both simulations use the "zoom-in" renormalization technique. A summary of their properties is in Table 1.

Simulation Suite	Volume Size	Force softening resolution	Dark matter particle mass	Gas particle mass	Star particle mass (at birth)
Marvel-ous dwarfs	25 Mpc^3	60pc	6660 $M_{\odot}$	1410 $M_{\odot}$	422 $M_{\odot}$
near-mint DCJL	50 Mpc^3	170pc	$4.2 \times 10^4 M_{\odot}$	$2.7 \times 10^4 M_{\odot}$	$8000 M_{\odot}$

Table 1

III. Results

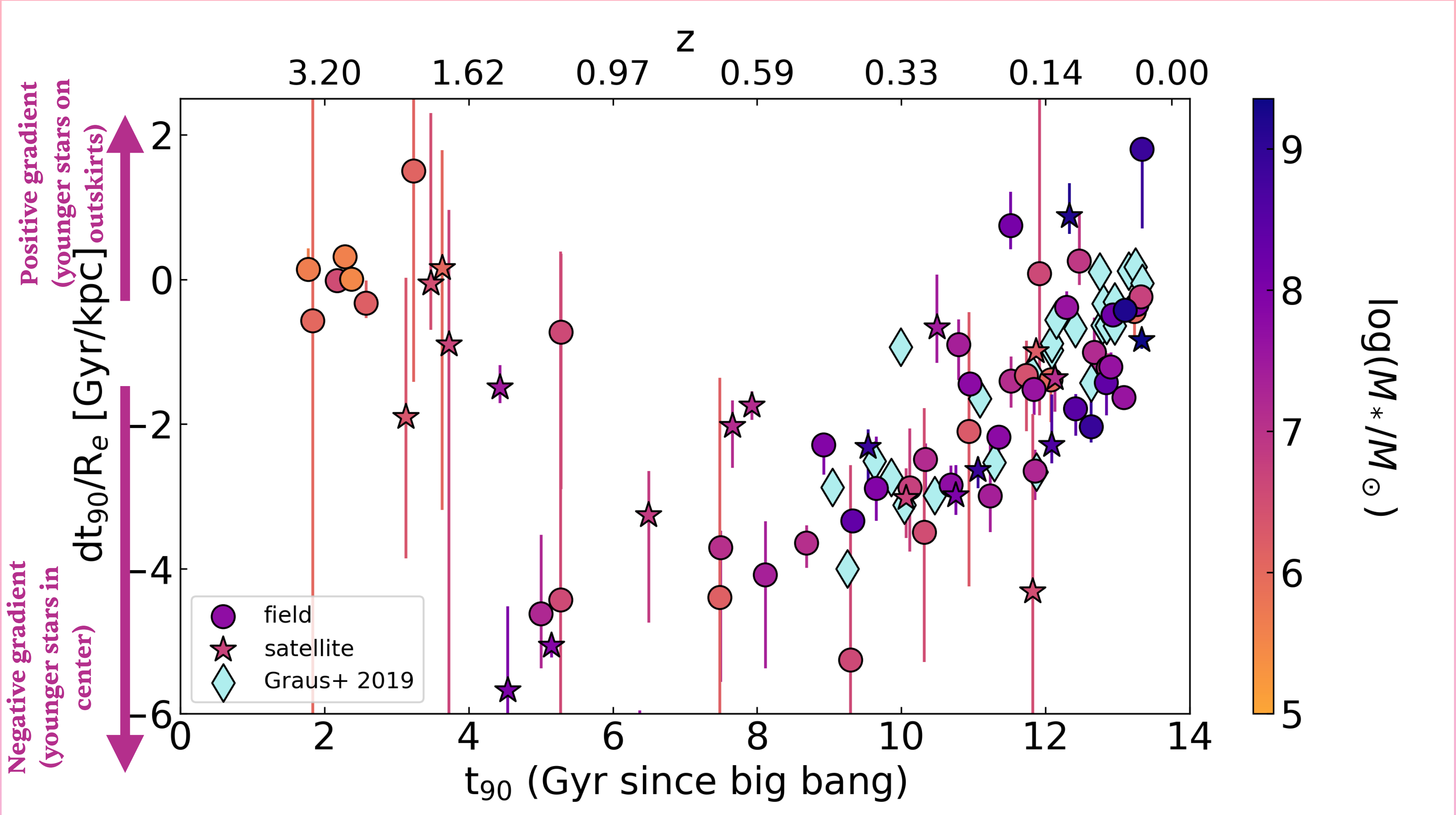
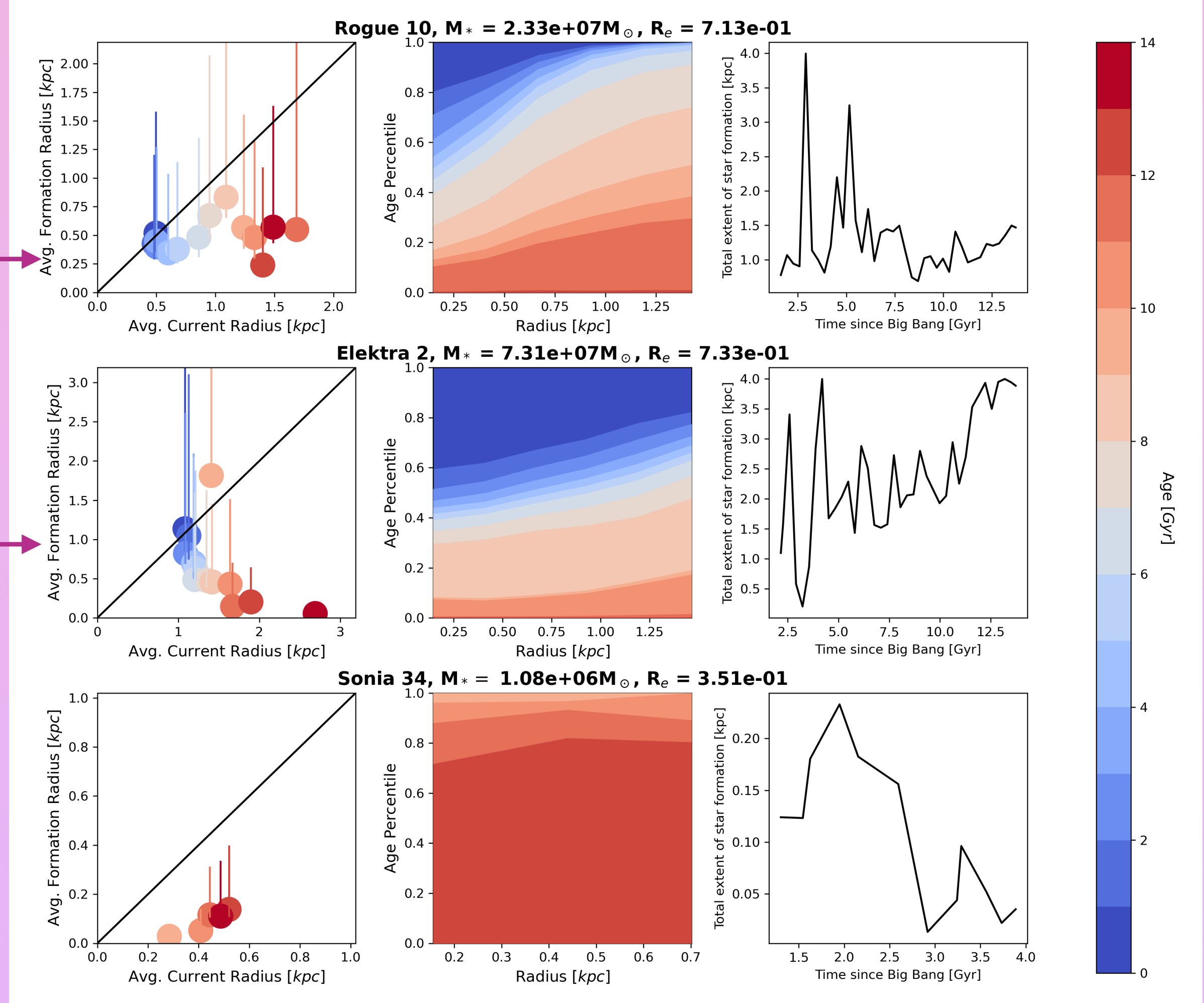


Figure 1

We plot global t_{90} (the age at which 90% of the stars have formed) vs. dt_{90}/dR_e, which quantifies the age gradient of each galaxy. The age gradient is computed by dividing the stars within one effective radius into 10 annular bins, measuring the t_{90} value in each bin, and taking the difference between the inner and outer bin. We normalize with respect to the effective radius. We repeat this for 100 random sight-lines and show the average here, with error bars enclosing 68% of the data and compare our results to the FIRE-2 galaxies presented in [3] (denoted by blue diamonds). **We find the same trend as in [3]; that more recent star formation leads to a flatter age gradient. Using our larger, more diverse sample, we find that 1) quenched galaxies have flat age gradients and 2) satellite and field galaxies follow the same trend.**

Stellar reshuffling or outside-in formation?



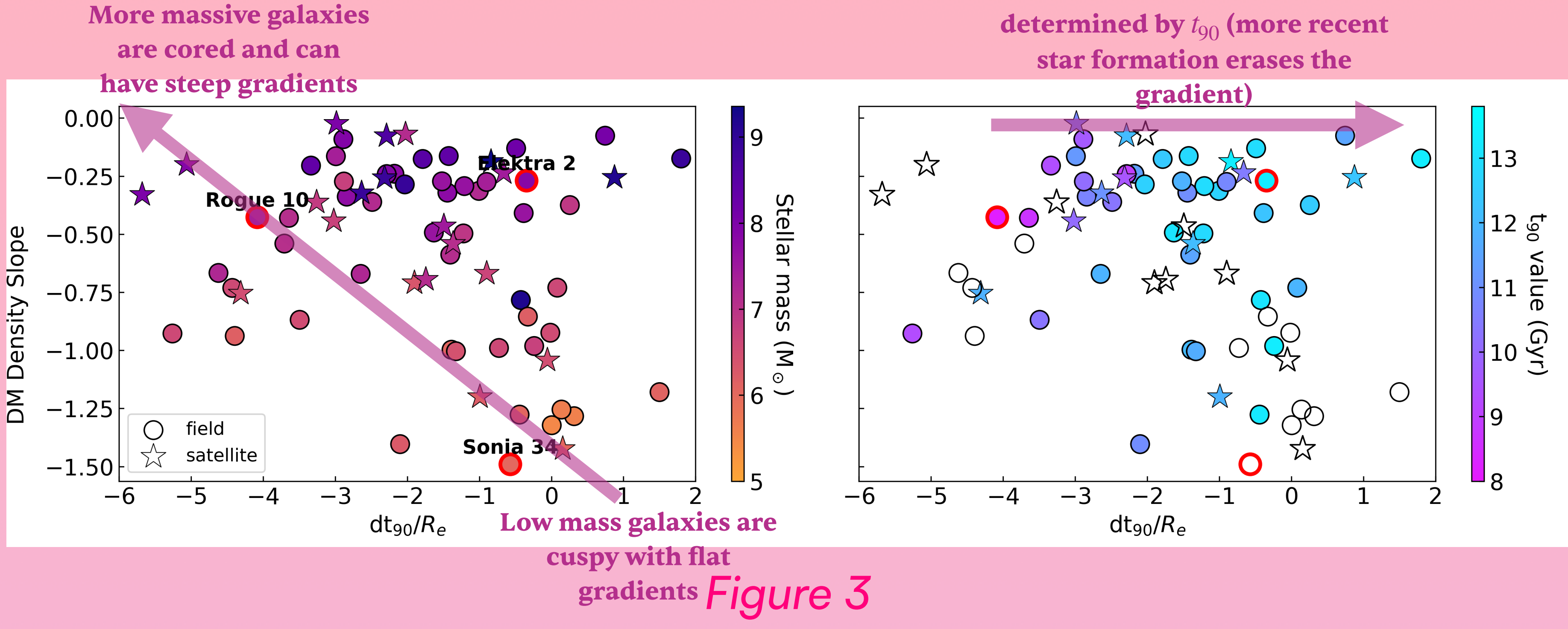
All stars formed at ~0.5 kpc; oldest stars were reshuffled to the outskirts

Oldest stars formed closest to the center, younger stars formed increasingly further away (inside-out!)

Figure 2

To see if our stars are reshuffled, we examine how stars move relative to their initial position for three galaxies in our sample (Rogue 10, a steep, negative age gradient, Elektra 2, a flat age gradient, and Sonia 34, a dwarf that quenched early in its history). In the leftmost column, we plot the average current radius vs. the average formation radius for stars in 1Gyr age bins. In the middle column, we show the age gradient by plotting the percent of stars in each age bin per radius out to $2 \times R_e$. In the last column, we plot the total extent of star formation vs. time. **We find that both steep and flat gradients form inside-out with the oldest stars getting pushed out over time, and that recent star formation flattens the gradient by igniting star formation across the galaxy.**

Reshuffling stars via gravitational potential fluctuations



More massive galaxies are cored and can have steep gradients

For cored galaxies, gradient is determined by t_{90} (more recent star formation erases the gradient)

Low mass galaxies are cuspy with flat gradients

Figure 3

Fig. 2 makes it clear that the stars in our simulations get reshuffled over time. Thus, we investigate stellar feedback by examining the dark matter density slope of our galaxies. Here, we plot the dark matter density slope versus the age gradient. The left panel is colored by stellar mass while the right panel is colored by t_{90}. We see that low mass galaxies are cuspy and have flat age gradients while higher mass galaxies have both steep and flat gradients, suggesting that **the processes that form dark matter cores also contributes to dwarf stellar age gradient formation.**

For the halos with cored dark matter density profiles (DM density slope > -0.5), the age gradient trends with t_{90}, suggesting that **more recent star formation flattens the age gradient by creating young stars across the galaxy.**

Comparison with Graus+ 2019

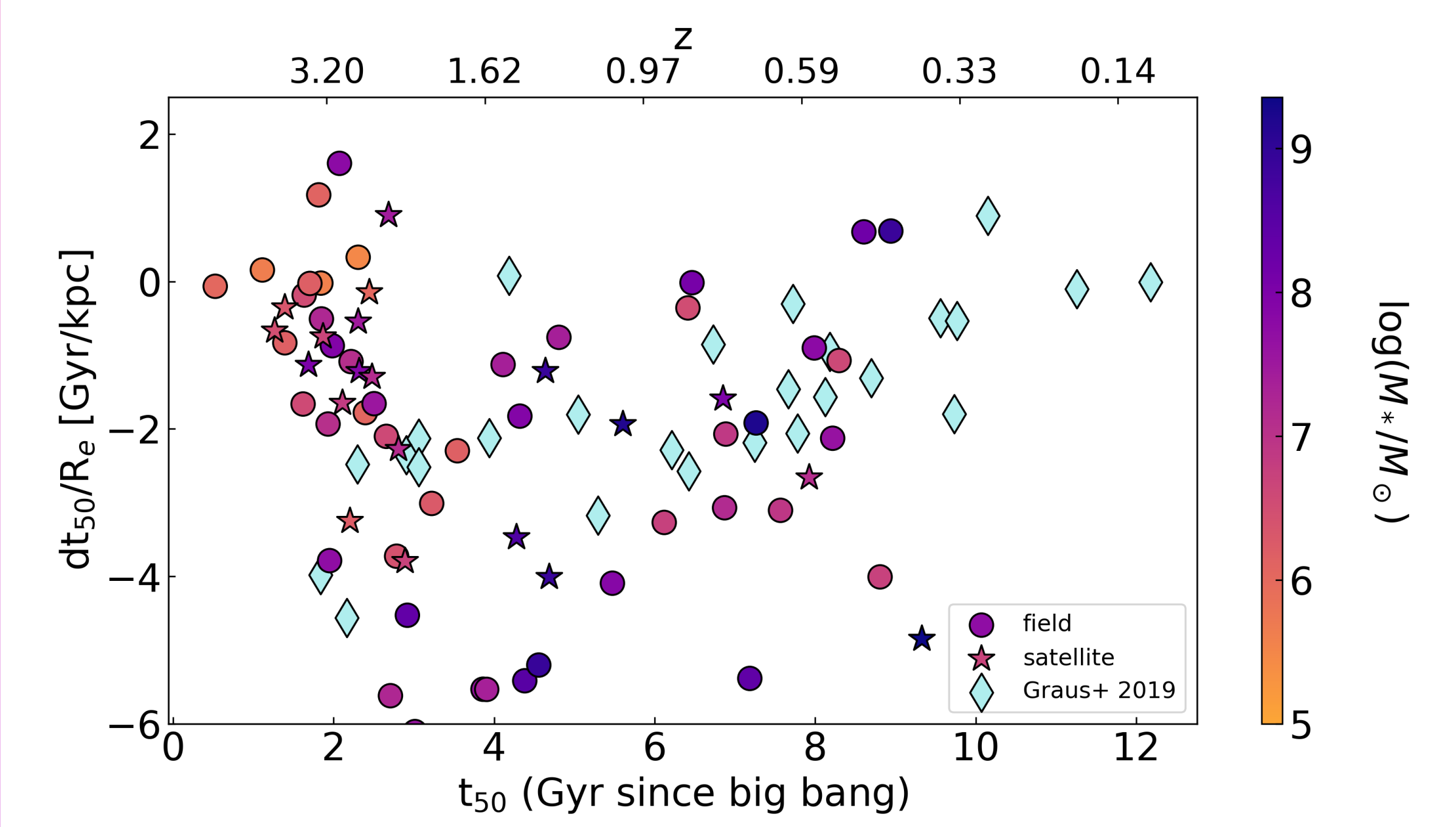


Figure 4

We further compare our results with [3], re-creating Fig. 1 using t_{50} values, or the time at which 50% of the galaxy's total stars have formed. We find that [3]'s gradients have already formed at this early time, with age gradient linearly trending with t_{50}, while our age gradients have not yet fallen into the trend seen at t_{90}. **We infer that the processes setting our age gradients occurs later than in FIRE-2, likely due to differences in the feedback models used in our respective simulations.**

IV. Conclusions

- Dwarf galaxies of all types ***do*** form their stars inside-out (not outside-in).
- Two main processes determine dwarf galaxy age gradients:
  1. **Stellar feedback drives the formation of dark matter cores and reshuffles the stars.**
  2. **Star formation in cored galaxies can erase age gradients.**
- Mergers have no conclusive impact on dwarf age gradients.
- Age gradients can be used to test the feedback models of different simulations.

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(2)Bellovary J. M., Cleary C. E., Munshi F., Tremmel M., Christensen C. R., Brooks A. M., Quinn T. R., 2019, Monthly Notices of the Royal Astronomical Society, 482, 2913-2923

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(4)Menon H., Wesolowski L., Zheng G., Jetley P., Kale L., Quinn T., Governato F., 2015, Computational Astrophysics and Cosmology, 2, 1

(5)Munshi F., Brooks A. M., Applebaum E., Christensen C. R., Quinn T., Sligh S., 2021, ApJ, 923, 35