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On the Korteweg-de Vries long-wave approximation of the Gross-Pitaevskii equation II

Fabrice Béthuel ¹, Philippe Gravejat ², Jean-Claude Saut ³, Didier Smets ⁴

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Abstract

In this paper, we proceed along our analysis of the Korteweg-de Vries approximation of the Gross-Pitaevskii equation initiated in [6]. At the long-wave limit, we establish that solutions of small amplitude to the one-dimensional Gross-Pitaevskii equation split into two waves with opposite constant speeds $\pm\sqrt{2}$, each of which are solutions to a Korteweg-de Vries equation. We also compute an estimate of the error term which is somewhat optimal as long as travelling waves are considered. At the cost of higher regularity of the initial data, this improves our previous estimate in [6].

1 Introduction

1.1 Statement of the results

In this paper, we proceed along our study initiated in [6] of the one-dimensional Gross-Pitaevskii equation

$$i\partial_t\Psi + \partial_x^2\Psi = \Psi(|\Psi|^2 - 1) \text{ on } \mathbb{R} \times \mathbb{R}, \quad (\text{GP})$$

supplemented with the boundary condition at infinity

$$|\Psi(x, t)| \rightarrow 1, \text{ as } |x| \rightarrow +\infty.$$

This boundary condition is suggested by the formal conservation of the Ginzburg-Landau energy

$$E(\Psi) = \frac{1}{2} \int_{\mathbb{R}} |\partial_x\Psi|^2 + \frac{1}{4} \int_{\mathbb{R}} (1 - |\Psi|^2)^2.$$

In this paper, we will only consider finite energy solutions to (GP).

The Gross-Pitaevskii equation is integrable by means of the inverse scattering method, and it has been formally analyzed within this framework in [16], and rigorously in [14]. Concerning the Cauchy problem, it can be shown (see [18, 13, 6]) that (GP) is globally well-posed in the spaces

$$X^k(\mathbb{R}) = \{u \in L^1_{\text{loc}}(\mathbb{R}, \mathbb{C}), \text{ s.t. } 1 - |u|^2 \in L^2(\mathbb{R}) \text{ and } \partial_x u \in H^{k-1}(\mathbb{R})\},$$

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for any $k \geq 1$. More precisely, we have

Proposition 1 ([6]). *Let $k \in \mathbb{N}^*$ and $\Psi_0 \in X^k(\mathbb{R})$. Then, there exists a unique solution $\Psi(\cdot, t)$ in $C^0(\mathbb{R}, X^k(\mathbb{R}))$ ¹ to (GP) with initial data Ψ_0 . Furthermore, the energy E is conserved along the flow.*

If u belongs to $X^1(\mathbb{R})$ and satisfies

$$E(u) < \frac{2\sqrt{2}}{3},$$

then it does not vanish, and we may write $u = |u| \exp i\theta$, where θ is continuous (see e.g. [4]). Here, we will focus on solutions with small energy, so that in view of the conservation of the energy, we may write

$$\Psi(\cdot, t) = \varrho(\cdot, t) \exp i\varphi(\cdot, t).$$

More precisely, we will consider initial data which are small long-wave perturbations of the constant one, namely

$$\begin{cases} \varrho(x, 0) = \left(1 - \frac{\varepsilon^2}{6} N_\varepsilon^0(\varepsilon x)\right)^{\frac{1}{2}}, \\ \varphi(x, 0) = \frac{\varepsilon}{6\sqrt{2}} \Theta_\varepsilon^0(\varepsilon x), \end{cases}$$

where $0 < \varepsilon < 1$ is a small parameter, and N_ε^0 and $W_\varepsilon^0 = \partial_x \Theta_\varepsilon^0$ are uniformly bounded in some Sobolev spaces $H^k(\mathbb{R})$ for sufficiently large k . We will add two additional assumptions on Θ_ε^0 and N_ε^0 . We will assume that

$$\|N_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + \|\partial_x \Theta_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} < +\infty. \quad (1)$$

Here, $\|\cdot\|_{\mathcal{M}(\mathbb{R})}$ denotes the norm defined on $L^1_{\text{loc}}(\mathbb{R})$ by

$$\|f\|_{\mathcal{M}(\mathbb{R})} = \sup_{(a,b) \in \mathbb{R}^2} \left| \int_a^b f(x) dx \right|. \quad (2)$$

We next introduce the slow coordinates

$$x^- = \varepsilon(x + \sqrt{2}t), \quad x^+ = \varepsilon(x - \sqrt{2}t), \quad \text{and} \quad \tau = \frac{\varepsilon^3}{2\sqrt{2}}t.$$

The definition of the new coordinates x^- and x^+ corresponds to reference frames travelling to the left and to the right respectively with speed $\sqrt{2}$ in the original coordinates (x, t) . We define accordingly the rescaled functions N_ε^\pm and Θ_ε^\pm as follows

$$\begin{aligned} N_\varepsilon^\pm(x^\pm, \tau) &= \frac{6}{\varepsilon^2} \eta(x, t) = \frac{6}{\varepsilon^2} \eta\left(\frac{x^\pm}{\varepsilon} \pm \frac{4\tau}{\varepsilon^3}, \frac{2\sqrt{2}\tau}{\varepsilon^3}\right), \\ \Theta_\varepsilon^\pm(x^\pm, \tau) &= \frac{6\sqrt{2}}{\varepsilon} \varphi(x, t) = \frac{6\sqrt{2}}{\varepsilon} \varphi\left(\frac{x^\pm}{\varepsilon} \pm \frac{4\tau}{\varepsilon^3}, \frac{2\sqrt{2}\tau}{\varepsilon^3}\right), \end{aligned} \quad (3)$$

where $\eta = 1 - \varrho^2$. Setting

$$\begin{aligned} U_\varepsilon^-(x^-, \tau) &= \frac{1}{2} \left(N_\varepsilon^-(x^-, \tau) + \partial_{x^-} \Theta^-(x^-, \tau) \right), \\ U_\varepsilon^+(x^+, \tau) &= \frac{1}{2} \left(N_\varepsilon^+(x^+, \tau) - \partial_{x^+} \Theta^+(x^+, \tau) \right), \end{aligned} \quad (4)$$

our main result is

¹Here, the space $X^k(\mathbb{R})$ is endowed with the distance

$$d_{X^k, A}(u, v) = \|u - v\|_{L^\infty([-A, A])} + \|\partial_x u - \partial_x v\|_{H^{k-1}(\mathbb{R})} + \| |u| - |v| \|_{L^2(\mathbb{R})},$$

for some given $A > 0$ (see e.g. [13, 5] for more details).

Theorem 1. Let $k \geq 0$ and $\varepsilon > 0$ be given. Assume that the initial data Ψ_0 belongs to $X^{k+6}(\mathbb{R})$ and satisfies the assumption

$$\|N_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + \|\partial_x \Theta_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + \|N_\varepsilon^0\|_{H^{k+5}(\mathbb{R})} + \varepsilon \|\partial_x^{k+6} N_\varepsilon^0\|_{L^2(\mathbb{R})} + \|\partial_x \Theta_\varepsilon^0\|_{H^{k+5}(\mathbb{R})} \leq K_0. \quad (5)$$

Let \mathcal{U}^- and \mathcal{U}^+ denote the solutions to the Korteweg-de Vries equations

$$\partial_\tau \mathcal{U}^- + \partial_{x^-}^3 \mathcal{U}^- + \mathcal{U}^- \partial_{x^-} \mathcal{U}^- = 0, \quad (\text{KdV})$$

and

$$\partial_\tau \mathcal{U}^+ - \partial_{x^+}^3 \mathcal{U}^+ - \mathcal{U}^+ \partial_{x^+} \mathcal{U}^+ = 0, \quad (6)$$

with the same initial value as U_ε^- , respectively U_ε^+ . Then, there exist positive constants ε_1 and K_1 , depending only on k and K_0 , such that

$$\|U_\varepsilon^-(\cdot, \tau) - \mathcal{U}^-(\cdot, \tau)\|_{H^k(\mathbb{R})} + \|U_\varepsilon^+(\cdot, \tau) - \mathcal{U}^+(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K_1 \varepsilon^2 \exp K_1 |\tau|, \quad (7)$$

for any $\tau \in \mathbb{R}$ provided $\varepsilon \leq \varepsilon_1$.

Remark 1. In the original time variable, the Korteweg-de Vries approximation is valid on a time interval $t \in [0, T_\varepsilon]$ with

$$T_\varepsilon = o\left(\frac{|\log(\varepsilon)|}{\varepsilon^3}\right).$$

Moreover, the approximation error remains of order $\mathcal{O}(\varepsilon^2)$ on a time interval $t \in [0, T'_\varepsilon]$ with $T'_\varepsilon = \mathcal{O}(\varepsilon^{-3})$.

In order to explain the statements of Theorem 1, it is presumably useful to recast them in the context of known results about the long-wave limit of the Gross-Pitaevskii equation. First, we rewrite (GP) in the slow coordinates $(y, s) = (\varepsilon x, \varepsilon t)$ and set

$$\begin{cases} \varrho(x, t) = \left(1 - \frac{\varepsilon^2}{6} n_\varepsilon(\varepsilon x, \varepsilon t)\right)^{\frac{1}{2}}, \\ \partial_x \varphi(x, t) = \frac{\varepsilon^2}{6\sqrt{2}} w_\varepsilon(\varepsilon x, \varepsilon t), \end{cases}$$

In this setting, (GP) translates into the system for n_ε and w_ε ,

$$\begin{cases} \partial_s n_\varepsilon - \sqrt{2} \partial_y w_\varepsilon = -\frac{\varepsilon^2}{3\sqrt{2}} \partial_y (n_\varepsilon w_\varepsilon), \\ \partial_s w_\varepsilon - \sqrt{2} \partial_y n_\varepsilon = -3\sqrt{2} \varepsilon^2 \partial_y \left(\frac{\partial_y^2 n_\varepsilon}{6 - \varepsilon^2 n_\varepsilon} + \frac{w_\varepsilon^2}{36} + \frac{\varepsilon^2}{2} \frac{(\partial_y n_\varepsilon)^2}{(6 - \varepsilon^2 n_\varepsilon)^2} \right). \end{cases} \quad (8)$$

It has been shown in [3] that for suitably small data and times, this system is well-approximated by the linear wave equation. More precisely, assume that $s \geq 2$ and

$$K(s) \varepsilon^2 \|(N_\varepsilon^0, W_\varepsilon^0)\|_{H^{s+1}(\mathbb{R}) \times H^s(\mathbb{R})} \leq 1,$$

where $K(s)$ refers to some positive constant depending only on s . Let (\mathbf{n}, \mathbf{w}) denote the solution of the free wave equation

$$\begin{cases} \partial_s \mathbf{n} - \sqrt{2} \partial_y \mathbf{w} = 0, \\ \partial_s \mathbf{w} - \sqrt{2} \partial_y \mathbf{n} = 0, \end{cases} \quad (9)$$

with initial data $(N_\varepsilon^0, W_\varepsilon^0)$. Then, for any $0 \leq t \leq T_\varepsilon$, we have

$$\begin{aligned} & \|(n_\varepsilon, w_\varepsilon)(\cdot, \varepsilon t) - (\mathbf{n}, \mathbf{w})(\cdot, \varepsilon t)\|_{H^{s-2}(\mathbb{R}) \times H^{s-2}(\mathbb{R})} \\ & \leq K(s) \varepsilon^3 t \left(\|(N_\varepsilon^0, W_\varepsilon^0)\|_{H^{s+1}(\mathbb{R}) \times H^s(\mathbb{R})} + \|(N_\varepsilon^0, W_\varepsilon^0)\|_{H^{s+1}(\mathbb{R}) \times H^s(\mathbb{R})}^2 \right), \end{aligned}$$

where $T_\varepsilon = (K(s)\varepsilon^3\|(N_\varepsilon^0, W_\varepsilon^0)\|_{H^{s+1}(\mathbb{R})\times H^s(\mathbb{R})})^{-1}$. In particular, when $\|(N_\varepsilon^0, W_\varepsilon^0)\|_{H^{s+1}(\mathbb{R})\times H^s(\mathbb{R})}$ remains uniformly bounded, then $T_\varepsilon = \mathcal{O}(\varepsilon^{-3})$, and the wave equation is a good approximation for times of order $o(\varepsilon^{-3})$. The general solution to (9) may be written as

$$(\mathbf{n}, \mathbf{w}) = (\mathbf{n}^+, \mathbf{w}^+) + (\mathbf{n}^-, \mathbf{w}^-),$$

where the functions $(\mathbf{n}^\pm, \mathbf{w}^\pm)$ are solutions to (9) given by the d'Alembert formulae,

$$\begin{aligned} (\mathbf{n}^+(y, s), \mathbf{w}^+(y, s)) &= (N^+(y - \sqrt{2}s), W^+(y - \sqrt{2}s)), \\ (\mathbf{n}^-(y, s), \mathbf{w}^-(y, s)) &= (N^-(y + \sqrt{2}s), W^-(y + \sqrt{2}s)), \end{aligned}$$

where the profiles N^\pm and W^\pm are real-valued functions on \mathbb{R} . Solutions may therefore be split into right and left going waves of speed $\sqrt{2}$. Since the functions $(\mathbf{n}^\pm, \mathbf{w}^\pm)$ are solutions to (9), it follows that

$$\partial_y(N^+ + W^+) = 0, \text{ and } \partial_y(N^- - W^-) = 0,$$

so that, if the functions decay to zero at infinity, then

$$N^\pm = \mp W^\pm = \frac{N_\varepsilon^0 \mp W_\varepsilon^0}{2}.$$

Theorem 1 extends our earlier results in [6] (see also [9] for an alternative approach and an extension to the higher dimensional case). It shows that the Korteweg-de Vries equation provides the appropriate approximation for time scales of order $\mathcal{O}(\varepsilon^{-3})$. The definition of the new coordinate x^+ , respectively x^- , corresponds to a reference frame travelling to the left, respectively to the right, with speed $\sqrt{2}$ in the original coordinates (x, t) . In the frame corresponding to x^- , the wave $(\mathbf{n}^-, \mathbf{w}^-)$, originally travelling to the left, is now stationary, whereas the right going wave $(\mathbf{n}^+, \mathbf{w}^+)$ now has a speed equal to $8\varepsilon^{-2}$. The coordinate x^- is therefore particularly appropriate for the study of waves travelling to the left, whereas the coordinate x^+ is appropriate for the study of waves travelling to the right. In [6], we imposed some additional assumptions which implied in particular the smallness of U_ε^+ , so that it was only the study of waves going to the left which was addressed. This approach simplifies somehow the analysis.

In this paper, we remove this smallness assumption, at the cost however of new assumption (1), and we analyze both waves at the same time. Finally, we would like to emphasize also that comparing Theorem 1 with Theorem 1.4 in [6], the error term now involves ε^2 instead of ε . As explained in [6], the ε^2 is somewhat optimal, as the specific examples provided by travelling waves show. This improvement is related to the fact that we use higher order derivatives. As a matter of fact, the same improvement holds in the setting of Theorem 1.4 of [6]. More precisely, we have

Theorem 2. *Let $\varepsilon > 0$ and $k \geq 0$ be given. Assume that the initial data Ψ_0 belongs to $X^{k+6}(\mathbb{R})$ and satisfies*

$$\|N_\varepsilon^0\|_{H^{k+5}(\mathbb{R})} + \varepsilon\|\partial_x^{k+6}N_\varepsilon^0\|_{L^2(\mathbb{R})} + \|\partial_x\Theta_\varepsilon^0\|_{H^{k+5}(\mathbb{R})} \leq K_0. \quad (10)$$

Let \mathcal{N}^\pm and \mathcal{W}^\pm denote the solutions to the Korteweg-de Vries equation

$$\partial_\tau \mathcal{U}^\pm \mp \partial_x^3 \mathcal{U}^\pm \mp \mathcal{U}^\pm \partial_x \mathcal{U}^\pm = 0,$$

with initial data N_ε^0 , respectively $\partial_x\Theta_\varepsilon^0$. There exists positive constants ε_2 and K_2 , depending possibly on K_0 and k , such that

$$\begin{aligned} \|\mathcal{N}^\pm(\cdot, \tau) - N_\varepsilon^\pm(\cdot, \tau)\|_{H^k(\mathbb{R})} + \|\mathcal{W}^\pm(\cdot, \tau) - \partial_x\Theta_\varepsilon^\pm(\cdot, \tau)\|_{H^k(\mathbb{R})} \\ \leq K_2(\varepsilon^2 + \|N_\varepsilon^0 \pm \partial_x\Theta_\varepsilon^0\|_{H^k(\mathbb{R})}) \exp K_2|\tau|, \end{aligned} \quad (11)$$

for any $\tau \in \mathbb{R}$, provided $\varepsilon \leq \varepsilon_2$.

Remark 2. If the term $\|N_\varepsilon^0 \pm \partial_x \Theta_\varepsilon^0\|_{H^k(\mathbb{R})}$ is small, then the Korteweg-de Vries approximation is valid on a time interval (in the original time variable) $t \in [0, T_\varepsilon]$ with

$$T_\varepsilon = o\left(\min\left\{\frac{|\log(\varepsilon)|}{\varepsilon^3}, \frac{|\log(\|N_\varepsilon^0 \pm \partial_x \Theta_\varepsilon^0\|_{H^k(\mathbb{R})})|}{\varepsilon^3}\right\}\right).$$

In particular, if $\|N_\varepsilon^0 \pm \partial_x \Theta_\varepsilon^0\|_{H^k(\mathbb{R})} \leq C\varepsilon^\alpha$, with $\alpha > 0$, then the approximation is valid on a time interval $t \in [0, T'_\varepsilon]$ with $T'_\varepsilon = o(\varepsilon^{-3}|\log(\varepsilon)|)$. Moreover, if $\|N_\varepsilon^0 \pm \partial_x \Theta_\varepsilon^0\|_{H^k(\mathbb{R})}$ is of order $\mathcal{O}(\varepsilon^2)$, then the approximation error remains of order $\mathcal{O}(\varepsilon^2)$ on a time interval $t \in [0, T''_\varepsilon]$ with $T''_\varepsilon = \mathcal{O}(\varepsilon^{-3})$.

The main difference between Theorems 1 and 2 is that the second one involves the functions N_ε^\pm and $\partial_x \Theta_\varepsilon^\pm$ instead of U_ε^\pm . The error term in (11) involves the quantity $\|N_\varepsilon^0 \pm \partial_x \Theta_\varepsilon^0\|_{H^k(\mathbb{R})}$, which is small if the wave travelling in the other direction is small. Let us also emphasize that, in contrast with the assumptions of Theorem 1, the assumptions of Theorem 2 do not involve any assumption on the \mathcal{M} -norm.

Finally, it is worthwhile to notice that similar issues have been addressed and solved in the case of the long-wave limit of the water wave system. In a seminal work [10], Craig proved the first rigorous convergence result towards the Korteweg-de Vries equation, under assumptions which are similar in spirit to the ones in Theorem 2, focusing on a wave travelling in a single direction. Schneider and Wayne [15] completed the analysis and were able to handle both left and right-going waves at the same time, a result similar in spirit to Theorem 1. Bona, Colin and Lannes provided a sharp error estimate in [7] (see also [17]). The asymptotics were fully justified in [1], as well as in the higher dimensional case. In another direction, Ben Youssef and Colin considered in [2] similar limits for general hyperbolic systems.

1.2 Some elements in the proofs

The proofs are somewhat parallel with the proofs in [6], so that we will try to emphasize the new ideas and ingredients. Concerning Theorem 1, the left and right going waves U_ε^- and U_ε^+ play the same role in estimate (7), so that we may focus for instance on the estimates on U_ε^- . In order to simplify our notation, we set $N_\varepsilon = N_\varepsilon^-$, $\Theta_\varepsilon = \Theta_\varepsilon^-$, $U_\varepsilon = U_\varepsilon^-$, $\mathcal{U} = \mathcal{U}^-$, and

$$x = x^- = \varepsilon(x + \sqrt{2}t).$$

We also introduce the new notation

$$V_\varepsilon(x, \tau) = \frac{1}{2}\left(N_\varepsilon(x, \tau) - \partial_x \Theta_\varepsilon(x, \tau)\right) = U_\varepsilon^+\left(x - \frac{8}{\varepsilon^2}\tau, \tau\right), \quad (12)$$

and compute the relevant equations for U_ε and V_ε ,

$$\partial_\tau U_\varepsilon + \partial_x^3 U_\varepsilon + U_\varepsilon \partial_x U_\varepsilon = f_\varepsilon - \varepsilon^2 r_\varepsilon, \quad (13)$$

where

$$f_\varepsilon \equiv \partial_x \left(\frac{1}{6}V_\varepsilon^2 - \partial_x^2 V_\varepsilon + \frac{1}{3}U_\varepsilon V_\varepsilon\right) \equiv \partial_x F_\varepsilon, \quad (14)$$

and

$$\partial_\tau V_\varepsilon + \frac{8}{\varepsilon^2} \partial_x V_\varepsilon = g_\varepsilon + \varepsilon^2 r_\varepsilon, \quad (15)$$

where

$$g_\varepsilon \equiv \partial_x \left(\partial_x^2 N_\varepsilon + \frac{1}{2}V_\varepsilon^2 - \frac{1}{6}U_\varepsilon^2 - \frac{1}{3}U_\varepsilon V_\varepsilon\right) \equiv \partial_x G_\varepsilon. \quad (16)$$

The remainder term r_ε is given by the formula

$$r_\varepsilon = \partial_x \left(\frac{N_\varepsilon \partial_x^2 N_\varepsilon}{6(1 - \frac{\varepsilon^2}{6} N_\varepsilon)} + \frac{(\partial_x N_\varepsilon)^2}{12(1 - \frac{\varepsilon^2}{6} N_\varepsilon)^2} \right) \equiv \partial_x R_\varepsilon. \quad (17)$$

On the left-hand side of (13), we recognize the (KdV) equation, whereas on the left-hand side of (15), we recognize the transport operator with constant speed $-8\varepsilon^{-2}$, which stems from the fact that we are working in moving frames with speed $\pm 4\varepsilon^{-2}$. It remains to establish that the terms on the right-hand side of (13) behave as error terms. The first step is to establish that all quantities are uniformly bounded on finite time intervals.

Proposition 2. *Let $k \in \mathbb{N}$. Given any $\varepsilon > 0$ sufficiently small, assume that the initial data $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+1}(\mathbb{R})$ and satisfies the assumption*

$$\|N_\varepsilon^0\|_{H^k(\mathbb{R})} + \varepsilon \|\partial_x^{k+1} N_\varepsilon^0\|_{L^2(\mathbb{R})} + \|\partial_x \Theta_\varepsilon^0\|_{H^k(\mathbb{R})} \leq K_0, \quad (18)$$

where K_0 is some given positive constant. Then, there exists a positive constant K depending only on K_0 and k , such that

$$\|N_\varepsilon(\cdot, \tau)\|_{H^k(\mathbb{R})} + \varepsilon \|\partial_x^{k+1} N_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} + \|\partial_x \Theta_\varepsilon(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K \exp K|\tau|, \quad (19)$$

for any $\tau \in \mathbb{R}$. In particular, we have

$$\|U_\varepsilon(\cdot, \tau)\|_{H^k(\mathbb{R})} + \|V_\varepsilon(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K \exp K|\tau|. \quad (20)$$

Remark 3. Here and in the sequel, when we write ε sufficiently small, we mean that $0 < \varepsilon \leq \varepsilon_0$, where ε_0 is some constant which depends only on K_0 , but not on the order of differentiation k . In the course of our proofs, the constant ε_0 is determined so that, when assumption (18) holds, the energy of Ψ is sufficiently small in order that (2.2) holds.

It follows from Proposition 2 that the quantity r_ε remains bounded on finite time intervals, so that the error term $\varepsilon^2 r_\varepsilon$ is of order ε^2 as desired in Theorem 1. In contrast, the term f_ε describes the interaction of the two waves and is therefore more delicate to handle. Since V_ε is not supposed to be small in Theorem 1 (in contrast with Theorem 2), f_ε is not small in general. However, due to the dynamics, the interaction turns out to be of lower order. Indeed, in view of (15), at leading order, the function V_ε is shifted to the left with speed $8\varepsilon^{-2}$. Since the definition of f_ε strongly depends on the function V_ε , a related property also holds for f_ε , so that the average interaction turns out to be small. To provide a rigorous justification of this last claim, we need however to localize the functions U_ε and V_ε . This leads us to use the norm $\|\cdot\|_{\mathcal{M}(\mathbb{R})}$.

As in [6], our proofs rely on energy methods. We introduce the difference $Z_\varepsilon \equiv U_\varepsilon - \mathcal{U}$, which satisfies the equation

$$\partial_\tau Z_\varepsilon + \partial_x^3 Z_\varepsilon + \mathcal{U} \partial_x Z_\varepsilon + Z_\varepsilon \partial_x \mathcal{U} + Z_\varepsilon \partial_x Z_\varepsilon = f_\varepsilon - \varepsilon^2 r_\varepsilon. \quad (21)$$

In order to compute the L^2 -norm of $\partial_x^k Z_\varepsilon$, we apply the differential operator ∂_x^k to (21), multiply the resulting equation by $\partial_x^k Z_\varepsilon$ and integrate on \mathbb{R} to obtain

$$\begin{aligned} \frac{1}{2} \partial_\tau \|\partial_x^k Z_\varepsilon\|_{L^2(\mathbb{R})}^2 &= - \int_{\mathbb{R}} \partial_x^{k+1} (\mathcal{U} Z_\varepsilon) \partial_x^k Z_\varepsilon - \frac{1}{2} \int_{\mathbb{R}} \partial_x^{k+1} (Z_\varepsilon^2) \partial_x^k Z_\varepsilon \\ &\quad + \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon - \varepsilon^2 \int_{\mathbb{R}} \partial_x^k r_\varepsilon \partial_x^k Z_\varepsilon. \end{aligned}$$

Setting

$$\mathcal{Z}_\varepsilon^k(\tau) \equiv \int_0^\tau \int_{\mathbb{R}} (\partial_x^k Z_\varepsilon)^2, \quad (22)$$

and integrating in time, we are led to the differential equation

$$\begin{aligned} \frac{1}{2} \partial_\tau \mathcal{Z}_\varepsilon^k(\tau) = & - \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (U Z_\varepsilon) \partial_x^k Z_\varepsilon - \frac{1}{2} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (Z_\varepsilon^2) \partial_x^k Z_\varepsilon \\ & + \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon - \varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^k r_\varepsilon \partial_x^k Z_\varepsilon. \end{aligned} \quad (23)$$

The proof of Theorem 1 then follows applying the Gronwall lemma to (23) provided we are first able to bound suitably all the terms on the right-hand side of (23). The first, second and fourth terms can be handled thanks to Proposition 2. Indeed, we will show in Section 4 that these terms can be bounded as follows

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (U Z_\varepsilon) \partial_x^k Z_\varepsilon \right| \leq K \left(\left| \int_0^\tau \int_{\mathbb{R}} (\partial_x^k Z_\varepsilon)^2 \right| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right), \quad (24)$$

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (Z_\varepsilon^2) \partial_x^k Z_\varepsilon \right| \leq K \left(\left| \int_0^\tau \int_{\mathbb{R}} (\partial_x^k Z_\varepsilon)^2 \right| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right), \quad (25)$$

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k r_\varepsilon \partial_x^k Z_\varepsilon \right| \leq K \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|. \quad (26)$$

For the third term, we will prove

Proposition 3. *Let $\varepsilon > 0$ be given sufficiently small. Given any $k \in \mathbb{N}$, assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+6}(\mathbb{R})$ and satisfies (5) for some positive constant K_0 . Then, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} & \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon \right| \\ & \leq K \varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right), \end{aligned} \quad (27)$$

for any $\tau \in \mathbb{R}$.

Combining (23) with bounds (24), (25) and (27), we will obtain

$$\partial_\tau \mathcal{Z}_\varepsilon^k(\tau) \leq K \left(\text{sign}(\tau) \mathcal{Z}_\varepsilon^k(\tau) + \varepsilon^4 \exp K|\tau| \right).$$

The proof of Theorem 1 will then follow applying the Gronwall lemma.

We next say a few words about the proof of Proposition 3. For sake of clarity, we assume here that $k = 0$. For given $\tau \in \mathbb{R}$, we then have

$$\begin{aligned} \int_0^\tau \int_{\mathbb{R}} f_\varepsilon Z_\varepsilon & = \int_0^\tau \int_{\mathbb{R}} \left(\frac{1}{6} \partial_x V_\varepsilon^2 - \partial_x^3 V_\varepsilon + \frac{1}{3} \partial_x (U_\varepsilon V_\varepsilon) \right) Z_\varepsilon \\ & = \int_0^\tau \int_{\mathbb{R}} \partial_x V_\varepsilon \left(\frac{1}{3} V_\varepsilon Z_\varepsilon - \partial_x^2 Z_\varepsilon + \frac{1}{3} U_\varepsilon Z_\varepsilon \right) + \frac{1}{3} \int_0^\tau \int_{\mathbb{R}} \partial_x U_\varepsilon V_\varepsilon Z_\varepsilon. \end{aligned} \quad (28)$$

For the first integral on the right-hand side, we use transport equation (15) and write

$$\partial_x V_\varepsilon = \frac{\varepsilon^2}{8} \left(-\partial_\tau V_\varepsilon + g_\varepsilon + \varepsilon^2 r_\varepsilon \right).$$

This change makes apparent an ε^2 factor, and then we continue the computation using integration by parts for the time and space variables as well as the bounds provided by Proposition 2. It remains to handle the second integral on the right-hand side of (28), which does not involve as before the spatial derivative $\partial_x V_\varepsilon$. We somewhat artificially introduce such a derivative considering an antiderivative Υ_ε of V_ε defined by

$$\Upsilon_\varepsilon(x, \tau) = \int_{-R}^x V_\varepsilon(y, \tau) dy, \quad (29)$$

where the positive number R will be suitably chosen in the course of the computations. We obtain

$$\int_0^\tau \int_{\mathbb{R}} \partial_x U_\varepsilon V_\varepsilon Z_\varepsilon = \int_0^\tau \int_{\mathbb{R}} \partial_x U_\varepsilon \partial_x \Upsilon_\varepsilon Z_\varepsilon.$$

The function Υ_ε satisfies a transport equation, namely

$$\partial_\tau \Upsilon_\varepsilon + \frac{8}{\varepsilon^2} \partial_x \Upsilon_\varepsilon = G_\varepsilon + \varepsilon^2 R_\varepsilon - G_\varepsilon(-R) - \varepsilon^2 R_\varepsilon(-R) + \frac{8}{\varepsilon^2} V_\varepsilon(-R), \quad (30)$$

so that it is possible to implement a similar argument as above replacing $\partial_x \Upsilon_\varepsilon$ by the expression provided by (30). In order to perform our computation, it turns out that we only need to obtain some control in time of the L^∞ -norm of Υ_ε , which essentially amounts to controlling the \mathcal{M} -norm of V_ε . At initial time, this corresponds to assumption (1) on N_ε^0 and $\partial_x \Theta_\varepsilon^0$. For later time, we have

Lemma 1. *Let $0 \leq E_0 < \frac{2\sqrt{2}}{3}$ and $\Psi_0 \in \mathcal{M}(\mathbb{R}) \cap X^4(\mathbb{R})$ be given such that $E(\Psi_0) \leq E_0$. Then, there exists a positive constant K , depending only on E_0 , such that*

$$\begin{aligned} \|\eta(\cdot, t)\|_{\mathcal{M}(\mathbb{R})} + \sqrt{2} \|\partial_x \varphi(\cdot, t)\|_{\mathcal{M}(\mathbb{R})} &\leq K \left(\|\eta^0\|_{\mathcal{M}(\mathbb{R})} + \sqrt{2} \|\partial_x \varphi^0\|_{\mathcal{M}(\mathbb{R})} \right. \\ &\left. + \left| \int_0^t \left(\|\partial_x^2 \eta(\cdot, s)\|_{L^\infty(\mathbb{R})} + \|\eta(\cdot, s)\|_{W^{2,\infty}(\mathbb{R})}^2 + \|\partial_x \varphi(\cdot, s)\|_{L^\infty(\mathbb{R})}^2 \right) ds \right| \right), \end{aligned} \quad (31)$$

for any $t \in \mathbb{R}$.

In the slow coordinate t , Lemma 1 provides a control on the norm $\|\Upsilon_\varepsilon\|_{L^\infty(\mathbb{R})}$, which is independent of ε and grows linearly in time.

Lemma 2. *Let $\varepsilon > 0$ be sufficiently small. Assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^4(\mathbb{R})$ and satisfies assumption (18) for $k = 3$ and some positive constant K_0 . Then, there exists a positive constant K , which does not depend on ε nor τ , such that*

$$\|N_\varepsilon(\cdot, \tau)\|_{\mathcal{M}(\mathbb{R})} + \|\partial_x \Theta_\varepsilon(\cdot, \tau)\|_{\mathcal{M}(\mathbb{R})} \leq K \left(\|N_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + \|\partial_x \Theta_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + |\tau| \right), \quad (32)$$

for any $\tau \in \mathbb{R}$. In particular, we have

$$\|U_\varepsilon(\cdot, \tau)\|_{\mathcal{M}(\mathbb{R})} + \|V_\varepsilon(\cdot, \tau)\|_{\mathcal{M}(\mathbb{R})} \leq K \left(\|U_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + \|V_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + |\tau| \right). \quad (33)$$

The proof of estimate (27) follows combining the bounds of Proposition 2 and Lemma 2.

We next give some elements of the proof of Theorem 2. Notice first that the functions N_ε^\pm and $\partial_x \Theta_\varepsilon^\pm$ associated to the coordinates x^+ and x^- play the same role in Theorem 2, so that we may focus again for the estimates on $N_\varepsilon \equiv N_\varepsilon^-$ and $\partial_x \Theta_\varepsilon \equiv \partial_x \Theta_\varepsilon^-$. Recall that the main differences with respect to Theorem 1 are that Theorem 2 addresses the functions N_ε and $\partial_x \Theta_\varepsilon$

instead of U_ε , and does not involve any assumption on \mathcal{M} -norms. The proof of Theorem 2 is however parallel to the one of Theorem 1. We write for the function N_ε ,

$$\|N_\varepsilon - \mathcal{N}\|_{H^k(\mathbb{R})} \leq \|V_\varepsilon\|_{H^k(\mathbb{R})} + \|U_\varepsilon - \mathcal{U}\|_{H^k(\mathbb{R})} + \|\mathcal{U} - \mathcal{N}\|_{H^k(\mathbb{R})}, \quad (34)$$

since by definition, $V_\varepsilon = N_\varepsilon - U_\varepsilon$. Similarly, the functions $\partial_x \Theta_\varepsilon$ and \mathcal{W} satisfy

$$\|\partial_x \Theta_\varepsilon - \mathcal{W}\|_{H^k(\mathbb{R})} \leq \|V_\varepsilon\|_{H^k(\mathbb{R})} + \|U_\varepsilon - \mathcal{U}\|_{H^k(\mathbb{R})} + \|\mathcal{U} - \mathcal{W}\|_{H^k(\mathbb{R})}, \quad (35)$$

so that the proof of (11) reduces to bound each of the terms on the right-hand side of (34) and (35). For the H^k -norm of V_ε , we invoke again energy estimates, based now on equation (15). This yields

Proposition 4. *Let $\varepsilon > 0$ be sufficiently small. Given any $k \in \mathbb{N}$, assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+6}(\mathbb{R})$ and satisfies (10) for some positive constant K_0 . Then, there exists a positive constant K depending only on K_0 and k , such that*

$$\|V_\varepsilon(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K(\|V_\varepsilon^0\|_{H^k(\mathbb{R})} + \varepsilon^2) \exp K|\tau|, \quad (36)$$

for any $\tau \in \mathbb{R}$.

Similarly, concerning the differences between the solutions to (KdV), \mathcal{U} and \mathcal{N} on one hand, and \mathcal{U} and \mathcal{W} on the other, we invoke a general stability result for the Korteweg-de Vries equation, which we recall for the sake of completeness.

Lemma 3. *Let $k \in \mathbb{N}$ be given. Consider two functions F^0 and G^0 in $H^{k+2}(\mathbb{R})$ and denote F and G the solutions to (KdV) with initial data F^0 , respectively G^0 . Then, there exists a constant K , depending only on k and the H^{k+2} -norms of F^0 and G^0 , such that*

$$\|F(\cdot, \tau) - G(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K\|F^0 - G^0\|_{H^k(\mathbb{R})} \exp K|\tau|, \quad (37)$$

for any $\tau \in \mathbb{R}$.

In view of Lemma 3, and the fact that

$$\mathcal{U}^0 - \mathcal{W}^0 = \mathcal{N}^0 - \mathcal{U}^0 = V_\varepsilon^0,$$

we are led to

$$\|\mathcal{U}(\cdot, \tau) - \mathcal{N}(\cdot, \tau)\|_{H^k(\mathbb{R})} + \|\mathcal{U}(\cdot, \tau) - \mathcal{W}(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K\|V_\varepsilon^0\|_{H^k(\mathbb{R})} \exp K|\tau|, \quad (38)$$

for any $\tau \in \mathbb{R}$. Going back to (35), it remains to estimate the term $\|U_\varepsilon - \mathcal{U}\|_{H^k(\mathbb{R})} = \|Z_\varepsilon\|_{H^k(\mathbb{R})}$. An upper bound for this term was given in Theorem 1 using bounds on the \mathcal{M} -norm of N_ε and $\partial_x \Theta_\varepsilon$. Here, we use instead the estimates of Proposition 4 to bound the interaction terms.

Proposition 5. *Let $\varepsilon > 0$ be given sufficiently small. Given any $k \in \mathbb{N}$, assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+6}(\mathbb{R})$ and satisfies (10) for some positive constant K_0 . Then, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon \right| &\leq K\varepsilon^2 \left(\varepsilon^2 + \|V_\varepsilon^0\|_{H^k(\mathbb{R})} + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \right) \exp K|\tau| \\ &+ K \left(\varepsilon^2 + \|V_\varepsilon^0\|_{H^k(\mathbb{R})} \right) \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|, \end{aligned} \quad (39)$$

for any $\tau \in \mathbb{R}$.

We then adapt the arguments of the proof of (7) in order to obtain that

$$\|U_\varepsilon(\cdot, \tau) - \mathcal{U}(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K(\varepsilon^2 + \|V_\varepsilon^0\|_{H^k(\mathbb{R})}) \exp K|\tau|, \quad (40)$$

for any $\tau \in \mathbb{R}$. Combining with inequalities (34) and (35), and bounds (36) and (38), this will complete the proof of Theorem 2.

1.3 Outline of the paper

This paper is organized as follows. In the next section, we provide the proofs to Proposition 2, and Lemmas 1 and 2. In Section 3, we prove Proposition 3. The proof of Theorem 1 is completed in Section 4, whereas we derive Proposition 4, Lemma 3, Proposition 5, and finally Theorem 2 in Section 5. In a separate appendix, we extend the arguments of the proof of Lemma 1 to provide a rigorous framework for the notion of mass and establish its conservation.

2 Bounds for the rescaled functions

In this section, we establish a certain number of bounds for the rescaled functions N_ε , $\partial_x \Theta_\varepsilon$, U_ε and V_ε , which are useful in the course of the proofs of Theorems 1 and 2. We first derive the Sobolev bounds of Proposition 2, and then we compute estimate (32) of Lemma 2.

2.1 Sobolev bounds

Two different arguments are under hand to derive the Sobolev bounds given by inequality (19). The first one relies on the integrability properties of (GP). It is proved in [6] that the quantities $E_1(\Psi) \equiv E(\Psi)$,

$$E_2(\Psi) \equiv \frac{1}{2} \int_{\mathbb{R}} |\partial_x^2 \Psi|^2 - \frac{3}{2} \int_{\mathbb{R}} \eta |\partial_x \Psi|^2 + \frac{1}{4} \int_{\mathbb{R}} (\partial_x \eta)^2 - \frac{1}{4} \int_{\mathbb{R}} \eta^3,$$

$$\begin{aligned} E_3(\Psi) &\equiv \frac{1}{2} \int_{\mathbb{R}} |\partial_x^3 \Psi|^2 + \frac{1}{4} \int_{\mathbb{R}} |\partial_x^3 \eta|^2 + \frac{5}{4} \int_{\mathbb{R}} |\partial_x \Psi|^4 + \frac{5}{2} \int_{\mathbb{R}} \partial_x^2 \eta |\partial_x \Psi|^2 - \frac{5}{2} \int_{\mathbb{R}} \eta |\partial_x^2 \Psi|^2 \\ &\quad - \frac{5}{4} \int_{\mathbb{R}} \eta (\partial_x \eta)^2 + \frac{15}{4} \int_{\mathbb{R}} \eta^2 |\partial_x \Psi|^2 + \frac{5}{16} \int_{\mathbb{R}} \eta^4, \end{aligned}$$

and

$$\begin{aligned} E_4(\Psi) &\equiv \frac{1}{2} \int_{\mathbb{R}} |\partial_x^4 \Psi|^2 + \frac{1}{4} \int_{\mathbb{R}} |\partial_x^3 \eta|^2 - \frac{7}{4} \int_{\mathbb{R}} \eta (\partial_x^2 \eta)^2 - \frac{7}{2} \int_{\mathbb{R}} \eta |\partial_x^3 \Psi|^2 + \frac{35}{8} \int_{\mathbb{R}} \eta^2 (\partial_x \eta)^2 \\ &\quad + \frac{35}{4} \int_{\mathbb{R}} \eta^2 |\partial_x^2 \Psi|^2 - \frac{35}{4} \int_{\mathbb{R}} (\partial_x \eta)^2 |\partial_x \Psi|^2 - \frac{7}{2} \int_{\mathbb{R}} |\partial_x \Psi|^2 |\partial_x^2 \Psi|^2 - 7 \int_{\mathbb{R}} \partial_x^2 \eta \langle \partial_x \Psi, \partial_x^3 \Psi \rangle \\ &\quad - 7 \int_{\mathbb{R}} |\partial_x \Psi|^2 \langle \partial_x \Psi, \partial_x^3 \Psi \rangle - \frac{35}{2} \int_{\mathbb{R}} \eta \partial_x^2 \eta |\partial_x \Psi|^2 - \frac{35}{4} \int_{\mathbb{R}} \eta^3 |\partial_x \Psi|^2 - \frac{35}{4} \int_{\mathbb{R}} \eta |\partial_x \Psi|^4 - \frac{7}{16} \int_{\mathbb{R}} \eta^5, \end{aligned}$$

are conserved along the Gross-Pitaevskii flow, provided that the initial datum Ψ_0 belongs to $X^4(\mathbb{R})$. Notice that, for $1 \leq k \leq 4$, the quantities E_k defined above give a control on the L^2 -norms of the functions $\partial_x^k \Psi$ and $\partial_x^{k-1} \eta$. As a matter of fact, invoking the Sobolev embedding theorem, one can establish that there exists some universal constant K such that

$$E_k(\psi) \leq K \left(\|\psi\|_{H^k(\mathbb{R})} + \|1 - |\psi|^2\|_{H^{k-1}(\mathbb{R})} \right)^{k+1},$$

for any function $\psi \in X^k(\mathbb{R})$. Similarly, there exists a positive constant $K(E_1(\psi), \dots, E_{k-1}(\psi))$, depending only on the quantities $E_1(\psi), \dots$ and $E_{k-1}(\psi)$, such that

$$\|\psi\|_{H^k(\mathbb{R})}^2 + \|1 - |\psi|^2\|_{H^{k-1}(\mathbb{R})}^2 \leq K(E_1(\psi), \dots, E_{k-1}(\psi)) E_k(\psi).$$

In particular, the conservation of the quantities $E_k(\Psi)$ along the Gross-Pitaevskii flow provides bounds on the Sobolev norms of the functions Ψ and η , which only depends on the X^k -norms of the initial datum Ψ_0 . In the rescaled variables, we obtain

Proposition 2.1 ([6]). *Let $0 \leq k \leq 3$ and $\varepsilon > 0$ be given sufficiently small. Assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+1}(\mathbb{R})$ and satisfies assumption (18) for some positive constant K_0 . Then, there exists a positive constant K , which does not depend on ε nor τ , such that*

$$\|N_\varepsilon(\cdot, \tau)\|_{H^k(\mathbb{R})} + \varepsilon \|\partial_x^{k+1} N_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} + \|\partial_x \Theta_\varepsilon(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K, \quad (2.1)$$

for any $\tau \in \mathbb{R}$.

Inequality (2.1) presents the advantage to be uniform in time. We will invoke this property to derive Lemma 2. We believe that inequality (2.1) remains valid for higher order Sobolev spaces. However, it seems rather involved to prove this claim since this requires to compute, or at least to describe precisely, the higher order invariants of (GP) (see [6] for more details).

In order to compute higher Sobolev bounds, we rely on the energy estimates derived in [3] in the context of the wave limit of the Gross-Pitaevskii equation mentioned above in the introduction. More precisely, given any $k \in \mathbb{N}$ and any positive number $E_0 < \frac{2\sqrt{2}}{3}$, we consider some initial datum $\Psi_0 \in X^k(\mathbb{R})$ such that $E(\Psi_0) \leq E_0$. Then, there exists a positive constant m_0 , depending only on E_0 , such that

$$m_0 \leq |\Psi(x, t)| \leq \frac{1}{m_0}, \quad (2.2)$$

for any $(x, t) \in \mathbb{R}^2$ (see [4] for more details). Under this additional assumption, the computation of energy estimates for system (8) achieved in Proposition 1 of [3], provides the inequality

$$\partial_t \Gamma_\varepsilon^k(t) \leq K(k, m_0) \varepsilon^2 (1 + \varepsilon^2 \|n_\varepsilon(\cdot, t)\|_{L^\infty}) (\|\partial_x n_\varepsilon(\cdot, t)\|_{L^\infty} + \|\partial_x y_\varepsilon(\cdot, t)\|_{L^\infty}) \left(\Gamma_\varepsilon^k(t) + \frac{\Gamma_\varepsilon^0(t)}{8} \right), \quad (2.3)$$

where $K(k, m_0)$ is some positive constant which does not depend on ε nor t , and where the function y_ε is defined by

$$y_\varepsilon = w_\varepsilon + \frac{i\varepsilon}{\sqrt{2}} \frac{\partial_x n_\varepsilon}{m_\varepsilon}, \quad \text{where } m_\varepsilon = 1 - \frac{\varepsilon^2}{6} n_\varepsilon,$$

while the notation $\Gamma_\varepsilon^k(t)$ refers to the functional

$$\Gamma_\varepsilon^k(t) \equiv \|\partial_x^k n_\varepsilon(\cdot, t)\|_{L^2(\mathbb{R})}^2 + \|m_\varepsilon(\cdot, t)^{\frac{1}{2}} \partial_x^k y_\varepsilon(\cdot, t)\|_{L^2(\mathbb{R})}^2. \quad (2.4)$$

In view of (2.2), and since we have

$$m_\varepsilon(x, t) = \left| \Psi\left(\frac{x}{\varepsilon}, \frac{t}{\varepsilon}\right) \right|,$$

the quantity Γ_ε^k controls the H^k -norms of n_ε and y_ε . Going back to the original setting, we have in particular,

$$\Gamma_\varepsilon^0(t) = \frac{144}{\varepsilon^3} E\left(\Psi\left(\cdot, \frac{t}{\varepsilon}\right)\right),$$

so that, by the conservation of the energy,

$$\Gamma_\varepsilon^0(t) = \frac{144}{\varepsilon^3} E(\Psi_0). \quad (2.5)$$

Proof of Proposition 2. In the case $k < 4$, Proposition 2 is a direct consequence of Proposition 2.1. In the case $k \geq 4$, the proof of Proposition 2 is obtained applying the Gronwall lemma to inequality (2.3), using identity (2.5) and bounds (2.1). We conclude rescaling the derived inequality in the variables N_ε and $\partial_x \Theta_\varepsilon$.

More precisely, invoking assumption (18) for $k = 0$, we first compute in the rescaled setting,

$$E(\Psi_0) = \frac{\varepsilon^3}{144} \int_{\mathbb{R}} \left(M_\varepsilon^0 (\partial_x \Theta_\varepsilon^0)^2 + (N_\varepsilon^0)^2 + \frac{\varepsilon^2 (\partial_x N_\varepsilon^0)^2}{2M_\varepsilon^0} \right) \leq K\varepsilon^3, \quad (2.6)$$

where $M_\varepsilon^0 \equiv 1 - \frac{\varepsilon^2}{6} N_\varepsilon^0$ and K is a positive constant depending only on K_0 . In particular, given any ε sufficiently small, assumption (2.2) holds for $m_0 = \frac{1}{2}$, so that in view of (2.3) and (2.5), we are led to

$$\Gamma_\varepsilon^k(t) \leq \Gamma_\varepsilon^k(0) \exp \left| \int_0^t A_\varepsilon(s) ds \right| + \frac{18}{\varepsilon^3} E(\Psi_0) \left(\exp \left| \int_0^t A_\varepsilon(s) ds \right| - 1 \right), \quad (2.7)$$

where

$$A_\varepsilon(t) \equiv K(k, m_0) \varepsilon^2 (1 + \varepsilon \|n_\varepsilon(\cdot, t)\|_{L^\infty(\mathbb{R})}) (\|\partial_x n_\varepsilon(\cdot, t)\|_{L^\infty(\mathbb{R})} + \|\partial_x y_\varepsilon(\cdot, t)\|_{L^\infty(\mathbb{R})}). \quad (2.8)$$

We now rescale inequality (2.7) in the variables N_ε and Θ_ε using the fact that

$$N_\varepsilon(x, \tau) = n_\varepsilon \left(x - \frac{4\tau}{\varepsilon^2}, \frac{2\sqrt{2}}{\varepsilon^2} \tau \right), \text{ and } \partial_x \Theta_\varepsilon(x, \tau) = w_\varepsilon \left(x - \frac{4\tau}{\varepsilon^2}, \frac{2\sqrt{2}}{\varepsilon^2} \tau \right).$$

In this scaling, definition (2.4) may be written as

$$\gamma_\varepsilon^k(\tau) \equiv \Gamma_\varepsilon^k \left(\frac{2\sqrt{2}\tau}{\varepsilon^2} \right) = \|\partial_x^k N_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}^2 + \|M_\varepsilon(\cdot, \tau)^{\frac{1}{2}} \partial_x^k Y_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}^2, \quad (2.9)$$

where $Y_\varepsilon \equiv \partial_x \Theta_\varepsilon + \frac{i\varepsilon}{\sqrt{2}} \frac{\partial_x N_\varepsilon}{M_\varepsilon}$ and $M_\varepsilon \equiv 1 - \frac{\varepsilon^2}{6} N_\varepsilon$. Similarly, definition (2.8) may be rescaled as

$$\mathcal{A}_\varepsilon(\cdot, \tau) \equiv \frac{2\sqrt{2}}{\varepsilon^2} A_\varepsilon \left(\frac{2\sqrt{2}\tau}{\varepsilon^2} \right) = K(k, m_0) (1 + \varepsilon \|N_\varepsilon(\cdot, \tau)\|_{L^\infty}) (\|\partial_x N_\varepsilon(\cdot, \tau)\|_{L^\infty} + \|\partial_x Y_\varepsilon(\cdot, \tau)\|_{L^\infty}),$$

so that inequality (2.7) becomes

$$\gamma_\varepsilon^k(\tau) \leq \gamma_\varepsilon^k(0) \exp \left| \int_0^\tau \mathcal{A}_\varepsilon(s) ds \right| + \frac{18}{\varepsilon^3} E(\Psi_0) \left(\exp \left| \int_0^\tau \mathcal{A}_\varepsilon(s) ds \right| - 1 \right).$$

Invoking assumption (18) for $k = 2$, and the Sobolev embedding theorem, Proposition 2.1 provides

$$|\mathcal{A}_\varepsilon(\cdot, \tau)| \leq K,$$

for any $\tau \in \mathbb{R}$, where K is some positive constant depending on k and K_0 . Hence, by (2.6),

$$\gamma_\varepsilon^k(\tau) \leq (\gamma_\varepsilon^k(0) + K) \exp K|\tau|.$$

The proof of (19) then follows from definition (2.9) and inequalities (2.2). Inequality (20) is a direct consequence of definitions (4) and (12). \square

2.2 Bounds in the space $\mathcal{M}(\mathbb{R})$

We turn first to the proof of Lemma 2. As mentioned in the introduction, inequality (32) is a rescaled version of inequality (31), using the Sobolev estimates of Proposition 2.1 to bound the integral on the right-hand side of (31).

Proof of Lemma 2. In view of definitions (3), inequality (31) may be recast in the variables N_ε and $\partial_x \Theta_\varepsilon$ as

$$\|N_\varepsilon(\cdot, \tau)\|_{\mathcal{M}(\mathbb{R})} + \|\partial_x \Theta_\varepsilon(\cdot, \tau)\|_{\mathcal{M}(\mathbb{R})} \leq \|N_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + \|\partial_x \Theta_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + K \left| \int_0^\tau \left(\|\partial_x^2 N_\varepsilon(\cdot, s)\|_{L^\infty(\mathbb{R})} + \|N_\varepsilon(\cdot, s)\|_{W^{2,\infty}(\mathbb{R})}^2 + \|\partial_x \Theta_\varepsilon(\cdot, s)\|_{L^\infty(\mathbb{R})}^2 \right) ds \right|,$$

so that by the Sobolev embedding theorem,

$$\|N_\varepsilon(\cdot, \tau)\|_{\mathcal{M}(\mathbb{R})} + \|\partial_x \Theta_\varepsilon(\cdot, \tau)\|_{\mathcal{M}(\mathbb{R})} \leq \|N_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + \|\partial_x \Theta_\varepsilon^0\|_{\mathcal{M}(\mathbb{R})} + K \left| \int_0^\tau \left(\|\partial_x^2 N_\varepsilon(\cdot, s)\|_{H^1(\mathbb{R})} + \|N_\varepsilon(\cdot, s)\|_{H^3(\mathbb{R})}^2 + \|\partial_x \Theta_\varepsilon(\cdot, s)\|_{H^1(\mathbb{R})}^2 \right) ds \right|. \quad (2.10)$$

Invoking assumption (18) for $k = 3$, we deduce from Proposition 2.1 that the integrand on the right-hand side of inequality (2.10) is bounded by some constant depending only on K_0 . This completes the proof of (32). Inequality (33) is then a direct consequence of definitions (4) and (12). \square

We next prove Lemma 1.

Proof of Lemma 1. The proof of Lemma 1 relies on the conservative form of the system of equations satisfied by η and $\partial_x \varphi$ which may be written as

$$\begin{cases} \partial_t \eta - 2\partial_x(\partial_x \varphi) = -2\partial_x(\eta \partial_x \varphi), \\ \partial_t(\partial_x \varphi) - \partial_x \eta = -\frac{1}{2}\partial_x^3 \eta - \partial_x \left(|\partial_x \varphi|^2 + \frac{\eta \partial_x^2 \eta}{2(1-\eta)} + \frac{(\partial_x \eta)^2}{4(1-\eta)^2} \right). \end{cases} \quad (2.11)$$

As already mentioned in the introduction, we recognize on the left-hand side of (2.11), a transport operator \mathcal{T} , given by

$$\mathcal{T} = (\partial_t - 2\partial_x, \partial_t - \partial_x).$$

Introducing the variables

$$u = \frac{1}{2}(\eta + \sqrt{2}\partial_x \varphi), \quad \text{and} \quad v = \frac{1}{2}(\eta - \sqrt{2}\partial_x \varphi), \quad (2.12)$$

we diagonalize the transport operator \mathcal{T} , so that (2.11) becomes

$$\begin{cases} \partial_t u - \sqrt{2}\partial_x u = -\partial_x(\eta \partial_x \varphi) - \frac{\sqrt{2}}{4}\partial_x^3 \eta - \sqrt{2}\partial_x \left(\frac{1}{2}|\partial_x \varphi|^2 + \frac{\eta \partial_x^2 \eta}{4(1-\eta)} + \frac{(\partial_x \eta)^2}{8(1-\eta)^2} \right), \\ \partial_t v + \sqrt{2}\partial_x v = -\partial_x(\eta \partial_x \varphi) + \frac{\sqrt{2}}{4}\partial_x^3 \eta + \sqrt{2}\partial_x \left(\frac{1}{2}|\partial_x \varphi|^2 + \frac{\eta \partial_x^2 \eta}{4(1-\eta)} + \frac{(\partial_x \eta)^2}{8(1-\eta)^2} \right). \end{cases} \quad (2.13)$$

Given any real numbers $a < b$, we deduce from the first equation of (2.13) that

$$\partial_t \left(\int_a^b u(x - \sqrt{2}t, t) dx \right) = \left[-\eta \partial_x \varphi - \frac{\sqrt{2}}{4}\partial_x^2 \eta - \sqrt{2} \left(\frac{1}{2}|\partial_x \varphi|^2 + \frac{\eta \partial_x^2 \eta}{4(1-\eta)} + \frac{(\partial_x \eta)^2}{8(1-\eta)^2} \right) \right]_{a-\sqrt{2}t}^{b-\sqrt{2}t}.$$

At this stage, it is worthwhile to recall that, since $E(\Psi_0) \leq E_0$, inequalities (2.2) hold for some positive number m_0 , depending only on E_0 , so that

$$\left| \partial_t \left(\int_a^b u(x - \sqrt{2}t, t) dx \right) \right| \leq K \left(\|\partial_x^2 \eta(\cdot, t)\|_{L^\infty(\mathbb{R})} + \|\eta(\cdot, t)\|_{W^{2,\infty}(\mathbb{R})}^2 + \|\partial_x \varphi(\cdot, t)\|_{L^\infty(\mathbb{R})}^2 \right),$$

where K is some positive constant, depending only on E_0 . Performing an integration in time, this may be recast as

$$\begin{aligned} \left| \int_a^b u(x - \sqrt{2}t, t) dx \right| &\leq \left| \int_a^b u(x, 0) dx \right| \\ &+ K \left| \int_0^t \left(\|\partial_x^2 \eta(\cdot, s)\|_{L^\infty(\mathbb{R})} + \|\eta(\cdot, s)\|_{W^{2,\infty}(\mathbb{R})}^2 + \|\partial_x \varphi(\cdot, s)\|_{L^\infty(\mathbb{R})}^2 \right) ds \right|. \end{aligned} \quad (2.14)$$

Applying the change of coordinates $y = x - \sqrt{2}t$ to the left-hand side of (2.14), and invoking definition (2), we are led to

$$\|u(\cdot, t)\|_{\mathcal{M}(\mathbb{R})} \leq \|u(\cdot, 0)\|_{\mathcal{M}(\mathbb{R})} + K \left| \int_0^t \left(\|\partial_x^2 \eta(\cdot, s)\|_{L^\infty(\mathbb{R})} + \|\eta(\cdot, s)\|_{W^{2,\infty}(\mathbb{R})}^2 + \|\partial_x \varphi(\cdot, s)\|_{L^\infty(\mathbb{R})}^2 \right) ds \right|.$$

The same proof applies to the second equation in (2.13) and this provides the same inequality for the function v . Combining with definitions (2.12), inequality (31) follows. \square

3 Estimates for the interaction terms

This section is devoted to the proof of Proposition 3 which provides estimates of the interaction term $\int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon$ in (23).

3.1 Proof of Proposition 3

Given any integer k and any number τ , the interaction term $\int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon$ may be written in view of definition (14),

$$\int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon = \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} \left(\frac{1}{6} V_\varepsilon^2 - \partial_x^2 V_\varepsilon + \frac{1}{3} U_\varepsilon V_\varepsilon \right) \partial_x^k Z_\varepsilon,$$

so that by the Leibniz formula,

$$\int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon = I_\varepsilon(\tau) + J_\varepsilon(\tau), \quad (3.1)$$

where we denote

$$I_\varepsilon(\tau) \equiv \int_0^\tau \int_{\mathbb{R}} \left(\frac{1}{6} \partial_x^{k+1} (V_\varepsilon^2) - \partial_x^{k+3} V_\varepsilon + \frac{1}{3} \sum_{j=0}^k C_{k+1}^j \partial_x^j U_\varepsilon \partial_x^{k+1-j} V_\varepsilon \right) \partial_x^k Z_\varepsilon,$$

and

$$J_\varepsilon(\tau) \equiv \frac{1}{3} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon V_\varepsilon \partial_x^k Z_\varepsilon. \quad (3.2)$$

In view of (3.1), the proof of Proposition 3 reduces to bound each term in the integrals $I_\varepsilon(\tau)$ and $J_\varepsilon(\tau)$ combining the estimates of Proposition 2 and Lemma 2 with some Hölder inequality and Sobolev embedding theorems. In particular, we will repetitively invoke the following bounds of the nonlinear functions f_ε , g_ε , r_ε , F_ε , G_ε and R_ε , as well as the following estimates of the time derivative $\partial_\tau U_\varepsilon$, and of the solution \mathcal{U} to (KdV) with initial datum U_ε^0 .

Lemma 3.1. *Let $\varepsilon > 0$ be given sufficiently small. Given any $k \in \mathbb{N}$, assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+6}(\mathbb{R})$ and satisfies (10) for some positive constant K_0 . Then, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} & \|\partial_\tau U_\varepsilon(\cdot, \tau)\|_{H^{k+2}(\mathbb{R})} + \|f_\varepsilon(\cdot, \tau)\|_{H^{k+2}(\mathbb{R})} + \|g_\varepsilon(\cdot, \tau)\|_{H^{k+2}(\mathbb{R})} + \|r_\varepsilon(\cdot, \tau)\|_{H^{k+2}(\mathbb{R})} \\ & + \|F_\varepsilon(\cdot, \tau)\|_{H^{k+3}(\mathbb{R})} + \|G_\varepsilon(\cdot, \tau)\|_{H^{k+3}(\mathbb{R})} + \|R_\varepsilon(\cdot, \tau)\|_{H^{k+3}(\mathbb{R})} \leq K \exp K|\tau|, \end{aligned} \quad (3.3)$$

for any $\tau \in \mathbb{R}$. Similarly, there exists a positive constant K depending only on K_0 such that

$$\|\partial_\tau \mathcal{U}(\cdot, \tau)\|_{H^{k+2}(\mathbb{R})} + \|\mathcal{U}(\cdot, \tau)\|_{H^{k+5}(\mathbb{R})} \leq K, \quad (3.4)$$

for any $\tau \in \mathbb{R}$. In particular, we have

$$\|\partial_\tau Z_\varepsilon(\cdot, \tau)\|_{H^{k+2}(\mathbb{R})} + \|Z_\varepsilon(\cdot, \tau)\|_{H^{k+5}(\mathbb{R})} \leq K \exp K|\tau|, \quad (3.5)$$

for any $\tau \in \mathbb{R}$.

Notice that the estimates of Lemma 3.1 do not contain any ε^2 factor. In order to make apparent such a factor, we rely on equations (15) and (30). Indeed, in view of (15) and (30), the space derivative of the functions V_ε and Υ_ε may be replaced by the time derivative of V_ε and Υ_ε respectively, up to some remainder terms, the whole being multiplied by the desired ε^2 factor.

Concerning the integral I_ε , all of its terms involve space derivatives of V_ε , so that we may invoke the argument above to gain a ε^2 factor. More precisely, we obtain

Lemma 3.2. *Let $\varepsilon > 0$ be given sufficiently small. Given any $k \in \mathbb{N}$, assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+6}(\mathbb{R})$ and satisfies (10) for some positive constant K_0 . Then, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} & \left| I_\varepsilon(\tau) - \frac{\varepsilon^2}{24} \sum_{j=1}^k C_k^{j-1} \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^j U_\varepsilon \right| \\ & \leq K \varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right), \end{aligned} \quad (3.6)$$

for any $\tau \in \mathbb{R}$.

The sum in the first line of (3.6), namely

$$\sum_{j=1}^k C_k^{j-1} \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^j U_\varepsilon \quad (3.7)$$

corresponds to some remainder terms mentioned above in the computation of the space derivatives of V_ε , related to the computation of the term

$$\sum_{j=0}^k C_{k+1}^j \partial_x^j U_\varepsilon \partial_x^{k+1-j} V_\varepsilon \partial_x^k Z_\varepsilon,$$

appearing in I_ε . The estimates of the sum (3.7) is more involved, so that we postpone its analysis in Lemma 3.4 below.

In contrast, the integral J_ε does not contain any derivative of V_ε . Our argument does not rely anymore on (15), but instead we introduce the function Υ_ε in the right-hand side of (3.2) for some suitably chosen number R . We then invoke (30) to gain some ε^2 factor. This provides

Lemma 3.3. *Let $\varepsilon > 0$ be given sufficiently small. Given any $k \in \mathbb{N}$, we assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+6}(\mathbb{R})$ and satisfies (5) for some positive constant K_0 . Then, given any $\tau \in \mathbb{R}$, there exist a positive number R_1 and a positive constant K , depending only on K_0 and k , such that*

$$\begin{aligned} & \left| J_\varepsilon(\tau) - \frac{\varepsilon^2}{24} \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \Upsilon_\varepsilon \partial_x^{k+1} U_\varepsilon \right| \\ & \leq K \varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right), \end{aligned} \quad (3.8)$$

for any choice of the number R of definition (29) in $(R_1, +\infty)$.

Once again, the integral on the left-hand side of (3.8) corresponds to some of the extra remainder terms in (30). The estimates of this integral are also more involved, so that we postpone its analysis in Lemma 3.4 below.

In order to achieve the proof of Proposition 3, it remains to estimate the interactions terms

$$K_\varepsilon(\tau) \equiv \frac{\varepsilon^2}{24} \int_0^\tau \int_{\mathbb{R}} \left(\partial_x^k f_\varepsilon \Upsilon_\varepsilon \partial_x^{k+1} U_\varepsilon + \sum_{j=1}^k C_k^{j-1} \partial_x^k f_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^j U_\varepsilon \right), \quad (3.9)$$

which appear on the left-hand side of (3.6) and (3.8). Using the bounds of Proposition 2 and Lemmas 2 and 3.1, we compute the estimate

$$|K_\varepsilon(\tau)| \leq K \varepsilon^2 \exp K|\tau|,$$

for any $\tau \in \mathbb{R}$. However, this bound is not sufficient to complete the proof of Theorem 1, since it would provide an ε factor instead of an ε^2 factor in (7). In order to gain some further ε factor, we iterate the argument, and replace once more the space derivatives of V_ε and Υ_ε , which appear in the expression of $K_\varepsilon(\tau)$, by the time derivatives of V_ε , respectively Υ_ε , plus some additional remainder terms. We obtain

Lemma 3.4. *Let $\varepsilon > 0$ be given sufficiently small. Given any $k \in \mathbb{N}$, assume that the initial datum $\Psi_0(\cdot) = \Psi(\cdot, 0)$ belongs to $X^{k+6}(\mathbb{R})$ and satisfies (5) for some positive constant K_0 . Then, given any $\tau \in \mathbb{R}$, there exist a positive number R_2 and a positive constant K , depending only on K_0 and k , such that*

$$|K_\varepsilon(\tau)| \leq K \varepsilon^4 \exp K|\tau|, \quad (3.10)$$

for any choice of the number R of definition (29) in $(R_2, +\infty)$.

Proposition 3 follows combining Lemmas 3.2, 3.3 and 3.4.

Proof of Proposition 3 completed. Given any $\tau \in \mathbb{R}$, we first fix the number R such that (3.8) and (3.10) hold. Then, in view of (3.1), (3.6), (3.8) and (3.9), we have

$$\begin{aligned} & \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon - K_\varepsilon(\tau) \right| \\ & \leq K \varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right), \end{aligned}$$

so that (27) is a direct consequence of (3.10). This concludes the proof of Proposition 3. \square

The rest of this section is devoted to the proofs of Lemmas 3.1, 3.2, 3.3 and 3.4.

3.2 Proof of Lemma 3.1

Concerning the nonlinear functions f_ε , F_ε , g_ε and G_ε , it follows from definitions (14) and (16), the Leibniz formula, the Hölder inequality and the Sobolev embedding theorem that

$$\begin{aligned} & \|f_\varepsilon\|_{H^k(\mathbb{R})} + \|g_\varepsilon\|_{H^k(\mathbb{R})} + \|F_\varepsilon\|_{H^{k+1}(\mathbb{R})} + \|G_\varepsilon\|_{H^{k+1}(\mathbb{R})} \\ & \leq K \left(\|U_\varepsilon\|_{H^{k+3}(\mathbb{R})} + \|V_\varepsilon\|_{H^{k+3}(\mathbb{R})} + \left(\|U_\varepsilon\|_{H^{k+1}(\mathbb{R})} + \|V_\varepsilon\|_{H^{k+1}(\mathbb{R})} \right)^2 \right), \end{aligned} \quad (3.11)$$

where K is some positive constant depending only on k . Similarly for r_ε and R_ε , we have in view of (17),

$$\begin{aligned} \|r_\varepsilon\|_{H^k(\mathbb{R})} + \|R_\varepsilon\|_{H^{k+1}(\mathbb{R})} & \leq K \|N_\varepsilon\|_{H^{k+1}(\mathbb{R})}^{k+2} \|N_\varepsilon\|_{H^{k+3}(\mathbb{R})} \\ & \leq K \left(\|U_\varepsilon\|_{H^{k+1}(\mathbb{R})} + \|V_\varepsilon\|_{H^{k+1}(\mathbb{R})} \right)^{k+2} \left(\|U_\varepsilon\|_{H^{k+3}(\mathbb{R})} + \|V_\varepsilon\|_{H^{k+3}(\mathbb{R})} \right). \end{aligned} \quad (3.12)$$

Notice that for (3.12), we also invoke the bound

$$m_0 \leq 1 - \frac{\varepsilon^2}{6} N_\varepsilon \leq \frac{1}{m_0},$$

which is a consequence of (2.2). Combining (3.11) and (3.12) with the bounds of Proposition 2, we obtain (3.3), except for the time derivative $\partial_\tau U_\varepsilon$. For this function, we have in view of (13),

$$\|\partial_\tau U_\varepsilon\|_{H^k(\mathbb{R})} \leq \|U_\varepsilon\|_{H^{k+3}(\mathbb{R})} + \|U_\varepsilon\|_{H^{k+1}(\mathbb{R})}^2 + \|f_\varepsilon\|_{H^k(\mathbb{R})} + \varepsilon^2 \|r_\varepsilon\|_{H^k(\mathbb{R})},$$

so that the bound for $\partial_\tau U_\varepsilon$ follows from the previous bounds on f_ε and r_ε combined with the bound on U_ε of Proposition 2.

For the uniform bound (3.4) on \mathcal{U} , we invoke the integrability properties of the Korteweg-de Vries equation. As a matter of fact, equation (KdV) owns an infinite number of invariant quantities which control the H^k -norms of the solutions (see e.g. [11]). Therefore, the H^k -norm of a solution \mathcal{U} at time τ is controlled by the H^k -norm of its initial datum $\mathcal{U}^0 = U_\varepsilon^0$. More precisely, there exists a positive constant K , depending only on $\|U_\varepsilon^0\|_{H^k(\mathbb{R})}$, such that

$$\|\mathcal{U}(\cdot, t)\|_{H^k(\mathbb{R})} \leq K,$$

for any $t \in \mathbb{R}$ (see [8]). This control is uniform with respect to ε provided that $\|U_\varepsilon^0\|_{H^k(\mathbb{R})}$ is bounded independently of ε . Since \mathcal{U} solves the Korteweg-de Vries equation, the H^{k-3} -norm of $\partial_\tau \mathcal{U}$ is then uniformly bounded with respect to ε . Thus, under assumption (5), we obtain inequality (3.4). Estimate (3.5) follows combining the definition of Z_ε with (3.3) and (3.4).

3.3 Proof of Lemma 3.2

Given any $\tau \in \mathbb{R}$, we split the expression of $I_\varepsilon(\tau)$ into three terms

$$I_\varepsilon(\tau) = I_1(\tau) + I_2(\tau) + I_3(\tau), \quad (3.13)$$

where

$$\begin{aligned} I_1(\tau) & \equiv \frac{1}{6} \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^{k+1} (V_\varepsilon^2), \\ I_2(\tau) & \equiv - \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^{k+3} V_\varepsilon, \end{aligned} \quad (3.14)$$

and

$$I_3(\tau) \equiv \frac{1}{3} \sum_{j=0}^k C_{k+1}^j \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^j U_\varepsilon \partial_x^{k+1-j} V_\varepsilon.$$

We now compute estimates of each term $I_k(\tau)$. For the first one, we have

Step 1. *Under the assumptions of Lemma 3.3, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} & \left| I_1(\tau) - \frac{\varepsilon^2}{48} \int_0^\tau \int_{\mathbb{R}} \partial_x^k (V_\varepsilon^2) \partial_x^k f_\varepsilon \right| \\ & \leq K \varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right). \end{aligned} \quad (3.15)$$

In order to obtain the ε^2 factor on the right-hand side of (3.15), we write the transport equation satisfied by $\partial_x^k (V_\varepsilon^2)$, namely

$$\partial_x \left(\partial_x^k (V_\varepsilon^2) \right) = -\frac{\varepsilon^2}{8} \partial_\tau \left(\partial_x^k (V_\varepsilon^2) \right) + \frac{\varepsilon^2}{4} \partial_x^k (g_\varepsilon V_\varepsilon) + \frac{\varepsilon^4}{4} \partial_x^k (r_\varepsilon V_\varepsilon), \quad (3.16)$$

and replace $\partial_x^{k+1} (V_\varepsilon^2)$ in (3.14) by its expression provided by (3.16). Integrating by parts in time and using the fact that $Z_\varepsilon^0 = 0$, the integral $I_1(\tau)$ becomes

$$\begin{aligned} I_1(\tau) &= -\frac{\varepsilon^2}{48} \int_{\mathbb{R}} \partial_x^k Z_\varepsilon(x, \tau) \partial_x^k (V_\varepsilon^2)(x, \tau) dx + \frac{\varepsilon^2}{48} \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^k Z_\varepsilon \partial_x^k (V_\varepsilon^2) \\ & \quad + \frac{\varepsilon^2}{24} \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^k (g_\varepsilon V_\varepsilon) + \frac{\varepsilon^4}{24} \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^k (r_\varepsilon V_\varepsilon). \end{aligned} \quad (3.17)$$

We now apply the Leibniz formula, the Hölder inequality and the Sobolev embedding theorem to obtain for the first term on the right-hand side of (3.17),

$$\left| \int_{\mathbb{R}} \partial_x^k Z_\varepsilon(x, \tau) \partial_x^k (V_\varepsilon^2)(x, \tau) dx \right| \leq K \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \|V_\varepsilon(\cdot, \tau)\|_{H^k(\mathbb{R})} \|V_\varepsilon(\cdot, \tau)\|_{H^{k+1}(\mathbb{R})}.$$

Hence, we deduce from (20) that there exists a positive constant K depending only on K_0 and k , such that

$$\left| \int_{\mathbb{R}} \partial_x^k Z_\varepsilon(x, \tau) \partial_x^k (V_\varepsilon^2)(x, \tau) dx \right| \leq K \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \exp K|\tau|. \quad (3.18)$$

Similarly, in view of Lemma 3.1, we have for the third and fourth terms

$$\begin{aligned} & \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^k (g_\varepsilon V_\varepsilon) \right| + \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^k (r_\varepsilon V_\varepsilon) \right| \\ & \leq K \left| \int_0^\tau \|\partial_x^k Z_\varepsilon\|_{L^2(\mathbb{R})} \|V_\varepsilon\|_{H^{k+1}(\mathbb{R})} (\|r_\varepsilon\|_{H^k(\mathbb{R})} + \|g_\varepsilon\|_{H^k(\mathbb{R})}) \right| \\ & \leq K \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|. \end{aligned} \quad (3.19)$$

The analysis of the second term on the right-hand side of (3.17) is more involved since estimate (3.15) requires to gain some further ε^2 factor. We first replace $\partial_\tau \partial_x^k Z_\varepsilon$ by its expression given by (21). We obtain

$$\int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^k Z_\varepsilon \partial_x^k (V_\varepsilon^2) = I_1^1(\tau) + I_1^2(\tau) + \int_0^\tau \int_{\mathbb{R}} \partial_x^k (V_\varepsilon^2) \partial_x^k f_\varepsilon, \quad (3.20)$$

where

$$I_1^1(\tau) \equiv - \int_0^\tau \int_{\mathbb{R}} \partial_x^k (V_\varepsilon^2) \left(\partial_x^{k+3} Z_\varepsilon + \partial_x^{k+1} (\mathcal{U} Z_\varepsilon) + \frac{1}{2} \partial_x^{k+1} (Z_\varepsilon^2) \right),$$

and

$$I_1^2(\tau) \equiv -\varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^k (V_\varepsilon^2) \partial_x^k r_\varepsilon.$$

We then estimate each of the above integral $I_1^j(\tau)$. Integrating by parts in space the first one, we have

$$I_1^1(\tau) = \int_0^\tau \int_{\mathbb{R}} \left(\partial_x^{k+3} (V_\varepsilon^2) \partial_x^k Z_\varepsilon + \partial_x^{k+1} (V_\varepsilon^2) \partial_x^k (\mathcal{U} Z_\varepsilon) + \frac{1}{2} \partial_x^{k+1} (V_\varepsilon^2) \partial_x^k (Z_\varepsilon^2) \right),$$

so that, using again the Leibniz formula, the Hölder inequality and the Sobolev embedding theorem,

$$|I_1^1(\tau)| \leq \left| \int_0^\tau \|V_\varepsilon\|_{H^{k+2}(\mathbb{R})} \|Z_\varepsilon\|_{H^k(\mathbb{R})} \left(\|V_\varepsilon\|_{H^{k+3}(\mathbb{R})} + \|V_\varepsilon\|_{H^{k+1}(\mathbb{R})} (\|\mathcal{U}\|_{H^{k+1}(\mathbb{R})} + \|Z_\varepsilon\|_{H^{k+1}(\mathbb{R})}) \right) ds \right|.$$

In view of the bounds of Proposition 2 and Lemma 3.1, we are led to

$$|I_1^1(\tau)| \leq K \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|. \quad (3.21)$$

Similarly, in view of the bounds of Proposition 2 and Lemma 3.1, we compute

$$|I_1^2(\tau)| \leq K\varepsilon^2 \left| \int_0^\tau \|V_\varepsilon\|_{H^k(\mathbb{R})} \|V_\varepsilon\|_{H^{k+1}(\mathbb{R})} \|r_\varepsilon\|_{H^k(\mathbb{R})} ds \right| \leq K\varepsilon^2 \exp K|\tau|. \quad (3.22)$$

Combining (3.20) with (3.21) and (3.22), we are led to

$$\begin{aligned} & \left| \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^k Z_\varepsilon \partial_x^k (V_\varepsilon^2) - \int_0^\tau \int_{\mathbb{R}} \partial_x^k (V_\varepsilon^2) \partial_x^k f_\varepsilon \right| \\ & \leq K \left(\varepsilon^2 \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right). \end{aligned}$$

In view of (3.17), (3.18) and (3.19), this completes the proof of Step 1.

We now turn to the integral $I_2(\tau)$ for which we have

Step 2. *Under the assumptions of Lemma 3.3, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} & \left| I_2(\tau) + \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} V_\varepsilon \partial_x^k f_\varepsilon \right| \\ & \leq K\varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right). \end{aligned} \quad (3.23)$$

The proof is similar to the proof of Step 1. In view of (15), we have integrating by parts in time and using the fact that $Z_\varepsilon^0 = 0$,

$$\begin{aligned} I_2(\tau) &= \frac{\varepsilon^2}{8} \int_{\mathbb{R}} \partial_x^k Z_\varepsilon(x, \tau) \partial_x^{k+2} V_\varepsilon(x, \tau) dx - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^k Z_\varepsilon \partial_x^{k+2} V_\varepsilon \\ & \quad - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} g_\varepsilon \partial_x^k Z_\varepsilon - \frac{\varepsilon^4}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} r_\varepsilon \partial_x^k Z_\varepsilon. \end{aligned} \quad (3.24)$$

Similarly to (3.18), we compute for the first term on the right-hand side of (3.24),

$$\left| \int_{\mathbb{R}} \partial_x^k Z_\varepsilon(x, \tau) \partial_x^{k+2} V_\varepsilon(x, \tau) dx \right| \leq K \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \exp K|\tau|, \quad (3.25)$$

while for the third and fourth terms, we have similarly to (3.19),

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} g_\varepsilon \partial_x^k Z_\varepsilon \right| + \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} r_\varepsilon \partial_x^k Z_\varepsilon \right| \leq K \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds. \quad (3.26)$$

Concerning the second term on the right-hand side of (3.24), we replace as above $\partial_\tau \partial_x^k Z_\varepsilon$ by its expression given by (21). This leads to

$$\int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^k Z_\varepsilon \partial_x^{k+2} V_\varepsilon = I_2^1(\tau) + I_2^2(\tau) + \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} V_\varepsilon \partial_x^k f_\varepsilon, \quad (3.27)$$

where

$$I_2^1(\tau) \equiv - \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} V_\varepsilon \left(\partial_x^{k+3} Z_\varepsilon + \partial_x^{k+1} (U Z_\varepsilon) + \frac{1}{2} \partial_x^{k+1} (Z_\varepsilon^2) \right),$$

and

$$I_2^2(\tau) \equiv -\varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} V_\varepsilon \partial_x^k r_\varepsilon.$$

Following the lines of the proofs of (3.21) and (3.22), we obtain

$$|I_2^1(\tau)| \leq K \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|.$$

and

$$|I_2^2(\tau)| \leq K \varepsilon^2 \exp K|\tau|.$$

By (3.27), we are led to

$$\begin{aligned} & \left| \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^k Z_\varepsilon \partial_x^{k+2} V_\varepsilon - \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} V_\varepsilon \partial_x^k f_\varepsilon \right| \\ & \leq K \left(\varepsilon^2 \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right). \end{aligned}$$

Estimate (3.23) follows combining with (3.24), (3.25) and (3.26).

We finally consider the finite sum $I_3(\tau)$.

Step 3. *Under the assumptions of Lemma 3.3, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} & \left| I_3(\tau) - \frac{\varepsilon^2}{24} \int_0^\tau \int_{\mathbb{R}} \partial_x^k (U_\varepsilon V_\varepsilon) \partial_x^k f_\varepsilon - \frac{\varepsilon^2}{24} \sum_{j=1}^k C_k^{j-1} \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^j U_\varepsilon \right| \\ & \leq K \varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right). \end{aligned} \quad (3.28)$$

The proof is similar to the proof of Steps 1 and 2. In view of (15), we have integrating by parts in time,

$$\begin{aligned} I_3(\tau) &= \frac{\varepsilon^2}{24} \sum_{j=0}^k C_{k+1}^j \left(- \int_{\mathbb{R}} \partial_x^k Z_\varepsilon(x, \tau) \partial_x^j U_\varepsilon(x, \tau) \partial_x^{k-j} V_\varepsilon(x, \tau) dx + \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^k Z_\varepsilon \partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon \right. \\ & \quad \left. + \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_\tau \partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon + \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^j U_\varepsilon \partial_x^{k-j} g_\varepsilon + \varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^j U_\varepsilon \partial_x^{k-j} r_\varepsilon \right). \end{aligned} \quad (3.29)$$

The estimates of the first, fourth and fifth integrals on the right-hand side of (3.29) are similar to (3.18) and (3.25) for the first one, (3.19) and (3.26), for the other ones. More precisely, we obtain

$$\left| \int_{\mathbb{R}} \partial_x^k Z_\varepsilon(x, \tau) \partial_x^j U_\varepsilon(x, \tau) \partial_x^{k-j} V_\varepsilon(x, \tau) dx \right| \leq K \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \exp K|\tau|, \quad (3.30)$$

respectively

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^j U_\varepsilon \partial_x^{k-j} g_\varepsilon \right| + \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_x^j U_\varepsilon \partial_x^{k-j} r_\varepsilon \right| \leq K \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|. \quad (3.31)$$

Similarly, for the third integral, we have

$$\begin{aligned} \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k Z_\varepsilon \partial_\tau \partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon \right| &\leq \left| \int_0^\tau \|\partial_x^k Z_\varepsilon\|_{L^2(\mathbb{R})} \|\partial_\tau U_\varepsilon\|_{H^k(\mathbb{R})} \|V_\varepsilon\|_{H^{k+1}(\mathbb{R})} \right| \\ &\leq K \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|, \end{aligned} \quad (3.32)$$

where we invoke (3.3) to bound the time derivative $\partial_\tau \partial_x^j U_\varepsilon$.

The second term on the right-hand side of (3.29) is more involved to estimate. We first introduce as above the expression of $\partial_\tau \partial_x^k Z_\varepsilon$ given by (21), so that

$$\sum_{j=0}^k C_{k+1}^j \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^k Z_\varepsilon \partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon = I_3^1(\tau) + I_3^2(\tau) + I_3^3(\tau), \quad (3.33)$$

where

$$I_3^1(\tau) \equiv - \sum_{j=0}^k C_{k+1}^j \int_0^\tau \int_{\mathbb{R}} \partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon \left(\partial_x^{3+k} Z_\varepsilon + \partial_x^{k+1} (\mathcal{U} Z_\varepsilon) + \partial_x^k (Z_\varepsilon \partial_x Z_\varepsilon) \right),$$

$$I_3^2(\tau) \equiv \sum_{j=0}^k C_{k+1}^j \int_0^\tau \int_{\mathbb{R}} \partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^k f_\varepsilon,$$

and

$$I_3^3(\tau) \equiv -\varepsilon^2 \sum_{j=0}^k C_{k+1}^j \int_0^\tau \int_{\mathbb{R}} \partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^k r_\varepsilon.$$

We then estimate each of the above sum $I_3^j(\tau)$. Integrating by parts in space the integrals in $I_3^1(\tau)$, we obtain

$$I_3^1(\tau) = \sum_{j=0}^k C_{k+1}^j \int_0^\tau \int_{\mathbb{R}} \left(\partial_x^3 \left(\partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon \right) \partial_x^k Z_\varepsilon + \partial_x \left(\partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon \right) \left(\partial_x^k (\mathcal{U} Z_\varepsilon) + \frac{1}{2} \partial_x^k (Z_\varepsilon^2) \right) \right).$$

Following the lines of the proof of (3.21), we are led to

$$|I_3^1(\tau)| \leq K \left| \int_0^\tau \int_{\mathbb{R}} \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|. \quad (3.34)$$

Concerning the integral $I_3^3(\tau)$, we have as in the proof of (3.22),

$$|I_3^3(\tau)| \leq K \varepsilon^2 \exp K|\tau|. \quad (3.35)$$

Finally, applying the Pascal rule and the Leibniz formula to $I_3^2(\tau)$, we obtain

$$I_3^2(\tau) = \int_0^\tau \int_{\mathbb{R}} \partial_x^k (U_\varepsilon V_\varepsilon) \partial_x^k f_\varepsilon + \sum_{j=1}^k C_k^{j-1} \int_0^\tau \int_{\mathbb{R}} \partial_x^j U_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^k f_\varepsilon.$$

Combining with (3.29), (3.30), (3.31), (3.32), (3.33), (3.34) and (3.35), estimate (3.28) follows.

We are now in position to complete the proof of Lemma 3.2.

End of the proof of Lemma 3.2. In view of identity (3.13), and estimates (3.15), (3.23) and (3.28), we have

$$\begin{aligned} & \left| I_\varepsilon(\tau) - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k \left(\frac{1}{6} V_\varepsilon^2 - \partial_x^2 V_\varepsilon + \frac{1}{3} U_\varepsilon V_\varepsilon \right) - \frac{\varepsilon^2}{24} \sum_{j=1}^k C_k^{j-1} \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^j U_\varepsilon \right| \\ & \leq K \varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right). \end{aligned} \quad (3.36)$$

On the other hand, in view of the definition of f_ε ,

$$\int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k \left(\frac{1}{6} V_\varepsilon^2 - \partial_x^2 V_\varepsilon + \frac{1}{3} U_\varepsilon V_\varepsilon \right) = \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} F_\varepsilon \partial_x^k F_\varepsilon = 0.$$

Combining with (3.36), this completes the proof of (3.6). \square

3.4 Proof of Lemma 3.3

The proof is similar to the proof of Lemma 3.2. Given any $\tau \in \mathbb{R}$, we introduce the function Υ_ε in the expression of the integral $J_\varepsilon(\tau)$. In view of (3.0) and (3.2), this yields

$$J_\varepsilon(\tau) = \frac{1}{3} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \partial_x^k Z_\varepsilon \partial_x \Upsilon_\varepsilon = \frac{1}{3} (J_1(\tau) + J_2(\tau) + J_3(\tau)), \quad (3.37)$$

where

$$\begin{aligned} J_1(\tau) & \equiv -\frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \partial_x^k Z_\varepsilon \partial_\tau \Upsilon_\varepsilon, \\ J_2(\tau) & \equiv \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \partial_x^k Z_\varepsilon (G_\varepsilon + \varepsilon^2 R_\varepsilon), \end{aligned} \quad (3.38)$$

and

$$J_3(\tau) \equiv \int_0^\tau \left(V_\varepsilon(-R, s) - \frac{\varepsilon^2}{8} (G_\varepsilon(-R, s) + \varepsilon^2 R_\varepsilon(-R, s)) \right) \left(\int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon(x, s) \partial_x^k Z_\varepsilon(x, s) dx \right) ds. \quad (3.39)$$

We now consider each of the above integrals $J_k(\tau)$. For the first one, we have

Step 1. *Under the assumptions of Lemma 3.3, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} & \left| J_1(\tau) - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \Upsilon_\varepsilon \partial_x^k f_\varepsilon \right| \\ & \leq K \varepsilon^2 \left((\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right). \end{aligned} \quad (3.40)$$

We first integrate by parts in time the integral $J_1(\tau)$, and use the fact that $Z_\varepsilon^0 = 0$ to derive

$$\begin{aligned} J_1(\tau) &= -\frac{\varepsilon^2}{8} \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon(x, \tau) \partial_x^k Z_\varepsilon(x, \tau) \Upsilon_\varepsilon(x, \tau) dx + \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} \partial_\tau U_\varepsilon \partial_x^k Z_\varepsilon \Upsilon_\varepsilon \\ &\quad + \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \partial_\tau \partial_x^k Z_\varepsilon \Upsilon_\varepsilon. \end{aligned} \quad (3.41)$$

We then invoke Proposition 2 and Lemmas 2 and 3.1 to bound each term on the right-hand side of (3.41). Notice in particular that in view of assumption (5), Lemma 2 provides

$$\|\Upsilon_\varepsilon(\cdot, s)\|_{L^\infty(\mathbb{R})} \leq \|V_\varepsilon(\cdot, s)\|_{\mathcal{M}(\mathbb{R})} \leq K(1 + |s|), \quad (3.42)$$

where K denotes some positive constant, possibly depending on K_0 , but neither on ε nor s .

Hence, applying the Hölder inequality to the first term on the right-hand side of (3.41), we are led to

$$\left| \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon(x, \tau) \partial_x^k Z_\varepsilon(x, \tau) \Upsilon_\varepsilon(x, \tau) dx \right| \leq \|\partial_x^{k+1} U_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \|\Upsilon_\varepsilon(\cdot, \tau)\|_{L^\infty(\mathbb{R})},$$

so that by (20) and (3.42),

$$\left| \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon(x, \tau) \partial_x^k Z_\varepsilon(x, \tau) \Upsilon_\varepsilon(x, \tau) dx \right| \leq K \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \exp K|\tau|. \quad (3.43)$$

Similarly, for the second term on the right-hand side of (3.41), we compute

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} \partial_\tau U_\varepsilon \partial_x^k Z_\varepsilon \Upsilon_\varepsilon \right| \leq K \left| \int_0^\tau (1 + |s|) \|\partial_x^{k+1} \partial_\tau U_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|$$

so that by (3.3),

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} \partial_\tau U_\varepsilon \partial_x^k Z_\varepsilon \Upsilon_\varepsilon \right| \leq K \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|. \quad (3.44)$$

We finally turn to the last term on the right-hand side of (3.41). In view of (21), we can write

$$\int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \partial_\tau \partial_x^k Z_\varepsilon \Upsilon_\varepsilon = J_1^1(\tau) + J_1^2(\tau) + \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \Upsilon_\varepsilon \partial_x^k f_\varepsilon, \quad (3.45)$$

where

$$J_1^1(\tau) \equiv - \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \Upsilon_\varepsilon \left(\partial_x^{k+3} Z_\varepsilon + \partial_x^{k+1} (Z_\varepsilon \mathcal{U}) + \frac{1}{2} \partial_x^{k+1} (Z_\varepsilon^2) \right),$$

and

$$J_1^2(\tau) \equiv -\varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \Upsilon_\varepsilon \partial_x^k r_\varepsilon.$$

Concerning the integral $J_1^1(\tau)$, we integrate by parts in space to obtain

$$J_1^1(\tau) = \int_0^\tau \int_{\mathbb{R}} \left(\partial_x^k Z_\varepsilon \partial_x^3 (\partial_x^{k+1} U_\varepsilon \Upsilon_\varepsilon) + \partial_x^k (Z_\varepsilon \mathcal{U}) \partial_x (\partial_x^{k+1} U_\varepsilon \Upsilon_\varepsilon) + \frac{1}{2} \partial_x^k (Z_\varepsilon^2) \partial_x (\partial_x^{k+1} U_\varepsilon \Upsilon_\varepsilon) \right),$$

so that

$$|J_1^1(\tau)| \leq \left| \int_0^\tau \|Z_\varepsilon\|_{H^k(\mathbb{R})} \|U_\varepsilon\|_{H^{k+4}(\mathbb{R})} (\|\Upsilon_\varepsilon\|_{L^\infty(\mathbb{R})} + \|V_\varepsilon\|_{H^3(\mathbb{R})}) (1 + \|\mathcal{U}\|_{H^{k+1}(\mathbb{R})} + \|Z_\varepsilon\|_{H^{k+1}(\mathbb{R})}) \right|.$$

Hence, by (20), (3.4), (3.5) and (3.42),

$$|J_1^1(\tau)| \leq K \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|. \quad (3.46)$$

Similarly, the integral $J_1^2(\tau)$ is bounded by

$$|J_1^2(\tau)| \leq K\varepsilon^2 \left| \int_0^\tau \|\partial_x^{k+1} U_\varepsilon\|_{L^2(\mathbb{R})} \|\Upsilon_\varepsilon\|_{L^\infty(\mathbb{R})} \|\partial_x^k r_\varepsilon\|_{L^2(\mathbb{R})} \right| \leq K\varepsilon^2 \exp K|\tau|. \quad (3.47)$$

Combining (3.45) with (3.46) and (3.47), we have

$$\begin{aligned} & \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \partial_\tau \partial_x^k Z_\varepsilon \Upsilon_\varepsilon - \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon \Upsilon_\varepsilon \partial_x^k f_\varepsilon \right| \\ & \leq K \left(\varepsilon^2 \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right), \end{aligned}$$

so that (3.40) follows from (3.41), (3.43) and (3.44).

We now turn to the second integral $J_2(\tau)$.

Step 2. *Under the assumptions of Lemma 3.3, there exists a positive constant K depending only on K_0 and k , such that*

$$|J_2(\tau)| \leq K\varepsilon^2 \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|, \quad (3.48)$$

for any $\tau \in \mathbb{R}$.

Applying the Hölder inequality and the Sobolev embedding theorem to definition (3.38), we obtain

$$|J_2(\tau)| \leq \frac{\varepsilon^2}{8} \left| \int_0^\tau \|\partial_x^{k+1} U_\varepsilon\|_{H^1(\mathbb{R})} \|\partial_x^k Z_\varepsilon\|_{L^2(\mathbb{R})} (\|G_\varepsilon\|_{L^2(\mathbb{R})} + \varepsilon^2 \|R_\varepsilon\|_{L^2(\mathbb{R})}) \right|,$$

so that (3.48) follows from (20) and (3.3).

Concerning the last integral $J_3(\tau)$, we finally derive

Step 3. *Under the assumptions of Lemma 3.3, given any $\tau \in \mathbb{R}$, there exist a positive number R_1 and a positive constant K , depending only on K_0 and k , such that*

$$|J_3(\tau)| \leq K\varepsilon^2 \left(\varepsilon^2 \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right), \quad (3.49)$$

for any choice of the number R of definition (29) in $(R_1, +\infty)$.

Combining estimates (20) and (3.3) with definition (3.39), we have

$$\begin{aligned} |J_3(\tau)| & \leq \left| \int_0^\tau \left(|V_\varepsilon(-R, \cdot)| + \varepsilon^2 \|G_\varepsilon\|_{L^\infty(\mathbb{R})} + \varepsilon^4 \|R_\varepsilon\|_{L^\infty(\mathbb{R})} \right) \|\partial_x^{k+1} U_\varepsilon\|_{L^2(\mathbb{R})} \|\partial_x^k Z_\varepsilon\|_{L^2(\mathbb{R})} \right| \\ & \leq K \left| \int_0^\tau \left(|V_\varepsilon(-R, s)| + \varepsilon^2 \right) \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|. \end{aligned} \quad (3.50)$$

We then invoke (3.5) to write

$$\left| \int_0^\tau |V_\varepsilon(-R, s)| \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \leq K' \exp K'|\tau| \left| \int_0^\tau |V_\varepsilon(-R, s)|^2 ds \right|^{\frac{1}{2}},$$

where K' is some further constant depending only on K_0 and k . Next, we have

$$|V_\varepsilon(-R, s)|^2 \leq \int_{-\infty}^{-R} \left((V_\varepsilon(x, s))^2 + (\partial_x V_\varepsilon(x, s))^2 \right) dx,$$

so that

$$\begin{aligned} & \left| \int_0^\tau |V_\varepsilon(-R, s)| \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \\ & \leq K' \exp K'|\tau| \left| \int_0^\tau \int_{-\infty}^{-R} \left((V_\varepsilon(x, s))^2 + (\partial_x V_\varepsilon(x, s))^2 \right) dx ds \right|^{\frac{1}{2}}. \end{aligned} \quad (3.51)$$

By the dominated convergence theorem, the integral on the right-hand side of (3.51) decays to 0 as $R \rightarrow +\infty$, so that there exists a positive number R_1 such that

$$\left| \int_0^\tau \int_{-\infty}^{-R} \left((V_\varepsilon(x, s))^2 + (\partial_x V_\varepsilon(x, s))^2 \right) dx ds \right| \leq \varepsilon^8, \quad (3.52)$$

for any $R > R_1$. Combining with (3.50) and (3.51), this provides (3.49).

We are now in position to complete the proof of Lemma 3.3.

End of the proof of Lemma 3.3. Estimate (3.8) follows from applying bounds (3.40), (3.48) and (3.49) to definition (3.37). \square

3.5 Proof of Lemma 3.4

Though the proof is similar to the proofs of Lemmas 3.2 and 3.3, the computations are somewhat more technical. In view of definition (14) and the fact that $\partial_x \Upsilon_\varepsilon = V_\varepsilon$, we first decompose the quantity $K_\varepsilon(\tau)$ as

$$K_\varepsilon(\tau) = \frac{\varepsilon^2}{24} \sum_{j=0}^k C_k^j \left(\frac{1}{6} K_1^j(\tau) - K_2^j(\tau) + \frac{1}{3} K_3^j(\tau) \right), \quad (3.53)$$

where

$$K_1^j(\tau) = \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (V_\varepsilon^2) \partial_x^j \Upsilon_\varepsilon \partial_x^{k+1-j} U_\varepsilon, \quad (3.54)$$

$$K_2^j(\tau) = \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+3} V_\varepsilon \partial_x^j \Upsilon_\varepsilon \partial_x^{k+1-j} U_\varepsilon, \quad (3.55)$$

and

$$K_3^j(\tau) = \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (U_\varepsilon V_\varepsilon) \partial_x^j \Upsilon_\varepsilon \partial_x^{k+1-j} U_\varepsilon. \quad (3.56)$$

We then estimate each of the above integrals $K_i^j(\tau)$.

Claim 1. *Let $i \in \{1, 2, 3\}$ and $0 \leq j \leq k$. Under the assumptions of Lemma 3.4, given any $\tau \in \mathbb{R}$, there exists a positive number R_2 , and a positive constant K , depending only on K_0 and k , such that*

$$|K_i^j(\tau)| \leq K \varepsilon^2 \exp K|\tau|, \quad (3.57)$$

for any choice of the number R of definition (29) in $(R_2, +\infty)$.

We postpone the proof of Claim 1 and first complete the proof of Lemma 3.4.

Proof of Lemma 3.4. Estimate (3.10) follows from combining decomposition (3.53) with bounds (3.57). \square

We now turn to the proof of Claim 1.

Proof of Claim 1. We split the proof in six cases according to the values of i and j .

Case 1. $i = 1$ and $1 \leq j \leq k$.

Using the fact that $\partial_x \Upsilon_\varepsilon = V_\varepsilon$, we have in view of definition (3.54),

$$K_1^j(\tau) = \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1}(V_\varepsilon^2) \partial_x^{j-1} V_\varepsilon \partial_x^{k+1-j} U_\varepsilon,$$

so that integrating by parts in space

$$K_1^j(\tau) = - \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{k+1}(V_\varepsilon^2) \partial_x^{j-1} V_\varepsilon \right) \partial_x^{k-j} U_\varepsilon. \quad (3.58)$$

In view of (15) and (3.16), we now have

$$\begin{aligned} \partial_x \left(\partial_x^{k+1}(V_\varepsilon^2) \partial_x^{j-1} V_\varepsilon \right) &= -\frac{\varepsilon^2}{8} \partial_\tau \left(\partial_x^{k+1}(V_\varepsilon^2) \partial_x^{j-1} V_\varepsilon \right) + \frac{\varepsilon^2}{4} \partial_x^{j-1} V_\varepsilon \left(\partial_x^{k+1}(g_\varepsilon V_\varepsilon) + \varepsilon^2 \partial_x^{k+1}(r_\varepsilon V_\varepsilon) \right) \\ &\quad + \frac{\varepsilon^2}{8} \partial_x^{k+1}(V_\varepsilon^2) \left(\partial_x^{j-1} g_\varepsilon + \varepsilon^2 \partial_x^{j-1} r_\varepsilon \right), \end{aligned}$$

so that (3.58) becomes after an integration by parts in time,

$$\begin{aligned} K_1^j(\tau) &= \frac{\varepsilon^2}{8} \left[\int_{\mathbb{R}} \partial_x^{k-j} U_\varepsilon \partial_x^{k+1}(V_\varepsilon^2) \partial_x^{j-1} V_\varepsilon \right]_0^\tau - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \left(\partial_\tau \partial_x^{k-j} U_\varepsilon \partial_x^{k+1}(V_\varepsilon^2) \partial_x^{j-1} V_\varepsilon \right. \\ &\quad \left. + 2 \partial_x^{k-j} U_\varepsilon \partial_x^{j-1} V_\varepsilon \left(\partial_x^{k+1}(g_\varepsilon V_\varepsilon) + \varepsilon^2 \partial_x^{k+1}(r_\varepsilon V_\varepsilon) \right) + \partial_x^{k-j} U_\varepsilon \partial_x^{k+1}(V_\varepsilon^2) \left(\partial_x^{j-1} g_\varepsilon + \varepsilon^2 \partial_x^{j-1} r_\varepsilon \right) \right). \end{aligned} \quad (3.59)$$

We finally argue as in the proof of Lemma 3.2 using bounds (20) and (3.3) to bound any term on the right-hand side of (3.59). This provides estimate (3.57) in case $i = 1$ and $1 \leq j \leq k$.

Case 2. $i = 1$ and $j = 0$.

When $j = 0$, we also integrate by parts in space to obtain

$$K_1^0(\tau) = - \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{k+1}(V_\varepsilon^2) \Upsilon_\varepsilon \right) \partial_x^{k-j} U_\varepsilon. \quad (3.60)$$

We then combine (3.16) with (30) to establish

$$\begin{aligned} \partial_x \left(\partial_x^{k+1}(V_\varepsilon^2) \Upsilon_\varepsilon \right) &= -\frac{\varepsilon^2}{8} \partial_\tau \left(\partial_x^{k+1}(V_\varepsilon^2) \Upsilon_\varepsilon \right) + \frac{\varepsilon^2}{4} \Upsilon_\varepsilon \left(\partial_x^{k+1}(g_\varepsilon V_\varepsilon) + \varepsilon^2 \partial_x^{k+1}(r_\varepsilon V_\varepsilon) \right) \\ &\quad + \frac{\varepsilon^2}{8} \partial_x^{k+1}(V_\varepsilon^2) \left(G_\varepsilon + \varepsilon^2 R_\varepsilon \right) - \frac{\varepsilon^2}{8} \partial_x^{k+1}(V_\varepsilon^2) \left(G_\varepsilon(-R, \cdot) + \varepsilon^2 R_\varepsilon(-R, \cdot) \right) + V_\varepsilon(-R, \cdot) \partial_x^{k+1}(V_\varepsilon^2), \end{aligned}$$

so that (3.60) becomes after an integration by parts in time,

$$\begin{aligned} K_1^0(\tau) &= \frac{\varepsilon^2}{8} \left[\int_{\mathbb{R}} \partial_x^{k-j} U_\varepsilon \partial_x^{k+1}(V_\varepsilon^2) \Upsilon_\varepsilon \right]_0^\tau - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^{k-j} U_\varepsilon \partial_x^{k+1}(V_\varepsilon^2) \Upsilon_\varepsilon \\ &\quad - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k-j} U_\varepsilon \left(2 \Upsilon_\varepsilon \left(\partial_x^{k+1}(g_\varepsilon V_\varepsilon) + \varepsilon^2 \partial_x^{k+1}(r_\varepsilon V_\varepsilon) \right) + \partial_x^{k+1}(V_\varepsilon^2) \left(G_\varepsilon + \varepsilon^2 R_\varepsilon \right) \right) \\ &\quad - \int_0^\tau \left(V_\varepsilon(-R, \cdot) - \frac{\varepsilon^2}{8} G_\varepsilon(-R, \cdot) - \frac{\varepsilon^4}{8} R_\varepsilon(-R, \cdot) \right) \int_{\mathbb{R}} \partial_x^{k-j} U_\varepsilon \partial_x^{k+1}(V_\varepsilon^2). \end{aligned} \quad (3.61)$$

We then estimate any terms on the right-hand side of (3.61) similarly to the terms on the right-hand side of (3.59). Using bounds (20), (3.3) and (3.42), we are led to

$$|K_1^0(\tau)| \leq K \left(\varepsilon^2 \exp K|\tau| + \left| \int_0^\tau \left(|V_\varepsilon(-R, s)| + \varepsilon^2 \|G_\varepsilon(\cdot, s)\|_{L^\infty} + \varepsilon^4 \|R_\varepsilon(\cdot, s)\|_{L^\infty} \right) \exp K|s| ds \right| \right),$$

so that by the Sobolev embedding theorem and (3.3),

$$|K_1^0(\tau)| \leq K \left(\varepsilon^2 \exp K|\tau| + \left| \int_0^\tau |V_\varepsilon(-R, s)| \exp K|s| ds \right| \right). \quad (3.62)$$

We then argue as in the proof of Step 3 of Lemma 3.3. Given any $R > R_1$, where R_1 is chosen so that (3.52) holds for any $R > R_1$, we obtain

$$\left| \int_0^\tau |V_\varepsilon(-R, s)| \exp K|s| ds \right| \leq K' \exp K'|\tau| \left| \int_0^\tau \int_{-\infty}^{-R} \left(V_\varepsilon^2 + (\partial_x V_\varepsilon)^2 \right) \right|^{\frac{1}{2}} \leq K' \varepsilon^4 \exp K'|\tau|, \quad (3.63)$$

where K' is some further positive constant depending only on K_0 and k . Combining with (3.62), this completes the proof of (3.57) in case $i = 1$ and $j = 0$.

Case 3. $i = 2$ and $1 \leq j \leq k$.

The proof is similar to Case 1. Using the fact that $\partial_x \Upsilon_\varepsilon = V_\varepsilon$, and integrating by parts the derivative $\partial_x^{k+3} V_\varepsilon$, we have in view of definition (3.55),

$$\begin{aligned} K_2^j(\tau) &= \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} V_\varepsilon \partial_x^{j+1} V_\varepsilon \partial_x^{k+1-j} U_\varepsilon + 2 \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} V_\varepsilon \partial_x^j V_\varepsilon \partial_x^{k+2-j} U_\varepsilon \\ &\quad + \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} V_\varepsilon \partial_x^{j-1} V_\varepsilon \partial_x^{k+3-j} U_\varepsilon, \end{aligned}$$

so that integrating by parts the derivatives of U_ε ,

$$\begin{aligned} K_2^j(\tau) &= - \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{k+1} V_\varepsilon \partial_x^{j+1} V_\varepsilon \right) \partial_x^{k-j} U_\varepsilon - 2 \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{k+1} V_\varepsilon \partial_x^j V_\varepsilon \right) \partial_x^{k+1-j} U_\varepsilon \\ &\quad - \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{k+1} V_\varepsilon \partial_x^{j-1} V_\varepsilon \right) \partial_x^{k+2-j} U_\varepsilon. \end{aligned} \quad (3.64)$$

In view of (15), we now remark that

$$\begin{aligned} \partial_x \left(\partial_x^l V_\varepsilon \partial_x^m V_\varepsilon \right) &= -\frac{\varepsilon^2}{8} \partial_\tau \left(\partial_x^l V_\varepsilon \partial_x^m V_\varepsilon \right) + \frac{\varepsilon^2}{8} \left(\partial_x^l V_\varepsilon \partial_x^m g_\varepsilon + \partial_x^m V_\varepsilon \partial_x^l g_\varepsilon \right) \\ &\quad + \frac{\varepsilon^4}{8} \left(\partial_x^l V_\varepsilon \partial_x^m r_\varepsilon + \partial_x^m V_\varepsilon \partial_x^l r_\varepsilon \right), \end{aligned} \quad (3.65)$$

for any $(l, m) \in \mathbb{N}^2$. We then introduce the expression of the functions $\partial_x(\partial_x^l V_\varepsilon \partial_x^m V_\varepsilon)$ given by (3.65) in the three integrals on the right-hand side of (3.64), integrate by parts in time as in the proof of Case 1, and bound the resulting terms using estimates (20) and (3.3). This provides inequality (3.57) in case $i = 2$ and $1 \leq j \leq k$.

Case 4. $i = 2$ and $j = 0$.

The proof is similar to Cases 2 and 3. We first integrate by parts as in (3.64) to obtain

$$\begin{aligned} K_2^0(\tau) &= - \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{k+1} V_\varepsilon \partial_x V_\varepsilon \right) \partial_x^{k-j} U_\varepsilon - 2 \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{k+1} V_\varepsilon V_\varepsilon \right) \partial_x^{k+1-j} U_\varepsilon \\ &\quad - \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{k+1} V_\varepsilon \Upsilon_\varepsilon \right) \partial_x^{k+2-j} U_\varepsilon. \end{aligned} \quad (3.66)$$

Concerning the first and the second integrals on the right-hand side of (3.66), we then replace the functions $\partial_x(\partial_x^{k+1}V_\varepsilon V_\varepsilon)$ and $\partial_x(\partial_x^{k+1}V_\varepsilon \partial_x V_\varepsilon)$ by their expression given by (3.65), integrate by parts in time as in the proof of Case 1, and bound the resulting terms using estimates (20) and (3.3). This provides

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x(\partial_x^{k+1}V_\varepsilon \partial_x V_\varepsilon) \partial_x^{k-j} U_\varepsilon \right| + \left| \int_0^\tau \int_{\mathbb{R}} \partial_x(\partial_x^{k+1}V_\varepsilon V_\varepsilon) \partial_x^{k+1-j} U_\varepsilon \right| \leq K\varepsilon^2 \exp K|\tau|. \quad (3.67)$$

In contrast, for the last integral on the right-hand side of (3.66), we combine (15) with (30) to establish

$$\begin{aligned} \partial_x(\partial_x^{k+1}V_\varepsilon \Upsilon_\varepsilon) &= -\frac{\varepsilon^2}{8} \partial_\tau(\partial_x^{k+1}V_\varepsilon \Upsilon_\varepsilon) + \frac{\varepsilon^2}{8} \Upsilon_\varepsilon(\partial_x^{k+1}g_\varepsilon + \varepsilon^2 \partial_x^{k+1}r_\varepsilon) + \frac{\varepsilon^2}{8} \partial_x^{k+1}V_\varepsilon(G_\varepsilon + \varepsilon^2 R_\varepsilon) \\ &\quad - \frac{\varepsilon^2}{8} \partial_x^{k+1}V_\varepsilon(G_\varepsilon(-R, \cdot) + \varepsilon^2 R_\varepsilon(-R, \cdot)) + V_\varepsilon(-R, \cdot) \partial_x^{k+1}V_\varepsilon, \end{aligned}$$

so that after an integration by parts in time,

$$\begin{aligned} &\int_0^\tau \int_{\mathbb{R}} \partial_x(\partial_x^{k+1}V_\varepsilon \Upsilon_\varepsilon) \partial_x^{k+2-j} U_\varepsilon = -\frac{\varepsilon^2}{8} \left[\int_{\mathbb{R}} \partial_x^{k+2-j} U_\varepsilon \partial_x^{k+1}V_\varepsilon \Upsilon_\varepsilon \right]_0^\tau \\ &+ \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \left(\partial_\tau \partial_x^{k+2-j} U_\varepsilon \partial_x^{k+1}V_\varepsilon \Upsilon_\varepsilon + \partial_x^{k+2-j} U_\varepsilon \left(\Upsilon_\varepsilon(\partial_x^{k+1}g_\varepsilon + \varepsilon^2 \partial_x^{k+1}r_\varepsilon) \right. \right. \\ &\left. \left. + \partial_x^{k+1}V_\varepsilon(G_\varepsilon + \varepsilon^2 R_\varepsilon) \right) \right) + \int_0^\tau \left(V_\varepsilon(-R, \cdot) - \frac{\varepsilon^2}{8} G_\varepsilon(-R, \cdot) - \frac{\varepsilon^4}{8} R_\varepsilon(-R, \cdot) \right) \int_{\mathbb{R}} \partial_x^{k+2-j} U_\varepsilon \partial_x^{k+1}V_\varepsilon. \end{aligned}$$

We finally argue as in the proof of Case 2. Using bounds (20), (3.3), (3.42) and (3.63), we are led to

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x(\partial_x^{k+1}V_\varepsilon \Upsilon_\varepsilon) \partial_x^{k+2-j} U_\varepsilon \right| \leq K\varepsilon^2 \exp K|\tau|,$$

so that (3.57) follows for $i = 2$ and $j = 0$ from (3.66) and (3.67).

Case 5. $i = 3$ and $1 \leq j \leq k$.

The proof is similar to Cases 1 and 3. Using the fact that $\partial_x \Upsilon_\varepsilon = V_\varepsilon$ and applying the Newton formula to (3.56), we are led to

$$K_3^j(\tau) = \sum_{l=0}^{k+1} C_{k+1}^l \mathcal{K}_l^j. \quad (3.68)$$

where the integrals \mathcal{K}_l^j are given by

$$\mathcal{K}_l^j \equiv \int_0^\tau \int_{\mathbb{R}} \partial_x^l V_\varepsilon \partial_x^{j-1} V_\varepsilon \partial_x^{k+1-l} U_\varepsilon \partial_x^{k+1-j} U_\varepsilon. \quad (3.69)$$

Assuming first that $l \geq j$, our arguments to estimate the integrals \mathcal{K}_l^j then depend on the parity of the difference $l - j$. When $l - j = 2m$ is even, we can write

$$\partial_x^l V_\varepsilon \partial_x^{j-1} V_\varepsilon = \frac{(-1)^m}{2} \partial_x \left((\partial_x^{j+m-1} V_\varepsilon)^2 \right) + \sum_{p=0}^{m-1} (-1)^p \partial_x \left(\partial_x^{l-1-p} V_\varepsilon \partial_x^{j-1+p} V_\varepsilon \right),$$

so that (3.69) becomes

$$\begin{aligned} \mathcal{K}_l^j &= \frac{(-1)^m}{2} \int_0^\tau \int_{\mathbb{R}} \partial_x \left((\partial_x^{j+m-1} V_\varepsilon)^2 \right) \partial_x^{k+1-l} U_\varepsilon \partial_x^{k+1-j} U_\varepsilon \\ &+ \sum_{p=0}^{m-1} (-1)^p \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{l-1-p} V_\varepsilon \partial_x^{j-1+p} V_\varepsilon \right) \partial_x^{k+1-l} U_\varepsilon \partial_x^{k+1-j} U_\varepsilon. \end{aligned}$$

We then replace the functions $\partial_x \left((\partial_x^{j+m-1} V_\varepsilon)^2 \right)$ and $\partial_x \left(\partial_x^{l-1-p} V_\varepsilon \partial_x^{j-1+p} V_\varepsilon \right)$ by their expressions given by (3.65) and argue as in the proof of Cases 1 and 3 to obtain that

$$|\mathcal{K}_l^j| \leq K \varepsilon^2 \exp K |\tau|. \quad (3.70)$$

In contrast, when $l - j = 2m + 1$ is odd, we can write

$$\partial_x^{k+1-l} U_\varepsilon \partial_x^{k+1-j} U_\varepsilon = \frac{(-1)^m}{2} \partial_x \left((\partial_x^{k-j-m} U_\varepsilon)^2 \right) + \sum_{p=0}^{m-1} (-1)^p \partial_x \left(\partial_x^{k-j-p} U_\varepsilon \partial_x^{k-l+1+p} U_\varepsilon \right), \quad (3.71)$$

so that (3.69) becomes after an integration by parts in space,

$$\begin{aligned} \mathcal{K}_l^j &= \frac{(-1)^{m+1}}{2} \int_0^\tau \int_{\mathbb{R}} \partial_x \left((\partial_x^{j-1} V_\varepsilon \partial_x^l V_\varepsilon) (\partial_x^{k-j-m} U_\varepsilon)^2 \right. \\ &\quad \left. - \sum_{p=0}^{m-1} (-1)^p \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{j-1} V_\varepsilon \partial_x^l V_\varepsilon \right) \partial_x^{k-j-p} U_\varepsilon \partial_x^{k-l+1+p} U_\varepsilon \right). \end{aligned}$$

We then complete the proof of (3.70) as in the case $l - j$ was even. The proof is similar when $j > l$ permuting the roles of j and l . Hence, (3.70) holds for any choice of j and k . In view of (3.68), this concludes the proof of (3.57) when $i = 3$ and $1 \leq j \leq k$.

Case 6. $i = 3$ and $j = 0$.

The proof is similar to Case 5. Applying the Newton formula to (3.56), we are led to

$$K_3^0(\tau) = \sum_{l=0}^{k+1} C_{k+1}^l \mathcal{K}_l^0. \quad (3.72)$$

where the integrals \mathcal{K}_l^0 are given by

$$\mathcal{K}_l^0 \equiv \int_0^\tau \int_{\mathbb{R}} \partial_x^l V_\varepsilon \Upsilon_\varepsilon \partial_x^{k+1-l} U_\varepsilon \partial_x^{k+1} U_\varepsilon. \quad (3.73)$$

When $l = 2m$ is even and positive, we can write using the fact that $\partial_x \Upsilon_\varepsilon = V_\varepsilon$,

$$\partial_x^l V_\varepsilon \Upsilon_\varepsilon = \frac{(-1)^m}{2} \partial_x \left((\partial_x^{m-1} V_\varepsilon)^2 \right) + \partial_x \left(\partial_x^{l-1} V_\varepsilon \Upsilon_\varepsilon \right) + \sum_{p=1}^{m-1} (-1)^p \partial_x \left(\partial_x^{l-1-p} V_\varepsilon \partial_x^{p-1} V_\varepsilon \right), \quad (3.74)$$

so that (3.73) becomes

$$\begin{aligned} \mathcal{K}_l^0 &= \frac{(-1)^m}{2} \int_0^\tau \int_{\mathbb{R}} \partial_x \left((\partial_x^{m-1} V_\varepsilon)^2 \right) \partial_x^{k+1-l} U_\varepsilon \partial_x^{k+1} U_\varepsilon + \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{l-1} V_\varepsilon \Upsilon_\varepsilon \right) \partial_x^{k+1-l} U_\varepsilon \partial_x^{k+1} U_\varepsilon \\ &\quad + \sum_{p=1}^{m-1} (-1)^p \int_0^\tau \int_{\mathbb{R}} \partial_x \left(\partial_x^{l-1-p} V_\varepsilon \partial_x^{p-1} V_\varepsilon \right) \partial_x^{k+1-l} U_\varepsilon \partial_x^{k+1} U_\varepsilon. \end{aligned} \quad (3.75)$$

We then rely on the arguments of the proofs of Cases 2 and 4 to bound any integrals on the right-hand side of (3.75) in order to obtain

$$|\mathcal{K}_l^0| \leq K \varepsilon^2 \exp K |\tau|. \quad (3.76)$$

When $l = 2m + 1$, we invoke (3.71) as in the proof of Case 5, instead of (3.74), and complete the proof of (3.76) similarly.

Finally, for $l = 0$, we write

$$\mathcal{K}_0^0 = \frac{1}{2} \int_0^\tau \int_{\mathbb{R}} \partial_x (\Upsilon_\varepsilon^2) (\partial_x^{k+1} U_\varepsilon)^2. \quad (3.77)$$

In view of (30), we have

$$\partial_x (\Upsilon_\varepsilon^2) = -\frac{\varepsilon^2}{8} \partial_\tau (\Upsilon_\varepsilon^2) + \frac{\varepsilon^2}{4} \Upsilon_\varepsilon \left(G_\varepsilon + \varepsilon^2 R_\varepsilon - G_\varepsilon(-R, \cdot) - \varepsilon^2 R_\varepsilon(-R, \cdot) \right) + 2V_\varepsilon(-R, \cdot) \Upsilon_\varepsilon,$$

so that integrating by parts in time, (3.77) becomes

$$\begin{aligned} \mathcal{K}_0^0 &= -\frac{\varepsilon^2}{16} \left[\int_{\mathbb{R}} \Upsilon_\varepsilon^2 (\partial_x^{k+1} U_\varepsilon)^2 \right]_0^\tau + \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \Upsilon_\varepsilon^2 \partial_x^{k+1} U_\varepsilon \partial_\tau \partial_x^{k+1} U_\varepsilon + \int_0^\tau \int_{\mathbb{R}} V_\varepsilon(-R, \cdot) \Upsilon_\varepsilon (\partial_x^{k+1} U_\varepsilon)^2 \\ &\quad + \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \Upsilon_\varepsilon \left(G_\varepsilon + \varepsilon^2 R_\varepsilon - G_\varepsilon(-R, \cdot) - \varepsilon^2 R_\varepsilon(-R, \cdot) \right) (\partial_x^{k+1} U_\varepsilon)^2. \end{aligned} \quad (3.78)$$

Using bounds (20), (3.3), (3.42) and (3.63) to estimate the right-hand side of (3.78), we deduce (3.76) for $l = 0$ provided we choose $R > R_1$ as above. Combining with (3.72), this completes the proof of (3.57) in case $i = 3$ and $j = 0$.

In view of the proofs of the six previous cases, we finally choose $R_2 = R_1$ to conclude the proof of Claim 1. \square

4 Proof of Theorem 1

We now turn to the proof of Theorem 1. As mentioned in the introduction, we focus on the coordinate $x = x^- = \varepsilon(x + \sqrt{2}t)$ and the associated functions $U_\varepsilon = U_\varepsilon^-$ and $\mathcal{U} = \mathcal{U}^-$. Given any $k \in \mathbb{N}$, we first recall identity (23), which may be written as

$$\begin{aligned} \partial_\tau \mathcal{Z}_\varepsilon^k(\tau) &= -2 \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (\mathcal{U} Z_\varepsilon) \partial_x^k Z_\varepsilon - \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (Z_\varepsilon^2) \partial_x^k Z_\varepsilon \\ &\quad + 2 \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon - 2\varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^k r_\varepsilon \partial_x^k Z_\varepsilon, \end{aligned}$$

with $Z_\varepsilon = U_\varepsilon - \mathcal{U}$. We then bound inductively any term on the right-hand side of (23) in order to apply a Gronwall lemma to the quantity $\mathcal{Z}_\varepsilon^k(\tau)$ defined by (22), and derive inequality (7).

For $k = 0$, identity (23) may be recast as

$$\partial_\tau \mathcal{Z}_\varepsilon^0(\tau) = - \int_0^\tau \int_{\mathbb{R}} \partial_x \mathcal{U} Z_\varepsilon^2 + 2 \int_0^\tau \int_{\mathbb{R}} f_\varepsilon Z_\varepsilon - 2\varepsilon^2 \int_0^\tau \int_{\mathbb{R}} r_\varepsilon Z_\varepsilon, \quad (4.1)$$

so that in view of Proposition 3, and bounds (3.3) and (3.4), we have

$$\partial_\tau \mathcal{Z}_\varepsilon^0(\tau) \leq K \left(|\mathcal{Z}_\varepsilon^0(\tau)| + \varepsilon^2 \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| + \varepsilon^2 (\|Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} + \varepsilon^2) \exp K|\tau| \right),$$

where K is a positive constant depending only on K_0 . Using the inequality $2|ab| \leq a^2 + b^2$ and the identity

$$\partial_\tau \mathcal{Z}_\varepsilon^0(\tau) = \|Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}^2, \quad (4.2)$$

we are led to the differential inequality

$$\partial_\tau \mathcal{Z}_\varepsilon^0(\tau) \leq K \left(\text{sign}(\tau) \mathcal{Z}_\varepsilon^0(\tau) + \varepsilon^4 \exp K|\tau| \right), \quad (4.3)$$

so that

$$|\mathcal{Z}_\varepsilon^0(\tau)| \leq K' \varepsilon^4 \exp K'|\tau|,$$

where K' is some further positive constant depending only on K_0 . Combining with (4.2) and (4.3), this provides (7) for $k = 0$ (and the functions U_ε^- and \mathcal{U}^-).

We now assume that (7) holds for any $0 \leq j \leq k-1$, i.e. that there exists a positive constant K depending only on K_0 and k , such that

$$\|Z_\varepsilon(\cdot, \tau)\|_{H^{k-1}(\mathbb{R})} \leq K \varepsilon^2 \exp K|\tau|, \quad (4.4)$$

for any $\tau \in \mathbb{R}$. We then bound any integral on the right-hand side of (23). For the first one, we compute by the Leibniz formula,

$$\int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1}(\mathcal{U}Z_\varepsilon) \partial_x^k Z_\varepsilon = \sum_{j=0}^{k-1} C_{k+1}^j \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1-j} \mathcal{U} \partial_x^j Z_\varepsilon \partial_x^k Z_\varepsilon + \left(k + \frac{1}{2}\right) \int_0^\tau \int_{\mathbb{R}} \partial_x \mathcal{U} (\partial_x^k Z_\varepsilon)^2,$$

so that by (3.4) and (4.4), we are led to

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1}(\mathcal{U}Z_\varepsilon) \partial_x^k Z_\varepsilon \right| \leq K \left(\left| \int_0^\tau \int_{\mathbb{R}} (\partial_x^k Z_\varepsilon)^2 \right| + \varepsilon^2 \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right). \quad (4.5)$$

The estimates of the second integral on the right-hand side of (23) are similar. The Leibniz formula yields

$$\int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1}(Z_\varepsilon^2) \partial_x^k Z_\varepsilon = \sum_{j=2}^{k-1} C_{k+1}^j \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1-j} Z_\varepsilon \partial_x^j Z_\varepsilon \partial_x^k Z_\varepsilon + (2k+1) \int_0^\tau \int_{\mathbb{R}} \partial_x Z_\varepsilon (\partial_x^k Z_\varepsilon)^2,$$

so that by the Hölder inequality and bounds (3.5) and (4.4), we are led to

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1}(Z_\varepsilon^2) \partial_x^k Z_\varepsilon \right| \leq K \left(\left| \int_0^\tau \|\partial_x Z_\varepsilon\|_{L^\infty} \|\partial_x^k Z_\varepsilon\|_{L^2}^2 \right| + \varepsilon^2 \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2} ds \right| \right). \quad (4.6)$$

We now recall that $\partial_x Z_\varepsilon = \frac{1}{2}(\partial_x N_\varepsilon + \partial_x^2 \Theta_\varepsilon) - \partial_x \mathcal{U}$, so that, combining bounds (2.1) and (3.4) with the Sobolev embedding theorem,

$$\|\partial_x Z_\varepsilon(\cdot, \tau)\|_{L^\infty(\mathbb{R})} \leq K,$$

for any $\tau \in \mathbb{R}$. Hence, by (4.6),

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1}(Z_\varepsilon^2) \partial_x^k Z_\varepsilon \right| \leq K \left(\left| \int_0^\tau \int_{\mathbb{R}} (\partial_x^k Z_\varepsilon)^2 \right| + \varepsilon^2 \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right). \quad (4.7)$$

Concerning the last integral on the right-hand side of (23), we invoke (3.3) to obtain

$$\left| \varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^k r_\varepsilon \partial_x^k Z_\varepsilon \right| \leq K \varepsilon^2 \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|.$$

Therefore, in view of (27), (4.5) and (4.7), we are led to the differential inequality

$$\partial_\tau \mathcal{Z}_\varepsilon^k(\tau) \leq K \left(\text{sign}(\tau) \mathcal{Z}_\varepsilon^k(\tau) + \varepsilon^4 \exp K|\tau| \right),$$

so that by the Gronwall lemma, inequality (7) also holds for the integer k . By induction, this completes the proof of (7) for the functions U_ε^- and \mathcal{U}^- .

We next say a few words of the proof for the functions U_ε^+ and \mathcal{U}^+ . Setting

$$V_\varepsilon^+(x, \tau) = \frac{1}{2}(N_\varepsilon^+(x, \tau) + \partial_x \Theta_\varepsilon^+(x, \tau)),$$

the functions U_ε^+ and V_ε^+ satisfy the system of equations

$$-\partial_\tau U_\varepsilon^+ + \partial_x^3 U_\varepsilon^+ + U_\varepsilon^+ \partial_x U_\varepsilon^+ = f_\varepsilon^+ - \varepsilon^2 r_\varepsilon^+, \quad (4.8)$$

where

$$f_\varepsilon^+ \equiv \partial_x \left(\frac{1}{6}(V_\varepsilon^+)^2 - \partial_x^2 V_\varepsilon^+ + \frac{1}{3}U_\varepsilon^+ V_\varepsilon^+ \right),$$

and

$$-\partial_\tau V_\varepsilon^+ + \frac{8}{\varepsilon^2} \partial_x V_\varepsilon^+ = g_\varepsilon^+ + \varepsilon^2 r_\varepsilon^+, \quad (4.9)$$

where

$$g_\varepsilon^+ \equiv \partial_x \left(\partial_x^2 N_\varepsilon^+ + \frac{1}{2}(V_\varepsilon^+)^2 - \frac{1}{6}(U_\varepsilon^+)^2 - \frac{1}{3}U_\varepsilon^+ V_\varepsilon^+ \right),$$

and the remainder term r_ε^+ is given by the formula

$$r_\varepsilon^+ = \frac{N_\varepsilon^+ \partial_x^3 N_\varepsilon^+}{6(1 - \frac{\varepsilon^2}{6} N_\varepsilon^+)} + \frac{(\partial_x N_\varepsilon^+)(\partial_x^2 N_\varepsilon^+)}{3(1 - \frac{\varepsilon^2}{6} N_\varepsilon^+)^2} + \frac{\varepsilon^2}{36} \frac{(\partial_x N_\varepsilon^+)^3}{(1 - \frac{\varepsilon^2}{6} N_\varepsilon^+)^3}.$$

Up to a reverse orientation of time, equations (4.8) and (4.9) are identical to equations (13) and (15). In particular, we can apply to the functions $\tau \mapsto U_\varepsilon^+(\cdot, -\tau)$ and $\tau \mapsto V_\varepsilon^+(\cdot, -\tau)$, the analysis developed above to prove (7) for the functions $U_\varepsilon = U_\varepsilon^-$ and V_ε . Given any $k \in \mathbb{N}$, the associated initial datum

$$(U_\varepsilon^+(\cdot, 0), V_\varepsilon^+(\cdot, 0)) = \left(\frac{1}{2}(N_\varepsilon^0 - \partial_x \Theta_\varepsilon^0), \frac{1}{2}(N_\varepsilon^0 + \partial_x \Theta_\varepsilon^0) \right),$$

also satisfies assumption (5), so that there exists some constant K depending only on K_0 and k , such that

$$\|U_\varepsilon^+(\cdot, -\tau) - U(\cdot, \tau)\|_{H^k(\mathbb{R})} \leq K \varepsilon^2 \exp K|\tau|, \quad (4.10)$$

for any $\tau \in \mathbb{R}$. Here, the function U denotes the solution to (KdV) with initial datum

$$U(\cdot, 0) = U_\varepsilon^+(\cdot, 0).$$

By the uniqueness of the solution to (6) for any fixed initial datum in $H^k(\mathbb{R})$, we notice that $U(\cdot, -\tau) = \mathcal{U}^+(\cdot, \tau)$. Reverting the orientation of time in (4.10), this completes the proof of (7) for the functions U_ε^+ and \mathcal{U}^+ .

5 Proof of Theorem 2

In this section, we provide the proof of Theorem 2. This first requires to show Proposition 4, Lemma 3 and Proposition 5.

5.1 Proof of Proposition 4

In order to estimate the H^k -norm of V_ε , we apply the differential operator ∂_x^k to (15), multiply the resulting equation by $\partial_x^k V_\varepsilon$ and integrate by parts on $\mathbb{R} \times (0, \tau)$. In view of definition (16), this yields

$$\int_{\mathbb{R}} (\partial_x^k V_\varepsilon(\cdot, \tau))^2 = \int_{\mathbb{R}} (\partial_x^k V_\varepsilon^0)^2 + \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1}(V_\varepsilon^2) \partial_x^k V_\varepsilon - 2L_1(\tau) + \frac{1}{3}L_2(\tau) - \frac{2}{3}L_3(\tau) + 2L_4(\tau), \quad (5.1)$$

where

$$\begin{aligned} L_1(\tau) &\equiv \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^{k+1} V_\varepsilon, \\ L_2(\tau) &\equiv \int_0^\tau \int_{\mathbb{R}} \partial_x^k (U_\varepsilon^2) \partial_x^{k+1} V_\varepsilon, \\ L_3(\tau) &\equiv \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (U_\varepsilon V_\varepsilon) \partial_x^k V_\varepsilon, \end{aligned}$$

and

$$L_4(\tau) \equiv \varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^k r_\varepsilon \partial_x^k V_\varepsilon.$$

We now estimate each integral $L_j(\tau)$ as in the proof of Theorem 1. For the first one, we have

Step 1. *Under the assumptions of Proposition 4, there exists a positive constant K depending only on K_0 and k , such that*

$$\begin{aligned} \left| L_1(\tau) + \frac{\varepsilon^2}{48} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^{k+1} (U_\varepsilon^2) \right| &\leq K \varepsilon^2 \left(\left(\varepsilon^2 + \|\partial_x^k V_\varepsilon^0\|_{L^2(\mathbb{R})} + \|\partial_x^k V_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \right) \exp K|\tau| \right. \\ &\quad \left. + \left| \int_0^\tau \exp K|s| \|\partial_x^k V_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right). \end{aligned} \quad (5.2)$$

In view of (15), we compute

$$\begin{aligned} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^{k+1} V_\varepsilon &= -\frac{\varepsilon^2}{8} \left[\int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^k V_\varepsilon \right]_0^\tau + \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^{k+2} U_\varepsilon \partial_x^k V_\varepsilon \\ &\quad + \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon (\partial_x^k g_\varepsilon + \varepsilon^2 \partial_x^k r_\varepsilon), \end{aligned}$$

so that by (20) and (3.3),

$$\begin{aligned} \left| L_1(\tau) - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^k g_\varepsilon \right| &\leq K \varepsilon^2 \left(\left(\varepsilon^2 + \|\partial_x^k V_\varepsilon^0\|_{L^2(\mathbb{R})} + \|\partial_x^k V_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \right) \exp K|\tau| \right. \\ &\quad \left. + \left| \int_0^\tau \exp K|s| \|\partial_x^k V_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right). \end{aligned} \quad (5.3)$$

In view of (16), we next write

$$\int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^k g_\varepsilon = \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \left(\partial_x^{k+3} V_\varepsilon + \frac{1}{2} \partial_x^{k+1} (V_\varepsilon^2) - \frac{1}{6} \partial_x^{k+1} (U_\varepsilon^2) - \frac{1}{3} \partial_x^{k+1} (U_\varepsilon V_\varepsilon) \right),$$

so that integrating by parts, we are led to

$$\begin{aligned} &\int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^k g_\varepsilon + \frac{1}{6} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^{k+1} (U_\varepsilon^2) \\ &= - \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+5} U_\varepsilon \partial_x^k V_\varepsilon - \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+3} U_\varepsilon \left(\frac{1}{2} \partial_x^k (V_\varepsilon^2) - \frac{1}{3} \partial_x^k (U_\varepsilon V_\varepsilon) \right). \end{aligned}$$

Combining (20) with the Leibniz formula, the Hölder inequality and the Sobolev embedding theorem, we deduce that

$$\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^k g_\varepsilon + \frac{1}{6} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+2} U_\varepsilon \partial_x^{k+1} (U_\varepsilon^2) \right| \leq K \left| \int_0^\tau \exp K|s| \|V_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|$$

Invoking (5.3), this completes the proof of (5.2).

We similarly derive for the fourth integral on the right-hand side of (5.1).

Step 2. *Under the assumptions of Proposition 4, there exists a positive constant K depending only on K_0 and k , such that*

$$\left| L_2(\tau) - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^k (U_\varepsilon^2) \partial_x^{k+3} U_\varepsilon \right| \leq K \varepsilon^2 \left(\left(\varepsilon^2 + \|\partial_x^k V_\varepsilon^0\|_{L^2(\mathbb{R})} + \|\partial_x^k V_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \right) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|V_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right| \right).$$

The proof is identical to the proof of Step 1, so that we omit it, and instead we turn to the fifth integral on the right-hand side of (5.1).

Step 3. *Under the assumptions of Proposition 4, there exists a positive constant K depending only on K_0 and k , such that*

$$|L_3(\tau)| \leq K \varepsilon^2 \left(\left(\varepsilon^2 + \|\partial_x^k V_\varepsilon^0\|_{L^2} + \|\partial_x^k V_\varepsilon(\cdot, \tau)\|_{L^2} \right) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|\partial_x^k V_\varepsilon(\cdot, s)\|_{L^2} ds \right| \right). \quad (5.4)$$

Using the Leibniz formula, we are led to

$$L_3(\tau) = \sum_{j=0}^{k+1} C_{k+1}^j \mathcal{L}_3^j(\tau), \quad (5.5)$$

where

$$\mathcal{L}_3^j(\tau) \equiv \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1-j} U_\varepsilon \partial_x^j V_\varepsilon \partial_x^k V_\varepsilon.$$

In view of (3.65), given any $0 \leq j \leq k$, we have integrating by parts in space, then in time,

$$\begin{aligned} \mathcal{L}_3^j(\tau) &= \frac{\varepsilon^2}{8} \left[\int_{\mathbb{R}} \partial_x^{k-j} U_\varepsilon \partial_x^j V_\varepsilon \partial_x^k V_\varepsilon \right]_0^\tau - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_\tau \partial_x^{k-j} U_\varepsilon \partial_x^j V_\varepsilon \partial_x^k V_\varepsilon \\ &\quad - \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k-j} U_\varepsilon (\partial_x^j V_\varepsilon \partial_x^k g_\varepsilon + \partial_x^k V_\varepsilon \partial_x^j g_\varepsilon) - \frac{\varepsilon^4}{8} \int_0^\tau \int_{\mathbb{R}} \partial_x^{k-j} U_\varepsilon (\partial_x^j V_\varepsilon \partial_x^k r_\varepsilon + \partial_x^k V_\varepsilon \partial_x^j r_\varepsilon), \end{aligned}$$

so that by (20) and (3.3),

$$|\mathcal{L}_3^j(\tau)| \leq K \varepsilon^2 \left(\varepsilon^2 + \left(\|\partial_x^k V_\varepsilon^0\|_{L^2} + \|\partial_x^k V_\varepsilon(\cdot, \tau)\|_{L^2} \right) \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|\partial_x^k V_\varepsilon(\cdot, s)\|_{L^2} ds \right| \right). \quad (5.6)$$

For $j = k + 1$, we can also invoke (3.65) to establish that

$$\begin{aligned} \mathcal{L}_3^{k+1}(\tau) &= \frac{1}{2} \int_0^\tau \int_{\mathbb{R}} U_\varepsilon \partial_x ((\partial_x^k V_\varepsilon)^2) = - \frac{\varepsilon^2}{16} \left[\int_{\mathbb{R}} U_\varepsilon (\partial_x^k V_\varepsilon)^2 \right]_0^\tau + \frac{\varepsilon^2}{16} \int_0^\tau \int_{\mathbb{R}} \partial_\tau U_\varepsilon (\partial_x^k V_\varepsilon)^2 \\ &\quad + \frac{\varepsilon^2}{8} \int_0^\tau \int_{\mathbb{R}} U_\varepsilon \partial_x^k V_\varepsilon (\partial_x^k g_\varepsilon + \varepsilon^2 \partial_x^k r_\varepsilon), \end{aligned}$$

so that (5.6) follows similarly. In view of (5.5), this completes the proof of (5.4).

Using (3.3), we now compute directly the next estimate of the integral $L_5(\tau)$.

Step 4. Under the assumptions of Proposition 4, there exists a positive constant K depending only on K_0 and k , such that

$$|L_4(\tau)| \leq K\varepsilon^2 \left| \int_0^\tau \exp K|s| \|\partial_x^k V_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|.$$

We finally complete the proof of (36) by induction.

End of the proof of Proposition 4. Let us denote

$$S_\varepsilon^k(\tau) = \sup_{s \in (0, \tau)} \|\partial_x^k V_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})}.$$

For $k = 0$, we have in view of (5.1), and Steps 1, 2, 3 and 4,

$$\begin{aligned} \int_{\mathbb{R}} V_\varepsilon(x, \tau)^2 dx &\leq \|V_\varepsilon^0\|_{L^2(\mathbb{R})}^2 + K\varepsilon^2 \left(\varepsilon^2 + \|V_\varepsilon^0\|_{L^2(\mathbb{R})} + \|V_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \right) \exp K|\tau| \\ &\quad + \left| \int_0^\tau \exp K|s| \|V_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|, \end{aligned}$$

so that

$$S_\varepsilon^0(\tau)^2 \leq \left(\|V_\varepsilon^0\|_{L^2(\mathbb{R})}^2 + K\varepsilon^4 \right) \exp K|\tau| + K\varepsilon^2 \exp K|\tau| S_\varepsilon^0(\tau).$$

Using the inequality $2ab \leq a^2 + b^2$, this completes the proof of (36) for $k = 0$.

We now assume that (36) holds for any $0 \leq k \leq \kappa - 1$ and establish it for $k = \kappa \geq 1$. Invoking the Leibniz formula, we compute

$$\int_0^\tau \int_{\mathbb{R}} \partial_x^{\kappa+1}(V_\varepsilon^2) \partial_x^\kappa V_\varepsilon = \sum_{j=2}^{\kappa-1} C_{\kappa+1}^j \int_0^\tau \int_{\mathbb{R}} \partial_x^{\kappa+1-j} V_\varepsilon \partial_x^j V_\varepsilon \partial_x^\kappa V_\varepsilon - (4\kappa + 2) \int_0^\tau \int_{\mathbb{R}} V_\varepsilon \partial_x^\kappa V_\varepsilon \partial_x^{\kappa+1} V_\varepsilon,$$

so that by the inductive assumption and bound (20),

$$\begin{aligned} \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{\kappa+1}(V_\varepsilon^2) \partial_x^\kappa V_\varepsilon \right| &\leq K \left(\|V_\varepsilon^0\|_{H^{\kappa-1}(\mathbb{R})} + \varepsilon^2 \right) \left(\left(\|V_\varepsilon^0\|_{H^{\kappa-1}(\mathbb{R})} + \varepsilon^2 \right) \exp K|\tau| \right. \\ &\quad \left. + \left| \int_0^\tau \exp K|s| \|\partial_x^\kappa V_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right). \end{aligned}$$

Combining with (5.1), the inductive assumption and Steps 1, 2, 3 and 4, we are led to

$$S_\varepsilon^\kappa(\tau)^2 \leq \|\partial_x^\kappa V_\varepsilon^0\|_{L^2(\mathbb{R})}^2 + K \left(\varepsilon^2 + \|V_\varepsilon^0\|_{H^{\kappa-1}(\mathbb{R})} \right) \left(\varepsilon^2 + \|V_\varepsilon^0\|_{H^\kappa(\mathbb{R})} + S_\varepsilon^\kappa(\tau) \right) \exp K|\tau|.$$

Using again the inequality $2ab \leq a^2 + b^2$, this completes the proof of (36) for $k = \kappa$. By induction, this concludes the proof of Proposition 4. \square

5.2 Proof of Lemma 3

Since F and G are solutions to (KdV), their difference $H \equiv F - G$ is solution to

$$\partial_\tau H + \partial_x^3 H + F \partial_x H + H \partial_x G = 0. \quad (5.7)$$

In order to prove (37), we now compute inductively energy estimates on (5.7).

For $k = 0$, we multiply (5.7) by H and integrate by parts on \mathbb{R} to obtain

$$\partial_\tau \left(\int_{\mathbb{R}} H^2 \right) = \int_{\mathbb{R}} (\partial_x F - 2\partial_x G) H^2. \quad (5.8)$$

Since F^0 and G^0 are in $H^2(\mathbb{R})$, we recall (see also the proof of (3.4)) that in view of the integrability properties of (KdV), there exists a constant K depending only on the H^2 -norms of F^0 and G^0 , such that

$$\|F(\cdot, \tau)\|_{H^2(\mathbb{R})} + \|G(\cdot, \tau)\|_{H^2(\mathbb{R})} \leq K,$$

for any $\tau \in \mathbb{R}$. Applying the Hölder inequality and the Sobolev embedding theorem to (5.8), we are led to

$$\left| \partial_\tau \left(\int_{\mathbb{R}} H^2 \right) \right| \leq K \int_{\mathbb{R}} H^2,$$

so that (37) follows from the Gronwall lemma.

We now assume that (37) holds for any $0 \leq k \leq \kappa - 1$ and derive it for $k = \kappa \geq 1$. For this purpose, we apply the differential operator ∂_x^κ to (5.7), multiply the resulting equation by $\partial_x^\kappa H$ and integrate by parts on \mathbb{R} . This provides

$$\frac{1}{2} \partial_\tau \left(\int_{\mathbb{R}} (\partial_x^\kappa H)^2 \right) = - \int_{\mathbb{R}} \partial_x^\kappa (F \partial_x H) \partial_x^\kappa H - \int_{\mathbb{R}} \partial_x^\kappa (H \partial_x G) \partial_x^\kappa H. \quad (5.9)$$

By the Leibniz formula, the first integral on the right-hand side of (5.9) reduces to

$$\int_{\mathbb{R}} \partial_x^\kappa (F \partial_x H) \partial_x^\kappa H = \sum_{j=1}^{\kappa} C_\kappa^j \int_{\mathbb{R}} \partial_x^j F \partial_x^{\kappa+1-j} H \partial_x^\kappa H - \frac{1}{2} \int_{\mathbb{R}} \partial_x F (\partial_x^\kappa H)^2.$$

In view of the integrability properties of (KdV), there again exists some constant K depending only on the $H^{\kappa+2}$ -norms of F^0 and G^0 , such that

$$\|F(\cdot, \tau)\|_{H^{\kappa+2}(\mathbb{R})} + \|G(\cdot, \tau)\|_{H^{\kappa+2}(\mathbb{R})} \leq K,$$

for any $\tau \in \mathbb{R}$. Hence, we are led to

$$\left| \int_{\mathbb{R}} \partial_x^\kappa (F \partial_x H) \partial_x^\kappa H \right| \leq K \|H\|_{H^\kappa(\mathbb{R})}^2.$$

The same estimate holds for the second integral on the right-hand side of (5.9). Invoking the inductive assumption, we deduce that

$$\left| \partial_\tau \left(\int_{\mathbb{R}} (\partial_x^\kappa H(x, \tau))^2 dx \right) \right| \leq K \left(\int_{\mathbb{R}} (\partial_x^\kappa H(x, \tau))^2 dx + \|F^0 - G^0\|_{H^{\kappa-1}(\mathbb{R})}^2 \exp K|\tau| \right).$$

Inequality (37) follows applying the Gronwall lemma. By induction, this concludes the proof of Lemma 3.

5.3 Proof of Proposition 5

The proof is a direct adaptation of the proof of Proposition 3 using only assumption (10). In view of (3.1), and Lemma 3.2 which remains valid under assumption (10), we have

$$\begin{aligned} \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^k Z_\varepsilon \right| &\leq K \left(\left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon V_\varepsilon \partial_x^k Z_\varepsilon \right| + \varepsilon^2 \sum_{j=1}^k \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^j U_\varepsilon \right| \right) \\ &+ \varepsilon^2 \left(\varepsilon^2 + \|\partial_x^k Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})} \right) \exp K|\tau| + \varepsilon^2 \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{H^k(\mathbb{R})} ds \right|, \end{aligned} \quad (5.10)$$

where K refers to some positive constant depending only on K_0 and k . We then invoke Proposition 4 to bound the first and the second integrals on the right-hand side of (5.10). Combining with (20) and (3.3), this leads to

$$\begin{aligned} & \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} U_\varepsilon V_\varepsilon \partial_x^k Z_\varepsilon \right| + \varepsilon^2 \sum_{j=1}^k \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^k f_\varepsilon \partial_x^{k-j} V_\varepsilon \partial_x^j U_\varepsilon \right| \\ & \leq K \left(\|V_\varepsilon^0\|_{H^k(\mathbb{R})} + \varepsilon^2 \right) \left(\varepsilon^2 \exp K|\tau| + \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right). \end{aligned}$$

In view of (5.10), this completes the proof of (39), and of Proposition 5.

5.4 Proof of Theorem 2 completed

As mentioned in the introduction, we first focus on the coordinate x^- and the associated functions $N_\varepsilon \equiv N_\varepsilon^-$ and $\Theta_\varepsilon \equiv \Theta_\varepsilon^-$. Theorem 2 then follows from combining decompositions (34) and (35) with estimates (36), (38) and (40), once (40) is established, which we do next.

Proof of inequality (40). The proof is an adaptation of the proof of Theorem 1. For $k = 0$, coming back to (4.1), we deduce from (39), (3.3) and (3.4) that

$$\begin{aligned} \partial_\tau \mathcal{Z}_\varepsilon^0(\tau) & \leq K \left(|\mathcal{Z}_\varepsilon^0(\tau)| + (\varepsilon^2 + \|V_\varepsilon^0\|_{L^2(\mathbb{R})}) \left| \int_0^\tau \exp K|s| \|Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right. \\ & \quad \left. + \varepsilon^2 (\varepsilon^2 + \|V_\varepsilon^0\|_{L^2(\mathbb{R})} + \|Z_\varepsilon(\cdot, \tau)\|_{L^2(\mathbb{R})}) \exp K|\tau| \right), \end{aligned}$$

where K is some positive constant depending only on K_0 . Using again the inequality $2|ab| \leq a^2 + b^2$ and identity (4.2), we are led to the differential inequality

$$\partial_\tau \mathcal{Z}_\varepsilon^0(\tau) \leq K \left(\text{sign}(\tau) \mathcal{Z}_\varepsilon^0(\tau) + (\varepsilon^2 + \|V_\varepsilon^0\|_{L^2(\mathbb{R})})^2 \exp K|\tau| \right),$$

so that

$$|\mathcal{Z}_\varepsilon^0(\tau)| \leq K' (\varepsilon^2 + \|V_\varepsilon^0\|_{L^2(\mathbb{R})})^2 \exp K'|\tau|,$$

where K' is some further positive constant depending only on K_0 . Combining with (4.2) and (4.3), this provides (40) for $k = 0$.

We now assume that (40) holds for any $0 \leq j \leq k-1$, i.e. that there exists a positive constant depending only on K_0 and k , such that

$$\|Z_\varepsilon(\cdot, \tau)\|_{H^{k-1}(\mathbb{R})} \leq K (\varepsilon^2 + \|V_\varepsilon^0\|_{H^{k-1}(\mathbb{R})}) \exp K|\tau|,$$

for any $\tau \in \mathbb{R}$. We then bound any integral on the right-hand side of (23). For the first and second ones, we have following the lines of the proofs of (4.5) and (4.7),

$$\begin{aligned} & \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (\mathcal{U} Z_\varepsilon) \partial_x^k Z_\varepsilon \right| + \left| \int_0^\tau \int_{\mathbb{R}} \partial_x^{k+1} (Z_\varepsilon^2) \partial_x^k Z_\varepsilon \right| \\ & \leq K \left(\left| \int_0^\tau \int_{\mathbb{R}} (\partial_x^k Z_\varepsilon)^2 \right| + (\varepsilon^2 + \|V_\varepsilon^0\|_{H^{k-1}(\mathbb{R})}) \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right| \right). \end{aligned} \quad (5.11)$$

Concerning the last integral on the right-hand side of (23), we invoke (3.3) to obtain

$$\left| \varepsilon^2 \int_0^\tau \int_{\mathbb{R}} \partial_x^k r_\varepsilon \partial_x^k Z_\varepsilon \right| \leq K \varepsilon^2 \left| \int_0^\tau \exp K|s| \|\partial_x^k Z_\varepsilon(\cdot, s)\|_{L^2(\mathbb{R})} ds \right|.$$

Therefore, in view of (39) and (5.11), we are led to the differential inequality

$$\partial_\tau \mathcal{Z}_\varepsilon^k(\tau) \leq K \left(\text{sign}(\tau) \mathcal{Z}_\varepsilon^k(\tau) + (\varepsilon^2 + \|V_\varepsilon^0\|_{H^k(\mathbb{R})})^2 \exp K|\tau| \right),$$

so that by the Gronwall lemma, inequality (40) also holds for the integer k . By induction, this completes the proof of (40). \square

We are now in position to end the proof of Theorem 2.

End of the proof of Theorem 2. As mentioned above, Theorem 2 is a direct consequence of decompositions (34) and (35) and estimates (36), (38) and (40), when the coordinate x^- is considered. For the functions N_ε^+ and $\partial_x \Theta_\varepsilon^+$, the proof reduces as in Theorem 1 to consider the system of equations (4.8)-(4.9) instead of the system (13)-(15). Since the functions $\tau \mapsto U_\varepsilon^+(\cdot, -\tau)$ and $\tau \mapsto V_\varepsilon^+(\cdot, -\tau)$ are solutions to (13) and (15), we can apply Propositions 4 and 5 to them in order to obtain inequalities (36) and (40) in the coordinate x^+ . Combining with the versions of (34) and (35) in the coordinate x^+ , and Lemma 3, this provides (11) in the coordinate x^+ , and concludes the proof of Theorem 2. \square

A Defining a notion of the mass for (GP)

The purpose of this appendix is to provide a framework where the notion of mass for the one-dimensional Gross-Pitaevskii equation may be rigorously handled. At least on a formal level, the mass may be defined by

$$m(\Psi) = \frac{1}{2} \int_{\mathbb{R}} (1 - |\Psi|^2), \quad (\text{A.1})$$

and it is a conserved quantity along the Gross-Pitaevskii flow. Indeed, a solution Ψ to (GP) satisfies the conservation law

$$\partial_t \eta = 2\partial_x (\langle i\Psi, \partial_x \Psi \rangle), \quad (\text{A.2})$$

where we denote as above $\eta \equiv 1 - |\Psi|^2$. Hence, we have

$$\partial_t m(\Psi) = \frac{1}{2} \int_{\mathbb{R}} \partial_t \eta = \int_{\mathbb{R}} \partial_x (\langle i\Psi, \partial_x \Psi \rangle) = 0,$$

provided that the functions Ψ and η are sufficiently smooth and decay suitably at infinity.

The quantity $m(\psi)$ is however not well-defined in general for an arbitrary function ψ in the energy space $X^1(\mathbb{R})$. Consider for instance, the function ψ defined by

$$\psi(x) = \frac{|x|}{|x|+1}, \quad \forall x \in \mathbb{R},$$

which belongs to $X^1(\mathbb{R})$, but for which $m(\psi) = +\infty$. In order to circumvent this difficulty, we introduce the set

$$X_{\mathcal{M}}(\mathbb{R}) \equiv \{\psi \in X^1(\mathbb{R}), \text{ s.t. } 1 - |\psi|^2 \in \mathcal{M}(\mathbb{R})\}.$$

We first claim that the Gross-Pitaevskii equation is well-posed in this new functional setting.

Lemma A.1. *Given any function $\Psi_0 \in X_{\mathcal{M}}(\mathbb{R})$, there exists a unique solution $\Psi(\cdot, t)$ to (GP) in $\mathcal{C}^0(\mathbb{R}, X_{\mathcal{M}}(\mathbb{R}))$ with initial datum Ψ_0 . Moreover, there exists a universal constant K such that*

$$\|\eta(t) - \eta(s)\|_{\mathcal{M}(\mathbb{R})} \leq K \left(E(\Psi_0)^{\frac{1}{2}} (1 + E(\Psi_0)^{\frac{1}{2}}) |t - s| + \|\eta(t) - \eta(s)\|_{L^2(\mathbb{R})} \right), \quad (\text{A.3})$$

for any $(s, t) \in \mathbb{R}^2$.

Remark A.1. In view of Proposition 1 and Lemma A.1, the Gross-Pitaevskii equation is also globally well-posed in the space

$$X_{\mathcal{M}}^k(\mathbb{R}) \equiv \{\psi \in X^k(\mathbb{R}), \text{ s.t. } 1 - |\psi|^2 \in \mathcal{M}(\mathbb{R})\},$$

for any $k \geq 2$.

Proof. We recall that in view of Proposition 1, the Gross-Pitaevskii equation is well-posed in $X^1(\mathbb{R})$ with conservation of the energy E , i.e.

$$E(\Psi(\cdot, t)) = E(\Psi_0), \quad (\text{A.4})$$

for any $t \in \mathbb{R}$. Therefore, the proof of Lemma A.1 reduces to show that the function $\eta(\cdot, t) \equiv 1 - |\Psi(\cdot, t)|^2$ associated to the unique solution $\Psi(\cdot, t)$ in the space $X^1(\mathbb{R})$ is continuous with values in $\mathcal{M}(\mathbb{R})$. This fact is a direct consequence of (A.3) which we show next.

For the proof of (A.3), we introduce a cut-off function $\chi \in C^\infty(\mathbb{R})$ such that $0 \leq \chi \leq 1$,

$$\chi(x) = 1, \text{ for } x \leq 0, \text{ and } \chi(x) = 0, \text{ for } x \geq 1,$$

and denote

$$\chi_{a,b}(x) = \begin{cases} \chi(a-x), & \text{for } x \leq a, \\ 1, & \text{for } a \leq x \leq b, \\ \chi(x-b), & \text{for } x \geq b, \end{cases}$$

for any given numbers $a < b$. When Ψ is a solution to (GP) in $X^1(\mathbb{R})$, identity (A.2) holds in the sense of distributions and involves quantities which are in $H^{-1}(\mathbb{R})$, so that we may multiply (A.2) by the test function $\chi_{a,b}$ and integrate by parts to obtain

$$\partial_t \left(\int_{\mathbb{R}} \eta \chi_{a,b} \right) = \int_{\mathbb{R}} \partial_t \eta \chi_{a,b} = 2 \int_{\mathbb{R}} \partial_x (\langle i\Psi, \partial_x \Psi \rangle) \chi_{a,b} = -2 \int_{\mathbb{R}} \langle i\Psi, \partial_x \Psi \rangle \partial_x \chi_{a,b}.$$

By the Cauchy-Schwarz inequality, we are led to

$$\left| \partial_t \left(\int_{\mathbb{R}} \eta \chi_{a,b} \right) \right| \leq 2 \|\Psi\|_{L^2(I(a,b))} \|\partial_x \Psi\|_{L^2(I(a,b))}, \quad (\text{A.5})$$

where we denote $I(a,b) = (a-1, a) \cup (b, b+1)$. We now recall that it is proved in [12] that there exists some universal constant K such that

$$\|\psi\|_{L^\infty} \leq K(1 + E(\psi)^{\frac{1}{2}}), \quad (\text{A.6})$$

for any $\psi \in L^2(\mathbb{R})$, so that (A.5) may be recast as

$$\left| \partial_t \left(\int_{\mathbb{R}} \eta \chi_{a,b} \right) \right| \leq K(1 + E(\Psi)^{\frac{1}{2}}) E(\Psi)^{\frac{1}{2}},$$

where K denotes a further positive constant, depending only on our choice of the function χ . Integrating in time and invoking the conservation of the energy provided by (A.4), we are led to

$$\left| \int_{\mathbb{R}} (\eta(\cdot, t) - \eta(\cdot, s)) \chi_{a,b} \right| \leq K(1 + E(\Psi_0)^{\frac{1}{2}}) E(\Psi_0)^{\frac{1}{2}} |t - s|. \quad (\text{A.7})$$

Notice finally that

$$\left| \int_{\mathbb{R}} \psi \chi_{a,b} - \int_a^b \psi \right| = \left| \int_{I(a,b)} \psi \chi_{a,b} \right| \leq K \|\psi\|_{L^2(I(a,b))}, \quad (\text{A.8})$$

for any function $\psi \in X^1(\mathbb{R})$, so that (A.3) is a consequence of (A.7) and (A.8) (for $\psi = \eta(t) - \eta(s)$). This completes the proof of Lemma A.1. \square

We now turn to the notion of mass and define

$$m^+(\psi) = \frac{1}{2} \left(\limsup_{x \rightarrow +\infty} \int_0^x (1 - |\psi|^2) + \limsup_{y \rightarrow -\infty} \int_y^0 (1 - |\psi|^2) \right), \quad (\text{A.9})$$

and

$$m^-(\psi) = \frac{1}{2} \left(\liminf_{x \rightarrow +\infty} \int_0^x (1 - |\psi|^2) + \liminf_{y \rightarrow -\infty} \int_y^0 (1 - |\psi|^2) \right), \quad (\text{A.10})$$

for any function $\psi \in X_{\mathcal{M}}(\mathbb{R})$. Recall that the above integrals are bounded and continuous functions of x and y , when ψ belongs to $X_{\mathcal{M}}(\mathbb{R})$, so that $m^+(\psi)$ and $m^-(\psi)$ are well-defined ².

We next show that both the quantities m^+ and m^- are conserved along the Gross-Pitaevskii flow provided that the initial datum Ψ_0 belongs to $X_{\mathcal{M}}(\mathbb{R})$.

Lemma A.2. *Given any function $\Psi_0 \in X_{\mathcal{M}}(\mathbb{R})$, we have*

$$m^+(\Psi(\cdot, t)) = m^+(\Psi_0), \text{ and } m^-(\Psi(\cdot, t)) = m^-(\Psi_0), \quad (\text{A.11})$$

for any $t \in \mathbb{R}$.

Proof. Given any numbers $a < b$, we deduce from (A.4), (A.5) and (A.6) that

$$\left| \partial_t \left(\int_{\mathbb{R}} \eta \chi_{a,b} \right) \right| \leq K (1 + E(\Psi_0)^{\frac{1}{2}}) \|\partial_x \Psi\|_{L^2(I(a,b))},$$

for any fixed $t \in \mathbb{R}$. Integrating this relation in time, combining with (A.8) and applying the Cauchy-Schwarz inequality in time, we are led to

$$\begin{aligned} & \left| \int_a^b \eta(x, t) dx - \int_a^b \eta(x, 0) dx \right| \\ & \leq K \left(1 + E(\Psi_0)^{\frac{1}{2}} \right) \int_0^t \left(\|\partial_x \Psi(\cdot, s)\|_{L^2(I(a,b))} + \|\eta(\cdot, s) - \eta(\cdot, 0)\|_{L^2(I(a,b))} \right) ds \\ & \leq K \left(1 + E(\Psi_0)^{\frac{1}{2}} \right) \left(\sqrt{|t|} \left| \int_0^t \int_{I(a,b)} \left(\frac{1}{2} |\partial_x \Psi(x, s)|^2 + \frac{1}{4} |\eta(x, s)|^2 \right) dx ds \right|^{\frac{1}{2}} + |t| \|\eta(\cdot, 0)\|_{L^2(I(a,b))} \right). \end{aligned} \quad (\text{A.12})$$

On the other hand, it follows from the conservation of the energy that

$$\left| \int_0^t \int_{\mathbb{R}} \left(\frac{1}{2} |\partial_x \Psi(x, s)|^2 + \frac{1}{4} |\eta(x, s)|^2 \right) dx ds \right| = |t| E(\Psi_0) < +\infty,$$

so that, by the dominated convergence theorem,

$$\int_0^t \int_{I(a,b)} \left(\frac{1}{2} |\partial_x \Psi(x, s)|^2 + \frac{1}{4} |\eta(x, s)|^2 \right) dx ds \rightarrow 0, \text{ as } a \rightarrow -\infty \text{ and } b \rightarrow +\infty.$$

Similarly, since $\eta(\cdot, 0)$ belongs to $L^2(\mathbb{R})$,

$$\|\eta(\cdot, 0)\|_{L^2(I(a,b))} \rightarrow 0, \text{ as } a \rightarrow -\infty \text{ and } b \rightarrow +\infty.$$

The conclusion then follows from (A.12), and definitions (A.9) and (A.10). \square

²In our definitions of $m^+(\psi)$ and $m^-(\psi)$, the number 0 may be replaced by any arbitrary other real number.

When the function $1 - |\psi|^2$ belongs to $L^1(\mathbb{R})$, the quantities $m^+(\psi)$ and $m^-(\psi)$ are equal to the mass of ψ defined by (A.1). However, for an arbitrary map in $X_{\mathcal{M}}(\mathbb{R})$, the quantities $m^+(\psi)$ and $m^-(\psi)$, which are preserved by the flow, may be different. In order to define a generalized notion of mass, we are led to restrict ourselves to an even smaller class of maps. More precisely, we consider the subset of $X_{\mathcal{M}}(\mathbb{R})$ defined by

$$\mathcal{X}_{\mathcal{M}}(\mathbb{R}) = \{\psi \in X_{\mathcal{M}}(\mathbb{R}), \text{ s.t } m^+(\psi) = m^-(\psi)\},$$

and define the generalized mass of an arbitrary function $\psi \in \mathcal{X}_{\mathcal{M}}(\mathbb{R})$ as the quantity

$$m(\psi) = m^+(\psi) = m^-(\psi) = \frac{1}{2} \left(\lim_{x \rightarrow +\infty} \int_0^x (1 - |\psi|^2) + \lim_{y \rightarrow -\infty} \int_y^0 (1 - |\psi|^2) \right). \quad (\text{A.13})$$

We then have

Proposition A.1. *Given any function $\Psi_0 \in \mathcal{X}_{\mathcal{M}}(\mathbb{R})$, there exists a unique solution $\Psi(\cdot, t)$ to (GP) in $\mathcal{C}^0(\mathbb{R}, \mathcal{X}_{\mathcal{M}}(\mathbb{R}))$ with initial datum Ψ_0 . Moreover, we have*

$$m(\Psi(\cdot, t)) = m(\Psi_0), \quad (\text{A.14})$$

for any $t \in \mathbb{R}$.

Proof. Proposition A.1 is a direct consequence of Lemmas A.1 and A.2. Given any function $\Psi_0 \in \mathcal{X}_{\mathcal{M}}(\mathbb{R})$, there exists a unique solution Ψ to (GP) in $\mathcal{C}^0(\mathbb{R}, X_{\mathcal{M}}(\mathbb{R}))$ with initial datum Ψ_0 . Since $m^+(\Psi_0) = m^-(\Psi_0)$, it follows from Lemma A.2 that

$$m^+(\Psi(\cdot, t)) = m^-(\Psi(\cdot, t)),$$

so that $\Psi(\cdot, t)$ belongs to $\mathcal{X}_{\mathcal{M}}(\mathbb{R})$. Equality (A.14) then follows from (A.11) and (A.13). \square

Remark A.2. As already mentioned, if the function $1 - |\Psi_0|^2$ belongs to $L^1(\mathbb{R})$, then the function Ψ_0 belongs to $\mathcal{X}_{\mathcal{M}}(\mathbb{R})$, and it follows from Proposition A.1 that the generalized mass of the solution $\Psi(\cdot, t)$ to (GP) with initial datum Ψ_0 is well-defined for any time $t \in \mathbb{R}$ and conserved by the flow. Notice however that we do not claim that the function $1 - |\Psi|^2$ remains in $L^1(\mathbb{R})$.

Remark A.3. In our proofs, we use several estimates involving control on the norm $\|\cdot\|_{\mathcal{M}}$ which are closely related to the conservation of the generalized mass. The conservation of the generalized mass itself does actually not provide any bound on the solution $\Psi(\cdot, t)$. We believe that this fact is of independent interest. In particular, it might be relevant for the physical phenomena the equation was designed to describe.

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