# Investigating Dwarf Galaxy Stability in MilkyWay@home

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## Contents

# 1 Introduction

This report presents an examination of the investigation of isolated dwarf galaxy (DG) instability in MilkyWay@home. Knowledge gathered from previous DG stability studies and analysis of large data sets from DG generation and evolution are used to reveal the current sources of DG instability within the MilkyWay@home n-body simulator.

# 2 Testing and Data Collection

Issues with DG stability were first noticed during testing of SIDM code; tests were done using the default/Siddhartha Shelton's (Sid's) parameters and Eric Mendelsohn's (Eric's) parameters (see Appendix):

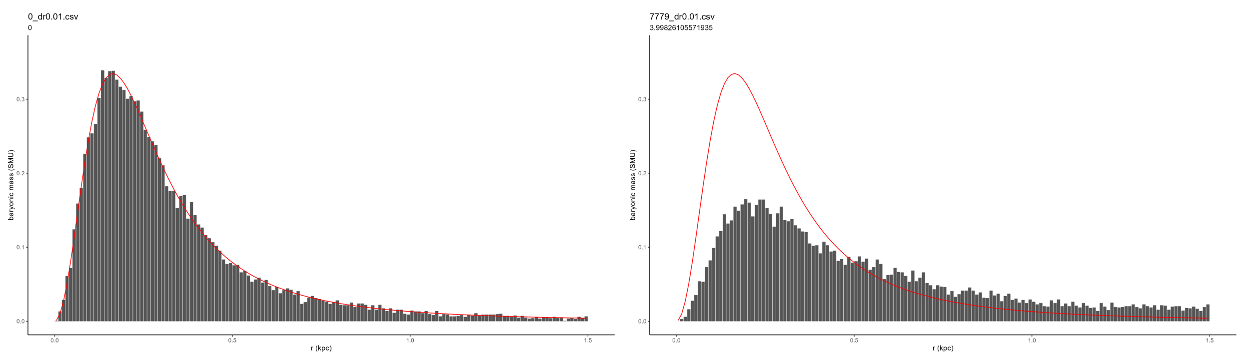



*Fig. 1 - Initial and final baryonic mass histograms of a Plummer + SIDM dwarf galaxy generated using Sid's parameters after 4.0 Gy of evolution (dr = 0.01)*

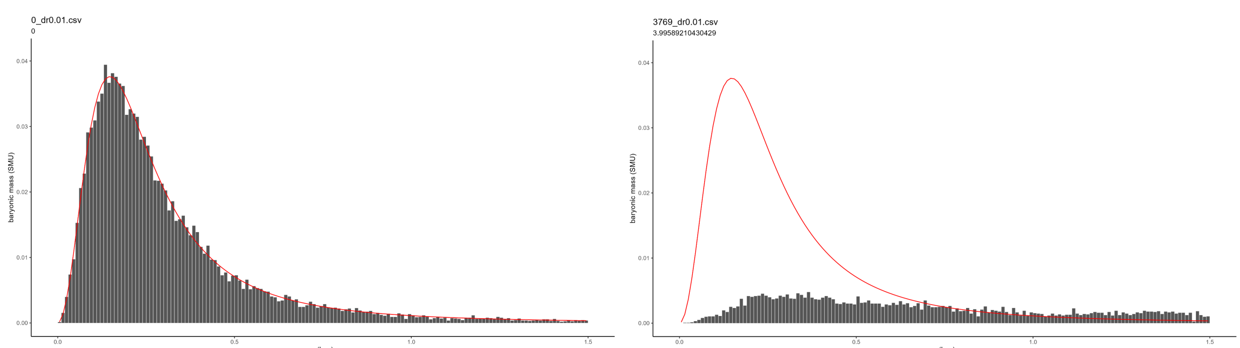



*Fig. 2 - Initial and final baryonic mass histograms of a Plummer + SIDM dwarf galaxy generated using Eric's parameters after 4.0 Gy of evolution (dr = 0.01)*

To determine whether the stability issues were unique to the SIDM code, further tests were done on the master branch using Plummer + Plummer and Plummer + NFW component dwarf galaxies:

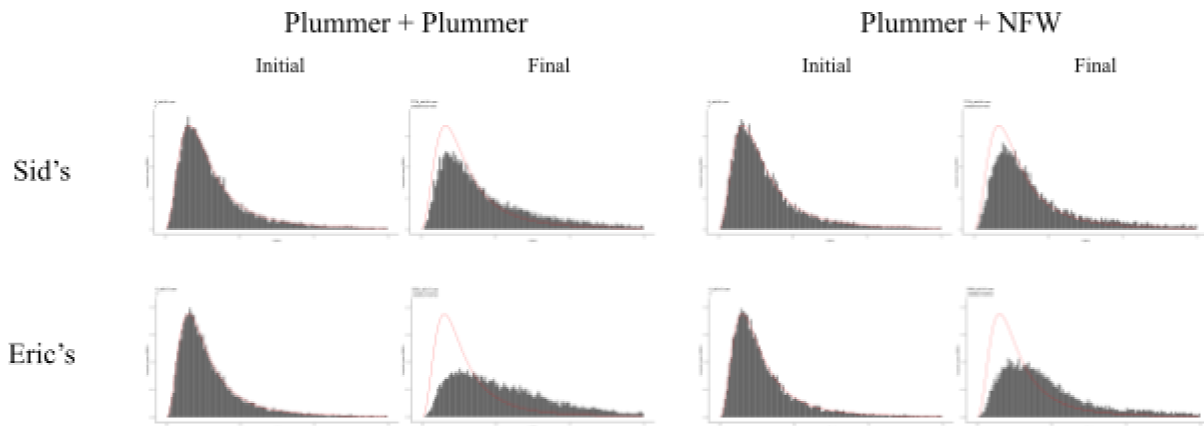



*Fig. 3 - Initial and final baryonic mass histograms of Plummer + Plummer and Plummer + NFW galaxies generated using Sid's and Eric's parameters in MilkyWay@home*

Tests were also done on a previous version (v1.80):

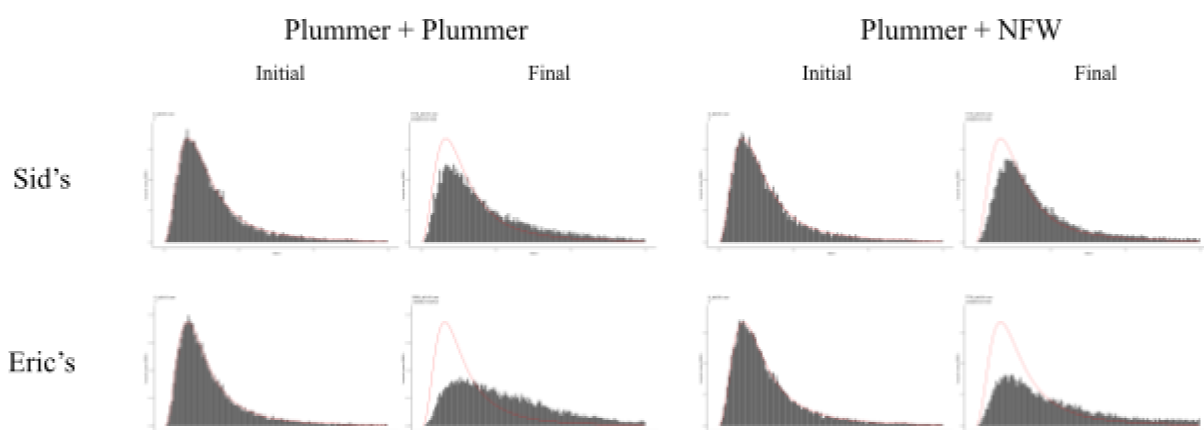



*Fig. 4 - Initial and final baryonic mass histograms of Plummer + Plummer and Plummer + NFW galaxies generated in v1.80 of MilkyWay@home*

DGs created using Plummer + Plummer and Plummer + NFW components were noted to be moderately more stable compared to their Plummer + SIDM counterparts, with the version change showing no impact on DG stability. This observation is supported by the lack of changes to the nbody_mixeddwarf.c file, which is responsible for most of DG generation.

| test | version | branch | params | components | initial | $t_{stable}$ | final |
|---|---|---|---|---|---|---|---|
| 202404132100 | current (Feb 2024) | master | Sid | plummer+plummer | ✓ | 0.5-1.0 Gy | ✓ |
| 202404141050 | v1.80 (May 2021) | master | Sid | plummer+plummer | ✓ | 0.5-1.0 Gy | ✓ |
| 202404132220 | current (Feb 2024) | master | Sid | plummer+nfw | ✓ | 0.5-1.0 Gy | ✓ |
| 202404141025 | v1.80 (May 2021) | master | Sid | plummer+nfw | ✓ | 0.5-1.0 Gy | ✓ |
| 202404021330 | current (Feb 2024) | master | Eric | plummer+plummer | ✓ | 2.5-3.0 Gy | ? |
| 202404082220 | v1.80 (May 2021) | master | Eric | plummer+plummer | ✓ | 2.5-3.0 Gy | ? |
| 202404021450 | current (Feb 2024) | master | Eric | plummer+nfw | ✓ | 2.5-3.0 Gy | ? |
| 202404082325 | v1.80 (May 2021) | master | Eric | plummer+nfw | ✓ | 2.5-3.0 Gy | ? |
| 202404131940 | current (Jan 2024) | sidm | Sid | plummer+sidm | ✓ | 1.5-2.0 Gy | ? |
| 202404072115 | current (Jan 2024) | sidm | Eric | plummer+sidm | ✓ | 3.0-3.5 Gy | ✗ |

*Fig. 5 - Summary of DG tests, each with a test ID number (date, time test was done), version/branch of MilkyWay@home the test was done on, what parameters/components were used, and the test results (further explained below).*

All galaxies were generated according to the theoretical component curves, as denoted by checkmarks (✓) in the "initial" column. After 4 Gy of evolution, a checkmark (✓) signifies that the galaxy maintained its structure with minimal deviation. A question mark (?) indicates a partial loss of structure, while a cross (✗) signifies a complete collapse of DG structure. The variable "$t_{stable}$" represents the time, measured in gigayears (Gy), it takes for a galaxy to reach an equilibrium/stability.

# 3 Causes of Instability

## 3.1 Intended Initial Instability

One cause of "instability" was previously examined by Siddhartha (2018). In section 4.1.1, he notes the following:

"After 4 Gyr of evolution, there is a significant shift in the radial profile. This is due to relaxation of the bodies in the structure, reaching an equilibrium state. As we will show … the dwarf galaxy is created very close to equilibrium. As the dwarf galaxy evolves in empty space, the virial ratio approaches one. However … the distribution maintains its general shape after 4 gigayears of evolution." [1]

By using previously collected data, Siddhartha's results have been reproduced. This replication substantiates the observed behavior of DGs generated using his parameters, providing an explanation for their dynamics.

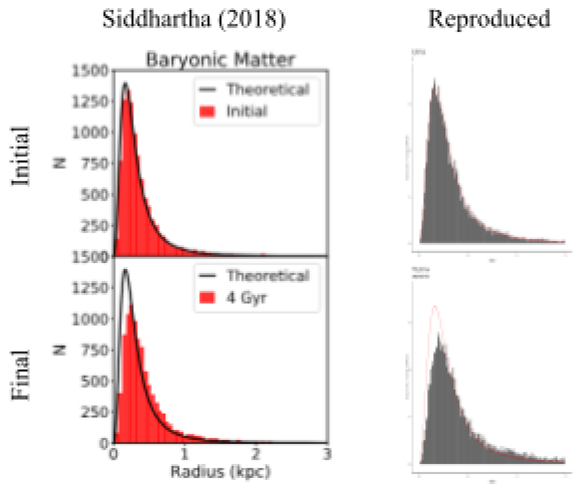



*Fig. 6 - Comparison of stability test results from Siddhartha (2018) and reproduced tests.*

## 3.2 Parameter Selection

Another prior study on DG stability examines the relationship between mass and scale radii of baryons and dark matter and overall baryon stability. The following graph, from Allen (2020), illustrates this relationship:

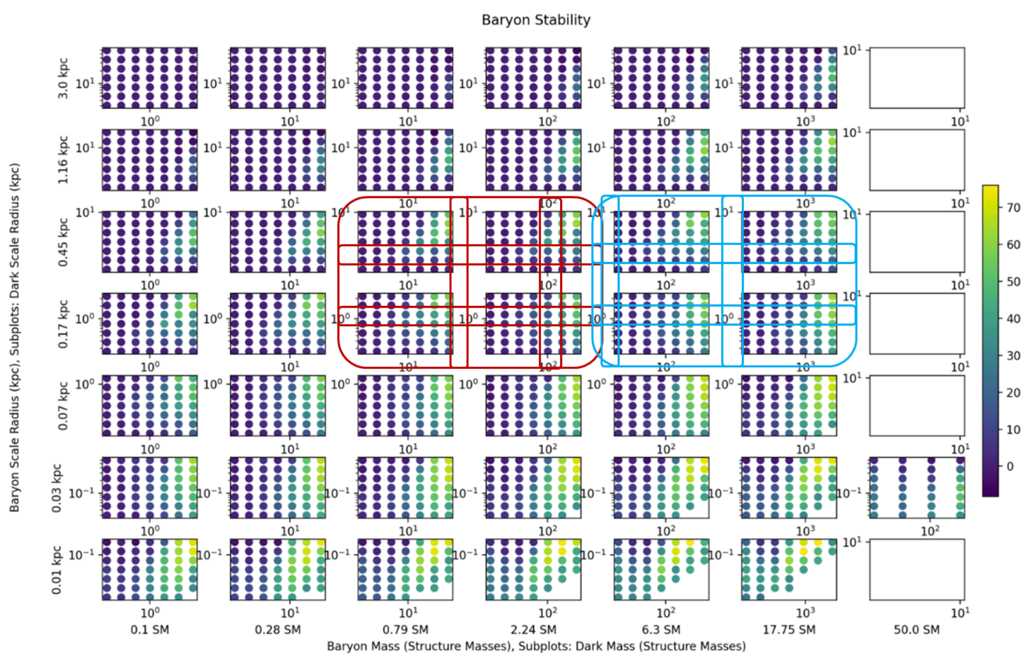



*Fig. 7 - Plot matrix relating various baryon/dark matter masses/scale radii to overall baryon stability. Baryonic mass and scale radii are used to select for specific columns/rows of plots and dark matter mass and scale radii are used to search within each plot.*

Sid's parameters—12.0 SM, 0.2 kpc (baryons), 48.0 SM, 0.8 kpc (dark matter), blue section—are well within a region of high baryon stability (0), as corroborated by previous tests. Conversely, Eric's parameters—1.22 SM, 0.181 kpc (baryons), 95.7 SM, 0.810 kpc (dark matter), red section—yield a stability score of approximately ~30-40, indicating partial stability. This is further supported by the observed partial collapse of his isolated dwarf galaxies.

### 3.2.1 New Parameters

To facilitate future testing of MilkyWay@home, new multiple sets of practical DG parameters are essential. Two papers, Valcke (2008) and González-Samaniego (2014), presented potential parameters. The paper by González-Samaniego was later excluded because I was unable to identify the amount of dark matter and the scale parameters used in their DG models. Valcke's paper proved to be more valuable; it was noted these researchers used a Sersic (Einasto) + Kuz'min Kutuzov (KK) model in their research of DG formation, evolution, and star formation.

| Run | $M_{g,i}$ | $M_{DM,i}$ | $a$ | $M_B$ | $M_V$ | $B-R$ | $M_{star}$ | % $M_{g,i}$ | % BO | $R_e$ | $\sigma_{1D,c}$ | $Z(Z_\odot)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C01 | 44 | 206 | 0.439 | −8.12 | −8.72 | 1.067 | 0.44 | 21.0 | 78.0 | 0.16 | 9.6 | 0.048 |
| C02 | 52 | 248 | 0.466 | −8.97 | −9.51 | 0.981 | 0.81 | 19.5 | 78.9 | 0.18 | 11.5 | 0.052 |
| C03 | 70 | 330 | 0.513 | −9.89 | −10.44 | 0.997 | 2.0 | 15.6 | 81.6 | 0.23 | 14.0 | 0.045 |
| C04 | 105 | 495 | 0.587 | −11.14 | −11.68 | 0.973 | 6.2 | 9.1 | 85.0 | 0.31 | 18.9 | 0.073 |
| C05 | 140 | 660 | 0.646 | −12.56 | −13.03 | 0.878 | 18 | 17.9 | 69.1 | 0.48 | 25.7 | 0.174 |
| C06 | 175 | 825 | 0.696 | −13.58 | −14.02 | 0.831 | 38 | 32.7 | 45.7 | 0.67 | 31.5 | 0.230 |
| C07 | 262 | 1238 | 0.797 | −14.20 | −14.83 | 1.105 | 122 | 36.6 | 16.5 | 0.76 | 39.3 | 0.379 |
| C08 | 349 | 1651 | 0.877 | −14.97 | −15.56 | 1.043 | 228 | 22.7 | 11.5 | 0.62 | 43.0 | 0.535 |
| C09 | 524 | 2476 | 1.004 | −15.11 | −15.77 | 1.162 | 393 | 17.4 | 6.80 | 0.57 | 46.7 | 0.620 |
| D01 | 873 | 4127 | 4.000 | −16.04 | −16.61 | 1.023 | 579 | 29.0 | 4.2 | 1.13 | 35.2 | 0.470 |
| D02 | 873 | 4127 | 6.000 | −16.37 | −16.82 | 0.843 | 488 | 39.4 | 4.4 | 1.26 | 30.9 | 0.373 |

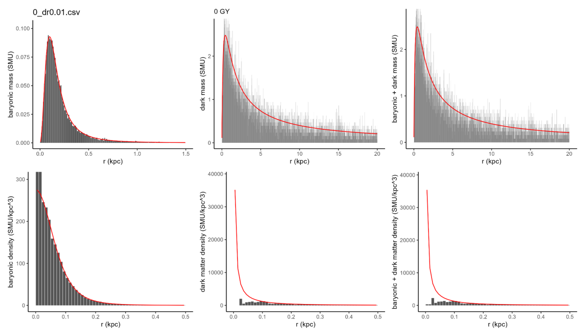
*Notes.* (1) Model name, (2) Initial gas mass ($10^6$ $M_\odot$), (3) Initial dark matter mass ($10^6$ $M_\odot$), (4) $a$ for the DM halo (kpc) (see equation 21), (5) Absolute magnitude in the blue band, (6) Absolute magnitude in the visual band, (7) $B-R$, (8) Total final star mass ($10^6$ $M_\odot$), (9) Percentage of initial gas mass remaining (<30 kpc), (10) Percentage of gas blown out (>30 kpc), (11) Half-light radius (kpc), (12) 1D central velocity dispersion (km $s^{-1}$) and (13) Metallicity ($Z_\odot$ = 0.02).

*Fig. 8 - Table of various model DG parameters from Valcke (2008).*

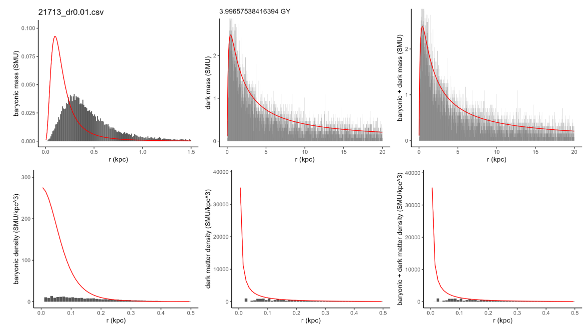
Parameters from the $M_{star}$ and $R_e$ $(1.3R_s)$, and $M_{DM,i}$ and $a$ columns are used to calculate inputs for baryonic Plummer and dark matter NFW components, respectively. The following are stability test results for each model DG:

# C01

Initial

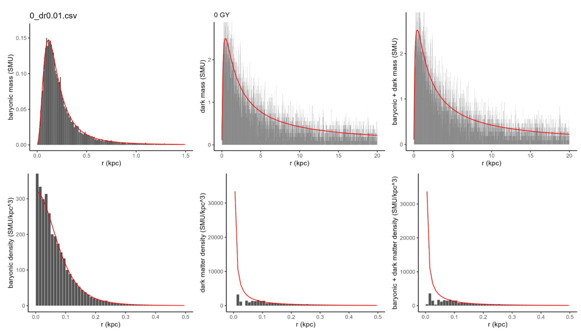



Final

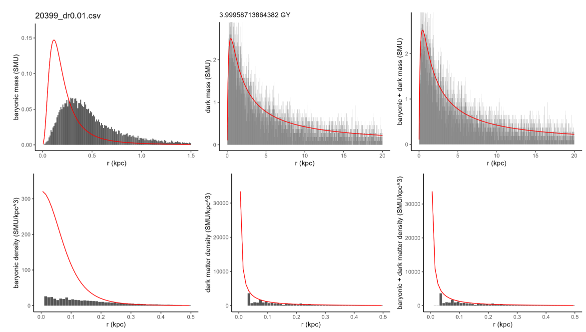



# C02

Initial

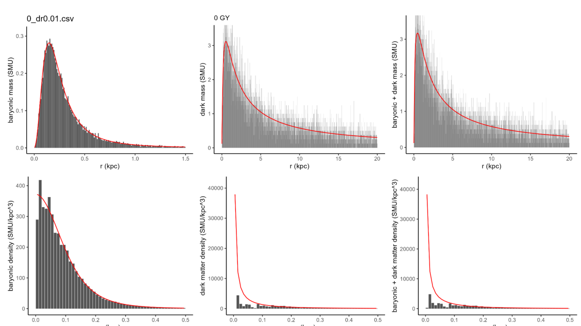



Final

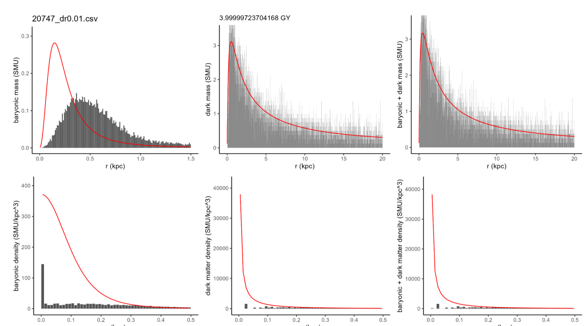



# C03

Initial

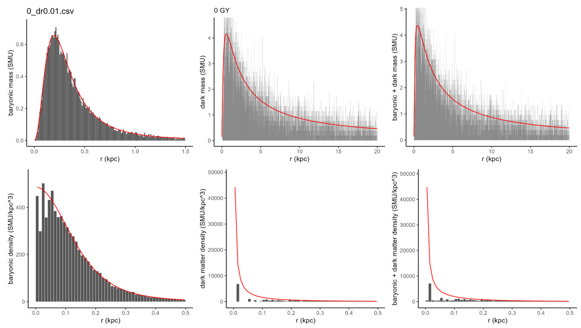



Final

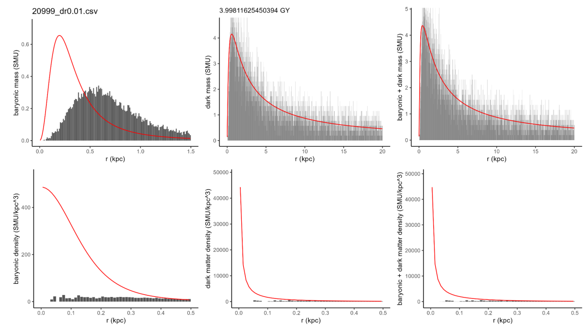


## C04

### Initial

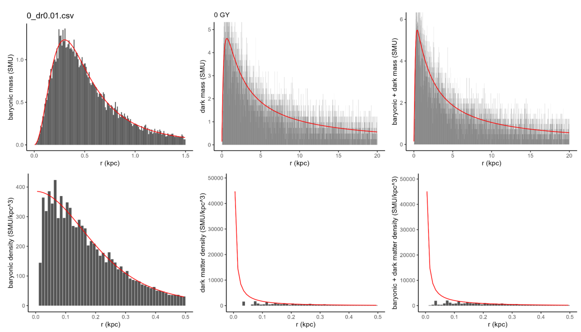



### Final

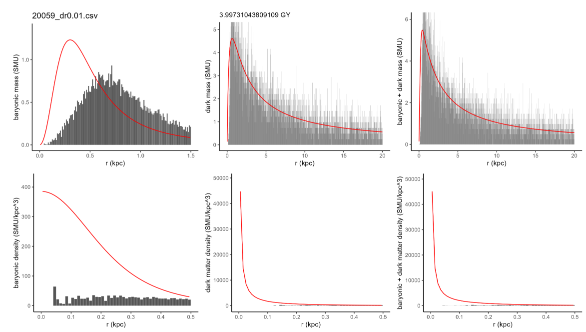



## C05

### Initial

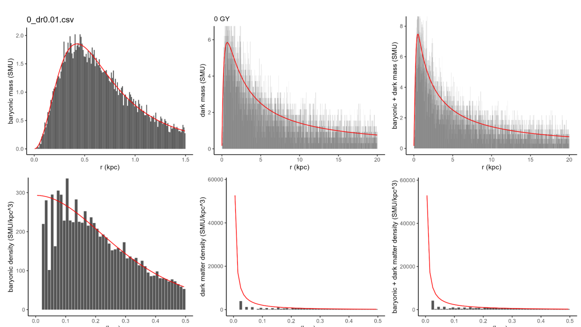



### Final

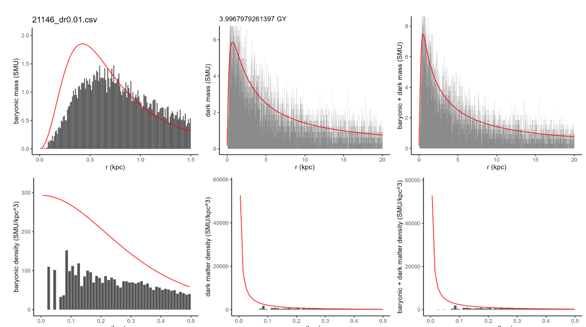



## C06

### Initial

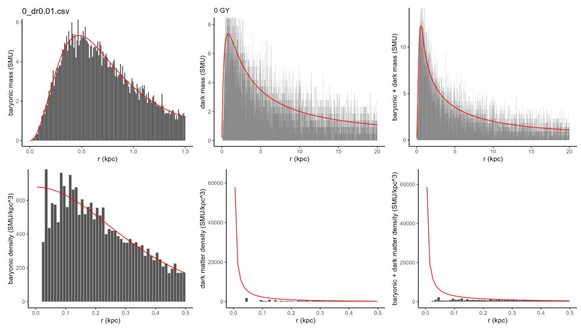



### Final



# C07

Initial



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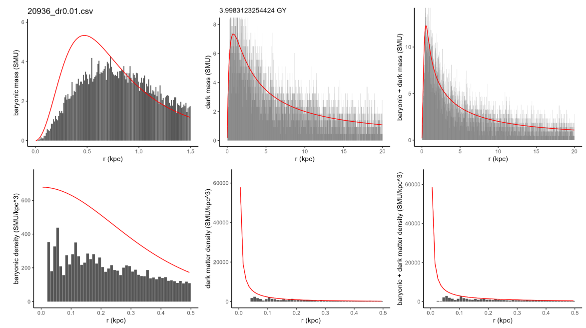
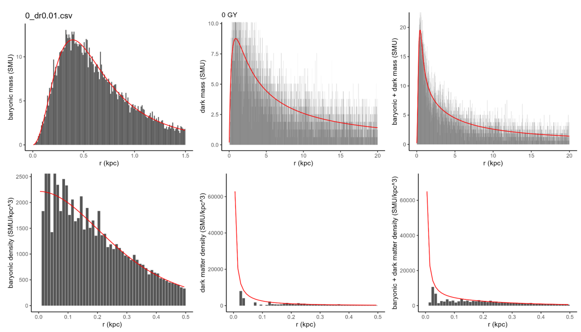
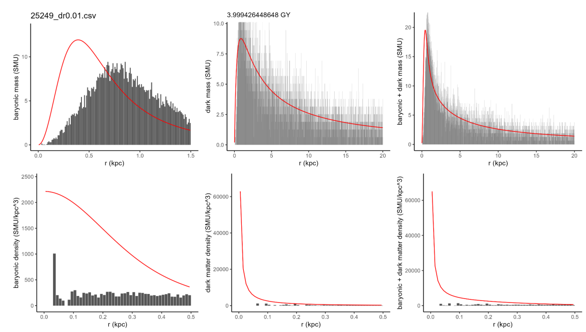


# C08

Initial

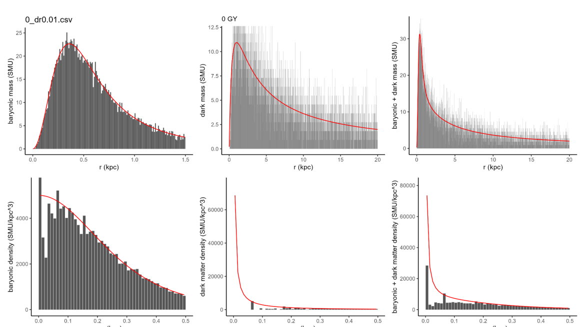


Final



# C09

Initial



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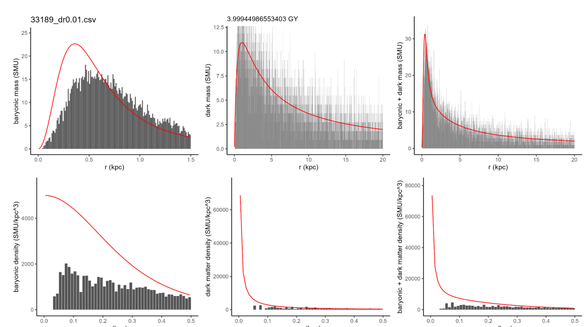
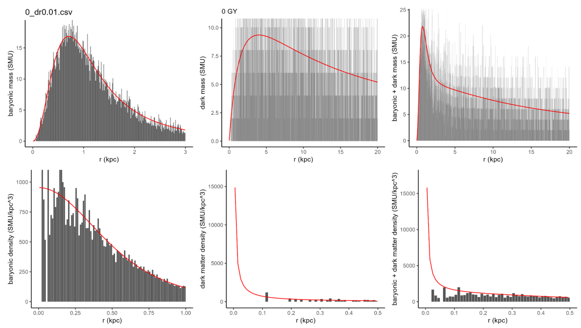
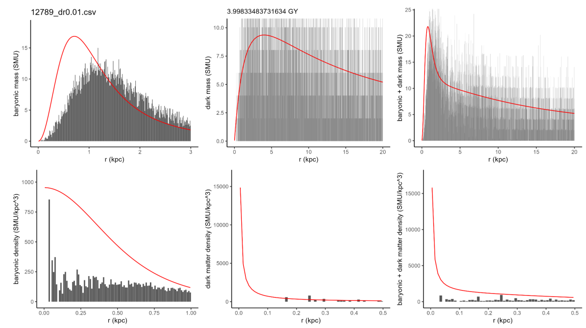


**D01**

Initial

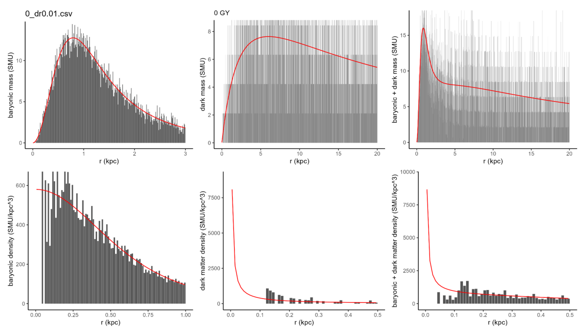



Final

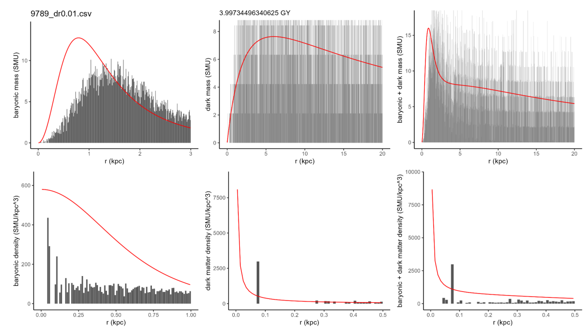



**D02**

Initial




Final




**Summary**

| DG | I | $t_{stable}$ | F |
|---|---|---|---|
| C01 | ✓ | 0.5-1.0 Gy | ? |
| C02 | ✓ | 0.5-1.0 Gy | ? |
| C03 | ✓ | 0.5-1.0 Gy | ? |
| C04 | ✓ | 0.5-1.0 Gy | ? |
| C05 | ✓ | 0.0-0.5 Gy | ? |
| C06 | ✓ | 0.0-0.5 Gy | ✓ |

| DG | I | $t_{stable}$ | F |
|---|---|---|---|
| C07 | ✓ | 0.0-0.5 Gy | ✓ |
| C08 | ✓ | 0.0-0.5 Gy | ? |
| C09 | ✓ | 0.0-0.5 Gy | ✓ |
| D01 | ✓ | 0.5-1.0 Gy | ? |
| D02 | ✓ | 0.5-1.0 Gy | ? |
| | | | |

# 4 Conclusions and Future Work

The stability of dwarf galaxies in the MilkyWay@home is influenced by a variety of factors. Some initial instability is to be expected within reasonable bounds. DGs are to be generated to match the theorized curves, reach an equilibrium state that deviates minimally from the theoretical curve, and additionally do so in a reasonable timeframe (e.g. maximum 1 Gy). The specific parameters that are used are a large factor in determining the stability of the DG. Please refer to figure 7 to quickly assess if your DG is likely to be stable. With these factors accounted for, the issue of dwarf galaxy stability has been isolated to the SIDM branch/code, which should be the focus of future investigation.

# 5 References

[1] S. Shelton, Constraining Dwarf Galaxy Properties Using Tidal Streams, December 2018, https://milkyway.cs.rpi.edu/milkyway/publications/Sid_thesis.pdf

[2] W. Allen, Predicting Dwarf Stability, August 2020

[3] S. Valcke, S. De Rijcke, H. Dejonghe, Simulations of the formation and evolution of isolated dwarf galaxies, Monthly Notices of the Royal Astronomical Society, Volume 389, Issue 3, September 2008, Pages 1111–1126, https://doi.org/10.1111/j.1365-2966.2008.13654.x

[4] A. González-Samaniego et al 2014 ApJ 785 58 (https://iopscience.iop.org/article/10.1088/0004-637X/785/1/58)

# 6 Appendix

Default/Sid's parameters used:

evolveTime: = 4.0 Gy
time_ratio = 1.0
rscale_l = 0.2 kpc
light_r_ratio = 0.2
mass_l = 12.0 SM
light_mass_ratio = 0.2
sigma (SIDM only) = 0.2

Eric's parameters used:

evolveTime = 4.0 Gy
time_ratio = 1.0
rscale_l = 0.181216 kpc
light_r_ratio = 0.182799
mass_l = 1.22251 SM
light_mass_ratio = 0.0126171
sigma (SIDM only) = 0.2

Copies and other versions of this report (along with other resources) can be accessed at https://github.com/Ascilius/DGA