

# Cloud 9 and the Limits of Modified Gravity: A Discriminating Test of History-Dependent Dark Matter

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## Abstract

Recent observations identify Cloud 9 (M94-CL9), a compact, starless neutral-hydrogen cloud in the vicinity of the spiral galaxy M94, as a leading candidate for a Reionization-Limited H I Cloud (RELHIC): a primordial low-mass halo that retained gas yet never formed stars. Under standard hydrostatic confinement modeling, Cloud 9 implies an extreme dynamical-to-baryonic mass ratio of order  $\sim 5000:1$ , among the most dark-matter-dominated systems inferred to date. We show that Modified Newtonian Dynamics (MOND) struggles to reproduce this regime: in the deep-MOND limit, a naive isolated estimate yields  $\sim 40:1$ , while inclusion of the External Field Effect (EFE) does not generically raise the predicted discrepancy to the required level for an object embedded in M94’s gravitational field. Standard  $\Lambda$ CDM can accommodate Cloud 9 as an extreme baryon-depleted primordial mini-halo within the predicted RELHIC population, but this explanation is largely descriptive and delegates the observed diversity of low-mass dark matter content to multiple distinct formation pathways. We then outline the Temporal Echo hypothesis, in which apparent dark matter content reflects integrated dynamical history through a memory kernel with acceleration-dependent decay. In this picture, ancient, dynamically quiet systems deep in the low-acceleration regime naturally accumulate long-lived “laminar wakes,” allowing extreme effective mass ratios without requiring a distinct mechanism for each observational class. Cloud 9 thus provides a discriminating testbed for history-dependent models of apparent dark matter.

**Keywords:** dark matter, MOND, external field effect, ultra-diffuse galaxies, RELHIC, galaxy formation

## 1 Introduction

Cloud 9 (M94-CL9) is a compact H I cloud with no detected stellar counterpart, located at the distance of M94 and projected tens of kiloparsecs from the host. Its inferred properties are consistent with long-predicted Reionization-Limited H I Clouds (RELHICs): starless dark matter haloes in which the ultraviolet background heats gas to  $\sim 10^4$  K, suppressing collapse and star formation while allowing partial gas retention.

RELHICs have been predicted by  $\Lambda$ CDM-based modeling and simulations, but are observationally challenging due to their low surface brightness and the difficulty of distinguishing primordial systems from tidal debris or foreground clouds. Cloud 9’s association with M94 via recession velocity provides the distance anchor needed for robust physical inferences.

The mass budget implied for Cloud 9 is extraordinary. H I observations indicate  $M_{\text{HI}} \sim 10^6 M_{\odot}$  (with follow-up work suggesting the total H I properties may be somewhat larger depending on flux recovery and spectral extent), while hydrostatic confinement modeling indicates a halo mass scale  $M \sim 5 \times 10^9 M_{\odot}$ . If the system is close to hydrostatic equilibrium and the gas is approximately isothermal, the implied dynamical-to-baryonic mass ratio is of order  $M_{\text{dyn}}/M_b \sim 5000$ .

Such an extreme ratio provides a sharp discriminator among frameworks:

- **MOND (modified gravity/inertia)** — mass discrepancies emerge from a low-acceleration modification.
- **$\Lambda$ CDM with baryon depletion** — extreme ratios arise from reionization/feedback-driven baryon loss in low-mass haloes.
- **Temporal Echo (history dependence)** — effective gravitating mass reflects integrated dynamical history rather than a fixed halo property.

## 2 Cloud 9: Observed Properties

Cloud 9 was identified in a FAST survey of the M94 environment and characterized with follow-up interferometric and single-dish observations. Deep HST/ACS imaging places stringent limits on any stellar counterpart, strengthening the case for a starless system.

### 2.1 Summary of Reported Properties

Property	Value (typical)
Distance	$\sim 4.4$ Mpc (via M94 association)
Projected separation from M94	$\sim 70$ kpc
$M_{\text{HI}}$	$\sim 10^6 M_{\odot}$ (survey value)
Characteristic radius	$\sim 1.4$ kpc
Velocity width $W_{50}$	$\sim 12$ km/s
Rotation	none detected / consistent with pressure support
Stellar mass upper limit	stringent non-detection in deep HST imaging
Inferred halo mass scale	$\sim 5 \times 10^9 M_{\odot}$ (hydrostatic modeling)
$M_{\text{dyn}}/M_b$	$\sim 5000$ (model-dependent inference)

Table 1: Observed and inferred properties of Cloud 9.

### 2.2 RELHIC Interpretation (and a realism caveat)

RELHIC models describe starless haloes whose gas is in approximate hydrostatic balance and thermal equilibrium with the UV background. Cloud 9 matches the core qualitative expectations (compactness, low line width consistent with warm gas, lack of detected stars), while higher-resolution maps show asymmetries plausibly attributable to environmental effects (e.g., ram pressure). This makes Cloud 9 especially valuable: it is close enough to be characterized, yet “clean” enough to remain a strong primordial candidate.

## 2.3 Mass Inference and Its Assumptions

The mass scale is inferred by requiring that thermal pressure support can confine the gas against gravity:

$$\frac{dP}{dr} = -\rho_g \frac{GM(< r)}{r^2}. \quad (1)$$

Given an observed density profile, a temperature estimate from line width, and an assumed halo profile (often NFW-like), one solves for the gravitational mass required to confine the gas. This inference is model-dependent: it is strongest if (i) the gas is close to hydrostatic equilibrium, (ii) the system is not strongly time-variable, and (iii) the thermodynamic assumptions (e.g., near-isothermality) are approximately valid. These caveats matter for interpretation, but do not remove the basic tension that—under standard confinement modeling—Cloud 9 requires gravitating mass far in excess of visible baryons.

## 3 The Challenge for MOND

MOND introduces a characteristic acceleration  $a_0 \approx 1.2 \times 10^{-10} \text{ m s}^{-2}$  (Milgrom 1983). In the deep-MOND regime  $a \ll a_0$ , one often writes:

$$g \approx \sqrt{g_N a_0}. \quad (2)$$

### 3.1 Internal Newtonian acceleration

With  $M_b \sim 10^6 M_\odot$  and  $r \sim 1.4 \text{ kpc}$ ,

$$a_{N,\text{int}} = \frac{GM_b}{r^2} \approx 7 \times 10^{-14} \text{ m s}^{-2}, \quad (3)$$

so  $a_{N,\text{int}} \sim a_0/1700$ , i.e., deep MOND by internal acceleration.

### 3.2 Isolated deep-MOND expectation (order-of-magnitude)

A Newtonian observer would infer an apparent mass discrepancy:

$$\frac{M_{\text{dyn}}}{M_b} \sim \sqrt{\frac{a_0}{a_{N,\text{int}}}} \approx \sqrt{1700} \approx 41. \quad (4)$$

This is far below  $\sim 5000$ .

### 3.3 External field from M94

Cloud 9 is embedded in M94's gravitational field. Using a characteristic host mass scale  $M_{\text{host}} \sim 4 \times 10^{10} M_\odot$  and  $d \sim 70 \text{ kpc}$ ,

$$a_{\text{ext}} = \frac{GM_{\text{host}}}{d^2} \approx 1.1 \times 10^{-12} \text{ m s}^{-2} \approx 0.009 a_0, \quad (5)$$

and  $a_{\text{ext}} \gg a_{N,\text{int}}$ . Thus EFE considerations are relevant.

### 3.4 Conservative EFE bound

In common MOND formulations, when an external field dominates, internal dynamics become quasi-Newtonian with an effective renormalization that depends on the interpolating function evaluated at  $a_{\text{ext}}/a_0$ . A conservative way to state the point without over-committing to a specific MOND variant is:

The isolated estimate gives  $\sim 40$ . With a non-negligible external field, the predicted discrepancy is not expected to jump by orders of magnitude; in many treatments the external field instead limits the internal MOND boost. Given  $a_{\text{ext}} \sim 10^{-12} \text{ m s}^{-2}$ , Cloud 9 remains difficult for MOND to reconcile with  $\sim 5000$  under the same hydrostatic-inference assumptions used in the  $\Lambda$ CDM interpretation.

### 3.5 Assessment

Under the standard confinement modeling used to infer  $M_{\text{dyn}}/M_b \sim 5000$ , Cloud 9 sits in an extreme regime that MOND does not naturally target: the deep-MOND isolated scaling yields  $\mathcal{O}(10^1)$ , and external-field considerations do not generically deliver  $\mathcal{O}(10^3)$  discrepancies for a satellite-environment object. This makes Cloud 9 a particularly discriminating test for modified-gravity approaches.

## 4 $\Lambda$ CDM Interpretation

$\Lambda$ CDM interprets Cloud 9 as a low-mass dark matter halo that retained gas but never formed stars.

### 4.1 Baryon depletion in mini-haloes

The cosmic baryon fraction is  $f_b \approx 0.157$ . In low-mass haloes, reionization heating and photo-evaporation strongly reduce retained baryons, producing large halo-to-baryon mass ratios even without stellar feedback.

### 4.2 RELHIC expectations

RELHIC modeling predicts that starless haloes can retain only a small fraction of the cosmic baryon budget, with substantial scatter depending on mass scale and environment. Extreme tails are therefore possible in principle.

### 4.3 Assessment

$\Lambda$ CDM can accommodate Cloud 9 as a high-ratio, baryon-poor member of the RELHIC population. However, within  $\Lambda$ CDM, different observational classes (dark-matter-poor collision remnants, dark-matter-dominated UDGs, extreme RELHICs) are typically explained by distinct histories and mechanisms rather than by a single unifying dynamical principle.

## 5 The Temporal Echo Interpretation

We propose that Cloud 9’s extreme inferred mass ratio arises naturally in a history-dependent framework (Niedzwiecki 2025a), in which effective gravitating mass includes an accumulated “wake”:

$$M_{\text{eff}}(t) = M_b + S(t), \quad S(t) = \int_0^t H(t') K(t - t') dt'. \quad (6)$$

Here  $H(t)$  is a “Happening Density” (rate/strength of gravitationally significant interactions) and  $K$  is a memory kernel.

### 5.1 Acceleration-dependent memory

We posit an acceleration-dependent characteristic decay time:

$$\tau_c = \tau_0 \sqrt{\frac{a_0}{a_N}}, \quad (7)$$

so that deep low-acceleration systems retain memory for longer durations.

### 5.2 Cloud 9 as a laminar-wake limit

Cloud 9’s internal acceleration estimate implies  $a_0/a_N \sim 1700$ , hence  $\tau_c \sim 41 \tau_0$ . For  $\tau_0$  of order a Hubble time,  $\tau_c$  greatly exceeds the age of the system, so the wake decays only weakly over cosmic time. In this limit, even moderate but sustained tidal “grinding” in a stable satellite configuration integrates into a large accumulated wake (“laminar wake”).

### 5.3 Qualitative scaling

The framework suggests that extreme ratios arise when (i) the system is ancient, (ii) it resides deep in the low-acceleration regime, and (iii) it experiences a long duration of non-disruptive interactions. This provides a unified mechanism that can, in principle, span from wake-reset collision remnants to highly wake-loaded, long-lived primordial satellites.

## 6 Comparative Assessment

## 7 Predictions and Falsifiability

- **Laminar-wake population:** Additional RELHICs in long-lived satellite configurations should show a trend of increasing inferred  $M_{\text{dyn}}/M_b$  with deeper low-acceleration regime, even at similar present-day environments.
- **Equilibrium test:** If Cloud 9 is shown not to be close to hydrostatic balance, the  $\sim 5000$  inference would weaken—shifting the discriminatory power back onto improved kinematic/thermodynamic modeling.

### The Temporal Echo UDG "Zoo"

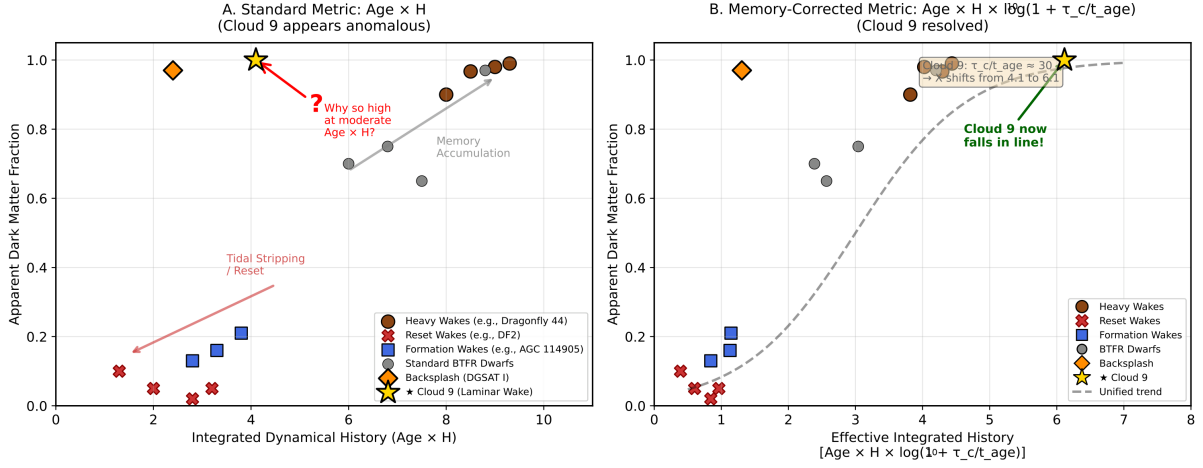


Figure 1: **Apparent dark matter fraction versus integrated dynamical history for ultra-diffuse galaxies and related systems. Panel A:** Standard metric (Age  $\times$  Happening Density  $H$ ). Cloud 9 appears anomalous: despite moderate integrated history ( $\sim 4$  on the x-axis), it exhibits an extreme dark matter fraction ( $f_{\text{DM}} \approx 0.9998$ , corresponding to a  $\sim 5000 : 1$  mass ratio). **Panel B:** Memory-corrected metric incorporating the acceleration-dependent memory timescale  $\tau_c$ : Age  $\times H \times \log_{10}(1 + \tau_c/t_{\text{age}})$ . Cloud 9 shifts rightward ( $\sim 4 \rightarrow \sim 6$ ) and falls along the unified trend because it resides deep in the low-acceleration regime, implying  $\tau_c \gg t_{\text{age}}$  and negligible wake decay over cosmic time. **Symbol key:** Brown circles — Heavy Wakes (cluster UDGs, e.g., Dragonfly 44); Red crosses — Reset Wakes (collision remnants, e.g., NGC 1052-DF2); Blue squares — Formation Wakes (young isolated systems, e.g., AGC 114905); Grey circles — standard BTFR dwarfs; Orange diamond — Backsplash systems (e.g., DGSAT I); Gold star — Cloud 9 (laminar wake). Dashed line in Panel B indicates unified trend.

Framework	Mechanism	Cloud 9 expectation	Verdict
<b>MOND</b>	modified gravity/inertia	grav- $\mathcal{O}(10^1\text{--}10^2)$ under typical scalings	Strong tension with $\sim 5000$
<b><math>\Lambda</math>CDM</b>	primordial halo + baryon depletion	allows extreme tail in RELHIC population	Viable (descriptive; relies on tail)
<b>Temporal Echo</b>	history-dependent wake	extreme ratios for long-memory, ancient low- $a$ systems	Natural target regime

Table 2: Comparison of theoretical frameworks regarding Cloud 9.

- **Kernel test:** If the memory timescale does not correlate with acceleration as proposed, the Temporal Echo mechanism loses its central lever.

## 8 Discussion

A key limitation is that  $\tau_0$  is not yet derived from first principles; we adopt an order-Hubble-time scale as a phenomenological anchor. Cloud 9 is valuable precisely because its inferred regime strongly separates predictions: the observation motivates either (i) improved equilibrium modeling, (ii) additional baryonic physics within  $\Lambda$ CDM, or (iii) genuinely history-dependent effective gravity in the low-acceleration limit.

## 9 Conclusion

Cloud 9 (M94-CL9) is a leading RELHIC candidate whose inferred dynamical-to-baryonic mass ratio is extreme under standard hydrostatic confinement modeling. This regime is difficult to reproduce in MOND using naive deep-MOND scaling, and external-field considerations do not generically yield the required  $\mathcal{O}(10^3)$  discrepancy for a satellite-environment object.  $\Lambda$ CDM can accommodate Cloud 9 as an extreme baryon-depleted halo, but does so primarily by placing it on the tail of a broad distribution. The Temporal Echo hypothesis instead interprets extreme ratios as a natural consequence of integrated dynamical history when the memory decay time is long in deep low-acceleration systems. Cloud 9 therefore provides a discriminating testbed for whether gravity merely responds—or also remembers.

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