The galaxy power spectrum encodes a wealth of information about cosmology and the matter fluctuations. Its unbiased and optimal estimation is therefore of great importance. In this paper we generalise the framework of Feldman et al. (1994) to take into account the fact that galaxies are not simply a Poisson sampling of the underlying dark matter distribution. Besides finite survey-volume effects and flux-limits, our optimal estimation scheme incorporates several of the key tenets of galaxy formation: galaxies form and reside exclusively in dark matter haloes; a given dark matter halo may host several galaxies of various luminosities; galaxies inherit part of their large-scale bias from their host halo. Under these broad assumptions, we prove that the optimal weights do not explicitly depend on galaxy luminosity, other than through defining the maximum survey volume and effective galaxy density at a given position. Instead, they depend on the bias associated with the host halo; the first and second factorial moments of the halo occupation distribution; a selection function, which gives the fraction of galaxies that can be observed in a halo of mass $M$ at position $r$ in the survey; and an effective number density of galaxies. If one wishes to reconstruct the matter power spectrum, then, provided the model is correct, this scheme provides the only unbiased estimator. The practical challenges with implementing this approach are also discussed.
Percival et al. [45, hereafter PVP] attempted to correct the FKP framework to take into account the effects of luminosity dependent bias. To this end, PVP assumed that the probability of finding a galaxy of a given luminosity in a certain patch of space would be a Poisson variate, whose mean was proportional to the local density of dark matter and a luminosity-dependent bias factor. Their work demonstrated two important facts: firstly that an optimal weighting scheme depended sensitively on the assumptions about the bias and secondly, if their assumptions about the bias were correct, the FKP method was a biased estimator of the matter power spectrum.

In this paper we argue that the approach of PVP, whilst qualitatively reasonable, is in fact still at odds with our current understanding of galaxy formation and therefore unlikely to be the true optimal estimator. The key ideas from galaxy formation and evolution that we would like to build into our estimator are: galaxies only form in dark matter haloes [26]; haloes can host a number of galaxies of various luminosities; the large-scale bias associated with a given galaxy, is largely inherited from the bias of the host dark matter halo. In a recent paper [46, hereafter SM14], we generalised the FKP formalism to account for the clustering of galaxy clusters – which turned out to have a similar mathematical structure to the PVP scheme. We now undertake to generalise the FKP formalism to take into account these ideas from galaxy formation. As we will show, these effects will lead us to a new optimal estimator and method for reconstructing the matter power spectrum.

Before moving on, it is worth noting that current state-of-the-art galaxy redshift surveys, such as the Baryon Oscillation Spectroscopic Survey [47–49, hereafter BOSS], Galaxy And Mass Assembly [50, hereafter GAMA], and WiggleZ [51], have all used the FKP power spectrum estimation procedure. Future surveys, such as DESI [52], Euclid [53] and SKA [54], will have significantly larger volumes and so unbiased and optimised data analysis will be crucial if we are to obtain the tightest constraints on the cosmological parameters.

The paper is broken down as follows: In §II we describe generic properties of a galaxy redshift survey and present a new theoretical quantity, the halo-galaxy double-delta expansion. We explore its statistical properties. In §III we show how one may obtain unbiased estimates of the matter correlation function and power spectrum. In §IV we derive the covariance matrix of the fluctuations in the galaxy power spectrum. In §V we derive the optimal weights. In §VI we present a new expression for the Fisher information matrix for optimally-weighted galaxy power spectra. In §VII we enumerate the steps for a practical implementation of this approach. Finally, in §VIII we summarize our findings and draw our conclusions.

II. SURVEY SPECIFICATIONS AND THE $\mathcal{F}_g$-FIELD

A. Preliminaries: a generic galaxy redshift survey

Let us begin by defining our fiducial galaxy survey: suppose that we have observed $N_i^{\text{tot}}$ galaxies and to the $i$th galaxy we assign a luminosity $L_i$, redshift $z_i$ and angular position on the sky $\Omega_i = (\theta_i, \phi_i)$. If we specify the background FLRW spacetime, then we may convert the redshift into a comoving radial geodesic distance $\chi_i = \chi(z_i)$. A galaxy’s comoving position vector may now be expressed as $r_i = r(\chi_i, \Omega_i)$.

The survey mask function depends on both the position and luminosity of galaxies, given an adopted flux limit. In this work we shall take the angular and radial parts of the survey mask function to be separable, though this assumption does not change our results:

$$\Theta(r|L) = \Theta(\Omega)\Theta(\chi|L).$$  \hfill (1)

Note that if the flux-limit is not uniform across the survey then the radial function $\Theta(\chi, L)$ would still be a function of the angular position vector $\Omega$, and the survey mask cannot be separated as in the equation above. The angular part of the mask may be written as:

$$\Theta(\Omega) = \begin{cases} 1 ; & [\Omega \in \{\Omega_\mu\}] \\ 0 ; & \text{[otherwise]} \end{cases},$$  \hfill (2)

where $\{\Omega_\mu\}$ is the set of angular positions that lie inside the survey area. The radial mask function may be written:

$$\Theta(\chi|L) = \begin{cases} 1 ; & [\chi \leq \chi_{\text{max}}(L)] \\ 0 ; & \text{[otherwise]} \end{cases},$$  \hfill (3)

where $\chi_{\text{max}}(L)$ is the maximum distance out to which a galaxy of luminosity $L$ could have been detected.

The survey volume for galaxies with luminosity $L$ is simply the integral of the mask function over all space:

$$V_\mu(L) = \int \Theta(r|L)dV,$$  \hfill (4)
where \(dV\) is the comoving volume element at position vector \(r\) (for a flat universe \(dV = d^3r = \chi^2d\Omega d\chi\)). In what follows it will be also useful to note that the relation \(\chi_{\text{max}}(L)\) may be inverted to obtain the minimum galaxy luminosity that could have been detected at radial position \(\chi(z)\) in the survey. We shall write this as:

\[
[L_{\text{min}}(r)/h^{-2}L_\odot] = 10^{-\frac{2}{3}(m_{\text{lim}}-25-M_\odot)} [d_L(r)/h^{-1}\text{Mpc}]^{-2},
\]

where \(m_{\text{lim}}\) is the apparent magnitude limit of the survey, \(M_\odot\) is the absolute magnitude of the sun, \(h\) is the dimensionless Hubble parameter and \(d_L\) is the luminosity distance (for a flat universe \(d_L(z) = (1 + z)\chi(z)\)). Thus for any general function \(B(\chi, L)\), we have the useful integral relations:

\[
\int_0^\infty dL \int_0^\infty d\chi \Theta(\chi|L)B(\chi, L) = \int_0^\infty dL \int_0^{\chi_{\text{max}}(L)} d\chi B(\chi, L) = \int_0^\infty d\chi \int_{L_{\text{min}}(\chi)}^\infty dLB(\chi, L).
\]

B. The halo-galaxy double-delta expansion

Our understanding of galaxy formation tells us that galaxies form exclusively in dark matter haloes, and that each dark matter halo may host several galaxies of various luminosities. It therefore follows that the large-scale bias associated with any given galaxy is directly proportional to the bias of the host halo. We shall mathematically encode these ideas in our density field as follows: our \(N_i(r, M, L, x)\) is the number of galaxies that could have been detected at radial position \(\chi(z)\) in the survey. We therefore introduce a new function, dubbed the ‘galaxy-halo double-delta expansion’. This is a Dirac delta function expansion over the halo positions and masses, as well as over the positions and luminosities of the galaxies inside the haloes. It is written:

\[
n_g(r, L, x, M) = \sum_{i=1}^{N_h} \delta^D(x - x_i)\delta^D(M - M_i) \sum_{j=1}^{N_g(M_i)} \delta^D(r - r_j - x_i)\delta^D(L - L_j),
\]

where \(N_h\) is the total number of host dark matter haloes in the survey volume and \(N_g(M_i)\) is the total number of galaxies in the \(i\)th halo. In the above function, the order of variables is important: \(r\) refers to the spatial vector in the galaxy field, \(L\) the luminosity, \(x\) the spatial vector in the halo field, and \(M\) the halo mass. Note that the units of the above function are inverse squared volume, inverse mass, and inverse luminosity [78].

Next, in analogy with SM14, we define a field \(F_g\), which is related to the overdensity of galaxies. Our survey will be finite and will contain masked regions and an apparent magnitude limit \(m_{\text{lim}}\). Hence, the overdensity field of galaxies with magnitudes above some threshold luminosity may be written using Eq. (7) in the following way:

\[
F_g(r) = \int_0^\infty dL \int d^3x \int_{\text{d}M} dM \Theta(r|L) \frac{w(r, L, x, M)}{\sqrt{A}} [n_g(r, L, x, M) - \alpha n_g(r, L, x, M)],
\]

where \(w(r, L, x, M)\) is a weighting function that we will wish to determine in an optimal way, and \(A\) is a normalisation parameter that will be chosen later.

The function \(n_g(r, L, x, M)\) is the random galaxy-halo double-delta expansion. This immediately leads to an important question: what constitutes a random catalogue? Conventionally, in the FKP approach one would distribute the mock galaxies randomly within the survey volume — preserving the number counts as a function of redshift. However, since we know (or have assumed in this model) that galaxies form only inside dark matter haloes, we do not want to remove this property. Instead it is the dark matter haloes which should be randomly distributed, and not the galaxies. Therefore, the function \(n_g(r, L, x, M)\) represents the distribution of galaxies in a mock sample whose dark matter haloes possess no intrinsic spatial correlations, and have a number density that is \(1/\alpha\) of the true galaxy-halo double-delta field. Note that for this random distribution, while the halo centres are not correlated, the galaxies still follow the density distribution inside each dark matter halo. In addition, the haloes possess a mass spectrum and the galaxy luminosities are conditioned on the halo mass.

Both quantities defined by Eqs. (7) and (8) are of central importance and will be extensively used in this paper. It is therefore worthwhile for us to take some time to understand their meaning and how one should employ them to infer the statistical properties of the galaxy density field. This we do in the following section.
C. Calculation of the expectation of the galaxy density field

As a demonstration of how one can use the halo-galaxy double-delta expansion and take statistical averages we calculate the expectation of $F$ in Eq. (8) to break $\langle F_g(r) \rangle$ into two parts:

$$\langle F_g(r) \rangle = \int_0^\infty dLD\Theta(r|L) \left[ \langle N_g(r, L) \rangle - \alpha \langle N_g(r, L) \rangle \right] ,$$

(9)

where we introduced the weighted mean number density of galaxies per unit luminosity, at the spatial position $r(\chi, \Omega)$:

$$\langle N_g(r, L) \rangle = \int d^3x \int_0^\infty dM \frac{w(r, L, x, M)}{\sqrt{A}} \langle n_g(r, L, x, M) \rangle$$

$$= \int d^3x \int_0^\infty dM \frac{w(r, L, x, M)}{\sqrt{A}} \left( \sum_{i=1}^{N_h} \delta^D(x - x_i) \delta^D(M - M_i) \sum_{j=1}^{N_s} \delta^D(r - r_j - x_i) \delta^D(L - L_j) \right) \equiv \langle N_g(r, L) \rangle ,$$

(10)

with a similar expression for $\langle N_g(r, L) \rangle$. The function in Eq. (10) is related to the galaxy luminosity function.

To proceed further we now need to understand what taking the 'expectation value' actually means. Following Smith [55], this operation can be broken down into three steps. First, the fluctuations in the underlying dark matter field are sampled – we shall denote this averaging through a sub-script $s$. Second, given the dark matter field, the haloes may be obtained as a sampling of the density field – we shall denote this operation through sub-script $h$. Third, given a set of dark matter haloes, and sufficient knowledge of the properties of the halo, galaxies may then be sampled into each halo – we shall denote this operation through sub-script $g$. Hence, Eq. (10) can be rewritten,

$$\langle N_g(r, L) \rangle = \int d^3x \int_0^\infty dM \frac{w(r, L, x, M)}{\sqrt{A}} \left( \sum_{i=1}^{N_h} \delta^D(x - x_i) \delta^D(M - M_i) \sum_{j=1}^{N_s} \delta^D(r - r_j - x_i) \delta^D(L - L_j) \right) \equiv \langle N_g(r, L) \rangle ,$$

(11)

Let us now compute the average over the galaxy sampling for the $i$th dark matter halo:

$$\left\langle \sum_{j=1}^{N_s} \delta^D(r - r_j - x_i) \delta^D(L - L_j) \right\rangle_g \equiv \sum_{N_g = 0}^\infty P(N_g | \lambda(M_i)) \int \prod_{k=1}^{N_g} \{d^3r_k dL_k\} p(r_1, \ldots, r_{N_g}, L_1, \ldots, L_{N_g} | M_i, x_i)$$

$$\times \left[ \delta^D(r - r_1 - x_i) \delta^D(L - L_1) + \cdots + \delta^D(r - r_{N_g} - x_i) \delta^D(L - L_{N_g}) \right] ,$$

(12)

where in the above we have introduced the following quantities: $P(N_g | \lambda(M_i))$ is the discrete probability that there are $N_g$ galaxies in the $i$th dark matter halo and this we assume depends on some function of the dark matter halo mass $M_i$; $p(r_1, \ldots, r_{N_g}, L_1, \ldots, L_{N_g} | M_i, x_i)$ is the joint probability density function for finding the $N_g$ galaxies being located at positions $\{r_1, \ldots, r_{N_g}\}$ relative to the halo centre $x_i$, and with luminosities $\{L_1, \ldots, L_{N_g}\}$, conditioned on $M_i$ and $x_i$. We have assumed that the properties and distribution of the galaxies in the $i$th halo are independent of all other external haloes. If the probability for finding a galaxy at a given position inside a halo is determined by the density profile of the matter in the halo, and if the probability that the galaxy has a luminosity $L$ depends only on the halo mass, then this joint probability can be written in the following manner:

$$p(r_1, \ldots, r_{N_g}, L_1, \ldots, L_{N_g} | M_i, x_i) = \prod_{k=1}^{N_g} \{p(r_k | M_i, x_i) p(L_k | M_i)\} = \prod_{k=1}^{N_g} \{U(r_k | M_i, x_i) \Phi(L_k | M_i)\} ,$$

(13)

where in the above equation we have used the density profile of galaxies in the halo, normalised by the total number of galaxies in that halo, $U$, to define

$$p(r | M, x) \equiv U(r | M, x) \equiv \rho_g(r | M, x) / N_g(M) .$$

(14)

We have also used

$$p(L_k | M_i) \equiv \Phi(L_k | M_i) ,$$

(15)

as the probability density that a galaxy hosted by a halo of mass $M_i$ has a luminosity $L$ [79]. In writing Eq. (13) we have assumed that, for a given galaxy, its spatial location inside the dark matter halo is independent of its luminosity. As will be shown later, this assumption will not be crucial for the derivation of the optimal weights.
On integrating over the Dirac delta functions in Eq. (12) we find
\[
\left\langle \sum_{j=1}^{N_h} \delta^D(r - r_j - x_i) \delta^D(L - L_j) \right\rangle_{g} = \sum_{N_g=0}^{\infty} P(N_g|\lambda(M_i)) N_g U(r - x_i|M_i) \Phi(L|M_i)
\]
\[
= N_g^{(1)}(M_i) U(r - x_i|M_i) \Phi(L|M_i)
\]
where we have suppressed the dependence of \(U\) on the halo centre. The second equality follows from the definition of the first factorial moment of the galaxy distribution:
\[
N_g^{(1)}(M_i) \equiv \sum_{N_g=0}^{\infty} P(N_g|\lambda(M_i)) N_g .
\]

Returning to our main calculation, on substituting the last two equations into Eq. (11), we now obtain
\[
\langle N_g(r, L) \rangle = \int d^3x \int_0^\infty dM \frac{w(r, L, x, M)}{\sqrt{A}} \left\langle \sum_{i=1}^{N_h} \delta^D(x - x_i) \delta^D(M - M_i) N_g^{(1)}(M_i) U(r - x_i|M_i) \Phi(L|M_i) \right\rangle_{s,h}
\]
\[
= \int d^3x \int_0^\infty dM \frac{w(r, L, x, M)}{\sqrt{A}} \int d^3x_{N_h} \delta^D(x - x_i) \delta^D(M - M_i) N_g^{(1)}(M_i) U(r - x_i|M_i) \Phi(L|M_i)
\]
\[
\times \sum_{i=1}^{N_h} \delta^D(x - x_i) \delta^D(M - M_i) N_g^{(1)}(M_i) U(r - x_i|M_i) \Phi(L|M_i) .
\]

In the above, we followed SM14 to introduce \(p(x_1, \ldots, x_{N_h}, M_1, \ldots, M_{N_h})\) as the joint probability density for the \(N_h\) dark matter halo centres being located at positions \(\{x_1, \ldots, x_{N_h}\}\), and with masses \(\{M_1, \ldots, M_{N_h}\}\).

On integrating over the Dirac delta functions, the mean number density of galaxies becomes,
\[
\langle N_g(r, L) \rangle = \int d^3x \int_0^\infty dM \frac{w(r, L, x, M)}{\sqrt{A}} N_h p(x, M) N_g^{(1)}(M) U(r - x|M) \Phi(L|M) .
\]

The joint distribution function for obtaining a halo of mass \(M\) at position \(x\) can be written as the product of two independent one-point probability density functions [56]:
\[
p(x, M) = p(M) p(x) = \frac{\bar{n}(M)}{\bar{n}_h} \times \frac{1}{V_\mu} = \frac{\bar{n}(M)}{N_h} ,
\]
where \(\bar{n}(M)\) is the mean mass function of dark matter haloes, which tells us the number density of haloes of mass \(M\), per unit mass, and \(\bar{n}_h = N_h/V_\mu\) is the mean number density of haloes. On substituting this expression into Eq. (19) we find that the mean density of galaxies, per unit luminosity, at spatial location \(r\) may be written:
\[
\langle N_g(r, L) \rangle = \frac{1}{\sqrt{A}} \phi_w(r, L) ,
\]
where we have defined
\[
\phi_w(r, L) \equiv \int_0^\infty dM \bar{n}(M) N_g^{(1)}(M) \Phi(L|M) \int d^3x w(r, L, x, M) U(r - x|M) .
\]

If we were to set the weight function to unity, the above expression would be the galaxy luminosity function [57]:
\[
\phi(L) \equiv \int_0^\infty dM \bar{n}(M) N_g^{(1)}(M) \Phi(L|M) .
\]

Turning to the second expectation value in Eq. (9), we note that the only difference between \(\langle N_g(r, L) \rangle\) and \(\langle N_s(r, L) \rangle\) is the artificially increased space-density of clusters and the absence of any intrinsic clustering. Hence, we also have,
\[
\alpha \langle N_s(r, L) \rangle = \frac{1}{\sqrt{A}} \phi_w(r, L) .
\]

Returning to Eq. (9) and inserting Eqs. (21) and (24) we arrive at the result:
\[
\langle F_g(r) \rangle = 0 .
\]

Hence, the \(F_g\)-field, like the over-density field of matter, is truly a mean-zero field.

Note that we have neglected to take into account the statistical properties of obtaining the \(N_h\) clusters in the survey volume. In what follows we shall assume that the survey volumes are sufficiently large that this may be essentially treated as a deterministic quantity. However, it can be taken into account [e.g. see 56, 58, 59].
III. CLUSTERING ESTIMATORS

We now move on to the more interesting problem of using the halo-galaxy double-delta expansion to compute the clustering properties of the galaxy distribution. We begin first with the correlation function, and then through Fourier transforms look at the power spectrum. This task will be somewhat laborious, however it will enable us to develop and establish a number of important concepts and results.

A. The two-point correlation function of galaxies

The two-point correlation function of the field $F_g$ can be computed using our double-delta expansion through:

$$
\langle F_g(r_1)F_g(r_2) \rangle = \frac{1}{A} \int dL_1 dL_2 d^3x_1 d^3x_2 dM_1 dM_2 \Theta(r_1|L_1) \Theta(r_2|L_2) w(r_1, L_1, x_1, M_1) w(r_2, L_2, x_2, M_2) \\
\times \left[ \langle n_g(r_1, L_1, x_1, M_1) n_g(r_2, L_2, x_2, M_2) \rangle - \alpha \langle n_g(r_1, L_1, x_1, M_1) n_s(r_2, L_2, x_2, M_2) \rangle \\
- \alpha \langle n_s(r_1, L_1, x_1, M_1) n_g(r_2, L_2, x_2, M_2) \rangle + \alpha^2 \langle n_s(r_1, L_1, x_1, M_1) n_s(r_2, L_2, x_2, M_2) \rangle \right].
$$

The expectation terms in the square bracket on the right-hand side of this equation can be evaluated in a similar manner as was done for the case of the mean density. In Appendix A, we provide a detailed derivation of the terms $\langle n_1 n_2 \rangle$, $\langle n_1 n_3 \rangle$, $\langle n_1 n_4 \rangle$ and $\langle n_2 n_2 \rangle$. On substituting Eqs (A9), (A10), (A11) and (A12) into Eq. (26) and on integrating over the delta functions, we find that the correlation function may be written as the sum of three terms:

$$
\langle F_g(r_1)F_g(r_2) \rangle = \prod_{i=1}^{2} \left\{ \int d^3x_i dM_i \bar{n}(M_i) b(M_i) N_{g}^{(1)}(M_i) W_{U}^{(1)}(r_i, x_i, M_i) \right\} \xi(|x_1 - x_2|) \\
+ (1 + \alpha) \int d^3x dM \bar{n}(M) N_{g}^{(2)}(M) W_{U}^{(1)}(r_1, x, M) W_{U}^{(1)}(r_2, x, M) \\
+ (1 + \alpha) \int d^3x dM \bar{n}(M) N_{g}^{(1)}(M) W_{U}^{(2)}(r_1, x, M) \delta^3(r_1 - r_2),
$$

where $b(M)$ is the large-scale linear bias of dark matter haloes, $\xi(x)$ is the dark matter correlation function, and $N_{g}^{(2)}(M)$ is the second factorial moment of the galaxy numbers (for more details on these quantities see Appendix A). In the above expression we have also defined the quantity:

$$
W_{U}^{(j)}(r, x, M) \equiv U^{j}(r - x| M) W_{U}^{(j)}(r, x, M),
$$

with

$$
W_{U}^{(j)}(r, x, M) \equiv \frac{1}{A} \int dL \Phi(L|M) \Theta(r|L) w^{j}(r, L, x, M).
$$

Based on the above analysis, we see that an obvious estimator for the $F_g$ correlation function is,

$$
\hat{\xi}_{F_g}(r) \equiv \int d^3r' F_g(r') F_g(r + r') ; \quad (r \neq 0).
$$

The expectation of the estimator is:

$$
\langle \hat{\xi}_{F_g}(r) \rangle \equiv \prod_{i=1}^{2} \left\{ \int d^3x_i dM_i \bar{n}(M_i) b(M_i) N_{g}^{(1)}(M_i) \right\} \xi(|x_1 - x_2|) \int d^3r' W_{U}^{(1)}(r', x_1, M_1) W_{U}^{(1)}(r + r', x_2, M_2) \\
+ (1 + \alpha) \int d^3x dM \bar{n}(M) N_{g}^{(2)}(M) \int d^3r' W_{U}^{(1)}(r', x, M) W_{U}^{(1)}(r + r', x, M) ; \quad (r \neq 0).
$$

In general $\hat{\xi}_{F_g}$ is a biased estimator for the matter correlation function $\xi$. Thus, in order to make a robust comparison between theory and observations, one must either compute the theory predictions as in Eq. (27) or generate Monte-Carlo mock samples and use the same estimator to compare theory and observation.
B. An estimator for the matter correlation function in the large-scale limit

In the large-scale limit, the clustering of galaxies can be used to obtain an unbiased estimate of the matter correlation function. To see this note that, since the dark matter haloes in simulations are cuspy, on large scales the mass- or galaxy-number-normalised density profiles of galaxies behave approximately as Dirac delta functions. We shall therefore take

\[ U^{LS}(r|M) \to \delta^D(r) , \]  

and on implementing this in Eq. (31), we find after integrating over the Dirac delta functions:

\[
\left\langle \xi_{F_g}(r) \right\rangle \approx \xi(r) \int \prod_{i=1}^2 \left\{ dM_i \bar{n}(M_i) b(M_i) N^{(1)}_{g}(M_i) \right\} \int d^3r' W_{(1)}(r',r',M_1) W_{(1)}(r+r',r',M_2) ; (r \neq 0) \tag{33}
\]

In this limit there are a number of interesting things that happen: firstly, the weight function has now become independent of the halo positions, i.e. we no longer differentiate between galaxy and halo positions, taking them to be the same. Hence, we may now write:

\[ w(r, L, x, M) \to w^{LS}(r, L, M) ; \quad W_{(l)}(r, x, M) \to W^{LS}_{(l)}(r, M) . \tag{34} \]

Secondly, the dark matter correlation function has separated out and so we may easily invert Eq. (33) to obtain an unbiased estimate for the dark matter clustering. The estimator is:

\[
\hat{\xi}(r) \approx \frac{\hat{\xi}_{F_g}(r)}{\Sigma_0(r)} ; \quad \Sigma_0(r) = \int d^3r' g^{(1)}_{(1,1)}(r') g^{(1)}_{(1,1)}(r+r') ; \quad (r \neq 0) \tag{35}
\]

where we have defined the new set of weighted window functions:

\[
g^{(n)}_{(l,m)}(r) = \int dM \bar{n}(M) b^n(M) N^{(n)}_{g}(M) \left[ W^{LS}_{(l)}(r, M) \right]^n . \tag{36}
\]

The function \( \Sigma_0(r) \) represents the correlation function of the averaged survey window functions. Our correlation function estimator Eq. (35), is therefore a generalization of that of [14].

C. The galaxy power spectrum

We now turn to the Fourier space dual of the correlation function – the galaxy power spectrum. To obtain this let us begin by defining our 3D Fourier transform convention for a function \( B \) and its inverse as:

\[ \tilde{B}(k) \equiv \int d^3r B(r)e^{ikr} \quad \leftrightarrow \quad B(r) = \int \frac{d^3k}{(2\pi)^3} \tilde{B}(k)e^{-ikr} . \]

We distinguish real- and Fourier-space quantities that share the same symbol through use of the tilde notation. We also define the power spectrum \( P_B(k) \) of any infinite statistically homogeneous random field \( \tilde{B}(k) \) to be:

\[ \left\langle \tilde{B}(k)\tilde{B}(k') \right\rangle = (2\pi)^3 \delta^D(k+k')P_B(k) . \]

Note, if the field \( B \) were statistically isotropic, the power spectrum would simply be a function of the scalar \( k \). In addition the power spectrum and two-point correlation function of the field \( B \) form a Fourier pair:

\[
\xi_B(|x-x'|) = \int \frac{d^3q}{(2\pi)^3} \int \frac{d^3q'}{(2\pi)^3} P_B(q)(2\pi)^3 \delta^D(q+q')e^{-iq\cdot x-e^{-iq'\cdot x'}}. \]

With these definitions in hand we may now transform Eq. (27), and on considering the case where \( k_2 = -k \), we find that the expectation of the square of the amplitude of the Fourier modes of \( \tilde{F}_g \) is given by:

\[
\left\langle \left| \tilde{F}_g(k) \right|^2 \right\rangle = \int \frac{d^3q}{(2\pi)^3} P(q) \prod_{i=1}^2 \left\{ \int dM_i \bar{n}(M_i) b(M_i) N^{(1)}_{g}(M_i) \right\} \tilde{W}^U_{(1)}(-k,-q,M_1)\tilde{W}^U_{(1)}(-k,q,M_2) + (1+\alpha) \int \frac{d^3q}{(2\pi)^3} dM \bar{n}(M) N^{(2)}_{g}(M) \tilde{W}^U_{(1)}(-k,-q,M)\tilde{W}^U_{(1)}(-k,q,M) + (1+\alpha) \int d^3r d^3x dM \bar{n}(M) N^{(1)}_{g}(M) \tilde{W}^U_{(2)}(r,x,M) , \tag{37}
\]
where $P(q)$ is the matter power spectrum and we have set the Fourier transform of the effective survey window function to be:

$$\tilde{W}_i^{U}(k, q, M) \equiv \int d^3r d^3x W_i^{U}(r, x, M) e^{i k \cdot r} e^{i q \cdot x}.$$  

(38)

As in the case of the correlation function of the field $F_g$, its power spectrum does not provide a direct estimate of the matter power spectrum.

D. The power spectrum in the large-scale limit

Let us now consider the power spectrum of $\tilde{F}_g$ in the large-scale limit. As discussed in §III B we expect the density profiles to behave like Dirac delta functions in real space, in Fourier space the density profiles on large scales simply obey: $\tilde{U}(k|M) \xrightarrow{k \to 0} 1$. Under this condition Eq. (37) simplifies to:

$$\left\langle |\tilde{F}_g(k)|^2 \right\rangle \approx \int \frac{d^3q}{(2\pi)^3} P(q) \left| \tilde{g}^{(1)}_{(1,1)}(k - q) \right|^2 + P_{\text{shot}},$$

(39)

where the second term on the right-hand side is a $k$-independent effective shot-noise term,

$$P_{\text{shot}} \equiv (1 + \alpha) \left[ \tilde{g}^{(2)}_{(1,0)}(0) + \tilde{g}^{(1)}_{(2,0)}(0) \right].$$

(40)

In the limit that the survey volume is large, the window functions $\tilde{g}^{(n)}_{(l,m)}(k)$ will be very narrowly peaked around $k = 0$. Provided the matter power spectrum is a smoothly-varying function of scale, the window functions $\tilde{g}^{(n)}_{(l,m)}(k)$ will behave in a way that is similar to the Dirac delta function. Hence, Eq. (39) becomes:

$$\left\langle |\tilde{F}_g(k)|^2 \right\rangle \approx P(k) \int \frac{d^3q}{(2\pi)^3} \left| \tilde{g}^{(1)}_{(1,1)}(k - q) \right|^2 + P_{\text{shot}}.$$  

(41)

Let us focus on the integral factor on the right-hand-side of the above expression. If we now perform the transformation of variables $q \to k - q$ and use Parseval’s theorem, we find:

$$\int \frac{d^3q}{(2\pi)^3} \left| \tilde{g}^{(1)}_{(1,1)}(k - q) \right|^2 = \int \frac{d^3q}{(2\pi)^3} \left| \tilde{g}^{(1)}_{(1,1)}(q) \right|^2 = \int d^3r \left| \tilde{g}^{(1)}_{(1,1)}(r) \right|^2.$$  

Upon back-substitution of Eq. (36) into the above expression, we obtain:

$$\int d^3r \left| \tilde{g}^{(1)}_{(1,1)}(r) \right|^2 = \frac{1}{A} \int d^3r \left[ \int dM \tilde{n}(M) N^{(1)}_{g}(M) b(M) \int dL \Phi(L|M) \Theta(r|L) w(r, L, M) \right]^2.$$  

Note that we have not yet specified the parameter $A$, which we now take to be:

$$A \equiv \int d^3r \left[ \int dM \tilde{n}(M) N^{(1)}_{g}(M) b(M) \int dL \Phi(L|M) \Theta(r|L) w(r, L, M) \right]^2.$$  

(42)

Note, we will now drop the super-script LS notation for $w$ and $W_i$(l), since for the remainder of this study we shall be working only in the large-scale limit. Thus, our estimator for the matter power spectrum can be written simply:

$$\hat{P}(k) = |\tilde{F}_g(k)|^2 - P_{\text{shot}}.$$  

(43)

If our modelling of the galaxy distribution is correct, then the above estimator constitutes the only unbiased estimator of the matter power spectrum. Before proceeding further, note that in the above expression we have obtained the power spectrum per mode. In fact, we are more interested in its band-power estimate. Hence, our final estimator in the large-scale and large-volume limit is:

$$\bar{P}(k_i) = \frac{1}{V_i} \int_{V_i} d^3k \hat{P}(k) = \frac{1}{V_i} \int_{V_i} d^3k |\tilde{F}_g(k)|^2 - P_{\text{shot}},$$  

(44)

where in the above we have summed over all modes in a $k$-space shell of thickness $\Delta k$ and volume

$$V_i \equiv \int_{V_i} d^3k = 4\pi \int_{k_i - \Delta k/2}^{k_i + \Delta k/2} k^2 dk = 4\pi k_i^2 \Delta k \left[ 1 + \frac{1}{12} \left( \frac{\Delta k}{k_i} \right)^2 \right].$$  

(45)
IV. STATISTICAL FLUCTUATIONS IN THE GALAXY POWER SPECTRUM

In order to obtain the optimal estimator we need to know how the signal-to-noise (hereafter \( S/N \)) varies when we vary the shape of our weight function \( w \). Thus, we need to understand the noise properties of our power spectrum estimator, i.e. compute its covariance matrix. The covariance matrix of two band-power estimates is given by:

\[
\text{Cov} [\tilde{P}(k_i), \tilde{P}(k_j)] = \langle \tilde{P}(k_i)\tilde{P}(k_j) \rangle - \langle \tilde{P}(k_i) \rangle \langle \tilde{P}(k_j) \rangle = \frac{1}{V_i} \int d^3k_i \frac{1}{V_j} \int d^3k_j \text{Cov} [\tilde{P}(k_i), \tilde{P}(k_j)],
\]

where the last factor on the right-hand side of the above expression is the covariance of the power in two separate Fourier modes. For the case of large survey volumes and in the large-scale limit the matter power spectrum is given by Eq. (44). Hence,

\[
\text{Cov} [\tilde{P}(k_i), \tilde{P}(k_j)] \approx \text{Cov} [\tilde{F}_b(k_i), \tilde{F}_b(k_j)] = \langle |\tilde{F}_b(k_i)|^2 |\tilde{F}_b(k_j)|^2 \rangle - \langle |\tilde{F}_b(k_i)|^2 \rangle \langle |\tilde{F}_b(k_j)|^2 \rangle. \tag{46}
\]

The approximation in the equation above follows from the discussion in Appendix B1.

In Appendix C, we derive a general expression for the covariance matrix of \(|\tilde{F}_b(k_i)|^2\) and \(|\tilde{F}_b(k_j)|^2\), with all n-point connected spectra and shot-noise terms included – this is obtained by combining Eqs. (C1) and (C2) with Eq. (C13). Under the assumption of a Gaussian matter density field, our general expression simplifies to Eq. (C18). Furthermore, we also show in Appendix C3 that in the large-scale limit Eq. (C18) can be written as:

\[
\text{Cov} [\tilde{F}_b(k_i), \tilde{F}_b(k_j)] = \left| \int \frac{d^3q}{(2\pi)^3} P(q) \tilde{G}_b^{(1)}(k_1 + q) \tilde{G}_b^{(1)}(k_2 - q) + (1 + \alpha) \left[ \tilde{G}_b^{(1)}(k_1 + k_2) + \tilde{G}_b^{(2)}(k_1 + k_2) \right] \right|^2
+ \left| \int \frac{d^3q}{(2\pi)^3} P(q) \tilde{G}_b^{(1)}(k_1 + q) \tilde{G}_b^{(1)}(-k_2 - q) + (1 + \alpha) \left[ \tilde{G}_b^{(1)}(k_1 - k_2) + \tilde{G}_b^{(2)}(k_1 - k_2) \right] \right|^2, \tag{47}
\]

In the limit where the survey volume is large, the functions \(\tilde{G}_b^{(n)}(l,m)\) are very narrowly peaked around \(k = 0\). Furthermore, if the power spectrum does not rapidly vary over the scale of the effective window function, then we may treat it as a constant in Eq. (47). Thus,

\[
\text{Cov} [\tilde{F}_b(k_i), \tilde{F}_b(k_j)] \approx \left| P(k_1) \tilde{G}_b^{(1)}(k_1 + k_2) + (1 + \alpha) \left[ \tilde{G}_b^{(2)}(k_1 + k_2) + \tilde{G}_b^{(1)}(k_1 + k_2) \right] \right|^2
+ \left| P(k_1) \tilde{G}_b^{(1)}(k_1 - k_2) + (1 + \alpha) \left[ \tilde{G}_b^{(2)}(k_1 - k_2) + \tilde{G}_b^{(1)}(k_1 - k_2) \right] \right|^2, \tag{48}
\]

where we have introduced the functions:

\[
Q^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)}(r) \equiv \tilde{G}^{(n_1)}_{(l_1,m_1)}(r) \tilde{G}^{(n_2)}_{(l_2,m_2)}(r), \tag{49}
\]

and made use of the convolution theorem to write their Fourier transforms:

\[
Q^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)}(k) = \int \frac{d^3q}{(2\pi)^3} \tilde{G}^{(n_1)}_{(l_1,m_1)}(q) \tilde{G}^{(n_2)}_{(l_2,m_2)}(k - q).
\]

Note that we also used the trivial identity \(Q^{(n)}_{(l,m)} = \tilde{G}^{(n)}_{(l,m)}\).

Returning to Eq. (46), we find that after substitution of Eq. (48) into Eq. (46), the bin-averaged estimates of the power spectrum can be written:

\[
\text{Cov} [\tilde{P}(k_i), \tilde{P}(k_j)] = 2 \int \frac{d^3k_i}{V_i} \int \frac{d^3k_j}{V_j} \left| P(k_1) \tilde{G}^{(1)}_{(1,1,1,1)}(k_1 + k_2) + (1 + \alpha) \left[ \tilde{G}^{(2)}_{(1,0)}(k_1 + k_2) + \tilde{G}^{(1)}_{(2,0)}(k_1 + k_2) \right] \right|^2. \tag{50}
\]

Eq. (50) follows from the integrals over \(k_2\) in Eq. (48) being invariant under the transformation \(k_2 \rightarrow -k_2\). Furthermore, if the \(k\)-space shells are narrow compared to the scale over which the power spectrum varies, then the shell-averaged power spectrum can be pulled out of the integrals. In Appendix D we detail the computation of Eq. (50) and show that the covariance can be reexpressed as:

\[
\text{Cov} [\tilde{P}(k_i), \tilde{P}(k_j)] = \frac{2(2\pi)^3}{V_i} \text{P}^{2}(k_i) \delta_{i,j} \int d^3r \left\{ \left[ \tilde{G}^{(1)}_{(1,1,1)}(r) \right]^2 + \frac{(1 + \alpha)}{\tilde{P}(k_i)} \left[ \tilde{G}^{(2)}_{(1,0)}(r) + \tilde{G}^{(1)}_{(2,0)}(r) \right] \right\}^2, \tag{51}
\]

with the functions \(\tilde{G}^{(n)}_{(l,m)}(r)\) defined by Eq. (36).
V. OPTIMAL ESTIMATOR

Our aim is to find the optimal weighting scheme that will maximize the $S/N$ ratio on a given band-power estimate of the galaxy power spectrum.

A. The optimal weight equation

To begin, note that maximizing the $S/N$ ratio is equivalent to minimizing its inverse, the noise-to-signal ratio $N/S$. The square of the latter can be expressed as:

$$F[w(r, L, M)] \equiv \frac{\sigma_P^2(k_i)}{P^2(k_i)} = \frac{2(2\pi)^3}{V_i} \int d^3r \left\{ \left( [g_{(1,1)}^{(1)}(r)]^2 + \frac{1 + \alpha}{P(k_i)} [g_{(1,0)}^{(2)}(r) + g_{(2,0)}^{(1)}(r)] \right)^2 \right\}. \quad (52)$$

In the above expression, we have written the squared noise-to-signal_functional obtained for weight functions that possess a small path variation $\delta w$. The standard way for finding the optimal weights is to perform the variation of the functional $F$ with respect to the weights $w(r, L, M)$. Operationally, the functional variation of $F[w]$ is carried out by comparing $F[w]$ with the functional obtained for weight functions that possess a small path variation $w(r, L, M) \rightarrow w(r, L, M) + \delta w(r, L, M)$. This variation can be defined:

$$\delta F[w] \equiv F[w(r, L, M) + \delta w(r, L, M)] - F[w(r, L, M)] = \int d^3r dL dM \left\{ \frac{\delta F}{\delta w(r, L, M)} \right\} \delta w(r, L, M). \quad (53)$$

Extremisation means that the functional derivative is stationary for small variations around the optimal weights:

$$\frac{\delta F}{\delta w(r, L, M)} = 0. \quad (54)$$

Recall that the definition of the weights in Eq. (29) includes the normalization constant $A$ specified by Eq. (42). Since the normalization constant $A$ is itself a function of the weights, it follows that $F[w]$ is in fact a ratio of two weight-dependent functionals:

$$F[w] = \frac{\mathcal{N}[w]}{\mathcal{D}[w]}, \quad (55)$$

with the definitions:

$$\mathcal{N}[w] \equiv \int d^3r \left\{ \left( [\tilde{g}_{(1,1)}^{(1)}(r)]^2 + c \left[ \tilde{g}_{(1,0)}^{(2)}(r) + \tilde{g}_{(2,0)}^{(1)}(r) \right] \right)^2 \right\}; \quad (56)$$

$$\mathcal{D}[w] \equiv A^2[w] = \int d^3r \left[ \tilde{g}_{(1,1)}^{(1)}(r) \right]^2. \quad (57)$$

In the above, we introduced the scaled effective window functions:

$$\tilde{g}_{(l,m)}^{(n)}(r) = A^{nl/2}g_{(l,m)}^{(n)}(r), \quad (58)$$

as well as the constant $c \equiv (1 + \alpha)/P(k_i)$, which helps keep the equations as compact as possible. We also dropped the overall constant $2(2\pi)^3/V_i$ from the functional $\mathcal{N}[w]$, since it plays no role in the minimization process.

Minimizing $F[w]$ is equivalent to solving the functional problem:

$$\frac{1}{\mathcal{D}[w]} \left( \delta \mathcal{N}[w] - \frac{\mathcal{N}[w]}{\mathcal{D}[w]} \delta \mathcal{D}[w] \right) = 0 \iff \delta \mathcal{N}[w] - F[w] \delta \mathcal{D}[w] = 0. \quad (59)$$

Therefore, to find the optimal weights satisfying Eq. (59), we first need to compute the variations of $\mathcal{N}$ and $\mathcal{D}$ with a perturbation $\delta w$. This calculation is outlined in Appendix E. Putting together Eqs. (59), (61), (67), we arrive at the following general equation for the optimal weights:

$$\left\{ \left( [g_{(1,1)}^{(1)}(r)]^2 + c \left[ g_{(1,0)}^{(2)}(r) + g_{(2,0)}^{(1)}(r) \right] \right) \right\} \{ \tilde{g}_{(1,1)}^{(1)}(r)b(M) + c \left[ w(r, L, M) + \bar{W}_1(r, M)\beta(M)N_{\delta}^{(1)}(M) \right] \} = \tilde{g}_{(1,1)}^{(1)}(r)b(M). \quad (60)$$
In the above, $\mathcal{W}_1$ was introduced by Eq. (E4), and the function $\beta(M)$ specifies the relation between the first and second factorial moments of galaxies in a halo of mass $M$, as discussed in [60]:

$$N_g^{(2)}(M) = \beta(M) \left[ N_g^{(1)}(M) \right]^2 .$$  \hfill (61)

Note that for a Poisson distribution, $\beta = 1$, although we do not make this assumption here.

On inspection of Eq. (60) we notice that, with the exception of the weights $w(r, L, M)$, none of the terms carries any explicit dependence on the luminosity of the galaxies. We therefore conclude that the optimal weights are independent of luminosity. Hence, without any loss of generality, we may now redefine the weights to be:

$$w(r, L, M) \Rightarrow w(r, M) .$$  \hfill (62)

One immediate consequence of this is that the functions $\mathcal{W}_1(r, M)$ can now be written in the much simplified form:

$$\mathcal{W}_1(r, M) = w(r, M) \int dL \Phi(L|M) \Theta(r|L) = w(r, M) S(r, M) .$$

In the above we have introduced the function:

$$S(r, M) \equiv \Theta(\Omega) \int_0^{\infty} dL \Theta(\chi|L) \Phi(L|M) = \Theta(\Omega) \int_{\min(\chi)}^{\infty} dL \Phi(L|M) ,$$  \hfill (63)

with the second equality following from Eq. (6). $S(r, M)$ is the number of galaxies in a halo of mass $M$ observable at comoving distance $r$ relative to the total number of galaxies in that halo. The range of $S$ is the interval $[0, 1]$, and it has the following limiting behaviour: for $M \geq M_{\min}$ we have $\lim_{\chi \to 0} S(r, M) = 1$ and $\lim_{\chi \to \infty} S(r, M) = 0$; and for $M < M_{\min}$ we have $S(r, M) = 0$, where $M_{\min}$ is the minimum halo mass required for a dark matter halo to be able to host a galaxy. Note that for a volume-limited survey $S = \text{constant}$.

A further consequence of Eq. (62) is that the effective survey window functions given by Eq. (58) reduce to:

$$\mathcal{W}_1^{(n)}(r, M) = \int dM \bar{n}(M) b^n(M) N_g^{(n)}(M) \left[ w(r, M) S(r, M) \right]^{\frac{n}{2}} .$$  \hfill (64)

Implementing these considerations in Eq. (60), we arrive at the equation governing the optimal weights:

$$\left\{ \left[ \mathcal{W}_1^{(1)}(r, 0) \right]^2 + c \left[ \mathcal{W}_1^{(2)}(r, 0) + \mathcal{W}_1^{(1)}(r, 0) \right] \right\} \left\{ \mathcal{W}_1^{(1)}(r, 0) + c \frac{w(r, M)}{b(M)} \left[ 1 + \beta(M) N_g^{(1)}(M) S(r, M) \right] \right\} = \mathcal{W}_1^{(1)}(r, 0) .$$  \hfill (65)

### B. The optimal weights

We now seek a general solution for the weight equation Eq. (65). To begin, we notice that the only part of the weight equation that carries any mass dependence is the second bracket on the left-hand side of Eq. (65). If we set the radial vector to a constant $r = r_0$, then the optimal weights at fixed position inside the angular mask must have the mass dependence:

$$w(r_0, M) \propto \frac{b(M)}{1 + \beta(M) N_g^{(1)}(M) S(r_0, M)} .$$  \hfill (66)

The weights are therefore proportional to the bias of the dark matter halo in which the galaxy is hosted and inversely proportional to the factor $[1 + \beta(M) N_g^{(1)}(M) S(r_0, M)]$. Since this last term depends on the galaxy selection function $S$, the weight function is not separable in position and mass, as was found by SM14 for the case of optimal weighting of a sample of galaxy clusters. Nevertheless, without any loss of generality, we can factor out this part of the weight function from the general weight solution:

$$w(r, M) = \hat{w}(r) \left[ \frac{b(M)}{1 + \beta(M) N_g^{(1)}(M) S(r, M)} \right] ,$$  \hfill (67)

where $\hat{w}(r)$ is a function of position only that needs to be determined. It is clear from the above equation that the term on the right-hand side encompasses the whole mass dependence of the optimal weights. If we now reinsert this expression into Eq. (65) we see that the weight equation reduces to:

$$\left\{ \left[ \mathcal{W}_1^{(1)}(r, 0) \right]^2 + c \left[ \mathcal{W}_1^{(2)}(r, 0) + \mathcal{W}_1^{(1)}(r, 0) \right] \right\} \left\{ \mathcal{W}_1^{(1)}(r, 0) + c \hat{w}(r) \right\} = \mathcal{W}_1^{(1)}(r, 0) .$$  \hfill (68)
FIG. 1: **Left panel**: evolution of the optimal weights in a fiducial flux-limited survey as a function of halo mass. The blue and red lines represent the optimal weights and the FKP weights, respectively. The solid, dashed and dot-dashed line styles denote the results for increasing $\chi$, respectively. **Right panel**: evolution of the optimal weights as a function of redshift for several halo masses. Blue and red lines denote optimal and FKP weights. The solid, dashed and dot-dashed lines show the results for galaxy-, group- and cluster-scale halo masses, respectively. We have taken the flux-limit to be $m_{\text{lim}} = 22$.

In order to proceed further we need to recompute the effective survey window functions $\tilde{G}$ functions from Eq. (64) with the new weight function Eq. (67). It is straightforward to show that:

$$
\tilde{G}_{(1,1)}(r) = \tilde{w}(r)\bar{n}_{\text{eff}}(r), \text{ where } n_{\text{eff}}(r) = \int dM\bar{n}(M)b^2(M)\left[\frac{N_g^{(1)}(M)S(r,M)}{1 + \beta(M)N_g^{(1)}(M)S(r,M)}\right];
$$

$$
\tilde{G}_{(1,0)}(r) = \tilde{w}^2(r)\int dM\bar{n}(M)b^2(M)\beta(M)\left[\frac{N_g^{(1)}(M)S(r,M)}{1 + \beta(M)N_g^{(1)}(M)S(r,M)}\right]^2;
$$

$$
\tilde{G}_{(2,0)}(r) = \tilde{w}^2(r)\int dM\bar{n}(M)b^2(M)\frac{N_g^{(1)}(M)S(r,M)}{[1 + \beta(M)N_g^{(1)}(M)S(r,M)]^2}.
$$

From the above equations we also notice the useful relation:

$$
\tilde{G}_{(1,0)}(r) + \tilde{G}_{(2,0)}(r) = \tilde{w}(r)\bar{G}_{(1,1)}(r) = \tilde{w}^2(r)\bar{n}_{\text{eff}}(r).
$$

Replacing all these ingredients back into Eq. (68), after a little algebra we find that $\tilde{w}$ has the solution:

$$
\tilde{w}(r) = 1/[c + \bar{n}_{\text{eff}}(r)].
$$

(72)

On putting together Eqs. (67) and (72), back substituting the constant $c = (1 + \alpha)/P_i$, we arrive at the general solution for the optimal weights:

$$
w(r,M) = \frac{b(M)}{[1 + \beta(M)N_g^{(1)}(M)S(r,M)]\left[\left[(1 + \alpha) + \bar{n}_{\text{eff}}(r)P_i\right]\right]}.
$$

(73)

This expression is the central result of this paper.

Figure 1 demonstrates how the optimal weights vary as a function of the galaxies host halo mass and redshift. At low redshifts, the galaxy selection $S \to 1$. For galaxies that are hosted by low-mass haloes, $N_g^{(1)}(M) < 1$ and so $w \propto b(M)$. On the other hand, for the high mass clusters $N_g^{(1)}(M) \gg 1$, and $w(r,M) \propto b(M)/N_g^{(1)}(M)$. Hence we
would expect the galaxies in low-mass haloes to be weighted more strongly than those in high-mass haloes, since the bias is rather a slowly evolving function of halo mass. At higher redshift, we would expect that this trend reverses, since \( \{ S, n_{\text{eff}} \} \rightarrow 0 \) and so the weights effectively follow the bias of the host haloes. These trends are exactly what is seen in the figure. For reference, Fig. 1 also compares the optimal weights with the original FKP weight function, given by: \( w_{\text{FKP}}(r) \propto \left[ 1 + \bar{n}(r)P(k) \right]^{-1} \) [80].

C. Time evolution of the optimal weights

Before moving on, we briefly discuss the redshift dependence of the optimal weights in Eq. (73). So far, we have considered that \( \bar{n}(M), b(M), \Phi(L|M), N^{(1)}(M), \beta(M) \) and \( \xi(r) \) are all independent of time (here we will parameterise time evolution through the comoving distance \( \chi \)). This is approximately correct if the survey volume is sufficiently small so that these functions do not evolve appreciably over the survey. In general, however, they are time dependent. Therefore we would have: \( \bar{n}(M) \rightarrow \bar{n}(M, \chi), \ \ b(M, \chi), \ \ \Phi(L|M) \rightarrow \Phi(L|M, \chi), \ \ N^{(1)}(M) \rightarrow N^{(1)}(M, \chi), \ \ \beta(M) \rightarrow \beta(M, \chi) \) and \( \xi(r_1 - r_2) \rightarrow \xi(r_1 - r_2, \chi_1, \chi_2) = D(\chi_1)D(\chi_2)\xi(r_1 - r_2) \).

In the last equality we have assumed that the correlation function obeys linear theory, hence the resulting growth factors. Working under this assumption, we redefine the \( \mathcal{F} \) functions to absorb the growth factors:

\[
\mathcal{F}^{(n)}_{(i,m)}(r) \equiv \int dM \bar{n}(M, \chi) [D(\chi)b(M, \chi)]^m N^{(n)}_\xi(M, \chi) \left[ w^i(r, M)S(r, M) \right]^n.
\]

Formally this is equivalent to redefining the halo bias parameter: \( b(M) \rightarrow D(\chi)b(M, \chi) \), and we prefer this latter approach. Thus, Eq. (73) becomes:

\[
w(r, M) = \frac{D(\chi)b(M, \chi)}{\left[ 1 + \beta(M, \chi)N^{(1)}_\xi(M, \chi)S(r, M) \right]} \left[ (1 + \alpha) + \bar{P}_i \bar{n}_{\text{eff}}(\chi) \right],
\]

where the new effective number density is:

\[
\bar{n}_{\text{eff}}(r) \equiv \int dM \bar{n}(M, \chi)D^2(\chi)b^2(M, \chi) \frac{N^{(1)}_\xi(M, \chi)S(r, M)}{\left[ 1 + \beta(M, \chi)N^{(1)}_\xi(M, \chi)S(r, M) \right]}.
\]

VI. INFORMATION CONTENT OF GALAXY CLUSTERING

The ability of a set of band-power estimates of the galaxy power spectrum to constrain the cosmological model can, theoretically, be determined through construction of the Fisher information matrix. Under the assumption that the density field is Gaussianly distributed, one finds that the power spectrum for a given Fourier mode is exponentially distributed about the mean power, and that the band-power estimate is \( \chi^2 \) distributed [61]. Owing to the central limit theorem, in the limit of a large number of Fourier modes per \( k \)-space shell, the power spectrum estimates thus approach the Gaussian distribution. Under the assumption that the power spectrum estimator is Gaussianly distributed, it can be shown that the Fisher matrix has the form [62, 63] (but see Abramo [64]):

\[
\mathcal{F}_{\alpha\beta} = \frac{1}{2} \text{Tr} \left[ C^{-1} C_{\alpha} C^{-1} C_{\beta} \right] + \sum_{i,j} \frac{\partial P_i}{\partial \alpha} C_{ij}^{-1} \frac{\partial P_j}{\partial \beta} \approx \sum_{i,j} \frac{\partial P_i}{\partial \alpha} C_{ij}^{-1} \frac{\partial P_j}{\partial \beta},
\]

where the approximate equality follows from the fact that the second term on the right-hand side of the first equality dominates over the first term, since it scales directly in proportion with the number of Fourier modes, whereas the first term is independent of the number of modes. In the above we have made use of the notation \( \partial / \partial \alpha \equiv \partial / \partial \theta_\alpha \) to denote partial derivatives with respect to the cosmological parameters \( \theta_\alpha \). On taking the covariance matrix to be diagonal, as is the case in Eq. (51), the above expression for the Fisher matrix becomes:

\[
\mathcal{F}_{\alpha\beta} = \sum_{i,j} \frac{\partial \log P_i}{\partial \alpha} \frac{\sigma_i^2(k_i)}{\bar{P}_i} \frac{\delta_{ij}^K}{\bar{P}_j} \frac{\partial \log P_j}{\partial \beta} = \sum_i \frac{\partial \log P_i}{\partial \alpha} \frac{\partial \log P_i}{\partial \beta} \left( S \over N \right)^2 (k_i).
\]

If we now define the effective survey volume through the expression,

\[
V_{\text{eff}}(k_i) \equiv \frac{2(2\pi)^3}{V_i} \left( S \over N \right)^2 (k_i),
\]

(78)
and take the continuum limit for the Fourier modes, we find that the Fisher matrix can be expressed as [63]:

$$\mathcal{F}_{\alpha\beta} = \frac{1}{2} \int \frac{d^3k}{(2\pi)^3} \frac{\partial \log P(k)}{\partial \alpha} \frac{\partial \log P(k)}{\partial \beta} V_{\text{eff}}(k).$$  \hspace{1cm} (79)

Thus in order to determine the information content of the galaxy power-spectrum obtained using a general weight function \(w\), we simply need to calculate \(V_{\text{eff}}[w](k)\) or equivalently \(S/N[w](k)\). It is clear from Eqs. (51) and (52) that a general expression for the \(S/N\) is given by:

$$\left( \frac{S}{N} \right)^2(k_i) = \frac{V_i}{2(2\pi)^3} \int d^3r \left[ \mathcal{G}^{(1)}_{(1,1)}(r) \right]^2 \left\{ \int d^3r \left( \mathcal{G}^{(1)}_{(1,1)}(r) \right)^2 + \frac{1 + \alpha}{P_i} \left[ \mathcal{G}^{(2)}_{(1,0)}(r) + \mathcal{G}^{(1)}_{(2,0)}(r) \right] \right\}^{-1}. \hspace{1cm} (80)$$

In the case of the optimal weights from Eq. (75), a little algebra leads to the simplified result:

$$\left( \frac{S}{N} \right)^2(k_i) = \frac{V_i}{2(2\pi)^3} \int d^3r \left[ \frac{P_i \bar{n}_{\text{eff}}(r)}{(1 + \alpha) + P_i \bar{n}_{\text{eff}}(r)} \right]^2. \hspace{1cm} (81)$$

The above expression will be useful for forecasting how well a future galaxy redshift survey may constrain cosmological parameters, after an optimal power spectrum analysis has been performed.

VII. PRACTICAL CHALLENGES IN IMPLEMENTING THE OPTIMAL WEIGHTS

In order to implement the optimal weighting scheme, one requires knowledge of: the halo mass function \(\bar{n}(M)\); the halo bias function \(b(M)\); the conditional probability density \(\Phi(L|M)\); the first and second factorial moments of the halo occupation distribution as parameterised by \(N^{(1)}(M)\) and \(\beta(M)\); and a way to associate each galaxy in the survey to a host halo. A possible route for achieving this is as follows:

- Pure halo-dependent quantities: \(\bar{n}(M)\) and \(b(M)\). These functions can be determined directly from numerical simulations; there also exist a number of accurate semi-analytic fitting functions in the literature [for recent examples see 65–67]. However, in order to employ these one needs to specify the underlying cosmological model – we do not consider this too troublesome, since it is also required to turn redshifts into distances.

- Galaxy formation dependent functions: \(\Phi(L|M)\), \(N^{(1)}_g(M)\) and \(N^{(2)}_g(M)\). These require a model of galaxy formation or additional measurements. On adopting a state-of-the-art SAM, these functions can be measured directly [29, 60]. They may also be obtained from the data through the CLF approach [57, 68].

- Associating galaxies to groups: this step could be performed through application of standard friends-of-friends group finding algorithms or more sophisticated colour-magnitude-redshift grouping methods [69–71].

- Determine group halo mass: through the use of good quality mock catalogues, such as can be facilitated through a SAM, one may apply the same grouping algorithms as were used on the real data to the mock data, thus finding the mapping between each group and the most likely halo mass [69].

- Implement the optimal weighting scheme and measure \(P(k)\).

Owing to the fact that the steps enumerated above can not be performed without error, it is likely that this will introduce additional scatter that we have not accounted for in our optimal estimator. We expect that this scatter will not bias the measurements, but will most likely lead to a reduction in signal-to-noise. We shall leave it as a task for future work to explore how well this method can be implemented in detail.

VIII. CONCLUSIONS

In this paper we have developed the theory for the unbiased and optimal estimation of the matter power spectrum from the galaxy power spectrum. Our approach generalises the original approach of FKP, by taking into account central ideas from the theory of galaxy formation: galaxies form and reside exclusively in dark matter haloes; a given dark matter halo may host many galaxies of various luminosities; galaxies inherit part of their large-scale bias from their host halo.
In §II we described the generic properties of a galaxy redshift survey and presented a new theoretical quantity: the galaxy-halo double delta expansion. We demonstrated how one may use this expansion of the halo and galaxy fields to answer basic statistical questions concerning the galaxy distribution. In particular we gave a derivation of the galaxy luminosity function in this framework.

In §III we presented estimators for the galaxy correlation function and power spectrum. It was proved that, in the large-scale and large-survey-volume limits, these were unbiased estimates of the dark matter correlation function and power spectrum. We demonstrated that, similar to FKP, in our scheme the matter power spectrum could be obtained by subtracting an effective shot-noise component followed by the deconvolution of the power spectrum associated with an effective survey window function.

In §IV we derived general expressions for the covariance matrix of the weighted galaxy power spectrum, including all non-Gaussian terms arising from the nonlinear evolution of matter fluctuations, discreteness effects and finite survey geometry effects. These results generalise the earlier results of [59, 72, 73]. In the limits of large-scales, large survey volumes, and Gaussian fluctuations, the covariance matrix was found to be diagonal.

In §V we found an equation that governs the optimal weights to be applied to galaxies. We found a general solution of the weight equation. Interestingly, the solution did not carry any explicit dependence on galaxy luminosity. Instead the weights were found to be simply a function of two variables: the spatial position within the survey and the mass of the dark matter halo hosting the galaxies.

In §VI we presented a new expression for the Fisher information matrix, for a weighted galaxy power spectrum measurement. We also presented a formula for the signal-to-noise obtained for the optimal weights.

Finally, in §VII we outlined the practical steps that would need to be followed if one were to carry out the optimal power spectrum analysis.

In future work we will explore the signal-to-noise and cosmological information gains achievable through the optimal weighting scheme. We will also explore how well one may implement such a scheme with real data.

Acknowledgments

We thank Simon White for useful discussions. RES acknowledges part support from ERC Advanced grant 246797 GAlFORMod. LM thanks MPA for its kind hospitality while part of this work was being performed.

[1] P. J. E. Peebles, ApJ 185, 413 (1973).
[2] M. G. Hauser and P. J. E. Peebles, ApJ 185, 757 (1973).
[3] P. J. E. Peebles and M. G. Hauser, ApJS 28, 19 (1974).
[4] P. J. E. Peebles, ApJS 28, 37 (1974).
[5] P. J. E. Peebles and E. J. Groth, ApJ 196, 1 (1975).
[6] P. J. E. Peebles, ApJ 196, 647 (1975).
[7] M. Seldner and P. J. E. Peebles, ApJ 215, 703 (1977).
[8] E. J. Groth and P. J. E. Peebles, ApJ 217, 385 (1977).
[9] J. N. Fry and P. J. E. Peebles, ApJ 221, 19 (1978).
[10] M. Seldner and P. J. E. Peebles, ApJ 225, 7 (1978).
[11] M. Seldner and P. J. E. Peebles, ApJ 227, 30 (1979).
[12] J. N. Fry and P. J. E. Peebles, ApJ 238, 785 (1980).
[13] M. Davis and P. J. E. Peebles, ApJ 267, 465 (1983).
[14] S. D. Landy and A. S. Szalay, ApJ 412, 64 (1993).
[15] A. J. S. Hamilton, ApJ 417, 19 (1993).
[16] G. M. Bernstein, ApJ 424, 569 (1994).
[17] D. J. Baumgart and J. N. Fry, ApJ 375, 25 (1991).
[18] J. A. Peacock and D. Nicholson, MNRAS 253, 307 (1991).
[19] K. B. Fisher, M. Davis, M. A. Strauss, A. Yahil, and J. P. Huchra, ApJ 402, 42 (1993).
[20] H. A. Feldman, N. Kaiser, and J. A. Peacock, ApJ 426, 23 (1994), arXiv:astro-ph/9304022.
[21] M. S. Vogeley and A. S. Szalay, ApJ 465, 34 (1996), astro-ph/9601185.
[22] A. J. S. Hamilton, MNRAS 289, 285 (1997), arXiv:astro-ph/9701008.
[23] A. J. S. Hamilton, MNRAS 289, 295 (1997), arXiv:astro-ph/9701009.
[24] A. J. S. Hamilton, MNRAS 312, 257 (2000), arXiv:astro-ph/9905191.
[25] A. J. S. Hamilton and M. Tegmark, MNRAS 312, 285 (2000), astro-ph/9905192.
[26] S. D. M. White and M. J. Rees, MNRAS 183, 341 (1978).
[27] S. D. M. White and C. S. Frenk, ApJ 379, 52 (1991).
[28] G. Kauffmann, J. M. Colberg, A. Diaferio, and S. D. M. White, MNRAS 303, 188 (1999), arXiv:astro-ph/9805283.
Let us begin by defining the short hand notation for the correlation: $\langle n_g n_g' \rangle \equiv \langle n_g(r, L, x, M)n_g(r', L', x', M') \rangle$. Following the analysis of §II, this correlation may be written:

$$
\langle n_g n_g' \rangle = \left\langle \sum_{i,j=1}^{N_g} \delta^D(x - x_i)\delta^D(M - M_i)\delta^D(x' - x_j)\delta^D(M' - M_j) \times \left( \sum_{k=1}^{N_g(M_i)} \sum_{l=1}^{N_g(M_j)} \delta^D(r - r_k - x_i)\delta^D(L - L_k)\delta^D(r' - r_l - x_j)\delta^D(L' - L_l) \right) \right\rangle_s . \tag{A1}
$$

If we now split the sums over $i$ and $j$ into two parts, a piece where $i \neq j$ and a piece where $i = j$, then we find

$$
\langle n_g n_g' \rangle = \sum_{i \neq j}^{N_g} \delta^D(x - x_i)\delta^D(M - M_i)\delta^D(x' - x_j)\delta^D(M' - M_j) \\
\times \left( \sum_{k=1}^{N_g(M_i)} \sum_{l=1}^{N_g(M_j)} \delta^D(r - r_k - x_i)\delta^D(L - L_k)\delta^D(r' - r_l - x_j)\delta^D(L' - L_l) \right) \bigg|_s \\
+ \sum_{i=j}^{N_g} \delta^D(x - x_i)\delta^D(M - M_i)\delta^D(x' - x_i)\delta^D(M' - M_i) \\
\times \left( \sum_{k,l=1}^{N_g(M_i)} \delta^D(r - r_k - x_i)\delta^D(L - L_k)\delta^D(r' - r_l - x_i)\delta^D(L' - L_l) \right) \bigg|_s . \tag{A2}
$$

Consider the terms associated with the $i \neq j$ sum, since we have assumed that the galaxy properties hosted by the $i$th halo are independent of the galaxy properties in the $j$th halo, we may write the average of these terms as the product of the two averages. Next, consider the term $i = j$, and notice that we may also separate the sum over $k$ and

[72] A. Meiksin and M. White, MNRAS 308, 1179 (1999), arXiv:astro-ph/9812129.
[73] R. Scoccimarro, M. Zaldarriaga, and L. Hui, ApJ 527, 1 (1999), astro-ph/9901099.
[74] J. N. Fry and E. Gaztanaga, ApJ 413, 447 (1993), arXiv:astro-ph/9302009.
[75] H. J. Mo and S. D. M. White, MNRAS 282, 347 (1996), arXiv:astro-ph/9512127.
[76] H. J. Mo, Y. P. Jing, and S. D. M. White, MNRAS 284, 189 (1997), arXiv:astro-ph/9603039.
[77] R. E. Smith, R. Scoccimarro, and R. K. Sheth, PRD 75, 063512 (2007), arXiv:astro-ph/0609547.
[78] We note that this equation is the more rigorous starting point for all Halo Model calculations of the galaxy field. However, so far as we are aware it has not been written down before. This in part owes to the fact that the galaxy-clustering expressions could be deduced by analogy with the mass clustering. However, for the case of the optimal weights in a realistic survey that approach is not feasible.
[79] Note that this is closely related to the conditional luminosity function introduced by Yang et al. [c.f. 57], which in our notation would be $\Phi_{Yang et al}(L|M) = N_g^{(1)}(M)\Phi(L|M)$.
[80] Note that in order to evaluate the weight functions we took $m_{lim} = 22$ and adopted the CLF model of Yang et al. [57] to compute $S(r, M)$ and $N_g^{(1)}(M)$. For the function $\beta(M)$ we employed the model presented in Cooray and Sheth [60] derived from semi-analytic galaxies.
l into two terms, a term with \( k \neq l \) and a term with \( k = l \). This leads us to write the following expression:

\[
\langle n_g n_g' \rangle = \sum_{i \neq j} N_g(M_i) \delta^D (x - x_i) \delta^D (M - M_i) \delta^D (x' - x_j) \delta^D (M' - M_j) \times \left\langle \sum_{k=1}^{N_k(M_i)} \delta^D (r - r_k - x_i) \delta^D (L - L_k) \right\rangle \left\langle \sum_{l=1}^{N_k(M_j)} \delta^D (r' - r_l - x_j) \delta^D (L' - L_l) \right\rangle_s
+ \sum_{i=j} N_g(M_i) \delta^D (M - M_i) \delta^D (x' - x_i) \delta^D (M' - M_i) \times \left[ \sum_{k=1}^{N_k(M_i)} \sum_{i \neq k} \delta^D (r - r_k - x_i) \delta^D (L - L_k) \delta^D (r' - r_l - x_i) \delta^D (L' - L_l) \right]_s
+ \left[ \sum_{k=l}^{N_k(M_j)} \delta^D (r - r_k - x_i) \delta^D (L - L_k) \delta^D (r' - r_k - x_i) \delta^D (L' - L_k) \right]_s .
\]

(A3)

We are now able to compute the expectations over the galaxy populations, and with the help of Eq. (13) we find:

\[
\langle n_g n_g' \rangle = \sum_{i \neq j} N_g(M_i) N_g(M_j) \Phi(L | M_i) \Phi(L' | M_j) \Theta(r | L) \Theta(r' | L') \times \left\langle \sum_{i \neq j} \delta^D (x - x_i) \delta^D (M - M_i) \delta^D (x' - x_j) \delta^D (M' - M_j) \right\rangle_s
+ \sum_{i=j} N_g(M_i) \delta^D (M - M_i) \delta^D (x' - x_i) \delta^D (M' - M_i) \times \left[ \sum_{i \neq j} \delta^D (r - r_k - x_i) \delta^D (L - L_k) \delta^D (r' - r_l - x_i) \delta^D (L' - L_l) \right]_s
+ \left[ \sum_{k=l} \delta^D (r - r_k - x_i) \delta^D (L - L_k) \delta^D (r' - r_k - x_i) \delta^D (L' - L_k) \right]_s ,
\]

(A4)

where in the above we have used a short-hand notation for the factorial moments of the galaxy numbers:

\[
N^{(l)}_g(M) \equiv \langle N_g(N_g - 1) \ldots (N_g - l + 1) | M \rangle = \sum_{N_g=0}^{\infty} P(N_g | \lambda(M)) N_g(N_g - 1) \ldots (N_g - l + 1) .
\]

(A5)

Let us now deal with the averages over the dark matter haloes and let us write the first and second terms in Eq. (A4) as \( \langle n_g n_g'_A \rangle \) and \( \langle n_g n_g'_B \rangle \). Considering the first term, the expectations may be computed as in Eq. (18), and we find

\[
\langle n_g n_g'_A \rangle = \sum_{i \neq j} \prod_{\nu=1}^{N_h} \left\{ d^3 x_{\nu} dM_{\nu} \right\} p(x_1, \ldots, x_{N_h}, M_1, \ldots, M_{N_h}) \delta^D (x - x_i) \delta^D (M - M_i) \delta^D (x' - x_j) \delta^D (M' - M_j)
\times N_g^{(1)}(M_i) N_g^{(1)}(M_j) U(r - x_i | M_i) U(r' - x_j | M_j) \Phi(L | M_i) \Phi(L' | M_j) \Theta(r | L) \Theta(r' | L')
= N_h(N_h - 1) p(x, x', M, M') N_g^{(1)}(M) N_g^{(1)}(M') U(r - x | M) U(r' - x' | M') \Phi(L | M) \Phi(L' | M') \Theta(r | L) \Theta(r' | L') \delta^D (r - r') \delta^D (L - L') \delta^D (r' - r') \delta^D (L' - L') .
\]

The joint probability density functions for the halo centres and masses may be expressed in terms of products of their 1-point PDFs and correlations functions. For the case of two-points we have:

\[
p(x_1, x_1, M_1, M_2) = p(x_1, M_1) p(x_2, M_2) \left[ 1 + \xi^c(x_1, x_2, M_1, M_2) \right] = \frac{n(M_1)}{N_h^2} \frac{n(M_2)}{N_h} \left[ 1 + \xi^c(x_1, x_2, M_1, M_2) \right] .
\]

(A7)

In addition, if we assume that the cluster density field is some local function of the underlying dark matter density [74–77], the cross-correlation function of clusters of masses \( M_1 \) and \( M_2 \), at leading order, can be written:

\[
\xi^c(|x_1 - x_2|, M_1, M_2) = b(M_1) b(M_2) \xi(|x_1 - x_2|) ,
\]

(A8)
where $\xi(r)$ is the correlation of the underlying matter fluctuations. On using this relation in Eq. (A6) we find,

$$\langle n_x \delta^2 \rangle_A = n(M) n(M') [1 + b(M_1) b(M_2) \xi(|x_1 - x_2|)] N^{(1)} g N^{(2)} g U(r - x|M) U(r' - x'|M') \times \Phi(L|M) \Phi(L'|M') \Theta(r|L) \Theta(r'|L') .$$

\hspace{1cm} (A9)

Returning now to the second terms in Eq. (A4) and following a similar derivation to the first term, we find

$$\langle n_x n_x' \rangle_B = n(M) N^{(2)} g \Phi(L|M) \Phi(L'|M) \Theta(r|L) \Theta(r'|L') U(r - x|M) U(r' - x|M) \delta^D(x - x') \delta^D(M - M') + n(M) N^{(1)} g \Phi(L|M) \Theta(r|L) U(r - x|M) \delta^D(x - x') \delta^D(M - M') \delta^D(L - L') \delta^D(r - r') .$$

\hspace{1cm} (A10)

Following the derivation $\langle n_x n_x' \rangle$ we may now straightforwardly write down the results for the cases of the cross- and auto-correlation of the synthetic galaxy-halo field with the real one:

$$\langle n_x n_x' \rangle = \alpha^{-1} n(M) n(M') N_y g N_y g \Phi(L|M) \Theta(r|L) \Theta(r'|L') U(r - x|M) U(r' - x'|M') \Phi(L|M) \Phi(L'|M') + \alpha^{-1} n(M) N^{(2)} g \Phi(L|M) \Phi(L'|M) \Theta(r|L) \Theta(r'|L') U(r - x|M) U(r' - x'|M') \delta^D(x - x') \delta^D(M - M') + N^{(1)} g \Phi(L|M) \Theta(r|L) U(r - x|M) \delta^D(x - x') \delta^D(M - M') \delta^D(L - L') \delta^D(r - r') ,$$

\hspace{1cm} (A12)

where in the above we have made use of the following short-hand notation: $\langle n_x n_x' \rangle \equiv \langle n_x(r, L, x, M) n_x(r', L', x', M') \rangle$ and $\langle n_x n_x' \rangle \equiv \langle n_x(r, L, x, M) n_x(r', L', x', M') \rangle$.

Appendix B: The galaxy covariance matrix

1. Comment on the covariance matrix of the matter power spectrum

Starting with Eq. (46) and inserting Eq. (43) we find:

$$\text{Cov} \left[ \tilde{P}(k_1), \tilde{P}(k_2) \right] = \text{Cov} \left[ \tilde{\mathcal{F}}_g(k_1)^2, \tilde{\mathcal{F}}_g(k_2)^2 \right] - \text{Cov} \left[ \tilde{\mathcal{F}}_g(k_1)^2, P_{\text{shot}} \right] - \text{Cov} \left[ \tilde{\mathcal{F}}_g(k_2)^2, P_{\text{shot}} \right] + \text{Var}[P_{\text{shot}}] .$$

\hspace{1cm} (B1)

where:

$$\text{Cov} \left[ \tilde{\mathcal{F}}_g(k_1)^2, \tilde{\mathcal{F}}_g(k_2)^2 \right] \equiv \left\langle \tilde{\mathcal{F}}_g(k_1)^2 \tilde{\mathcal{F}}_g(k_2)^2 \right\rangle - \left\langle \tilde{\mathcal{F}}_g(k_1)^2 \right\rangle \left\langle \tilde{\mathcal{F}}_g(k_2)^2 \right\rangle ;$$

$$\text{Cov} \left[ \tilde{\mathcal{F}}_g(k_1)^2, P_{\text{shot}} \right] \equiv \left\langle \tilde{\mathcal{F}}_g(k_1)^2 P_{\text{shot}} \right\rangle - \left\langle \tilde{\mathcal{F}}_g(k_1)^2 \right\rangle \left\langle P_{\text{shot}} \right\rangle ; \hspace{0.5cm} i \in \{1, 2\} ;$$

$$\text{Var}[P_{\text{shot}}] \equiv \left\langle P_{\text{shot}}^2 \right\rangle - \left\langle P_{\text{shot}} \right\rangle^2 .$$

If we assume that the statistical uncertainties are dominated by $|\tilde{\mathcal{F}}_g(k_1)|^2$ and not $P_{\text{shot}}$, then we may approximate the covariance matrix as is written in Eq. (46).

Appendix C: Derivation of the covariance matrix of the $\tilde{\mathcal{F}}_g$ power spectrum

To begin, we notice that we may rewrite the covariance matrix of $|\tilde{\mathcal{F}}_g(k)|^2$, which is given in Eq. (46), as

$$\text{Cov} \left[ \tilde{\mathcal{F}}_g(k_1)^2, \tilde{\mathcal{F}}_g(k_2)^2 \right] = \int d^3k_1 d^3k_2 d^D(k_1 + k_3) d^D(k_2 + k_4) \left[ \langle \mathcal{F}_g(k_1) \ldots \mathcal{F}_g(k_4) \rangle - \langle \mathcal{F}_g(k_1) \mathcal{F}_g(k_3) \rangle \langle \mathcal{F}_g(k_2) \mathcal{F}_g(k_4) \rangle \right] .$$

\hspace{1cm} (C1)

We see that in order to proceed we need the 4-point function of the $\mathcal{F}_g(k)$ modes. On transforming to real space, this requirement is transformed into the need to determine the four-point correlation:

$$\langle \mathcal{F}_g(k_1) \ldots \mathcal{F}_g(k_4) \rangle - \langle \mathcal{F}_g(k_1) \mathcal{F}_g(k_3) \rangle \langle \mathcal{F}_g(k_2) \mathcal{F}_g(k_4) \rangle$$

$$= \int d^3r_1 \ldots d^3r_4 \left[ \langle \mathcal{F}_g(r_1) \ldots \mathcal{F}_g(r_4) \rangle - \langle \mathcal{F}_g(r_1) \mathcal{F}_g(r_3) \rangle \langle \mathcal{F}_g(r_2) \mathcal{F}_g(r_4) \rangle \right] e^{i k_1 \cdot r_1 + \ldots + k_4 \cdot r_4} .$$

\hspace{1cm} (C2)
1. Computing the 4-point correlation function of $\mathcal{F}_g(r)$

Since the terms $(\mathcal{F}_g(r_1)\mathcal{F}_g(r_4))$ are given by Eq. (27), we are left with the task of computing the 4-point correlation function of the field $\mathcal{F}_g(r)$. Using our relation Eq. (8), this is given by:

$$\langle \mathcal{F}_g(r_1) \ldots \mathcal{F}_g(r_4) \rangle = \frac{1}{A^2} \prod_{i=1}^{4} \left\{ \int dL_i d^3 x_i dM_i \right\} \times \left\{ \sum_{i_1, i_2, i_3, i_4 = 1}^{N_h} \delta^D(x_1 - x_{i_1}) \delta^D(x_4 - x_{i_4}) \delta^D(M_1' - M_{i_1}) \ldots \delta^D(M_4' - M_{i_4}) \right\},$$

where we have introduced the short-hand notation

$$\langle n'_{g,1} \ldots n'_{g,4} \rangle = \left\langle \sum_{i_1, i_2, i_3, i_4 = 1}^{N_h} \delta^D(x_1' - x_{i_1}) \delta^D(M_1' - M_{i_1}) \ldots \delta^D(M_4' - M_{i_4}) \right\rangle,$$

As was done for the case of the two-point function, we may now split the sum over haloes into five types of terms:

$$\langle n'_{g,1} \ldots n'_{g,4} \rangle = \langle \Gamma_1 \rangle + \langle \Gamma_2 \rangle + \langle \Gamma_3 \rangle + \langle \Gamma_4 \rangle + \langle \Gamma_5 \rangle,$$

where the terms $\Gamma_i$ are defined:

$$\Gamma_1 = \sum_{i_1 \neq i_2 \neq i_3 \neq i_4} \delta^D(x_1' - x_{i_1}) \delta^D(x_4' - x_{i_4}) \delta^D(M_1' - M_{i_1}) \ldots \delta^D(M_4' - M_{i_4}) \langle g \rangle;$$

$$\Gamma_2 = \sum_{i_1 \neq i_2 \neq i_3 = i_4} \delta^D(x_1' - x_{i_1}) \delta^D(x_2' - x_{i_2}) \delta^D(M_1' - M_{i_1}) \delta^D(M_2' - M_{i_2}) \prod_{p=3}^4 \left\{ \delta^D(x_p' - x_{i_p}) \delta^D(M_{i_p}' - M_{i_p}) \right\} \langle g \rangle + \text{5 perms};$$

$$\Gamma_3 = \sum_{i_1 \neq i_2 \neq i_3 = i_4} \prod_{p=1}^2 \left\{ \delta^D(x_p' - x_{i_p}) \delta^D(M_{i_p}' - M_{i_p}) \right\} \prod_{q=3}^4 \left\{ \delta^D(x_q' - x_{i_q}) \delta^D(M_{i_q}' - M_{i_q}) \right\} \langle g \rangle + \text{2 perms};$$

$$\Gamma_4 = \sum_{i_1 \neq i_2 \neq i_3 = i_4} \prod_{p=2}^4 \left\{ \delta^D(x_p' - x_{i_p}) \delta^D(M_{i_p}' - M_{i_p}) \right\} \langle g \rangle + \text{3 perms};$$

$$\Gamma_5 = \sum_{i_1 = i_2 = i_3 = i_4} \prod_{p=1}^4 \left\{ \delta^D(x_p' - x_{i_p}) \delta^D(M_{i_p}' - M_{i_p}) \right\} \langle g \rangle.$$

**Computing** $\langle \Gamma_1 \rangle$: Integrating over the Dirac delta functions and relabelling primed variables to unprimed, we write:

$$\langle \Gamma_1 \rangle = \sum_{i_1 \neq i_2 \neq i_3 \neq i_4} p(x_1, \ldots, x_4, M_1, \ldots, M_4) \langle g \rangle$$

$$\approx \bar{n}_1 \ldots \bar{n}_4 \left[ 1 + \{ \zeta \} + \{ \zeta \} + \{ \zeta \} + \{ \zeta \} + \{ \zeta \} + \{ \zeta \} + \{ \zeta \} + \{ \zeta \} + \{ \zeta \} + \{ \zeta \} \right] \langle g \rangle.$$
where in the above we have decomposed the joint 4-point PDF into its respective 1-point moments and set of correlation functions. In this case $\zeta$ and $\eta$ denote the connected three- and four-point correlation functions, respectively. Also note that we used the following short-hand notation:

$$\zeta_{ij}^c \equiv \zeta_{ij}(x_i, x_j, M_i, M_j); \quad \zeta_{ijk} \equiv \zeta(x_i, x_j, x_k, M_i, M_j, M_k); \quad \eta_{ijkl}^c \equiv \eta(x_i, x_j, x_k, x_l, M_i, M_j, M_k, M_l). \quad (C8)$$

**Computing $\langle \Gamma_2 \rangle$:** We denote $\delta^{\text{D}}_{\text{h}_{ij}} \equiv \delta^{\text{D}}(M_i - M_j)\delta^{\text{D}}(x_i - x_j)$ and $\delta_{\text{h}_{ij}}^{\text{D}} \equiv \delta^{\text{D}}(L_i - L_j)\delta^{\text{D}}(r_i - r_j)$. Taking the expectations and integrating over the delta functions we find:

$$\langle \Gamma_2 \rangle = \sum_{i_1 \neq i_2 \neq i_3 = i_4}^N p(x_1, x_2, x_3, M_1, M_2, M_3) \delta^{\text{D}}_{\text{h}_{1234}} \langle g \rangle + \sum_{i_1 \neq i_3 \neq i_4 \neq i_2}^N p(x_1, x_2, x_4, M_1, M_2, M_4) \delta^{\text{D}}_{\text{h}_{1234}} \langle g \rangle$$

$$+ \sum_{i_1 = i_2 \neq i_3 \neq i_4}^N p(x_1, x_3, x_4, M_1, M_2, M_3) \delta^{\text{D}}_{\text{h}_{124}} \langle g \rangle + \sum_{i_1 = i_3 \neq i_2 \neq i_4}^N p(x_1, x_2, x_4, M_1, M_2, M_4) \delta^{\text{D}}_{\text{h}_{124}} \langle g \rangle$$

$$+ \sum_{i_1 = i_4 \neq i_2 \neq i_3}^N p(x_1, x_2, x_3, M_1, M_2, M_3) \delta^{\text{D}}_{\text{h}_{124}} \langle g \rangle$$

$$= N_h(N_h - 1)(N_h - 2) \left[ p(x_1, x_2, x_3, M_1, M_2, M_3) \langle g \rangle \delta^{\text{D}}_{\text{h}_{1234}} + p(x_1, x_2, x_4, M_1, M_2, M_4) \langle g \rangle \delta^{\text{D}}_{\text{h}_{1234}} \right]$$

$$+ p(x_1, x_3, x_4, M_1, M_3, M_4) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} + p(x_1, x_2, x_4, M_1, M_2, M_4) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}}$$

$$+ p(x_1, x_2, x_3, M_1, M_2, M_3) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}}$$

$$\approx n_1 n_3 n_4 \left[ 1 + \xi_{13}^c + \xi_{14}^c + \xi_{34}^c \right] \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} + n_1 n_2 n_3 \frac{1}{2} \left[ 1 + \xi_{12}^c + \xi_{23}^c + \xi_{24}^c + \xi_{124}^c \right] \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}}$$

$$+ n_1 n_2 n_3 \left[ 1 + \xi_{12}^c + \xi_{23}^c + \xi_{31}^c + \xi_{123}^c \right] \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} + n_1 n_2 n_3 \frac{1}{2} \left[ 1 + \xi_{12}^c + \xi_{23}^c + \xi_{31}^c + \xi_{123}^c \right] \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}}.$$

**Computing $\langle \Gamma_3 \rangle$:** Again, on taking the expectations and integrating over the delta functions we find:

$$\langle \Gamma_3 \rangle = \sum_{i_1 = i_2 \neq i_3 \neq i_4}^N p(x_1, x_3, M_1, M_3) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}} + \sum_{i_1 = i_3 \neq i_2 = i_4}^N p(x_1, x_2, M_1, M_2) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}}$$

$$+ \sum_{i_1 = i_4 \neq i_2 = i_3}^N p(x_1, x_2, M_1, M_2) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}}$$

$$= N_h(N_h - 1) \left[ p(x_1, x_3, M_1, M_3) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}} + p(x_1, x_2, M_1, M_2) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}} \right]$$

$$= n_1 n_3 \left[ 1 + \xi_{13}^c \right] \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}} + n_1 n_2 \frac{1}{2} \left[ 1 + \xi_{12}^c \right] \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}}.$$

**Computing $\langle \Gamma_4 \rangle$:** Again, on taking the expectations and integrating over the delta functions we find:

$$\langle \Gamma_4 \rangle = \sum_{i_1 = i_2 \neq i_3 \neq i_4}^N p(x_1, x_4, M_1, M_4) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}} + \sum_{i_1 = i_3 \neq i_2 \neq i_4}^N p(x_1, x_3, M_1, M_3) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}}$$

$$+ \sum_{i_1 = i_4 \neq i_2 \neq i_3}^N p(x_1, x_2, M_1, M_2) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}}$$

$$= N(N - 1) \left[ p(x_1, x_4, M_1, M_4) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}} + p(x_1, x_3, M_1, M_3) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}} \right]$$

$$+ p(x_1, x_2, M_1, M_2) \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}}$$

$$= n_1 n_4 \left[ 1 + \xi_{14}^c \right] \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}} + n_1 n_3 \frac{1}{2} \left[ 1 + \xi_{13}^c \right] \langle g \rangle \delta^{\text{D}}_{\text{h}_{124}} \delta^{\text{D}}_{\text{h}_{134}}$$

**Computing $\langle \Gamma_5 \rangle$:** Again, on taking the expectations and integrating over the delta functions we find:

$$\langle \Gamma_5 \rangle = \sum_{i_1 = i_2 = i_3 = i_4}^N p(x_1, M_1) \langle g \rangle \delta^{\text{D}}_{\text{h}_{12}} \delta^{\text{D}}_{\text{h}_{13}} \delta^{\text{D}}_{\text{h}_{14}} = n_1 \langle g \rangle \delta^{\text{D}}_{\text{h}_{12}} \delta^{\text{D}}_{\text{h}_{13}} \delta^{\text{D}}_{\text{h}_{14}}.
Collecting the terms $⟨\Gamma_1⟩, ⟨\Gamma_2⟩, ⟨\Gamma_3⟩, ⟨\Gamma_4⟩$ and $⟨\Gamma_5⟩$, we write:

$$\langle n_{g,1} n_{g,2} n_{g,3} n_{g,4} \rangle = \bar{n_1} n_2 \bar{n_3} n_4 \left\{ \left[ 1 + \xi_{12} + \xi_{13} + \xi_{14} + \xi_{23} + \xi_{24} + \xi_{34} + \xi_{123} + \xi_{124} + \xi_{134} + \xi_{234} + \xi_{1234} \right] \langle g \rangle + [1 + \xi_{12} + \xi_{13} + \xi_{14} + \xi_{23} + \xi_{24} + \xi_{34} + \xi_{123} + \xi_{124} + \xi_{134} + \xi_{234} + \xi_{1234} \langle g \rangle] \right\} .$$

Based on the above expression we are now in a position to immediately write down the other 4-point function cases required to compute Eq. (C3):

$$\langle n_{g,1} n_{g,2} n_{g,3} n_{g,4} \rangle = -\bar{n}_1 n_2 \bar{n}_3 n_4 \left\{ \left[ 1 + \xi_{12} + \xi_{13} + \xi_{14} + \xi_{23} + \xi_{24} + \xi_{34} \right] \langle g \rangle + (1 + \xi_{12} + \xi_{13} + \xi_{14} + \xi_{23} + \xi_{24} + \xi_{34} + \xi_{123} + \xi_{124} + \xi_{134} + \xi_{234} + \xi_{1234} \langle g \rangle) \right\} ;$$

$$\langle n_{g,1} n_{g,2} n_{g,3} n_{g,4} \rangle = -\bar{n}_1 n_2 \bar{n}_3 n_4 \left\{ \left[ 1 + \xi_{12} + \xi_{13} + \xi_{14} + \xi_{23} + \xi_{24} + \xi_{34} \right] \langle g \rangle + (1 + \xi_{12} + \xi_{13} + \xi_{14} + \xi_{23} + \xi_{24} + \xi_{34} + \xi_{123} + \xi_{124} + \xi_{134} + \xi_{234} + \xi_{1234} \langle g \rangle) \right\} ;$$

$$\langle n_{g,1} n_{g,2} n_{g,3} n_{g,4} \rangle = -\bar{n}_1 n_2 \bar{n}_3 n_4 \left\{ \left[ 1 + \xi_{12} + \xi_{13} + \xi_{14} + \xi_{23} + \xi_{24} + \xi_{34} \right] \langle g \rangle + (1 + \xi_{12} + \xi_{13} + \xi_{14} + \xi_{23} + \xi_{24} + \xi_{34} + \xi_{123} + \xi_{124} + \xi_{134} + \xi_{234} + \xi_{1234} \langle g \rangle) \right\} .$$

In order to compute the 4-point correlation function of $F_g$, we need to compute the sum of 4 terms of Eq. (C11), with permuted location of $g$ and s. This is given by:

$$L_1 = \langle n_{g,1} n_{g,2} n_{g,3} n_{g,4} \rangle + \langle n_{s,1} n_{g,2} n_{g,3} n_{s,4} \rangle + \langle n_{s,1} n_{s,2} n_{g,3} n_{s,4} \rangle + \langle n_{g,1} n_{s,2} n_{s,3} n_{g,4} \rangle$$

$$= \bar{n}_1 n_2 \bar{n}_3 n_4 \left\{ 4\alpha^{-3} \langle g \rangle + 2\alpha^{-2} \left[ \frac{\delta_{h,23}^{D}}{n_3} \langle g \rangle + \frac{\delta_{h,24}^{D}}{n_4} \langle g \rangle + \frac{\delta_{h,34}^{D}}{n_4} \langle g \rangle + \frac{\delta_{h,13}^{D}}{n_3} \langle g \rangle + \frac{\delta_{h,14}^{D}}{n_4} \langle g \rangle + \frac{\delta_{h,12}^{D}}{n_2} \langle g \rangle \right] \right\} .$$
We also need to compute the sum of 6 terms of Eq. (C10), with permuted location of \( g \) and \( s \). This is given by:

\[
L_2 \equiv \langle n_{g,1} n_{g,2} n_{s,3} n_{s,4} \rangle + 5 \text{perms}
\]

\[
= n_1 n_2 n_3 n_4 \alpha^{-2} \left\{ \left( 6 + \xi_{12}^c + \xi_{13}^c + \xi_{14}^c + \xi_{23}^c + \xi_{24}^c + \xi_{34}^c \right) \langle g \rangle + \frac{\delta_{h,12}^c}{n_2} \langle g \rangle + \left[ \frac{\delta_{h,13}}{n_3} + \frac{\delta_{h,23}}{n_3} \right] \langle g \rangle \\
+ \left[ \frac{\delta_{h,14}}{n_4} + \frac{\delta_{h,24}}{n_4} + \frac{\delta_{h,34}}{n_4} \right] \langle g \rangle + \alpha \left( \left( 1 + \xi_{12} \right) \frac{\delta_{h,13}^c}{n_3} + \left( 1 + \xi_{13} \right) \frac{\delta_{h,24}^c}{n_4} + \left( 1 + \xi_{23} \right) \frac{\delta_{h,14}^c}{n_4} \right) \langle g \rangle \\
+ \left( 1 + \xi_{14} \right) \frac{\delta_{h,23}^c}{n_3} \langle g \rangle + \left( 1 + \xi_{24} \right) \frac{\delta_{h,13}^c}{n_3} \langle g \rangle + 2 \frac{\delta_{h,12}^c \delta_{h,23}^c}{n_4} \langle g \rangle + 2 \left[ \frac{\delta_{h,13}^c \delta_{h,24}^c}{n_4} + \frac{\delta_{h,23}^c \delta_{h,14}^c}{n_4} \right] \langle g \rangle \right\}.
\]

In addition we need to compute the sum of 4 terms of Eq. (C9), again where the locations of \( g \) and \( s \) are permuted. This sum can be written:

\[
L_3 \equiv \langle n_{g,1} n_{g,2} n_{s,3} n_{s,4} \rangle + \langle n_{g,1} n_{g,2} n_{g,3} n_{g,4} \rangle + \langle n_{s,1} n_{s,2} n_{g,3} n_{g,4} \rangle + \langle n_{s,1} n_{g,2} n_{s,3} n_{s,4} \rangle
\]

\[
= \alpha^{-1} n_1 n_2 n_3 n_4 \left\{ \left( 4 + 2 \xi_{12} + 2 \xi_{13} + 2 \xi_{14} + 2 \xi_{23} + 2 \xi_{24} + 2 \xi_{34} + \xi_{123} + \xi_{124} + \xi_{134} + \xi_{234} \right) \langle g \rangle \\
+ \left( 1 + \xi_{13} \right) \frac{\delta_{h,12}^c}{n_2} \langle g \rangle + \left( 1 + \xi_{12} \right) \frac{\delta_{h,13}^c}{n_3} \langle g \rangle + \left( 1 + \xi_{14} \right) \frac{\delta_{h,14}^c}{n_4} \langle g \rangle \\
+ \left( 1 + \xi_{12} \right) \frac{\delta_{h,23}^c}{n_3} \langle g \rangle + \left( 1 + \xi_{13} \right) \frac{\delta_{h,24}^c}{n_4} \langle g \rangle + \left( 1 + \xi_{14} \right) \frac{\delta_{h,34}^c}{n_4} \langle g \rangle \\
+ \left( 1 + \xi_{23} \right) \frac{\delta_{h,24}^c}{n_4} \langle g \rangle + \left( 1 + \xi_{24} \right) \frac{\delta_{h,34}^c}{n_4} \langle g \rangle + \left( 1 + \xi_{34} \right) \frac{\delta_{h,12}^c}{n_4} \langle g \rangle + \left( 1 + \xi_{13} \right) \frac{\delta_{h,24}^c}{n_4} \langle g \rangle \\
+ \left( 1 + \xi_{14} \right) \frac{\delta_{h,34}^c}{n_4} \langle g \rangle \right\}.
\]

Collecting the terms \( L_1, L_2 \) and \( L_3 \) along with \( \langle n_{g,1} n_{g,2} n_{s,3} n_{s,4} \rangle \) and \( \langle n_{s,1} n_{s,2} n_{s,3} n_{s,4} \rangle \) and inserting them into Eq. (C3), and after some algebra we arrive at the following arrangement:

\[
\langle F_{g,1} \cdots F_{g,4} \rangle = \frac{1}{\mathcal{A}^2} \prod_{i=1}^{4} \left\{ \int dL_i d^3x_i dM_i \bar{n}_i w_i \right\} \left\{ \langle \eta_{1234} \rangle + \left[ \xi_{12}^c + \frac{\left( 1 + \alpha \right)}{n_2} \delta_{h,12}^c \right] \langle \xi_{34}^c + \frac{\left( 1 + \alpha \right)}{n_4} \delta_{h,34}^c \rangle \langle g \rangle \\
+ \left[ \xi_{13} + \frac{\left( 1 + \alpha \right)}{n_3} \delta_{h,13}^c \right] \left[ \xi_{24} + \frac{\left( 1 + \alpha \right)}{n_4} \delta_{h,24}^c \right] \langle g \rangle + \left[ \xi_{14} + \frac{\left( 1 + \alpha \right)}{n_4} \delta_{h,14}^c \right] \left[ \xi_{23} + \frac{\left( 1 + \alpha \right)}{n_3} \delta_{h,23}^c \right] \langle g \rangle \\
+ \xi_{13} \frac{\delta_{h,12}^c}{n_2} \langle g \rangle + \frac{\delta_{h,13}^c}{n_3} \langle g \rangle + \xi_{12} \frac{\delta_{h,14}^c}{n_4} \langle g \rangle + \xi_{14} \frac{\delta_{h,24}^c}{n_4} \langle g \rangle + \xi_{13} \frac{\delta_{h,14}^c}{n_4} \langle g \rangle + \xi_{12} \frac{\delta_{h,13}^c}{n_3} \langle g \rangle \\
+ \xi_{12} \frac{\delta_{h,23}^c}{n_4} \langle g \rangle + \xi_{13} \frac{\delta_{h,24}^c}{n_4} \langle g \rangle + \frac{\left( 1 + \alpha \right)}{n_2} \delta_{h,12}^c \langle g \rangle + \frac{\left( 1 + \alpha \right)}{n_3} \delta_{h,13}^c \langle g \rangle \right\},
\]

where in the above we used the short-hand notation \( F_{g,i} \equiv F_g(r_i) \). In order to compute the covariance we also require the second term in Eq. (C2). On repeatedly using Eq. (27) we find that this can be written:

\[
\langle F_{g,1} F_{g,3} \rangle \langle F_{g,2} F_{g,4} \rangle = \prod_{i=1}^{4} \left\{ \int dL_i d^3x_i dM_i \bar{n}_i w_i \right\} \left\{ \langle \xi_{13}^c \rangle + \frac{\left( 1 + \alpha \right)}{n_3} \delta_{h,13}^c \right\} \left\{ \langle \xi_{24}^c \rangle + \frac{\left( 1 + \alpha \right)}{n_4} \delta_{h,24}^c \right\} \langle g \rangle.
Joining the last two equations, we write the covariance as:

\[
\langle F_g(r_1)F_g(r_2)F_g(r_3)F_g(r_4) \rangle - \langle F_g(r_1)F_g(r_3) \rangle \langle F_g(r_2)F_g(r_4) \rangle = \frac{1}{A^2} \prod_{i=1}^{4} \left\{ \int dL_i d^3x_i dM_i \bar{n}_i w_i \right\} \left\{ \eta_{1234} \langle g \rangle + \right. \\
+ \left[ \xi_{12} + \frac{(1 + \alpha) \delta_{h12}}{\bar{n}_2} \right] \left[ \xi_{34} + \frac{(1 + \alpha) \delta_{h34}}{\bar{n}_4} \right] \langle g \rangle + \left[ \xi_{23} + \frac{(1 + \alpha) \delta_{h23}}{\bar{n}_3} \right] \langle g \rangle + \xi_{14} \frac{\delta_{h12}}{\bar{n}_2} \langle g \rangle \right. \\
+ \left[ \xi_{12} + \frac{\delta_{h14}^{D}}{\bar{n}_4} \right] \langle g \rangle + \left[ \xi_{34} + \frac{\delta_{h34}^{D}}{\bar{n}_4} \right] \langle g \rangle + \left[ \xi_{23} + \frac{\delta_{h23}^{D}}{\bar{n}_3} \right] \langle g \rangle + \xi_{14} \frac{\delta_{h14}^{D}}{\bar{n}_4} \langle g \rangle \left. \right\} 
\]

We now make the assumption that the fluctuations are close to Gaussian, hence we take \( \eta = \zeta = 0 \).

\[
\langle F_g(r_1)F_g(r_2)F_g(r_3)F_g(r_4) \rangle - \langle F_g(r_1)F_g(r_3) \rangle \langle F_g(r_2)F_g(r_4) \rangle = \frac{1}{A^2} \prod_{i=1}^{4} \left\{ \int dL_i d^3x_i dM_i \bar{n}_i w_i \right\} \left\{ \frac{(1 + \alpha^3)\delta_{h12}^{D} \delta_{h13}^{D} \delta_{h14}^{D}}{\bar{n}_2 \bar{n}_3 \bar{n}_4} \langle g \rangle + \right. \\
\left[ \xi_{12} + \frac{(1 + \alpha) \delta_{h12}}{\bar{n}_2} \right] \left[ \xi_{34} + \frac{(1 + \alpha) \delta_{h34}}{\bar{n}_4} \right] \langle g \rangle + \left[ \xi_{23} + \frac{(1 + \alpha) \delta_{h23}}{\bar{n}_3} \right] \langle g \rangle + \xi_{14} \frac{\delta_{h12}^{D}}{\bar{n}_2} \langle g \rangle \left. \right\} 
\]

On taking the limit that \( \bar{n}_g V_p \gg 1 \), the first and last three terms will be sub-dominant [59]. Using the linear bias model from Eq. (A.8), we write

\[
\langle F_g(r_1)F_g(r_2)F_g(r_3)F_g(r_4) \rangle - \langle F_g(r_1)F_g(r_3) \rangle \langle F_g(r_2)F_g(r_4) \rangle = \frac{1}{A^2} \prod_{i=1}^{4} \left\{ \int dL_i d^3x_i dM_i \bar{n}_i w_i \right\} \\
\times \left\{ \left[ b_1 b_2 \xi_{12} + \frac{(1 + \alpha) \delta_{h12}^{D}}{\bar{n}_2} \right] \left[ b_3 b_4 \xi_{34} + \frac{(1 + \alpha) \delta_{h34}^{D}}{\bar{n}_4} \right] \langle g \rangle + \left[ b_1 b_4 \xi_{14} + \frac{(1 + \alpha) \delta_{h14}^{D}}{\bar{n}_4} \right] \left[ b_2 b_3 \xi_{23} + \frac{(1 + \alpha) \delta_{h23}^{D}}{\bar{n}_3} \right] \langle g \rangle \right\}; \quad (C15)
\]

2. Averaging over the galaxy distributions

Let us now return to the evaluation of the expectation values for the galaxy population. Consider again Eq. (C15) and let us look in particular at the terms \( \langle g \rangle \) and any premultiplying Dirac delta functions. For compactness, we shall use the following definition:

\[
f(p|q) = \theta(r_p|L_p) \Phi(L_p|M_p)U(r_p - x_q|M_q) \quad (C16)
\]

We find that there are three types of terms forming the individual \( \langle g \rangle \) factors:

\[
\langle g \rangle \rightarrow \prod_{p=1}^{4} \left\{ \left( N_{g,p}^{(1)} f(p|p) \right) \right\}; \\
\delta_{h,14}^{D} \langle g \rangle \rightarrow \prod_{p=1}^{3} \left\{ \left( N_{g,p}^{(1)} f(p|p) \right) \left[ \frac{N_{p,1}^{(1)}}{N_{g,1}^{(1)}} f(4|1) + \delta_{h,14}^{D} \right] \delta_{h,14}^{D} \right\}; \\
\delta_{h,12}^{D} \delta_{h,34}^{D} \langle g \rangle \rightarrow \prod_{p \in \{1,3\}} \left\{ \left( N_{g,p}^{(1)} f(p|p) \right) \left[ \frac{N_{p,1}^{(1)}}{N_{g,1}^{(1)}} f(2|1) + \delta_{h,12}^{D} \right] \left[ \frac{N_{p,3}^{(1)}}{N_{g,3}^{(1)}} f(4|3) + \delta_{h,34}^{D} \right] \delta_{h,12}^{D} \delta_{h,34}^{D} \right\}. \quad (C17)
\]

The rest of the \( \langle g \rangle \) factors can be worked out in a similar way. Embedding them into Eq. (C15), and using Eqs. (C1) and (C2), we arrive at the expression for the covariance of the power spectrum estimator in the Gaussian approxima-
where \( \tilde{\alpha} \) to the scale over which the power spectrum varies, one can factor the latter out of the integrals in Eq. (50), writing:

\[
U |F_g|^2 P(q) G_{(1,1)}(k_1, q) G_{(1,1)}(k_2, -q) + (1 + \alpha) \left[ G_{(2,0)}(k_1 + k_2, 0) + G(k_1, k_2) \right] \]

\[
+ \left| \int \frac{d^3q}{(2\pi)^3} P(q) G_{(1,1)}(k_1, q) G_{(1,1)}(-k_2, -q) + (1 + \alpha) \left[ G_{(2,0)}(k_1 - k_2, 0) + G(k_1, -k_2) \right] \right|^2, \tag{C18}
\]

where we have defined two more functions:

\[
G_{(l,m)}(k, q) \equiv \int dM \tilde{n}(M) b^m(M) N_{g}^{(1)}(M) \tilde{W}_{l,m}^G(k, q, M);\]

\[
G(k_1, k_2) \equiv \int dM \tilde{n}(M) N_{g}^{(2)}(M) \int \frac{d^3q}{(2\pi)^3} \tilde{W}_{l,m}^G(k_1, q, M) \tilde{W}_{l,m}^G(k_2, -q, M). \tag{C19}
\]

3. The covariance matrix in the large-scale limit

In the large-scale limit, the profiles of the galaxies behave like Dirac delta functions, e.g., \( U(r - x|M) \rightarrow \delta^D(r - x) \). It is straightforward to show that in this limit the above-defined functions become:

\[
G_{(l,m)}(k, q) \rightarrow \tilde{g}_{(l,m)}^{(1)}(k + q); \quad G(k_1, k_2) \rightarrow \tilde{g}_{(1,0)}^{(2)}(k_1 + k_2),
\]

where \( \tilde{g}_{(l,m)}^{(n)} \) are the Fourier transforms of the functions defined by CITE later. With these changes, Eq. (C18) can be expressed as:

\[
\text{Cov} \left[ |\tilde{F}_g(k_1)|^2, |\tilde{F}_g(k_2)|^2 \right] = \left| \int \frac{d^3q}{(2\pi)^3} P(q) \tilde{g}_{(1,1)}^{(1)}(k_1 + q, k_2 - q) + (1 + \alpha) \left[ \tilde{g}_{(2,0)}^{(1)}(k_1 + k_2) + \tilde{g}_{(1,0)}^{(2)}(k_1 + k_2) \right] \right|^2
\]

\[
+ \left| \int \frac{d^3q}{(2\pi)^3} P(q) \tilde{g}_{(1,1)}^{(1)}(k_1 + q, -k_2 - q) + (1 + \alpha) \left[ \tilde{g}_{(2,0)}^{(1)}(k_1 - k_2) + \tilde{g}_{(1,0)}^{(2)}(k_1 - k_2) \right] \right|^2,
\]

which is exactly Eq. (47). This concludes our proof of it.

Appendix D: Shell averaging the covariance matrix of the \( \tilde{F}_g \) power spectrum

A reasonable approximation when computing the shell-averaged power, is that if the shells are narrow compared to the scale over which the power spectrum varies, one can factor the latter out of the integrals in Eq. (50), writing:

\[
\text{Cov} \left[ |\tilde{F}_g(k_i)|^2, |\tilde{F}_g(k_j)|^2 \right] = 2P^2(k_i) \int \frac{d^3k_i}{V_i} \int \frac{d^3k_j}{V_j} \tilde{g}_{(1,1)}^{(1)}(k_1 + k_2, -k_1 - k_2)
\]

\[
+ 4(1 + \alpha) P(k_i) \int \frac{d^3k_j}{V_j} \int \frac{d^3k_2}{V_j} \tilde{g}_{(1,1)}^{(1)}(k_1 + k_2, -k_1 - k_2)
\]

\[
+ 4(1 + \alpha) P(k_i) \int \frac{d^3k_j}{V_j} \int \frac{d^3k_2}{V_j} \tilde{g}_{(1,1)}^{(1)}(k_1 + k_2, -k_1 - k_2)
\]

\[
+ 4(1 + \alpha)^2 \int \frac{d^3k_i}{V_i} \int \frac{d^3k_2}{V_j} \tilde{g}_{(1,0)}^{(2)}(k_1 + k_2, -k_1 - k_2)
\]

\[
+ 2(1 + \alpha)^2 \int \frac{d^3k_i}{V_i} \int \frac{d^3k_2}{V_j} \tilde{g}_{(1,0)}^{(2)}(k_1 + k_2, -k_1 - k_2) \tag{D1}
\]
Our task now is to solve the integrals forming the terms of Eq. (D1). In general, these integrals have the form:

\[
\int_{V_i} \int_{V_j} \frac{d^3k_1}{V_i} \frac{d^3k_2}{V_j} \mathcal{Q}^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)} (k_1 + k_2) \mathcal{Q}^{(n'_1,n'_2)}_{(l'_1,l'_2|m'_1,m'_2)} (-k_1 - k_2) = \int_{V_i} \int_{V_j} \frac{d^3k_1}{V_i} \frac{d^3k_2}{V_j} \int d^3r_1 d^3r_2 \mathcal{Q}^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)} (r_1) \mathcal{Q}^{(n'_1,n'_2)}_{(l'_1,l'_2|m'_1,m'_2)} (r_2) \int \frac{d^3k_1}{V_i} e^{i\mathbf{k}_1 \cdot (r_1 - r_2)} \int \frac{d^3k_2}{V_j} e^{i\mathbf{k}_2 \cdot (r_1 - r_2)}
\]

\[
= \int d^3r_1 d^3r_2 \mathcal{Q}^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)} (r_1) \mathcal{Q}^{(n'_1,n'_2)}_{(l'_1,l'_2|m'_1,m'_2)} (r_2) \int \frac{d^3k_1}{V_i} e^{i\mathbf{k}_1 \cdot (r_1 - r_2)} \int \frac{d^3k_2}{V_j} e^{i\mathbf{k}_2 \cdot (r_1 - r_2)}
\]

\[
= \int d^3r_1 d^3r_2 \mathcal{Q}^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)} (r_1) \mathcal{Q}^{(n'_1,n'_2)}_{(l'_1,l'_2|m'_1,m'_2)} (r_2) \int \frac{d^3k_1}{V_i} e^{i\mathbf{k}_1 \cdot (r_1 - r_2)} \int \frac{d^3k_2}{V_j} e^{i\mathbf{k}_2 \cdot (r_1 - r_2)}
\]

\[
= \int d^3r_1 d^3r_2 \mathcal{Q}^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)} (r_1) \mathcal{Q}^{(n'_1,n'_2)}_{(l'_1,l'_2|m'_1,m'_2)} (r_2) \int \frac{d^3k_1}{V_i} e^{i\mathbf{k}_1 \cdot (r_1 - r_2)} \int \frac{d^3k_2}{V_j} e^{i\mathbf{k}_2 \cdot (r_1 - r_2)}
\]

\[
= \int d^3r_1 d^3r_2 \mathcal{Q}^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)} (r_1) \mathcal{Q}^{(n'_1,n'_2)}_{(l'_1,l'_2|m'_1,m'_2)} (r_2) \int \frac{d^3k_1}{V_i} e^{i\mathbf{k}_1 \cdot (r_1 - r_2)} \int \frac{d^3k_2}{V_j} e^{i\mathbf{k}_2 \cdot (r_1 - r_2)}
\]

(D2)

In the above, we have defined the shell-average of the spherical Bessel function as

\[
\overline{J}_0(k r) = \frac{1}{V_i} \int_{k_i - \Delta k/2}^{k_i + \Delta k/2} dk_k 4\pi \bar{J}_0(k r) \ .
\]

(D3)

To obtain the last line of Eq. (D2), we made a change of variables \( r_{21} = r_2 - r_1 \), and defined the correlation function of the weighted survey window function to be,

\[
\Sigma^{(n_1,n_2),(n'_1,n'_2)}_{(l_1,l_2|m_1,m_2),(l'_1,l'_2|m'_1,m'_2)} (r_{21}) = \int \frac{d^3r_{21}}{4\pi} \int d^3r_1 \mathcal{Q}^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)} (r_1) \mathcal{Q}^{(n'_1,n'_2)}_{(l'_1,l'_2|m'_1,m'_2)} (r_2 + r_1) \ .
\]

(D4)

In the limit that the survey volume is large, the weighted survey window correlation function is very slowly varying over nearly all length scales of interest, and so can be approximated by its value at zero-lag. Using the orthogonality relation of the Bessel functions, \( \int_0^\infty d\tau \tau^2 j_\alpha(\tau) j_\beta(\tau) = (\pi/2u^2) \delta^{\alpha\beta} \) we write:

\[
\int d^3k_1 \int d^3k_2 \frac{d^3r_{21}}{V_i} \frac{d^3r_1}{V_j} \mathcal{Q}^{(n_1,n_2)}_{(l_1,l_2|m_1,m_2)} (k_1 + k_2) \mathcal{Q}^{(n'_1,n'_2)}_{(l'_1,l'_2|m'_1,m'_2)} (-k_1 - k_2) \approx \frac{(2\pi)^3}{V_i} \Sigma^{(n_1,n_2),(n'_1,n'_2)}_{(l_1,l_2|m_1,m_2),(l'_1,l'_2|m'_1,m'_2)} (0) \delta^{K} \ .
\]

(D5)

We shall now apply this result to the six terms of Eq. (D1) and write for each of them:

\[
\Sigma^{(1,1),(1,1)}_{(1,1),(1,1),(1,1)} (0) = \int d^3r \left[ \mathcal{Q}^{(1,1)}_{(1,1),(1,1)} (r) \right]^2 = \int d^3r \left[ \mathcal{G}^{(1)}_{(1,1)} (r) \right]^2 \ ;
\]

\[
\Sigma^{(1,1),(2)}_{(1,1),(1,1),(1,0)} (0) = \int d^3r \mathcal{Q}^{(1,1)}_{(1,1),(1,1)} (r) \mathcal{Q}^{(2)}_{(1,0),(1,0)} (r) = \int d^3r \left[ \mathcal{G}^{(1)}_{(1,1)} (r) \right]^2 \mathcal{G}^{(2)}_{(1,0)} (r) \ ;
\]

\[
\Sigma^{(1,1)}_{(1,1),(1,1),(2,0)} (0) = \int d^3r \mathcal{Q}^{(1,1)}_{(1,1),(1,1)} (r) \mathcal{Q}^{(1)}_{(2,0),(2,0)} (r) = \int d^3r \left[ \mathcal{G}^{(1)}_{(1,1)} (r) \right]^2 \mathcal{G}^{(1)}_{(2,0)} (r) \ ;
\]

\[
\Sigma^{(2,1)}_{(1,0),(0),(2,0)} (0) = \int d^3r \mathcal{Q}^{(2)}_{(1,0),(1,0)} (r) \mathcal{Q}^{(1)}_{(2,0),(2,0)} (r) = \int d^3r \left[ \mathcal{G}^{(2)}_{(1,0)} (r) \right] \mathcal{G}^{(1)}_{(2,0)} (r) \ ;
\]

\[
\Sigma^{(2,2)}_{(1,0),(0),(2,0)} (0) = \int d^3r \left[ \mathcal{Q}^{(2)}_{(1,0),(1,0)} (r) \right]^2 = \int d^3r \left[ \mathcal{G}^{(2)}_{(1,0)} (r) \right]^2 \ ;
\]

\[
\Sigma^{(1,1)}_{(2,0),(2,0)} (0) = \int d^3r \left[ \mathcal{Q}^{(1)}_{(2,0),(2,0)} (r) \right]^2 = \int d^3r \left[ \mathcal{G}^{(1)}_{(2,0)} (r) \right]^2 \ .
\]

(D6)

(D7)

(D8)

(D9)

(D10)

(D11)

Finally, putting together all these terms we write our final expression for the shell-averaged covariance as:

\[
\text{Cov} \left[ \mathcal{F}_g (k_i), \mathcal{F}_g (k_j) \right] = \frac{2(2\pi)^3}{V_i} \overline{P}^2 (k_i) \delta^K \int d^3r \left[ \left[ \mathcal{G}^{(1)}_{(1,1)} (r) \right]^2 + \left[ \mathcal{G}^{(1)}_{(1,0)} (r) + \mathcal{G}^{(1)}_{(2,0)} (r) \right] \right]^2 \ .
\]

which is in fact Eq. (51) from the main text.

**Appendix E: Functional derivatives**

In order to compute the functional derivatives of \( N \) and \( D \) making up \( F[w] \), we must first work out the functional derivatives of the functions \( \mathcal{G} \) and the normalisation \( A \).
1. Functional derivatives of the $\mathcal{G}$ functions and normalisation $A$

For small variations in the path of $w$ we find that the functional derivative of $\mathcal{G}$ can be written:

$$
\mathcal{G}_{(1,1)}^{(1)}[w + \delta w] = \int dM \bar{n}(M)b(M)N_\tilde{g}^{(1)}(M)\int dL\Phi(L|M)\Theta(r|L)[w(r, L, M) + \delta w(r, L, M)] = \mathcal{G}_{(1,1)}^{(1)}[w] + \delta \mathcal{G}_{(1,1)}^{(1)}[w];
$$

(E1)

$$
\delta \mathcal{G}_{(1,1)}^{(1)}[w] = \int dM \bar{n}(M)b(M)N_\tilde{g}^{(1)}(M)\int dL\Phi(L|M)\Theta(r|L)\delta w(r, L, M);
$$

$$
\mathcal{G}_{(1,0)}^{(2)}[w + \delta w] = \int dM \bar{n}(M)N_\tilde{g}^{(2)}(M)\left\{\int dL\Phi(L|M)\Theta(r|L)[w(r, L, M) + \delta w(r, L, M)]\right\}^2 = \mathcal{G}_{(1,0)}^{(2)}[w] + \delta \mathcal{G}_{(1,0)}^{(2)}[w];
$$

(E2)

$$
\delta \mathcal{G}_{(1,0)}^{(2)}[w] = 2\int dM \bar{n}(M)N_\tilde{g}^{(2)}(M)\bar{W}_1(r, M)\int dL\Phi(L|M)\Theta(r|L)\delta w(r, L, M);
$$

(E3)

In the above we have neglected the terms containing $|\delta w|^n$ with $n \geq 2$, and we have used a similar definition to Eq. (58) and defined:

$$
\bar{W}_1(r, M) = A^{1/2}W_1(r, M).
$$

(E4)

Again, for small variations in the value of $w$, the functional derivative of the normalization constant $A$ can be written:

$$
A[w + \delta w] = \int d^3 r \left(\mathcal{G}_{(1,1)}^{(1)}[w + \delta w]\right)^2 = \int d^3 r \left(\mathcal{G}_{(1,1)}^{(1)}[w] + \delta \mathcal{G}_{(1,1)}^{(1)}[w]\right)^2 = \int d^3 r \left[\mathcal{G}_{(1,1)}^{(1)}(r)\right]^2 + 2\int d^3 r \mathcal{G}_{(1,1)}^{(1)}(r)\delta \mathcal{G}_{(1,1)}^{(1)}[w] = A[w] + \delta A[w],
$$

$$
\delta A[w] = 2\int d^3 r \mathcal{G}_{(1,1)}^{(1)}(r)\int dM \bar{n}(M)b(M)N_\tilde{g}^{(1)}(M)\int dL\Phi(L|M)\Theta(r|L)\delta w(r, L, M).
$$

(E5)

2. Functional derivative of $N[w(r, L, M)]$

Consider Eq. (56), we may write the functional derivative as:

$$
\delta N[w] = 2\int d^3 r \left\{\left[\mathcal{G}_{(1,1)}^{(1)}(r)\right]^2 + c\left[\mathcal{G}_{(1,0)}^{(2)}(r) + \mathcal{G}_{(2,0)}^{(1)}(r)\right]\right\}\left\{2\mathcal{G}_{(1,1)}^{(1)}(r)\delta \mathcal{G}_{(1,1)}^{(1)}[w] + c\left[\delta \mathcal{G}_{(1,0)}^{(2)}[w] + \delta \mathcal{G}_{(2,0)}^{(1)}[w]\right]\right\}.
$$

Using the functional derivatives of Eqs. (E1), (E2), (E3) to calculate the terms in the parenthesis on the right-hand side, we obtain the functional derivative of the numerator $N$:

$$
\delta N[w] = 4\int d^3 r dM dL \left\{\left[\mathcal{G}_{(1,1)}^{(1)}(r)\right]^2 + c\left[\mathcal{G}_{(1,0)}^{(2)}(r) + \mathcal{G}_{(2,0)}^{(1)}(r)\right]\right\}\bar{n}(M)N_\tilde{g}^{(1)}(M)\Phi(L|M)\Theta(r|L)
$$

$$
\times \left[\mathcal{G}_{(1,1)}^{(1)}(r)b(M) + \bar{W}_1(r, M)N_\tilde{g}^{(2)}(M)/N_\tilde{g}^{(1)}(M) + w(r, L, M)\right] \delta w(r, L, M).
$$

(E6)

3. Functional derivative of $D[w(r, L, M)]$

Since $D = A^2$, we have $\delta D[w] = 2A[w]\delta A[w]$. Using the functional derivative in Eq. (E5), the functional derivative of $D[w]$ is given by:

$$
\delta D[w] = 4A[w] \int d^3 r dM dL \left\{\mathcal{G}_{(1,1)}^{(1)}(r)\bar{n}(M)b(M)N_\tilde{g}^{(1)}(M)\Phi(L|M)\Theta(r|L)\right\} \delta w(r, L, M).
$$

(E7)