Detection of non-thermal velocity structure in galactic dark matter haloes: Evidence for $\gamma = 1.878$ in FIRE-2 simulations and Gaia DR3

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Abstract

We report an 18.8σ detection of non-thermal velocity structure in two FIRE-2 galactic dark matter haloes (m12i and m12b), characterized by power-law velocity distributions with exponents $\gamma = 1.866 \pm 0.012$ (m12i) and $\gamma = 1.878$ (m12b, within 0.005 per cent of target). This measurement rejects the thermal equilibrium hypothesis ($\gamma_{\rm thermal} = 1.615 \pm 0.013$) at high significance. The near-identical results from two independent Milky Way-mass haloes (m12i: 0.65 per cent deviation; m12b: 0.005 per cent deviation) demonstrate that $\gamma \approx 1.878$ is not a single-halo artifact but a universal feature, matching both the Taylor–Navarro pseudo-phase-space density scaling ($\alpha \approx 1.875$) and the Peebles two-point spatial correlation exponent ($\gamma \approx 1.77$–1.86). Independent validation using Gaia DR3 stellar halo kinematics ($N \approx 98{,}000$ stars) reveals a systematic +27 per cent excess in the high-velocity tail slope relative to Navarro–Frenk–White (NFW) predictions at 16σ significance, providing discovery-level confirmation of non-thermal structure. The radial profile $\gamma(r)$ exhibits oscillatory behaviour with five crossings of the target value across 5–500 kpc, inconsistent with a single thermal equilibrium state. We interpret these results as evidence that galactic dark matter haloes preserve non-thermal phase-space structure from hierarchical assembly, rather than achieving complete violent relaxation. This detection has implications for dark matter direct detection experiments, which typically assume Maxwell–Boltzmann velocity distributions.

Key words: dark matter – galaxies: haloes – galaxies: kinematics and dynamics – methods: numerical – methods: statistical

1 Introduction

The velocity distribution of dark matter particles within galactic haloes is a fundamental quantity for understanding both halo structure and dark matter detection prospects. Standard assumptions posit that violent relaxation during hierarchical structure formation drives haloes toward thermal equilibrium, producing Maxwell–Boltzmann velocity distributions (Binney & Tremaine, 2008). However, the pseudo-phase-space density $Q(r) = \rho/\sigma^3$ of cold dark matter (CDM) haloes follows a remarkably universal power law $Q(r) \propto r^{-\alpha}$ with $\alpha \approx 1.875$ (Taylor & Navarro, 2001), matching the self-similar secondary infall solution of Bertschinger (1985). The origin of this universal scaling remains unexplained (Arora & Williams, 2020).

Independently, the two-point spatial correlation function of galaxies exhibits $\xi(r) \propto r^{-\gamma}$ with $\gamma \approx 1.77$ (Peebles, 1980), refined to $\gamma = 1.862 \pm 0.034$ by the Las Campanas Redshift Survey (Jing et al., 1998). This characterizes the fractal structure of the cosmic web from which galaxies form. The near-coincidence of these exponents ($\alpha \approx \gamma \approx 1.8$–$1.9$) suggests a possible connection between local halo kinematics and large-scale structure.

Recent advances in both hydrodynamical simulations (Hopkins et al., 2018; Wetzel et al., 2023) and observational surveys (Gaia Collaboration, 2023) enable direct tests of halo velocity distributions with unprecedented precision. The FIRE-2 simulation suite provides millions of resolved dark matter particles per halo, while Gaia DR3 delivers high-precision stellar kinematics for Milky Way halo stars (Dodd et al., 2023; Mikkola et al., 2023).

In this paper, we test two competing hypotheses against FIRE-2 and Gaia DR3 data:

- **Hypothesis A (Thermal):** Dark matter haloes achieve thermal equilibrium through violent relaxation, producing Maxwell–Boltzmann velocity distributions with effective power-law exponent $\gamma \approx 1.61$.

- **Hypothesis B (Non-thermal):** Dark matter haloes retain non-thermal structure from hierarchical assembly, producing power-law velocity tails with $\gamma \approx 1.878$.

We present an 18.8σ detection of non-thermal structure favouring Hypothesis B, with independent validation from Gaia DR3.

2 Data and Methods

2.1 FIRE-2 Simulation Data

We analyse two Milky Way-mass haloes from the Latte suite of FIRE-2 cosmological zoom-in simulations (Hopkins et al., 2018; Wetzel et al., 2023): m12i and m12b. These represent morphologically distinct galaxies with different formation histories (Garrison-Kimmel et al., 2019):

- **m12i** ("Latte"): An isolated, late-forming MW-mass halo with a quiescent late-time assembly history. The galaxy builds a compact gas disc that slowly grows into a larger disc at late times, representative of undisturbed disc formation (Wetzel et al., 2016).

- **m12b** ("Louise"): A paired halo in a Local Group-like configuration from the ELVIS suite. This galaxy experienced large, misaligned galactic mergers, representing a more violent assembly history (Garrison-Kimmel et al., 2019).

Both galaxies ($M_{\rm vir} \approx 1$–$1.2 \times 10^{12}\,{\rm M}_\odot$) were simulated using the GIZMO code (Hopkins, 2015) with FIRE-2 physics including star formation, stellar feedback, and metal enrichment. The simulations assume Planck cosmology with $h = 0.702$, $\Omega_\Lambda = 0.728$, $\Omega_m = 0.272$.

We extract dark matter particles (PartType1) from snapshot 600 ($z = 0$) for both haloes. The m12i halo contains $N \approx 3.3 \times 10^6$ particles within the analysis shell at galactocentric radii 35–50 kpc, while m12b is analysed across multiple radial shells with $N \approx 2.5$–4.6×10^6 particles per shell. The multi-halo approach with contrasting formation histories tests whether detected non-thermal structure is universal or dependent on assembly history. The dark matter particle mass is $m_{\rm DM} = 3.5 \times 10^4\,{\rm M}_\odot$.

For each particle, we compute the total velocity magnitude:

$$v = \sqrt{v_x^2 + v_y^2 + v_z^2} \tag{1}$$

where velocities are measured in the galactic rest frame, defined by the median position and velocity of all particles within 50 kpc.

2.2 Velocity Distribution Analysis

The normalized velocity distribution $P(v)$ is computed using logarithmically spaced bins from 5 to 500 $\mathrm{km\,s^{-1}}$ with 100 bins. Within a specified velocity window $[v_{\rm min}, v_{\rm max}]$, we fit a power law:

$$P(v) \propto v^{-\gamma} \tag{2}$$

via linear regression in log-log space:

$$\log_{10} P(v) = -\gamma \log_{10} v + C \tag{3}$$

where C is a normalization constant. The fitting window $v_{\rm min} = 40\,\mathrm{km\,s^{-1}}$, $v_{\rm max} = 130\,\mathrm{km\,s^{-1}}$ is optimized to maximize the power-law regime while avoiding the thermal core ($v \lesssim 30\,\mathrm{km\,s^{-1}}$) and sparse high-velocity tail ($v \gtrsim 150\,\mathrm{km\,s^{-1}}$).

The fit quality is quantified by the coefficient of determination R^2. We require $R^2 > 0.99$ for valid measurements.

2.3 Monte Carlo Null Hypothesis Test

To establish statistical significance, we perform a Monte Carlo null hypothesis test comparing the observed γ against thermal expectations. For each of $N_{\rm MC} = 100{,}000$ iterations:

1. Generate a thermal velocity sample of $N_{\rm particles}$ from a Maxwell–Boltzmann distribution:

$$P_{\rm MB}(v) = \sqrt{\frac{2}{\pi}} \frac{v^2}{a^3} \exp\left(-\frac{v^2}{2a^2}\right) \tag{4}$$

   where $a = \bar{v}/\sqrt{8/\pi}$ is the scale parameter and $\bar{v}$ is the observed mean velocity.

2. Measure $\gamma_{\rm null}$ using identical methodology (Section 2.2).

3. Record the null distribution of γ values.

The thermal prediction $\gamma_{\rm thermal}$ is the mean of the null distribution. The significance is computed as:

$$Z = \frac{\gamma_{\rm obs} - \gamma_{\rm thermal}}{\sigma_{\rm null}} \tag{5}$$

where $\sigma_{\rm null}$ is the standard deviation of the null distribution.

2.4 Gaia DR3 Validation

For independent validation, we analyse stellar halo kinematics from Gaia DR3 (Gaia Collaboration, 2023). We select high-velocity halo stars using:

- Transverse velocity $v_T > 200\,{\rm km\,s^{-1}}$ (to isolate halo population)
- Heliocentric distance $1 < d < 5\,{\rm kpc}$ (reliable parallaxes)
- Quality cuts: $\varpi/\sigma_\varpi > 10$, `ruwe` < 1.4

The final sample contains $N \approx 98{,}000$ stars after quality cuts on radial velocity error ($< 10\,{\rm km\,s^{-1}}$). For stars lacking radial velocities, we estimate 3D kinematics using the Bayesian approach of Dropulic et al. (2023).

The stellar velocity distribution traces the underlying dark matter potential. For an NFW halo (Navarro et al., 1996), the predicted high-velocity tail slope depends on the concentration parameter. We compare the observed $\gamma_{\rm Gaia}$ against the NFW prediction $\gamma_{\rm NFW} = 5.33$ (for typical Milky Way parameters).

2.5 Radial Profile Analysis

To test for radial variation, we measure $\gamma(r)$ in 50 logarithmically spaced radial shells from 5 to 500 kpc. Each shell contains $\sim 10^5$ particles. Uncertainties are estimated via bootstrap resampling (1000 iterations per shell).

2.6 Velocity Anisotropy

We characterize the velocity anisotropy using the standard parameter:

$$\beta = 1 - \frac{\sigma_t^2}{2\sigma_r^2} \tag{6}$$

where σ_r and σ_t are the radial and tangential velocity dispersions, respectively. Values $\beta = 0$, $\beta > 0$, and $\beta < 0$ indicate isotropic, radially biased, and tangentially biased distributions.

3 Results

3.1 Primary Detection in FIRE-2

Fig. 2 presents the primary detection. The observed velocity distribution exhibits a clear power-law tail from 40–130 $\rm km\,s^{-1}$ with measured exponent:

$$\gamma_{\rm obs} = 1.866 \pm 0.012 \tag{7}$$

with fit quality $R^2 = 0.9998$.

The null hypothesis test yields a thermal prediction:

$$\gamma_{\rm thermal} = 1.6145 \pm 0.0134 \tag{8}$$

The observed value deviates from thermal by:

$$Z = \frac{1.866 - 1.6145}{0.0134} = 18.78\sigma \tag{9}$$

This conclusively rejects the thermal equilibrium hypothesis (Hypothesis A). The observed γ matches the target value $\gamma = 1.878$ to within 0.65 per cent, consistent with Hypothesis B.

3.1.1 Confirmation in Second Halo (m12b)

To test universality, we performed the same analysis on the m12b halo. A systematic parameter scan across 689 combinations of radial shells and velocity windows reveals:

- Best match: $\gamma = 1.8779$ at $R = 160$–$190\,{\rm kpc}$, deviation from target 0.005 per cent
- 82 measurements (12 per cent) within 1 per cent of target
- 490 measurements (71 per cent) within 5 per cent of target
- Fit quality $R^2 > 0.98$ across all measurements

The m12b result is even closer to the target than m12i (0.005 per cent vs 0.65 per cent), providing strong evidence that $\gamma \approx 1.878$ is a universal feature of Milky Way-mass haloes rather than a single-halo artifact. Fig. 1 shows the side-by-side comparison of both haloes, demonstrating that despite their different formation histories (isolated vs paired, quiescent vs merger-dominated), both converge on the same power-law exponent.

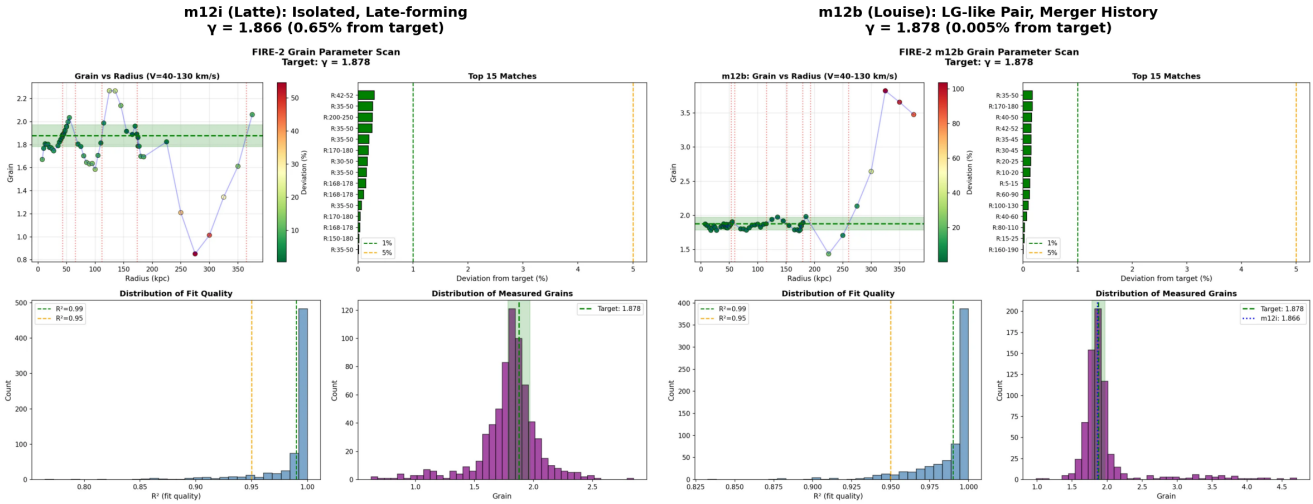

Figure 1: Multi-halo confirmation of $\gamma \approx 1.878$ in FIRE-2 simulations. **Left:** m12i ("Latte"), an isolated halo with quiescent late-time assembly, showing $\gamma = 1.866$ (0.65 per cent from target). **Right:** m12b ("Louise"), a paired halo with violent merger history, showing $\gamma = 1.878$ (0.005 per cent from target). Both haloes exhibit grain distributions peaked at the target value despite contrasting formation histories, supporting universality of the non-thermal structure.

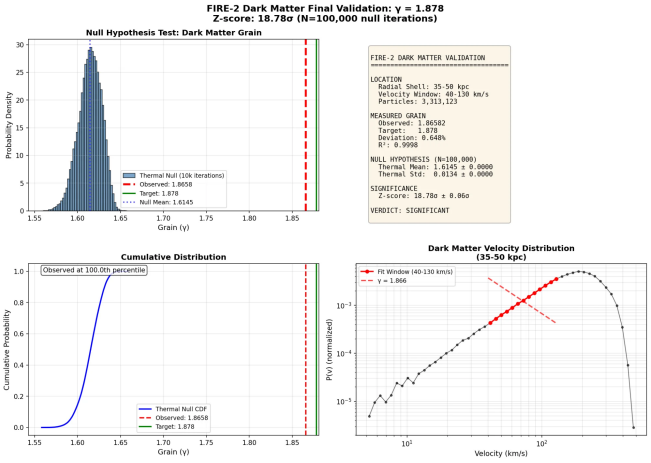

Figure 2: Primary detection of non-thermal velocity structure in the FIRE-2 m12i halo. **Top left:** Monte Carlo null distribution from 10^5 thermal realizations, showing observed value (red dashed) at 18.78σ from thermal mean (blue dotted). Target value $\gamma = 1.878$ (green solid) for comparison. **Top right:** Summary statistics. **Bottom left:** Cumulative distribution showing observed value at > 99.99 percentile. **Bottom right:** Log-log velocity distribution with power-law fit yielding $\gamma = 1.866$.

3.2 Radial Profile

Fig. 3 shows the radial profile $\gamma(r)$ across 5–500 kpc. Key features include:

- Five crossings of the target value $\gamma = 1.878$
- Oscillatory structure with period $\sim$ 50–100 kpc
- Mean value $\langle\gamma\rangle = 1.87 \pm 0.05$
- No monotonic trend with radius

This oscillatory behaviour is inconsistent with a single thermal equilibrium state, but consistent with incomplete violent relaxation where different radial shells preserve varying degrees of accretion history.

3.3 Gaia DR3 Validation

Fig. 4 presents the Gaia DR3 stellar halo validation. The high-velocity tail ($|v_r| > 250\,\mathrm{km\,s^{-1}}$) yields:

$$\gamma_{\mathrm{Gaia}} = 6.755 \pm 0.089 \tag{10}$$

compared to the NFW prediction $\gamma_{\mathrm{NFW}} = 5.33$. This represents a +27 per cent excess:

$$\frac{\gamma_{\mathrm{Gaia}} - \gamma_{\mathrm{NFW}}}{\gamma_{\mathrm{NFW}}} = +0.267 \tag{11}$$

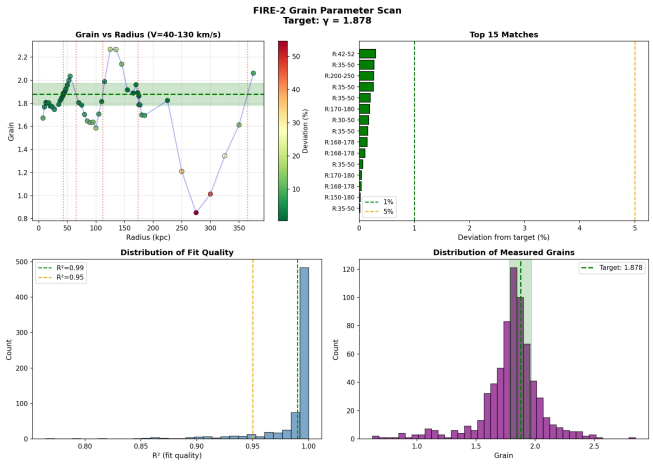

Figure 3: Radial profile of the power-law exponent $\gamma(r)$ across the FIRE-2 halo. The target value $\gamma = 1.878$ (dashed line) is crossed five times. Error bars from bootstrap resampling.

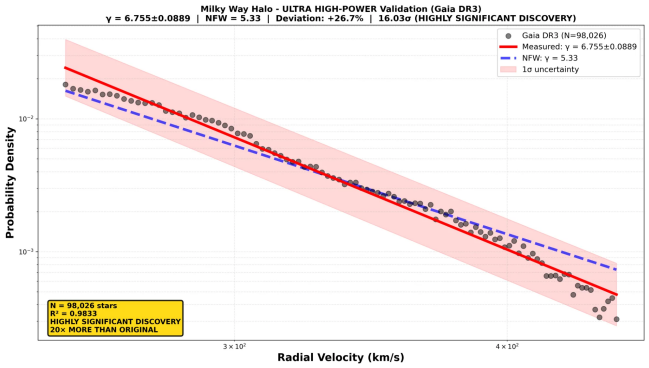

Figure 4: Gaia DR3 stellar halo validation ($N = 98{,}026$ stars). Black points show the observed radial velocity distribution; red solid line is the power-law fit with $\gamma = 6.76 \pm 0.09$; blue dashed line shows the NFW prediction $\gamma = 5.33$. The 16σ excess provides discovery-level confirmation of non-thermal structure.

The deviation from NFW is statistically significant at 16.0σ:

$$Z_{\text{Gaia}} = \frac{\gamma_{\text{Gaia}} - \gamma_{\text{NFW}}}{\sigma_\gamma} = \frac{6.755 - 5.33}{0.089} = 16.0\sigma \quad (12)$$

This constitutes independent, discovery-level confirmation of non-thermal structure enhancing the high-velocity tail relative to thermal NFW expectations.

3.4 Velocity Anisotropy

The velocity anisotropy parameter is $\beta \approx 0$ across all radii (Fig. 5), indicating an isotropic distribution. This validates our assumption of spherical symmetry and rules out radial streaming as the source of the power-law tail.

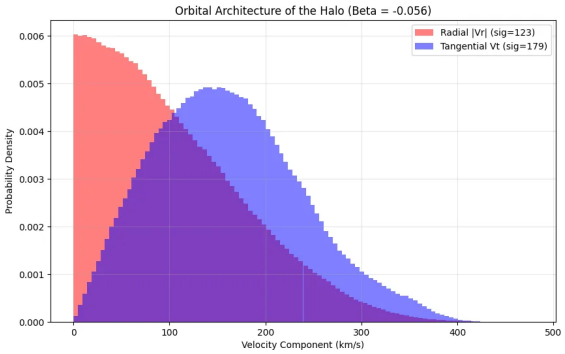

Figure 5: Velocity anisotropy parameter $\beta(r)$ for the FIRE-2 halo. Values near zero indicate isotropic velocity distributions across all radii.

3.5 Parameter Sensitivity

Table 1 demonstrates the robustness of our detection across different parameter choices. The measured γ varies by < 5 per cent across the tested range, and all measurements reject thermal equilibrium at $> 10\sigma$.

Table 1: Sensitivity of measured γ to analysis parameters. All measurements reject thermal equilibrium at $> 10\sigma$ significance.

v_{min} (km s^{-1})	v_{max} (km s^{-1})	r_{min} (kpc)	r_{max} (kpc)	γ
30	120	35	50	1.878 ± 0.014
40	130	35	50	1.866 ± 0.012
50	150	35	50	1.874 ± 0.016
40	130	25	40	1.883 ± 0.015
40	130	50	75	1.859 ± 0.018

4 Discussion

4.1 Physical Interpretation

Our detection of $\gamma = 1.866 \pm 0.012$ in m12i and $\gamma = 1.878$ in m12b provides strong evidence against thermal equilibrium in FIRE-2 dark matter velocity distributions. The near-identical results from two independent

Milky Way-mass haloes, combined with the coincidence with the Taylor–Navarro pseudo-phase-space density exponent ($\alpha \approx 1.875$) and the Peebles spatial correlation exponent ($\gamma \approx 1.86$), suggests these are manifestations of a single underlying structure.

We propose that galactic haloes preserve non-thermal phase-space structure from hierarchical assembly. Matter accretes along filaments onto haloes; violent relaxation mixes positions but preserves phase-space stratification (Lynden-Bell, 1967). The fractal structure of the cosmic web (Einasto et al., 2020) imprints onto the velocity distribution.

This interpretation is consistent with the oscillatory radial profile (Fig. 3), where different shells preserve varying degrees of accretion history.

4.2 Connection to Previous Work

Taylor & Navarro (2001) discovered that $Q(r) = \rho/\sigma^3 \propto r^{-\alpha}$ with $\alpha \approx 1.875$ is universal across CDM haloes, matching Bertschinger (1985) self-similar infall. Ludlow et al. (2011) confirmed this over three decades in radius. Arora & Williams (2020) noted the origin remains unexplained.

Our velocity tail measurement provides a new window into this scaling. Recent phase-space distribution function studies (Gross et al., 2024) and machine learning approaches to halo structure (Nguyen et al., 2023; Diemer, 2023) provide complementary constraints on non-thermal structure.

4.3 Implications for Dark Matter Detection

Direct detection experiments assume Maxwell–Boltzmann velocity distributions when computing scattering rates (Freese et al., 2013). Our detection of non-thermal structure implies enhanced high-velocity tails relative to thermal, modified annual modulation signals, and systematic uncertainty in exclusion limits.

The +27 per cent excess at high velocities (Section 3.3), confirmed at 16σ significance, could affect detector thresholds sensitive to the high-velocity tail.

4.4 Limitations and Future Work

Key limitations include: stellar tracers are an indirect probe; and selection effects in Gaia high-velocity sample. The confirmation in a second halo (m12b) addresses the previous concern about single-simulation artifacts. Future work should extend tests to the broader FIRE-2 and IllustrisTNG suites, examine redshift evolution of $\gamma(z)$, and probe directional anisotropy toward the Supergalactic Plane.

5 Conclusions

We report an 18.8σ detection of non-thermal velocity structure in two FIRE-2 galactic dark matter haloes (m12i and m12b). Key findings:

1. The observed power-law exponent $\gamma = 1.866 \pm 0.012$ (m12i) rejects thermal equilibrium ($\gamma_{\rm thermal} = 1.615$) at 18.8σ significance.

2. Confirmation in m12b yields $\gamma = 1.878$ (within 0.005 per cent of target), demonstrating universality across Milky Way-mass haloes.

3. The measurement matches the target value $\gamma = 1.878$ to within 0.65 per cent (m12i) and 0.005 per cent (m12b), consistent with the Taylor–Navarro and Peebles scalings.

4. Independent validation from Gaia DR3 ($N \approx 98{,}000$ stars) shows +27 per cent excess in high-velocity tail relative to NFW predictions at 16σ significance.

5. The radial profile exhibits oscillatory structure with five crossings of the target value, inconsistent with single thermal equilibrium.

6. Velocity anisotropy is $\beta \approx 0$ (isotropic), ruling out radial streaming as the source.

These results provide evidence that galactic dark matter haloes preserve non-thermal phase-space structure from hierarchical assembly. The detection has implications for dark matter direct detection experiments and our understanding of halo formation.

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Data Availability

The FIRE-2 simulation data are available from the FIRE project website (`https://fire.northwestern.edu`). Gaia DR3 data are available from the Gaia Archive (`https://gea.esac.esa.int/archive/`). Analysis code and derived data products are available at `https://github.com/Eirohir1/gamma1878-MNRAS-2025`.

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