

Ergodicity and mixing for locally monotone stochastic evolution equations

JONAS TÖLLE

(Aalto University, Finland)

joint work with GERARDO BARRERA (IST Lisboa, Portugal)

arXiv:2412.01381

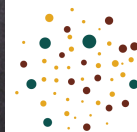
Probability and Stochastic Analysis Seminar

Bernoulli Center, EPFL, Switzerland

15. October 2025



**Funded by
the European Union**



Stochastic Interacting Systems:
Limiting Behavior, Evaluation,
Regularity and Applications

LiBERA

Table of contents

- 1 Motivation
- 2 Invariant measures
- 3 Main result
- 4 Sketch of the proof

Bibliography

Consider the stochastic incompressible 2D Navier-Stokes equations (NSE) with additive Wiener noise on a Lipschitz domain of finite width¹ $\mathcal{O} \subset \mathbb{R}^2$, viscosity $\nu > 0$,

$$dX_t = [\nu \Delta X_t + (X_t \cdot \nabla) X_t] dt + B dW_t, \quad t > 0,$$

$$\nabla \cdot X_t = 0, \quad t \geq 0,$$

$$X_0 = x \in L^2_{\text{sol}}(\mathcal{O}; \mathbb{R}^2) =: H,$$

with no-slip boundary condition $X_t = 0$ on $\partial\mathcal{O}$. Alternatively, $\mathcal{O} = \mathbb{T}^2$, $\int_{\mathbb{T}^2} X_t dz = 0$

By the spectral Galerkin method, if $B \in \text{HS}(U, H)$ and if $\{W_t\}_{t \geq 0}$ is a cylindrical Wiener noise modelled on a separable Hilbert space U , there exists a unique adapted Markovian strong solution

$$X^x \in L^2([0, T] \times \Omega; H^1_{\text{sol}, 0}(\mathcal{O}; \mathbb{R}^2)).$$

1. That is, $\mathcal{O}$ fits between two parallel lines. Possibly unbounded, but satisfies a Poincaré inequality.

The 2D NSE is an example of a *locally monotone drift SPDE*.

$$dX_t = A(X_t) dt + B dW_t, \quad t \geq 0.$$

Let $V \subset H \equiv H^* \subset V^*$ be a Gelfand triple.

V separable, reflexive Banach space, H separable Hilbert space.

$A: V \rightarrow V^*$ is called *monotone* if there exists $K \in \mathbb{R}$,

$$\langle A(u) - A(v), u - v \rangle \leq K \|u - v\|_H^2, \quad u, v \in V.$$

If $H = V = \mathbb{R}$, $f: \mathbb{R} \rightarrow \mathbb{R}$ is monotone **iff** $x \mapsto f(x) - Kx$ is non-increasing.

A is called *locally monotone* in V if there exists $\rho: V \rightarrow \mathbb{R}$, locally bounded and measurable, and $K \in \mathbb{R}$, such that

$$\langle A(u) - A(v), u - v \rangle \leq (K + \rho(u)) \|u - v\|_H^2, \quad u, v \in H.$$

Further examples of locally monotone drift SPDEs

- Stochastic power-law fluid equations
- Stochastic Allen-Cahn equation
- Stochastic Burgers equation

Non-monotone perturbations of monotone drift SPDEs

- Stochastic p -Laplace equation + perturbation
- Stochastic porous medium-type equations + perturbation

(not covered by our ergodicity result)

Further examples of locally monotone drift SPDEs

- Stochastic power-law fluid equations on a domain of finite width $\mathcal{O} \subset \mathbb{R}^d$, $p \in (1, \infty)$,

$$dX_t = [\nabla \cdot S(e(X_t)) + (X_t \cdot \nabla) X_t] dt + B dW_t, \quad t > 0,$$

$$\nabla \cdot X_t = 0, \quad t \geq 0,$$

$$X_0 = x \in L^2_{\text{sol}}(\mathcal{O}; \mathbb{R}^d),$$

where

$$e(u)_{i,j} := \frac{1}{2}(\partial_i u_j + \partial_j u_i),$$

and

$$S(z) := 2\nu(1 + |z|)^{p-2}z.$$

Further examples of locally monotone drift SPDEs

- Stochastic power-law fluid equations on $\mathcal{O} \subset \mathbb{R}^d$, $p \in (1, \infty)$, $d = 2, 3$.

$$p > 2$$

dilatant, or shear-thickening
oobleck

(mixture of water and corn-starch)

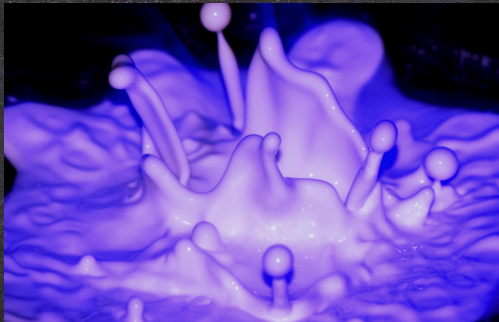


Image source: Rachel Grosskrueger (CU Boulder)

$$p < 2$$

pseudoplastic, or shear-thinning
hair gel, blood, whipped cream

(polymeric molecules)



Image source: Shutterstock

$$p = 2$$

Newtonian, Navier-Stokes equations
Examples: water, glycerol, ethanol

viscous stress $\propto$ local strain rate



Image source: TROUT55/Getty Images

Further examples of locally monotone drift SPDEs

- Stochastic Allen-Cahn equation on $\mathcal{O} \subset \mathbb{R}^d$, $d = 1, 2, 3$.

$$dX_t = [\nu \Delta X_t + g(X_t)] dt + B dW_t, \quad t > 0,$$

$$X_0 = x \in L^2(\mathcal{O}).$$

Typically, $g(z) = z - z^3$.

- Stochastic Burgers equation on $\mathcal{O} \subset \mathbb{R}^d$, $d = 1, 2, 3$.

$$dX_t = [\nu \Delta X_t + \langle \mathbf{f}(X_t), \nabla X_t \rangle] dt + B dW_t, \quad t > 0,$$

$$X_0 = x \in L^2(\mathcal{O}).$$

1D stochastic Burgers, $d = 1$, $\mathbf{f}(z) = z$.

Existence and uniqueness of solutions to the examples for any finite time horizon $T > 0$ have been discussed in Liu, Röckner [LR10].

What about $T \rightarrow \infty$?

Replacing the noise $B dW$ by a deterministic forcing $f \in L^2_{\text{sol}}$, the 2D NSE with no-slip boundary condition is known to have **exponential convergence** to the stationary solution [Tem01], when **the viscosity is large enough** relative to constants depending only on the **domain**, the **first eigenvalue** of the Stokes operator, and the L^2_{sol} -norm of the **deterministic forcing** f .

Without forcing, the solution has **exponential decay** to zero.

What about the stochastic case?

Set $P_t F(x) := \mathbb{E}[F(X_t^x)]$, $t \geq 0$, $F \in \mathcal{B}_b(H)$, $x \in H$ and define P_t^* by duality

$$\langle P_t^* \mu, F \rangle = \langle P_t F, \mu \rangle, \quad t \geq 0, \quad \mu \in \mathcal{M}_1(H), \quad F \in C_b(H).$$

Definition 1. A probability measure $\mu \in \mathcal{M}_1(H)$ is said to be invariant for $\{P_t\}$ if $P_t^* \mu = \mu$ for every $t \geq 0$.

$\{P_t\}_{t \geq 0}$ is called Feller if $P_t(C_b(H)) \subset C_b(H)$ for every $t \geq 0$.

$\{P_t\}$ is called weak* mean ergodic if for some invariant measure μ ,

$$\frac{1}{T} \int_0^T P_t^* \nu dt \rightharpoonup \mu, \quad \text{as } T \rightarrow \infty$$

for every $\nu \in \mathcal{M}_1(H)$ which is equivalent to the uniqueness of μ .

Proposition 2. (Krylov-Bogoliubov).

If for a Feller semigroup $\{P_t\}$ and some $x \in H$, $t_n \nearrow \infty$, $\mu \in \mathcal{M}_1(H)$,

$$\frac{1}{t_n} \int_0^{t_n} \text{Law}(X_s^x) ds \rightharpoonup \mu \quad \text{as } n \rightarrow \infty$$

then μ is an invariant measure for $\{P_t\}$.

Remark 3. This method can be used to prove that the stochastic 2D NSE with additive Gaussian forcing admits an invariant measure by standard a priori estimates.

Definition 4. A Feller semigroup $\{P_t\}$ is said to have the strong Feller property if

$$P_t(\mathcal{B}_b(H)) \subset C_b(H) \quad \text{for every } t > 0.$$

A Feller semigroup $\{P_t\}$ is said to be *irreducible* if for every $t > 0$ and for every $x \in H$ and for every non-empty open set $O \subset H$,

$$P_t \mathbb{1}_O(x) > 0.$$

Theorem 5. If $\{P_t\}$ is strong Feller and irreducible, it admits a unique invariant measure μ such that for every $x \in H$

$$\|P_t^* \delta_x - \mu\|_{\text{TV}} \rightarrow 0 \quad \text{as } t \rightarrow \infty.$$

- In 1995, Flandoli and Maslowski [FM95] proved the strong Feller property and irreducibility of the stochastic 2D NSE with non-degenerate Gaussian noise.
- In 2001–2002, the (exponential) ergodicity of the stochastic 2D NSE with either non-degenerate forcing or large viscosity ν was proved by Bricmont, Kupiainen, and Lefevere [BKL02]; E, Mattingly, and Sinai [EMS01]; Kuksin and Shirikyan [KS01]; Mattingly [Mat02]; ...
- In 2002, the general well-posedness theory for the stochastic 2D NSE was discussed by Menaldi and Sritharan [MS02].
- In 2006, Hairer and Mattingly [HM06] provided a minimal non-degeneracy condition of the noise for the *asymptotic strong Feller property* and *weak irreducibility* with a minimal number of four forced modes.
- **And many others ...**

Recently, there has been a lot of progress for multiplicative noise, Lévy noise, pure jump noise, and coupling techniques.

Denote by P_n the Galerkin projection on the first n Fourier modes. If the noise coefficient B is *mildly degenerate*, that is, $B \in \text{HS}(H)$ and for every $\nu > 0$, there exists $N = N(\nu, \|B\|_{\text{HS}(H)})$ such that, if

$$\text{Rg}(B) \supset P_n(H),$$

for some $n \geq N$, then the stochastic 2D NSE admits a unique invariant measure, and the *Foias-Prodi estimate* holds in the stochastic case for some $C = C(x, y, B, \mathcal{O}, \nu) > 0$, and $\delta = \delta(B, \mathcal{O}, \nu) > 0$ such that

$$\mathbb{E}[\|X_t^x - X_t^y\|_H^2] \leq Ce^{-\delta t}$$

see Glatt-Holtz, Mattingly, Richards [GMR17]. Thus, we get exponential mixing. The estimates rely on the properties of the **exponential martingale**.

Definition 6. A Feller semigroup $\{P_t\}$ is said to satisfy the e -property if for every $\varphi \in \text{Lip}_b(H)$, for every $x \in H$, for every $\varepsilon > 0$, there exists $\delta > 0$ such that

$$|P_t\varphi(x) - P_t\varphi(y)| < \varepsilon$$

for every $t \geq 0$ and for every $y \in H$ with $\|x - y\| < \delta$.

This type of uniform equicontinuity for bounded Lipschitz functions could be viewed a **coupling condition at infinity**.

It has been conjectured by Szarek and Worm [SW12] that

“It seems that all known examples of Markov processes with the asymptotic strong Feller property satisfy the e -property as well.”

Jaroszewska constructed a counter-example in 2013 in an unpublished preprint.

Originally developed by Lasota and Szarek [LS06], the “lower bound technique” can be described as follows in the work of Komorowski, Peszat and Szarek [KPS10].

Theorem 7. *Assume that $\{P_t\}$ is Feller and has the e -property. Assume that there exists $z \in H$ such that for every bounded set $J \subset H$ and every $\delta > 0$*

$$\inf_{x \in J} \liminf_{T \rightarrow \infty} \frac{1}{T} \int_0^T P_t \mathbb{1}_{B(z, \delta)}(x) dt > 0.$$

Suppose further that for every $\varepsilon > 0$ and every $x \in H$ there exists a bounded Borel set $K \subset H$ such that

$$\liminf_{T \rightarrow \infty} \frac{1}{T} \int_0^T P_t \mathbb{1}_K(x) dt > 1 - \varepsilon.$$

Then there exists a unique invariant probability measure μ for $\{P_t\}$, and $\{P_t\}$ is weak mean ergodic.*

The following conditions (more generally for couplings) have been inspired by Butkovsky, Kulik and Scheutzow [BKS20] (adapted to our situation). For a lower semi-continuous function $U: H \rightarrow [0, \infty)$ and a measurable function $S: H \rightarrow [0, \infty]$,

$$\|X_t^x - X_t^y\|_H^2 \leq \|x - y\|_H^2 \exp\left(-\zeta t + \kappa \int_0^t S(X_s^x) ds\right), \quad t \geq 0,$$

$$U(X_t^x) + \mu \int_0^t S(X_s^x) ds \leq U(x) + bt + M_t, \quad t \geq 0,$$

where $\mu > 0$ and $b \geq 0$, such that

$$\zeta > \frac{\kappa b}{\mu},$$

and M is a continuous local martingale with $M_0 = 0$ and for $b_1, b_2 \geq 0$,

$$d\langle M \rangle_t \leq b_1 S(X_t^x) dt + b_2 dt, \quad t \geq 0.$$

Consider

$$(1) \quad dX_t = A(X_t) dt + B dW_t, \quad t > 0, \quad X_0 = x_0,$$

where $\{BW_t\}$ is as before, i.e., $\{W_t\}$ is a **cylindrical Wiener process** on a separable Hilbert space U and $B \in \text{HS}(U, H)$.

The drift $A: V \rightarrow V^*$ is *hemicontinuous* (i.e., weakly continuous along rays) and for $\alpha \geq 2$, $\delta_1 > 0$, $u \in V$,

$$2\langle A(u), u \rangle \leq -\delta_1 \|u\|_V^\alpha \quad (\text{coercivity})$$

and for $\delta_2 > 0$, $C_2 \geq 0$, $u, v \in V$,

$$2\langle A(u) - A(v), u - v \rangle \leq (-\delta_2 + \rho(u)) \|u - v\|_H^2, \quad (\text{local monotonicity})$$

where for $\beta \geq 0$

$$0 \leq \rho(u) \leq C_2 \|u\|_V^\alpha \|u\|_H^\beta \quad u \in V.$$

Moreover, for $K > 0$, $u \in V$,

$$\|A(u)\|_{V^*}^{\frac{\alpha}{\alpha-1}} \leq K(1 + \|u\|_V^\alpha)(1 + \|u\|_H^\beta) \quad (\text{boundedness}).$$

Liu and Röckner (for Wiener noise) [LR10] and Brzezniak, Liu, and Zhu (for Lévy noise) [BLZ14] proved the following.

Theorem 8. *Under the previous hypotheses, for every initial datum*

$$x_0 \in L^{\beta+2}(\Omega, \mathcal{F}_0, \mathbb{P}; H)$$

there exists a unique continuous strong adapted solution $\{X_t\}$ with

$$X \in L^\alpha([0, T]; V) \cap L^2([0, T]; H) \quad \mathbb{P}\text{-a.s.}$$

such that every progressively measurable V -valued version of X satisfies (1) $\mathbb{P}$ -a.s.

Note that our assumptions are intentionally not the most general ones, and exclude e.g. the stochastic p -Laplace equation, $p \neq 2$, or time-dependent drift.

Assume also that there exist $\delta_4 > 0$ and $C_4 \in \mathbb{R}$ such that for all $u \in V$,

$$2\langle A(u), u \rangle \leq C_4 - \delta_4 \|A(u)\|_{V^*} \quad (\text{cone condition}).$$

Remark 9. This condition is satisfied for the 2D NSE and the power law fluid equations. Unfortunately, it is quite restrictive for *semilinear equations* with drift $A = A_0 + F$ because it forces the nonlinear perturbation F of the dissipative principal term A_0 to have **at most quadratic growth**.

For this reason, our result does not cover stochastic Allen-Cahn equations with cubic nonlinearity.

Assume that the noise is spatially regular: $B \in \text{HS}(U, V)$ (if V is a Hilbert space, otherwise assume a small ball property in V).

To control the exponential martingale, we need to assume that

$$\alpha \geq 2, \quad 0 \leq \beta \leq \alpha - 2,$$

and a relation between $\|B\|_{\text{HS}(U, H)}^2 \geq 0$, $\delta_1, \delta_2 > 0$, $C_2 \geq 0$, and $c_0 > 0$ such that

$$\|v\|_V \geq c_0 \|v\|_H, \quad v \in V,$$

as follows: If $\beta = 0$, $\alpha = 2$, we assume that there exists $\gamma \in [0, \delta_2]$

$$\|B\|_{\text{HS}(U, H)}^2 \leq \frac{\delta_1}{C_2} (\delta_2 - \gamma) \wedge \frac{1}{4} \delta_1 c_0^2$$

If $\alpha > 2$, or $\beta > 0$, we assume an additional condition of similar type.

For the **2D NSE**, we have that $\alpha = 2$, $\beta = 0$, $\delta_1 = 2\nu$, $\delta_2 = \nu c_0^2$, $C_2 = \frac{4}{\nu}$,

see [BKS20]. Here, c_0 is the inverse of the Poincaré constant of the domain $\mathcal{O} \subset \mathbb{R}^2$. Note that in [BKS20], it is assumed also that there exists $n \in \mathbb{N}$ with

$$\text{Rg}(B) \supset P_n(H),$$

which we do not have to assume here.

For the **1D Burgers equation**, we have that there exists $\varepsilon \in (0, 2\nu c_0^2)$, and $C = C(\varepsilon, c_0, \mathcal{O}) > 0$, such that:

$$\alpha = 2, \beta = 0, \delta_1 = 2\nu, \delta_2 = 2\nu c_0^2 - \varepsilon, C_2 = C.$$

Certainly, the **stochastic heat equation** is also covered with:

$$\alpha = 2, \beta = 0, \delta_1 = 2\nu, \delta_2 = 2\nu c_0^2, C_2 = 0.$$

Theorem 10. (Barrera, T., 2025+) Under the previous hypotheses, the semi-group associated to (1) is Markovian and Feller, and satisfies the e -property and is weak* mean ergodic. The unique invariant probability measure μ on $(H, \mathcal{B}(H))$ admits finite $(\alpha + \beta)$ -moments in H . If $\beta = 0$, μ admits α -moments in V .

The existence and uniqueness of μ is proved by the e -property and the lower-bound technique.

Let $\tau^x(\varepsilon) := \inf \{t \geq 0 : \mathcal{W}_2(\text{Law}(X_t^x), \mu) \leq \varepsilon\}$ be the **Markovian mixing time** with prescribed error $\varepsilon > 0$, here $\mathcal{W}_2$ denotes the Wasserstein-2-distance.

Theorem 11. (Barrera, T., 2025+) Under the previous hypotheses, if $\gamma > 0$, there exists a constant $K \geq 0$, such that we obtain the following upper bound:

$$\tau^x(\varepsilon) \leq \frac{2}{\gamma} \left[\frac{C_2 \|x\|_H^{\beta+2}}{4\delta_1(\beta+2)} + \log \left(\|x\|_H + \left(\frac{K}{2c_0^\alpha \delta_1(\beta+2)} \right)^{1/(\alpha+\beta)} \right) + \log \left(\frac{1}{\varepsilon} \right) \right].$$

Theorem 12. (Barrera, T., 2025+) Assume that there exists $\gamma \in (0, \nu c_0^2]$, such that

$$\|B\|_{\text{HS}(U, H)}^2 \leq \frac{1}{8} \nu^2 (\nu c_0^2 - \gamma) \wedge \frac{1}{2} \nu c_0^2,$$

then we obtain the following upper bound for the ε -mixing time

$$\tau^x(\varepsilon) \leq \frac{2}{\gamma} \left[\frac{2\|x\|_H^2}{\nu^2} + \log \left(\|x\|_H + \frac{\|B\|_{\text{HS}(U, H)}}{\sqrt{\nu} c_0} \right) + \log \left(\frac{1}{\varepsilon} \right) \right]$$

for the stochastic 2D Navier-Stokes equations.

We first need to verify the e -property.

By a Galerkin approximation and Itô's lemma, we obtain the following pathwise a priori estimate for some constant $C > 0$, not depending on $T > 0$,

$$\begin{aligned} \|X_t^x\|_H^{\beta+2} + \delta_1 \frac{\beta+2}{4} \int_0^T \|X_t\|_V^\alpha \|X_t\|_H^\beta dt \\ \leq \|x\|^{\beta+2} + CT + M_T, \end{aligned}$$

where $t \mapsto M_t$ is a local martingale with $M_0 = 0$. The absolutely continuous terms on the RHS have been compensated with the 2nd term on the LHS by our hypotheses and Young's inequality.

For the 2D NSE, these types of estimates are well-known. In particular, applied for $\beta = 0$, we obtain the existence of at least one invariant measure by the Krylov-Bogoliubov theorem whenever the Sobolev embedding $V \subset H$ is compact.

Recall:

Definition 13. A Feller semigroup $\{P_t\}$ is said to satisfy the e -property if for every $\varphi \in \text{Lip}_b(H)$, for every $x \in H$, for every $\varepsilon > 0$, there exists $\delta > 0$ such that

$$|P_t\varphi(x) - P_t\varphi(y)| < \varepsilon$$

for every $t \geq 0$ and for every $y \in H$ with $\|x - y\| < \delta$.

$$|P_t\varphi(x) - P_t\varphi(y)| \leq \|\varphi\|_{\text{Lip}}^2 \mathbb{E}[\|X_t^x - X_t^y\|_H^2]$$

Note that if A is monotone, we get that

$$\mathbb{E}[\|X_t^x - X_t^y\|_H^2] = \|x - y\|_H^2 + 2\mathbb{E} \int_0^t \langle A(X_s^x) - A(X_s^y), X_s^x - X_s^y \rangle ds \leq \|x - y\|_H^2.$$

Note that because we have additive noise, for $0 < \gamma < \delta_2$, by local monotonicity,

$$\begin{aligned} & \frac{d}{dt} \|X_t^x - X_t^y\|_H^2 \\ & \leq \|X_t^x - X_t^y\|_H^2 (-\delta_2 + C_2 \|X_t^x\|_V^\alpha \|X_t^x\|_H^\beta), \quad t > 0. \end{aligned}$$

Hence by Gronwall's lemma,

$$\begin{aligned} & \mathbb{E} \|X_T^x - X_T^y\|_H^2 \\ & \leq \|x - y\|_H^2 \mathbb{E} \left[\exp \left(-\delta_2 T + C_2 \int_0^T \|X_t^x\|_V^\alpha \|X_t^x\|_H^\beta dt \right) \right], \quad T \geq 0. \end{aligned}$$

We are left with controlling the exponential moments, which is not obvious.

By our assumption $\alpha \geq \beta - 2$, we can even obtain for another constant $\tilde{C} > 0$,

$$\begin{aligned} & \|X_t^x\|_H^{\beta+2} + \delta_1 \frac{\beta+2}{4} \int_0^T \|X_t\|_V^\alpha \|X_t\|_H^\beta dt \\ & \leq \|x\|^{\beta+2} + \tilde{C}T + M_T - \frac{1}{2} \langle M \rangle_T. \end{aligned}$$

Now,

$$\mathbb{E} \left[\exp \left(M_T - \frac{1}{2} \langle M \rangle_T \right) \right] = 1.$$

Hence, for the e -property, we just need

$$\delta_2 \geq \frac{4C_2}{\delta_1(\beta+2)} \tilde{C},$$

which follows from our hypotheses.

Consider the deterministic counterpart to (1),

$$du_t^x = A(u_t^x)dt, \quad t > 0, \quad u_0^x = x,$$

and note that by coercivity, for every $R > 0$,

$$\lim_{t \rightarrow \infty} \sup_{\|x\|_H \leq R} \|u_t^x\|_H = 0.$$

Let us prove that for any $T > 0$, for any $\varepsilon > 0$, and any $K \subset H$ bounded, we have

$$\mathbb{P}(\|X_T^x - u_T^x\|_H^2 < \varepsilon) > 0,$$

uniformly for $x \in K$.

To prove this **stochastic stability** for finite times with positive probability, we use a pathwise argument to estimate $\|Y_t^x - u_t^x\|_H^2$, where $Y_t^x := X_t^x - BW_t$ is the solution to the random PDE

$$dY_t = A(Y_t + BW_t)dt, \quad t > 0, \quad Y_0 = x.$$

To control the error terms with positive probability, we need the *small ball property* of $\{BW_t\}$ in V , that is,

$$\mathbb{P}\left(\sup_{0 \leq t \leq T} \|BW_t\|_V < \delta\right) > 0.$$

which is automatically satisfied if V is a Hilbert space and $B \in \text{HS}(U, V)$. For the pathwise argument, we also need the non-standard assumption that there exist $\delta_4 > 0$ and $C_4 \in \mathbb{R}$ such that for all $u \in V$,

$$2\langle A(u), u \rangle \leq C_4 - \delta_4 \|A(u)\|_{V^*}.$$

We obtain

$$\begin{aligned} & \mathbb{P}\left(\sup_{0 \leq t \leq T} \|X_t^x - u_t^x\|_H^2 < \varepsilon\right) \\ & \geq \mathbb{P}\left(\sup_{0 \leq t \leq T} \|Y_t^x - u_t^x\|_H^2 < \frac{\varepsilon}{4}, \sup_{0 \leq t \leq T} \|L_t\|_H^2 < \frac{\varepsilon}{4}\right) > 0. \end{aligned}$$

However, in the estimates for $\sup_{0 \leq t \leq T} \|Y_t^x - u_t^x\|_H^2$, we in fact need the stronger requirement

$$\mathbb{P}\left(\sup_{0 \leq t \leq T} \|L_t\|_V^2 < \delta\right) > 0,$$

and an application of the stochastic Gronwall lemma by Sarah Geiss [Gei24] (see also von Renesse and Scheutzow [vRS10]).

Now, for every $\delta > 0$, and every $z \in K$, there exists $\gamma_1 > 0$, and $T_0 > 0$ such that

$$P_T \mathbb{1}_{B_\delta(0)}(z) = \mathbb{P}(\|X_{T_0}^z\|_H \leq \delta) \geq \mathbb{P}\left(\|X_{T_0}^z - u_{T_0}^z\|_H \leq \frac{\delta}{2}\right) \geq \gamma_1 > 0.$$

By a well-know trick used for instance by Es-Sarhir and von Renesse [EvR12], we may use the Markov property of the semigroup (shifting by T_0) to obtain

$$\liminf_{T \rightarrow \infty} \frac{1}{T} \int_0^T P_t \mathbb{1}_{B_\delta(0)}(x) dt \geq \liminf_{T \rightarrow \infty} \gamma_1 \frac{1}{T} \int_0^T P_t \mathbb{1}_K(x) dt > 0.$$

Here, we have also used that the coercivity implies for every $\varepsilon > 0$ and every bounded set J , there exists a bounded set K with

$$\inf_{x \in J} \liminf_{T \rightarrow \infty} \frac{1}{T} \int_0^T P_t \mathbb{1}_K(x) dt > 1 - \varepsilon.$$

Thus, the conditions of Komorowski, Peszat and Szarek [KPS10] can be verified. This proves our main result. The moment estimates follow from our a priori estimate and the fact that $V \subset H$ is a continuous linear embedding.

Theorem 14. *(Barrera, T.) Under the previous hypotheses, the semigroup associated to (1) is Markovian and Feller, and satisfies the e -property and is weak* mean ergodic. The unique invariant probability measure μ on $(H, \mathcal{B}(H))$ admits finite $(\alpha + \beta)$ -moments in H . If $\beta = 0$, μ admits α -moments in V .*

Remark 15.

- Due to our method, our proof is restricted to locally monotone equations, where ρ depends **only on one variable** and not on both (i.e., *fully locally monotone*).
- The **V -regularity** of the noise and the **cone condition** are technical assumptions.

- We have proved **ergodicity, mixing, and upper bounds for ε -mixing times** of **locally monotone drift** SPDEs with possibly **degenerate Wiener noise** with **spatial regularity** in the more regular space V under quantitative conditions. The embedding $V \subset H$ does not need to be compact, so we include examples with possibly **unbounded domains** that satisfy a **Poincaré inequality**.
- Further examples are the **stochastic power law fluid equations** for $p > 2$, the **stochastic heat equation**, and the **stochastic 1D Burgers equation**.
- Semilinear SPDEs like the **stochastic Allen-Cahn equation**, and *fully locally monotone* SPDEs like the **stochastic Cahn-Hilliard equation** are not covered by our results, nor is the **stochastic p -Laplace equation** (work in progress).

Bibliography

- [BKL02] J. Bricmont, A. Kupiainen, and R. Lefevere. Exponential mixing of the 2D stochastic Navier-Stokes dynamics. *Comm. Math. Phys.*, 230(1):87–132, 2002.
- [BKS20] Oleg Butkovsky, Alexei Kulik, and Michael Scheutzow. Generalized couplings and ergodic rates for SPDEs and other Markov models. *Ann. Appl. Probab.*, 30(1):1–39, 2020.
- [BLZ14] Zdzisław Brzeźniak, Wei Liu, and Jiahui Zhu. Strong solutions for SPDE with locally monotone coefficients driven by Lévy noise. *Nonlinear Anal. Real World Appl.*, 17:283–310, 2014.
- [EMS01] Weinan E, J. C. Mattingly, and Ya. Sinai. Gibbsian dynamics and ergodicity for the stochastically forced Navier-Stokes equation. *Comm. Math. Phys.*, 224(1):83–106, 2001. Dedicated to Joel L. Lebowitz.
- [EvR12] Abdelhadi Es-Sarhir and Max-K. von Renesse. Ergodicity of stochastic curve shortening flow in the plane. *SIAM J. Math. Anal.*, 44(1):224–244, 2012.
- [FM95] Franco Flandoli and Bohdan Maslowski. Ergodicity of the 2-D Navier-Stokes equation under random perturbations. *Comm. Math. Phys.*, 172(1):119–141, 1995.
- [Gei24] Sarah Geiss. Sharp convex generalizations of stochastic Gronwall inequalities. *J. Differential Equations*, 392:74–127, 2024.

- [GMR17]** Nathan Glatt-Holtz, Jonathan C. Mattingly, and Geordie Richards. On unique ergodicity in nonlinear stochastic partial differential equations. *J. Stat. Phys.*, 166(3-4):618–649, 2017.
- [HM06]** Martin Hairer and Jonathan C. Mattingly. Ergodicity of the 2D Navier-Stokes equations with degenerate stochastic forcing. *Ann. of Math. (2)*, 164(3), 2006.
- [HM08]** Martin Hairer and Jonathan C. Mattingly. Spectral gaps in Wasserstein distances and the 2D stochastic Navier-Stokes equations. *Ann. Probab.*, 36(6):2050–2091, 2008.
- [KPS10]** Tomasz Komorowski, Szymon Peszat, and Tomasz Szarek. On ergodicity of some Markov processes. *Ann. Probab.*, 38(4):1401–1443, 2010.
- [KS01]** Sergei Kuksin and Armen Shirikyan. Ergodicity for the randomly forced 2D Navier-Stokes equations. *Math. Phys. Anal. Geom.*, 4(2):147–195, 2001.
- [LR10]** Wei Liu and Michael Röckner. SPDE in Hilbert space with locally monotone coefficients. *J. Funct. Anal.*, 259(11):2902–2922, 2010.
- [LS06]** Andrzej Lasota and Tomasz Szarek. Lower bound technique in the theory of a stochastic differential equation. *J. Differential Equations*, 231(2):513–533, 2006.
- [Mat02]** Jonathan C. Mattingly. Exponential convergence for the stochastically forced Navier-Stokes equations and other partially dissipative dynamics. *Comm. Math. Phys.*, 230(3):421–462, 2002.
- [MS02]** Jose-Luis Menaldi and Sivaguru S. Sritharan. Stochastic 2-D Navier-Stokes equation. *Appl. Math. Optim.*, 46(1):31–53, 2002.
- [SW12]** Tomasz Szarek and Daniël T. H. Worm. Ergodic measures of Markov semigroups with the e-property. *Ergodic Theory Dynam. Systems*, 32(3):1117–1135, 2012.
- [Tem01]** Roger Temam. *Navier-Stokes equations*. AMS Chelsea Publishing, Providence, RI,

2001. Theory and numerical analysis, Reprint of the 1984 edition.

[vRS10] Max-K. von Renesse and Michael Scheutzow. Existence and uniqueness of solutions of stochastic functional differential equations. *Random Oper. Stoch. Equ.*, 18(3):267–284, 2010.

Thank you for your attention!