142. Gaia and the search for axions

According to the standard model of Big Bang cosmology, ΛCDM, dark matter comprises some 26% of the mass–energy density of the observable Universe. Here, Λ denotes the contribution of dark energy, while CDM (for 'cold dark matter') conveys the present consensus that this missing matter is (dynamically) 'cold'.

'Cold' here, in turn, means that the dark matter particles had only small velocities in the early Universe, travelling only limited distances before they slowed through cosmic expansion. Their *free streaming length*, smaller than the size of the earliest protogalaxies, set the minimum scale for later structure formation.

Early evidence for the existence of dark matter came from estimates of the (virial) mass of the Coma cluster of galaxies (Zwicky, 1937) and, later, from galaxy rotation curves (Rubin & Ford, 1970; Freeman, 1970). More recent evidence comes from gravitational lensing, and the pattern of anisotropies in the cosmic microwave background. Numerical particle models of the formation and evolution of the Universe's large-scale structure, such as Illustris, give strong support for the ΛCDM paradigm.

While alternatives to *cold* dark matter and modified theories of gravity (e.g. MOND) are still being explored, I will continue with the current consensus that cold dark matter exists, although its nature remains unknown.

The Standard Model of particle physics classifies all known fundamental particles, and describes three of the four known fundamental forces (excluding gravity). Known particles are divided into two categories. The (spin half) fermions comprise the six quarks (the building blocks of protons and neutrons), and six leptons (the electron, the muon, the tau, and their associated neutrinos), each with their own anti-particle.

Bosons comprise the spin-1 'gauge bosons' that mediate the fundamental forces: 8 gluons (mediating the strong nuclear force that binds the quarks), the photon (mediating the electromagnetic force), the W and Z bosons (the weak nuclear force); and the scalar (spin-0) Higgs boson, whose discovery at the LHC in 2012 confirmed the existence of the Higgs field, which gives mass to other particles via the Higgs mechanism.

Beyond the Standard Model, there are many other particles have been postulated with the goal of further unification of the fundamental forces, quite independently of efforts to understand dark matter and dark energy. Amongst these are the graviton (a hypothetical elementary particle invoked to mediate the force of gravity), sterile neutrinos, and many others that are predicted by the numerous *supersymmetry theories* which aim to unify the equations of force and matter.

Also beyond the Standard Model are a whole class of 'weakly interacting massive particles', or WIMPs, hypothesised to interact via gravity. Suggestions that some were produced in the early Universe makes them amongst the favoured candidates for cold dark matter.

Experimental efforts to detect WIMPs include the search for products of WIMP annihilation (including γ-rays, neutrinos and cosmic rays in nearby galaxies), experiments to measure the collision of WIMPs with nuclei in the laboratory, as well as attempts to directly produce WIMPs in colliders such as the LHC.

The axion is another hypothetical elementary particle, originally proposed to solve the 'strong CP' problem in particle physics. The 'problem' is that quantum chromodynamics (QCD), which describes the strong force that binds quarks together, allows for a term that violates the combined symmetry of charge conjugation (C) and parity (P), leading to an imbalance between matter and anti-matter in the early Universe.

The existence of a particle much lighter than the electron, which therefore interacts only very weakly with other particles, was proposed by Peccei & Quinn (1977). It adjusts the interactions involved in the strong-force such that the CP-violating term is suppressed to a very small value, thereby explaining the high degree of matter–antimatter symmetry observed in the Universe.

Aside from fundamental particles such as WIMPS or axions postulated as dark matter candidates, macroscopic candidates have also been considered, notably the class of 'massive compact halo objects' or MACHOs (e.g. Calcino et al., 2018), and primordial black holes (Carr & Kühnel, 2022). No more on these here!

EXPERIMENTAL SEARCHES for axions have been underway for several decades. Most are based on the Primakoff effect, in which axions are converted to photons (and vice versa) in strong electromagnetic fields. Amongst the 'haloscopes' searching for signatures from the Galaxy's dark matter halo are the Axion Dark Matter Experiment (Bartram et al., 2021), HAYSTAC (Brubaker et al., 2017), CULTASK (Bartram et al., 2021), and ORGAN (McAllister et al., 2017). The underground argon-based DEAP–3600 in Sudbury, Canada, for example, has undertaken specific analyses motivated by the latest halo stream results from Gaia and SDSS.

Null results have led to an increased interest in alternatives to ΛCDM, and alternative dark matter scenarios, including 'fuzzy dark matter' and warm dark matter. In the following, I will outline how Gaia is contributing.

SPECIFIC PHASES of stellar evolution can provide various constraints. The hot end of the white dwarf luminosity function, populated by the rare short-lived DO stars, provides constraints on the cooling of the white dwarf population as a whole, and on the properties of any particles emitted by them. The cooling of hot white dwarfs is dominated by the radiation of neutrinos, with the shape of the hot end of the luminosity function strongly constraining the magnetic dipole moment of the neutrino (Miller Bertolami, 2014a), as well as offering the opportunity to probe the possible existence of the axion (Miller Bertolami et al., 2014b). Various studies, based on Gaia data, have been reported (Reindl et al., 2018; Córsico et al., 2022; Chen, 2022).

The tip of the red-giant branch similarly provides constraints on any energy loss leading to a larger core mass at He-ignition, and thus to a brighter luminosity than predicted by standard models. From the Gaia DR2 distance of ω Cen, Capozzi & Raffelt (2020) gave a limit on the neutrino dipole moment of $\mu_\nu < 1.2 \times 10^{-12} \mu_{\rm B}$, and on the axion–electron coupling of $g_{\rm ae} < 1.3 \times 10^{-13}$.

Pombo & Saltas (2023) have argued that the recent Gaia discovery of a Sun-like star closely orbiting a black hole (El-Badry et al., 2023) provides a challenge for theories of the system's evolution, and proposed instead that the central dark object is a stable clump of bosonic particles of spin-0, or spin-1, referred to as a boson star.

LOW-FREQUENCY GRAVITATIONAL WAVES can provide a probe of the stochastic background generated in the early Universe as a result of inflation, cosmic strings, or first-order phase transitions, including the effects of axions (essay #136). Beyond the reach of LIGO and Virgo due to seismic noise, contributions from Gaia are being evaluated (e.g. Aoyama et al., 2021; Gouttenoire, 2023).

Weak lensing provides another possible probe of dark matter microphysics and primordial fluctuations on sub-Galactic scales (e.g. Mondino et al., 2020).

THE STELLAR STREAMS discovered in our Galaxy's halo by Gaia, originating from disrupted globular clusters or captured satellite galaxies, probe both our Galaxy's dark matter halo, and the detailed substructure of the stream themselves. Amongst these studies, Amorisco & Loeb (2018) used numerical simulations of the stream's thickness within a *fuzzy dark matter* halo to place a lower limit on the boson mass of 1.5×10^{-22} eV.

Other simulations are leading to improvements to the 'standard halo model', and to revised constraints on the signal models for WIMPs and axions used, for example, in DEAP–3600 (Evans et al., 2019; Necib et al., 2019; Buch et al., 2020; O'Hare et al., 2020; Banik et al., 2021).

Focusing of dark matter streams has also been postulated as a link between solar activity and the orbits of the major planets (Perryman & Zioutas, 2022; essay #28).

THE HIGH DARK MATTER content of ultra-faint dwarf galaxies, such as Crater II and Antlia II (found with Gaia), are challenges for the standard interpretation of dark matter (essay #128), and indeed for models of modified gravity (de Martino, 2020). Broadhurst et al. (2020) argued that Antlia II favours dark matter as a Bose–Einstein condensate, with an ultralight boson of mass 1.1×10^{-22} eV (perhaps the axion generic in string theory) accounting for its large size and slow-moving stars.

Similar results for Crater II, based on agreement between the galaxy's profile and the core–halo profile predicted by 'wave dark matter' as a Bose–Einstein condensate, ΨDM, was reported by Pozo et al. (2022).

MORE SPECULATIVELY, Guo et al. (2019) considered a 'dark photon' model with ultralight particle mass (also applicable to axions). A periodic oscillation of the Gaia satellite results in the angular deflections of target stars due to aberration. They found that this could probe an unexplored parameter space, with a coupling as small as $\epsilon \sim 10^{-24}$ in the mass range $10^{-23} - 10^{-21}$ eV.

Chakrabarty et al. (2021) attribute a pair of triangular features in the Gaia stellar data at symmetric locations on opposite sides of the Galactic Centre to a caustic ring in the halo's dark matter distribution. They argue that dust, gravitationally entrained by cold axion flows, can explain the sharpness of the triangular features.

Finally, Chiang et al. (2023) argue that ultralight axion-like particles with $m_{\rm a} \sim 10^{-22}$ eV, or 'fuzzy dark matter', behave like cold dark matter on cosmological scales, and exhibit a kpc-size de Broglie wavelength capable of alleviating the (sub-)galactic-scale problems of ΛCDM. Substructures inside a fuzzy dark matter halo experience gravitational perturbations, resulting in stellar heating sufficient to account for the Galactic disk thickening over a Hubble time. The age–velocity dispersion relation in the solar vicinity, explained in the context of such heating, yields $m_{\rm a} \gtrsim 0.4 \times 10^{-22}$ eV.