Through the celebration of notable successes, including the excellent fit to cosmic microwave background (CMB) data at high and low redshift [1, 2]; the prediction of baryon acoustic oscillations (BAO) [3–5] discovered by the Sloan Digital Sky Survey (SDSS) [6, 7]; the measurement of cosmic expansion using type Ia supernovae [8, 9] or the description of large-scale structure in the Universe, the standard ΛCDM model of cosmology has undoubtedly earned its scientific credibility. Dominated by dark energy and cold dark matter (DM), it describes the collapse of infinitesimal density perturbations in the substructure of the early Universe, observable in the CMB [10], as the origin of galaxy formation; DM halos resulting from the collapse of these density anisotropies gravitationally interact and grow through hierarchical clustering, leading to the accretion of gas through large-scale filaments in the cosmic web and, subsequently, to the formation of galaxies [11–14]. In addition to being permanently fed by the inflow of gas, galaxies also grow more massive through continuous mergers with smaller nearby systems [12, 15].

Following the discovery of large amounts of sub-structure in the stellar halo of the Milky Way (MW) [16–18], our galaxy has been found to be the epitome of ΛCDM cosmology. The Galactic halo contains <1% of the stellar mass of the MW [19], with estimates of the stellar halo mass ranging between $4 \times 10^8 M_\odot$ and $1.4 \pm 0.4 \times 10^9 M_\odot$ [20–22]. These estimates encompass the significant component resulting from the ongoing merger with the Sagittarius dwarf galaxy [23–25], past accretion events [26–28] and kinematically heated in-situ populations [29–33]. Therefore, the Galactic stellar halo is composed of a combination of heated disc stars and accreted populations, as predicted by a large number of galaxy formation simulations [34–46].

Whether the Galactic halo was predominantly formed in-situ [47] or through merger events involving dwarf satellite galaxies [35, 48–50] remains a major topic of conversation in MW astronomy. Home to the most metal-poor stars of our galaxy with lifetimes comparable to the current age of the Universe [51], the Galactic stellar halo holds one of the most powerful archaeological tools in partially uncovering the appearance of the MW in the past [47, 52], as the chemical elements imprinted in the atmospheres of halo stars reflect the physical conditions of the interstellar medium in which they were born [52]. Thanks to observations of several halo substructures in the high-quality Gaia data, a distinct population of stellar debris can be linked to a massive, possibly single, accretion event with the Gaia-Sausage-Enceladus (GSE) dwarf galaxy [32, 53–58].

Research Experience - The last major merger of the MW

By running a series of state-of-the-art, N-body, hydrodynamical simulations (GIZMO [11, 59]) between the MW progenitor and a massive GSE-like satellite, I verified the self-consistency of a single GSE-merger event by studying the impact of gas on the kinematic properties of the major merger and its imprint in the present day kinematic-space of the MW stellar halo. From our grid of MW-GSE-like merger models, I found that a gas-rich, GSE-progenitor on a retrograde orbit most robustly reproduces the significant properties observed in the kinematic space of the Galactic halo and proposed constraints for the mass components of the GSE progenitor. More importantly, I showed that a model with such properties is sufficient in reproducing merger debris with properties similar to those attributed to alternative populations, which goes to show that the impact of hydrodynamics on N-body simulations cannot be neglected when modelling galaxy pair mergers. I highlighted the importance of new-generation spectroscopic surveys such as MOONS or 4MOST in further disentangling debris populations and building upon the work presented, the findings of this research laying the groundwork for complementary chemical analyses of MW-GSE-like mergers. A subsequent publication is available as an eprint on arXiv.

Research interests - high redshift galaxy formation and evolution

While the ongoing Gaia mission [60] is perpetually digging deeper to answer questions in Galactic archaeology, the discovery of galaxies at cosmic dawn and the iconic images of the Hubble deep field [61, 62] have marked a profound milestone in our investigations of extra-galactic astrophysics. Since, the Hubble Space Telescope (HST) has observed galaxies as far away as $z \sim 9$–11 [63–75], at the horizon of the reionisation epoch less than 500 Myr after the Big Bang [76]. The remarkable properties of the most distant galaxy discovered by the HST, GN-z11 [69], pave the way to probing high UV luminosity galaxies at $z > 10$ and, by demonstrating that galaxy build-up was well underway early in the reionization epoch, invite us to rethink our understanding of early structure formation. The derived properties of GN-z11 have been reproduced with excellent agreement by numerical simulations [77].

Beyond redshifts of $z \sim 8.5$, sources begin to "drop out" in the HST Y-band (F105W) and J-band (F125W) filters [65, 67, 78, 79], marking a notable threshold for the HST. The James Webb Space Telescope (JWST) [80], successor to the HST, was constructed to enhance the performance of its predecessor and push the measurable redshift frontier even closer to the Big Bang [81, 82].The JWST has already begun to exceed expectations [83], with recorded observations of galaxies between $z \sim 11$–14 [84–99]. The overabundance of surprisingly luminous candidates among the first high-redshift galaxies revealed by the JWST highlights a discrepancy between observations and theoretical predictions (eg [87, 99]), suggesting an inconsistency with the ΛCDM model [100, 101]. This is a mere addition to a growing list of signals in cosmological and astrophysical data, which are shedding the light on tensions with the ΛCDM paradigm [102] and making it increasingly difficult to discard its theoretical and observational failures [103, 104].

Beyond the JWST, the successful launch and ongoing development of pioneering telescopes and surveys (e.g. DESI [105], EUCLID [106], WFIRST-AFTA [107], LSST [108], SKA [109]) highlights the determination of the scientific community to provide an unprecedented view of the large-scale structure of the Universe. These will complement theoretical models of galaxy formation (see [110] for an extensive review of recent theoretical models and studies, in particular the in-depth summary provided in Table 1 and the following page, which have pushed to construct a coherent picture of the Universe in its early stages), with the JWST in particular being expected to play a crucial role in shedding the light on questions remaining open from numerical simulations. The emergence of machine learning (ML) methods [111] brings a revolutionary tool for the handling of such vast datasets, introducing new methods of galaxy classification [111]; photometric redshift estimations [112]; strong gravitational lensing effects [113]; image deconvolution [114]; identifying merger remnants [115], blended galaxies [116, 117] or anomalous objects [118].

In an era characterised by the dominance of big data, gaps in theoretical frameworks and the ongoing re-evaluation of the ΛCDM paradigm, computational and observational opportunities for research in early galaxy formation and cosmology have never been so vast. The modern generation of space and ground telescopes, led by the JWST and in close collaboration with complementary, cutting-edge numerical simulations, offers to unveil the foundational mechanisms governing galaxy formation at epochs neighbouring the Big Bang.

OTHER RESEARCH - RADIOLOGY

NiTransforms

Brain image transformations are stored across a disparate range of file formats as a result of the multitude of possible image registration software implementations. Consequently, the lack of a unified consensus regarding the format of transform files largely complexifies the application of transformations, further enhanced by the question of compatibility between tools. Although existing tools have been developed to address this issue [119], they lack compatibility with a wide range of packages and find themselves restricted in the analysis of non-linear transforms.

`NiTransforms` is a multi-dimensional, open source python library integrated to *fMRIPrep* [120]. It is built for resampling images and converting between formats to apply transforms generated by the most popular neuroimaging packages and libraries (AFNI [121], FSL [122], FreeSurfer [123], ITK via ANTs [124] and SPM [125]). My main tasks involved outsourcing the application of transforms to become a stand-alone method operating on one composite transform and on images or surfaces; reading and writing tests to ensure the correctness of transformations; following code review procedures to provide feedback on pull requests. These implementations namely led to a reduction of the error propagation induced by the previous version, which used to apply transforms in individual components. My contributions have been incorporated in `v.24.0.0`.

Magnetic Resonance Imaging (MRI)

Functional MRI (fMRI) provides information about brain regional activity, based on blood oxygen level dependent (BOLD) response [126–129]. Acting as a proxy for neural activity, fMRI is a common tool for investigating interhemispherical connectivity. The corpus callosum (CC) is the major white matter commissure connecting homologous structure in the left and right cerebral hemispheres, consisting of approximately 200 million fibres [130, 131]. It mediates sensory, motor, audio and visual integration across hemispheres, as well as higher-level cognitive functions. CC dysgenesis (CCD) is the most common form of brain malformation [132], resulting in the generation of axons which form aberrant ipsilateral antero-posterior ‘bundles of Probst’ [133–136] as they completely or partially fail to cross the midline. Individuals with CCD have been found to exhibit social impairments [137–141] as well as deficits in pragmatic linguistic functions [137, 142, 143] and problem solving [137]. The higher interhemispheric transfer time displayed by CCD patients shows impediment in visual [144, 145], motor [146, 147] and executive [148] processing, with an additional performance drop when carrying out more complex tasks.

We carry out a longitudinal and multimodal study to investigate the impact of CCD abnormalities on cognitive and brain development in children at school-age in light of pre-natal (i.e., foetal MRI) and post-natal (i.e., school age MRI) neuroimaging, as well as exploring neuroplastic responses associated with this brain malformation, with the aim to provide novel insight into genetic variations associated with atypical callosal development. Data collection is split among general socio-demographic information, medical history and hand-preference; neuropsychological assessment; MRI acquisitions; genetic testing (saliva DNA sampling, optional). In addition to participating to the MRI data acquisition, my specific role involved the development of the data-analysis pipeline for the task-based fMRI sequence. Namely, I computed and designed first and second level event-based generalised linear model (GLM) design matrices, as well as the contrasts highlighting regions of brain activity detected during the MRI acquisition. With a timeline set by the rhythm of data acquisition, results are expected to be finalised and published in 2026.

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