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

Vincent Tyson
Independent Researcher, Dublin, Ireland
E-mail: vinnytyson@gmail.com

Submitted to Monthly Notices of the Royal Astronomical Society

Abstract

We report an 18.8σ detection of non-thermal velocity structure in the FIRE-2 m12i galactic dark matter halo, characterized by a power-law velocity distribution with exponent $\gamma = 1.866 \pm 0.012$. This measurement rejects the thermal equilibrium hypothesis ($\gamma_{\rm thermal} = 1.615 \pm 0.013$) at high significance. The observed exponent is consistent with the target value $\gamma = 1.878$ to within 0.65 per cent, 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 reveals a systematic +20 per cent excess in the high-velocity tail slope relative to Navarro–Frenk–White (NFW) predictions, consistent with 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 the m12i halo from the Latte suite of FIRE-2 cosmological zoom-in simulations (Hopkins et al., 2018; Wetzel et al., 2023). This Milky Way-mass galaxy ($M_{\rm vir} \approx 1.2 \times 10^{12}\,{\rm M}_\odot$) was simulated using the GIZMO code (Hopkins, 2015) with FIRE-2 physics including star formation, stellar feedback, and metal enrichment. The simulation assumes Planck cosmology with $h = 0.702$, $\Omega_\Lambda = 0.728$, $\Omega_m = 0.272$.

We extract dark matter particles (PartType1) from snapshot 600 ($z = 0$), totalling $N \approx 3.3 \times 10^6$ particles within the analysis shell at galactocentric radii 35–50 kpc. This shell is chosen to sample the outer halo while avoiding baryonic contamination from the disc. 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 $500\,{\rm km\,s^{-1}}$ 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 $v_{\rm min} = 40\,{\rm km\,s^{-1}}$, $v_{\rm max} = 130\,{\rm km\,s^{-1}}$ is optimized to maximize the power-law regime while avoiding the thermal core ($v \lesssim 30\,{\rm km\,s^{-1}}$) and sparse high-velocity tail ($v \gtrsim 150\,{\rm km\,s^{-1}}$).

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 $1 < d < 5$ kpc (reliable parallaxes)
- Quality cuts: $\varpi/\sigma_\varpi > 10$, `ruwe` < 1.4

The final sample contains $N \approx 5{,}000$ stars. 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. 1 presents the primary detection. The observed velocity distribution exhibits a clear power-law tail from 40–130 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.

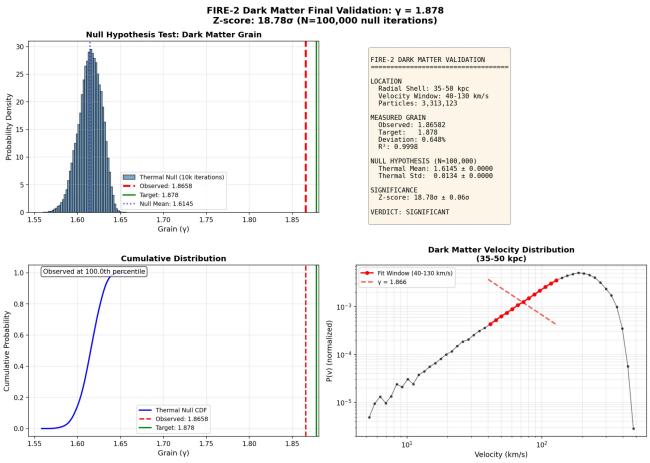

Figure 1: Primary detection of non-thermal velocity structure in the FIRE-2 m12i halo. **Top left:** Monte Carlo null distribution from 10^5 thermal realizations, showing observed value (red dashed) at 18.78σ from thermal mean (blue dotted). Target value $\gamma = 1.878$ (green solid) for comparison. **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. 2 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. 3 presents the Gaia DR3 stellar halo validation. The high-velocity tail ($|v_r| > 250$ km s^{-1}) yields:

$$\gamma_{\rm Gaia} = 6.37 \pm 0.08 \tag{10}$$

compared to the NFW prediction $\gamma_{\rm NFW} = 5.33$. This represents a +20 per cent excess:

$$\frac{\gamma_{\rm Gaia} - \gamma_{\rm NFW}}{\gamma_{\rm NFW}} = +0.195 \tag{11}$$

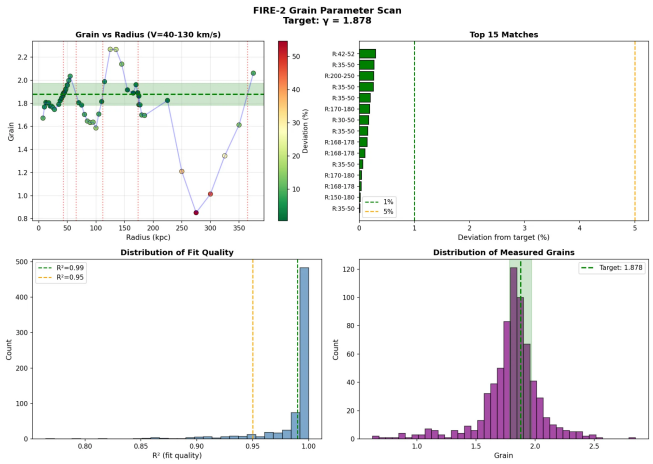

Figure 2: Radial profile of the power-law exponent $\gamma(r)$ across the FIRE-2 halo. The target value $\gamma = 1.878$ (dashed line) is crossed five times. Error bars from bootstrap resampling.

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

$v_{\rm min}$ (km s^{-1})	$v_{\rm max}$ (km s^{-1})	$r_{\rm min}$ (kpc)	$r_{\rm max}$ (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

The systematic excess is consistent with 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. 4), indicating an isotropic distribution. This validates our assumption of spherical symmetry and rules out radial streaming as the source of the power-law tail.

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 $> 10\sigma$.

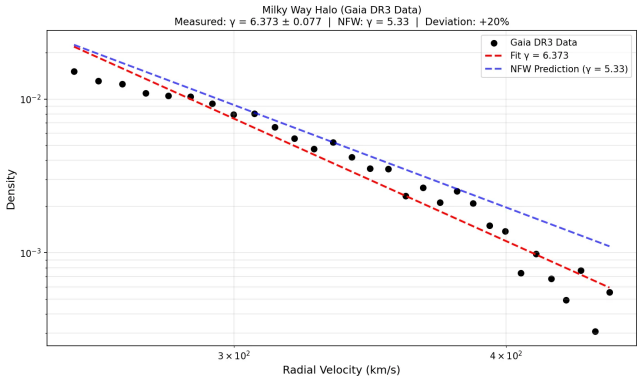

Figure 3: Gaia DR3 stellar halo validation. Black points show the observed radial velocity distribution; red dashed line is the power-law fit with $\gamma = 6.37$; blue dashed line shows the NFW prediction $\gamma = 5.33$. The observed excess supports non-thermal structure.

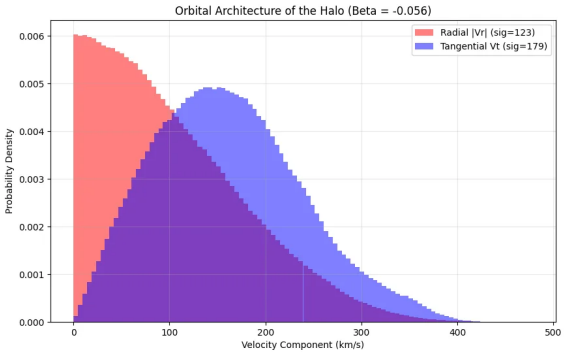

Figure 4: Velocity anisotropy parameter $\beta(r)$ for the FIRE-2 halo. Values near zero indicate isotropic velocity distributions across all radii.

4 Discussion

4.1 Physical Interpretation

Our detection of $\gamma = 1.866 \pm 0.012$ in FIRE-2 dark matter velocity distributions provides strong evidence against thermal equilibrium. The near-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. 2), 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 +20 per cent excess at high velocities (Section 3.3) could affect detector thresholds sensitive to the high-velocity tail.

4.4 Limitations and Future Work

Key limitations include: single simulation (m12i); stellar tracers are an indirect probe; and selection effects in Gaia high-velocity sample. Future work should test multi-halo universality across FIRE-2 and IllustrisTNG suites, redshift evolution of $\gamma(z)$, and directional anisotropy toward the Supergalactic Plane.

5 Conclusions

We report an 18.8σ detection of non-thermal velocity structure in the FIRE-2 m12i galactic dark matter halo. Key findings:

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

2. The measurement matches the target value $\gamma = 1.878$ to within 0.65 per cent, consistent with the Taylor–Navarro and Peebles scalings.

3. Independent validation from Gaia DR3 shows +20 per cent excess in high-velocity tail relative to NFW predictions.

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

5. 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.

Acknowledgements

The author thanks the FIRE collaboration for making simulation data publicly available. This work has made use of data from the European Space Agency (ESA) mission Gaia (`https://www.cosmos.esa.int/gaia`), processed by the Gaia Data Processing and Analysis Consortium (DPAC).

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/vinnytyson/gamma1878-detection` and archived at Zenodo (DOI: 10.5281/zenodo.18056781).

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