

A fully discrete approximation of the one-dimensional stochastic heat equation

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A fully discrete approximation of the one-dimensional stochastic heat equation driven by multiplicative space–time white noise is presented. The standard finite difference approximation is used in space and a stochastic exponential method is used for the temporal approximation. Observe that the proposed exponential scheme does not suffer from any kind of CFL-type step size restriction. When the drift term and the diffusion coefficient are assumed to be globally Lipschitz this explicit time integrator allows for error bounds in $L^q(\Omega)$, for all $q \geq 2$, improving some existing results in the literature. On top of this we also prove almost sure convergence of the numerical scheme. In the case of nonglobally Lipschitz coefficients, under a strong assumption about pathwise uniqueness of the exact solution, convergence in probability of the numerical solution to the exact solution is proved. Numerical experiments are presented to illustrate the theoretical results.

Keywords: stochastic heat equation; multiplicative noise; finite difference scheme; stochastic exponential integrator; $L^q(\Omega)$ -convergence.

1. Introduction

We study an explicit full numerical discretization of the one-dimensional stochastic heat equation

$$\begin{aligned} \frac{\partial}{\partial t} u(t, x) &= \frac{\partial^2}{\partial x^2} u(t, x) + f(t, x, u(t, x)) + \sigma(t, x, u(t, x)) \frac{\partial^2}{\partial t \partial x} W(t, x) \quad \text{in } (0, \infty) \times (0, 1), \\ u(t, 0) &= u(t, 1) = 0 \quad \text{for } t \in (0, \infty), \\ u(0, x) &= u_0 \quad \text{for } x \in [0, 1], \end{aligned} \tag{1.1}$$

where W is a Brownian sheet on $[0, \infty) \times [0, 1]$ defined on some probability space $(\Omega, \mathcal{F}, \mathbb{P})$ satisfying the usual conditions, and u_0 is a continuous function in $[0, 1]$ such that $u_0(0) = u_0(1) = 0$. Assumptions on the coefficients f and σ will be specified below. As far as the spatial discretization is concerned, we use a standard finite difference scheme, as in Gyöngy (1998b). In order to discretize (1.1) with respect to the time variable we consider an exponential method similar to the time integrators used in Cohen *et al.* (2013), Cohen & Quer-Sardanyons (2016) and Anton *et al.* (2016) for stochastic wave equations or in Cohen & Dujardin (2017) and Anton & Cohen (2018) for stochastic Schrödinger equations.

Our main aim is to improve the temporal rate of convergence that has been obtained by Gyöngy (1999). Indeed, in Gyöngy (1999), the explicit as well as the semiimplicit Euler–Maruyama scheme have been applied for the time discretization of problem (1.1). When the functions f and σ are globally Lipschitz continuous in the third variable, a temporal convergence order of $\frac{1}{8}$ — in the $L^q(\Omega)$ -norm, for all $q \geq 2$, is obtained for these numerical schemes (see Theorem 3.1 in Gyöngy, 1999 for a precise statement). Our first objective is to see if an explicit exponential method can provide a higher rate of convergence. In the present work we answer this question positively and obtain the temporal rate $\frac{1}{4}$ — (see the first part of Theorem 3.9 below). We note that, as in Gyöngy (1999), the latter estimate for the $L^q(\Omega)$ -error holds for any fixed $t \in (0, T]$ and uniformly in the spatial variable, where $T > 0$ is some fixed time horizon. On the other hand, we should also remark that, in Gyöngy (1999), a rate of convergence $\frac{1}{4}$ could be obtained only in the case where the initial condition u_0 belongs to $C^3([0, 1])$. Finally, as in Gyöngy (1999), we also prove that the exponential scheme converges almost surely to the solution of (1.1), uniformly with respect to time and space variables (cf. Theorem 3.11).

Our second objective consists of refining the abovementioned temporal rate of convergence in order to end up with a convergence order that is exactly $\frac{1}{4}$ and with an estimate that is uniform both with respect to time and space variables. To this end we assume that the initial condition u_0 belongs to some fractional Sobolev space (see (2.11) for the precise definition). Indeed, as it can be deduced from the second part of Theorem 3.9 and well-known Sobolev embedding results, in order to have the rate $\frac{1}{4}$, the hypothesis on u_0 implies that it is δ -Hölder continuous for all $\delta \in (0, \frac{1}{2})$. Eventually, as in Gyöngy (1999), we remove the globally Lipschitz assumption on the coefficients f and σ and, assuming that pathwise uniqueness holds for equation (1.1), we prove convergence in probability for the proposed explicit exponential integrator (see Theorem 5.4 below). In the case of nonglobally Lipschitz coefficients similar results as those presented here can also be obtained for other numerical methods. For instance, in Bréhier & Goudenège (2018) and Bréhier *et al.* (2018) a splitting algorithm has been applied to the Allen–Cahn equation with a polynomial nonlinearity, obtaining strong convergence of order $\frac{1}{4}$ and convergence in probability of order $\frac{1}{4}$ —. Other related results can be found, for example, in Jentzen & Puskas (2015), Kovács *et al.* (2015), Becker & Jentzen (2016), Liu & Qiao (2018) and Wang (2018).

We should point out that there are also other important advantages in using the exponential method proposed here. Namely, first, it does not suffer a step size restriction (imposed by a CFL condition) as the explicit Euler–Maruyama scheme from Gyöngy (1999). Secondly, it is an explicit scheme and therefore has implementation advantages over the implicit Euler–Maruyama scheme studied in Gyöngy (1999). These facts will be illustrated numerically.

The numerical analysis of the stochastic heat equation (1.1) is an active research area. Without being too exhaustive, beside the abovementioned papers (Gyöngy, 1998b and Gyöngy, 1999), we mention the following works regarding numerical discretizations of stochastic parabolic partial differential equations: Gyöngy (1998b), Yan (2005), Barth & Lang (2012) and Sauer & Stannat (2015) (spatial approximations); Gaines (1995), Gyöngy & Nualart (1995), Gyöngy & Nualart (1997), Allen *et al.* (1998), Shardlow (1999), Printems (2001), Davie & Gaines (2001), Du & Zhang (2002), Hausenblas (2003), Pettersson & Signahl (2005), Walsh (2005), Millet & Morien (2005), Müller-Gronbach & Ritter (2007), Jentzen & Kloeden (2009), Jentzen (2009), Cox & van Neerven (2010), Jentzen *et al.* (2011), Jentzen (2011); Kloeden *et al.* (2011), Lord & Tambue (2013), Wang & Gan (2013), Barth & Lang (2013), Cox & van Neerven (2013), Jentzen & Röckner (2015), Becker *et al.* (2016) and Wang (2017) (temporal and full discretizations); Ta *et al.* (2015) and Lang *et al.* (2017) (stability); and Shardlow (2003), Debussche & Printems (2009), Debussche (2011), Jentzen & Kurniawan (2015) and Andersson & Larsson (2016) (weak approximations). Observe that most of these references are concerned with an

interpretation of stochastic partial differential equations in Hilbert spaces, and thus error estimates are provided in the $L^2([0, 1])$ norm (or similar norms). The reader is referred to the monographs [Jentzen & Kloeden \(2011\)](#), [Kruse \(2014\)](#) and [Lord *et al.* \(2014\)](#) for a more comprehensive reference list.

In the present publication we follow a similar approach to [Cohen & Quer-Sardanyons \(2016\)](#) and [Gyöngy \(1999\)](#). The main idea consists of establishing suitable *mild* forms for the spatial approximation u^M and for the fully discretization scheme $u^{M,N}$. The obtained mild equations, together with some auxiliary results and, taking into account the hypotheses on the coefficients and initial data, will allow us to deal with the $L^q(\Omega)$ -error

$$\left(\mathbb{E}[|u^M(t, x) - u^{M,N}(t, x)|^q] \right)^{\frac{1}{q}},$$

for all $q \geq 2$. The $L^q(\Omega)$ -error comparing u^M with the exact solution of (1.1) has already been studied in [Gyöngy \(1998b\)](#).

The paper is organized as follows. In Section 2, we recall the spatial discretization u^M of (1.1) from [Gyöngy \(1998b\)](#) and prove some properties of u^M needed in the sequel. Section 3 is devoted to study the proposed full discretization by an exponential scheme in the case of globally Lipschitz continuous coefficients. More precisely, first, we introduce the full discretization scheme and prove that it satisfies a suitable mild form. Secondly, we establish three auxiliary results, which will be invoked in the convergence results' proofs. Next we state and prove the main result on $L^q(\Omega)$ -convergence. Section 3 concludes with a result on almost sure convergence. In Section 4, we provide numerical experiments illustrating the results on strong convergence and almost sure convergence as well as on computational times for various numerical schemes. Finally, Section 5 is devoted to the convergence in probability of the numerical solution to the exact solution of (1.1), in the case where the coefficients f and σ are nonglobally Lipschitz continuous.

Observe that, throughout this article, C will denote a generic constant that may vary from line to line.

2. Spatial discretization

In this section, we begin by stating the assumptions we will make and by recalling the mild solution of (1.1). Then the remainder of the section is dedicated to recalling the finite difference approximation from [Gyöngy \(1998b\)](#) and proving some (new) results about it.

We shall make the following assumptions on the coefficients of the stochastic heat equation (1.1): for a given positive real number T , there exist a constant C such that

$$|f(t, x, u) - f(t, y, v)| + |\sigma(t, x, u) - \sigma(t, y, v)| \leq C(|x - y| + |u - v|), \quad (\text{L})$$

for all $t \in [0, T]$, $x, y \in [0, 1]$, $u, v \in \mathbb{R}$, and

$$|f(t, x, u)| + |\sigma(t, x, u)| \leq C(1 + |u|), \quad (\text{LG})$$

for all $t \in [0, T]$, $x \in [0, 1]$, $u \in \mathbb{R}$. Assume also that the initial condition u_0 defines a continuous function on $[0, 1]$ with $u_0(0) = u_0(1) = 0$. The assumptions (L) and (LG) imply existence and uniqueness of a solution u of equation (1.1) on the time interval $[0, T]$, see e.g., Theorem 3.2 and Exercise 3.4 in

Walsh (1986). Let us recall that, for a stochastic basis $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbb{P})$, a solution to equation (1.1) is an \mathcal{F}_t -adapted continuous process $\{u(t, x), (t, x) \in [0, T] \times [0, 1]\}$ satisfying that, for every $\Phi \in C^\infty(\mathbb{R}^2)$ such that $\Phi(t, 0) = \Phi(t, 1) = 0$ for all $t \geq 0$, we have

$$\begin{aligned} \int_0^1 u(t, x) \Phi(t, x) dx &= \int_0^1 u_0(x) \Phi(t, x) dx \\ &+ \int_0^t \int_0^1 u(s, x) \left(\frac{\partial^2 \Phi}{\partial x^2}(s, x) + \frac{\partial \Phi}{\partial s}(s, x) \right) dx ds \\ &+ \int_0^t \int_0^1 f(s, x, u(s, x)) \Phi(s, x) dx ds \\ &+ \int_0^t \int_0^1 \sigma(s, x, u(s, x)) \Phi(s, x) W(ds, dx), \quad \mathbb{P}\text{-a.s.}, \end{aligned} \quad (2.1)$$

for all $t \in [0, T]$. It is well known that the above equation implies the following *mild* form for (1.1):

$$\begin{aligned} u(t, x) &= \int_0^1 G(t, x, y) u_0(y) dy + \int_0^t \int_0^1 G(t-s, x, y) f(s, y, u(s, y)) dy ds \\ &+ \int_0^t \int_0^1 G(t-s, x, y) \sigma(s, y, u(s, y)) W(ds, dy), \quad \mathbb{P}\text{-a.s.}, \end{aligned} \quad (2.2)$$

where $G(t, x, y)$ is the Green function of the linear heat equation with homogeneous Dirichlet boundary conditions:

$$G(t, x, y) = \sum_{j=1}^{\infty} e^{-j^2 \pi^2 t} \varphi_j(x) \varphi_j(y), \quad t > 0, x, y \in [0, 1],$$

with $\varphi_j(x) := \sqrt{2} \sin(j\pi x)$, $j \geq 1$. Note that these functions form an orthonormal basis of $L^2([0, 1])$.

We proceed to recall the finite difference discretization and some results obtained in Gyöngy (1998b). In addition to this, we show new regularity results for the approximated Green function $G^M(t, x, y)$ defined below, and for the space discrete approximation, which will be needed in the sequel.

Let $M \geq 1$ be an integer and define the grid points $x_m = \frac{m}{M}$ for $m = 0, \dots, M$ and the mesh size $\Delta x = \frac{1}{M}$. We now use the standard finite difference scheme for the spatial approximation of (1.1) from Gyöngy (1998b). Let the process $u^M(t, \cdot)$ be defined as the solution of the system of stochastic differential equations (for $m = 1, \dots, M-1$)

$$\begin{aligned} du^M(t, x_m) &= M^2 \left(u^M(t, x_{m+1}) - 2u^M(t, x_m) + u^M(t, x_{m-1}) \right) dt \\ &+ f(t, x_m, u^M(t, x_m)) dt \\ &+ M \sigma(t, x_m, u^M(t, x_m)) d(W(t, x_{m+1}) - W(t, x_m)) \end{aligned} \quad (2.3)$$

with Dirichlet boundary conditions

$$u^M(t, 0) = u^M(t, 1) = 0,$$

and initial value

$$u^M(0, x_m) = u_0(x_m),$$

for $m = 1, \dots, M-1$. For $x \in [x_m, x_{m+1})$ we define

$$u^M(t, x) := u^M(t, x_m) + (Mx - m)(u^M(t, x_{m+1}) - u^M(t, x_m)). \quad (2.4)$$

We use the notations $u_m^M(t) := u^M(t, x_m)$ and $W_m^M(t) := \sqrt{M}(W(t, x_{m+1}) - W(t, x_m))$, for $m = 1, \dots, M-1$ and write the system (2.3) as

$$\begin{aligned} du_m^M(t) &= M^2 \sum_{i=1}^{M-1} D_{mi} u_i^M(t) dt + f(t, x_m, u_m^M(t)) dt \\ &\quad + \sqrt{M} \sigma(t, x_m, u_m^M(t)) dW_m^M(t), \end{aligned}$$

with initial value

$$u_m^M(0) = u_0(x_m),$$

for $m = 1, \dots, M-1$, where $D = (D_{mi})_{m,i}$ is a square matrix of size $M-1$, with elements $D_{mm} = -2$, $D_{mi} = 1$ for $|m-i| = 1$, $D_{mi} = 0$ for $|m-i| > 1$. Also $W^M(t) := (W_m^M(t))_{m=1}^{M-1}$ is an $M-1$ -dimensional Wiener process. Observe that the matrix $M^2 D$ has eigenvalues

$$\lambda_j^M := -4 \sin^2 \left(\frac{j\pi}{2M} \right) M^2 = -j^2 \pi^2 c_j^M,$$

where

$$\frac{4}{\pi^2} \leq c_j^M := \frac{\sin^2 \left(\frac{j\pi}{2M} \right)}{\left(\frac{j\pi}{2M} \right)^2} \leq 1,$$

for $j = 1, 2, \dots, M-1$ and every $M \geq 1$.

Using the variation of constants formula, the exact solution to (2.3) reads

$$\begin{aligned} u^M(t, x_m) &= \frac{1}{M} \sum_{l=1}^{M-1} \sum_{j=1}^{M-1} \exp\left(\lambda_j^M t\right) \varphi_j(x_m) \varphi_j(x_l) u_0(x_l) \\ &\quad + \int_0^t \frac{1}{M} \sum_{l=1}^{M-1} \sum_{j=1}^{M-1} \exp\left(\lambda_j^M(t-s)\right) \varphi_j(x_m) \varphi_j(x_l) f\left(s, x_l, u^M(s, x_l)\right) ds \\ &\quad + \int_0^t \frac{1}{\sqrt{M}} \sum_{l=1}^{M-1} \sum_{j=1}^{M-1} \exp\left(\lambda_j^M(t-s)\right) \varphi_j(x_m) \varphi_j(x_l) \sigma\left(s, x_l, u^M(s, x_l)\right) dW_l^M(s), \end{aligned} \quad (2.5)$$

where we recall that $\varphi_j(x) := \sqrt{2} \sin(jx\pi)$ for $j = 1, \dots, M-1$.

We next define the discrete kernel $G^M(t, x, y)$ by

$$G^M(t, x, y) := \sum_{j=1}^{M-1} \exp\left(\lambda_j^M t\right) \varphi_j^M(x) \varphi_j(\kappa_M(y)), \quad (2.6)$$

where $\kappa_M(y) := \frac{[My]}{M}$, $\varphi_j^M(x) := \varphi_j(x_l)$ for $x = x_l$ and

$$\varphi_j^M(x) := \varphi_j(x_l) + (Mx - l)(\varphi_j(x_{l+1}) - \varphi_j(x_l)), \quad \text{if } x \in (x_l, x_{l+1}].$$

With these definitions in hand one sees that the semidiscrete solution u^M satisfies the mild equation:

$$\begin{aligned} u^M(t, x) &= \int_0^1 G^M(t, x, y) u_0(\kappa_M(y)) dy \\ &\quad + \int_0^t \int_0^1 G^M(t-s, x, y) f(s, \kappa_M(y), u^M(s, \kappa_M(y))) dy ds \\ &\quad + \int_0^t \int_0^1 G^M(t-s, x, y) \sigma(s, \kappa_M(y), u^M(s, \kappa_M(y))) dW(s, y) \end{aligned} \quad (2.7)$$

\mathbb{P} -a.s., for all $t \geq 0$ and $x \in [0, 1]$.

Next, we proceed by collecting some useful results for the error analysis of the fully discrete numerical discretization presented in the next subsection. The following two results are proved in Gyöngy (1998b). Recall that u^M is the space discrete approximation given by (2.7) and that u is the exact solution given by equation (2.2).

PROPOSITION 2.1 (Proposition 3.6 in Gyöngy, 1998b). Assume that $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$ and that the functions f and σ satisfy the condition (LG). Then, for every $p \geq 1$, there exists a constant C such that

$$\sup_{M \geq 1} \sup_{(t, x) \in [0, T] \times [0, 1]} \mathbb{E}[|u^M(t, x)|^{2p}] \leq C.$$

THEOREM 2.2 (Theorem 3.1 in Gyöngy, 1998b). Assume that f and σ satisfy the conditions (L) and (LG), and that $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$. Then, for every $0 < \alpha < \frac{1}{4}$, $p \geq 1$ and for every $t > 0$, there is a constant $C = C(\alpha, p, t)$ such that

$$\sup_{x \in [0, 1]} \left(\mathbb{E}[|u^M(t, x) - u(t, x)|^{2p}] \right)^{\frac{1}{2p}} \leq C(\Delta x)^\alpha. \quad (2.8)$$

We recall that $\Delta x = 1/M$ is the mesh size in space. Moreover, $u^M(t, x)$ converges to $u(t, x)$ almost surely as $M \rightarrow \infty$, uniformly in $t \in [0, T]$ and $x \in [0, 1]$, for every $T > 0$.

If u_0 is sufficiently smooth (e.g., $u_0 \in C^3([0, 1])$) then for every $T > 0$, estimate (2.8) holds with $\alpha = \frac{1}{2}$ and with the same constant C for all $t \in [0, T]$ and integer $M \geq 1$.

We will also make use of the following estimates on the discrete Green function.

LEMMA 2.3 There is a constant C such that the following estimates hold:

(i) For all $0 < s < t \leq T$

$$\sup_{M \geq 1} \sup_{x \in [0, 1]} \int_0^s \int_0^1 |G^M(t - r, x, y) - G^M(s - r, x, y)|^2 dy dr \leq C(t - s)^{1/2}. \quad (2.9)$$

(ii) For all $t \in (0, T]$

$$\sup_{M \geq 1} \sup_{x \in [0, 1]} \int_0^1 |G^M(t, x, y)|^2 dy \leq C \frac{1}{\sqrt{t}}.$$

(iii) For all $0 < s < t \leq T$ and $\alpha \in \left(\frac{1}{2}, \frac{5}{2}\right)$

$$\sup_{M \geq 1} \sup_{x \in [0, 1]} \int_0^1 |G^M(t, x, y) - G^M(s, x, y)|^2 dy \leq Cs^{-\alpha}(t - s)^{\alpha - \frac{1}{2}}.$$

Proof. Recall that

$$G^M(t, x, y) = \sum_{j=1}^{M-1} \exp\left(\lambda_j^M t\right) \varphi_j^M(x) \varphi_j(\kappa_M(y)),$$

where $\kappa_M(y) = \frac{[My]}{M}$, $\varphi_j^M(x) = \varphi_j\left(\frac{l}{M}\right)$ for $x = \frac{l}{M}$ and

$$\varphi_j^M(x) = \varphi_j\left(\frac{l}{M}\right) + (Mx - l) \left(\varphi_j\left(\frac{l+1}{M}\right) - \varphi_j\left(\frac{l}{M}\right) \right), \quad \text{if } x \in \left(\frac{l}{M}, \frac{l+1}{M}\right].$$

We first prove (i). Observe that a general version of this result is used in the proof of Gyöngy (1998b, Lem. 3.6) (see the term A_1^{2p} therein). Using the definition of the discrete Green function we have

$$\begin{aligned} & \int_0^s \int_0^1 |G^M(t-r, x, y) - G^M(s-r, x, y)|^2 dy dr \\ &= \int_0^s \int_0^1 \left| \sum_{j=1}^{M-1} (\exp(\lambda_j^M(t-r)) - \exp(\lambda_j^M(s-r))) \varphi_j^M(x) \varphi_j(\kappa_M(y)) \right|^2 dy dr. \end{aligned}$$

At this point, we use the fact that the vectors

$$e_j = \left(\sqrt{\frac{2}{M}} \sin \left(j \frac{k}{M} \pi \right), k = 1, \dots, M-1 \right), \quad j = 1, \dots, M-1,$$

form an orthonormal basis of \mathbb{R}^{M-1} , which implies that

$$\int_0^1 \varphi_j(\kappa_M(y)) \varphi_l(\kappa_M(y)) dy = \delta_{\{j=l\}}. \quad (2.10)$$

Hence, using also the definitions of φ_j^M and λ_j^M ,

$$\begin{aligned} & \int_0^s \int_0^1 |G^M(t-r, x, y) - G^M(s-r, x, y)|^2 dy dr \\ &= \int_0^s \sum_{j=1}^{M-1} |\exp(\lambda_j^M(t-r)) - \exp(\lambda_j^M(s-r))|^2 |\varphi_j^M(x)|^2 dr \\ &\leq C \sum_{j=1}^{M-1} \int_0^s \exp(\lambda_j^M(s-r))^2 dr |1 - \exp(\lambda_j^M(t-s))|^2 \\ &\leq C \sum_{j=1}^{M-1} \int_0^s \exp(-2j^2 \pi^2 c_j^M(s-r)) dr (1 - \exp(-j^2 \pi^2 c_j^M(t-s)))^2 \\ &\leq C \sum_{j=1}^{\infty} j^{-2} (j^4(t-s)^2 \wedge 1). \end{aligned}$$

Here we have used that $1 - \exp(-x) \leq x$ and that $(c_j^M)^{-1}$ is bounded. Let $N := \left\lceil \frac{1}{\sqrt{t-s}} \right\rceil$, where $[\cdot]$ denotes the integer part and observe that (by comparing sums with integrals)

$$\begin{aligned} \sum_{j=1}^{\infty} j^{-2} (j^4 (t-s)^2 \wedge 1) &= \sum_{j=1}^N j^2 (t-s)^2 + \sum_{j=N+1}^{\infty} j^{-2} \\ &\leq C(t-s)^2 (N+1)^3 + (N+1)^{-1} \\ &\leq C(t-s)^2 \left(\left\lceil \frac{\sqrt{t-s}+1}{\sqrt{t-s}} \right\rceil \right)^3 + (N+1)^{-1} \\ &\leq C(t-s)^2 \left(\left\lceil \frac{1}{\sqrt{t-s}} \right\rceil \right)^3 + \left(\frac{1}{\sqrt{t-s}} \right)^{-1} \\ &\leq C(t-s)^{\frac{1}{2}}. \end{aligned}$$

This proves part (i). The proof of (ii) follows by similar arguments as those used in the proofs of (Walsh 2005, Lem. 8.1 and Thm. 8.2). First note that, as above, we have

$$\begin{aligned} \int_0^1 |G^M(t, x, y)|^2 dy &= \int_0^1 \left| \sum_{j=1}^{M-1} \exp(\lambda_j^M t) \varphi_j^M(x) \varphi_j(\kappa_M(y)) \right|^2 dy \\ &\leq C \sum_{j=1}^{M-1} \exp(-2j^2 \pi^2 c_j^M t). \end{aligned}$$

The estimate in (ii) now follows from the inequality

$$\sum_{j=1}^{M-1} \exp(-2j^2 \pi^2 c_j^M t) \leq C \left(M \wedge \frac{1}{\sqrt{2c_j^M \pi \sqrt{t}}} \right),$$

which is proved in (Walsh 2005, Lem. 8.1).

We now prove (iii). Using the definition of the discrete Green function, properties of φ_j and the definition of λ_j^M we have

$$\begin{aligned} \int_0^1 |G^M(t, x, y) - G^M(s, x, y)|^2 dy &\leq \sum_{j=1}^{M-1} |\exp(\lambda_j^M t) - \exp(\lambda_j^M s)|^2 \\ &\leq \sum_{j=1}^{M-1} |\exp(-j^2 \pi^2 c_j^M s)|^2 |1 - \exp(-j^2 \pi^2 c_j^M (t-s))|^2. \end{aligned}$$

Since $1 - \exp(-x) \leq x$ and $\exp(-x^2) \leq C_\alpha |x|^{-\alpha}$, for all $\alpha \in \mathbb{R}$, it follows that

$$\begin{aligned} \int_0^1 |G^M(t, x, y) - G^M(s, x, y)|^2 dy &\leq C_\alpha \sum_{j=1}^{M-1} j^{-2\alpha} s^{-\alpha} (1 \wedge j^4 (t-s)^2) \\ &\leq \tilde{C}_1 (t-s)^2 s^{-\alpha} \sum_{j=1}^N j^{4-2\alpha} + \tilde{C}_2 s^{-\alpha} \sum_{j=N+1}^{\infty} j^{-2\alpha}, \end{aligned}$$

where $N = \left\lceil \frac{1}{\sqrt{t-s}} \right\rceil$ and \tilde{C}_1 and \tilde{C}_2 are independent of t and s . We now estimate these two terms as we did in the proof of part (i). Namely, whenever $\alpha < \frac{5}{2}$ we have that

$$\begin{aligned} (t-s)^2 s^{-\alpha} \sum_{j=1}^N j^{4-2\alpha} &\leq C (t-s)^2 s^{-\alpha} (N+1)^{5-2\alpha} \\ &\leq C (t-s)^{\alpha-1/2} s^{-\alpha}, \end{aligned}$$

using the fact that $N+1 \leq \frac{1+\sqrt{t-s}}{\sqrt{t-s}} \leq \frac{C_T}{\sqrt{t-s}}$. For the second term, if $\alpha > \frac{1}{2}$ we obtain

$$\begin{aligned} s^{-\alpha} \sum_{j=N+1}^{\infty} j^{-2\alpha} &= s^{-\alpha} (N+1)^{-2\alpha} + s^{-\alpha} \sum_{j=N+2}^{\infty} j^{-2\alpha} \leq C s^{-\alpha} (N+1)^{1-2\alpha} \\ &\leq (t-s)^{\alpha-1/2} s^{-\alpha}. \end{aligned}$$

Collecting these two estimates leads to the conclusion of the theorem. \square

For the numerical analysis of the exponential method applied to the nonlinear stochastic heat equation (1.1) presented in the next section, the initial data u_0 will be in the space $H^\alpha([0, 1])$, which we now define. We recall that $\varphi_j(x) = \sqrt{2} \sin(jx\pi)$, for $j \geq 1$, form an orthonormal basis of $L^2([0, 1])$ and observe that they are eigenfunctions of the Laplacian operator on $[0, 1]$ with Dirichlet boundary conditions, with eigenvalues given by $j^2\pi^2$, $j \geq 1$, respectively. Then, for any $\alpha \geq 0$, we define the space $H^\alpha([0, 1])$ to be the set of measurable functions $g: [0, 1] \rightarrow \mathbb{R}$ in $L^2([0, 1])$ such that

$$\|g\|_\alpha = \left(\sum_{j=1}^{\infty} (1+j^2)^\alpha |\langle g, \varphi_j \rangle|^2 \right)^{1/2} < \infty. \quad (2.11)$$

The inner product in the above sum stands for the usual $L^2([0, 1])$ inner product. For the sake of simplicity the space $H^\alpha([0, 1])$ will be denoted by H^α . Note that this space is a subspace of the fractional Sobolev space of fractional order α and integrability order $p = 2$ (see [Triebel, 1992](#)). Moreover, for any $\alpha > \frac{1}{2}$, the space H^α is continuously embedded in the space of δ -Hölder-continuous functions for all $\delta \in (0, \alpha - \frac{1}{2})$ (see, e.g., [Di Nezza et al., 2012](#), Thm. 8.2). In the sequel we will essentially restrict to the case $\alpha > \frac{1}{2}$, and thus the Dirichlet boundary condition on the initial datum u_0 will make full sense.

Finally, we need the following regularity results for the finite difference approximation u^M given by (2.7).

PROPOSITION 2.4 Assume that f and σ satisfy the condition (LG).

1. Assume that $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$. For any $0 < s \leq t \leq T$, any $p \geq 1$, and $\frac{1}{2} < \alpha < \frac{5}{2}$, we have

$$\sup_{M \geq 1} \sup_{x \in [0, 1]} \mathbb{E}[|u^M(t, x) - u^M(s, x)|^{2p}] \leq Cs^{-\alpha p} (t - s)^{\nu p},$$

where $\nu = \frac{1}{2} \wedge (\alpha - \frac{1}{2})$.

2. Let $\beta > \frac{1}{2}$ and assume that $u_0 \in H^\beta([0, 1])$ with $u_0(0) = u_0(1) = 0$. For any $0 \leq s \leq t \leq T$ and any $p \geq 1$, we have

$$\sup_{M \geq 1} \sup_{x \in [0, 1]} \mathbb{E}[|u^M(t, x) - u^M(s, x)|^{2p}] \leq C(t - s)^{\tau p},$$

where $\tau = \frac{1}{2} \wedge (\beta - \frac{1}{2})$.

Proof. For ease of presentation we consider functions $f(u)$ and $\sigma(u)$ depending only on u . Let us first define

$$\begin{aligned} F^M(t, x) &:= \int_0^t \int_0^1 G^M(t - s, x, y) f(u^M(s, y)) dy ds \\ H^M(t, x) &:= \int_0^t \int_0^1 G^M(t - s, x, y) \sigma(u^M(s, y)) dW(s, y). \end{aligned}$$

Then we have

$$\begin{aligned} u^M(t, x) - u^M(s, x) &= \int_0^1 (G^M(t, x, y) - G^M(s, x, y)) u_0(\kappa_M(y)) dy \\ &\quad + F^M(t, x) - F^M(s, x) \\ &\quad + H^M(t, x) - H^M(s, x). \end{aligned}$$

By (Gyöngy 1998b, Lem. 3.6), the last two terms can be estimated by

$$\mathbb{E}[|F^M(t, x) - F^M(s, x)|^{2p}] + \mathbb{E}[|H^M(t, x) - H^M(s, x)|^{2p}] \leq C|t - s|^{\frac{p}{2}}. \quad (2.12)$$

It remains to estimate the term involving u_0 .

Assume first that $u_0 \in C([0, 1])$. We use the third part of Lemma 2.3 to get the following estimate:

$$\begin{aligned}
 & \left(\mathbb{E} \left[\left| \int_0^1 (G^M(t, x, y) - G^M(s, x, y)) u_0(\kappa_M(y)) \, dy \right|^{2p} \right] \right)^{1/p} \\
 &= \left| \int_0^1 (G^M(t, x, y) - G^M(s, x, y)) u_0(\kappa_M(y)) \, dy \right|^2 \\
 &\leq C \int_0^1 |G^M(t, x, y) - G^M(s, x, y)|^2 |u_0(\kappa_M(y))|^2 \, dy \\
 &\leq C s^{-\alpha} (t - s)^{\alpha - \frac{1}{2}}.
 \end{aligned}$$

Collecting the above estimates and taking into account that $s^{-\alpha p} \geq T^{-\alpha p}$ in (2.12), we get

$$\sup_{M \geq 1} \sup_{x \in [0, 1]} \mathbb{E}[|u^M(t, x) - u^M(s, x)|^{2p}] \leq C s^{-\alpha p} (t - s)^{\nu p},$$

where $\nu = \frac{1}{2} \wedge (\alpha - \frac{1}{2})$.

Assume now that $u_0 \in H^\beta([0, 1])$ for some $\beta > \frac{1}{2}$. Using the explicit expression of G^M , Cauchy–Schwarz inequality and that $1 - \exp(-x) \leq x$ we have

$$\begin{aligned}
 & \left| \int_0^1 (G^M(t, x, y) - G^M(s, x, y)) u_0(\kappa_M(y)) \, dy \right|^{2p} \\
 &= \left| \sum_{j=1}^{M-1} (\exp(\lambda_j^M t) - \exp(\lambda_j^M s)) \langle u_0(\kappa_M(y)), \varphi_j(\kappa_M(y)) \rangle \varphi_j^M(x) \right|^{2p} \\
 &\leq \left(\sum_{j=1}^{M-1} |\exp(\lambda_j^M t) - \exp(\lambda_j^M s)| |\langle u_0, \varphi_j \rangle| \right)^{2p} \\
 &\leq C \left(\sum_{j=1}^{M-1} j^{-2\beta} |\exp(\lambda_j^M t) - \exp(\lambda_j^M s)|^2 \right)^p \left(\sum_{j=1}^{\infty} j^{2\beta} |\langle u_0, \varphi_j \rangle|^2 \right)^p \\
 &\leq C \left(\sum_{j=1}^{M-1} j^{-2\beta} \exp(2\lambda_j^M s) |\exp(\lambda_j^M (t - s)) - 1|^2 \right)^p \|u_0\|_\beta^{2p} \\
 &\leq C \left(\sum_{j=1}^{\infty} j^{-2\beta} (j^4 (t - s)^2 \wedge 1) \right)^p.
 \end{aligned}$$

Here we have used that $\langle u_0(\kappa_M(y)), \varphi_j(\kappa_M(y)) \rangle = \langle u_0, \varphi_j \rangle$, which can be verified by a simple calculation (see equation (21) in [Quer-Sardanyons & Sanz-Solé, 2006](#)). Furthermore, for $\beta > \frac{5}{2}$, we have

$$\sum_{j=1}^{\infty} j^{-2\beta} (j^4(t-s)^2 \wedge 1) \leq C(t-s)^2.$$

On the other hand, if $\beta \in (\frac{1}{2}, \frac{5}{2}]$,

$$\sum_{j=1}^{\infty} j^{-2\beta} (j^4(t-s)^2 \wedge 1) = (t-s)^2 \sum_{j=1}^N j^{4-2\beta} + \sum_{j=N+1}^{\infty} j^{-2\beta},$$

where $N = \left\lceil \frac{1}{\sqrt{t-s}} \right\rceil$, and $\lceil \cdot \rceil$ denotes the integer part. Note that

$$(t-s)^2 \sum_{j=1}^N j^{4-2\beta} \leq C(t-s)^{\beta-\frac{1}{2}}$$

and

$$\sum_{j=N+1}^{\infty} j^{-2\beta} \leq C(t-s)^{\beta-\frac{1}{2}}.$$

Hence, we arrive at the estimate

$$\mathbb{E} \left[\left| \int_0^1 (G^M(t, x, y) - G^M(s, x, y)) u_0(\kappa_M(y)) dy \right|^{2p} \right] \leq C(t-s)^{\gamma p}, \quad (2.13)$$

where $\gamma = 2 \wedge (\beta - \frac{1}{2})$, for $\beta > \frac{1}{2}$. By estimates (2.12) and (2.13) we have

$$\begin{aligned} \sup_{M \geq 1} \sup_{x \in [0, 1]} \mathbb{E}[|u^M(t, x) - u^M(s, x)|^{2p}] &\leq C(|t-s|^{\frac{p}{2}} + |t-s|^{\gamma p}) \\ &\leq C|t-s|^{\tau p}, \end{aligned}$$

where $\tau = \frac{1}{2} \wedge (\beta - \frac{1}{2})$, for $\beta > \frac{1}{2}$. □

3. Full discretization

This section is devoted to introduce the time discretization of the semidiscrete problem presented in the previous section, which will be denoted by $u^{M,N}$. Next we prove some properties of $u^{M,N}$, which will be needed in the sequel and we state and prove the main result of the present section (cf. Theorem 3.8 below), namely the $L^{2p}(\mathcal{Q})$ -convergence of the fully discrete scheme to the exact solution u . Finally, we establish almost sure convergence of the fully discrete approximation $u^{M,N}$ to the exact solution of the stochastic heat equation (1.1).

We start by discretizing the space discrete solution (2.5) in time using an exponential integrator. For an integer $N \geq 1$ and some fixed final time $T > 0$, let $\Delta t = \frac{T}{N}$ and define the discrete times $t_n = n\Delta t$ for $n = 0, 1, \dots, N$. For simplicity of presentation we consider that the functions f and σ only depend on the third variable. Let us now consider the mild equation (2.5) on the small time interval $[t_n, t_{n+1}]$ written in a more compact form (recall the notation $u_m^M(t) = u^M(t, x_m)$) as follows:

$$u^M(t_{n+1}) = e^{A\Delta t} u^M(t_n) + \int_{t_n}^{t_{n+1}} e^{A(t_{n+1}-s)} F(u^M(s)) ds + \int_{t_n}^{t_{n+1}} e^{A(t_{n+1}-s)} \Sigma(u^M(s)) dW^M(s),$$

with the finite difference matrix $A := M^2 D$, the vector $F(u^M(s))$ with entries $f(u_m^M(s))$ for $m = 1, 2, \dots, M-1$ and the diagonal matrix $\Sigma(u^M(s))$ with elements $\sqrt{M}\sigma(u_m^M(s))$ for $m = 1, 2, \dots, M-1$. The matrix D has been defined in Section 2. We next discretize the integrals in the above mild equation by freezing the integrands at the left endpoints of the intervals, so we obtain the explicit exponential integrator (omitting the explicit dependence on M for clarity)

$$\begin{aligned} \mathcal{U}^0 &:= u^M(0), \\ \mathcal{U}^{n+1} &:= e^{A\Delta t} (\mathcal{U}^n + F(\mathcal{U}^n)\Delta t + \Sigma(\mathcal{U}^n)\Delta W^n), \end{aligned} \tag{3.1}$$

where the terms $\Delta W^n := W^M(t_{n+1}) - W^M(t_n)$ denote the $(M-1)$ -dimensional Wiener increments. The above formulation of the exponential integrator will be used for the practical computations presented below.

REMARK 3.1 In some particular situations, alternative approximations of the integrals in the mild equations are possible, see for instance Jentzen & Kloeden (2009), Hochbruck & Ostermann (2010) and Lord & Tambue (2013). This could possibly lead to better numerical schemes or improved error estimates, which will be investigated in future works.

For the theoretical parts presented below we will make use of the discrete Green function G^M (see (2.6)) in order to write the numerical scheme in a more suitable form. We thus obtain the approximation $U_m^{n+1} \approx u(t_{n+1}, x_m)$ given by (with a slight abuse of notations for the functions f and σ)

$$\begin{aligned} U_m^{n+1} &= \frac{1}{M} \sum_{l=1}^{M-1} \sum_{j=1}^{M-1} \exp(\lambda_j^M \Delta t) \varphi_j(x_m) \varphi_j(x_l) U_l^n \\ &\quad + \Delta t \frac{1}{M} \sum_{l=1}^{M-1} \sum_{j=1}^{M-1} \exp(\lambda_j^M \Delta t) \varphi_j(x_m) \varphi_j(x_l) f(U_l^n) \\ &\quad + \frac{1}{\sqrt{M}} \sum_{l=1}^{M-1} \sum_{j=1}^{M-1} \exp(\lambda_j^M \Delta t) \varphi_j(x_m) \varphi_j(x_l) \sigma(U_l^n) (W_l^M(t_{n+1}) - W_l^M(t_n)). \end{aligned}$$

The above equation can be written in the equivalent form

$$\begin{aligned} U_m^{n+1} &= \int_0^1 G^M(t_{n+1} - t_n, x_m, y) U_{M\kappa_M(y)}^n dy \\ &\quad + \int_{t_n}^{t_{n+1}} \int_0^1 G^M(t_{n+1} - t_n, x_m, y) f(U_{M\kappa_M(y)}^n) dy ds \\ &\quad + \int_{t_n}^{t_{n+1}} \int_0^1 G^M(t_{n+1} - t_n, x_m, y) \sigma(U_{M\kappa_M(y)}^n) W(ds, dy), \end{aligned}$$

where we recall that

$$G^M(t, x, y) = \sum_{j=1}^{M-1} \exp(\lambda_j^M t) \varphi_j^M(x) \varphi_j(\kappa_M(y)),$$

and $\kappa_M(y) = \frac{[My]}{M}$, $\varphi_j^M(x) = \varphi_j(x_l)$ for $x = x_l$ and $\varphi_j^M(x) = \varphi_j(x_l) + (Mx - l)(\varphi_j(x_{l+1}) - \varphi_j(x_l))$ for $x \in (x_l, x_{l+1}]$. In order to exhibit a more convenient mild form of the numerical solution U_m^n we iterate the integral equation above to obtain

$$\begin{aligned} U_m^{n+1} &= \int_0^1 G^M(t_{n+1}, x_m, y) u_0(\kappa_M(y)) dy \\ &\quad + \sum_{r=0}^n \int_{t_r}^{t_{r+1}} \int_0^1 G^M(t_{n+1} - t_r, x_m, y) f(U_{M\kappa_M(y)}^r) dy ds \\ &\quad + \sum_{r=0}^n \int_{t_r}^{t_{r+1}} \int_0^1 G^M(t_{n+1} - t_r, x_m, y) \sigma(U_{M\kappa_M(y)}^r) W(ds, dy), \end{aligned}$$

for all $m = 1, \dots, M-1$ and $n = 0, 1, \dots, N$. This implies that

$$\begin{aligned} U_m^{n+1} &= \int_0^1 G^M(t_{n+1}, x_m, y) u_0(\kappa_M(y)) dy \\ &\quad + \int_0^{t_{n+1}} \int_0^1 G^M(t_{n+1} - \kappa_N^T(s), x_m, y) f\left(U_{M\kappa_M(y)}^{\kappa_N^T(s)/\Delta t}\right) dy ds \\ &\quad + \int_0^{t_{n+1}} \int_0^1 G^M(t_{n+1} - \kappa_N^T(s), x_m, y) \sigma\left(U_{M\kappa_M(y)}^{\kappa_N^T(s)/\Delta t}\right) W(ds, dy), \end{aligned} \quad (3.2)$$

where we have used the notation $\kappa_N^T(s) := T\kappa_N(\frac{s}{T})$. Set $u^{M,N}(t_n, x_m) := U_m^n$. Then equation (3.2) yields

$$\begin{aligned} u^{M,N}(t_n, x_m) &= \int_0^1 G^M(t_n, x_m, y) u_0(\kappa_M(y)) dy \\ &+ \int_0^{t_n} \int_0^1 G^M\left(t_n - \kappa_N^T(s), x_m, y\right) f\left(u^{M,N}(\kappa_N^T(s), \kappa_M(y))\right) dy ds \\ &+ \int_0^{t_n} \int_0^1 G^M\left(t_n - \kappa_N^T(s), x_m, y\right) \sigma\left(u^{M,N}(\kappa_N^T(s), \kappa_M(y))\right) W(ds, dy). \end{aligned} \quad (3.3)$$

At this point, we will introduce the *weak* form associated to the full discretization scheme, and in particular to equation (3.3). This will allow us to define a continuous version of the scheme, which will be denoted by $u^{M,N}(t, x)$, with $(t, x) \in [0, T] \times [0, 1]$. More precisely, let $\{v(t, x), (t, x) \in [0, T] \times [0, 1]\}$ be the unique \mathcal{F}_t -adapted continuous random field satisfying the following: for all $\Phi \in C^\infty(\mathbb{R}^2)$ with $\Phi(t, 0) = \Phi(t, 1) = 0$ for all t , it holds

$$\begin{aligned} \int_0^1 v(t, \kappa_M(y)) \Phi(t, y) dy &= \int_0^1 u_0(\kappa_M(y)) \Phi(t, y) dy \\ &+ \int_0^t \int_0^1 v(s, \kappa_M(y)) \left(\Delta_M \Phi(s, y) + \frac{\partial \Phi}{\partial s}(s, y) \right) dy ds \\ &+ \int_0^t \int_0^1 f(v(\kappa_N^T(s), \kappa_M(y))) \Phi(s, y) dy ds \\ &+ \int_0^t \int_0^1 \sigma(v(\kappa_N^T(s), \kappa_M(y))) \Phi(s, y) W(ds, dy), \quad \mathbb{P}\text{-a.s.}, \end{aligned} \quad (3.4)$$

for all $t \in [0, T]$. Here, Δ_M denotes the discrete Laplacian, which is defined by, recalling that $\Delta x = \frac{1}{M}$,

$$\Delta_M \Phi(s, y) := (\Delta x)^{-2} \{ \Phi(s, y + \Delta x) - 2\Phi(s, y) + \Phi(s, y - \Delta x) \}.$$

Let us prove that, on the time–space grid points, the random field v fulfills equation (3.3). That is, we have the following result.

LEMMA 3.2 With the above notations at hand, we have that, for all $m = 1, \dots, M-1$ and $n = 0, 1, \dots, N$,

$$\begin{aligned} v(t_n, x_m) &= \int_0^1 G^M(t_n, x_m, y) u_0(\kappa_M(y)) dy \\ &+ \int_0^{t_n} \int_0^1 G^M\left(t_n - \kappa_N^T(s), x_m, y\right) f\left(v(\kappa_N^T(s), \kappa_M(y))\right) dy ds \\ &+ \int_0^{t_n} \int_0^1 G^M\left(t_n - \kappa_N^T(s), x_m, y\right) \sigma\left(v(\kappa_N^T(s), \kappa_M(y))\right) W(ds, dy). \end{aligned} \quad (3.5)$$

Proof. We will follow some of the arguments developed in the proof of (Walsh 1986, Thm. 3.2). Indeed, for any $\phi \in C^\infty(\mathbb{R})$ and any $(t, y) \in [0, T] \times [0, 1]$, we define

$$G_t^M(\phi, y) := \int_0^1 G^M(t, z, y) \phi(z) dz.$$

Since the Green function G^M solves the discretized homogeneous heat equation with Dirichlet boundary conditions, that is, we have $G^M(t, x, 0) = G^M(t, x, 1) = 0$ and, for any fixed $x \in (0, 1)$,

$$\frac{\partial}{\partial t} G^M(t, x, y) - \Delta_M G^M(t, x, y) = 0,$$

we can infer that

$$\begin{aligned} G_t^M(\phi, y) &= \int_0^1 \left(G^M(0, z, y) + \int_0^t \Delta_M G^M(s, z, y) ds \right) \phi(z) dz \\ &= \int_0^1 G^M(0, z, y) \phi(z) dz + \int_0^t \int_0^1 \Delta_M G^M(s, z, y) \phi(z) dz ds. \end{aligned}$$

Hence, $\frac{\partial}{\partial t} G_t^M(\phi, y) = \int_0^1 \Delta_M G^M(t, z, y) \phi(z) dz$. On the other hand, since

$$\Delta_M G_t^M(\phi, y) = \int_0^1 \Delta_M G^M(t, z, y) \phi(z) dz,$$

we deduce that

$$\frac{\partial}{\partial t} G_t^M(\phi, y) - \Delta_M G_t^M(\phi, y) = 0, \quad (3.6)$$

with $(t, y) \in [0, T] \times [0, 1]$.

At this point, we take $\Phi(s, y) = G_{t-\kappa_N^T(s)}^M(\phi, y)$, with $t \in [0, T]$ and $\phi \in C^\infty(\mathbb{R})$, and plug this Φ in (3.4). Thus, by (3.6) we get that

$$\begin{aligned} \int_0^1 v(t, \kappa_M(y)) G_{t-\kappa_N^T(t)}^M(\phi, y) dy &= \int_0^1 u_0(\kappa_M(y)) G_t^M(\phi, y) dy \\ &\quad + \int_0^t \int_0^1 f\left(v(\kappa_N^T(s), \kappa_M(y))\right) G_{t-\kappa_N^T(s)}^M(\phi, y) dy ds \\ &\quad + \int_0^t \int_0^1 \sigma\left(v(\kappa_N^T(s), \kappa_M(y))\right) G_{t-\kappa_N^T(s)}^M(\phi, y) W(ds, dy). \end{aligned}$$

Let $(\phi_\varepsilon)_{\varepsilon \geq 0}$ be an approximation of the Dirac delta δ_x , for some $x \in (0, 1)$ (e.g., ϕ_ε could be taken to be Gaussian kernels), so that we have

$$\begin{aligned} \int_0^1 v(t, \kappa_M(y)) G_{t-\kappa_N^T(t)}^M(\phi_\varepsilon, y) dy &= \int_0^1 u_0(\kappa_M(y)) G_t^M(\phi_\varepsilon, y) dy \\ &+ \int_0^t \int_0^1 f(v(\kappa_N^T(s), \kappa_M(y))) G_{t-\kappa_N^T(s)}^M(\phi_\varepsilon, y) dy ds \\ &+ \int_0^t \int_0^1 \sigma(v(\kappa_N^T(s), \kappa_M(y))) G_{t-\kappa_N^T(s)}^M(\phi_\varepsilon, y) W(ds, dy). \end{aligned}$$

Then, as it is done in the proof of (Walsh 1986, Thm. 3.2), take $\varepsilon \rightarrow 0$ in the latter equation, so we will end up with

$$\begin{aligned} &\int_0^1 G^M(t - \kappa_N^T(t), x, y) v(t, \kappa_M(y)) dy \\ &= \int_0^1 G^M(t, x, y) u_0(\kappa_M(y)) dy \\ &+ \int_0^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) f(v(\kappa_N^T(s), \kappa_M(y))) dy ds \\ &+ \int_0^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) \sigma(v(\kappa_N^T(s), \kappa_M(y))) W(ds, dy). \end{aligned} \quad (3.7)$$

Note that this equation, which is valid for any $(t, x) \in [0, T] \times [0, 1]$, is very similar to the one we would like to get, that is, (3.5). In fact, taking $t = t_n$ and $x = x_m$ in (3.7) for some $n \in \{0, \dots, N\}$ and $m \in \{1, \dots, M-1\}$, respectively, we have, using the explicit expression of G^M ,

$$\begin{aligned} \int_0^1 G^M(0, x_m, y) v(t_n, \kappa_M(y)) dy &= \int_0^1 \left(\sum_{j=1}^{M-1} \varphi_j(x_m) \varphi_j(\kappa_M(y)) \right) v(t_n, \kappa_M(y)) dy \\ &= \sum_{j=1}^{M-1} \varphi_j(x_m) \int_0^1 \varphi_j(\kappa_M(y)) v(t_n, \kappa_M(y)) dy \\ &= \sum_{k=1}^{M-1} v(t_n, x_k) \frac{1}{M} \sum_{j=1}^{M-1} \varphi_j(x_m) \varphi_j(x_k) \\ &= v(t_n, x_m), \end{aligned}$$

where in the last step we have applied (2.10). This concludes the lemma's proof. \square

As a consequence of Lemma 3.2 and comparing equations (3.3) and (3.5) we deduce that $u^{M,N}(t_n, x_m) = v(t_n, x_m)$ for all $m = 1, \dots, M-1$ and $n = 0, 1, \dots, N$. Thus, we can define a continuous version of $u^{M,N}$ as follows: for any $(t, x) \in [0, T] \times [0, 1]$, set

$$u^{M,N}(t, x) := \int_0^1 G^M(t - \kappa_N^T(t), x, y) v(t, \kappa_M(y)) dy.$$

Observe that, by (3.7), the random field $\{u^{M,N}(t, x), (t, x) \in [0, T] \times [0, 1]\}$ satisfies

$$\begin{aligned} u^{M,N}(t, x) &:= \int_0^1 G^M(t, x, y) u_0(\kappa_M(y)) dy \\ &+ \int_0^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) f(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) dy ds \\ &+ \int_0^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) \sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) W(ds, dy). \end{aligned} \quad (3.8)$$

The above mild form of the fully discrete approximation will be used in the proof of the main result of the paper (see Theorem 3.8).

REMARK 3.3 It can be easily proved that, if t_n is any discrete time and $x \in (x_m, x_{m+1})$, then $u^{M,N}(t_n, x)$ turns out to be the linear interpolation between $u^{M,N}(t_n, x_m)$ and $u^{M,N}(t_n, x_{m+1})$. This is consistent with the definition of the space discrete approximation $u^M(t, x)$ whenever $x \in (x_m, x_{m+1})$ (see (2.4)).

3.1 Some properties of the fully discrete solution

This section is devoted to provide three results establishing properties of the full approximation $u^{M,N}$, which will be needed in the sequel.

First, we note that the full approximation (3.8) is bounded. Indeed, the proof of the following proposition is very similar to that of Proposition 2.1 above and is therefore omitted.

PROPOSITION 3.4 Assume that $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$ and that the functions f and σ satisfy the condition (LG). Then, for every $p \geq 1$, there exists a constant C such that

$$\sup_{M, N \geq 1} \sup_{(t, x) \in [0, T] \times [0, 1]} \mathbb{E}[|u^{M,N}(t, x)|^{2p}] \leq C.$$

Next we define the following quantities:

$$w^{M,N}(t, x) := u^{M,N}(t, x) - \int_0^1 G^M(t, x, y) u_0(\kappa_M(y)) dy$$

and

$$w^M(t, x) := u^M(t, x) - \int_0^1 G^M(t, x, y) u_0(\kappa_M(y)) dy,$$

where we recall that u^M stands for the spatial discretization introduced in Section 2. Then we have the following result.

PROPOSITION 3.5 Assume that $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$ and that f and σ satisfy condition (LG). Then, for every $p \geq 1$, $t, r \in [0, T]$ and $x, z \in [0, 1]$, we have

$$\mathbb{E}[|w^M(t, x) - w^M(r, z)|^{2p}] \leq C \left(|t - r|^{1/4} + |x - z|^{1/2} \right)^{2p} \quad (3.9)$$

$$\mathbb{E}[|w^{M,N}(t, x) - w^{M,N}(r, z)|^{2p}] \leq C \left(|t - r|^{1/4} + |x - z|^{1/2} \right)^{2p}, \quad (3.10)$$

where the constant C does not depend on M , neither on N .

Proof. Inequality (3.9) is proved in (Gyöngy 1998b, Prop. 3.7). Let us now show inequality (3.10). By definition, we have

$$\begin{aligned} w^{M,N}(t, x) &= \int_0^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) f(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) dy ds \\ &\quad + \int_0^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) \sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) W(ds, dy) \\ &=: F^{M,N}(t, x) + H^{M,N}(t, x), \end{aligned}$$

and hence

$$w^{M,N}(t, x) - w^{M,N}(r, z) = F^{M,N}(t, x) - F^{M,N}(r, z) + H^{M,N}(t, x) - H^{M,N}(r, z).$$

Therefore,

$$\begin{aligned} \mathbb{E}[|w^{M,N}(t, x) - w^{M,N}(r, z)|^{2p}] &\leq C(\mathbb{E}[|F^{M,N}(t, x) - F^{M,N}(r, z)|^{2p}] \\ &\quad + \mathbb{E}[|H^{M,N}(t, x) - H^{M,N}(r, z)|^{2p}]). \end{aligned}$$

We will next prove that

$$\mathbb{E}[|H^{M,N}(t, x) - H^{M,N}(r, z)|^{2p}] \leq C \left(|t - r|^{1/4} + |x - z|^{1/2} \right)^{2p}.$$

The estimate for $F^{M,N}$ follows in a similar way. We have

$$\begin{aligned} |H^{M,N}(t, x) - H^{M,N}(r, z)|^{2p} &\leq C(|H^{M,N}(t, x) - H^{M,N}(r, x)|^{2p} \\ &\quad + |H^{M,N}(r, x) - H^{M,N}(r, z)|^{2p}) \end{aligned}$$

and define

$$\begin{aligned} A^{2p} &:= \mathbb{E}[|H^{M,N}(t, x) - H^{M,N}(r, x)|^{2p}] \\ B^{2p} &:= \mathbb{E}[|H^{M,N}(r, x) - H^{M,N}(r, z)|^{2p}]. \end{aligned}$$

Then $A^{2p} \leq C(A_1^{2p} + A_2^{2p})$, where, for $r \leq t$ without loss of generality,

$$\begin{aligned} A_1^{2p} &= \mathbb{E} \left[\left| \int_0^r \int_0^1 \left(G^M(t - \kappa_N^T(s), x, y) \right) - G^M \left(r - \kappa_N^T(s), x, y \right) \right. \right. \\ &\quad \times \left. \left. \sigma \left(u^{M,N}(\kappa_N^T(s), \kappa_M(y)) \right) W(ds, dy) \right|^{2p} \right] \\ A_2^{2p} &= \mathbb{E} \left[\left| \int_r^t \int_0^1 G^M \left(t - \kappa_N^T(s), x, y \right) \sigma \left(u^{M,N}(\kappa_N^T(s), \kappa_M(y)) \right) W(ds, dy) \right|^{2p} \right]. \end{aligned}$$

Using Burkholder–Davis–Gundy’s inequality, Lemma 2.3, assumption (LG) on σ , Minkowski’s inequality and Proposition 3.4, we have the estimates

$$\begin{aligned} A_1^2 &= \left(\mathbb{E} \left[\left| \int_0^r \int_0^1 (G^M(t - \kappa_N^T(s), x, y) - G^M(r - \kappa_N^T(s), x, y)) \sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) W(ds, dy) \right|^{2p} \right] \right)^{1/p} \\ &\leq C \left(\mathbb{E} \left[\left(\int_0^r \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(r - \kappa_N^T(s), x, y)|^2 |\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y)))|^2 dy ds \right)^p \right] \right)^{1/p} \\ &= C \left\| \left\| \int_0^r \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(r - \kappa_N^T(s), x, y)|^2 |\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y)))|^2 dy ds \right\| \right\|_p \\ &\leq C \int_0^r \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(r - \kappa_N^T(s), x, y)|^2 \|\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y)))\|_{2p}^2 dy ds \\ &\leq C \int_0^r \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(r - \kappa_N^T(s), x, y)|^2 dy ds \\ &\leq C(t - r)^{1/2}, \end{aligned}$$

where we set $|||\cdot|||_{2p} = (\mathbb{E}[|\cdot|^{2p}])^{1/(2p)}$. Using similar arguments we have

$$\begin{aligned}
 A_2^2 &= \left(\mathbb{E} \left[\left| \int_r^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) \sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) W(ds, dy) \right|^{2p} \right] \right)^{1/p} \\
 &\leq C \left(\mathbb{E} \left[\left(\int_r^t \int_0^1 |G^M(t - \kappa_N^T(s), x, y)|^2 |\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y)))|^2 dy ds \right)^p \right] \right)^{1/p} \\
 &\leq C \int_r^t \int_0^1 |G^M(t - \kappa_N^T(s), x, y)|^2 |||\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y)))|||_{2p}^2 dy ds \\
 &\leq C \int_r^t \frac{1}{(t - \kappa_N^T(s))^{1/2}} ds \\
 &\leq C \int_r^t \frac{1}{(t - s)^{1/2}} ds \\
 &\leq C(t - r)^{1/2}.
 \end{aligned}$$

Thus, we obtain

$$\mathbb{E}[|H^{M,N}(t, x) - H^{M,N}(r, x)|^{2p}] \leq C|t - r|^{p/2},$$

and we remark that this estimate is uniform with respect to $x \in [0, 1]$.

It remains to estimate the term B . We have

$$B^{2p} := \mathbb{E} \left[\left| \int_0^r \int_0^1 (G^M(r - \kappa_N^T(s), x, y) - G^M(r - \kappa_N^T(s), z, y)) \sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) W(ds, dy) \right|^{2p} \right],$$

and estimating B as we did for A_1 and A_2 , we obtain

$$\begin{aligned}
 B^2 &\leq C \int_0^r \int_0^1 |G^M(r - \kappa_N^T(s), x, y) - G^M(r - \kappa_N^T(s), z, y)|^2 dy ds \\
 &\leq C \int_0^r \sum_{j=1}^{M-1} \exp(-2j^2 \pi^2 c_j^M(r - \kappa_N^T(s))) |\varphi_j^M(x) - \varphi_j^M(z)|^2 ds \\
 &\leq C \int_0^r \sum_{j=1}^{M-1} \exp(-2j^2 \pi^2 c_j^M(r - s)) |\varphi_j^M(x) - \varphi_j^M(z)|^2 ds.
 \end{aligned}$$

At this point, we note that the latter term also appears in the proof of (Gyöngy 1998b, Lem. 3.6), so we can estimate it in the same way and obtain

$$\mathbb{E}[|H^{M,N}(r, x) - H^{M,N}(r, z)|^{2p}] \leq C|x - z|^p,$$

with a constant C independent of r . Collecting the estimates obtained so far we obtain the bound

$$\mathbb{E}[|H^{M,N}(t, x) - H^{M,N}(r, z)|^{2p}] \leq C \left(|t - r|^{1/4} + |x - z|^{1/2} \right)^{2p},$$

which finally leads to (3.10). \square

Finally, we shall also need the following regularity result for the full approximation.

PROPOSITION 3.6 Assume that f and σ satisfy condition (LG).

1. If $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$, then for any $s, t \in [0, T]$ and $x \in [0, 1]$, $p \geq 1$ and $\frac{1}{2} < \alpha < \frac{5}{2}$, we have

$$\mathbb{E}[|u^{M,N}(t, x) - u^{M,N}(s, x)|^{2p}] \leq Cs^{-\alpha p} |t - s|^{\tau p},$$

where $\tau = \frac{1}{2} \wedge (\alpha - \frac{1}{2})$ and with a constant C independent of M, N and x .

2. Let $\beta > \frac{1}{2}$ and assume that $u_0 \in H^\beta([0, 1])$ with $u_0(0) = u_0(1) = 0$. Then, for any $s, t \in [0, T]$ and $x, z \in [0, 1]$, and any $p \geq 1$, we have

$$\mathbb{E}[|u^{M,N}(t, x) - u^{M,N}(s, z)|^{2p}] \leq C(|t - s|^{\tau p} + |x - z|^{2\tau p}),$$

where $\tau = \frac{1}{2} \wedge (\beta - \frac{1}{2})$ and with a constant C independent of M and N .

Proof. The proof can be built on the proof of Proposition 2.4, so we will only sketch the main steps.

To start with, part 1 can be proved by following the same arguments used in the proof of part 1 of Proposition 2.4 and it is based on three estimates. First, one applies that

$$\int_0^1 |G^M(t, x, y) - G^M(s, x, y)|^2 dy \leq Cs^{-\alpha} |t - s|^{\alpha - \frac{1}{2}},$$

which corresponds to part (iii) in Lemma 2.3. Secondly, we have

$$\int_s^t \int_0^1 |G^M(t - \kappa_N^T(r), x, y)|^2 dy dr \leq C|t - s|^{\frac{1}{2}},$$

which can be verified by using (ii) of Lemma 2.3. Finally, it holds that

$$\int_0^s \int_0^1 |G^M(t - \kappa_N^T(r), x, y) - G^M(s - \kappa_N^T(r), x, y)|^2 dy dr \leq C|t - s|^{\frac{1}{2}}.$$

The latter estimate can be checked by doing some simple modifications in the proof of part (i) in Lemma 2.3.

As far as part 2 is concerned, the time increments can be analyzed following the same steps as those used in the proof of part 2 in Proposition 2.4. We will sketch the proof for the spatial increments. More precisely, taking into account equation (3.8), in order to control the term $\mathbb{E}[|u^{M,N}(t, x) - u^{M,N}(t, z)|^{2p}]$

first we need to estimate the expression

$$\left| \int_0^1 (G^M(t, x, y) - G^M(t, z, y)) u_0(\kappa_M(y)) \, dy \right|^{2p}.$$

Using the same techniques as in the proof of part 2 in Proposition 2.4, the above term can be bounded by

$$\|u_0\|_{H^\beta}^{2p} \left| \sum_{j=1}^{M-1} j^{-2\beta} |\varphi_j^M(x) - \varphi_j^M(z)|^2 \right|^p,$$

where we recall that $\beta > \frac{1}{2}$. Next, it can be easily proved that $|\varphi_j^M(x) - \varphi_j^M(z)| \leq C(1 \wedge j(z-x))$, where the constant C does not depend on M and we have assumed, without losing generality, that $x < z$. Hence,

$$\left| \int_0^1 (G^M(t, x, y) - G^M(t, z, y)) u_0(\kappa_M(y)) \, dy \right|^{2p} \leq C \left(\sum_{j=1}^{\infty} j^{-2\beta} (1 \wedge j^2(z-x)^2) \right)^p.$$

The latter series can be estimated, up to some constant, by $(z-x)^{(2\beta-1)p}$.

As far as the spatial increments of the remaining two terms in equation (3.8) is concerned, applying Burkholder–Davis–Gundy and Minkowski’s inequalities, as well as the linear growth on f and σ and Proposition 3.4, the analysis reduces to control the term

$$\left(\int_0^t \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(t - \kappa_N^T(s), z, y)|^2 \, dy \, ds \right)^p.$$

The same arguments as above yield that this term can be bounded by

$$\begin{aligned} \left(\int_0^t \sum_{j=1}^{M-1} e^{2\lambda_j^M(t-s)} (1 \wedge j^2(z-x)^2) \, ds \right)^p &\leq C \left(\sum_{j=1}^{\infty} j^{-2} (1 \wedge j^2(z-x)^2) \right)^p \\ &\leq C(z-x)^p. \end{aligned}$$

This concludes the proof. \square

REMARK 3.7 Whenever $u_0 \in H^\beta([0, 1])$ for some $\beta > \frac{1}{2}$, the above result implies, thanks to Kolmogorov’s continuity criterion, that the random field $u^{M,N}$ has a version with Hölder-continuous sample paths.

3.2 Main result: strong convergence

We are now ready to formulate and prove the main result of this section. Recall that u^M is the space discrete approximation given by (2.7) and $u^{M,N}$ is the full discretization given by (3.8).

THEOREM 3.8 Assume that f and σ satisfy the conditions (L) and (LG).

1. If $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$, then for any $p \geq 1$, $0 < \mu < \frac{1}{4}$ and $t \in [0, T]$, there exists a constant $C = C(p, \mu, t)$ such that

$$\sup_{x \in [0, 1]} \left(\mathbb{E}[|u^{M,N}(t, x) - u^M(t, x)|^{2p}] \right)^{\frac{1}{2p}} \leq C(\Delta t)^\mu.$$

2. Let $\beta > \frac{1}{2}$ and assume that $u_0 \in H^\beta([0, 1])$ with $u_0(0) = u_0(1) = 0$. Then, for any $p \geq 1$, we have

$$\sup_{t \in [0, T]} \sup_{x \in [0, 1]} \left(\mathbb{E}[|u^{M,N}(t, x) - u^M(t, x)|^{2p}] \right)^{\frac{1}{2p}} \leq C(\Delta t)^\nu,$$

where $\nu = \frac{1}{4} \wedge (\frac{\beta}{2} - \frac{1}{4})$.

Proof. We have, using the notation $|||\cdot|||_{2p} = (\mathbb{E}[|\cdot|^{2p}])^{1/(2p)}$,

$$\begin{aligned} & |||u^{M,N}(t, x) - u^M(t, x)|||_{2p} \\ & \leq ||| \int_0^t \int_0^1 \left(G^M(t - \kappa_N^T(s), x, y) f(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) \right. \\ & \quad \left. - G^M(t - s, x, y) f(u^M(s, \kappa_M(y))) \right) dy ds |||_{2p} \\ & \quad + ||| \int_0^t \int_0^1 \left(G^M(t - \kappa_N^T(s), x, y) \sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) \right. \\ & \quad \left. - G^M(t - s, x, y) \sigma(u^M(s, \kappa_M(y))) \right) W(ds, dy) |||_{2p} \\ & =: A + B. \end{aligned}$$

We show in detail the estimates for B . It will then be clear that similar estimates can be made for A . First, we note that

$$B^2 \leq C(B_1^2 + B_2^2),$$

where

$$B_1^2 = ||| \int_0^t \int_0^1 (G^M(t - \kappa_N^T(s), x, y) - G^M(t - s, x, y)) \sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) W(ds, dy) |||_{2p}^2$$

and

$$B_2^2 = \left\| \int_0^t \int_0^1 G^M(t-s, x, y) (\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) - \sigma(u^M(s, \kappa_M(y)))) W(ds, dy) \right\|_{2p}^2.$$

By Burkholder–Davis–Gundy and Minkowski's inequalities we have

$$\begin{aligned} B_1^2 &= \left(\mathbb{E} \left[\left| \int_0^t \int_0^1 (G^M(t - \kappa_N^T(s), x, y) - G^M(t - s, x, y)) \sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y))) W(ds, dy) \right|^{2p} \right] \right)^{1/p} \\ &\leq C \left(\mathbb{E} \left[\left(\int_0^t \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(t - s, x, y)|^2 |\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y)))|^2 dy ds \right)^p \right] \right)^{1/p} \\ &= C \left\| \int_0^t \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(t - s, x, y)|^2 |\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y)))|^2 dy ds \right\|_p \\ &\leq C \int_0^t \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(t - s, x, y)|^2 \|\sigma(u^{M,N}(\kappa_N^T(s), \kappa_M(y)))\|_{2p}^2 dy ds. \end{aligned}$$

By assumption (LG) and Proposition 3.3 we obtain

$$\begin{aligned} B_1^2 &\leq \sup_{(s,y) \in [0,T] \times [0,1]} \|\sigma(u^{M,N}(s, y))\|_{2p}^2 \\ &\quad \times \int_0^t \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(t - s, x, y)|^2 dy ds \\ &\leq C(\Delta t)^{1/2}. \end{aligned}$$

Here we have also used that

$$\sup_{x \in [0,1]} \int_0^t \int_0^1 |G^M(t - \kappa_N^T(s), x, y) - G^M(t - s, x, y)|^2 dy ds \leq C(\Delta t)^{1/2},$$

where the constant C does not depend on M . This is only a slight variation of (2.9) in Lemma 2.3. The proof is very similar and is therefore omitted.

Concerning the term B_2 using analogous arguments we have

$$\begin{aligned} B_2^2 &\leq C \int_0^t \int_0^1 |G^M(t - s, x, y)|^2 dy \\ &\quad \times \sup_{y \in [0,1]} \|\sigma(u^{M,N}(\kappa_N^T(s), y)) - \sigma(u^M(s, y))\|_{2p}^2 ds. \end{aligned}$$

By the Lipschitz assumption on σ and (ii) in Lemma 2.3 we get

$$\begin{aligned}
 B_2^2 &\leq C \int_0^t \int_0^1 |G^M(t-s, x, y)|^2 dy \sup_{x \in [0,1]} \|u^{M,N}(\kappa_N^T(s), x) - u^M(s, x)\|_{2p}^2 ds \\
 &\leq C \int_0^t \frac{1}{\sqrt{t-s}} \left(\sup_{x \in [0,1]} \|u^{M,N}(\kappa_N^T(s), x) - u^{M,N}(s, x)\|_{2p}^2 \right. \\
 &\quad \left. + \sup_{x \in [0,1]} \|u^{M,N}(s, x) - u^M(s, x)\|_{2p}^2 \right) ds \\
 &\leq C \int_0^t \frac{1}{\sqrt{t-s}} \sup_{x \in [0,1]} \|u^{M,N}(\kappa_N^T(s), x) - u^{M,N}(s, x)\|_{2p}^2 ds \\
 &\quad + C \int_0^t \frac{1}{\sqrt{t-s}} \sup_{x \in [0,1]} \|u^{M,N}(s, x) - u^M(s, x)\|_{2p}^2 ds. \tag{3.11}
 \end{aligned}$$

At this point, We need to distinguish between the two different cases of the initial value u_0 .

If we assume $u_0 \in C([0, 1])$, then we apply Proposition 3.6 to the first term in (3.11), so we get

$$\begin{aligned}
 \int_0^t \frac{1}{\sqrt{t-s}} \sup_{x \in [0,1]} \|u^{M,N}(\kappa_N^T(s), x) - u^{M,N}(s, x)\|_{2p}^2 ds &\leq C(\Delta t)^\tau \int_0^t (t-s)^{-\frac{1}{2}} s^{-\alpha} ds \\
 &= C(\Delta t)^\tau B\left(1-\alpha, \frac{1}{2}\right) t^{\frac{1}{2}-\alpha},
 \end{aligned}$$

where B denotes the beta function. In order to obtain the last equality we need to restrict the range on α to $(\frac{1}{2}, 1)$ (part 1 in Proposition 3.6 was valid for any $\alpha \in (\frac{1}{2}, \frac{5}{2})$). In this case, notice that we have $\tau = \frac{1}{2} \wedge (\alpha - \frac{1}{2}) = \alpha - \frac{1}{2}$. Plugging the above estimate in (3.11) and taking into account that we obtained the bound $B_1^2 \leq C(\Delta t)^{\frac{1}{2}}$ we have thus proved that

$$B^2 \leq C(t)(\Delta t)^{\alpha-\frac{1}{2}} + C \int_0^t \frac{1}{\sqrt{t-s}} \sup_{x \in [0,1]} \|u^{M,N}(s, x) - u^M(s, x)\|_{2p}^2 ds.$$

As commented at the beginning of the proof, the analysis of the term A^2 can be performed in a similar way, in such a way that the same type of estimate can be obtained. Summing up, we have that

$$z(t) \leq C(t)(\Delta t)^{\alpha-\frac{1}{2}} + C \int_0^t \frac{1}{\sqrt{t-s}} z(s) ds,$$

where $z(s) := \sup_{x \in [0,1]} \|u^{M,N}(s, x) - u^M(s, x)\|_{2p}^2$. Then applying a version of Gronwall's lemma (see for instance Pachpatte, 2006, Chap. 1) we conclude this part of the proof.

If we instead assume $u_0 \in H^\beta([0, 1])$ for some $\beta > \frac{1}{2}$, then we apply part 2 of Proposition 3.6 to the first term in (3.11), obtaining

$$\int_0^t \frac{1}{\sqrt{t-s}} \sup_{x \in [0,1]} \|u^{M,N}(\kappa_N^T(s), x) - u^{M,N}(s, x)\|_{2p}^2 ds \leq C(\Delta t)^\tau,$$

where $\tau = \frac{1}{2} \wedge (\beta - \frac{1}{2})$. Hence, in this case we get that

$$z(t) \leq C(\Delta t)^\tau + C \int_0^t \frac{1}{\sqrt{t-s}} z(s) ds,$$

and we conclude applying again a version of Gronwall's lemma; see for instance (Gyöngy 1998b, Lem. 3.4). \square

Combining Theorems 2.2 and 3.4, we arrive at the following error estimate for the full discretization.

THEOREM 3.9 Let f and σ satisfy conditions (L) and (LG).

1. Assume that $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$. Then, for every $p \geq 1$, $t \in (0, T]$, $0 < \alpha_1 < \frac{1}{4}$ and $0 < \alpha_2 < \frac{1}{4}$, there are constants $C_i = C_i(t)$, $i = 1, 2$, such that

$$\sup_{x \in [0,1]} \left(\mathbb{E}[|u^{M,N}(t, x) - u(t, x)|^{2p}] \right)^{\frac{1}{2p}} \leq C_1(\Delta x)^{\alpha_1} + C_2(\Delta t)^{\alpha_2}.$$

2. Let $\beta > \frac{1}{2}$ and assume that $u_0 \in H^\beta([0, 1])$ with $u_0(0) = u_0(1) = 0$. Then, for every $p \geq 1$, $t \in (0, T]$, $0 < \alpha_1 < \frac{1}{4}$, there are constants $C_1 = C_1(t)$ and C_2 such that

$$\sup_{x \in [0,1]} \left(\mathbb{E}[|u^{M,N}(t, x) - u(t, x)|^{2p}] \right)^{\frac{1}{2p}} \leq C_1(\Delta x)^{\alpha_1} + C_2(\Delta t)^\tau,$$

where $\tau = \frac{1}{4} \wedge (\frac{\beta}{2} - \frac{1}{4})$.

REMARK 3.10 For ease of presentation, we stated the above results for functions f and σ depending only on u . Observe that the above results remain true in the case of functions f and σ depending on (t, x, u) if one replaces the condition (L) by the following one:

$$|f(t, x, u) - f(s, y, v)| + |\sigma(t, x, u) - \sigma(s, y, v)| \leq C(|t - s|^{1/4} + |x - y|^{1/2} + |u - v|) \quad (\text{H})$$

for all $s, t \in [0, T]$, $x, y \in [0, 1]$, $u, v \in \mathbb{R}$. In this case, the fully discrete solution reads

$$\begin{aligned} u^{M,N}(t, x) &= \int_0^1 G^M(t, x, y) u_0(\kappa_M(y)) \, dy \\ &+ \int_0^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) f(\kappa_N^T(s), \kappa_M(y), u^{M,N}(\kappa_N^T(s), \kappa_M(y))) \, dy \, ds \\ &+ \int_0^t \int_0^1 G^M(t - \kappa_N^T(s), x, y) \sigma(\kappa_N^T(s), \kappa_M(y), u^{M,N}(\kappa_N^T(s), \kappa_M(y))) \, W(ds, dy), \end{aligned}$$

where we recall that $\kappa_M = \frac{[My]}{M}$ and $\kappa_N^T(s) = T\kappa_N(\frac{s}{T})$.

3.3 Almost sure convergence

In this subsection we prove almost sure convergence of the fully discrete approximation $u^{M,N}$ (3.8) to the exact solution u of the stochastic heat equation (1.1) with globally Lipschitz continuous coefficients. The main result is the following.

THEOREM 3.11 Assume that the functions f and σ satisfy the conditions (LG) and (L) and that $u_0 \in C([0, 1])$ with $u_0(0) = u_0(1) = 0$. Then, the full approximation $u^{M,N}(t, x)$ converges to $u(t, x)$ almost surely, as $M, N \rightarrow \infty$, uniformly in $t \in [0, T]$ and $x \in [0, 1]$.

Proof. In Gyöngy (1998b, Thm. 3.1), it was shown that $u^M(t, x)$ converges to $u(t, x)$ almost surely uniformly in (t, x) as $M \rightarrow \infty$. It is therefore enough to show that $u^{M,N}(t, x)$ converges to $u^M(t, x)$ almost surely, as $N \rightarrow \infty$, uniformly in (t, x) and $M \in \mathbb{N}$. To achieve this, it suffices to prove that $w^{M,N}(t, x)$ converges to $w^M(t, x)$ almost surely in (t, x) as $N \rightarrow \infty$. This is because the terms involving u_0 in the approximations u^M given by (2.7) and $u^{M,N}$ given by (3.8) are the same. We first observe that

$$|w^{M,N}(t, x) - w^M(t, x)|^{2p} \leq C(A_1 + A_2 + A_3),$$

where

$$\begin{aligned} A_1 &= \sum_{n=0}^N \sum_{i=0}^N \left| w^{M,N}(t_n, x_i) - w^M(t_n, x_i) \right|^{2p} \\ A_2 &= \sup_{n=0, \dots, N} \sup_{i=0, \dots, N} \sup_{|x-x_i| \leq 1/N} \sup_{|t-t_n| \leq \Delta t} \left| w^{M,N}(t, x) - w^{M,N}(t_n, x_i) \right|^{2p} \\ A_3 &= \sup_{n=0, \dots, N} \sup_{i=0, \dots, N} \sup_{|x-x_i| \leq 1/N} \sup_{|t-t_n| \leq \Delta t} \left| w^M(t, x) - w^M(t_n, x_i) \right|^{2p} \end{aligned}$$

and we recall that x_i and t_n are the discrete points in space and time, respectively, given by $x_i = \frac{i}{N}$ for $i = 0, 1, \dots, N$ and $t_n = n\Delta t$ for $n = 0, 1, \dots, N$. By Theorem 3.8 we obtain

$$\mathbb{E}[A_1] \leq C \left(\frac{1}{N} \right)^{2\mu p - 2},$$

for all $0 < \mu < \frac{1}{4}$. Also, by Proposition 3.5 we have

$$\mathbb{E}[A_2 + A_3] \leq C \left(\frac{1}{N} \right)^{2p\delta}$$

for $\delta \in (0, 1/4)$. Using that

$$\left(\frac{1}{N} \right)^{2\mu p - 2} + \left(\frac{1}{N} \right)^{2p\delta} \leq 2 \left(\frac{1}{N} \right)^{2p \min(\delta, \mu) - 2}$$

we thus get

$$\mathbb{E} \left[\sup_{M \geq 1} \sup_{(t,x) \in [0,T] \times [0,1]} |w^{M,N}(t,x) - w^M(t,x)|^{2p} \right] \leq C \left(\frac{1}{N} \right)^{2p \min(\delta, \mu) - 2},$$

where the constant C does not depend on M , neither on N . Hence, using Markov's inequality we obtain that

$$\mathbb{P} \left(\sup_{M \geq 1} \sup_{(t,x) \in [0,T] \times [0,1]} |w^{M,N}(t,x) - w^M(t,x)|^{2p} > \left(\frac{1}{N} \right)^2 \right) \leq C \left(\frac{1}{N} \right)^{2p \min(\delta, \mu) - 4}$$

for all integers $N \geq 1$. It thus follows that

$$\sum_{N=1}^{\infty} \mathbb{P} \left(\sup_{M \geq 1} \sup_{(t,x) \in [0,T] \times [0,1]} |w^{M,N}(t,x) - w^M(t,x)|^{2p} > \left(\frac{1}{N} \right)^2 \right) < \infty$$

for p large enough. By the Borel–Cantelli lemma we now know that for sufficiently large p we have

$$\sup_{M \geq 1} \sup_{(t,x) \in [0,T] \times [0,1]} |w^{M,N}(t,x) - w^M(t,x)|^{2p} \leq \frac{1}{N^2},$$

with probability one. Taking the limit $N \rightarrow \infty$ concludes the proof. \square

4. Numerical experiments

This section is devoted to performing numerical experiments in order to illustrate the theoretical results obtained so far, that is, Theorem 3.8 for the strong convergence and Theorem 3.11 for the almost sure convergence. In addition, we compare the computational time of the proposed exponential integrator with two classical time integrators.

We start by numerically illustrating the results from Theorem 3.8. To do so, we first discretize the problem (1.1), with $u_0(x) = \cos(\pi(x - 1/2))$, $f(u) = u/2$, $\sigma(u) = 1 - u$ with centered finite differences using the mesh $\Delta x = 2^{-9}$. The time discretizations are done using the semiimplicit Euler–Maruyama scheme (see e.g., Gyöngy, 1999), the Crank–Nicolson–Maruyama (CNM) scheme (see e.g., Walsh, 2005) and the explicit exponential integrator (3.1) with step sizes Δt ranging from 2^{-1} to 2^{-16} . The loglog plots of the errors $\sup_{(t,x) \in [0,0.5] \times [0,1]} \mathbb{E}[|u^{M,N}(t,x) - u^M(t,x)|^2]$ are shown in Figure 1. The reference

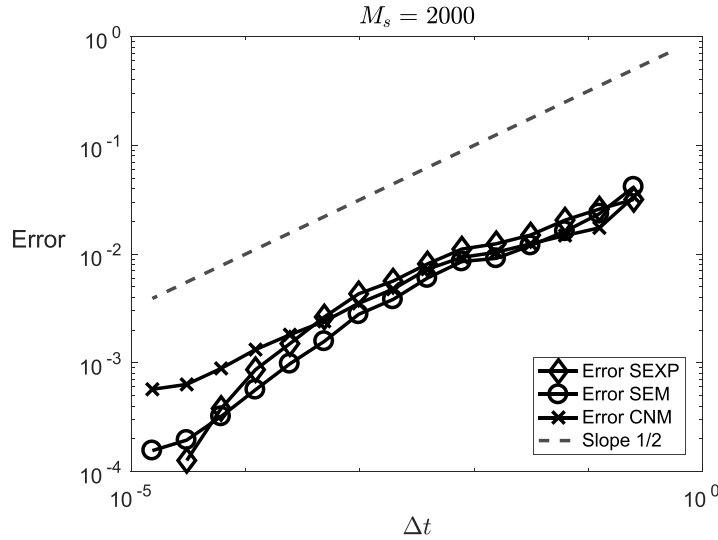


FIG. 1. Temporal rates of convergence for the stochastic exponential integrator (SEXP), the semiimplicit Euler–Maruyama scheme (SEM), and the CNM scheme. The reference line has slope 1/2 (dashed line).

solution is computed with the exponential integrator using $\Delta x_{\text{ref}} = 2^{-9}$ and $\Delta t_{\text{ref}} = 2^{-16}$. The expected values are approximated by computing averages over $M_s = 2000$ samples. In this figure, convergence of order 1/2 for the exponential integrator is observed. One can remark that the convergence rate of the exponential scheme, for smaller step sizes, is closer to the deterministic one. This may be due to the fact that the exact solution to the considered problem rapidly dissipates or to the fact that the reference solution is computed using the exponential scheme. We would also like to mention the difficulty to catch the precise rate of convergence in this setting, compared to, for instance, the case of deterministic problems.

Next we compare the computational costs of the explicit stochastic exponential method (3.1), the SEM and the CNM scheme for the numerical integration of problem (1.1) with the same parameters as in the previous numerical experiments. We run the numerical methods over the time interval $[0, 1]$. We discretize the spatial domain $[0, 1]$ with a mesh $\Delta x = 2^{-9}$. We run 100 samples for each numerical method. For each method and each sample, we run several time steps and compare the error at final time with a reference solution provided for the same sample with the same method for the very small time step $\Delta t_{\text{ref}} = 2^{-16}$. Figure 2 shows the total computational time for all the samples, for each method and each time step, as a function of the averaged final error we obtain.

We observe that the computational cost of the CNM scheme is slightly higher than the cost of the SEM scheme, which is a little bit higher than the one for the explicit scheme (3.1).

We proceed now to numerically illustrate Theorem 3.11. To do so, we first discretize the stochastic heat equation (1.1), with $u_0(x) = \cos(\pi(x - 1/2))$, $f(u) = 1 - u$, $\sigma(u) = \sin(u)$ with centered finite differences using the mesh $\Delta x = 2^{-9}$. The time discretization is done using the explicit exponential integrator (3.1) with step sizes Δt ranging from 2^{-10} to 2^{-20} (only every second power). Figure 3 displays, for a fixed spatial discretization, profiles of one realization of the numerical solution at the fixed time $T = 0.5$ as well as a reference solution computed with the exponential integrator using

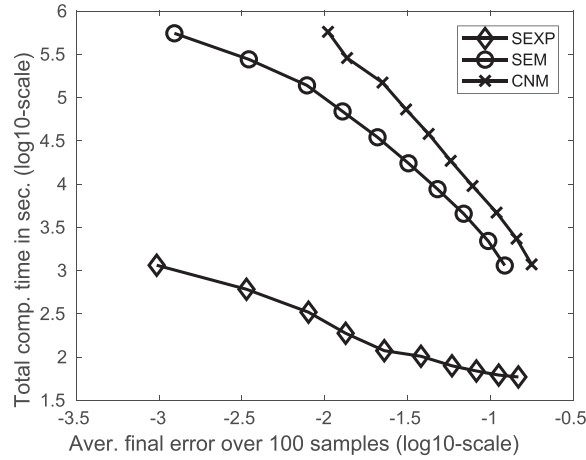


FIG. 2. Computational time as a function of the averaged final error for the following numerical methods: the stochastic exponential scheme (3.1) (SEXP), the SEM scheme and the CNM scheme.

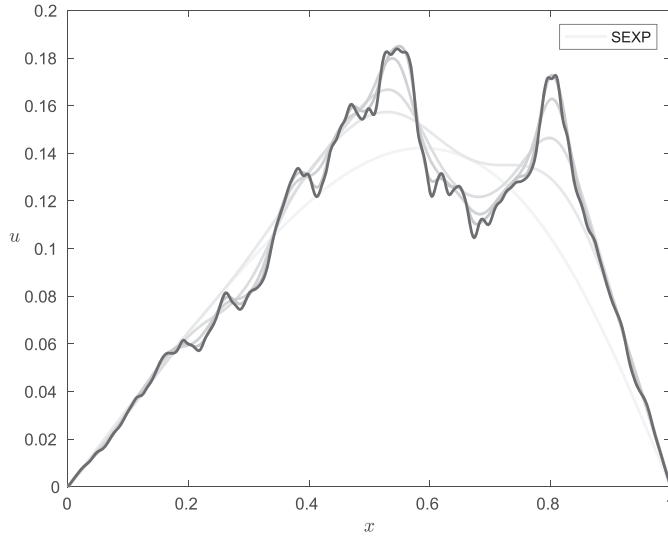


FIG. 3. Almost sure convergence of the stochastic exponential integrator (SEXP). The reference solution is displayed in red.

$\Delta x_{\text{ref}} = 2^{-9}$ and $\Delta t_{\text{ref}} = 2^{-20}$. Convergence to this reference solution as the time step goes to zero (from light to dark grey plots) is observed.

5. Convergence analysis for nonglobally Lipschitz continuous coefficients

In this section, we remove the globally Lipschitz assumption on the coefficients f and σ in equation (1.1) and we prove convergence in probability of the fully discrete approximation $u^{M,N}$ given by (3.8) to

the exact solution u of (1.1). Throughout the section we will assume that the initial condition u_0 belongs to H^β for some $\beta > \frac{1}{2}$.

Furthermore, we shall consider the following hypotheses:

(PU) Pathwise uniqueness holds for problem (1.1): whenever u and v are carried by the same filtered probability space and if both u and v are solutions to problem (1.1) on the stochastic time interval $[0, \tau]$, then $u(t, \cdot) = v(t, \cdot)$ for all $t \in [0, \tau]$, almost surely.

(C) The coefficient functions $f(t, x, u)$ and $\sigma(t, x, u)$ are continuous in the variable u .

REMARK 5.1 For general conditions ensuring pathwise uniqueness in equation (1.1) we refer the reader to Gyöngy & Pardoux (1993a,b). Nevertheless, note that pathwise uniqueness for parabolic stochastic partial differential equations is an active research topic. Indeed, we mention, for instance, the works of Gyöngy (1998a) (Lipschitz coefficients); Mytnik & Perkins (2011) and Mytnik & Neuman (2015) (Hölder coefficients); and Da Prato *et al.* (2013, 2015) (additive noise), where this question is investigated. These results provide examples of parabolic stochastic partial differential equations where assumption (PU) is fulfilled.

In order to prove the main result of the section (cf. Theorem 5.4) we will follow a similar approach as in Gyöngy (1998b) (see also Pettersson & Signahl, 2005). More precisely, we will first use the results from Section 3 to deduce that the family of laws determined by $u^{M,N}$ is tight in the space of continuous functions. Then we will apply Skorokhod's representation theorem and make use of the weak form (3.4) corresponding to the fully discrete approximation $u^{M,N}$. Finally, a suitable passage to the limit and assumption (PU) will let us conclude the proof.

We will use the above strategy in a successful way thanks the following two auxiliary results.

LEMMA 5.2 (Lemma 4.5 in Gyöngy, 1998b). For all $k \geq 0$, let $z^k = \{z^k(t, x) : t \geq 0, x \in [0, 1]\}$ be a continuous \mathcal{F}_t^k -adapted random field and let $W^k = \{W^k(t, x) : t \geq 0, x \in [0, 1]\}$ be a Brownian sheet carried by some filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t^k)_{t \geq 0}, P)$. Assume also that, for every $\varepsilon > 0$

$$\lim_{k \rightarrow \infty} P \left(\sup_{t \in [0, T]} \sup_{x \in [0, 1]} (|z^k - z^0| + |W^k - W^0|)(t, x) \geq \varepsilon \right) = 0.$$

Let $h = h(t, x, r)$ be a bounded Borel function of $(t, x, r) \in \mathbb{R}_+ \times [0, 1] \times \mathbb{R}$, which is continuous in $r \in \mathbb{R}$. Then, letting $k \rightarrow \infty$,

$$\begin{aligned} \int_0^t \int_0^1 h(s, x, z^k(s, x)) \, dx \, ds &\longrightarrow \int_0^t \int_0^1 h(s, x, z^0(s, x)) \, dx \, ds, \\ \int_0^t \int_0^1 h(s, x, z^k(s, x)) \, W^k(ds, dx) &\longrightarrow \int_0^t \int_0^1 h(s, x, z^0(s, x)) \, W^0(ds, dx), \end{aligned}$$

in probability for every $t \in [0, T]$.

LEMMA 5.3 (Lemma 4.4 in Gyöngy, 1998b). Let E be a Polish space equipped with the Borel σ -algebra. A sequence of E -valued random elements $(z_n)_{n \geq 1}$ converges in probability if and only if, for every pair of subsequences $z_l := z_{n_l}$ and $z_m := z_{n_m}$, there exists a subsequence $v_k := (z_{l_k}, z_{m_k})$ converging weakly to a random element v supported on the diagonal $\{(x, y) \in E \times E : x = y\}$.

We are now ready to state and prove the main result of this section.

THEOREM 5.4 Assume that the coefficients f and σ satisfy condition (LG) and that hypotheses (PU) and (C) are fulfilled. Then, there exists a random field $u = \{u(t, x) : t \geq 0, x \in [0, 1]\}$ such that, for every $\varepsilon > 0$,

$$\mathbb{P} \left(\sup_{t \in [0, T]} \sup_{x \in [0, 1]} |u^{M_k, N_k}(t, x) - u(t, x)| \geq \varepsilon \right) \rightarrow 0,$$

as k tends to infinity, for all sequences of positive integers $(M_k, N_k)_{k \geq 1}$ such that $M_k, N_k \rightarrow \infty$, as $k \rightarrow \infty$, where we recall that $u^{M, N}$ denotes the fully discrete solution (3.8). Furthermore, the random field u is the unique solution to the stochastic heat equation (1.1).

Proof. We first show that the sequence $(u^{M, N})_{M, N \geq 1}$ defines a tight family of laws in the space $C([0, T] \times [0, 1])$. To do so, we invoke part 2 in Proposition 3.6 on the regularity of the numerical solution and we apply the tightness criterion on the plane (Bardina et al., 2010, Thm. 2.2), which generalizes a well-known result of Billingsley. Furthermore, Prokhorov's theorem implies that the sequence of laws $(u^{M, N})_{M, N \geq 1}$ is relatively compact in $C([0, T] \times [0, 1])$.

Fix any pair of sequences $(M_k, N_k)_{k \geq 1}$ such that $M_k, N_k \rightarrow \infty$, as $k \rightarrow \infty$. Then, the laws of $v_k := u^{M_k, N_k}$, $k \geq 1$, form a tight family in the space $C([0, T] \times [0, 1])$.

Let now $(v_j^1)_{j \geq 1}$ and $(v_\ell^2)_{\ell \geq 1}$ be two subsequences of $(v_k)_{k \geq 1}$. By Skorokhod's Representation Theorem, there exist subsequences of positive integers $(j_r)_{r \geq 1}$ and $(\ell_r)_{r \geq 1}$ of the indices j and ℓ , a probability space $(\widehat{\Omega}, \widehat{\mathcal{F}}, (\widehat{\mathcal{F}}_t)_{t \geq 1}, \widehat{\mathbb{P}})$ and a sequence of continuous random fields $(z_r)_{r \geq 1}$ with $z_r := (\tilde{u}_r, \bar{u}_r, \widehat{W}_r)$, $r \geq 1$, such that

1. $z_r \xrightarrow[r \rightarrow \infty]{} z := (\tilde{u}, \bar{u}, \widehat{W})$ a.s. in $C([0, T] \times [0, 1], \mathbb{R}^3)$, where the random field z is defined on $(\widehat{\Omega}, \widehat{\mathcal{F}}, (\widehat{\mathcal{F}}_t)_{t \geq 1}, \widehat{\mathbb{P}})$, \widehat{W} is a Brownian sheet defined on this basis and $\widehat{\mathcal{F}}_t = \sigma(z(s, x), (s, x) \in [0, t] \times [0, 1])$ (and conveniently completed).
2. For every $r \geq 1$, the finite-dimensional distributions of z_r coincide with those of the random field $\zeta_r := (v_{j_r}^1, v_{\ell_r}^2, W)$, and thus $\text{law}(z_r) = \text{law}(\zeta_r)$ for all $r \geq 1$.

Note that \widehat{W}_r is a Brownian sheet defined on $(\widehat{\Omega}, \widehat{\mathcal{F}}, (\widehat{\mathcal{F}}_t)_{t \geq 1}, \widehat{\mathbb{P}})$, where $\widehat{\mathcal{F}}_t^r = \sigma(z_r(s, x), (s, x) \in [0, t] \times [0, 1])$ (and conveniently completed).

We now fix $(t, x) \in [0, T] \times [0, 1]$. Since the laws of z_r and ζ_r coincide and the first two components of ζ_r satisfy the weak form (3.4), so do the components of z_r . Namely, for all $\Phi \in C^\infty(\mathbb{R}^2)$ with $\Phi(t, 0) = \Phi(t, 1) = 0$ for all t , it holds

$$\begin{aligned} \int_0^1 \tilde{u}_r(t, \kappa_M(y)) \Phi(t, y) dy &= \int_0^1 u_0(\kappa_M(y)) \Phi(t, y) dy \\ &+ \int_0^t \int_0^1 \tilde{u}_r(s, \kappa_M(y)) \left(\Delta_M \Phi(s, y) + \frac{\partial \Phi}{\partial s}(s, y) \right) dy ds \\ &+ \int_0^t \int_0^1 f(\tilde{u}_r(\kappa_N^T(s), \kappa_M(y))) \Phi(s, y) dy ds \\ &+ \int_0^t \int_0^1 \sigma(\tilde{u}_r(\kappa_N^T(s), \kappa_M(y))) \Phi(s, y) W(ds, dy), \quad \widehat{\mathbb{P}}\text{-a.s.}, \end{aligned} \quad (5.1)$$

for all $t \in [0, T]$, and also

$$\begin{aligned} \int_0^1 \bar{u}_r(t, \kappa_M(y)) \Phi(t, y) dy &= \int_0^1 u_0(\kappa_M(y)) \Phi(t, y) dy \\ &+ \int_0^t \int_0^1 \bar{u}_r(s, \kappa_M(y)) \left(\Delta_M \Phi(s, y) + \frac{\partial \Phi}{\partial s}(s, y) \right) dy ds \\ &+ \int_0^t \int_0^1 f(\bar{u}_r(\kappa_N^T(s), \kappa_M(y))) \Phi(s, y) dy ds \\ &+ \int_0^t \int_0^1 \sigma(\bar{u}_r(\kappa_N^T(s), \kappa_M(y))) \Phi(s, y) W(ds, dy), \quad \widehat{\mathbb{P}}\text{-a.s.}, \end{aligned} \quad (5.2)$$

for all $t \in [0, T]$. We recall that Δ_M denotes the discrete Laplacian, which is defined by

$$\Delta_M \Phi(s, y) := (\Delta x)^{-2} \{ \Phi(s, y + \Delta x) - 2\Phi(s, y) + \Phi(s, y - \Delta x) \},$$

where we remind that $\Delta x = \frac{1}{M}$.

Taking $r \rightarrow \infty$ in the above formulas (5.1) and (5.2), and using Lemma 5.2, we show that the random fields \tilde{u} and \bar{u} are solutions of (2.1), and hence of equation (1.1), on the same stochastic basis $(\widehat{\Omega}, \widehat{\mathcal{F}}, (\widehat{\mathcal{F}}_t)_{t \geq 1}, \widehat{\mathbb{P}})$. Thus, by the pathwise uniqueness assumption, we obtain that $\tilde{u}(t, x) = \bar{u}(t, x)$ for all $(t, x) \in [0, T] \times [0, 1]$ $\widehat{\mathbb{P}}$ -a.s. Hence, by Lemma 5.3, we get that $\{u^{M_k, N_k}\}_{k \geq 1}$ converges in probability to u , uniformly on $[0, T] \times [0, 1]$, the solution of the stochastic heat equation (1.1). \square

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REFERENCES

- ALLEN, E. J., NOVOSEL, S. J. & ZHANG, Z. (1998) Finite element and difference approximation of some linear stochastic partial differential equations. *Stochastics Stochastics Rep.*, **64**, 117–142.
- ANDERSSON, A. & LARSSON, S. (2016) Weak convergence for a spatial approximation of the nonlinear stochastic heat equation. *Math. Comp.*, **85**, 1335–1358.
- ANTON, R. & COHEN, D. (2018) Exponential integrators for stochastic Schrödinger equations driven by Itô noise. *Special Issue on SPDEs of J. Comput. Math.*, **36**, 276–309.
- ANTON, R., COHEN, D., LARSSON, S. & WANG, X. (2016) Full discretization of semilinear stochastic wave equations driven by multiplicative noise. *SIAM J. Numer. Anal.*, **54**, 1093–1119.

- BARDINA, X., JOLIS, M. & QUER-SARDANYONS, L. (2010) Weak convergence for the stochastic heat equation driven by Gaussian white noise. *Electron. J. Probab.*, **15**, 1267–1295.
- BARTH, A. & LANG, A. (2012) Simulation of stochastic partial differential equations using finite element methods. *Stochastics*, **84**, 217–231.
- BARTH, A. & LANG, A. (2013) L^p and almost sure convergence of a Milstein scheme for stochastic partial differential equations. *Stochastic Process. Appl.*, **123**, 1563–1587.
- BECKER, S. & JENTZEN, A. (2016) Strong convergence rates for nonlinearity-truncated Euler-type approximations of stochastic Ginzburg–Landau equations. *Stochastic Process. Appl.* Available at <http://www.sciencedirect.com/science/article/pii/S0304414918300255>.
- BECKER, S., JENTZEN, A. & KLOEDEN, P. E. (2016) An exponential Wagner-Platen type scheme for SPDEs. *SIAM J. Numer. Anal.*, **54**, 2389–2426.
- BRÉHIER, C. E., CUI, J. & HONG, J. (2018) Strong convergence rates of semi-discrete splitting approximations for stochastic Allen–Cahn equation. dry052. Available at <http://dx.doi.org/10.1093/imanum/dry052>.
- BRÉHIER, C. E. & GOUDENÈGE, L. (2018) Analysis of some splitting schemes for the stochastic Allen–Cahn equation. arXiv:1801.06455.
- COHEN, D. & DUJARDIN, G. (2017) Exponential integrators for nonlinear Schrödinger equations with white noise dispersion. *Stochastics and Partial Differential Equations: Analysis and Computations*. US: Springer, pp. 1–22.
- COHEN, D., LARSSON, S. & SIGG, M. (2013) A trigonometric method for the linear stochastic wave equation. *SIAM J. Numer. Anal.*, **51**, 204–222.
- COHEN, D. & QUER-SARDANYONS, L. (2016) A fully discrete approximation of the one-dimensional stochastic wave equation. *IMA J. Numer. Anal.*, **36**, 400–420.
- COX, S. & VAN NEERVEN, J. (2010) Convergence rates of the splitting scheme for parabolic linear stochastic Cauchy problems. *SIAM J. Numer. Anal.*, **48**, 428–451.
- COX, S. & VAN NEERVEN, J. (2013) Pathwise Hölder convergence of the implicit-linear Euler scheme for semi-linear SPDEs with multiplicative noise. *Numer. Math.*, **125**, 259–345.
- DA PRATO, G., FLANDOLI, F., PRIOLA, E. & RÖCKNER, M. (2013) Strong uniqueness for stochastic evolution equations in Hilbert spaces perturbed by a bounded measurable drift. *Ann. Probab.*, **41**, 3306–3344.
- DA PRATO, G., FLANDOLI, F., PRIOLA, E. & RÖCKNER, M. (2015) Strong uniqueness for stochastic evolution equations with unbounded measurable drift term. *J. Theoret. Probab.*, **28**, 1571–1600.
- DAVIE, A. M. & GAINES, J. G. (2001) Convergence of numerical schemes for the solution of parabolic stochastic partial differential equations. *Math. Comp.*, **70**, 121–134.
- DEBUSSCHE, A. (2011) Weak approximation of stochastic partial differential equations: the nonlinear case. *Math. Comp.*, **80**, 89–117.
- DEBUSSCHE, A. & PRINTEMS, J. (2009) Weak order for the discretization of the stochastic heat equation. *Math. Comp.*, **78**, 845–863.
- DI NEZZA, E., PALATUCCI, G. & VALDINOCI, E. (2012) Hitchhiker’s guide to the fractional Sobolev spaces. *Bull. Sci. Math.*, **136**, 521–573.
- DU, Q. & ZHANG, T. (2002) Numerical approximation of some linear stochastic partial differential equations driven by special additive noises. *SIAM J. Numer. Anal.*, **40**, 1421–1445.
- GAINES, J. G. (1995) Numerical experiments with S(P)DE’s. *Stochastic Partial Differential Equations (Edinburgh, 1994)*. London Math. Soc. Lecture Note Ser., vol. 216. Cambridge: Cambridge Univ. Press, pp. 55–71.
- GYÖNGY, I. (1998a) Existence and uniqueness results for semilinear stochastic partial differential equations. *Stochastic Process. Appl.*, **73**, 271–299.
- GYÖNGY, I. (1998b) Lattice approximations for stochastic quasi-linear parabolic partial differential equations driven by space-time white noise I. *Potential Anal.*, **9**, 1–25.
- GYÖNGY, I. (1999) Lattice approximations for stochastic quasi-linear parabolic partial differential equations driven by space-time white noise II. *Potential Anal.*, **11**, 1–37.
- GYÖNGY, I. & NUALART, D. (1995) Implicit scheme for quasi-linear parabolic partial differential equations perturbed by space-time white noise. *Stochastic Process. Appl.*, **58**, 57–72.

- GYÖNGY, I. & NUALART, D. (1997) Implicit scheme for stochastic parabolic partial differential equations driven by space-time white noise. *Potential Anal.*, **7**, 725–757.
- GYÖNGY, I. & PARDOUX, E. (1993a) On quasi-linear stochastic partial differential equations. *Probab. Theory Related Fields*, **94**, 413–425.
- GYÖNGY, I. & PARDOUX, E. (1993b) Weak and strong solutions of white-noise driven parabolic spdes. *Prepub. Laboratoire de Mathématiques Marseille*. Université de Provence: Laboratoire de Mathématiques Marseille, pp. 1–32.
- HAUSENBLAS, E. (2003) Approximation for semilinear stochastic evolution equations. *Potential Anal.*, **18**, 141–186.
- HOCHBRUCK, M. & OSTERMANN, A. (2010) Exponential integrators. *Acta Numer.*, **19**, 209–286.
- JENTZEN, A. (2009) Pathwise numerical approximation of SPDEs with additive noise under non-global Lipschitz coefficients. *Potential Anal.*, **31**, 375–404.
- JENTZEN, A. (2011) Higher order pathwise numerical approximations of SPDEs with additive noise. *SIAM J. Numer. Anal.*, **49**, 642–667.
- JENTZEN, A. & KLOEDEN, P. E. (2009) Overcoming the order barrier in the numerical approximation of stochastic partial differential equations with additive space-time noise. *Proc. R. Soc. Lond. Ser. A Math. Phys. Eng. Sci.*, **465**, 649–667.
- JENTZEN, A. & KLOEDEN, P. E. (2011) *Taylor Approximations for Stochastic Partial Differential Equations*. CBMS-NSF Regional Conference Series in Applied Mathematics, vol. 83. Philadelphia, PA: Society for Industrial and Applied Mathematics.
- JENTZEN, A., KLOEDEN, P. & WINKEL, G. (2011) Efficient simulation of nonlinear parabolic SPDEs with additive noise. *Ann. Appl. Probab.*, **21**, 908–950.
- JENTZEN, A. & KURNIAWAN, R. (2015) Weak convergence rates for euler-type approximations of semilinear stochastic evolution equations with nonlinear diffusion coefficients. arXiv:1501.03539.
- JENTZEN, A. & PUSNIK, P. (2015) Strong convergence rates for an explicit numerical approximation method for stochastic evolution equations with non-globally Lipschitz continuous nonlinearities. arXiv:1504.03523.
- JENTZEN, A. & RÖCKNER, M. (2015) A Milstein scheme for SPDEs. *Found. Comput. Math.*, **15**, 313–362.
- KLOEDEN, P. E., LORD, G. J., NEUENKIRCH, A. & SHARDLOW, T. (2011) The exponential integrator scheme for stochastic partial differential equations: pathwise error bounds. *J. Comput. Appl. Math.*, **235**, 1245–1260.
- KOVÁCS, M., LARSSON, S. & LINDGREN, F. (2015) On the backward Euler approximation of the stochastic Allen–Cahn equation. *J. Appl. Probab.*, **52**, 323–338.
- KRUSE, R. (2014) *Strong and Weak Approximation of Semilinear Stochastic Evolution Equations*. *Lecture Notes in Mathematics*, vol. 2093. Cham: Springer.
- LANG, A., PETERSSON, A. & THALHAMMER, A. (2017) Mean-square stability analysis of approximations of stochastic differential equations in infinite dimensions. *BIT Num. Math.*, **57**, 963–990.
- LIU, Z. & QIAO, Z. (2018) Strong approximation of stochastic Allen–Cahn equation with white noise. arXiv:1801.09348.
- LORD, G. J., POWELL, C. E. & SHARDLOW, T. (2014) *An Introduction to Computational Stochastic PDEs*. *Cambridge Texts in Applied Mathematics*. New York: Cambridge University Press.
- LORD, G. J. & TAMBUE, A. (2013) Stochastic exponential integrators for the finite element discretization of SPDEs for multiplicative and additive noise. *IMA J. Numer. Anal.*, **33**, 515–543.
- MILLET, A. & MORIEN, P. (2005) On implicit and explicit discretization schemes for parabolic SPDEs in any dimension. *Stochastic Process. Appl.*, **115**, 1073–1106.
- MÜLLER-GRONBACH, T. & RITTER, K. (2007) An implicit Euler scheme with non-uniform time discretization for heat equations with multiplicative noise. *BIT*, **47**, 393–418.
- MYTNIK, L. & NEUMAN, E. (2015) Pathwise uniqueness for the stochastic heat equation with Hölder continuous drift and noise coefficients. *Stochastic Process. Appl.*, **125**, 3355–3372.
- MYTNIK, L. & PERKINS, E. (2011) Pathwise uniqueness for stochastic heat equations with Hölder continuous coefficients: the white noise case. *Probab. Theory Related Fields*, **149**, 1–96.

- PACHPATTE, B. G. (2006) *Integral and Finite Difference Inequalities and Applications*, vol. 205. North Holland: Elsevier Science B.V.
- PETTERSSON, R. & SIGNAHL, M. (2005) Numerical approximation for a white noise driven SPDE with locally bounded drift. *Potential Anal.*, **22**, 375–393.
- PRINTEMS, J. (2001) On the discretization in time of parabolic stochastic partial differential equations. *M2AN Math. Model. Numer. Anal.*, **35**, 1055–1078.
- QUER-SARDANYONS, L. & SANZ-SOLÉ, M. (2006) Space semi-discretisations for a stochastic wave equation. *Potential Anal.*, **24**, 303–332.
- SAUER, M. & STANNAT, W. (2015) Lattice approximation for stochastic reaction diffusion equations with one-sided Lipschitz condition. *Math. Comp.*, **84**, 743–766.
- SHARDLOW, T. (1999) Numerical methods for stochastic parabolic PDEs. *Numer. Funct. Anal. Optim.*, **20**, 121–145.
- SHARDLOW, T. (2003) Weak convergence of a numerical method for a stochastic heat equation. *BIT*, **43**, 179–193.
- TA, C., WANG, D. & NIE, Q. (2015) An integration factor method for stochastic and stiff reaction-diffusion systems. *J. Comput. Phys.*, **295**, 505–522.
- TRIEBEL, H. (1992) *Theory of Function Spaces II*. Monographs in Mathematics, vol. 84. Basel: Birkhäuser.
- WALSH, J. B. (1986) An introduction to stochastic partial differential equations. *École d'été de Probabilités de Saint-Flour, XIV—1984. Lecture Notes in Mathematics*, vol. 1180. Berlin: Springer, pp. 265–439.
- WALSH, J. B. (2005) Finite element methods for parabolic stochastic PDE's. *Potential Anal.*, **23**, 1–43.
- WANG, X. (2017) Strong convergence rates of the linear implicit euler method for the finite element discretization of spdes with additive noise. *IMA J. Numer. Anal.*, **37**, 965.
- WANG, X. (2018) An efficient explicit full discrete scheme for strong approximation of stochastic Allen–Cahn equation. arXiv:1802.09413.
- WANG, X. & GAN, S. (2013) A Runge–Kutta type scheme for nonlinear stochastic partial differential equations with multiplicative trace class noise. *Numer. Algorithms*, **62**, 193–223.
- YAN, Y. (2005) Galerkin finite element methods for stochastic parabolic partial differential equations. *SIAM J. Numer. Anal.*, **43**, 1363–1384 (electronic).