# Dark Matter Deficient Galaxies (DMDGs) and Their Member Star Clusters Form Simultaneously during High-velocity Galaxy Collisions

Joohyun Lee (UT Austin), Eun-jin Shin (Seoul Nat. U.), Ji-hoon Kim (Seoul Nat. U.)

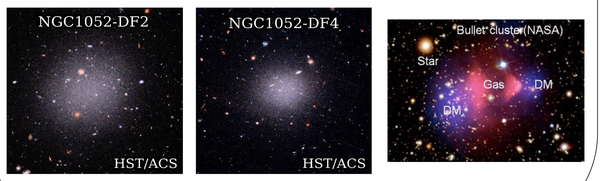

## Abstract

Recently, two dark matter deficient dwarf galaxies, NGC1052-DF2 and NGC1052-DF4 are discovered. We report a suite of galaxy collision simulations using the adaptive mesh refinement code ENZO with 1.25 pc resolution, which demonstrates that high-velocity galaxy collisions induce the formation of dark matter deficient galaxies (DMDGs) and their star clusters (SCs) simultaneously. With this numerical resolution, we resolve the structure of the produced DMDGs and the detailed formation history of their SCs, which are possible progenitors of the DMDG's member globular clusters (GCs). In particular, we show that a galaxy collision with a high relative velocity of ∼300 km/s, invoking severe shock compression, spawns multiple massive SCs ($M_{\rm star} \sim 10^6 {\rm M}_\odot$). The resulting DMDG of $M_{\rm star} \sim 3.5 \times 10^8 {\rm M}_\odot$ hosts 10 luminous gravitationally bound SCs. Our study suggests that DMDGs and their luminous member SCs could form simultaneously in high-velocity galaxy collisions while being in line with the observation of NGC1052-DF2 and NGC1052-DF4.


## 1. Introduction

NGC1052-DF2 (DF2) and NGC1052-DF4 (DF4), Ultra Diffuse Galaxies (UDGs) with $M_{\rm star} \sim 2 \times 10^8 {\rm M}_\odot$ are found to have little dark matter (DM), contradicting the LCDM cosmology. Moreover, several observations of DF2 and DF4 found an unconventionally bright population of GCs.

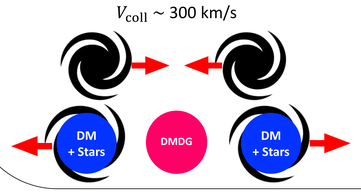
Silk (2019) suggested that the **high-velocity collision of gas-rich dwarf galaxies** may produce DMDGs. In this scenario, due to the collision-less nature, DM halos pass through but gas content is impeded by the ram pressure. Shock-compressed gas forms stars efficiently, invoking simultaneous formation of massive GCs and DMDG. This is analogous to the famous **"Bullet Cluster"**, so we name it **Bullet Dwarf** or **Mini-bullet**.




## 2. Method

We use **ENZO** to simulate the dwarf galaxy head-on collision with a **spatial resolution** of **1.25 pc** and **star particle mass resolution** of **200** $\rm M_\odot$. Our fiducial run is a co-planar prograde-prograde collision of two identical disk galaxies with a relative velocity of ∼300 km/s and a pericentric distance of 1 kpc. **DICE** code provided the initial condition of colliding gas-rich dwarf disk galaxies with $M_{\rm total} \sim 6 \times 10^9 {\rm M}_\odot$ and $M_{\rm gas} \sim 1.7 \times 10^9 {\rm M}_\odot$.

Subgrid star formation and feedback physics are implemented using a method similar to Cen & Ostriker (1992).




$M_{\rm star} = 4.21 \times 10^8 {\rm M}_\odot$
$M_{\rm gas} = 1.68 \times 10^9 {\rm M}_\odot$
$M_{\rm DM} = 3.88 \times 10^9 {\rm M}_\odot$

## 3. Formation of DMDGs

We find a DMDG of $M_{\rm star} = 3.47 \times 10^8 {\rm M}_\odot$ with almost no DM. The result is in line with our previous work (Shin et al. 2020), which demonstrated the formation of $M_{\rm star} \sim 10^8 {\rm M}_\odot$ DMDGs in 80pc-resolution simulations, validating resolution convergence of the **Mini-bullet** scenario.

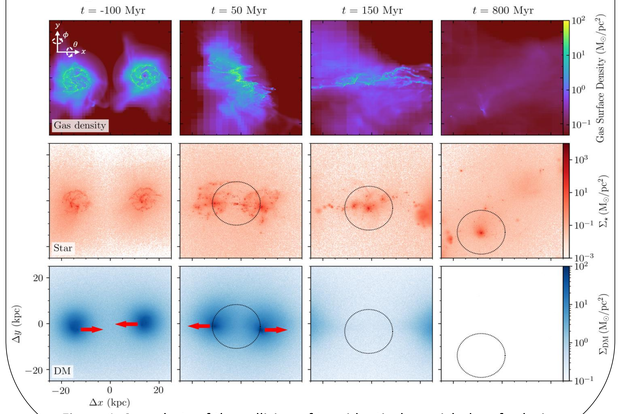



Figure 1. Snapshots of the collision of two identical gas-rich dwarf galaxies.

## 4. Simultaneous Formation of SCs

SCs are identified with the HOP group-finding algorithm. 800 Myr after the collision, 42 bound SCs are found to orbit DMDGs. SCs are formed in dense gas clumps of which surface density is $\Sigma \geq 10^3 \ {\rm M}_\odot \ {\rm pc}^{-2}$, efficiently forming stars and enabling the formation of massive ($\sim 10^6 {\rm M}_\odot$) SCs.

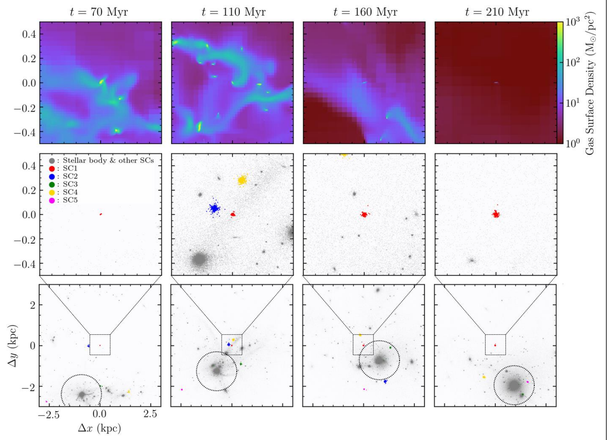



Figure 2. Snapshots centered on the most massive SC (red).

DMDG stars and massive SCs are formed **simultaneously**. Most stars are formed within 150 Myr after the collision. SC population is bright and massive, being in line with the observation of DF2 and DF4.

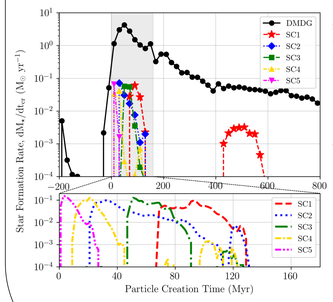



Figure 3. Snapshots of the collision of two identical gas-rich dwarf galaxies.

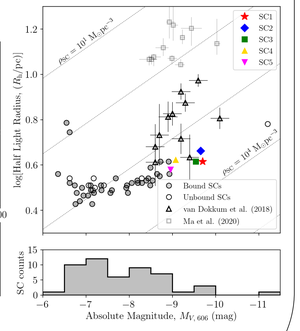



Figure 4. Absolute magnitude vs. Half-light radii of the SCs.

## 5. Future work

Following the recent observation of ultra-diffuse galaxies near NGC1052, including DF2 and DF4, which suggested the Mini-bullet scenario as a plausible event that is responsible for the formation of a trail of ∼10 dwarf galaxies, we aim to examine the galaxy collision-induced DMDG formation scenario in a more realistic, observation-matching setup.

The first step is to take into account the effect of the host galaxy and dynamics of orbiting before and after the galaxy collision, by following the full history of colliding dwarf galaxies and produced DMDGs in a larger simulation volume. We expect our results to provide predictions on what future observation should detect. The next step is to examine the likelihood of the Mini-bullet scenario in a cosmological context. This will involve modeling of self-consistent emergence of the initial condition and statistical analysis of the probability that a Mini-bullet galaxy pair can be found in the LCDM cosmology universe.

The Mini-bullet scenario presents a unique opportunity to test the collision-less DM model and constrain alternative DM models, such as self-interacting DM, just as the Bullet Cluster. By providing a new upper limit to the DM scattering cross section.

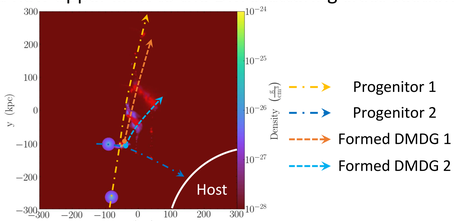



Figure 5. Orbits of colliding two dwarf galaxies and produced DMDGs around a massive host galaxy with $M_{\rm halo} \sim 6 \times 10^{12} {\rm M}_\odot$ from 1 Gyr simulation

## References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## Further info & Movies

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