# 259. More on streams and sub-halos

THIS IS THE THIRD of my current series of essays on stellar streams in our Galaxy's halo, and one of several on the topic extending back over the past four years. As I said in my previous introductions, the subject of stellar streams is at the forefront of Gaia's scientific impacts – and it continues to develop rapidly.

Some of the recent work has aimed to quantify their sensitivity to perturbations from dark-matter *sub-halos*. This is considered to be a major route for testing cold dark matter and alternative dark-matter models. In their recent review, Bonaca & Price-Whelan (2025) said: *'Perhaps most excitingly, [future observations] will be able to reveal the presence of dark-matter sub-halos below the threshold for galaxy formation ($\lesssim 10^6 M_\odot$), and provide the most stringent test of the cold dark-matter paradigm on small scales.'*

I WILL START with a qualitative picture. According to the current standard cosmological model, ΛCDM, the dark matter halo of our Galaxy is highly clumpy, with a swarm of perhaps thousands of self-gravitating, invisible 'sub-halos' orbiting within the main Galactic potential. These follow a steep mass function, with smaller sub-halos being substantially more numerous than larger ones (e.g. Madau et al., 2008).

Compared to the Milky Way, $M \sim 10^{12} M_\odot$, the most massive sub-halos ($10^8 - 10^{10} M_\odot$) pulled in enough baryonic matter to form stars, forming the Milky Way's satellite dwarf galaxies, notably the Magellanic Clouds and Sagittarius. Intermediate sub-halos ($10^6 - 10^8 M_\odot$, of dimensions 100–1000 pc) are typically dark, starless clumps that lack visible matter because their gravity was too weak to retain gas during the Universe's reionisation era. Depending on the nature of dark matter, the smallest sub-halos may extend down to $10^{-6} M_\odot$.

Because sub-halos are remnants of the smaller primordial structures that merged hierarchically to build the Galaxy, they retain significant momentum. Within our Galaxy's rest frame, typical orbital velocities are in the range 100–500 km s$^{-1}$, and they are constantly shaped by tidal stripping and dynamical friction as they move through the halo (e.g. Adams et al., 2025).

THESE DARK MATTER sub-halos are moving through the Galactic halo on high-velocity orbits, acting as gravitational 'bullets' that can punch through the relatively static stream tracks, resulting in gaps or spurs in a given stream's density profile (e.g. Ibata et al., 2002; Johnston et al., 2002; Siegal-Gaskins & Valluri, 2008; Yoon et al., 2011; Carlberg, 2012; Erkal et al., 2016; Barry et al., 2023; Adams et al., 2025; Menker & Benson, 2026).

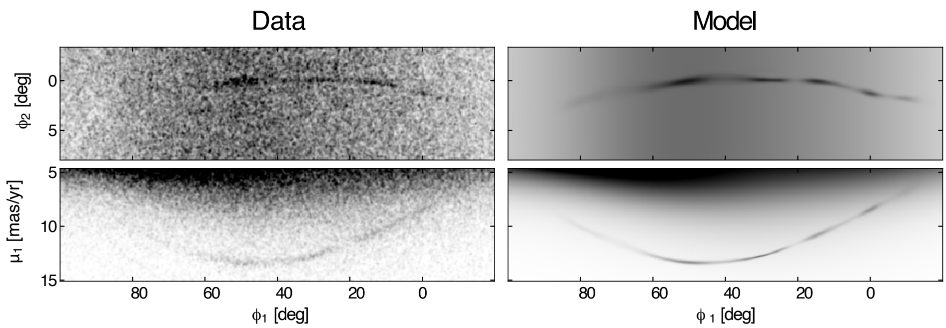
I should mention that other ways of demonstrating the existence of dark sub-halos have been suggested: these include searches for $\gamma$-ray emission due to dark matter annihilation (Lake, 1990; Calcáneo-Roldán & Moore, 2000; Diemand et al., 2007), detecting the coherent vertical velocities of disk stars attributable to the passage of such sub-structures through the Galactic disk (Feldmann & Spolyar, 2015), or through gravitational lensing (as detailed by Adams et al., 2025, §1).

IN MY PREVIOUS discussion of this topic with Gaia in essay 184 (July 2024), I gave some context, and described the evidence for dark-matter sub-halo effects in the GD–1 and Pal 5 streams.

Let me recap the status at that time. Following the discovery of the GD–1 stream from SDSS data (Grillmair & Dionatos, 2006), ground-based observations provided the first evidence for gaps along the stream (Koposov et al., 2010; Carlberg & Grillmair, 2013), confirming it as an excellent candidate for the study of gaps induced by dark sub-halos (Amorisco et al., 2016; de Boer et al., 2018; Koppelman & Helmi, 2020).

Further evidence for gaps and 'wiggles' attributable to perturbations came from the Gaia DR2 astrometry (Price-Whelan & Bonaca, 2018; de Boer et al., 2020). Alternative explanations as epicyclic overdensities due to tidal stripping near pericentre passages (Ibata et al., 2020), were themselves questioned by Banik et al. (2021a), who again invoked a population of dark substructures with masses in the range $10^7 - 10^9 M_\odot$.

Similar studies for the Pal 5 stream (essay 109) also suggested the presence of two gaps due to sub-halos of $10^6 - 10^7 M_\odot$ and $10^7 - 10^8 M_\odot$ (Erkal et al., 2017; Bonaca et al., 2020b; Banik et al., 2021a; Banik et al., 2021b).




I CAN SUMMARISE by stating that sub-halo impacts likely to cause gaps in these stellar streams have been variously studied both analytically and in simulations. These sorts of gaps, found in streams such as GD–1 and Pal 5, have been shown to be *consistent* with impacts from dark matter sub-halos of order $10^7 M_\odot$.

However, it should be kept in mind that other effects can also give rise to stream perturbations, including epicyclic density variations (Küpper et al., 2012; Ibata et al., 2020), progenitor disruptions (Webb & Bovy, 2019), or other satellites and baryonic structures such as the central bar (Erkal et al., 2017; Pearson et al., 2017; Banik & Bovy, 2019; Bonaca et al., 2020a; de Boer et al., 2020).

But in addition to gaps, sub-halos leave other signatures which should allow them to be definitively identified in the future. These include velocity perturbations and angular deflections – both the shift in position perpendicular to the stream's orbital plane, and the radial velocity motion, can provide important observables in assessing the effects of an impact (Lu et al., 2026).

And rather than identifying individual gaps, the cumulative history of sub-halo impacts can also be probed with the power spectrum of density fluctuations (Bovy et al., 2017). Binary star distributions may also provide further insights (Phillips et al., 2026).

INVESTIGATIONS of the GD–1 stream have continued. An improved model of the stellar stream density and membership has been developed by Tavangar & Price-Whelan (2025) based on Gaia DR3. Their model includes off-track or non-Gaussian components to the stream density, meaning that they can capture anomalous features such as the GD–1 steam's spur, and resulting in an enlarged catalogue of 1689 probable member stars.

An extract of their results (above) shows their data (left panels) and the model (right panels) in positional space ($\phi_2$ versus $\phi_1$), and proper motion space ($\mu_1$ versus $\phi_1$), where $\phi_1$ increases monotonically along the the stream. These models are aimed at replicating the observed density profiles, including the gaps and other off-track features, rather than modelling the structure as a result of interactions with putative sub-halos.

MORE DETAILED MODELS have been made by Adams et al. (2025). They generated many realisations of the sub-halo population within a Milky Way mass halo, accounting for the effects of tidal stripping and dynamical friction, and evaluating the impacts of sub-halos that pass close to a GD–1-like stream.

They found that sub-halos with masses in the range $2 \times 10^6 M_\odot - 10^8 M_\odot$ at the time of the stream–sub-halo encounter, corresponding to masses an order of magnitude larger at the time of infall, are the likeliest to produce gaps in a stream like GD–1. Gaps occur on average about 3 times per realisation of the host system, and have typical widths of $5 - 27°$, and fractional underdensities 10–30%, with larger gaps being caused by heavier sub-halos. The stream–sub-halo encounters responsible for these gaps have impact parameters 0.1-1.5 kpc, and relative velocities 200–410 km s$^{-1}$.

RECENTLY, Lu et al. (2026) extended these studies to 50 confirmed streams, taken from the compilation by Bonaca & Price-Whelan (2025). They based their models on observation sets comprising Gaia data, along with combinations of DESI, LSST, and Via spectroscopy. It has also been estimated, for example, that a gap caused by a sub-halo of a few $10^5 M_\odot$ could be detectable with LSST photometry alone (Drlica-Wagner et al., 2019).

With an idealised Gaia data set, the minimum detectable sub-halo mass for GD–1 is around $6 \times 10^6 M_\odot$. This can be improved by an order of magnitude assuming a 10-yr LSST sensitivity. A minimum stream length of about 20° is required in order to capture such perturbations, providing at least 8° of angular coverage for the impact analysis.

Lu et al. (2026) derived a simple function that provides an estimate of the minimum detectable sub-halo mass based on the stream width, Galactic centre distance, and stream density (their Eq. 27). This led to a ranked list which identifies promising candidates in order of sub-halo impact detectability (their Table 5).

They identified the most promising streams, with the best sensitivity to low-mass sub-halos, as C–12, ATLAS–Aliqa Uma, 300S, NGC 6397, Pal 5 and GD–1.