Large Deviations of a Network of Neurons with Dynamic Sparse Random Connections

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Abstract
In this work we determine the limiting dynamics of a system of interacting particles indexed by a lattice $\mathbb{Z}^d$. The connections are random, sparse and unscaled, so that the system converges in the large size limit due to the probability of a connection between any two particles decreasing as the system size increases. The particles are also subject to noise (such as independent Brownian Motions). The method of proof is to assume a process-level (or Level 3) LDP for the double-layer empirical measure for the noise and connections, and then apply a series of transformations to this to obtain an LDP for the process-level empirical measure of our system. Although it is not explicitly necessary, we expect that most applications of this work should involve an assumption of stationarity of the probability law for the noise and connections under translations of the lattice, so that the system converges to an ergodic probability law in the large size limit. This work synthesizes the theory of large-size limits of interacting particles with that of random graphs and matrices. It should therefore be relevant to neuroscience and social networks theory in particular.

1 Introduction
In this paper we determine a Large Deviation Principle for an asymptotically large system of interacting processes on a lattice with sparse random connections. We are motivated in particular by the study of interacting neurons in neuroscience [9], but this work ought to be adaptable to other phenomena such as mathematical finance, social networks, population genetics or insect swarms [36, 1].

Classical mean-field models are perhaps the most common method used to scale up from the level of individual particles to the level of populations [7, 2].

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For a group of neurons indexed from 1 to $N$, the evolution equation of a mean field model is typically of the following form (an $\mathbb{R}^N$-valued SDE)

$$
\frac{dX^j_t}{dt} = \left[ g(X^j_t) + \frac{1}{N} \sum_{k=1}^{N} h_t(X^j_t, X^k_t) \right] dt + \sigma(X^j_t) dW^j_t.
$$

(1)

We set $X^j_0 = 0$. Here $g$ is Lipschitz, $h$ is Lipschitz and bounded, and $\sigma$ is Lipschitz. $(W^j)_{j \in \mathbb{N}}$ are independent Brownian Motions representing internal / external noise. Asymptoting the number of particles $N$ to $\infty$, we find that in the limit $X^j$ is independent of $X^k$ (for $j \neq k$), and each $X^j$ is governed by the same law [39]. Since the $(X^j)_{j \in \mathbb{N}}$ become more and more independent, it is meaningful to talk of their mean as being representative of the group as a whole. In reaching this limit, three crucial assumptions have been made: that the external noise is uncorrelated, that the connections between the particles are homogeneous and that the connections are scaled by the inverse of the size of the system. We will relax each of these assumptions in our model (which is outlined in Section 2.1).

The major difference between the model in Section 2.1 and the mean field model outlined above is the model of the connections. In the mean field model, the network is completely connected, with a uniform connection strength of $N^{-1}$. In our work, the connections are sparse and random, and typically (although not necessarily) sampled from a spatially-stationary probability law (i.e. a law that is invariant under translations of the lattice). The system does not blow up as $N \to \infty$ because the probability of a connection between particles decreases as the lattice distance increases. One reason that the mean-field model in (1) converges as $N \to \infty$ is because the probability law is invariant under any permutation of the indices. By contrast, the system of this paper is only invariant under a translation of the lattice (with periodic boundary conditions), a much weaker assumption that can accommodate a richer diversity of emergent phenomena.

Our network has the structure of a sparse random graph with edges which are directed and weighted. In neuroscience and social network theory in particular, there is an enormous literature devoted to the study of complex networks [38, 36]. In the mathematics literature, the papers [16, 17, 12, 3] determine the limiting behavior for dynamics on Erdos-Renyi random graphs where the typical number of afferent edges on each node diverges with the system size. In the large $N$ limit, the behavior of such networks becomes analogous to the mean-field equations in (1). By contrast, in the model of this paper, as the network grows, the typical number of afferent edges per neuron does not diverge with $N$. In the model of this paper, the connection strength between any two vertices is random, such that the probability of a strong connection decreases as the lattice distance increases. Furthermore the connections are correlated, with the correlation between two connections dependent on the lattice distance between the heads and tails. We are able to obtain an understanding of the limiting behavior because the joint law of the dynamics and edges is invariant under a translation of the lattice. This means that instead of working with the
standard empirical measure, we must work with the ‘Level 3’ empirical process that understands correlations between different particles [22].

The main result of this paper is a Large Deviation Principle (LDP) for the interacting particle model in Section 2.1. A Large Deviation Principle is a very useful mathematical technique that allows us to estimate finite-size deviations of the system from its limit behaviour. There has been much effort in recent years to understand such finite-size phenomena in mathematical models of neural networks - see for instance [8, 11, 24]. More generally, there exists a well-developed literature on the Large Deviations and other asymptotics of weakly-interacting particle systems (see for example [4, 34, 14, 10, 15, 26, 6]). These are systems of \( N \) particles, each evolving stochastically, and usually only interacting via the empirical measure.

This paper is structured as follows. In Section 2 we outline a general model of interacting particles on a lattice with random connections, and state a large deviation principle under a set of assumptions. In Section 3 we outline an extended example of this theory which satisfies the assumptions of Section 2. This example considers a sparse network of Fitzhugh-Nagumo neurons, with Hebbian learning on the connections, and the probability of a connection between two neurons being given by a Gibbs distribution. The remaining sections are dedicated to the proof of the main result in Theorem 1. The proof essential demonstrates that the empirical process can be approximated arbitrarily well by a continuous filtering of the empirical process containing the connections and noise.

Notation:

If \( \mathcal{X} \) is some separable topological space, then we denote the \( \sigma \)-algebra generated by the open sets by \( \mathcal{B}(\mathcal{X}) \), and the set of all probability measures on \( (\mathcal{X}, \mathcal{B}(\mathcal{X})) \) by \( \mathcal{P}(\mathcal{X}) \). We always endow \( \mathcal{P}(\mathcal{X}) \) with the topology of weak convergence.

Elements of the processes in this paper are indexed by the lattice points \( \mathbb{Z}^d \); for \( j \in \mathbb{Z}^d \) we write \( j = (j(1), \ldots, j(d)) \). Let the particles be indexed by the set \( V_n \subset \mathbb{Z}^d \), which is such that \( j \in V_n \) if \( |j(m)| \leq n \) for all \( 1 \leq m \leq d \). The number of elements in \( V_n \) is written as \( |V_n| := (2n + 1)^d \).

Let \( |X| \) denote the Euclidean norm on \( \mathbb{R}^m \). For any \( s \in [0, T] \), we endow \( \mathcal{C}([0, s], \mathbb{R}^m) \) with the norm \( \|U\|_s := \sup_{\tau \in [0, s]} |U_\tau| \), and we write \( T := \mathcal{C}([0, T], \mathbb{R}^m) \). In the model outlined in the next section, the activity over time of each particle is a \( T \)-valued random variable. The state space for the connections between the particles is taken to be a complete separable metric space \( \mathcal{E} \), with metric \( d_\mathcal{E}(\cdot, \cdot) \). Let \( \pi^{V_n} : T^{\mathbb{Z}^d} \to T^{V_n} \) be the projection \( \pi^{V_n}(X) := (X_j)_{j \in V_n} \). We endow \( T^{\mathbb{Z}^d} \) with the cylindrical topology (generated by sets \( O \subset T^{\mathbb{Z}^d} \) such that \( \pi^{V_n} O \) is open in \( T^{V_n} \)). Let \( d^P \) be the Levy-Prokhorov metric on \( \mathcal{P}(T^{V_n}) \) generated by the norm \( \|x\|_{T,m} := \sum_{j \in V_n} \|x_j\|_T \) on \( T^{V_n} \). The following metric on \( \mathcal{P}(T^{\mathbb{Z}^d}) \) metrizes weak convergence,

\[
d^P(\mu, \nu) := \sum_{j=1}^{\infty} \min \left( 2^{-j}, d^P(\pi^\mathbb{Z}^d_j \mu, \pi^\mathbb{Z}^d_j \nu) \right),
\]

(2)
where \( \pi_{ij}^{TV} \) is the projection onto the marginal in \( \mathcal{P}(TV_j) \). Thanks to the Komolgorov Extension Theorem, \( dP \) is complete (i.e. each Cauchy Sequence converges to a unique limit), since each \( dP_j \) is complete over \( \mathcal{P}(TV_j) \) [5].

It may be noted that many papers on the convergence of networks of interacting particles use the Wasserstein Metric rather than the above Levy Prokhorov metric. However the implementation of the Wasserstein metric is complicated by the fact that the map \( \Psi^n \) (which maps the noise and connections to the solution and is defined in (20)) is not continuous with respect to the cylindrical topology. This is why we use the Levy-Prokhorov metric in this paper.

2 Outline of Model and Preliminary Definitions

In this section we outline our finite model of \((2n + 1)^d \) stationary interacting particles indexed over the cube \( V_n \). In Subsection 2.2 we outline our assumptions on the model. The main result of this paper is stated in Theorem 1.

2.1 Outline of Model and Main Result

For \( n \in \mathbb{Z}^+ \), there are \( |V_n| \) particles in our network. The joint probability law (of both the dynamics and the connections) is assumed to be invariant under a translation of the lattice (assuming periodic boundary conditions). There are three components to the dynamics of our network: the internal dynamics term \( b \), the interaction term \( \Lambda^k(J^{n,j,k}, U_j, U^{(j+k)} \mod V_n) \) and the noise term \( W^{n,j} \).

The form of our interaction term differs from standard mean-field models in that it is not scaled by some function of the network size \( |V_n| \), and it is not homogeneous throughout the network. It depends also on the random connection \( J^{n,j,k} \) between the particles at nodes \( j \) and \((j + k) \mod V_n \) (here \( k \in V_n \) is the vector distance between the two particles relative to the toroidal topology). \( J^{n,j,k} \) are correlated random variables taking values in \( \mathcal{E} := \{0, 1\} \).

We assume that \( W^n := (W^{n,j})_{j \in V_n, t \in [0,T]} \) is a \( TV_n \)-valued random variable (such as, but not necessarily, independent Brownian motions). The system we study in this paper is governed by the following evolution equation: for \( j \in V_n \) and \( t \in [0,T] \),

\[
U^j_t = \int_0^t \left( b(U^j_s) + \sum_{k \in V_n} \Lambda^k_s(J^{n,j,k}, U^j_s, U^{(j+k)} \mod V_n) \right) ds + W^{n,j}_t. \tag{3}
\]

Here \((j + k) \mod V_n := l \in V_n \), such that \((j(p) + k(p)) \mod (2n + 1) = l(p) \) for all \( 1 \leq p \leq d \). Thus one may think of the particles as existing on a \( d \)-dimensional torus. It is noted in Lemma 3 that there exists a unique solution to (3) for every \( W^n \in TV_n \). The thrust of this article is to understand the asymptotic behaviour of the network as \( n \to \infty \).

Because the probability of a connection decreases with lattice distance, the network is very sparse. This means that the standard empirical measure in \( \mathcal{P}(C([0,T], \mathbb{R}^m)) \) is not the appropriate object to capture the emergent behavior.
Rather, because the system is invariant under a translation of the lattice, the process-level empirical measure \( \hat{\mu}_n \) is a more appropriate limiting object. This is a reduced macroscopic variable commonly used in statistical mechanics \(^{22}\). Let

\[
S^k : \mathcal{T}^d \to \mathcal{T}^d
\]

(for some \( k \in \mathbb{Z}^d \)) be the shift operator (i.e. \( (S^k x)^m := x^{m+k} \)). Let \( \mathcal{P}_S(\mathcal{T}^d) \) be the set of all stationary probability measures, i.e. such that for all \( k \in \mathbb{Z}^d \),

\[
\mu \circ (S^k)^{-1} = \mu.
\]

Denote the empirical measure \( \hat{\mu}_n : \mathcal{T}^d \to \mathcal{P}_S(\mathcal{T}^d) \) by

\[
\hat{\mu}_n(X) := \frac{1}{|V_n|} \sum_{j \in V_n} \delta_{S^j X},
\]

where \( \hat{X} \in \mathcal{T}^d \) is the \( V_n \)-periodic interpolant, i.e. \( \hat{X}^j := \hat{X}^j \mod V_n \). If \( X \in \mathcal{T}^d \), then in a slight abuse of notation we write \( \hat{\mu}_n(X) := \hat{\mu}_n(\pi_{V_n} X) \).

We now outline the main result of this paper.

**Theorem 1** Let the law of \( \hat{\mu}_n(U) \) be \( \Pi_n \in \mathcal{P}(\mathcal{P}_S(\mathcal{T}^d)) \). Under the assumptions outlined in Section 2.2, \( (\Pi_n)_{n \in \mathbb{Z}^+} \) satisfy a Large Deviation Principle with good rate function \( I \) (i.e. \( I \) has compact level sets). That is, for all closed subsets \( A \) of \( \mathcal{P}_S(\mathcal{T}^d) \),

\[
\lim_{n \to \infty} \frac{1}{|V_n|} \log \Pi_n(A) \leq - \inf_{\gamma \in A} I(\gamma). 
\]

(5)

For all open subsets \( O \) of \( \mathcal{P}_S(\mathcal{T}^d) \),

\[
\lim_{n \to \infty} \frac{1}{|V_n|} \log \Pi_n(O) \geq - \inf_{\gamma \in O} I(\gamma).
\]

(6)

The rate function is

\[
I(\mu) := \inf_{\nu \in \mathcal{P}_S(\mathcal{T}^d)} \left\{ I_Y(\nu) : \Psi(\nu) = \mu \right\},
\]

where \( \mathcal{P}_S(\mathcal{T}^d) \) is defined in \(^9\), \( \Psi : \mathcal{P}_S(\mathcal{T}^d) \to \mathcal{P}_S(\mathcal{T}^d) \) is defined in \(^{19,22,23}\) and \( I_Y \) is defined in Assumption 4.

From now on, if a sequence of probability laws satisfies (5) and (6) for some \( I \) with compact level sets, then to economise space we say that it satisfies an LDP with a good rate function \( I \). Theorem 1 is useful because it allows us to understand the asymptotic behaviour of averages over the entire network, as is noted in the following corollary.

**Corollary 2** Suppose that there is a unique \( \mu_Y \in \mathcal{P}_S(\mathcal{T}^d) \) such that \( I_Y(\mu_Y) = 0 \) (see Assumption 4 for the definitions of these terms). For some positive integer \( q \), let \( g : \mathcal{T}^d \to \mathbb{R} \) be continuous and bounded. Then, writing \( H_n = \frac{1}{|V_n|} \sum_{j \in V_n} g(S^j U) \),

\[
\lim_{n \to \infty} H_n = \mathbb{E}^{\Psi(\mu_Y)}[g], \quad \mathbb{P}\text{-almost-surely.}
\]
2.2 Assumptions

We employ the following assumptions.

In many interacting particle models, such as the Fitzhugh-Nagumo model in Section 3, the internal dynamics term $b$ is not Lipschitz. In particular, $b$ is usually strongly decaying when the activity is greatly elevated, so that $b$ always acts to restore the particle to its resting state. This decay is necessary in order for the neurons to exhibit their characteristic ‘spiking’ behaviour. The following assumptions can accommodate this non-Lipschitz behaviour.

**Assumption 1** The following one-sided growth and Lipschitz conditions are assumed. It is assumed that there exists a positive constant $C$ such that for all $z, y \in \mathbb{R}^m$, and all $1 \leq p \leq m$, writing $b = (b_1, \ldots, b_m)$,

$$
\begin{align*}
    b_p(z) &\leq C|z| \\
    -b_p(z) &\leq C|z| \\
    b_p(z) - b_p(y) &\leq C|z - y| \\
    b_p(y) - b_p(z) &\leq C|z - y|.
\end{align*}
$$

This paper is primarily intended to model sparse networks. The system converges, not because there are $O(|V_n|)$ connections which decrease in magnitude either uniformly as the network grows (as in mean-field models) or as the lattice distance increases (as in [26]), but rather because the probability of there being a connection between two particles decreases as the lattice distance increases. We are primarily concerned with models where, if there is a connection between two particles, then it is strong, even if they are a long way apart on the lattice. The interactions $\Lambda^k_s(\cdot, \cdot, \cdot)$ in many of the networks that we want to study are typically nonlinear. See for example the model of the interactions in [2], and also the example model in Section 3.

**Assumption 2** We assume that if there is no connection, the interaction is identically $0$, i.e.

$$\Lambda^k_s(0, \cdot, \cdot) = 0. \quad (7)$$

Assume that for all $k \in \mathbb{Z}^d$, $\Lambda^k_s(\cdot, \cdot, \cdot)$ is continuous on $[0, T] \times E \times T \times T$, and for each $s \in [0, T]$, $\Lambda^k_s$ is $\mathcal{B}(\mathbb{R})/\mathcal{B}(\mathcal{C}([0, s], \mathbb{R})) \times \mathcal{B}(\mathcal{C}([0, s], \mathbb{R}))$-measurable. For all $x, y \in E$, $t \in [0, T]$, $U, X, Z \in T$ and $k \in \mathbb{Z}^d$

$$
\begin{align*}
    |\Lambda^k_t(x, U, X) - \Lambda^k_t(x, U, Z)| &\leq \|X - Z\|_t, \\
    |\Lambda^k_t(x, U, X) - \Lambda^k_t(x, Z, X)| &\leq \|U - Z\|_t, \\
    |\Lambda^k_t(x, U, X) - \Lambda^k_t(y, U, X)| &\leq \big(\|U\|_t + \|X\|_t\big)|x - y|.
\end{align*}
$$

We also assume that

$$|\Lambda^k_t(x, X, Z)| \leq (1 + \|X\|_t). \quad (8)$$

Since, in contrast to the great majority of papers on interacting particles surveyed in the introduction, the magnitude of the interactions is independent of
the network size, the effect of the interactions grows rapidly as the entire system grows. The following bound ensures that the system does not blowup as the size scales to infinity.

**Assumption 3** We assume that there exist positive constants $a_1, a_2 > 0$, a constant $\rho > 1$ and a positive integer $m_0$ such that for all $m \geq m_0$,

$$
\mathbb{E}\left[ \exp\left( a_1 |V_m| 2^\rho + 2 \exp \left( (4 + 2\rho)TC_J |V_m| \right) \sum_{j \in V_n} \left( \sum_{k \notin V_m} |J_n^{j,k}| \right)^2 \right) \right] \\
\leq \exp \left( a_2 |V_n| \right)
$$

$$
\mathbb{E}\left[ \exp\left( a_1 |V_m| \rho + 1 \exp \left( (3 + \rho)TC_J |V_m| \right) \sum_{j \in V_n} \sum_{k \notin V_n} |J_n^{j,k}| \right) \right] \\
\leq \exp \left( a_2 |V_n| \right)
$$

The heart of the method in this paper is to recognize that the solution $U$ of (3) can be written as an ergodic transformation in an ambient higher-dimensional space $\tilde{T}^\mathbb{Z}^d$ containing both the noise and the connections. The Large Deviation Principle for $U$ can then be obtained from the (assumed) Large Deviation Principle of $W^n$ and $J^n$ using transformation methods, since the empirical measure for $U$ can be written as a function of the double layer empirical measure which incorporates both $W^n$ and $J^n$ (see Lemma 3).

We now define the ambient space $\tilde{T}^\mathbb{Z}^d$ containing both the connections and the disorder. Let $\tilde{T} = T \times \mathbb{E}^\mathbb{Z}^d$, with $\mathbb{E}^\mathbb{Z}^d$ endowed with the cylindrical topology and $\tilde{T}$ with the product topology. Note that $\tilde{T}$ is separable. For $l \in \mathbb{Z}^d$, let $S^l : \tilde{T}^\mathbb{Z}^d \to \tilde{T}^\mathbb{Z}^d$ be $(S^l)_{X^j} := X^{j+l}$. Let $\mathcal{P}(\tilde{T}^\mathbb{Z}^d)$ be the set of all stationary measures, i.e. such that $\mu \in \mathcal{P}(\tilde{T}^\mathbb{Z}^d)$ if and only if for all $k \in \mathbb{Z}^d$,

$$
\mu \circ (S^k)^{-1} = \mu. \quad (9)
$$

For $j \in V_n$ and $k \notin V_n$, let $J_n^{j,k} = 0$ (note that this doesn’t affect the dynamics in (3)). Let $\tilde{Y}^n$ be the $\tilde{T}^\mathbb{Z}^d$-valued random variable such that $\tilde{Y}^n_{p} := (W^{n,p} \mod V_n, J_n^{n,p} \mod V_n)_{k \in \mathbb{Z}^d}$. Let the law of

$$
\tilde{\mu}^n(\tilde{Y}^n) := \frac{1}{|V_n|} \sum_{k \in V_n} \delta_{S^k \tilde{Y}^n} \quad (10)
$$

be $\Pi_{\tilde{Y}} \in \mathcal{P}(\mathcal{P}(\tilde{T}^\mathbb{Z}^d))$. $\tilde{\mu}^n(\tilde{Y}^n)$ is sometimes known as the double-layer empirical measure, as it incorporates both the noise and the random environment [13].

**Assumption 4** The series of laws $(\Pi_{\tilde{Y}})_{n \in \mathbb{Z}^+}$ is assumed to satisfy a Large Deviation Principle with good rate function $I_{\tilde{Y}} : \mathcal{P}(\tilde{T}^\mathbb{Z}^d) \to \mathbb{R}^+$. In many proofs of level-3 Large Deviations results, one starts from an i.i.d process, and applies standard transformation methods (either an exponential
change of measure, as with LDPs for Gibbs distributions [32], or a moving average transformation [20, 25, 26]). If $W^n$ is independent of $J^n$, and the empirical measures of $\hat{\mu}^n(W^n)$ and $\hat{\mu}^n(J^n)$ each satisfy LDPs obtained through these transformations, then generally $\hat{\mu}^n(Y^n)$ will satisfy an LDP as well. An example of this is given in Section 3.

Assumption 5 It is assumed that there exist positive constants $\varepsilon_1, \varepsilon_2$ such that

$$\lim_{n \to \infty} \frac{1}{|V_n|} \log \mathbb{E} \left[ \exp \left( \varepsilon_1 \sum_{j \in V_n} \|W^{n,j}\|_T^2 \right) \right] \leq \exp \left( |V_n| \varepsilon_2 \right).$$

(11)

3 An Example Application: A Fitzhugh-Nagumo Neural Network with Gibbsian Random Connectivity and Learning

In this section we outline an example from neuroscience of a model satisfying (3) and the assumptions of Section 2.2. Most of these assumptions are satisfied relatively easily, and we therefore omit the proofs. Of course there are many other sorts of model which would fit the framework of this paper.

We take the internal dynamics to be that of the Fitzhugh-Nagumo model, the connection matrix to be random and Gibbsian, with the interaction terms driven by the firing rates of the pre and post synaptic neurons, and the connections evolving according to a learning rule. We take $d \in \{1, 2, 3\}$. For $j \in V_n$, the governing equations are

$$dv^j_t = dW^{n,j}_t + \left( \sum_{k \in V_n} G^k_t(J^{n,j,k}, v^j_t, v^{(j+k)}_t \mod V_n) \times f(v^j_t) f(v^{(j+k)}_t \mod V_n) + v^j_t - \frac{1}{3}(v^j_t)^3 - w^j_t \right) dt,$$

$$dw^j_t = (v^j_t + a - cw^j_t) dt.$$  

(12)

We take $v^j_0 = v^j_0 = 0$ as initial conditions. Here $a$ and $c$ are positive constants, and $f$ is bounded and Lipschitz. The internal dynamics of the above equation is that of the famous Fitzhugh-Nagumo model [28, 35, 29, 30]. This model distills the essential mathematical features of the Hodgkin-Huxley model, yielding excitation and transmission properties from the analysis of the biophysics of sodium and potassium flows. The variable $v$ is the ‘fast’ variable which corresponds approximately to the voltage, and $w$ is the ‘slow’ recovery variable which is dominant after the generation of an action potential.

We take the independent inputs to be uncorrelated Ornstein-Uhlenbeck Processes $\{W^{n,j}_t\}_{j \in V_n}$. It has been proved in [26, Lemma 17] that Assumption 5 is satisfied.
3.1 Model of Interactions

The interaction term is a simplification of the chemical synapse models in [19, 23]. It is assumed that the existence of a connection between neurons \( j \) and \( k \) is random and determined by the random variable \( J_{n,j,k} \in \{0, 1\} \). The model of \( J_{n,j,k} \) is outlined in the following section. In the formalism of the previous section, \( \mathcal{E} = \{0, 1\} \), with \( 0 = 0 \). Letting \( \bar{J} \) be the maximal connection strength (so that \( C_J = \bar{J} \) in Assumption 2), we define \( d_{\mathcal{E}}(0, 1) = \bar{J} \) and \( d_{\mathcal{E}}(0, 0) = d_{\mathcal{E}}(1, 1) = 0 \). We specify that

\[
G_{k0}(0, \cdot, \cdot) = 0.
\]

Otherwise, we take \( G_{k}^1(1, \cdot, \cdot) \) to evolve according to the following learning rule.

We use the following classical Hebbian Learning model (refer to [33] for a more detailed description, and in particular equation 10.6) to specify \( G_{k} \).

The ‘activity’ of neuron \( j \) at time \( t \) is given as \( v(U_jt) \). Here \( v: \mathbb{C} \rightarrow \mathbb{C} \) is Lipschitz continuous, positive and bounded. The evolution equation is defined to be, for \( X, Y \in \mathcal{T} \),

\[
\frac{d}{dt} G_{k}^1(1, X, Y) = J^{corr} (\bar{J} - G_{k}^1(1, X, Y)) v(X_t)v(Y_t) - J^{dec} G_{k}^1(1, X, Y).
\]  

(14)

Here \( J^{corr}, J^{dec}, \bar{J} \) are non-negative constants (if we let them be zero then we obtain weights which are constant in time). Initially, if \( J_{n,j,k} \neq 0 \), we stipulate that

\[
G_{k0}^1(1, X, Y) := G_{ini}
\]

(15)

where \( G_{ini} \in [0, \bar{J}] \) is a constant stipulating the initial strength of the weights. It is straightforward to show that there is a unique solution to the above differential equation for all \( X, Y \in \mathcal{C}([0, T], \mathbb{R}^2) \). One may show that \( G_{k}^1(1, \cdot, \cdot) \leq \bar{J} \). In effect, the solution defines \( G_{k}^1(1, \cdot, \cdot) \) as a function \( \mathcal{C}([0, t], \mathbb{R}) \times \mathcal{C}([0, t], \mathbb{R}) \rightarrow \mathbb{R} \), which can be shown to be uniformly Lipschitz in both of its variables, where \( \mathcal{C}([0, t], \mathbb{R}) \) is endowed with the supremum norm.

The random connections \( J_{n,j,k} \) are assumed to be identically zero once \( |k-j| \) (modulo the torus) exceeds some threshold.

4 Proof of Theorem 1

We obtain the LDP for \( (\Pi^n)_{n \in \mathbb{Z}^+} \) by applying a series of transformations to the LDP for \( (\Pi^y)_{n \in \mathbb{Z}^+} \) (which is assumed in Assumption 4). The proof of our main result in Theorem 1 is outlined just below. The rest of the document consists of lemmas auxiliary to this proof.

We must first define a metric on the space \( \mathcal{P}(\mathcal{T}^d) \), which, as noted in the previous section, is the space in which the double layer empirical measure \( \hat{\mu}^n(J^m) \) lives. Recalling that \( V_q := \{(j,k) \in \mathbb{Z}^d: j,k \in V_q \} \) and \( \mathcal{T}^{V_q} := \{(Y^j, \omega^{j,k})_{(j,k) \in V_q} | Y^j \in \mathcal{T} \text{ and } \omega^{j,k} \in \mathcal{E} \} \), let \( d_{\mathcal{P}}^q \) be the Levy-Prokhorov metric.
on $\mathcal{P}(\mathcal{T}^d)$ generated by the following metric on $\mathcal{T}^d$,
\begin{equation}
\tilde{d}_g(\mathcal{V}, Z) := \sum_{j \in V_q} \| R^j - X^j \|_T + \left( \sum_{j, k \in V_q} d_g(\omega^{j,k}, \beta^{j,k})^2 \right)^{\frac{1}{2}} ,
\end{equation}
where $\mathcal{V} := (R^j, \omega^{j,k})_{j, k \in V_q}$, $Z := (X^j, \beta^{j,k})_{j, k \in V_q}$. Let $\pi^P_T : \mathcal{P}(\mathcal{T}^d) \to \mathcal{P}(\mathcal{T}^d)$ be the projection onto the marginal measure over $\mathcal{T}^d$ and define $\tilde{d}^P$ be the following complete metric on $\mathcal{P}(\mathcal{T}^d)$ (which metrizes weak convergence with respect to the cylindrical topology),
\begin{equation}
\tilde{d}^P(\mu, \nu) = \sum_{j=1}^\infty \min \left( 2^{-j}, \tilde{d}_j^P(\pi^P_T \mu, \pi^P_T \nu) \right). \tag{17}
\end{equation}

**Proof:** [Proof of Theorem 1]

For $c \in \mathbb{R}^+$, recalling the definition of $\mathcal{P}_S(\mathcal{T}^d)$ in (9), let
\begin{equation}
\mathcal{A}_c = \left\{ \mu \in \mathcal{P}_S(\mathcal{T}^d) \left| E^\mu \left[ \|X^0\|_T^2 \right] \leq c \text{ and for all } m \geq m_0 \right. \right\}
\end{equation}
where $m_0$ and $\rho$ are defined in Assumption 3. It may be observed that $\mathcal{A}_c$ is a closed subset of $\mathcal{P}_S(\mathcal{T}^d)$.

We now define maps $\Psi, \Psi^m : \mathcal{T}^d \to \mathcal{T}^d$. These are used to transform the LDP for $(\Pi^n)_{n \in \mathbb{Z}^+}$ into an LDP for $(\Pi^n)_{n \in \mathbb{Z}^+}$. Using the above definitions, for $Z \in \mathcal{T}^{d^+}$, with $Z^j := (R^j, (\omega^{j,k})_{k \in \mathbb{Z}^d})$, we define $\Psi(Z) := X$ to be such that for any $t \in [0, T]$ and $j \in \mathbb{Z}^d$,
\begin{equation}
X^j_t := \int_0^t \left( b(X^j_s) + \sum_{k \in \mathbb{Z}^d} \Lambda^k_s(\omega^{j,k}, X^j, X^{j+k}) \right) ds + R^j_t. \tag{19}
\end{equation}

Define $\Psi^m : \mathcal{T}^{d^d} \to \mathcal{T}^{d^d}$ to be $\Psi^m(Z) := Z$, where $Z$ satisfies
\begin{equation}
Z^j_t := \int_0^t \left( b(Z^j_s) + \sum_{k \in \mathbb{Z}^d} \Lambda^k_s(\omega^{j,k}, Z^j, Z^{j+k}) \right) ds + R^j_t. \tag{20}
\end{equation}

In fact both $\Psi$ and $\Psi^m$ are only well-defined on a subset of $\mathcal{T}^{d^d}$ (the domain of $\Psi^m$ is explained at the start of Section 5, and the domain of $\Psi$ may be inferred from Lemma 12). Let
\begin{equation}
\hat{\Psi}^m : \bigcup_{c \in \mathbb{R}^+} \mathcal{A}_c \to \mathcal{P}_S(\mathcal{T}^d) \tag{21}
\end{equation}
be \( \hat{\Psi}^m(\mu) = \mu \circ (\Psi^m)^{-1} \). In Section 5 we prove that \( \hat{\Psi}^m \) is well-defined and continuous on \( A_c \). It follows from Lemma 3 that \( \hat{\Psi}^n(\hat{\mu}(Y^n)) = \hat{\mu}^n(U) \).

Now, there exists a continuous function \( \hat{\Psi}^m : \mathcal{P}_S(\mathbb{T}^d) \rightarrow \mathcal{P}_S(\mathbb{T}^d) \) such that \( \hat{\Psi}^m(\mu) = \hat{\Psi}^m(\mu) \) for all \( \mu \in A_m \). To see this, note that we may identify \( \mathcal{P}_S(\mathbb{T}^d) \) as a closed convex subset of the locally-convex vector space \( \mathcal{M} \) of all finite Borel measures on \( \mathbb{T}^d \) (where \( \mathcal{M} \) has the topology of weak convergence). Since \( A_m \) is closed, the existence of \( \hat{\Psi}^m \) follows from [21, Theorem 4.1].

We define \( \hat{\Psi} : \mathcal{P}_S(\mathbb{T}^d) \rightarrow \mathcal{P}_S(\mathbb{T}^d) \) as follows.

\[
\hat{\Psi}(\mu) = \mu \circ \Psi^{-1} \text{ if } \mu \in \cup_{c \geq 0} A_c \tag{22}
\]
\[
\hat{\Psi}(\mu) = \beta \text{ otherwise, for some arbitrary fixed } \beta \in \mathcal{P}_S(\mathbb{T}^d). \tag{23}
\]

Note that it does not matter how we define \( \hat{\Psi} \) outside of \( \cup_{c \geq 0} A_c \).

We use [18, Theorem 4.2.23] to prove the result. First note that by Assumption 4, the laws \( (\Pi^n)_{n \in \mathbb{Z}^+} \) satisfy an LDP with good rate function. To use [18, Theorem 4.2.23], since \( \hat{\Psi}^m(\hat{\mu}(Y^n)) = \hat{\mu}^n(U) \) (as noted in Lemma 3), we must first verify the ‘exponentially good approximations’ property, namely that for arbitrary \( \alpha, \delta > 0 \), there exists an \( m \) such that

\[
\lim_{n \to \infty} \frac{1}{|V_n|} \log \mathbb{P}\left(\hat{\mu}^n(Y^n) \notin A_c \right) \leq -\alpha. \tag{24}
\]

To see this, by Lemma 11, there exists a \( c \in \mathbb{R}^+ \) such that

\[
\lim_{n \to \infty} \frac{1}{|V_n|} \log \mathbb{P}\left(\hat{\mu}^n(Y^n) \notin A_c \right) \leq -\alpha. \tag{25}
\]

But by Lemma 12, there exists an \( m \geq c \) such that if \( \hat{\mu}^n(Y^n) \in A_c \), then \( d^P(\hat{\Psi}^m(\hat{\mu}(Y^n)), \hat{\Psi}^n(\hat{\mu}(Y^n))) \leq \delta. \) This establishes (24).

To apply the result in [18, Theorem 4.2.23], we also require that for each \( \alpha \in \mathbb{R}^+ \), writing \( A_\alpha = \{ \mu \in \mathcal{P}_S(\mathbb{T}^d) | \Pi^\alpha(\mu) \leq \alpha \} \),

\[
\lim_{m \to \infty} \sup_{\mu \in A_\alpha} d^P(\hat{\Psi}(\mu), \hat{\Psi}^m(\mu)) = 0. \tag{26}
\]

Thanks to Lemma 13, it suffices to prove that for any \( c \in \mathbb{R}^+ \),

\[
\lim_{m \to \infty} \sup_{\mu \in A_c} d^P(\hat{\Psi}(\mu), \hat{\Psi}^m(\mu)) = 0. \tag{27}
\]

Now once \( m \geq c \), \( \hat{\Psi}^m(\mu) = \mu \circ (\Psi^m)^{-1} \), and since \( \hat{\Psi}(\mu) = \lim_{m \to \infty} \hat{\Psi}^m(\mu) \) (thanks to Lemma 12),

\[
\lim_{m \to \infty} \sup_{\mu \in A_c} d^P(\hat{\Psi}(\mu), \hat{\Psi}^m(\mu)) \leq 2 \lim_{m \to \infty} \sup_{n \geq m} \sup_{\mu \in A_c} d^P(\hat{\Psi}^m(\mu), \hat{\Psi}^n(\mu)). \tag{27}
\]

(27) follows as a consequence of the above and Lemma 12.

The theorem now follows from the fact that the laws \( (\Pi^n)_{n \in \mathbb{Z}^+} \) satisfy an LDP with good rate function, \( \hat{\Psi}^m \) is continuous, (24), (26) and [18, Theorem 4.2.23]. □

The following lemma notes that \( \Psi^n \) preserves \( V_n \)-periodicity.
Lemma 3. For each \( W^n \in \mathcal{T}^V_n \), there exists a unique solution \( U \) to (3). This solution satisfies, for all \( p \in \mathbb{Z}^d \),

\[
\Psi^n(\tilde{Y}^n)^p = U^p \mod V_n.
\]

Furthermore

\[
\hat{\mu}^n(U) = \hat{\mu}^n(\tilde{Y}^n) \circ (\Psi^n)^{-1}.
\] (28)

Proof: The existence and uniqueness of the solution (3) follows from Lemma 4. It follows from the definition that for all \( j \in \mathbb{Z}^d \), \( \Psi^n(S_j \tilde{Y}^n) = S_j \Psi(\tilde{Y}^n) \). (28) follows directly from this and the definition of the empirical measure. \( \square \)

Proof: [Proof of Corollary 2] The assumptions mean that \( \mu_Y \) is the unique probability measure such that \( I_Y(\mu_Y) = 0 \). This means, in turn, that \( \Psi(\mu_Y) \) is the unique zero of \( I \). It can then be shown using the Borel-Cantelli Lemma that \( \hat{\mu}^n(U) \rightarrow \Psi(\mu_Y) \) almost surely (see for instance [22, Theorem II.6.4]). \( \square \)

5 Existence and continuity of \( \bar{\Psi}^m \)

The map \( \Psi^m \) (as defined in (20)) is not well-defined on all of \( \tilde{T}^\mathbb{Z}^d \), and it is not necessarily continuous on closed subsets either. Our first task therefore is to define \( \Psi^m \) on a weighted subspace \( \tilde{T}^\mathbb{Z}^d \) (which we outline in further detail below). We then show that the induced map \( \mu \rightarrow \mu \circ (\Psi^m)^{-1} \) is continuous on the closed sets \( A_c \subset \mathcal{P}(\tilde{T}^\mathbb{Z}^d) \). The integer \( m \) is fixed throughout this section.

We start by defining the weights \( \{\lambda^j_m\}_{j \in \mathbb{Z}^d} \) which are used to modulate the convergence (similar methods have been used previously in, for example, [37]). For \( \theta \in [-\pi, \pi]^d \), let \( \kappa^k_m = 1_{k \in \mathbb{Z}_m}, \tilde{\kappa}_m(\theta) = \sum_{k \in \mathbb{Z}^d} \kappa^k_m \exp(-i \langle \theta, k \rangle) \) and

\[
\tilde{\lambda}_m(\theta) = h \left( \rho |V_m| - \tilde{\kappa}_m(\theta) \right)^{-1},
\]

where we recall that \( \rho > 1 \) is used in the definition of \( A_c \) in (18) and \( h \) is chosen to ensure that

\[
\frac{1}{(2\pi)^d} \int_{[-\pi, \pi]^d} \tilde{\lambda}_m(\theta) d\theta = 1.
\] (29)

Let \( \lambda^j_m = \frac{1}{(2\pi)^d} \int_{[-\pi, \pi]^d} \exp(i \langle \theta, j \rangle) \tilde{\lambda}_m(\theta) d\theta \). In the case that \( \rho = 2 \), it was proved in [26, Lemma 5] that

\[
\sum_{j \in \mathbb{Z}^d} \lambda^j_m = 1,
\]

(30)

\[
\lambda^j_m > 0,
\]

(31)

\[
\sum_{k \in \mathbb{Z}_m} \lambda^{j-k}_m \kappa^k_m \leq \rho |V_m| \lambda^j_m.
\]

(32)
The above identities easily generalise to any \( p > 1 \). An immediate consequence of (32) is, for any non-negative \((v^j)_{j \in \mathbb{Z}^d} \subset \mathbb{R}\),

\[
\sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda^j_m v^j + k \leq \rho |V_m| \sum_{j \in \mathbb{Z}^d} \lambda^j_m v^j,
\]

as long as the above sums are finite. Let \( \overline{T} \mathbb{Z}^d \) be the space of all \( Z := (R^j, (\omega^{j,k})_{k \in \mathbb{Z}^d})_{j \in \mathbb{Z}^d} \in \overline{T} \mathbb{Z}^d \) such that

\[
\sum_{j \in \mathbb{Z}^d} \lambda^j_m \| R^j \|^2_T < \infty
\]

\[
\sum_{j \in \mathbb{Z}^d} \lambda^j_m \sum_{k \in \mathbb{Z}^d} |\omega^{j,k}|^2_E < \infty.
\]

Define \( \Psi^m : \overline{T}(\mathbb{Z})^d \rightarrow \mathbb{Z}^d \) as follows. Using the above definitions, for \( Z \in \overline{T}(\mathbb{Z})^d \), with \( Z := (R^j, (\omega^{j,k})_{k \in \mathbb{Z}^d})_{j \in \mathbb{Z}^d} \), we define \( \Psi^m(Z) := X = (X^j_{\rho})_{j \in \mathbb{Z}^d, \rho \in [0, T]} \) to be such that for any \( t \in [0, T] \) and \( j \in \mathbb{Z}^d \),

\[
X^j_t := \int_0^t \left( \mathbf{b}(X^j_s) + \sum_{k \in V_m} \sum_{\lambda^j_m} \Lambda^k_s(\omega^{j,k}, X^j, X^{(j+k) \text{mod} V_m}) \right) ds + R^j_{\rho}.
\]

**Lemma 4** For each \( Z \in \overline{T}(\mathbb{Z})^d \), \( \Psi^m(Z) \) exists and is unique.

**Proof:** Fix \( Z = (R^j, (\omega^{j,k})_{j,k \in \mathbb{Z}^d})_{j \in \mathbb{Z}^d} \in \overline{T}(\mathbb{Z})^d \). We assume that \( \omega^{j,k} = 0 \) if \( j - k \notin V_m \), because if \( \Psi^m(Z) \) were to exist then it would be independent of these values. We prove the existence in two steps. We start by finding a series of periodic approximations \( \mathcal{Z}(p) \) of \( Z \). \( \Psi^m(\mathcal{Z}(p)) \) can be shown to exist through the Cauchy-Peano existence theorem, and then it will be shown that \( \{ \Psi^m(\mathcal{Z}(p)) \}_{p \in \mathbb{Z}^+} \) is Cauchy, yielding the lemma.

For \( p \in \mathbb{Z}^+ \), let \( \mathcal{Z}(p) \in \overline{T}(\mathbb{Z})^d \) have the property that, writing \( \mathcal{Z}(p)^j = (R(p)^j, (\beta(p)^{j,k})_{k \in \mathbb{Z}^d})_j \), \( R(p)^j = R(p)^a, \beta(p)^{j,k} = \beta(p)^{a,k} \), where \( a = j \text{ mod } V_p \). Very similarly to [26, Lemma 6], we can choose \( \{ \mathcal{Z}(p) \}_{p \in \mathbb{Z}^+} \) such that

\[
\lim_{p \rightarrow \infty} \sum_{j \in \mathbb{Z}^d} \lambda^j_m \| R(p)^j - R^j \|_T = 0
\]

\[
\lim_{p \rightarrow \infty} \sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda^j_m d_E(\beta(p)^{j,k}, \beta^{j,k})^2 = 0.
\]

Now \( \Psi^m(\mathcal{Z}(p)) \) must exist for any \( p \in \mathbb{Z}^+ \). In brief, this is because for any \( r \in \mathbb{Z}^d \), if the solution were to exist then \( S^r \Psi^m(\mathcal{Z}(p)) = \Psi^m(S^r \mathcal{Z}(p)) \). We can therefore reduce the existence of \( \Psi^m(\mathcal{Z}(p)) \) to the existence of a solution to a finite-dimensional ordinary differential equation indexed over \( V_p \), as in [26, Lemma 7]. The solution \( \Psi^m(\mathcal{Z}(p)) \) exists for any \( p \in \mathbb{Z}^+ \) thanks to the
generalised form of the Cauchy-Peano existence theorem in [26, Lemma 8]. Now, by Lemma 8,
\[
\sum_{j \in \mathbb{Z}^d} \lambda^j_m \| \Psi^m(\mathcal{Z}(q))^j - \Psi^m(\mathcal{Z}(p))^j \|_T \leq \exp \left( TC + (1 + \rho)TC_j|V_m| \right) \times
\]
\[
\left[ 2 \sum_{j \in \mathbb{Z}^d} \lambda^j_m \| R(p)^j - R(q)^j \|_T + T(1 + \sqrt{\rho})|V_m| \right] \left( \sum_{j \in \mathbb{Z}^d} \lambda^j_m \| \Psi^m(\mathcal{Z}(p))^j \|_T^2 \right)^{\frac{1}{2}} \times
\]
\[
\left( \sum_{j \in \mathbb{Z}^d, k \in \mathbb{V}_m} \lambda^j_m d_{\mathcal{E}}(\beta(p)^{j,k}, \beta(q)^{j,k}) \right)^{\frac{1}{2}}.
\]
By Lemma 9, since \((A + B)^2 \leq 2A^2 + 2B^2\) and \(|\cdot|_{\mathcal{E}} \leq C_J\),
\[
\| \Psi^m(\mathcal{Z}(p))^j \|_T^2 \leq 2 \left[ \exp \left( 2T(C + 2C_J|V_m|) \right) + 4 \exp \left( 2T(C + C_J|V_m|) \right) \right] \| R(p)^j \|_T^2.
\]
This means that
\[
\sum_{j \in \mathbb{Z}^d} \lambda^j_m \| \Psi^m(\mathcal{Z}(p))^j \|_T^2 \leq 2 \exp \left( 2T(C + 2C_J|V_m|) \right) (1 + 4 \sum_{j \in \mathbb{Z}^d} \lambda^j_m \| R(p)^j \|_T^2).
\]
Since
\[
\lim_{p \rightarrow \infty} \sum_{j \in \mathbb{Z}^d} \lambda^j_m \| R(p)^j \|_T^2 = \sum_{j \in \mathbb{Z}^d} \lambda^j_m \| R^j \|_T^2,
\]
there must exist a uniform upper bound \(L\) such that
\[
\sum_{j \in \mathbb{Z}^d} \lambda^j_m \| \Psi^m(\mathcal{Z}(p))^j \|_T \leq L \text{ for all } p \in \mathbb{Z}^+.
\]
It is therefore a consequence of (37)-(38) that
\[
\limsup_{q \rightarrow \infty} \sup_{p \geq q} \sum_{j \in \mathbb{Z}^d} \lambda^j_m \| \Psi^m(\mathcal{Z}(q))^j - \Psi^m(\mathcal{Z}(p))^j \|_T = 0.
\]
Let
\[
\Psi^m(\mathcal{Z})^j = \lim_{p \rightarrow \infty} \Psi^m(\mathcal{Z}(p))^j.
\]
To show that \(\Psi^m(\mathcal{Z})\) satisfies (36), we must verify that
\[
\int_0^t \sum_{k \in \mathbb{V}_m} \Lambda^k_s(\beta(p)^{j,k}, \Psi^m(\mathcal{Z}(p))^j, \Psi^m(\mathcal{Z}(p))^{j+k}) ds \rightarrow \int_0^t \sum_{k \in \mathbb{V}_m} \Lambda^k_s(\beta^{j,k}, \Psi^m(\mathcal{Z})^j, \Psi^m(\mathcal{Z})^{j+k}) ds
\]
\[
\int_0^t b(\Psi^m_s(\mathcal{Z}(p))^j) ds \rightarrow \int_0^t b(\Psi^m_s(\mathcal{Z})^j) ds.
\]
In fact the above identities follow from Assumptions 1 and 2 and the dominated convergence theorem. The uniqueness of \(\Psi^m(\mathcal{Z})\) follows from Lemma 8.

Recall that \(\Psi^m(\mu) := \mu \circ (\Psi^m)^{-1}\). The following lemma notes that this is well-defined for \(\mu \in \mathcal{A}_c\) (\(\mathcal{A}_c\) is defined in (18)).
Lemma 5 \( \check{\Psi}^m : \mathcal{A}_c \to \mathcal{P}_S(T^{\mathbb{Z}_d}) \) is well-defined and uniformly continuous. That is, for all \( \epsilon \) there exists a \( \delta \) such that for all \( \mu, \nu \in \mathcal{A}_c \), satisfying \( d^P(\mu, \nu) \leq \delta \), \( d^P(\check{\Psi}^m(\mu), \check{\Psi}^m(\nu)) \leq \epsilon \). Furthermore,

\[
\mathbb{E}^\mu \left[ \| \check{\Psi}^m(Z) \|_{T}^2 \right] < \infty, \tag{39}
\]

the above expectation being the same for all \( j \in \mathbb{Z}_d \) since \( \check{\Psi}^m(\mu) \) is stationary.

**Proof:** We first observe that if \( \mu \in \mathcal{A}_c \), and \( \mu \) is the law of \( \{Z^j\}_{j \in \mathbb{Z}_d} \), where \( Z^j = (R^j, (\omega^{j,k})_{k \in \mathbb{Z}_d}) \), then since

\[
\mathbb{E}^\mu \left[ \sum_{j \in \mathbb{Z}_d} \lambda_m^j \| R^j \|_{T}^2 \right] \leq c \sum_{j \in \mathbb{Z}_d} \lambda_m^j < \infty,
\]

\( \sum_{j \in \mathbb{Z}_d} \lambda_m^j \| R^j \|_{T}^2 < \infty, \mu \)-almost surely. Similarly, since \( \mathbb{E}^\mu \left[ \sum_{k \in \mathbb{Z}_d} \| \omega^{j,k} \|_{\mathbb{L}^2}^2 \right] < \infty \) (by the stationarity of \( \mu \), this integral is independent of \( j \)), it must be that \( \sum_{j \in \mathbb{Z}_d, k \in \mathbb{Z}_d} \lambda_m^j \| \omega^{j,k} \|_{\mathbb{L}^2}^2 < \infty, \mu \)-almost surely. Thanks to Lemma 4, this means that \( \Psi^m(Z) \) exists for \( \mu \) almost-every \( Z \), and therefore that \( \check{\Psi}^m(\mu) \) is well-defined.

The bound in Lemma 9 implies (39), since \( \mathbb{E} \left[ \| R^j \|_{T}^2 \right] \leq c \).

Now it is an immediate consequence of the definition of the metric in (2) that for any \( s \in \mathbb{Z}^+ \),

\[
\lim_{\gamma \to 0} \sup_{\mu, \nu \in \mathcal{A}_c, d^P(\mu, \nu) \leq \gamma} d^P\left( \nu \circ (\Psi^m)^{-1}, \mu \circ (\Psi^m)^{-1} \right) \leq 2^{-s-1} + \sum_{r=1}^s \lim_{\gamma \to 0} \sup_{\mu, \nu \in \mathcal{A}_c, d^P(\mu, \nu) \leq \gamma} d^P\left( \pi_{V_r}^P(\nu \circ (\Psi^m)^{-1}), \pi_{V_r}^P(\mu \circ (\Psi^m)^{-1}) \right). \tag{40}
\]

It thus suffices for us to prove that for an arbitrary \( r \in \mathbb{Z}^+ \),

\[
\lim_{\gamma \to 0} \sup_{\mu, \nu \in \mathcal{A}_c, d^P(\mu, \nu) \leq \gamma} d^P\left( \pi_{V_r}^P(\nu \circ (\Psi^m)^{-1}), \pi_{V_r}^P(\mu \circ (\Psi^m)^{-1}) \right) = 0. \tag{41}
\]

Let \( \mathcal{B}^{V_r} \) be the set of all \( V_r \) cylinder sets, that is every \( B \in \mathcal{B}^{V_r} \subset \mathcal{B}(T^{\mathbb{Z}_d}) \) is such that \( B = (\pi_{V_r})^{-1}B_2 \) for some \( B_2 \in \mathcal{B}(T^{\mathbb{Z}_d}) \). For \( \delta > 0 \), let \( \mathcal{B}^\delta \subset \mathcal{B} \) be the \( \delta \)-interior relative to the norm on \( T^{\mathbb{Z}_d} \), i.e. such that

\[
B^\delta = \left\{ X \in T^{\mathbb{Z}_d} \left| \sum_{j \in V_r} \| X^j - Y^j \|_{T} \leq \delta \right\} \right. \subset B \right\}. \tag{42}
\]

Let \( \check{B} = (\Psi^m)^{-1}(B) \) and \( \check{B}^\delta = (\Psi^m)^{-1}(B^\delta) \). We use Lemma 6 to establish (41). This lemma implies that for any \( \delta \) there exists a \( \gamma \) such that

\[
\sup_{\mu, \nu \in \mathcal{A}_c, d^P(\mu, \nu) \leq \gamma} \left( \nu(\check{B}) - \mu(\check{B}^\delta) \right) \leq \delta. \tag{43}
\]
It follows from the above equation and the definition of the Prokhorov metric that

$$
sup_{\mu,\nu \in \mathcal{A}, d^P(\mu,\nu) \leq \gamma} d^P_P(\mu,\nu) \leq \gamma d^P_P(\nu(\Psi^{-1}_m), \mu(\Psi^{-1}_m)) \leq \delta. \quad (44)
$$

Since \( \delta \) is arbitrary, \((41)\) is an immediate consequence of this, which completes the proof. \( \square \) The variables in the following lemma are defined in the proof of Lemma 5.

**Lemma 6** For any \( r \in \mathbb{Z}^+ \) and \( \delta > 0 \),

$$
\lim_{\gamma \to 0} sup_{\mu,\nu \in \mathcal{A}, d^P(\mu,\nu) \leq \gamma} sup_{B \in \mathcal{B}^r} (\nu(B) - \mu(B^\delta)) \leq \delta. \quad (45)
$$

**Proof:** For \( \epsilon > 0 \) and \( q > m \), let \( \mathcal{H}^r_q \subset \mathcal{T}^d_{X_m} \) be the subset of all \( \mathcal{Z} = (R^j, \beta_{j,k})_{j,k \in \mathbb{Z}^d} \) such that, writing \( \mathcal{Z} = \Psi_m(\mathcal{Z}) \),

$$
\sum_{j \in V^r} \lambda^j_m \| R^j \|_T \leq \epsilon, \quad (46)
$$

$$
\sum_{j \in \mathbb{Z}^d} \lambda^j_m \| Z^j \|_T^2 \leq \epsilon^{-1}, \quad (47)
$$

$$
\sum_{j \notin V^r, k \in V_m} \lambda^j_m \| \beta_{j,k} \|_E^2 \leq \epsilon^2. \quad (48)
$$

Writing \( \tilde{B}^r_q = \tilde{B} \cap \mathcal{H}^r_q \) and \( \tilde{B}^\delta_{q,c} = \tilde{B}^\delta \cap \mathcal{H}^r_q \), it may be observed that

$$
\nu(\tilde{B}) - \mu(\tilde{B}^\delta) \leq \nu(\tilde{B}^r_q) - \mu(\tilde{B}^\delta_{q,c}) + \nu((\mathcal{H}^r_q)^c). \quad (49)
$$

Suppose that \( \mathcal{X}, \mathcal{Z} \in \mathcal{H}^r_q \), with \( \mathcal{X} := (Q^j, \omega_{j,k})_{j,k \in \mathbb{Z}^d}, \mathcal{Z} := (R^j, \beta_{j,k})_{j,k \in \mathbb{Z}^d} \in \mathcal{T}^d_{X_m} \). Let \( \mathcal{X} = \Psi_m(\mathcal{X}) \) and \( \mathcal{Z} = \Psi_m(\mathcal{Z}) \). By Lemma 8, for any \( r \in \mathbb{Z}^+ \),

$$
\sum_{j \in V^r} \lambda^j_m \| X^j - Z^j \|_T \leq A_m \left( H^q_1 + H^q_2 \right),
$$

where \( A_m = T \exp(T(C + T(1 + \rho)C_J |V_m|)) \),

\[
H^q_1 = 2 \sum_{j \in V^r} \lambda^j_m \| Q^j - R^j \|_T \\
+ (1 + \sqrt{\rho}) |V_m| \frac{1}{2} \left( \sum_{j \in \mathbb{Z}^d} \lambda^j_m \| Z^j \|_s^2 \right)^{\frac{1}{2}} \left( \sum_{j \in V^r, k \in V_m} \lambda^{j,k}_m d_E(\omega_{j,k}, \beta_{j,k})^2 \right)^{\frac{1}{2}}
\]
\[ H_q^2 = 2 \sum_{j \notin V_q} \lambda_m^j \| Q^j - R^j \|_T \]
\[ + (1 + \sqrt{\rho}) |Q_m^q| \left( \sum_{j \in \mathbb{Z}^d} \lambda_m^j \| Z^j \|^2 \right)^{\frac{1}{2}} \left( \sum_{j \notin V_q, k \in V_m} \lambda_m^j d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k})^2 \right)^{\frac{1}{2}} \]
\[ \leq 2 \sum_{j \notin V_q} \lambda_m^j \left( \| Q^j \|_T + \| R^j \|_T \right) \]
\[ + (1 + \sqrt{\rho}) \sqrt{2} |Q_m^q| \left( \sum_{j \in \mathbb{Z}^d} \lambda_m^j \| Z^j \|^2 \right)^{\frac{1}{2}} \left( \sum_{j \notin V_q, k \in V_m} \lambda_m^j \left( \| \omega^{j,k} \|^2 + \| \beta^{j,k} \|^2 \right) \right)^{\frac{1}{2}}, \]
recalling that \( |\cdot|_{\mathcal{E}} = d_{\mathcal{E}}(\cdot, 0) \). We have used the inequalities
\[ \sqrt{F + G} \leq \sqrt{F} + \sqrt{G}, \]
and \((F + G)^2 \leq 2F^2 + 2G^2\). Using the definition of \( \mathcal{H}_q^\epsilon \), and also the Cauchy-Schwarz Inequality, we find that
\[ H_q^2 \leq 4 \epsilon + \sqrt{2}(1 + \sqrt{\rho}) |Q_m^q| \epsilon^{-\frac{1}{2}} \epsilon\]
\[ = 4 \epsilon + \sqrt{2}(1 + \sqrt{\rho}) |Q_m^q| \epsilon^{-\frac{1}{2}}. \]
Take \( \epsilon \) to be sufficiently small that \( H_q^2 \leq \frac{\delta}{4 A_m} \) and
\[ 4 \epsilon \left( \frac{1}{2} \epsilon^{-1} \exp \left( - 2T(C + 2C|V_m|) \right) - 1 \right)^{-1} \leq \frac{\delta}{4}. \] (50)

We find that
\[ \sum_{j \in V_r} \lambda_m^j \| X^j - Z^j \|_T \leq A_m \tilde{d}_q(\mathcal{X}, \mathcal{Z}) \left( 2 + (1 + \sqrt{\rho}) |Q_m^q| \epsilon^{-\frac{1}{2}} \right) + \frac{\delta}{2}. \] (51)

By Lemma 7, and noting (50), we may take \( q \) to be sufficiently large that for all \( \nu \in \mathcal{A}_c \),
\[ \nu \left( \mathcal{H}_q^\epsilon \right) \leq \frac{\delta}{2}. \] (52)

The lemma will follow once we have established the following claim.

**Claim:**

We claim that for \( \gamma \) sufficiently small,
\[ \sup_{\mu, \nu \in \mathcal{A}_c, d^\delta(\mu, \nu) \leq \gamma} \nu(\bar{B}) - \mu(\bar{B}^\delta) \leq 2^q \gamma + \frac{\delta}{2}. \] (53)

Thanks to (49) and (52), it suffices to prove that, for \( \gamma \) sufficiently small,
\[ \sup_{\mu, \nu \in \mathcal{A}_c, d^\delta(\mu, \nu) \leq \gamma} \nu(\bar{B}_q^\epsilon) - \mu(\bar{B}_q^\delta) \leq \gamma 2^q. \]
For $\eta > 0$, let $\tilde{B}_q^{\eta, \epsilon} \subset \tilde{B}_q^\epsilon$ be the $\eta$ relative interior, that is

$$\tilde{B}_q^{\eta, \epsilon} = \left\{ X \in \tilde{B}_q^\epsilon \left| X \in \tilde{B}_q^\epsilon \right. \right\}.$$

It follows from (51) that if $\eta \leq \delta_2^2 A_m \left( 2 + (1 + \sqrt{\rho}) |V_m|^{1/2} \right)$, then

$$\tilde{B}_q^{\eta, \epsilon} \subseteq \tilde{B}_q^\delta.$$

This means that if (55) is satisfied, then $\nu(\tilde{B}_q^\delta) - \mu(\tilde{B}_q^{\eta, \epsilon}) \leq \nu(\tilde{B}_q^\delta) - \mu(\tilde{B}_q^{n, \epsilon}) \leq d_q^P(\nu, \mu) \leq \eta$, thanks to the definition of the Prokhorov Metric. Now it follows from the definition that if $d_q^P(\mu, \nu) \leq \gamma$, then $d_q^P(\nu, \mu) \leq 2\gamma$. We have thus established our claim in (53).

**Lemma 7** For all $\mu \in \mathcal{A}_c$, and $q$ sufficiently large,

$$\mu((\mathcal{H}_q^\epsilon)^c) \leq \sqrt{e} \epsilon^{-1} \sum_{j \notin V_q} \lambda_m^j + cL(m, \epsilon),$$

where $L(m, \epsilon)$ is defined in (57) and $\mathcal{H}_q$ is defined in (46)-(48).

**Proof:** We suppose that $\mu$ is the law of $Z = (R^j, \beta^j, k)_{j \in \mathbb{Z}^d}$ and write $Z = \Psi_m(Z)$. We obtain bounds on each of (46)-(48). By Chebyshev's Inequality,

$$\mu \left( \sum_{j \notin V_q} \lambda_m^j \|R^j\|_T \geq \epsilon \right) \leq \epsilon^{-1} \mathbb{E}^\mu \left[ \sum_{j \notin V_q} \lambda_m^j \|R^j\|_T \right] \leq \epsilon^{-1} \sum_{j \notin V_q} \lambda_m^j \mathbb{E}^\mu \left[ \|R^j\|_T^2 \right]^{1/2} \leq \sqrt{e} \epsilon^{-1} \sum_{j \notin V_q} \lambda_m^j,$$

using the definition of $\mathcal{A}_c$ in (18). By Lemma 9, the bound $|\cdot|_C \leq C_J$ of Assumption 2, and the fact that $(A + B)^2 \leq 2(A^2 + B^2)$, for each $j \in \mathbb{Z}^d$,

$$\|Z^j\|_T^2 \leq 2(1 + 4 \|R^j\|_T^2) \exp \left( 2T(C + 2C_J |V_m|) \right),$$

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and therefore
\[
\|R^j\|^2_T \geq \frac{1}{4} \left( \frac{1}{2} \|Z^j\|^2_T \exp \left( -2T(C + 2C_J|V_m|) \right) - 1 \right)
\]
\[
\sum_{j \in \mathbb{Z}^d} \lambda_m^j \|R^j\|^2_T \geq \frac{1}{4} \left( \frac{1}{2} \sum_{j \in \mathbb{Z}^d} \lambda_m^j \|Z^j\|^2_T \exp \left( -2T(C + 2C_J|V_m|) \right) - 1 \right),
\]
after summing over \( j \). Hence, writing
\[
L(m, \epsilon) = 4 \left( \frac{1}{2} \epsilon^{-1} \exp \left( -2T(C + 2C_J|V_m|) \right) - 1 \right)^{-1},
\]
and noting that \( \sum_{j \in \mathbb{Z}^d} \lambda_m^j = 1 \),
\[
\mu \left[ \sum_{j \in \mathbb{Z}^d} \lambda_m^j \|Z^j\|^2_T \geq \epsilon^{-1} \right] 
\leq \mu \left[ \sum_{j \in \mathbb{Z}^d} \lambda_m^j \|R^j\|^2_T \geq \frac{1}{4} \left( \frac{1}{2} \epsilon^{-1} \exp \left( -2T(C + 2C_J|V_m|) \right) - 1 \right) \right] 
\leq L(m, \epsilon) \mathbb{E}^\mu \left[ \sum_{j \in \mathbb{Z}^d} \lambda_m^j \|R^j\|^2_T \right] 
\leq cL(m, \epsilon),
\]
where we have made use of Chebyshev’s Inequality. Finally, observe that thanks to Assumption 2,
\[
\sum_{j \notin V_q} \lambda_m^j \sum_{k \in V_m} |\beta^{j,k}|_F^2 \leq \sum_{j \notin V_q} \lambda_m^j |V_m|C_J^2.
\]
Since \( \sum_{j \in \mathbb{Z}^d} \lambda_m^j = 1 \), for \( q \) sufficiently large the above must be less than or equal to \( \epsilon^2 \), so that (48) is satisfied. \( \square \)

**Lemma 8** Suppose that \( \mathcal{X} = (Q^j, \omega^{j,k})_{j,k \in \mathbb{Z}^d} \in \hat{T}_{\lambda_m}^{\mathbb{Z}^d} \) and \( \mathcal{Z} = (R^j, \beta^{j,k})_{j,k \in \mathbb{Z}^d} \in \hat{T}_{\lambda_m}^{\mathbb{Z}^d} \cap \hat{T}_{\lambda_m}^{\mathbb{Z}^d} \). Suppose that for \( n \geq m \) there exist solutions \( \mathcal{X} = \Psi^n(\mathcal{X}) \) and \( \mathcal{Z} = \Psi^n(\mathcal{Z}) \) to (36). Then
\[
\sum_{j \in \mathbb{Z}^d} \lambda_m^j \|X^j - Z^j\|_T \leq \exp(TC + T(1 + \rho)C_J|V_m|)
\]
\[
\times \left[ (1 + \sqrt{p})T|V_m|^{\frac{1}{2}} \left( \sum_{j \in \mathbb{Z}^d} \lambda_m^j \|Z^j\|^2_T \right)^{\frac{1}{2}} \left( \sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda_m^j d_{\mathbf{P}}(\omega^{j,k}, \beta^{j,k})^2 \right)^{\frac{1}{2}} 
\right.
\]
\[
+ 2 \sum_{j \in \mathbb{Z}^d} \lambda_m^j \|Q^j - R^j\|_T + T \sum_{j \in \mathbb{Z}^d, k \in V_m - V_n} \lambda_m^j |\beta^{j,k}|_F \left( \|Z^j\|_T + 1 \right)].
\]
Proof: Observe that

\[
X^j_t - Z^j_t = \int_0^t \left( b(X^j_s) - b(Z^j_s) - \sum_{k \in V_m - V_m} \Lambda^k_s(\beta^{j,k}, Z^j, Z^{j+k}) + \sum_{k \in V_m} \Lambda^k_s(\omega^{j,k}, X^j, X^{j+k}) - \Lambda^k_s(\beta^{j,k}, Z^j, Z^{j+k}) \right) ds + Q^j_t - R^j_t
\]

\[
+ \int_0^t \left( b(X^j_s) - b(Z^j_s) - \sum_{k \in V_m - V_m} \Lambda^k_s(\beta^{j,k}, Z^j, Z^{j+k}) + \sum_{k \in V_m} \Lambda^k_s(\omega^{j,k}, X^j, X^{j+k}) - \Lambda^k_s(\beta^{j,k}, Z^j, Z^{j+k}) \right) ds + Q^j_t - R^j_t.
\]

Let's first assume that \(X^j_t \geq Z^j_t\). In this case, define \([\tau, \gamma]\) to be such that \(X^j_t \geq Z^j_t\) for all \(t \in [\tau, \gamma]\) and \(\tau\) is as small as possible. Applying the inequalities of Assumptions 1 and 2, we find that for \(1 \leq p \leq m\), and \(s \in [\tau, \gamma]\),

\[
b_p(X^j_s) - b_p(Z^j_s) \leq C|X^j_s - Z^j_s|.
\]

This means that

\[
\sup_{1 \leq p \leq m} |X^{p,j}_t - Z^{p,j}_t| \leq \sup_{1 \leq p \leq m} |X^{p,j}_0 - Z^{p,j}_0| + \int_0^t \left( C \|X^j - Z^j\|_s \right) ds + Q^j_t - R^j_t,
\]

\[
+ \sum_{k \in V_m - V_m} |\beta^{j,k}|_{\mathcal{E}} \left( \|Z^j\|_s + 1 \right) C_J |V_m| \|X^j - Z^j\|_s + C_J \sum_{k \in V_m} \|X^{j+k} - Z^{j+k}\|_s
\]

\[
+ \sum_{k \in V_m} d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k}) \left( \|Z^j\|_s + \|Z^{j+k}\|_s \right) ds + Q^j_t - R^j_t + Q^j_t - R^j_t.
\]

We take \(\tau\) to be such that, either \(\tau = 0\), or \(X^j_\tau < Z^j_\tau\) as \(t \to \tau^-\). Now since if \(\tau = 0\), then \(X^j_\tau - Z^j_\tau = Q_0^j - R_0^j\), whichever of these cases holds we find that for
all \( t \in [\tau, \gamma] \),

\[
|X^j - Z^j|_t \leq 2 \|Q^j - R^j\|_T + \int_{\tau}^{t} \left( C \|X^j - Z^j\|_s + C_J |V_m| \|X^j - Z^j\|_s 
+ C_J \sum_{k \in V_m} \|X^{j+k} - Z^{j+k}\|_s + \sum_{k \in V_m} d_\xi(\omega^{j,k}, \beta^{j,k}) \left( \|Z^j\|_s + \|Z^{j+k}\|_s \right) + \sum_{k \in V_n - V_m} |\beta^{j,k}|_\xi \left( \|Z^j\|_s + 1 \right) \right) ds
\]

\[
\leq 2 \|Q^j - R^j\|_T + \int_{0}^{t} \left( (C + C_J |V_m|) \|X^j - Z^j\|_s + C_J \sum_{k \in V_m} \|X^{j+k} - Z^{j+k}\|_s 
+ \|Z^j\|_s \sum_{k \in V_m} d_\xi(\omega^{j,k}, \beta^{j,k}) + ( \sum_{k \in V_m} \|Z^{j+k}\|_s^2 )^{\frac{1}{2}} \left( \sum_{k \in V_m} d_\xi(\omega^{j,k}, \beta^{j,k})^2 \right)^{\frac{1}{2}} + \sum_{k \in V_n - V_m} |\beta^{j,k}|_\xi \left( \|Z^j\|_s + 1 \right) \right) ds.
\]

We could demonstrate the same inequality if \([\tau, \gamma]\) were such that \(X^j_t \leq Z^j_t\) for all \( t \in [\tau, \gamma] \).
We thus find that, making use of the Cauchy-Schwarz inequality,

\[
\sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| X^j - Z^j \right\|_s \leq 2 \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| Q^j - R^j \right\|_T \\
+ \int_0^t \left[ (C + C_J |V_m|) \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| X^j - Z^j \right\|_s + C_J \sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda_m^j \left\| X^{j+k} - Z^{j+k} \right\|_s \right. \\
+ \left. \left( \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| Z^j \right\|_s \right)^{\frac{1}{2}} \left( \sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda_m^j d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k}) \right)^{\frac{1}{2}} \right] \left( \sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda_m^j d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k}) \right)^{\frac{1}{2}} \\
+ \sum_{j \in \mathbb{Z}^d, k \in V_m - V_m} \lambda_m^j |\beta^{j,k}|_{\mathcal{E}} \left( \left\| Z^j \right\|_s + 1 \right) ds \\
\leq 2 \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| Q^j - R^j \right\|_T \\
+ \int_0^t \left[ (C + C_J |V_m|) \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| X^j - Z^j \right\|_s + \rho C_J |V_m| \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| X^j - Z^j \right\|_s \right. \\
+ \left. |V_m|^{\frac{1}{2}} \left( \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| Z^j \right\|_s \right)^{\frac{1}{2}} \left( \sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda_m^j d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k}) \right)^{\frac{1}{2}} \right] \left( \sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda_m^j d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k}) \right)^{\frac{1}{2}} \\
+ \sum_{j \in \mathbb{Z}^d, k \in V_m - V_m} \lambda_m^j |\beta^{j,k}|_{\mathcal{E}} \left( \left\| Z^j \right\|_s + 1 \right) ds,
\]

by (33), and using Jensen’s Inequality to obtain the bound

\[
(\sum_{k \in V_m} d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k}))^2 \leq |V_m| \sum_{k \in V_m} d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k})^2. \quad \text{Hence by Gronwall’s Inequality,}
\]

\[
\sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| X^j - Z^j \right\|_T \leq \exp(\left(\frac{1}{2}\right) \left( \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| Z^j \right\|_s \right)^{\frac{1}{2}} \left( \sum_{j \in \mathbb{Z}^d, k \in V_m} \lambda_m^j d_{\mathcal{E}}(\omega^{j,k}, \beta^{j,k}) \right)^{\frac{1}{2}} \\
+ 2 \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left\| Q^j - R^j \right\|_T + T \sum_{j \in \mathbb{Z}^d, k \in V_m - V_m} \lambda_m^j |\beta^{j,k}|_{\mathcal{E}} \left( \left\| Z^j \right\|_T + 1 \right) \right].
\]
Lemma 9  Suppose that $Z = (R^i, \omega^j,k)_{j,k \in \mathbb{Z}^d} \in T^\mathbb{Z}^d$ and $\Psi^m(Z)$ exists. Then
\[
\|\Psi^m(Z)^j\|_T \leq \exp \left( T(C + 2 \sum_{k \in V_m} |\omega^j,k|_\xi) \right) + 2 \exp \left( T(C + \sum_{k \in V_m} |\omega^j,k|_\xi) \right)\|R^j\|_T.
\]

Proof: Suppose that $[\tau, \gamma] \subseteq [0, T]$ is such that $\Psi^m(Z)^j \geq 0$ for all $t \in [\tau, \gamma]$. Then, making use of Assumption 1, for $t \in [\tau, \gamma]$,
\[
|\Psi^m(Z)^j| \leq |\Psi^m(Z)^j| + R^j - R^j = \int_\tau \left( C \|\Psi^m(Z)^j\|_s + \sum_{k \in V_m} |\omega^j,k|_\xi (1 + \|\Psi^m(Z)^j\|_s) \right) ds.
\]

We take $\tau$ to be such that, either $\tau = 0$ (in which case $\Psi^m(Z)_0 = R^j$) or $\Psi^m(Z)^j = 0$. Whichever is the case, we find that
\[
|\Psi^m(Z)^j| \leq \int_0^t \left( C \|\Psi^m(Z)^j\|_s + \sum_{k \in V_m} |\omega^j,k|_\xi (1 + \|\Psi^m(Z)^j\|_s) \right) ds + 2 \|R^j\|_t.
\]

We would obtain the same inequality if we had assumed that $\Psi^m(Z)^j \leq 0$ for all $t \in [\tau, \gamma]$. Since any $t \in [0, T]$ must satisfy either $\Psi^m(Z)^j \geq 0$ or $\Psi^m(Z)^j \leq 0$, we find that for all $t \in [0, T]$,
\[
\|\Psi^m(Z)^j\|_t \leq \int_0^t \left( C \|\Psi^m(Z)^j\|_s + \sum_{k \in V_m} |\omega^j,k|_\xi (1 + \|\Psi^m(Z)^j\|_s) \right) ds + 2 \|R^j\|_t.
\]

By Gronwall’s Inequality,
\[
\|\Psi^m(Z)^j\|_T \leq \exp \left( T(C + \sum_{k \in V_m} |\omega^j,k|_\xi) \right) \left( 2 \|R^j\|_T + T \sum_{k \in V_m} |\omega^j,k|_\xi \right).
\]

The lemma follows directly from this. \(\Box\)

The following lemma is needed to prove Lemma 12.

Lemma 10  For any $j \in \mathbb{Z}^d$,
\[
\lim_{m \to \infty} |V_m| \lambda^j_m \geq \frac{\rho - 1}{\rho^2}.
\]

Proof: We first bound $h$ using (29). Observe that, since $\tilde{\kappa}_m(\theta) \leq |V_m|$, 
\[
\frac{1}{(2\pi)^d} \int_{[-\pi, \pi]^d} \left( \rho|V_m| - \tilde{\kappa}_m(\theta) \right)^{-1} d\theta \leq \frac{1}{(2\pi)^d(\rho - 1)} \int_{[-\pi, \pi]^d} |V_m|^{-1} d\theta = \frac{1}{(\rho - 1)|V_m|}.
\]
This means that \( h \geq |V_m|(\rho - 1) \). We use a Taylor expansion to bound \( \lambda^j_m \) as follows,

\[
\lambda^j_m = \frac{h}{(2\pi)^d} \int_{[-\pi,\pi]^d} \exp(i(j, \theta)) \left( \frac{\rho |V_m| - \tilde{\kappa}_m(\theta)}{\rho |V_m|} \right)^{-1} d\theta \\
= \frac{h}{\rho |V_m| (2\pi)^d} \sum_{k=0}^{\infty} \int_{[-\pi,\pi]^d} \exp(i(j, \theta)) \left( \frac{\tilde{\kappa}_m(\theta)}{\rho |V_m|} \right)^k d\theta \\
\geq \frac{h}{\rho |V_m| (2\pi)^d} \int_{[-\pi,\pi]^d} \exp(i(j, \theta)) \left( \kappa_m^j \right) d\theta. \quad (58)
\]

This last step is due to the fact that for any \( k \in \mathbb{Z}^+ \)

\[
\int_{[-\pi,\pi]^d} \exp(i(j, \theta)) \left( \frac{\kappa_m^j}{\rho |V_m|} \right)^k d\theta \geq 0.
\]

For example, if \( k = 2 \) in the above, then from the convolution formula for Fourier Series,

\[
\frac{1}{\rho |V_m| (2\pi)^d} \int_{[-\pi,\pi]^d} \exp(i(j, \theta)) \left( \kappa_m^j \right) d\theta = \frac{1}{\rho^2 |V_m|^2} \sum_{r \in \mathbb{Z}^d} \kappa_m^{j-r} \kappa_m^r.
\]

This is non-negative because each \( \kappa_m^r \) is non-negative. This result easily generalises to \( k > 2 \). Coming back to (58), we see that

\[
\lambda^j_m \geq \frac{h}{\rho |V_m| (2\pi)^d} \frac{\kappa_m^j}{\rho |V_m|} \geq \frac{|V_m|(\rho - 1)}{\rho^2 |V_m|^2} \kappa_m^j, \quad (59)
\]

since \( h \geq |V_m|(\rho - 1) \). Once \( m \) is large enough that \( j \in V_m \), we have the lemma. \( \square \)

### 6 Lemmas Auxiliary to the Proof of Theorem 1

The three main results of this Section are Lemmas 11, 12 and 13. They are all needed to complete the proof of Theorem 1. For the following lemma recall that \( \mathcal{A}_c \) is defined in (18).

**Lemma 11**

\[
\lim_{c \to \infty} \lim_{n \to \infty} \frac{1}{|V_n|} \log P\left( \hat{\mu}^n(Y^n) \notin \mathcal{A}_c \right) = -\infty. \quad (60)
\]
Proof: For any $m > m_0$,
\[
\mathbb{P}\left(\hat{\mu}^n(Y^n) \notin \mathcal{A}_c\right) \leq \mathbb{P}\left(\sum_{j \in V_n} \|W_{n,j}\|_T^2 > c|V_n|\right) + \\
\mathbb{P}\left(|V_m|^{2+2\rho} \exp\left[(4+2\rho)TC_{j}|V_m|\right] \sum_{j \in V_n} \left(\sum_{k \notin V_m} |J_{n,j,k}|_E\right)^2 > c|V_n|\right) \\
+ \mathbb{P}\left(|V_m|^{1+\rho} \exp\left[(3+\rho)TC_{j}|V_m|\right] \sum_{j \in V_n,k \notin V_m} |J_{n,j,k}|_E > c|V_n|\right).
\]

We bound these two terms using the exponential Chebyshev Inequality. Using Assumption 5,
\[
\mathbb{P}\left(\sum_{j \in V_n} \|W_{n,j}\|_T^2 > c|V_n|\right) = \mathbb{P}\left(\epsilon_1 \sum_{j \in V_n} \|W_{n,j}\|_T^2 > \epsilon_1 c|V_n|\right) \\
\leq \exp\left(-\epsilon_1 c|V_n|\right) \mathbb{E}\left[\exp\left(\epsilon_1 \sum_{j \in V_n} \|W_{n,j}\|_T^2\right)\right] \\
\leq \exp\left(-\epsilon_1 c|V_n| + \epsilon_2|V_n|\right).
\]

Making similar use of Assumption 3, we find that
\[
\mathbb{P}\left(|V_m|^{2+2\rho} \exp\left[(4+2\rho)TC_{j}|V_m|\right] \sum_{j \in V_n} \left(\sum_{k \notin V_m} |J_{n,j,k}|_E\right)^2 > c|V_n|\right) \\
\leq \exp\left(-c\alpha_1|V_n| + a_2|V_n|\right)
\]
\[
\mathbb{P}\left(|V_m|^{1+\rho} \exp\left[(3+\rho)TC_{j}|V_m|\right] \sum_{j \in V_n,k \notin V_m} |J_{n,j,k}|_E > c|V_n|\right) \\
\leq \exp\left(-c\alpha_1|V_n| + a_2|V_n|\right).
\]

We thus see that
\[
\lim_{n \to \infty} \frac{1}{|V_n|} \log \mathbb{P}\left(\hat{\mu}^n(Y^n) \notin \mathcal{A}_c\right) \leq \max\{-c\alpha_1 + a_2, -\epsilon_1 c + \epsilon_2\}.
\]

The lemma follows directly from the above. □

Lemma 12 For any $c, \delta > 0$, there exists an $m \in \mathbb{Z}^+$ such that
\[
\sup_{n \geq m} \sup_{\mu \in \mathcal{A}_c} d^P(\tilde{\Psi}^m(\mu), \tilde{\Psi}^n(\mu)) \leq \delta.
\]

For all $\mu \in \bigcup_{c \geq 0} \mathcal{A}_c$,
\[
\mu \circ \Psi^{-1} = \lim_{m \to \infty} \tilde{\Psi}^m(\mu).
\]
Proof: Let \( r \in \mathbb{Z}^+ \) be such that \( 2^{-r} \leq \frac{\delta}{2} \). It follows from the definition of the metric \( d^P \) in (2) that

\[
d^P(\tilde{\Psi}^m(\mu), \tilde{\Psi}^n(\mu)) \leq 2^{-r} + d^P_r(\tilde{\Psi}^m(\mu), \tilde{\Psi}^n(\mu)).
\]

For (61), it thus suffices for us to show that for fixed \( r \in \mathbb{Z}^+ \) and \( \delta > 0 \), there exists an \( m \in \mathbb{Z}^+ \) such that

\[
\sup_{n \geq m} \sup_{\mu \in \mathcal{A}} d^P_r(\tilde{\Psi}^m(\mu), \tilde{\Psi}^n(\mu)) \leq \delta.
\]

(63)

Let \( X_j = (Q_j, (\omega^{j,k})_{k \in \mathbb{Z}^d}) \), \( X = \Psi^m(\mathcal{X}) \) and \( Z = \Psi^n(\mathcal{X}) \). By Lemma 8,

\[
\sum_{j \in \mathbb{Z}^d} \lambda^j_m \|X^j - Z^j\|_T \leq T \exp \left(T(2C + (1 + \rho)C_J|V_m|)\right) \times \sum_{j \in \mathbb{Z}^d, k \in V_n - V_m} \lambda^j_m |\omega^{j,k}|_E \left(\|Z^j\|_T + 1\right).
\]

We multiply both sides of the above equation by \(|V_m|\) and use Lemma 9, finding that

\[
|V_m| \sum_{j \in \mathbb{Z}^d} \lambda^j_m \|X^j - Z^j\|_T \leq |V_m|T \exp \left(2TC\right) \times \sum_{j \in \mathbb{Z}^d, k \in V_n - V_m} \lambda^j_m |\omega^{j,k}|_E \left(\exp \left((3 + \rho)TC_J|V_m|\right) + \exp \left((2 + \rho)TC_J|V_m|\right) \right) \times \exp \left((1 + \rho)TC_J|V_m|\right).
\]

Let \( m \) be sufficiently large that

\[
\sup_{j \in V_r} |V_m| \lambda^j_m \geq \frac{\rho - 1}{\rho^2},
\]

26
which is possible thanks to Lemma 10. We then use Chebyshev’s Inequality to find that

\[
\mu \left( \sum_{j \in V_r} \|X^j - Z^j\|_T > \epsilon \right) \leq \mu \left( \frac{\rho^2}{\rho - 1} |V_m| \sum_{j \in \mathbb{Z}^d} \lambda_m^j \|X^j - Z^j\|_T > \epsilon \right)
\]

\[
\leq \frac{\rho^2}{\rho - 1} \epsilon^{-1} |V_m| T \exp (2TC) \mathbb{E}^\mu \left[ 2 \exp \left( (3 + \rho)TC, |V_m| \right) \right] \sum_{j \in \mathbb{Z}^d, k \in V_m - V_m} \lambda_m^j |\omega^{j,k}|_\varepsilon 
\]

\[
+ \exp \left( (2 + \rho)TC, |V_m| \right) \sum_{j \in \mathbb{Z}^d, k \in V_m - V_m} \lambda_m^j |\omega^{j,k}|_\varepsilon \|Q^j\|_T 
\]

\[
\leq \frac{2\rho^2}{\rho - 1} c \epsilon^{-1} T \exp (2TC) |V_m|^{-\rho} + \frac{\rho^2}{\rho - 1} c \epsilon^{-1} |V_m| T \exp (2TC + (2 + \rho)TC, |V_m|) \times 
\]

\[
\mathbb{E}^\mu \left[ \sum_{j \in \mathbb{Z}^d} \lambda_m^j \left( \sum_{k \in V_m - V_m} |\omega^{j,k}|_\varepsilon \right)^2 \right]^\frac{1}{2} \times \mathbb{E}^\mu \left[ \sum_{j \in \mathbb{Z}^d} \lambda_m^j |Q^j\|_T^2 \right]^\frac{1}{2} 
\]

\[
\leq \frac{2\rho^2 c}{\rho - 1} \epsilon^{-1} T \exp (2TC) |V_m|^{-\rho} + \frac{\rho^2}{\rho - 1} c \epsilon^{-1} |V_m|^{-\rho} T \exp (2TC),
\]

(64)

where we have used the Cauchy-Schwarz Inequality, and twice used the definition of \( A_c \) in (18). Since \( \rho > 1 \), for \( m \) sufficiently large the above equation is less than \( \delta \), yielding (61). We now prove (62). Let \( \{p_k\}_{k=1}^\infty \subset \mathbb{Z}^+ \) be such that \( p_k > k \) and

\[
\mu \left( \sum_{j \in V_r} \|\Psi^{p_k}(X)^j - \Psi^{p_{k+1}}(X)^j\|_T > 2^{-k} \right) \leq 2^{-k}.
\]

It follows from the Borel-Cantelli Lemma and the two previous equations that \( \{\Psi^{p_k}(X)\}_{k=1}^\infty \) converges almost surely. Let \( Y^j = \lim_{k \to \infty} \Psi^{p_k}(X)^j \) and \( \epsilon_m = |V_m|^{-\frac{1}{2}(1-\rho)} \). Then it follows from (64) that, since \( \rho > 1 \),

\[
\sum_{m=1}^\infty \mu \left( \sum_{j \in V_r} \|\Psi^m(X) - \Psi^{p_m}(X)\| > \epsilon_m \right) \leq \frac{3\rho^2 c}{\rho - 1} T \exp (2TC) \sum_{m=1}^\infty |V_m|^{-\frac{1}{2}\rho} < \infty.
\]

(65)

By the Borel-Cantelli Lemma, for all \( j \in V_r, \Psi^m(X)^j \to Y^j \) almost surely. It remains for us to show that \( Y \) satisfies the relation in (19). It suffices to show that for all \( t \in [0, T] \),

\[
\int_0^t \sum_{k \in \mathbb{Z}^d} \Lambda^{k}(\omega^{j,k}, \Psi^m(X)^j, \Psi^m(X)^{j+k}) \ ds \to \int_0^t \sum_{k \in \mathbb{Z}^d} \Lambda^{k}(\omega^{j,k}, Y^j, Y^{j+k}) \ ds
\]

(66)

\[
\int_0^t b(\Psi^m(X)^j) \ ds \to \int_0^t b(Y^j) \ ds
\]

(67)
It follows from an application of the Borel-Cantelli Lemma to (18) that, \( \mu \) almost surely, there must exist some \( q \in \mathbb{Z}^+ \) such that \( \omega^{j,k} = 0 \) for all \( k \notin V_q \). Since \( r \) is arbitrary, we may assume that \( r \geq q \). Since \( \Psi^m(\mathcal{X})^{j+k} \rightarrow Y^{j+k} \) for all \( k \in V_q \), (66) follows from Assumption 2 and the dominated convergence theorem. (67) follows from Assumption 1 and the dominated convergence theorem. □

**Lemma 13** For each \( \alpha \in \mathbb{R}^+ \), there exists \( c \in \mathbb{R}^+ \) such that

\[
\left\{ \mu \in \mathcal{P}_S(\overline{T}^d) \mid I_\gamma(\mu) \leq \alpha \right\} \subseteq \mathcal{A}_c.
\]  

**Proof:** Suppose that \( I_\gamma(\mu) \leq \alpha \). By [18, Theorem 4.5.10], for all \( f \in C_b(\overline{T}^d) \), where \( C_b(\overline{T}^d) \) is the set of all bounded continuous functions on \( \overline{T}^d \) which are \( \mathcal{B}(\overline{T}^d) \)-measurable for some \( q \in \mathbb{Z}^+ \),

\[
\mathbb{E}^\mu[f] - \lim_{n \to \infty} \frac{1}{|V_n|} \log \mathbb{E}\left[ \exp \left( \sum_{j \in V_n} f(S^jY^n) \right) \right] \leq \alpha.
\]  

We will show that in order that (68) is satisfied, it suffices to take

\[
c = \max \left\{ \frac{\alpha + \varepsilon_2}{\varepsilon_1}, \frac{\alpha + a_2}{a_1} \right\},
\]  

(70)

where the constants \( \varepsilon_1, \varepsilon_2, a_1, a_2 \) are defined in Assumptions 3 and 5. For \( r \in \mathbb{Z}^+ \), let \( \phi_r(\mathcal{Y}^n) := \varepsilon_1 \sigma_r(\|W^n.0\|_T^2) \), where \( \sigma_r : \mathbb{R}^+ \to \mathbb{R}^+ \) is continuous and bounded, and \( \sigma_r(x) \to x \) as \( r \to \infty \). Substituting \( f = \phi_r \) into (69), taking \( r \to \infty \), and using Assumption 5, we find that

\[
\varepsilon_1 \mathbb{E}^\mu[\|X^n\|^2_T] \leq \alpha + \varepsilon_2.
\]  

(71)

This means that if \( c \geq (\alpha + \varepsilon_2)/\varepsilon_1 \), then the first condition for membership of \( \mathcal{A}_c \) is satisfied (see (18)). Next, we define for \( r \in \mathbb{Z}^+ \), \( r > m \geq m_0 \)

\[
\phi_r(\mathcal{Y}^n) = a_1 |V_m|^{2r+2} \exp \left( 2T(2 + \rho)C_J|V_m| \right) \left( \sum_{k \in V_r - V_m} |J^{n,k}|_\mathcal{E} \right)^2.
\]

Substituting \( f = \phi_r \) into (69), taking \( r \to \infty \), and using Assumption 3 we find that

\[
\mathbb{E}^\mu[a_1 |V_m|^{2r+2} \exp \left( 2T(2 + \rho)C_J|V_m| \right) \sum_{j \in V_n} \left( \sum_{k \notin V_m} |J^{n,j,k}|_\mathcal{E} \right)^2] \leq \alpha + a_2.
\]

This means that the second condition for membership of \( \mathcal{A}_c \) is satisfied once \( c \geq a_1^{-1}(\alpha + a_2) \). We similarly find using Assumption 3 that

\[
\mathbb{E}^\mu[a_1 |V_m|^{r+1} \exp \left( T(3 + \rho)C_J|V_m| \right) \sum_{j \in V_n} \sum_{k \notin V_m} |J^{n,j,k}|_\mathcal{E}] \leq \alpha + a_2,
\]

(72)
which means that the third condition for membership of $A_c$ is satisfied once $c \geq a_1^{-1}(\alpha + a_2)$.

\[\square\]

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