# 184. Stellar streams and sub-halos

An increasing number of accreted stellar structures are being identified in our Galaxy's halo. Some are attributed to captured dwarf galaxies, others to disrupted globular clusters, some of still uncertain origin. With 20 stellar streams tabulated by Grillmair & Carlin (2016), to around 100 known today (e.g. Mateu, 2023), some were found from the Sloan Digital Sky Survey, others from LAMOST and the Dark Energy Survey, with the majority of the most recent being identified by Gaia.

Members of these stellar streams are characterised by their common orbital motion, and generally very low metallicity. Search algorithms include `Streamfinder`, which determines stream membership probabilities based on the similarity of their orbits with those of their neighbours (Malhan & Ibata, 2018), and `StarGo`, which searches for streams and sub-structures clustered in dynamical space using neural-networks (Yuan et al., 2019).

As I noted in essay 156, analyses of these streams is enabling substantial progress in reconstructing the assembly history of the Milky Way, and in inferring the shape and mass of its dark matter halo.

A specific application that I will look at here is the use of these stellar streams in placing constraints on the existence and nature of the numerous dark matter sub-halos (halos within halos) that are predicted, in the standard ΛCDM cosmology, to exist surrounding the Milky Way (e.g. Springel et al., 2008; Zavala & Frenk, 2019).

An absence of such sub-halo driven perturbations in the Gaia data might be a challenge for standard ΛCDM.

It is now well established, observationally as well as in N-body simulations, that satellite galaxies interacting and merging with the Milky Way can result in tidal heating of the disk, in tilts and warps, and can trigger the growth of asymmetric structures such as the central bar, and the Galaxy phase-space spiral (Antoja et al., 2018).

Lower mass sub-halos, $\lesssim 10^9 M_\odot$, being largely devoid of gas and dust, are far more challenging to detect. The morphology and flux-ratios of strongly-lensed quasars currently suggests consistency with ΛCDM, albeit at low statistical significance (Ritondale et al., 2019; Hsueh et al., 2020; O'Riordan & Vegetti, 2024).

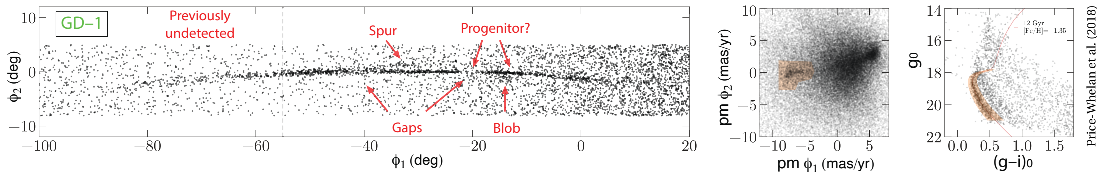
Various other ways of demonstrating the existence of dark sub-halos have been suggested: these include searches for $\gamma$-ray emission as a result of dark matter annihilation (Lake, 1990; Calcáneo-Roldán & Moore, 2000; Diemand et al., 2007), or through detecting the coherent vertical velocities of disk stars attributable to the passage of such sub-structures through the Galactic disk (Feldmann & Spolyar, 2015), or from the gravitational scattering of stars in tidal streams (Ibata et al., 2002; Johnston et al., 2002; Siegal-Gaskins & Valluri, 2008).

In the latter, the underlying idea is that a narrow, dynamically cold stellar stream is susceptible to heating by repeated close encounters with the massive dark sub-halos, resulting in characteristic features such as gaps whose details depend on the sub-halo mass and distance from the progenitor (e.g. Sanders et al., 2016; Bovy et al., 2017), and which were considered detectable with Gaia (Ibata et al., 2002; Feldmann & Spolyar, 2015).

As graphically described by Erkal & Belokurov (2015): *'Around a Milky Way-like galaxy, more than a thousand of these sub-halos will not be able to form stars but are dense enough to survive even deep down in the potential well of their host. There, within the stellar halo, these dark pellets will bombard tidal streams as they travel around the Galaxy, causing small but recognisable damage to the stream density distribution.'*

The importance of such searches was underlined by Bullock & Boylan-Kolchin (2017): *'Observational programs to constrain or discover and characterise the number of truly dark low-mass halos are among the most important, and achievable, goals in this field over the next decade. These efforts will either further verify the ΛCDM paradigm or demand a substantial revision in our understanding of the nature of dark matter.'*

Today, some of the most discussed features are those in the GD–1 stream. This was discovered, from SDSS, to span 63°, with a retrograde orbit with pericentre 14 kpc and apocentre 26 kpc (Grillmair & Dionatos, 2006). Based on their SDSS data, the discoverers considered that there was 'no evidence of perturbations by large mass concentrations in the nearby halo'.




Follow-up ground-based observations, including radial velocities, provided the first evidence for gaps along the stream (Koposov et al., 2010; Carlberg & Grillmair, 2013). The distant retrograde orbit suggested that interactions with disk sub-structure were unlikely, 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 insights came with the availability of the Gaia DR2 proper motions, from which the GD–1 stream was detected as one of the highest contrast features in the Galaxy halo (Malhan et al., 2018). Additional stars surrounding the stream were detected by Price-Whelan & Bonaca (2018), including an off-track 'spur', perhaps suggesting the presence of massive perturbers (Bonaca et al., 2019), or that the progenitor originated within a larger system (Malhan & Ibata, 2019).

The 'exquisite astrometry from Gaia' allowed a clean separation of the stream from Milky Way stars (Price-Whelan & Bonaca, 2018), and showed clear evidence for high-contrast gaps along the stream (see the figure above). Here, $\phi_1$ and $\phi_2$ are angles on the sky in the coordinate system based on the stream itself.

Also working with the DR2 proper motions, and with improved filtering, de Boer et al. (2020) confirmed these various 'gaps' and 'wiggles'. They argued that a striking sinusoidal wiggle at high $\phi_1$, straddling a gap feature at $\phi_1 \sim -3^\circ$, cannot be the characteristic S-shape signature of stellar debris torn off the stream's progenitor, since it has the wrong orientation with respect to the stream's orbit. They concluded that this feature must instead come from a perturbation to the stream.

Again basing their analysis on DR2, but adding Pan-STARRS photometry, and new ground-based radial velocities, Ibata et al. (2020) reached a different conclusion. They found that the density profile exhibits high contrast periodic peaks separated by 2.64±0.18 kpc. Their N-body simulations suggested that this morphology could be modelled with simple epicyclic motion in a smooth Galactic potential, partly compounded by incompleteness in Gaia's sky-scanning pattern in DR2.

Such epicyclic *overdensities* arise because tidal stripping mainly occurs near pericentric passages, leading to bursts of debris along the stream (Küpper et al., 2010; Küpper et al., 2012; Sanders et al., 2016; Bovy et al., 2017). Ibata et al. (2020) concluded that massive dark sub-halos do *not* appear to be required to explain the density clumping along the stream.

But, in turn, Banik et al. (2021a) argued that the power induced by episodic tidal stripping is far below that induced by dark matter sub-structures. They argued that the stellar density variations cannot be due to known baryonic structures, such as giant molecular clouds, globular clusters, or the Milky Way's bar or spiral arms (a similar conclusion was drawn by Doke & Hattori, 2022), and instead (in a joint analysis of the GD–1 and Pal 5 streams) requires a population of dark sub-structures with masses in the range $10^7 - 10^9 M_\odot$.

They went on to infer a total abundance of dark sub-halos corresponding to a mass fraction in the sub-halos $f_{\rm sub} = 0.14^{+0.11}_{-0.07}$ percent, compatible with hydrodynamical simulations of cold dark matter with baryons.

More is being inferred about the likely progenitor of the GD–1 stream. Although its location remains unknown, the N-body simulations by Webb & Bovy (2019) suggest that it probably lies between $-45^\circ < \phi_1 < -30^\circ$, and that it either completely disrupted ~2.5 Gyr ago, or it disrupted only 500 Myr ago, resulting in the underdensity at $\phi_1 \sim -40^\circ$.

From 43 spectroscopically confirmed stream members, Gialluca et al. (2021) measured a radial velocity dispersion of $2.1 \pm 0.3\,{\rm km\,s^{-1}}$, constant over the 15° region surveyed. Compared with an unperturbed model of the GD–1 stream having a velocity dispersion of $0.5\,{\rm km\,s^{-1}}$, the observed dispersion implies that the stream has undergone dynamical heating. They hypothesise that GD–1 originated from a globular cluster which, prior to its accretion by the Milky Way, orbited a dwarf galaxy with a cored density profile. They infer that imprints of its original host galaxy, including the inner slope of its dark matter halo, remain observable in the stream today.

In further modelling using Gaia DR3, Ibata et al. (2024) insist on the periodicity of the high contrast peaks, and suggest a two-component stream model (a kinematically cold part with dispersion $7\,{\rm km\,s^{-1}}$, and a hot part with dispersion $29\,{\rm km\,s^{-1}}$), consistent with simulations where globular clusters form at random locations within dark matter sub-halos and are subsequently accreted onto large galaxies (Carlberg, 2020; Malhan et al., 2021; Carlberg & Agler, 2023).

Similar studies for the Pal 5 stream (essay 109) suggest 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., 2020; Banik et al., 2021a; Banik et al., 2021b). Again, much more can be expected with Gaia DR4.