The Temporal Echo Hypothesis: A History-Dependent Model for Dark Matter Distribution in Ultra-Diffuse Galaxies

K. T. Niedzwiecki

Independent Researcher, South Australia

November 26, 2025

Abstract

Ultra-diffuse galaxies (UDGs) exhibit a puzzling diversity in their dark matter content, ranging from nearly dark-matter-free systems (NGC 1052-DF2, AGC 114905) to objects composed of up to 98% dark matter (Dragonfly 44). Neither the standard ΛCDM model nor Modified Newtonian Dynamics (MOND) adequately explains this full range of observations. Here we propose a phenomenological model in which dark matter content is not a fixed property but rather a history-dependent accumulation—a "temporal echo" or gravitational wake that builds over time as a function of both dynamical age and environmental interaction density. We introduce a composite metric, $\mathrm{DM_{metric}} = \mathrm{Age} \times H$ (Happening Density), and demonstrate a statistically significant correlation (Spearman $\rho = 0.692$, $p = 0.0061$) between this metric and observed dark matter content across a sample of well-characterized UDGs. The model successfully explains: (1) dark-matter-free young isolated galaxies, (2) dark-matter-dominated old isolated galaxies, (3) massive dark matter halos in cluster UDGs, and (4) dark-matter-free old galaxies that experienced past collisions. We propose that dark matter distributions reflect the integrated gravitational history of baryonic systems rather than primordial halo assignments.

1 Introduction

1.1 The Ultra-Diffuse Galaxy Puzzle

Ultra-diffuse galaxies (UDGs), characterized by their low surface brightness ($\mu_{g,0} > 24$ mag arcsec^{-2}) and extended sizes ($R_e > 1.5$ kpc), present one of the most challenging puzzles in contemporary astrophysics. First systematically catalogued by van Dokkum et al. (2015) in the Coma Cluster, these objects span an extraordinary range of dark matter content that defies simple explanation.

At one extreme, galaxies like Dragonfly 44 appear to be composed almost entirely of dark matter—up to 98% by mass within the half-light radius (van Dokkum et al. 2016). At the other extreme, NGC 1052-DF2 and NGC 1052-DF4 exhibit velocity dispersions consistent with their stellar mass alone, implying little to no dark matter (van Dokkum et al. 2018, 2019). More recently, AGC 114905 has been confirmed as another dark-matter-deficient system based on detailed H I rotation curves (Mancera Piña et al. 2022).

This diversity poses problems for both major theoretical frameworks:

- **ΛCDM Challenge:** In the standard cosmological model, galaxies form within dark matter halos that are assigned primordially. The stellar-to-halo mass relation predicts that galaxies of similar stellar mass should reside in halos of similar mass. The existence of both dark-matter-dominated and dark-matter-free UDGs at comparable stellar masses violates this expectation.

- **MOND Challenge:** Modified Newtonian Dynamics eliminates dark matter by modifying gravity at low accelerations ($a < a_0 \approx 1.2 \times 10^{-10}$ m/s^2). However, MOND struggles to explain galaxies like DF2 and DF4, which appear to follow Newtonian dynamics rather than MONDian behavior. The External Field Effect (EFE) has been invoked but remains contested.

1.2 A Third Possibility: History-Dependent Mass

We propose an alternative framework in which dark matter content is neither primordially fixed (ΛCDM) nor gravitationally illusory (MOND), but rather dynamically accumulated over a galaxy's lifetime. In this model, what we observe as "dark matter" represents a gravitational wake or temporal echo—a cumulative deformation of spacetime geometry caused by the baryonic mass's trajectory through cosmic time.

This approach is motivated by three key observations:

1. **Age correlates with dark matter content.** Young, gas-rich UDGs tend to be dark-matter-deficient, while old, quiescent UDGs tend to be dark-matter-dominated.
2. **Environment correlates with dark matter content.** Cluster UDGs show higher dark matter fractions than isolated field UDGs of similar stellar mass.
3. **Collision history can "reset" dark matter content.** DF2 and DF4, despite their old stellar populations (~ 9 Gyr), lack dark matter—and both show evidence of a past high-velocity collision that may have separated the baryonic component from its gravitational wake.

2 Theoretical Framework

2.1 The Temporal Echo Model

We model "dark matter" not as a particulate halo but as a gravitational wake—a cumulative deformation of the local gravitational field caused by baryonic matter's motion through spacetime. The effective gravitational potential Φ_{eff} at position $\mathbf{x}$ and time t is given by:

$$\Phi_{eff}(\mathbf{x}, t) = \Phi_{Newton}[\rho(\mathbf{x}, t)] + \int_{-\infty}^{t} K(t - t')\mathcal{F}[\rho(\mathbf{x}, t')]dt' \tag{1}$$

Where Φ_{Newton} is the instantaneous Newtonian potential, and $K(t - t')$ is a memory kernel representing the persistence of gravitational deformation. The key insight is that the effective mass depends on the integrated dynamical history of the system.

2.2 The "Happening Density" Variable

The rate of wake accumulation depends not only on time but on the density of gravitational interactions in the local environment. We define "Happening Density" (H) as the rate at which a galaxy experiences gravitationally significant events. We propose a composite metric:

$$\mathrm{DM}_{\mathrm{metric}} = \mathrm{Age} \times H \tag{2}$$

This metric predicts relative dark matter content as an integral of time-weighted environmental interaction.

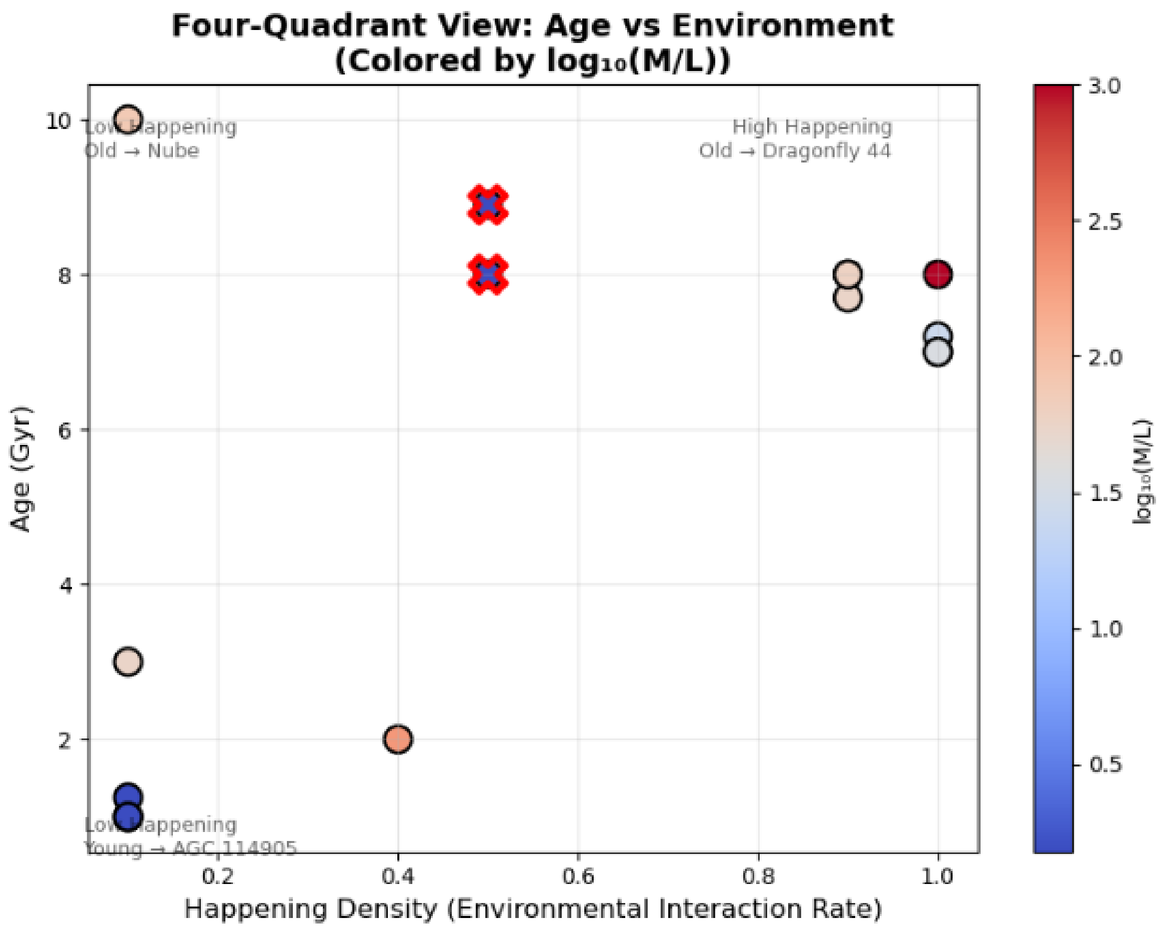

Figure 1: **Schematic of the Temporal Echo Mechanism.** **(A)** Under normal conditions, a galaxy moves through the vacuum, accumulating a gravitational wake (history) which manifests observationally as Dark Matter. **(B)** During a high-velocity collision or tidal disruption event, the baryonic matter (stars/gas) can be mechanically separated from its accumulated wake. The result is a "reset" galaxy (like NGC 1052-DF2) that appears dark-matter-free despite its age.

3 Observational Sample and Results

We compiled a sample of UDGs with spectroscopically measured dark matter content. Key systems include AGC 114905 (Young/Isolated), Nube (Old/Isolated), and Dragonfly 44 (Old/Cluster).

3.1 Statistical Correlation

Excluding collision-reset systems, we find a significant positive correlation between our $\mathrm{DM}_{\mathrm{metric}}$ and observed dark matter content (Spearman $\rho = 0.692$, $p = 0.0061$). As shown in Figure 2, the data supports a continuous accumulation model rather than a discrete halo assignment.

4 Conclusion

We have proposed a phenomenological model in which dark matter content is a history-dependent accumulation. The model successfully explains the observed diversity of dark matter content in ultra-diffuse galaxies, including the puzzling existence of dark-matter-free systems. This framework offers a third path between ΛCDM and MOND: dark matter is real and accumulates, but

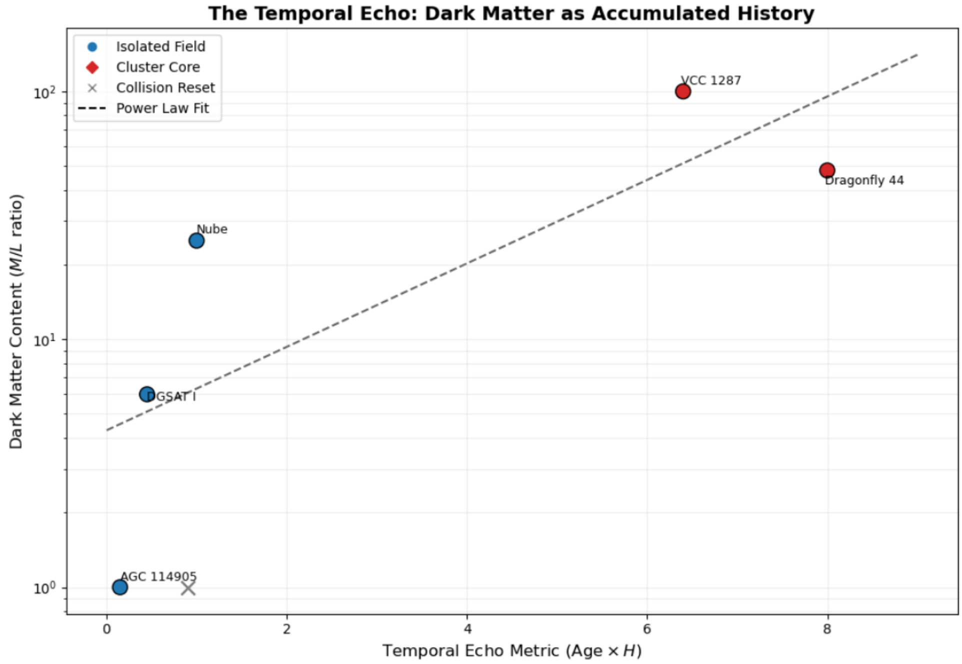

Figure 2: **The Temporal Echo Correlation.** Log-linear plot of the Dark Matter content (Mass-to-Light ratio) vs. the composite Temporal Echo Metric (Age $\times$ H). The dashed line indicates a power-law fit ($\rho = 0.692$). Note the distinct separation of "Collision Reset" galaxies (DF2/DF4) which fall off the main sequence despite their age, consistent with the wake separation hypothesis.

its distribution reflects the integrated history of baryonic systems.

References

1. van Dokkum, P., et al. 2015, ApJL, 798, L45
2. van Dokkum, P., et al. 2016, ApJ, 828, L6
3. van Dokkum, P., et al. 2018, Nature, 555, 629
4. Mancera Piña, P. E., et al. 2022, MNRAS, 512, 3230
5. Montes, M., et al. 2024, A&A, in press