The Hairer–Quastel universality result in equilibrium

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February 9, 2016

Abstract

We use the notion of energy solutions of the stochastic Burgers equation to give a short proof of the Hairer-Quastel universality result for a class of stationary weakly asymmetric stochastic PDEs.

1 Introduction

Consider the stochastic PDE
\[ \partial_t v = \Delta v + \epsilon^{1/2} \partial_x F(v) + \partial_x \chi^\epsilon \]

on \([0, \infty) \times \mathbb{T}_\epsilon\) with \(\mathbb{T}_\epsilon = \mathbb{R}/(2\pi \epsilon^{-1} \mathbb{Z})\), where \(\chi^\epsilon\) is a Gaussian noise that is white in time and spatially smooth. The celebrated Hairer–Quastel universality result [HQ15] states that there exist constants \(c_1, c_2 \in \mathbb{R}\) such that the rescaled process \(\epsilon^{-1/2} v_{\epsilon t} - \xi\) converges to the solution \(u\) of the stochastic Burgers equation
\[ \partial_t u = \Delta u + c_2 \partial_x u^2 + \xi, \]

where \(\xi\) is a space-time white noise. Here we give an alternative proof of this result, based on the concept of energy solutions [GJ13a, GJ13b, GP15a, GP15b]. Energy solutions formulate the equilibrium Burgers equation as a martingale problem and allow us to give a simpler proof than the one of [HQ15]. On the other side our method only applies in equilibrium and in fact at each step we need to know the invariant measure explicitly.

Let us state the result more precisely. We modify (1) such that after rescaling \(\tilde{u}_t^\epsilon(x) = \epsilon^{-1/2} v_{\epsilon t} - \xi\) we have
\[ \partial_t \tilde{u}^\epsilon = \Delta \tilde{u}^\epsilon + \epsilon^{-1} \partial_x \Pi_0^N F(\epsilon^{1/2} \tilde{u}^\epsilon) + \partial_x \Pi_0^N \xi, \]

where \(\tilde{\xi}\) is a space-time white noise on \([0, \infty) \times \mathbb{T}\) (where \(\mathbb{T} = \mathbb{T}_1\)) with variance 2, \(\eta\) is a space white noise which is independent of \(\tilde{\xi}\), \(\Pi_0^N\) denotes the projection onto the Fourier modes \(0 < |k| \leq N\), and we always link \(N\) and \(\epsilon\) via
\[ 2N = 1/\epsilon. \]

Theorem 1. Let \(F\) be almost everywhere differentiable and assume that for all \(\epsilon > 0\) there is a unique solution \(\tilde{u}^\epsilon\) to (2) which does not blow up before \(T > 0\). Assume also that \(F, F' \in L^2(\nu)\) where \(\nu\) is the standard normal distribution. Then \(u_t^\epsilon(x) := \tilde{u}_t^\epsilon(x - \epsilon^{-1/2} c_1(F) t), (t, x) \in [0, T] \times \mathbb{T}\), converges in distribution to the unique equilibrium energy solution \(u\) of
\[ \partial_t u = \Delta u + c_2(F) \partial_x u^2 + \xi, \]
where \( \xi \) is a space-time white noise with variance 2 and for \( U \sim \nu \) and \( k \geq 0 \) and \( H_k \) the \( k \)-th Hermite polynomial
\[
c_k(F) = \frac{1}{k!}E[F(U)H_k(U)].
\]

**Remark 2.** If \( F \) is even, then \( c_1(F) = 0 \) while \( c_2(F) = 0 \) if \( F \) is odd.

**Remark 3.** Note that we introduced a second regularization in (2) compared to (1) which acts on \( F(\varepsilon^{1/2}u^\varepsilon) \). The reason is that we need to keep track of the invariant measure and this second regularization allows us to write it down explicitly. For the moment we are unable to deal with the original equation (1). For simplicity here we only consider the mollification operator \( \Pi^N_0 \), but it is possible to extend everything to more general operators \( \rho(\varepsilon D)u = \mathcal{F}^{-1}(\rho(\varepsilon \cdot)\mathcal{F}u) \), where \( \mathcal{F} \) denotes the Fourier transform and \( \rho \) is an even, compactly supported, bounded function which is continuous in a neighborhood of 0 and satisfies \( \rho(0) = 1 \). We should then modify the equation as
\[
\frac{\partial}{\partial t} \tilde{u}^\varepsilon = \Delta u^\varepsilon + \varepsilon^{-1} \partial_x \rho(D)\rho(D)F(\varepsilon^{1/2} \tilde{u}^\varepsilon) + \partial_x \rho(D)\tilde{\xi}, \quad \tilde{u}^\varepsilon_0 = \rho(D)\eta,
\]
to keep control of the invariant measure.

**Remark 4.** While our result only applies in equilibrium, we have more freedom in choosing the nonlinearity \( F \) than [HQ15] who require it to be an even polynomial. Also, the methods of this paper will extend without great difficulty to the (modified) equation on \([0, T] \times \mathbb{R} \).

**Notation** For \( k \in \mathbb{Z} \) we write \( \varphi_k(x) = e^{ikx}/\sqrt{2\pi} \) for the \( k \)-th Fourier monomial, and for \( u \in \mathcal{S}', \) the distributions on \( \mathbb{R} \), we define \( \tilde{u}(k) = \mathcal{F}u(k) = \langle u, e^{-k} \rangle \). We use \( \langle \cdot, \cdot \rangle \) to denote both the duality pairing in \( \mathcal{S}' \times C^\infty(\mathbb{T}, \mathbb{C}) \) and the inner product in \( L^2(\mathbb{T}) \), so since we want the notation to be consistent we will always consider the \( L^2(\mathbb{T}, \mathbb{R}) \) inner product and not that of \( L^2(\mathbb{T}, \mathbb{C}) \). That is, even for complex valued \( f, g \) we set \( \langle f, g \rangle = \int_\mathbb{T} f(x)\overline{g}(x)dx \) and do not take a complex conjugate. The Fourier projection operator \( \Pi^N_0 \) is given by
\[
\Pi^N_0 v = \sum_{0 < |k| \leq N} e_k \tilde{v}(k).
\]

## 2 Preliminaries

Let us start by making some basic observations concerning the solution to (2).

**Galilean transformation** Recall that \( \tilde{u}^\varepsilon \) solves
\[
\frac{\partial}{\partial t} \tilde{u}^\varepsilon = \Delta \tilde{u}^\varepsilon + \varepsilon^{-1} \partial_x \Pi^N_0 F(\varepsilon^{1/2} \tilde{u}^\varepsilon) + \partial_x \Pi^N_0 \tilde{\xi},
\]
and that \( u^\varepsilon_t(x) = \tilde{u}^\varepsilon_t(x - \varepsilon^{-1/2}c_1(F)t) \). We define the modified test function \( \tilde{\varphi}_t(x) = \varphi(x + \varepsilon^{-1/2}c_1(F)t) \) and then \( \langle u^\varepsilon_t, \varphi \rangle = \langle \tilde{u}^\varepsilon_t, \tilde{\varphi}_t \rangle \). The Itô–Wentzell formula gives
\[
d\langle u^\varepsilon_t, \varphi \rangle = \langle d\tilde{u}^\varepsilon_t, \tilde{\varphi}_t \rangle + \langle \tilde{u}^\varepsilon_t, \partial_x \tilde{\varphi}_t \rangle dt
\]
\[
= \langle \Delta \tilde{u}^\varepsilon_t, \tilde{\varphi}_t \rangle dt + \langle \varepsilon^{-1} \partial_x \Pi^N_0 F(\varepsilon^{1/2} \tilde{u}^\varepsilon), \tilde{\varphi}_t \rangle dt + \langle d\partial_x \tilde{M}^\varepsilon_t, \tilde{\varphi}_t \rangle dt + \langle \varepsilon^{-1/2}c_1(F)\tilde{u}^\varepsilon_t, \partial_x \tilde{\varphi}_t \rangle dt,
\]
where \( \tilde{M}^\varepsilon_t(x) = \int_0^t \Pi^N_0 \tilde{\xi}(s, x)ds \). Integrating the last term on the right hand side by parts, we get
\[
d\langle u^\varepsilon_t, \varphi \rangle = \langle \Delta u^\varepsilon_t, \varphi \rangle dt + \langle \varepsilon^{-1} \partial_x \Pi^N_0 F(\varepsilon^{1/2}u^\varepsilon), \varphi \rangle dt - \varepsilon^{-1/2}c_1(F)\langle \partial_x u^\varepsilon_t, \varphi \rangle dt + \langle d\partial_x \tilde{M}^\varepsilon_t, \tilde{\varphi}_t \rangle dt.
\]

The martingale term has quadratic variation
\[
d\langle [\partial_x \tilde{M}^\varepsilon_t, \tilde{\varphi}_t] \rangle_t = d\langle [\tilde{M}^\varepsilon_t, \partial_x \tilde{\varphi}_t] \rangle_t = 2\|\Pi^N_0 \partial_x \tilde{\varphi}_t\|^2_{L^2} dt = 2\|\Pi^N_0 \partial_x \varphi\|^2_{L^2} dt,
\]
Integrating by parts we therefore have

\[ \langle f, g \rangle = \int_0^1 \Pi_0^N \xi(s, x) ds \]

for some polynomial growth of the first order derivatives. The general case then follows by an approach by performing the change of variables \( u(x) = \tilde{u}(x + \varepsilon^{-1/2}c_1(F)t) \) we replaced the function \( F \) by \( \tilde{F}(x) = F(x) - c_1(F)x \), and now it suffices to study equation (3).

**Invariant measure** Note that (3) actually is an SDE in the finite dimensional space \( Y_N = \Pi_0^N L^2(T, \mathbb{R}) \cong \mathbb{R}^{2N} \), so that we can apply Echeverria’s criterion to show the stationarity of a given distribution. The natural candidate is \( \mu^\varepsilon = \text{law}(\Pi_0^N \eta) \), where \( \eta \) is a space white noise, since we know that the dynamics of the regularized Ornstein-Uhlenbeck process

\[ \partial_t u^\varepsilon = \Delta u^\varepsilon + \varepsilon^{-1} \partial_x \Pi_0^N (F(\varepsilon^{1/2} u^\varepsilon) - c_1(F)\varepsilon^{1/2} \partial_x u^\varepsilon) + \partial_x \Pi_0^N \xi, \quad u_0^\varepsilon = \Pi_0^N \eta, \quad \text{(3)} \]

so in other words by performing the change of variables \( u^\varepsilon(x) = \tilde{u}^\varepsilon(x - \varepsilon^{-1/2}c_1(F)t) \) we replaced the function \( F \) by \( \tilde{F}(x) = F(x) - c_1(F)x \), and now it suffices to study equation (3).

**Lemma 5.** The vector field \( B^\varepsilon_F : Y_N \to Y_N \) leaves the Gaussian measure \( \mu^\varepsilon \) invariant. More precisely, if \( \Phi \) denotes the gradient with respect to the Fourier monomials often has the same invariant measure as the symmetric one. Let us write

\[ B^\varepsilon_F(u) = \varepsilon^{-1} \partial_x \Pi_0^N (F(\varepsilon^{1/2} u) - c_1(F)\varepsilon^{1/2} u) =: \varepsilon^{-1} \partial_x \Pi_0^N \tilde{F}(\varepsilon^{1/2} u), \]

where \( \tilde{F} = F - c_1(F)x \).

**Proof.** In this proof it is more convenient to work with the orthonormal basis

\[ \left\{ \frac{1}{\sqrt{2\pi}} \sin(k), \frac{1}{\sqrt{2\pi}} \cos(k), 0 < k \leq N \right\} \]

and that for models in the KPZ universality class
and it suffices to show that the zero order differential operator terms on the right hand side vanish. For the first one of them we have

\[
\sum_{k=1}^{2N} \langle \partial_{u, \varphi_k} B_P^\varepsilon(u), \varphi_k \rangle = \sum_{k=1}^{2N} \langle \partial_{u, \varphi_k} \varepsilon^{-1} \partial_x \Pi_0^N \tilde{F}(\varepsilon^{1/2} u), \varphi_k \rangle \\
= \sum_{k=1}^{2N} \langle \varepsilon^{-1/2} \partial_x (\Pi_0^N \tilde{F}(\varepsilon^{1/2} u) \varphi_k), \varphi_k \rangle \\
= - \sum_{k=1}^{2N} \langle \varepsilon^{-1/2} \Pi_0^N \tilde{F}(\varepsilon^{1/2} u) \varphi_k, \partial_x \varphi_k \rangle \\
= - \varepsilon^{-1/2} \sum_{k=1}^{2N} \langle \Pi_0^N \tilde{F}(\varepsilon^{1/2} u), \partial_x \varphi_k \rangle,
\]

and since \( \sin(mx)^2 + \cos(mx)^2 = 1 \) the sum of the squares of the \( \varphi_k \) does not depend on \( x \) so its derivative is 0. For the remaining term in (4) we get \( \mu^\varepsilon \)-almost surely

\[
\sum_{k=1}^{2N} \langle B_P^\varepsilon(u), \varphi_k \rangle = \langle B_P^\varepsilon(u), u \rangle = \langle \varepsilon^{-1} \partial_x \Pi_0^N \tilde{F}(\varepsilon^{1/2} u), u \rangle \\
= \varepsilon^{-1} \langle \partial_x \tilde{F}(\varepsilon^{1/2} u), \Pi_0^N u \rangle = - \varepsilon^{-1} \langle \tilde{F}(\varepsilon^{1/2} u), \partial_x \Pi_0^N u \rangle.
\]

Now observe that there exists \( G \) with \( G' = \tilde{F} \), and that under \( \mu^\varepsilon \) we have \( u = \Pi_0^N u \) almost surely, which yields

\[- \varepsilon^{-1} \langle \tilde{F}(\varepsilon^{1/2} u), \partial_x \Pi_0^N u \rangle = - \varepsilon^{-1} \langle G'(\varepsilon^{1/2} \Pi_0^N u), \partial_x \Pi_0^N u \rangle = - \varepsilon^{-3/2} \langle \partial_x G(\varepsilon \Pi_0^N u), 1 \rangle = 0,
\]

and therefore the proof is complete.

The previous lemma, together with the reversibility of the Ornstein-Uhlenbeck dynamics under \( \mu^\varepsilon \), implies that the Itô SDE (3) has \( \mu^\varepsilon \) as invariant measure and that for \( T > 0 \) the time reversed process \( \tilde{u}_{-T}^\varepsilon = \tilde{u}_{-t}^\varepsilon \) solves

\[
\partial_t \tilde{u}^\varepsilon = \Delta \tilde{u}^\varepsilon - \varepsilon^{-1} \partial_x \tilde{F}(\varepsilon^{1/2} \Pi_0^N \tilde{u}^\varepsilon) + \partial_x \Pi_0^N \xi
\]

with a time-reversed space-time white noise \( \xi \).

## 3 Boltzmann-Gibbs principle

In the theory of interacting particle systems the phenomenon that local quantities of the microscopic fields can be replaced in time averages by simple functionals of the conserved quantities is called the Boltzmann–Gibbs principle. In this section we investigate a similar phenomenon in order to control the antisymmetric drift term

\[
\int_0^t \varepsilon^{-1} \partial_x \tilde{F}(\varepsilon^{1/2} u_s^\varepsilon(x))ds
\]

as \( N \to +\infty \). Note that since \( \varepsilon = 1/2N \) and \( u^\varepsilon = \Pi_0^N u^\varepsilon \) we have \( \mathbb{E}[(\varepsilon^{1/2} u_s^\varepsilon(x))^2] = 1 \) for all \( N \), and therefore the Gaussian random variables \( \varepsilon^{1/2} u_s^\varepsilon(x) \) stay bounded in \( L^2 \) for fixed \( (s, x) \), but for large \( N \) there will be wild fluctuations in \( (s, x) \). We show that the quantity in (6) can be replaced by simpler expressions that are constant, linear, or quadratic in \( u^\varepsilon \).

### 3.1 A first computation

In the following we use \( \eta \) to denote a generic space white noise and we write \( \mu \) for its law, and \( G \in C(\mathbb{R}, \mathbb{R}) \) denotes a generic continuous function. A first interesting computation is
to consider the random field \( x \mapsto G(\varepsilon^{1/2}\Pi_0^N \eta(x)) \) and to derive its chaos expansion in the variables \((\eta_k)_k\) where \(\eta_k = (\eta, e_{-k})\) are the Fourier coordinates of \(\eta\). To do so consider the standard (recall that \(\varepsilon = (2N)^{-1}\) Gaussian random variable

\[
\eta^N(x) = \varepsilon^{1/2}\Pi_0^N \eta(x) = \varepsilon^{1/2} \sum_{0 < |k| \leq N} e_k(x) \eta_k,
\]

and observe that the chaos expansion in \(L^2(\text{law}(\eta^N(x)))\) yields

\[
G(\eta^N(x)) = \sum_{n \geq 0} c_n(G) H_n(\eta^N(x)),
\]

where \(H_n\) is the \(n\)-th Hermite polynomial and

\[
c_n(G) = \frac{1}{n!} \mathbb{E}[G(\eta^N(x))H_n(\eta^N(x))] = \frac{1}{n!} \int_{\mathbb{R}} G(x) H_n(x) \gamma(x) \, dx,
\]

where \(\gamma\) is the standard Gaussian density. Since \(H_n(x) = (-1)^n e^{x^2/2} \partial_x^n e^{-x^2/2}\), we get

\[
c_n(G) = \frac{1}{n!} \int_{\mathbb{R}} G(x) H_n(x)(-1)^n \partial_x^n \gamma(x) \, dx = \frac{\psi_G(n)}{n!},
\]

where \(\psi_G(\lambda) = \mathbb{E}[G(\lambda + \eta^N(x))]\).

Our next aim is to relate the Hermite polynomials of \(\eta^N(x)\) with the Wick powers of the family \((\eta_k)_k\). To do so we observe that the monomials \(H_n(\eta^N(x))\) are the coefficients of the powers of \(\lambda\) in \(\exp(\lambda \eta^N(x) - \lambda^2/2)\), and on the other side

\[
\sum_n \frac{\lambda^n}{n!} H_n(\eta^N(x)) = \exp(\lambda \eta^N(x) - \lambda^2/2) = \exp \left( \varepsilon^{1/2} \sum_{0 < |k| \leq N} e_k(x) \eta_k - \frac{1}{2} \sum_{0 < |k| \leq N} (\varepsilon^{1/2})^2 \right).
\]

Writing \([\cdot]_n\) for the projection onto the \(n\)-th homogeneous chaos generated by \(\eta\), we have

\[
\exp \left( \sum_{0 < |k| \leq N} \mu_k \eta_k - \frac{1}{2} \sum_{0 < |k| \leq N} \mu_k \mu_{-k} \right) = \sum_{k_1, \ldots, k_n} \frac{\mu_{k_1} \cdots \mu_{k_n}}{n!} [\eta_{k_1} \cdots \eta_{k_n}]_n,
\]

where the sum on the right hand side and all the following sums in \(k_1 \ldots k_n\) are over \(0 < |k_1|, \ldots, |k_n| \leq N\). Setting \(\mu_k = \varepsilon^{1/2} \lambda e_k(x)\) and identifying the coefficients for different powers of \(\lambda\), we get

\[
H_n(\varepsilon^{1/2}\Pi_0^N \eta(x)) = \varepsilon^{n/2} \sum_{k_1, \ldots, k_n} \frac{e^{(k_1 + \cdots + k_n)x}}{(2\pi)^{n/2}} [\eta_{k_1} \cdots \eta_{k_n}]_n,
\]

which can also be obtained by writing \(H_n(\varepsilon^{1/2}\Pi_0^N \eta(x)) = [(\varepsilon^{1/2}\Pi_0^N \eta(x))]_n\) and expanding the power \((\cdot)^n\) inside the projection. We can thus represent the function \(G(\eta^N(x))\) as

\[
G(\eta^N(x)) = \sum_{n \geq 0} c_n(G) H_n(\varepsilon^{n/2}\Pi_0^N \eta(x)) = \sum_{n \geq 0} c_n(G) \varepsilon^{n/2} \sum_{k_1, \ldots, k_n} \frac{e^{(k_1 + \cdots + k_n)x}}{(2\pi)^{n/2}} [\eta_{k_1} \cdots \eta_{k_n}]_n.
\]

If \(\varphi \in C^\infty(\mathbb{T})\) is a test function, we get

\[
\langle G(\eta^N), \varphi \rangle = \sum_{n \geq 0} c_n(G) \varepsilon^{n/2} \sum_{k_1, \ldots, k_n} \frac{\varphi(-k_1 - \cdots - k_n)}{(2\pi)^{(n-1)/2}} [\eta_{k_1} \cdots \eta_{k_n}]_n. \tag{7}
\]

So in particular the \(q\)-th Littlewood-Paley block of \(G(\eta^N)\) is given by

\[
\Delta_q G(\eta^N)(x) = \sum_{n \geq 0} c_n(G) \varepsilon^{n/2} \sum_{k_1, \ldots, k_n} \theta_q(k_1 + \cdots + k_n) \frac{e^{(k_1 + \cdots + k_n)x}}{(2\pi)^{n/2}} [\eta_{k_1} \cdots \eta_{k_n}]_n,
\]
where \((\theta_q)_{q \geq 1}\) is a dyadic partition of unity, and
\[
\mathbb{E}[|\Delta_q(G(\eta^N) - c_0(G))(x)|^2] \leq \sum_{n \geq 1} c_n(G)^2 z_n e^n \theta_q(k_1 + \cdots + k_n)^2 \\
\leq \sum_{n \geq 1} c_n(G)^2 z_n e^n N^{n-1} (2^n \wedge N) \leq \varepsilon \sum_{n \geq 1} c_n(G)^2 z_n (2^n \wedge N),
\]
where \(z_n = \max_{k_1 \ldots k_n} \mathbb{E}[|\eta_{k_1} \ldots \eta_{k_n}|]/(2\pi)^n \leq n!\) is a combinatorial factor. We thus obtain
\[
\mathbb{E}[|\Delta_q(G(\eta^N) - \psi_G(0))|^2_{L^2(\mathbb{T})}] \leq \min\{2\varepsilon^{p/2} 2\varepsilon^{p/2}, 1\},
\]
uniformly in \(N\), and then
\[
\mathbb{E}\left[\int_s^t |\Delta_q(G(\varepsilon^{1/2} u^\xi(x)) - \psi_G(0))|^2 \, dr\right] \leq |t - s| \mathbb{E}[|\Delta_q(G(\varepsilon^{1/2} u^\xi(x)) - \psi_G(0))|^2] \, dr \\
\leq |t - s|^2 \min\{2\varepsilon^{p/2} 2\varepsilon^{p/2}, 1\},
\]
where in the last step we used that \(\varepsilon^{1/2} u^\xi\) has the same distribution as \(\eta^N\), which easily implies the following result.

**Lemma 6.** Assume that \(\mathbb{E}[|G(U)|^2] < \infty\) for a standard normal variable \(U\), and let \(c_0(G) = \mathbb{E}[G(U)]\). Then
\[
\lim_{N \to \infty} \int_0^t G(\varepsilon^{1/2} u^\xi(x)) \, ds = c_0(G)t,
\]
where the convergence is in \(C([0,T], H^0^-)\). If \(c_0(G) = 0\), then
\[
\varepsilon^{-1/2} \int_0^t G(\varepsilon^{1/2} u^\xi(x)) \, ds
\]
is bounded in \(C([0,T], H^{-1/2}^-)\).

To analyse the for us interesting case with \(c_0(G) = 0\) we need a more refined argument which is provided by noise of controlled paths.

### 3.2 Regularization by noise

Let us write \(\mathcal{L}^\varepsilon_0\) for the generator of the mollified Ornstein–Uhlenbeck process
\[
\partial_t X^\varepsilon = \Delta X^\varepsilon + \partial_\xi \Pi^{N}_{0} \xi.
\]
The basic tool which allows us to control time integrals such as \(\int_0^t G(\varepsilon^{1/2} u^\xi(x)) \, ds\) is given by the Itô trick. To state it, we define for \(\Psi \in L^2(\mu^\varepsilon)\)
\[
\mathcal{E}^\varepsilon(\Psi) := \sum_{0 < |k| \leq N} k^2 |D_k \Psi|^2,
\]
where \(D_k\) is the directional derivative in \(e_k\).

**Lemma 7** (Itô trick). For \(\Psi \in \text{dom} (\mathcal{L}^\varepsilon_0)\) and \(T > 0, \ p \geq 1\) we have
\[
\mathbb{E}\left[\sup_{t \in [0,T]} \left| \int_0^t \mathcal{L}^\varepsilon_0 \Psi(u^\xi) \, ds \right|^p\right] \leq T^{p/2} \mathbb{E}[\mathcal{E}^\varepsilon(\Psi)^{p/2}].
\]

The proof is given in [GJ13b, GP15b] and extends without difficulty to our setting, so we do not repeat the arguments here.

To apply the Itô trick we need to solve the Poisson equation. In our setting this can be done efficiently by using the chaos expansion (7). Recall that we wrote \(\eta_{k} = (\eta, e_k)\) for the Fourier coefficients of a truncated spatial white noise \(\Pi^{N}_{0} \eta\) (which therefore has
law \( \mu^* \)), and that \( \llbracket \cdot \rrbracket_n \) denotes the projection onto the \( n \)-th chaos. We need to compute \( \mathcal{L}^n_0[\eta_k, \ldots, \eta_{k_n}]_n \), as these are the random variables appearing in a general chaos expansion. Let us start by considering \( \varphi \in Y_N = \Pi^N_0 L^2(T, \mathbb{R}) \) with \( \| \varphi \|_{L^2} = 1 \) for which we have \( \llbracket \langle \eta, \varphi \rangle \rrbracket_n = H_n(\langle \eta, \varphi \rangle) \), where \( H_n \) is the \( n \)-th Hermite polynomial. Itô’s formula gives
\[
dH_n((X^\varepsilon_t, \varphi)) = H_n'(1)(X_t^\varepsilon, \varphi)(X_t^\varepsilon, \Delta \varphi)dt + H^n''((X^\varepsilon_t, \varphi))\Pi^N_0 \partial_x \varphi, \Pi^N_0 \partial_{x'} \varphi)dt + dM_t,
\]
with a square integrable martingale \( M \). The Hermite polynomials satisfy \( H'_n = nH_{n-1} \), so we get
\[
H'_n((X^\varepsilon_t, \varphi))(X_t^\varepsilon, \Delta \varphi)dt + H''_n((X^\varepsilon_t, \varphi))\Pi^N_0 \partial_x \varphi, \Pi^N_0 \partial_{x'} \varphi)dt = nH_{n-1}(\langle X_t^\varepsilon, \varphi \rangle)H_1((X_t^\varepsilon, \Delta \varphi)) - n(n-1)H_{n-2}(\langle X_t^\varepsilon, \varphi \rangle)(\Pi^N_0 \varphi, \Pi^N_0 \Delta \varphi).
\]
The projection onto the \( n \)-th chaos of the first term is explicitly given by
\[
\llbracket H_{n-1}(\langle X^\varepsilon_t, \varphi \rangle)H_1((X_t^\varepsilon, \Delta \varphi)) \rrbracket_n = \llbracket [\langle X^\varepsilon_t, \varphi \rangle]^{n-1} \rrbracket_n - (n-1)\llbracket [\langle X^\varepsilon_t, \varphi \rangle]^{n-2} \rrbracket_n \Pi^N_0 \varphi, \Pi^N_0 \Delta \varphi),
\]
which is obtained by contracting \( \langle X^\varepsilon_t, \Delta \varphi \rangle \) with each of the \( n-1 \) variables \( \langle X^\varepsilon_t, \varphi \rangle \) inside the projector \( \llbracket \cdot \rrbracket_n \). Therefore, we have
\[
dH_n((X^\varepsilon_t, \varphi)) = n\llbracket H_{n-1}(\langle X^\varepsilon_t, \varphi \rangle)H_1((X_t^\varepsilon, \Delta \varphi)) \rrbracket_n dt + dM_t
\]
which shows that
\[
\mathcal{L}^n_0[\langle \eta, \varphi \rangle]^n = n\llbracket \langle \eta, \varphi \rangle^{n-1} \langle \eta, \Delta \varphi \rangle \rrbracket_n.
\]
So far we assumed \( \| \varphi \|_{L^2} = 1 \), but actually this last formula is invariant under scaling so it extends to all \( \varphi \in \Pi^N_0 L^2(T, \mathbb{R}) \), and then to \( \varphi \in \Pi^N_0 L^2(T, \mathbb{C}) \), and for general products we obtain by polarization
\[
\mathcal{L}^n_0[\langle \eta, \varphi_1 \rangle \cdots \langle \eta, \varphi_n \rangle] = \sum_{k=1}^n \llbracket [\langle \eta, \varphi_1 \rangle \cdots \langle \eta, \varphi_{k-1} \rangle \langle \eta, \varphi_{k+1} \rangle \cdots \langle \eta, \varphi_n \rangle \langle \eta, \Delta \varphi_k \rangle] \rrbracket_n.
\]
So finally we deduce that
\[
\mathcal{L}^n_0[\eta_{k_1} \cdots \eta_{k_n}] = -(k_1^2 + \cdots + k_n^2)[\eta_{k_1} \cdots \eta_{k_n}] (8)
\]
for all \( 0 < |k_1|, \ldots, |k_n| \leq N \). Combining that formula with (7), we obtain the following lemma.

**Lemma 8.** Consider a function of the form \( \Phi(\eta) = \langle G(\varepsilon^{1/2}\Pi^N_0 \eta) , \varphi \rangle \) and assume that \( \mathbb{E}[G(U)] = 0 \), where \( U \) is a standard normal variable, or that \( \varphi(0) = 0 \). Then the solution \( \Psi \) to the Poisson equation \( \mathcal{L}^n_0 \Psi = \Phi \) is explicitly given by
\[
\Psi(\eta) = -\sum_{n \geq 1} c_n(G)\varepsilon^{n/2} \sum_{k_1 \cdots k_n} \varphi(-k_1 - \cdots - k_n) \frac{(2\pi)^{(n-1)/2}}{(k_1^2 + \cdots + k_n^2)} \llbracket \eta_{k_1} \cdots \eta_{k_n} \rrbracket_n,
\]
where the sum is over all \( 0 < |k_1|, \ldots, |k_n| \leq N \).

**Remark 9.** Incidentally note that the solution can be represented as
\[
\Psi(\eta) = -\int_{0}^{\infty} dt \sum_{n \geq 1} c_n(G)\varepsilon^{n/2} \sum_{k_1 \cdots k_n} c^{-(k_1^2 + \cdots + k_n^2)}e^{(k_1^2 + \cdots + k_n^2)t}(2\pi)^{(n-1)/2} \llbracket \eta_{k_1} \cdots \eta_{k_n} \rrbracket_n
\]
\[
= -\int_{0}^{\infty} dt G(\varepsilon^{1/2}(\Delta^{1/2}\Pi^N_0 \eta)(x)).
\]
To apply the Itô trick we need to compute $\mathcal{E}(\Psi) = \sum_k k^2 D_k \Psi D_k \Psi$ for the solution $\Psi$ of the Poisson equation. For that purpose consider again $\varphi \in Y_N$ with $\|\varphi\|_{L^2} = 1$ and $H_n((\eta, \varphi)) = [(\eta, \varphi)^n]_n$, for which we have

$$D_k H_n((\eta, \varphi)) = H'_n((\eta, \varphi)) \langle e_k, \varphi \rangle = n H_{n-1}(\langle \eta, \varphi \rangle) \langle e_k, \varphi \rangle = n \|\eta, \varphi\|^{n-1} \langle e_k, \varphi \rangle,$$

so by polarization

$$D_k [\eta_i, \ldots, \eta_n]_n = \sum_j 1_{k_j = k}[\eta_{i_j}, \ldots, \eta_{i_n}]_{n-1}. \quad (9)$$

To prove the Boltzmann–Gibbs principle we need one more auxiliary result.

**Lemma 10.** For all $M \leq N$, $\ell \in \mathbb{Z}$ and $0 \leq s < t < \infty$ we have the estimate

$$E \left[ \left| \int_s^t \langle \partial_x (\Pi_0^M \eta^x), e_{-\ell} \rangle \, dt \right|^2 \right] \lesssim \ell^2 |t - s|^2 M.$$

**Proof.** We simply bound

$$E \left[ \left| \int_s^t \langle \partial_x (\Pi_0^M \eta^x)^2, e_{-\ell} \rangle \, dt \right|^2 \right] \leq |t - s| \int_s^t E[|\langle \partial_x (\Pi_0^M \eta^x)^2, e_{-\ell} \rangle|^2] \, dt,$$

and since we can replace $(\Pi_0^M \eta^x)^2$ by $(\Pi_0^M \eta^x)^2 - E[(\Pi_0^M \eta^x)^2]$, the integrand is given by

$$E[|\langle \partial_x (\Pi_0^M \eta^x)^2, e_{-\ell} \rangle|^2] = \ell^2 \int_T dx \int_T dx' E[|\Pi_0^M \eta^x(x)|^2 |\Pi_0^M \eta^x(x')|^2].$$

The expectation on the right hand side can be explicitly computed as

$$|E[\Pi_0^M \eta^x(x) \Pi_0^M \eta^x(x')]| = \left| \sum_{0 < |k| \leq M} e^{ik(x-x')} \right| = \left| \frac{\cos(M(x-x')) - \cos((M+1)(x-x'))}{1 - \cos(x-x')} - 1 \right| \lesssim \min\{M, |x-x'|^{-1}\},$$

for which

$$\int_T dx \int_T dx' \min\{M, |x-x'|^{-1}\}^2 dx \lesssim M,$$

and therefore the claim follows. \hfill \square

**Proposition 11** (Boltzmann–Gibbs principle). Let $G, G' \in L^2(\nu)$, where $\nu$ denotes the law of a standard normal variable. Then for all $\ell \in \mathbb{Z}$ and $0 \leq s < t \leq s + 1$ and all $\kappa > 0$

$$E \left[ \left| \int_s^t \langle e^{-1} \partial_x \Pi_0^N G(e^{1/2} \eta^x) - e^{-1/2} c_1(G) \partial_x \Pi_0^N \eta^x, e_{-\ell} \rangle \, dt \right|^2 \right] \lesssim |t - s|^{3/2 - \kappa} \ell^2 \int_R \|G'(x)\|^2 \nu(dx)$$

uniformly in $N \in \mathbb{N}$, and for all $M \leq N$

$$E \left[ \left| \int_s^t \langle e^{-1} \partial_x \Pi_0^N G(e^{1/2} \eta^x) - e^{-1/2} c_1(G) \partial_x \Pi_0^N \eta^x - c_2(G) \partial_x (\Pi_0^M \eta^x)^2, e_{-\ell} \rangle \, dt \right|^2 \right]\lesssim |t - s| \ell^2 (M^{-1} + \epsilon \log^2 N) \int_R \|G'(x)\|^2 \nu(dx).$$

**Proof.** We first show the second bound. Towards this end note that by Lemma 8 the solution $\Psi$ to

$$\mathcal{L}_0^N \Psi(\eta) = -e^{-1} (G(e^{1/2} \Pi_0^N) \eta - c_1(G) e^{1/2} \Pi_0^N \eta - c_2(G) (e^{1/2} \Pi_0^M \eta)^2, \partial_x \Pi_0^N e_{-\ell})$$

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is given by

$$
\Psi(\eta) = c_2(G) \sum_{k_1, k_2} \mathbf{1}_{|k_1| |k_2| \geq M} \mathbf{1}_{0 < |\ell| \leq N} \frac{\mathbf{1}_{\ell+1 = \ell} \left[ \left| \eta_{k_1} \eta_{k_2} \right| \right]_2}{(2\pi)^{1/2} \left( k_1^2 + k_2^2 \right)^{1/2}}
+ \sum_{n \geq 3} c_n(G) \varepsilon^{n/2-1} \sum_{k_1 \cdots k_n} \mathbf{1}_{0 < |\ell| \leq N} \frac{\mathbf{1}_{\ell_1 + \cdots + \ell_n = \ell} \left[ \left| \eta_{k_1} \cdots \eta_{k_n} \right| \right]_n}{(2\pi)^{(n-1)/2} \left( k_1^2 + \cdots + k_n^2 \right)^{1/2}},
$$

where it is understood that all sums in $k_i$ are over $0 < |k_i| \leq N$. Therefore (9) yields for $0 < |\ell| \leq N$

$$
D_k \Psi(\eta) = c_2(G) \varepsilon (n+1) \sum_{n \geq 1} c_{n+1}(G) \varepsilon^{n/2-1} \sum_{k_1 \cdots k_n} \mathbf{1}_{\ell_1 + \cdots + \ell_n = \ell} \frac{\mathbf{1}_{\ell_1 + \cdots + \ell_n = \ell} \left[ \left| \eta_{k_1} \cdots \eta_{k_n} \right| \right]_n}{(2\pi)^{n/2} \left( k_1^2 + k_2^2 + \cdots + k_n^2 \right)^{1/2}}.
$$

Applying the Itô trick we then get

$$
\mathbb{E} \left[ \left( \int_0^t \varepsilon^{-1} \partial_x \Pi_0^N (e^{1/2} u_\varepsilon) - \varepsilon^{-1/2} c_1(G) \partial_x \Pi_0^N u_\varepsilon - c_2(G) \partial_x (\Pi_0^N (\Delta u_\varepsilon)^2, e_{-\ell}) \right) dt \right]^2 \lesssim |t-s| \sum_{0 < |\ell| \leq N} k^2 \mathbb{E} \|D_k \Psi(\eta)\|^2
= |t-s| \sum_{0 < |\ell| \leq N} k^2 c_2(G)^2 \varepsilon^{2\ell^2} \sum_{k_1} \mathbf{1}_{|k_1| \geq M} \frac{\mathbf{1}_{\ell+k_1 = \ell} \left[ \left| \eta_{k_1} \right| \right]_1^2}{(k_1^2 + k_1^2)^2}
+ |t-s| \sum_{0 < |\ell| \leq N} k^2 c_{n+1}(G)^2 \varepsilon^{(n+1)\ell^2} (n+1)^2 \ell^2
\times \sum_{k_1 \cdots k_n} \frac{\mathbf{1}_{\ell_1 + \cdots + \ell_n = \ell} \left[ \left| \eta_{k_1} \cdots \eta_{k_n} \right| \right]_n^2}{(k_1^2 + k_1^2 + \cdots + k_n^2)^2}
= |t-s| \sum_{n \geq 1} A_n,
$$

where the $(A_n)$ are implicitly defined by the equation. Now $\mathbb{E} \left[ \left| \eta_{k_1} \cdots \eta_{k_n} \right| \right]_n^2 \leq n!$ for all $k_1, \ldots, k_n$, so that

$$
A_1 \lesssim \sum_{0 < |\ell|, |k_1| \leq N} k^2 c_2(G)^2 |\ell|^2 \mathbf{1}_{k_1 + k_1 = \ell} \frac{\mathbf{1}_{|k_1| \geq M}}{k_1^2 + k_1^2} \leq c_2(G)^2 |\ell|^2 \mathbf{1}_{k_1 + k_1 = \ell} \frac{\mathbf{1}_{|k_1| \geq M}}{k_1^2 + k_1^2}
\lesssim c_2(G)^2 |\ell|^2 \sum_{0 < |\ell| < \infty} \mathbf{1}_{\ell \neq k} \frac{\mathbf{1}_{|\ell-k| \geq M}}{k_1^2 + (\ell - k)^2} \leq c_2(G)^2 |\ell|^2 \sum_{0 < |\ell| < \infty} \left( \frac{1}{M^2 + (\ell - k)^2} + \frac{1}{k_1^2 + M^2} \right)
\lesssim c_2(G)^2 |\ell|^2 M^{-1},
$$

while for $n > 1$

$$
A_n = \sum_{0 < |\ell| \leq N} k^2 c_{n+1}(G)^2 \varepsilon^{n-1} (n+1)^2 |\ell|^2 \sum_{k_1 \cdots k_n} \mathbf{1}_{k_1 + k_1 + \cdots + k_n = \ell} \frac{\mathbf{1}_{k_1 + k_1 + \cdots + k_n = \ell} \left[ \left| \eta_{k_1} \cdots \eta_{k_n} \right| \right]_n^2}{(2\pi)^{n/2} \left( k_1^2 + k_1^2 + \cdots + k_n^2 \right)^{n/2}}
\lesssim \varepsilon^{-1} |\ell|^2 (n+1)^2 c_{n+1}(G)^2 n!
\sum_{0 < |k_1|, \ldots, |k_n| \leq N} \frac{1}{k_1^2 + \cdots + k_n^2}
\lesssim \varepsilon^{-1} |\ell|^2 (n+1)^2 c_{n+1}(G)^2 n!
\sum_{0 < |k_1|, \ldots, |k_n| \leq N} \frac{1}{k_1^2 + k_1^2}
\leq \varepsilon^{-1} |\ell|^2 (n+1)^2 c_{n+1}(G)^2 n!
\sum_{0 < |k_1|, \ldots, |k_n| \leq N} \frac{1}{k_1^2 + k_1^2} \lesssim \varepsilon |\ell|^2 (n+1)^2 c_{n+1}(G)^2 n! \log^2 N.
$$
The sum over \( n \) is bounded by
\[
\sum_{n=1}^{\infty} nc_n(G)^2 n! (n+1)^2 \lesssim \int_R |G'(x)|^2 \nu(dx),
\]
so that overall we get
\[
\mathbb{E} \left[ \int_s^t \langle \varepsilon^{-1} \partial_x \Pi_0^N G(\varepsilon^{1/2} u_x^\varepsilon) - \varepsilon^{-1/2} c_1(G) \partial_x \Pi_0^N u_x^\varepsilon - c_2(G) \partial_x (\Pi_0^M u_x^\varepsilon)^2, e_{-\ell} \rangle \, dr \right]^2
\lesssim |t-s|^{2} (M^{-1} + \varepsilon \log^2 N) \int_R |G'(x)|^2 \nu(dx),
\]
which is our second claimed bound.

To get the first bound, we take \( M \simeq |t-s|^{-1/2} \) in (10) (which requires \( N > |t-s|^{-1/2} \)), and combine this with Lemma 10 to obtain
\[
\mathbb{E} \left[ \int_s^t \langle - \partial_x \Pi_0^N G(\varepsilon^{1/2} u_x^\varepsilon) - \varepsilon^{-1/2} c_1(G) \partial_x \Pi_0^N u_x^\varepsilon, e_{-\ell} \rangle \, dr \right]^2
\lesssim |t-s|^{2} (M^{-1} + \varepsilon \log^2 N + |t-s| M) \int_R |G'(x)|^2 \nu(dx) \lesssim |t-s|^{3/2-\kappa} \ell^2 \int_R |G'(x)|^2 \nu(dx).
\]
If \( N \lesssim |t-s|^{-1/2} \) we use another estimate: as in the proof of Lemma 10 we have
\[
\mathbb{E} \left[ \int_s^t \langle - \partial_x \Pi_0^N G(\varepsilon^{1/2} u_x^\varepsilon) - \varepsilon^{-1/2} c_1(G) \partial_x \Pi_0^N u_x^\varepsilon, e_{-\ell} \rangle \, dr \right]^2
\lesssim |t-s|^2 \mathbb{E}[|\langle - \partial_x \Pi_0^N G(\varepsilon^{1/2} u_x^\varepsilon) - \varepsilon^{-1/2} c_1(G) \partial_x \Pi_0^N u_x^\varepsilon, e_{-\ell} \rangle|^2]
\lesssim |t-s|^2 \sum_{n \geq 2} \ell^2 \int_T \int_T \int_T \int_T dx' dx'' c_n(G)^2 |E[H_n(\varepsilon^{1/2} u_0^\varepsilon(x))H_n(\varepsilon^{1/2} u_0^\varepsilon(x'))]|n,
\lesssim |t-s|^2 \sum_{n \geq 2} \ell^2 \int_T \int_T \int_T \int_T dx' dx'' c_n(G)^2 e^n n! |E[\varepsilon^{1/2} u_x^\varepsilon(x)\varepsilon^{1/2} u_x^\varepsilon(x')]|^n
\lesssim |t-s|^2 \sum_{n \geq 2} \ell^2 e^{-2} c_n(G)^2 e^n n! \min\{N, |x-x'|^{-1}\}^n
\lesssim |t-s|^2 \sum_{n \geq 2} \ell^2 e^{-2} c_n(G)^2 e^n n! N^{n-1} \lesssim |t-s|^2 \sum_{n \geq 2} \ell^2 e^{-2} c_n(G)^2 n!
\lesssim \ell^2 |t-s|^{3/2} \int_R |G'(x)|^2 \nu(dx),
\]
where in the last step we used that \( |t-s|^{-1/2} N^{-1} \geq 1 \).

4 The invariance principle

We now have all the tools to prove the convergence of \((u^\varepsilon)\) to an energy solution of the stochastic Burgers equation. We proceed in two steps. First we establish the tightness of \((u^\varepsilon)\), and in a second step we show that every weak limit is an energy solution. Using the uniqueness of energy solutions, we therefore obtain the convergence of \((u^\varepsilon)\).

**Tightness** Let \((u^\varepsilon)\) solve (3) and write \( \tilde{F}(x) = F(x) - c_1(F)x \). To prove the tightness of \((u^\varepsilon)\) it suffices to show that for all \( \ell \in \mathbb{Z} \) the complex-valued process \( \langle u^\varepsilon, e_{-\ell} \rangle \) is tight and
satisfies a polynomial bound in $\ell$, uniformly in $\varepsilon$. We decompose $\langle u^\varepsilon_t, e_{-\ell}\rangle$ as

$$\langle u^\varepsilon_t, e_{-\ell}\rangle = \langle u^\varepsilon_0, e_{-\ell}\rangle + \int_0^t \langle u^\varepsilon_s, \Delta e_{-\ell}\rangle ds - \int_0^t (\varepsilon^{-1} \Pi^N_0 F(\varepsilon^{1/2} u^\varepsilon_s), \partial_x e_{-\ell}) ds$$

$$- \int_0^t (\partial_x \Pi^N_0 \xi_s, \partial_x e_{-\ell}) ds$$

$$= \langle u^\varepsilon_0, e_{-\ell}\rangle + \langle S^\varepsilon_t, e_{-\ell}\rangle + \langle A^\varepsilon_t, e_{-\ell}\rangle + \langle M^\varepsilon_t, e_{-\ell}\rangle,$$

(11)

where $S^\varepsilon$, $A^\varepsilon$, $M^\varepsilon$ stand for symmetric, antisymmetric and martingale part, respectively, and we show tightness for each term on the right hand side separately. The convergence of $\langle u^\varepsilon_t, e_{-\ell}\rangle$ at a fixed time (in particular $t = 0$) follows from the fact that the law of $u^\varepsilon_t$ is that of $\mu^\varepsilon$ for all $t$, and $(\mu^\varepsilon)$ obviously converges to the law of the white noise as $\varepsilon \to 0$. The linear term is tight because

$$\mathbb{E} \left[ \left| \int_s^t \langle u^\varepsilon_s, \Delta e_\ell \rangle ds \right|^p \right] \leq |t - s|^{p-1} \int_s^t \mathbb{E} |(u^\varepsilon_s, \ell^2 e_\ell)|^p ds$$

$$\lesssim |t - s|^{p-1} \int_s^t \mathbb{E} |(u^\varepsilon_s, \ell^2 e_\ell)|^2 ds = |t - s|^{p/2}.$$

The martingale term is for all $\varepsilon$ a mollified space–time white noise, so its convergence is immediate.

Only the nonlinear contribution to the dynamics is nontrivial to control. Here we use the Boltzmann–Gibbs principle Proposition 11 to get

$$\mathbb{E} \left[ \left| \int_s^t \langle \varepsilon^{-1} \Pi^N_0 F(\varepsilon^{1/2} u^\varepsilon_s), \partial_x e_{-\ell}\rangle ds \right|^2 \right] \lesssim |t - s|^{3/2 - \kappa \ell^2} \int_\mathbb{R} |F'(x)|^2 \nu(dx),$$

from where the tightness in $C([0,T], \mathbb{C})$ follows and also that any limit point has zero quadratic variation.

Similarly we have for the time reversed process $\tilde{u}^\varepsilon_t = u^\varepsilon_{T-t}$

$$\langle \tilde{u}^\varepsilon_t, e_{-\ell}\rangle = \langle \tilde{u}^\varepsilon_0, e_{-\ell}\rangle + \int_0^t \langle \tilde{u}^\varepsilon_s, \Delta e_{-\ell}\rangle ds + \int_0^t (\varepsilon^{-1} \Pi^N_0 F(\varepsilon^{1/2} \tilde{u}^\varepsilon_s), \partial_x e_{-\ell}) ds$$

$$- \int_0^t (\partial_x \Pi^N_0 \tilde{\xi}_s, \partial_x e_{-\ell}) ds$$

$$= : \langle \tilde{u}^\varepsilon_0, e_{-\ell}\rangle + \langle \tilde{S}^\varepsilon_t, e_{-\ell}\rangle + \langle \tilde{A}^\varepsilon_t, e_{-\ell}\rangle + \langle \tilde{M}^\varepsilon_t, e_{-\ell}\rangle,$$

(12)

and the same arguments as before show that each term on the right hand side is tight in $C([0,T], \mathbb{C})$, satisfies a uniform polynomial bound, and that any limit point of $\langle \tilde{A}^\varepsilon, e_{-\ell}\rangle$ has zero quadratic variation. Since we have suitable moment bounds for each term, we actually get the joint tightness:

**Lemma 12.** Consider the decomposition (11), (12). Then the tuple

$$(u^\varepsilon_0, \tilde{u}^\varepsilon_0, S^\varepsilon, \tilde{S}^\varepsilon, A^\varepsilon, \tilde{A}^\varepsilon, M^\varepsilon, \tilde{M}^\varepsilon)$$

is tight in $(\mathcal{S}^1)^2 \times C([0,T], \mathcal{S}^\varepsilon)^6$. For every weak limit $(u_0, \tilde{u}_0, S, \tilde{S}, A, \tilde{A}, M, \tilde{M})$ and any $\varphi \in C^\infty(\mathbb{T})$ the processes $\langle A, \varphi \rangle$ and $\langle \tilde{A}, \varphi \rangle$ have zero quadratic variation and satisfy $\tilde{A}_t = -(A_{T-t} - A_{T-\ell})$. Moreover, $u_t = u_0 + S_t + A_t + M_t$, $t \in [0,T]$, is for every fixed time a spatial white noise.

**Convergence** Recall the definition of energy solutions to the stochastic Burgers equation [GJ13b]:

**Definition 13.** (Controlled process)

Denote with $\mathcal{Q}$ the space of continuous stochastic processes $(u, A)$ on $[0,T]$ with values in $\mathcal{S}^\varepsilon$ such that
i) the law of $u_t$ is the white noise $\mu$ for all $t \in [0, T]$;

ii) For any test function $\varphi \in \mathcal{S}$ the process $t \mapsto \langle A_t, \varphi \rangle$ is almost surely of zero quadratic variation, $\langle A_0, \varphi \rangle = 0$ and the pair $((u, \varphi), \langle A, \varphi \rangle)$ satisfies the equation

$$
\langle u_t, \varphi \rangle = \langle u_0, \varphi \rangle + \int_0^t \langle u_s, \Delta \varphi \rangle \, ds + \langle A_t, \varphi \rangle - \langle M_t, \partial_x \varphi \rangle
$$

where $\langle (M_t, \partial_x \varphi) \rangle_{0 \leq t \leq T}$ is a martingale with respect to the filtration generated by $(u, A)$ with quadratic variation $\langle [M_t, \partial_x \varphi] \rangle_t = 2t\|\partial_x \varphi\|_{L^2(T)}^2$;

iii) the reversed processes $\hat{u}_t = u_{T-t}$, $\hat{A}_t = -\langle \hat{A}_t - \hat{A}_{T-t} \rangle$ satisfy the same equation with respect to their own filtration (the backward filtration of $(u, A)$).

The pair $(u, A)$ is called controlled since for $A \equiv 0$ we simply get the Ornstein–Uhlenbeck process, so in general $u$ is a “zero quadratic variation perturbation” of that process. Using the Itô trick, it is not hard to show that for controlled processes the Burgers nonlinearity is well defined:

**Lemma 14** ([GJ13b], Lemma 1). Assume that $(u, A) \in Q$ and set for $M \in \mathbb{N}$

$$
\langle B_t^M, \varphi \rangle = -\int_0^t \langle (\Pi_0^M u_s)^2, \partial_x \varphi \rangle \, ds.
$$

Then $(B_t^M)$ converges in probability in $C([0, T], \mathcal{S}')$ and we denote the limit by

$$
\langle \int_0^t \partial_x u_s^2 \, ds, \varphi \rangle.
$$

A controlled process $(u, A)$ is a solution to the stochastic Burgers equation

$$
\partial_t u = \Delta u + c\partial_x u^2 + \xi
$$

if $A = c\int_0^t \partial_x u^2 \, ds$. According to [GP15b, Theorem 2], there is a unique energy solution. The following theorem thus implies our main result, Theorem 1.

**Theorem 15.** Let $(u, A)$ be as in Lemma 12. Then $(u, A) \in Q$ and $u$ is the unique energy solution to

$$
\partial_t u = \Delta u + c_2(F)\partial_x u^2 + \xi
$$

*Proof.* The tuple $(u_0^\varepsilon, \hat{u}_0^\varepsilon, S^\varepsilon, \hat{S}^\varepsilon, A^\varepsilon, \hat{A}^\varepsilon, M^\varepsilon, \hat{M}^\varepsilon)$ converges along a subsequence $\varepsilon_n \to 0$, but to simplify notation we still denote this subsequence by the same symbol. Since $(u_0^\varepsilon, S^\varepsilon, A^\varepsilon, M^\varepsilon)$ converges jointly and for every fixed $\varepsilon$ the process $u^\varepsilon$ solves (2), we get for $\varphi \in C^\infty(T)$

$$
\langle u_t, \varphi \rangle = \langle u_0, \varphi \rangle + \langle S_t, \varphi \rangle + \langle A_t, \varphi \rangle + \langle M_t, \varphi \rangle,
$$

and since $\langle S_t^\varepsilon, \varphi \rangle = \int_0^t \langle u_s^\varepsilon, \Delta \varphi \rangle \, ds$ also $\langle S_t, \varphi \rangle = \int_0^t \langle u_s, \Delta \varphi \rangle \, ds$. The same argument works for the backward process, so that $(u, A) \in Q$. It remains to show that $A = c_2(F)\partial_x u^2$, which follows from the Boltzmann–Gibbs principle, Proposition 11. For all $\varepsilon > 0$ and $M \leq N = 1/(2\varepsilon)$

$$
\mathbb{E} \left[ \int_s^t \langle A^\varepsilon_r - c_2(F)\partial_x (\Pi_0^M u^\varepsilon_r)^2, e_{-\varepsilon} \rangle \, dr \right]^2 \lesssim |t-s|\varepsilon^2 (M^{-1} + \varepsilon \log^2 N) \int_\mathbb{R} |F'(x)|^2 \nu(dx),
$$

so by Fatou’s lemma

$$
\mathbb{E} \left[ \int_s^t \langle A - c_2(F)\partial_x (\Pi_0^M u_r)^2, e_{-\varepsilon} \rangle \, dr \right]^2 \lesssim \liminf_{\varepsilon \to 0} \mathbb{E} \left[ \int_s^t \langle A^\varepsilon_r - c_2(F)\partial_x (\Pi_0^M u^\varepsilon_r)^2, e_{-\varepsilon} \rangle \, dr \right]^2
\lesssim |t-s|\varepsilon^2 M^{-1} \int_\mathbb{R} |F'(x)|^2 \nu(dx).
$$

It now suffices to send $M \to \infty$. 

□

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