Stellar Streams in Chameleon Gravity

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Theories of gravity that incorporate new scalar degrees of freedom typically require ‘screening mechanisms’ to ensure consistency with Solar System tests. One widely-studied mechanism—the chameleon mechanism—can lead to violations of the equivalence principle (EP), as screened and unscreened objects fall differently. If the stars are screened but the surrounding dark matter is not, EP-violation can lead to asymmetry between leading and trailing streams from tidally disrupted dwarf galaxies in the Milky Way halo. We provide analytic estimates of the magnitude of this effect for realistic Galactic mass distributions, demonstrating that it is an even more sensitive probe than suggested previously. Using a restricted N-body code, we simulate 4 satellites with a range of masses and orbits, together with a variety of strengths of the fifth force and screening levels of the Milky Way and satellite. The ratio of the cumulative number function of stars in the leading and trailing stream as a function of longitude from the satellite is computable from simulations, measurable from the stellar data and can provide a direct test of chameleon gravity. We forecast constraints for streams at large Galactocentric distances, which probe deeper into chameleon parameter space, using the specific example case of Hu-Sawicki $f(R)$ gravity. Streams in the outer reaches of the Milky Way halo (with apocentres between 100 and 200 kpc) provide easily attainable constraints at the level of $|f(R_0)| = 10^{-7}$. Still more stringent constraints at the level of $10^{-7.5}$ or even $10^{-8}$ are plausible provided the environmental screening of the satellite is accounted for, and screening of the Milky Way’s outer halo by the Local Group is not yet triggered in this range. These would be among the tightest astrophysical constraints to date. We note three further signatures of chameleon gravity: (i) the trailing stellar stream may become detached from the dark matter progenitor if all the stars are lost, (ii) in the extreme fifth force regime, striations in the stellar trailing tail may develop from material liberated at successive pericentric passages, (iii) if the satellite is fully screened, its orbital frequency is lower than that of the associated dark matter, which is preferentially liberated into the leading tidal tail.

I. INTRODUCTION

Stellar streams and substructures are the wreckage of dwarf galaxies and globular clusters that have fallen into and are being torn apart by the Milky Way’s tidal field. In the past, such substructures have usually been identified as over-densities of resolved stars, as in the ‘Field of Streams’ image from the Sloan Digital Sky Survey [1]. There, using multi-band photometry, the stellar halo of the Milky Way was revealed as being composed of criss-crossing stellar streams, the detritus of satellite galaxies. However, streams and substructure remain kinematically cold and so identifiable in phase space long after they have ceased to be recognisable in star counts against the stellar background of the Galaxy [2]. The debris persists for a large fraction of a Hubble time, sometimes longer, so substructures in phase space remain to the present day. Searches in phase space for streams are much more powerful than searches in configuration space.

The Gaia satellite is a scanning satellite of the European Space Agency that is monitoring all objects brighter than magnitude $G \approx 20$ around 70 times over a period of 5 years (though the mission lifetime has recently been extended) [3, 4]. Its telescopes are providing magnitudes, parallaxes, proper motions and broad band colours for over a billion stars in the Galaxy ($\approx$ 1 per cent of the Milky Way stellar population) within the Gaia-sphere – or within roughly 20 kpc of the Sun for main sequence stars, 100 kpc for giants. We now possess detailed phase space information, often with spectroscopic and chemical data from cross-matches with other surveys. This has led
to the discovery of abundant streams and substructures [5–8]. Streams discovered by Gaia are already being followed up spectroscopically to give six-dimensional (6D) phase space data [9]. Bright tracers such as blue horizontal branch stars or RR Lyraes can be seen out to distances of 250 kpc, assuming Gaia’s limiting magnitude of G $\sim$ 20.5. Stars near the tip of the red giant branch can be seen even further out to at least 600 kpc. In future, this should enable Gaia to provide astrometry for very distant streams, perhaps beyond the edge of the Milky Way’s dark halo.

If a stream were a simple orbit, then the positions and velocities of stars would permit the acceleration and force field to be derived directly from the 6D data. Streams are more complex than orbits [10–11], but the principle remains the same – their evolution constrains the matter distribution and theory of gravity. Although this idea has been in the literature for some years, exploitation has been sparse primarily because of the limited number of streams with 6D data before Gaia. For example, Thomas et al. [12] show that streams from globular clusters are fated to a subclass of scalar-tensor theories of gravity [24].

There are several varieties of screening mechanism, but the principle remains the same – their evolution constrains the matter distribution and theory of gravity. Although this idea has been in the literature for some years, exploitation has been sparse primarily because of the limited number of streams with 6D data before Gaia. For example, Thomas et al. [12] show that streams from globular clusters are fated to a subclass of scalar-tensor theories of gravity [24].

The key parameter is the present-day cosmic background value of the scalar field, $f_{R0}$. In the present work, we do not assume Hu-Sawicki $f(R)$ gravity, but sometimes use the parameter $f_{R0}$ as a concrete example to illustrate the possible constraints achievable from stellar streams, noting that constraints are also obtainable in the wider chameleon space.

A complete compendium of current constraints on $f(R)$ gravity and chameleon gravity more generally can be found in the review article by Burrage and Sakstein [25]. It is worth noting that some of the strongest constraints to date have come from weak-field astrophysical probes. Indeed, Baker et al. [26] identify a ‘desert’ in modified gravity parameter space accessible only to galaxy-scale probes, and have launched the ‘Novel Probes’ project, aimed at connecting theorists with observers in order to devise tests to probe this region. Accordingly, several recent works [27,28] have studied imprints of screened modified gravity on galaxy scales.

In chameleon theories, main sequence stars will have sufficiently deep potential wells to self-screen against the fifth force. A diffuse dark matter or gaseous component of sufficiently low mass, however, will be unscreened. As a result, the EP is effectively violated, leading to a number of distinct signatures, as listed by Hui et al. [33]. Indeed, several of the galaxy-scale studies mentioned in the previous paragraph searched for signatures in this list, as well as other signatures of EP-violation.

The present work explores the idea that effective EP-violation of chameleon gravity should give rise to the fifth force in chameleon theories before providing a new calculation of the magnitude of the effect, extending the original work of Kesden and Kamionkowski [13–14]. We will show that tidal streams in the Milky Way, observable with Gaia, can provide constraints that are comparable to, or stronger than, other astrophysical probes. Section II gives a brief introduction to the fifth force in chameleon theories before providing a new calculation of the magnitude of the effect, extending the original work of Kesden and Kamionkowski [13–14]. Next, Section III describes the Milky Way and satellite galaxies that we use in our simulation code, the methodology and validation of which are in turn described respectively in Sections IV and V. Section VI describes results for a range of tidal streams, inspired by examples discovered recently in large photometric surveys or the Gaia datasets. Finally, Section VII gives some concluding remarks.

II. THEORY

A. Chameleon Fifth Forces

In scalar-tensor gravity theories, new scalar degrees of freedom in the gravitational sector couple to matter, giving rise to gravitational strength ‘fifth forces’. Chameleon theories are a class of scalar-tensor theories in which these fifth forces are suppressed in regions of high-density or deep gravitational potential [21]. In this section, we cover
consider a spherical overdensity embedded within a region of average cosmic density. If the gravitational well of the object is sufficiently deep, a central region of radius $r_{\text{scr}}$ will be ‘screened’, such that no fifth forces act within the region; $r_{\text{scr}}$ is the ‘screening radius’ of the object. Outside the screening radius, an unscreened test particle will experience an acceleration due to the fifth force given by Eq. (3.6) of Ref \[25\]

$$a_5(r) = 2\beta^2 G \frac{(M(r) - M(r_{\text{scr}}))}{r^2}, \quad (1)$$

where $M(r)$ is the mass enclosed within radius $r$, and $\beta$ is the coupling strength. In other words, the fifth force is sourced only by the mass lying between the screening radius and the test particle. We have also assumed here that the Compton wavelength of the theory is much larger than the characteristic length scales of the system.

Eq. (1) gives the fifth force experienced by an unscreened test particle outside the screening radius of an overdense object, but the situation is complicated further in the case where instead of a test particle, we have another extended object – for example, a star or dwarf galaxy situated outside the screening radius of its host galaxy. In this case, the acceleration of object $i$ (mass $M_i$, radius $r_i$, screening radius $r_{\text{scr},i}$) due to the fifth force is given by

$$a_5(r) = 2\beta^2 Q_i \frac{G(M(r) - M(r_{\text{scr},i}))}{r^2}, \quad (2)$$

where $Q_i$ is the ‘scalar charge’ of object $i$, given in turn by

$$Q_i = \left(1 - \frac{M(r_{\text{scr},i})}{M_i}\right). \quad (3)$$

Thus, the test object experiences the full fifth force only if it is fully unscreened (i.e., $r_{\text{scr}} = 0$) and experiences no fifth force if it is fully screened ($r_{\text{scr}} = r_i$). In the intermediate case where the object is partially screened, it experiences a reduced fifth force. In this work, we assume stars to be fully self-screened (i.e. $Q = 0$), and dark matter to be fully unscreened (i.e. $Q = 1$). For the satellite galaxies (i.e. the stream progenitors), we explore a number of regimes, spanning fully screened, partially screened, and fully unscreened.

A commonly used parametrisation of chameleon theories is in terms of the coupling strength $\beta$ and the ‘self-screening parameter’ $\chi_c$. The latter parameter determines which astrophysical objects are fully or partially screened, and can be used to calculate their screening radii. Note that in the case of Hu–Sawicki $f(R)$ gravity, $\beta$ is fixed to $\sqrt{1/6}$, while $\chi_c = -f_{R0}$.

In order to derive constraints in the $\beta/\chi_c$ plane or $f_{R0}$ space from stellar streams around the Milky Way, we would need to adopt some prescription to convert $\chi_c$ to Milky Way and satellite screening radii. Analytical formulae exist in the case of an isolated spherical body \[44\] \[35\], but such a treatment would neglect the environmental contribution of the Local Group to the Milky Way’s screening, the environmental contribution of the Milky Way to the satellite’s screening, and the impact of the non-sphericity of the Milky Way. The calculation

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**FIG. 1.** Top: Contour map of the effective potential for the dark matter $\Phi_{\text{eff,DM}}$ as given by Eq. (3). Bottom: Contour map of the effective potential for the stars $\Phi_{\text{eff,stars}}$, as given by Eq. (9). In both panels, the satellite is at the origin and the Galactic centre is at (-50, 0, 0) kpc. The inner and outer Lagrange points are marked by crosses. The asymmetry of the Lagrange points for the stellar effective potential illustrates the cause of the stream asymmetries under chameleon gravity. (Parameters used are: $M = 10^{12} M_\odot$, $m = 10^{13} M_\odot$, and $\beta = 0.5$.)
therefore requires numerical methods in more realistic scenarios [27]. In this work, we instead use $\beta$, $r_{\text{scr,MW}}$, and $r_{\text{scr, sat}}$ as input parameters for reasons of computational ease. However, in Section V(D) we investigate the connection between $f_{R0}$ and $r_{\text{scr,MW}}$ in order to forecast model constraints from future data.

## B. Stream Asymmetries

### 1. A Physical Picture

We begin with a physical picture of the cause of stream asymmetries. Consider a satellite represented by a point mass $m$. For the moment, let us neglect any fifth forces and assume that the Milky Way and can also be represented as a point mass $M$, so both satellite and the Milky Way are moving on circular orbits with frequency $\Omega$ around their common center of mass.

We use a coordinate system whose origin is at the centre of the satellite. Then, a star at position $r_s$ moves in an ‘effective’ gravitational potential given by [e.g., 36, 37]

$$\Phi_{\text{eff}}(r_s) = -\frac{Gm}{r_s} - \frac{GM}{|r_h - r_s|} - \frac{1}{2} \frac{\Omega^2}{r_s - r_{\text{cm}}}^2. \tag{4}$$

where $r_h$ is the position of the point mass representing the Milky Way and $r_{\text{cm}}$ is the position of the centre of mass. We use the convention $r_s = |r_s|$ to denote the modulus of any vector. The first two terms are the gravitational potentials of the satellite and Milky Way respectively, while the final term provides the centrifugal force due to the frame of reference, which is rotating about the centre of mass with frequency $\Omega$

$$\Omega = \sqrt{\frac{G(M + m)}{r_h^3}}. \tag{5}$$

In practice, the mass of a typical satellite $m$ is at least two orders of magnitude less than the mass of the Milky Way, and so its contribution to the frequency can be neglected.

The stationary points of the effective potential $\Phi_{\text{eff}}$ are the Lagrange points or equilibria at which the net force on a star at rest vanishes. In the circular restricted three-body problem, there are five Lagrange points. Matter is pulled out of the satellite at the ‘L1’ and ‘L2’ saddle points, henceforth the ‘inner’ and ‘outer’ Lagrange points. These are situated either side of the satellite, co-linear with the satellite and Milky Way. Leading (trailing) streams originate at the inner (outer) Lagrange points, which lie at (see Sec 8.3.1 of Binney and Tremaine [37])

$$r_1 \approx \left(\frac{m}{3M}\right)^{1/3} r_h, \tag{6}$$

with respect to the satellite centre.

Now consider how the system behaves if a fifth force acts on the dark matter. Neglecting any screening, and assuming the satellite is dark matter dominated, the orbit will circle more quickly with frequency given by

$$\Omega' = \sqrt{\frac{G'(M + m)}{r_h^3}} \approx \sqrt{\frac{G'M}{r_h^3}} \tag{7}$$

where $G' \equiv (1 + 2\beta^2)G$. The effective potential experienced by a dark matter particle in this system is

$$\Phi_{\text{eff,DM}}(r_s) = -\frac{G'm}{r_s} - \frac{G'M}{|r_h - r_s|} - \frac{1}{2} \frac{\Omega'^2}{r_s - r_{\text{cm}}}^2. \tag{8}$$

This is tantamount to a linear rescaling of Eq. (4), and the locations of the critical points are therefore unchanged relative to the standard gravity case. However, the effective potential is different for a star which does not feel the fifth force, namely

$$\Phi_{\text{eff,}\ast}(r_s) = -\frac{Gm}{r_s} - \frac{GM}{|r_h - r_s|} - \frac{1}{2} \frac{\Omega^2}{r_s - r_{\text{cm}}}^2. \tag{9}$$

This is not a linear multiple of Eq. (4), and the locations of the Lagrange points are consequently altered. The two panels of Figure 1 shows contour maps of the effective potentials for dark matter and stars, for $M = 10^{12}M_\odot, m = 10^{10}M_\odot, r_h = 50$ kpc, and $\beta = 0.5$. Also indicated on the diagram are the locations of the inner and outer Lagrange points of the potentials.

In the dark matter case, the points are approximately equidistant from the satellite centre. However, a significant asymmetry is visible in the stellar effective potential, with the outer Lagrange point being much closer to the satellite and at a lower effective potential. Thus, stars are much more likely to be stripped from the satellite at the outer Lagrange point, and the trailing stream will consequently be more populated than the leading one.

Physically, we can understand this effect in terms of force balance. The stars are being dragged along by the satellite, which is orbiting at an enhanced rotation speed due to the fifth force. This enhanced speed means that the outward centrifugal force on the stars is greater than the inward gravitational attraction by the Milky Way. The consequence of this net outward force is that stars can be stripped from the satellite more easily if they are at larger Galactocentric radii than the satellite, and less easily if they are at smaller radii. This is reflected in the positions of the Lagrange points.

Stars unbound from the satellite will be on a slower orbit around the Milky Way than their progenitor. If $\beta$ is sufficiently large, then stars that are initially in the leading stream can fall behind and end in the trailing stream.

### 2. Circular Restricted Three-Body Problem

We now solve for the stream asymmetries in the circular restricted three-body problem, following and correcting Ref [13]. This is a useful preliminary before passing
to the general case. In Newtonian gravity, the forces balance at the inner and outer Lagrange points, and so

\[- \frac{GM}{(r_h - r_t)^2} + \frac{Gm}{r_t^2} + \frac{G(M + m)}{r_t^3} \left( \frac{Mr_h}{M + m} - r_t \right) = 0, \tag{10}\]

\[- \frac{GM}{(r_h + r_t)^2} - \frac{Gm}{r_t^2} + \frac{G(M + m)}{r_t^3} \left( \frac{Mr_h}{M + m} + r_t \right) = 0. \tag{11}\]

We recall that the inertial frame is rotating about the centre of mass, and so the centrifugal terms in Eqs. (10) and (11) depend on the distance of the Lagrange point to the centre of mass, not the Galactic centre (cf. Eqs. (14) and (15) of Ref. [13]).

We now define \( u = r_t/r_h \) and \( u' = r'_t/r_h \) for the inner and outer Lagrange points respectively, and obtain

\[ u^3 = \frac{m}{M} \frac{(1 - u^3)(1 - u^2)}{3 - 3u + u^2}, \tag{12}\]

\[ u'^3 = \frac{m}{M} \frac{(1 - u'^3)(1 + u'^2)}{3 + 3u' + u'^2}. \tag{13}\]

Solving, we find that

\[ u \approx \left( \frac{m}{3M} \right)^{1/3} \left( 1 - \frac{u}{3} \right), \tag{14}\]

\[ u' \approx \left( \frac{m}{3M} \right)^{1/3} \left( 1 + \frac{u'}{3} \right), \tag{15}\]

so the natural asymmetry is

\[ \Delta r_{\text{nat}} = (u' - u)r_h \approx \frac{2}{3} \left( \frac{m}{3M} \right)^{2/3} r_h. \tag{16}\]

Now introducing a fifth force, the force balance equations for stars not directly coupling to the fifth force become

\[- \frac{GM}{(r_h - r_t)^2} + \frac{Gm}{r_t^2} + \Omega^2 (1 + 2\beta^2) \left( \frac{Mr_h}{M + m} - r_t \right) = 0, \tag{17}\]

\[- \frac{GM}{(r_h + r_t)^2} - \frac{Gm}{r_t^2} + \Omega^2 (1 + 2\beta^2) \left( \frac{Mr_h}{M + m} + r_t \right) = 0. \tag{18}\]

Proceeding as before

\[ u \approx \left( \frac{m}{3M} \right)^{1/3} \left( 1 - \frac{u}{3} + \frac{2\beta^2 M}{3} u^2 \right), \tag{19}\]

\[ u' \approx \left( \frac{m}{3M} \right)^{1/3} \left( 1 + \frac{u'}{3} - \frac{2\beta^2 M}{3} u'^2 \right). \tag{20}\]

The last term on the right-hand side produces an asymmetry with opposite sign to the natural asymmetry. Note that as \( u \propto (m/M)^{1/3} \), the \( M/m \) factor makes this term actually the largest. The condition for the asymmetry due to the fifth force to overwhelm the Newtonian one is then just

\[ 2\beta^2 \gtrsim 3^{1/3} \left( \frac{m}{M} \right)^{2/3}, \tag{21}\]

where only leading terms are kept. This result can be compared with Eq. (29) of Ref. [13]. Although the scaling is the same, the numerical factor is different (remember on comparing results that \( 2\beta^2 \) in our paper corresponds to \( \beta^2 f_{5f} f_{\text{sat}} \) in theirs). In fact, the changes are very much to the advantage of the fifth force, as smaller values of \( \beta \) now give detectable asymmetries.

The two most massive of the Milky Way dwarf spheroidals are Sagittarius with dark matter mass \( 2.8 \times 10^7 M_\odot \) and Fornax at \( 1.3 \times 10^8 M_\odot \) [38]. These will allow values of \( \beta^2 \gtrsim 2 \times 10^{-3} \) to be probed. For the smallest dwarf spheroidals such as Segue 1 with a mass of \( 6 \times 10^5 M_\odot \), then values of \( \beta^2 \gtrsim 2 \times 10^{-4} \) are in principle accessible. It should be noted that the Segue 1 is an ambiguous object, and it is not entirely clear if it is a dark matter dominated dwarf or a globular cluster [39].

3. General Case

The circular restricted three-body problem is somewhat unrealistic, as the Galaxy’s matter distributions is extended. In particular, there is a significant difference in the enclosed host mass within the inner and outer Lagrange points and this plays a role in the strength of the asymmetry. We now proceed to give a mathematical analysis of the general case [40–42].

The satellite is now moving on a orbit with instantaneous angular frequency \( \Omega \). We work in a (non-inertial) reference frame rotating at \( \Omega \) with origin at the centre of the satellite. A star at location \( r_s \) now feels the following forces: (i) a gravitational attraction by the satellite, (ii) a gravitational attraction by the host galaxy; (iii) an inertial force because the satellite is falling into the host and so the reference frame is not inertial and (iv) the Euler, Coriolis and centrifugal forces because the reference frame is rotating. Note that (iii) was not necessary in our earlier treatment of the circular restricted three-body problem because there we chose an inertial frame tied to the centre of mass.

The equation of motion for a star or dark matter particle is

\[ \ddot{r}_s = -Gm(r_s) \frac{r_s}{r_s^3} - GM(|r_s - r_h|) \frac{(r_s - r_h)}{|r_s - r_h|^3} - GM(r_h) \frac{r_h}{r_h^3} - \Omega \times r_s - 2\Omega \times \dot{r}_s \tag{22}\]

\[- \Omega \times (\Omega \times r_s) \]

Save for the assumption that the matter distributions in the satellite \( m(r_s) \) and the host \( M(r_h) \) are spherically symmetric, this expression is general.
We now assume that the star or dark matter particle is following a circular orbit around the satellite with orbital frequency $\Omega$, and that $r_s/r_h \ll 1$. By careful Taylor expansion, we obtain

$$\ddot{r}_s = -GM(r_s) \frac{r_s}{r_s^3} + GM(r_h) \frac{(3 - n)(r_s \cdot r_h) r_h}{|r_h|^5}$$

$$- GM(r_h) \frac{r_s}{r_s^3} - \dot{\Omega} \times r_s - 2\Omega \times (\Omega \times r_s)$$

$$+ \dot{\Omega} \times (\Omega \times r_s)$$

(23)

where $n(r_h)$ is the logarithmic gradient of $M(r_h)$.

To calculate the tidal radius, we now specialise to the case of a particle whose orbit lies in the same plane as the satellite’s orbit. The satellite’s circular frequency is $\Omega^2 = GM(r_h)/r_h^3$. The tidal radius is defined as the distance from the centre of the satellite at which there is no net acceleration, i.e., the forces on the particle towards the host and the satellite balance. This gives the tidal radius as

$$r_t = \frac{1}{(1 - n + 2\Omega_s/\Omega)^{1/3}} \left( \frac{m(r_s)}{M(r_h)} \right)^{1/3} r_h.$$  

(24)

When satellite and host are point masses, then $n = 0$ and $\Omega = \Omega_s$, and we recover the result previously found in Eq. (6).

We now define $u = r_t/r_h$ and $u' = r'/r_h$ for the inner and outer Lagrange points respectively, and obtain

$$u^3 = \frac{m(r_s)}{M(r_h)} \frac{1 - u^{2-n}u'}{1 - (1-u)^{2-n} + (1-u)^{2-n}u(2\Omega_s/\Omega - 1)}$$

$$u'^3 = \frac{m(r_s)}{M(r_h)} \frac{1 + u'^{2-n}u'}{(1 + u')^{2-n} - 1 + (1 + u')^{2-n}u'(2\Omega_s/\Omega - 1)}$$

(25)

(26)

We now solve for the difference in the positions of the Lagrange points with respect to the satellite centre $u' - u$. This is the natural stream asymmetry

$$\Delta r_{\text{nat}} \approx (u' - u) r_h = \left( \frac{m(r_s)}{M(r_h)} \right)^{2/3} \frac{(2-n)(3-n)r_h}{3(1-n + 2\Omega_s/\Omega)^{5/3}}$$

(27)

In the restricted three-body problem, $n = 0$ and $\Omega = \Omega_s$, so we recover our previous result in Eq. (16).

We wish to compare this asymmetry to the asymmetry produced by adding the modified gravity acceleration of the satellite to the equation of motion. Now specialising to the case $\Omega = \Omega_s$ to reduce complexity, we find the asymmetry due to the fifth force is

$$\Delta r_5 \approx - \frac{4}{3(3-n)} \beta^2 r_h.$$  

(28)

So, the requirement that the dark matter asymmetry overwhelms the natural asymmetry is

$$2\beta^2 \gg \frac{(2-n)(3-n)}{2(3-n)^{2/3}} \left( \frac{m}{M} \right)^{2/3}$$

(29)

which again reduces to Eq. (21) in the restricted three body case, as it should. For galactic dynamics, a reasonable choice is $n = 1$, which corresponds to a galaxy with a flat rotation curve, isothermal sphere. Assuming the stars in the satellite satisfy $\Omega = \Omega$, then tidal streams in galaxies with flat rotation curves are much more sensitive probes of the dark matter asymmetry. As we move from $n = 0$ (the point mass case) to $n = 1$ (the isothermal sphere), we gain an additional factor of $\approx 2.3$ in sensitivity. The changes are again in our favour. The asymmetries in tidal streams are therefore an even more delicate probe of the fifth force than suggested by the analysis in Ref [13].

III. MILKY WAY AND SATELLITE MODELS

In our simulations, we follow the evolution of a large number of tracer particles, stripped from a satellite galaxy and forming tidal tails. The test particles are accelerated by the gravity field of both the Milky Way and the satellite, together with any fifth force contributions. We begin by describing our models for the Milky Way and satellite.

A. Milky Way Model

We model the Milky Way potential with a static bulge, disc, and halo. For the Galactic bulge, we adopt a Hernquist sphere with-density-potential pair

$$\Phi = -\frac{GM_b}{r + a_H}, \quad \rho = \frac{M_b a_H}{2\pi r (r + a_H)^3},$$

(30)

and $a_H$ and $M_b$ give the scale radius and total bulge mass respectively. The mass enclosed in a given radius is

$$M(r) = M_b \frac{r^2}{(r + a_H)^2}.$$  

(31)

For all of our simulations, we adopt the parameter choices of Law and Majewski [14] and set $a_H = 0.7$ kpc and $M_{\text{bulge}} = 3.4 \times 10^{10} M_\odot$.

For the disc, we use a Miyamoto-Nagai profile [15],

$$\Phi = -\frac{GM_{\text{disc}}}{\sqrt{R^2 + (a_{\text{MN}} + \sqrt{z^2 + b_{\text{MN}}^2})^2}}.$$  

(32)

where $R$ and $z$ are cylindrical coordinates. $M_{\text{disc}}$, $a$, and $b$ represent the total mass, scale radius, and scale height respectively. For our Milky Way model, we again adopt the choices of Law and Majewski [14], specifically $M_{\text{disc}} = 10^{11} M_\odot$, $a_{\text{MN}} = 6.5$ kpc, $b_{\text{MN}} = 0.26$ kpc. The mass enclosed with a given spherical radius $r$ does not have an analytic form. When required (see section III C), we calculate it numerically.
Finally, we adopt a Navarro-Frenk-White (NFW) profile \(^{[16]}\) for the dark matter halo,

$$\Phi = -4\pi G \rho_0 r_s^3 \frac{\ln \left(1 + \frac{r}{r_s}\right)}{r}, \quad (33)$$

where \(\rho_0\) and \(r_s\) are the scale density and scale radius respectively. The enclosed mass within a spherical radius \(r\) is given by

$$M(r) = 4\pi \rho_0 r_s^3 \left(\ln \left(1 + \frac{r}{r_s}\right) - \frac{r}{1 + \frac{r}{r_s}}\right). \quad (34)$$

We adopt the parameters \(M_{\text{vir}} = 10^{12} M_\odot\) and \(c_{\text{vir}} = 12\), which can be converted to values of \(a\) and \(\rho_0\) with

$$r_s = \frac{1}{c_{\text{vir}}} \left(\frac{3M_{\text{vir}}}{4\pi \Delta \rho_c}\right)^{1/3},$$

$$\rho_0 = \frac{4\pi r_s^3}{3} \left[\ln(1 + c_{\text{vir}}) - \frac{c_{\text{vir}}}{1 + c_{\text{vir}}}\right]. \quad (35)$$

So, at a given point, the acceleration on a test particle (neglecting any fifth forces for the moment) due to the Milky Way is given by the sum of the accelerations due to the disc, bulge and halo.

### B. Satellite Model

We model the satellite with a truncated Hernquist sphere with the density cut off at a radius \(r_t\). The reason for this sharp truncation will become clear in the discussion of the fifth force in \(\text{[16]}\). Defining a reduced radius \(x \equiv r/a_s\) (thus \(x_t \equiv r_t/a_s\)) where \(a_s\) is the scale radius of the profile, the density-potential pair is given by

$$\Phi(x) = \begin{cases} 
-\frac{Gm}{r_t} \left[1 + \frac{(1+x_t^2)}{x_t^2} \left(1 + \frac{1}{1+x_t} - \frac{1}{1+x_t^2}\right)\right], & x \leq x_t, \\
-\frac{Gm}{r_t}, & x > x_t.
\end{cases}$$

$$\rho(x) = \begin{cases} 
\frac{A}{x(1+x)}, & x \leq x_t, \\
0, & x > x_t.
\end{cases}$$

The density normalisation \(A\) is related to the total satellite mass \(m\) by

$$A = \frac{(1+x_t)^2}{x_t^2} \frac{m}{2\pi a_s^3}. \quad (37)$$

The mass enclosed within a reduced radius \(x\) is then

$$m(x) = \begin{cases} 
m \frac{x^2(1+x_t)^2}{x_t^2(1+x)^2}, & x \leq x_t, \\
m, & \text{otherwise}. \quad (38)
\end{cases}$$

For all satellites, we adopt truncation radii of \(r_t = 10 a_s\), or equivalently \(x_t = 10\).

The acceleration on any given test particle due to the satellite can then be calculated from the above relations. For self-consistency, the initial phase-space distribution of the tracer particles is that of a truncated Hernquist profile. Of course, this self-consistency is lost as the simulation advances in time, as many of the tracer particles are tidally removed by the Milky Way, but our assumed satellite potential remains unchanged in mass and shape. However, we will show in \(\text{[16]}\) that this assumption of an unchanging satellite potential is largely harmless.

### C. Fifth Forces

In addition to gravity, the satellite and the tracer particles also experience accelerations due to the fifth force. The satellite feels a fifth force sourced by the Milky Way, while the tracer particles also feel a fifth force sourced by the satellite. We assume spherical fifth force profiles in both cases. For the satellite, this is consistent with its gravitational potential, although the sphericity of the satellite may be distorted by its tidal disruption. For the Milky Way, the spherical symmetry is inconsistent with the presence of the disc. The scalar field profiles of disc galaxies have correspondingly discoid shapes \(\text{[27]}\). However, the scalar field profile is roughly spherical when \(r_{\text{scr, MW}}\) is much larger than the disc scale radius of 6.5 kpc (cf. Figure \(\text{[13]}\)). Even when this is not the case, it is unlikely that relaxing the assumption of spherical symmetry will have an appreciable qualitative impact on our results.

Eq. \((2)\) can be rewritten to give the expression for the modified gravity acceleration due to the satellite on tracer particle \(i\), situated at position \(x\),

$$a_{\text{5,sat}}^i(x) = 2\beta^2 Q_i Q_{\text{sat}}(r)a_{N\text{-sat}}(x), \quad (39)$$

where \(\beta\) is the coupling strength of the fifth force (an input parameter of our simulations), \(a_{N\text{-sat}}\) is the Newtonian acceleration due to the satellite, and \(Q_i\) and \(Q_{\text{sat}}(r)\) are the scalar charges of particle \(i\) and the satellite respectively. The latter is given by

$$Q_{\text{sat}}(r) = \begin{cases} 
1 - \frac{m(r_{\text{scr,sat}})}{m}, & \text{if } r \geq r_t, \\
1 - \frac{m(r_{\text{scr,sat}})}{m(r)}, & \text{if } r_t > r \geq r_{\text{scr,sat}}, \\
0, & \text{otherwise}. \quad (40)
\end{cases}$$

Here, \(m(r)\) is the satellite mass enclosed by radius \(r\), and \(r_{\text{scr,sat}}\) is its screening radius. \(Q_i\), meanwhile, differs between the particle types. As we assume the stars are fully screened against the fifth force, \(Q_i = 0\) for the star tracer particles. On the other hand, we take \(Q_i = 1\) for the dark matter tracer particles, which we assume to be a diffuse, unscreened component.
TABLE I. Parameters for each of the 4 progenitors. Here, \( \mathbf{x}_0 \) and \( \mathbf{v}_0 \) give the present position and velocity respectively (note that we run the simulations backwards then forwards again, so that the satellites end at their position now), \( a \) and \( m \) are the Hernquist scale radius and total mass of the satellite, and \( t_{max} \) is the total time over which each simulation is run; the farther orbits require more time to undergo an appreciable number of orbital periods. Note that \( 10^{17} \) seconds is \( \sim 3 \) Gyr. The parameters for Satellite A resemble the Pal-5 stream, B the Sagittarius stream, C the Orphan stream, and D a hypothetical stream at large distance.

| ID | \( \mathbf{x}_0 \) (kpc) | \( \mathbf{v}_0 \) (km/s) | \( a \) (kpc) | \( m \) \( (10^9M_\odot) \) | \( t_{max} \) \( (10^7 \text{s}) \) |
|----|-----------------|-----------------|--------|-----------------|-----------------|
| A  | (7.7, 0.2, 16.4) | (-44, -117, -16) | 0.01   | 0.0003          | 1               |
| B  | (19.0, 2.7, -6.9) | (230, -35, 195) | 0.5    | 5               | 1               |
| C  | (90, 0, 0)       | (0, 0, 80)      | 0.5    | 2.5             | 1.5             |
| D  | (150, 0, 0)      | (0, 0, 100)     | 1      | 5               | 2.5             |

Similarly, the modified gravity acceleration due to the Milky Way on particle \( i \) (which can now also represent the satellite) at \( \mathbf{x} \) is given by

\[
\mathbf{a}^{\text{MW}}_{i}(\mathbf{x}) = 2\beta Q_i Q_{\text{MW}}(r) a_{\text{N,MW}}(\mathbf{x}),
\]

where the symbols have analogous meanings to those above. The scalar charge of the Milky Way is given by

\[
Q_{\text{MW}}(r) = \begin{cases} 
1 - \frac{M(r_{\text{scr,MW}}, r_{\text{sat,MW}})}{M(r)}, & \text{if } r \geq r_{\text{scr,MW}}, \\
0, & \text{otherwise}.
\end{cases}
\]

If particle \( i \) represents the satellite, then we take the limiting value of the satellite scalar charge \( Q_i = Q_{\text{sat}}(r = r_{\text{sat}}) \). This is valid as long as the the Milky Way centre does not fall within the truncation radius of the satellite centre, which does not happen in this work.

The formalism given in this subsection demonstrates the utility of truncating the mass profile of the satellite. By so doing, we have made it straightforward to model the satellite as being fully screened \( (r_{\text{scr,sat}} = r_{\text{t}}) \), fully unscreened \( (r_{\text{scr,sat}} = 0) \), or partially screened \( (0 < r_{\text{scr,sat}} < r_{\text{t}}) \).

It is worth remarking that we have used the superposition principle to compute the joint fifth force of Milky Way and satellite on the tracer particles. Strictly speaking, the superposition is not valid in highly non-linear theories of gravity like chameleon gravity. In particular, environmental screening can affect the screening radii of objects. Linearity is, however, restored once the screening radii are fixed (as we do by hand), so that from that point on we can apply the superposition principle for computing the joint fifth force.

IV. METHODS

Approximate methods for quickly generating realistic streams by stripping stars at the tidal radius of a progenitor are now well established \[47–49\]. The methods work as restricted N-body simulations, in which we follow the orbital evolution of a large number of massless tracer particles. The stream particles are integrated in a fixed Galactic potential, together with the potential of the moving satellite. This method robustly reproduces the morphology of streams, in particular the locations of the apocentres of the leading and trailing branches, yet provides two to three orders of magnitude speed-up compared to conventional N-body experiments \[49\].

All of our code is made publicly available as the python 3 package smoggy (Streams under MOdified GravitY) \[50\]. Animations of the simulations depicted in Figures \[4, 6, 10 \] and \[14 \] are given as Supplemental Material accompanying this article \[51\].

A. Tracer Particles

To generate the initial phase space distribution of \( N \) tracer particles, we use a Markov Chain Monte Carlo technique to generate \( 2N \) samples from possible equilibrium distribution functions (DFs) for the Hernquist
model. The choice of equilibrium includes the isotropic DF \[ \text{Eq. (43)} \]

\[
f(\tilde{E}) = \frac{1}{\sqrt{2}(2\pi)^3} \left( \frac{\sqrt{\tilde{E}}}{(1 - \tilde{E})^{3/2}} \right) \times \left( 1 - 2\tilde{E} \right) \left( 8\tilde{E}^2 - 8\tilde{E} - 3 \right) + \frac{3\sin^{-1}\sqrt{\tilde{E}}}{\sqrt{\tilde{E} (1 - \tilde{E})}} \]

and the radially anisotropic DF \[ \text{Eq. (52)} \]

\[
f(\tilde{E}) = \frac{3}{4\pi^3} \frac{\tilde{E}}{G\tilde{L}}. \]

Here, \( E \) is the specific (binding) energy of a particle, \( a_\text{S} \) is the scale radius, \( M' = (1 + x_i)^2 m/x_i^2 \) is the untruncated mass of the satellite, while \( \tilde{E} = E a_\text{S}/GM' \) is the dimensionless binding energy. The DFs differ in the anisotropy of the velocity distributions. In fact, our simulations show similar results for stream generation, irrespective of the anisotropy, so the choice of equilibrium is not so important.

Given these \( 2N \) samples, we integrate the orbits of the particles in the satellite potential (i.e. neglecting fifth forces and the Milky Way) for \( 10^{15} \) seconds (\( \approx 3 \) Gyr). At the end of this, we randomly downsample \( N \) of these particles, excluding any particles for which the orbit ever strayed beyond the truncation radius. This gives a suitable equilibrium distribution of positions and velocities for the test particles in our simulations.

B. Orbit Integration

To calculate the trajectories of the various particles, we use a second-order leapfrog integrator. Under such a scheme, the velocities \( \mathbf{v} \) and positions \( \mathbf{x} \) of the particles are updated at each timestep \( i \) via

\[
\mathbf{v}_{i+1/2} = \mathbf{v}_{i-1/2} + a(x_i) \Delta t, \]

\[
\mathbf{x}_{i+1} = \mathbf{x}_i + \mathbf{v}_{i+1/2} \Delta t, \tag{45}
\]

where \( \Delta t \) represents the timestep size, and \( a(x) \) represents the accelerations calculated using the expressions given in Sections IIIA, IIIB, and IIIC. At the start of the simulation (i.e. timestep \( i = 0 \)), the ‘desynchronised’ velocities \( v_{-1/2} \) are obtained using

\[
v_{-1/2} = v_0 - \frac{1}{2} a(x_0) \Delta t. \tag{46}
\]

From here, Eq. (45) can be used repeatedly to advance the system in time.

Our method for choosing the timestep size \( \Delta t \) is as follows. During the relaxation phase in which the orbits are integrated in the satellite potential for \( 10^{17} \) seconds, we calculate the total energies of all particles at the start and end. We repeat this, iteratively reducing the timestep size, until the energies of all particles are conserved to within 2%. Through experimentation, we found that energy conservation is a good proxy for numerical convergence and this 2% criterion gives accurate, converged results. The final timestep size chosen by this process is then used again for the main simulation. In practice, we find \( \Delta t \sim \mathcal{O}(10^{11}) \) seconds typically.

C. Simulations

We simulate the generation of streams from 4 progenitors. Satellite A is inspired by the Palomar 5 stream \[29\], B the Sagittarius stream \[44\], C the Orphan stream \[8\], and D is a hypothetical stream at large Galactocentric distance, of the kind that is likely to be found in the later Gaia data releases. The parameters for these 4 progenitors are given in Table I.

Figure 2 shows the evolution of the orbits over \( \sim 3 \) Gyr for each of the 4 satellites, under standard gravity. Also shown are lines indicating the disc-plane Milky Way screening radii for a range of values of \( f_{\text{MW}} \). These calculations were performed using the scalar field solver within the \( f(R) \) N-body code MG-GADGET \[53\] for the Milky Way model described in IIIA. We demonstrate later that significant stream asymmetries develop when the orbit is mostly outside the Milky Way screening radius, so these lines give a preview of the modified gravity constraints achievable.

For each satellite, we explore a variety of modified gravity scenarios by varying 3 input parameters: the coupling strength \( \beta \), the satellite screening radius \( r_{\text{scr,sat}} \), and the Milky Way screening radius \( r_{\text{scr,MW}} \). First, we consider 4 coupling strengths: \( \beta = \{0.1, 0.2, 0.3, 0.4\} \). The strength of the fifth force relative to gravity is given by \( 2\beta^2 \), so this corresponds to the range from 2% – 32%. The most extreme case can therefore be used as an approximate analogue for \( f(R) \) gravity, where the strength of the fifth force is 1/3 that of gravity.

For the satellite screening radius, we explore a range of regimes, from fully screened to fully unscreened, and encompassing a variety of partially screened regimes in between. Using the upper case of Eq. (40), we recast the screening radius \( r_{\text{scr,sat}} \) as the scalar charge \( Q_{\text{sat}} \), and consider a range of values of \( Q_{\text{sat}} \) from 0 to 1 in steps of 0.1. We recall that \( Q_{\text{sat}} = 0 \) corresponds to the fully screened case, so here \( r_{\text{scr,sat}} = 10a \), where \( a \) is the Hernquist scale radius of the satellite in question. \( Q_{\text{sat}} = 1 \) is the fully unscreened case, so \( r_{\text{scr,sat}} = 0 \).

Finally, we consider a range of values for the Milky Way screening radius \( r_{\text{scr,MW}} \). As the orbital distances of each satellite are different, it is useful to select a different range of values for \( r_{\text{scr,MW}} \) for each satellite. For each satellite, we define a maximum screening radius \( r_{\text{scr,max}} \), approximately equal to the apocentric distance of the orbit under standard gravity. These values are \( r_{\text{scr,max}} = 20, 50, 90, 150 \) kpc for satellites A, B, C, and D.
respective. Then, we choose a range of 11 values such that \( r_{\text{scr, MW}}/r_{\text{scr, max}} \) runs from 0 to 1 in steps of 0.1.

Altogether, we run 485 simulations for each satellite: \( 4 \times 11 \times 11 = 484 \) modified gravity simulations plus one standard gravity (\( \beta = 0 \)) simulation.

D. Assumptions

The previous subsections have given details about the various parts of our code, but for clarity we provide a list of all of our simplifying assumptions:

1. We neglect self-gravity between the tracer particles, both before and after they are stripped from the satellite, as is typical in Lagrange stripping codes [11, 49].

2. We assume the gravitational attraction on the tracer particles due to the satellite can be approximated as that due to a (truncated) Hernquist sphere, whose orbit is only governed by the Milky Way potential. This assumption has been verified against full N-body simulations of stream formation by others [17, 49].

3. We assume the depth and radial extent of the satellite potential well does not change over time. While this assumption could be relaxed in the standard gravity case, it is a greatly helpful one in the chameleon case. Thus, to allow a fair comparison between results in the two cases, we make the assumption universally.

4. We assume a static, axisymmetric model for the Milky Way potential, composed of a disc, bulge, and halo. Dynamical friction is therefore not modelled, though the effect is negligible at these low mass ratios [55]. We neglect any effects due to the Large Magellanic Cloud or other Milky Way satellites (cf. Koposov et al. [8]).

5. While we typically sample equal numbers of stellar and dark matter particles, we assume the mass profiles of our satellites to be dark matter dominated. So, the satellites feel the full fifth force in the absence of screening.

6. The initial density profile and kinematics of the stellar and dark matter particles in the satellites are assumed to be the same. This simplifies the fifth force calculation, and allows us to ensure any difference in the stellar and dark matter streams is due to the fifth force rather than initial conditions.

Assumptions [1-6] apply equally in the standard gravity and modified gravity simulations. The following three assumptions, however, apply only in the simulations including a fifth force.

7. We adopt spherical fifth force profiles around both the Milky Way and the satellite, despite the Milky Way potential being non-spherical.

8. Furthermore, we assume this spherical screening surface of the satellite remains fixed throughout the satellite’s orbit. In reality, the radius would vary as the Galactocentric distance of the satellite changes, due to environmental screening, and the shape of the screening surface (and surrounding fifth force profile) would likely become aspherical as the satellite approached the Milky Way’s screening radius and non-linear effects warp the screening surface.

9. The Compton wavelength of the scalar field is assumed to be much larger than relevant length scales. In the context of Hu-Sawicki \( f(R) \) gravity, the Compton wavelength is given by \( \lambda_C \approx 32 \sqrt{|f_{R0}|/10^{-7}} \text{ Mpc} \) [50], so this assumption starts to break down at around \( f_{R0} \sim 10^{-8} \).

V. CODE VALIDATION

As validation, we compare the results of our code for disruption of the Sagittarius dwarf galaxy under standard Newtonian gravity with the results of Law and Majewski [44]. They simulate the formation of the stream using a full N-body disintegration of the satellite in a static Milky Way potential, so assumptions (1)-(3) in the list in [17] are not made in their work. In other words, the gravitational attractions of the satellite and stream are there treated in fully self-consistent manner.

To set up this test, we adopt the Milky Way potential of Ref. [44], i.e. the same Hernquist bulge and Miyamoto-Nagai disc described in [17] but with a triaxial logarithmic dark matter halo replacing the spherically symmetric NFW halo. The parameters and initial conditions for the satellite are the same as those for Satellite B, given in Table [1].

As a first test, we integrate the orbit of the satellite in this potential backwards for \( 2.5 \times 10^{17} \) seconds (\( \sim 8 \) Gyr). The distance of the satellite from the Galactic centre as a function of time is shown in the left-hand panel of Figure [3]. This shows excellent agreement with Figure 7 from Law and Majewski [44].

It is also desirable to check the morphology of the streams generated with our method. As a second test, we integrate the orbit of the satellite backwards for \( 10^{17} \) seconds (\( \sim 3 \) Gyr), and then forwards again with 16000 tracer particles. The resulting leading and trailing streams from this simulation are shown in the right-hand pair of panels in Figure [3]. The detailed morphologies of these streams closely resemble those of the streams depicted in Figure 8 of Law and Majewski [44], considering only the orange and magenta particles in that figure (i.e., particles liberated within the last 3 Gyr).
FIG. 3. Our reproduction of a simulation from Law and Majewski [44] Left: Distance of the simulated Sagittarius dwarf from the Galactic centre over 8 Gyr (to be compared to the results in Figure 7 from Ref [44]). Middle and right: First wrap of the leading and trailing streams respectively (to be compared to the results in the two left-hand panels of Figure 8 of Ref [44]).

The curve represents the orbital path of the satellite, culminating in the current position of the Sagittarius dwarf, represented by the filled circle. The green points are the positions of the simulation particles. The satellite orbit has been integrated over 3 Gyr up to the present day, so the morphology of the streams should resemble only the orange and magenta particles from the original figure. This successful reproduction of literature results serves as a test of our code, and checks several of our simplifying assumptions.

Despite this reassuring agreement between the results from our simplified code and those from full N-body simulations, it is worth noting that several of the assumptions stated in [IVD] are not addressed by this test. In particular, this test does not validate the assumptions made in the treatment of the fifth force. However, the aim of the present work is to provide a qualitative understanding of the effects of chameleon gravity on stellar streams. Future work aiming to derive quantitative constraints from observational data will likely require either a relaxation or a more careful justification of some of these assumptions.

VI. RESULTS

A. Standard Gravity

Figure 4 shows the images from the standard gravity simulations for all 4 satellites listed in Table I. Each of the four quarters of the Figure represents one of the satellites, as labelled in the top corner. The large subpanel in each quarter shows an image of the stream particles at the end of the simulation. As the stellar and dark matter particles are sampled from the same probability distribution initially (see assumption 6 in §IV) and there is no EP-violation by a fifth force in these standard gravity simulations, the stars and dark matter particles are indistinguishable and are thus not plotted separately in this Figure. The three smaller subpanels in each quarter show the average velocity along the stream, velocity dispersion along the stream, and velocity dispersion perpendicular to the stream, all as a function of stream longitude and all calculated in bins of particles along the stream. The bins are created adaptively, such that each bin contains 25 particles, including only the particles which have been stripped from the progenitor. Within each bin, the unit vector giving the direction ‘along the stream’ is taken as the (normed) average velocity vector of all particles in the bin. This Figure illustrates the diversity of our simulated streams, with a variety of morphologies and Galactocentric distances represented.

B. Unscreened Fifth Force

First, we discuss the results from an unscreened, EP-violating fifth force coupling only to dark matter ($r_{\text{scr,sat}} = r_{\text{scr,MW}} = 0$). This is the case studied by Kesden and Kamionkowski [13, 14]. This case also applies in screened modified gravity with a (formally) universal coupling if stars self-screen, but screening is not triggered otherwise. In our work, the strength of the fifth force relative to gravity is given by $2\beta^2$, in keeping with the recent modified gravity literature, whereas Kesden and Kamionkowski used $\beta^2$. Thus, the simulation depicted in Figure 6 (for example ($\beta = 0.2$, $F_5/F_N = 0.08$), is most comparable to the ‘$\beta = 0.3$’ ($F_5/F_N = 0.09$) simulation in Refs [13] [14].

Figure 5 shows the shape of Satellite B’s orbit for a variety of values of $\beta$. In the absence of screening, the introduction of a fifth force as in Eq. (1) is tantamount to an overall linear rescaling of the Milky Way mass or gravitational constant by a factor of $1 + 2\beta^2$. As a conse-
FIG. 4. The simulated streams under standard gravity. The four quarters represent our 4 satellites: A (upper left), B (upper right), C (lower left), and D (lower right). In each quarter, the largest subpanel shows an image of all stream particles in the orbital plane, at the end of the simulation. No distinction is made between star and dark matter particles. The colours differentiate leading and trailing streams, with the darker shade being the trailing stream. For Satellite B, additional shades are used to distinguish multiple wraps. The black cross shows the position of the centre of the Milky Way, while the filled circle shows the final position of the Satellite, with an arrow indicating its instantaneous direction of travel. The side-panels show three quantities calculated in bins of particles: average velocity along the stream, velocity dispersion along the stream, and velocity dispersion perpendicular to the stream. Here again, the colours differentiate leading and trailing streams, with the darker shade being the trailing stream. For Satellite B, additional shades show three quantities calculated in bins of particles: average velocity along the stream, velocity dispersion along the stream, and velocity dispersion perpendicular to the stream. Here again, the colours differentiate leading and trailing streams, with the darker shade being the trailing stream. For Satellite B, additional shades

sequence, the orbital period of the satellite is shorter and the apocentric distance smaller, as is apparent in Figure 3.

Figure 5 shows the positions of the dark matter and star particles in the simulation with $r_{\text{scr, sat}} = r_{\text{scr, MW}} = 0$ and $\beta = 0.2$ for Satellite C, at 11 equally spaced snapshots over time (recall that animations of selected simulations are available online). The most striking feature is the asymmetry of the stellar stream. The preponderance of star particles populate the trailing stream, rather than the leading stream. The enhanced rotation speed of the satellite due to the fifth force means that the outward centrifugal acceleration of the stars outweighs the inward gravitational acceleration by the Milky Way. Consequently, stars are more likely to leave the satellite via the outer Lagrange point. Also, even some of the stars which are disrupted from the inner Lagrange point can eventually end up in the trailing stream, once sufficient time has passed for them to be overtaken by the satellite. Meanwhile, the dark matter particles experience the same fifth force as the satellite, and so there is (almost) no preferential disruption via either Lagrange point. The dark matter stream that forms, is consequently almost symmetric around the progenitor.

These effects are also apparent in Figure 5, which shows the longitude difference $\Delta \Lambda = \Lambda - \Lambda_{\text{sat}}$ as a function of time for all particles in the simulations without screening with $\beta$ increasing in strength from 0.0 to 0.4 in steps of 0.1 for all 4 satellites. Here, $\Lambda$ is the longitude in the instantaneous orbital plane of the satellite and increases in the direction of the satellite’s motion, so particles in the leading stream have positive $\Delta \Lambda$. The
dark matter particles are stripped almost equally into the leading and trailing streams, leading to streams that are nearly symmetric about the progenitor for all values of $\beta$. For the stars, however, as $\beta$ increases, the particles are increasingly disrupted into negative longitudes, i.e. the trailing streams.

Sometimes, the satellite can be stripped completely of all of its stars. Then, the spatial separation between satellite and stream can be very large indeed, as no new stars become unbound from the satellite in order to bridge the gap. This occurs in Satellite A for both $\beta = 0.3$ and 0.4, as it loses all of its stars at its first pericentric passage. Satellite A, which is significantly less massive than our other satellites, does not have a sufficiently deep potential well for its stars to remain bound under the enhanced centrifugal force from the Milky Way. Some caution is needed because assumption 3 for example, may begin to break down when the disruption of the satellite due to the Milky Way is so severe. However, all our satellites are, by assumption, dark matter dominated. Even in the simulations where the satellites lose all of their stars, they still retain a large fraction of their dark matter particles, and thus most of their assumed mass.

C. Chameleon Screening

We now show results from the chameleon simulations, i.e. the simulations with screening. Unlike the dark matter force investigated in the previous subsection, the fifth force here is universally coupled. However, as discussed in the Sections 1 and 11, an effective EP-violation arises because main sequence stars are self-screened against the fifth force in parameter regimes of interest.

Figure 8 is the analogue of Figure 5 now showing the effect on the satellite’s orbit of a varying Milky Way screening radius. In the case of the outermost screening radius of 45 kpc, the entire orbit is situated within $r_{\text{scr}, \text{MW}}$ so this can be taken as equivalent to the standard gravity case. Following along this orbit from plotted position of the progenitor, the other orbits peel away one by one, in order of increasing screening radius. In other words, once the orbit passes outside the screening radius, the fifth force becomes active and the orbit starts to diverge from the standard gravity case. Recalling from Eq. (1) that the fifth force is proportional to the mass between the test particle and the screening radius, the divergences do not become noticeable as soon as the orbit passes out of a given screening radius, but some time after, once this enclosed mass is large enough for an appreciable fifth force.

Looking instead at the impact of the Milky Way screening radius on stream asymmetries, one observable quantity is the ratio of the number of stars in the leading to the trailing stream,

$$\alpha = \frac{N_{\text{lead}}}{N_{\text{trail}}}.$$  \hspace{1cm} (47)

Figure 9 shows this quantity as a function of Milky Way screening radius for all satellites, assuming $Q_{\text{sat}} = 1$, i.e. fully unscreened satellites. To ensure a fair comparison between simulations, $\alpha$ is computed in each case at the moment of the satellite’s third pericentric passage. As the $r_{\text{scr}, \text{MW}}$ increases, the asymmetry is progressively reduced. This appears to particularly be the case when $r_{\text{scr}, \text{MW}}$ lies between the pericentre and apocentre of the orbit. This makes sense, as most tidal disruption occurs at and around pericentric passage. Therefore, screening the pericentre has the consequence of reducing the asymmetry of this disruption process. For all of our satellites, the streams are indistinguishable from those in the standard gravity case once $r_{\text{scr}, \text{MW}}$ exceeds the apocentric distance.

We have observed in our simulations interesting signatures of chameleon gravity other than the stellar asymmetry. Examples of these are depicted in Figure 10. First, in the extreme (high $\beta$) fifth force regime, the orbital paths of released stars around the Milky Way differ appreciably from their progenitor. However, because stars are released from the progenitor at different times, this also means that the liberated stars can be on different Milky Way orbits from each other. If most releases occur at pericentric passages, this can lead to a ‘striping’
FIG. 6. The simulation depicted here is Satellite C with no screening and a fifth force coupling only to dark matter with $\beta = 0.2$. The large panel shows an image of the stellar (purple) and dark matter (green) streams at the end of the simulation, while the smaller panels above show the evolution over time. The interval between images is $1.5 \times 10^{16}$ seconds ($\sim 0.48$ Gyr, as labelled). The cross and large filled circle respectively indicate the positions of the Milky Way and satellite centres. In the large panel, 50 unbound particles have been randomly chosen from each species, and arrows of the corresponding colour are shown indicating their velocities. An animation of this simulation is included in the Supplemental Material accompanying this article. This Figure shows the formation of an asymmetric stellar stream over time.
FIG. 7. The longitude difference $\Delta \Lambda = \Lambda - \Lambda_{\text{sat}}$ as a function of time for all 4 satellites without screening. Each column shows a different fifth force coupling from $\beta = 0$ to 0.4 in steps of 0.1. Here, $\Lambda$ is longitude in the orbital plane of the satellite, increasing in the direction of the satellite’s orbit. Lines are drawn for all particles in the simulations. Complementing Figure 6, this Figure shows the development over time of the asymmetry of the stellar streams, and the increased magnitude of this effect with $\beta$. 
FIG. 8. Satellite B’s orbit in its orbital plane, shown for \( r_{\text{scr,MW}} = 0, 8, 24, 50, 85 \) kpc, and \( r_{\text{scr,sat}} = 0, \beta = 0.4 \). The dotted circles indicate the position of the screening radius in each case. The cross indicates the Galactic centre and the filled circle shows the final position of the satellite, i.e. the current observed position of the Sagittarius dwarf galaxy. This Figure illustrates the effect of a Milky Way screening radius on the satellite orbital shapes.

Secondly, if the satellite itself is fully screened or almost so (i.e. low \( Q_{\text{sat}} \)), then it orbits the Milky Way more slowly than the dark matter that has been released and inhabits unscreened space. Then, we observe the opposite asymmetry to that of the stars: the dark matter is preferentially disrupted into the leading stream rather than the trailing stream. This effect is shown in the lower panel of Figure 10. While interesting, this effect is of course not readily accessible to observations.

D. Future Constraints

The later Gaia data releases will likely enable the discovery of stellar streams at large distances from the Galactic centre. As shown in Figure 9, such streams are able to probe larger Milky Way screening radii, and therefore ‘weaker’, or more screened, regions of modified gravity parameter space, potentially down to the level at which screening by our Local Group is triggered.

Figure 11 shows \( \alpha \) evaluated for all of our simulations of satellite D, as a function of \( r_{\text{scr,MW}} \), \( Q_{\text{sat}} \), and \( \beta \). As with Figure 9, \( \alpha \) is computed in each simulation at the

FIG. 9. The asymmetry parameter \( \alpha \equiv \frac{N_{\text{lead}}}{N_{\text{trail}}} \), for all simulations with \( Q_{\text{sat}} = 1 \). The 4 panels correspond to the 4 satellites and the different textures of line correspond to different values of \( \beta \). In each panel, the shaded region indicates the radial range of the satellite’s orbit. As with the horizontal lines in Figure 2, the vertical dashed lines here show the locations of Milky Way screening radii for various values of \( \log_{10}|f_R| \). This Figure shows the Milky Way screening radius can affect the stream asymmetry. Streams at larger Galactocentric distances are sensitive to larger screening radii, and therefore weaker modified gravity regimes.
moment of the satellite’s third pericentric passage. This Figure illustrates many of our earlier points; increasing $\beta$ increases the magnitude of the asymmetry, but the asymmetry is reduced by increasing $r_{\text{scr,sat}}$ (reducing $Q_{\text{sat}}$) or $r_{\text{scr,MW}}$. In the $\beta = 0.4$ case, approximately comparable to $f(R)$ gravity, the asymmetries grow large when $r_{\text{scr,MW}} \lesssim 100$ kpc, assuming the satellite is fully unscreened ($Q_{\text{sat}} = 1$). Notably, this lies between the apocentre and pericentre of the satellite’s orbit. Most tidal disruption occurs at pericentric passage, but here there is still enough disruption outside the screening radius, and sufficient numbers of leading stars lagging behind the satellite, that a large asymmetry develops anyway.

We can again use Hu-Sawicki $f(R)$ gravity to give an indication of the kinds of constraints attainable here. Figure 12 shows how the Milky Way screening radius depends on the parameter $f_{R0}$. These calculations were performed using the scalar field solver within the $f(R)$ N-body code MG-GADGET [54], calculating the fifth forces in the Milky Way model described in [41]. MG-GADGET uses a Newton-Gauss-Seidel relaxation method to solve the $f(R)$ equations of motion, calculating the scalar fields and fifth forces everywhere in a given simulation volume. Such methods were first explored in the work of Oyaizu 57, and the subsequent years have seen a proliferation of codes simulating a myriad of modified gravity cosmologies 58–65. It should be noted that this Figure should only be treated as approximate, as the environmental contribution to the scalar field by our Local Group has been neglected.

We see that Satellite D is able to probe the region $\log_{10} f_{R0} \ll -7.2$. However, if the satellite itself is partially screened, the sensitivity is greatly reduced. It is natural therefore to wonder about the degree to which a satellite would be screened at these values of $f_{R0}$ and this region of the Milky Way’s halo.

Figure 13 shows the scalar field profile around the Milky Way for $f_{R0} = -10^{-7}$, again inferred using MG-GADGET. A Hernquist sphere identical to Satellite D has been inserted at Galactocentric ($X = 100, Y = 0, Z = 100$) kpc. There is a clear screened region in the centre of the Milky Way halo, with $r_{\text{scr,MW}} \approx 80$ kpc. The satellite, however, is unscreened, except for the self-screening of host stars. Therefore, in an $f(R)$ Universe, this satellite would provide very asymmetric streams. This is demonstrated in Figure 14, which shows a simulation with a similar setup: Satellite D with $\beta = 0.4$, $r_{\text{scr,MW}} = 90$ kpc and conservatively, $Q_{\text{sat}} = 0.5$. The left-hand panel shows the stream, while the right-panel shows a more sophisticated observable signature than the asymmetry parameter: the cumulative number function of stars in each stream as a function of longitude in the orbital plane of the satellite. The difference in the two curves is rather striking, and should be clearly discernible in the data.

The examples shown in Figures 13 and 14 serve as proof of concept, demonstrating that stellar streams in the outer reaches of our Galaxy’s halo are a sensitive probe of modified gravity. The observation of highly symmetric streams at large Galactocentric distances would rule out sizeable fifth forces that couple differently to dark matter and stars in the outskirts of the Milky Way. This in turn would provide sensitive constraints on screened modified gravity theories. For instance, looking at Figure 12, symmetric streams at distances of $\sim 150–200$ kpc would require $|f_{R0}| \lesssim 10^{-7.5}$ or even...
FIG. 11. The asymmetry parameter $\alpha \equiv N_{\text{lead}}/N_{\text{trail}}$ for the unbound stellar particles in all simulations of satellite D with screening, shown here as a function of $Q_{\text{sat}}$ and $r_{\text{scr, MW}}$, with different panels corresponding to different values of $\beta$. This Figure shows the effects of varying all of our parameters on the stream asymmetries.

On the other hand, observations of highly asymmetric streams would strengthen the case for screened modified gravity theories. It should be noted, however, that mild asymmetries can arise due to dynamical effects. Indeed, an asymmetry between the leading and trailing streams is expected from Eq. (27). This may be compounded by dynamical interactions with dark subhaloes or other satellites [66], asymmetries in the stellar populations in the progenitor satellite [67, 68], effects of the Galactic bar [53] and regions of chaos in the Galactic potential [69]. Such effects would have to be carefully weighed before a modified gravity interpretation could be seriously considered for such observations.

VII. CONCLUSIONS

We have investigated the possible imprints of chameleon gravity on stellar streams from dwarf galaxies around the Milky Way. While canonical chameleon theories are universally coupled, an effective violation of the equivalence principle (EP) arises because of the self-screening of main sequence stars, as noted by Hui et al. [33]. Consequently, stars are preferentially stripped from the progenitor into the trailing stream rather than the leading stream.

We have created a restricted N-body code (smoggy; made publicly available [70]), and used it to simulate the formation of tidal streams from progenitors, with a variety of masses and Galactocentric distances. We considered a range of modified gravity scenarios (coupling strength, Milky Way screening level, satellite screening level) in each case.

As found by Kesden and Kamionkowski [13, 14], an EP-violating fifth force that couples to dark matter but not baryons causes asymmetries to develop in stellar streams with dark matter-dominated progenitors. The stars are preferentially disrupted via the outer Lagrange points into the trailing streams. We have corrected and augmented the analytic calculations of Ref [13] for...
point masses so that they are also applicable to extended
Galactic mass distributions like isothermal spheres. The
effect of these changes is to make the test more sensitive
to EP-violating fifth forces. For the most massive dwarf
spheroidals, like the Sagittarius or Fornax, the criterion
given in Eq. (29) suggests values of $\beta^2 \gtrsim 10^{-3}$ can be
probed. For the smallest dwarf spheroidals such as Segue
1 with a mass of $6 \times 10^8 M_\odot$, then values of $\beta^2 \gtrsim 10^{-4}$
are in principle accessible. As a rule of thumb for a satellite
with mass $m$ at a location enclosing a Milky Way mass
$M$, the form of the criterion suitable for a flat rotation
curve galaxy is

$$\beta^2 \gtrsim 2^{-5/3} \left(\frac{m}{M}\right)^{2/3}. \quad (48)$$

This asymmetry also occurs in the chameleon context,
when screening radii are introduced to the Milky Way
and satellite, and with stars self-screening. The magni-
tude of the asymmetry depends on the coupling strength
$\beta$, the Milky Way screening radius, as well as the de-
gree of screening of the stream progenitor; large values
of $\beta$ give large asymmetries, but these are reduced with
increasing $r_{\text{scr}, \text{MW}}$ and $r_{\text{scr}, \text{sat}}$.

Our simulations—the most comprehensive to date for
the formation of tidal streams under chameleon gravity—
have revealed further interesting effects. First, the trail-
ing stellar stream may become detached from the dark
matter progenitor if all the stars are exhausted by ear-
lier pericentric stripping. As an example, this effect is
visible in Figure 7 and occurs for low mass satellites in
the extreme fifth force regime. Second, prominent stri-
ations in the stellar trailing tail may exist if stars are
stripped at repeated pericentric passages by a strong fifth
force. Thirdly, if the satellite is fully screened, its or-
bital frequency is lower than that of its associated dark
matter. This leads to strong asymmetries in the dark
matter distribution, which is preferentially liberated into
the leading tidal tail. Taking Hu-Sawicki $f(R)$ gravity
with $f_{R0} = -10^{-7}$ as an example, we derive a Milky
Way screening radius of around 80 kpc. A massive dwarf
spheroidal galaxy at a distance of $\approx 150$ kpc—such
as Fornax—would be fully unscreened (except for self-
screening stars) and produce highly asymmetric streams
under tidal disruption.

The ratio of the cumulative number function of stars
in the leading and trailing stream as a function of longi-
tude from the satellite is computable from simulations,
measurable from the observational data and can provide
a direct test of theories with screening mechanism, like
chameleon gravity. The later Gaia data releases may lead
to discoveries of stellar streams at distances $\gtrsim 100$ kpc
from the Galactic centre. These streams will be a sen-
sitive probe of modified gravity; such highly asymmetric
streams at these distances would be tell-tale signatures
of modified gravity.

On the other hand, if the data uncover a number of
very symmetric streams, then constraints down to the
level of $f_{R0} \sim -10^{-8}$—the tightest constraints to date—
could be attainable if the screening of the satellite and
other nuisance parameters are carefully taken into ac-
count, and assuming that the Local Group does not yet
environmentally screen the whole Milky Way halo at
these $f_{R0}$ values. Also, our assumption that the Compt-
ton wavelength is much larger than relevant length scales
begins to break down at such values of $f_{R0}$, and Yukawa
suppression will become appreciable below $f_{R0} \sim 10^{-8}$.
Of course, the investigation need not be limited to Hu-
Sawicki $f(R)$ gravity. Sensitive constraints will also be
attainable in the general chameleon parameter space, and
we merely use $f(R)$ gravity as a fiducial theory.

Finally, we note that other screened modified gravity
theories can also be probed with stellar streams. For in-
stance, the symmetron screening mechanism [71, 72] has
a simple density threshold as a screening criterion. Con-
sequently, there will necessarily be a region of parameter
space in which the stars are screened, but the surround-
ing diffuse dark matter component is not. In this regime,
stream asymmetries will also be present and are worthy
of future investigation.
FIG. 14. Left: An image of a simulation of Satellite D, with $r_{scr, MW} = 90$ kpc, $Q_{sat} = 0.5$, $\beta = 0.4$. The dotted circle shows the location of the Milky Way screening radius, while the cross and filled circle show the locations of the Milky Way and satellite centres respectively. The arrow shows the current direction of motion of the satellite. Right: Cumulative number of stars in either stream, as a function of longitude in the instantaneous orbital plane of the satellite. An Animations of this simulation is included in the Supplemental Material accompanying this article. This Figure, taken together with Figure 13, shows that $f(R)$ gravity with $f(R) \sim -10^{-7}$ should give a clear observational signature in stellar streams between 100 and 200 kpc.

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https://github.com/aneeshnaik/smoggy

See Supplemental Material at [URL will be inserted by publisher] for animations of the simulations depicted in Figures 4, 6, 10 and 13

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