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# STRONG $L^2$ CONVERGENCE OF TIME NUMERICAL SCHEMES FOR THE STOCHASTIC 2D NAVIER-STOKES EQUATIONS

HAKIMA BESSAIH AND ANNIE MILLET

ABSTRACT. We prove that some time discretization schemes for the 2D Navier-Stokes equations on the torus subject to a random perturbation converge in  $L^2(\Omega)$ . This refines previous results which only established the convergence in probability of these numerical approximations. Using exponential moment estimates of the solution of the stochastic Navier-Stokes equations and convergence of a localized scheme, we can prove strong convergence of fully implicit and semi-implicit time Euler discretizations, and of a splitting scheme. The speed of the  $L^2(\Omega)$ -convergence depends on the diffusion coefficient and on the viscosity parameter.

## 1. INTRODUCTION

An incompressible fluid flow dynamic is described by the so-called incompressible Navier-Stokes equations. The fluid flow is defined by a velocity field and a pressure term that evolve in a very particular way. These equations are parametrized by the viscosity coefficient  $\nu > 0$ . Their quantitative and qualitative properties depend on the dimensional setting. For example, while the well posedness of global weak solutions of the 2D Navier-Stokes is well known and established, the uniqueness of global weak solutions for the 3D case is completely open. In this paper, we will focus on the 2D incompressible Navier-Stokes equations in a bounded domain  $D = [0, L]^2$ , subject to an external forcing defined as:

$$\partial_t u - \nu \Delta u + (u \cdot \nabla)u + \nabla \pi = G(u)dW \quad \text{in } (0, T) \times D, \quad (1.1)$$

$$\operatorname{div} u = 0 \quad \text{in } (0, T) \times D, \quad (1.2)$$

where  $T > 0$ . The process  $u : \Omega \times (0, T) \times D \rightarrow \mathbb{R}^2$  is the velocity field with initial condition  $u_0$  in  $D$  and periodic boundary conditions  $u(t, x + Lv_i) = u(t, x)$  on  $(0, T) \times \partial D$ , where  $v_i$ ,  $i = 1, 2$  denotes the canonical basis of  $\mathbb{R}^2$ , and  $\pi : \Omega \times (0, T) \times D \rightarrow \mathbb{R}$  is the pressure.

The external force is described by a stochastic perturbation and will be defined in detail later. Here  $G$  is a diffusion coefficient with global Lipschitz conditions. Let  $(\Omega, \mathcal{F}, (\mathcal{F}_t), \mathbb{P})$  denote a filtered probability space and  $W$  be a Wiener process to be precisely defined later.

There is an extensive literature concerning the deterministic models and we refer to the books of Temam; see [17, 18] for known results. The stochastic case has also been widely investigated, see [11] for some very general results and the references therein. For the 2D case, unique global weak and strong solutions (in the PDE sense) are constructed for both additive and multiplicative noise, and without being exhaustive, we refer to [7, 10].

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Numerical schemes and algorithms have been introduced to best approximate and construct solutions for PDEs. A similar approach has started to emerge for stochastic models and in particular SPDEs and has known a strong interest by the probability community. Many algorithms based on either finite difference, finite element or spectral Galerkin methods (for the space discretization), and on either Euler schemes, Crank-Nicolson or Runge-Kutta schemes (for the temporal discretization) have been introduced for both the linear and nonlinear cases. Their rates of convergence have been widely investigated. The literature on numerical analysis for SPDEs is now very extensive. When the models are either linear, have global Lipschitz properties or more generally some monotonicity property, then there is extensive literature, see [1, 2]. Moreover, in this case the convergence is proven to be in mean square. When nonlinearities are involved that are not of Lipschitz or monotone type, then a rate of convergence in mean square is difficult to obtain. Indeed, because of the stochastic perturbation, there is no way of using the Gronwall lemma after taking the expectation of the error bound because it involves a nonlinear term that is usually in a quadratic form. One way of getting around it is to localize the nonlinear term in order to get a linear inequality and then use the Gronwall lemma. This gives rise to a rate of convergence in probability, that was first introduced by J. Printems [16].

The stochastic Navier-Stokes equations with a multiplicative noise (1.1) have been investigated by Z. Brzezniak, E. Carelli and A. Prohl in [8]. There, space discretization based on finite elements and Euler schemes for the time discretization have been implemented. The numerical scheme was proven to converge in probability with a particular rate. A similar problem has been investigated by E. Carelli and A. Prohl in [9], with more focus on various Euler schemes including semi-implicit and fully implicit ones. This gave rise to a slightly different rate of convergence, although still in probability. Again, the main tool used is the localization of the nonlinear term over a probability space of "large" probability. In [3], the authors used a splitting method, based on the Lie-Trotter formula, proving again some rate of convergence in probability of the numerical scheme. In [12], P. Dörsek studied a semigroup splitting and used cubature approximations, obtaining interesting results for an additive noise. When the noise is additive, a pathwise argument was used by H. Breckner in [7]; convergence almost sure and in mean was obtained, although no rate of convergence was explicitly given. To the best of our knowledge there is no result about a strong speed of convergence for the stochastic Navier-Stokes equations in the current literature.

Numerical schemes for stochastic nonlinear models with local Lipschitz nonlinearities related with the Navier-Stokes equations have been studied by several authors. For nonlinear parabolic SPDEs, in [6] D. Blömker and A. Jentzen proved a speed of convergence in probability of Galerkin approximations of the stochastic Burgers equation, which is a simpler nonlinear PDE which has some similarity with the Navier-Stokes equation. In [5], an abstract stochastic nonlinear evolution equation in a separable Hilbert space was investigated, including the GOY and Sabra shell models. These adimensional models are phenomenological approximations of the Navier-Stokes equations. The authors proved the convergence in probability in a fractional Sobolev space  $H^s$ ,  $0 \leq s < \frac{1}{4}$ , of a space-time numerical scheme defined in terms of a Galerkin approximation in space, and a semi-implicit Euler-Maruyama scheme in time. For the Burgers as well as more general nonlinear SPDEs subject to space-time white noise driven perturbation, A. Jentzen, D. Salinova and T. Welti proved in [15] the strong convergence of the scheme but did not give a rate of convergence.

In this paper, we focus on the stochastic 2D Navier-Stokes equations and would like to go one step further, that is, obtain a strong speed of convergence in mean square instead of the convergence in probability. In fact, the main goal is twofold. On one hand, we will improve the convergence from convergence in probability to  $L^2(\Omega)$ -convergence, the so-called strong convergence in mean square. On the other hand, we will also improve the rate of convergence from logarithmic to almost polynomial.

To explain the method, the paper will deal with two different algorithms: the splitting scheme used in [3] and the implicit Euler schemes used in [9]. In the case of a diffusion coefficient  $G$  with linear growth conditions, which may depend on the solution and its gradient for the Euler schemes, we prove that the speed of convergence of both schemes is any negative power of the logarithm of the time mesh  $\frac{T}{N}$  when the initial condition belongs to  $\mathbb{W}^{1,2}$  and is divergence free. In the case of an additive noise - or under a slight generalization of such a noise - we prove that the strong  $L^2(\Omega)$  speed of convergence of the fully or semi implicit Euler schemes introduced by Carelli and Prohl in [9] is polynomial in the time mesh. This speed depends on the viscosity coefficient  $\nu$  and on the length of the time interval  $T$ . When  $T$  is small, or when  $\nu$  is large, this speed is close to the best one which can be achieved in time, that is almost  $\frac{1}{4}$ . This is consistent with the time regularity of the strong solution to the stochastic Navier-Stokes equations, due to the scaling between the time and space variables in the heat kernel, and to the stochastic integral.

Let us try to explain the steps of our method here before going into more details later on in the paper. As we explained earlier, the main difficulty that prevents getting the strong convergence in mean square is due to the nonlinear term  $(u \cdot \nabla)u$ . Indeed, in order to bound the error  $e_k := u(t_k) - u_N(t_k)$  over the grid points  $t_k$ ,  $k = 1, \dots, N$ , in some implicit Euler method, one has to upper bound

$$\mathbb{E} \|(u(t_k) \cdot \nabla)u(t_k) - (u_N(t_k) \cdot \nabla)u_N(t_k)\|_{V'}.$$

To close the estimates and use some Gronwall lemma, the tool used in [9] (as well as in [3]) is to localize on a subspace of  $\Omega$ . However, in both previous results, the localization set was depending on the discretization. In this work, we make slightly different computations, based on the antisymmetry of the bilinear term, and localize on sets which only depend on the solution to the stochastic Navier Stokes equations (1.1), such as  $\Omega_N^M$  defined by (4.6) for the Euler schemes. Hence, one obtains for example

$$\mathbb{E} \left( \mathbf{1}_{\Omega_N^M} \max_{1 \leq k \leq N} |e_k|_{\mathbb{L}^2}^2 \right) \leq C \exp [C_1(M)T] \left( \frac{T}{N} \right)^\eta,$$

where  $\eta < \frac{1}{2}$  and  $C_1(M)$  is a constant depending on the bound  $M$  of the  $\mathbb{L}^2$ -norm of  $\nabla u$  imposed on the localization set  $\Omega_N^M$ . The exponent  $\eta$  is natural and related to the time regularity of the solution  $u$  when the initial condition  $u_0$  belongs to  $\mathbb{W}^{1,2}$ .

In order to prove the strong speed of convergence, we will use the partition of  $\Omega$  into  $\Omega_N^M$  and its complement for some threshold  $M$  depending on  $N$ . More precisely, we have to balance the upper estimate of the moments localized on the set  $\Omega_N^{M(N)}$  for some well chosen sequence  $M(N)$ , going to infinity as  $N$  does, and a similar upper estimate of the  $L^2(\Omega)$  moment of the error localized on the complement of the set  $\Omega_N^{M(N)}$ . This is performed by upper estimating moments of  $u(t_k)$  and of  $u_N(t_k)$  uniformly in  $N$  and  $k$ , estimating

$\mathbb{P}((\Omega_N^{M(N)})^c)$ , and using the Hölder inequality

$$\mathbb{E}\left(1_{(\Omega_N^{M(N)})^c} \max_{1 \leq k \leq N} |e_k|_{\mathbb{L}^2}^2\right) \leq \left(\mathbb{P}((\Omega_N^{M(N)})^c)\right)^{\frac{1}{p}} \left[\mathbb{E}\left(\sup_{0 \leq s \leq T} |u(s)|_{\mathbb{L}^2}^{2q} + \max_{0 \leq k \leq N} |u_N(t_k)|_{\mathbb{L}^2}^{2q}\right)\right]^{\frac{1}{q}},$$

where  $p$  and  $q$  are conjugate exponents. A similar bound was already used in [14] in a different numerical framework. The upper estimate of the probability of the "bad" set depends on the assumptions on the diffusion coefficient. Note that since we are localizing on a set which does not depend on the discretization scheme, only moments of the solution to the stochastic Navier Stokes equation (1.1) have to be dealt with.

In the case of globally Lipschitz coefficient  $G$ , we use bounds of various moments of  $u$  in  $\mathbb{W}^{1,2}$ . For both schemes, the strong speed of convergence is again in the logarithmic scale; when the initial condition is deterministic, it is any negative power of  $\ln(N)$ .

In the case of an additive noise, we use a slight extension of exponential moments of the solution of (1.1) in vorticity formulation proved previously by M. Hairer and J. Mattingly in [13], given by  $\mathbb{E}(\sup_{t \in [0, T]} \exp(\alpha_0 |\nabla u(t)|_{\mathbb{L}^2}^2)) < \infty$  for some  $\alpha_0 > 0$ . This yields a better speed of convergence, due to that fact that the polynomial Markov inequality is replaced by an exponential one.

For the implicit Euler scheme the strong speed of convergence is polynomial with exponent  $\gamma < \frac{1}{2}$  that depends on the viscosity  $\nu$ . Note that for large  $\nu$ ,  $\gamma$  approaches  $\frac{1}{2}$ . For the splitting scheme, the strong speed of convergence we obtain in this paper is better than that of the convergence in probability proven in [3], although not polynomial; it is of the form  $c \exp(-C\sqrt{N})$ .

In this paper, we only deal with time discretization, unlike in [9] where a space-time discretization is studied. Furthermore, in order to keep the paper in a reasonable size and present simple arguments to follow by the reader, we assume that  $G$  does not depend on time. We add relevant comments and remarks on the assumptions to be added in case of time dependent coefficients for the implicit Euler schemes (see section 4.5).

The paper is organized as follows. Section 2 recalls basic properties of the 2D Navier Stokes equations, functional spaces and strong solutions. We formulate the assumptions on the noise. The splitting scheme is described in Section 3 and various moments estimates previously used in [3] are recalled. The strategy for proving the strong speed of convergence is described and explained in details. The same strategy is used for the Euler schemes in Section 4, which is devoted to the fully implicit and semi implicit Euler schemes studied previously in [9]. Their strong speed of convergence is proved with a rate of convergence that is polynomial when the exponential moment is used. Finally, Section 5 provides on one hand an improved moment estimate for an auxiliary process used in the splitting scheme, and on the other hand the proof for the exponential moment estimates of the gradient of the solution to (1.1).

As usual, except if specified otherwise,  $C$  denotes a positive constant that may change throughout the paper, and  $C(a)$  denotes a positive constant depending on the parameter  $a$ .

## 2. NOTATIONS AND PRELIMINARY RESULTS

Let  $\mathbb{L}^p := L^p(D)^2$  (resp.  $\mathbb{W}^{k,p} := W^{k,p}(D)^2$ ) denote the usual Lebesgue and Sobolev spaces of vector-valued functions endowed with the norms  $|\cdot|_{\mathbb{L}^2}$  (resp.  $\|\cdot\|_{\mathbb{W}^{k,p}}$ ). In what follows, we will consider velocity fields that have mean zero over  $[0, L]^2$ . Let  $\mathbb{L}_{per}^2$  denote

the subset of  $\mathbb{L}^2$  periodic functions with mean zero over  $[0, L]^2$ , and let

$$H := \{u \in \mathbb{L}_{per}^2 : \operatorname{div} u = 0 \text{ weakly in } D\}, \quad V := H \cap \mathbb{W}^{1,2}$$

be separable Hilbert spaces. The space  $H$  inherits its inner product denoted by  $(\cdot, \cdot)$  and its norm from  $\mathbb{L}^2$ . The norm in  $V$ , inherited from  $\mathbb{W}^{1,2}$ , is denoted by  $\|\cdot\|_V$ . Moreover, let  $V'$  be the dual space of  $V$  with respect to the Gelfand triple,  $\langle \cdot, \cdot \rangle$  denotes the duality between  $V'$  and  $V$ . Let  $A = -\Delta$  with its domain  $\operatorname{Dom}(A) = \mathbb{W}^{2,2} \cap H$ .

Let  $b : V^3 \rightarrow \mathbb{R}$  denote the trilinear map defined by

$$b(u_1, u_2, u_3) := \int_D (u_1(x) \cdot \nabla u_2(x)) \cdot u_3(x) dx,$$

which by the incompressibility condition satisfies  $b(u_1, \bar{u}_2, u_3) = -b(u_1, u_3, \bar{u}_2)$  for  $u_i \in V$ ,  $i = 1, 2, 3$ . There exists a continuous bilinear map  $B : V \times V \mapsto V'$  such that

$$\langle B(u_1, u_2), u_3 \rangle = b(u_1, u_2, u_3), \quad \text{for all } u_i \in V, i = 1, 2, 3.$$

The map  $B$  satisfies the following antisymmetry relations:

$$\langle B(u_1, u_2), u_3 \rangle = -\langle B(u_1, u_3), u_2 \rangle, \quad \langle B(u_1, u_2), u_2 \rangle = 0 \quad \text{for all } u_i \in V. \quad (2.1)$$

Furthermore, the Gagliardo-Nirenberg inequality implies that for  $X := H \cap \mathbb{L}^4(D)$  we have

$$\|u\|_X^2 \leq \bar{C} |u|_{\mathbb{L}^2} |\nabla u|_{\mathbb{L}^2} \leq \frac{\bar{C}}{2} \|u\|_V^2 \quad (2.2)$$

for some positive constant  $\bar{C}$ . For  $u \in V$  set  $B(u) := B(u, u)$  and recall some well-known properties of  $B$ , which easily follow from the Hölder and Young inequalities: given any  $\beta > 0$  we have

$$|\langle B(u_1, u_2), u_3 \rangle| \leq \beta \|u_3\|_V^2 + \frac{1}{4\beta} \|u_1\|_X \|u_2\|_X, \quad (2.3)$$

$$|\langle B(u_1) - B(u_2), u_1 - u_2 \rangle| \leq \beta \|u_1 - u_2\|_V^2 + C_\beta |u_1 - u_2|_{\mathbb{L}^2}^2 \|u_1\|_X^4, \quad (2.4)$$

for  $u_i \in V$ ,  $i = 1, 2, 3$ , where

$$C_\beta = \frac{\bar{C}^2 3^3}{4^4 \beta^3}, \quad (2.5)$$

and  $\bar{C}$  is defined by (2.2).

Let  $K$  be a separable Hilbert space and  $(W(t), t \in [0, T])$  be a  $K$ -cylindrical Wiener process defined on the probability space  $(\Omega, \mathcal{F}, (\mathcal{F}_t), \mathbb{P})$ . For technical reasons, we assume that the initial condition  $u_0$  belongs to  $L^p(\Omega; V)$  for some  $p \in [2, \infty]$ , and only consider *strong solutions* in the PDE sense. Given two Hilbert spaces  $H_1$  and  $H_2$ , let  $\mathcal{L}_2(H_1, H_2)$  denote the set of Hilbert-Schmidt operators from  $H_1$  to  $H_2$ . The diffusion coefficient  $G$  satisfies the following assumption:

**Condition (G1)** Assume that  $G : V \rightarrow \mathcal{L}_2(K, H)$  is continuous and there exist positive constants  $K_i$ ,  $i = 0, 1$  and  $L_1$  such that for  $u, v \in V$ :

$$\|G(u)\|_{\mathcal{L}_2(K, H)}^2 \leq K_0 + K_1 |u|_{\mathbb{L}^2}^2, \quad (2.6)$$

$$\|G(u) - G(v)\|_{\mathcal{L}_2(K, H)}^2 \leq L_1 |u - v|_{\mathbb{L}^2}^2. \quad (2.7)$$

Finally, note that the following identity involving the Stokes operator  $A$  and the bilinear term holds (see e.g. [17] Lemma 3.1):

$$\langle B(u), Au \rangle = 0, \quad u \in \operatorname{Dom}(A). \quad (2.8)$$

We also suppose that  $G$  satisfies the following assumptions:

**Condition (G2)** The coefficient  $G : \text{Dom}(A) \rightarrow \mathcal{L}_2(K, V)$  and there exist positive constants  $K_i$ ,  $i = 0, 1$ , and  $L_1$  such that for every  $u, v \in \text{Dom}(A)$ :

$$\|G(u)\|_{\mathcal{L}_2(K, V)}^2 \leq K_0 + K_1 \|u\|_V^2, \quad (2.9)$$

$$\|G(u) - G(v)\|_{\mathcal{L}_2(K, V)}^2 \leq L_1 \|u - v\|_V^2. \quad (2.10)$$

We define a strong solution of (1.1) as follows (see Definition 2.1 in [9]):

**Definition 2.1.** *We say that equation (1.1) has a strong solution if:*

- $u$  is an adapted  $V$ -valued process,
- $\mathbb{P}$  a.s. we have  $u \in C([0, T]; V) \cap L^2(0, T; \text{Dom}(A))$ ,
- $\mathbb{P}$  a.s.

$$\begin{aligned} (u(t), \phi) + \nu \int_0^t (\nabla u(s), \nabla \phi) ds + \int_0^t \langle [u(s) \cdot \nabla] u(s), \phi \rangle ds \\ = (u_0, \phi) + \int_0^t (\phi, G(u(s)) dW(s)) \end{aligned}$$

for every  $t \in [0, T]$  and every  $\phi \in V$ .

As usual, by projecting (1.1) on divergence free fields, the pressure term is implicitly in the space  $V$  and can be recovered afterwards. Proposition 2.2 in [4] (see also [3], Theorem 4.1) shows the following:

**Theorem 2.2.** *Assume that  $u_0$  is a  $V$ -valued,  $\mathcal{F}_0$ -measurable random variable such that  $\mathbb{E}(\|u_0\|_V^{2p}) < \infty$  for some real number  $p \in [2, \infty)$ . Assume that the conditions (G1) and (G2) are satisfied. Then there exists a unique solution  $u$  to equation (1.1). Furthermore, for some positive constant  $C$  we have*

$$\mathbb{E} \left( \sup_{t \in [0, T]} \|u(t)\|_V^{2p} + \int_0^T \|Au(s)\|_{\mathbb{L}^2}^2 (1 + \|u(s)\|_V^{2(p-1)}) ds \right) \leq C [1 + \mathbb{E}(\|u_0\|_V^{2p})]. \quad (2.11)$$

### 3. TIME SPLITTING SCHEME

In this section, we prove the strong  $L^2(\Omega)$  convergence of the splitting scheme introduced in [3].

**3.1. Description of the splitting scheme.** Let  $N > 1$ ,  $h = \frac{T}{N}$  denote the time mesh, and  $t_i = \frac{iT}{N}$ ,  $i = 0, \dots, N$  denote a partition of the time interval  $[0, T]$ . Let  $F : V \rightarrow V'$  be defined by

$$F(u) = \nu Au + B(u, u). \quad (3.1)$$

Note that the formulation of (G2) is slightly different from that used in [3]. They are equivalent due to the inequality  $\|\nabla u\|_{\mathbb{L}^2} \leq C \|\text{curl } u\|_{\mathbb{L}^2}$  for  $u \in V$ , where  $\text{curl } u = \partial_{x_1} u_2 - \partial_{x_2} u_1$ .

Set  $t_{-1} = -\frac{T}{N}$ . For  $t \in [t_{-1}, 0)$  set  $y^N(t) = u^N(t) = u_0$  and  $\mathcal{F}_t = \mathcal{F}_0$ . The approximation  $(y^N, u^N)$  is defined by induction as follows. Suppose that the processes  $u^N(t)$  and  $y^N(t)$  are defined for  $t \in [t_{i-1}, t_i)$  and that  $y^N(t_i^-)$  is  $H$ -valued and  $\mathcal{F}_{t_i^-}$ -measurable. Then for  $t \in [t_i, t_{i+1})$ ,  $u^N(t)$  with initial condition  $y^N(t_i^-)$  at time  $t_i$ , is the unique solution of equation:

$$\frac{d}{dt} u^N(t) + F(u^N(t)) = 0, \quad t \in [t_i, t_{i+1}), \quad u^N(t_i) = u^N(t_i^+) = y^N(t_i^-). \quad (3.2)$$

Then  $u^N(t_{i+1}^-)$  is well-defined,  $H$ -valued and  $\mathcal{F}_{t_i}$ -measurable. Then set  $y^N(t_i) = u^N(t_{i+1}^-)$ , and for  $t \in [t_i, t_{i+1})$  define  $y^N(t)$  as the unique solution of equation

$$dy^N(t) = G(y^N(t))dW(t), \quad t \in [t_i, t_{i+1}), \quad y^N(t_i) = y^N(t_i^+) = u^N(t_{i+1}^-). \quad (3.3)$$

Finally, set  $u^N(T) = y^N(T) = y^N(T^-)$ . The processes  $u^N$  and  $y^N$  are well-defined and have finite moments as proved in [3], Lemma 4.2.

**Theorem 3.1.** *Let  $u_0$  be a  $V$ -valued,  $\mathcal{F}_0$  random variable such that  $\mathbb{E}(\|u_0\|_V^{2p}) < \infty$  for some real number  $p \geq 2$ . Suppose that  $G$  satisfies conditions **(G1)** and **(G2)**. Then there exists a positive constant  $C$  such that for every integer  $N \geq 1$*

$$\sup_{t \in [0, T]} \mathbb{E}(\|u^N(t)\|_V^{2p} + \|y^N(t)\|_V^{2p}) + \mathbb{E} \int_0^T (1 + \|u^N(t)\|_V^{2(p-1)}) |Au^N(t)|_{\mathbb{L}^2}^2 dt \leq C. \quad (3.4)$$

The following result gives a bound of the difference between  $u^N$  and  $y^N$  (see [3], Proposition 4.3).

**Proposition 3.2.** *Let  $u_0$  be  $\mathcal{F}_0$ -measurable such that  $\mathbb{E}(\|u_0\|_V^4) < \infty$  and  $G$  satisfies conditions **(G1)** and **(G2)**. Then there exists a positive constant  $C := C(T)$  such that for every integer  $N \geq 1$*

$$\mathbb{E} \int_0^T \|y^N(t) - u^N(t)\|_V^2 dt \leq \frac{C}{N}. \quad (3.5)$$

For technical reasons, let us consider the process  $(z^N(t), t \in [0, T])$  which mixes  $u^N$  and  $y^N$ , and is defined by

$$z^N(t) = u_0 - \int_0^t F(u^N(s))ds + \int_0^t G(y^N(s))dW(s). \quad (3.6)$$

The process  $z^N$  is a.s. continuous on  $[0, T]$ . Note that  $z^N(t_k) = y^N(t_k^-) = u^N(t_k)$  for  $k = 0, 1, \dots, N$ . The following result gives bounds of the  $V$ -norm of  $z^N - u^N$  and  $z^N - y^N$ . It is an extension of Lemma 4.4 in [3].

**Proposition 3.3.** *Let  $u_0$  be  $V$ -valued,  $\mathcal{F}_0$ -measurable such that  $\mathbb{E}(\|u_0\|_V^{2p}) < \infty$  for some integer  $p \geq 2$  and let  $G$  satisfy conditions **(G1)** and **(G2)**. Then there exists a constant  $C := C(p, T)$  such that for every integer  $N \geq 1$*

$$\mathbb{E} \left( \sup_{t \in [0, T]} \|z^N(t) - u^N(t)\|_V^{2p} \right) \leq \frac{C}{N^{p-1}} \quad \text{and} \quad \sup_{t \in [0, T]} \mathbb{E}(\|z^N(t) - u^N(t)\|_V^{2p}) \leq \frac{C}{N^p}. \quad (3.7)$$

Note that combining (3.5) and (3.7), we deduce that if  $\mathbb{E}(\|u_0\|_V^4) < \infty$ ,

$$\mathbb{E} \int_0^T \|z^N(t) - y^N(t)\|_V^2 dt \leq \frac{C}{N} \quad (3.8)$$

for some constant  $C := C(T)$  independent of  $N$ .

*Proof.* For  $t \in [t_k, t_{k+1})$ ,  $k = 0, \dots, N-1$  we have

$$z^N(t) - u^N(t) = \int_{t_k}^t G(y^N(s))dW(s).$$

Since  $z^N(T) = u^N(T)$ , for any  $p \geq 2$  the Burkholder-Davies-Gundy inequality implies

$$\mathbb{E} \left( \sup_{t \in [0, T]} \|z^N(t) - u^N(t)\|_V^{2p} \right) = \mathbb{E} \left( \sup_{0 \leq k < N} \sup_{t \in [t_k, t_{k+1})} \|z^N(t) - u^N(t)\|_V^{2p} \right)$$



$$\begin{aligned}
&\leq C_p \sum_{k=0}^{N-1} \mathbb{E} \left( \left| \int_{t_k}^{t_{k+1}} \|G(s, y^N(s))\|_{\mathcal{L}_2(K, V)}^2 ds \right|^p \right) \\
&\leq C_p \sum_{k=0}^{N-1} \left( \frac{T}{N} \right)^p \sup_{t \in [0, T]} (K_0 + K_1 \mathbb{E}(\|y^N(t)\|_V^{2p})).
\end{aligned}$$

Inequality (3.4) concludes the proof of the first part of (3.7). Furthermore,

$$\sup_{t \in [0, T]} \mathbb{E}(\|z^N(t) - u^N(t)\|_V^{2p}) = \sup_{0 \leq k < N} \sup_{t \in [t_k, t_{k+1}]} \mathbb{E}(\|z^N(t) - u^N(t)\|_V^{2p}).$$

A similar argument concludes the proof.  $\square$

**3.2. A localized  $L^2(\Omega)$  convergence.** Recall that  $X = \mathbb{L}^4(D) \cap H$  is an interpolation space between  $H$  and  $V$  such that (2.2) holds. For every  $M > 0$ , set

$$\tilde{\Omega}_M(t) := \left\{ \omega \in \Omega : \sup_{s \in [0, t]} \|u(s)(\omega)\|_X^4 \leq M \right\}. \quad (3.9)$$

Note that once more, and unlike [3], this set only depends on the solution  $u$  of (1.1) and does not depend on the scheme. Let  $\tau_M =: \inf\{t \geq 0 : \|u(t)\|_X^4 \geq M\} \wedge T$ ; then  $\tau_M = T$  on  $\tilde{\Omega}_M(T)$ . The following result improves Proposition 5.1 in [3]. Note that in our case, both processes  $u$  and  $z^N$  have a.s. continuous trajectories.

**Proposition 3.4.** *Let  $u_0$  be  $V$ -valued,  $\mathcal{F}_0$ -measurable such that  $\mathbb{E}(\|u_0\|_V^8) < \infty$  and suppose that  $G$  satisfies the conditions **(G1)** and **(G2)**. Then, there exist constants  $C$  and  $\widetilde{C}(M)$  such that*

$$\mathbb{E} \left( \sup_{t \in [0, \tau_M]} \|z^N(t) - u(t)\|_{\mathbb{L}^2}^2 + \int_0^{\tau_M} [\|u^N(t) - u(t)\|_V^2 + \|y^N(t) - u(t)\|_V^2] dt \right) \leq \frac{C}{N} e^{T\widetilde{C}(M)}, \quad (3.10)$$

where

$$\widetilde{C}(M) := \frac{3^3 \bar{C}^2}{2^5 \beta^3 \nu^3} M + C(\nu, L_1, \beta, \epsilon), \quad (3.11)$$

and  $\bar{C}$  is the constant defined in (2.2) and  $\beta < 1$ .

*Proof.* Let us apply the Itô formula to  $\|z^N(t \wedge \tau_M) - u(t \wedge \tau_M)\|_{\mathbb{L}^2}^2$ . This is possible even if  $z^N$  and  $u$  are not regular enough. Indeed, we can use the Yosida approximation  $e^{-\delta A}(z^N(t) - u(t))$  for some  $\delta > 0$ , apply the Itô formula to this smooth processes, and then pass to the limit as  $\delta \rightarrow 0$  (see e.g. [10], step 4 of the proof of Theorem 2.4). This implies

$$\|z^N(t \wedge \tau_M) - u(t \wedge \tau_M)\|_{\mathbb{L}^2}^2 = \sum_{i=1}^2 T_i(t \wedge \tau_M) + I(t \wedge \tau_M), \quad (3.12)$$

where

$$\begin{aligned}
T_1(t \wedge \tau_M) &= -2 \int_0^{t \wedge \tau_M} \langle F(u^N(s)) - F(u(s)), z^N(s) - u(s) \rangle ds, \\
T_2(t \wedge \tau_M) &= \int_0^{t \wedge \tau_M} \|G(y^N(s)) - G(u(s))\|_{\mathcal{L}_2(K, H)}^2 ds, \\
I(t \wedge \tau_M) &= 2 \int_0^{t \wedge \tau_M} (z^N(s) - u(s), [G(y^N(s)) - G(u(s))] dW(s)).
\end{aligned}$$

The Lipschitz property **(G1)** implies

$$T_2(t \wedge \tau_M) \leq 2L_1 \left[ \int_0^{t \wedge \tau_M} |z^N(s) - u(s)|_{\mathbb{L}^2}^2 ds + \int_0^{t \wedge \tau_M} |z^N(s) - y^N(s)|_{\mathbb{L}^2}^2 ds \right]. \quad (3.13)$$

Furthermore,  $T_1(t \wedge \tau_M) = \sum_{i=1}^4 T_{1,i}(t \wedge \tau_M)$ , where

$$\begin{aligned} T_{1,1}(t \wedge \tau_M) &= -2\nu \int_0^{t \wedge \tau_M} \langle Au^N(s) - Au(s), u^N(s) - u(s) \rangle ds, \\ T_{1,2}(t \wedge \tau_M) &= -2\nu \int_0^{t \wedge \tau_M} \langle Au^N(s) - Au(s), z^N(s) - u^N(s) \rangle ds, \\ T_{1,3}(t \wedge \tau_M) &= -2 \int_0^{t \wedge \tau_M} \langle B(u^N(s), u^N(s)) - B(u(s), u(s)), u^N(s) - u(s) \rangle ds, \\ T_{1,4}(t \wedge \tau_M) &= -2 \int_0^{t \wedge \tau_M} \langle B(u^N(s), u^N(s)) - B(u(s), u(s)), z^N(s) - u^N(s) \rangle ds. \end{aligned}$$

The definition of  $A$  implies that

$$T_{1,1}(t \wedge \tau_M) = -2\nu \int_0^{t \wedge \tau_M} |\nabla u^N(s) - \nabla u(s)|_{\mathbb{L}^2}^2 ds. \quad (3.14)$$

The Cauchy Schwarz and Young inequalities imply that for any  $\beta_2 > 0$ ,

$$T_{1,2}(t \wedge \tau_M) \leq \nu\beta_2 \int_0^{t \wedge \tau_M} |\nabla u^N(s) - \nabla u(s)|_{\mathbb{L}^2}^2 ds + \frac{\nu}{\beta_2} \int_0^t \|z^N(s) - u^N(s)\|_V^2 ds. \quad (3.15)$$

Using the inequality (2.4), we deduce that for any  $\beta_3 > 0$  and  $\epsilon > 0$ ,

$$\begin{aligned} T_{1,3}(t \wedge \tau_M) &\leq 2\nu\beta_3 \int_0^{t \wedge \tau_M} (|\nabla u^N(s) - \nabla u(s)|_{\mathbb{L}^2}^2 + |u^N(s) - u(s)|_{\mathbb{L}^2}^2) ds \\ &\quad + 2C_{\nu\beta_3} \int_0^{t \wedge \tau_M} \|u(s)\|_X^4 |u^N(s) - u(s)|_{\mathbb{L}^2}^2 ds \\ &\leq 2\nu\beta_3 \int_0^{t \wedge \tau_M} |\nabla[u^N(s) - u(s)]|_{\mathbb{L}^2}^2 ds + 2(\nu\beta_3 + C_{\nu\beta_3}M)(1 + \epsilon) \int_0^{t \wedge \tau_M} |z^N(t) - u(t)|_{\mathbb{L}^2}^2 ds \\ &\quad + C(\nu, \beta_3, \epsilon) \int_0^{t \wedge \tau_M} (1 + \|u(s)\|_X^4) |z^N(t) - u^N(t)|_{\mathbb{L}^2}^2 ds. \end{aligned} \quad (3.16)$$

Finally, since  $B$  is bilinear, the Hölder inequality implies

$$\begin{aligned} T_{1,4}(t \wedge \tau_M) &= 2 \int_0^{t \wedge \tau_M} \left[ \langle B(u^N(s) - u(s), z^N(s) - u^N(s)), u^N(s) \rangle \right. \\ &\quad \left. + \langle B(u(s), z^N(s) - u^N(s)), u^N(s) - u(s) \rangle \right] ds \\ &\leq 2 \int_0^{t \wedge \tau_M} \|u^N(s) - u(s)\|_X [\|u^N(s)\|_X + \|u(s)\|_X] \|z^N(s) - u^N(s)\|_V ds. \end{aligned}$$

Using the interpolation inequality (2.2) and the Young inequality, we deduce that for any  $\beta_4 > 0$ , there exists a positive constant  $C(\nu, \beta_4)$  such that

$$\begin{aligned} &\sqrt{C} |\nabla(u^N(s) - u(s))|_{\mathbb{L}^2}^{\frac{1}{2}} |u^N(s) - u(s)|_{\mathbb{L}^2}^{\frac{1}{2}} \|z^N(s) - u^N(s)\|_V [\|u^N(s)\|_X + \|u(s)\|_X] \\ &\leq \nu\beta_4 |\nabla(u^N(s) - u(s))|_{\mathbb{L}^2}^2 + C|z^N(s) - u(s)|_{\mathbb{L}^2}^2 + C|z^N(s) - u^N(s)|_{\mathbb{L}^2}^2 \\ &\quad + C(\nu, \beta_4) [\|u^N(s)\|_X^2 + \|u(s)\|_X^2] \|z^N(s) - u^N(s)\|_V^2. \end{aligned}$$

This implies

$$\begin{aligned} T_{1,4}(t \wedge \tau_M) &\leq \nu\beta_4 \int_0^{t \wedge \tau_M} |\nabla[u^N(s) - u(s)]|_{\mathbb{L}^2}^2 ds + C \int_0^{t \wedge \tau_M} |z^N(s) - u(s)|_{\mathbb{L}^2}^2 ds \\ &\quad + C(\nu, \beta_4) \int_0^{t \wedge \tau_M} \left( |u^N(s) - z^N(s)|_{\mathbb{L}^2}^2 + [\|u^N(s)\|_X^2 + \|u(s)\|_X^2] \|z^N(s) - u^N(s)\|_V^2 \right) ds. \end{aligned} \quad (3.17)$$

Collecting the upper estimates (3.13)–(3.17), we deduce that for  $\beta_2 + 2\beta_3 + \beta_4 < 2$  and  $t \in [0, T]$ ,

$$\begin{aligned} &\sup_{0 \leq s \leq t} |z^N(s \wedge \tau_N) - u(s \wedge \tau_N)|_{\mathbb{L}^2}^2 + \nu(2 - \beta_2 - 2\beta_3 - \beta_4) \int_0^{t \wedge \tau_N} |\nabla[u^N(s) - u(s)]|_{\mathbb{L}^2}^2 ds \\ &\leq R(t) + \sup_{s \in [0, t]} I(s \wedge \tau_N) + \left[ 2(1 + \epsilon)C_{\nu\beta_3}M + 2L_1 + C(\nu, \beta_3, \epsilon) \right] \int_0^{t \wedge \tau_M} |z^N(s) - u(s)|_{\mathbb{L}^2}^2 ds, \end{aligned} \quad (3.18)$$

where, gathering all error terms, we let

$$\begin{aligned} R(t) &= \int_0^{t \wedge \tau_M} \left( 2L_1 |z^N(s) - y^N(s)|_{\mathbb{L}^2}^2 + C(\nu, \beta_2, \beta_3, \beta_4) \|z^N(s) - u^N(s)\|_V^2 \right) ds \\ &\quad + C(\nu, \beta_3, \epsilon) \left\{ \int_0^{t \wedge \tau_M} \|u(s)\|_X^8 ds \right\}^{\frac{1}{2}} \left\{ \int_0^{t \wedge \tau_M} |z^N(s) - u^N(s)|_{\mathbb{L}^2}^4 ds \right\}^{\frac{1}{2}} \\ &\quad + C(\nu, \beta_4) \int_0^{t \wedge \tau_M} [\|u^N(s)\|_X^2 + \|u(s)\|_X^2] \|z^N(s) - u^N(s)\|_V^2 ds. \end{aligned}$$

The Cauchy-Schwarz inequality, the integrability property  $\mathbb{E}(\|u_0\|_V^8) < \infty$ , and the upper estimates (2.11), (3.4), (3.7) and (3.8) imply the existence of some positive constant  $C$  (depending on the parameter  $\beta_i$  and  $\epsilon$  such that for every  $N, M$ ,

$$\mathbb{E} \left( \sup_{t \in [0, T]} R(t) \right) \leq \frac{C}{N}. \quad (3.19)$$

Using the Burkholder-Davis-Gundy inequality, then the Young inequality and the Lipschitz condition **(G1)** on  $G$ , we deduce that for any  $\delta > 0$ ,

$$\begin{aligned} &\mathbb{E} \left( \sup_{t \in [s \leq t]} I(t) \right) \leq 6\mathbb{E} \left( \left\{ \int_0^{t \wedge \tau_M} \|G(s, y^N(s)) - G(s, u(s))\|_{\mathcal{L}_2(K, H)}^2 |u^N(s) - u(s)|_{\mathbb{L}^2}^2 ds \right\}^{\frac{1}{2}} \right) \\ &\leq 6\mathbb{E} \left( \sup_{s \in [0, t \wedge \tau_M]} |z^N(s) - u(s)|_{\mathbb{L}^2} \left\{ \int_0^{t \wedge \tau_M} L_1 |y^N(s) - u(s)|_{\mathbb{L}^2}^2 ds \right\}^{\frac{1}{2}} \right) \\ &\leq \delta \mathbb{E} \left( \sup_{s \in [0, t]} |z^N(s \wedge \tau_M) - u(s \wedge \tau_M)|_{\mathbb{L}^2}^2 \right) + C(\delta) \mathbb{E} \int_0^{t \wedge \tau_M} |z^N(s) - u(s)|_{\mathbb{L}^2}^2 ds \\ &\quad + C(\delta) \mathbb{E} \int_0^{t \wedge \tau_M} |y^N(s) - z^N(s)|_{\mathbb{L}^2}^2 ds \\ &\leq \delta \mathbb{E} \left( \sup_{s \in [0, t]} |z^N(s \wedge \tau_M) - u(s \wedge \tau_M)|_{\mathbb{L}^2}^2 \right) + C(\delta) \mathbb{E} \int_0^{t \wedge \tau_M} |z^N(s) - u(s)|_{\mathbb{L}^2}^2 ds + \frac{C(\delta)}{N}, \end{aligned} \quad (3.20)$$

where the last inequality is a consequence of (3.8). The upper estimates (3.18)–(3.20) imply that if  $\delta < 1$  and  $\bar{C}(\beta) := 2 - \beta_2 + 2\beta_3 + \beta_4 > 0$ ,

$$\begin{aligned} & (1 - \delta) \mathbb{E} \left( \sup_{s \in [0, t]} |z^N(s \wedge \tau_M) - u(s \wedge \tau_M)|_{\mathbb{L}^2}^2 \right) + \nu \bar{C}(\beta) \mathbb{E} \int_0^{t \wedge \tau_M} |\nabla [u^N(s) - u(s)]|_{\mathbb{L}^2}^2 ds \\ & \leq \frac{C}{N} + \left[ 2(1 + \epsilon) C_{\nu\beta_3} M + C(L_1, \nu, \beta_3, \epsilon, \delta) \right] \mathbb{E} \int_0^t |z^N(s \wedge \tau_M) - u(s \wedge \tau_M)|_{\mathbb{L}^2}^2 ds. \end{aligned} \quad (3.21)$$

The Gronwall inequality (disregarding the second term on the left hand side of (3.21)) proves that

$$\mathbb{E} \left( \sup_{s \in [0, t]} |z^N(s \wedge \tau_M) - u(s \wedge \tau_M)|_{\mathbb{L}^2}^2 \right) \leq \frac{C}{N} \exp(T \widetilde{C(M)}),$$

where  $\widetilde{C(M)}$  is defined by (3.11). Indeed, the term  $\beta_3 < 1$  has to be chosen first since the other positive constants  $\beta_2$  and  $\beta_4$ , which have to satisfy  $\beta_2 + \beta_4 < 2(1 - \beta_3)$ , only appear in the "error" term  $R(t)$ . Using this inequality in (3.21), the definition of  $C_{\nu\beta_3}$  given in (2.5), (3.7) and (3.8), and changing the ratio  $\frac{1+\epsilon}{(1-\delta)\beta_3^3}$  into  $\frac{1}{\beta^3}$  for some  $\beta \in (0, 1)$ , we conclude the proof of (3.10).  $\square$

**3.3. Strong  $L^2(\Omega)$  speed of convergence of the splitting scheme.** Since  $\tau_M = T$  on  $\tilde{\Omega}_M$ , we can rewrite (3.10) as

$$\mathbb{E} \left( \mathbf{1}_{\tilde{\Omega}_M} \left\{ \sup_{t \in [0, T]} |z^N(t) - u(t)|_{\mathbb{L}^2}^2 + \int_0^T [\|u^N(t) - u(t)\|_V^2 + \|y^N(t) - u(t)\|_V^2] dt \right\} \right) \leq \frac{C}{N} e^{T \tilde{C(M)}}.$$

The previous section provides an upper bound of the  $L^2(\Omega)$  - norm of the maximal error on each time step localized on the set  $\Omega_M$ . In order to deduce the strong speed of convergence, we next have to analyze this error on the complement of this localization set.

The first step is described in the following simple upper estimates, which follow from the Hölder inequality. Hence, we suppose that  $\mathbb{E}(\|u_0\|_V^{2q}) < \infty$  and that  $p$  and  $q$  are conjugate exponents; then

$$\mathbb{E} \left( \mathbf{1}_{\tilde{\Omega}_M^c} \sup_{t \in [0, T]} |z^N(t) - u(t)|_{\mathbb{L}^2}^2 \right) \leq C \left[ \mathbb{P}(\tilde{\Omega}_M^c) \right]^{\frac{1}{p}} \left[ \mathbb{E} \left( \sup_{t \in [0, T]} (|z^N(t)|_{\mathbb{L}^2}^{2q} + |u(t)|_{\mathbb{L}^2}^{2q}) \right) \right]^{\frac{1}{q}}. \quad (3.22)$$

Note that we have the similar upper estimate

$$\begin{aligned} & \mathbb{E} \left( \mathbf{1}_{\tilde{\Omega}_M^c} \int_0^T \|z^N(t) - u(t)\|_V^2 dt \right) \\ & \leq C \left[ \mathbb{P}(\tilde{\Omega}_M^c) \right]^{\frac{1}{p}} \left[ \mathbb{E} \int_0^T (\|z^N(t) - u^N(t)\|_V^{2q} + \|u^N(t)\|_V^{2q} + \|u(t)\|_V^{2q}) dt \right]^{\frac{1}{q}} \leq C \left[ \mathbb{P}(\tilde{\Omega}_M^c) \right]^{\frac{1}{p}}, \end{aligned}$$

where the last upper estimate is deduced from (2.11), (3.4) and (3.7). Theorem 2.2 shows that  $\mathbb{E}(\sup_{t \in [0, T]} \|u(t)\|_V^2) < \infty$ . We next prove that  $\mathbb{E}(\sup_{t \in [0, T]} |z^N(t)|_{\mathbb{L}^2}^{2q})$  is bounded by a constant independent of  $N$ .

**Lemma 3.5.** *Let  $p \geq 2$  and  $u_0$  be  $V$ -valued,  $\mathcal{F}_0$ -measurable such that  $\mathbb{E}(\|u_0\|_V^{2p+1}) < \infty$ . Suppose that  $G$  satisfies the conditions **(G1)** and **(G2)**. Then there exists a positive*

constant  $C_p$  such that for every integer  $N \geq 1$ ,

$$\mathbb{E} \left( \sup_{t \in [0, T]} \|z^N(t)\|_{\mathbb{L}^2}^{2p} + \nu \int_0^T \|z^N(t)\|_V^{2p} dt \right) \leq C_p.$$

The proof of this lemma is given in the Appendix, Section 5.1.

We next have to make sure that the threshold  $M(N)$  is chosen to balance the upper estimates (3.10) and (3.22).

**Case 1: Linear growth diffusion coefficient.** Suppose that  $\mathbb{E}(\|u_0\|_V^{2q}) < \infty$ . Then using the Gagliardo-Nirenberg inequality (2.2), we deduce

$$\begin{aligned} \mathbb{P}(\tilde{\Omega}_{M(N)}^c) &= \mathbb{P} \left( \sup_{t \in [0, T]} \|u(t)\|_X^4 \geq M(N) \right) = \mathbb{P} \left( \sup_{t \in [0, T]} \|u(t)\|_V^4 \geq \frac{4M(N)}{\bar{C}^2} \right) \\ &\leq \frac{\bar{C}^q}{2^q M(N)^{\frac{q}{2}}} \mathbb{E} \left( \sup_{t \in [0, T]} \|u(t)\|_V^{2q} \right) \leq \frac{C}{M(N)^{\frac{q}{2}}}, \end{aligned}$$

where the last upper estimate is a consequence of (2.11). To balance the right hand sides of (3.10) and (3.22), we choose  $M(N) \rightarrow \infty$  as  $N \rightarrow \infty$  such that

$$\frac{1}{N} \exp(TC(\widetilde{M(N)})) \asymp C(q) \frac{1}{M(N)^{\frac{q-1}{2}}}. \quad (3.23)$$

Taking logarithms and using (3.11), this comes down to

$$-\ln(N) + 2(1 + \epsilon)C_{\nu\beta}M(N)T \asymp -\frac{q-1}{2} \ln(M(N)),$$

for some  $\beta \in (0, 1)$  and  $\epsilon \in (0, 1)$ , where  $C_{\nu\beta}$  is defined in (2.5). Let

$$M(N) := \frac{1}{2(1 + \epsilon)C_{\nu\beta}T} \left[ \ln(N) - \frac{q-1}{2} \ln(\ln(N)) \right] \asymp C(\nu, \beta, \epsilon, T) \ln(N). \quad (3.24)$$

Then  $M(N) \rightarrow \infty$  as  $N \rightarrow \infty$  and (3.23) is satisfied. This yields the following result, where the first upper estimate follows from (3.23) and (3.7), while the second one is deduced from the fact that  $y^N(t_k^+) = u^N(t_{k+1}^-)$ .

**Theorem 3.6.** *Suppose that  $u_0$  is  $V$ -valued such that  $\mathbb{E}(\|u_0\|_V^{2q+1}) < \infty$  for some  $q \geq 4$  and that  $G$  satisfies conditions **(G1)** and **(G2)**. Then there exists a constant  $C > 0$  such that*

$$\begin{aligned} &\mathbb{E} \left( \sup_{t \in [0, T]} [\|z^N(t) - u(t)\|_{\mathbb{L}^2}^2 + \|u^N(t) - u(t)\|_{\mathbb{L}^2}^2] \right. \\ &\quad \left. + \int_0^T [\|z^N(s) - u(s)\|_V^2 + \|u^N(s) - u(s)\|_V^2 + \|y^N(s) - u(s)\|_V^2] ds \right) \leq \frac{C}{\ln(N)^{\frac{q-1}{2}}}, \end{aligned} \quad (3.25)$$

$$\mathbb{E} \left( \sup_{k=1, \dots, N} [\|u^N(t_k^+) - u(t_k)\|_{\mathbb{L}^2}^2 + \|y^N(t_k^+) - u(t_k)\|_{\mathbb{L}^2}^2] \right) \leq \frac{C}{\ln(N)^{\frac{q-1}{2}}}. \quad (3.26)$$

**Remark 3.7.** *Note that if  $u_0$  is a deterministic element of  $V$ , or more generally if  $\|u_0\|_V$  has moments of all orders (for example if  $u_0$  is a  $V$ -valued Gaussian random variable independent of the noise  $W$ ), then the speed of convergence of the current splitting scheme is any negative power of  $\ln(N)$ .*

**Case 2: Additive noise.** Suppose that  $G(u) := G \in \mathcal{L}_2(K, V)$ , that is the noise is additive, or more generally that  $G$  satisfies the conditions **(G1)** and **(G2)** with  $K_1 = 0$ , that is  $\|G(u)\|_{\mathcal{L}_2(K, V)}^2 \leq K_0$ . Then for any constant  $\alpha > 0$  using an exponential Markov inequality and the Gagliardo-Nirenberg inequality (2.2), we deduce

$$\mathbb{P}(\tilde{\Omega}_M^c) \leq \mathbb{P}\left(\sup_{t \in [0, T]} \|u(t)\|_X^2 \geq \sqrt{M}\right) \leq \mathbb{P}\left(\sup_{t \in [0, T]} \|u(t)\|_V^2 \geq \frac{2\sqrt{M}}{\bar{C}}\right). \quad (3.27)$$

We next prove that for an additive noise, or in a slightly more general setting, for  $\alpha > 0$  small enough,  $\mathbb{E}[\exp(\alpha \sup_{t \in [0, T]} \|u(t)\|_V^2)] < \infty$ . In the case of an additive noise, this result is a particular case of [13], Lemma A.1. In this reference, the periodic Navier Stokes equation is written in vorticity formulation  $\xi(t) = \partial_1 u_2(t) - \partial_2 u_1(t)$ . The velocity  $u$  projected on divergence free fields can be deduced from  $\xi$  by the Biot-Savart kernel, and  $\|\nabla u(t)\|_{\mathbb{L}^2} \leq C\|\xi(t)\|_{\mathbb{L}^2}$ . We extend this result to the case of a more general diffusion coefficient whose Hilbert-Schmidt norm is bounded. Recall that the Poincaré inequality implies the existence of a constant  $\tilde{C} > 0$  such that if we set  $\|u\|^2 := \|\nabla u\|_{\mathbb{L}^2}^2 + \|Au\|_{\mathbb{L}^2}^2$  for  $u \in \text{Dom}(A)$ , then we have

$$\|u\|_V^2 = \|u\|_{\mathbb{L}^2}^2 + \|\nabla u\|_{\mathbb{L}^2}^2 \leq \tilde{C}\|u\|^2. \quad (3.28)$$

**Lemma 3.8.** *Let  $u_0 \in V$  and  $G$  satisfy conditions **(G1)** and **(G2)** with  $K_1 = 0$ , that is  $\|G(t, u)\|_{\mathcal{L}_2(K, V)}^2 \leq K_0$ . Then the solution  $u$  to (1.1) satisfies*

$$\mathbb{E}\left\{\exp\left[\alpha\left(\sup_{0 \leq s \leq T} \|u(s)\|_V^2\right) + \nu \int_0^T |Au(s)|_{\mathbb{L}^2}^2 ds\right]\right\} \leq 3 \exp(\alpha[\|u_0\|_V^2 + TK_0]) \quad (3.29)$$

for  $\alpha \in (0, \alpha_0]$  and  $\alpha_0 = \frac{\nu}{4K_0\bar{C}}$ , where  $\tilde{C}$  is defined in (3.28).

In order to make this paper as self-contained as possible, we prove this lemma in the appendix, section 5.2.

Let  $u_0 \in V$ ; then for  $\alpha_0 = \frac{\nu}{4K_0\bar{C}}$ , the inequalities (3.27) and (3.29) imply

$$\mathbb{P}(\tilde{\Omega}_M^c) \leq 3e^{\alpha_0 K_0 T} \exp\left(-2\alpha_0 \frac{\sqrt{M}}{\bar{C}}\right),$$

where  $\bar{C}$  is defined by (2.2). We then have to choose  $M(N) \rightarrow \infty$  as  $N \rightarrow \infty$  to balance the right hand sides of (3.10) and (3.22), that is such that for some  $p > 1$ ,

$$\exp\left(-\frac{2\alpha_0 \sqrt{M(N)}}{p\bar{C}} T\right) \asymp c_2 \frac{T}{N} \exp(C\widetilde{M(N)}T)$$

for some positive constant  $c_2$ . Taking logarithms, we look for  $M(N)$  such that

$$-\frac{2\alpha_0}{p\bar{C}} \sqrt{M(N)} \asymp -\ln(N) + 2(1 + \epsilon)C_{\nu\beta}M(N)T,$$

where  $\beta \in (0, 1)$ ,  $\epsilon > 0$  and  $C_{\nu\beta}$  is defined by (2.5). Set  $X = \sqrt{M(N)}$ ,  $a_2 = 2(1 + \epsilon)C_{\nu\beta}T$  and  $a_1 = \frac{2\alpha_0}{p\bar{C}}$ . We have to solve the equation  $a_2 X^2 + a_1 X - \ln(N) = 0$ . The positive

root of this polynomial is equal to  $\sqrt{\frac{\ln(N)}{a_2}} + O(1)$  as  $N \rightarrow \infty$  and  $\exp\left(-\frac{2\alpha_0 \sqrt{M(N)}}{p\bar{C}}\right) \asymp C \exp\left(-2\alpha_0 \frac{\sqrt{\ln(N)}}{\sqrt{a_2} p\bar{C}}\right)$ . Thus, we deduce the following rate of convergence of the splitting scheme.

**Theorem 3.9.** *Let  $u_0 \in V$  and  $G$  satisfy the conditions **(G1)** and **(G2)** with  $K_1 = 0$ , that is  $\|G(s, u)\|_{\mathcal{L}(K, V)}^2 \leq K_0$ . Then*

$$\mathbb{E} \left( \sup_{t \in [0, T]} [|z^N(t) - u(t)|_{\mathbb{L}^2}^2 + |u^N(t) - u(t)|_{\mathbb{L}^2}^2] \right) \quad (3.30)$$

$$+ \int_0^T [\|z^N(s) - u(s)\|_V^2 + \|u^N(s) - u(s)\|_V^2 + \|y^N(s) - u(s)\|_V^2] ds \leq C e^{-\gamma \sqrt{\ln(N)}},$$

$$\mathbb{E} \left( \sup_{k=1, \dots, N} [|u^N(t_k^+) - u(t_k)|_{\mathbb{L}^2}^2 + |y^N(t_k^+) - u(t_k)|_{\mathbb{L}^2}^2] \right) \leq C e^{-\gamma \sqrt{\ln(N)}}, \quad (3.31)$$

where

$$\gamma < \frac{\alpha_0}{C^2} \sqrt{\frac{2^9 \nu^3}{3^3 T}}.$$

Note that when  $\nu$  increases, the upper bound of the exponent  $\gamma$  increases.

**Remark 3.10.** *Note that the statements of Theorems 3.6 and 3.9 are valid if the diffusion coefficient  $G$  depends on the time parameter  $t \in [0, T]$  and satisfies the global growth and Lipschitz versions of **(G1)** and **(G2)**. We have removed the time dependence of  $G$  to focus on the main arguments used to obtain strong convergence results.*

#### 4. EULER TIME SCHEMES

**4.1. Description of the fully implicit scheme and first results.** In this section, we have to be more specific in the definition of the noise. Let  $\mathcal{K}$  be a Hilbert space,  $Q$  be a trace-class operator in  $\mathcal{K}$  and  $W := (W(t), t \in [0, T])$  be a  $\mathcal{K}$ -valued Wiener process with covariance  $Q$ . Let  $K = Q^{\frac{1}{2}} \mathcal{K}$  denote the RKHS of the Gaussian process  $W$ . Let  $\mathcal{G} : \mathcal{K} \rightarrow H$  be a linear operator and suppose that analogs of conditions **(G1)** and **(G2)** are satisfied with  $\mathcal{G}$  instead of  $G$ , and the operator norms  $\mathcal{L}(\mathcal{K}, H)$  (resp.  $\mathcal{L}(\mathcal{K}, V)$ ) instead of the Hilbert-Schmidt norms  $\mathcal{L}_2(K, H)$  (resp.  $\mathcal{L}_2(\mathcal{K}, V)$ ), with constants  $\bar{K}_i$ ,  $i = 0, 1$  and  $\bar{L}_1$ . Then the diffusion coefficient  $G = \mathcal{G} \circ Q^{-\frac{1}{2}}$  satisfies conditions **(G1)** and **(G2)** with constants  $K_i = \text{Trace}(Q) \bar{K}_i$  and  $L_1 = \text{Trace}(Q) \bar{L}_1$ .

Let us first recall the fully implicit time discretization scheme of the stochastic 2D Navier-Stokes introduced by E. Carelli and A. Prohl in [9]. As in the previous section, let  $t_k = \frac{kT}{N}$ ,  $k = 0, \dots, N$ , denote the time grid. When studying a space time discretization using finite elements, one needs to have a stable pairing of the velocity and the pressure which satisfy the discrete LBB-condition (see e.g. [9], page 2469 and pages 2487-2489). Stability issues are crucial and the pressure has to be discretized together with the velocity. In this section, our aim is to obtain bounds for the strong error of an Euler time scheme. Thus, as in the previous section, we may define the scheme for the velocity projected on divergence free fields (see [9], Section 3).

**Fully implicit Euler scheme** *Let  $u_0$  be a  $V$ -valued,  $\mathcal{F}_0$ -measurable random variable and set  $u_N(t_0) = u_0$ . For  $k = 1, \dots, N$ , find  $u_N(t_k) \in V$  such that  $\mathbb{P}$  a.s. for all  $\phi \in V$ ,*

$$\begin{aligned} (u_N(t_k) - u_N(t_{k-1}), \phi) + \frac{T}{N} \left[ \nu (\nabla u_N(t_k), \nabla \phi) + \langle B(u_N(t_k), u_N(t_k)), \phi \rangle \right] \\ = (G(u_N(t_{k-1})) \Delta_k W, \phi), \end{aligned} \quad (4.1)$$

where  $\Delta_k W = W(t_k) - W(t_{k-1})$ .

In the study of the Euler discretization schemes, we will need some Hölder regularity of the solution. This is proved by means of semigroup theory; see [16], Proposition 3.4 and [9], Lemma 2.3.

**Proposition 4.1.** *Let  $u_0$  be  $\mathcal{F}_0$ -measurable such that  $\mathbb{E}(\|u_0\|_V^{2p}) < \infty$  for some  $p \in [2, 4]$ . Let  $G$  satisfy conditions **(G1)** and **(G2)**. Then for  $\eta \in (0, \frac{1}{2})$ , we have*

$$\mathbb{E}(\|u(t) - u(s)\|_{\mathbb{L}^4}^p) \leq C |t - s|^{\eta p}, \quad (4.2)$$

$$\mathbb{E}(\|u(t) - u(s)\|_V^p) \leq C |t - s|^{\frac{\eta p}{2}}. \quad (4.3)$$

Let us recall Lemma 3.1 in [9], which proves moment estimates of the solution to (4.1). Note that here only dyadic moments are computed because of the induction argument which relates two consecutive dyadic numbers (see step 4 of the proof of Lemma 3.1 in [8]).

**Lemma 4.2.** *Let  $u_0$  be  $\mathcal{F}_0$ -measurable such that  $\mathbb{E}(\|u_0\|_V^{2q}) < \infty$  for some integer  $q \in [2, \infty)$ . Assume that  $G$  satisfies the conditions **(G1)** and **(G2)**. Then there exists a  $\mathbb{P}$  a.s. unique sequence of solutions  $\{u_N(t_k)\}_{k=1}^N$  of (4.1), such that each random variable  $u_N(t_k)$  is  $\mathcal{F}_{t_k}$ -measurable and satisfies:*

$$\sup_{N \geq 1} \mathbb{E} \left( \max_{1 \leq k \leq N} \|u_N(t_k)\|_V^{2q} + \nu \frac{T}{N} \sum_{k=1}^N \|u_N(t_k)\|_V^{2q-2} |Au_N(t_k)|_{\mathbb{L}^2}^2 \right) \leq C(T, q), \quad (4.4)$$

where  $C(T, q)$  is a constant which depends on  $T$ , the constants  $K_i$ ,  $i = 0, 1$  in conditions **(G1)** and **(G2)**, and also depends on  $\mathbb{E}(\|u_0\|_V^{2q})$ .

For  $k = 0, \dots, N$ , let  $e_k := u(t_k) - u_N(t_k)$  denote the error of this scheme (note that  $e_0 = 0$ ). Then for any  $\phi \in V$  and  $j = 1, \dots, N$ , we have

$$\begin{aligned} (e_j - e_{j-1}, \phi) + \int_{t_{j-1}}^{t_j} \left[ \nu (\nabla u(s) - \nabla u_N(t_j), \nabla \phi) + \langle B(u(s)) - B(u_N(t_j)), \phi \rangle \right] ds \\ = \left( \phi, \int_{t_{j-1}}^{t_j} [G(u(s)) - G(u_N(t_{j-1}))] dW(s) \right). \end{aligned} \quad (4.5)$$

**4.2. A localized convergence result.** The first result states a localized upper bounds of the error terms. This is due to the nonlinear term, but unlike [9], it depends on  $u$  and not on  $u_N$ . Given  $M > 0$  and  $k = 1, \dots, N$ , set

$$\Omega_k^M := \left\{ \omega \in \Omega : \max_{1 \leq j \leq k} |\nabla u(t_j)|_{\mathbb{L}^2}^2 \leq M \right\} \in \mathcal{F}_{t_k}. \quad (4.6)$$

The following proposition is one of the main results of this section. The modification with respect to Theorem 3.1 in [9] is the localization set which does not depend on the approximation. This will be crucial to obtain a speed of  $L^2(\Omega)$ - strong convergence, and not only that the scheme converges in probability.

**Proposition 4.3.** *Let  $G$  satisfy the growth and Lipschitz conditions **(G1)** and **(G2)**. Let  $u_0$  be such that  $\mathbb{E}(\|u_0\|_V^8) < \infty$ . Then for  $\Omega_k^M$  defined by (4.6) and  $N$  large enough, we have for every  $k = 1, \dots, N$ :*

$$\mathbb{E} \left( 1_{\Omega_{k-1}^M} \max_{1 \leq j \leq k} \left[ |e_j|_{\mathbb{L}^2}^2 + \nu \frac{T}{N} \sum_{j=1}^k |\nabla e_j|_{\mathbb{L}^2}^2 \right] \right) \leq C \exp [C_1(M)T] \left( \frac{T}{N} \right)^\eta, \quad (4.7)$$



for some constant  $C > 0$ ,  $\eta \in (0, \frac{1}{2})$ , and

$$C_1(M) = \frac{(1 + \bar{\epsilon})\bar{C}^2}{2\nu} M + C(\bar{\epsilon}) L_1, \quad (4.8)$$

where  $\bar{C}$  is defined in (2.2), and  $\bar{\epsilon}$  is arbitrary close to 0.

*Proof.* We follow the scheme of the arguments in [9], pages 2480-2484, but the upper estimate of the duality involving the difference of the bilinear terms is dealt with differently, which leads to a different localization set. Furthermore, in order to describe the strong speed of convergence of the scheme, we need a more precise control of various constants appearing in some upper estimates. Hence we give a detailed proof below.

**Step 1: Upper estimates for the bilinear term**

Let us consider the duality between the difference of bilinear terms and  $e_j$ , that is the upper estimate of  $\int_{t_{j-1}}^{t_j} \langle B(u(s)) - B(u_N(t_j)), e_j \rangle ds$ . For every  $s \in (t_{j-1}, t_j]$ , using the bilinearity of  $B$  and the antisymmetry property (2.1), we deduce

$$\langle B(u(s), u(s)) - B(u_N(t_j), u_N(t_j)), e_j \rangle = \sum_{i=1}^3 T_i(s), \quad (4.9)$$

where, since  $\langle B(v, u_N(t_j)), e_j \rangle = \langle B(v, u(t_j)), e_j \rangle$  for every  $v \in V$ ,

$$\begin{aligned} T_1(s) &:= \langle B(e_j, u_N(t_j)), e_j \rangle = \langle B(e_j, u(t_j)), e_j \rangle, \\ T_2(s) &:= \langle B(u(s) - u(t_j), u(t_j)), e_j \rangle, \\ T_3(s) &:= \langle B(u(s), u(s) - u(t_j)), e_j \rangle = -\langle B(u(s), e_j), u(s) - u(t_j) \rangle. \end{aligned}$$

Note that, unlike the first formulation of  $T_1(s)$ , the second one only depends on the error and on the solution to (1.1), and not on the approximation scheme. The Hölder inequality and (2.2) yield for every  $\delta_1 > 0$  and  $\bar{C}$  defined in the interpolation inequality (2.2)

$$\begin{aligned} \int_{t_{j-1}}^{t_j} |T_1(s)| ds &\leq \bar{C} \frac{T}{N} |e_j|_{\mathbb{L}^2} |\nabla e_j|_{\mathbb{L}^2} |\nabla u(t_j)|_{\mathbb{L}^2} \\ &\leq \delta_1 \nu \frac{T}{N} |\nabla e_j|_{\mathbb{L}^2}^2 + \frac{\bar{C}^2}{4\delta_1 \nu} \frac{T}{N} |e_j|_{\mathbb{L}^2}^2 |\nabla u(t_j)|_{\mathbb{L}^2}^2, \end{aligned}$$

where the last upper estimate follows from the Young inequality (with conjugate exponents 2 and 2). A similar argument using the Hölder and Young inequalities with exponents 4, 4 and 2 imply that for any  $\delta_2 > 0$  and  $\gamma_2 > 0$ ,

$$|T_2(s)| \leq \delta_2 \nu |\nabla e_j|_{\mathbb{L}^2}^2 + \gamma_2 |e_j|_{\mathbb{L}^2}^2 + C(\nu, \delta_2, \gamma_2) \|u(t_j) - u(s)\|_{\mathbb{L}^4}^2 |\nabla u(t_j)|_{\mathbb{L}^2}^2.$$

Using the Cauchy-Schwarz inequality we deduce

$$\begin{aligned} \int_{t_{j-1}}^{t_j} |T_2(s)| ds &\leq \delta_2 \nu \frac{T}{N} |\nabla e_j|_{\mathbb{L}^2}^2 + \gamma_2 \frac{T}{N} |e_j|_{\mathbb{L}^2}^2 \\ &\quad + C(\nu, \delta_2, \gamma_2) |\nabla u(t_j)|_{\mathbb{L}^2}^2 \int_{t_{j-1}}^{t_j} \|u(t_j) - u(s)\|_{\mathbb{L}^4}^2 ds. \end{aligned}$$

Similar computations using the Hölder and Young inequalities imply

$$\int_{t_{j-1}}^{t_j} |T_3(s)| ds \leq \delta_3 \nu \frac{T}{N} |\nabla e_j|_{\mathbb{L}^2}^2 + \frac{1}{4\nu\delta_3} \int_{t_{j-1}}^{t_j} \|u(s)\|_{\mathbb{L}^4}^2 \|u(t_j) - u(s)\|_{\mathbb{L}^4}^2 ds \quad (4.10)$$

for any  $\delta_3 > 0$ . Note that

$$\nu \int_{t_{j-1}}^{t_j} (\nabla(u(s) - u_N(t_j)), \nabla e_j) ds = \nu \frac{T}{N} |\nabla e_j|_{\mathbb{L}^2}^2 + \nu \int_{t_{j-1}}^{t_j} (\nabla(u(s) - u(t_j)), \nabla e_j) ds.$$

Using the Cauchy-Schwarz and Young inequalities, we deduce

$$\nu \int_{t_{j-1}}^{t_j} |(\nabla(u(s) - u(t_j)), \nabla e_j)| ds \leq \delta_0 \nu \frac{T}{N} |\nabla e_j|_{\mathbb{L}^2}^2 + \frac{\nu}{4\delta_0} \int_{t_{j-1}}^{t_j} |\nabla(u(s) - u(t_j))|_{\mathbb{L}^2}^2 ds$$

for any  $\delta_0 > 0$ . Hence using the above upper estimates in (4.5) with  $\phi = e_j$ , we deduce

$$\begin{aligned} (e_j - e_{j-1}, e_j) + \nu \frac{T}{N} |\nabla e_j|_{\mathbb{L}^2}^2 &\leq \nu \sum_{r=0}^3 \delta_r \frac{T}{N} |\nabla e_j|_{\mathbb{L}^2}^2 + \left( \gamma_2 + \frac{\bar{C}^2}{4\delta_1 \nu} |\nabla u(t_j)|_{\mathbb{L}^2}^2 \right) \frac{T}{N} |e_j|_{\mathbb{L}^2}^2 \\ &+ \sum_{l=1}^3 \tilde{T}_j(l) + \left( \int_{t_{j-1}}^{t_j} [G(u(s)) - G(u_N(t_{j-1}))] dW(s), e_j \right), \end{aligned} \quad (4.11)$$

where

$$\begin{aligned} \tilde{T}_j(1) &= \frac{\nu}{4\delta_0} \int_{t_{j-1}}^{t_j} |\nabla(u(s) - u(t_j))|_{\mathbb{L}^2}^2 ds, \\ \tilde{T}_j(2) &= C(\nu, \delta_2, \gamma_2) |\nabla u(t_j)|_{\mathbb{L}^2}^2 \int_{t_{j-1}}^{t_j} \|u(s) - u(t_j)\|_{\mathbb{L}^4}^2 ds, \\ \tilde{T}_j(3) &= \frac{1}{4\nu\delta_3} \int_{t_{j-1}}^{t_j} \|u(s)\|_{\mathbb{L}^4}^2 \|u(t_j) - u(s)\|_{\mathbb{L}^4}^2 ds. \end{aligned}$$

Using the time regularity (4.3) with  $p = 2$ , we deduce

$$\mathbb{E}(\tilde{T}_j(1)) \leq C \frac{\nu}{4\delta_0} \left( \frac{T}{N} \right)^{1+\eta}. \quad (4.12)$$

The Cauchy-Schwarz inequality, (2.11) with  $p = 2$  and (4.2) imply

$$\mathbb{E}(\tilde{T}_j(2)) \leq C(\nu, \delta_2, \gamma_2) \left( \frac{T}{N} \right)^{1+2\eta}, \quad (4.13)$$

$$\mathbb{E}(\tilde{T}_j(3)) \leq C \frac{1}{4\nu\delta_3} \left( \frac{T}{N} \right)^{1+2\eta}. \quad (4.14)$$

## Step 2: Localization

In order to use a discrete version of the Gronwall lemma to upper estimate  $|e_j|_{\mathbb{L}^2}^2$ , due to the factor  $|\nabla u(t_j)|_{\mathbb{L}^2}^2$  on the RHS of (4.11), we have to localize on the random set  $\Omega_{j-1}^M$  defined in (4.6). The shift of index is due to the fact that, in order to deal with the stochastic integral, we have to make sure that the localization set is  $\mathcal{F}_{t_{j-1}}$ -measurable. This set depends on  $j$ , but we will need to add the localized inequalities (4.11) and take expected values.

Note that for  $1 \leq j \leq k$ ,  $\Omega_k^M \subset \Omega_j^M$ . Hence, since  $e_0 = 0$ , as proved in [9], estimate (3.25), we have

$$\begin{aligned} \max_{1 \leq j \leq k} \sum_{l=1}^j 1_{\Omega_{l-1}^M} (|e_l|_{\mathbb{L}^2}^2 - |e_{l-1}|_{\mathbb{L}^2}^2) &= \max_{1 \leq j \leq k} \left( 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 + \sum_{l=2}^j (1_{\Omega_{l-2}^M} - 1_{\Omega_{l-1}^M}) |e_{l-1}|_{\mathbb{L}^2}^2 \right) \\ &\geq \max_{1 \leq j \leq k} 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2. \end{aligned} \quad (4.15)$$

Thus, we will localize  $|e_j|_{\mathbb{L}^2}^2$  on the set  $\Omega_{j-1}^M$  and - shifting the index by one - control some "error term"  $|e_j - e_{j-1}|_{\mathbb{L}^2}^2$  localized on the same set. Note that this localization set only depends on the projection of the solution  $u$  of equation (1.1) on divergence free fields, and not on its approximation.

Adding the inequalities (4.11) with  $\phi = e_j$  localized on the set  $\Omega_{j-1}^M$ , using  $e_0 = 0$  and the identity  $(a, a - b) = \frac{1}{2}[|a|_{\mathbb{L}^2}^2 - |b|_{\mathbb{L}^2}^2 + |a - b|_{\mathbb{L}^2}^2]$ , we deduce for  $k = 1, \dots, N$

$$\begin{aligned} & \max_{1 \leq j \leq k} \left( \frac{1}{2} 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 + \frac{1}{2} \sum_{l=1}^j 1_{\Omega_{l-1}^M} |e_l - e_{l-1}|_{\mathbb{L}^2}^2 \right) \\ & \leq \frac{1}{2} \left( \max_{1 \leq j \leq k} \sum_{l=1}^j 1_{\Omega_{l-1}^M} (|e_l|_{\mathbb{L}^2}^2 - |e_{l-1}|_{\mathbb{L}^2}^2) + \sum_{l=1}^j 1_{\Omega_{l-1}^M} |e_l - e_{l-1}|_{\mathbb{L}^2}^2 \right) \\ & \leq \max_{1 \leq j \leq k} \sum_{1 \leq l \leq j} 1_{\Omega_{l-1}^M} (e_l - e_{l-1}, e_l). \end{aligned}$$

The upper estimates (4.11) for  $j = 1, \dots, k$  imply for any  $\epsilon > 0$

$$\begin{aligned} & \max_{1 \leq j \leq k} \left[ \frac{1}{2} 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 + \sum_{l=1}^j 1_{\Omega_{l-1}^M} |e_l - e_{l-1}|_{\mathbb{L}^2}^2 + \nu \left( 1 - \sum_{r=0}^3 \delta_r \right) \frac{T}{N} \sum_{l=1}^j 1_{\Omega_{l-1}^M} |\nabla e_l|_{\mathbb{L}^2}^2 \right] \\ & \leq \left[ \gamma_2 + (1 + \epsilon) \frac{\bar{C}^2 M}{4\delta_1 \nu} \right] \frac{T}{N} \sum_{j=1}^k 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 + \sum_{i=1}^3 \sum_{j=1}^k \tilde{T}_j(i) \\ & + C(\nu, \delta_1, \epsilon) \frac{T}{N} \sum_{j=1}^k 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 |\nabla [u(t_j) - u(t_{j-1})]|_{\mathbb{L}^2}^2 + M_k(1) + M_k(2), \quad (4.16) \end{aligned}$$

where

$$\begin{aligned} M_k(1) &= \sum_{j=1}^k 1_{\Omega_{j-1}^M} \left( e_{j-1}, \int_{t_{j-1}}^{t_j} [G(u(s)) - G(u_N(t_{j-1}))] dW(s) \right), \\ M_k(2) &= \sum_{j=1}^k 1_{\Omega_{j-1}^M} \left( e_j - e_{j-1}, \int_{t_{j-1}}^{t_j} [G(u(s)) - G(u_N(t_{j-1}))] dW(s) \right). \end{aligned}$$

The inequalities (4.12)–(4.14) imply the existence of a constant  $C$  depending on  $T, \nu, \delta_i, i = 0, \dots, 3$  and  $\gamma_2$  such that

$$\sum_{i=1}^3 \sum_{j=1}^N \mathbb{E}(\tilde{T}_j(i)) \leq C \left( \frac{T}{N} \right)^\eta. \quad (4.17)$$

The Cauchy-Schwarz inequality, (2.11) and (4.4) for  $p = q = 2$ , and the time regularity (4.3) for  $p = 4$  imply the existence of a constant  $C$  such that

$$\frac{T}{N} \sum_{j=1}^N \mathbb{E} \left( |e_j|_{\mathbb{L}^2}^2 |\nabla [u(t_j) - u(t_{j-1})]|_{\mathbb{L}^2}^2 \right) \leq C \left( \frac{T}{N} \right)^\eta. \quad (4.18)$$

We next upper estimate  $\mathbb{E}(\max_{1 \leq k \leq N} M_k(2))$ . The Cauchy-Schwarz inequality, the Itô isometry and then the Young inequality imply that for any  $\tilde{\delta}_2 > 0$

$$\begin{aligned} \mathbb{E}\left(\max_{1 \leq j \leq k} M_j(2)\right) &\leq \sum_{j=1}^k \left\{ \mathbb{E}(1_{\Omega_{j-1}^M} |e_j - e_{j-1}|_{\mathbb{L}^2}^2) \right\}^{\frac{1}{2}} \\ &\quad \times \left\{ \mathbb{E}\left(1_{\Omega_{j-1}^M} \int_{t_{j-1}}^{t_j} \|G(u(s)) - G(u_N(t_{j-1}))\|_{\mathcal{L}_2(K,H)}^2 ds\right) \right\}^{\frac{1}{2}} \\ &\leq \tilde{\delta}_2 \sum_{j=1}^k \mathbb{E}(1_{\Omega_{j-1}^M} |e_j - e_{j-1}|_{\mathbb{L}^2}^2) \\ &\quad + \frac{1}{4\tilde{\delta}_2} \sum_{j=1}^k \int_{t_{j-1}}^{t_j} \mathbb{E}\left(1_{\Omega_{j-1}^M} \|G(u(s)) - G(u_N(t_{j-1}))\|_{\mathcal{L}_2(K,H)}^2\right) ds. \end{aligned}$$

The Lipschitz condition **(G1)** and (4.3) imply for any  $\epsilon > 0$  and  $s \in [t_{l-1}, t_l]$ ,

$$\begin{aligned} &\mathbb{E}(1_{\Omega_{l-1}^M} \|G(u(s)) - G(u_N(t_{l-1}))\|_{\mathcal{L}_2(K,H)}^2) \\ &\leq (1 + \epsilon) \mathbb{E}(1_{\Omega_{l-1}^M} \|G(u(t_{l-1})) - G(u_N(t_{l-1}))\|_{\mathcal{L}_2(K,H)}^2) \\ &\quad + \left(1 + \frac{1}{\epsilon}\right) \mathbb{E}(1_{\Omega_{l-1}^M} \|G(u(s)) - G(u(t_{l-1}))\|_{\mathcal{L}_2(K,H)}^2) \\ &\leq L_1 (1 + \epsilon) \mathbb{E}\left(1_{\Omega_{l-1}^M} |e_{l-1}|_{\mathbb{L}^2}^2\right) + C(\epsilon) \left(\frac{T}{N}\right)^\eta. \end{aligned} \quad (4.19)$$

Since  $\Omega_j^M \subset \Omega_{j-1}^M$  and  $e_0 = 0$ , we deduce for any  $k = 2, \dots, N$ ,

$$\begin{aligned} \mathbb{E}\left(\max_{1 \leq j \leq k} M_j(2)\right) &\leq \tilde{\delta}_2 \frac{T}{N} \sum_{j=1}^k \mathbb{E}(1_{\Omega_{j-1}^M} |e_j - e_{j-1}|_{\mathbb{L}^2}^2) + \frac{1 + \epsilon}{4\tilde{\delta}_2} L_1 \frac{T}{N} \sum_{j=1}^{k-1} \mathbb{E}\left(1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2\right) \\ &\quad + C(\epsilon, \tilde{\delta}_2) T \left(\frac{T}{N}\right)^\eta. \end{aligned} \quad (4.20)$$

Since  $1_{\Omega_{l-1}^M}$  and  $e_{l-1}$  are  $\mathcal{F}_{t_{l-1}}$ -measurable, using the Burkholder-Davies-Gundy inequality, the Young inequality, (4.19), and using once more the inclusion  $\Omega_j^M \subset \Omega_{j-1}^M$ , we deduce that for any  $\tilde{\delta}_1 > 0$ ,

$$\begin{aligned} \mathbb{E}\left(\max_{1 \leq j \leq k} M_j(1)\right) &\leq 3 \sum_{l=1}^k \mathbb{E}\left[\left\{1_{\Omega_{l-1}^M} \int_{t_{l-1}}^{t_l} \|G(u(s)) - G(u_N(t_{l-1}))\|_{\mathcal{L}_2(K,H)}^2 |e_{l-1}|_{\mathbb{L}^2}^2 ds\right\}^{\frac{1}{2}}\right] \\ &\leq 3 \mathbb{E}\left[\left(\max_{1 \leq l \leq k} 1_{\Omega_{l-1}^M} |e_{l-1}|_{\mathbb{L}^2}\right) \left\{\sum_{l=1}^k 1_{\Omega_{l-1}^M} \int_{t_{l-1}}^{t_l} \|G(u(s)) - G(u_N(t_{l-1}))\|_{\mathcal{L}_2(K,H)}^2 ds\right\}^{\frac{1}{2}}\right] \\ &\leq \tilde{\delta}_1 \mathbb{E}\left(\max_{1 \leq l \leq k} 1_{\Omega_{l-1}^M} |e_{l-1}|_{\mathbb{L}^2}^2\right) + \frac{9(1 + \epsilon)}{4\tilde{\delta}_1} L_1 \frac{T}{N} \sum_{j=1}^{k-1} \mathbb{E}\left(1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2\right) + C(\epsilon, \tilde{\delta}_1) \left(\frac{T}{N}\right)^\eta. \end{aligned} \quad (4.21)$$

Collecting the upper estimates (4.16)–(4.21) and taking  $\tilde{\delta}_2 = 1$ , we deduce for  $k = 2, \dots, N$

$$\mathbb{E}\left(\max_{1 \leq j \leq k} \left\{\frac{1}{2} 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 + \nu \left(1 - \sum_{i=0}^3 \delta_i\right) \frac{T}{N} \sum_{l=1}^j 1_{\Omega_{l-1}^M} |\nabla e_l|_{\mathbb{L}^2}^2\right\}\right)$$

$$\begin{aligned}
&\leq \left[ \tilde{\delta}_1 + \gamma_2 + (1 + \epsilon) \frac{\bar{C}^2 M T}{4\delta_1 \nu} \right] \mathbb{E} \left( \max_{1 \leq j \leq k} 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 \right) \\
&\quad + \left[ (1 + \epsilon) \frac{\bar{C}^2 M}{4\delta_1 \nu} + \gamma_2 + \frac{1 + \epsilon}{4} \left( \frac{1}{\tilde{\delta}_2} + \frac{9}{\tilde{\delta}_1} \right) L_1 \right] \frac{T}{N} \sum_{j=1}^{k-1} \mathbb{E} (1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2) + C \left( \frac{T}{N} \right)^\eta.
\end{aligned} \tag{4.22}$$

### Step 3: Discrete Gronwall lemma

Fix  $\alpha \in (0, 1)$  and choose  $\delta_1 \in (0, 1 - \alpha)$ . Then

$$\nu(1 - \delta_1) \geq \alpha \nu.$$

Fix  $\tilde{\epsilon} \in (0, 1)$  and  $\gamma_2 \in (0, \frac{\tilde{\epsilon}}{2}(\frac{1}{2} - \tilde{\delta}_1))$ ; suppose that  $N$  is large enough to imply

$$\frac{1}{2} - \tilde{\delta}_1 - \left( \gamma_2 + (1 + \epsilon) \frac{\bar{C}^2 M}{4\delta_1 \nu} \right) \frac{T}{N} \geq (1 - \tilde{\epsilon}) \left( \frac{1}{2} - \tilde{\delta}_1 \right),$$

and choose  $\delta_i$ ,  $i = 0, 2, 3$  such that  $\delta_0 + \delta_2 + \delta_3 < \frac{\alpha}{2} \nu$ . Then for  $N$  large enough,

$$\begin{aligned}
&(1 - \tilde{\epsilon}) \left( \frac{1}{2} - \tilde{\delta}_1 \right) \mathbb{E} \left( \max_{1 \leq j \leq k} 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 \right) + \frac{\alpha \nu T}{2N} \sum_{j=1}^k \mathbb{E} (1_{\Omega_{j-1}^M} |\nabla e_j|_{\mathbb{L}^2}^2) \\
&\leq \left[ (1 + \epsilon) \frac{\bar{C}^2 M}{4\delta_1 \nu} + C(\gamma_2, \tilde{\delta}_1, \epsilon) L_1 \right] \frac{T}{N} \sum_{j=1}^{k-1} \mathbb{E} (1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2) + C \left( \frac{T}{N} \right)^\eta.
\end{aligned}$$

Set

$$C_1(M) := \frac{\frac{(1+\epsilon)\bar{C}^2}{4\delta_1\nu}M + (1+\epsilon)C(\gamma_2, \tilde{\delta}_1)}{(1-\tilde{\epsilon})\left(\frac{1}{2}-\tilde{\delta}_1\right)}. \tag{4.23}$$

Neglecting the second term on the left hand side and using a discrete version of the Gronwall lemma, we deduce that

$$\mathbb{E} \left( \max_{1 \leq j \leq k} 1_{\Omega_{j-1}^M} |e_j|_{\mathbb{L}^2}^2 \right) \leq C e^{C_1(M)T} \left( \frac{T}{N} \right)^\eta.$$

Once these inequalities hold, choosing  $\epsilon \sim 0$ ,  $\tilde{\delta}_1 \sim 0$ ,  $\gamma_2 \sim 0$ ,  $\delta_1 \sim 1$ ,  $\delta_i \sim 0$  for  $i = 0, 2, 3$ , we may take  $C_1(M)$  such that

$$C_1(M) = \frac{(1 + \bar{\epsilon}) \bar{C}^2 M}{2\nu} + C(\bar{\epsilon}) L_1,$$

where  $\bar{C}$  is the constant defined in (2.2) and  $\bar{\epsilon} > 0$  is arbitrary close to 0. Indeed, given  $\bar{\epsilon} > 0$ , we choose the other constants so that  $\frac{1+\epsilon}{\delta_1(2-4\tilde{\delta}_1)} \leq \frac{1+\bar{\epsilon}}{2}$ . Plugging this in the previous upper estimate and using the inclusions  $\Omega_k^M \subset \Omega_j^M$  for  $j = 1, \dots, k$ , we deduce (4.7) and (4.8).  $\square$

**4.3. Strong speed of convergence of the implicit Euler scheme.** As in section 3.3, let us use the Hölder inequality with conjugate exponents  $2^{q-1}$  and  $p = \frac{2^{q-1}}{2^{q-1}-1}$ . We obtain

$$\mathbb{E} \left( 1_{(\Omega_N^M)^c} \max_{1 \leq k \leq N} |e_k|_{\mathbb{L}^2}^2 \right) \leq C \left[ \mathbb{P}((\Omega_N^M)^c) \right]^{\frac{1}{p}}$$

$$\times \left[ \mathbb{E} \left( \sup_{0 \leq s \leq T} \|u(s)\|_{\mathbb{L}^2}^{2q} + \max_{0 \leq k \leq N} \|u_N(t_k)\|_{\mathbb{L}^2}^{2q} \right) \right]^{\frac{1}{2q-1}}, \quad (4.24)$$

$$\begin{aligned} \mathbb{E} \left( \mathbf{1}_{(\Omega_N^M)^c} \frac{T}{N} \sum_{k=1}^N \|\nabla e_k\|_{\mathbb{L}^2}^2 \right) &\leq C \left[ \mathbb{P}((\Omega_N^M)^c) \right]^{\frac{1}{p}} \\ &\times \left[ \mathbb{E} \left( \sup_{0 \leq s \leq T} \|\nabla u(s)\|_{\mathbb{L}^2}^{2q} + \max_{0 \leq k \leq N} \|\nabla u_N(t_k)\|_{\mathbb{L}^2}^{2q} \right) \right]^{\frac{1}{2q-1}}. \end{aligned} \quad (4.25)$$

The inequalities (2.11) and (4.4) prove that if  $\mathbb{E}(\|u_0\|_V^{2q}) < \infty$ , the second factors on the right hand sides of (4.24) and (4.25) are bounded by a constant independent of  $N$ .

We now upper estimate the probability of the complement of the localization set and to balance the upper estimates of the  $L^2$  moments localized on the set  $\Omega_N^M$  and its complement. To obtain a strong speed of convergence will require the threshold  $M$  to depend on  $N$ . Two cases are studied.

### Case 1: Linear growth diffusion coefficient

Suppose that  $G$  satisfies conditions **(G1)** and **(G2)** and that  $\mathbb{E}(\|u_0\|^{2q}) < \infty$ . Then (2.11) implies

$$\begin{aligned} \mathbb{P} \left( (\Omega_N^{M(N)})^c \right) &\leq \mathbb{P} \left( \sup_{0 \leq s \leq T} \|\nabla u(s)\|_{\mathbb{L}^2}^2 > M(n) \right) \\ &\leq \left( \frac{1}{M(N)} \right)^{2q-1} \mathbb{E} \left( \sup_{0 \leq s \leq T} \|u(s)\|_V^{2q} \right) \leq C_q M(N)^{-2q-1}. \end{aligned} \quad (4.26)$$

If we suppose that  $\mathbb{E}(\|u_0\|_V^{2q}) < \infty$ , in order to balance the upper estimates (4.24), (4.25) with (4.26) and (4.7), we have to choose  $M(N) \rightarrow \infty$  as  $N \rightarrow \infty$ , such that as  $N \rightarrow \infty$ ,

$$\left( \frac{T}{N} \right)^\eta \exp[C_1(M(N))T] \asymp C(q)M(N)^{-2q-1+1}.$$

where  $C_1(M(N))$  is defined in (4.8). Fix  $\bar{\epsilon} > 0$ ; taking logarithms and neglecting constants leads to

$$-\eta \ln(N) + \frac{(1 + \bar{\epsilon})\bar{C}^2 M(N)T}{2\nu} \asymp -(2q-1) \ln(M(N)) + O(1) \quad \text{as } N \rightarrow \infty.$$

Let

$$M(N) := \frac{2\nu}{(1 + \bar{\epsilon})\bar{C}^2 T} \left\{ \eta \ln(N) - (2q-1) \ln(\ln(N)) \right\} \asymp \frac{2\nu\eta \ln(N)}{(1 + \bar{\epsilon})\bar{C}^2 T}. \quad (4.27)$$

Then, for this choice of  $M(N)$ , we have

$$-\eta \ln(N) + C_1(M(N))T = -\ln [(\ln(N))^{2q-1-1}] + O(1),$$

which implies  $\left( \frac{T}{N} \right)^\eta \exp[C_1(M(N))T] \asymp C(\ln(N))^{-2q-1+1}$  for some positive constant  $C$ .

Furthermore,  $M(N)^{-2q-1+1} \asymp C(\ln(N))^{-2q-1+1}$  for some positive constant  $C$ . Similar computations with sum of the  $V$  norms of the error on the time grid yield

$$\mathbb{E} \left( \max_{1 \leq k \leq N} \|e_k\|_{\mathbb{L}^2}^2 + \nu \frac{T}{N} \sum_{k=1}^N \|\nabla e_k\|_{\mathbb{L}^2}^2 \right) \leq C(\ln(N))^{-(2q-1-1)},$$

for some constant  $C$  depending on  $T$ ,  $q$  and the coefficients  $K_i$ ,  $i = 0, 1$ . This completes the proof of the following

**Theorem 4.4.** *Let  $u_0$  be such that  $\mathbb{E}(\|u_0\|_V^{2q}) < \infty$  for some  $q \geq 3$ ,  $G$  satisfy assumptions **(G1)** and **(G2)**. Then the fully implicit scheme  $u_N$  solution of (4.1) converges in  $L^2(\Omega)$  to the solution  $u$  of (1.1). More precisely, for  $N$  large enough we have*

$$\mathbb{E}\left(\max_{1 \leq k \leq N} \|u(t_k) - u_N(t_k)\|_{\mathbb{L}^2}^2 + \frac{T}{N} \sum_{k=1}^N |\nabla[u(t_k) - u_N(t_k)]|_{\mathbb{L}^2}^2\right) \leq C[\ln(N)]^{-(2^q-1-1)}. \quad (4.28)$$

**Remark 4.5.** *Note that, as for the splitting scheme, if  $u_0$  is a deterministic element of  $V$  and  $G$  satisfies the conditions **(G1)** and **(G2)**, we have*

$$\mathbb{E}\left(\max_{1 \leq k \leq N} \|u(t_k) - u_N(t_k)\|_{\mathbb{L}^2}^2 + \frac{T}{N} \sum_{k=1}^N |\nabla[u(t_k) - u_N(t_k)]|_{\mathbb{L}^2}^2\right) \leq C[\ln(N)]^{-\gamma}$$

for any  $\gamma > 0$ . This upper estimate is also true if  $\|u_0\|_V$  has moments of all orders, for example if  $u_0$  is a  $V$ -valued Gaussian random variable independent of the noise  $W$ .

**Case 2: Additive noise** Suppose that  $G(u) := G \in \mathcal{L}_2(K, V)$ , that is the noise is additive, or more generally that the conditions **(G1)** and **(G2)** are satisfied with  $K_1 = 0$ . Using an exponential Markov inequality, we deduce that for any constant  $\alpha > 0$

$$\mathbb{P}\left((\Omega_N^{M(N)})^c\right) \leq \exp(-\alpha M(N)) \mathbb{E}\left[\exp\left(\alpha \sup_{0 \leq t \leq T} |\nabla u(t)|_{\mathbb{L}^2}^2\right)\right]. \quad (4.29)$$

Recall that Lemma 3.8 implies that for  $\alpha \in (0, \alpha_0]$ , where  $\alpha_0 = \frac{\nu}{4K_0\bar{C}}$  and  $\tilde{C}$  is defined in (3.28), we have  $\mathbb{E}[\sup_{t \in [0, T]} \exp(\alpha \|u(t)\|_V^2)] < \infty$ . Using (4.7) with (4.8), (4.29) and (3.29), we choose  $M(N)$  such that

$$\left(\frac{T}{N}\right)^\eta \exp\left(\frac{(1+\bar{\epsilon})\bar{C}^2 M(N) T}{2} \nu\right) = c_2 \exp\left(-\frac{\nu M(N)}{p4K_0\tilde{C}}\right), \quad (4.30)$$

for some  $p > 1$ ,  $\bar{\epsilon} > 0$ , and some positive constant  $c_2$ , where  $\bar{C}$  (resp.  $\tilde{C}$ ) is defined by (2.2) (resp. (3.28)). For any  $p \in (1, \infty)$  since  $u_0$  is deterministic,  $\mathbb{E}(\|u_0\|_V^q) < \infty$  for conjugate exponents  $p$  and  $q$ . Set

$$M(N) := \frac{\eta \ln(N)}{\frac{\nu}{p4K_0\bar{C}} + \frac{(1+\bar{\epsilon})\bar{C}^2 T}{2\nu}}$$

for some  $\bar{\epsilon} > 0$ . Then  $M(N) \rightarrow \infty$  as  $n \rightarrow \infty$ , and both hand sides of (4.30) are equal to some constant multiple of  $N^{-\beta\eta}$ , where, choosing  $p$  close enough to 1 and  $\bar{\epsilon} \sim 0$ , we have  $\beta < \frac{\frac{\nu}{4K_0\bar{C}}}{\frac{\nu}{4K_0\bar{C}} + \frac{\bar{C}^2 T}{2\nu}}$ . Since  $\eta < \frac{1}{2}$  can be chosen as close to  $\frac{1}{2}$  as wanted, this yields the following rate of convergence.

**Theorem 4.6.** *Let  $u_0 \in V$ ,  $G$  satisfy assumptions **(G1)** and **(G2)** with  $K_1 = L_1 = 0$ . Let  $u$  denote the solution of (1.1) and  $u_N$  be the fully implicit scheme solution of (4.1). Then for  $N$  large enough,  $\bar{C}$  (resp.  $\tilde{C}$ ) defined by (2.2) (resp. (3.28)),*

$$\mathbb{E}\left(\max_{1 \leq k \leq N} \|u(t_k) - u_N(t_k)\|_{\mathbb{L}^2}^2 + \frac{T}{N} \sum_{k=1}^N |\nabla[u(t_k) - u_N(t_k)]|_{\mathbb{L}^2}^2\right) \leq C\left(\frac{T}{N}\right)^\gamma, \quad (4.31)$$

where  $\gamma < \frac{1}{2} \left( \frac{\frac{\nu}{4K_0\bar{C}}}{\frac{\nu}{4K_0\bar{C}} + \frac{\bar{C}^2 T}{2\nu}} \right)$ .

Note that if  $\nu$  is large, the speed of convergence of the  $H$  and  $V$  norms in Theorem 4.6 is "close" to  $C(T)N^{-\frac{1}{2}}$ . Intuitively, it cannot be better because of the stochastic integral and the scaling between the time and space parameters in the heat kernel, which is behind the time regularity of the solution stated in (4.3).

**4.4. Semi-implicit Euler scheme.** In this section, we prove the strong  $L^2(\Omega)$  convergence of a discretization scheme with a linearized drift. Let  $v_N$  be defined on the time grid  $(t_k, k = 0, \dots, N)$  as follows.

**Semi implicit Euler scheme** Let  $u_0$  be a  $V$ -valued  $\mathcal{F}_0$ -measurable random variable and set  $v_N(0) = u_0$ . For  $k = 1, \dots, N$ , let  $v_N(t) \in V$  be such that  $\mathbb{P}$  a.s. for all  $\phi \in V$ ,

$$\begin{aligned} (v_N(t_k) - v_N(t_{k-1}), \phi) + \frac{T}{N} \left[ \nu (\nabla v_N(t_k), \nabla \phi) + \langle B(v_N(t_{k-1}), v_N(t_k)), \phi \rangle \right] \\ = (G(v_N(t_{k-1})) \Delta_k W, \phi), \end{aligned} \quad (4.32)$$

where  $\Delta_k W = W(t_k) - W(t_{k-1})$ .

Note that since in general  $\langle B(u, v), Av \rangle \neq 0$  for  $u, v \in \text{Dom}(A)$ , the moments of  $v_N$  are bounded in a weaker norm than that of the fully implicit scheme  $u_N$ .

**Lemma 4.7.** *Let  $u_0 \in L^{2q}(\Omega, V)$  for some integer  $q \geq 2$  be  $\mathcal{F}_0$ -measurable and let  $G$  satisfy the condition **(G1)**. Then each random variable  $v_N(t_k)$ ,  $k = 0, \dots, N$  is  $\mathcal{F}_{t_k}$ -measurable such that*

$$\sup_N \mathbb{E} \left( \max_{1 \leq k \leq N} |v_N(t_k)|_{\mathbb{L}^2}^{2q} + \nu \frac{T}{N} \sum_{k=1}^N |v_N(t_k)|_{\mathbb{L}^2}^{2q-1} \|v_N(t_k)\|_V^2 \right) \leq C(T, q). \quad (4.33)$$

For  $k = 0, \dots, N$ , set  $\bar{e}_k = u(t_k) - v_N(t_k)$ . Unlike [9], we will not compare the schemes  $u_N$  and  $v_N$  since the norm of the difference would require a localization in terms of the gradient of  $u_N$ . Instead of that, we prove the following analog of Proposition 4.3.

**Proposition 4.8.** *Let  $G$  satisfy the growth and Lipschitz conditions **(G1)** and **(G2)**, and  $u_0$  be  $\mathcal{F}_0$ -measurable such that  $\mathbb{E}(\|u_0\|_V^8) < \infty$ . Then for  $\Omega_k^M$  defined by (4.6) and  $N$  large enough, we have for  $k = 1, \dots, N$  and  $\eta < \frac{1}{2}$*

$$\mathbb{E} \left( 1_{\Omega_{k-1}^M} \left[ \max_{1 \leq j \leq k} |\bar{e}_j|_{\mathbb{L}^2}^2 + \nu \frac{T}{N} \sum_{j=1}^k |\nabla \bar{e}_j|_{\mathbb{L}^2}^2 \right] \right) \leq C \left( \frac{T}{N} \right)^\eta \exp [C_1(M)T], \quad (4.34)$$

where  $C > 0$  is some constant and  $C_1(M)$  is defined by (4.8) for any  $\bar{\epsilon} > 0$ .

*Proof.* Many parts of the argument are similar to the corresponding ones in the proof of Proposition 4.3; we only focus on the differences.

We first consider the duality between the difference of bilinear terms and  $\bar{e}_j$ , that is upper estimate  $\int_{t_{j-1}}^{t_j} \langle B(u(s), u(s)) - B(v_N(t_{j-1}), v_N(t_j)), \bar{e}_j \rangle ds$ . For every  $s \in [t_{j-1}, t_j]$ , using the bilinearity and antisymmetry of  $B$  we deduce

$$\langle B(u(s), u(s)) - B(v_N(t_{j-1}), v_N(t_j)), \bar{e}_j \rangle = \sum_{i=1}^3 \bar{T}_i(s),$$

where

$$\begin{aligned} \bar{T}_1(s) &:= \langle B(\bar{e}_{j-1}, v_N(t_j)), \bar{e}_j \rangle = \langle B(\bar{e}_{j-1}, u(t_j)), \bar{e}_j \rangle, \\ \bar{T}_2(s) &:= \langle B(u(s) - u(t_{j-1}), u(t_j)), \bar{e}_j \rangle, \end{aligned}$$



$$\bar{T}_3(s) := \langle B(u(s), u(s) - u(t_j)), \bar{e}_j \rangle = -\langle B(u(s), \bar{e}_j), u(s) - u(t_j) \rangle.$$

Using the Hölder inequality, (2.2) and the Young inequality, we deduce that for every  $\delta_1 > 0$ ,

$$\begin{aligned} \int_{t_{j-1}}^{t_j} |\bar{T}_1(s)| ds &\leq \bar{C} \frac{T}{N} |\bar{e}_{j-1}|_{\mathbb{L}^2}^{\frac{1}{2}} |\bar{e}_j|_{\mathbb{L}^2}^{\frac{1}{2}} |\nabla \bar{e}_{j-1}|_{\mathbb{L}^2}^{\frac{1}{2}} |\nabla \bar{e}_j|_{\mathbb{L}^2}^{\frac{1}{2}} |\nabla u(t_j)|_{\mathbb{L}^2} \\ &\leq \frac{\delta_1}{2} \nu \frac{T}{N} |\nabla \bar{e}_{j-1}|_{\mathbb{L}^2}^2 + \frac{\delta_1}{2} \nu \frac{T}{N} |\nabla \bar{e}_j|_{\mathbb{L}^2}^2 \\ &\quad + \frac{\delta_1 \bar{C}^2}{8\delta_1 \nu} \frac{T}{N} |\bar{e}_{j-1}|_{\mathbb{L}^2}^2 |\nabla u(t_j)|_{\mathbb{L}^2}^2 + \frac{\delta_1 \bar{C}^2}{8\delta_1 \nu} \frac{T}{N} |\bar{e}_j|_{\mathbb{L}^2}^2 |\nabla u(t_j)|_{\mathbb{L}^2}^2. \end{aligned} \quad (4.35)$$

The upper estimates of  $\int_{t_{j-1}}^{t_j} \bar{T}_i(s) ds$ ,  $i = 2, 3$  are similar to the corresponding ones in the first step of the proof of Theorem 4.3. This yields the following analog of (4.11) with the same upper estimates (4.12) – (4.14) of the terms  $\tilde{T}_j(i)$ ,  $i = 1, 2, 3$

$$\begin{aligned} (\bar{e}_j - \bar{e}_{j-1}, \bar{e}_j) + \nu |\nabla \bar{e}_j|_{\mathbb{L}^2}^2 &\leq \nu(\delta_0 + \frac{1}{2}\delta_1 + \delta_2 + \delta_3) \frac{T}{N} |\nabla \bar{e}_j|_{\mathbb{L}^2}^2 + \frac{1}{2}\delta_1 \nu \frac{T}{N} |\nabla \bar{e}_{j-1}|_{\mathbb{L}^2}^2 \\ &\quad + \left( \gamma_2 + \frac{\bar{C}^2}{8\delta_1 \nu} |\nabla u(t_j)|_{\mathbb{L}^2}^2 \right) \frac{T}{N} |\bar{e}_j|_{\mathbb{L}^2}^2 + \frac{\bar{C}^2}{8\delta_1 \nu} |\nabla u(t_j)|_{\mathbb{L}^2}^2 |\bar{e}_{j-1}|_{\mathbb{L}^2}^2 \\ &\quad + \sum_{i=1}^3 \tilde{T}_j(i) + \left( \bar{e}_j, \int_{t_{j-1}}^{t_j} [G(u(s)) - G(v_N(t_{j-1}))] dW(s) \right). \end{aligned} \quad (4.36)$$

Once adding these estimates localized on the set  $\Omega_{t_{j-1}}^M$ , we deduce an upper estimate similar to (4.16) where  $e_j$  is replaced by  $\bar{e}_j$ . Following the same steps as in the proof of Proposition 4.3, we conclude the proof.  $\square$

The arguments in section 4.3 prove that the statements of Theorems 4.4 and 4.6 remain valid if we replace the solution  $u_N(t_k)$  of the fully implicit Euler scheme by the solution  $v_N(t_k)$  of the semi implicit one.

**4.5. Time dependent coefficients.** For the sake of simplicity, we have supposed that the diffusion coefficient  $G$  does not depend on time. An easy modification of the proofs of this section shows that the statements of Theorems 4.4, 4.6 for the fully or semi implicit Euler schemes remain true if we suppose that  $G : [0, T] \times V \rightarrow \mathcal{L}_2(K, H)$  (resp.  $G : [0, T] \times \text{Dom}(A) \rightarrow \mathcal{L}_2(K, V)$ ) satisfies the following global linear growth and Lipschitz conditions similar to those imposed in assumptions **(G1)** and **(G2)**

$$\begin{aligned} \|G(t, u)\|_{\mathcal{L}_2(K, H)}^2 &\leq K_0 + K_1 |u|_{\mathbb{L}^2}^2, \quad \|G(t, u)\|_{\mathcal{L}_2(K, V)}^2 \leq K_0 + K_1 \|u\|_V^2, \\ \|G(t, u) - G(t, v)\|_{\mathcal{L}_2(K, H)}^2 &\leq L_1 |u - v|_{\mathbb{L}^2}^2, \\ \|G(t, u) - G(t, v)\|_{\mathcal{L}_2(K, V)}^2 &\leq L_1 \|u - v\|_V^2, \end{aligned}$$

for  $u, v \in V$  (resp.  $u, v \in \text{Dom}(A)$ ). Furthermore, the diffusion coefficient  $G$  should also satisfy the following time regularity condition

**(G3)** There exists a constant  $C > 0$  such that for any  $u, v \in V$  and  $s, t \in [0, T]$ :

$$\|G(t, u) - G(s, u)\|_{\mathcal{L}_2(K, H)}^2 \leq C |t - s|^{\frac{1}{2}} (1 + \|u\|_{\mathbb{L}^2}^2).$$

In that case, the fully implicit scheme  $u_N$  (resp. semi implicit scheme  $v_N$ ) is defined replacing  $G(u_N(t_{k-1}))$  by  $G(t_{k-1}, u_N(t_{k-1}))$  (resp. by  $G(t_{k-1}, v_N(t_{k-1}))$ ) on the right hand side of (4.1).

## 5. APPENDIX

In this section we prove two technical lemmas used to obtain the strong convergence results.

**5.1. Proof of Lemma 3.5.** First note that using (3.4) and (3.7), we deduce that if  $\mathbb{E}(\|u_0\|_V^{2p}) < \infty$  then

$$\sup_{N \geq 1} \mathbb{E} \int_0^T \|z^N(s)\|_V^{2p} dt \leq C(p).$$

Thus only moments of  $\sup_{t \in [0, T]} |z^N(t)|_{\mathbb{L}^2}^{2p}$  have to be dealt with.

The process  $z^N$  defined by (3.6) is not regular enough to apply directly Itô's formula to  $|z^N(t)|_{\mathbb{L}^2}^{2p}$ . Hence, as in the proof of Proposition 3.4, we need to apply Itô's formula on the smooth Galerkin approximations of the processes  $u^N$ ,  $y^N$  and  $z^N$ , and then pass to the limit. This yields for every  $t \in [0, T]$

$$\begin{aligned} |z^N(t)|_{\mathbb{L}^2}^2 &= |u_0|_{\mathbb{L}^2}^2 - 2 \int_0^t \langle F(u^N(s)), z^N(s) \rangle ds + \int_0^t \|G(y^N(s))\|_{\mathcal{L}_2(K, H)}^2 ds \\ &\quad + 2 \int_0^t (z^N(s), G(y^N(s)) dW(s)). \end{aligned}$$

Using once more the Itô formula, we deduce

$$|z^N(t)|_{\mathbb{L}^2}^{2p} = |u_0|_{\mathbb{L}^2}^{2p} + I(t) + \sum_{i=1}^3 J_i(t), \quad (5.1)$$

where

$$\begin{aligned} I(t) &= 2p \int_0^t (z^N(s), G(y^N(s)) dW(s)) |z^N(s)|_{\mathbb{L}^2}^{2(p-1)}, \\ J_1(t) &= -2p\nu \int_0^t |z^N(s)|_{\mathbb{L}^2}^{2(p-1)} (\nabla u^N(s), \nabla z^N(s)) ds \\ J_2(t) &= -2p \int_0^t |z^N(s)|_{\mathbb{L}^2}^{2(p-1)} \langle B(u^N(s), u^N(s)), z^N(s) \rangle ds \\ J_3(t) &= +p \int_0^t |z^N(s)|_{\mathbb{L}^2}^{2(p-1)} \|G(y^N(s))\|_{\mathcal{L}_2(K, H)}^2 ds \\ &\quad + 2p(p-1) \int_0^t \|G^*(y^N(s))z^N(s)\|_K^2 |z^N(s)|_{\mathbb{L}^2}^{2(p-2)} ds. \end{aligned}$$

The Hölder and Young inequalities imply

$$|J_1(t)| \leq 2(p-1)\nu \int_0^t |z^N(s)|_{\mathbb{L}^2}^{2p} ds + \nu \int_0^t [|\nabla z^N(s)|_{\mathbb{L}^2}^{2p} + |\nabla u^N(s)|_{\mathbb{L}^2}^{2p}] ds$$

Using again the Hölder and Young inequalities with exponents  $\frac{2p+1}{2p-1}$  and  $\frac{2p+1}{2}$ , we deduce

$$\begin{aligned} |J_2(t)| &\leq 2p \int_0^t |z^N(s)|_{\mathbb{L}^2}^{2(p-1)} |\nabla z^N(s)|_{\mathbb{L}^2} \|u^N(s)\|_X^2 ds \\ &\leq \frac{(2p-1)2p}{2p+1} \int_0^t \|z^N(s)\|_V^{2p+1} ds + \frac{4p}{2p+1} \left(\frac{\bar{C}}{2}\right)^{\frac{2p+1}{2}} \int_0^t \|u^N(s)\|_V^{2p+1} ds, \end{aligned}$$

where  $\bar{C}$  is the constant defined in (2.2). Finally, using the growth condition **(G1)**, we deduce

$$\begin{aligned} |J_3(t)| &\leq (2p^2 - p) \int_0^t |z^N(s)|_{\mathbb{L}^2}^{2(p-1)} [K_0 + K_1 |y^N(s)|_{\mathbb{L}^2}^2] ds \\ &\leq (2p-1)(p-1) \int_0^t |z^N(s)|_{\mathbb{L}^2}^{2p} ds + C(p) K_1^p \int_0^t \|y^N(s)\|_{\mathbb{L}^2}^{2p} ds + C(p) K_0 T. \end{aligned}$$

where  $C(p)$  is a constant depending on  $p$ . The inequalities (3.4) and (3.7), and the above estimates of  $J_i(t)$  for  $i = 1, 2, 3$ , imply the existence of a positive constant  $C(p)$  depending on  $p$  such that for every integer  $N \geq 1$ ,

$$\sum_{i=1}^3 \mathbb{E} \left( \sup_{t \in [0, T]} |J_i(t)| \right) \leq C(p). \quad (5.2)$$

Furthermore, the Burkholder-Davies-Gundy inequality, the growth condition in **(G1)** and the Young inequality imply

$$\begin{aligned} \mathbb{E} \left( \sup_{t \in [0, T]} |I(s)| \right) &\leq 6p \mathbb{E} \left( \left\{ \int_0^T |z^N(s)|_{\mathbb{L}^2}^{4p-2} \|G(y^N(s))\|_{\mathcal{L}_2(K, H)}^2 ds \right\}^{\frac{1}{2}} \right) \\ &\leq \frac{1}{2} \mathbb{E} \left( \sup_{t \in [0, T]} |z^N(t)|_{\mathbb{L}^2}^{2p} \right) + C(p) \mathbb{E} \int_0^T [K_0^p + K_1^p |y^N(s)|_{\mathbb{L}^2}^{2p}] ds \\ &\leq \frac{1}{2} \mathbb{E} \left( \sup_{t \in [0, T]} |z^N(t)|_{\mathbb{L}^2}^{2p} \right) + C(p), \end{aligned} \quad (5.3)$$

where the last inequality is deduced from (3.4).

The upper estimates (5.1)–(5.3), (2.11), (3.4) and (3.7) conclude the proof.  $\square$

**5.2. Proof of Lemma 3.8.** We prove the existence of exponential moments for the square of the  $V$  norm of the solution  $u$  of (1.1).

*Proof of Lemma 3.8.* Let  $\alpha > 0$ ; we apply the Itô formula to the square of the  $V$  norm of the process  $u$  solution of (1.1). As explained in the proofs of Proposition 3.4 and of the previous Lemma, the Itô formula has to be performed on smooth processes, for example a Galerkin or a Yosida approximation of  $u$ , and then pass to the limit or use computations similar to those in [10], step 4 of the Appendix on page 416. This yields

$$\begin{aligned} \alpha \|u(t)\|_V^2 + \alpha \nu \int_0^t \| |u(s)| \|^2 ds &= \alpha \|u_0\|_V^2 + \alpha \int_0^t \|G(s, u(s))\|_{\mathcal{L}_2(K, V)}^2 ds \\ &\quad + 2\alpha \int_0^t (u(s), G(s, u(s)) dW(s))_V - \alpha \nu \int_0^t \| |u(s)| \|^2 ds, \end{aligned} \quad (5.4)$$

where for  $u, v \in V$  we set  $(u, v)_V = (u, v) + (\nabla u, \nabla v)$  and recall that  $\| |u| \|^2 := |\nabla u|_{\mathbb{L}^2}^2 + |Au|_{\mathbb{L}^2}^2$ .

Let  $M(t) := 2\alpha \int_0^t (u(s), G(s, u(s)) dW(s))_V$ ; then  $M$  is a martingale with quadratic variation

$$\begin{aligned} \langle M \rangle_t &\leq 4\alpha^2 \int_0^t \|u(s)\|_V^2 \|G(s, u(s))\|_{\mathcal{L}_2(K, V)}^2 ds \leq 4\alpha^2 K_0 \int_0^t \|u(s)\|_V^2 ds, \\ &\leq 4\alpha^2 K_0 \tilde{C} \int_0^t \| |u(s)| \|^2 ds, \end{aligned}$$

where the last inequality follows from (2.9) and the definition of  $\tilde{C}$  in (3.28).

Let  $\alpha_0 := \frac{\nu}{4K_0C}$ ; then we deduce

$$M_t - \alpha\nu \int_0^t |||u(s)|||^2 ds \leq M_t - \frac{\alpha_0}{\alpha} \langle M \rangle_t.$$

Therefore, using the previous inequality and classical exponential martingale arguments, we deduce

$$\begin{aligned} \mathbb{P} \left[ \sup_{0 \leq t \leq T} \left( M_t - \alpha\nu \int_0^t |||u(s)|||^2 ds \right) \geq K \right] &\leq \mathbb{P} \left[ \sup_{0 \leq t \leq T} \left( M_t - \frac{\alpha_0}{\alpha} \langle M \rangle_t \right) \geq K \right] \\ &\leq \mathbb{P} \left[ \sup_{0 \leq t \leq T} \exp \left( \frac{2\alpha_0}{\alpha} M_t - \frac{1}{2} \left\langle \frac{2\alpha_0}{\alpha} M \right\rangle_t \right) \geq \exp \left( \frac{2\alpha_0}{\alpha} K \right) \right] \\ &\leq \exp \left( -\frac{2\alpha_0}{\alpha} K \right) \mathbb{E} \left[ \exp \left( \frac{2\alpha_0}{\alpha} M_T - \frac{1}{2} \left\langle \frac{2\alpha_0}{\alpha} M \right\rangle_T \right) \right] \leq \exp \left( -\frac{2\alpha_0}{\alpha} K \right) \end{aligned}$$

for any  $K > 0$ . Set

$$X = \exp \left( \alpha \left\{ \sup_{t \in [0, T]} 2 \int_0^t (u(s), G(s, u(s)))_V - \nu \int_0^t |||u(s)|||^2 ds \right\} \right);$$

then for  $\alpha \in (0, \alpha_0]$ , we deduce that  $\mathbb{P}(X \geq e^K) \leq \exp(-K \frac{2\alpha_0}{\alpha}) \leq e^{-2K} = (e^{-K})^2$  for any  $K > 0$ .

Using this inequality for any  $C = e^K > 1$  with  $K > 0$ , we deduce  $\mathbb{E}(X) \leq 2 + \int_0^\infty \mathbb{P}(X \geq C) dC \leq 3$ . Since (5.4) implies

$$\begin{aligned} \alpha \left( \sup_{t \in [0, T]} \left[ \|u(t)\|_V^2 + \nu \int_0^t |||u(s)|||^2 ds \right] \right) &\leq \alpha \|u_0\|_V^2 + \alpha K_0 T \\ &+ \sup_{t \in [0, T]} \left( \alpha \left\{ 2 \int_0^t (u(s), G(s, u(s)))_V - \nu \int_0^t |||u(s)|||^2 ds \right\} \right), \end{aligned}$$

we conclude the proof of (3.29).  $\square$

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