260. Sub-halos and the Milky Way disk

In my previous essay, I looked at using stellar streams to detect intermediate-mass dark matter sub-halos. These are predicted, by the standard cosmological model ΛCDM (cold dark matter), to exist within our Galaxy's overall dark matter halo. Moving on high-velocity orbits, they can 'punch through' the relatively linear and static streams, resulting in gaps (and other phase-space features) in the stream's density profile.

Gaps are seen in, e.g., the GD–1 and Pal 5 streams. But whether they are due to sub-halos of mass $10^6 - 10^8\,M_\odot$, or to other mechanisms, is uncertain. More generally, unambiguous evidence for them remains elusive, while their existence (and mass function) would provide a stringent test of ΛCDM at these lower mass scales.

It has been known since at least the 1980s, that sub-structures and satellite galaxies interacting and merging with the Milky Way can significantly affect the dynamical state of its stellar disk (e.g. Carr & Lacey, 1987; Toth & Ostriker, 1992; Quinn et al., 1993). More detailed studies have been made since, including the possible detection (with Gaia) of their 'stellar wakes' as they pass through the halo (Buschmann et al., 2018; Põder et al., 2025).

Studies by Feldmann & Spolyar (2015) showed that low-mass sub-structures (or sub-halos) will leave a kinematic imprint in the velocity field of *disk* stars that could (potentially) be measured with Gaia. Their numerical simulations were based on a dark body of mass $1.1 \times 10^9\,M_\odot$, the impact occurring at 11 kpc from the Galactic centre with a speed of 290 km s^{-1}, and for three test orbits: vertical, prograde, and retrograde.

They found that such disk passages result in coherent variations in the vertical velocities of disk stars, with kinematic signals (of 1–5 km s^{-1}) clearly distinguishing them from other disturbances such as spiral waves.

Assuming ΛCDM, they predicted that 2–20 dark matter sub-halos with virial masses $10^8 - 10^9\,M_\odot$ would collide with the disk per dynamical time (~ 200 Myr). Given the long (~ 100 Myr) lifetimes of the relevant kinematic disturbances, they predicted that several such signatures would be present in the disk at any given time.

With the Gaia data, significant small-scale phase-space structures are indeed now seen in the disk kinematics. However, rather similar to the case of stellar streams, where gaps are clearly seen but it is uncertain whether they are due to dark matter sub-halos, we cannot yet be certain that (at least part of) these disk structures result from the passage of dark matter sub-halos.

The fact that the distribution function of stars in the solar neighbourhood exhibits clear deviations from dynamic equilibrium was identified in SDSS data by Widrow et al. (2012). The correlations between the vertical velocity and height above the Galactic mid-plane subsequently identified in the Gaia data were manifest as a prominent spiral in the relevant phase-space distribution (Antoja et al., 2018; Bennett & Bovy, 2019).

This Gaia 'phase-space spiral' (aka the Gaia 'snail') reflects the response of the Galactic disk to one or several perturbations to the dynamics of the solar neighbourhood. The evolution of a perturbation into a spiral pattern occurs as a result of phase mixing: simulations show that, because the frequency of vertical oscillations near the Galactic mid-plane changes with height, the distribution of stars from their equilibrium trajectories progressively 'winds up' into a spiral. The spiral properties depend on the gravitational potential of the Galactic disk, as well as on the source of the perturbation (e.g. Tremaine, 1999; Widrow et al., 2012; Widmark et al., 2021; Banik et al., 2022; Banik et al., 2023).

The Sagittarius dwarf galaxy was soon considered to be the most probable cause of this perturbation (e.g. Gómez et al., 2013; Laporte et al., 2018; 2019). Assuming that it is due to a single event, it is then possible to 'unwind' the spiral to determine how long ago the perturbation occurred (Binney & Schönrich, 2018; Gandhi et al., 2022; Darragh-Ford et al., 2023).

But, in reality, the Gaia phase-space spiral is found to be inconsistent with a *single* perturbation epoch, and instead suggests that multiple events generated it over the past 500 Myr (e.g. Bennett & Bovy, 2021; Bennett et al., 2022; Frankel et al., 2023; Antoja et al., 2023).

Since at least one halo fragment, viz. the host of the Sagittarius dwarf galaxy, has come close enough to the solar neighbourhood to affect the vertical dynamics of the stellar disk, many more lower-mass halos have presumably passed by in even closer proximity, and will have caused other perturbations to the Gaia snail. The question then is how such signals might be manifest, and whether they are unambiguously detectable.

Various simulations over the past decade or so have considered the effects of higher mass perturbers (of order $10^9 - 10^{10} M_\odot$), and on larger Galaxy-scale structures, such as breathing and bending modes (e.g. Kazantzidis et al., 2008; Feldmann & Spolyar, 2015; Grand et al., 2016; Moetazedian & Just, 2016; Buschmann et al., 2018; Chequers et al., 2018; Vasiliev & Belokurov, 2020; García-Conde et al., 2024).

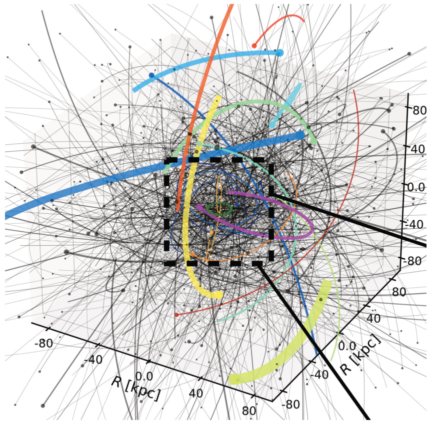
According to the predictions of ΛCDM, the existence of the known luminous satellites of the Local Goup implies the presence of a large population of Galactic sub-halos (e.g. Klypin et al., 1999; Moore et al., 1999). Based on the current understanding of galaxy formation, and in particular how the properties of Milky Way satellites depend on their host dark-matter halos, the overwhelming majority of these sub-halos are not expected to contain enough luminous material to be detected in the visible (e.g. Nadler et al., 2020).

Perturbations caused by such dark sub-halos are found to be, on average, orders of magnitude weaker than those caused by luminous satellite galaxies. But their ubiquity predicted by ΛCDM models makes them a plausible source of strong perturbations to the dynamics of the solar neighbourhood.

Recent work by Gilman et al. (2025) has investigated whether the phase-space structure seen by Gaia actually emerges, at least in part, from this sort of ongoing perturbations by dark lower-mass Galactic sub-halos.

They developed a probabilistic model for generating sub-halo orbits, then combined it with a prescription for calculating the response of the disk to external perturbations. This was further combined with a phenomenological treatment for the diffusion of phase-space spirals caused by gravitational scattering between stars and giant molecular clouds (Tremaine et al., 2023). This process steadily erases the kinematic signatures of the older ($\gtrsim 0.6$ Gyr) events.

In a little more detail, their model for the mass distribution and orbital properties of the sub-halo population is based on the semi-analytic model `galacticus` (Benson, 2012). This circumvents the computationally expensive numerical integration of billions of particles, and instead deals directly with derived quantities, notably the sub-halo mass, position, velocity, central density and tidal radius. These models are themselves calibrated with N-body simulations.



Gilman et al. (2025)

Despite the computational advantages over N-body simulations, using `galacticus` to generate thousands of realisations of the sub-halo population, while resolving them down to $5 \times 10^5 - 10^6 M_\odot$, and tracking their orbits, is still computationally intractable. Instead, they use their semi-analytic model to calibrate a forward model for sub-halo masses and orbits that can be evaluated on the fly (their §2.3.3).

In short, their model predicts that 249 ± 65 sub-halos with masses $10^7 - 10^8 M_\odot$ passed within 50 kpc of the Galactic centre in the last 2.4 Gyr. For comparison, Feldmann & Spolyar (2015) estimated that 500 sub-halos more massive than $10^7 M_\odot$ passed within 25 kpc of the solar neighbourhood in the past 2 Gyr.

The figure above shows one of their simulations of dark sub-halos ($10^{6.5} - 10^8 M_\odot$) and dwarf galaxies, shown as black and coloured curves respectively. Only sub-halo orbits passing within 80 kpc of the solar position in the past 1.2 Gyr are included. Line widths are scaled to the square root of the sub-halo mass.

In conclusion, given that their orbits bring them close to the solar neighbourhood, Gilman et al. (2025) found that the less-massive sub-halos constitute a more probable source of significant perturbation to the dynamics of the solar neighbourhood than the less-numerous and more-distant dwarf galaxies.

Assuming a sub-halo abundance given by ΛCDM, they found that their disturbances excite fluctuations in the vertical number count asymmetry of 1–3%, and in the mean vertical velocity near the Galactic mid-plane of 0.1–0.4 km s^{-1}, both of which should persist to the present day. They also result in correlations between vertical frequency and orbital angle that could be mistakenly attributed to a single past disturbance.

Finally, while they may contribute to the disequilibrium measured by Gaia to at least the same level as the Sagittarius dwarf galaxy, they cannot *alone* explain all the properties of the Gaia phase-space spiral.