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# HIGH SPEED EXCITED MULTI-SOLITONS IN NONLINEAR SCHRÖDINGER EQUATIONS

RAPHAËL CÔTE AND STEFAN LE COZ

ABSTRACT. We consider the nonlinear Schrödinger equation in  $\mathbb{R}^d$

$$i\partial_t u + \Delta u + f(u) = 0.$$

For  $d \geq 2$ , this equation admits travelling wave solutions of the form  $e^{i\omega t}\Phi(x)$  (up to a Galilean transformation), where  $\Phi$  is a fixed profile, solution to  $-\Delta\Phi + \omega\Phi = f(\Phi)$ , but *not the ground state*. This kind of profiles are called excited states. In this paper, we construct solutions to NLS behaving like a sum of  $N$  excited states which spread up quickly as time grows (which we call multi-solitons). We also show that if the flow around one of these excited states is linearly unstable, then the multi-soliton is not unique, and is unstable (asymptotically and orbitally).

## 1. INTRODUCTION

**Setting of the problem.** We consider the nonlinear Schrödinger equation

$$(NLS) \quad iu_t + \Delta u + f(u) = 0$$

where  $u : \mathbb{R} \times \mathbb{R}^d \rightarrow \mathbb{C}$  and  $f : \mathbb{C} \rightarrow \mathbb{C}$  is defined for any  $z \in \mathbb{C}$  by  $f(z) = g(|z|^2)z$  with  $g \in \mathcal{C}^1([0, +\infty), \mathbb{R})$ .

Equation (NLS) admits special travelling wave solutions called solitons: given a frequency  $\omega_0 > 0$ , an initial phase  $\gamma_0 \in \mathbb{R}$ , initial position and speed  $x_0, v_0 \in \mathbb{R}^d$  and a solution  $\Phi_0 \in H^1(\mathbb{R}^d)$  of

$$(1) \quad -\Delta\Phi_0 + \omega_0\Phi_0 - f(\Phi_0) = 0,$$

a *soliton* solution of (NLS) travelling on the line  $x = x_0 + v_0 t$  is given by

$$(2) \quad R_{\Phi_0, \omega_0, \gamma_0, v_0, x_0}(t, x) := \Phi_0(x - v_0 t - x_0) e^{i(\frac{1}{2}v_0 \cdot x - \frac{1}{4}|v_0|^2 t + \omega_0 t + \gamma_0)}.$$

Among solutions of (1), it is common to distinguish between *ground states*, and *excited states*. A *ground state* (or *least energy solution*) minimizes among all solutions of (1) the action  $S_0$ , defined for  $v \in H^1(\mathbb{R}^d)$  by

$$S_0(v) := \frac{1}{2} \|\nabla v\|_{L^2(\mathbb{R}^d)}^2 + \frac{\omega_0}{2} \|v\|_{L^2(\mathbb{R}^d)}^2 - \int_{\mathbb{R}^d} F(v) dx,$$

where  $F(z) := \int_0^{|z|} g(s^2) s ds$  for all  $z \in \mathbb{C}$ . An *excited state* is a solution to (1) which is not a ground state. In general, we shall refer to any solution of (1) as *bound state*. We also mention the existence of a particular type of excited states, the *vortices*. A vortex is a special solution of (1) which is non-trivially complex-valued, i.e. with a non-zero angular momentum. Vortices can be constructed following the ansatz described by Lions in [27]. We shall sometimes abuse terminology and call ground

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state (resp. excited state) a soliton build with a ground state (resp. an excited state).

A multi-soliton is a solution of (NLS) built with solitons. More precisely, let  $N \in \mathbb{N} \setminus \{0, 1\}$ ,  $\omega_1, \dots, \omega_N > 0$ ,  $\gamma_1, \dots, \gamma_N \in \mathbb{R}$ ,  $v_1, \dots, v_N \in \mathbb{R}^d$ ,  $x_1, \dots, x_N \in \mathbb{R}^d$  and  $\Phi_1, \dots, \Phi_N \in H^1(\mathbb{R}^d)$  solutions of (1) (with  $\omega_0$  replaced by  $\omega_1, \dots, \omega_N$ ). Set

$$(3) \quad R_j(t, x) := R_{\Phi_j, \omega_j, \gamma_j, v_j, x_j}(t, x), \quad R(t, x) := \sum_{j=1}^N R_j(t, x).$$

Due to the non-linearity, the function  $R$  is not a solution of (NLS) anymore. What we call *multi-soliton* is a solution  $u$  of (NLS) defined on  $[T_0, +\infty)$  for some  $T_0 \in \mathbb{R}$  and such that

$$\lim_{t \rightarrow +\infty} \|u(t) - R(t)\|_{H^1(\mathbb{R}^d)} = 0.$$

In this paper, we are concerned with existence, non-uniqueness and instability of multi-solitons build on excited states, which we will refer to as excited multi-solitons.

**History and known results.** Solitons and multi-solitons play a crucial role in understanding the dynamics of nonlinear dispersive evolution equations such as Korteweg-de Vries equations or nonlinear Schrödinger equations (see e.g. [37] for a general overview).

To fix ideas, consider the pure-power nonlinearity  $f(u) = |u|^{p-1}u$ . Equation (NLS) is  $L^2$ -critical (resp. subcritical, resp. supercritical) if  $p = 1 + \frac{4}{d}$  (resp.  $p < 1 + \frac{4}{d}$ ,  $p > 1 + \frac{4}{d}$ ). The *soliton resolution conjecture* states that, at least in the  $L^2$ -subcritical case, a generic solution will eventually decompose into a sum of *ground state* solitons and a small radiative term, in some sense we will not try to make precise. However, this conjecture remains widely open, except when the equation is completely integrable (like the classical Korteweg-de Vries equation  $u_t + u_{xxx} + uu_x = 0$ ) and explicit solutions are known [25, 35].

Nevertheless, multi-solitons *based on ground states* are supposed to be generic objects for large time; in contrast *excited* multi-solitons are believed to be singular objects of the flow of (NLS). However, their existence shows that a global approach of the large time dynamics must take care of them.

The first existence result of multi-solitons in a non-integrable setting was obtained by Merle [31] for multi-solitons composed of ground states for the  $L^2$ -critical nonlinear Schrödinger equation. The  $L^2$ -subcritical case was treated by Martel and Merle [29] (see also Martel [28] for the generalized Korteweg-de Vries equation) and the  $L^2$ -supercritical case by Côte, Martel and Merle [13]. No excited multi-solitons were ever constructed and our result (Theorem 1) is the first in that direction: we construct excited multi-solitons based on excited states which move fast away from one another.

Study of the dynamics around *ground-states* solitons and multi-solitons, in particular stability properties, has attracted a lot of attention since the beginning of the 80's (see e.g. [2, 8, 21, 22, 38, 39, 40]). The main result states that ground-states solitons are orbitally stable only in the  $L^2$ -subcritical case.

So far, little is known about the stability of excited state solitons. All excited states are conjectured to be unstable, regardless of any assumption on the non-linearity. For results on instability with a supercritical nonlinearity, see Grillakis [19] and Jones [36] in the case of real and radial excited states and Mizumachi for

vortices [32, 33]. Partial results in the  $L^2$ -subcritical case are available in the works of Chang, Gustafson, Nakanishi and Tsai [10], Grillakis [20] and Mizumachi [34].

Here we show that under a very natural assumption of instability of the linearized flow around one excited state, the excited multi-soliton is not unique, and unstable in a strong sense.

**Statement of the results.** We make the following assumptions on the nonlinearity (recall that  $f(z) = g(|z|^2)z$  for  $z \in \mathbb{C}$ ).

(A1)  $g(0) = 0$ .

(A2) There exist  $C > 0$  and  $1 < p < 1 + \frac{4}{d-2}$  if  $d \geq 3$ ,  $1 < p < +\infty$  if  $d = 1, 2$  such that  $|s^2 g'(s^2)| \leq Cs^{p-1}$  for  $s \geq 1$ .

(A3) There exists  $s_0 > 0$  such that  $F(s_0) > \frac{s_0^2}{2}$ .

Assumptions (A1)-(A3) guarantee that, except in dimension  $d = 1$  where all bound states are ground states, there exist ground states and infinitely many excited states (see e.g. [3, 4, 5, 20, 24]). In particular, excited states can have arbitrarily large energy and  $L^\infty(\mathbb{R}^d)$ -norm. Note that every solution of (1) is exponentially decaying (see e.g. [6]). More precisely, for all  $\Phi_0$  solution to (1) we have  $e^{\sqrt{\omega}|x|}(|\Phi_0| + |\nabla\Phi_0|) \in L^\infty(\mathbb{R}^d)$  for all  $\omega < \omega_0$ .

Assumptions (A1)-(A2) ensure well-posedness in  $H^1(\mathbb{R}^d)$  of (NLS), see e.g. [7] (the equation is then  $H^1$ -subcritical). In particular, for any  $u_0 \in H^1(\mathbb{R}^d)$  there exists a unique maximal solution  $u$  such that energy, mass and momentum are conserved. Recall that energy, mass and momentum are defined in the following way.

$$\begin{aligned} E(u) &:= \frac{1}{2} \|\nabla u\|_{L^2(\mathbb{R}^d)}^2 - \int_{\mathbb{R}^d} F(u) dx, \\ M(u) &:= \|u\|_{L^2(\mathbb{R}^d)}^2, \\ P(u) &:= \Im \int_{\mathbb{R}^d} \bar{u} \nabla u dx. \end{aligned}$$

Notice that (A3) makes the equation focusing.

Let  $\omega_\star$  and  $v_\star$  be given by

$$\begin{aligned} \omega_\star &:= \frac{1}{2} \min \{\omega_j, j = 1, \dots, N\}, \\ v_\star &:= \frac{1}{9} \min \{|v_j - v_k|; j, k = 1, \dots, N, j \neq k\}. \end{aligned}$$

Also introduce  $\alpha := \sin\left(\frac{\sqrt{\pi}\Gamma(\frac{d-1}{2})}{N^2\Gamma(\frac{d}{2})}\right)$  (this constant appears naturally in Claim 7).

Our first result is the existence of multi-solitons composed of excited states as soon as the relative speeds  $v_j - v_k$  of the solitons are sufficiently large.

**Theorem 1.** *Assume (A1)-(A3).*

*There exists  $v_\sharp := v_\sharp(\Phi_1, \dots, \Phi_N) > 0$  such that if  $v_\star > \alpha^{-1}v_\sharp$  then the following holds.*

*There exist  $T_0 \in \mathbb{R}$  and a solution of (NLS)  $u \in \mathcal{C}([T_0, +\infty), H^1(\mathbb{R}^d))$  such that for all  $t \in [T_0, +\infty)$  we have*

$$\|u(t) - R(t)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_\star^{\frac{1}{2}}v_\star t}.$$

We now turn to the non-uniqueness and instability of a multi-soliton.

Assume that the flow around one of the  $R_j$  is linearly unstable, i.e. has an eigenvalue off the imaginary axis. As the  $R_j$  all play the same role, we can assume it is  $R_1$ .

(A4)  $L = -i\Delta + i\omega_1 - idf(\Phi_1)$  has an eigenvalue  $\lambda \in \mathbb{C}$  with  $\rho := \Re(\lambda) > 0$ .

This assumption is very natural if one expects  $R_1$  to be unstable. Actually, (A4) holds for any real radial bound state in the  $L^2$ -supercritical case. For excited states, (A4) is believed to hold for a wide class of non-linearities.

Under assumption (A4), solitons are nonlinearly unstable, as described in the following Theorem.

**Theorem 2.** *Assume  $g$  is  $C^\infty$  and (A1)-(A4) are satisfied. There exists a one parameter family of solutions to (NLS) converging to the excited soliton  $R_1$  as  $t \rightarrow +\infty$ . More precisely, let  $a \in \mathbb{R}$ . There exist  $T_0 \in \mathbb{R}$  large enough, a solution  $u$  to (NLS) defined on  $[T_0, +\infty)$ , and a constant  $C > 0$  such that*

$$\forall t \geq T_0, \quad \|u(t) - R_1(t) - aY(t)\|_{H^1(\mathbb{R}^d)} \leq Ce^{-2\rho t},$$

where  $Y(t)$  is a non-zero solution to the linearized flow around  $R_1$  (see (26)). In particular,  $R_1(t)$  is unstable (asymptotically and orbitally).

From Theorem 2 we infer the following result of non-uniqueness and instability for high relative speeds multi-solitons.

**Theorem 3.** *Assume  $g$  is  $C^\infty$  and (A1)-(A4) are satisfied. There exists  $v_{\natural} := v_{\natural}(\Phi_1, \dots, \Phi_N) > 0$  such that if  $v_* > v_{\natural}$  then there exists a one parameter family of multi-solitons. More precisely let  $a \in \mathbb{R}$ , there exist  $T_0 \in \mathbb{R}$  large enough, a solution  $u$  to (NLS) defined on  $[T_0, +\infty)$ , and a constant  $C > 0$  such that*

$$\forall t \geq T_0, \quad \|u(t) - R(t) - aY(t)\|_{H^1(\mathbb{R}^d)} \leq Ce^{-2\rho t},$$

where  $Y(t)$  is a solution to the linearized flow (see (26)). In particular, a multi-soliton is not unique and unstable (asymptotically and orbitally).

**Scheme of proofs and comments.** Our strategy for the proof of the existence result (Theorem 1) is inspired from the works [13, 29, 31]: we take a sequence of time  $T_n \rightarrow +\infty$  and a set of final data  $u_n(T_n) = R(T_n)$ . Our goal is to prove that the solutions  $u_n$  to (NLS) backwards in time (which approximate a multi-soliton) exist up to some time  $T_0$  independent of  $n$ , and enjoy uniform  $H^1(\mathbb{R}^d)$  decay estimates on  $[T_0, T_n]$ . A compactness argument then shows that  $(u_n)$  converges to a multi-soliton solution to (NLS) defined on  $[T_0, +\infty)$ .

As in [13, 29], the uniform backward  $H^1(\mathbb{R}^d)$ -estimates rely on slow variation of localized conservation laws as well as coercivity of the Hessian of the action around each component of the multi-soliton. However, this Hessian has negative “bad directions” on which it is not coercive. When dealing with ground states, these were ruled out either by modulation and conservation of the mass (as in [29]) or with the help of explicit knowledge of eigenfunctions of the operator corresponding to the linearization of (NLS) around a soliton (as in [13]). In both cases, this could be done only because of the knowledge of precise spectral properties for ground states; this does no longer hold when dealing with the more general case of excited states.

Our remark is that the Hessian fails to be  $H^1(\mathbb{R}^d)$ -coercive only up to a  $L^2(\mathbb{R}^d)$ -scalar product with the bad directions. Hence the first step in our analysis is to

find uniform  $L^2(\mathbb{R}^d)$ -backward estimates without the help of the Hessian. This rules out the “bad directions” and we can now take advantage of the coercivity of the Hessian to obtain the  $H^1(\mathbb{R}^d)$ -estimates. The main drawback of our approach is that the bootstrap of the  $L^2(\mathbb{R}^d)$ -estimates requires that the soliton components are well-separated. Thus we have to work with high-speed solitons.

To obtain the instability result (Theorem 2), we rely on a fixed point argument for smooth functions exponentially convergent (in time). This is possible because we now assume smoothness on the non-linearity. The main difficulty is to construct a very good approximate solution to the multi-soliton. Actually we build such a profile at arbitrary exponential order. This method is inspired by [15, 16, 17, 18] in the case of a single ground state, for the nonlinear wave or Schrödinger equations. It was also recently developed by Combet [11, 12] for multi-solitons in the context of the  $L^2$ -supercritical generalized Korteweg-de Vries equation.

However, an important difference in our case is that we consider excited states, and the linearized flow around them is much less understood than that around a ground state soliton. For example, to our knowledge, the exponential decay of eigenfunctions was not known in general (see [23] for a partial result). We prove it in Appendix A, see Proposition 19. Also, the unstable eigenvalue has no reason to be real, and this will make the construction of the profile much more intricate than in the ground state soliton case. This is the purpose of Proposition 16. Once the approximation profile is derived, the proofs of Theorem 2 and 3 follow from a fixed point argument around the profile.

The paper is organized as follows. In Section 2 we prove Theorem 1. Section 3 is devoted to the proofs of Theorems 2 and 3. In Appendix we prove the exponential decay of eigenfunctions for matrix Schrödinger operators.

## 2. EXISTENCE

**2.1. Approximate solutions and convergence toward a multi-soliton.** Let  $(T_n)_{n \geq 1} \subset \mathbb{R}$  be an increasing sequence of time such that  $T_n \rightarrow +\infty$  and  $(u_n)$  be solutions to (NLS) such that  $u_n(T_n) = R(T_n)$ . We call  $u_n$  an *approximate multi-soliton*.

The proof of Theorem 1 relies on the following proposition.

**Proposition 1** (Uniform estimates). *There exists  $v_{\sharp} := v_{\sharp}(\Phi_1, \dots, \Phi_N) > 0$  such that if  $v_{\star} > \alpha^{-1}v_{\sharp}$  then the following holds. There exist  $n_0 \in \mathbb{N}$ ,  $T_0 > 0$  such that for all  $n \geq n_0$  the solution  $u_n$  is defined on  $[T_0, T_n]$  and for all  $t \in [T_0, T_n]$  we have*

$$(4) \quad \|u_n(t) - R(t)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_{\star}^{\frac{1}{2}}v_{\star}t}.$$

In this section, assuming Proposition 1, we prove Theorem 1 by establishing the convergence of the approximate multi-solitons  $u_n$  to a multi-soliton  $u$  existing on  $[T_0, +\infty)$ . Our proof follows the same line as in [13, 29].

Since the approximate multi-solitons  $u_n$  are constructed by solving (NLS) backward in time, to prove Theorem 1 we first need to make sure that the initial data  $u_n(T_0)$  converge to some initial datum  $u_0$ .

For notational simplicity we assume  $n_0 = 0$ .

**Lemma 2.** *There exists  $u_0 \in H^1(\mathbb{R}^d)$  such that, possibly for subsequence only,  $u_n(T_0) \rightarrow u_0$  strongly in  $H^s(\mathbb{R}^d)$  as  $n \rightarrow +\infty$  for any  $s \in [0, 1)$ .*

Lemma 2 is a consequence of the following claim.

**Claim 3** ( $L^2(\mathbb{R}^d)$ -compactness). *Take  $\delta > 0$ . There exists  $r_\delta > 0$  such that for all  $n$  large enough we have*

$$(5) \quad \int_{|x|>r_\delta} |u_n(T_0)|^2 dx \leq \delta.$$

*Proof.* Let  $T_\delta$  be such that  $e^{-\alpha\omega_*^{\frac{1}{2}}v_*T_\delta} \leq \sqrt{\frac{\delta}{4}}$ . Then, by Proposition 1, we have

$$(6) \quad \|u_n(T_\delta) - R(T_\delta)\|_{H^1(\mathbb{R}^d)} \leq \sqrt{\frac{\delta}{4}}.$$

Let  $\rho_\delta$  be such that

$$(7) \quad \int_{|x|>\rho_\delta} |R(T_\delta)|^2 dx < \frac{\delta}{4}.$$

From (6)-(7) we infer

$$(8) \quad \int_{|x|>\rho_\delta} |u_n(T_\delta)|^2 dx < \frac{\delta}{2}.$$

We define a  $C^1$  cut-off function  $\tau : \mathbb{R} \rightarrow \mathbb{R}$  such that  $\tau(s) = 0$  if  $s \leq 0$ ,  $\tau(s) = 1$  if  $s \geq 1$ ,  $\tau(s) \in [0, 1]$  and  $|\tau'(s)| \leq 2$  if  $s \in [0, 1]$ . Let  $\kappa_\delta$  to be determined later and consider

$$\Upsilon(t) := \int_{\mathbb{R}^d} |u_n(t)|^2 \tau\left(\frac{|x| - \rho_\delta}{\kappa_\delta}\right) dx.$$

To obtain (5) from (8) we need to establish a link between  $\Upsilon(T_0)$  and  $\Upsilon(T_\delta)$ . Differentiating in time, we obtain after simple calculations (see e.g. [29, Claim 2])

$$\Upsilon'(t) = \frac{1}{\kappa_\delta} \mathfrak{Im} \int_{\mathbb{R}^d} \bar{u}_n \nabla u_n \cdot \frac{x}{|x|} \tau'\left(\frac{|x| - \rho_\delta}{\kappa_\delta}\right) dx.$$

Since  $\|u_n(t)\|_{H^1(\mathbb{R}^d)}$  is bounded independently of  $n$  and  $t$ , there exists

$$C_0 := \sup_{n \in \mathbb{N}} \sup_{t \in [T_0, T_n]} \|u_n(t)\|_{H^1(\mathbb{R}^d)}^2 > 0$$

such that

$$|\Upsilon'(t)| \leq \frac{C_0}{\kappa_\delta}.$$

Choose  $\kappa_\delta$  such that  $\frac{C_0}{\kappa_\delta} T_\delta < \frac{\delta}{2}$ . Then, by integrating between  $T_0$  and  $T_\delta$  we obtain

$$(9) \quad \Upsilon(T_0) - \Upsilon(T_\delta) \leq \frac{\delta}{2}.$$

From (8) we infer that

$$\Upsilon(T_\delta) = \int_{\mathbb{R}^d} |u_n(T_\delta)|^2 \tau\left(\frac{|x| - \rho_\delta}{\kappa_\delta}\right) dx \leq \int_{|x|>\rho_\delta} |u_n(T_\delta)|^2 dx \leq \frac{\delta}{2}.$$

Combining with (9) we obtain

$$\Upsilon(T_0) \leq \delta.$$

Now set  $r_\delta := \kappa_\delta + \rho_\delta$ . Then from the definition of  $\tau$  it is easy to see that

$$\int_{|x|>r_\delta} |u_n(T_0)|^2 dx \leq \Upsilon(T_0) \leq \delta,$$

which proves the claim.  $\square$

*Proof of Lemma 2.* Since  $u_n(T_0)$  is bounded in  $H^1(\mathbb{R}^d)$ , there exists  $u_0 \in H^1(\mathbb{R}^d)$  such that up to a subsequence  $u_n(T_0) \rightharpoonup u_0$  weakly in  $H^1(\mathbb{R}^d)$ . Hence,  $u_n(T_0) \rightarrow u_0$  strongly in  $L^2_{\text{loc}}(\mathbb{R}^d)$  and actually strongly in  $L^2(\mathbb{R}^d)$  by Claim 3. By interpolation we get the desired conclusion.  $\square$

*Proof of Theorem 1.* Let  $u_0$  be given by Lemma 2 and let  $u \in \mathcal{C}([T_0, T^*), H^1(\mathbb{R}^d))$  be the corresponding maximal solution of (NLS). By (A1)-(A2), there exists  $0 < \sigma < 1$  such that  $1 < p < 1 + \frac{4}{N-2\sigma}$  and

$$|f(z_1) - f(z_2)| \leq C(1 + |z_1|^{p-1} + |z_2|^{p-1})|z_1 - z_2| \text{ for all } z_1, z_2 \in \mathbb{C}.$$

This implies that the Cauchy problem for (NLS) is well-posed in  $H^\sigma(\mathbb{R}^d)$  (see [7, 9]). Combined with Lemma 2 this implies that  $u_n(t) \rightarrow u(t)$  strongly in  $H^\sigma(\mathbb{R}^d)$  for any  $t \in [T_0, T^*)$ . By boundedness of  $u_n(t)$  in  $H^1(\mathbb{R}^d)$ , we also have  $u_n(t) \rightharpoonup u(t)$  weakly in  $H^1(\mathbb{R}^d)$  for any  $t \in [T_0, T^*)$ . By Proposition 1, for any  $t \in [T_0, T^*)$  we have

$$(10) \quad \|u(t) - R(t)\|_{H^1(\mathbb{R}^d)} \leq \liminf_{n \rightarrow +\infty} \|u_n(t) - R(t)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_*^{\frac{1}{2}} v_* t}.$$

In particular, since  $R(t)$  is bounded in  $H^1(\mathbb{R}^d)$  there exists  $C > 0$  such that for any  $t \in [T_0, T^*)$  we have

$$(11) \quad \|u(t)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_*^{\frac{1}{2}} v_* t} + \|R(t)\|_{H^1(\mathbb{R}^d)} \leq C.$$

Recall that, by the blow up alternative (see e.g. [7]), either  $T^* = +\infty$  or  $T^* < +\infty$  and  $\lim_{t \rightarrow T^*} \|u\|_{H^1(\mathbb{R}^d)} = +\infty$ . Therefore (11) implies that  $T^* = +\infty$ . From (10) we infer that for all  $t \in [T_0, +\infty)$  we have

$$\|u(t) - R(t)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_*^{\frac{1}{2}} v_* t}.$$

This concludes the proof.  $\square$

**2.2. Uniform backward estimates.** This section is devoted to the proof of Proposition 1. This proof relies on a bootstrap argument. Indeed, from the definition of the final datum  $u_n(T_n)$  and continuity of  $u_n$  in time, it follows that (4) holds on an interval  $[t^\dagger, T_n]$  for  $t^\dagger$  close enough to  $T_n$ . Then the following Proposition 4 shows that we can actually improve to a better estimate, hence leaving enough room to extend the interval on which the original estimate holds.

**Proposition 4.** *There exists  $v_\sharp := v_\sharp(\Phi_1, \dots, \Phi_N) > 0$  such that if  $v_* > \alpha^{-1} v_\sharp$  then the following holds. There exist  $n_0 \in \mathbb{N}$ ,  $T_0 > 0$  such that for all  $n \geq n_0$  the solution  $u_n$  is defined on  $[T_0, T_n]$ . Let  $t^\dagger \in [T_0, T_n]$  and  $n \geq n_0$ . If for all  $t \in [t^\dagger, T_n]$  we have*

$$(12) \quad \|u_n(t) - R(t)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_*^{\frac{1}{2}} v_* t}$$

*then for all  $t \in [t^\dagger, T_n]$  we have*

$$(13) \quad \|u_n(t) - R(t)\|_{H^1(\mathbb{R}^d)} \leq \frac{1}{2} e^{-\alpha\omega_*^{\frac{1}{2}} v_* t}.$$

Before proving Proposition 4, we indicate precisely how it is used to obtain Proposition 1.

*Proof of Proposition 1.* Let  $T_0, n_0$  be given by Proposition 4 and let  $n \geq n_0$ . Since  $u_n(T_n) = R(T_n)$  and  $u_n$  is continuous in  $H^1(\mathbb{R}^d)$ , for  $t$  close enough to  $T_n$  we have

$$(14) \quad \|u_n(t) - R(t)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_*^{\frac{1}{2}} v_* t}.$$



Let  $t^\dagger$  be the minimal time such that (14) holds:

$$t^\dagger := \min\{\tau \in [T_0, T_n]; (14) \text{ holds for all } t \in [\tau, T_n]\}.$$

We prove by contradiction that  $t^\dagger = T_0$ . Indeed, assume that  $t^\dagger > T_0$ . Then

$$\|u_n(t^\dagger) - R(t^\dagger)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_*^{\frac{1}{2}}v_*t^\dagger}$$

and by Proposition 4 we can improve this estimate in

$$\|u_n(t^\dagger) - R(t^\dagger)\|_{H^1(\mathbb{R}^d)} \leq \frac{1}{2}e^{-\alpha\omega_*^{\frac{1}{2}}v_*t^\dagger}.$$

Hence, by continuity of  $u_n(t)$  in  $H^1(\mathbb{R}^d)$ , there exists  $T_0 \leq t^\ddagger < t^\dagger$  such that (14) holds for all  $t \in [t^\ddagger, t^\dagger]$ . This contradicts the minimality of  $t^\dagger$  and finishes the proof.  $\square$

The proof of Proposition 4 is done in two steps. First, assuming (12) we prove that we can control the  $L^2(\mathbb{R}^d)$ -norm of  $(u_n - R)$ . To obtain the full control on the  $H^1(\mathbb{R}^d)$ -norm of  $(u_n - R)$  as in (13) we use the linearization of an action-like functional. This linearization is coercive (i.e. controls the  $H^1(\mathbb{R}^d)$ -norm) up to a finite number of non-positive directions that can all be controlled due to the  $L^2(\mathbb{R}^d)$ -estimate.

Let  $T_0 > 0$  large enough. Fix  $n \in \mathbb{N}$ . For notational convenience, the dependency on  $n$  is understood for  $u$  and we drop the subscript  $n$ . Set  $v := u - R$ . Let  $t^\dagger \in [T_0, T_n]$  and assume that for all  $t \in [t^\dagger, T_n]$  we have

$$\|v(t)\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha\omega_*^{\frac{1}{2}}v_*t}.$$

*Step 1:  $L^2(\mathbb{R}^d)$ -control.*

**Lemma 5.** *For all  $K > 0$  and  $m \in \mathbb{N} \setminus \{0\}$  there exists  $v_\sharp = v_\sharp(K, m, \Phi_1, \dots, \Phi_N) > 0$  such that if  $v_* > \alpha^{-1}v_\sharp$  then for all  $t \in [t^\dagger, T_n]$  we have*

$$\|v(t)\|_{L^2(\mathbb{R}^d)} \leq \frac{1}{\sqrt{2mK}}e^{-\alpha\omega_*^{\frac{1}{2}}v_*t}.$$

*Proof.* First note that by identifying  $\mathbb{C}$  to  $\mathbb{R}^2$  and viewing  $f : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  we can consider

$$df(z).w = g(|z|^2)w + 2\Re(z\bar{w})g'(|z|^2)z.$$

The function  $v$  satisfies

$$iv_t + \mathcal{L}v + \mathcal{N}(v) = 0,$$

where

$$\mathcal{L}v := \Delta v + df(R).v$$

and the remaining nonlinear term  $\mathcal{N}(v)$  verifies

$$|(i\mathcal{N}(v), v)_{L^2(\mathbb{R}^d)}| \leq \eta(\|v\|_{H^1(\mathbb{R}^d)})\|v\|_{H^1(\mathbb{R}^d)}^2,$$

where  $\eta$  is a decreasing function satisfying  $\eta(s) \rightarrow 0$  when  $s \rightarrow 0$ . Take any  $t \in [t^\dagger, T_n]$ . We have

$$\frac{1}{2} \frac{d}{dt} \|v\|_{L^2(\mathbb{R}^d)}^2 = (v_t, v)_{L^2(\mathbb{R}^d)} = (i\mathcal{L}v, v)_{L^2(\mathbb{R}^d)} + (i\mathcal{N}(v), v)_{L^2(\mathbb{R}^d)}.$$

We have

$$\begin{aligned}
& (i\mathcal{L}v, v)_{L^2(\mathbb{R}^d)} \\
&= \Re \int_{\mathbb{R}^d} i(\Delta v + df(R).v) \bar{v} dx, \\
&= \Re \int_{\mathbb{R}^d} i(\Delta v + g(|R|^2)v + 2g'(|R|^2)\Re(R\bar{v})R)\bar{v} dx, \\
&= \Re \int_{\mathbb{R}^d} i(-|\nabla v|^2 + g(|R|^2)|v|^2 + 2g'(|R|^2)\Re(R\bar{v})R\bar{v}) dx, \\
&= - \int_{\mathbb{R}^d} 2g'(|R|^2)\Re(R\bar{v})\Im(R\bar{v}) dx.
\end{aligned}$$

Therefore,

$$\begin{aligned}
|(i\mathcal{L}v, v)_{L^2(\mathbb{R}^d)}| &\leq \int_{\mathbb{R}^d} 2|g'(|R|^2)||R|^2|v|^2 dx \\
&\leq \frac{C_{\mathcal{L}}}{2} \|v\|_{L^2(\mathbb{R}^d)}^2,
\end{aligned}$$

where this last constant  $C_{\mathcal{L}}$  depends only on  $g$  and  $\|R\|_{L^\infty(\mathbb{R}^d)}$ . By the bootstrap assumption on  $v$ , this implies

$$|(i\mathcal{L}v, v)_{L^2(\mathbb{R}^d)}| \leq \frac{C_{\mathcal{L}}}{2} e^{-2\alpha\omega_*^{\frac{1}{2}}v_*t}.$$

In addition, it is easy to see that

$$|(i\mathcal{N}(v), v)_{L^2(\mathbb{R}^d)}| \leq \eta(\|v\|_{H^1(\mathbb{R}^d)})\|v\|_{H^1(\mathbb{R}^d)}^2 \leq \eta(e^{-\alpha\omega_*^{\frac{1}{2}}v_*t})e^{-2\alpha\omega_*^{\frac{1}{2}}v_*t}.$$

In short, if  $T_0$  is large enough so that  $\eta(e^{-\alpha\omega_*^{\frac{1}{2}}v_*t}) \leq \frac{C_{\mathcal{L}}}{2}$ , we have obtained that

$$\left| \frac{d}{dt} \|v\|_{L^2(\mathbb{R}^d)}^2 \right| \leq 2C_{\mathcal{L}} e^{-2\alpha\omega_*^{\frac{1}{2}}v_*t}.$$

Therefore, by integration between  $t$  and  $T_n$  we get

$$(15) \quad \|v(t)\|_{L^2(\mathbb{R}^d)}^2 - \|v(T_n)\|_{L^2(\mathbb{R}^d)}^2 \leq \frac{C_{\mathcal{L}}}{\alpha\omega_*^{\frac{1}{2}}v_*} (e^{-2\alpha\omega_*^{\frac{1}{2}}v_*t} - e^{-2\alpha\omega_*^{\frac{1}{2}}v_*T_n}).$$

Now, we take  $v_{\sharp}$  such that

$$\frac{C_{\mathcal{L}}}{\omega_*^{\frac{1}{2}}v_{\sharp}} < \frac{1}{2mK},$$

Since  $v_* > \alpha^{-1}v_{\sharp}$  and  $v(T_n) = 0$  we get from (15) that

$$\|v(t)\|_{L^2(\mathbb{R}^d)} \leq \frac{1}{\sqrt{2mK}} e^{-\alpha\omega_*^{\frac{1}{2}}v_*t},$$

which is the desired conclusion.  $\square$

*Step 2:  $H^1(\mathbb{R}^d)$ -control.* The idea of the second step of the proof of Proposition 4 is reminiscent of the technique used to prove stability for a single soliton in the subcritical case (see e.g. [21, 22, 26, 39, 40]). Indeed, it is well-known that the linearization of the action functional  $S_0$ , whose critical points are the solutions of (1), is coercive in  $H^1(\mathbb{R}^d)$  on a space of finite codimension in  $L^2(\mathbb{R}^d)$ . At large time, the components of the multi-soliton are well-separated and thus it is possible to localize the analysis around each soliton to gain an  $H^1(\mathbb{R}^d)$ -local control, up to a space of finite codimension in  $L^2(\mathbb{R}^d)$ . But due to Lemma 5 we are able to control the remaining  $L^2(\mathbb{R}^d)$ -directions, hence to close the proof. The idea of looking at localized versions of the invariants of (NLS) was introduced in [31] and later developed in [13, 28, 29, 30]. We shall therefore be sketchy in the proofs, highlighting only the main differences with the previous works.

We start with the case of a single soliton.

**Lemma 6** (Coercivity for a soliton). *Let  $\omega_0 > 0$ ,  $\gamma_0 \in \mathbb{R}$ ,  $x_0, v_0 \in \mathbb{R}^d$  and a solution  $\Phi_0 \in H^1(\mathbb{R}^d)$  of (1). Then there exist  $K_0 = K_0(\Phi_0) > 0$ ,  $\nu_0 \in \mathbb{N} \setminus \{0\}$  and  $\tilde{X}_0^1, \dots, \tilde{X}_0^{\nu_0} \in L^2(\mathbb{R}^d)$  such that for  $k = 1, \dots, \nu_0$  we have  $\|\tilde{X}_0^k\|_{L^2(\mathbb{R}^d)} = 1$  and for any  $w \in H^1(\mathbb{R}^d)$  we have*

$$\|w\|_{H^1(\mathbb{R}^d)}^2 \leq K_0 H_0(t, w) + K_0 \sum_{k=1}^{\nu_0} (w, X_0^k(t))_{L^2(\mathbb{R}^d)}^2 \text{ for all } t \in \mathbb{R},$$

where

$$\begin{aligned} X_0^k(t) &:= e^{i(\frac{1}{2}v_0 \cdot x - \frac{1}{4}|v_0|^2 t + \omega_0 t + \gamma_0)} \tilde{X}_0^k(x - v_0 t - x_0), \\ H_0(t, w) &:= \|\nabla w\|_{L^2(\mathbb{R}^d)}^2 + \left( \omega_0 + \frac{|v_0|^2}{4} \right) \|w\|_{L^2(\mathbb{R}^d)}^2 - v_0 \cdot \mathfrak{Im} \int_{\mathbb{R}^d} \bar{w} \nabla w dx \\ &\quad - \int_{\mathbb{R}^d} (g(|R_0|^2)|w|^2 + 2g'(|R_0|^2)\mathfrak{Re}(R_0 \bar{w})^2) dx, \end{aligned}$$

and  $R_0(t, x)$  is the soliton given by (2).

Lemma 6 follows from standard arguments. We included a proof in Appendix B for the reader's convenience.

We introduce now the localization procedure around each component of the multi-soliton.

We begin by the selection of a particular direction of propagation.

**Claim 7.** *Let  $0 < \alpha < \sin\left(\frac{\sqrt{\pi}\Gamma(\frac{d-1}{2})}{N(N-1)\Gamma(\frac{d}{2})}\right)$ . Then there exists an orthonormal basis  $(e_1, \dots, e_d)$  of  $\mathbb{R}^d$  such that for all  $j, k = 1, \dots, N$ , we have*

$$|(v_j - v_k, e_1)_{\mathbb{R}^d}| \geq \alpha |v_j - v_k|.$$

*Proof.* For  $j \neq k$ , set  $v_{jk} := \frac{v_j - v_k}{|v_j - v_k|}$ . The claim will be proved if we show that the measure of the set

$$\Lambda := \bigcup_{\substack{j, k=1, \dots, N \\ j \neq k}} \{w \in \mathbb{S}^{d-1}, |(v_{jk}, w)_{\mathbb{R}^d}| \leq \alpha\}$$

is smaller than the measure of the surface of the unit sphere  $\mathbb{S}^{d-1}$ .

Take  $j, k = 1, \dots, N$ ;  $j \neq k$ . Without loss of generality, assume that  $v_{jk} = (1, 0, \dots, 0)$ . Take  $w \in \mathbb{S}^{d-1}$  and let  $(\theta_1, \dots, \theta_{d-1})$  be the spherical coordinates of  $w$ . Then we have

$$(v_{jk}, w)_{\mathbb{R}^d} = \cos \theta_1.$$

Therefore, after easy calculations we get

$$\mu(\{w \in \mathbb{S}^{d-1}, |(v_{jk}, w)_{\mathbb{R}^d}| \leq \alpha\}) \leq 2 \arcsin(\alpha) \frac{\pi^{\frac{d-1}{2}}}{\Gamma(\frac{d-1}{2})}$$

where  $\mu$  is the Lebesgues measure on  $\mathbb{S}^{d-1}$  and  $\frac{\pi^{\frac{d-1}{2}}}{\Gamma(\frac{d-1}{2})}$  is the area of the  $(d-2)$ -unit sphere. By subadditivity of the measure this leads to

$$\mu(\Lambda) \leq N(N-1) \arcsin(\alpha) \frac{\pi^{\frac{d-1}{2}}}{\Gamma(\frac{d-1}{2})}.$$

Now, remember that

$$0 < \alpha < \sin \left( \frac{\sqrt{\pi} \Gamma(\frac{d-1}{2})}{N(N-1) \Gamma(\frac{d}{2})} \right).$$

This implies

$$\mu(\Lambda) \leq N(N-1) \arcsin(\alpha) \frac{\pi^{\frac{d-1}{2}}}{\Gamma(\frac{d-1}{2})} < \frac{\pi^{\frac{d}{2}}}{\Gamma(\frac{d}{2})} = \mu(\mathbb{S}^{d-1}).$$

Therefore  $\mu(\mathbb{S}^{d-1} \setminus \Lambda) > 0$  and we can pick up  $e_1 \in \mathbb{S}^{d-1}$  such that for all  $j, k = 1, \dots, N$ , we have

$$|(v_j - v_k, e_1)_{\mathbb{R}^d}| \geq \alpha |v_j - v_k|.$$

Completing  $e_1$  into an orthonormal basis  $(e_1, \dots, e_d)$  of  $\mathbb{R}^d$  finishes the proof.  $\square$

By invariance of (NLS) with respect to orthonormal transformations we can assume without loss of generality that the basis  $(e_1, \dots, e_d)$  is the canonical basis of  $\mathbb{R}^d$ . Up to a changes of indices, we can also assume that  $v_1^1 < \dots < v_N^1$  where the exponent 1 in  $v_j^1$  denote the first coordinate of  $v_j = (v_j^1, \dots, v_j^d)$ .

Let  $\psi : \mathbb{R} \rightarrow \mathbb{R}$  be a  $\mathcal{C}^\infty$  cut-off function such that  $\psi(s) = 0$  for  $s < -1$ ,  $\psi(s) \in [0, 1]$  if  $s \in [-1, 1]$  and  $\psi(s) = 1$  for  $s > 1$ . We define

$$m_j := \frac{1}{2}(v_{j-1}^1 + v_j^1) \text{ for } j = 2, \dots, N,$$

$$\psi_1(t, x) := 1, \psi_j(t, x) := \psi\left(\frac{1}{\sqrt{t}}(x^1 - m_j t)\right) \text{ for } j = 2, \dots, N.$$

Then we can define

$$\phi_j = \psi_j - \psi_{j+1} \text{ for } j = 1, \dots, N-1, \phi_N := \psi_N.$$

We introduce localized versions of the energy, charge and momentum

$$E_j(t, w) := \frac{1}{2} \int_{\mathbb{R}^d} |\nabla w|^2 \phi_j dx - \int_{\mathbb{R}^d} F(w) \phi_j dx,$$

$$M_j(t, w) := \int_{\mathbb{R}^d} |w|^2 \phi_j dx, P_j(t, w) := \mathcal{A} \int_{\mathbb{R}^d} (\nabla w) \bar{w} \phi_j dx.$$

We denote by  $S_j$  a localized action defined for  $w \in H^1(\mathbb{R}^d)$  by

$$S_j(t, w) := E_j(t, w) + \frac{1}{2} \left( \omega_j + \frac{|v_j|^2}{4} \right) M_j(t, w) - \frac{1}{2} v_j \cdot P_j(t, w)$$

and by  $H_j$  a localized linearized defined for  $w \in H^1(\mathbb{R}^d)$  by

$$\begin{aligned} H_j(t, w) := & \int_{\mathbb{R}^d} |\nabla w|^2 \phi_j dx - \int_{\mathbb{R}^d} (g(|R_j|^2)|w|^2 + 2g'(|R_j|^2)\Re(R_j \bar{w})^2) \phi_j dx \\ & + \left( \omega_j + \frac{|v_j|^2}{4} \right) \int_{\mathbb{R}^d} |w|^2 \phi_j dx - v_j \cdot \Im \int_{\mathbb{R}^d} \bar{w} \nabla w \phi_j dx. \end{aligned}$$

We define an action-like functional for multi-solitons

$$\mathcal{S}(t, w) := \sum_{j=1}^N S_j(t, w)$$

and a corresponding linearized

$$\mathcal{H}(t, w) := \sum_{j=1}^N H_j(t, w).$$

We have the following coercivity property on  $\mathcal{H}$ .

**Lemma 8** (Coercivity for the multi-soliton). *There exists  $K = K(\Phi_1, \dots, \Phi_N) > 0$  such that for all  $t$  large enough and for all  $w \in H^1(\mathbb{R}^d)$  we have*

$$\|w\|_{H^1(\mathbb{R}^d)}^2 \leq K \mathcal{H}(t, w) + K \sum_{j=1}^N \sum_{l=1}^{\nu_j} (w, X_j^l(t))_{L^2(\mathbb{R}^d)}^2,$$

where  $(\nu_j)$ ,  $(X_j^l)$  are given for each  $R_j$  by Lemma 6.

*Proof.* It is a consequence of Lemma 6 (see [30, Lemma 4.1]).  $\square$

**Lemma 9.** *The following equality holds*

$$S_j(t, u(t)) = S_j(t, R_j) + H_j(t, v) + O(e^{-3\alpha\omega_*^{\frac{1}{2}}v_*t}) + o(\|v\|_{H^1(\mathbb{R}^d)}^2).$$

The proof relies on the following claim.

**Claim 10.** *For all  $x \in \mathbb{R}^d$  and  $j, k = 1, \dots, N$  the following inequalities holds.*

$$(|R_k(t, x)| + |\nabla R_k(t, x)|) \phi_j(t, x) \leq C e^{-2\alpha\omega_*^{\frac{1}{2}}v_*t} e^{-\frac{\omega_*^{\frac{1}{2}}}{2}|x-v_kt-x_k|} \text{ for } j \neq k,$$

$$(|R_j(t, x)| + |\nabla R_j(t, x)|)(1 - \phi_j(t, x)) \leq C e^{-2\alpha\omega_*^{\frac{1}{2}}v_*t} e^{-\frac{\omega_*^{\frac{1}{2}}}{2}|x-v_jt-x_k|}.$$

*Proof.* The claim follows immediately from the support properties of  $\phi_j$ , the definitions of  $\omega_*$  and  $v_*$  and exponential decay of  $\Phi_j$ .  $\square$

*Proof of Lemma 9.* The proof is done by writing  $u(t) = R(t) + v(t)$  and expanding in the definition of  $S_j$ . We start with the terms of order 0 in  $v$ . By Claim 10 we have

$$(16) \quad S_j(t, R) = S_j(t, R_j) + O(e^{-4\alpha\omega_*^{\frac{1}{2}}v_*t}).$$

We now look at the terms of order 1 in  $v$ . Still by Claim 10, taking in addition into account that  $\|v\|_{H^1(\mathbb{R}^d)} = O(e^{-\alpha\omega_*^{\frac{1}{2}}v_*t})$  and remembering the equation solved by  $R_j$  (see (41)) we obtain,

$$(17) \quad \langle S'_j(t, R), v \rangle = \langle S'_j(t, R_j), v \rangle + O(e^{-3\alpha\omega_*^{\frac{1}{2}}v_*t}) = O(e^{-3\alpha\omega_*^{\frac{1}{2}}v_*t}),$$

$$(18) \quad \langle S''_j(t, R)v, v \rangle = H_j(t, v) + O(e^{-3\alpha\omega_*^{\frac{1}{2}}v_*t}) + o(\|v\|_{H^1(\mathbb{R}^d)}^2).$$

Gathering (16)-(18) we obtain the following expansion

$$S_j(t, u(t)) = S_j(t, R_j) + H_j(t, v) + O(e^{-3\alpha\omega_*^{\frac{1}{2}}v_*t}) + o(\|v\|_{H^1(\mathbb{R}^d)}^2),$$

which concludes the proof.  $\square$

We can now write a Taylor-like expansion for  $\mathcal{S}$ .

**Lemma 11.** *We have*

$$\mathcal{S}(t, u) - \mathcal{S}(t, R) = \mathcal{H}(t, v) + o(\|v\|_{H^1(\mathbb{R}^d)}^2) + O(e^{-3\alpha\omega_*^{\frac{1}{2}}v_*t}).$$

*Proof.* In view of Lemma 9 all we need to prove is

$$\mathcal{S}(t, R) = \sum_{j=1}^N S_j(t, R_j) + O(e^{-3\alpha\omega_*^{\frac{1}{2}}v_*t}),$$

which follows immediately from Claim 10.  $\square$

**Lemma 12.** *The following estimate holds.*

$$\left| \frac{\partial \mathcal{S}(t, u(t))}{\partial t} \right| \leq \frac{C}{\sqrt{t}} e^{-2\alpha\omega_*^{\frac{1}{2}}v_*t}.$$

*Proof.* We remark that

$$\mathcal{S}(t, w) = E(w) + \sum_{j=1}^N \left( \frac{1}{2} \left( \omega_j + \frac{|v_j|^2}{4} \right) M_j(t, w) - \frac{1}{2} v_j \cdot P_j(t, w) \right).$$

Since the energy  $E$  is conserved by the flow of (NLS), to estimate the variations of  $\mathcal{S}(t, u(t))$  we only have to study the variations of the localized masses  $M_j(t, u(t))$  and momentums  $P_j(t, u(t))$ . Take any  $j = 2, \dots, N$ . We have

$$(19) \quad \begin{aligned} & \frac{1}{2} \frac{\partial}{\partial t} \int_{\mathbb{R}^d} |u(t)|^2 \psi_j(t, x) dx \\ &= \frac{1}{\sqrt{t}} \int_{\mathbb{R}^d} \left( \mathfrak{Im}(\bar{u} \partial_1 u) - |u|^2 \frac{x^1 + m_j t}{4t} \right) \psi' \left( \frac{1}{\sqrt{t}} (x^1 - m_j t) \right) dx. \end{aligned}$$

Define  $I_j := [m_j t - \sqrt{t}, m_j t + \sqrt{t}] \times \mathbb{R}^{d-1}$ . From (19) and the support properties of  $\psi$  we obtain

$$\left| \frac{\partial}{\partial t} \int_{\mathbb{R}^d} |u(t)|^2 \psi_j(t, x) dx \right| \leq \frac{C}{\sqrt{t}} \int_{I_j} |\nabla u|^2 + |u|^2 dx.$$

Similarly, for the first component of  $P_j$  we have

$$(20) \quad \frac{1}{2} \frac{\partial}{\partial t} \int_{\mathbb{R}^d} \bar{u} \partial_1 u \psi_j dx = \\ \frac{1}{\sqrt{t}} \int_{\mathbb{R}^d} \left( |\partial_1 u|^2 - g(|u|^2) |u|^2 + F(u) - \bar{u} \partial_1 u \frac{x^1 + m_j t}{2t} \right) \psi' \left( \frac{1}{\sqrt{t}} (x^1 - m_j t) \right) \\ - \frac{1}{4t} |u|^2 \psi''' \left( \frac{1}{\sqrt{t}} (x^1 - m_j t) \right) dx.$$

Combining (20) with the support properties of  $\psi$  and (A1)-(A2) we obtain

$$\left| \frac{\partial}{\partial t} \int_{\mathbb{R}^d} \bar{u} \partial_1 u \psi_j dx \right| \leq \frac{C}{\sqrt{t}} \left( \int_{I_j} |\nabla u|^2 + |u|^2 dx + \left( \int_{I_j} |\nabla u|^2 + |u|^2 dx \right)^{\frac{p+1}{2}} \right).$$

Similar arguments lead for  $k \geq 2$  to

$$\left| \frac{\partial}{\partial t} \int_{\mathbb{R}^d} \bar{u} \partial_k u \psi_j dx \right| \leq \frac{C}{\sqrt{t}} \int_{I_j} |\nabla u|^2 + |u|^2 dx.$$

Now, we remark that

$$\frac{1}{2} \int_{I_j} (|\nabla u|^2 + |u|^2) dx \leq \int_{I_j} |\nabla R|^2 + |R|^2 dx + \|u - R\|_{H^1(\mathbb{R}^d)}^2.$$

Recall that by hypothesis we have

$$\|u - R\|_{H^1(\mathbb{R}^d)} = \|v\|_{H^1(\mathbb{R}^d)} \leq e^{-\alpha \omega_*^{\frac{1}{2}} v_* t}.$$

In addition, the decay properties of each  $\Phi_k$  and the definition of  $I_j$  imply

$$\int_{I_j} (|\nabla u|^2 + |u|^2) dx \leq C e^{-2\alpha \omega_*^{\frac{1}{2}} v_* t}.$$

Consequently,

$$\left| \frac{\partial}{\partial t} \int_{\mathbb{R}^d} |u(t)|^2 \psi_j(t, x) dx \right| + \left| \frac{\partial}{\partial t} \int_{\mathbb{R}^d} \bar{u} \nabla u \psi_j dx \right| \leq \frac{C}{\sqrt{t}} e^{-2\alpha \omega_*^{\frac{1}{2}} v_* t}.$$

Note that the previous inequality is trivial for  $j = 1$  since  $\psi_1 = 1$  and the mass and momentum are conserved. Plugging the previous into the expressions of  $M_j$  and  $P_j$  gives

$$\left| \frac{\partial}{\partial t} (M_j(t, u) + P_j(t, u)) \right| \leq \frac{C}{\sqrt{t}} e^{-2\alpha \omega_*^{\frac{1}{2}} v_* t}$$

and the desired conclusion readily follows.  $\square$

*Proof of Proposition 4.* Let  $K = K(\Phi_1, \dots, \Phi_N)$  and  $m := \sum_{j=1}^N \nu_j$  be given by Lemma 8. Since  $\|X_j^k(t)\|_{L^2(\mathbb{R}^d)} = 1$  for any  $t, j, k$ , by Lemma 5, there exists  $v_{\sharp} = v_{\sharp}(\Phi_1, \dots, \Phi_N)$  such that if  $v_* > \alpha^{-1} v_{\sharp}$  we have for  $j = 1, \dots, N$ ,  $k = 1, \dots, \nu_j$  that

$$(21) \quad (v(t), X_j^k(t))_{L^2(\mathbb{R}^d)}^2 \leq \|v(t)\|_{L^2(\mathbb{R}^d)}^2 \leq \frac{1}{2mK} e^{-2\alpha \omega_*^{\frac{1}{2}} v_* t}.$$

Using Lemma 12 we obtain

$$(22) \quad \mathcal{S}(t, u(t)) - \mathcal{S}(T_n, u(T_n)) \leq \int_t^{T_n} \left| \frac{\partial \mathcal{S}(s, u(s))}{\partial s} \right| ds \leq \frac{C}{\sqrt{t}} e^{-2\alpha \omega_*^{\frac{1}{2}} v_* t}.$$

Note that since  $u_n(T_n) = R(T_n)$  we have

$$(23) \quad \mathcal{S}(T_n, u(T_n)) - \mathcal{S}(T_n, R(T_n)) = 0$$

By Lemma 11, (22)-(23) imply

$$(24) \quad \mathcal{H}(t, v) \leq \frac{C e^{-2\alpha\omega_*^{\frac{1}{2}} v_* t}}{\sqrt{t}} + o(\|v\|_{H^1(\mathbb{R}^d)}^2).$$

Combining (21)-(24) and Lemma 8 we get

$$\|v\|_{H^1(\mathbb{R}^d)}^2 \leq \left( \frac{C}{\sqrt{t}} + \frac{1}{2} \right) e^{-2\alpha\omega_*^{\frac{1}{2}} v_* t} + o(\|v\|_{H^1(\mathbb{R}^d)}^2)$$

and we easily obtain the desired conclusion if  $T_0$  is chosen large enough.  $\square$

### 3. NON-UNIQUENESS AND INSTABILITY

**3.1. Construction of approximation profiles.** For notational brevity we drop in this subsection the subscript 1 indicating that we work with the first excited state. Hence we will write (in this subsection only)  $\mathbb{R}_1(t, x) = R(t, x)$ ,  $\Phi_1 = \Phi$ , etc.

Note first  $df(z).w = g(|z|^2)w + 2\mathcal{R}e(z\bar{w})g'(|z|^2)z$  is not  $\mathbb{C}$ -linear. This is why we shall identify  $\mathbb{C}$  with  $\mathbb{R}^2$  and use the notation  $a + ib = \begin{pmatrix} a \\ b \end{pmatrix}$  ( $a, b \in \mathbb{R}$ ), so as to consider operators with real entries. Given a vector  $v \in \mathbb{C}^2$ , we denote  $v^+$  and  $v^-$  its components (so that if  $v$  represents a complex number,  $v^+$  is the real part and  $v^-$  the imaginary part). To avoid confusion, we will denote with a index whether we consider the operator with  $\mathbb{C}$ ,  $\mathbb{R}^2$ , or  $\mathbb{C}^2$ -valued functions.

Thus, as we consider

$$\mathcal{L}v = -i\Delta v - idf(R).v, \quad L_{\mathbb{C}}v = -i\Delta v + i\omega v - idf(\Phi).v,$$

and the non-linear operators

$$\mathcal{N}_{\mathbb{C}}(v) = if(R+v) - if(R) - idf(R).v,$$

$$\mathcal{M}_{\mathbb{C}}(v) = e^{-i\omega t} \mathcal{N}(e^{i\omega t} v) = if(\Phi+v) - if(\Phi) - idf(\Phi).v,$$

then for instance

$$L_{\mathbb{R}^2} \begin{pmatrix} v^+ \\ v^- \end{pmatrix} = \begin{pmatrix} J & \Delta - \omega + I^- \\ -\Delta + \omega - I^+ & -J \end{pmatrix} \begin{pmatrix} v^+ \\ v^- \end{pmatrix}.$$

with  $\Phi^+$  and  $\Phi^-$  the real and imaginary parts of  $\Phi$  and

$$J = 2\Phi^+\Phi^-g'(|\Phi|^2), \quad I^{\pm} = g(|\Phi|^2) + 2\Phi^{\pm 2}g'(|\Phi|^2).$$

Now  $L_{\mathbb{R}^2}$  is as an (unbounded)  $\mathbb{R}$ -linear operator on  $H^2(\mathbb{R}^d, \mathbb{R}^2) \rightarrow L^2(\mathbb{R}^d, \mathbb{R}^2)$ . So as to have some eigenfunctions, we can complexify, and we are interested in  $L_{\mathbb{C}^2} : H^2(\mathbb{R}^d, \mathbb{C}^2) \rightarrow L^2(\mathbb{R}^d, \mathbb{C}^2)$ , which is a  $\mathbb{C}$ -linear operator with real entries.

Let  $\alpha > 0$  be the decay rate given by Proposition 19 for eigenfunctions of  $L$  with eigenvalue  $\lambda$  (see (A4)). Possibly taking a smaller value of  $\alpha$ , we can assume  $\alpha \in (0, \sqrt{\omega})$ . For  $\mathbb{K} = \mathbb{R}, \mathbb{R}^2, \mathbb{C}$  or  $\mathbb{C}^2$ , denote

$$(25) \quad \mathcal{H}(\mathbb{K}) = \{v \in H^\infty(\mathbb{R}^d, \mathbb{K}) \mid e^{\alpha|x|} |D^a v| \in L^\infty(\mathbb{R}^d) \text{ for all multi-index } a\}.$$

We have gathered in the following proposition some properties of  $L_{\mathbb{C}^2}$  that shall be needed for our analysis.

**Proposition 13** (Properties of  $L_{\mathbb{C}^2}$ ).



- (i) The eigenvalue  $\lambda = \rho + i\theta \in \mathbb{C}$  of  $L_{\mathbb{C}^2}$  can be chosen with maximal real part. We denote  $Z(x) = \begin{pmatrix} Z^+(x) \\ Z^-(x) \end{pmatrix} \in H^2(\mathbb{R}^d, \mathbb{C}^2)$  an associated eigenfunction.
- (ii)  $\Phi \in \mathcal{H}(\mathbb{R}^2)$  and  $Z \in \mathcal{H}(\mathbb{C}^2)$ .
- (iii) Let  $\mu \notin \text{Sp}(L_{\mathbb{R}^2})$ , and  $A \in \mathcal{H}(\mathbb{C}^2)$ . Then there exists a solution  $X \in \mathcal{H}(\mathbb{R}^2)$  to  $(L - \mu I)X = A$ , and  $(L - \mu I)^{-1}$  is a continuous operator on  $\mathcal{H}(\mathbb{C}^2)$ .

Exponential decay of eigenvalues of  $L$  is a fact of independent interest. Hence we have stated the result under general assumptions in the Appendix A (see Proposition 19). Notice that we treat all possible eigenvalues (in particular without assuming  $|\mathfrak{Im} \lambda| < \omega$ , as it is the case for example in [23]).

*Proof.* (i) It is well known that the spectrum of  $L_{\mathbb{C}^2}$  is composed of essential spectrum on  $\{iy, y \in \mathbb{R}, |y| \geq \omega\}$  and eigenvalues symmetric with respect to the real and imaginary axes (see e.g. [19, 23]). The set of eigenvalues with positive real part is non-empty due to (A4). As  $L_{\mathbb{C}^2}$  is a compact perturbation of  $\begin{pmatrix} 0 & \Delta - \omega \\ -\Delta + \omega & 0 \end{pmatrix}$  there exists an eigenvalue  $\lambda$  with maximal real part.

(ii) Exponential decay of  $\Phi$ ,  $\nabla\Phi$  is a well-known fact (see e.g. [7]). Then using the equation satisfied by  $\Phi$ , one deduces that  $\Phi \in \mathcal{H}(\mathbb{R}^2)$ . The decay and regularity of the eigenfunction  $Z$  rely essentially on the decay and regularity of  $\Phi$ . Therefore, we leave the proof to Appendix A, Proposition 19 and Proposition 24.

(iii) Regularity of  $X$  follows from a simple bootstrap argument. For the exponential decay, we use the properties of fundamental solutions of Helmholtz equations (see Proposition 24).  $\square$

To conclude with the notations, we define the decay class  $O(\chi(t))$ , which we will use for functions decaying exponentially in time.

**Definition 14.** Let  $\xi \in C^\infty(\mathbb{R}^+, H^\infty(\mathbb{R}^d))$  and  $\chi : \mathbb{R}^+ \rightarrow (0, +\infty)$ . Then we denote

$$\xi(t) = O(\chi(t)) \quad \text{as } t \rightarrow +\infty,$$

if, for all  $s \geq 0$ , there exist  $C(s) > 0$  such that

$$\forall t \geq 0, \quad \|\xi(t)\|_{H^s(\mathbb{R}^d)} \leq C(s)\chi(t).$$

Let  $Y_1 := \mathfrak{Re}(Z) = \begin{pmatrix} \mathfrak{Re}(Z^+) \\ \mathfrak{Re}(Z^-) \end{pmatrix}$  and  $Y_2 := \mathfrak{Im}(Z) = \begin{pmatrix} \mathfrak{Im}(Z^+) \\ \mathfrak{Im}(Z^-) \end{pmatrix}$ . Then  $Y_1, Y_2 \in \mathcal{H}(\mathbb{R}^2)$ , and

$$\begin{cases} L_{\mathbb{R}^2} Y_1 &= \rho Y_1 - \theta Y_2, \\ L_{\mathbb{R}^2} Y_2 &= \theta Y_1 + \rho Y_2. \end{cases}$$

Denote

$$Y(t) = e^{-\rho t}(\cos(\theta t)Y_1 + \sin(\theta t)Y_2).$$

**Lemma 15.** The function  $Y$  verifies for all  $t \in \mathbb{R}$  the following equation.

$$(26) \quad \partial_t Y + L_{\mathbb{R}^2} Y = 0.$$

*Proof.* Indeed, we compute

$$\begin{aligned}
& \partial_t(e^{-\rho t}(\cos(\theta t)Y_1 + \sin(\theta t)Y_2)), \\
&= e^{-\rho t}((-\rho \cos(\theta t) - \theta \sin(\theta t))Y_1 + (-\rho \sin(\theta t) + \theta \cos(\theta t))Y_2), \\
& L_{\mathbb{R}^2}(e^{-\rho t}(\cos(\theta t)Y_1 + \sin(\theta t)Y_2)), \\
&= e^{-\rho t}(\cos(\theta t)LY_1 + \sin(\theta t)LY_2), \\
&= e^{-\rho t}(\cos(\theta t)(\rho Y_1 - \theta Y_2) + \sin(\theta t)(\theta Y_1 + \rho Y_2)), \\
&= e^{-\rho t}((\rho \cos(\theta t) + \theta \sin(\theta t))Y_1 + (\rho \sin(\theta t) - \theta \cos(\theta t))Y_2).
\end{aligned}$$

So that  $(\partial_t + L_{\mathbb{R}^2})(Y(t)) = 0$ .  $\square$

**Proposition 16.** *Let  $N_0 \in \mathbb{N}$  and  $a \in \mathbb{R}$ . Then there exists a profile  $W^{N_0} \in C^\infty([0, +\infty), \mathcal{H}(\mathbb{R}^2))$ , such that as  $t \rightarrow +\infty$ ,*

$$\partial_t W^{N_0} + L_{\mathbb{R}^2} W^{N_0} = \mathcal{M}_{\mathbb{R}^2}(W^{N_0}) + O(e^{-\rho(N_0+1)t}),$$

and  $W^{N_0}(t) = aY(t) + O(e^{-2\rho t})$ .

**Remark 17.** *Notice that  $W^{N_0}(t, x)$  is a real valued vector. If we go back and consider  $W^{N_0}$  as a function taking values in  $\mathbb{C}$ , we then have, by definition of  $\mathcal{M}$ , with  $U^{N_0}(t) = R(t) + e^{i\omega t}W^{N_0}(t)$ ,*

$$i\partial_t U^{N_0} + \Delta U^{N_0} + f(U^{N_0}) = O(e^{-\rho(N_0+1)t}).$$

For the proof of Proposition 16, we write  $W$  for  $W^{N_0}$  (for simplicity in notation) and we look for  $W$  in the following form

$$(27) \quad W(t, x) = \sum_{k=1}^{N_0} e^{-\rho kt} \left( \sum_{j=0}^k A_{j,k}(x) \cos(j\theta t) + B_{j,k}(x) \sin(j\theta t) \right),$$

where  $A_{j,k} = \begin{pmatrix} A_{j,k}^+ \\ A_{j,k}^- \end{pmatrix}$  and  $B_{j,k} = \begin{pmatrix} B_{j,k}^+ \\ B_{j,k}^- \end{pmatrix}$  are some functions of  $\mathcal{H}(\mathbb{R}^2)$  to be determined.

We start by the expansion of  $\mathcal{M}(W)$ .

**Claim 18.** *We have*

$$\mathcal{M}_{\mathbb{R}^2}(W) = \sum_{\kappa=2}^{N_0} e^{-\kappa\rho t} \sum_{j=0}^{\kappa} \left( \tilde{A}_{j,\kappa}(x) \cos(j\theta t) + \tilde{B}_{j,\kappa}(x) \sin(j\theta t) \right) + O(e^{-(N_0+1)\rho t})$$

where  $\tilde{A}_{j,\kappa}, \tilde{B}_{j,\kappa} \in \mathcal{H}(\mathbb{R}^2)$  depend on  $A_{l,n}$  and  $B_{l,n}$  only for  $l \leq n \leq \kappa - 1$ .

*Proof.* First we use a Taylor expansion. Due to smoothness of  $f$  and  $\Phi \in \mathcal{H}(\mathbb{R}^2)$ , and as  $\mathcal{M}_{\mathbb{R}^2}$  is at least quadratic in  $v$ , there exists a polynomial  $P_{N_0} \in \mathcal{H}(\mathbb{R}^2)[X, Y]$  with coefficients in  $\mathcal{H}(\mathbb{R}^2)$ , and valuation at least 2, such that :

$$\mathcal{M}_{\mathbb{R}^2}(v) = P_{N_0}(v^+, v^-) + O(|v|^{N_0+1}) = \sum_{m=2}^{N_0} \sum_{j=0}^m \left( P_{j,m}(x) v_+^j v_-^{m-j} \right) + O(v^{N_0+1}),$$

where  $P_{j,m}, Q_{j,m} \in \mathcal{H}(\mathbb{R})$ .

Consider now the term  $W_+^n W_-^{m-n}$  and use (27). It writes

$$\left( \sum_{k=1}^{N_0} e^{-\rho kt} \left( \sum_{l=0}^k A_{l,k}^+ \cos(l\theta t) + B_{l,k}^+ \sin(l\theta t) \right) \right)^n \\ \times \left( \sum_{k=1}^{N_0} e^{-\rho kt} \left( \sum_{l=0}^k A_{l,k}^- \cos(l\theta t) + B_{l,k}^- \sin(l\theta t) \right) \right)^{m-n}.$$

Now, the multinomial development gives

$$\sum_{\substack{i_1 + \dots + i_{N_0} = n \\ j_1 + \dots + j_{N_0} = m-n}} \frac{n!}{i_1! \dots i_{N_0}!} \frac{(m-n)!}{j_1! \dots j_{N_0}!} e^{-\rho t \sum_{k=1}^{N_0} k(i_k + j_k)} \\ \times \prod_{k=1}^{N_0} \left[ \left( \sum_{l=0}^k \left( A_{l,k}^+(x) \cos(l\theta t) + B_{l,k}^+(x) \sin(l\theta t) \right) \right)^{i_k} \right. \\ \left. \times \left( \sum_{l=0}^k \left( A_{l,k}^-(x) \cos(l\theta t) + B_{l,k}^-(x) \sin(l\theta t) \right) \right)^{j_k} \right].$$

Fix some  $(i_k)_k, (j_k)_k$  and define the decay rate  $\kappa = \sum_{k=1}^{N_0} k(i_k + j_k)$ . Then

$$\kappa \geq \sum_{k=1}^{N_0} (i_k + j_k) = n + (m - n) = m \geq 2.$$

The product factor is a trigonometric polynomial in  $t$ , it can be linearized into a sum of sin and cos with frequency  $\ell\theta$  and  $\ell \leq \sum_k k(i_k + j_k) = \kappa$ .

Of course, as  $W \in \mathcal{H}(\mathbb{R}^2)$ , the higher order terms (i.e. with  $\kappa \geq N_0 + 1$ ) all fit into  $O(e^{-(N_0+1)\rho t})$ .

It is now clear that  $\tilde{A}_{j,\kappa}$  and  $\tilde{B}_{j,\kappa}$  are polynomial in  $A_{j,k}, B_{j,k}, P_{n,m}$ , and  $Q_{n,m}$ . It remains to see that the  $A_{j,k}$  or  $B_{j,k}$  that intervene (i.e.  $i_k + j_k > 0$ ) come with  $k \leq \kappa - 1$ . Let  $a$  be the maximal index such that  $i_a + j_a > 0$ . Recall  $i_1 + \dots + i_{N_0} + j_1 + \dots + j_{N_0} = m \geq 2$ . If  $i_a + j_a \geq 2$ , we have  $2a \leq a(i_a + j_a) \leq \kappa$  so that (as  $\kappa \geq m \geq 2$ )  $a \leq \kappa - 1$ . If  $i_a + j_a = 1$ , there exist  $b \geq 1, b \neq a$ , such that  $i_b + j_b \geq 1$  and

$$\kappa = \sum_k k(i_k + j_k) \geq a(i_a + j_a) + b(i_b + j_b) \geq a + 1.$$

Finally the product has the desired properties.  $\square$

*Proof of Proposition 16.* By definition of  $W$ , we can compute:

$$(\partial_t W + L_{\mathbb{R}^2} W) = \sum_{k=1}^{N_0} e^{-\rho kt} \left( \sum_{j=0}^k (L_{\mathbb{R}^2} A_{j,k} + j\theta B_{j,k} - k\rho A_{j,k}) \cos(j\theta t) \right. \\ \left. + (L_{\mathbb{R}^2} B_{j,k} - j\theta A_{j,k} - k\rho B_{j,k}) \sin(j\theta t) \right).$$

From the computations of Claim 18, it suffices to solve for all  $0 \leq j \leq k \leq N_0$

$$(28) \quad \begin{cases} L_{\mathbb{R}^2} A_{j,k} + j\theta B_{j,k} - k\rho A_{j,k} = \tilde{A}_{j,k}, \\ L_{\mathbb{R}^2} B_{j,k} - j\theta A_{j,k} - k\rho B_{j,k} = \tilde{B}_{j,k}. \end{cases}$$

Obviously, one starts to solve for  $k = 1$ , then from this  $k = 2$  etc. so that at all stages  $\tilde{A}_{j,k}$  and  $\tilde{B}_{j,k}$  are well defined (remark that  $\tilde{A}_{j,1} = \tilde{B}_{j,1} = 0$ ).

We initialized the induction process by setting  $A_{1,1} = aY_1$ ,  $B_{1,1} = aY_2$ , and  $A_{0,1} = B_{0,1} = 0$ . Assume that  $A_{j,k}$  and  $B_{j,k}$  are constructed up to  $k \leq k_0 - 1$  and belong to  $\mathcal{H}(\mathbb{R}^2)$ , we now construct  $A_{j,k_0}$ ,  $B_{j,k_0}$  for all  $j \leq k_0$ . By Claim 18, all  $\tilde{A}_{j,k_0}$  and  $\tilde{B}_{j,k_0}$  are constructed for  $j \leq k_0$  and belong to  $\mathcal{H}(\mathbb{R}^2)$ .

Consider now the operator  $L_{j,k_0} = L_{\mathbb{C}^2} - (k_0\rho + ij\theta) \text{Id}$ ,  $L_{j,k_0} : \mathcal{H}(\mathbb{C}^2) \rightarrow \mathcal{H}(\mathbb{C}^2)$ . As  $e = \rho + i\theta$  is an eigenvalue of  $L_{\mathbb{C}^2}$  with maximal real part, for all  $k_0 \geq 2$  and all  $j$ ,  $k_0\rho + ij\theta \notin \text{Sp}(L)$  so that  $L_{j,k_0}$  is invertible. Let  $X = L_{j,k_0}^{-1}(\tilde{A}_{j,k_0} + i\tilde{B}_{j,k_0})$ , and define  $C := \Re(X) = \begin{pmatrix} \Re(X^+) \\ \Re(X^-) \end{pmatrix}$ ,  $D := \Im(X) = \begin{pmatrix} \Im(X^+) \\ \Im(X^-) \end{pmatrix}$ , so that  $C, D \in \mathcal{H}(\mathbb{R}^2)$  and  $X = C + iD$ . Then we compute

$$\begin{aligned} \tilde{A}_{j,k_0} + i\tilde{B}_{j,k_0} &= L_{j,k_0}(C + iD) \\ &= L_{\mathbb{R}^2}C + iL_{\mathbb{R}^2}D - k_0\rho C - ik_0D - ij\theta C + j\theta D \\ &= (L_{\mathbb{R}^2}C - k_0\rho C + j\theta D) + i(L_{\mathbb{R}^2}D - j\theta C - k_0\rho D). \end{aligned}$$

Hence  $A_{j,k_0} = C$  and  $B_{j,k_0} = D$  are solutions to the system (28).  $\square$

We now switch back notation from vector valued functions to complex valued functions and summarize what we have obtained. We use again the subscript 1. Hence we can consider  $V_1^{N_0}$ ,  $U_1^{N_0}$  defined by

$$V_1^{N_0}(t, x) := e^{i\omega t} W^{N_0}(t, x), \quad U_1^{N_0}(t, x) := R_1(t, x) + V_1^{N_0}(t, x).$$

Then we define

$$\begin{aligned} Err_1^{N_0}(t, x) &:= i\partial_t U_1^{N_0} + \Delta U_1^{N_0} + f(U_1^{N_0}) \\ &= i\partial_t V_1^{N_0} + \Delta V_1^{N_0} + f(R_1(t) + V_1^{N_0}) - f(R_1(t)) \\ &= i(\partial_t V_1^{N_0} + \mathcal{L}_{\mathbb{C}} V_1^{N_0} - \mathcal{N}_{\mathbb{C}}(V_1^{N_0})) \\ &= ie^{i\omega t}(\partial_t W^{N_0} + L_{\mathbb{C}} W^{N_0} - \mathcal{M}_{\mathbb{C}}(W^{N_0})). \end{aligned}$$

By Proposition 16,  $Err_1^{N_0}(t, x) = O(e^{-(N_0+1)\rho t})$ . Also, from (27) we deduce  $V_1^{N_0}(t) = ae^{i\omega t} Y(t) + O(e^{-2\rho t})$ , so that for all  $s \geq 0$ , there exists  $C(N_0, s)$  such that

$$(29) \quad \forall t \geq 0, \quad \|V_1^{N_0}(t)\|_{H^s(\mathbb{R}^d)} \leq C(N_0, s)e^{-\rho t}.$$

### 3.2. Proofs of Theorems 2 and 3.

*Proof of Theorem 2.* Let  $N_0$  to be determined later, we do a fixed point around  $U_1^{N_0}(t)$ . Suppose  $u = U_1^{N_0}(t) + w(t)$  (with  $w(t) \rightarrow 0$  as  $t \rightarrow +\infty$ ) is a solution to (NLS), then

$$i\partial_t w + \Delta w + f(U_1^{N_0} + w) - f(U_1^{N_0}) - Err_1^{N_0}(t) = 0$$

From this, Duhamel's Formula gives, for  $t \leq s$ ,

$$w(s) = e^{i\Delta(s-t)} w(t) + i \int_t^s e^{i\Delta(s-\tau)} \left( f((U_1^{N_0} + w)(\tau)) - f(U_1^{N_0}(\tau)) - Err_1^{N_0}(\tau) \right) d\tau,$$

so that

$$e^{-i\Delta s}w(s) = e^{-i\Delta t}w(t) + i \int_t^s e^{-i\Delta\tau} \left( f((U_1^{N_0} + w)(\tau)) - f(U_1^{N_0}(\tau)) - Err_1^{N_0}(\tau) \right) d\tau.$$

Letting  $s \rightarrow +\infty$ , as  $w(s) \rightarrow 0$ , we are looking for a solution to the fixed point equation

$$w(t) = -i \int_t^{+\infty} e^{i\Delta(t-\tau)} (f((U_1^{N_0} + w)(\tau)) - f(U_1^{N_0}(\tau)) - Err_1^{N_0}(\tau)) d\tau.$$

Hence, we define the map

$$v \mapsto \Psi(v) = -i \int_t^{+\infty} e^{i\Delta(t-\tau)} (f((R_1 + V_1^{N_0} + v)(\tau)) - f((R_1 + V_1^{N_0})(\tau)) - Err_1^{N_0}(\tau)) d\tau.$$

Fix  $\sigma > \frac{d}{2}$ , so that  $H^\sigma(\mathbb{R}^d)$  is an algebra, and let  $B, T_0$  to be determined later. For  $w \in \mathcal{C}((T_0, +\infty), H^\sigma(\mathbb{R}^d))$  define

$$\|w\|_{X_{T_0, N_0}^\sigma} = \sup_{t \geq T_0} e^{(N_0+1)\rho t} \|w(t)\|_{H^\sigma(\mathbb{R}^d)},$$

to be the norm of the Banach space

$$X_{T_0, N_0}^\sigma := \left\{ w \in \mathcal{C}((T_0, +\infty), H^\sigma(\mathbb{R}^d)) \mid \|w\|_{X_{T_0, N_0}^\sigma} < +\infty \right\}.$$

Consider the ball of radius  $B$  of  $X_{T_0, N_0}^\sigma$

$$X_{T_0, N_0}^\sigma(B) := \left\{ w \in X_{T_0, N_0}^\sigma \mid \|w\|_{X_{T_0, N_0}^\sigma} \leq B \right\}.$$

By (29), we can assume  $T_0$  is large enough so that

$$\|V_1^{N_0}\|_{H^\sigma(\mathbb{R}^d)} \leq 1 \text{ and also } B e^{-(N_0+1)\rho T_0} \leq 1.$$

Our problem is to find a fixed point for  $\Psi$ , we will find it in  $X_{T_0, N_0}^\sigma(B)$  for adequate parameters.

Notice that for  $t \geq T_0$ ,  $\|V_1^{N_0}(t)\|_{H^\sigma(\mathbb{R}^d)} \leq 1$ . Hence, we will always work in the  $H^\sigma(\mathbb{R}^d)$ -ball of radius  $r_\sigma = \|\Phi_1\|_{H^\sigma(\mathbb{R}^d)} + 2$ . Due to  $\mathcal{C}^{\sigma+1}$  smoothness of  $f$ , there exists a constant  $K_\sigma$  such that

$$\forall a, b \in B_{H^\sigma(\mathbb{R}^d)}(r_\sigma), \quad \|f(a) - f(b)\|_{H^\sigma(\mathbb{R}^d)} \leq K_\sigma \|a - b\|_{H^\sigma(\mathbb{R}^d)}.$$

In particular, for all  $t$ ,

$$\|f(R_1(t) + V_1^{N_0}(t) + v) - f(R_1(t) + V_1^{N_0}(t))\|_{H^\sigma(\mathbb{R}^d)} \leq K_\sigma \|v\|_{H^\sigma(\mathbb{R}^d)}.$$

Hence, as  $e^{i\Delta(t-s)}$  is an isometry in  $H^\sigma(\mathbb{R}^d)$ , for any  $v \in X_{T_0, N_0}^\sigma(B)$  we have

$$\begin{aligned} & \|\Psi(v)(t)\|_{H^\sigma(\mathbb{R}^d)} \\ &= \left\| \int_t^{+\infty} e^{i\Delta(t-\tau)} \left[ f(R_1 + V_1^{N_0} + v) - f(R_1 + V_1^{N_0}) - Err_1^{N_0} \right] (\tau) d\tau \right\|_{H^\sigma(\mathbb{R}^d)} \\ &\leq \int_t^{+\infty} (\|f(R_1 + V_1^{N_0} + v) - f(R_1 + V_1^{N_0})\|_{H^\sigma(\mathbb{R}^d)} + \|Err_1^{N_0}(\tau)\|_{H^\sigma(\mathbb{R}^d)}) d\tau \\ &\leq \int_t^{+\infty} (K_\sigma \|v\|_{H^\sigma(\mathbb{R}^d)} + C(N_0, \sigma) e^{-(N_0+1)\rho\tau}) d\tau \\ &\leq \frac{K_\sigma B + C(N_0, \sigma)}{(N_0 + 1)\rho} e^{-(N_0+1)\rho t}. \end{aligned}$$

First choose  $N_0$  large enough so that  $\frac{K_\sigma}{(N_0+1)\rho} \leq \frac{1}{2}$ . Then choose  $B = 2\frac{C(N_0, \sigma)}{(N_0+1)\rho}$ . Finally choose  $T_0$  large enough so that  $C(N_0, \sigma)e^{-\rho T_0} \leq 1$ . Hence we get

$$\|\Psi(v)(t)\|_{H^\sigma(\mathbb{R}^d)} \leq B e^{-(N_0+1)\rho t}.$$

This shows that  $\Psi$  maps  $X_{T_0, N_0}^\sigma(B)$  to itself. Let us now show that  $\Psi$  is a contraction in  $X_{T_0, N_0}^\sigma(B)$ . Let  $v, w \in X_{T_0, N_0}^\sigma(B)$  then we have

$$\Psi(v)(t) - \Psi(w)(t) = -i \int_t^{+\infty} e^{i\Delta(t-s)} (f(R_1 + V_1^{N_0} + v) - f(R_1 + V_1^{N_0} + w)) ds.$$

As previously, we have

$$\begin{aligned} & e^{(N_0+1)\rho t} \|\Psi(v)(t) - \Psi(w)(t)\|_{H^\sigma(\mathbb{R}^d)} \\ &= e^{(N_0+1)\rho t} \left\| \int_t^{+\infty} e^{i\Delta(t-s)} (f(R_1 + V_1^{N_0} + v) - f(R_1 + V_1^{N_0} + w)) ds \right\|_{H^\sigma(\mathbb{R}^d)} \\ &\leq e^{(N_0+1)\rho t} \int_t^{+\infty} \|f(R_1 + V_1^{N_0} + v) - f(R_1 + V_1^{N_0} + w)\|_{H^\sigma(\mathbb{R}^d)} ds \\ &\leq e^{(N_0+1)\rho t} \int_t^{+\infty} K_\sigma \|v(s) - w(s)\|_{H^\sigma(\mathbb{R}^d)} ds \\ &\leq K_\sigma e^{(N_0+1)\rho t} \int_t^{+\infty} e^{-(N_0+1)\rho s} \|v - w\|_{X_{T_0, N_0}^\sigma} ds \\ &\leq K_\sigma e^{(N_0+1)\rho t} \|v - w\|_{X_{T_0, N_0}^\sigma} \frac{e^{-(N_0+1)\rho t}}{(N_0+1)\rho} \\ &\leq \frac{K_\sigma}{(N_0+1)\rho} \|v - w\|_{X_{T_0, N_0}^\sigma}. \end{aligned}$$

Taking the supremum over  $t \geq T_0$ , we deduce that

$$\|\Psi(v) - \Psi(w)\|_{X_{T_0, N_0}^\sigma} \leq \frac{K_\sigma}{(N_0+1)\rho} \|v - w\|_{X_{T_0, N_0}^\sigma} \leq \frac{1}{2} \|v - w\|_{X_{T_0, N_0}^\sigma}.$$

Hence,  $\Psi$  is a contraction on  $X_{T_0, N_0}^\sigma(B)$ , and has a unique fixed point  $\bar{v}$ . Notice that we have obtained a unique fixed point for any  $\sigma \geq \frac{d}{2}$ : from this we deduce that  $\bar{v}$  does not depend on  $\sigma$ , and hence,  $\bar{v} \in C^\infty([T_0, +\infty), H^\infty(\mathbb{R}^d))$ . Then  $\bar{u} = R_1 + V_1^{N_0} + \bar{v}$  is the desired solution.  $\square$

*Proof of Theorem 3.* The proof is essentially a generalization of that of Theorem 2. Let  $N_0$  to determined later and  $a \in \mathbb{R}$ , from this we dispose of a profile  $V_1^{N_0}(t)$ ,  $U_1^{N_0}(t)$ , an error term  $Err_1^{N_0}(t)$  associated to  $R_1(t)$ , and an eigenvalue  $\lambda = \rho + i\theta$  of  $L$ . We look for a solution of the form  $u(t) = U_1^{N_0}(t) + \sum_{j \geq 2} R_j(t) + w(t)$ . Then  $w$  satisfies

$$i\partial_t w + \Delta w + f(U_1^{N_0} + \sum_{j \geq 2} R_j + w) - f(U_1^{N_0}) - \sum_{j \geq 2} f(R_j) - Err_1^{N_0} = 0.$$

Hence considering the map

$$v \mapsto \Psi(v) = -i \int_t^{+\infty} e^{i\Delta(t-s)} (f((U_1^{N_0} + \sum_{j \geq 2} R_j + v)(s)) - f(U_1^{N_0}(s)) - \sum_{j \geq 2} f(R_j(s) - Err_1^{N_0}(s))) ds,$$

we are looking for a fixed point for  $\Psi$ , in the set  $X_{T_0, N_0}^\sigma(B)$  (defined in the proof of Theorem 2) for adequate parameters  $T_0, N_0, B, \sigma$ . Let  $\sigma > \frac{d}{2}$ . As previously, let  $T_0$  large enough so that  $\|V_1^{N_0}(t)\|_{H^s(\mathbb{R}^d)} \leq 1$  for  $t \geq T_0$ , and  $Be^{-(N_0+1)\rho T_0} \leq 1$ , so that we remain in a ball of radius 1 in  $H^\sigma(\mathbb{R}^d)$ .

Using exponential localization of the solitons  $R_j$  and of the profile  $U_1^{N_0}$ , we deduce as in the proof of Theorem 2 that for some  $K_\sigma = K(f, \|U_1^{N_0}\|_{H^\sigma(\mathbb{R}^d)} + \sum_{j \geq 2} \|R_j\|_{H^\sigma(\mathbb{R}^d)} + 1)$ , we have

$$\begin{aligned} \|f((U_1^{N_0} + \sum_{j \geq 2} R_j + v)) - f(U_1^{N_0}) - \sum_{j \geq 2} f(R_j)\|_{H^\sigma(\mathbb{R}^d)} \\ \leq K_\sigma \|v\|_{H^\sigma(\mathbb{R}^d)} + O(e^{-2\alpha\sqrt{\omega_*}v_*t}), \end{aligned}$$

possibly by taking a smaller value of  $\omega_*$  such that  $\omega_* \leq \alpha_1$ , where  $\alpha_1$  is the (exponential) decay rate of  $U_1^{N_0}$ . Notice that  $\alpha_1$  is independent of  $N_0$ , due to the construction of  $U_1^{N_0}$ . Hence we have as in Theorem 2:

$$\begin{aligned} \|\Psi(v)(t)\|_{H^\sigma(\mathbb{R}^d)} &= \left\| \int_t^{+\infty} e^{i\Delta(t-s)} (f(U_1^{N_0} + \sum_{j \geq 2} R_j + v) - f(U_1^{N_0}) - \sum_{j \geq 2} f(R_j) - Err_1^{N_0}) ds, \right\|_{H^\sigma(\mathbb{R}^d)} \\ &\leq \int_t^{+\infty} \|f(U_1^{N_0} + \sum_{j \geq 2} R_j + v) - f(U_1^{N_0}) - \sum_{j \geq 2} f(R_j)\|_{H^\sigma(\mathbb{R}^d)} + \|Err_1^{N_0}\|_{H^\sigma(\mathbb{R}^d)} ds \\ &\leq \int_t^{+\infty} (K_\sigma \|v\|_{H^\sigma(\mathbb{R}^d)} + C(N_0, \sigma)e^{-(N_0+1)\rho s} + C(\sigma)e^{-2\alpha\sqrt{\omega_*}v_*s}) ds \\ &\leq \frac{K_\sigma B + C(N_0, \sigma)}{(N_0 + 1)\rho} e^{-(N_0+1)\rho t} + \frac{C(\sigma)}{2\alpha\sqrt{\omega_*}v_*} e^{-2\alpha\sqrt{\omega_*}v_*t}. \end{aligned}$$

First choose  $N_0$  large enough so that  $\frac{K_\sigma}{(N_0+1)\rho} \leq \frac{1}{3}$  and set  $B := \frac{3C(N_0, \sigma)}{(N_0+1)\rho}$ . Recall that  $v_* > v_{\natural}$ . We chose  $v_{\natural}$  large enough so that from the choice of  $\omega_*, v_*$ , we have

$$\frac{C(\sigma)}{2\alpha\sqrt{\omega_*}v_*} \leq \frac{B}{3}, \text{ and } 2\alpha\sqrt{\omega_*}v_* \geq (N_0 + 1)\rho.$$

Finally choose  $T_0$  large enough so that

$$Be^{-(N_0+1)\rho T_0} \leq 1, \text{ and } C(N_0, \sigma)e^{-\rho T_0} \leq 1.$$

From this,  $\|\Psi(v)(t)\|_{H^\sigma(\mathbb{R}^d)} \leq Be^{-(N_0+1)\rho t}$  for  $t \geq T_0$ , i.e.  $\Psi$  maps  $X_{T_0, N_0}^\sigma(B)$  to itself. Similar computations show that  $\Psi$  is a contracting map, so that it has a unique fixed point  $\bar{w}$ . Again as in Theorem 2,  $\bar{w}$  does not depend on  $\sigma$  and  $\bar{w} \in C^\infty([T_0, +\infty), H^\infty(\mathbb{R}^d))$ . Then  $\bar{u} = U_1^{N_0} + \sum_{j \geq 2} R_j(t) + \bar{w}(t)$  fulfills the requirements.  $\square$

APPENDIX A. EXPONENTIAL DECAY OF EIGENFUNCTIONS TO MATRIX  
SCHRÖDINGER OPERATORS

We consider an operator  $L : H^2(\mathbb{R}^d, \mathbb{C}^2) \subset L^2(\mathbb{R}^d, \mathbb{C}^2) \rightarrow L^2(\mathbb{R}^d, \mathbb{C}^2)$  of the form

$$L = \begin{pmatrix} W_1 & -\Delta + \omega + V_1 \\ \Delta - \omega + V_2 & W_2 \end{pmatrix}$$

where  $\omega > 0$  and  $V_1, V_2, W_1, W_2$  are complex-valued potentials satisfying the following assumptions.

(VW1) There exists  $q \in (\max\{2, \frac{d}{2}\}, +\infty]$  such that  $V_k, W_k \in L^q(\mathbb{R}^d)$  for  $k = 1, 2$ .

(VW2)  $\lim_{|x| \rightarrow +\infty} V_k(x) = \lim_{|x| \rightarrow +\infty} W_k(x) = 0$  for  $k = 1, 2$ .

Assumptions (VW1)-(VW2) are probably not optimal, but they are sufficient in the context in which we want to apply the following Proposition 19.

Our goal is to prove that if  $L$  has an eigenvalue which does not belong to the set  $\{iy, y \in \mathbb{R}, |y| \geq \omega\}$  (which is the essential spectrum of  $L$ , see e.g. [23]) then the corresponding eigenvectors are exponentially decaying at infinity. Note that it was previously known only for eigenfunctions corresponding to eigenvalues lying in the strip  $\{z \in \mathbb{C}, |\Re(z)| < \omega\}$  and with a restricted class of potentials (see [23]).

**Proposition 19.** *Assume that (VW1)-(VW2) hold. Take  $u, v \in H^2(\mathbb{R}^d, \mathbb{C})$ ,  $\lambda \in \mathbb{C} \setminus \{iy, y \in \mathbb{R}, |y| \geq \omega\}$ , and suppose that for  $U := \begin{pmatrix} u \\ v \end{pmatrix}$  we have  $LU = \lambda U$ . Then there exist  $C > 0$  and  $\alpha > 0$  such that for all  $x \in \mathbb{R}^d$  we have*

$$|u(x)| + |v(x)| \leq Ce^{-\alpha|x|}.$$

Our proof consists in obtaining estimates on fundamental solutions to Helmholtz equations and considering the eigenvalue problem  $LU = \lambda U$  as an inhomogeneous problem.

**A.1. Fundamental solutions.** For a given  $\mu \in \mathbb{C}$ , a fundamental solution of the Helmholtz equation in  $\mathbb{R}^d$  is a solution of

$$(-\Delta - \mu)g_\mu^d = \delta_0.$$

Setting  $\nu := \frac{d-2}{2}$  fundamental solutions of the Helmholtz equation are given by

$$g_\mu^d(x) := \frac{i\pi\mu^{\frac{\nu}{2}}}{2|x|^\nu(2\pi)^{\frac{d}{2}}} H_\nu^1(\sqrt{\mu}|x|),$$

where  $H_\nu^1$  is the first Hankel function (see e.g. [1]). For  $\mu = \rho e^{i\theta}$  with  $\rho \geq 0$  and  $\theta \in [0, 2\pi)$  we defined  $\sqrt{\mu}$  by  $\sqrt{\mu} := \rho^{\frac{1}{2}} e^{i\frac{\theta}{2}}$ . Defining  $\sqrt{\cdot}$  in this way ensures in particular that  $g_\mu^d$  is square integrable for  $\mu \notin \mathbb{R}^+$ . The fundamental solutions  $g_\mu^d$  verify the recurrence relation

$$g_\mu^{d+2}(x) = -\frac{\partial}{\partial r} g_\mu^d(x) \frac{1}{2\pi|x|}.$$

We deduce the following formula for the fundamental solution. For  $d = j + 2l$  where  $j = 1, 2$  and  $l \in \mathbb{N} \setminus \{0\}$ , we have

$$(30) \quad g_\mu^{j+2l} = \sum_{k=1}^l a_l^k (-1)^k (g_\mu^j)^{(k)} |x|^{-2l+k},$$



where the coefficients  $(a_l^k)$  are positive and the exponent  $(k)$  denotes the  $k^{\text{th}}$  derivative.

**Lemma 20** (Estimates on fundamental solutions). *Let  $\mu \in \mathbb{C} \setminus \mathbb{R}^+$ . Then there exists  $\tau > 0$  and  $C > 0$  such that*

$$|g_\mu^d(x)| \leq C g_{-\tau}^d(x) \text{ for all } x \in \mathbb{R}^d \setminus \{0\}.$$

*In particular,  $g_\mu^d$  is exponentially decaying at infinity with decay rate  $\sqrt{\tau}$ , i.e.  $|g_\mu^d(x)| \leq C e^{-\sqrt{\tau}|x|}$  for  $|x|$  large enough.*

We separated the proof of Lemma 20 into two proofs depending on the oddness of  $d$ .

*Proof for odd  $d$ .* We have  $\sqrt{\mu} = \rho^{\frac{1}{2}} e^{i\frac{\theta}{2}}$ . Choose  $\tau > 0$  such that  $\sqrt{\tau} = \rho^{\frac{1}{2}} \sin \frac{\theta}{2}$ . It is well-known that  $g_\mu^1(x) = \frac{i}{2\sqrt{\mu}} e^{i\sqrt{\mu}|x|}$ . It follows from easy computations that

$$|g_\mu^1(x)| \leq \frac{1}{2\sqrt{\rho}} e^{-\rho^{\frac{1}{2}} \sin \frac{\theta}{2} |x|}.$$

Since

$$g_{-\tau}^1(x) = \frac{1}{2\sqrt{\rho} \sin \frac{\theta}{2}} e^{-\rho^{\frac{1}{2}} \sin \frac{\theta}{2} |x|}$$

this readily implies that for all  $x \in \mathbb{R}^d$  we have

$$|g_\mu^1(x)| \leq C g_{-\tau}^1(x),$$

which proves the lemma for  $d = 1$ .

Similar calculations lead to

$$(31) \quad |(g_\mu^1)^{(k)}| \leq C (-1)^k (g_{-\tau}^1)^{(k)} \text{ for all } k \in \mathbb{N}.$$

Assume now that  $d \geq 3$  and take  $l \in \mathbb{N} \setminus \{0\}$  such that  $d = 1 + 2l$ . Combining (30) and (31) gives

$$|g_\mu^{1+2l}(x)| \leq C g_{-\tau}^{1+2l}(x) \text{ for all } x \in \mathbb{R}^d \setminus \{0\},$$

which is the desired conclusion.  $\square$

*Proof for even  $d$ .* Let  $\nu \in \mathbb{N}$  and  $z \in \mathbb{C}$ . We have the following asymptotic expansions on the Hankel functions (see [1]).

$$\begin{aligned} iH_0^1(z) &\approx -\frac{2}{\pi} \ln(z) && \text{for } |z| \text{ close to } 0, \\ iH_\nu^1(z) &\approx \frac{\nu! z^{-\nu}}{2^{-\nu} \pi} && \text{for } |z| \text{ close to } 0, \nu \neq 0, \\ H_\nu^1(z) &\approx \sqrt{\frac{2}{\pi z}} e^{i(z - \frac{\nu\pi}{2} - \frac{\pi}{4})} && \text{for } |z| \text{ close to } +\infty. \end{aligned}$$

Therefore, we can infer the following estimates on the fundamental solutions. Recall that  $d = 2 + 2\nu$  and  $\mu = \rho e^{i\theta}$ .

$$(32) \quad |g_\mu^2(x)| \leq C |\ln(\rho^{\frac{1}{2}} |x|)| \quad \text{for } |x| \text{ close to } 0,$$

$$(33) \quad |g_\mu^d(x)| \leq C |x|^{-\nu} \quad \text{for } |x| \text{ close to } 0, \nu \neq 0,$$

$$(34) \quad |g_\mu^d(x)| \leq C |x|^{-(\nu+1)} e^{-\rho^{\frac{1}{2}} \sin(\frac{\theta}{2}) |x|} \quad \text{for } |x| \text{ close to } +\infty.$$

For  $\tau > 0$ , the function  $g_{-\tau}^d$  verifies  $g_{-\tau}^d > 0$  and

$$(35) \quad g_{-\tau}^2(x) \approx C |\ln(\tau^{\frac{1}{2}}|x|)| \quad \text{for } |x| \text{ close to } 0,$$

$$(36) \quad g_{-\tau}^d(x) \approx C|x|^{-\nu} \quad \text{for } |x| \text{ close to } 0, \nu \neq 0$$

$$(37) \quad g_{-\tau}^d(x) \approx C|x|^{-(\nu+1)}e^{-\tau^{\frac{1}{2}}|x|} \quad \text{for } |x| \text{ close to } +\infty.$$

Choose  $\tau > 0$  such that  $\tau^{\frac{1}{2}} = \sqrt{\rho} \sin \frac{\theta}{2}$ . Then we infer from (32)-(37) and the continuity of fundamental solutions that there exists  $C > 0$  such that

$$|g_{\mu}^d(x)| \leq C g_{-\tau}^d(x) \text{ for all } x \in \mathbb{R}^d \setminus \{0\},$$

which finishes the proof.  $\square$

**A.2. Exponential decay.** We start with a regularity result on eigenfunctions.

**Lemma 21.** *Assume that (VW1) is satisfied. Take  $\lambda \in \mathbb{C} \setminus \{iy, y \in \mathbb{R}, |y| \geq \omega\}$ ,  $u, v \in H^2(\mathbb{R}^d, \mathbb{C})$  and assume that for  $U := \begin{pmatrix} u \\ v \end{pmatrix}$  we have  $LU = \lambda U$ . Then  $u, v \in W^{2,r}(\mathbb{R}^d)$  for any  $r \in [2, q]$ . In particular,  $u, v \in C^0(\mathbb{R}^d)$  and  $\lim_{|x| \rightarrow +\infty} u(x) = \lim_{|x| \rightarrow +\infty} v(x) = 0$ .*

*Proof.* The result follows from a classical bootstrap argument. Let the sequence  $(r_n)$  be defined by

$$\begin{cases} r_0 &= 2, \\ \frac{1}{r_{j+1}} &= \frac{1}{q} + \frac{d-2r_j}{dr_j}, \end{cases}$$

where  $q$  is given by (VW1). An elementary analysis of  $(r_j)$  shows that there exists  $j_0$  such that for all  $0 \leq j < j_0$  we have  $r_{j+1} > r_j$ ,  $\frac{d-2r_j}{dr_j} > 0$  and  $\frac{d-2r_{j_0}}{dr_{j_0}} < 0$ .

By induction, it is easy to see that for all  $j = 0, \dots, j_0$  we have  $u, v \in W^{2,r_j}(\mathbb{R}^d)$ . For  $j = 0$  it is by definition of  $u, v$ . Take any  $0 \leq j < j_0$  and assume that  $u, v \in W^{2,r_j}(\mathbb{R}^d)$ . Since  $\frac{d-2r_j}{dr_j} > 0$ , by Sobolev embeddings we infer that  $u, v \in L^{\frac{dr_j}{d-2r_j}}(\mathbb{R}^d)$ . Then, (VW1) and Hölder inequality imply

$$W_1 u, V_1 v, V_2 u, W_1 v \in L^{r_{j+1}}(\mathbb{R}^d).$$

Combined with  $U = (u, v)^T$  satisfying  $LU = \lambda U$ , this leads to  $u, v \in W^{2,r_{j+1}}(\mathbb{R}^d)$ .

In particular, we have  $u, v \in W^{2,r_{j_0}}(\mathbb{R}^d)$ . Since  $\frac{d-2r_{j_0}}{dr_{j_0}} < 0$ , from Sobolev embeddings we infer  $u, v \in L^\infty(\mathbb{R}^d)$ . Then by (VW1) we get

$$W_1 u, V_1 v, V_2 u, W_1 v \in L^q(\mathbb{R}^d).$$

As before, combined with  $LU = \lambda U$ , this leads to  $u, v \in W^{2,q}(\mathbb{R}^d)$ . The conclusion follows by interpolation.  $\square$

For the rest of the proof, it is easier to work with the operator

$$L' := iPLP^{-1} = \begin{pmatrix} -\Delta + \omega + V'_1 & W'_1 \\ W'_2 & \Delta - \omega + V'_2 \end{pmatrix},$$

where  $P = \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix}$ . The potentials  $V'_1, V'_2, W'_1, W'_2$  verify also (VW1)-(VW2). The spectrum of  $L'$  is  $\text{Sp}(L') = \text{Sp}(iPLP^{-1}) = i \text{Sp}(L)$ . Hence if  $\lambda \in \mathbb{C}$  is an eigenvalue

of  $L$  with eigenvector  $U$  then  $\lambda' := i\lambda$  is an eigenvalue of  $L'$  with eigenvector  $U' = \begin{pmatrix} u' \\ v' \end{pmatrix} := PU$ .

Write  $L' - \lambda'I = H + K$  where

$$H := \begin{pmatrix} -\Delta + \omega - \lambda' & 0 \\ 0 & \Delta - \omega - \lambda' \end{pmatrix} \text{ and } K := \begin{pmatrix} V'_1 & W'_1 \\ W'_2 & V'_2 \end{pmatrix}.$$

Take

$$F := \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} := KU' = \begin{pmatrix} V'_1 u' + W'_1 v' \\ W'_2 u' + V'_2 v' \end{pmatrix}.$$

It is well known that we can represent  $u'$  and  $v'$  in the following way

$$u' = g_{-\omega+\lambda'}^d * f_1 \text{ and } v' = -g_{-\omega-\lambda'}^d * f_2.$$

Let  $\mu_1 := -\omega + \lambda'$  and  $\mu_2 := -\omega - \lambda'$ . From the assumptions on  $\lambda'$  we infer that  $\mu_1, \mu_2$  satisfy the hypothesis of Lemma 20. Let  $\tau_1, \tau_2$  be given by Lemma 20 and set  $\tau := \min\{\tau_1, \tau_2\}$ . Take

$$\begin{aligned} \tilde{F} &:= \begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} := \begin{pmatrix} |f_1| \\ |f_2| \end{pmatrix}, \\ \tilde{u} &:= g_{-\tau}^d * \tilde{f}_1 \text{ and } \tilde{v} := g_{-\tau}^d * \tilde{f}_2. \end{aligned}$$

**Claim 22.** *There exists  $C > 0$  such that*

$$|u'| \leq C\tilde{u} \text{ and } |v'| \leq C\tilde{v}.$$

*Proof.* This readily follows from Lemma 20.  $\square$

**Lemma 23.** *Set  $w := \tilde{u} + \tilde{v}$ . There exists  $C > 0$  and  $\alpha > 0$  such that*

$$w(x) \leq Ce^{-\alpha|x|} \text{ for all } x \in \mathbb{R}^d.$$

The proof of Lemma 23 follows closely the proof of Theorem 1.1 in [14].

*Proof.* Set  $f := \tilde{f}_1 + \tilde{f}_2$ . We first note that  $w \in \mathcal{C}^0(\mathbb{R}^d)$ . Indeed, by definition  $w$  satisfies

$$(38) \quad -\Delta w + \tau w = f.$$

Since, by (VW1) and Lemma 21,  $f \in L^q(\mathbb{R}^d)$  this implies  $w \in W^{2,q}(\mathbb{R}^d)$  and in particular  $w \in \mathcal{C}^0(\mathbb{R}^d)$ .

Now, we claim that there exists  $R > 0$  such that for all  $x \in \mathbb{R}^d$  verifying  $|x| > R$  we have

$$(39) \quad \frac{\tau w(x) - f(x)}{w(x)} \geq \frac{\tau}{2}.$$

Indeed, setting  $T(x) := (|V'_1| + |V'_2| + |W'_1| + |W'_2|)$ , by Claim 22 we have

$$f \leq T(x)(|u'| + |v'|) \leq CT(x)(\tilde{u} + \tilde{v}) = CT(x)w.$$

Therefore

$$\frac{\tau w(x) - f(x)}{w(x)} \geq \tau - CT(x).$$

By (VW2), we can take  $R$  large enough so that  $CT(x) \leq \frac{\tau}{2}$  for  $|x| > R$ , which proves (39).

Note that  $w \geq 0$  by definition. Since  $w \in C^0(\mathbb{R}^d) \cap W^{2,q}(\mathbb{R}^d)$ , there exists  $C_R$  such that for all  $x \in \mathbb{R}^d$  with  $|x| < R$  we have

$$0 \leq w(x) \leq C_R.$$

Define  $\psi(x) := C_R e^{-\sqrt{\frac{\tau}{2}}(|x|-R)}$ . It is easy to see that

$$(40) \quad \begin{aligned} -\Delta\psi + \frac{\tau}{2}\psi &\geq 0 \text{ on } \mathbb{R}^d \setminus \{0\}, \\ w(x) - \psi(x) &\leq 0 \text{ on } \{x \in \mathbb{R}^d, |x| < R\}. \end{aligned}$$

Therefore we only have to prove that  $w(x) \leq \psi(x)$  for  $|x| > R$ . We proceed by contradiction. Assume that there exists  $x_0 \in \mathbb{R}^d$  with  $|x_0| > R$  such that  $w(x_0) > \psi(x_0)$ . Define the set

$$\Omega := \{x \in \mathbb{R}^d, w(x) > \psi(x)\}.$$

Then  $\Omega$  is a non-empty open set, for all  $x \in \Omega$  we have  $|x| > R$  and for all  $x \in \partial\Omega$  we have  $w(x) - \psi(x) = 0$ . On  $\Omega$ , by (38), (39) and (40) we have

$$\begin{aligned} \Delta(w - \psi) &= \Delta w - \Delta\psi = \tau w - f - \Delta\psi \\ &= \frac{\tau w - f}{w} w - \Delta\psi \geq \frac{\tau}{2}(w - \psi) > 0. \end{aligned}$$

By the maximum principle, this implies that  $w - \psi \leq 0$  on  $\Omega$ , a contradiction. Thus, for all  $x \in \mathbb{R}^d$  we have

$$w(x) \leq \psi(x) = C_R e^{-\sqrt{\frac{\tau}{2}}(|x|-R)} = C_R e^{\sqrt{\frac{\tau}{2}}R} e^{-\sqrt{\frac{\tau}{2}}|x|} = C e^{-\sqrt{\frac{\tau}{2}}|x|}.$$

This ends the proof.  $\square$

*Proof of Proposition 19.* The statement is an immediate consequence of Lemma 21, Claim 22 and Lemma 23.  $\square$

**A.3. Higher regularity and decay.** Upon assuming more regularity and decay, we can obtain more regularity and decay on the solutions to  $(L - \lambda I) = A$ .

The new assumption is the following.

(VW3)  $V_1, V_2, W_1, W_2 \in \mathcal{H}(\mathbb{C})$ .

Recall that  $\mathcal{H}$  was defined in (25).

**Proposition 24.** *Assume that (VW1)-(VW3) hold.*

- (i) *Let  $\lambda, u$  and  $v$  be as in Proposition 19. Then  $u, v \in \mathcal{H}(\mathbb{C})$ .*
- (ii) *Let  $\lambda \notin \text{Sp}(L)$  and take  $A \in \mathcal{H}(\mathbb{C}^2)$ . Then there exists  $X \in \mathcal{H}(\mathbb{C}^2)$  such that  $(L - \lambda \text{Id})X = A$ .*

*Proof.* (i) The assertion follows from similar arguments to those used in the proof of Proposition 19, provided we remark that (using the same notations)  $D^a u' = g_{-\omega+\lambda}^d * D^a f_1$ ,  $D^a v' = -g_{-\omega-\lambda}^d * D^a f_2$  and  $D^a f_1, D^a f_2$  satisfy the same properties as  $f_1$  and  $f_2$ .

(ii) Since  $\lambda \notin \text{Sp}(L)$  the operator  $L - \lambda \text{Id}$  is invertible, hence the existence of  $X \in H^2(\mathbb{R}^d, \mathbb{C}^2)$  such that  $(L - \lambda \text{Id})X = A$ . Regularity of  $X$  follows from a standard bootstrap argument as explained in the proof of Proposition 19 (ii). We now recall that  $L = -iP^{-1}L'P$ . Hence, if we define  $X' = PX$ ,  $\lambda' = i\lambda$ , and  $A' = iPA$  then

$$(L' - \lambda' \text{Id})X' = A'.$$

Recall that  $L' - \lambda'I = H + K$ . Set  $Y = \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} := KX'$  and  $A' = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$ . Then we can represent  $X' = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$  in the following way

$$x_1 = g_{-\omega+\lambda'}^d * (y_1 + a_1) \text{ and } x_2 = -g_{-\omega-\lambda'}^d * (y_2 + a_2).$$

The terms  $g_{-\omega+\lambda'}^d * a_1$  and  $g_{-\omega-\lambda'}^d * a_2$  are clearly exponentially decaying, with decay rate  $\alpha$ . Since  $V_1, V_2, W_1, W_2 \in \mathcal{H}(\mathbb{C}^2)$ , it follows that each component of  $Y$  is also exponentially decaying with rate  $\alpha$ . Hence  $g_{-\omega+\lambda'}^d * y_1$  and  $g_{-\omega-\lambda'}^d * y_2$  are exponentially decaying with decay rate  $\alpha$ . The decay rate of the derivatives of  $X'$  is follows immediately if we remark that for any multiindex  $a$  we have  $D^a x_k = g_{-\omega+\lambda'}^d * D^a(y_k + a_k)$  for  $k = 1, 2$ .  $\square$

## APPENDIX B. COERCIVITY FOR A SOLITON

This section is devoted to the proof of Lemma 6.

*Proof of Lemma 6.* We first remark that  $R_0$  is solution of

$$(41) \quad -\Delta R_0 + \left( \omega_0 + \frac{|v_0|^2}{4} \right) R_0 - f(R_0) + iv_0 \nabla R_0 = 0.$$

Therefore it is a critical point of the functional  $\tilde{S}_0$  defined for  $w \in H^1(\mathbb{R}^d)$  by

$$\begin{aligned} \tilde{S}_0(w) := & \frac{1}{2} \|\nabla w\|_{L^2(\mathbb{R}^d)}^2 + \frac{1}{2} \left( \omega_0 + \frac{|v_0|^2}{4} \right) \|w\|_{L^2(\mathbb{R}^d)}^2 \\ & - \int_{\mathbb{R}^d} F(w) dx - \frac{1}{2} v_0 \cdot \mathcal{A} \int_{\mathbb{R}^d} \bar{w} \nabla w dx. \end{aligned}$$

The quadratic form  $H_0$  is precisely

$$H_0(t, w) = \left\langle \tilde{S}_0''(R_0) w, w \right\rangle.$$

Consider  $z$  such that  $w = e^{i(\frac{1}{2}v_0 \cdot x - \frac{1}{4}|v_0|^2 t + \omega_0 t + \gamma_0)} z(x - v_0 t - x_0)$ . Then it is easy to see that

$$\begin{aligned} H_0(t, w) = \tilde{H}_0(z) := & \|\nabla z\|_{L^2(\mathbb{R}^d)}^2 + \omega_0 \|z\|_{L^2(\mathbb{R}^d)}^2 \\ & - \int_{\mathbb{R}^d} (g(|\Phi_0|^2)|z|^2 + 2g'(|\Phi_0|^2)\Re(\Phi_0 \bar{z})) dx. \end{aligned}$$

It is well-known that up to a finite number of non-positive directions  $\tilde{H}_0(z)$  controls the  $H^1(\mathbb{R}^d)$ -norm of  $z$ . Indeed, the self-adjoint operator corresponding to the quadratic form  $\tilde{H}_0$  (viewed on  $H^1(\mathbb{R}^d, \mathbb{R}^2)$ ) is a compact perturbation of  $\begin{pmatrix} -\Delta + \omega_0 & 0 \\ 0 & -\Delta + \omega_0 \end{pmatrix}$ , hence its spectrum lies on the real line and its essential spectrum is  $[\omega_0, +\infty)$ . Since in addition the quadratic form  $\tilde{H}_0$  is bounded from below on the unit  $L^2(\mathbb{R}^d)$ -sphere, the corresponding operator admits only a finite number of eigenvalues in  $(-\infty, \omega'_0)$  for any  $\omega'_0 < \omega_0$ . In particular, there exist  $\tilde{K}_0 > 0$ ,  $\nu_0 \in \mathbb{N}$  and  $\tilde{X}_0^1, \dots, \tilde{X}_0^{\nu_0} \in L^2(\mathbb{R}^d)$  such that  $\|\tilde{X}_0^k\|_{L^2(\mathbb{R}^d)} = 1$  for any  $k$  and

$$\|z\|_{H^1(\mathbb{R}^d)}^2 \leq \tilde{K}_0 \tilde{H}_0(z) + \tilde{K}_0^2 \sum_{k=1}^{\nu_0} \left( z, \tilde{X}_0^k \right)_{L^2(\mathbb{R}^d)}^2.$$

Since

$$\|\nabla w\|_{L^2(\mathbb{R}^d)}^2 = \frac{3}{2}\|\nabla z\|_{L^2(\mathbb{R}^d)}^2 + \frac{3|v_0|^2}{4}\|z\|_{L^2(\mathbb{R}^d)}^2$$

there exists  $K_0 > 0$  such that

$$\|w\|_{H^1(\mathbb{R}^d)}^2 \leq K_0 H_0(t, w) + K_0 \sum_{k=1}^{\nu_0} (w, X_0^k(t))_{L^2(\mathbb{R}^d)}^2,$$

where  $X_0^k(t) := e^{i(\frac{1}{2}v_0 \cdot x - \frac{1}{4}|v_0|^2 t + \omega_0 t + \gamma_0)} \tilde{X}_0^k(x - v_0 t - x_0)$ .  $\square$

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