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A great challenge in present-day physics is to understand whether the observed internal dynamics of galaxies is due to dark matter matter or due to a modification of the law of gravity. Recently, van Dokkum et al.[1] reported that the ultra-diffuse dwarf galaxy NGC1052-DF2 lacks dark matter, and they claimed that this would – paradoxically – be problematic for modified gravity theories like Milgromian dynamics (MOND[2,3]). However, NGC1052-DF2 is not isolated, so that a valid prediction of its internal dynamics in MOND cannot be made without properly accounting for the external gravitational fields from neighbouring galaxies. Including this external field effect following Haghi et al.[4] shows that NGC1052-DF2 is consistent with MOND.

In any viable cosmological model, both primordial and tidal dwarf galaxies, which form in gas-rich tidal debris when galaxies interact, should exist. Within the standard dark-matter based cosmological model, primordial dwarfs are dark-matter dominated, whereas tidal dwarf galaxies contain very little (if any) dark matter[5]. In MOND – a classical potential theory of gravity derivable from a Lagrangian with conserved energy, total momentum and angular momentum [2,6] – the two types of dwarf galaxies cannot be distinguished. Until now, all known dwarf galaxies have shown similar dynamical behaviour, possibly implying falsification of the dark-matter models[7]. The discovery by van Dokkum et al.[1] of a galaxy lacking dark matter would thus constitute an important verification of the standard dark-matter cosmological model.

Given the density distribution of baryonic matter, ρ, the gravitational potential of

Milgromian gravitation, ϕ, is determined by the generalised nonlinear Poisson equation[6] $\vec{\nabla} \cdot \left[\mu\left(|\vec{\nabla}\phi|/a_o\right)\vec{\nabla}\phi\right] = 4\,\pi\,G\,\rho$, where the function $\mu\left(|\vec{\nabla}\phi|/a_o\right)$ describes the transition from the Newtonian ($|\vec{\nabla}\phi|/a_o \gg 1$) to the Milgromian ($|\vec{\nabla}\phi|/a_o \ll 1$) regime[3,9], $a_0 = 3600\,\mathrm{km^2 s^{-2} kpc^{-1}}$ is Milgrom's constant[2,3] and G is Newton's universal constant of gravitation. An equation of this form has been used in investigations of classical models of quark dynamics and is therefore not without precedent in physics[6]. One implication of this equation is that the coupling strength of an object described by ρ depends on the position of another object, whereas its inertial mass is given only by its baryonic component. This breaking of the equivalence of the active gravitating and inertial mass of an object constitutes a prediction of a new physical phenomenon, which does not exist in standard gravitation models and may be visualised as the phantom dark-matter halo (incorporated in ϕ) being reduced in the presence of a sufficiently strong constant external field[8]. This may be related to the quantum vacuum[9]. A dwarf galaxy in the vicinity of a major galaxy may thus lose its phantom dark-matter halo appearing as a purely Newtonian system[3,10,11].

Following van Dokkum et al.[1] we assume *NGC1052-DF2* is located at a distance of $D = 20\,\mathrm{Mpc}$ from the Earth in the *NGC1052* group, has a globular cluster population with an effective radius of $r_e = 3.1\,\mathrm{kpc}$ (the stellar body has $r_e \approx 2.2\,\mathrm{kpc}$), an absolute V-band magnitde $M_V = -15.4$ and a mass-to-light ratio of the stellar population of $M_{\mathrm{DF2}}/L_V = 2$, where M_{DF2} is the baryonic mass of *NGC1052-DF2* and L_V is its absolute luminosity in the visual photometric band. If *NGC1052-DF2* were isolated, then its MOND internal acceleration would be $a_i = 570\,\mathrm{km^2 s^{-2} kpc^{-1}} = 0.15\,a_0$. This weak gravity would imply a MONDian velocity dispersion of $\sigma_{\mathrm{M}} \approx \left((4/81)\,G\,M_{\mathrm{DF2}}\,a_o\right)^{1/4} \approx 20\,\mathrm{km/s}$. The 2σ (3σ)

confidence range for the observed velocity dispersion of the globular clusters, calculated using the robust biweight estimator[12], is $0.0 - 14.2\,\mathrm{km/s}$ ($0.0 - 19.7\,\mathrm{km/s}$), falsifying MOND with high significance[1].

This inference is only correct if *NGC1052-DF2* is sufficiently isolated and at the distance of $D \approx 20\,\mathrm{Mpc}$. The bright elliptical host galaxy *NGC1052* has a baryonic mass[13,14] $M_{\mathrm{NGC1052}} \approx 10^{11}\,M_{\odot}$. The projected separation between *NGC1052-DF2* and *NGC1052* is $D_{\mathrm{sep}} = 80\,\mathrm{kpc}$ if both are at the same distance of $D = 20\,\mathrm{Mpc}$. At this separation, the acceleration induced by the MOND external-field (EF) of the host, $a_e = \sqrt{a_0 \times G \times M_{\mathrm{NGC1052}}}/D_{\mathrm{sep}}$, is $a_e \approx 0.14\,a_0$, such that $a_i \approx a_e \ll a_0$. Because the accelaration by the external-field is as important as internal galactic acceleration, it needs to be properly taken into account in calculating the velocity dispersion in MOND, σ_{M}. This is true for any object of mass m whenever its physical size $r_e > (m/M)^{1/2}\,D_{\mathrm{sep}}$ and the external field is caused by another object of mass M at a distance of D_{sep}.

Using a MOND N-body integrator[15], Haghi et al.[4] quantified the global 1-D line-of-sight velocity dispersion ($\sigma_{\mathrm{M,EF}}$) of a non-isolated stellar system lying in the intermediate external-field regime (see Supplementary Information for more details). The dependence of the velocity dispersion of *NGC1052-DF2*, $\sigma_{\mathrm{M,EF}}$, on D_{sep} and M_{NGC1052} is shown in Fig. 1. The velocity dispersion declines from the isolated, asymptotic value $\sigma_{\mathrm{M}} = 20\,\mathrm{km/s}$ with decreasing D_{sep} and increasing mass because the external field of *NGC1052* suppresses the phantom dark-matter halo, leading to Newtonian behaviour in the case of $a_e \gg a_i$. For the nominal host mass[14], $M_{\mathrm{NGC1052}} = 10^{11}\,M_{\odot}$ and for $D_{\mathrm{sep}} = 113\,\mathrm{kpc}$, the MOND velocity dispersion is in agreement within the 2σ confidence range of the observational value of van Dokkum et al.[1], as shown by the star in Fig. 1. Thus, the estimate of the internal velocity dispersion of the globular cluster system of *NGC1052-DF2* according to MOND is $\sigma_{\rm M,EF} = 14\,{\rm km/s}$ for $M_{\rm NGC1052} = 10^{11}\,M_\odot$ and $D_{\rm sep} = 113\,{\rm kpc}$ (Fig. 1), in agreement with the observed value within the 2σ confidence level. *NGC1052-DF2* is thus consistent with an important MOND prediction.

For the external-field to suppress the phantom dark-matter halo of *NGC1052-DF2*, this galaxy needs to be close to *NGC1052*. In ref.[1] the distance of *NGC1052-DF2* is estimated using the surface-brightness fluctuation method. The calculations performed here show that *NGC1052-DF2* falsifies MOND if its distance from Earth is $D > 18\,{\rm Mpc}$ and its physical separation from *NGC 1052* or any other massive galaxy is $D_{\rm sep} > 300\,{\rm kpc}$. In this case, the external field becomes negligible and the galaxy has too small a velocity dispersion for its stellar mass in MOND. On the other hand, the observed apparent luminosity of the galaxy is $l_V = L_V/D^2$. In Milgromian dynamics, $\sigma_{\rm M} \propto M_{\rm DF2}^{1/4} \propto L_V^{1/4} \propto D^{1/2}$, so *NGC1052-DF2* would be consistent with MOND at the 2σ confidence level if $D < 13\,{\rm Mpc}$ even if it were isolated. We note that the velocity dispersion predicted by Newtonian dynamics is also proportional to $D^{1/2}$ for a galaxy without dark matter. Future high-precision observations will ascertain the distance of *NGC1052-DF2* and will constrain its gravitating mass using stellar velocities within *NGC1052-DF2*, instead of globular cluster velocities. As a word of caution, if this galaxy is not in virial equilibrium then using the globular clusters as tracers for the mass may be unreliable, independently of the underlying cosmological model.

Online Supplementary Information contains the external field effect calculation in MOND.

References

1. van Dokkum, P. *et al.* A galaxy lacking dark matter. *Nature* **555**, 629–632 (2018). `1803.10237`.

2. Milgrom, M. A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *Astrophys. J.* **270**, 365–370 (1983).

3. Famaey, B. & McGaugh, S. S. Modified Newtonian Dynamics (MOND): Observational Phenomenology and Relativistic Extensions. *Living Reviews in Relativity* **15**, 10 (2012). `1112.3960`.

4. Haghi, H. *et al.* Testing fundamental physics with distant star clusters: theoretical models for pressure-supported stellar systems. *Mon. Not. R. Astron. Soc.* **395**, 1549–1557 (2009). `0902.1846`.

5. Ploeckinger, S. *et al.* Tidal dwarf galaxies in cosmological simulations. *Mon. Not. R. Astron. Soc.* **474**, 580–596 (2018). `1710.09380`.

6. Bekenstein, J. & Milgrom, M. Does the missing mass problem signal the breakdown of Newtonian gravity? *Astrophys. J.* **286**, 7–14 (1984).

7. Kroupa, P. The Dark Matter Crisis: Falsification of the Current Standard Model of Cosmology. *Publications of the Astronomical Society of Australia* **29**, 395–433 (2012). `1204.2546`.

8. Milgrom, M. Solutions for the modified Newtonian dynamics field equation. *Astrophys. J.* **302**, 617–625 (1986).

9. Milgrom, M. The modified dynamics as a vacuum effect. *Physics Letters A* **253**, 273–279 (1999). astro-ph/9805346.

10. McGaugh, S. S. MOND Prediction for the Velocity Dispersion of the Feeble Giant Crater II. *Astrophys. J. Lett.* **832**, L8 (2016). 1610.06189.

11. Thomas, G. F. *et al.* Stellar streams as gravitational experiments. II. Asymmetric tails of globular cluster streams. *Astron. Astrophys.* **609**, A44 (2018). 1709.01934.

12. Beers, T. C., Flynn, K. & Gebhardt, K. Measures of location and scale for velocities in clusters of galaxies - A robust approach. *Astron. J.* **100**, 32–46 (1990).

13. Fernández-Ontiveros, J. A., López-Sanjuan, C., Montes, M., Prieto, M. A. & Acosta-Pulido, J. A. The most recent burst of star formation in the massive elliptical galaxy NGC 1052. *Mon. Not. R. Astron. Soc.* **411**, L21–L25 (2011). 1011.2498.

14. Bellstedt, S. *et al.* The SLUGGS Survey: A comparison of total-mass profiles of early-type galaxies from observations and cosmological simulations, to 4 effective radii. *Mon. Not. R. Astron. Soc.* (2018). 1803.02373.

15. Londrillo, P. & Nipoti, C. N-MODY: a code for collisionless N-body simulations in modified Newtonian dynamics. *Memorie della Societa Astronomica Italiana Supplement* **13**, 89–+ (2009). 0803.4456.

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P.K. conceived the work and wrote the mansucript; H.H. and A.H.Z. performed the external field calculations; O.M. and B.J. contributed observational expertise on galaxies; I.B., X.W. and H.Z. contributed MOND expertise; J.D. contributed dwarf galaxy expertise. All co-authors contributed to the manuscript with comments and passages.

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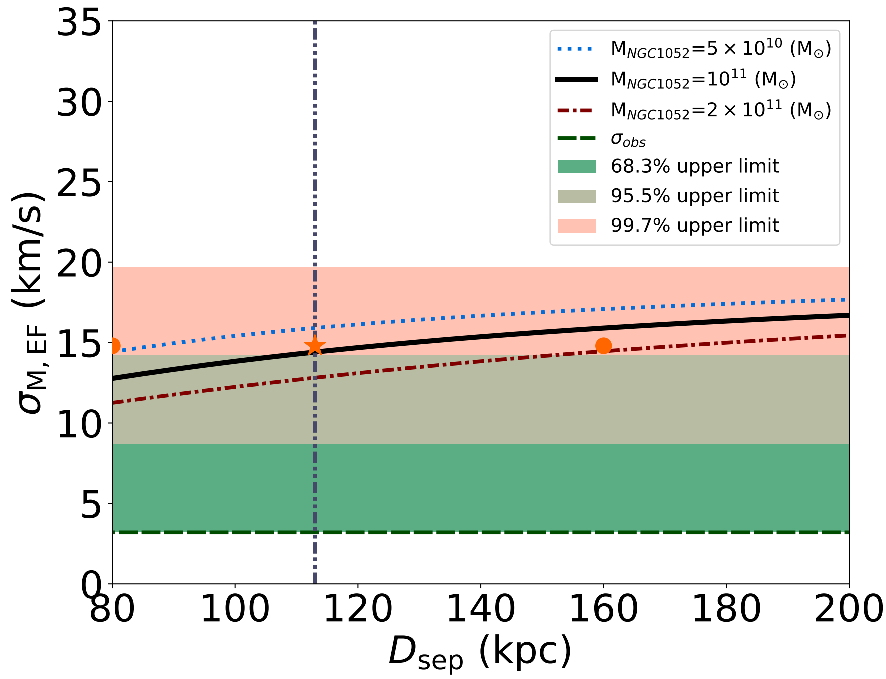

Figure 1 MOND velocity dispersion and external field

The line-of-sight MOND velocity dispersion, $\sigma_{\rm M,EF}$, of *NGC1052-DF2* is shown as a function of the separation, $D_{\rm sep}$, between *NGC1052-DF2* and *NGC1052*. The star (at $D_{\rm sep} = 113\,{\rm kpc}$, $M_{\rm NGC1052} \approx 10^{11}\,M_\odot$) and the two orange points (at $D_{\rm sep} = 80\,{\rm kpc}$, $M_{\rm NGC1052} \approx 5 \times 10^{10}\,M_\odot$ and at 160 kpc, $M_{\rm NGC1052} \approx 2 \times 10^{11}\,M_\odot$) correspond to the $a_e = 0.1\,a_0$ entry in table 1 of Haghi et al. (2009)[4] without interpolation. The vertical dash-dotted line indicates the more likely distance $D_{\rm sep} = (2)^{1/2}\,80 = 113{\rm kpc}$. The 1σ, 2σ and 3σ upper confidence limits on the observed velocity dispersion[1], $\sigma_{\rm obs} = 3.2^{+5.5}_{-3.2}\,{\rm km/s}$, are coloured as indicated in the key. The measured value is shown as the long-dashed horizontal line. Our interpolation of the values in table 1 of Haghi et al.[4] (equation 1 in Supplementary Information) is shown for $M_{\rm NGC1052} = 5 \times 10^{10}\,M_\odot, 1 \times 10^{11}\,M_\odot$ and $2 \times 10^{11}\,M_\odot$ by the dotted, solid and dash-dotted lines, respectively.

Supplementary Information

The external field effect in MOND: In a self-bound gravitational system with baryonic mass M and half-mass radius r_h, its components experience a Newtonian internal acceleration, $a_N \equiv G\,M/\,(2\,r_h^2)$, which is in Newtonian gravitation linearly additive to any external acceleration a_e. If this external acceleration is constant across the system then it does not influence the internal eigengravitation. However, in MOND, the internal gravitation is suppressed by the external field if it is sufficiently strong. This is known since the original work by Milgrom (1983, ApJ 270, 365)[2] and follows from the Lagrangian formulation of MOND which implies the generalised non-linear Poisson equation (Bekenstein & Milgrom 1984, ApJ 286, 7)[6]. The details of computing the acceleration on the systems's constituents are simple only in the limits where the internal acceleration is much larger than Milgrom's constant a_0 (in which case the system is Newtonian), or when the external field is negligible and the internal acceleration is much smaller than a_0. In the latter case the system is in the deep MOND limit such that its MOND internal acceleration is $a_i = \sqrt{(G\,M\,a_0)}/r_e$ for a system with effective radius r_e, and effectively behaves as if it is embedded in a dark-matter halo which can be described mathematically as a Newtonian isothermal logarithmic potential. This Milgromian potential is referred to as a phantom dark-matter halo as it is not made of particles, and this limiting case was used by van Dokkum et al.[1] to calculate the value of the velocity dispersion predicted by MOND. In the case when the external field is significant compared to the internal acceleration and when both are smaller than or comparable to Milgrom's constant a_0 then the calculations become less straightforward, and again, only in the limiting cases can calculations be performed. For example, when $a_e > a_0$ and $a_i \ll a_e$ forces from different masses can be superposed (Banik & Zhao 2015, arXiv150908457B), though this is generally not correct as MOND is non-linear. Effectively an external field truncates (or reduces or "melts") the phantom dark-matter halo of the system. The external field effect thereby allows observational tests for MOND, because it has no counterpart in Newtonian dynamics. Simplified descriptions of the external-field effect are available in Wu & Kroupa (2015, MNRAS 446, 330) and an in-depth discussion is found in the major review by Famaey & McGaugh (2012)[3].

Observational evidence for the MOND external-field effect has been found in the form of falling rotation curves of disk galaxies (Wu & Kroupa 2015, MNRAS, 446, 330; Hees et al. 2016, MNRAS, 455, 449; Haghi et al. 2016, MNRAS 458, 4172), and in the asymmetric tidal tail of the globular star cluster Pal 5 (Thomas et al. 2018[11]). The successful prediction of the very low velocity dispersion of the ultra-diffuse dwarf satellite galaxy Crater II[10] and the velocity dispersions of Andromeda satellite galaxies (McGaugh & Milgrom 2013, ApJ 775, 139) are highly relevant for the problem at hand.

Haghi et al.[4] quantified the global 1-D line-of-sight velocity dispersion ($\sigma_{\rm M,EF}$) of a non-isolated stellar system lying in the intermediate external-field regime, using the code N-MODY, which has a N-body MOND mean-field potential solver developed by Ciotti, Londrillo & Nipoti (2006, ApJ 640, 741)[15]. Haghi et al.[4] fit their results for $\sigma_{\rm M,EF}$ in the intermediate regime ($a_i \approx a_e < a_0$) for different values of the external field. They quantified the different asymptotic behavior in fig. 5 of Haghi et al.[4] (i.e. in the Newtonian, the deep-

MOND and and the external-field-dominated regime). The formulation was presented as their eq. 16 and 17 with coefficients provided for different values of a_e in their table 1.

Thus, for example, the $M = 10^{11}\,M_\odot$, $D_{\rm sep} = \sqrt{2} \times 80 = 113\,$kpc case corresponds to $a_e = 0.1\,a_0$. Adopting the three coefficients tabulated in the row $a_e = 0.1\,a_0$ in table 1 of Haghi et al. (2009)[4], we use their eqs. 13, 15 and 17, to obtain $\sigma = 14.8\,$km/s. This is indicated by the star symbol in Fig. 1. Likewise for other values of $D_{\rm sep}$ and M combinations, we can work out a_e, and the corresponding $\sigma_{M,EF}$, and these are plotted as curves in Fig. 1.

The interpolation to other-than-the tabulated values of a_e in table 1 in Haghi et al. (2009)[4] is not unique and for the purpose of documentation we provide in the following one possible analytical formulation (eq. 1) for the data in their table 1 allowing $\sigma_{\rm M,EF}$ to be calculated as a function of the internal field in the system with mass M exposed to an external field, a_e. The one-dimensional (line of sight) velocity dispersion, $\sigma_{\rm M,EF}$ (in km/s),

$$\log_{10}\sigma_{\rm M,EF} = \log_{10}\sigma_{\rm M} + F(a_e), \tag{1}$$

where the velocity dispersion of an isolated system

$$\sigma_{\rm M} = \left(\frac{4}{81}\,G\,M\,a_0\right)^{\frac{1}{4}} \times \left(1 + 0.56\exp\left(3.02\,x\right)\right)^{0.184}, \tag{2}$$

where $x \equiv \log_{10}\left(a_N/a_0\right)$ and

$$F(a_e) = -\frac{A(a_e)}{4}\left(\ln\left[\exp\left(-\frac{x}{A(a_e)}\right) + B(a_e)\right] + C(a_e)\right), \tag{3}$$

with G being Newton's gravitational constant. Note that Eq. 2 supersedes the equation used by van Dokkum et al.[1] by a correction factor which ensures the correct behaviour as the internal acceleration approaches the Newtonian value.

The functions A, B, C are fits to the data in table 1 in Haghi et al.[4]:

$$A(a_e) = \frac{5.3}{\left(10.56 + (y+2)^{3.22}\right)}, \tag{4}$$

$$B(a_e) = 0.44 \exp\left(-4.26\, y\right), \tag{5}$$

$$C(a_e) = -12.83 \ln\left(\exp\left(\frac{-(y+2)}{1.28}\right) + 0.85\right), \tag{6}$$

where $y \equiv \log_{10}(a_e/a_0)$. The important issue is to obtain an accurate fit to the combination of A, B and C given in eq. 15 of Haghi et al. (2009)[4] – fitting the coefficients individually is less important.

These formulae reproduce well the previous analytical velocity dispersion estimators in systems in the isolated deep-MOND regime [that is, $\sigma_{\rm M,EF} \approx \sigma_M = (4\,G\,M\,a_0/81)^{1/4}$] (Milgrom, M. 1994, ApJ 429, 540; McGaugh, S. & Milgrom, M., 2013, ApJ 775, 139) and for the deep-MOND external-field-dominated regime ($\sigma_{\rm M,EF} \propto 1/\sqrt{(a_e)}$, eq. 2 of McGaugh 2016[10]). We note that the three orange points in Fig. 1 can be obtained directly from the $a_e = 0.1\,a_0$ line in table 1 of Haghi et al. (2009)[4] without interpolation.