

Euclid preparation

LXXXVIII. 3D reconstruction of the cosmic web with Euclid Deep spectroscopic samples

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ABSTRACT

The ongoing *Euclid* mission is aimed at measuring spectroscopic redshifts for approximately two million galaxies using the $H\alpha$ line emission detected in near-infrared slitless spectroscopic data from the Euclid Deep Fields, leveraging both the red and blue grisms. These measurements will reach a flux limit of 5×10^{-17} erg cm⁻² s⁻¹ in the redshift range $0.4 < z < 1.8$, paving the way to numerous scientific investigations involving galaxy evolution, extending well beyond the mission's core objectives. The achieved $H\alpha$ luminosity depth will lead to a sufficiently high sampling, enabling the reconstruction of the large-scale galaxy environment. Here, we assess the quality of the reconstruction of the galaxy cosmic web environment with the expected spectroscopic dataset in Euclid Deep Fields. The analysis was carried out on the Flagship and GAEA galaxy mock catalogues. The quality of the reconstruction was first evaluated using simple geometrical and topological statistics measured on the cosmic web network; namely, the length of filaments, the area of walls, the volume of voids, and its connectivity and multiplicity. We then quantified how accurately gradients in galaxy properties can be recovered, with respect to the distance from filaments. As expected, the small-scale redshift-space distortions, such as Fingers of God (FoG) effects, have a strong impact on filament lengths and connectivity; however, they can be mitigated by compressing galaxy groups identified with an anisotropic group finder prior to a skeleton extraction. The cosmic web reconstruction is biased when relying solely on $H\alpha$ emitters. This limitation can be mitigated by applying stellar mass weighting during the cosmic web reconstruction. However, this approach introduces non-trivial biases that need to be accounted for when comparing to theoretical predictions. Redshift uncertainties pose the greatest challenge in recovering the expected dependence of galaxy properties, although the well-established stellar mass transverse gradients towards filaments can still be observed to a lesser extent.

Key words. galaxies: evolution – cosmology: observations – large-scale structure of Universe

1. Introduction

Since the first observations in the late 1970s, which revealed the existence of coherent patterns on scales larger than those of galaxy clusters, mapping the large-scale structure of the Universe has become possible thanks to large galaxy redshift surveys. Early observations of the nearby Universe have uncovered complex structures of interconnected superclusters (e.g. Davis et al. 1982) and enabled unexpected discoveries of the first large cosmic voids (e.g. Kirshner et al. 1981), providing a preliminary hint that the spatial distribution of galaxies is highly inhomogeneous. It was quickly confirmed that this is a general feature of the large-scale distribution of galaxies, once observations from surveys covering wider areas on the sky started to become available. Beginning with the first redshift slices of the Center of Astrophysics redshift survey (CfA, de Lapparent et al. 1986), the progressively increasing depth and coverage offered by the next generations of surveys such as Las Campanas Redshift Survey (LCRS, Shectman et al. 1996), 2dF Galaxy Redshift Survey (2dFGRS, Colless et al. 2001), Sloan Digital Sky Survey (SDSS, York et al. 2000; Abazajian et al. 2009, for DR7), 6dF Galaxy Survey (6dFGS, Jones et al. 2004, 2009), and Galaxy and Mass Assembly (GAMA, Driver et al. 2011) have allowed us to map the large-scale structure of the nearby Universe ($z \lesssim 0.3$) in unprecedented detail. These surveys have revealed a cosmic landscape where galaxies are distributed within high-density peaks, intermediate-density filaments, and walls, enclosing low-

density, nearly empty voids. This view has been extended up to $z \approx 1$ by the VIMOS Public Extragalactic Redshift Survey (VIPERS, Guzzo et al. 2014), which encompasses a volume and galaxy sampling density comparable to those of spectroscopic surveys of the local Universe. Further improvement, in terms of significantly increased galaxy number density and depth compared to any of these surveys in the comparable redshift range, will be achieved by the ongoing Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration 2016) collaboration, which has already collected high-confidence spectroscopic redshifts (McCullough et al. 2024) for more than ten million galaxies (DESI Collaboration 2025).

Mapping the large-scale structure in three dimensions at even higher redshifts ($z \gtrsim 1$) is currently impossible with existing spectroscopic surveys, due to their rapidly decreasing completeness and sampling number density. For the time being, the density field at high redshifts is observationally accessible only through the tomographic reconstruction using the Lyman- α forest absorption of light from bright background sources, such as quasars, typically at $z \sim 2.5$ –3 (e.g. Lee & White 2016; Ravoux et al. 2020). The redshift range $1 \lesssim z \lesssim 2$, near the peak epoch of star formation (e.g. Madau & Dickinson 2014) remains largely uncharted territory in understanding the co-evolution of galaxies and large-scale structures.

The web-like pattern observed in the distribution of galaxies, spanning scales from a few to over a hundred megaparsecs and revealed by large galaxy redshift surveys, is now

understood within the framework of the so-called cosmic web (e.g. [Klypin & Shandarin 1983, 1993](#); [Bond et al. 1996](#)). This structure connects observed galaxy clusters through a network of filaments, which arise from initial fluctuations in the primordial density field and are amplified by anisotropic gravitational collapse ([Lynden-Bell 1964](#); [Zel'dovich 1970](#)) during later cosmic times. One of the most important features of this network is that it naturally sets the large-scale environment within which galaxies form and evolve. Since more than a decade now, interest has been shifting from extensively studied high-density regions, such as galaxy groups and clusters (e.g. [Davis & Geller 1976](#); [Dressler 1980](#); [Dressler et al. 1997](#); [Goto et al. 2003](#); [Blanton et al. 2003a](#); [Baldry et al. 2006](#); [Bamford et al. 2009](#); [Cucciati et al. 2010](#); [Burton et al. 2013](#); [Cucciati et al. 2017](#), and references therein), towards intermediate-density filaments and walls. These anisotropic large-scale environments seem to play a role in shaping at least some of the galaxy properties. Indeed, observational studies of the local and higher- z Universe ($z \lesssim 0.9$) have demonstrated that more massive and/or passive galaxies tend to reside closer to large-scale filaments, compared to their lower-mass and/or star-forming counterparts (e.g. [Chen et al. 2017](#); [Kuutma et al. 2017](#); [Malavasi et al. 2017](#); [Kraljic et al. 2018](#); [Laigle et al. 2018](#); [Winkel et al. 2021](#)). This trend is qualitatively aligned with results from large hydrodynamical simulations ([Kraljic et al. 2018](#); [Laigle et al. 2018](#); [Hasan et al. 2023](#); [Bulichi et al. 2024](#)) and with theoretical expectations ([Musso et al. 2018](#)), since the assembly history of galaxies encoded in a conditional excursion set is biased by the eigenvalues and eigenvectors of anisotropic tides.

The role of the cosmic web in modulating other galaxy properties (i.e. beyond stellar mass and star formation activity) could also be modelled in this framework, but it has so far only been explored at low redshifts ($z \lesssim 0.2$). In particular, it was found that after controlling for stellar mass, halo mass, or density, a clear signature of the impact of the cosmic filaments, walls, and nodes can be found for the galaxy age, stellar metallicity, and element abundance ratio $[\alpha/\text{Fe}]$ ([Winkel et al. 2021](#)), gas-phase metallicity ([Donnan et al. 2022](#)), or H I fraction ([Kleiner et al. 2017](#); [Crone Odekon et al. 2018](#)). Another property of galaxies that is characterised by a dependence on their large-scale environment, as expected by the tidal torque theory (for a review, see [Schäfer 2009](#) and [Codis et al. 2015](#) for the corresponding theory of constrained tidal torques near filaments), is their angular momentum (or spin) orientation, as identified in low- z observations (e.g. [Lee & Erdogdu 2007](#); [Tempel et al. 2013](#); [Tempel & Libeskind 2013](#); [Zhang et al. 2013, 2015](#); [Pahwa et al. 2016](#); [Krolewski et al. 2019](#); [Kraljic et al. 2021](#); [Barsanti et al. 2022](#)).

An alternative approach to studying the impact of the cosmic network on galaxy properties involves analysing its connectivity; namely, the number of filaments connected to a given node of the cosmic web. This serves as a probe for the geometry of accretion at halo and galaxy scales ([Codis et al. 2018b](#)). When applied to SDSS data (see also, e.g. [Darragh Ford et al. 2019](#); [Sarron et al. 2019](#); [Einasto et al. 2020, 2021](#); [Smith et al. 2023](#), for measurements on galaxy groups and cluster scales), more massive galaxies were found to exhibit higher connectivity ([Kraljic et al. 2020b](#)), a result consistent with theoretical predictions ([Codis et al. 2018b](#)). At fixed stellar mass, galaxy properties such as star formation activity and morphology also show some dependence on connectivity: less star-forming and less rotation-supported galaxies tend to be more connected. This trend is qualitatively consistent with the findings of hydrodynamical simulations ([Kraljic et al. 2020b](#)).

Our understanding of how the anisotropic large-scale environment shapes galaxy properties remains observationally constrained to the low-redshift Universe ($z \lesssim 0.9$), with the majority of studies focusing on the nearby Universe ($z \lesssim 0.2$). However, ongoing and upcoming surveys, such as *Euclid* ([Laureijs et al. 2011](#)), the Prime Focus Spectrograph (PFS) Galaxy Evolution survey ([Greene et al. 2022](#)) at the Subaru Telescope, MOONRISE (the main GTO MOONS extra-galactic survey, [Maiolino et al. 2020](#)) at the Very Large Telescope (VLT), and Nancy Grace Roman Space Telescope (Roman; [Akeson et al. 2019](#)), will enable us to extend these analyses to redshifts between 1 and 2. This epoch is critical for unraveling the details of gas accretion onto galaxies, its conversion into stars, and the physical processes responsible for the quenching of star formation.

The ongoing *Euclid* survey ([Euclid Collaboration: Mellier et al. 2025](#)) will primarily focus on characterising the nature of dark energy and understanding the distribution of dark matter in the Universe. However, while *Euclid* has been specifically prepared to meet these core science objectives, it will also address a wide range of other scientific questions. This “byproduct” research will be notably made possible by an extensive database of approximately two million galaxies observed over a 53 deg^2 area (so-called Euclid Deep Fields; hereafter, EDFs). It will, for the first time, enable detailed tracing of the large-scale environment of galaxies between redshifts 1 and 2, providing new insights into its connection to galaxy growth and properties.

In this paper, we examine the extent to which the cosmic web environment of galaxies can be reconstructed using the upcoming spectroscopic dataset in EDFs. We use Euclid Deep mock galaxy catalogues to evaluate the quality of cosmic web reconstruction. Specifically, we investigate how factors such as the selection function, redshift-space distortions, and anticipated uncertainties in redshift measurements affect the reconstruction quality. This analysis has been conducted using various geometrical and topological properties of the cosmic web. We also examine how accurately stellar-mass gradients towards cosmic web filaments can be recovered. A key objective of this study is to provide practical guidelines for cosmic web reconstruction using the EDF dataset. While this paper focuses on the three-dimensional (3D) reconstruction of the cosmic web, its two-dimensional (2D) counterpart is discussed in [Euclid Collaboration: Malavasi et al. \(2025\)](#), while the reconstruction of cluster-scale filaments is addressed in [Sarron et al. \(in prep.\)](#). In the present approach, the skeleton is used as an effective summary statistics. An alternative is simulation-based inference via forward modelling, which aims to match the full data set to mocks without constructing specific estimators (e.g. [Cranmer et al. 2020](#)). These methods have recently gained some traction given the available computing power (e.g. [Angulo et al. 2021](#); [Kobayashi et al. 2022](#); [Hou et al. 2024](#)). Similarly, alternative approaches exist for the reconstruction of the large-scale environment (see [Libeskind et al. 2018](#), for a detailed comparison of different estimators).

The paper is organised as follows. Section 2 presents the Euclid Deep Survey and simulated galaxy catalogues, together with methods used to create mock data and extract the cosmic web. Section 3 quantifies the quality of the cosmic web reconstruction and its ability to recover the stellar-mass gradients with respect to cosmic filaments. Section 4 provides guidelines for cosmic web reconstruction with the Euclid Deep dataset, outlines possible science cases, and discusses possible synergies with other surveys. Section 5 summarises the key results and

concludes. Finally, Appendix A investigates the impact of the selection function of galaxies and reduced sampling on the distribution of filament lengths, while Appendix B focuses on their impact on connectivity and multiplicity. Appendix C complements the analysis of stellar mass gradients.

2. Data

2.1. The Euclid Deep Survey (EDS)

This survey is described in [Euclid Collaboration: Mellier et al. \(2025\)](#), but we summarise its main characteristics below. In brief, it includes three non-contiguous fields: EDF North (EDF-N, 20 deg²), EDF Fornax (EDF-F, 10 deg²), and EDF South (EDF-S, 23 deg²). Altogether, they cover 53 deg² and will eventually reach a 5 σ point source depth of at least two magnitudes deeper than Euclid Wide Survey (EWS, [Euclid Collaboration: Scaramella et al. 2022](#)), namely, ~ 28.2 AB mag in I_E and 26.4 AB mag in Y_E , J_E , and H_E . These fields will be complemented by deep photometry from the Cosmic DAWN survey in the UV, optical, and IR, which will be very valuable for deriving reliable masses and star formation histories for the observed galaxies ([Euclid Collaboration: McPartland et al. 2025](#); [Euclid Collaboration: Zalesky et al. 2025](#)). In addition, the Euclid Auxiliary Fields (EAF), designed to serve the calibration of the VIS and NISP instruments, will reach a nearly similar depth to the EDF, with the special case of the self-calibration field, which will be ultra-deep (29.4 AB mag in I_E and 27.7 AB mag in Y_E , J_E , and H_E in 2.5 deg²). The EAF will cover a total of 9 deg² distributed over seven fields, all of them already having deep multi-wavelength coverage in a large number of bands covering the whole electromagnetic spectrum. The forecasts presented in this paper are relevant for both the EDF and at least the three largest EAF (COSMOS, SXDS, and the self-calibration field).

On the spectroscopic side, the red grisms will allow the detection of H α emitters over $0.84 < z < 1.88$ and will operate over the full survey (EWS, EDS, and EAF). The blue grism will operate only on the EDF and EAF, and will allow the H α detection down to $z = 0.41$. Since the forecasts presented in the present work concern the EDS, we adopted the redshift range $0.4 < z < 1.8$ throughout this paper. The expected flux limit in the EDFs is 5×10^{-17} erg cm⁻² s⁻¹ for sources with S/N > 3.5. These objects virtually all meet the expected photometric magnitude limits of the EDS.

2.2. Performance of the EDS for cosmic web mapping

Redshift accuracy: The red grisms have a resolving power of $\mathcal{R}_{RG} \geq 480$ for sources with 0''.5 diameter and the blue grism has a resolving power of $\mathcal{R}_{BG} \geq 400$. The expected redshift accuracy is $\sigma(z) < 0.001(1+z)$, confirmed by the analysis using the first *Euclid* Quick Data Release (Q1; [Euclid Collaboration: Le Brun et al. 2026](#)).

Completeness and purity: Slitless spectroscopy is essentially dispersed imaging. The features of the various overlapping spectra must be separated from each other by taking advantage of the fact that the same field is observed with several dispersion angles. A complex extraction and decontamination process produces 1D spectra, performed with the OU-SIR unit ([Euclid Collaboration: Copin et al. 2026](#)). The probability distri-

bution function of the redshift can then be determined from these spectra using a spectral template fitting algorithm, performed by the OU-SPE unit ([Euclid Collaboration: Le Brun et al. 2026](#)). The algorithm returns the most probable redshift as the first solution, which is then used for cosmic web reconstruction. In addition, a reliability score is assigned to each galaxy and a threshold is determined to obtain a good compromise between the completeness and purity of the galaxy sample¹.

This threshold will exclude a significant fraction of galaxies above the flux limit, leading to incompleteness and a higher flux cut. For the cosmic web reconstruction, we will need a high level of purity and, thus, a very high OSU-SPE reliability cut. Similarly to [Hamaus et al. \(2022\)](#), we assume that it will lead to a completeness of 60% and a higher flux limit (see Sect. 2.3.3). This high purity will, in turn, allow us to neglect the existence of catastrophic redshift failures in our current analysis.

2.3. Mock catalogues

To make forecasts about the quality of the cosmic web reconstruction with the upcoming Euclid data, we relied on two simulated sets: Euclid Flagship 2 and GAEA simulations.

2.3.1. Flagship galaxy mock catalogues

The Euclid Flagship Simulation (Flagship, hereafter) is described in great detail in [Euclid Collaboration: Castander et al. \(2025\)](#). Here, we only summarise its main features.

The Flagship lightcone, produced on the fly out to $z = 3$, is based on an N -body dark matter simulation of four trillion dark matter particles in a periodic box of $3600 h^{-1}$ hMpc on a side, leading to the particle mass resolution of $\sim 10^9 h^{-1} M_\odot$. The simulation was performed using the code PKDGRAV3 ([Potter & Stadel 2016](#)), with cosmological parameters of $h = 0.67$, $\Omega_m = 0.319$, $\Omega_b = 0.049$, $n_s = 0.96$, and $A_s = 2.1 \times 10^{-9}$.

Dark matter halos, identified with the ROCKSTAR halo finder ([Behroozi et al. 2013](#)), were populated by galaxies using a combination of halo occupation distribution (HOD) and abundance matching (AM) techniques, satisfying some of the observed relations between galaxy properties. Following the HOD prescription, each halo was assigned a central galaxy and a number of satellites depending on the halo mass, reproducing observational constraints of galaxy clustering in the Local Universe ([Zehavi et al. 2011](#)). Luminosities were assigned to galaxies by performing abundance matching between the halo mass function and the galaxy luminosity function, calibrated on local observations ([Blanton et al. 2003b, 2005](#)) in a way that allowed us to match the observed clustering of galaxies as a function of color ([Zehavi et al. 2011](#)).

The star formation rate (SFR) was computed from the rest-frame ultraviolet luminosity, following the [Kennicutt \(1998\)](#) relation for a Chabrier initial mass function (IMF; [Chabrier 2003](#)). The stellar mass was computed from the galaxy luminosity and the stellar mass-to-luminosity ratio. The H α line flux was computed from the SFR using the [Kennicutt \(1998\)](#) relation adapted to the [Chabrier \(2003\)](#) IMF, using the unextinguished ultraviolet absolute magnitude. The dust extinguished H α flux was then computed following [Calzetti et al. \(2000\)](#) and [Saito et al. \(2020\)](#). Finally, the resulting H α flux distribution was calibrated

¹ Completeness is defined as the fraction of objects recovered with a correct redshift from a full sample above a certain intrinsic flux limit and in a certain redshift range, while purity is the fraction of correctly measured redshifts in the recovered sample.

based on the empirical models of Pozzetti et al. (2016); namely, model 1 and model 3 (hereafter, m1 and m3).

A validation of the Flagship galaxy catalogue by comparing it with observations is presented in Euclid Collaboration: Castander et al. (2025), showing good agreement for many galaxy properties, distributions, and relations. Among them, we see that the stellar mass function and the SFR-stellar mass relation show good consistency when compared to observational data up to $z \sim 3$.

The full galaxy catalogue covers one octant of the sky ($\sim 5157 \text{ deg}^2$) centred at approximately the North Galactic Pole ($145 \text{ deg} < \text{RA} < 235 \text{ deg}$, $0 \text{ deg} < \text{Dec} < 90 \text{ deg}$), sampling a redshift range $0 < z < 3$. However, only a limited area ($150 \text{ deg} < \text{RA} < 155 \text{ deg}$, $5 \text{ deg} < \text{Dec} < 10 \text{ deg}$), with no magnitude or line flux cut, can be used to simulate the EDF (see Sect. 2.3.3). The Flagship catalogues were accessed through CosmoHub (Carretero et al. 2017; Tallada et al. 2020).

2.3.2. The GAEA lightcone

Galaxy Evolution and Assembly (GAEA)² is a semi-analytic model (see, e.g. De Lucia et al. 2014; Hirschmann et al. 2016; Fontanot et al. 2017) run on the Millennium simulation (Springel et al. 2005) containing 2160^3 dark matter particles in a periodic box of $500 h^{-1} \text{ hMpc}$ on one side, leading to a particle mass resolution of $8.6 \times 10^8 h^{-1} M_\odot$. The Millennium simulation was performed using the code GADGET (Springel et al. 2001) with cosmological parameters $h = 0.73$, $\Omega_m = 0.25$, $\Omega_b = 0.045$, $n_s = 1$, and $\sigma_8 = 0.9$. From this simulation, a lightcone was created following Zoldan et al. (2017).

The GAEA semi-analytic model traces the evolution of galaxy populations within DM halos by self-consistently treating gas, metal and energy recycling, as well as chemical enrichment, using physically or observationally motivated prescriptions. Two versions of this model have been implemented. These are described in Hirschmann et al. (2016) and Fontanot et al. (2020) and, respectively, denoted as ECLH and ECLQ in the following. One of the major differences between these two models is an improved prescription for active galactic nucleus (AGN) feedback in ECLQ. While both ECLH and ECLQ models include radio-mode AGN feedback, ECLQ also includes a quasar-driven wind component, following an improved modelling of cold-gas accretion onto the supermassive black hole, based on both analytic approaches and high-resolution simulations.

To compute the dust-attenuated $H\alpha$ flux, the non-attenuated $H\alpha$ luminosity was derived from the SFR following the Kennicutt et al. (1994) relation (rescaled to follow the Chabrier 2003 IMF). The obtained $H\alpha$ flux was then attenuated by dust following the dust attenuation curve of Calzetti et al. (2000). GAEA was shown to aptly reproduce a number of observations, such as the evolution of the galaxy stellar mass function and the cosmic SFR density up to $z \sim 7$ (Fontanot et al. 2017), or the evolution of the stellar mass-gas metallicity relation up to $z \sim 2$ (Hirschmann et al. 2016). The full galaxy catalogue covers a region on the plane of the sky with a diameter of 5.27 deg ($\sim 22 \text{ deg}^2$), samples a redshift range $0 < z < 4$, including all galaxies with magnitude $H \leq 25$ (i.e. deep enough to allow for the construction of EDF mocks; see Sect. 2.3.3).

2.3.3. Mocking the EDS

To mimic the EDFs, from the full Flagship volume, we selected the $\sim 25 \text{ deg}^2$ region with no magnitude or line flux cut, in the redshift range $0.4 < z < 1.8$. The same redshift selection is applied to the GAEA galaxy catalogues, having comparable sky coverage.

Flux limit: In this work, we selected all galaxies with an $H\alpha$ flux limit of $6 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$, which is a more conservative threshold compared to the predicted limit (see Sect. 2.1). This selection ensures that (as expected) all objects satisfy the EDS photometric magnitude limits. To assess the impact of galaxy selection on the quality of cosmic web reconstruction, we also considered a stellar mass-limited sample of galaxies for each mock. To keep the same total number density, we selected from each mock, ordered in decreasing stellar mass, the same number of galaxies as in its flux-limited counterpart. The resulting stellar mass limits are $10^{9.5} M_\odot$, $10^{9.8} M_\odot$, for the Flagship m1 and m3 models, respectively, and $10^{9.8} M_\odot$ for both GAEA models. The M_* - and $H\alpha$ flux-limited samples therefore contain by construction different populations of galaxies. $H\alpha$ flux-limited samples have fewer satellites (and therefore more centrals), missing an important fraction of quiescent massive galaxies compared to M_* -limited catalogues. In the following, flux-limited catalogues are denoted as \mathcal{D} , while mass-limited catalogues are denoted as M_* in the subscript (i.e. \mathcal{D}_{M_*}).

Completeness: To mimic the expected sample completeness of 60% due to observational effects (see Sect. 2.2), we randomly discarded 40% of our galaxies (as done in e.g. Hamaus et al. 2022). We note that the incompleteness will not be truly random. However, since the incompleteness has not been characterised in detail against parameters, such as the local projected density, a more precise model remains currently unavailable. In the following, the corresponding catalogues are denoted with ‘60%’ in the subscript (e.g. $\mathcal{D}_{60\%}$).

Redshift uncertainties: To model the redshift uncertainties associated with Euclid measurement, we perturbed galaxy redshifts, as taken from the mocks, using a Gaussian redshift-dependent error with an RMS of $\sigma_z = 0.001(1 + z)$. For each model, we make five realisations and the corresponding catalogues are denoted with ‘noise’ in the subscript in the following (e.g. $\mathcal{D}_{\text{noise}}$).

Fiducial realisation: Applying all these constraints to the selection of galaxies, namely, with a $H\alpha$ flux limit of $6 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$, redshift uncertainty $\sigma_z = 0.001(1 + z)$, and completeness of 60%, leads to fiducial realisations mimicking the EDFs, denoted in the following as $\mathcal{D}_{\text{noise},60\%}$.

2.3.4. Qualitative assessment of the mocks

As they are based on different N -body simulations and using different methods to assign galaxies to dark matter halos and to compute their properties, the Flagship and GAEA simulations are expected to provide different predictions in terms of galaxy distribution, galaxy clustering, and their dependence on stellar mass or $H\alpha$ flux. In this section, we provide a qualitative assessment of the mock catalogues without additional observational biases (i.e. using true redshifts and a full sampling) by focusing

² <https://sites.google.com/inaf.it/gaea/>

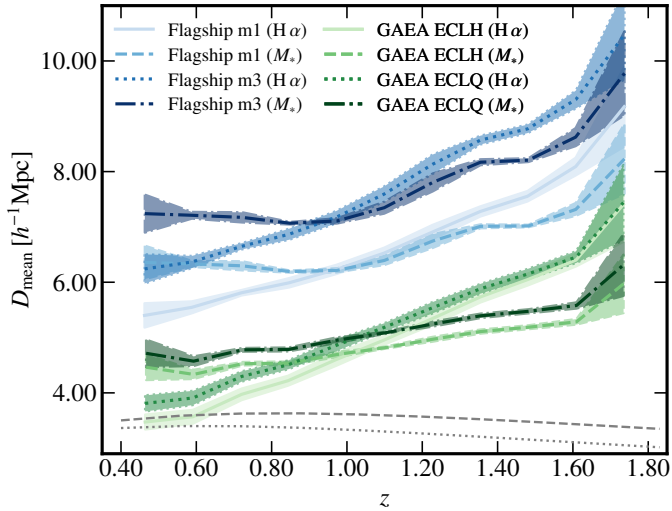


Fig. 1. Mean intergalactic separation in Flagship (blue colours) and GAEA (green colours) simulations for all considered models (m1 and m3 for Flagship, ECLH and ECLQ for GAEA). For each model, the fiducial galaxy selection based on the $H\alpha$ flux ($H\alpha$) is compared to the stellar mass-based selection (M_*). Shaded regions correspond to the standard deviation across five mocks for each model. Dotted and dashed grey lines represent the corresponding redshift uncertainties converted into distances for Flagship and GAEA simulations, respectively. GAEA models show smaller differences between each other and compared to the Flagship simulation models, in particular for the $H\alpha$ selection of galaxies. Above $z \sim 0.9$, the $H\alpha$ selection follows the selection more closely, based on stellar mass for the Flagship simulation, with respect to GAEA.

on their mean intergalactic separation, stellar mass and $H\alpha$ luminosity functions, and main sequence and $H\alpha$ -dependent galaxy clustering.

Mean intergalactic separation: The mean number density of $H\alpha$ -selected galaxies across the entire redshift range is higher in GAEA compared to Flagship, $1.2 \times 10^{-2} (h^{-1} \text{hMpc})^{-3}$ and $9.7 \times 10^{-3} (h^{-1} \text{hMpc})^{-3}$ for ECLH and ECLQ GAEA models, respectively, and $3.9 \times 10^{-3} (h^{-1} \text{hMpc})^{-3}$ and $2.5 \times 10^{-3} (h^{-1} \text{hMpc})^{-3}$ for the two Flagship models m1 and m3, respectively. This translates into the smaller mean intergalactic separations for GAEA compared to Flagship, shown in Fig. 1. The two GAEA models show very little difference in mean intergalactic separations in particular when galaxy selection is based on the $H\alpha$ flux and above $z \sim 0.9$. The two Flagship models show larger differences in the mean intergalactic separation compared to GAEA, regardless of galaxy selection, which is roughly constant across the entire redshift range considered in this work. For comparison, the mean galaxy separations are shown also for the M_* -limited samples for all mocks. As expected, they show a flatter redshift dependence compared to $H\alpha$ galaxy selection for all the mocks, especially at redshifts below $z \sim 1.4$. We anticipate that the expected large redshift uncertainties (see the dotted lines in Fig. 1) are going to play a major role in reducing the quality of the cosmic web reconstruction.

Stellar mass and $H\alpha$ luminosity functions: The stellar mass (SMF) and $H\alpha$ luminosity functions (LF) for all Flagship and GAEA models are displayed in Fig. 2 in three different redshift bins. To highlight the impact of $H\alpha$ flux selection on these observables, we also show the results for samples with-

out any $H\alpha$ flux limit. The SMFs of Flagship and GAEA models are compared with the COSMOS2020 observational dataset (Shuntov et al. 2022), while for the LFs the models are compared to data from the Emission Line COSMOS catalogue (Saito et al. 2020), HST-NICMOS (Shim et al. 2009), HST WISP (Colbert et al. 2013), and HiZELS (Sobral et al. 2013).

Overall, the SMFs of Flagship and GAEA galaxies without the $H\alpha$ flux limit (dashed lines) agree well with the observational measurements in all redshift bins³. This is not surprising, particularly for GAEA, since the SMF was used to calibrate their models.

The application of an $H\alpha$ flux limit translates non-trivially to the change in the SMF in a model-dependent way. The SMFs for the $H\alpha$ flux-limited samples show a reduced amplitude at all stellar masses for all models except GAEA ECLH for which the SMFs overlap at the high-mass end (the stellar mass at which the deviation occurs depends on the redshift). Overall, the SMFs follow a qualitatively similar trend for all models. The steep increase at the high-mass end is followed by a shallower slope at intermediate masses and a downturn of the SMF at low masses. The stellar mass at which the SMFs start to decrease at the low-mass end increases with increasing redshift and depends on the model. For Flagship it corresponds to $\sim 10^{9.5} M_\odot$, $10^{9.5} M_\odot$, and $10^{9.65} M_\odot$ in the three increasing redshift bins, while for GAEA the corresponding masses are slightly higher, particularly in the two highest redshift bins ($10^{9.75} M_\odot$ and $10^{10.15} M_\odot$).

The $H\alpha$ LF of observed galaxies at low redshifts ($0.4 < z < 0.9$; Colbert et al. 2013; Saito et al. 2020) is well reproduced by Flagship, the model m3 in particular. This is expected, given that the LF of galaxies was among the observables used to calibrate the Flagship mocks. GAEA mocks reproduce reasonably well the LF of galaxies at the faint end, whereas they over-predict the number of observed galaxies at the bright end. At intermediate redshifts ($0.9 < z < 1.3$), the $H\alpha$ LF of the observed galaxies (Shim et al. 2009; Colbert et al. 2013) lies well within the range spanned by the four galaxy mocks, making them a fairly good representation of galaxies at luminosities $L_{H\alpha} \gtrsim 10^{41.8} \text{erg s}^{-1}$, corresponding to the $H\alpha$ flux limit of EDS at $z = 1.3$. At higher redshifts ($1.3 < z < 1.7$), the $H\alpha$ LFs of all mocks under-predict observations (Colbert et al. 2013; Saito et al. 2020) below $L_{H\alpha} \sim 10^{42.8} \text{erg s}^{-1}$, while at higher luminosities, most models agree well with observations. GAEA in particular reproduces well the observed LF at the bright end in spite of the fact that this observable has not been used to calibrate the models.

We note that the drop (down turn) of the LF at the faint end for the $H\alpha$ flux-limited sample is a consequence of the relatively large width of the redshift bins. The luminosity at which the two LFs (for full and $H\alpha$ flux-limited samples) start to deviate corresponds to the $H\alpha$ flux limit of the upper bound of each redshift bin. This corresponds to the $H\alpha$ luminosity of $10^{40.51} \text{erg s}^{-1}$, $10^{41.37} \text{erg s}^{-1}$, $10^{41.77} \text{erg s}^{-1}$, and $10^{42.07} \text{erg s}^{-1}$, at redshifts 0.4, 0.9, 1.3, and 1.7, respectively.

Main sequence: Figure 3 shows the relation between the stellar mass and star formation rate of galaxies in the Flagship and GAEA simulations in two redshift bins, $0.4 < z < 0.9$ (top panels) and $0.9 < z < 1.8$ (bottom panels). We only show models m3 and ECLH, but the results are similar for m1 and ECLQ. All galaxy mocks recover the expected correlation between

³ We note that we have not transformed the stellar masses of mock galaxies to units of the Hubble constant used in the observed galaxy catalogues.

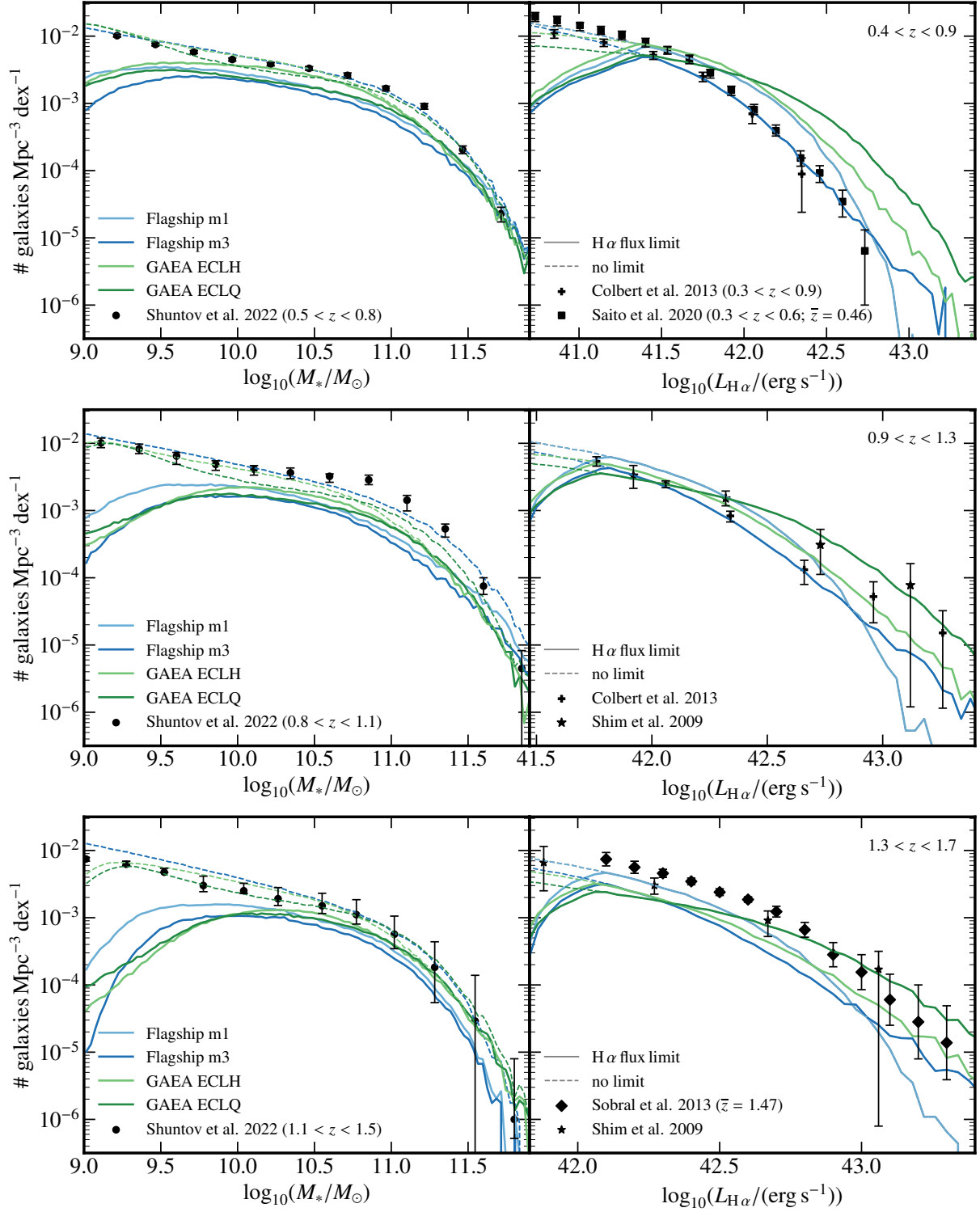


Fig. 2. Stellar mass (left) and $H\alpha$ luminosity functions (right) in three redshift bins, $0.4 < z < 0.9$ (top), $0.9 < z < 1.3$ (middle), and $1.3 < z < 1.7$ (bottom), in all models considered in this work for $H\alpha$ flux limited samples (coloured solid lines) and for samples without any limit (coloured dashed lines). Black symbols correspond to observational data at these redshifts, COSMOS2020 (Shuntov et al. 2022) for stellar mass functions and the Emission Line COSMOS catalogue (Saito et al. 2020), HST-NICMOS (Shim et al. 2009), HST WISP (Colbert et al. 2013), and HiZELS (Sobral et al. 2013) for $H\alpha$ luminosity functions.

the SFR and $H\alpha$ luminosity. Comparison with the compilation of observational data from Popesso et al. (2023) confirms that, in general, there is good agreement between observations and simulations. The shape of the star-forming main sequence for $H\alpha$ flux-limited sample (solid black lines) is better reproduced

in GAEA compared to Flagship across a wide range of stellar masses in both redshift bins. However, both models show a shift compared to the observed main sequence. In GAEA, galaxies lie below, whereas in Flagship, they tend to be above the observed relation.

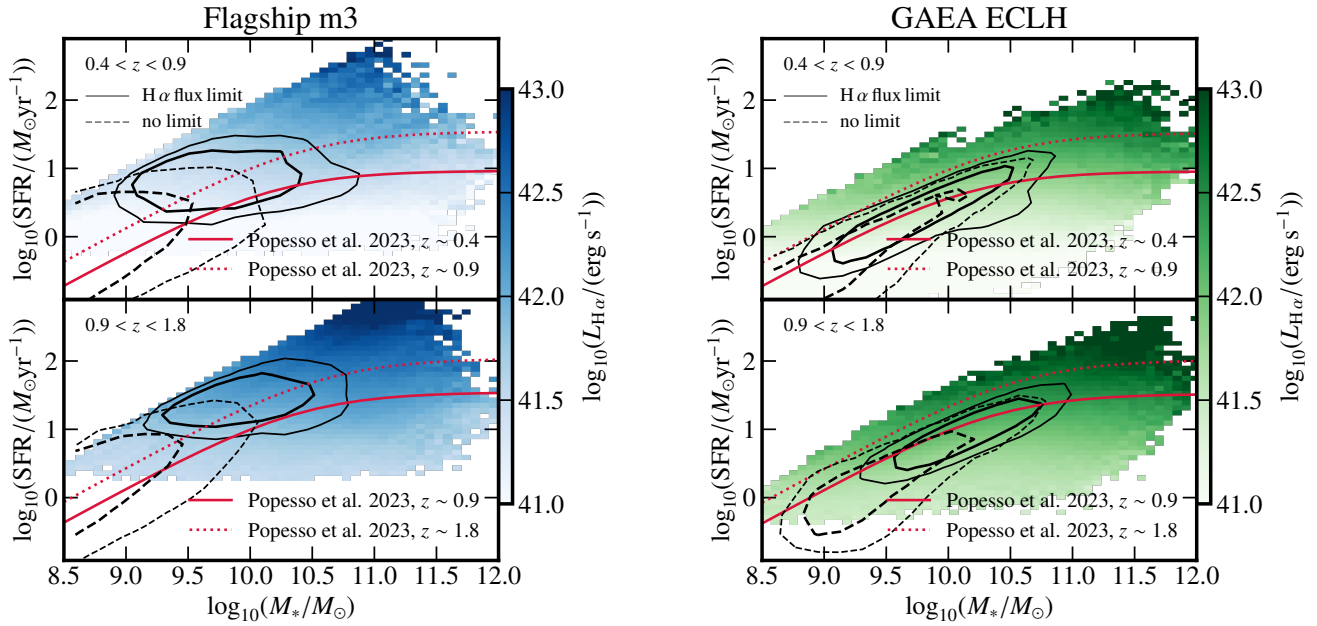


Fig. 3. Star-forming main sequence in the Flagship (left) and GAEA (right) simulations (models m3 and ECLH, respectively) at $0.4 < z < 0.9$ (top) and $0.9 < z < 1.8$ (bottom), color-coded by the $H\alpha$ luminosity, which essentially correlates with SFR. The red lines correspond to the compilation of observational data presented in Popesso et al. (2023). The contours encompass 50% and 75% of the galaxy distribution for $H\alpha$ flux-limited sample (solid lines) and for the sample without any limit (dashed lines).

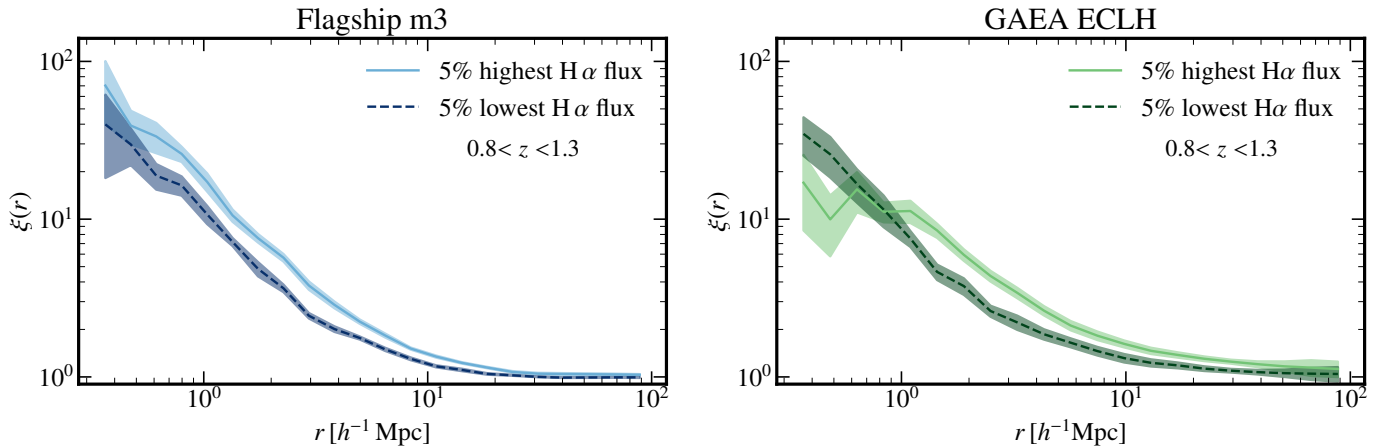


Fig. 4. Two-point correlation functions of galaxies in the redshift range $0.8 < z < 1.3$ for galaxies with the 5% highest and lowest $H\alpha$ flux in the Flagship m3 (left) and GAEA ECLH (right) mocks. Shaded regions correspond to jackknife error bars. At small separations ($\lesssim 1 h^{-1}$ Mpc), brightest galaxies show enhanced clustering in Flagship compared to their low $H\alpha$ flux counterparts, while the brightest galaxies in GAEA show comparable (or reduced) clustering to their lower brightness counterparts. At larger separations ($\gtrsim 1 h^{-1}$ Mpc), the brightest galaxies are more clustered compared to their low $H\alpha$ flux counterparts in all mocks.

Galaxy clustering: Figure 4 shows the two-point correlation functions of galaxies, relying on the Landy–Szalay estimator (Landy & Szalay 1993), in the redshift range $0.8 < z < 1.3$ for the 5% $H\alpha$ flux-brightest and the 5% least bright galaxies in the Flagship m3 and GAEA ECLH mocks. Similar results are found in Flagship m1 and GAEA ECLQ. In both simulations, the clustering is generally higher for the 5% brightest galaxies compared to their 5% lowest $H\alpha$ flux counterparts at large separations ($\gtrsim 1 h^{-1}$ hMpc). At separations $\lesssim 1 h^{-1}$ hMpc, the 5% brightest galaxies in GAEA show reduced clustering with respect to their lower-brightness counterparts, whereas in Flagship, the clustering of the brightest galaxies continues to be higher, presumably better tracing the substructures. We note that galaxy clustering

was among the constraints used during the construction of Flagship mocks to set the number of satellites and assign colour types to galaxies, while this information was not considered at all for the GAEA models. We note also that the considered redshift range bin is quite large. However, the median (and also mean) redshifts of the 5% highest and lowest $H\alpha$ flux galaxies are comparable ($\bar{z} \sim 1.0$ for Flagship m3 and GAEA ECLH; $\bar{z} \sim 1.0$ for the 5% highest and $\bar{z} \sim 1.1$ for the 5% lowest $H\alpha$ flux sample in Flagship m1 and GAEA ECLQ). Therefore, the observed differences in the clustering of these populations are unlikely to be driven by their redshifts alone. We finally note that qualitatively similar results are found when considering 10% cut in the $H\alpha$ flux, and/or for higher redshift range, e.g. $1.3 < z < 1.8$.

Table 1. Optimal linking lengths (in units of the mean intergalactic separation).

	Flagship		GAEA	
	m3	m1	ECLH	ECLQ
\mathcal{D}	(0.07,14)	(0.07,15)	(0.09,19)	(0.09,20)
\mathcal{D}_{M_*}	(0.07,12)	(0.07,14)	(0.09,16)	(0.09,17)
${}^a\mathcal{D}_{\text{noise},60\%}$	(0.07,25)	(0.07,28)	(0.09,29)	(0.09,29)

Notes. Values in parenthesis (b_{\perp} , R) indicate the linking length perpendicular to the line-of-sight b_{\perp} and the radial expansion factor $R = b_{\parallel}/b_{\perp}$, relating the projected (b_{\perp}) and line-of-sight (b_{\parallel}) linking lengths. ^(a) Same values for linking lengths are applied for M_* and H α -limited samples.

2.4. Cosmic web reconstruction

To extract the cosmic web network, we rely on the publicly available and widely used structure finder DisPerSE (Sousbie 2011; Sousbie et al. 2011). To account for the redshift-space distortions that affect any 3D galaxy distribution relying on redshift-based distance measurements, we follow the method outlined in Kraljic et al. (2018). This approach has been previously adopted for the cosmic web reconstruction in 3D space using spectroscopic surveys, such as GAMA or SDSS (Kraljic et al. 2018, 2020b). Here, we only briefly describe its main steps.

To minimise the impact of redshift-space distortions induced by the random motions of galaxies within virialised haloes, the so-called Fingers of God (FoG) effect (e.g. Jackson 1972), we first need to identify the galaxy groups. This is done using an anisotropic friends of friends (FoF) algorithm that operates on the projected perpendicular and parallel separations of galaxies (see Treyer et al. 2018, for details on the group finder algorithm) calibrated on the Flagship and GAEA mock catalogues. Table 1 shows the resulting optimal linking lengths, in units of the mean intergalactic separation, for all models used in this work.

The next step consists of the radial compression of the groups such that the dispersions of their member galaxies in transverse and radial directions are equal (see also e.g. Tegmark et al. 2004). The resulting isotropic galaxy distribution within the groups about their centres minimises the impact of elongated structures along the line-of-sight (i.e. the FoG effect) that could be misidentified as filaments of the cosmic web.

Finally, DisPerSE is used to coherently identify all the components of the cosmic web (i.e. voids, walls, filaments, and nodes) directly from the inhomogeneous distribution of galaxies, relying on discrete Morse theory (Forman 2001). To deal with such a discrete data set, DisPerSE builds on the Delaunay tessellation allowing one to provide a scale-free Delaunay Tessellation Field Estimator (DTFE; Schaap & van de Weygaert 2000) density and reconstruct the local topology. In this work we will consider the cosmic web reconstruction relying on both the non-weighted and stellar mass-weighted Delaunay tessellation. To deal with noisy data, such as galaxy catalogues, DisPerSE implements the concept of the topological persistence allowing to effectively filter out the topologically less robust features, i.e. features that would disappear or change after resampling or adding a noise to the underlying field of the galaxy distribution. The level of filtering is controlled by the persistence threshold N_{σ} , such that higher values of N_{σ} select structures that are topologically more robust with respect to noise. The fiducial value used throughout this work is $N_{\sigma} = 5$. This higher value, compared to the more commonly used $N_{\sigma} = 3$, allows us to bet-

ter highlight challenges of reconstructing cosmic web structures when working with H α flux-limited, rather than stellar mass-limited, noisy data (see Sect. 3). Lastly, the cosmic web skeleton was smoothed in post-processing three times.

For illustration, Figs. 5 and 6 show a $\sim 40 h^{-1}$ hMpc thick slice of the distribution of galaxies within the redshift range $0.4 < z < 0.85$ from the Flagship and GAEA mock catalogues (models m3 and ECLH, respectively) together with the corresponding network of filaments, reconstructed using unweighted Delaunay tessellation, for the reference catalogue, i.e. without FoG effect and with 100% completeness (top), after adding redshift error, 60% sampling and FoG effect (middle), and after correcting for the FoG effect (bottom). This visual inspection allows us to already identify some of the key factors impacting the quality of the cosmic web reconstruction, namely, the FoG effect, redshift uncertainty, and the incompleteness of the underlying galaxy sample. In the following, catalogues including redshift-space distortions are denoted with 'wFoG' in the superscript (e.g. $\mathcal{D}^{\text{wFoG}}$), while catalogues with applied correction for the FoG effect include 'FoG,corr' in the superscript (e.g. $\mathcal{D}^{\text{FoG,corr}}$).

3. Results

To assess the quality of the cosmic web reconstruction expected for the EDFs, we considered three different measures. These involve geometrical and topological properties of the cosmic web and transverse stellar-mass gradients of galaxies with respect to filaments of the cosmic web; namely, the observed and theoretically expected trend of increasing galaxies' stellar mass with their decreasing distance from filaments.

3.1. The geometrical cosmic web measures

Geometrical measures of individual cosmic web components, such as the length of filaments, the area of walls, and the volume of voids, provide a straightforward way to assess the impact of different parameters on the quality of the cosmic web reconstruction. We explore in particular the impact of the FoG effect, redshift errors, and incompleteness of the galaxy sample.

Figure 7 shows the probability distribution function (PDF) of the lengths of filaments⁴, areas of walls, and volumes of voids for Flagship mock, m3 model (m1 model leads to the same conclusions) for the cosmic web reconstruction with (left) and without (right) the stellar mass-weighted Delaunay tessellation. Similarly, Fig. 8 presents the PDF of the filaments' lengths for GAEA mock, model ECLH (the same conclusions apply to the ECLQ model). For walls and voids (not shown), qualitatively similar results and conclusions to those of Flagship are obtained.

As expected, the FoG effect has a strong impact on the filaments of the cosmic web, and much less so on its other components. When this effect is not corrected for, the reconstructed filaments tend to be too long as manifested by the shift of the distribution of filaments' lengths towards larger values ($\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$) compared to the reference sample without redshift-space distortions ($\mathcal{D}_{60\%}$). After correcting for the FoG effect ($\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$), the distributions of filaments' lengths are in excellent agreement, both in terms of medians and overall shape for Flagship. For GAEA, the correction is not perfect, showing some residual deficit of long and excess of intermediate length filaments. We

⁴ In practice, half length of filaments, measured as the curvilinear distance between filament-type saddle points and maxima, the nodes of the cosmic web.

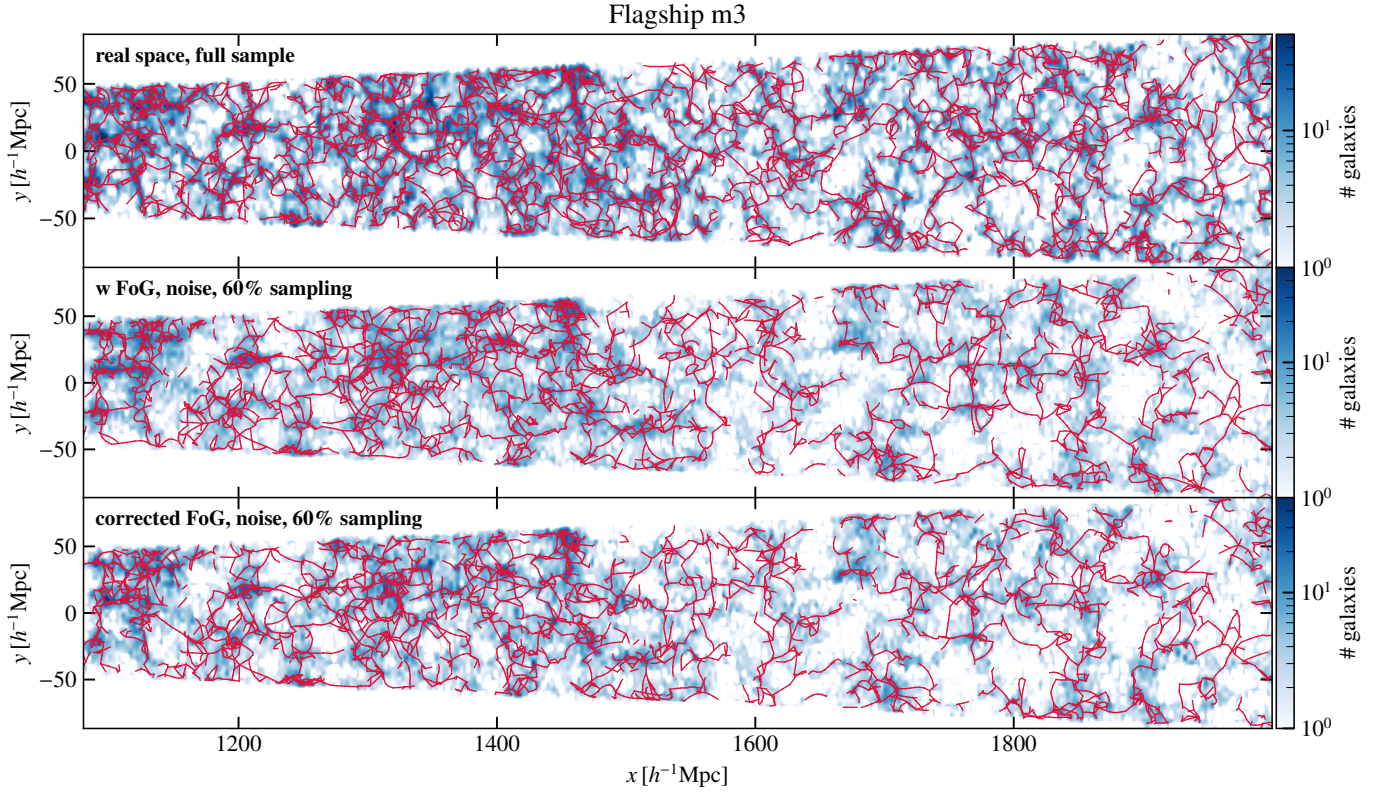


Fig. 5. Visualisation of a $\sim 40 h^{-1}$ Mpc thick slice of the galaxy distribution from the Flagship m3 mock and the corresponding cosmic web skeleton reconstructed without weighting Delaunay tessellation for the reference catalogue without the FoG effect, without added noise and with 100% completeness (\mathcal{D} ; top), with the FoG, added redshift error and 60% sampling ($\mathcal{D}_{\text{noise,60\%}}^{\text{wFoG}}$; middle), and after correcting for the FoG effect ($\mathcal{D}_{\text{noise,60\%}}^{\text{FoG,corr}}$; bottom). For the sake of clarity, only $0.4 < z < 0.85$ range of the lightcone is shown.

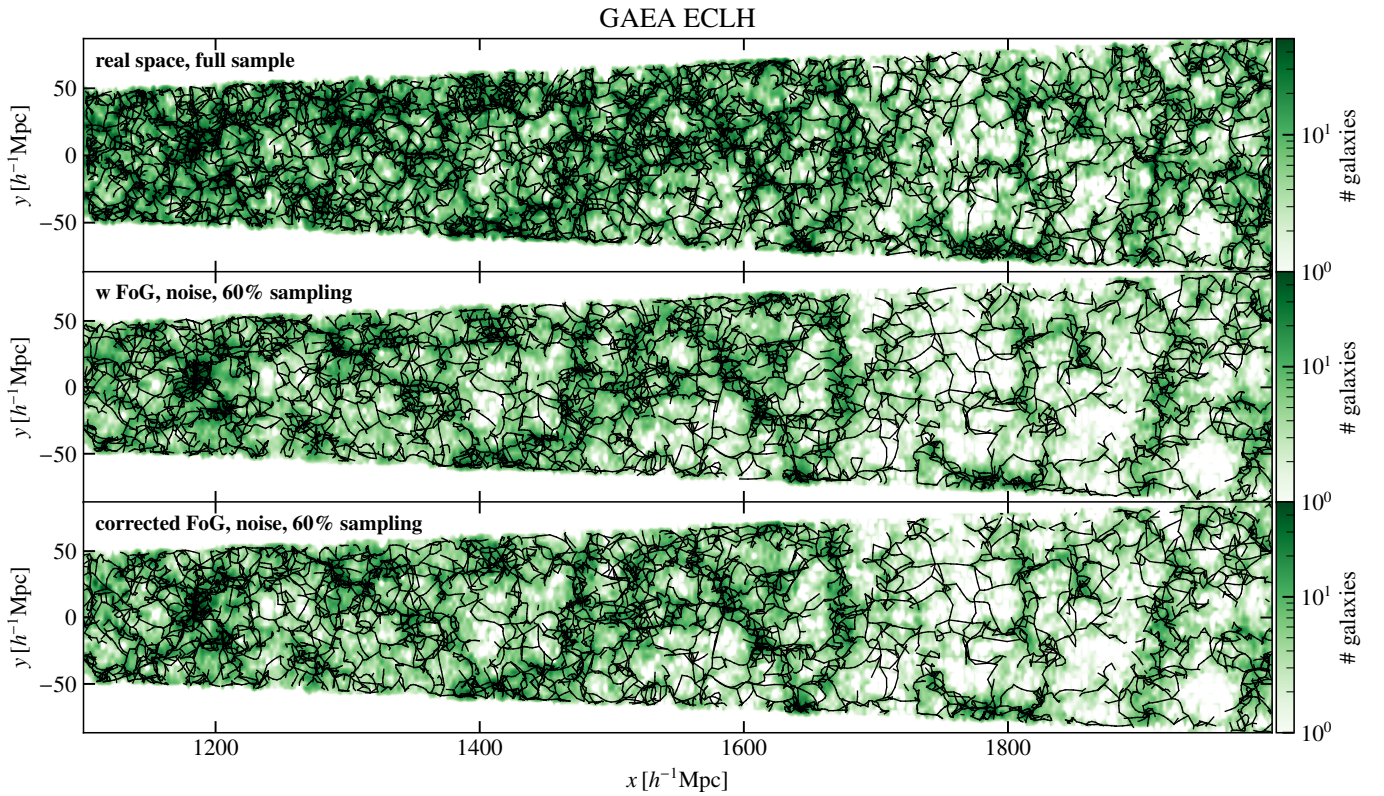


Fig. 6. Same as in Fig. 5, but for the GAEA ECLH mock. The higher galaxy number density of the GAEA ECLH mock compared to Flagship m3 (Fig. 5) can be clearly seen.

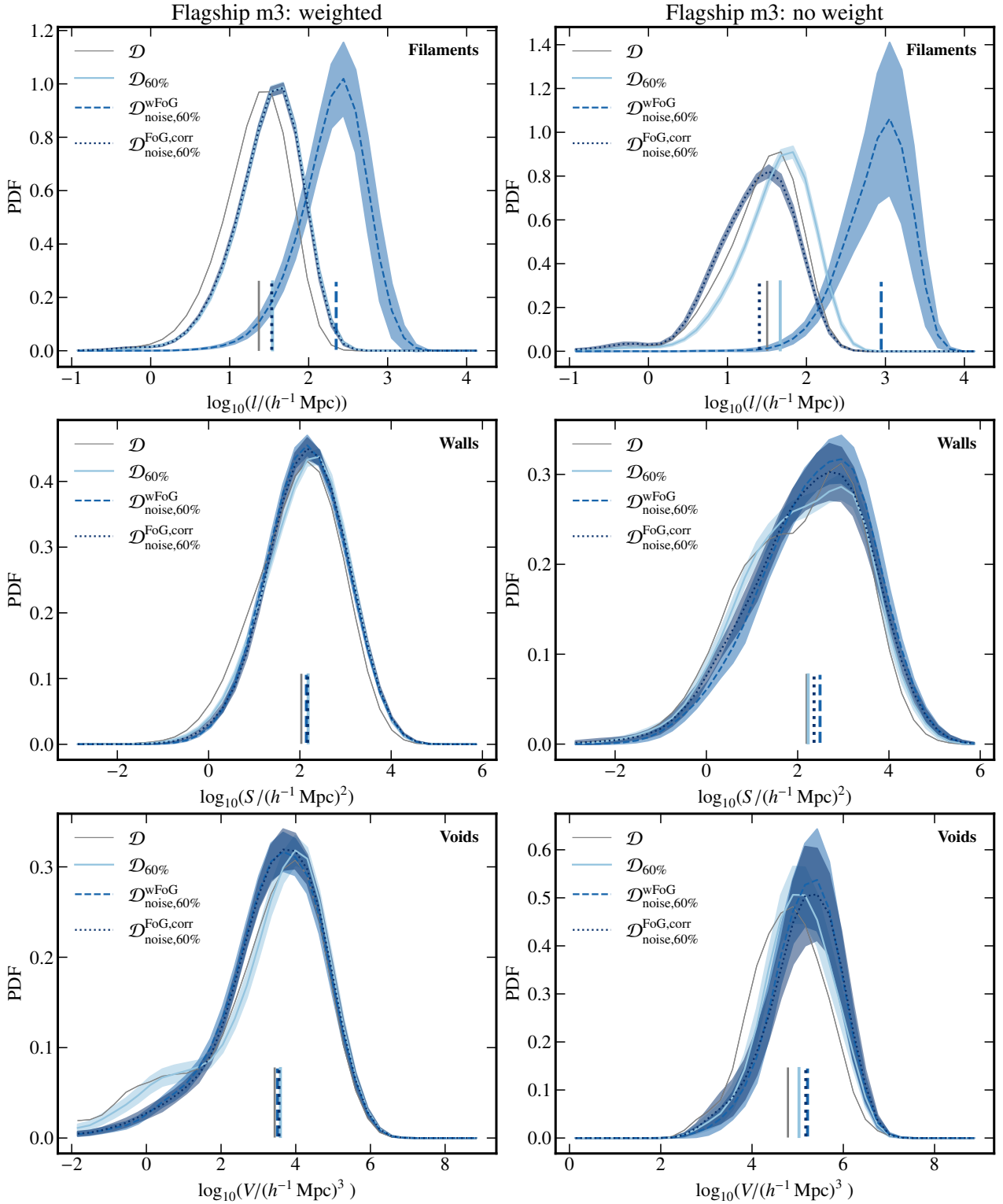


Fig. 7. PDF of filament lengths (top), wall areas (middle) and void volumes (bottom) for Flagship mocks (model m3) without redshift-space distortions for full (\mathcal{D} ; solid grey lines), and 60% ($\mathcal{D}_{60\%}$; solid coloured lines) sampling, including the FoG effect ($\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$; dashed coloured lines) and after the compression of FoG ($\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$; dotted coloured lines) for the Flagship (model m3) simulation. PDFs obtained using the stellar mass-weighted Delaunay tessellation for the cosmic web reconstruction (left) are compared with the reconstruction without weighting (right). Vertical lines indicate the medians of the distributions. Shaded regions correspond to the standard deviation across five mocks. The FoG mainly impacts the length of filaments which tend to be longer. After the compression of groups, the PDFs are in a good agreement with the reference distribution. Weighting the tessellation helps bringing in better agreement the distributions of the reference catalogue without the FoG effect ($\mathcal{D}_{60\%}$) and after the correction for the FoG effect ($\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$). For the PDFs of void volumes obtained for the reconstruction without weighted tessellation, to avoid spurious border effects, only voids with volume larger than the volume corresponding to the mean intergalactic separation are considered.

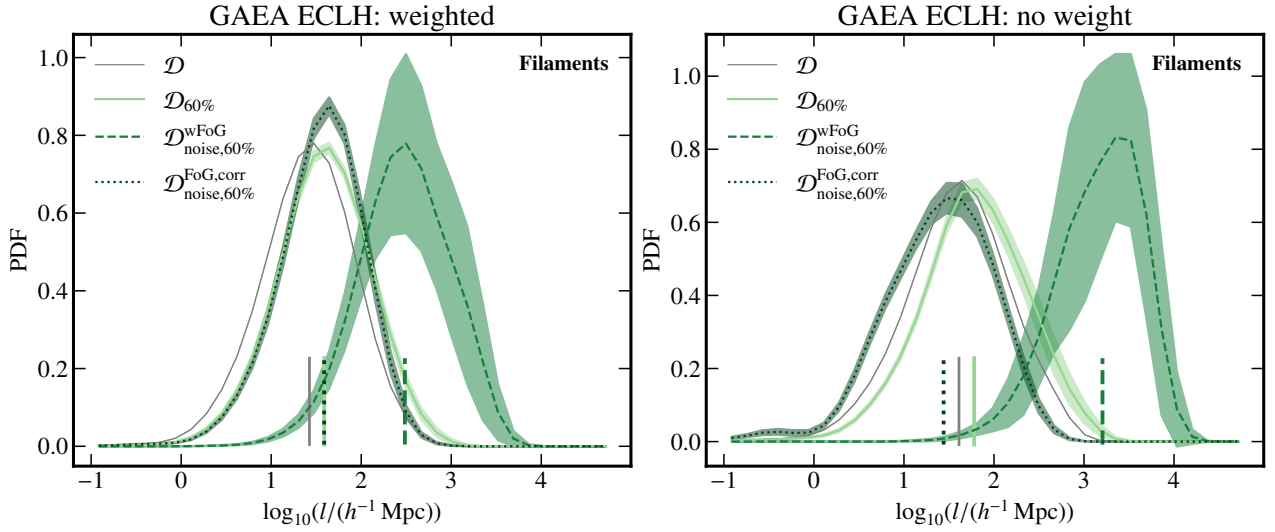


Fig. 8. Same as in Fig. 7, but for GAEA mocks (model ECLH) and filament lengths alone.

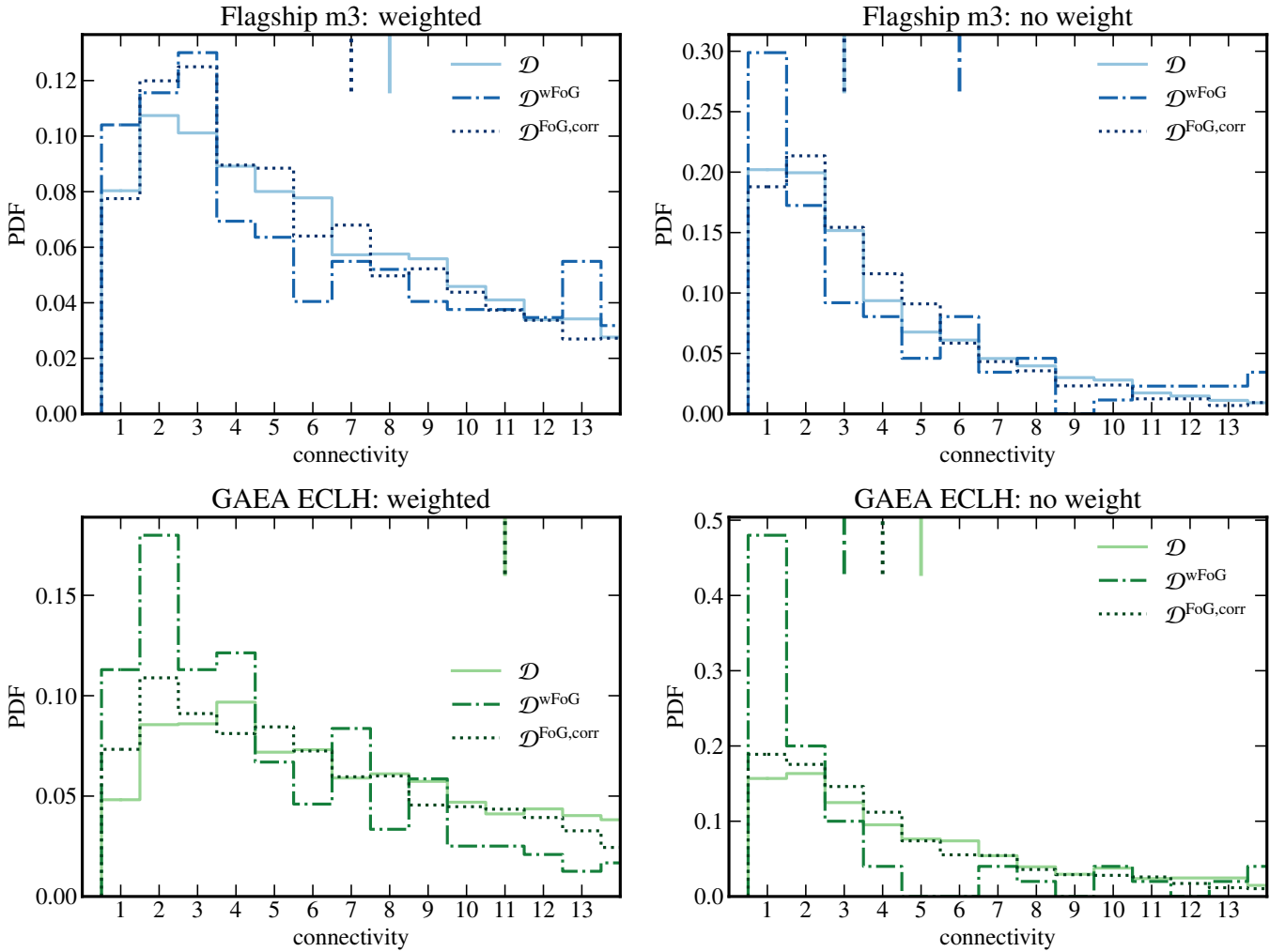


Fig. 9. PDFs of the connectivity of central galaxies for the H α -limited selection of galaxies in the full sample without redshift error (\mathcal{D}) for Flagship model m3 (top) and GAEA model ECLH (bottom) mocks, with stellar mass weighting of the skeleton (left) and without weighting (right). In each panel, vertical lines indicate the medians of distributions. For a better visibility, the histograms are limited to the connectivity values below 14. Mean and median values for all distributions are reported in Tables B.1 and B.2. The redshift-space distortions have a strong impact on the connectivity of galaxies, but this effect that can be reasonably corrected for.

note, however, that the medians of the distributions are comparable.

Weighting the Delaunay tessellation by the stellar mass of galaxies turns out to be important for recovering a better agreement between the distributions before and after correcting for the FoG effect when the galaxy sample is not stellar mass-limited, as is the case for the EDS. As can be seen, the agreement between the distributions of filaments' lengths does improve once the correction of the FoG effect is applied, but it is not as good as in the case of weighting. This is a direct consequence of the galaxy sample being H α flux- rather than stellar mass-limited (see Fig. A.1). For stellar mass-limited galaxy samples the method used to deal with the FoG is efficient even without weighting the tessellation. The sample selection based on the H α flux is also responsible for our failure to correct completely for the FoG effect seen for GAEA. The underlying reason is the inability to properly reconstruct galaxy groups, virialised structures responsible for small-scale redshift-space distortions, when the sample is not stellar mass-limited. As discussed in Sect. 2.3.4, Flagship and GAEA mocks show different clustering on small scales, with brightest galaxies tracing presumably more closely substructures in Flagship models, therefore resembling more the stellar mass selection.

The incompleteness of the galaxy sample manifests, as expected, by a shift of the distributions towards higher values (compare $\mathcal{D}_{60\%}$ vs. \mathcal{D} in Figs. 7 and 8), in particular for the filaments' lengths. Walls and voids are impacted to a much lesser degree, especially when weighting is applied.

The redshift error, on top of the sample selection (whether it is stellar mass- or H α flux-selected), strongly impacts our ability to correct for the FoG effect (see Fig. A.3). However, the correction works better for the stellar mass-limited sample.

In summary, the small-scale redshift-space distortions strongly impact the cosmic web reconstruction, filamentary network in particular, regardless of the sample selection and regardless of the weighting of the tessellation. The applied correction for the FoG effect works better for stellar mass-limited samples. On top of the sample selection, the redshift uncertainties hinder our ability to correct for the FoG effect.

3.2. Connectivity and multiplicity

The connectivity and multiplicity of the cosmic web, namely, the number of filaments that are globally and locally connected, respectively, to the nodes of the cosmic web, where massive galaxy groups and clusters predominantly reside, are interesting topological measures. They are expected to depend on the underlying cosmology and to impact the assembly of galaxies and hence their properties. It is therefore important to assess our ability to recover these quantities from the expected configuration for the EDFs.

We start by considering the distribution of connectivity, defined as the number of filaments connected to a given node of the cosmic web. Figure 9 shows the histograms of connectivity of central galaxies⁵ in the H α flux-limited sample measured in the Flagship and GAEA mocks (models m3 and ECLH, respectively, but qualitatively similar results are obtained for models m1 and ECLQ). The FoG effect has a strong impact on the connectivity of galaxies at the nodes of the cosmic web ($\mathcal{D}^{\text{wFoG}}$),

modifying both the shape of the distribution, but also its median (indicated by a vertical line), regardless of the sample selection; namely, by including M_* -limited samples ($\mathcal{D}_{M_*}^{\text{wFoG}}$; see Fig. B.1). The correction of the FoG effect works very well for the M_* -limited sample and reasonably well for the H α flux-limited sample in terms of the overall shape of distributions, but also their mean and median values (see Tables B.1 and B.2). The weighting of the tessellation by stellar mass for the H α flux-based selection (left panels of Fig. 9) tends to artificially increase connectivity even in the absence of redshift-space distortions, for example, with a median value of 8 (11) as opposed to a median value of 3 (5) without weighting for Flagship m3 (GAEA ECLH). For the M_* -limited selection, the impact of weighting of the tessellation by stellar mass on the connectivity is very weak (see Fig. B.1). Adding redshift errors and incompleteness decreases the quality of the cosmic web reconstruction, in particular for the H α -based selection (Fig. 10) due to the reduced ability to correct for FoG. In this configuration, stellar mass weighting of the tessellation improves the cosmic web reconstruction (see Tables B.1 and B.2).

Next, we explore the multiplicity and our ability to recover this local property of the cosmic web, defined as the connectivity minus the number of bifurcation points (i.e. points where filaments split, even though they are not extrema, Pogosyan et al. 2009), associated with each node. Figure 11 shows the multiplicity of central galaxies in Flagship and GAEA mocks (models m3 and ECLH, respectively, but almost identical results are obtained for the Flagship model m1 and the GAEA model ECLQ) for the fiducial sample ($\mathcal{D}_{\text{noise},60\%}$). Similarly to the connectivity, not correcting for the FoG effect modifies the distribution of multiplicity, but to a much lesser extent, in particular when the Delaunay tessellation is weighted by stellar mass. The mean and median values of the multiplicity agree very well across all mocks for weighted tessellation. For cosmic web reconstruction without weighting the tessellation, the correction of the FoG effect is needed to obtain good agreement between the distributions of multiplicity (Tables B.3–B.4). Qualitatively similar conclusions apply to the M_* -limited samples. The multiplicity of the cosmic web therefore appears to be a more robust topological property compared to connectivity given its weak sensitivity to the FoG effect, redshift error, sample completeness, and its selection.

Beyond the statistical measurements of connectivity and multiplicity, it is of interest to explore these quantities as a function of different galaxy properties. In this work, we focus on stellar mass. Figure 12 shows the connectivity of central galaxies as a function of their stellar mass for the Flagship and GAEA mocks (models m3 and ECLH, respectively, with qualitatively similar conclusions for m1 and ECLQ) for the fiducial sample ($\mathcal{D}_{\text{noise},60\%}$). Regardless of the sample selection, i.e. H α - or M_* -limited (see Fig. B.2), central galaxies in the reference sample follow the expected trend, where the connectivity increases with increasing stellar mass, for the probed stellar mass range and when no weighting is applied prior to the cosmic web reconstruction (right panels of Fig. 12). Weighting of the Delaunay tessellation introduces a bias at lower stellar masses, in particular for the H α -based galaxy selection, leading to an increase of the connectivity with decreasing stellar mass (left panels of Fig. 12). As already seen from the global distributions, the redshift-space distortions have a strong impact on the connectivity of the cosmic web. This leaves a clear signature in the form of a shift of the M_* -connectivity relation towards higher values of connectivity, for mocks with FoG compared to the reference sample, regardless of the tessellation weighting. The applied correction of the FoG effect allows us to recover reasonably well the M_* -

⁵ We focus on central galaxies to limit the complications due to the non-linear nature of the satellite population and to ease the comparison with theoretical predictions (for a more detailed discussion on the effect of satellites on connectivity, see Kraljic et al. 2020b).

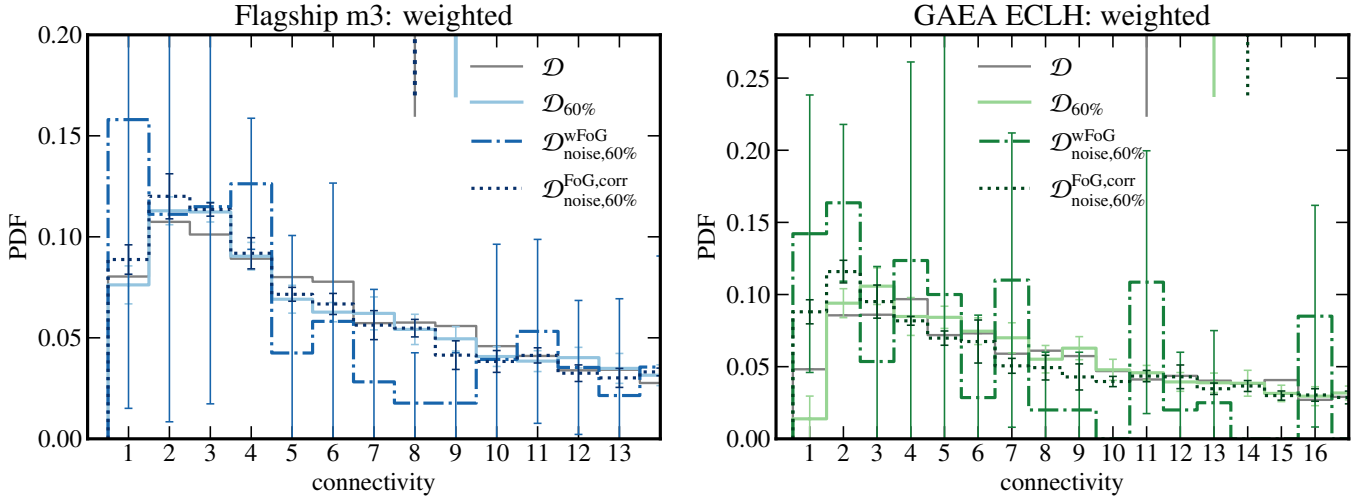


Fig. 10. PDFs of the connectivity of central galaxies for the $H\alpha$ -limited selection of galaxies in the fiducial sample ($\mathcal{D}_{\text{noise},60\%}$; coloured lines) for Flagship model m3 (left) and GAEA model ECLH (right) mocks, with stellar mass weighting of the skeleton. The full sample without noise (\mathcal{D}) is shown for comparison (grey lines). In each panel, vertical lines indicate the medians of distributions and error bars correspond to the standard deviation across five mocks. For a better visibility, the histograms are limited to the connectivity values below 14. Mean and median values for all distributions are reported in Tables B.1 and B.2. Redshift errors and incompleteness of the sample decrease the quality of the cosmic web reconstruction, which can be improved by stellar mass weighting.

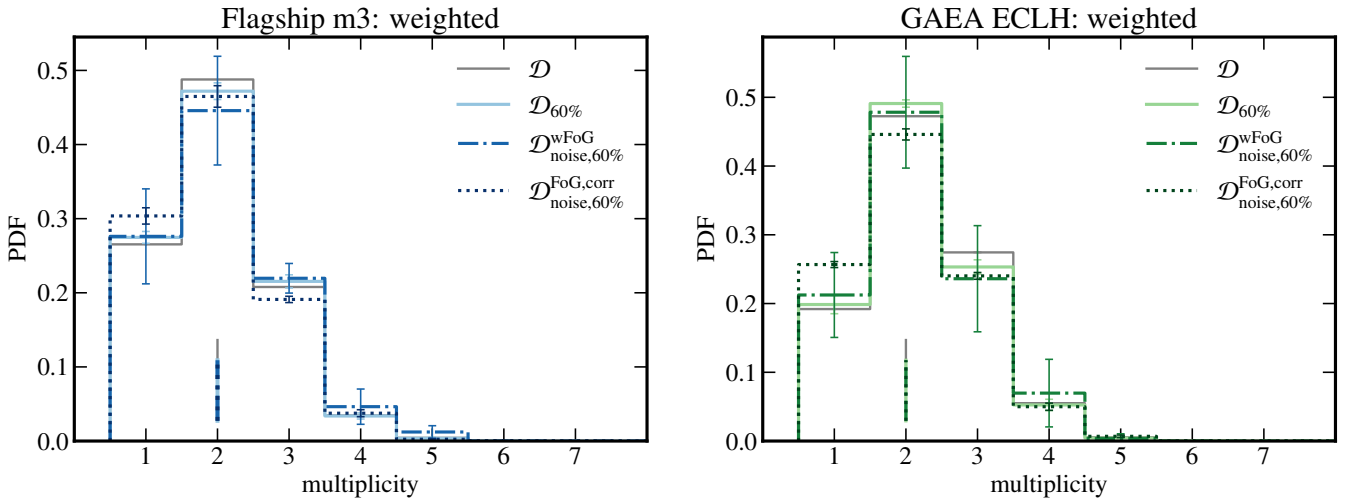


Fig. 11. PDFs of the multiplicity of central galaxies for an $H\alpha$ -limited selection of galaxies in the fiducial sample ($\mathcal{D}_{\text{noise},60\%}$; coloured lines) for Flagship model m3 (left) and GAEA model ECLH (right) mocks, with stellar mass weighting of the skeleton. The full sample without noise (\mathcal{D}) is shown for a comparison (grey lines). In each panel, vertical lines indicate the medians of distributions and error bars correspond to the standard deviation across five mocks. The mean and median values for all distributions are reported in Tables B.3 and B.4. The multiplicity of the cosmic web shows only a weak sensitivity to the FoG effect, redshift error, and sample completeness.

connectivity relation of the reference samples, in particular for weighted tessellations. Weighting the tessellation by stellar mass is crucial for recovering the M_* -connectivity trend if the sample is $H\alpha$ flux-limited, in the presence of the redshift errors, and for reduced sampling, albeit with an introduced bias at lower masses.

Figure 13 shows the multiplicity of central galaxies as a function of their stellar mass for the Flagship and GAEA mocks (models m3 and ECLH, respectively, with qualitatively similar conclusions for m1 and ECLQ) for the fiducial sample ($\mathcal{D}_{\text{noise},60\%}$). As in the case of connectivity, the multiplicity of central galaxies increases with increasing stellar mass for galaxies in all reference catalogues (\mathcal{D}) regardless of sample selection (see Fig. B.3 for the M_* -limited sample; \mathcal{D}_{M_*}) and without tes-

sellation weighting (see Fig. B.4). At the lowest stellar mass end (below $10^{9.5} M_\odot$), accessible only in the $H\alpha$ flux-selected samples, multiplicity tends to increase when stellar mass-weighted tessellation is used for the cosmic web reconstruction. Contrary to connectivity, the redshift-space distortions do not strongly modify the amplitude of the M_* -and-multiplicity relation. The impact of FoG on this relation is overall very limited for the reconstruction with the stellar mass-weighted tessellation, but critically reduces our ability to recover the trend when the sample is $H\alpha$ flux-limited ($\mathcal{D}^{\text{wFoG}}$, $\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$) and no weighting is applied. The applied FoG correction significantly improves our ability to recover the M_* -multiplicity relation in all mocks, but as for connectivity, the quality of this correction decreases with added redshift errors.

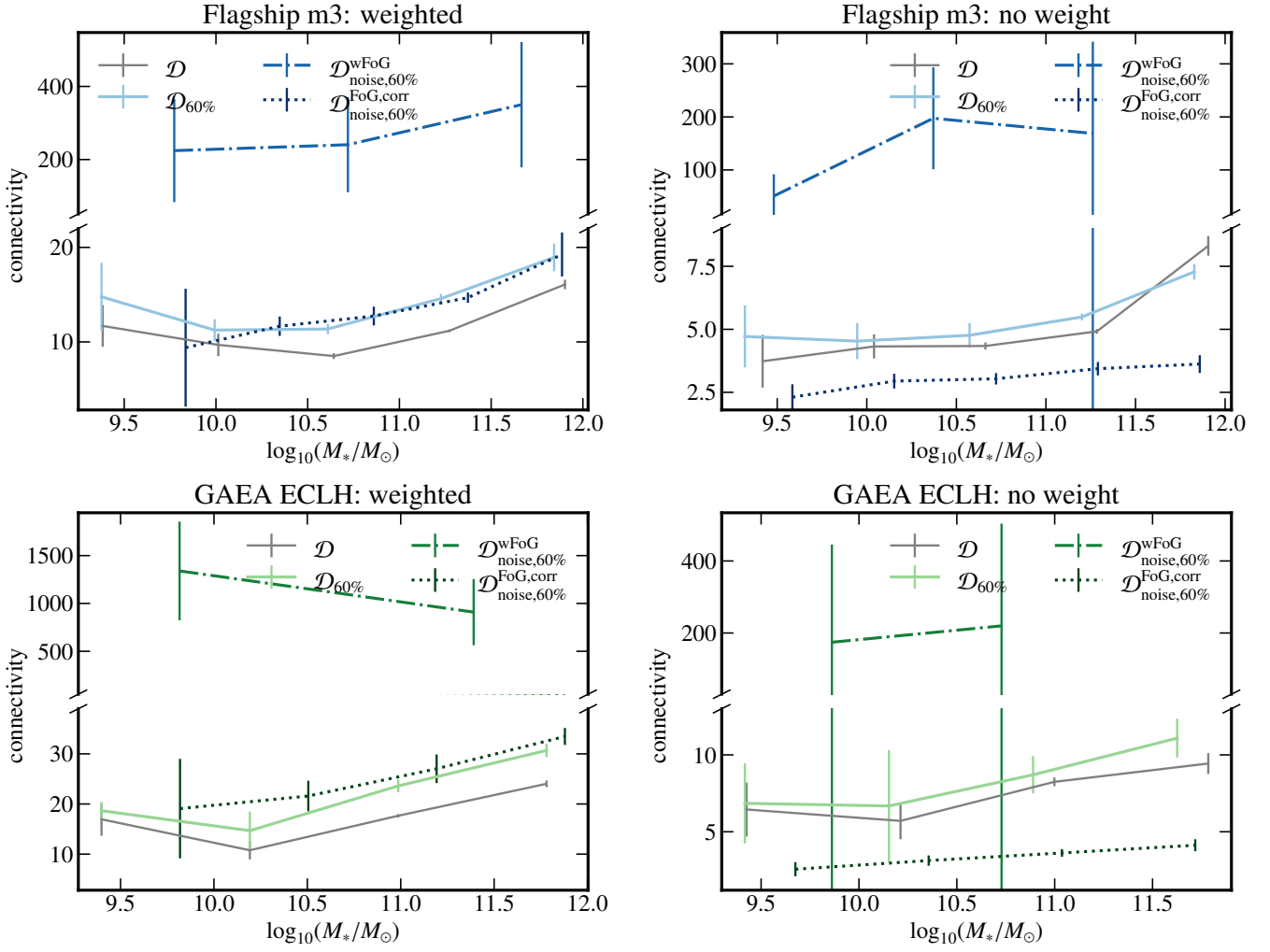


Fig. 12. Connectivity of central galaxies as a function of their stellar mass in Flagship model m3 (top) and GAEA model ECLH (bottom) mocks for the fiducial galaxy sample $\mathcal{D}_{\text{noise, 60\%}}$, with stellar mass weighting of the skeleton (left) and without weighting (right). As expected, connectivity increases with stellar mass, with weighting of the Delaunay tessellation introducing a bias at lower stellar masses leading to reversed trend. Correction for the FoG effect is needed to recover reasonably well the M_* -connectivity relation, in particular for weighted tessellations.

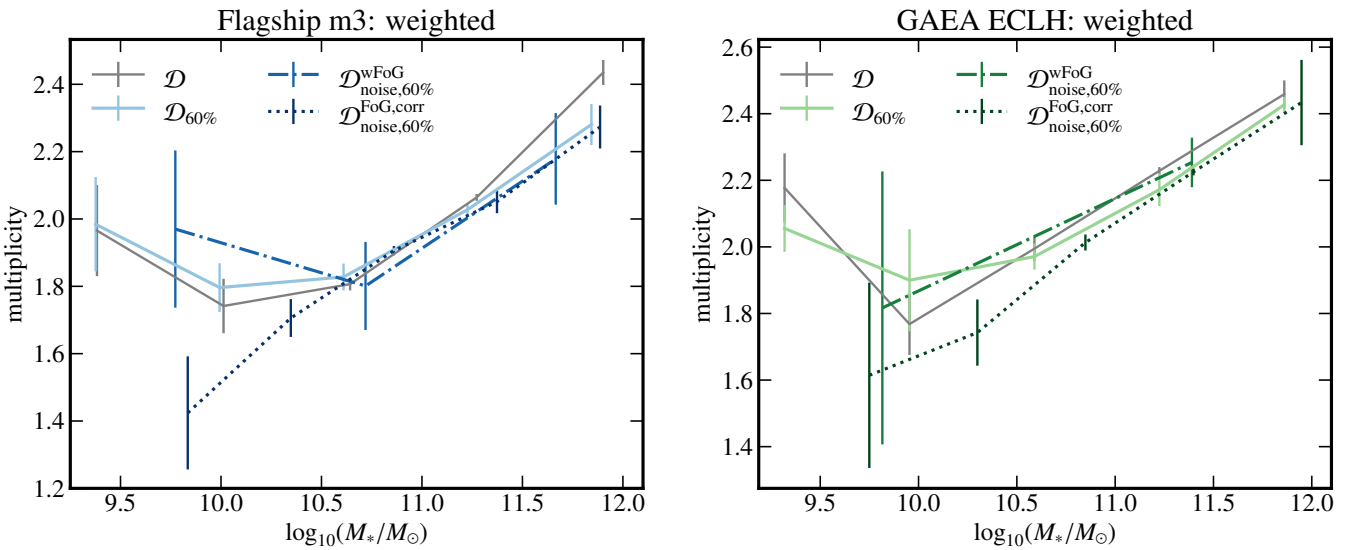


Fig. 13. Multiplicity of central galaxies as a function of their stellar mass in Flagship model m3 (left) and GAEA model ECLH (right) mocks for the fiducial sample, with stellar mass weighting of the skeleton. As for connectivity, multiplicity increases with M_* , with a reversed trend at low M_* . In contrast to connectivity, the redshift-space distortions do not strongly modify the amplitude of the M_* -multiplicity relation.

In summary, for $H\alpha$ flux-limited samples, as in the case of EDF, the multiplicity appears to be a more robust quantity, compared to connectivity. Indeed, even without weighting the tessellation, and after applying a correction for the FoG effect, we are able to recover the M_* -multiplicity relation in the presence of redshift error and reduced sampling. However, given that the range of multiplicity values is quite restrained, we anticipate that it might still be difficult to retrieve correlations between the multiplicity of galaxies located at nodes of the cosmic web and their properties beyond stellar mass (e.g. morphology or star formation activity).

3.3. Stellar-mass gradients

As explained by the theory of biased clustering (e.g. Kaiser 1984; Efstathiou et al. 1988), the mass of galaxies is expected to depend on their large-scale environment, such that more massive galaxies are preferentially formed in over-dense regions (e.g. Bond & Myers 1996; Pogosyan et al. 1996; Malavasi et al. 2017; Kraljic et al. 2018; Laigle et al. 2018). We go on to explore the stellar-mass gradients with respect to filaments of the cosmic web and our ability to recover this trend with the EDS below.

Figure 14 shows the PDFs of the distances of galaxies to their closest filament for the Flagship m3 model and for the reconstruction of the cosmic web with weighted tessellation as a function of stellar mass and redshift. The equivalent PDFs for the reconstruction without weighting are presented in Fig. C.2. Similar results are obtained for the Flagship m1 model and both GAEA models. The distances are normalised by the mean intergalactic separation to take into account the effect of decreasing the density of galaxies with increasing redshift. After accounting for these redshift variations, stellar-mass gradients, where more massive galaxies are preferentially located closer to filaments compared to their lower-mass counterparts, exhibit only minimal evolution in the redshift range $0.4 < z < 1.8$, with galaxies typically found closer to the filaments of the cosmic web at lower redshifts.

Stellar-mass gradients towards filaments of the cosmic web are recovered in the reference sample (\mathcal{D} , first rows of Figs. 14 and C.2) regardless of whether the weighting of Delaunay tessellation is applied or not. We note that the bimodality seen for the distributions without weights is due to our choice for a relatively high value of the persistence threshold N_σ applied to select filaments. This is caused by the removal of topologically less significant filaments for higher N_σ , which leaves some galaxies associated with filaments further away.

Reducing sample completeness weakens this signal ($\mathcal{D}_{60\%}$, Figs. C.1 and C.2), especially when the cosmic web is reconstructed without stellar mass-weighted tessellation. Redshift errors further reduce our ability to detect the stellar-mass gradients across the entire mass range ($\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$, Fig. C.1), in particular for reconstructions without tessellation weighting. Correcting for the FoG effect does not significantly improve the strength of the signal ($\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$, second rows of Figs. 14 and C.2).

4. Discussion

4.1. Guidelines for cosmic web reconstruction with the spectroscopic Euclid Deep dataset

One of the major difficulties identified in this work hampering the reconstruction of the cosmic web in three dimensions is the galaxy selection function. An $H\alpha$ flux-limited (rather than

a stellar mass-limited selection of galaxies) is suboptimal for the reconstruction of the cosmic web in three dimensions. In addition, the redshift errors expected for the EDS further reduce the quality of the cosmic web reconstruction. In this section, we summarise and discuss possible choices to deal with these issues together with their implications.

Any cosmic web reconstruction in three dimensions employing galaxy redshift-based distances needs to account for the redshift-space distortions. Widely used methods to correct for such an effect on small scales depend on a reliable detection of galaxy groups and clusters. The optimisation of a group finder is typically performed on galaxy mocks designed to capture the specificities of a given survey. We have at our disposal two sets of mock catalogues, the Flagship and GAEA simulations, each providing two models of $H\alpha$ flux of galaxies. As all these models reasonably represent galaxy populations at $0.4 < z < 1.8$, based on comparisons with observational datasets of the galaxies' main sequence, stellar mass, and $H\alpha$ luminosity functions, we used them to optimise the anisotropic group finder.

However, due to inherent differences in the modelling of $H\alpha$ flux, Flagship and GAEA show some fundamental differences; for example, in the clustering of galaxies on small scales (below $\sim 1 h^{-1}$ hMpc; see Fig. 4) or number density of galaxies across the entire redshift range (see Fig. 1). All of these non-trivial differences make it difficult to homogenise the cosmic web reconstruction. Consequently, we decided to treat each model as a plausible representation of our Universe and optimised the reconstruction process individually. The resulting optimal linking lengths are reported in Table 1. We note that these values are different for the Flagship and GAEA mocks, but they are reasonably close, not only to each other but also to the values adopted for the FoF algorithm-based group reconstruction method concentrating on lower redshift spectroscopic surveys (e.g. Robotham et al. 2011; Duarte & Mamon 2014; Treyer et al. 2018). This means that the exact choice of the linking lengths for the reconstruction of galaxy groups in the EDS will have to be made once the data are available on the basis of the comparison with the two mocks.

When reconstructing the cosmic web from discrete galaxy samples that are $H\alpha$ flux- rather than stellar mass-limited, weighting the Delaunay tessellation by stellar mass of galaxies might improve the quality of the reconstruction, in particular in the presence of redshift errors with an RMS of $0.001(1+z)$. However, this only holds for certain quantities. Among those explored in this work, geometrical cosmic web quantities (i.e. the length of filaments, the area of walls, and the volume of voids) are better recovered when stellar mass weighting is applied.

For topological cosmic web measurements, such as connectivity and multiplicity, the recommendation to apply weighing is less obvious. The main reason is that the stellar mass-weighted tessellation modifies the connectivity of the reconstructed filamentary network by typically shifting it towards higher values. Hence, the comparison with theoretical predictions and existing measurements from hydrodynamical simulations (e.g. Kraljic et al. 2020b; Galárraga-Espinosa et al. 2024) and low-redshift mass- or volume-limited samples (e.g. Kraljic et al. 2020b) becomes less obvious; this should be properly taken into account when interpreting any such connectivity measurement. However, stellar mass weighting helps to recover the M_* -connectivity correlation. Interestingly, the multiplicity of the cosmic web seems to be very weakly affected by weighting, allowing us to reconstruct the correlation between the stellar mass of central galaxies and the number of locally connected

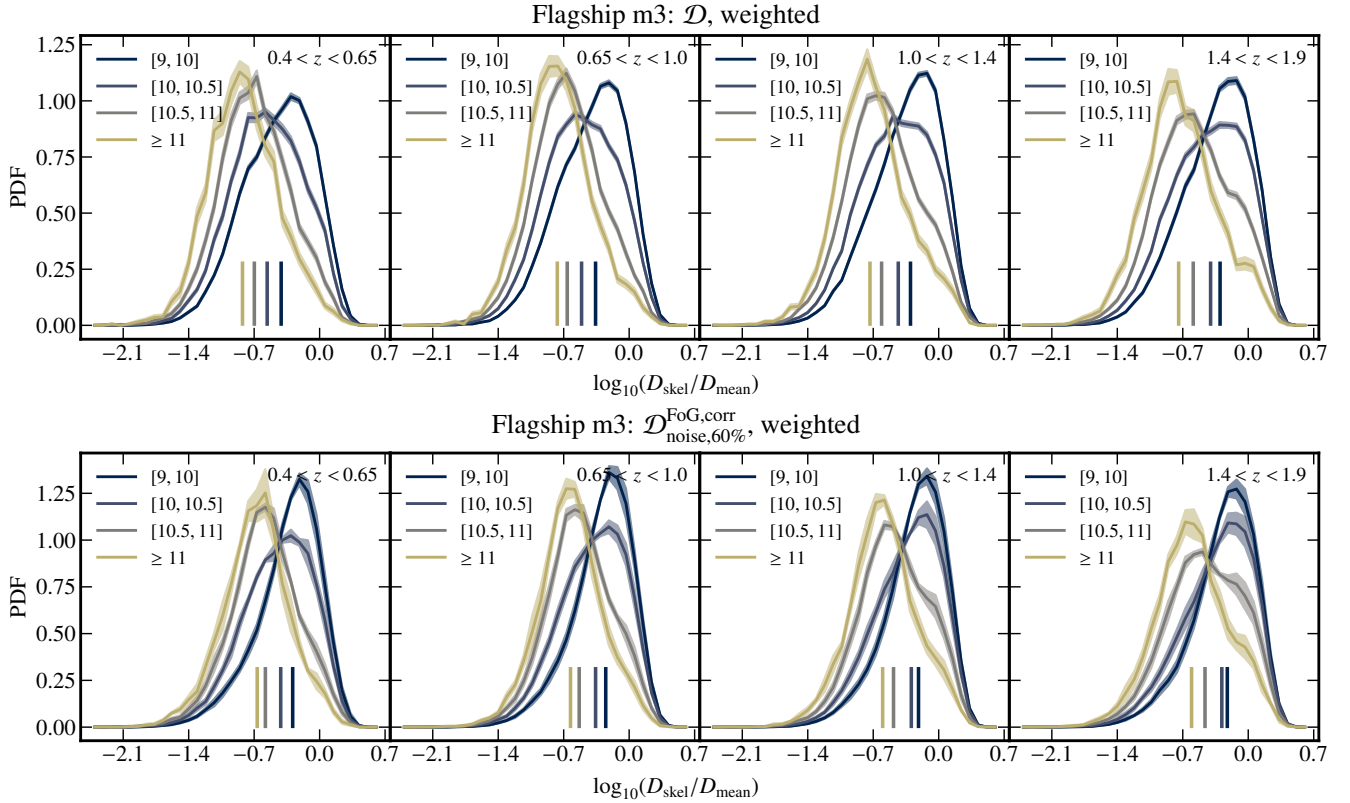


Fig. 14. PDFs of the closest filament’s distance, normalised by the redshift dependent mean intergalactic separation, for galaxies in the Flagship mock (model m3) in different stellar mass bins (coloured lines; with numbers indicating $\log_{10}(M_*/M_\odot)$ values) and the cosmic web reconstructed using the stellar mass-weighted Delaunay tessellation. Stellar-mass gradients are shown as a function of redshift from the lowest redshift bin (left) to the highest one (right). Stellar-mass gradients, with more massive galaxies located closer to the filaments than their lower mass counterparts, present in the reference H α flux-limited sample (\mathcal{D} ; top), are recovered when the FoG correction is performed ($\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$; bottom) for the sample with reduced completeness and added redshift error. Vertical lines indicate medians, and the shaded regions are the bootstrap errors for the \mathcal{D} catalogue and the standard deviation across five mocks for the remaining ones.

filaments, as well as the global measure of the multiplicity such as its PDF. We therefore recommend using multiplicity rather than connectivity.

Finally, the segregation of galaxies by stellar mass with respect to their distance to the filaments of the cosmic web, as explored in this work, is found to be strongly impacted by the redshift error expected for the EDS. The stellar-mass gradients are recovered even without weighting by the stellar mass of galaxies. However, this signal is quite weak, and we anticipate that measuring gradients of quantities beyond stellar mass of galaxies, for example, gradients of the specific SFR (sSFR) would be very challenging in this regard. A significant improvement can be obtained by weighting the tessellation by stellar mass. Weighting the tessellation by stellar mass may seem to lead to stellar-mass gradients somewhat by construction. However, the stellar-mass gradients with respect to the filaments are naturally present and recovered in the reference sample without any weighting for the cosmic web reconstruction. In addition, the tests we conducted revealed that weighting by stellar masses randomly assigned to galaxies from the same catalogue significantly reduces the presence of stellar-mass gradients. We therefore conclude that while the stellar mass weighting of the tessellation clearly biases to some extent the cosmic web reconstruction (by construction more massive galaxies will follow the cosmic web more closely), the stellar-mass gradients are inherently present in the distribution of galaxies on large scales.

4.2. Science cases with Euclid Deep Survey

The current study focuses on the technical aspects of cosmic web reconstruction within EDS, with the aim of providing basic guidelines for future analysis. Validation has been performed by analysing some of the more fundamental properties of the cosmic web, with correlations involving filaments on the one hand and stellar mass of galaxies on the other. *Euclid* data provide the foundation to extend this analysis to other properties beyond their stellar mass, potentially allowing us to study the co-evolution of galaxies and the cosmic web at epochs close to cosmic noon.

It will be of particular interest to assess the impact of the cosmic web on the star formation of galaxies. Through measurements of the H α flux of galaxies, *Euclid* will provide access to their SFR for the spectroscopic sample within the EDS. It will therefore be possible to perform the analysis of the gradients of the sSFR of galaxies with respect to the distance to filaments and walls of the cosmic web. At low redshifts, galaxies with lower sSFR (or redder colours) are found to be located closer to filaments and walls, compared to galaxies with higher sSFR (or bluer colours) at fixed M_* . Qualitatively similar trends are found in cosmological hydrodynamical simulations, with such a behaviour persisting up to at least redshift $z \sim 1$, and weakening or vanishing at $z \sim 2$ (e.g. Xu et al. 2020; Hasan et al. 2023; Bulichi et al. 2024), with a hint of a reversal with increasing sSFR in the vicinity of filaments (Bulichi et al. 2024). *Euclid* will allow us to test these predictions, and extend to higher

redshifts our knowledge on the impact of the cosmic web on the star formation activity of galaxies.

Low-redshift studies, both observational and numerical, also highlight the important role of connectivity (and multiplicity) of the cosmic web in shaping galaxy properties beyond their stellar mass. At fixed M_* , galaxies at the nodes of the cosmic web with higher number of connected filaments tend to have lower sSFR and to be less rotationally supported compared to galaxies with lower connectivity (Kraljic et al. 2020b). As connectivity is a practical observational proxy for past and present accretion of galaxies and therefore controls their assembly history, it is of great importance to extend this kind of study to higher redshifts. *Euclid* will allow us to infer the cosmic evolution of connectivity (and multiplicity) of the cosmic web and its impact on various galaxy properties, such as sSFR and morphology, as well as metallicity, to name a few. In particular, detailed morphological information will be obtained from photometry (with various methods: profile-fitting, non-parametric estimates, deep learning; Euclid Collaboration: Bretonnière et al. 2023) provided by the VIS instrument (Euclid Collaboration: Cropper et al. 2025). The *Euclid* pipeline includes a model-fitting algorithm evaluated through the *Euclid* Morphology Challenge using simulated datasets. *Euclid* is expected to deliver robust structural parameters for more than 400 million galaxies, with a less than 10% scatter for single Sérsic profiles down to $I_E = 23$ and double Sérsic profiles down to $I_E = 21$. For complex morphologies, performance can be improved using the Zoobot convolutional neural network (CNN) and larger crowd-sourced datasets. Zoobot's adaptability to new morphological labels was demonstrated with peculiar galaxies, highlighting its utility for detailed *Euclid* catalogues (Euclid Collaboration: Aussel et al. 2024).

Besides morphology measurements, the VIS instrument will provide precise estimates of the position angle of galaxies that jointly with access to large-scale structure will enable us to investigate the alignment of angular momentum (or spin) of galaxies with respect to the filaments and walls of the cosmic web. At low redshifts ($z \lesssim 0.2$), statistical studies using data from the SDSS, SDSS-IV MaNGA and SAMI surveys revealed that rotationally supported, disk-dominated low-mass galaxies tend to have their spin aligned with their neighbouring filaments and walls, while bulge-dominated (S0-type) massive galaxies have their spin preferentially in the perpendicular direction (e.g. Tempel et al. 2013; Tempel & Libeskind 2013; Welker et al. 2020; Kraljic et al. 2021). As suggested by hydrodynamical cosmological simulations, such a spin alignment signal is expected to be stronger at $z \gtrsim 1$ (e.g. Dubois et al. 2014; Codis et al. 2018a; Wang et al. 2018; Kraljic et al. 2020a), making the EDS an ideal data set for measuring the 3D orientation of galaxies' angular momentum with respect to large-scale filaments and walls at high redshift.

Understanding the co-evolution of galaxies and large-scale structure is of interest not only in the context of galaxy formation and evolution, but it is also of paramount importance for cosmology. An important example is the spin alignment of galaxies with regard to large-scale structure, as it is a known source of contamination for weak-lensing-based dark energy surveys (e.g. Chisari et al. 2017). Another example is cosmic connectivity and its evolution that is expected to depend on cosmology (e.g. Codis et al. 2018b; Mainieri et al. 2024; Boldrini & Laigle 2025) and, therefore, it could be an interesting probe of cosmological models beyond Λ CDM. Beyond connectivity, other cosmic web properties, such as exclusion zones present in the cross-correlations of critical points of the density field that were found to behave as standard rulers, repre-

sent a promising tool for constraining cosmological parameters (Shim et al. 2024).

4.3. Synergies with other surveys

Connecting the evolution of galaxies and the large-scale cosmic web requires spectroscopic surveys with high spatial sampling across a wide area in order to properly sample a wide range of cosmic environments. The EDS will in this regard be complementary to the PFS Galaxy Evolution survey (PFS hereafter; Greene et al. 2022). The PFS main continuum-selected sample of $\sim 3 \times 10^5$ galaxies with $J < 22.8$ in the redshift range $0.7 \lesssim z \lesssim 1.7$ will allow one to capture $\sim 90\%$ of the population with $M_* \gtrsim 10^{10} M_\odot$. With 70% average completeness, PFS will enable the observation of multiple galaxies in groups with halo masses down to $\sim 10^{13} M_\odot$. This makes it ideal not only for studying the assembly history of galaxy groups, but also for the cosmic web-related analysis, thanks to an improved reconstruction of the large-scale structure (Kraljic et al., in prep.).

The EDS is also complementary to the main guaranteed time observation (GTO) MOONS extra-galactic survey at the VLT (MOONRISE; Maiolino et al. 2020), an upcoming massively multiplexed spectroscopic survey that enables the study of galaxy properties with rest-frame optical line coverage up to $z \sim 2$. With its unique observing capabilities and strategy, MOONS is expected to capture the environment of galaxies across four orders of magnitude in over-density, from large under-dense void regions to high-density groups and clusters at $z \sim 1-2$. This will, in turn, allow for the reconstruction of the cosmic web (particularly the filaments connected to galaxy clusters) and facilitate the study of their impact on galaxy properties at the peak of the cosmic SFR in the Universe.

In the comparable redshift range $z \sim 1-2$, additional complementarity will be provided by the planned Nancy Grace Roman Space Telescope (Roman; Akeson et al. 2019). Galaxy samples from Roman's deeper observations with the High-Latitude Wide-Area Survey (HLWAS; Wang et al. 2022), in particular its deep and ultra-deep tiers covering, respectively, ~ 19 and $\sim 5 \text{ deg}^2$ areas, are expected to allow for a reconstruction of the cosmic web with a mean galaxy number density comparable to that of EDS (Hasan et al. 2025). However, thanks to the larger wavelength coverage of Roman grisms, the emission lines [OIII] will be detectable beyond $z \sim 1.9$, extending the Roman redshift coverage to $z \sim 2.8$ (Zhai et al. 2021). This represents a true complementarity to *Euclid*, pushing potentially the cosmic web reconstruction in 3D to even higher redshifts.

Another potential complementarity with the EDS will be offered, at lower redshifts, by DESI, which is already collecting spectra (e.g. DESI Collaboration 2024, 2025). In particular, the DESI magnitude-limited Bright Galaxy Survey (BGS; Hahn et al. 2023), comprising approximately ten million galaxies over the redshift range $0 < z < 0.6$, will provide a galaxy sample up to two magnitudes fainter than the SDSS Main Galaxy Sample (Strauss et al. 2002), with doubled median redshift ($z \approx 0.2$). With significantly higher number density than any previous survey in this redshift range, spectra and photometry for ten million galaxies, BGS will enable measurements of their physical properties and the reconstruction of the cosmic web in three dimensions. This will in turn enable studies of the connection between the large-scale environment and galaxies, by focusing on their properties and statistics (e.g. the mass-metallicity relation, the star-forming main sequence, and stellar mass and luminosity functions at lower redshifts).

Finally, the Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer (SPHEREx, Bock et al. 2025) and the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST, Ivezić et al. 2019) will both provide photometric data on wavelength range complementary to the *Euclid* ground-based and NIR photometric filters. On the one hand, SPHEREx, launched on 11 March 2025, will provide an all-sky low-resolution spectro-photometric survey in 102 narrow-bands from 0.75 to 5.0 μm , at a depth comparable to the *Euclid* spectroscopic survey but with much lower spatial ($6''2$ pixels) and spectral ($\lambda/\Delta\lambda = 35\text{--}130$) resolutions. The EDFs and SPHEREx deep fields are planned to overlap (Doré et al. 2018), making SPHEREx a tool of choice to mitigate the fraction of catastrophic outliers in the *Euclid* spectroscopic survey, by providing additional constraints for line identification on a larger wavelength range. On the other hand, LSST, will provide a 18 000 deg^2 coverage of the south hemisphere, thereby overlapping with EDFs and EDFF. In these fields, LSST will provide deep optical photometry in six filters *ugrizy*, covering the wavelength range 0.32–1.05 μm (in a range where *Euclid* has only one broad-band). This photometry could also be used to help tuning the spectroscopic solution of galaxies in the spectroscopic EDS. Beyond constraining the redshifts, these photometric data will be valuable in improving the stellar mass measurements of the *Euclid* galaxies, which, in turn, is pivotal to weighting the density field at the stage of skeleton extraction.

5. Conclusions

In this study, we investigated the quality of the reconstruction of the cosmic web with the expected spectroscopic dataset of galaxies in the EDFs in the redshift range $0.4 < z < 1.8$, with an $H\alpha$ flux limit of $6 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$. This analysis was carried out using the Flagship and GAEA mock galaxy catalogues. Our main findings are as follows:

- Geometry of the cosmic web: The small-scale redshift-space distortions strongly impact the cosmic web reconstruction, and its filamentary network in particular, regardless of the sample selection ($H\alpha$ flux- or M_* -limited) and regardless of what weighting of the tessellation by the stellar mass of galaxies is chosen. The correction applied for the FoG effect works better for stellar mass-limited samples. In addition to sample selection, the redshift uncertainties hinder our ability to correct for the FoG effect.
- Connectivity of the cosmic web: For the overall properties of the PDF of the connectivity, the correction of the FoG effect works very well for the M_* -limited sample and reasonably well for the $H\alpha$ flux-limited sample. Weighting the tessellation by stellar mass for the $H\alpha$ flux-based selection artificially enhances the connectivity, even in the absence of redshift-space distortions. Adding noise and incompleteness reduces the quality of the cosmic web reconstruction for both $H\alpha$ -based and M_* -based galaxy selections, due to the diminished ability to correct for FoG effects. In this configuration, stellar mass weighting of the tessellation significantly improves the cosmic web reconstruction, particularly for an $H\alpha$ -based galaxy selection. Weighting is similarly crucial to recover the M_* -connectivity relation when the sample is $H\alpha$ flux-limited, in the presence of redshift errors, and for reduced sampling.
- Multiplicity of the cosmic web: For $H\alpha$ flux-limited samples (in contrast to the case of M_* -limited samples), the multiplicity appears to be a more robust quantity compared to the connectivity. Even without weighting the tessellation, the

applied correction for the FoG effect enables us to recover the M_* -multiplicity relation. This holds true even in the presence of redshift errors and reduced sampling.

- Stellar-mass gradients: In cases where more massive galaxies are preferentially located closer to filaments compared to their lower-mass counterparts, stellar-mass gradients can be recovered regardless of whether the tessellation is weighted by stellar mass. However, the redshift error and limited sampling significantly weaken the strength of the measured signal for the $H\alpha$ flux-limited sample in the absence of tessellation weighting.

In this work, we performed the cosmic web reconstruction in three dimensions using simulated spectroscopic redshifts in the range $0.4 < z < 1.8$, expected in EDFs. The reconstruction methodology will therefore be applicable once the EDS data will be available and the performance of spectroscopic measurements fully assessed in this redshift range. The first results using the *Euclid* Quick Data Release (Q1) of the Spectroscopic Processing Functions of the *Euclid* pipeline (Euclid Collaboration: Le Brun et al. 2026) in the redshift range $0.9 < z < 1.8$ are promising. It was shown that a success rate above 80%, and excellent redshift precision ($\sim 10^{-3}$) and accuracy (better than 3×10^{-5}) can be reached in only one visit. The final EDS will be made of about 40 visits and with much better performance.

The analysis of the cosmic web in two dimensions using photometric redshifts from the Q1 release, focussed on the galaxy morphology and shape alignments at $0.5 < z < 0.9$, is presented in Euclid Collaboration: Laigle et al. (2026), while in Euclid Collaboration: Gouin et al. (2026), the focus is on cosmic connectivity of galaxy clusters at $0.2 < z < 0.7$.

The present work is centred on the technical aspects of cosmic web reconstruction, with the goal of providing guidelines for future applications to real data. For this reason, we specifically only considered trends with the stellar mass of galaxies, leaving the exploration of the impact of the cosmic web on other galaxy properties for future studies. *Euclid* will enable such investigations for the first time across cosmic time, up to $z \approx 1.8$.

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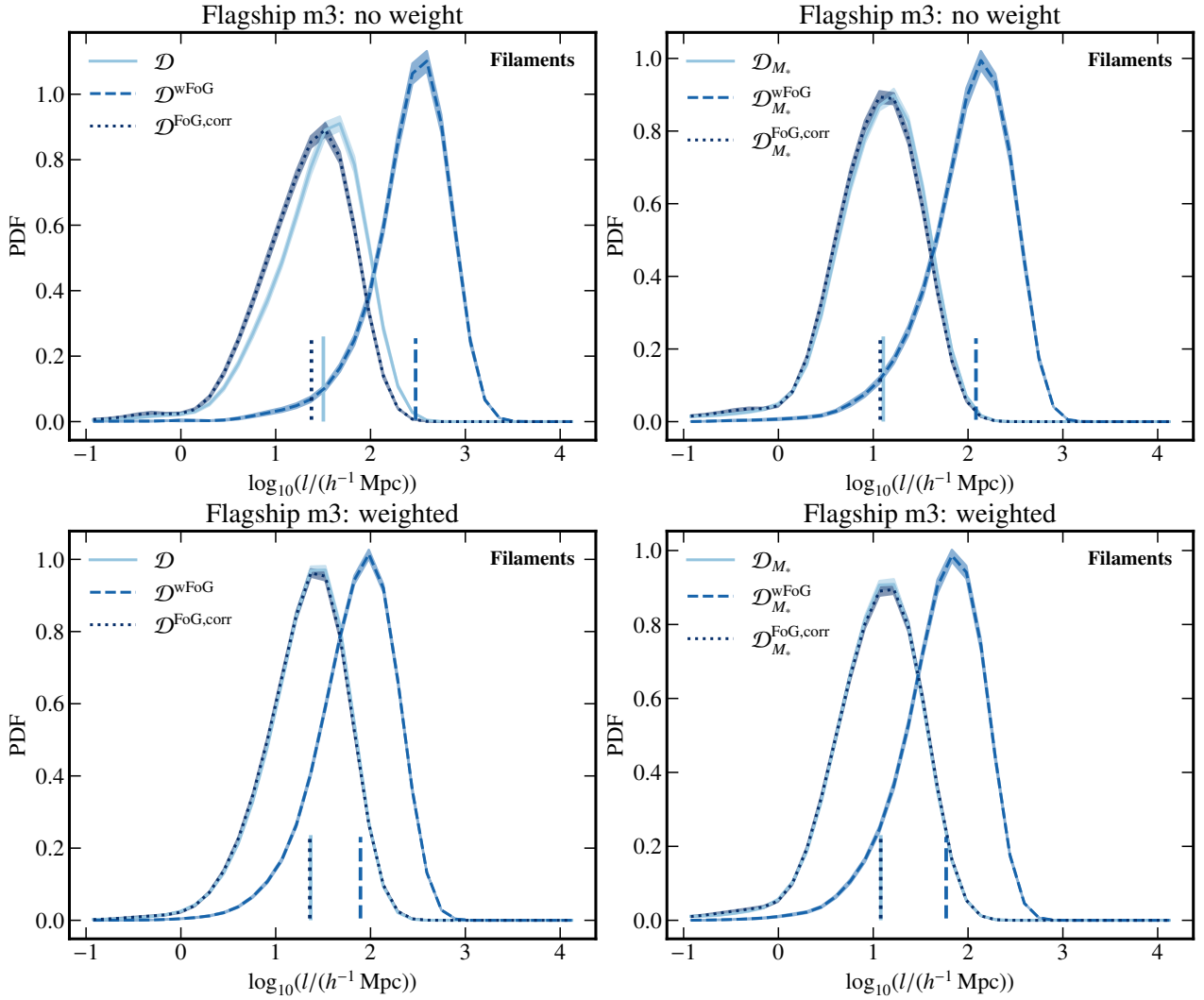


Fig. A.1. PDF of filament lengths for $H\alpha$ - (*left*) and stellar mass-limited (*right*) samples. Top and bottom panels compare non-weighted and weighted tessellations, respectively, for the Flagship m3 model. Vertical lines indicate the medians of distributions. Shaded regions correspond to the bootstrap error bars. For the stellar mass-limited galaxy sample, weighting of the Delaunay tessellation for the cosmic web reconstruction is not required to obtain a good agreement for the distribution of filaments' length.

Appendix A: Cosmic web statistics

Figure A.1 illustrates the effect of the selection function of galaxies and the mass weighting of the Delaunay tessellation on the distribution of filament lengths in the Flagship m3 model (see Fig. A.2 for the GAEA ECLH model with weighting). For the $H\alpha$ -limited samples (left panels), weighting of the tessellation by stellar mass is necessary to correct for the FoG effect (compare the top left and bottom left panels). For a M_* -limited sample (right panels), weighting is not needed to obtain a good agreement for the distribution of filaments' length after correcting for the FoG effect (compare top right and middle right panels). This behaviour is recovered in all models used in this work. Figure A.3 highlights the effect of the reduced sampling on the distribution of filament lengths. As expected, reduced sampling (60%, as estimated for the EDF) shifts the distribution of lengths of filaments to higher values, regardless of sample selection ($H\alpha$ - and M_* -limited sample, left and right panels, respectively).

Appendix B: Connectivity and multiplicity

Figure B.1 shows the PDFs of the connectivity of central galaxies for M_* - limited selection of galaxies in the full sample without redshift error (\mathcal{D}) for Flagship (model m3, top panels) and GAEA (model ECLH, bottom panels), with stellar mass weighting of the Delaunay tessellation (left) and without weighting (right). The stellar mass weighting impacts the PDF of the connectivity to a much lesser degree when the galaxy sample is M_* -limited compared to an $H\alpha$ -limited selection. After correcting for the FoG effect, the shape of the distributions and their medians (vertical lines) are in very good agreement with the measurements in the absence of redshift-space distortions without tessellation weighting for both Flagship and GAEA. Stellar mass weighting introduces some spurious effects, preventing us from completely correcting for the FoG effect in GAEA. However, the distribution of the connectivity and its median are substantially improved. The mean and median values of connectivity for all mocks and selections are reported in Tables B.1 and B.2.

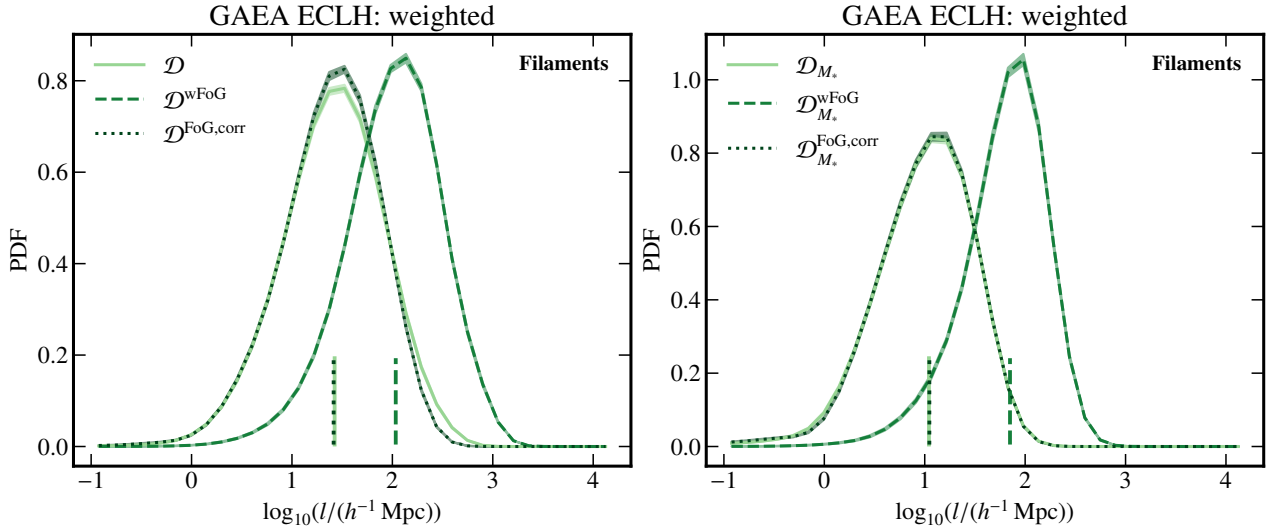


Fig. A.2. Same as in Fig. A.1 (bottom) i.e. using the stellar mass-weighted tessellation for the cosmic web reconstruction, but for the GAEA ECLH model.

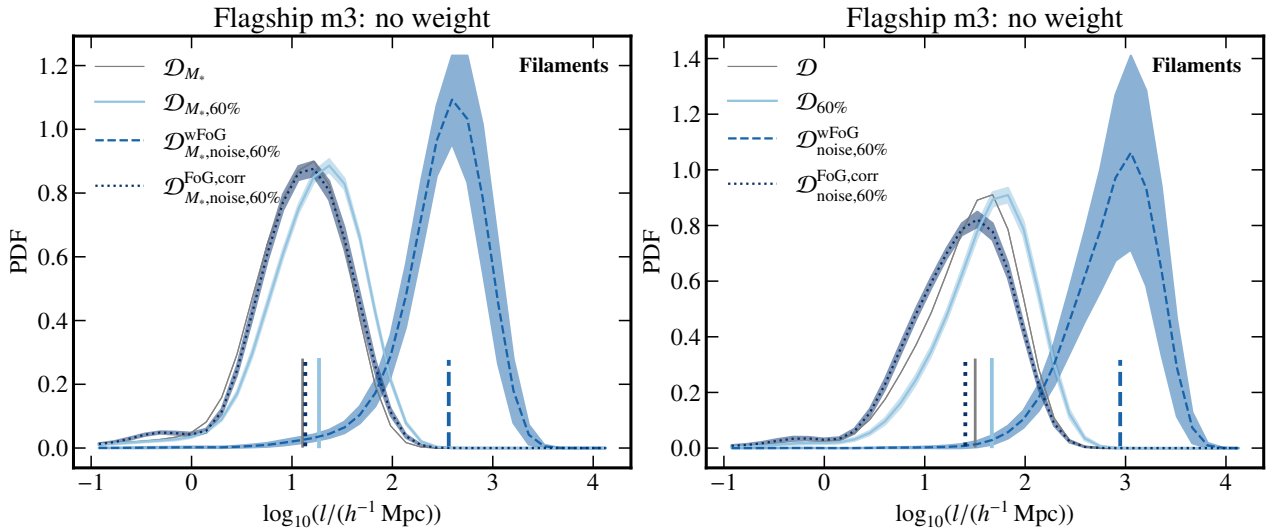


Fig. A.3. PDF of filaments' length for stellar mass-limited (left) and $H\alpha$ -limited (right) samples with 60% sampling.

Regarding the multiplicity, in general, PDFs of the multiplicity and their median values are only weakly impacted by the FoG effect when stellar mass-weighted tessellation is used for cosmic web extraction. Without weighting, the applied FoG compression efficiently corrects for the redshift-space distortion for the distribution of the multiplicity and its median value. These conclusions apply to all tested models (i.e. including M_* -limited samples). The mean and median values of multiplicity for all mocks and selections are reported in Tables B.3 and B.4.

Figure B.2 illustrates the mean connectivity of central galaxies as a function of their stellar mass in the model m3 of the Flagship (left) and model ECLH of GAEA (right) for M_* -limited samples with reduced sampling and redshift uncertainties ($\mathcal{D}_{\text{noise},60\%}$) with tessellation weighting, but qualitatively similar results are obtained without weighting. Regardless of weighting, the FoG effect increases the connectivity by an order of magnitude at all stellar masses. The method used to correct for the small-scale redshift-space distortions helps bring the connectivity close to the values obtained for the sample without FoG. Weighting the tessellation for the M_* -limited sample does not seem to introduce the bias seen for the selection of galaxies based on their $H\alpha$ flux, that is the increasing connectivity at low stellar masses. Similar conclusions apply to all other models.

Figure B.3 shows the mean multiplicity of central galaxies as a function of their stellar mass in the model m3 of Flagship (left) and model ECLH of GAEA (right) for M_* -limited samples with reduced sampling and redshift uncertainties ($\mathcal{D}_{\text{noise},60\%}$) with tessellation weighting, but qualitatively similar results are found without weighting. The multiplicity appears to be a more robust quantity than the connectivity, given that the FoG effect has an overall much weaker impact on its values, in particular when the tessellation is weighted by stellar mass.

Figure B.4 shows the multiplicity of central galaxies as a function of their stellar mass for the Flagship and GAEA mocks (models m3 and ECLH, respectively), with qualitatively similar conclusions for m1 and ECLQ) for the fiducial sample ($\mathcal{D}_{\text{noise},60\%}$) without stellar mass-weighted tessellation. The multiplicity of central galaxies increases with increasing stellar mass for galaxies in

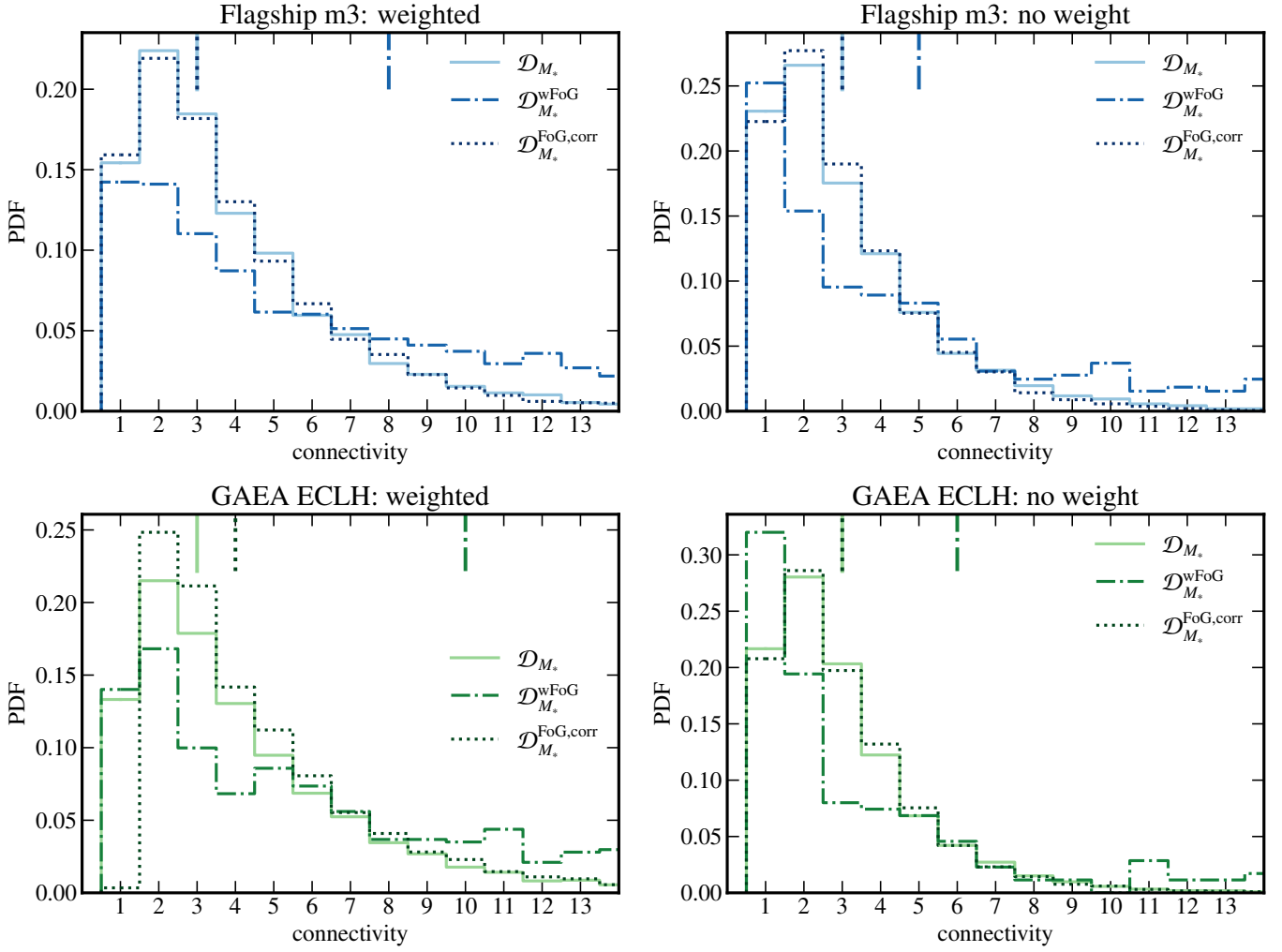


Fig. B.1. Same as in Fig. 9, but for the M_* -limited galaxy selection. The mean and median values for all distributions are reported in Tables B.1 and B.2.

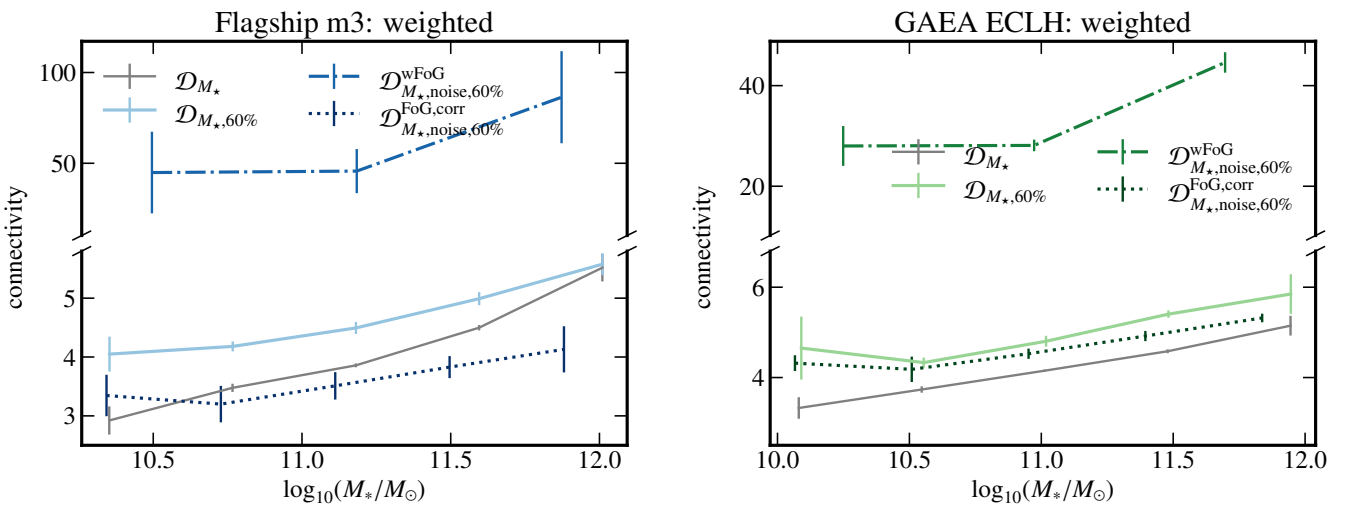


Fig. B.2. Connectivity of central galaxies as a function of their stellar mass in the Flagship (model m3) and GAEA (model ECLH) mocks, *right* and *left* panels, respectively, for M_* -limited samples ($\mathcal{D}_{M_*,\text{noise},60\%}$), with M_* -weighted tessellation (qualitatively similar results are obtained without weighting).

all reference catalogues (\mathcal{D}), catalogues with reduced sampling and redshift uncertainties ($\mathcal{D}_{\text{noise},60\%}$). The applied FoG correction significantly improves our ability to recover the M_* -multiplicity relation.

Table B.1. Median and mean connectivity for the Flagship m3 and Flagship m1 mocks for tessellations with and without stellar mass weighting.

	Flagship m3				Flagship m1			
	median		mean		median		mean	
	no weight	weight	no weight	weight	no weight	weight	no weight	weight
\mathcal{D}	3	8	4.95 ± 0.11	10.94 ± 0.17	3	7	4.52 ± 0.06	10.07 ± 0.11
$\mathcal{D}^{\text{wFoG}}$	6	19	50.60 ± 9.31	58.54 ± 3.8	6.5	17	48.83 ± 7.51	53.12 ± 2.47
$\mathcal{D}^{\text{FoG,corr}}$	3	7	4.15 ± 0.06	10.95 ± 0.18	3	7	3.79 ± 0.04	10.55 ± 0.12
\mathcal{D}_{M_*}	3	3	3.18 ± 0.03	3.99 ± 0.03	3	3	3.19 ± 0.02	4.24 ± 0.03
$\mathcal{D}_{M_*}^{\text{wFoG}}$	5	8	17.12 ± 1.49	16.64 ± 0.72	5	8	18.19 ± 1.45	18.51 ± 0.67
$\mathcal{D}_{M_*}^{\text{FoG,corr}}$	3	3	3.04 ± 0.02	3.93 ± 0.03	2	3	2.96 ± 0.02	4.21 ± 0.03
$\mathcal{D}_{60\%}$	4	9	5.51 ± 0.45	14.56 ± 0.87	3	8	5.03 ± 0.29	12.96 ± 0.53
$\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$	32	99	160.71 ± 247.66	282.84 ± 156.16	24	86	153.18 ± 270.71	275.60 ± 139.61
$\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$	3	8	3.25 ± 0.14	13.87 ± 0.81	2	8	2.95 ± 0.09	13.26 ± 0.57
$\mathcal{D}_{M_*,60\%}$	3	4	3.40 ± 0.11	4.62 ± 0.14	3	4	3.38 ± 0.09	5.02 ± 0.12
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{wFoG}}$	10.5	23.5	46.30 ± 27.75	56.03 ± 23.76	13	28	62.97 ± 50.37	80.22 ± 26.05
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{FoG,corr}}$	2	3	2.68 ± 0.15	3.64 ± 0.22	2	3	2.59 ± 0.11	4.15 ± 0.19

Table B.2. Median and mean connectivity for the GAEA ECLH and GAEA ECLQ mocks for tessellations with and without stellar mass weighting.

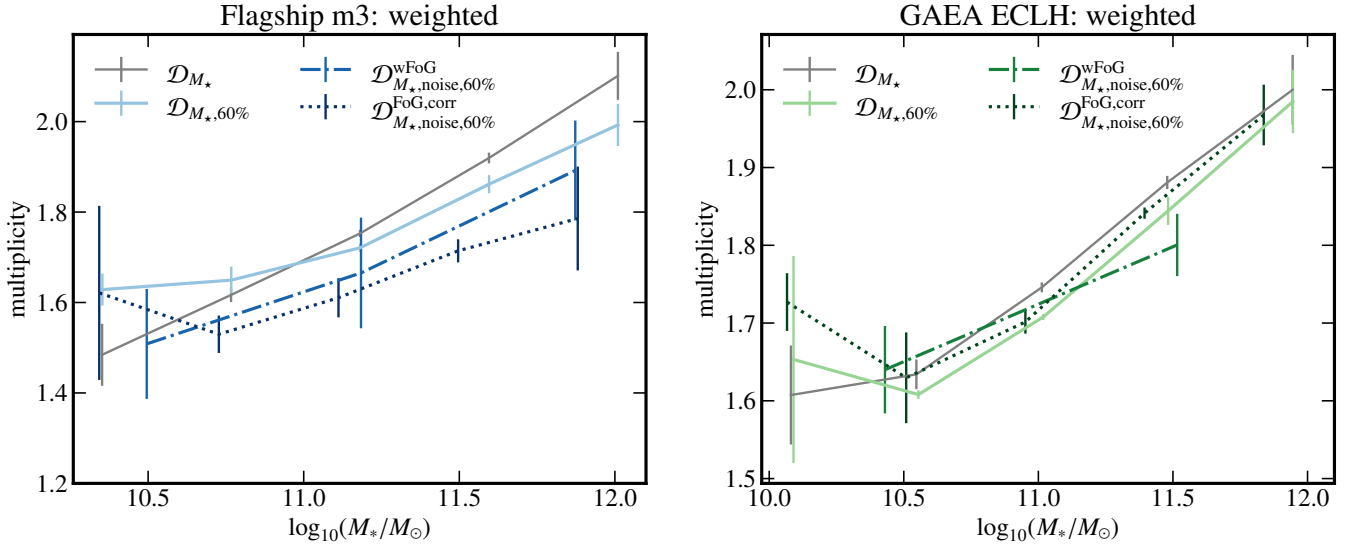
	GAEA ECLH				GAEA ECLQ			
	median		mean		median		mean	
	no weight	weight	no weight	weight	no weight	weight	no weight	weight
\mathcal{D}	5	11	8.20 ± 0.38	19.09 ± 0.44	6	16	14.97 ± 1.37	34.07 ± 1.45
$\mathcal{D}^{\text{wFoG}}$	3	18	116.33 ± 32.70	129.37 ± 13.09	3	18	128.77 ± 50.96	164.69 ± 20.19
$\mathcal{D}^{\text{FoG,corr}}$	4	11	5.43 ± 0.12	19.24 ± 0.40	5	19	7.75 ± 0.26	37.27 ± 1.19
\mathcal{D}_{M_*}	3	3	3.05 ± 0.02	4.26 ± 0.03	3	4	3.13 ± 0.02	5.21 ± 0.04
$\mathcal{D}_{M_*}^{\text{wFoG}}$	6	10	30.66 ± 4.06	27.13 ± 1.41	8	11	33.85 ± 4.36	35.67 ± 2.26
$\mathcal{D}_{M_*}^{\text{FoG,corr}}$	3	4	3.04 ± 0.02	4.73 ± 0.03	3	4	3.08 ± 0.02	5.18 ± 0.04
$\mathcal{D}_{60\%}$	5	13	9.31 ± 1.61	25.25 ± 2.50	7	19	17.84 ± 6.21	46.69 ± 7.49
$\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$	145	253.5	495.88 ± 486.04	852.72 ± 944.33	33	126	616.36 ± 1460.80	1340.72 ± 1704.38
$\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$	3	14	3.61 ± 0.21	26.30 ± 1.94	3	20	4.18 ± 0.32	43.05 ± 4.45
$\mathcal{D}_{M_*,60\%}$	3	4	3.28 ± 0.10	5.02 ± 0.15	3	5	3.41 ± 0.12	6.55 ± 0.24
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{wFoG}}$	7	12	35.57 ± 12.73	33.81 ± 5.95	7	12	36.59 ± 14.23	42.94 ± 9.00
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{FoG,corr}}$	3	4	3.14 ± 0.10	4.71 ± 0.16	3	4	3.20 ± 0.12	5.90 ± 0.25

Table B.3. Median and mean multiplicity for the Flagship m3 and Flagship m1 mocks for tessellations with and without stellar mass weighting.

	Flagship m3				Flagship m1			
	median		mean		median		mean	
	no weight	weight	no weight	weight	no weight	weight	no weight	weight
\mathcal{D}	2	2	1.58 ± 0.01	2.03 ± 0.01	2	2	1.62 ± 0.01	2.07 ± 0.01
$\mathcal{D}^{\text{wFoG}}$	1	2	1.48 ± 0.06	2.07 ± 0.03	1	2	1.48 ± 0.04	2.13 ± 0.02
$\mathcal{D}^{\text{FoG,corr}}$	2	2	1.62 ± 0.01	2.04 ± 0.01	2	2	1.62 ± 0.01	2.07 ± 0.01
\mathcal{D}_{M_*}	2	2	1.62 ± 0.01	1.78 ± 0.01	2	2	1.63 ± 0.01	1.81 ± 0.01
$\mathcal{D}_{M_*}^{\text{wFoG}}$	1	2	1.55 ± 0.03	1.77 ± 0.02	1	2	1.52 ± 0.03	1.83 ± 0.02
$\mathcal{D}_{M_*}^{\text{FoG,corr}}$	2	2	1.65 ± 0.01	1.79 ± 0.01	2	2	1.63 ± 0.01	1.83 ± 0.01
$\mathcal{D}_{60\%}$	1	2	1.56 ± 0.05	2.02 ± 0.04	1	2	1.58 ± 0.04	2.06 ± 0.03
$\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$	1	2	1.57 ± 0.64	2.07 ± 0.25	1	2	1.29 ± 0.35	2.19 ± 0.18
$\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$	1	2	1.52 ± 0.04	1.97 ± 0.04	1	2	1.51 ± 0.03	2.04 ± 0.03
$\mathcal{D}_{M_*,60\%}$	2	2	1.59 ± 0.03	1.76 ± 0.03	2	2	1.59 ± 0.02	1.80 ± 0.02
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{wFoG}}$	1	2	1.53 ± 0.27	1.74 ± 0.16	1.5	2	1.55 ± 0.27	1.91 ± 0.14
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{FoG,corr}}$	1	2	1.56 ± 0.06	1.66 ± 0.05	1	2	1.53 ± 0.04	1.71 ± 0.04

Table B.4. Median and mean multiplicity for the GAEA ECLH and GAEA ECLQ mocks for tessellations with and without stellar mass weighting.

	GAEA ECLH				GAEA ECLQ			
	median		mean		median		mean	
	no weight	weight	no weight	weight	no weight	weight	no weight	weight
\mathcal{D}	2	2	1.69 ± 0.02	2.21 ± 0.01	2	2	1.61 ± 0.03	2.22 ± 0.02
$\mathcal{D}^{\text{wFoG}}$	1	2	1.36 ± 0.07	2.07 ± 0.04	1	2	1.28 ± 0.07	2.08 ± 0.04
$\mathcal{D}^{\text{FoG,corr}}$	2	2	1.61 ± 0.01	2.14 ± 0.01	2	2	1.62 ± 0.02	2.19 ± 0.02
\mathcal{D}_{M_*}	2	2	1.66 ± 0.01	1.78 ± 0.01	2	2	1.65 ± 0.01	1.80 ± 0.01
$\mathcal{D}_{M_*}^{\text{wFoG}}$	1	2	1.46 ± 0.04	1.78 ± 0.02	1	2	1.54 ± 0.04	1.79 ± 0.03
$\mathcal{D}_{M_*}^{\text{FoG,corr}}$	2	2	1.67 ± 0.01	1.80 ± 0.01	2	2	1.67 ± 0.01	1.85 ± 0.01
$\mathcal{D}_{60\%}$	2	2	1.64 ± 0.07	2.17 ± 0.05	2	2	1.59 ± 0.11	2.15 ± 0.07
$\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$	1	2	1.50 ± 0.81	2.18 ± 0.33	1	2	1.28 ± 0.63	2.15 ± 0.46
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{FoG,corr}}$	1	2	1.49 ± 0.04	2.10 ± 0.05	1	2	1.47 ± 0.05	2.05 ± 0.06
$\mathcal{D}_{M_*,60\%}$	2	2	1.60 ± 0.03	1.76 ± 0.02	2	2	1.60 ± 0.03	1.80 ± 0.03
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{wFoG}}$	1	2	1.43 ± 0.11	1.76 ± 0.08	1	2	1.50 ± 0.13	1.81 ± 0.09
$\mathcal{D}_{M_*,\text{noise},60\%}^{\text{FoG,corr}}$	2	2	1.63 ± 0.03	1.77 ± 0.03	2	2	1.62 ± 0.04	1.81 ± 0.04

**Fig. B.3.** Multiplicity of central galaxies as a function of their stellar mass in Flagship (model m3) and GAEA (model ECLH) mocks, *left* and *right* panels, respectively, for M_* -limited samples ($\mathcal{D}_{M_*,\text{noise},60\%}$), with M_* -weighted tessellation (qualitatively similar results are obtained without weighting).

Appendix C: Stellar-mass gradients

Figure C.1 shows the PDFs of the distances of galaxies to their closest filament for the Flagship m1 model (the results for the Flagship m3 and GAEA models are comparable) and for the reconstruction of the cosmic web with weighting the tessellation as a function of stellar mass and redshift, for $H\alpha$ flux-limited sample with reduced sampling ($\mathcal{D}_{60\%}$, first row) and when redshift error and FoG are added ($\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$, second row). Stellar-mass gradients, with more massive galaxies located closer to the filaments than their lower mass counterparts, present in the reference $H\alpha$ flux-limited sample are recovered.

Figure C.2 shows the PDFs of the distances of galaxies to their closest filament for the Flagship m1 model (the results for the Flagship m3 and GAEA models are comparable) and for the reconstruction of the cosmic web without weighting the tessellation as a function of stellar mass and redshift. The distances are normalised by the mean intergalactic separation to take into account the effect of decreasing the density of galaxies with increasing redshift.

The first row shows the PDFs for the reference sample (\mathcal{D}), while the second row shows the PDFs after correction of the FoG effect ($\mathcal{D}_{\text{noise},60\%}^{\text{FoG,corr}}$). When the cosmic web is reconstructed without weighting the Delaunay tessellation, reduced galaxy sampling tends to decrease the stellar mass gradient signal (not shown), as in the case of the reconstruction including the weighting. Redshift errors have the strongest impact, by significantly reducing our ability to recover the stellar-mass gradients towards filaments of the cosmic web (not shown). Correcting for the FoG effect only mildly improves the signal.

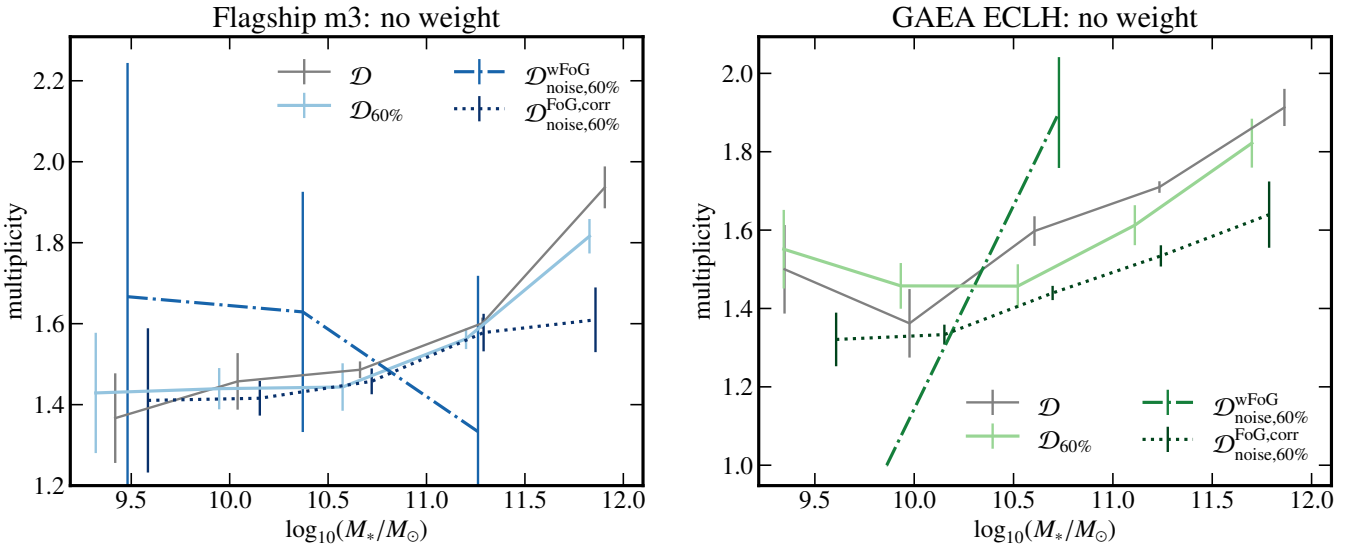


Fig. B.4. Same as in Fig. 13, but without any stellar mass weighting of the skeleton.

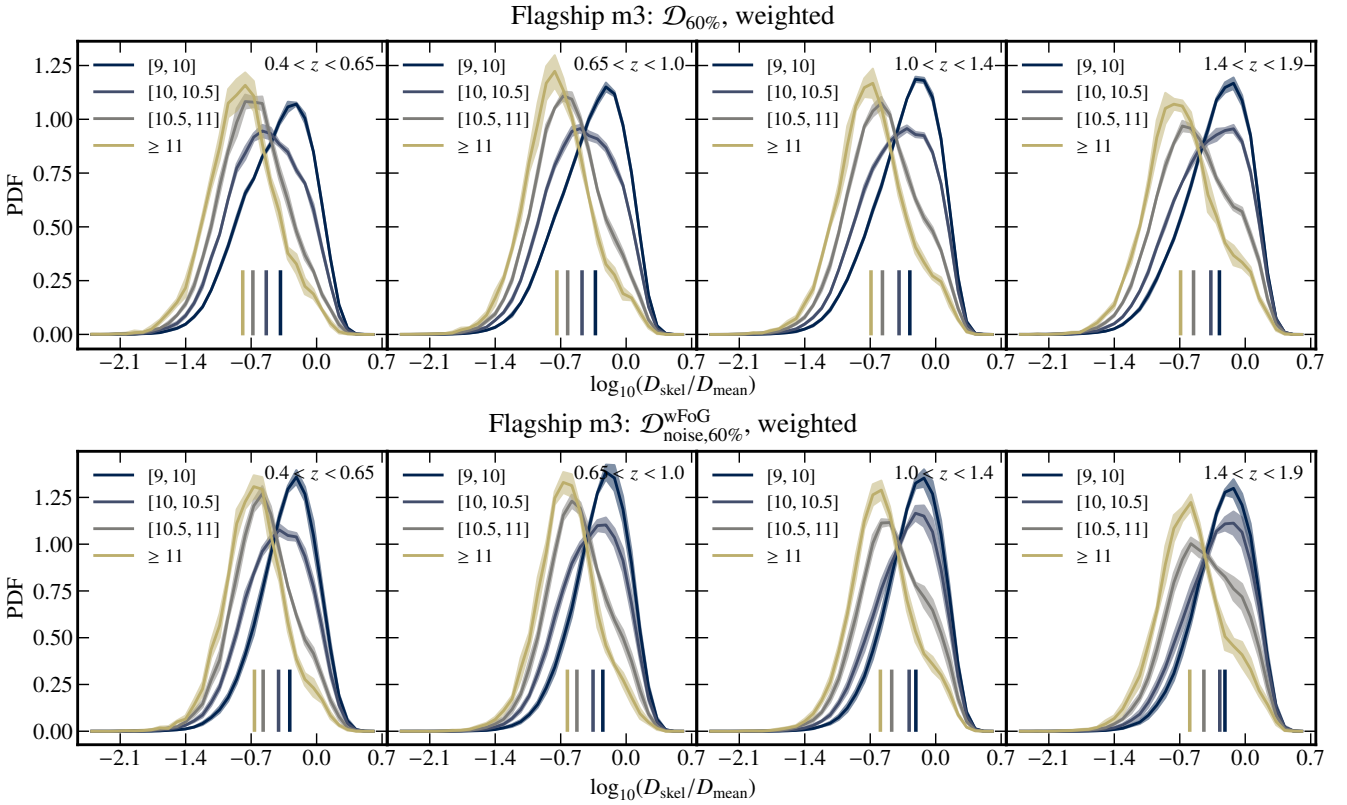


Fig. C.1. Same as in Fig. 14, but for a catalogue with reduced sampling ($\mathcal{D}_{60\%}$; top) and with added redshift error and FoG ($\mathcal{D}_{\text{noise},60\%}^{\text{wFoG}}$; bottom). Stellar-mass gradients are recovered in all configurations.

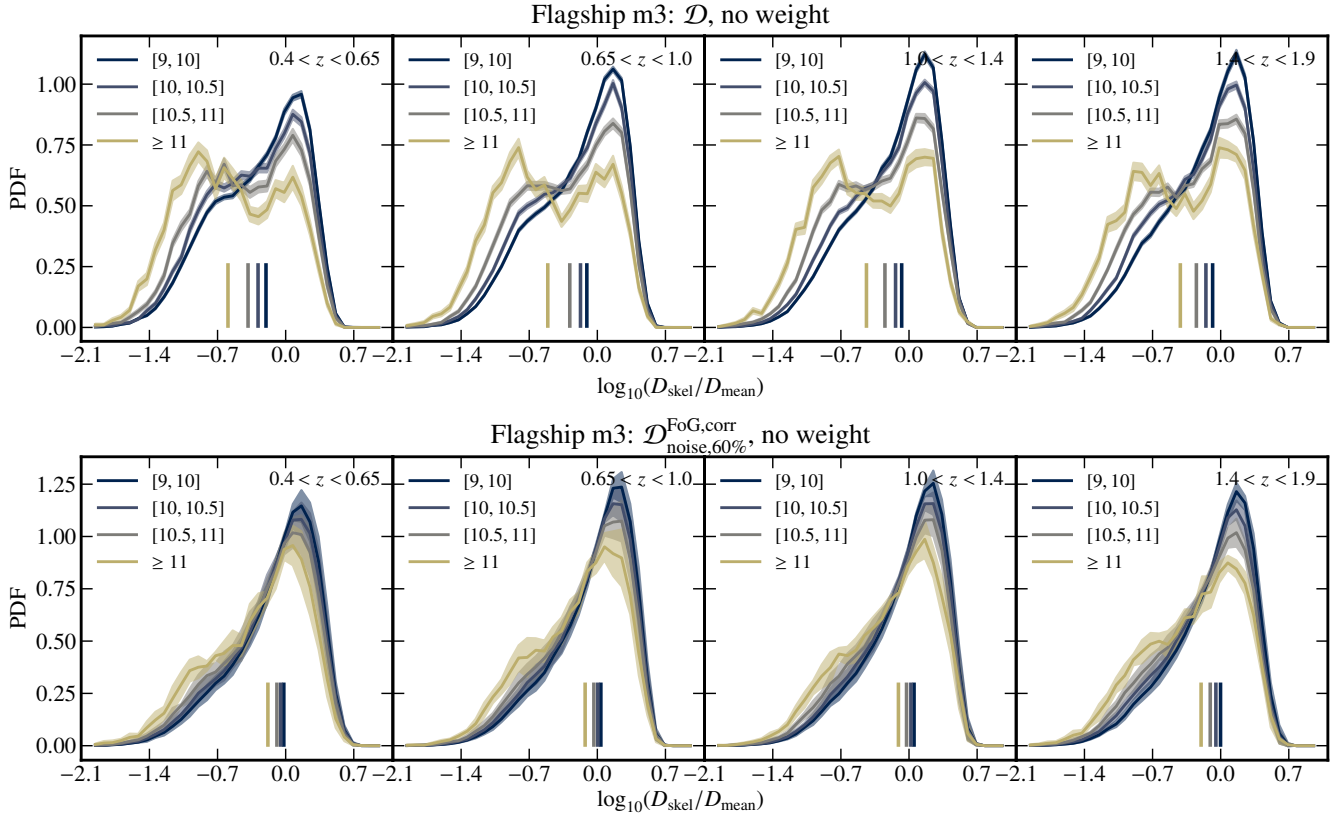


Fig. C.2. Same as in Fig. 14, but for the reconstruction without stellar mass-weighted Delaunay tessellation. The error on redshift in combination with the redshift-space distortions strongly reduce the stellar-mass gradients, that are only slightly improved after the correction of the FoG effect.