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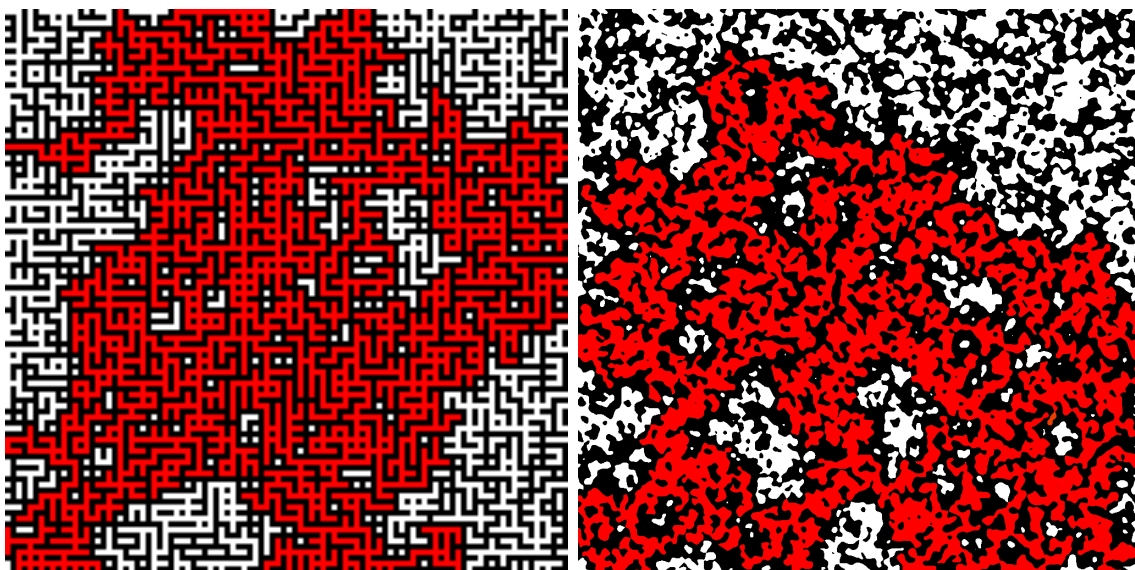
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# Percolation of random nodal lines

VINCENT BEFFARA AND DAMIEN GAYET

May 27, 2016



*Left: critical Bernoulli percolation. In red, a percolating cluster  
Right: analytic percolation. In red, a percolating nodal domain*

## Abstract

We prove a Russo-Seymour-Welsh percolation theorem for nodal domains and nodal lines associated to a natural infinite dimensional space of real analytic functions on the real plane. More precisely, let  $U$  be a smooth connected bounded open set in  $\mathbb{R}^2$  and  $\gamma, \gamma'$  two disjoint arcs of positive length in the boundary of  $U$ . We prove that there exists a positive constant  $c$ , such that for any positive scale  $s$ , with probability at least  $c$  there exists a connected component of  $\{x \in \bar{U}, f(sx) > 0\}$  intersecting both  $\gamma$  and  $\gamma'$ , where  $f$  is a random analytic function in the Wiener space associated to the real Bargmann-Fock space. For  $s$  large enough, the same conclusion holds for the zero set  $\{x \in \bar{U}, f(sx) = 0\}$ . As an important intermediate result, we prove that sign percolation for a general stationary Gaussian field can be made equivalent to a correlated percolation model on a lattice.

Keywords: Percolation, analytic random function.

MATHEMATICS SUBJECT CLASSIFICATION 2010: 60K35, 26E05.

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## 1 Introduction

In this paper, we prove that for a natural infinite dimensional space of analytic functions, for any fixed open connected set  $U$  in the real plane, with uniform probability there exist connected components of the zero set of the random function which cross arbitrary large homothetical copies of  $U$ . This result lies at the intersection of two almost disjoint fields of geometric probability. The first one involves the geometry of zeros of smooth Gaussian functions on the affine real space or on a compact manifold, the other concerns percolation, Ising model and Gaussian free field for instance. A main qualitative difference between the two fields is the presence in the second one of large scale phenomena arising from the microscopic behaviour, beginning with Russo-Seymour-Welsh theory in percolation, see below. Our result establishes the first large scale phenomenon happening in the first field, using methods coming from both fields. Note that our model is defined globally, not microscopically.

In this introduction, we first recall some topics and results in these classical domains, then we state our main results, we discuss how the Bargmann-Fock space is related to random algebraic geometry, we recall the Bogomolny-Schmidt conjecture and lastly we propose some open questions.

**Geometry and topology of random nodal sets.** For a stationary (*i.e.* invariant in distribution under translations) Gaussian field  $f$  on the affine space  $\mathbb{R}^n$ , two main subjects have been studied, namely the statistics of the volume and the Euler characteristic of zero sets of  $f$  in a large ball, see for instance the book [1] and references therein. Since these

observables can be computed locally by integral geometry and the Gaussian field is smooth, the main tool is the Kac-Rice formula.

On a compact manifold, two very natural types of Gaussian random functions have been studied. If  $M$  is equipped with a Riemannian metric, we can consider Gaussian random independent sums of eigenfunctions of the Laplacian with eigenvalues less than a parameter  $L$ . If  $M$  denotes the complex or real projective space, one can study random homogeneous polynomials of degree  $d$  with Gaussian independent coefficients (more generally holomorphic sections of the  $d$ -th power of a holomorphic line bundle over a Kähler manifold or its real part). For nodal sets of positive dimension, their mean volume was first studied [7] (in the Riemannian case), then their mean Euler characteristic [32] was computed (in the algebraic case). With [28] and [16], the subject changed since observables which cannot be computed locally were estimated, beginning with the number of components the zero set of the random function. The universal presence of given diffeomorphic types (included arrangements of ovals) in the zero sets began with [18], see the survey [3] for further references. In both models, the correlation function of the Gaussian field rescales naturally under the action of the parameter (the eigenvalue bound  $L$  or the degree  $d$ ) to a universal kernel on the affine space. Finding the limit of this rescaling is trivial for standard geometries like the round sphere or the flat torus, and in general can be extracted from deep results of semi-classical analysis [24] and complex analysis [40, 41]. In the algebraic case, this universal kernel is precisely the kernel we use in this paper, see [8]. Hence, this is an important motivation for studying the Bargmann-Fock space.

**Percolation.** The main contribution of this paper is to bring to the topic of random nodal lines ideas and techniques originated from percolation theory. In its simplest form, Bernoulli percolation [12] is defined as follows: color each vertex of a periodic lattice  $\mathcal{T}$  independently either black or white, with probability  $p$  and  $1 - p$  respectively, and define the random subgraph  $G$  of  $\mathcal{T}$  formed of all the vertices colored black and of the edges joining them. There exists a critical parameter  $p_c$  such that  $G$  has a.s. no infinite connected component if  $p < p_c$ , and a.s. at least one infinite component if  $p > p_c$ ; what will be relevant to us is the behavior of  $G$  at the critical point, in dimension 2. We refer the reader to [21, 6] for further references on the model.

If  $\mathcal{T}$  is a periodic triangulation of the plane with enough symmetry (in practice, one typically works on the triangular lattice or the "Union-Jack lattice", *i.e.* the face-centered square lattice), it is a classical result tracing back to Kesten [25] that  $p_c = 1/2$ ; the fundamental reason for this being a *duality* between white and black clusters on  $\mathcal{T}$ , each cluster being surrounded by a cluster of the other color. It was proved by Harris [23] that at the critical point, with probability 1 the random graph  $G$  has no infinite component.

One crucial technique on critical two-dimensional percolation, which we will extend to the setup of random nodal lines, is known as Russo-Seymour-Welsh theory [34, 35] and leads to the *box-crossing property* of Bernoulli percolation: namely, for every  $\rho > 1$  there exists a positive bound  $c(\rho)$  such that every rectangle of size  $\rho s \times s$  is traversed in its long dimension by a black cluster with probability at least  $c(\rho)$ , uniformly in  $s$ . This readily extends to the crossing of *quads*, which are regions of the form  $sU$  where  $U$  is a simply connected domain with two disjoint marked boundary intervals  $\gamma$  and  $\gamma'$ : the probability that  $sU$  contains a black cluster connecting  $s\gamma$  to  $s\gamma'$  is bounded below uniformly in  $s$ .

The box-crossing property has many consequences. First, it implies that even though there is no infinite cluster, every box of size  $n$  contains a black cluster of diameter of order  $n$ . It also implies the non-existence of an infinite cluster and moreover quantifies it: the probability that the origin is in a cluster of diameter  $L$  is then bounded above by  $L^{-\eta}$  for

some  $\eta > 0$ . It is the main tool used in the control of the geometry of critical clusters [2], and a fundamental ingredient in the obtention of Schramm-Loewner Evolution as a scaling limit [38, 13].

Russo-Seymour-Welsh theory has been extended to dependent models [14], as well as to some random [11, 39] or non-planar [30, 5] lattices. It remains an open problem to generalize it to triangulations without symmetries. Our main statement in this paper is that the box-crossing property applies to random nodal lines.

**The main result.** Let  $\mathcal{A}$  be the space of real analytic functions on  $\mathbb{R}^2$ , and  $\langle \cdot, \cdot \rangle_{BF}$  the scalar product defined, when it exists, by

$$\forall f, g \in \mathcal{A}, \langle f, g \rangle_{BF} = \int_{\mathbb{C}^2} F(z) \overline{G(z)} e^{-\|z\|^2} \frac{dx}{\pi^2}, \quad (1.1)$$

where  $F$  and  $G$  are the the complex extensions of  $f$  and  $g$ . The real Bargmann-Fock space  $\mathcal{F}$  is the space of functions in  $\mathcal{A}$  which have finite norm for this product. This Hilbert space induces a natural abstract Wiener space  $\mathcal{W}(\mathcal{F})$  of analytic functions, see Appendix 6.1. More concretely, we can choose a Hilbert basis of  $\mathcal{F}$ , for instance the monomials  $(\frac{1}{\sqrt{i!j!}} x_1^i x_2^j)_{i,j \in \mathbb{N}}$ . Then, a random function of  $\mathcal{W}(\mathcal{F})$  is of the form

$$\forall x = (x_1, x_2) \in \mathbb{R}^2, f(x) = \sum_{i,j=0}^{\infty} a_{ij} \frac{1}{\sqrt{i!j!}} x_1^i x_2^j, \quad (1.2)$$

where the coefficients  $(a_{ij})_{i,j \in \mathbb{N}}$  are independent real Gaussian normal variables. For almost all coefficients, this sum does not converge in  $\mathcal{F}$ , but almost surely it converges uniformly on every compact of  $\mathbb{R}^2$ , so that it converges as analytic functions. Note that the correlation function of this Gaussian field equals

$$\forall (x, y) \in (\mathbb{R}^2)^2, e_{\mathcal{W}(\mathcal{F})}(x, y) = \mathbf{E}_{\mathcal{W}(\mathcal{F})}(f(x)f(y)) = \exp\langle x, y \rangle.$$

A more convenient way to see this set of random functions is to choose, as our space of random analytic functions,

$$\mathcal{W} = \left\{ x \mapsto f(x) \exp\left(-\frac{1}{2}\|x\|^2\right), f \in \mathcal{W}(\mathcal{F}) \right\} \quad (1.3)$$

instead of  $\mathcal{W}(\mathcal{F})$ . Notice that the signs and the zeros of the functions are not changed when passing from one space to the other. Then, it is immediate to see that the correlation function associated to  $\mathcal{W}$  equals

$$\forall (x, y) \in (\mathbb{R}^2)^2, e_{\mathcal{W}}(x, y) = \mathbf{E}_{\mathcal{W}}(g(x)g(y)) = \exp\left(-\frac{1}{2}\|x - y\|^2\right). \quad (1.4)$$

In other words, this model is in fact the analytic stationary Gaussian field on  $\mathbb{R}^2$  with covariance  $e_{\mathcal{W}}$ .

**Theorem 1.1** *Let  $\Gamma = (U, \gamma, \gamma')$  be a quad, that is a triple given by a smooth bounded open connected set  $U \subset \mathbb{R}^2$ , and two disjoint compact smooth arcs in  $\partial U$ . Then, there exists a positive constant  $c$  such that for any positive  $s$ , with probability at least  $c$  there exists a connected component of  $\{x \in \bar{U}, f(sx) > 0\}$  intersecting both  $\gamma$  and  $\gamma'$ , where  $f$  is a random element of  $\mathcal{W}(\mathcal{F})$  or  $\mathcal{W}$ . For  $s$  large enough, the same conclusion holds for the nodal set  $\{x \in \bar{U}, f(sx) = 0\}$ .*

**Remark 1.2** *In fact, we prove the more general Theorem 4.7 which holds for  $f$  being a  $C^3$  random stationary Gaussian field whose correlation function is positive, is invariant under horizontal symmetry, and decreases polynomially with the distance between points, for a degree larger or equal to 68. This number should not be taken too seriously, since on the one hand, it can be lowered if the constants in the proofs are more accurately estimated, and on the other hand, the natural degree should be 4, see Theorem 4.5 for a family of discrete percolation processes for which this is the case.*

The usual consequences of the box-crossing property for percolation include estimates for the probabilities of various connection events, and they all apply here. We do not make a full list but just choose to mention one striking corollary:

**Theorem 1.3** *With probability 1, none of the sets  $f^{-1}(\{0\})$ ,  $f^{-1}(\mathbb{R}_+^*)$  and  $f^{-1}(\mathbb{R}_-^*)$  has an unbounded connected component.*

**Some heuristics.** In Theorem 1.1, the first assertion concerning nodal positive domains can be seen as the statement of a box-crossing type property for the random coloring of the plane given by the sign of the function  $f$ . We therefore have to prove that a crossing where  $f$  is positive exists with uniformly positive probability, which is precisely the kind of results produced by Russo-Seymour-Welsh theory.

Moreover, the second assertion can be deduced from the first one, if there is enough independence for the sign of  $f$  between two disjoint domains. Indeed, the simultaneous existence of a path from  $\gamma$  to  $\gamma'$  along which  $f$  is positive, and a similar path along which it is negative, implies the existence of a component of the zero set of  $f$  in between.

The biggest issue to overcome is the rigidity created by the analyticity of the function  $f$ . We are basing our approach on a RSW result for dependent models by Tassion [39], but even though the correlation kernel of  $f$  has fast decay, this does not imply that the restrictions of  $f$  to disjoint open sets are decorrelated — to the contrary, analytic continuation shows that the restriction of  $f$  to any neighborhood specifies  $f$  in the whole plane. Even knowing the sign of  $f$  on an open set  $V$  can be enough to reconstruct  $f$  up to a multiplicative constant, as soon as  $V$  intersects the zero set of  $f$ .

To address the issue, we will discretize the model by considering the restriction of  $f$  to the vertices of a lattice of mesh  $\varepsilon$  lying in our rescaled domain  $sU$ . The mesh has to be chosen with some care: it has to be coarse enough for the restricted model to have small correlation, and to avoid the effects of the rigidity; but at the same time it should be fine enough to ensure that the knowledge of the sign of  $f$  on the lattice suffices to determine the topology of its nodal domains.

**Discretization.** One of our main tools is Theorem 1.4, which holds for general stationary Gaussian fields, hence has its own interest.

**Theorem 1.4** *Let  $f$  be a  $C^3$  random stationary Gaussian field on  $\mathbb{R}^2$  satisfying the non-degeneracy condition (3.5) for  $m = 3$  (see below),  $\mathcal{T}$  be a periodic lattice, and  $\mathcal{E}$  be its set of edges. Fix  $\delta > 0$  and  $\eta > 0$ . Then there exists  $s(\delta, \eta) > 0$ , such that for every  $s \geq s(\delta, \eta)$  and every  $\varepsilon \leq s^{-8-\eta}$ , with probability at least  $1 - \delta$  the following event happens :*

$$\forall e \in \varepsilon \mathcal{E} \cap [-s, s]^2, \#(e \cap f^{-1}(\{0\})) \leq 1. \quad (1.5)$$

This theorem proves that for every scale  $s$  large enough, the discretization on a lattice of mesh small enough (polynomially decreasing with  $s$ ), provides on the box  $[-s, s]^2$  a

family of percolation processes which are equivalent to the continuous percolation process. Indeed, under the event (1.5), two adjacent vertices in  $\varepsilon\mathcal{T}$  are of same sign for  $f$  if and only if  $f$  is of this constant sign on the edge between them, so that a percolation for positive signs in  $\varepsilon\mathcal{T}$  through the length of any rectangle inside  $[-s, s]^2$  means exactly the existence of an analogous continuous positive percolation for the field.

**Bargmann-Fock and polynomials.** Consider a real random homogeneous polynomial of degree  $d$ ,

$$P(X) = \sum_{|I|=d} a_I \sqrt{\frac{(d+n)!}{I!}} X^I, \quad (1.6)$$

where  $X = (X_0, \dots, X_n) \in \mathbb{R}P^n$  are the projective coordinates,  $I = (i_0, \dots, i_n) \in \mathbb{N}^{n+1}$ ,  $|I| = i_0 + \dots + i_n$ ,  $I! = i_0! \dots i_n!$ ,  $X^I = X_0^{i_0} \dots X_n^{i_n}$  and the  $(a_I)_I$  are independent normal random coefficients. This measure on polynomials is very natural because it has a geometric nature: the monomials form an orthonormal basis for the Fubini-Study  $L^2$ -norm

$$\|P\|^2 = \int_{\mathbb{C}P^n} \|P(z)\|_{FS}^2 d\text{vol}(z),$$

where the  $\|\cdot\|_{FS}$  denotes the Fubini-Study norm on the  $d$ -th power  $\mathcal{O}(d)$  of the hyperplane bundle over the complex projective space, and  $d\text{vol}$  is the uniform volume form on  $\mathbb{C}P^n$  of total volume equal to 1. Note that we integrate over the complex manifold  $\mathbb{C}P^n$  and not  $\mathbb{R}P^n$ . Kostlan [26] and independently Shub and Smale [37] proved, for instance, that with this measure and for  $n = 1$ , the average number of real roots of a real polynomial of degree  $d$  is precisely  $\sqrt{d}$ , for every  $d$ . This algebraic random model is in fact very general and holds in the realm of holomorphic sections of the high powers  $d$  of an ample line bundle over any compact complex manifold (see [36]), as well as the real version of them (see [16]).

On the chart  $X_0 \neq 0$  of  $\mathbb{R}P^n$ , consider now the affine rescaled coordinates  $\forall i \in \{1, \dots, n\}$ ,  $x_i = \sqrt{d} \frac{X_i}{X_0}$ . The associated affine random polynomial  $p$  satisfies

$$\forall x \in \mathbb{R}^n, p(x) := \frac{1}{X_0^d} P\left(\frac{x}{\sqrt{d}} X_0\right) = \sum_{|J| \leq d} a_{(d-|J|, J)} \sqrt{\frac{(d+n)!}{(d-|J|)! J!}} \frac{x^J}{d^{n/2}} \xrightarrow{d \rightarrow \infty} \sum_{J \in \mathbb{N}^n} \tilde{a}_J \frac{x^J}{\sqrt{J!}},$$

where the coefficients  $(\tilde{a}_J)_{J \in \mathbb{N}^n}$  are independent normal variables. In particular for  $n = 2$  the limit is precisely the random function  $f$  given by (1.2). Moreover, the Fubini-Study  $L^2$ -norm of the rescaled polynomials converges the norm (1.1). In fact, the more general process of random holomorphic sections of large powers of ample holomorphic line bundles over projective manifolds (and their real counterpart) rescale asymptotically to this universal process, too. This gives to the Bargmann-Fock space a universal algebraic origin.

**The Bogomolny-Schmidt conjecture.** In [9] and [10], the authors studied the nodal lines of random sums of Gaussian waves in the real plane:

$$\forall x \in \mathbb{R}^2, g(x) = \sum_{m=-\infty}^{\infty} a_m J_{|m|}(r) e^{im\phi} \quad (1.7)$$

Here  $(r, \phi)$  denotes the polar coordinates of  $x$ ,  $J_k$  denotes the  $k$ -th Bessel function, and  $(a_m)_{m \in \mathbb{Z}}$  are independent normal coefficients. The correlation function for this model equals (see [10])

$$e(x, y) = \mathbf{E}(g(x)g(y)) = J_0(\|x - y\|), \quad (1.8)$$



hence is stationary, depends only on the distance between points, and decays polynomially in this distance, with degree  $1/2$ .

The authors associated to this random analytic model a discrete percolation-like model, and gave heuristic evidence that both model should be close. In particular, their work suggests that nodal lines should cross arbitrary large rectangles of fixed shape, with uniformly bounded probability. Numerical evidence was then obtained by several authors.

As we will explain it below, see Remark 4.6, our main result does not apply for this model since the decorrelation decay is too weak. Moreover, one of the main ingredient of the proof of Theorem 1.1 is the important FKG inequality given by condition 1. of Definition 2.1 below. Indeed in our case, it is the consequence of the positivity of the correlation function, but for random waves, the sign of the correlation function is not constant.

On the other hand, Theorem 1.4 applies to the model of random waves. Since the association of the model to a discrete percolation in [9] is based on two simplifications, namely the periodic distribution of the critical points and the independence of the process in space, Theorem 1.4 could be more realistic mathematical way to handle the problem.

**Questions.** From this present work natural questions arise.

- **What is the mean number of finite connected components per square?**

In [28] and [29], the authors proved the existence of a non explicit asymptotic equivalence of the number of connected components of the nodal sets. In [20], [18], [17] and [19], the authors gave explicit lower and upper bounds for the expected Betti numbers of the nodal sets. However, these bounds are different, although the upper ones allow to get an asymptotic equivalent of the Euler characteristic (see [27]). In [9], the authors gave a heuristic way to compute the equivalence. Since their bond percolation has no correlation, they can use computations that give asymptotics for connected components of the percolation. Theorem 1.4 might possibly give new estimates of these constants, if discrete computations for correlated models can be performed.

- **Do our random nodal lines converge to  $SLE(6)$ ?**

In a celebrated paper [38], Smirnov proved that for the triangle lattice, percolation lines converge, as the scale of the lattice tends to zero, to  $SLE(6)$ . Can we prove a similar result for our nodal lines? This is conjectured to hold, and supported by numerical evidence, in the case of random plane waves. In the case of percolation, RSW bounds are crucial, as is the obtention of a conformally invariant observable.

- **Do algebraic nodal lines behave like critical percolation?**

As explained before, our stationary model is in fact the universal model that arises in a very general algebraic situation. It is very likely that the following counterpart of Theorem 1.1 is true: *Fix a smooth bounded open set  $U$  in  $\mathbb{R}^2$  and two arcs  $\gamma, \gamma'$  in its boundary. Then, there exists a positive constant  $c$ , such that for any degree  $d$  large enough, for a random polynomial*

$$p(x_1, x_2) = \sum_{i+j \leq d} a_{ij} \frac{x_1^i x_2^j}{\sqrt{i!} \sqrt{j!}}$$

*with i.i.d. Gaussian coefficients  $a_{ij}$ , with probability at least  $c$  there is a connected component in  $U$  of the vanishing locus of  $p$  touching both  $\gamma$  and  $\gamma'$ . This model*



converges to our analytic model, but unfortunately, it is no more invariant by translation. This loss of symmetries, though small and vanishing in the limit, is fatal to some of the arguments we use.

**Structure of the article.** In Section 2, we recall the main steps of Tassion’s theorem in order to keep track of all the constants involved in the proofs. In Section 3, we obtain some simple results for general Gaussian fields and their link with the FKG inequalities. In Section 4, we first state a RSW theorem for the sign over a fixed lattice of a general correlated Gaussian with sufficiently correlation decay. Then we give the proof of Theorem 1.1, assuming that Theorem 1.4 is true. In the last Section 5, we prove Theorem 1.4, which shows that on large rectangles, the percolation process given by the sign of the random function is equivalent to the discrete percolation process given by the sign on the vertices of a lattice with sufficiently small mesh size, which is quantitatively estimated. In the annex, we explain the general construction of the Wiener space associated to a Hilbert space, and we state a quantitative implicit function theorem that is used for the proof of Theorem 1.4.

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## 2 Tassion’s theorem

### 2.1 Statement

**Notations, definitions and conditions.** We consider a random process  $\Omega$  on the plane  $\mathbb{R}^2$ , such that any point of  $\mathbb{R}^2$  has a random colour, black or white. In this article, we will consider two main processes. Firstly, for any random Gaussian field  $f$  on  $\mathbb{R}^2$ ,  $\Omega(f)$  will denote the colouring by sign (black if positive, white in the other case). Secondly, if  $\mathcal{T}$  is a lattice,  $\Omega(f, \mathcal{T})$  will denote the following colouring : a point  $x$  in  $\mathbb{R}^2$  is black if  $x$  belongs to an edge between two vertices at which  $f$  is positive, and white in the other case, see Definition 3.1.

- Recall that there exists a natural partial order on the elements of  $\Omega$ , choosing *white* < *black* at every point of  $\mathbb{R}^2$ . By definition, a *black-increasing* event  $\mathcal{A}$  of the colouring process  $\Omega$  is such that for any  $\phi, \psi \in \Omega$  with  $\phi \in \mathcal{A}$  and  $\phi \leq \psi$ , then  $\psi \in \mathcal{A}$ .
- For any  $\rho \geq 1$  and  $s > 0$ , denote by  $f_s(\Omega, \rho)$  be the probability that there exists a left-right black crossing in the rectangle  $[0, \rho s] \times [0, s]$ , that is a continuous curve of black points contained inside the rectangle and joining  $\{0\} \times [0, s]$  to  $\{\rho s\} \times [0, s]$ .

**Definition 2.1** *Fix a colouring process  $\Omega$  as defined above, let us set the following conditions:*

1. (FKG inequality) *If  $\mathcal{A}, \mathcal{B}$  are two black-increasing events, we have*

$$P[\mathcal{A} \cap \mathcal{B}] \geq P[\mathcal{A}]P[\mathcal{B}].$$

2. (Symmetries) The measure is invariant under  $\mathbb{Z}^2$ -translation,  $\pi/2$ -rotation centered at elements of  $\mathbb{Z}^2$  and reflection with respect to the horizontal axis ( $Ox$ ).
3. (Percolation through squares) There exists  $c_0(\Omega) > 0$  such that

$$\forall s \in \mathbb{N}^*, f_s(\Omega, 1) \geq c_0(\Omega).$$

When no confusion is possible, we will omit the reference to  $\Omega$ .

We will use a recent theorem proved by V. Tassion, which establishes a RSW-type theorem in a general setting. Unfortunately, the statements in the article [39] are not explicit enough to be directly applied here for two reasons.

- The first reason is not very fundamental, and can be omitted in a first reading. In [39], the two conditions 2. and 3. hold for any real translation and real sizes. More precisely, the analogous of condition 3. was the stronger condition

$$\forall s \geq 1, f_s(\Omega, 1) \geq c_0(\Omega), \tag{2.1}$$

see [39, (1)]. Since we apply Tassion's theorem to the sign of a fixed function on lattices which are  $\varepsilon$ -rescaled copies of the Union Jack lattice  $\mathcal{T}$ , we can only get uniform percolation, in fact with probability  $1/2$ , on squares which are union of fundamental squares of  $\varepsilon\mathcal{T}$ . Changing even a bit these squares changes a priori the probability of percolation, and it is not clear how. This is the reason why we replace (2.1) by 3.

- The second reason is crucial for our work. The article [39] is written for a fixed model, so that the constants arising in its theorems and their proofs are not in general explicit. However, as explained before, we need to apply these results for a family of processes  $\Omega(f, \varepsilon\mathcal{T})$ , see Definition 3.1 below, where the mesh will have a decreasing size  $\varepsilon$ . For this reason, we have to keep track all of the involved constants.

**Tassion's quantitative theorem.** Here is a quantitative version of the main Theorem of [39]. We emphasize that this statement is essentially the one given by Tassion and does not add any important information.

**Theorem 2.2** (see Tassion [39]) *For any  $\nu \in ]0, 1/2[$ , there exists  $t_\nu(\Omega) \in [1, +\infty[$  given by formula (2.7) below and a positive continuous function  $P_\nu$  defined on  $[1, +\infty[ \times ]0, 1[$ , such that for any model  $\Omega$  satisfying the conditions of Definition 2.1, we have*

$$\forall \rho \geq 1, \forall s \in \mathbb{N}^*, s \geq t_\nu(\Omega), f_s(\Omega, \rho) \geq P_\nu(\rho, c_0(\Omega)),$$

where  $c_0(\Omega)$  is given by condition 3. in Definition 2.1.

**Remark 2.3** *In [39], the result is stated without the restriction  $s \geq t_\nu(\Omega)$ , since, on one hand,  $t_\nu(\Omega) < +\infty$  is implied by the additional condition (iii) of [39, Remark 2.2]. On the other hand, if we know that  $t_\nu(\Omega)$  is finite, we still need to uniformly estimate the probability of percolating in boxes of sizes smaller than  $t_\nu(\Omega)$ , which can be done easily for an individual process. However, these probabilities have no reason to be uniformly bounded from below for any models.*

The continuous model  $\Omega(f)$  associated to the signs of the random analytic field with correlation  $e_{\mathcal{W}}$  given by (1.4) satisfies the three conditions of Definition 2.1. However, there is no direct control of the parameter  $t_\nu(\Omega)$ , because this parameter is related to the independence of the field at different points. As explained before, in our case, the analytic continuation principle means that local knowledge on the function is enough to determine it globally, so that a priori  $t_\nu(\Omega)$  is infinite and Theorem 2.2 empty. To bypass this obstruction, we will discretize our continuous model, in order to extract the relevant information without discovering too much. In order to satisfy the symmetry assumption 2. in Definition 2.1, we choose a symmetric periodic triangulation invariant by horizontal reflection and  $\pi/2$  rotation, for instance the face-centered square lattice, see Definition 3.3. Since we fixed the scale  $s$  to 1, we will consider a lattice with mesh size  $\varepsilon > 0$ . We will need to adapt this size to the size of the rectangles, see Theorem 1.4, which is the reason why we need to keep track of the constants in Tassion's theorem.

The rest of this section summarizes the principal lemmas of [39] and is devoted to the explanation of their quantitative refinements that we need for our own results. We do not repeat the whole proofs of the lemmas; instead we only explain in which way our weaker and quantitative conditions change them. The reader not interested in these technical refinements is advised to read Tassion's article [39] and then to go on with Section 3, where Theorem 4.5 gives an explicit bound of  $t_\nu(\Omega)$  for the cases we are interested in. However, even if this bound is proved in Section 3, it depends on other parameters which we introduce in the rest of this present section. In particular, we introduce

- the function  $\phi(\Omega, \cdot)$  given by (2.3),
- the function  $\alpha(\Omega, \cdot)$  given by Lemma 2.7,
- the parameter  $s(\Omega)$  given by (2.5),
- and the main parameter  $t_\nu(\Omega)$  given by (2.7).

## 2.2 Control of the constants

We consider in this subsection a random process  $\Omega$  on the plane  $\mathbb{R}^2$ , such that any point of  $\mathbb{R}^2$  has a random colour, black or white, and which satisfies the three conditions of Definition 2.1. We follow the lemmas of [39], keeping track of the constants, in order to get the quantitative Theorem 2.2, and in particular an upper bound for the important parameter  $t_\nu(\Omega)$ . Moreover, we must take in account the weaker condition 3. in the proofs.

**Notations.** We begin with further notations, which are chosen when possible to be close to the ones in [39].

- For any  $n \in \mathbb{N}^*$  and any  $s \geq 0$ , define  $B_s = [-s, s]^n \subset \mathbb{R}^n$ .
- For  $n = 2$  and any  $0 \leq s \leq t < \infty$ ,  $A_{s,t}$  denotes the annulus  $B_t \setminus B_s$ .
- For any  $s > 0$ , define  $\mathcal{A}_s = \{\text{there exists a black circuit in the annulus } A_{s,2s}\}$ .
- For any  $S \subset \mathbb{R}^2$ ,  $\sigma(S)$  denotes the sigma-algebra defined by the events measurable with respect to the colouring in  $S$ .
- For any pair  $(S, T)$  of subsets of  $\mathbb{R}^2$ , denote by  $\phi(\Omega, S, T)$  the number

$$\phi(\Omega, S, T) = \sup_{\mathcal{A} \in \sigma(S), \mathcal{B} \in \sigma(T)} |\mathbf{P}[\mathcal{A} \cap \mathcal{B}] - \mathbf{P}[\mathcal{A}]\mathbf{P}[\mathcal{B}]|, \quad (2.2)$$

and by  $\phi(\Omega, \cdot)$  the function

$$s \in \mathbb{R}_+^* \mapsto \phi(\Omega, s) = \phi(\Omega, A_{2s,4s}, \mathbb{R}^2 \setminus A_{s,5s}), \quad (2.3)$$

see (iii) of [39, Remark 2.2].

**Remark 2.4** • *In particular, on an event with probability at least  $1 - \phi(\Omega, s)$ , the signs on  $A_{2s,4s}$  and the signs on  $\mathbb{R}^2 \setminus A_{s,5s}$  can be coupled with the realization of a pair of independent colorings.*

- *We will need a polynomial decay with sufficiently high degree of  $\phi(\Omega, \cdot)$  twice in our proofs. Firstly, in Tassion's argument in order to get sign percolation on large rectangles, see Lemma 2.10 below, and secondly in the topological argument given above: the existence of a percolating nodal line will be given by the percolation of a positive line and a parallel negative line. We must then know that the two latter events are almost independent, see the end of the proof of Proposition 4.8.*
- *In our case where the colour is given by the sign of a random Gaussian field  $f$ , the polynomial decay of  $\phi(\Omega, \cdot)$  is the consequence of the polynomial decay of the correlation function of  $f$ , see Proposition 4.1.*

From now on to the end of this section, we explain how the proofs of [39] can be amended. We do not repeat the arguments, so that again, the interested reader may prefer to first first read the original version.

**Amending Tassion's lemmas.** The following Lemma from [39] will be useful. It compares the probabilities of crossing a rectangle and the existence of a black circuit. We added the third assertion for a comparison of these probabilities between two different rectangles.

**Lemma 2.5** ([39, Corollary 1.3]) *Let  $s, s' \in \mathbb{N}^*$  with  $s \leq s'$ . Then*

1.  $\sqrt{f_s(\Omega, 2)} \geq P[\mathcal{A}_s] \geq f_s(\Omega, 3)^4$ ,
2.  $f_s(\Omega, 1 + i\kappa) \geq f_s(\Omega, 1 + \kappa)^i f_s(\Omega, 1)^{i-1}$  for any  $\kappa > 0$  and any  $i \geq 1$ ,
3. Let  $\rho, \rho' > 1$ . Then,  $f_{s'}(\Omega, \rho') \geq f_s(\Omega, \rho)^{1+2 \max(0, \frac{\rho'}{\rho-1}(\frac{s'}{s} - \frac{\rho'}{\rho}))}$ .

**Proof.** The last assertion is trivial if  $\rho' s' \leq \rho s$ , since then  $f_{s'}(\Omega, \rho') \geq f_s(\Omega, \rho)$ . In the other case, using the condition 2. of Definition 2.1, it can be proved using a sequence of rectangles translated and  $\pi/2$ -rotating from  $[0, \rho s] \times [0, s]$ , alternatively horizontal and vertical, in order to cross the larger rectangle  $[0, \rho' s'] \times [0, s']$ .  $\square$

**Remark 2.6** *If the lower bounds  $f_s(\Omega, \rho)$  given by Theorem 2.2 for an integer  $s$  hold for rectangles translated by elements of  $\mathbb{R}^2$ , not only by of  $\mathbb{Z}^2$ , then by similar arguments than in the latter proof, we can replace  $s \in \mathbb{N}^*$  by  $s \geq 1$ .*

The quantitative parameter  $t_\nu(\Omega)$  of Theorem 2.2 is itself related to the important function  $s \mapsto \alpha(\Omega, s)$  defined in [39, Lemma 2.1]. We recall its definition. For this, let  $s \geq 1$  and  $-s/2 \leq \alpha \leq \beta \leq s/2$ , and let us set (see Fig. 2.2 for an illustration)

- $\mathcal{H}_s(\alpha, \beta)$  to be the event that there exists a black path in the square  $B_{s/2}$ , from the left side to  $\{s/2\} \times [\alpha, \beta]$ ;

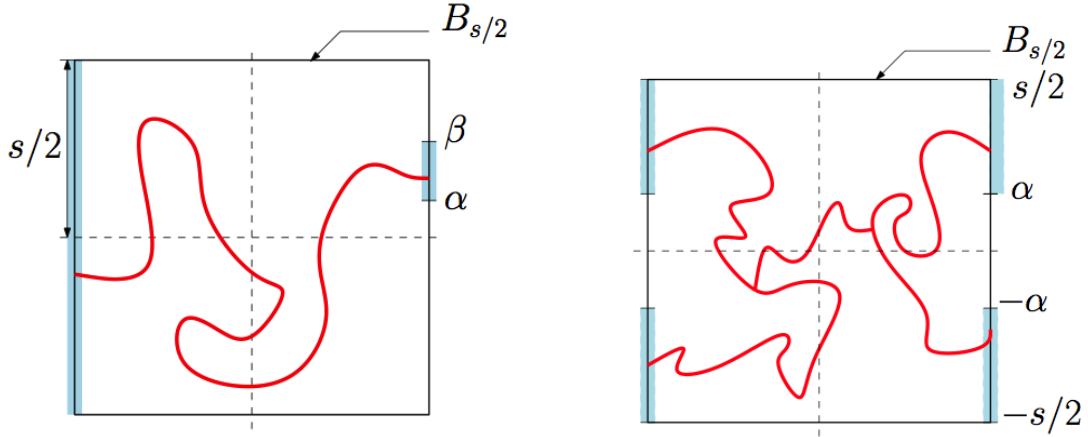


Fig. 2.2. The events  $\mathcal{H}_s(\alpha, \beta)$  and  $\mathcal{X}_s(\alpha)$  (from [39])

- $\mathcal{X}_s(\alpha)$  to be the event that there exists in  $B_{s/2}$  a black path  $\gamma_{-1}$  from  $\{-s/2\} \times [-s/2, -\alpha]$  to  $\{-s/2\} \times [\alpha, s/2]$ , a black path  $\gamma_1$  from  $\{s/2\} \times [-s/2, -\alpha]$  to  $\{s/2\} \times [\alpha, s/2]$ , and a black path from  $\gamma_{-1}$  to  $\gamma_1$ .

**Lemma 2.7** ([39, Lemma 2.1]) *There exists a universal polynomial  $Q_1 \in \mathbb{R}[X]$ , positive on  $]0, 1[$ , such that for every  $s \in 2\mathbb{N}^*$ , there exists  $\alpha(\Omega, s) \in [0, s/4]$  satisfying the following two properties:*

(P1)  $\mathbf{P}[\mathcal{X}_s(\alpha(\Omega, s))] \geq Q_1(c_0(\Omega))$ .

(P2) If  $\alpha(\Omega, s) < s/4$ , then  $\mathbf{P}[\mathcal{H}_s(0, \alpha(\Omega, s))] \geq c_0(\Omega)/4 + \mathbf{P}[\mathcal{H}_s(\alpha(\Omega, s), s/2)]$ .

**Proof.** In [39],  $\alpha(\Omega, s)$  is denoted by  $\alpha_s$ , and  $Q_1(c_0)$  by  $c_1$ , which is equal to  $c_0(c_0/8)^4$ . The only place in the proof where the condition 3. is needed is the lower bound  $c_0 \leq 2\mathbf{P}[\mathcal{H}(0, s/2)]$ , which is a direct consequence of the equality  $c_0 = \mathbf{P}[\mathcal{H}(-s/2, s/2)]$  and the second symmetry of condition 2. The latter holds by condition 3. of Definition 2.1. and since  $s \in 2\mathbb{N}^*$ .  $\square$

The following lemma allows to get a black circuit (and hence a percolation in a rectangle by Lemma 2.5) at any large scale, if we have a good control of the function  $\alpha(\Omega, \cdot)$ . First, for any  $s \in \mathbb{N}^*$ , define

$$k(s) \in \{0, \dots, 5\}, s + k(s) \equiv 0 \pmod{6}. \quad (2.4)$$

**Lemma 2.8** ([39, Lemma 2.2.]) *There exist two universal polynomial  $q_2, \tilde{q}_2 \in \mathbb{R}[X]$ , positive on  $]0, 1[$ , such that if  $Q_2(c_0) := \min(q_2(c_0), \tilde{q}_2(c_0))$ , then*

$$\forall s \in 3\mathbb{N}^*, \alpha(\Omega, s + k(s)) \leq 2[\alpha(\Omega, 2s/3)] \Rightarrow \mathbf{P}[\mathcal{A}_{s+k(s)}] \geq Q_2(c_0),$$

**Proof.** First, we prove the lemma without the floors, the integer condition on  $s$  and with  $k(s) = 0$ . In [39],  $Q_2(c_0)$  is denoted by  $c_2$ . The polynomials can be extracted from the alternative or  $f_s(\Omega, 4/3) \geq Q_1(c_0)(c_0/4)^2$  given by the proof of [39, Lemma 2.2.], and Lemma 2.5. In the first case of the alternative,  $f_s(\Omega, 2) \geq Q_1(c_0)^5$ , so that

$$\mathbf{P}[\mathcal{A}_s] \geq f_s(\Omega, 3)^4 \geq (f_s(\Omega, 2)^2 f_s(\Omega, 1))^4 \geq Q_1(c_0)^{40} c_0^4 := q_2(c_0).$$

The second case is similar. Now, we add the floors, the integer condition and the integer  $k(s)$ . In the proof of [39, Lemma 2.2.], we change  $\alpha_{2s/3}$  into  $\lfloor \alpha_{2s/3} \rfloor$  any time it appears, and we change a bit the square  $R$  into

$$R = \left( -\frac{1}{6}(s + k(s)), -\lfloor \alpha_{2s/3} \rfloor \right) + B_{(s+k(s))/2},$$

while  $R' = \left( (s + k(s))/6, -\lfloor \alpha_{2s/3} \rfloor \right) + B_{(s+k(s))/2}$ . Then thanks to these floors and the restriction  $s + k(s) \in 6\mathbb{N}$ ,  $R$ ,  $R'$  and  $B_{s/3}$  have vertices with integral coordinates, so that condition 3. of Definition 2.1 can be applied. Moreover, since

$$\alpha(\Omega, s + k(s)) \leq 2\lfloor \alpha(\Omega, 2s/3) \rfloor \leq 2\alpha(\Omega, 2s/3),$$

we still get the intersection of the events  $\mathcal{X}(\alpha(\Omega, 2s/3))$  in  $B_{s/3}$  and with the event  $\mathcal{E}$  and  $\mathcal{E}'$ , with the same probabilities without the integer and floor additions.  $\square$

**Lemma 2.9** ([39, Lemma 3.1]) *There exists a universal continuous positive function  $Q_3$  defined on  $]0, 1[$ , such that the following holds: for every  $s \geq 1$  and  $t \in 2\mathbb{N}^*$ ,  $t \geq 4s$ , if  $\mathbf{P}[\mathcal{A}_s] \geq Q_2(c_0)$  and  $\alpha(\Omega, t) \leq s$ , then  $\mathbf{P}[\mathcal{A}_t] \geq Q_3(c_0)$ .*

**Proof.** In [39],  $Q_3(c_0)$  is denoted by  $c_3$ , and is proved to be equal to  $Q_2(c_0)(c_0/4)^2$ , with  $Q_2$  from Lemma 2.8. The integer constraint allows to apply the proof since the restricted condition 3. then applies for the boxes  $[-t, 0] \times [-t/2, t/2]$  and  $[0, t] \times [-t/2, t/2]$ .  $\square$

Now, define the integer

$$s(\Omega) = \max \{s \in \mathbb{N}^*, \phi(\Omega, s) \geq Q_3(c_0)/2\}, \quad (2.5)$$

where  $\phi(\Omega, \cdot)$  is defined by (2.3) and  $Q_3$  is given by Lemma 2.9. The parameter  $s(\Omega)$  estimates the scale  $s$  from which events on rings of size  $s$  and separated from each other by  $s$  are almost independent, see Remark 2.4. In [39],  $s(\Omega)$  is denoted by  $s_0$ , without the condition of being an integer, see the condition before [39, Lemma 3.2].

**Lemma 2.10** ([39, Lemma 3.2]) *There exists a continuous positive universal function  $\tau_1 : ]0, 1[ \rightarrow [4, \infty[$  such that for any  $s \in \mathbb{N}^*$ ,  $s \geq s(\Omega)$ , if  $\mathbf{P}[\mathcal{A}_s] \geq Q_2(c_0)$ , then there exists  $s' \in [4s, \tau_1(c_0)s] \cap \mathbb{N}^*$  such that  $\alpha(\Omega, s') \geq s$ .*

**Proof.** In [39],  $\tau_1(c_0)$  is denoted by  $C_1$ , where  $C_1$  is any constant satisfying  $C_1 \geq 4$  and

$$(1 - c_3/2)^{\log_5(C_1)} < c_0/2,$$

with  $c_3 = Q_3(c_0)$ , where  $Q_3$  is defined by Lemma 2.9. The formulation with the integer condition is straightforward since in the proof  $5^i s \in \mathbb{N}^*$ , and we just choose  $\lfloor C_1 s \rfloor$  instead of  $C_1 s$ .  $\square$

We can now define the main quantitative parameter  $t_\nu(\Omega)$ . For any  $\nu \in ]0, 1/2[$ , set

$$\gamma(\nu) = 1 + \log_{4/(3+2\nu)}(3/2 + \nu) > 1 \quad (2.6)$$

and

$$t_\nu(\Omega) = (3/2 + \nu)s_\nu(\Omega)^{\gamma(\nu)}\alpha(\Omega, s_\nu(\Omega))^{1-\gamma(\nu)}, \quad (2.7)$$

where

$$s_\nu(\Omega) = \max(s(\Omega), \lfloor 6/\nu \rfloor + 1), \quad (2.8)$$

see (2.5) for the definition of  $s(\Omega)$  and Lemma 2.7 for  $\alpha(\Omega, \cdot)$ . In the rest of the article, we will write  $\alpha(\cdot)$  instead of  $\alpha(\Omega, \cdot)$  when the process  $\Omega$  is explicit.

**Lemma 2.11** ([39, Lemma 3.3]) *For any  $\tau \in ]0, 1/2[$ , there exists a continuous universal function  $\tau_{3,\nu} : ]0, 1[ \rightarrow [4, \infty[$  and an infinite sequence  $(s_i)_{i \in \mathbb{N}^*} \in (6\mathbb{N}^*)^{\mathbb{N}^*}$  such that*

- $s_1 \leq t_\nu(\Omega)$
- $\forall i \geq 1, 4s_i \leq s_{i+1} \leq \tau_{3,\nu}(c_0)s_i,$
- and  $P[\mathcal{A}_{s_i}] > Q_2(c_0).$

**Proof.** In order to obtain the existence and an estimate of  $s_1$ , let us define the following sequence  $(\sigma_p)_{p \in \mathbb{N}}$ :  $\sigma_0 = s_\nu(\Omega) \in \mathbb{N}^*$ , see (2.8), and for any  $p \in \mathbb{N}^*$ ,

$$\sigma_{p+1} = \frac{3}{2}\sigma_p + k\left(\frac{3}{2}\sigma_p\right) \in 6\mathbb{N}^*$$

where the function  $k$  is defined by (2.4). For any  $s \geq 6/\nu$ ,  $k(s) \leq \nu s$ , so that

$$\forall p \in \mathbb{N}, \sigma_p \leq (3/2 + \nu)^p s_\nu(\Omega).$$

Denote by  $N$  the first  $p \in \mathbb{N}^*$ , such that  $\alpha(\Omega, \sigma_{p+1}) \leq 2\alpha(\Omega, \sigma_p)$ . Then

$$(3/2 + \nu)^N s_\nu(\Omega) \geq \sigma_N > \alpha(\Omega, \sigma_N) > 2^N \alpha(s_\nu(\Omega))$$

so that

$$N \leq \log\left(\frac{s_\nu(\Omega)}{\alpha(s_\nu(\Omega))}\right) \log^{-1}\left(\frac{4}{3 + 2\nu}\right).$$

Choose

$$s_1 := \sigma_{N+1} \leq (3/2 + \nu)^{N+1} s_\nu(\Omega).$$

Then  $s_1 \leq t_\nu(\Omega)$ , by (2.7). Moreover by Lemma 2.8, we have  $\mathbf{P}[\mathcal{A}_{s_1}] \geq Q_2(c_0)$ . The existence of the rest of the sequence  $(s_i)_{i \geq 2}$  follows the same lines than [39]. If  $\nu = 0$ ,  $\tau_{3,0}(c_0)$  is denoted by  $C_3$  by Tassion and is defined by  $C_3 = C_1^{1+\log_4/3(3/2)}$ , where  $C_1$  is our  $\tau_1(c_0)$  defined by Lemma 2.10. In the case  $\nu > 0$  we just change  $C_3$  into

$$\tau_{3,\nu}(c_0) = C_1^{1+\log_4/(3+2\nu)(3/2+\nu)}.$$

This concludes the proof.  $\square$

**Proof of Theorem 2.2.** For any  $i \geq 1$ , we want to prove uniform percolation for integer sizes between  $s_i$  and  $s_{i+1}$ . By assertions 3. and 1. of Lemma 2.5, for all integer  $i \geq 1$ ,

$$f_{s_i}(\Omega, \rho) \geq f_{s_i}(\Omega, 2)^{1+2 \max(0, \rho-2)} \geq \mathbf{P}[\mathcal{A}_{s_i}]^{2+4 \max(0, \rho-2)} \geq Q_2(c_0)^{2+4 \max(0, \rho-2)},$$

so that by the same assertion, for any  $s \in [s_i, s_{i+1}] \cap \mathbb{N}^*$ ,

$$f_s(\Omega, \rho) \geq f_{s_i}(\Omega, \rho)^{1+2 \max\left(0, \frac{\rho}{\rho-1} \left(\frac{s_{i+1}}{s_i} - 1\right)\right)} \geq Q_2(c_0)^{(2+4 \max(0, \rho-2))(1+2(\tau_{3,\nu}(c_0)-1)\frac{\rho}{\rho-1})}.$$

The right-hand side can be chosen to be the universal function  $P_\nu(\rho, c_0)$ .  $\square$

### 3 Gaussian fields

In this section we introduce some natural conditions for the Gaussian fields we will work with, and we prove some more or less elementary percolation properties on the associated processes on lattices or on  $\mathbb{R}^2$ .



### 3.1 Various conditions.

Let  $f : \mathbb{R}^2 \rightarrow \mathbb{R}$  be a centered Gaussian field, that is for every  $x \in \mathbb{R}^n$ ,  $f(x)$  is a random centered Gaussian variable. Let  $\mathcal{T}$  be a lattice in  $\mathbb{R}^2$ ,  $\mathcal{E}$  its set of edges and  $\mathcal{V}$  its set of vertices.

**Definition 3.1** *Let us define the two following processes on  $\mathbb{R}^2$ :*

- $\Omega(f)$  denotes the colouring by sign, that is  $x \in \mathbb{R}^2$  is black if  $f(x) > 0$  and white in the other case.
- $\Omega(f, \mathcal{T})$  denotes the following colouring on  $\mathbb{R}^2$ : if  $x \in \mathbb{R}^2$  belongs to an edge  $e \in \mathcal{E}$  whose two extremities  $v_1 \in \mathcal{V}$  and  $v_2 \in \mathcal{V}$  satisfy  $f(v_1) > 0$  and  $f(v_2) > 0$ , then  $x$  is black;  $x$  is white otherwise.

**Remark 3.2** *Since outside a set of vanishing measure,  $f$  does not vanish on  $\mathcal{V}$ , a.s. a vertex  $v \in \mathcal{V}$  is white if and only if  $f(v) < 0$ .*

In the proof of the main Theorem 1.1 (but not Theorem 1.4), we will need lattices with the following properties.

**Definition 3.3** *For any lattice  $\mathcal{T} \subset \mathbb{R}^2$ , define the following conditions:*

- (Periodicity)  $\mathcal{T}$  is a periodic,
- (Triangulation)  $\mathcal{T}$  is a triangulation,
- (Symmetry)  $\mathcal{T}$  is invariant by the reflection with respect to the horizontal axis, and by  $\pi/2$ -rotation.
- (Integrality) There exists  $N \in \mathbb{N}^*$ , such that  $\mathcal{V} \subset (\frac{1}{N}\mathbb{Z})^2$ .

**Remark 3.4** • *As a lattice satisfying the symmetry conditions, one can choose the face-centered square lattice, though the specific choice will not be relevant in our proofs.*

- *The triangulation condition is needed for duality reasons, only to ensure condition 3. of Definition 2.1 for  $\Omega(f, \mathcal{T})$ , see Lemma 4.2.*

Recall that the correlation function  $e$  of  $f$  is defined by  $e(x, y) = \mathbf{E}(f(x)f(y))$  for any  $(x, y)$  in  $(\mathbb{R}^n)^2$ . Depending on the nature of the results, we will impose to the field  $f$  to fulfill part or all of the following conditions.

- (Stationarity) There exists a function  $K : \mathbb{R}^n \rightarrow \mathbb{R}$  such that

$$\forall x, y \in V^2, e(x, y) = K(x - y). \quad (3.1)$$

In this case, we normalize  $f$  so that  $\forall x \in \mathbb{R}^n, K(0) = e(x, x) = 1$ .

- (Positivity)

$$K \geq 0. \quad (3.2)$$

- (Invariance by conjugation when  $n = 2$ )

$$\forall (a, b) \in \mathbb{R}^2, K(a, -b) = K(a, b). \quad (3.3)$$

- (Polynomial decay)

$$\exists \alpha > 0, \exists \beta, \forall x \in \mathbb{R}^n, |K(x)| \leq \beta \|x\|^{-\alpha}. \quad (3.4)$$

- (Non-degeneracy) There exists  $m \in \mathbb{N}$ , such that for any  $k \in \{0, \dots, m\}$ , the following mapping

$$(v_1, \dots, v_k) \in (\mathbb{R}^n)^k \mapsto d^{2k} K(0)(v_1, v_1, \dots, v_k, v_k) \quad (3.5)$$

is non-degenerate.

**Lemma 3.5** *For any  $p \in \mathbb{N}$  and any  $\alpha > 0$ , the stationary Gaussian field associated to the real Bargmann-Fock space, with correlation  $e_{\mathcal{W}}(x, y) = \exp(-\frac{1}{2}\|x - y\|^2)$ , see (1.4), satisfies all of these hypotheses.*

**Proof.** Only the last condition has to be clarified. For any  $p$ ,

$$d^{2p} K(0)(v_1, v_1, \dots, v_p, v_p) = (-1)^p \|v_1\|^2 \cdots \|v_p\|^2,$$

so that condition (3.5) holds.  $\square$

**Remark 3.6** *Note that if  $f$  is stationary ( $f$  satisfies (3.1)), the covariance function  $e$  is symmetric, that is  $\forall (x, y) \in (\mathbb{R}^2)^2$ ,  $e(x, y) = e(y, x) = K(x - y)$ , so that any odd derivative of  $K$  at 0 vanishes. In particular, two derivatives of different parity of  $f$  are independent random variables.*

### 3.2 The FKG inequality.

One of the crucial ingredients of the proof of Theorem 1.1, is the Fortuin-Kasteleyn-Ginibre (FKG) inequality for our model, see § 2.1 and condition 1. in Definition 2.1. The following theorem gives a link between positive correlation and FKG inequality.

**Theorem 3.7 (see Pitt [31])** *Let  $\varphi = (\varphi_i)_{1 \leq i \leq k}$  be a Gaussian vector in  $\mathbb{R}^k$  with non-negative covariance function. Then  $\varphi$  satisfies the FKG property: for any two bounded, nondecreasing, measurable functions  $F, G : \mathbb{R}^k \rightarrow \mathbb{R}$ , one has*

$$E[F(\varphi)G(\varphi)] \geq E[F[\varphi]]E[G[\varphi]]. \quad (3.6)$$

*In particular, if  $\mathcal{A}$  and  $\mathcal{B}$  are increasing events on  $\varphi$ , then  $P[\mathcal{A} \cap \mathcal{B}] \geq P[\mathcal{A}]P[\mathcal{B}]$ .*

In our case,  $\phi$  will denote the sign of  $f$  at the vertices of a lattice, and typically  $\mathcal{A}$  and  $\mathcal{B}$  will denote a black crossing of a rectangle, or the existence of a black circuit in a ring.

**Remark 3.8** *This theorem will be enough for our purposes here, because all the events we will consider will actually depend on the value of the random field  $f$  at finitely many points; but the results readily extends by approximation to continuous increasing functionals of the whole field.*

The following lemma is an immediate corollary of this theorem.

**Lemma 3.9** *For any stationary random Gaussian field  $f$  satisfying condition (3.2) (positivity) and any lattice  $\mathcal{T}$ , the processes  $\Omega(f)$  and  $\Omega(f, \mathcal{T})$  introduced in Definition 3.1 satisfy condition 1. (FKG) of Definition 2.1.*

**Remark 3.10** *In the particular case of the Gaussian field given by the real analytic functions in the Wiener space  $\mathcal{W}$ , see (1.4) or (1.2), the expansion of the field in a monomial basis gives a decomposition of the form  $f = \sum_{i \in I} a_i f_i$  where the  $a_i$  are i.i.d. Gaussian variables, and where the  $f_i$  are positive in the first quadrant. A monotone functional of  $f$  depending only on the values of  $f$  in that quadrant can then be seen as a monotone functional of the  $(a_i)_{i \in I}$ , and the inequality (3.6) follows directly from the statement of the Harris-FKG inequality for a product measure. Going from the quadrant to the whole space then follows from stationarity.*

### 3.3 Elementary percolation

We will need the following two simple lemmas in the proof of the main results.

**Lemma 3.11** *(Uniform percolation on a small box) Let  $f$  be a stationary Gaussian field on  $\mathbb{R}^n$  satisfying condition (3.5) for  $m = 2$ . Then if  $B_\lambda = [-\lambda, \lambda]^n$ ,*

$$\forall \delta > 0, \exists \lambda > 0, \mathbf{P}[f|_{B_\lambda} > 0] \geq 1/2 - \delta.$$

**Proof.** Fix  $u > 0$ , such that  $f(0) \geq u$  with probability at least  $1/2 - \delta/2$ . By Markov inequality and Lemma 5.2 below applied to  $p = 1$ ,

$$\forall s \leq 2, \mathbf{P}\left[\|f\|_{C^1(B_\lambda)} \leq \frac{u}{2\sqrt{2}\lambda}\right] \geq 1 - \left(\frac{2\sqrt{2}\lambda}{u}\right)(C_1\sqrt{\ln 2}).$$

If  $\lambda = \left(\frac{\delta}{2}\right)u(2\sqrt{2}C_1\sqrt{\ln 2})^{-1}$ , the two events happen simultaneously with probability larger than  $1/2 - \delta$ , and in this case by Taylor applied between 0 and any point of  $B_\lambda$ , we obtain  $f|_{B_\lambda} > 0$ .  $\square$

The following Lemma asserts that trivially the percolation process associated to  $f$  has uniform positive probability of happening in rectangles inside a fixed square.

**Lemma 3.12** *(Uniform percolation on a box) Let  $f$  be a stationary Gaussian field on  $\mathbb{R}^2$  satisfying condition (3.2)(positivity) and (3.5)(non-degeneracy) for  $m = 2$ . Then*

$$\forall s > 0, \mathbf{P}[f|_{B_s} > 0] > 0.$$

**Proof.** By stationarity and by Lemma 3.11 applied for  $\delta = 1/4$ , there exists  $\lambda > 0$  such that for any fixed box  $b$  which is a translation of  $B_\lambda$ , with probability at least  $1/4$  we have  $f|_b > 0$ . Since being positive on a box is an increasing event, the FKG property given by Theorem 3.7 implies that the wanted probability is larger than  $1/4^N$ , where  $N$  denotes the number of cubes like  $b$  needed to cover  $B_s$ .  $\square$

**Remark 3.13** *Note that if  $f$  satisfies the conditions of Lemma 3.12, then*

$$\forall s > 0, \exists a > 0, \forall \mathcal{T}, \mathbf{P}[f|_{\mathcal{V} \cap B_s} > 0] \geq a,$$

where  $\mathcal{T} \subset \mathbb{R}^2$  is a lattice and  $\mathcal{V}$  its set of vertices.

## 4 Discretized percolation

We begin with a discrete correlated percolation problem on a periodic lattice  $\mathcal{T}$ . Then we explain how to transfer our continuous percolation problem to a discrete one.

#### 4.1 A correlated discrete percolation

Let  $\mathcal{T}$  be a periodic graph,  $\mathcal{V}$  be its set of vertices,  $\mathcal{E}$  be its set of edges and

- $a_{\mathcal{T}}$  denotes the mean number of vertices of  $\mathcal{V}$  in a unit square of  $\mathbb{R}^2$ .

**Quantitative independence.** Let  $f$  be a centered Gaussian field on  $\mathcal{V}$ . We give a quantitative estimate for the function  $\phi(\Omega(f, \mathcal{T}), \cdot)$  defined by (2.3). Recall that this function estimates the independence of events in two disjoint rings and is obtained by a union bound. Note that this parameter can be defined without any assumptions on  $f$  or  $\mathcal{T}$ .

**Proposition 4.1** *There exists a constant  $C > 0$ , such that for any random Gaussian stationary field  $f$  on any lattice  $\mathcal{T}$ , for any pair of subsets  $(S, T)$  of  $\mathbb{R}^2$ ,*

$$\phi(\Omega(f, \mathcal{T}), S, T) \leq C \sum_{v \in S \cap \mathcal{V}, v \in T \cap \mathcal{V}} |K(v - w)|, \quad (4.1)$$

where  $K$  is defined by (3.1). Moreover, if  $f$  satisfies in addition the condition (3.4) (polynomial decay with degree  $\alpha > 0$ ), then there exists  $C' > 0$  depending only on  $C$  and the constants  $\alpha, \beta$  of condition (3.4) such that

$$\begin{aligned} \forall s \geq 1, \phi(\Omega(f, \mathcal{T}), s) &\leq C' a_{\mathcal{T}}^2 s^{4-\alpha} \\ \text{and } \forall S, T \subset \mathbb{R}^2, \phi(\Omega(f, \mathcal{T}), S, T) &\leq C' a_{\mathcal{T}}^2 \text{area}(S) \text{area}(T) (\text{dist}(S, T))^{-\alpha}. \end{aligned}$$

**Proof.** By [33], for any  $v$  and  $w$  two different vertices of  $\mathcal{V}$ ,

$$|\mathbf{P}[f(v)f(w) > 0] - \frac{1}{2}| = \frac{1}{\pi} |\arcsin(K(v - w))|,$$

so that there exists  $C > 0$  such that this difference is uniformly bounded by  $C|K(v - w)|$ . Fix  $\mathcal{A} \in \sigma(S)$  and  $\mathcal{B} \in \sigma(T)$ , where for any subset  $M \subset \mathbb{R}^2$ ,  $\sigma(M)$  denotes the  $\sigma$ -algebra defined by the events measurable with respect to the signs of  $f$  on  $M \cap \mathcal{V}$ . Then for any vertex  $w$  in  $T \cap \mathcal{V}$ ,

$$|\mathbf{P}[f(w) > 0 | \sigma(S)] - \frac{1}{2}| \leq C \sum_{v \in S \cap \mathcal{E}} |K(v - w)|,$$

so that  $|\mathbf{P}[\mathcal{B} | \mathcal{A}] - \mathbf{P}[\mathcal{B}]| \leq C \sum_{v \in S \cap \mathcal{E}, v \in T \cap \mathcal{E}} |K(v - w)|$ , which is the first assertion of the Proposition. Now, for any  $s > 0$ , there exist  $C', C'', C''' > 0$  depending only on  $C, \alpha$  and  $\beta$ , such that

$$\begin{aligned} \phi(\Omega(f, \mathcal{T}), s) &\leq 4\pi^2 a_{\mathcal{T}} C' \int_{r \in [0, s] \cup [5s, +\infty[} \int_{t \in [2s, 4s]} \max_{\|w\|=r, \|v\|=t} |K(v - w)| r dr dt \\ &\leq C'' a_{\mathcal{T}}^2 \int_{r \in [0, s] \cup [5s, \infty[} \int_{t \in [2s, 4s]} \frac{rt}{|r - t|^\alpha} dr dt \leq C''' a_{\mathcal{T}}^2 s^{4-\alpha}, \end{aligned}$$

The second assertion can be proved in a very similar way.  $\square$

**Estimates.** In this paragraph, we obtain some bounds for the parameters  $c_0(\Omega(f, \mathcal{T}))$  of Definition 2.1 and  $\alpha(\Omega(f, \mathcal{T}), \cdot)$  of Lemma 2.7.

**Lemma 4.2** *Let  $f$  be a stationary Gaussian field on  $\mathbb{R}^2$  satisfying the conditions (3.3.) (invariance by conjugation) and (3.5.) (non-degeneracy) for  $m = 3$ , and  $\mathcal{T}$  be a lattice satisfying the conditions of Definition 3.3. Then  $\Omega(f, \mathcal{T})$  satisfies condition 2. (symmetry) and condition 3. (percolation through squares) of Definition 2.1. More precisely,*

$$\forall s \in \mathbb{N}^*, f_s(\Omega(f, \mathcal{T}), 1) = c_0(\Omega(f, \mathcal{T})) = 1/2.$$

**Proof.** Since the covariant function of  $f$  and  $\mathcal{T}$  are invariant under the symmetries of the axes and  $\pi/2$ -rotation, the process  $\Omega(f, \mathcal{T})$  satisfies condition 2. of Definition 2.1. Moreover, since  $\mathcal{T}$  is a triangulation, since the vertices lie on  $(\frac{1}{N}\mathbb{Z})^2$ , on any square  $B_s$  with  $s \in \mathbb{N}^*$ , either there is an horizontal black crossing in  $\mathcal{V}$ , that is an arc  $c$  in  $\mathcal{T}$  joining  $\{-s\} \times [-s, s]$  to  $\{s\} \times [-s, s]$  in  $B_s$  such that  $f_{|c \cap \mathcal{V}} > 0$ , or there is a vertical negative arc. Since the coefficients  $(a_{ij})_{ij}$  are centered Gaussian, since the square, the measure and  $\mathcal{T}$  are invariant under a  $\pi/2$ -rotation, both events happen with the same probability, so that they both have probability equal to 1/2. By invariance under translation, the probability of a black crossing in any square is 1/2. In other words, for any  $s \in \mathbb{N}^*$ ,  $f_s(\Omega(f, \mathcal{T}), 1) = 1/2$ .  $\square$

**Remark 4.3** *Note that Lemma 4.2 does not require the polynomial decay of the correlation nor its positivity, and holds in particular for the random wave model given by (1.7).*

In the proof of Theorem 1.1 we will need an estimate of the parameters  $t_\nu(\Omega(f, \varepsilon\mathcal{T}))$  for our discretized processes, which implies in particular an estimate for  $\alpha(s(\Omega(f, \varepsilon\mathcal{T})))$ , where  $\alpha(\Omega, \cdot)$  is defined in Lemma 2.7 and  $s(\Omega(f, \varepsilon\mathcal{T}))$  by (2.5).

**Lemma 4.4** *Suppose that  $f$  is a stationary Gaussian field defined on  $\mathbb{R}^2$  and satisfying condition (3.2), (3.3) and (3.5) for  $m = 2$ . Then, there exist  $a, b > 0$ , such that after changing the universal polynomial  $Q_1$  in Lemma 2.7 into  $aQ_1$ , the following holds: for any periodic lattice  $\mathcal{T}$  satisfying all of the conditions of Definition 3.3,*

$$\forall s \in \mathbb{N}^*, \alpha(\Omega(f, \mathcal{T}), s) \geq b.$$

**Proof.** Recall that  $\alpha(\Omega, s)$  is a constant that must satisfy the two conditions (P1) and (P2) of Lemma 2.7. Denote by  $b^+$  and  $b^-$  the two squares

$$b^\pm = [\pm s/2 - \lambda/2, \pm s/2 + \lambda/2] \times [-\lambda/2, \lambda/2]$$

and by  $\mathcal{A}^\pm$  the black-increasing events  $\mathcal{A}^\pm = \{f_{|b^\pm \cap \mathcal{V}} > 0\}$ , where  $\mathcal{V}$  is the set of vertices of  $\mathcal{T}$ . By Lemma 3.11 and the the FKG inequality given by Lemma 3.9, there exists  $\tau > 0$  depending only on  $f$  such that  $\forall s \geq 1$ ,  $\mathbf{P}[\mathcal{A}^+ \cap \mathcal{A}^-] \geq \tau^2$ . Assume that  $\alpha(\Omega(f, \mathcal{T}), s) < \lambda/4$ . Then we have

$$\{\mathcal{X}_s(\alpha(\Omega(f, \mathcal{T}), s))\} \cap \mathcal{A}^+ \cap \mathcal{A}^- \subset \{\mathcal{X}_s(\lambda/4)\}$$

so that, again by FKG inequality and (P1),  $\mathbf{P}[\mathcal{X}_s(\lambda/4)] \geq Q_1(c_0)\tau^2$ , where  $Q_1$  is defined in Lemma 2.7, so that  $\lambda/4$  satisfies (P1) after replacing  $Q_1$  by  $\tau^2 Q_1$ . Moreover,

$$\begin{aligned} \mathbf{P}[\mathcal{H}_s(0, \lambda/4)] - \mathbf{P}[\mathcal{H}_s(\lambda/4, s/2)] &\geq \mathbf{P}[\mathcal{H}_s(0, \alpha(\Omega(f, \mathcal{T}), s))] - \mathbf{P}[\mathcal{H}_s(\alpha(\Omega(f, \mathcal{T}), s), s/2)] \\ &\geq c_0/4, \end{aligned}$$

so that  $\lambda/4$  satisfies condition **(P2)**. In conclusion, we can replace  $\alpha(\Omega(f, \mathcal{T}), s)$  by  $\lambda/4$ .  $\square$

The following Theorem 4.5 provides a large family of correlated percolations on lattices, and has its own interest. Moreover, it provides a bound for the main parameter  $t_\nu(\Omega)$  which will be used in the proof of the main Theorem 1.1. Recall that  $\gamma(\nu) = 1 + \log_{4/(3+2\nu)}(3/2 + \nu)$ , see (2.6).

**Theorem 4.5** *Let  $f$  be a stationary Gaussian field satisfying the conditions (3.2) (positivity), (3.3) (symmetry), (3.4) (polynomial decay) for  $\alpha > 4$  and (3.5) (non-degeneracy) for  $m = 2$ . Then, for any  $\nu \in ]0, 1/2[$ , there exists a constant  $C_\nu > 0$  depending only on the parameters of condition (3.4), such that for any periodic lattice  $\mathcal{T}$  satisfying the conditions of Definition 3.3, the process  $\Omega(f, \mathcal{T})$  satisfies the conditions of Theorem 2.2, with*

$$t_\nu(\Omega(f, \mathcal{T})) \leq C_\nu a_{\mathcal{T}}^{\frac{2\gamma(\nu)}{\alpha-4}}. \quad (4.2)$$

Moreover, for any such lattice  $\mathcal{T}$ , for any  $\rho \geq 1$ , there exists  $c > 0$ ,

$$\forall s \in \mathbb{N}^*, f_s(\Omega(f, \mathcal{T}), \rho) \geq c.$$

**Proof.** For any lattice  $\mathcal{T}$  satisfying the hypotheses, by Lemma 3.9 and Lemma 4.2,  $\Omega(f, \mathcal{T})$  satisfies all of the conditions of Definition 2.1, so that Theorem 2.2 applies. By Lemma 2.9 and the existence of the universal function  $Q_3$ , by Lemma 4.2 and the existence of the universal parametre  $c_0(\Omega(f, \mathcal{T})) = 1/2$ , by the definition of  $s(\Omega)$  given by (2.5) and by Proposition 4.1, there exists a constant  $C > 0$  depending only on the parameters  $\alpha, \beta$  of the polynomial decay 3.4 such that for any  $\mathcal{T}$

$$s(\Omega(f, \mathcal{T})) \leq C a_{\mathcal{T}}^{2/(\alpha-4)}. \quad (4.3)$$

Moreover by Lemma 4.4, there exists  $a > 0$ , such that for any lattice  $\mathcal{T}$ ,

$$\alpha(s(\Omega(f, \mathcal{T}))) \geq a,$$

so that by (2.7), by (4.3) and the definition (2.8) of  $s_\nu(\Omega)$ , the parameter  $t_\nu(\Omega(f, \mathcal{T}))$  satisfies the upper bound (4.2).

Now by Remark 3.13, there exists  $a > 0$ , such that

$$\mathbf{P}(f|_{B_{\rho t_\nu(\Omega(f, \mathcal{T}))} \cap \mathcal{V}} > 0) \geq a,$$

hence the second result.  $\square$

**Remark 4.6** *For random sums of Gaussian waves, the stationary correlation function is given by (1.8), so that  $\forall x \in \mathbb{R}^2, |K(x)| \leq \|x\|^{-1/2}$ . Hence, a priori Theorem 4.5 does not apply in this case. Notice that the FKG inequality also fails to hold in that model, so it is beyond the techniques that we develop here for several reasons.*

## 4.2 Proof of Theorem 1.1

This section is devoted to the proof of the main result of this paper:

**Theorem 4.7** *Let  $f : \mathbb{R}^2 \rightarrow \mathbb{R}$  be a random Gaussian field satisfying conditions (3.1), (3.2), (3.3), (3.4) for  $\alpha \geq 68$  and (3.5) for  $m = 3$ . Let  $\Gamma = (U, \gamma, \gamma')$  be a quad, that is a triple given by a smooth bounded open connected set  $U \subset \mathbb{R}^2$ , and two disjoint compact smooth arcs in  $\partial U$ . Then, there exists a positive constant  $c$  such that:*

1. for any positive  $s$ , with probability at least  $c$  there exists a connected component of  $\{x \in \bar{U}, f(sx) > 0\}$  intersecting both  $\gamma$  and  $\gamma'$ ;
2. there exists  $s_0 > 0$ , such that for any  $s \geq s_0$ , with probability at least  $c$  there exists a connected component of  $\{x \in \bar{U}, f(sx) = 0\}$  intersecting both  $\gamma$  and  $\gamma'$ ,

**Proof of Theorem 1.1.** By Lemma 3.5, the correlation function given by (1.3) for random elements of  $\mathcal{W}$  (or the Wiener space  $\mathcal{W}(\mathcal{F})$  associated to the Bargmann-Fock space) satisfies the conditions of Theorem 4.7.  $\square$

Theorem 4.7 will be an easy consequence of the following main proposition:

**Proposition 4.8** *Let  $f : \mathbb{R}^2 \rightarrow \mathbb{R}$  be a random Gaussian field satisfying the hypotheses of Theorem 4.7. Let  $(R_i)_{i \in I}$  and  $(S_j)_{j \in J}$  be two finite families of horizontal or vertical rectangles, such that:  $\forall (i, j) \in I \times J, R_i \cap S_j = \emptyset$ . Then there exists  $c > 0$  such that*

1. for any positive  $s$ , the following event  $\Omega_R(s)$  happen with probability at least  $c$ : for every  $i \in I$ , there exists a positive path crossing  $sR_i$  in its length ;
2. for any positive  $s$ , the following event  $\Omega_S(s)$  happen with probability at least  $c$ : for every  $j \in J$ , there exists a negative path crossing  $sS_j$  in the length;
3. there exists  $s_0 > 0$ , such that for any  $s \geq s_0$ ,  $\mathbf{P}[\Omega_R(s) \cap \Omega_S(s)] \geq c$ .

**Proof of Theorem 4.7.** Let  $U \subset \mathbb{R}^2$  be a connected smooth bounded open set and  $\gamma, \gamma' \subset \partial U$  two disjoint connected arcs in the boundary of  $U$ . First, it is clear that there exist a pair of rectangles  $R_+$  and  $R_-$  together with a finite family of horizontal or vertical rectangles  $(R_i \subset U)_{i \in I}$  (resp.  $S_+, S_-$  and  $(S_j \subset U)_{j \in J}$ ) such that, writing  $\tilde{I} = I \cup \{\pm\}$  and  $\tilde{J} = J \cup \{\pm\}$ ,

- $\forall (i, j) \in (\tilde{I} \times \tilde{J}), R_i \cap S_j = \emptyset$ ,
- the arc  $\gamma$  traverses  $R_-$  and  $S_-$  through their shortest width,
- the arc  $\gamma'$  traverses  $R_+$  and  $S_+$  through their shortest width,
- if for all  $i \in \tilde{I}$ , there exists a path  $\gamma_i$  crossing  $R_i$  in its length, then  $\cup_{i \in \tilde{I}} \gamma_i$  is connected.
- if for all  $j \in \tilde{J}$ , there exists a path  $\gamma'_j$  crossing  $S_j$  in its length,  $\cup_{j \in \tilde{J}} \gamma'_j$  is connected.

By Proposition 4.8 for any  $s > 0$ , with probability  $c$  there exists a positive path, i.e. a connected component of  $\{x \in \mathbb{R}^2, f(x) > 0\}$ , (resp. a negative path) in  $s(\cup_{i \in \tilde{I}} R_i)$  (resp.  $s(\cup_{j \in \tilde{J}} S_j)$ ), hence the first assertion.

By the second assertion of Proposition 4.8, there exists  $s_0 > 0$ , such that for  $s \geq s_0$ , both events happen with probability at least  $c > 0$ , so that a crossing nodal line appears between them with at least the same probability.  $\square$

### 4.3 Proof of Proposition 4.8

**Heuristics of the proof.** As explained in the introduction, we need to use a family of intermediary processes which are percolations on lattices of smaller and smaller mesh as the rectangles to be crossed become larger. More precisely, fix  $\mathcal{T}$  a periodic graph and  $\mathcal{V}$  its set of vertices. For any  $\varepsilon > 0$ , we will consider the rescaled lattice  $\varepsilon\mathcal{T}$ , so that  $\varepsilon\mathcal{V}$  denotes its associated set of vertices and  $\varepsilon\mathcal{E}$  its set of edges. Note that

$$\forall \varepsilon > 0, a_{\varepsilon\mathcal{T}} = a_{\mathcal{T}}\varepsilon^{-2}, \quad (4.4)$$



where  $a_{\mathcal{T}}$  is the mean number of vertices of  $\mathcal{V}$  per unit square, see § 4.1. For any  $\varepsilon > 0$  and any random field  $f$  on  $\mathbb{R}^2$ , the restriction of  $f$  to  $\varepsilon\mathcal{V}$  define the random colouring discrete process

$$\Omega_{\varepsilon} = \Omega(f, \varepsilon\mathcal{T}) \quad (4.5)$$

given by Definition 3.1. We assume for a moment that Theorem 1.4 is true (its proof is postponed to the last section 5). Let  $R > 0$  be such that  $B_R$  contains all of the rectangles  $(R_i)_{i \in I}$  and  $(S_j)_{j \in J}$ . For any  $\sigma > 0$ , Theorem 1.4 gives a size  $\varepsilon(\sigma)$  such that with a large probability percolation for the process  $\Omega_{\varepsilon(\sigma)}$  in a rectangle in  $B_{R\sigma}$  is equivalent to continuous percolation for the process  $\Omega(f)$ , see Definition 3.1. Then, by Tassion's Theorem, if  $\mathcal{T}$  satisfies the conditions of Definition 3.3, there is a size  $t_{\nu}(\Omega_{\varepsilon(\sigma)})$ , such that with probability at least  $c > 0$ , percolation happens for  $\Omega_{\varepsilon(\sigma)}$  in the length of given rectangles of sizes larger than  $t_{\nu}(\Omega_{\varepsilon(\sigma)})$ . Since the correlation function of  $f$  decreases polynomially for a sufficiently high degree, this size can be chosen to be smaller than  $\sigma$ , so that we get percolation for the process  $\Omega(f)$  for the rectangles of size  $\sigma$ . If the two families of rectangles are far from each others, again by the polynomially decay of the correlation, positive and negative crossings happen simultaneously.

**Proof of Proposition 4.8.** Fix  $\mathcal{T}$  any lattice satisfying the conditions of Definition 3.3. We begin to prove uniform percolation on one unique rectangle, but for the family of discretized percolations defined by  $\Omega_{\varepsilon}$ , see (4.5), where  $\varepsilon \in (\mathbb{N}^*)^{-1}$  will depend on the size  $s$  of the rectangle. By Lemma 3.9, for any  $\varepsilon > 0$  the process  $\Omega_{\varepsilon}$  satisfies condition 1. of Definition 2.1, and by Lemma 4.2, for any  $\varepsilon \in (\mathbb{N}^*)^{-1}$  it satisfies the two other conditions 2. and 3., with  $c_0(\Omega_{\varepsilon}) = 1/2$ . Hence, the hypotheses of Theorem 2.2 are fulfilled. This implies, if  $\rho \geq 1$  and  $\nu \in ]0, 1/2[$  are fixed, that

$$\forall \varepsilon \in (\mathbb{N}^*)^{-1}, \forall s \in \mathbb{N}^*, s \geq t_{\nu}(\Omega_{\varepsilon}), f_s(\Omega_{\varepsilon}, \rho) \geq P_{\nu}(\rho, 1/2),$$

where  $P_{\nu}$  is the universal function defined in Theorem 2.2. By Theorem 4.5 and (4.4), if

$$\gamma(\nu) = 1 + \log_{4/(3+2\nu)}(3/2 + \nu),$$

see (2.6), there exists  $C_{\nu} > 0$  such that

$$\forall \varepsilon \in (\mathbb{N}^*)^{-1}, t_{\nu}(\Omega_{\varepsilon}) \leq C_{\nu} a_{\mathcal{T}}^{\frac{2\gamma(\nu)}{\alpha-4}} \varepsilon^{-\frac{4\gamma(\nu)}{\alpha-4}}. \quad (4.6)$$

Fix  $\nu \in ]0, 1/2[$  such that  $\gamma(\nu) < 2$  and choose

$$\eta = \gamma^{-1}(\alpha - 4) - 32,$$

which is positive since  $\gamma(\nu) < 2$  and  $\alpha \geq 68$ . Choose  $R > 0$  such that

$$\left( \cup_{i \in I} R_i \cup_{j \in J} S_j \right) \subset B_R$$

and define for any  $\sigma \geq 2$

$$\varepsilon(\sigma) = \left( \lfloor (R\sigma)^{8+\frac{\eta}{16}} \rfloor + 1 \right)^{-1} \in (\mathbb{N}^*)^{-1}. \quad (4.7)$$

This choice is motivated by Theorem 1.4. By (4.6), there exists a constant  $C > 0$  such that

$$\forall \sigma \geq 2, t_{\nu}(\Omega_{\varepsilon(\sigma)}) \leq C \sigma^{\frac{32+\eta/2}{\alpha-4}} \gamma = C \sigma^{\frac{32+\eta/2}{32+\eta}} = o(\sigma).$$

Hence, there exists  $s_1 \geq 2$  not depending on  $\rho \geq 1$  so that by Theorem 2.2,

$$\forall s \in \mathbb{N}^*, s \geq s_1, f_s(\Omega_{\varepsilon(s)}, \rho) \geq P_{\nu}(\rho, 1/2). \quad (4.8)$$

Now we turn to the simultaneous discrete percolation through our two sets of rectangles. For this, for any  $i \in I$  (resp.  $j \in J$ ), denote by  $\rho_i$  (resp.  $\rho'_j$ ) the quotient of the length and the width of  $R_i$  (resp.  $S_j$ ). If

$$c := \min_{(i,j) \in I \times J} (P_\nu(\rho_i, 1/2), P_\nu(\rho'_j, 1/2)) > 0,$$

then by (4.8),

$$\forall s \in \mathbb{N}^*, s \geq s_1, \min_{(i,j) \in I \times J} (f_s(\Omega_{\varepsilon(s)}, \rho_i), f_s(\Omega_{\varepsilon(s)}, \rho'_j)) \geq c. \quad (4.9)$$

For  $s \geq 1$ , define  $\Omega_+(s)$  the event that for every  $i \in I$ , there exists a positive path crossing for  $\Omega_{\varepsilon(s)}$  in the length of  $sR_i$ . We denote by  $\Omega_-(s)$  the analogous event, where we change the sign and the  $R_i$ 's are replaced by the  $S_j$ 's. By the FKG inequalities given by Lemma 3.9,

$$\forall s \in \mathbb{N}^*, s \geq s_1, \mathbf{P}[\Omega_+(s)] \geq c^{|I|} \text{ and } \mathbf{P}[\Omega_-(s)] \geq c^{|J|}. \quad (4.10)$$

Now, we want to obtain percolation for the continuous process  $\Omega(f)$ . For this, first fix

$$\delta = c^{|I|+|J|} \leq \min(c^{|I|}, c^{|J|}). \quad (4.11)$$

By Theorem 1.4 and (4.7), there is  $s_2 := s_2(\delta/4, \eta)$  such that for  $s \geq s_2$ , with probability at least  $1 - \delta/4$ , any positive crossing in the lattice  $\varepsilon(s)\mathcal{T} \cap B_{Rs}$  will produce a continuous positive crossing for  $\Omega(f)$ , as well as for the negative crossings. Hence by (4.10) and (4.11),

$$\forall s \in \mathbb{N}^*, s \geq \max(s_1, s_2), \min(\mathbf{P}[\Omega_R(s)], \mathbf{P}[\Omega_S(s)]) \geq 3\delta/4,$$

where  $\Omega_R$  and  $\Omega_S$  are defined in Proposition 4.8. Moreover, by Lemma 3.12 applied to  $s = R \max(s_1, s_2)$ , there exists  $a > 0$ , such that for any rectangle in  $B_{R \max(s_1, s_2)}$ , with probability at least  $a$ , there exists a (trivial) positive (resp. negative) crossing of this rectangle. Summarizing, and using again FKG inequality for the latter elementary percolations,

$$\forall s \in \mathbb{N}^* \cup [0, \max(s_1, s_2)], \min(\mathbf{P}[\Omega_R(s)], \mathbf{P}[\Omega_S(s)]) \geq \min(3\delta/4, a^{|I|}, |a|^{|J|}). \quad (4.12)$$

In order to remove the integer condition, note that we can translate our lattice  $\mathcal{T}$  by any vector in a fundamental square of  $\mathcal{T}$ . Since the Gaussian field is stationary, the probabilities obtained for the translated rectangles (again with integer sizes) the associated estimates (4.12) are the same. Remark 2.6 concludes.

For the second assertion, we prove that the two events  $\Omega_+(s)$  and  $\Omega_-(s)$  defined below happen simultaneously with uniform positive probability. By (4.10) it is enough to prove that these two events are almost independent. Let  $M, \mu > 0$  be such that

$$M = \max(\text{area}(\cup_i R_i), \text{area}(\cup_j S_j)) \text{ and } \mu = \text{dist}(\cup_i R_i, \cup_j S_j).$$

Proposition 4.1 shows that there exist  $C', C'' > 0$ , such that for any  $s \geq 1$ , with probability at least

$$1 - C' M^2 a_{\mathcal{T}}^2 s^4 \varepsilon(s)^{-4} (\mu s)^{-\alpha} \geq 1 - C'' s^{36-\alpha-\eta/4} = 1 - C'' s^{(4-\alpha)(1-\frac{1}{4\gamma(\nu)})},$$

the signs on  $s(\cup_i R_i) \cap \varepsilon(s)\mathcal{V}$  and  $s(\cup_j S_j) \cap \varepsilon(s)\mathcal{V}$  can be coupled with the realization of a pair of independent colourings, where  $\nu \in ]0, 1/2[$  was chosen above so that  $1 < \gamma(\nu) < 2$  and  $\varepsilon(s)$  is defined by (4.7). Since  $\alpha > 4$  and  $4\gamma(\nu) > 1$ , there exists  $s_3 \geq 1$  such that this

probability is larger than  $1 - \delta/4$  for  $s \geq s_3$ , where  $\delta$  is defined by (4.11). Consequently, by (4.10),

$$\forall s \in \mathbb{N}^*, s \geq \max(s_1, s_3), \mathbf{P}[\Omega_+(s) \cap \Omega_-(s)] \geq \mathbf{P}[\Omega_+(s)]\mathbf{P}[\Omega_-(s)] - \delta/4 \geq 3\delta/4,$$

and hence by the definition of  $s_2$  above,

$$\forall s \in \mathbb{N}^*, s \geq \max(s_1, s_2, s_3), \mathbf{P}[\Omega_R(s) \cap \Omega_S(s)] \geq \delta/2.$$

We can remove the integer condition as above, so that the second assertion of Proposition 4.8 is proved.  $\square$

**Remark 4.9** *Note that we only need in fact  $\alpha > 32(1 + \log_{4/3}(3/2)) + 4$ . There are at least two other potential sources of lowering this degree, namely in [39, Lemma 2.2] and in the size of the box given by the quantitative implicit theorem given by Corollary 6.3. Recall, see Remark 1.2, that the expected optimal degree is believed to be 4, see Theorem 4.5 for support for this guess.*

## 5 Proof of Theorem 1.4

The goal of this section is to prove the main Theorem 1.4. This theorem states that for any stationary Gaussian field satisfying condition (3.5) for  $m = 3$ , with an arbitrary large probability, for any  $s$  large enough and  $\varepsilon$  small enough (depending on  $s$ ), any random nodal line in  $B_s$  will cross the edges of  $\varepsilon\mathcal{T}$  at most once. In this case, for any pair of adjacent vertices with same sign,  $f$  does not vanish on the associated edge and has the sign of the vertices. We recall the result.

**Theorem 1.4.** *Let  $f$  be a  $C^3$  random stationary Gaussian field on  $\mathbb{R}^2$  satisfying the non-degeneracy condition (3.5) for  $m = 3$ ,  $\mathcal{T}$  be a periodic lattice, and  $\mathcal{E}$  be its set of edges. Fix  $\delta > 0$  and  $\eta > 0$ . Then there exists  $s(\delta, \eta) > 0$ , such that for every  $s \geq s(\delta, \eta)$  and every  $\varepsilon \leq s^{-8-\eta}$ , with probability at least  $1 - \delta$  the following event happens :*

$$\forall e \in \varepsilon\mathcal{E} \cap B_s, \#(e \cap f^{-1}(0)) \leq 1. \quad (5.1)$$

**Remark 5.1** *Under the event 5.1, any black percolation in  $B_s$  associated to  $\Omega(f, \varepsilon\mathcal{T})$  will provide an associated continuous path over which  $f$  is positive, hence giving a continuous percolation on  $B_s$  associated to  $\Omega(f)$ . This theorem has its own interest since it gives a very general link between continuous percolation and discrete percolation.*

### 5.1 Quantitative bounds.

First, we prove some results on Gaussian fields that will be useful when in the second part we will add a lattice. Recall that  $B_s = [-s, s]^n$ .

**Lemma 5.2** *Let  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  be a  $C^3$  stationary Gaussian field satisfying condition 3.5 for  $m = 3$ . Fix  $p > 0$ . Then there exists  $C_p > 0$ , such that for every  $s \geq 2$ ,*

$$\mathbf{E}(\|f\|_{C^2(B_s)}^p) \leq C_p(\ln s)^{p/2}.$$

**Proof.** We begin with  $p = 1$ . We use a classical result by Dudley. For this, define the semi-distance on  $\mathbb{R}^n$  by

$$\forall x, y \in \mathbb{R}^n, d^2(x, y) = \mathbf{E}\left(\left(f(x) - f(y)\right)^2\right).$$

In our case,  $d(x, y) = \sqrt{2}\sqrt{1 - K(x - y)}$ . For any  $\eta > 0$ , denote by  $N_s(\varepsilon)$  the number of balls for  $d$  of size  $\varepsilon$  needed to cover  $B_s = [-s, s]^n$ . Then by [1, Theorem 1.3.3] (see also for instance [15]), there exists a universal constant  $C > 0$  such that

$$\forall s > 0, \mathbf{E}(\|f\|_{L^\infty(B_s)}) \leq C \int_0^{\text{diam}(B_s)/2} \sqrt{\ln N_s(\varepsilon)} d\varepsilon.$$

Here,  $\text{diam}(B_s)$  is the diameter of  $B_s$  for the pseudo-metric  $d$ . Since  $d \leq \sqrt{2}$ , we get  $\text{diam}(B_s) \leq \sqrt{2}$ . Moreover, by Taylor, since  $dK(0) = 0$  by Remark 3.6 and since  $d^2K(0)$  is negative non-degenerate by condition (3.5), there exist  $c, C' > 0$  such that

$$\forall (x, y) \in (\mathbb{R}^n)^2, \|x - y\| \leq 1, c\|x - y\|^2 \leq d(x, y) \leq C'\|x - y\|^2.$$

Hence,

$$\exists c' > 0, \forall \varepsilon > 0, \forall s \geq 2, 1 \leq N_s(\varepsilon) \leq c' \left(\frac{s}{\sqrt{\varepsilon}}\right)^n,$$

so that there is  $c_0 > 0$ , for all  $s \geq 2$ ,

$$\mathbf{E}(\|f\|_{L^\infty(B_s)}) \leq c_0 \sqrt{\ln s}. \quad (5.2)$$

Now, for any  $i \in \{1, \dots, n\}$ ,  $\frac{\partial f}{\partial x_i}$  is a Gaussian field with covariance function

$$\forall (x, y) \in (\mathbb{R}^n)^2, \mathbf{E}(\partial_{x_i} f(x) \partial_{x_i} f(y)) = \partial_{x_i, y_i}^2 (K(x - y)) = -(\partial_{x_i}^2 K)(x - y).$$

Consequently, the pseudo-metric  $d_i$  associated to  $\partial_{x_i} f$  equals

$$\forall (x, y) \in (\mathbb{R}^n)^2, d_i(x, y) = \sqrt{2} \sqrt{-\partial_{x_i}^2 K(0) + (\partial_{x_i}^2 K)(x - y)}.$$

Then  $\mathbb{R}^n$  has diameter bounded by  $(-2\partial_{x_i}^2 K(0))^{1/2}$ . Since  $d^2 \partial_{x_i}^2 K(0)$  equals the quadratic form

$$X \in \mathbb{R}^n \mapsto d^4 K(0)(X, X, \partial_{x_i}, \partial_{x_i})$$

which is non-degenerate by condition 3.5, using again Taylor we get that  $d_i$  is equivalent for bounded  $x, y$  to the flat metric, so that as before there is a constant  $c'' > 0$  such that  $N_s(\varepsilon)$  for this field is bounded by  $c'' \left(\frac{s}{\sqrt{\varepsilon}}\right)^n$ . Hence, there exists  $c_{i,1} > 0$  such that for every  $s \geq 2$ ,  $\mathbf{E}(\|\partial_{x_i} f\|_{L^\infty(B_s)}) \leq c_{i,1} \sqrt{\ln s}$  and summing up for  $i \in \{1, \dots, n\}$ , we obtain the existence of  $c_1 > 0$ , such that

$$\forall s \geq 2, \mathbf{E}(\|df\|_{L^\infty(B_s)}) \leq c_1 \sqrt{\ln s}.$$

Similarly, there exists  $c_2 > 0$  such that for every  $s \geq 2$ ,  $\mathbf{E}(\|d^2 f\|_{L^\infty(B_s)}) \leq c_2 \sqrt{\ln s}$ . Note that for this latter estimate we need  $f$  to be  $C^3$  and condition 3.5 for  $m = 3$ . Adding the three estimates, we have proved the result for  $p = 1$ .

Now, by the Borell-TIS inequality (see Theorem 2.1.1 in [1]),

$$\forall u \geq 0, \mathbf{P}[\|f\|_{L^\infty(B_s)} \geq \mathbf{E}\|f\|_{L^\infty(B_s)} + u] \leq \exp\left(-\frac{u^2}{2 \sup_{x \in B_s} e(x, x)}\right),$$

where  $e(x, x) = K(0) = 1$ , so that by (5.2),

$$\forall u \geq 0, \mathbf{P}[\|f\|_{L^\infty(B_s)} \geq c_0\sqrt{\ln s} + u] \leq \exp\left(-\frac{1}{2}u^2\right).$$

Hence, if  $p > 0$ , there exists  $c''' > 0$  such that  $\mathbf{E}(\|f\|_{L^\infty(B_s)}^p)$  is bounded from above (after integration by parts) by

$$p(c_0\sqrt{\ln s})^p + p \int_0^\infty (u + c_0\sqrt{\ln s})^{p-1} \exp\left(-\frac{1}{2}u^2\right) du \leq c'''(\ln s)^{p/2}.$$

The same estimate holds for the higher derivatives.  $\square$

When we add to the Gaussian field a lattice, we need to understand the scale  $\varepsilon$  at which the zero set of  $f$  is trivial, that is a local graph, on a large box of a given size, and to quantify the probability of this event and all of the involved signs. For this, we must show that  $f$  is often quantitatively transverse when it vanishes, that is its derivative is bounded by a positive controlled uniform constant, and that the nodal line is not too much curved. The last condition is ensured by Lemma 5.2. The following Lemma proves the first condition, and is a quantitative version of Bulinskaya's theorem. It is essentially given by Lemma 7 of [29]. We follow here their proof, but keeping track of the constants depending on  $s$  and therefore using Lemma 5.2.

**Lemma 5.3** (see [29]) *Let  $f$  be a  $C^3$  stationary Gaussian field on  $\mathbb{R}^n$  satisfying condition (3.5) for  $m = 3$ . Fix  $\delta > 0$  and  $\eta > 0$ . Then, there exists  $\mu(\delta, \eta) > 0$ , such that*

$$\forall s \geq 2, \mathbf{P}\left[\min_{x \in B_s} \max(|f(x)|, |df(x)|) < \mu(\delta, \eta)s^{-n-\eta}\right] \leq \delta.$$

As in the aforementioned article, the proof of Lemma 5.3 will need the following Lemma.

**Lemma 5.4** ([29]) *Let  $f$  be a  $C^2$  stationary Gaussian field on  $\mathbb{R}^n$  satisfying condition (3.5) for  $m = 1$ . For any  $x \in \mathbb{R}^n$ , define the random variable*

$$\Phi(x) = \frac{1}{|f(x)||df(x)|^n} \in \mathbb{R}_+ \cup \{+\infty\}.$$

*Then, for any  $0 < \alpha < 1$ ,  $\Phi(x)^\alpha$  is integrable and there exists  $C_\alpha > 0$ , such that for any  $x \in \mathbb{R}^n$ ,  $\mathbf{E}(\Phi(x)^\alpha) \leq C_\alpha$ .*

**Proof.** By invariance under translation, we only need to prove the existence of a finite  $C_\alpha$  for a fixed  $x$ . Since  $f$  is stationary,  $\mathbf{E}(f(x)df(x)) = d_x^{1,0}e(x, x) = dK(0)$  vanishes, see Remark 3.6, so that  $f(x)$  and  $df(x)$  are independent. For any  $0 < \alpha < 1$ , we then have

$$\mathbf{E}(\Phi(x)^\alpha) = \mathbf{E}(|f(x)|^{-\alpha})\mathbf{E}(|df(x)|^{-n\alpha}).$$

By the coarea formula,

$$\mathbf{E}(|f(x)|^{-\alpha}) = \int_{y \in \mathbb{R}} \frac{1}{|y|^\alpha} \int_{f, f(x)=y} e(x, x)^{-1/2} d\mu_x(f) dy$$

which converges since  $e(x, x) = K(0) = 1$  and  $\alpha < 1$ . Here,  $d\mu_x(f)$  denotes the Gaussian measure of the random variable  $f(x)$ . Likewise,

$$\mathbf{E}(|df(x)|^{-n\alpha}) = \int_{Y \in \mathbb{R}^n} \frac{1}{|Y|^{n\alpha}} \int_{f, df(x)=Y} |\det d_{x,y}^{1,1}e(x, x)|^{-1/2} d\mu_x(f) dY,$$

where  $dY$  is the Lebesgue measure on  $\mathbb{R}^n$ . This integral converges since  $\alpha < 1$  and  $d_{x,y}^{1,1}e(x,x) = -d^2K(0)$  which is non-degenerate by condition (3.5) for  $m = 1$ .  $\square$

**Proof of Lemma 5.3** (see Lemma 7 of [29]). Define

$$W = 1 + \|f\|_{C^2(B_s)},$$

where  $B_s = [-s, s]^n$ . For any  $0 < \tau < 1$ , define

$$D_\tau(s) = \{x \in B_s, \max(|f(x)|, |df(x)|) \leq \tau\}$$

and  $\Omega_\tau$  the event

$$\Omega_\tau = \{D_\tau(s) \neq \emptyset\}.$$

Under  $\Omega_\tau$ , let  $x \in D_\tau(s)$ . Then for every  $y$  belonging to the round ball  $B(x, \tau)$ ,

$$\begin{aligned} |f(y)| &\leq \tau + \|df\|_{L^\infty(B_s)}\tau \leq W\tau. \\ |df(y)| &\leq \tau + \|d^2f\|_{L^\infty(B_s)}\tau \leq W\tau. \end{aligned}$$

Consequently, there exists  $C > 0$  such that for  $t > 0$ ,

$$\forall s \geq 2, \int_{B_s} \Phi^t(y) dy \geq \int_{B(x, \tau)} \Phi^t(y) dy \geq C\tau^{n-t(1+n)}W^{-t(1+n)},$$

where  $\Phi$  is given by Lemma 5.4. Therefore,

$$\forall s \geq 2, \mathbf{E}\left(W^{t(1+n)} \frac{1}{\text{Vol}(B_s)} \int_{B_s} \Phi^t(y) dy\right) \geq \mathbf{P}[\Omega_\tau] C\tau^{n-t(1+n)} \frac{1}{\text{Vol}(B_s)},$$

and if  $\frac{1}{p} + \frac{1}{q} = 1$ , by Hölder inequality applied two times, for the variables  $f$  and  $y \in B_s$ , we obtain

$$\mathbf{P}[\Omega_\tau] \leq \frac{1}{C} \text{Vol}(B_s) \tau^{t(1+n)-n} \left(\mathbf{E}(W^{t(1+n)p})\right)^{1/p} \left(\frac{1}{\text{Vol}(B_s)} \int_{B_s} \mathbf{E}(\Phi^{tq}(y)) dy\right)^{1/q}.$$

By Lemma 5.2, there exists  $C' > 0$  such that

$$\forall s \geq 2, \mathbf{E}(W^{t(1+n)p}) \leq C' (\ln s)^{\frac{p}{2}t(1+n)}.$$

Moreover, by Lemma 5.4, if  $qt < 1$ , then  $\mathbf{E}(\Phi^{tq}(\cdot))$  is uniformly bounded, and then there exists  $C_{q,t} > 0$  such that

$$\forall \tau \in ]0, 1[, \forall s \geq 2, \mathbf{P}(\Omega_\tau) \leq C_{q,t} \text{Vol}(B_s) \tau^{t(1+n)-n} (\ln s)^{\frac{t}{2}(1+n)}.$$

Hence, choosing  $\tau$ , for any  $s \geq 2$ , as

$$\tau = \delta^{(t(1+n)-n)^{-1}} \left(C_{q,t} \text{Vol}(B_s) (\ln s)^{\frac{t}{2}(1+n)}\right)^{-(t(1+n)-n)^{-1}},$$

we have  $\mathbf{P}(\Omega_\tau) \leq \delta$ . Now, we can choose  $t > 1$  close enough to 1, and then  $q$  such that  $1 < q < 1/t$ , so that

$$(t(1+n) - n)^{-1} < 1 + \frac{\eta}{n+1}.$$

Hence, we get the result since  $\text{Vol}(B_s) = (2s)^n$ .  $\square$

## 5.2 The lattice and the field.

Recall that  $\mathcal{T}$  denotes a periodic lattice on  $\mathbb{R}^2$ , and  $\mathcal{E}$  denotes its set of edges. For any  $\varepsilon > 0$ , we want to understand the link between the nodal line of the random  $f$  and the signs on the edges of the rescaled lattice  $\varepsilon\mathcal{T}$ ; other saying, between  $\Omega(f)$  and  $\Omega(f, \varepsilon\mathcal{T})$ . So, we want to prove that double intersections with edges do not happen, with high probability. For this, let  $v \in \mathbb{S}^1 \subset \mathbb{R}^2$  be one of the directions of the edges, and let

- $H(v, \varepsilon)$  be the subset of  $\varepsilon\mathcal{E}$  defined by the edges of  $\varepsilon\mathcal{E}$  parallel to  $v$ .

We want to estimate the mean number of nodal points  $x$  which are  $\theta$ -close to  $H(v, \varepsilon)$  for  $\theta > 0$  and such that the tangent of  $f^{-1}(0)$  at  $x$  is parallel to  $v$ . Note that if  $f^{-1}(0)$  is a local graph over an edge  $e \in \varepsilon\mathcal{E}$ , a double intersection of  $f^{-1}(0)$  with  $e$  gives birth to such a critical point.

**Lemma 5.5** *Let  $f$  be a  $C^2$  stationary Gaussian field on  $\mathbb{R}^2$  satisfying condition (3.5) for  $m = 1$ . For every  $\varepsilon, \theta, s > 0$ , every direction  $v \in \mathbb{S}^1 \subset \mathbb{R}^2$ , define*

$$C_\varepsilon(\theta, s, v, f) = \{x \in B_s, \text{dist}(x, H(v, \varepsilon)) \leq \theta, f(x) = 0 \text{ and } df(x)(v) = 0\}. \quad (5.3)$$

*Then, outside a set of vanishing measure,  $C_\varepsilon(\theta, s, v, f)$  is finite, and there exists  $\beta > 0$  depending only on  $f$  such that*

$$\forall \varepsilon, \theta, s > 0, \forall v \in \mathbb{S}^1, \mathbf{E}(\#C_\varepsilon(\theta, s, v, f)) \leq \beta \frac{s^2}{\varepsilon} \theta,$$

*so that  $\mathbf{P}[C_\varepsilon(\theta, s, v, f) = \emptyset] \geq 1 - \beta \frac{s^2}{\varepsilon} \theta$ .*

**Remark 5.6** *In [20] and [17], the authors gave an explicit bound for the number of critical point of the restriction of a fixed Morse function (here the latter is a coordinate in the direction given by  $v$ ) in order to bound the mean Betti numbers of random nodal hypersurfaces.*

**Proof.** Denote by  $F : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  the Gaussian field defined by

$$\forall x \in \mathbb{R}^2, F(x) = (f, df(x)(v)).$$

This field is  $C^1$  and non-degenerate. Indeed, the associated covariance at  $x$  is the matrix

$$\begin{pmatrix} e & d_x e(v) \\ d_y e(v) & d_x d_y e(v, v) \end{pmatrix}_{|(x,x)},$$

where  $e(x, y) = \mathbf{E}(f(x), f(y)) = K(x - y)$  denotes the covariance of  $f$ . This matrix is non-degenerate since the anti-diagonal terms vanish by Remark 3.6, since  $e(x, x) = K(0) = 1$  and since  $d_x d_y e(x, x)(v, v) = -d^2 K(0)(v, v)$  is not degenerate by condition (3.5) for  $m = 1$ . Applying Theorem 6.2 of [4] where, with the notations of this monograph,  $u = 0$  and

$$B = \{x \in B_s, \text{dist}(x, H(v, \varepsilon)) \leq \theta\},$$

we have

$$\mathbf{E}(\#C_\varepsilon(\theta, s, v, f)) = \int_B \mathbf{E}(|\det dZ(x)| | Z(x) = 0) p_{Z(x)} dx,$$

where  $p_{Z(x)}$  denotes the density of  $Z$ . Since  $B$  is compact, this integral is finite and depends continuously on  $K(0) = 1$  and  $d^2 K(0)(v, v)$ , as far as the latter is positive. But



$d^2K(0)(v, v)$  is bounded from above for any  $v \in \mathbb{S}^1$  and uniformly bounded from below by a positive constant. By invariance under translations,  $p_Z$  is independent on  $x$  as well as  $\mathbf{E}(|\det Z'(x)| | Z(x) = 0)$ , so that

$$\exists C > 0, \forall v \in \mathbb{S}^1, \mathbf{E}(\#C_\varepsilon(\theta, s, v, f)) \leq C \text{Vol}(B),$$

hence the result.  $\square$

We can now give the prove of Theorem 1.4.

**Proof of Theorem 1.4.** Let  $N \in \mathbb{N}^*$  be the number of directions of the edges of the lattice  $\mathcal{T}$ , and choose  $v \in \mathbb{S}^1$  one of these directions. Fix  $\delta, \eta > 0$  and for any  $s \geq 1$  define the functions

$$\lambda(s) = \mu\left(\frac{\delta}{3N}, \frac{\eta}{6}\right)(2s)^{-2-\frac{\eta}{6}} \text{ and } k(s) = \frac{C_1}{\left(\frac{\delta}{3N}\right)} \sqrt{\ln(2s)},$$

where  $C_1$  and  $\mu$  are given by Lemma 5.2 and Lemma 5.3 respectively. Let us consider the event

$$\Omega_\delta = \left\{ \min_{x \in B_{2s}} \max(|f(x)|, |df(x)|) \geq \lambda(s) \right\} \cap \left\{ \|f\|_{C^2(B_{2s})} \leq k(s) \right\}. \quad (5.4)$$

By Lemmas 5.2 and 5.3 and Markov inequality, we have

$$\forall s \geq 1, \mathbf{P}[\Omega_\delta] \geq 1 - \frac{2\delta}{3N}.$$

Let  $\psi$  be the function defined by

$$\forall s \geq 1, \psi(s) = (k/\lambda)(s) \in \mathbb{R}_+^*.$$

Choose  $s_1(\delta, \eta) \geq 2$ , such that for any  $s \geq s_1(\delta, \eta)$ ,  $\psi(s) \geq 1$  and define for every  $s \geq 1$ ,

$$\varepsilon_1(s) = \left(\frac{1}{4}\psi^{-1}(s)\right)^2.$$

Note that if  $\mu_{\mathcal{T}} > 0$  denotes the length of the largest edge in  $\mathcal{E}$ , then

$$\forall s \geq s_1(\delta, \eta), \forall \varepsilon \leq \varepsilon_1(s)/\mu_{\mathcal{T}}, \forall e \in \varepsilon\mathcal{E}, \forall x \in e, e \subset b[x, \varepsilon_1(s)] \subset B_{2s},$$

where for any  $(x_1, x_2) \in \mathbb{R}^2$  and any  $\varepsilon > 0$ ,

$$b[(x_1, x_2), \varepsilon] = \{(y_1, y_2) \in \mathbb{R}^2, \max(|y_1 - x_1|, |y_2 - x_2|) \leq \varepsilon\},$$

see (6.2) below. Let us rotate the axes  $(Ox)$  and  $(Oy)$  such that the direction  $v$  is horizontal. Fix  $s \geq s_1(\delta, \eta)$ ,  $\varepsilon \leq \varepsilon_1(s)/\mu_{\mathcal{T}}$ , an horizontal edge  $e \in \varepsilon\mathcal{E}$  intersecting  $B_s$  and  $x \in e \cap f^{-1}(0)$ . Since

$$\max\left(\left|\frac{\partial f}{\partial x_1}(x)\right|, \left|\frac{\partial f}{\partial x_2}(x)\right|\right) \geq \frac{|df(x)|}{\sqrt{2}},$$

under the event  $\Omega_\delta$  defined by (5.4), we can apply the quantitative version of the implicit function theorem given by Corollary 6.3. It states that the nodal subset  $f^{-1}(0) \cap b[x, \varepsilon_1(s)] \subset B_{2s}$  is the restriction of a graph over  $(Oy)$  or  $(Ox)$ . In the first case,  $f^{-1}(0) \cap b$  crosses  $e$  at most once, that is  $\#(f^{-1}(0) \cap e) \leq 1$ .

Let us now consider the second case. Suppose that  $f^{-1}(0)$  crosses at least two times the horizontal edge  $e$ , which we can assume to be part of  $(Ox)$ , and denote by  $\phi$  the implicit function over  $b[x, \varepsilon_1(s)] \cap (Ox) \supset e$ , whose graph equals  $f^{-1}(0) \cap b[x, \varepsilon_1(s)]$ . Then, by

Rolle's theorem, there exists a critical point  $y \in e$  of  $\phi|_e$  and by Taylor's theorem applied to  $\phi|_e$  between  $y$  and  $x$ , we obtain

$$|\phi(y)| \leq \frac{\mu_{\mathcal{T}}^2 \varepsilon^2}{2} \|\phi''\|_{L^\infty(e)} \leq 50\mu_{\mathcal{T}}^2 \varepsilon^2 \psi^3(s),$$

where we used the estimate (6.3) of Corollary 6.3. This implies that  $y \in C_\varepsilon(\theta(\varepsilon, s), 2s, v, f)$ , see (5.3) in Lemma 5.5 for the definition of  $C_\varepsilon$ , with  $\theta$  defined by

$$\forall \varepsilon > 0, s \geq 1, \theta(\varepsilon, s) = 50\mu_{\mathcal{T}}^2 \varepsilon^2 \psi^3(s). \quad (5.5)$$

Now, denote by  $\Omega'_\delta$  the event

$$\Omega'_\delta = \{C_\varepsilon(\theta(\varepsilon, s), 2s, v, f) = \emptyset\},$$

and for every  $s \geq 1$ , let

$$\varepsilon_2(s) = \left(\frac{\delta}{3N}\right) (50\mu_{\mathcal{T}}^2 \beta s^2 \psi^3(s))^{-1},$$

where  $\beta$  is given by Lemma 5.5. By the latter, for any  $s \geq 1$ ,

$$\forall \varepsilon \leq \varepsilon_2(s), \mathbf{P}[\Omega'_\delta] \geq 1 - \frac{\delta}{3N}.$$

In conclusion, for any  $s \geq s_1(\delta, \eta)$  and any  $\varepsilon \leq \min(\varepsilon_1(s)/\mu_{\mathcal{T}}, \varepsilon_2(s))$ , under the event  $\Omega_\delta \cap \Omega'_\delta$  which has probability greater than  $1 - \delta/N$ , the nodal subset  $f^{-1}(0) \cap B_s$  crosses at most once any edge  $e \in \mathcal{E}\mathcal{V}$  in the direction  $v$ . After consideration of the  $N$  directions, this happens for any edge in  $\mathcal{E}\mathcal{E} \cap B_s$  with probability at least  $1 - \delta$ . Lastly, since there exists  $s_2(\delta, \eta) \geq s_1(\delta, \eta)$ , such that

$$\forall s \geq s_2(\delta, \eta), s^{-8-\eta} \leq \min(\varepsilon_1(s)/\mu_{\mathcal{T}}, \varepsilon_2(s)),$$

we obtain the result.  $\square$

## 6 Appendix

### 6.1 Abstract Wiener spaces

Our main field of interest is the Gaussian field with Gaussian covariance function. While it makes sense in itself, there is a natural way to view it as “the Gaussian in the Bargmann-Fock space”, even though this is a priori not well-defined in infinite dimension. This appendix follows [22].

**The definition** Let  $(\mathcal{H}, \|\cdot\|)$  be a Hilbert separable space of infinite dimension. Note the scalar product induces a natural Gaussian measure  $\mu_G$  on any finite dimensional subspace  $G \subset \mathcal{H}$ . Let  $N : \mathcal{H} \rightarrow \mathbb{R}^+$  be another norm, which satisfies the following condition: for any  $\varepsilon > 0$ , there exists a finite dimension subspace  $H_\varepsilon \subset \mathcal{H}$ , such that for any finite dimensional subspace  $H_1$  of  $H_\varepsilon^\perp$ ,

$$\mu_{H_1}(\{x \in H_1, N(x) > \varepsilon\}) < \varepsilon. \quad (6.1)$$

Such a norm is called *measurable* in the literature. Denote by  $B$  the completion of  $\mathcal{H}$  for  $N$ : then there is a unique measure  $\mu$  on  $B$  than agrees with  $\mu_G$  on any cylindrical event based on  $G$ . More precisely: for every finite-dimensional subspace  $G \subset \mathcal{H}$ , and for

every measurable  $A \subset G$ , letting  $\tilde{A}$  denote the closure in  $B$  of  $A + G^\perp$  in  $B$ , one has  $\mu(\tilde{A}) = \mu_G(A)$ .

The measured Banach space  $(B, N, \mu)$  is called the *abstract Wiener space* associate to  $\mathcal{H}$ , relative to the measurable norm  $N$ . Of course if  $\mathcal{H}$  is finite-dimensional, then  $B = \mathcal{H}$ ,  $N = \|\cdot\|$  and  $\mu = \mu_{\mathcal{H}}$  is the standard Gaussian measure on  $\mathcal{H}$ . If on the other hand  $\mathcal{H}$  is infinite-dimensional, then it is negligible for the Wiener measure, *i.e.*  $\mu(\mathcal{H}) = 0$ .

**The canonical example** If  $(\mathcal{H}, \|\cdot\|_\nabla) = H^1([0, 1])$  equipped with the Dirichlet inner product defined by

$$\|f\|_\nabla^2 := \int_0^1 |f'(x)|^2 dx$$

and if the measurable norm is chosen to be the supremum norm,  $N(f) = \|f\|_{L^\infty([0,1])}$  (which is indeed measurable), then  $B = C(0, 1)$  and  $\mu$  is the law of standard Brownian motion. In other words, the abstract Wiener space in this setup is the usual Wiener space of stochastic analysis.

**The Bargmann-Fock Wiener space** For any  $R > 0$ , we denote by  $D(0, R) \subset \mathbb{R}^2$  the centered disc of radius  $R$  and  $N_R$  the semi-norm on  $\mathcal{F}$  given by  $N_R = \|\cdot\|_{L^\infty(B(0,R))}$ . This in fact defines a norm on  $\mathcal{F}$ , because by analytic continuation, if  $N_R(f) = 0$ , then  $f$  is identically 0 in  $\mathbb{R}^2$ .

**Lemma 6.1** *For any  $R > 0$ , the norm  $N_R$  satisfies condition (6.1), *i.e.* it is measurable.*

**Proof.** Fix  $\varepsilon > 0$ ,  $N \in \mathbb{N}$  and define  $H_N = \mathbb{R}_N[x_1, x_2] \subset \mathcal{F}$  the subspace of real polynomials of degree less than  $N$  in two variables. Let  $H_1 \subset H_N^\perp$  be any finite dimensional subspace orthogonal to  $H_N$ . Any  $f \in H_1$  can be written as

$$\forall x = (x_1, x_2) \in \mathbb{R}^2, f(x) = \sum_{i+j>N} a_{ij} \frac{x_1^i x_2^j}{\sqrt{i!j!}},$$

where  $\sum a_{ij}^2 < \infty$  and the sum is locally uniformly convergent. By Cauchy-Schwarz:

$$N_R(f)^2 \leq \left( \sum a_{ij}^2 \right) \left( \sum_{i+j>N} \frac{R^{2(i+j)}}{i!j!} \right) = \|f\|_{BF}^2 \left( \sum_{k>N} \frac{(2R^2)^k}{k!} \right) =: m_N \|f\|_{BF}^2.$$

Then we obtain the explicit upper bound:

$$\mu_{H_1}[N_R(f) > \varepsilon] \leq \mu_{H_1} [\|f\|_{BF}^2 > \varepsilon^2/m_N] \leq \varepsilon^{-2} m_N E_{H_1} [\|f\|_{BF}^2].$$

The expectation in the last term is finite because  $H_1$  is finite-dimensional; it is in fact equal to  $\dim H_1$ . Besides,  $m_N$  goes to 0 as  $N \rightarrow \infty$ : for  $N$  large enough, one has  $m_N < \varepsilon^3/\dim H_1$ , and therefore  $\mu_{H_1}[N_R(f) > \varepsilon] < \varepsilon$  which is what we needed.  $\square$

We can construct a family of abstract Wiener spaces  $(B_R, N_R)$  associated to these norms. In fact we get something much better: by regularity of analytic continuation, the norms  $N_R$  are pairwise equivalent, and the completion we obtain therefore does not actually depend on  $R$ . The natural extension of the notion of abstract Wiener space with which we work is therefore the space  $L_{loc}^\infty$  equipped with the collection of seminorms  $(N_R)$  and with the measure  $\mu$  obtained from Gross's construction (which does not depend on  $R$ ).

## 6.2 A quantitative implicit function theorem

For each  $\delta > 0$  and any  $x = (x_1, x_2) \in \mathbb{R}^p \times \mathbb{R}^q$ , define

$$b[x, \delta] = \{(y_1, y_2) \in \mathbb{R}^p \times \mathbb{R}^q, \|y_1 - x_1\| \leq \delta, \|y_2 - y_1\| \leq \delta\}. \quad (6.2)$$

**Theorem 6.2** *Let  $f : \mathbb{R}^{p+q} \rightarrow \mathbb{R}^q$  be a  $C^2$  function and  $x = (x_1, x_2) \in \mathbb{R}^p \times \mathbb{R}^q$  such that  $f(x) = 0$  and the partial derivative  $d_{x_2}f(x) : \mathbb{R}^q \rightarrow \mathbb{R}^q$  is invertible. Choose  $\delta > 0$  such that*

$$\sup_{y \in b[x, \delta]} \|Id_{\mathbb{R}^q} - (d_{x_2}f(x))^{-1}d_{x_2}f(y)\| \leq 1/2.$$

Let  $C = \sup_{y \in b[x, \delta]} \|d_{x_1}f(y)\|$ ,  $M = \|d_{x_2}f(x)^{-1}\|$ ,

$$\delta' = \delta(2MC)^{-1}$$

and  $I_{\delta'} := \{y_1 \in \mathbb{R}^p : \|y_1 - x_1\| < \delta'\}$ . Then there exists  $\phi : I_{\delta'} \rightarrow \mathbb{R}^q$  a  $C^2$  function such that

$$\forall y = (y_1, y_2) \in \mathbb{R}^p \times \mathbb{R}^q, \|y_1 - x_1\| < \delta', \|y_2 - x_2\| < \delta, f(y) = 0 \Leftrightarrow y_2 = \phi(y_1).$$

**Corollary 6.3** *Let  $k > 0$ ,  $\lambda > 0$  be such that  $k/\lambda \geq 1$ ,  $U \subset \mathbb{R}^2$  an open set,  $f$  be a  $C^2$  function  $f : \mathbb{R}^2 \rightarrow \mathbb{R}$  such that  $\|df\|_{C^1(U)} \leq k$ . Fix  $x \in \mathbb{R}^2$  satisfying  $f(x) = 0$  and  $|\partial_{x_2}f(x)| \geq \frac{\lambda}{\sqrt{2}}$ . Then if*

$$\varepsilon = \left(\frac{\lambda}{4k}\right)^2,$$

the nodal set  $b[x, \varepsilon] \cap f^{-1}(0)$  is the graph over  $I_\varepsilon$  of a  $C^2$  function  $\phi$ . Moreover,

$$\|\phi''\|_{L^\infty(I_\varepsilon)} \leq 100\left(\frac{k}{\lambda}\right)^3. \quad (6.3)$$

**Proof.** Fix  $\delta = \frac{\lambda}{4\sqrt{2}k}$ . By the mean value theorem,

$$\forall y \in b[x, \delta], |\partial_{x_2}f(y) - \partial_{x_2}f(x)| \leq \sqrt{2}\delta k = \frac{\lambda}{4}, \quad (6.4)$$

so that

$$\sup_{y \in b[x, \delta]} |1 - (\partial_{x_2}f(x))^{-1}\partial_{x_2}f(y)| \leq 1/(2\sqrt{2}) \leq 1/2.$$

Using the notations of Theorem 6.2, we thus have  $M \leq \frac{\sqrt{2}}{\lambda}$ ,  $C \leq k$ , so that  $\delta' \geq \left(\frac{\lambda}{4k}\right)^2$ . Since  $k \geq \lambda$ ,  $\delta \geq \left(\frac{\lambda}{4k}\right)^2$ , which implies the first assertion. Now, since

$$\forall t \in I_{\delta'}, f(t, \phi(t)) = 0,$$

then  $\forall t \in I_{\delta'}$ ,  $\partial_{x_1}f + \partial_{x_2}f\phi'(t) = 0$  so that  $|\phi'(t)| \leq \frac{k}{\lambda/\sqrt{2}-\lambda/4} \leq \frac{4k}{\lambda}$  by (6.4) and the hypothesis on  $\partial_{x_2}f(x)$ , and

$$\forall t \in I_{\delta'}, \partial_{x_1}^2f + 2\partial_{x_1x_2}^2f\phi'(t) + \partial_{x_2}^2f\phi'(t)^2 + \partial_{x_2}f\phi''(t) = 0.$$

This implies  $|\phi''(t)| \leq \frac{4k}{\lambda} \left(1 + \frac{8k}{\lambda} + \frac{16k^2}{\lambda^2}\right) \leq 100(k/\lambda)^3$  since  $k \geq \lambda$ .  $\square$

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