194. Cosmological simulations and Gaia

IN THE EARLY 1980S, when Hipparcos was accepted by ESA, space astrometry was far from the mainstream of astronomy. Its goal was to extend distance measurements to ~100 pc, determine luminosities in the upper parts of the Hertzsprung–Russell diagram, and map distances and motions in the solar neighbourhood.

It was a bold choice by ESA's advisory committees, but somewhat reluctantly accepted more widely. Some doubted its feasibility, and further advances below a milli-arcsec seemed implausible. The rich complexities of dynamical phenomena across the Galaxy's vastness were unknown, beyond reach, and never discussed.

HOW THE LANDSCAPE has changed in the decades since! In the curious way that science advances across many fronts in parallel, Gaia is, today, central to problems being tackled in stellar evolution, in exoplanet science, in solar system studies, and in cosmology.

In the last of these fields, impressive developments in numerical simulations are now guiding many of Gaia's advances: amongst them, interpreting stellar streams, modelling resonant motions, characterising the dynamics of local group galaxies, and comprehending the multiple manifestations of past satellite interactions.

Here, I will briefly outline these cosmological simulations. I will then show how Gaia is confirming many of their detailed predictions, and helping in their interpretation and presumably their future development.

OVER THE PAST 20 years, very large massively parallel N-body simulations, resting on the Big Bang ΛCDM paradigm, have been developed to investigate how dark and baryonic matter structures have evolved over time (Vogelsberger et al., 2020).

My introduction here will refer only to CDM simulations on the largest cosmological scales, but they are also used to study effects on smaller systems. From a substantial literature I could mention, as examples, galaxy and halo formation (e.g. Navarro & White, 1994), black hole accretion (e.g. Di Matteo et al., 2008), and the first protostars (e.g. Yoshida et al., 2008).

THE FIRST OF the very large-scale projects was the Millennium Simulation (Springel et al., 2005). The simulation followed the growth of dark matter structures from $z = 127$ to the present. It used 2160^3 particles, each representing $10^9 M_\odot$ of dark matter, within a cube of side 700 Mpc. It occupied the main supercomputer of the Max Planck Society, Garching, for more than a month.

Successive versions incorporated improved parameters and input physics. Millennium II (Boylan-Kolchin et al., 2009) simulated a smaller volume with the same number of particles, each of $7 \times 10^6 M_\odot$. Millennium XXL (Angulo et al., 2012) used a cube of side 4 Gpc, with 6720^3 particles each representing $7 \times 10^9 M_\odot$.

Other such simulations now include Bolshoi (Klypin et al., 2011; Trujillo-Gomez et al., 2011), Eris (Guedes et al., 2011), the widely-cited EAGLE (Schaye et al., 2015), HESTIA (for the Local Group, Libeskind et al., 2020), and NewHorizon (Dubois et al., 2021), along with 'zoomed-in' developments such as ARTEMIS (Font et al., 2020).

I WILL SAY more on just one of these, Illustris (Vogelsberger et al., 2014a; Genel et al., 2014). This simulation started 12 Myr after the Big Bang, evolved over 13 Gyr, and used 12 billion resolution elements in a cube of side 100 Mpc. It generates (for example) elliptical and spiral galaxies, galaxy clusters, the distribution of hydrogen on large scales, and the metal and hydrogen content of galaxies on small scales (Vogelsberger et al., 2014b).

Galaxy formation processes include, amongst others, stellar evolution and feedback, gas recycling, chemical enrichment (following nine elements independently), and black hole growth and mergers (e.g. Vogelsberger et al., 2013; see also Somerville & Davé, 2015).

The Illustris framework has been used for other derivatives, specifically: Auriga (high-resolution simulations of Milky Way-like dark matter halos; Grand et al., 2017); IllustrisTNG ('The Next Generation'; Pillepich et al., 2018); Thesan (for the reionisation epoch; Kannan et al., 2022); MillenniumTNG (for the massive end of the halo mass function; Hernández-Aguayo et al., 2023); and TNG-Cluster (for galaxy clusters; Nelson et al., 2024).

I WILL GIVE a few of the growing number of examples where these simulations are guiding interpretation of the Gaia data. And I refer to essay 118 for some specific words on the ΛCDM 'missing satellites' problem, the 'core–cusp' problem, the 'too-big-to-fail' problem, and the 'plane of satellites' problem.

MAJOR MERGERS: it is now accepted that the Gaia–Sausage–Enceladus (GSE) merger played a key role in the formation of our Galaxy's inner stellar halo (Helmi et al., 2018; Gallart et al., 2019), as well as the disk (Haywood et al., 2018; Xiang & Rix, 2022). Are these discoveries supported by cosmological simulations?

Dillamore et al. (2022) showed that about one-third of galaxies from the ARTEMIS simulations contain accreted stars on highly radial orbits, similar to the GSE event. The major mergers also result in disk rotation, and changes in shape and orientation of their dark matter halos. Early mergers result in retrograde stars, analogous to the 'splash' or 'plume' feature also discovered with Gaia (Di Matteo et al., 2019; Belokurov et al., 2020).

Khoperskov et al. (2023a) similarly analysed six M31 and Milky Way analogues from the HESTIA simulations of the Local Group. They found that all experienced between one to four mergers with stellar mass ratios between 0.2–1, with five them occurring 7–11 Gyr ago. The most massive mergers result in a sharp increase in the orbit eccentricity of disk stars of the main progenitor.

THE CENTRAL BAR: Gaia is providing new insights into the morphology and dynamics of our Galaxy's central bar (essays 112 and 196). Arising as a consequence of stellar orbits, are they also influenced by past mergers?

IllustrisTNG, NewHorizon, and EAGLE all confirm the emergence of bars, but with a large variation in bar fractions, ranging from 5–55% (Cavanagh et al., 2022).

Fragkoudi et al. (2020) showed that, in their Auriga simulations, galaxies which best reproduce the chemodynamical properties of the Milky Way bulge have quiescent merger histories since $z \sim 3.5$. Their last major merger was more than 12 Gyr ago, with any subsequent mergers having a stellar mass ratio of 1:20 or lower.

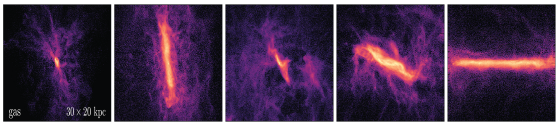
In turn, this suggests an upper limit of a few percent for the mass ratio of the GSE merger event. They inferred that the Milky Way has had an 'uncommonly quiet merger history', and hence an essentially *in situ* bulge.

EVOLUTION OF THE MILKY WAY: as I described in essay 190, Chandra et al. (2024) used [Fe/H] and [α/Fe] estimates for 9.9 million Gaia red giants to characterise their angular momentum as a function of metallicity. Taking this as a proxy for age, they identified three distinct evolutionary phases: a disordered/chaotic protogalaxy, a hot old high-α disk, and a cold young disk with more ordered and circular orbits.

Does this proposed 'three-phase evolution' of the Milky Way find any support from these large-scale cosmological simulations?

Semenov et al. (2024) had already selected a representative sample of 61 Milky Way-like galaxies from the TNG50 simulations (the highest-resolution box from IllustrisTNG). Of these, 11 matched the 'early spin-up' previously inferred by Belokurov & Kravtsov (2022).

Chandra et al. (2024) showed that halo #519311, one of the earliest of their spin-up galaxies, exhibits a 'three-phase' structure in the orbit circularity versus metallicity space 'remarkably similar' to the Milky Way. This halo also experiences a gas-rich major merger 8 Gyr ago, albeit slightly later than the estimated GSE merger. The merger adds a large amount of low-metallicity gas and angular momentum, from which the kinematically cold low-α stellar disk is subsequently born.



Chandra et al. (2023)

MANY MORE Gaia studies are calling on these cosmological simulations to assist their interpretation.

I counted more than 20 other papers between 2018 and mid-2024 using EAGLE or Illustris to further the understanding of the GSE-like accretion event, where I will simply list some of the most recent (viz. Wu et al., 2022; Belokurov et al., 2023; Dillamore et al., 2023; Carollo et al., 2023; Khoperskov et al., 2023a; 2023b; Rey et al., 2023; Lane & Bovy, 2024; Carrillo et al., 2024).

VARIOUS STUDIES EMPLOY these simulations in interpreting the improved globular cluster orbits (Chen & Gnedin, 2022; Ishchenko et al., 2023a; 2023b; Chen & Gnedin, 2024; Ishchenko et al., 2024), and the improved orbits of the dwarf spheroidals (Pardy et al., 2020; Pawlowski & Kroupa, 2020; Borukhovetskaya et al., 2022; Martínez-García et al., 2023).

THEY ARE ALSO being used in discussions of the mass of M31 (Patel & Mandel, 2023), warping in the orbits of Cepheids (Dehnen et al., 2023), Milky Way analogues (Grand et al., 2018), infall times for Local Group galaxies (Barmentloo & Cautun, 2023), hypervelocity stars and the Galactic escape speed (Deason et al., 2019), the Milky Way mass profile and halo mass (Li et al., 2020), halo anisotropy (Bozorgnia et al., 2020), and the cosmological core–cusp problem (Wang et al., 2022).

AND, OF COURSE, more accurate and complex data sets, more stringent tests, and greater clarity on the accuracy and fidelity of the ΛCDM parameterisation, will come with future Gaia data releases.