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# PATHOLOGICAL SET WITH LOSS OF REGULARITY FOR NONLINEAR SCHRÖDINGER EQUATIONS

RÉMI CARLES AND LOUISE GASSOT

ABSTRACT. We consider the mass-supercritical, defocusing, nonlinear Schrödinger equation. We prove loss of regularity in arbitrarily short times for regularized initial data belonging to a dense set of any fixed Sobolev space for which the nonlinearity is supercritical. The proof relies on the construction of initial data as a superposition of disjoint bubbles at different scales. We get an approximate solution with a time of existence bounded from below, provided by the compressible Euler equation, which enjoys zero speed of propagation. Introducing suitable renormalized modulated energy functionals, we prove spatially localized estimates which make it possible to obtain the loss of regularity.

## 1. INTRODUCTION

We consider the defocusing nonlinear Schrödinger equation, for  $m \in \mathbb{N}$ :

$$(1.1) \quad i\partial_t \psi + \frac{1}{2}\Delta \psi = |\psi|^{2m}\psi, \quad \psi|_{t=0} = f_0,$$

where  $x \in \mathbb{R}^d$  and  $f_0 \in H^s(\mathbb{R}^d)$ . We assume that the nonlinearity is  $L^2$ -supercritical,

$$s_c = \frac{d}{2} - \frac{1}{m} > 0,$$

and we suppose that  $0 < s < s_c$ : the nonlinearity is  $H^s$ -supercritical. For technical reasons, we also assume  $s \leq 2$  (which is no further restriction when  $d \leq 4$ ). Our goal is to improve [12, Theorem 1.4], recalled below, and prove some loss on regularity in the spirit of [23]. We emphasize the fact that our analysis remains valid for compact geometries, typically for (1.1) on the torus  $\mathbb{T}^d$ .

**1.1. Context.** It is known that when  $s \geq s_c$ , then the Cauchy problem (1.1) is locally well-posed in  $H^s(\mathbb{R}^d)$  (see [14]), whereas when  $s < s_c$ , then the Cauchy problem is ill-posed, as established initially in [21]. In [15], the notion of norm inflation was introduced, and proven in the case of (1.1): there exists a sequence of initial data  $(f_0^h)_{h \in (0,1]}$  in  $\mathcal{S}(\mathbb{R}^d)$  going to zero

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in  $H^s$ , but such that the corresponding maximal solutions  $(\psi^h)_{h \in (0,1]}$  are defined on  $[0, t^h]$  for some  $t^h \rightarrow 0$  and  $\psi^h(t^h)$  goes to infinity in  $H^s$ :

$$\|f_0^h\|_{H^s} \xrightarrow{h \rightarrow 0} 0, \quad \|\psi^h(t^h)\|_{H^s} \xrightarrow{h \rightarrow 0} +\infty.$$

It turns out that this norm inflation mechanism also occurs around any initial data, as proven initially in [29] in the case of the wave equation (see also [31, 32]), and more recently in [33] for a fourth-order Schrödinger equation.

The question of norm inflation becomes more delicate when replacing the sequence  $(f_0^h)_h$  of initial data by the sequence  $(\iota_h * f_0)_h$ , where the approximate identity  $\iota_h$  is given by

$$\iota_h(x) = \frac{1}{h^d} \iota\left(\frac{x}{h}\right),$$

with  $\iota \in \mathcal{C}_c^\infty(\mathbb{R}^d)$  and  $\int_{\mathbb{R}^d} \iota(x) dx = 1$ . In this case, it has been shown in [12, Theorem 1.4], in the case  $d = 3$ , that there exists a dense set of functions  $f_0 \in H^s(\mathbb{R}^3)$  (called *pathological set*) such that norm inflation holds for this sequence of regularized initial data:

$$\|\iota_{h_k} * f_0 - f_0\|_{H^s} \xrightarrow{k \rightarrow \infty} 0, \quad \|\psi^{h_k}(t^{h_k})\|_{H^s} \xrightarrow{k \rightarrow \infty} +\infty.$$

The construction of such a pathological set was first evidenced in [28] for the wave equation, then extended to Schrödinger equations in [12] by removing a finite speed of propagation argument. The result is also valid on  $\mathbb{T}^3$ .

On the other hand, ill-posedness for the range of exponents  $s < s_c$  was strengthened in [1] as a loss of regularity result (extending the cubic case from [13]; see also [30]). More precisely, there exists a sequence of initial data  $(f_0^h)_{h \in (0,1]} \subset \mathcal{S}(\mathbb{R}^d)$ , global weak solutions  $(\psi^h)_{h \in (0,1]}$ , and  $t^h \rightarrow 0$ , such that:

$$\|f_0^h\|_{H^s} \xrightarrow{h \rightarrow 0} 0, \quad \|\psi^h(t^h)\|_{H^\sigma} \xrightarrow{h \rightarrow 0} +\infty, \quad \text{for all } \sigma > \frac{s}{1 + m(s_c - s)}.$$

This result is an analogue of the original loss of regularity theorem from Lebeau [23] concerning energy-supercritical wave equations ( $s_c > 1$ ),

$$(\partial_{tt} - \Delta)u + u^{2m+1} = 0,$$

which is as follows. There exists  $f_0$  in  $H^s$  and  $t^{h_k} \rightarrow 0$  such that the solution  $\psi$  to the wave equation satisfies that for every  $\sigma > I(s)$ ,

$$\|\psi(t^{h_k})\|_{H^\sigma} \xrightarrow{k \rightarrow +\infty} +\infty.$$

The exponent  $I(s)$  is given by  $I(s) = \frac{s}{1+m(s_c-s)}$  when  $s \geq s_{\text{sob}}$ ,

$$s_{\text{sob}} = \frac{dm}{2m+2} \text{ being such that } \dot{H}^{s_{\text{sob}}}(\mathbb{R}^d) \hookrightarrow L^{2m+2}(\mathbb{R}^d),$$

and  $I(s) = 1$  when  $s \leq s_{\text{sob}}$  (note that  $I(s_{\text{sob}}) = 1$ ). The result from [23] uses in a crucial fashion the property that (weak) solutions to the nonlinear wave equation enjoy finite speed of propagation. It is mostly because of this

that the result of [1] concerns a sequence of initial data (one bubble) rather than some fixed data (superposition of disjoint bubbles) like in [23]. In this paper, we prove a result which is essentially the same as in [23], by looking at the sequence of initial data  $(\iota_h * f_0)_h$  regularized by convolution. Of course there is no finite speed of propagation for (1.1). Instead, our argument takes advantage of a finite propagation speed property at the level of compressible Euler equations, which naturally appears in the WKB analysis of the semi-classical version of (1.1).

**1.2. Main results.** Our first result is in the spirit of [31, Theorem 1.33], and states that the main result from [1] is valid not only at the origin, but near any initial datum in  $H^s(\mathbb{R}^d)$ :

**Theorem 1.1** (Loss of regularity near any initial datum). *Let  $0 < s < s_c$ , with  $s \leq 2$ . For any  $f_0 \in H^s(\mathbb{R}^d)$ , there exists a sequence  $f_{0,k} \in C_c^\infty(\mathbb{R}^d)$  and times  $t_k \rightarrow 0$  as  $k \rightarrow \infty$ , such that*

$$\|f_0 - f_{0,k}\|_{H^s} \xrightarrow{k \rightarrow \infty} 0, \quad \|\psi_k(t_k)\|_{H^\sigma} \xrightarrow{k \rightarrow \infty} +\infty, \quad \forall \sigma > \frac{s}{1 + m(s_c - s)},$$

where for any (fixed)  $k$ ,  $\psi_k \in L^\infty(\mathbb{R}; H^1 \cap L^{2m+2})$  solves (1.1) with initial datum  $f_{0,k}$ .

As a corollary of this result, in the energy-supercritical case  $s_c > 1$ , taking  $s = s_{\text{sob}}$  yields  $f_{0,k}$  converging to  $f_0$  in the energy space  $H^1 \cap L^{2m+2}$ , while  $\psi_k$  is instantaneously unbounded in  $H^\sigma$  for any  $\sigma > 1$ , since  $I(s_{\text{sob}}) = 1$ . Like in [28], one may ask how the above phenomenon depends on the approximating sequence  $(f_{0,k})_k$ , and consider a general approximate identity. Our main result is as follows, and somehow unites the results from [1, 13, 30] on the one hand, and [12] on the other hand:

**Theorem 1.2** (Loss of regularity for regularized data). *Let  $0 < s < s_c$ , with  $s \leq 2$ . There exists a dense pathological set of initial data  $f_0$  in  $H^s(\mathbb{R}^d)$  such that the following holds. For  $h > 0$ , let  $\psi^h$  be the solution to (1.1) with initial data  $\iota_h * f_0$ . There exist a sequence of parameters  $h_k \rightarrow 0$  and times  $t_k \rightarrow 0$  as  $k \rightarrow \infty$ , such that*

$$\|\iota_{h_k} * f_0 - f_0\|_{H^s} \xrightarrow{k \rightarrow \infty} 0, \quad \|\psi^{h_k}(t_k)\|_{H^\sigma} \xrightarrow{k \rightarrow \infty} +\infty, \quad \forall \sigma > \frac{s}{1 + m(s_c - s)}.$$

*Remark 1.3.* We shall see in the proof that this result is also valid in  $\mathbb{T}^d$ .

*Remark 1.4.* Note that as mentioned in [12, Theorem 1.4 and Proposition 2.10], as soon as the Cauchy problem is globally well-posed in  $H^k(\mathbb{R}^d)$  for some  $k > \frac{d}{2}$ , then the set of initial data  $f_0$  satisfying Theorem 1.2 contains a dense  $G_\delta$  set.

The pathological set of initial data, on which norm inflation or loss of regularity happens, is the counterpart of the set of initial data such that probabilistic well-posedness holds, initiated by Bourgain [6, 7] for the cubic Schrödinger equation on  $\mathbb{T}^2$ , then developed by Burq and Tzvetkov [10, 11]

for the cubic wave equation on manifolds, and by Burq, Thomann and Tzvetkov [9] for the nonlinear Schrödinger equation on  $\mathbb{R}$ . Indeed, as mentioned in [12, Theorem 1.3], the generic well-posedness result from Bényi, Oh and Pocovnicu [3] on the cubic Schrödinger equation on  $\mathbb{R}^3$  implies that for  $\frac{1}{4} < s < s_c$ , there exists a probability measure  $\mu$  supported on  $H^s(\mathbb{R}^3)$  and a dense set  $\Sigma \subset H^s(\mathbb{R}^3)$  with full  $\mu$ -measure such that the following holds. For every  $f_0 \in \Sigma$ , the solution  $\psi^h$  to (1.1) with initial data  $\iota_h * f_0$  is well-defined up to some time  $T(f_0)$  and converge to some limiting distributional solution  $\psi$  to (1.1) with initial data  $f_0$  on  $[0, T(f_0)]$ :

$$\|\iota_h * f_0 - f_0\|_{H^s} \xrightarrow{h \rightarrow 0} 0, \quad \|\psi^h - \psi\|_{L^\infty([0, T], H^s(\mathbb{R}^3))} \xrightarrow{h \rightarrow 0} 0.$$

This result was improved in [4], with the lower bound  $s > \frac{1}{5}$ , and in [27] with the lower bound  $s > \frac{1}{7}$ . Consequently, the full-measure set  $\Sigma$  must be disjoint from the pathological set. In particular, if the pathological set contains a dense  $G_\delta$  set, this cannot be the case for  $\Sigma$ . This conflict between full measure (probability one for initial data) and density (of the pathological set) is also striking in view of the results of [22] (see also [16, 27] where the initial Sobolev regularity is lowered), since for the cubic Schrödinger equation on  $\mathbb{R}^4$  (which is an energy-critical equation), it is proved that for all initial data in  $H^s(\mathbb{R}^4)$  with  $\frac{5}{6} < s < 1$ , the nonlinear evolution of the randomization of  $f$  is almost surely global in time and stable in the sense that it is asymptotically linear (scattering).

*Remark 1.5.* For  $d \geq 5$ , it was proven in [26] that for certain values of  $m$  at least, concerning energy-supercritical cases ( $s_c > 1$ ), there exists a finite co-dimensional manifold of smooth initial data with spherical symmetry such that the solution blows up in finite time  $T_* > 0$ , with

$$\|\psi(t)\|_{L^\infty(\mathbb{R}^d)} \xrightarrow{t \rightarrow T_*} +\infty.$$

A common feature of our analysis with the approach in [26] is the use of hydrodynamical formulations, measuring a strong interaction between the phase and the amplitude for the solution of (1.1), an aspect already at the origin of the results in [13]. In particular, it is proven in [26] that there exists  $1 < \sigma < s_c$  such that

$$\|\psi(t)\|_{H^\sigma(\mathbb{R}^d)} \xrightarrow{t \rightarrow T_*} +\infty.$$

Our main result concerns the whole range  $\sigma > \frac{s}{1+m(s_c-s)}$ , which, for  $s_c > 1$  and  $s = s_{\text{sob}}$ , corresponds exactly to  $\sigma > 1$ .

**1.3. Scheme of the proof.** The general strategy mixes ideas from [1] and [12]. In [1], and like in [8, 15], the general data are of the form

$$f_0^h(x) = h^{s-d/2} a\left(\frac{x}{h}\right).$$

Introducing  $\varepsilon = h^{m(s_c-s)}$  and the change of unknown function

$$u^\varepsilon(t, x) = h^{d/2-s}\psi^h(h^2\varepsilon t, hx),$$

the family of function  $(u^\varepsilon)_{0<\varepsilon\leq 1}$  solves the semiclassical version of (1.1),

$$i\varepsilon\partial_t u^\varepsilon + \frac{\varepsilon^2}{2}\Delta u^\varepsilon = |u^\varepsilon|^{2m}u^\varepsilon,$$

with initial data  $u^\varepsilon|_{t=0} = a$  independent of  $\varepsilon$ . The solution  $u^\varepsilon$  becomes instantaneously  $\varepsilon$ -oscillatory, in the sense that there exists  $\tau > 0$  (independent of  $\varepsilon$ ) such that

$$\|u^\varepsilon(\tau)\|_{\dot{H}^1} \approx \frac{1}{\varepsilon}.$$

In principle, this property can be shown thanks to WKB analysis, as in [13] for the cubic case  $m = 1$ , and in [30] for analytic data. However the proof in [1] is cheaper in the sense that it merely requires the use of modulated energy functionals, without justifying WKB analysis. Using various interpolation estimates and the property  $\|u^\varepsilon(\tau)\|_{L^2} = \|a\|_{L^2}$  (independent of  $\varepsilon$ ), one infers

$$\|u^\varepsilon(\tau)\|_{\dot{H}^\sigma} \approx \frac{1}{\varepsilon^\sigma}, \quad \forall \sigma \geq 0.$$

The result follows when using the scaling to go back to  $\psi^h$ , with  $t^h = h^2\varepsilon\tau$ .

The proof of Theorem 1.1 can be viewed as a consequence of the proof of Theorem 1.2, as we explain in Appendix B, so we now focus on the proof of the latter. Instead of starting from one concentrating data, we start from a superposition of such bubbles, like in [23] initially, along a sequence  $h_k \rightarrow 0$  as  $k \rightarrow +\infty$  (see Section 2). As pointed out above, we also regularize this sum of bubbles, like in [12]. We then adapt the modulated energy analysis along the bubble corresponding to the scale  $h_k$ . The more direct approach is interesting under the constraint  $s < s_{\text{sob}}$  (Section 4). It is improved in Section 5 by considering a renormalized modulated energy. However, unlike in the case of a single bubble recalled above, this is not enough to conclude directly, as the  $L^2$ -norm of the rescaled function  $u^\varepsilon$  is not uniformly bounded, due to the (initial) bubbles corresponding to  $\ell < k$ . In the spirit of [23], we pick bubbles with initial pairwise disjoint supports. Using a finite propagation speed for the approximate bubbles involved in the modulated energy functionals, due to Makino, Ukai and Kawashima [25] (see Section 3), we prove spatially localized estimates in Section 6, and then conclude. In an appendix, we provide an alternative proof of the most delicate result of Section 6, which does not use Fourier analysis, and is thus more flexible for different geometries.

## 2. PATHOLOGICAL SET OF INITIAL DATA

**2.1. Definition.** Following [28, 12], we consider pathological initial data as a superposition of bubbles displaying norm inflation at different scales, of

the form

$$f_0 = \varphi_0 + \sum_{k=k_0}^{\infty} \varphi_k,$$

for some  $k_0 \geq 1$ . The background  $\varphi_0 \in \mathcal{C}_c^\infty(\mathbb{R}^d)$  automatically satisfies that  $\mathbb{R}^d \setminus \text{supp}(\varphi_0)$  is a large set, in particular it contains a ball  $\overline{B}(0, r_0)$ . In order to extend our result to  $\mathbb{T}^d$ , one should assume that  $\mathbb{T}^d \setminus \text{supp}(\varphi_0)$  contains an open set  $B(0, r_0)$ . As such, we will choose bubbles  $\varphi_k$  with pairwise disjoint supports inside of  $\overline{B}(0, r_0)$ .

We fix some parameter  $M > 1$ , and define the scale

$$h_k := e^{-M^k}.$$

Each bubble  $\varphi_k$  is a rescaling of a profile  $\alpha_k \in \mathcal{C}_c^\infty(\mathbb{R}^d)$  at scale  $h_k > 0$ :

$$(2.1) \quad \varphi_k(x) = \frac{1}{|\log(h_k)|} h_k^{s-\frac{d}{2}} \alpha_k\left(\frac{x}{h_k}\right).$$

We assume for simplicity that

$$\alpha_k(x) = \alpha\left(x - \frac{x_k}{h_k}\right)$$

for some fixed profile  $\alpha \in \mathcal{C}_c^\infty(\mathbb{R}^d)$ , where the position  $x_k \in \mathbb{R}^d$  will be characterized later on. The radial case can be handled by considering instead, for instance,  $\alpha_k(x) = \alpha(|x|^2 - r_k^2/h_k^2)$  with  $\alpha \in \mathcal{C}_c^\infty(\mathbb{R}_+)$ . The logarithmic factor aims at guaranteeing the convergence of the above series in  $H^s$ , but its presence can be forgotten to grasp the main ideas and details of the computations. Let  $\psi_k$  solve (1.1) with regularized initial data defined from  $f_0$  as

$$\psi_k|_{t=0} := \iota_{h_k/100} * f_0.$$

We note that for any fixed  $k$ , we can find such a global in time solution,  $\psi_k \in L^\infty(\mathbb{R}; H^1 \cap L^{2m+2})$ , as a weak solution, from [18]. If  $s_c \leq 1$ ,  $\psi_k$  is actually the unique, global, mild solution, and it is smooth for all time by propagation of regularity. If  $s_c > 1$ , as there exists a unique local solution to (1.1) in  $H^N(\mathbb{R}^d)$  for  $N > d/2$  by standard arguments, at least locally in time, the weak solution is the unique, smooth, solution. Note that this means that for any  $k$ ,  $\psi_k$  remains smooth locally in time, on a time interval which may shrink to  $\{0\}$  as  $k$  goes to infinity, in agreement with the result from [26]. We expect that this regularized solution will display a norm inflation in  $H^\sigma$  around the  $k$ -th bubble at some time  $t_k$  to be defined in the next paragraph.

**2.2. Semiclassical form.** In order to show a loss of regularity result in the spirit of Lebeau [23], we rather consider the rescaled equation from [1] following [13]: consider

$$(2.2) \quad \varepsilon_k = h_k^{m(s_c-s)} |\log(h_k)|^m \xrightarrow[k \rightarrow \infty]{} 0,$$

where this limit stems from the assumption  $s < s_c$ . Rescale the function  $\psi$  as

$$u_k(t, x) = |\log(h_k)| h_k^{\frac{d}{2}-s} \psi_k(h_k^2 \varepsilon_k t, h_k x).$$

The equation satisfied by  $u_k$  is the semiclassical Schrödinger equation

$$(2.3) \quad i\varepsilon_k \partial_t u_k + \frac{\varepsilon_k^2}{2} \Delta u_k = |u_k|^{2m} u_k \quad ; \quad u_k|_{t=0} = u_{0,k}.$$

According to the definition, the initial data  $u_{0,k}$  is given by the following formula.

**Lemma 2.1** (Rescaled initial data). *One can write*

$$u_{0,k}(x) = j * \left( \varphi_{0,k} + \sum_{\ell=k_0}^{\infty} \varphi_{\ell,k} \right),$$

where  $j = \iota_{1/100}$ ,

$$\varphi_{0,k}(x) = |\log(h_k)| h_k^{d/2-s} \varphi_0(h_k x),$$

and for  $\ell \geq k_0$ ,

$$\varphi_{\ell,k}(x) = \frac{|\log(h_k)|}{|\log(h_\ell)|} \left( \frac{h_k}{h_\ell} \right)^{d/2-s} \alpha_\ell \left( \frac{h_k}{h_\ell} x \right).$$

*Proof.* We have

$$u_{0,k}(x) = \mathcal{R}_k (\iota_{h_k/100} * f_0),$$

where  $\mathcal{R}_k$  is the scaling transformation

$$\mathcal{R}_k f(x) = |\log(h_k)| h_k^{d/2-s} f(h_k x).$$

We first write this initial data in a more convenient way. When  $k \geq 1$ ,  $\ell \geq k_0$  and  $h > 0$  we have

$$\begin{aligned} \mathcal{R}_k (\iota_h * \varphi_\ell)(x) &= \frac{|\log(h_k)|}{|\log(h_\ell)|} \left( \frac{h_k}{h_\ell} \right)^{d/2-s} \int \frac{1}{h^d} \iota \left( \frac{y}{h} \right) \alpha_\ell \left( \frac{h_k}{h_\ell} x - \frac{y}{h_\ell} \right) dy \\ &= \frac{|\log(h_k)|}{|\log(h_\ell)|} \left( \frac{h_k}{h} \right)^d \left( \frac{h_k}{h_\ell} \right)^{d/2-s} \int \iota \left( \frac{h_k}{h} y \right) \alpha_\ell \left( \frac{h_k}{h_\ell} (x - y) \right) dy. \end{aligned}$$

When  $h = h_k/100$ , then  $h_k/h$  is independent of  $k$ , so that

$$(2.4) \quad \mathcal{R}_k (\iota_{h_k/100} * \varphi_\ell) = j * \varphi_{\ell,k}.$$

The same argument works in the case  $\ell = 0$ . □



**2.3. Norms of the bubbles.** We now estimate the Sobolev norms of the initial data.

**Lemma 2.2** (Sobolev norms of the initial bubbles). *Let  $s' \geq 0$ . When  $\ell < k$ , we have*

$$\|j * \varphi_{\ell,k}\|_{\dot{H}^{s'}} \lesssim \frac{|\log(h_k)|}{|\log(h_\ell)|} \left(\frac{h_k}{h_\ell}\right)^{s'-s},$$

whereas when  $\ell > k$ , there holds

$$\|j * \varphi_{\ell,k}\|_{\dot{H}^{s'}} \lesssim \frac{|\log(h_k)|}{|\log(h_\ell)|} \left(\frac{h_\ell}{h_k}\right)^s.$$

As a consequence, when  $\ell < k$ , then  $\|j * \varphi_{\ell,k}\|_{\dot{H}^{s'}}$  is large when  $s' < s$  but small when  $s' > s$ , and when  $\ell > k$ , then  $\|j * \varphi_{\ell,k}\|_{\dot{H}^{s'}}$  is small for every  $s'$ .

*Proof.* When  $k > \ell$ , we have  $h_k/h_\ell \rightarrow 0$ , so the initial data  $j * \varphi_{\ell,k}$  spread as  $k \rightarrow \infty$ . When  $k < \ell$ , the initial data  $j * \varphi_{\ell,k}$  rather concentrate, but the convolution prevents the growth of Sobolev norms.

More precisely, let  $s' \geq 0$ , then

$$\|\varphi_{\ell,k}\|_{\dot{H}^{s'}} \lesssim \frac{|\log(h_k)|}{|\log(h_\ell)|} \left(\frac{h_k}{h_\ell}\right)^{s'-s}.$$

Note that in  $L^\infty$ , we get a small norm when  $\ell < k$  and  $s < s_c < d/2$ :

$$\|\varphi_{\ell,k}\|_{L^\infty} \lesssim \frac{|\log(h_k)|}{|\log(h_\ell)|} \left(\frac{h_k}{h_\ell}\right)^{d/2-s}.$$

We now remark that the  $L^1$ -norms of  $j$  and its derivatives are bounded independently of  $k$ . Using Young inequality, we deduce that if  $0 \leq \beta \leq s'$ , then

$$(2.5) \quad \|j * \varphi_{\ell,k}\|_{\dot{H}^{s'}} \leq \|j\|_{W^{1,\beta}} \|\varphi_{\ell,k}\|_{\dot{H}^{s'-\beta}} \lesssim \frac{|\log(h_k)|}{|\log(h_\ell)|} \left(\frac{h_k}{h_\ell}\right)^{s'-\beta-s}.$$

As a consequence, when  $\ell < k$ , choosing  $\beta = 0$  we get the first inequality of the statement, and when  $\ell > k$ , we choose  $\beta = s'$  so that we get the second inequality of the statement.  $\square$

From these estimates, one can deduce upper bounds on the Sobolev norms of  $u_{0,k}$ :

$$\|u_{0,k}\|_{\dot{H}^{s'}} \lesssim \sum_{\ell < k} \frac{|\log(h_k)|}{|\log(h_\ell)|} \left(\frac{h_k}{h_\ell}\right)^{s'-s} + \sum_{\ell \geq k} \frac{|\log(h_k)|}{|\log(h_\ell)|} \left(\frac{h_\ell}{h_k}\right)^s.$$

In the case  $s' = s$ , the sum over bubbles  $\ell < k$  is convergent, but a logarithmic factor remains,  $\sum_{\ell < k} \frac{|\log(h_k)|}{|\log(h_\ell)|} \lesssim |\log(h_k)|$ . Therefore, we get the upper

bounds

$$\|u_{0,k}\|_{\dot{H}^{s'}} \lesssim \begin{cases} \left(\frac{h_k}{h_{k-1}}\right)^{s'-s} + 1 & \text{if } s' > s, \\ |\log(h_k)| & \text{if } s' = s, \\ h_k^{s'-s} + 1 & \text{if } s' < s. \end{cases}$$

The logarithmic unboundedness in the case  $s' = s$  is essentially irrelevant for the rest of this paper, as in case it appears, it is always multiplied by a positive power of  $h_k$ . For  $s' = 0$ , using the conservation of mass, we deduce the estimate

$$(2.6) \quad \|u_k(t)\|_{L^2} \lesssim h_k^{-s}.$$

As pointed out in the introduction, this estimate is in sharp contrast with the case of a single bubble considered in [1]: this above bound, which is sharp, shows that the  $L^2$ -norm of the initial data is not uniformly bounded in  $k$ . This forces us to adapt the arguments from [1] at several stages: modulated energy estimates, and interpolation steps to estimate  $u_k$  in homogeneous Sobolev spaces.

One can also estimate the semiclassical energy of  $u_k$ , which is (formally) conserved by the flow of (2.3):

$$E_k(t) = \frac{\varepsilon_k^2}{2} \|\nabla u_k(t)\|_{L^2}^2 + \frac{1}{m+1} \|u_k(t)\|_{L^{2m+2}}^{2m+2}.$$

Strictly speaking, for weak solutions (a case we may have to consider, if  $s_c > 1$ , as explained in Section 2.1), the energy is not necessarily conserved, but it is a nonincreasing function of time; see [18]. Let  $0 < s \leq s_c$ . From the Sobolev embedding  $\dot{H}^{s_{\text{sob}}} \hookrightarrow L^{2m+2}$ , we get

$$E_k(t) \leq E_k(0) \lesssim \left( \varepsilon_k^2 \left(\frac{h_k}{h_{k-1}}\right)^{2(1-s)} + \left(\frac{h_k}{h_{k-1}}\right)^{2(m+1)(s_{\text{sob}}-s)} \right) |\log(h_k)| + 1.$$

In view of (2.2) and the algebraic relation

$$ms_c + 1 = (m+1)s_{\text{sob}},$$

the first term on the right hand side is controlled by the second one, and

$$(2.7) \quad E_k(t) \lesssim \left(\frac{h_k}{h_{k-1}}\right)^{2(m+1)(s_{\text{sob}}-s)} |\log(h_k)| + 1.$$

Note that  $E_k$  stays bounded when  $s < s_{\text{sob}}$ , but tends to infinity otherwise.

*Remark 2.3* (WKB analysis). We emphasize that due to the unboundedness, in  $L^2(\mathbb{R}^d)$ , of  $u_{0,k}$ , and possibly also  $\varepsilon_k \nabla u_{0,k}$  (if  $s > s_{\text{sob}}$ ), WKB analysis for (2.3) is not obvious at all. Typically in the cubic case  $m = 1$ , where the beautiful idea of Grenier [19] makes it possible to justify WKB analysis in Sobolev spaces, the limit  $k \rightarrow \infty$  in (2.3) is unclear. This is so even in Zhidkov spaces  $X^s(\mathbb{R}^d)$  ( $f \in X^s$ ,  $s > 1$ , if  $f \in L^\infty$  and  $\nabla f \in H^{s-1}$ ), where WKB is justified in [2]. We have seen above that  $\varepsilon_k \nabla u_{0,k}$  need not

be bounded uniformly in  $k$ . We will bypass this difficulty by considering suitable modulated energy functionals, in Sections 4 and 5.

### 3. ANALYSIS OF SEMICLASSICAL BUBBLES

In view of Lemma 2.1, and of the semiclassical analysis from [1], introduce the hydrodynamical system associated to the initial mode  $\ell$ , at scale  $k$ :

$$(3.1) \quad \begin{cases} \partial_t \phi_{\ell,k} + \frac{1}{2} |\nabla \phi_{\ell,k}|^2 + |a_{\ell,k}|^{2m} = 0, & \phi_{\ell,k}|_{t=0} = 0, \\ \partial_t a_{\ell,k} + \nabla \phi_{\ell,k} \cdot \nabla a_{\ell,k} + \frac{1}{2} a_{\ell,k} \Delta \phi_{\ell,k} = 0, & a_{\ell,k}|_{t=0} = j * \varphi_{\ell,k}. \end{cases}$$

We use the convention to denote  $(\phi_{k,k}, a_{k,k}) = (\phi_k, a_k)$ .

**3.1. Cauchy problem and zero speed of propagation.** Discarding the dependence upon the parameters  $\ell$  and  $k$ , the set of equations (3.1) can be written in a universal way,

$$(3.2) \quad \begin{cases} \partial_t \phi + \frac{1}{2} |\nabla \phi|^2 + |a|^{2m} = 0, & \phi|_{t=0} = 0, \\ \partial_t a + \nabla \phi \cdot \nabla a + \frac{1}{2} a \Delta \phi = 0, & a|_{t=0} = a_{\text{init}}, \end{cases}$$

with the common feature that  $a_{\text{init}} \in C_c^\infty(\mathbb{R}^d)$ . The following result will be of constant use in the rest of this paper:

**Lemma 3.1.** *Let  $a_{\text{init}} \in C_c^\infty(\mathbb{R}^d)$ . There exists  $T > 0$  and a unique solution  $(\phi, a) \in \mathcal{C}([0, T]; H^\infty(\mathbb{R}^d))$  to (3.2). Moreover,  $(\phi, a)$  remains compactly supported for  $t \in [0, T]$ , and*

$$\text{supp } \phi(t, \cdot), \text{ supp } a(t, \cdot) \subset \text{supp } a_{\text{init}}.$$

*Proof.* This result is a consequence of the analysis from [25], whose main ideas we recall. Change of unknown function  $(\phi, a)$  to

$$(V, A) = (\nabla \phi, a^m).$$

It solves

$$(3.3) \quad \begin{cases} \partial_t V + V \cdot \nabla V + \nabla (|A|^2) = 0, & V|_{t=0} = 0, \\ \partial_t A + V \cdot \nabla A + \frac{m}{2} A \text{div } V = 0, & A|_{t=0} = (a_{\text{init}})^m, \end{cases}$$

which turns out to be a symmetric hyperbolic system, with a constant symmetrizer. Indeed, denote  $U = (\text{Re}(A), \text{Im}(A), V)^T$ : the system (3.3) becomes

$$(3.4) \quad \partial_t U + \sum_{j=1}^d M_j(U) \partial_j U = 0,$$

where

$$\sum_{j=1}^d M_j(U) \xi_j = \begin{pmatrix} V \cdot \xi & 0 & \frac{m}{2} \text{Re}(A) \xi^T \\ 0 & V \cdot \xi & \frac{m}{2} \text{Im}(A) \xi^T \\ 2 \text{Re}(A) \xi & 2 \text{Im}(A) \xi & V \cdot \xi \text{I}_d \end{pmatrix}.$$

Hence the matrices  $M_j \in \mathcal{M}_{d+2}(\mathbb{R})$  are such that  $SM_j \in \mathcal{S}_{d+2}(\mathbb{R})$ , with

$$S = \begin{pmatrix} m\mathbf{I}_d & 0 \\ 0 & 4\mathbf{I}_2 \end{pmatrix}.$$

Local existence in  $H^\sigma(\mathbb{R}^d)$  with  $\sigma > d/2 + 1$  is then standard for (3.4) hence for (3.3); see e.g. [24]. We emphasize tame estimates, which show that the lifespan  $T$  is independent of  $\sigma > d/2 + 1$ . Let  $\Lambda = 1 - \Delta$ : by symmetry,

$$\frac{d}{dt} \langle S\Lambda^\sigma U, \Lambda^\sigma U \rangle = 2 \langle S\Lambda^\sigma \partial_t U, \Lambda^\sigma U \rangle.$$

In view of (3.4),

$$\langle S\Lambda^\sigma \partial_t U, \Lambda^\sigma U \rangle = - \sum_{j=1}^d \langle S\Lambda^\sigma (M_j(U) \partial_j U), \Lambda^\sigma U \rangle.$$

Write

$$\begin{aligned} \langle S\Lambda^\sigma (M_j(U) \partial_j U), \Lambda^\sigma U \rangle &= \langle SM_j(U) \partial_j \Lambda^\sigma U, \Lambda^\sigma U \rangle \\ &\quad - \langle S[M_j(U), \Lambda^\sigma] \partial_j U, \Lambda^\sigma U \rangle. \end{aligned}$$

Since  $SM_j$  is symmetric,

$$\langle SM_j(U) \partial_j \Lambda^\sigma U, \Lambda^\sigma U \rangle = -\frac{1}{2} \langle \Lambda^\sigma U, \partial_j (SM_j(U)) \Lambda^\sigma U \rangle,$$

As  $SM_j$  is linear in its argument, we readily infer

$$|\langle SM_j(U) \partial_j \Lambda^\sigma U, \Lambda^\sigma U \rangle| \lesssim \|S \partial_j M_j(U)\|_{L^\infty} \|U\|_{H^\sigma}^2 \lesssim \|\nabla U\|_{L^\infty} \|U\|_{H^\sigma}^2.$$

By commutator estimate (see [20]), we have

$$|\langle S[M_j(U), \Lambda^\sigma] \partial_j U, \Lambda^\sigma U \rangle| \lesssim \|\nabla U\|_{L^\infty} \|U\|_{H^\sigma}^2.$$

We infer:

$$(3.5) \quad \frac{d}{dt} \langle S\Lambda^\sigma U, \Lambda^\sigma U \rangle \lesssim \|\nabla U\|_{L^\infty} \langle S\Lambda^\sigma U, \Lambda^\sigma U \rangle.$$

To return to the initial unknown  $(\phi, a)$ , we integrate the first equation from (3.2) with respect to time

$$\phi(t) = -\frac{1}{2} \int_0^t |V(\tau)|^2 d\tau - \int_0^t |A(\tau)|^2 d\tau.$$

We check that  $V = \nabla \phi$ , as

$$\partial_t (\nabla \phi - V) = \nabla \partial_t \phi - \partial_t V = 0.$$

We go back to  $a$  by now viewing the second equation in (3.2) as a transport equation with smooth coefficients. This leads to the local existence result of the lemma.

We now move to the zero propagation speed property, established initially in [25, Theorem 2]. We see that there exists  $C \geq 0$  such that for every  $j$ ,

$$|M_j(U)| \leq C|U|.$$

Fix  $(t, x)$  in  $[0, T] \times \mathbb{R}^d$ . Since the solution is well-defined on  $[0, t]$ , we can define

$$C'(t, x) := \sup_{t' \in [0, t], 1 \leq j \leq d} |\partial_j U_k(t', x)| < +\infty.$$

Using the equation, for  $t' \in [0, t]$  there holds

$$|\partial_t U_k(t', x)| \leq d C C'(t, x) |U_k(t', x)|.$$

Using Gronwall lemma, we deduce that  $U_k(t, x) = 0$  if and only if  $U_k(0, x) = 0$ , hence

$$\text{supp}(A(t), V(t)) = \text{supp}(A, V)|_{t=0} = \text{supp } a_{\text{init}}.$$

We go back to the unknown  $(\phi, a)$  like described above.  $\square$

*Remark 3.2* (Lifespan of the bubbles without convolution). Introduce bubbles without the initial convolution,

$$(3.6) \quad \begin{cases} \partial_t \check{\phi}_{\ell, k} + \frac{1}{2} |\nabla \check{\phi}_{\ell, k}|^2 + |\check{a}_{\ell, k}|^{2m} = 0, & \check{\phi}_{\ell, k}|_{t=0} = 0, \\ \partial_t \check{a}_{\ell, k} + \nabla \check{\phi}_{\ell, k} \cdot \nabla \check{a}_{\ell, k} + \frac{1}{2} \check{a}_{\ell, k} \Delta \check{\phi}_{\ell, k} = 0, & \check{a}_{\ell, k}|_{t=0} = \varphi_{\ell, k}. \end{cases}$$

Using the convention  $(\check{\phi}_{\ell, \ell}, \check{a}_{\ell, \ell}) = (\check{\phi}_\ell, \check{a}_\ell)$ , we check the algebraic relations

$$(3.7) \quad \begin{aligned} \check{\phi}_{\ell, k}(t, x) &= \frac{\varepsilon_k}{\varepsilon_\ell} \check{\phi}_\ell \left( \left( \frac{\varepsilon_k h_k^2}{\varepsilon_\ell h_\ell^2} \right) t, \frac{h_k}{h_\ell} x \right), \\ \check{a}_{\ell, k}(t, x) &= \frac{|\log h_k|}{|\log h_\ell|} \left( \frac{h_k}{h_\ell} \right)^{d/2-s} \check{a}_\ell \left( \left( \frac{\varepsilon_k h_k^2}{\varepsilon_\ell h_\ell^2} \right) t, \frac{h_k}{h_\ell} x \right), \end{aligned}$$

where we recall notation

$$\varepsilon_k = h_k^{m(s_c - s)} |\log h_k|^m.$$

Using a virial computation, showing that if a global smooth solution exists for (3.6), then it is dispersive, the authors in [25] show that  $T$ , in Lemma 3.1, is necessarily finite. In view of (3.7), this implies that for  $\ell < k$ ,  $(\check{\phi}_{\ell, k}, \check{a}_{\ell, k})$  remains smooth on  $[0, T_{\ell, k}]$ , with

$$T_{\ell, k} = \frac{\varepsilon_\ell h_\ell^2}{\varepsilon_k h_k^2} T \xrightarrow[k \rightarrow \infty]{} +\infty,$$

while for  $\ell > k$ ,  $(\check{\phi}_{\ell, k}, \check{a}_{\ell, k})$  remains smooth on  $[0, T_{\ell, k}]$  for the same expression of  $T_{\ell, k}$ , which now goes to zero as  $k$  goes to infinity.

*Remark 3.3* (On low modes). The scaling (3.7) also shows that for  $\ell < k$  and  $t \approx 1$ , nonlinear effects are negligible in (3.6), a remark reminiscent of the strategy adopted in the proof of [12, Proposition 2.6], where the *linear* evolution of “low modes” is considered. Actually, in this régime, even the linear evolution of the initial data is negligible: the low modes are essentially constant in time, a remark which is exploited in the introduction of a renormalized modulated energy functional in Section 5.

**3.2. Superposition principle.** Let us assume that the points  $x_\ell$  are chosen so that the profiles  $j * \varphi_{\ell,k}$  have disjoint supports. We recall that  $\alpha_k(x) = \alpha(x - \frac{x_k}{h_k})$ . Assuming that  $\alpha$  and  $j = \iota(\cdot/100)$  are supported in  $\overline{B}(0, r_1)$  for some small constant  $r_1 > 0$ , we have

$$\text{supp}(j * \varphi_{\ell,k}) \subset \overline{B}\left(\frac{x_\ell}{h_k}, 2r_1 \frac{h_\ell}{h_k}\right).$$

Choosing the points  $x_\ell$  sufficiently far away from each other so that

$$|x_\ell - x_{\ell+1}| > 4r_1 h_\ell,$$

the bubbles are therefore disjoint.

In this case, we may use a nonlinear superposition principle. Introduce the following intermediate approximate solution with initial data including all the scales  $\ell \leq k$ :

$$(3.8) \quad \begin{cases} \partial_t \tilde{\phi}_k + \frac{1}{2} |\nabla \tilde{\phi}_k|^2 + |\tilde{a}_k|^{2m} = 0, & \tilde{\phi}_k|_{t=0} = 0, \\ \partial_t \tilde{a}_k + \nabla \tilde{\phi}_k \cdot \nabla \tilde{a}_k + \frac{1}{2} \tilde{a}_k \Delta \tilde{\phi}_k = 0, & \tilde{a}_k|_{t=0} = \sum_{\ell \leq k} j * \varphi_{\ell,k}. \end{cases}$$

Lemma 3.1 implies that

$$(\tilde{\phi}_k, \tilde{a}_k) = \sum_{\ell \leq k} (\phi_{\ell,k}, a_{\ell,k}),$$

where each bubble is given by (3.1). In view of the above analysis, we also introduce  $(\tilde{V}_k, \tilde{A}_k) = (\nabla \tilde{\phi}_k, \tilde{a}_k^m)$ , which solves

$$(3.9) \quad \begin{cases} \partial_t \tilde{V}_k + \tilde{V}_k \cdot \nabla \tilde{V}_k + \nabla (|\tilde{A}_k|^2) = 0, & \tilde{V}_k|_{t=0} = 0, \\ \partial_t \tilde{A}_k + \tilde{V}_k \cdot \nabla \tilde{A}_k + \frac{m}{2} \tilde{A}_k \text{div} \tilde{V}_k = 0, & \tilde{A}_k|_{t=0} = \left( \sum_{\ell \leq k} j * \varphi_{\ell,k} \right)^m. \end{cases}$$

Since the functions  $j * \varphi_{\ell,k}$  have pairwise disjoint supports, we may also write

$$\tilde{A}_k|_{t=0} = \sum_{\ell \leq k} (j * \varphi_{\ell,k})^m.$$

Like above, the zero speed of propagation from Lemma 3.1 then implies the relation

$$(\tilde{V}_k, \tilde{A}_k) = \sum_{\ell \leq k} (V_{\ell,k}, A_{\ell,k}),$$

where each  $(V_{\ell,k}, A_{\ell,k})$  solves the same system as  $(\tilde{V}_k, \tilde{A}_k)$ , with initial datum

$$(V_{\ell,k}, A_{\ell,k})|_{t=0} = (0, (j * \varphi_{\ell,k})^m).$$

**3.3. Refined estimates for the bubbles.** Like Lemma 3.1, the following lemma will be crucial for the rest of this paper:

**Lemma 3.4** (Uniform estimates for the bubbles). *There exist  $C > 0$  and  $T > 0$  such that the smooth solutions  $(\tilde{V}_k, \tilde{A}_k)$  have a lifespan  $T_k$  which is uniformly bounded from below:  $T_k \geq T > 0$ . Moreover, for every  $t \in [0, T]$ , for every  $k \geq 1$  and for every integer  $\sigma$ , there holds*

$$\begin{aligned} \|\nabla|^\sigma \tilde{V}_k(t)\|_{L^2} + \|\nabla|^\sigma \tilde{A}_k(t)\|_{L^2} &\leq C \|\nabla|^\sigma \tilde{A}_k(0)\|_{L^2} \\ &\lesssim 1 + \left(\frac{h_k}{h_{k-1}}\right)^{\sigma+1+m(s_c-s)-\frac{d}{2}}. \end{aligned}$$

Note that in particular, the Sobolev norms are bounded as soon as  $\sigma+1 \geq \frac{d}{2}$ . Considering the equation satisfied by  $(\tilde{V}_k, \tilde{A}_k)$ , this implies that

$$\|\nabla|^\sigma \tilde{V}_k(t)\|_{L^\infty} + \|\nabla|^\sigma \tilde{A}_k(t)\|_{L^\infty} \lesssim \|\nabla|^\sigma \tilde{A}_k(0)\|_{L^\infty} \lesssim 1 + \left(\frac{h_k}{h_{k-1}}\right)^{\sigma+1+m(s_c-s)}.$$

*Proof.* The proof relies on the symmetry of the hyperbolic system (3.9). Let  $N > 1 + d/2$  and  $\sigma \leq N$  be integers, and  $D^\sigma$  denote the family of differential operators in space, of order  $\sigma$ . In particular, the notation  $\|D^\sigma U\|_{L^2}$  stands for

$$\|D^\sigma U\|_{L^2} = \sum_{|\beta|=\sigma} \|\partial_x^\beta U\|_{L^2}.$$

Like in the framework recalled in the proof of Lemma 3.1, denote

$$U_k = (\operatorname{Re}(\tilde{A}_k), \operatorname{Im}(\tilde{A}_k), \tilde{V}_k)^T.$$

It solves (3.4). First, we examine its initial data. In view of Section 2.3, since  $\sigma$  is an integer, and the initial bubbles have pairwise disjoint supports, Leibniz rule and Hölder inequality yield

$$\|D^\sigma U_k(0)\|_{L^2} = \sum_{\ell \leq k} \|D^\sigma (j * \varphi_{\ell,k})^m\|_{L^2} \lesssim 1 + \left(\frac{h_k}{h_{k-1}}\right)^{\sigma-ms+(m-1)\frac{d}{2}}.$$

We rewrite the last power as

$$\sigma - ms + (m-1)\frac{d}{2} = \sigma + 1 - \frac{d}{2} + m(s_c - s).$$

In particular, for  $d \leq 2$ ,  $U_k(0)$  is uniformly bounded in  $H^N(\mathbb{R}^d)$  (we choose  $\sigma = 0$ ), and for  $d \leq 4$ ,  $\nabla U_k(0)$  is uniformly bounded in  $H^{N-1}(\mathbb{R}^d)$  (we choose  $\sigma = 1$ ). We start by proving Lemma 3.4 in the case  $d \leq 4$ . For  $1 \leq n \leq d$ ,  $\partial_n U$  solves

$$\partial_t \partial_n U_k + \sum_{j=1}^d M_j(U_k) \partial_j \partial_n U_k = - \sum_{j=1}^d M_j(\partial_n U_k) \partial_j U_k.$$

We proceed classically, like in the proof of Lemma 3.1, by viewing the term on the right hand side as a perturbative (semilinear) term, and compute

$$\begin{aligned} \frac{d}{dt} \langle S\Lambda^{N-1} \partial_n U_k, \Lambda^{N-1} \partial_n U_k \rangle &= - \sum_{j=1}^d \langle S\Lambda^{N-1} (M_j(U_k) \partial_j \partial_n U_k), \Lambda^{N-1} \partial_n U_k \rangle \\ &\quad - \sum_{j=1}^d \langle S\Lambda^{N-1} (M_j(\partial_n U_k) \partial_j U_k), \Lambda^{N-1} \partial_n U_k \rangle. \end{aligned}$$

Using the fact that  $H^{N-1}(\mathbb{R}^d)$  is a Banach algebra, and since  $M_j$  is linear in its argument, the last term is controlled by  $\|\nabla U_k\|_{H^{N-1}}^3$ . For the first term on the right hand side, we proceed exactly like in the proof of Lemma 3.1, and write

$$\begin{aligned} &\langle S\Lambda^{N-1} (M_j(U_k) \partial_j \partial_n U_k), \Lambda^{N-1} \partial_n U_k \rangle \\ &= \langle S (M_j(U_k) \partial_j \Lambda^{N-1} \partial_n U_k), \Lambda^{N-1} \partial_n U_k \rangle \\ &\quad + \langle S ([\Lambda^{N-1}, M_j(U_k)] \partial_j \partial_n U_k), \Lambda^{N-1} \partial_n U_k \rangle. \end{aligned}$$

By symmetry, the first term on the right hand side is controlled by

$$\|\nabla U_k\|_{L^\infty} \|\nabla U_k\|_{H^{N-1}}^2,$$

and by Kato-Ponce commutator estimate, the last term is estimated similarly:

$$\begin{aligned} \frac{d}{dt} \langle S\Lambda^{N-1} \partial_n U_k, \Lambda^{N-1} \partial_n U_k \rangle &\lesssim \|\nabla U_k\|_{L^\infty} \|\nabla U_k\|_{H^{N-1}}^2 + \|\nabla U_k\|_{H^{N-1}}^3 \\ &\lesssim \|\nabla U_k\|_{H^{N-1}}^3, \end{aligned}$$

where we have used the Sobolev embedding. Summing over  $n \in \{1, \dots, d\}$ , and recalling the equivalence of norms

$$\langle S\Lambda^{N-1} \nabla U_k, \Lambda^{N-1} \nabla U_k \rangle \sim \|\nabla U_k\|_{H^{N-1}}^2,$$

we infer that there exists  $T > 0$  independent of  $k$  such that  $(\nabla U_k)_k$  is uniformly bounded in  $L^\infty([0, T]; H^{N-1})$ , and Lemma 3.4 follows in the case  $d \leq 4$ .

When  $d \geq 5$ , we replace the above quantity  $\|\nabla U_k\|_{H^{N-1}}$  by  $\|D^{\sigma_0} U_k\|_{H^{N-\sigma_0}}$  for  $\sigma_0 > 1$ :

$$\|U_k\|_{\sigma_0, N} := \|D^{\sigma_0} U_k\|_{H^{N-\sigma_0}} = \sum_{\sigma=\sigma_0}^N \|D^\sigma U_k\|_{L^2}.$$

Three conditions are required:

- The initial norm  $\|U_k(0)\|_{\sigma_0, N}$  is bounded uniformly in  $k$ .
- The norm  $\|\cdot\|_{\sigma_0, N}$  controls the  $L^\infty$ -norm of  $\nabla U_k$ ,

$$\|\nabla U_k\|_{L^\infty} \lesssim \|U_k\|_{\sigma_0, N}.$$

- This norm controls each term in the analogue of the above energy estimates.



As we have seen above, the first condition is fulfilled for  $\sigma_0 \geq \frac{d}{2} - 1$ , and we choose

$$(3.10) \quad \sigma_0 = \begin{cases} \frac{d}{2} - 1 & \text{if } d \text{ is even,} \\ \lfloor \frac{d}{2} \rfloor & \text{if } d \text{ is odd.} \end{cases}$$

The second condition is satisfied, in view of the following elementary result, valid in any space dimension:

**Lemma 3.5.** *Let  $d \geq 1$ ,  $\sigma_0$  given by (3.10), and  $K > \frac{d}{2}$ . There exists  $C = C(d, K)$  such that for every  $f \in H^\sigma(\mathbb{R}^d)$ ,*

$$\|f\|_{L^\infty} \leq C \|D^{\sigma_0} f\|_{H^{K-\sigma_0}}.$$

*Proof of Lemma 3.5.* We use the inverse Fourier transform to infer

$$\|f\|_{L^\infty} \lesssim \int_{\mathbb{R}^d} |\widehat{f}(\xi)| d\xi.$$

Cauchy-Schwarz inequality yields

$$\left( \int_{\mathbb{R}^d} |\widehat{f}(\xi)| d\xi \right)^2 \lesssim \left( \int_{\mathbb{R}^d} |\xi|^{2\sigma_0} \langle \xi \rangle^{2(K-\sigma_0)} |\widehat{f}(\xi)|^2 d\xi \right) \left( \int_{\mathbb{R}^d} \frac{1}{|\xi|^{2\sigma_0} \langle \xi \rangle^{2(K-\sigma_0)}} d\xi \right).$$

Since  $2K > d$ , the last integral is convergent at infinity, and our definition of  $\sigma_0$  makes it convergent near zero, as we always have  $d - 1 - 2\sigma_0 > -1$ .  $\square$

Resume the strategy presented for  $d \leq 4$ : the equation satisfied by  $D^{\sigma_0} U_k$  is of the form

$$\partial_t D^{\sigma_0} U_k + \sum_{j=1}^d M_j(U_k) \partial_j D^{\sigma_0} U_k = - \sum_{j=1}^d [D^{\sigma_0}, M_j(U_k)] \partial_j U_k.$$

When considering

$$\frac{d}{dt} \langle S \Lambda^{N-\sigma_0} D^{\sigma_0} U_k, \Lambda^{N-\sigma_0} D^{\sigma_0} U_k \rangle,$$

the terms coming from  $M_j(U_k) \partial_j D^{\sigma_0} U_k$  (left hand side above) are treated like before, by using symmetry and Kato-Ponce commutator estimate, as  $D^{\sigma_0} U_k$  is estimated in the inhomogeneous Sobolev space  $H^{N-\sigma_0}$ . To control the terms coming from the right hand side, by Leibniz rule and Cauchy-Schwarz inequality, we have to estimate a combination of terms of the form

$$\|D^{\sigma_1} U_k D^{\sigma_2} U_k\|_{L^2}, \quad \sigma_1, \sigma_2 \geq 1, \quad \sigma_0 + 1 \leq \sigma_1 + \sigma_2 \leq N + 1.$$

Let us fix such exponents  $\sigma_1, \sigma_2$ . We have that

$$\|D^{\sigma_1} U_k D^{\sigma_2} U_k\|_{L^2} \leq \|D^{\sigma_1} U_k\|_{L^p} \|D^{\sigma_2} U_k\|_{L^q}, \quad \frac{1}{p} + \frac{1}{q} = \frac{1}{2}.$$

In view the Sobolev embedding  $\dot{H}^{d(1/2-1/p)}(\mathbb{R}^d) \hookrightarrow L^p(\mathbb{R}^d)$ , we infer

$$\|D^{\sigma_1} U_k D^{\sigma_2} U_k\|_{L^2} \leq \|D^{\sigma_1} U_k\|_{\dot{H}^{d/q}} \|D^{\sigma_2} U_k\|_{\dot{H}^{d/p}}.$$

By symmetry of the roles, we assume that  $\sigma_1 \geq \sigma_2$ . In everything that follows we assume that  $\frac{d}{q}$  is an integer. We get

$$\begin{aligned} \|D^{\sigma_1} U_k D^{\sigma_2} U_k\|_{L^2} &\leq \|D^{\sigma_1+d/q} U_k\|_{L^2} \|D^{\sigma_2+[d/p]} U_k\|_{\dot{H}^{d/p-[d/p]}} \\ &\leq \|D^{\sigma_1+d/q} U_k\|_{L^2} \|D^{\sigma_2+[d/p]} U_k\|_{H^1}. \end{aligned}$$

From a bootstrap argument based on the control of  $\|\nabla U_k(t)\|_{L^\infty}$  uniformly in  $k$  and  $t \in [0, T]$ , it suffices to check that we may find such  $p$  and  $q$ , satisfying in addition

$$\sigma_0 \leq \sigma_1 + [d/q] \leq N, \quad \sigma_0 \leq \sigma_2 + [d/p] \leq N - 1.$$

We proceed as follows.

- If  $\sigma_1 \geq \sigma_0$ , we choose  $q = \infty$  and  $p = 2$ . We get that

$$\sigma_1 + [d/q] = \sigma_1 \in [\sigma_0, N],$$

$$\sigma_2 + [d/p] \geq [d/2] \geq \sigma_0.$$

Moreover, since  $2\sigma_2 \leq \sigma_1 + \sigma_2 \leq N + 1$ , we have

$$\sigma_2 + [d/p] \leq \frac{N+1}{2} + \frac{d}{2},$$

which is bounded above by  $N - 1$  when  $N$  is chosen large enough.

- Otherwise, we have  $\sigma_2 \leq \sigma_1 \leq \sigma_0 - 1$ . If  $d = 1$  we have  $\sigma_0 = 0$  hence this case does not occur. Let  $q \in [2, \infty)$  such that  $\frac{d}{q}$  is an integer and

$$\sigma_1 + \frac{d}{q} = \sigma_1 + [d/q] = \sigma_0.$$

In particular we check that  $\sigma_1 + [d/q] \in [\sigma_0, N]$ . Then  $\sigma_1 + \sigma_2 \geq \sigma_0 + 1$  hence

$$\frac{d}{p} = \frac{d}{2} - \frac{d}{q} = \frac{d}{2} - \sigma_0 + \sigma_1 \geq \frac{d}{2} + 1 - \sigma_2.$$

Therefore, we have

$$\sigma_2 + \frac{d}{p} \geq \frac{d}{2} + 1.$$

In particular,

$$\sigma_2 + [d/p] \geq \frac{d}{2} \geq \sigma_0.$$

Finally,

$$\sigma_2 + [d/p] \leq \sigma_1 + \frac{d}{2} \leq \sigma_0 - 1 + \frac{d}{2},$$

which is bounded above by  $N - 1$  when  $N$  is chosen large enough.  $\square$

## 4. MODULATED ENERGY ESTIMATE

We now use the approximate bubbles analyzed in the previous section in order to establish some information regarding the actual solution  $u_k$  to (2.3). We emphasize that even in the case of a single bubble,  $\tilde{a}_k e^{i\tilde{\phi}_k/\varepsilon}$  must not be expected to approximate  $u_k$  in  $L^2$ , due to phase modulations; see [13]. But even if phase modulations are taken into account, the unboundedness of  $u_{0,k}$  in  $L^2$  is an issue to justify WKB analysis, see Remark 2.3. We follow the strategy of [1, Theorem 4.1], and introduce a modulated energy functional

$$H_k(t) = \frac{1}{2} \|(\varepsilon_k \nabla - i\tilde{V}_k)u_k\|_{L^2}^2 + \int_{\mathbb{R}^d} (F(|u_k|^2) - F(\tilde{\rho}_k) - (|u_k|^2 - \tilde{\rho}_k)f(\tilde{\rho}_k)) dx,$$

where  $\tilde{\rho}_k = |\tilde{a}_k|^2$ ,  $f(y) = y^m$ , and

$$F(y) = \int_0^y f(z) dz = \frac{y^{m+1}}{m+1}.$$

Denote the kinetic part by

$$K_k(t) = \frac{1}{2} \|(\varepsilon_k \nabla - i\tilde{V}_k)u_k\|_{L^2}^2$$

and the potential part by

$$P_k(t) = \int_{\mathbb{R}^d} (F(|u_k|^2) - F(\tilde{\rho}_k) - (|u_k|^2 - \tilde{\rho}_k)f(\tilde{\rho}_k)) dx.$$

We know from [1] that the potential part is bounded from below by

$$P_k(t) \geq c \int_{\mathbb{R}^d} ||u_k|^2 - \tilde{\rho}_k| (|u_k|^{2m} + (\tilde{\rho}_k)^m) dx,$$

for some  $c > 0$  depending only on  $m$ . In particular,  $H_k$  is the sum of two nonnegative terms.

We first detail the case  $s < s_{\text{sob}}$  (with  $s \leq 2$ ), for the sake of clarity. When  $t = 0$ , we get, in view of Section 2.3,

$$K_k(0) = \frac{1}{2} \|\varepsilon_k \nabla u_{0,k}\|_{L^2}^2 \lesssim \varepsilon_k^2 h_k^{2(1-s)} |\log(h_k)|.$$

Under the assumption  $s < s_{\text{sob}}$ ,  $K_k(0) = \mathcal{O}(\varepsilon_k^2)$  as  $k \rightarrow \infty$ . Indeed, we note the algebraic relation

$$\varepsilon_k^2 h_k^{2(1-s)} |\log(h_k)| = |\log h_k|^{2m+1} h_k^{2m(s_c-s)+2(1-s)} = |\log h_k|^{2m+1} h_k^{(2m+2)(s_{\text{sob}}-s)}.$$

As for the initial potential part, we first use the fact that  $P_k$  corresponds to the beginning of a Taylor expansion,

$$P_k = \frac{1}{2} \int_{\mathbb{R}^d} (|u_k|^2 - \tilde{\rho}_k)^2 \int_0^1 f'(\tilde{\rho}_k + \theta(|u_k|^2 - \tilde{\rho}_k)) d\theta dx.$$

Considering this quantity at time  $t = 0$ , and using the fact that the supports of the initial bubbles  $j * \varphi_{\ell,k}$  are pairwise disjoint,

$$\text{supp } j * \varphi_{\ell,k} \cap \text{supp } j * \varphi_{\ell',k} = \emptyset, \quad \forall \ell \neq \ell',$$

we obtain the rough bound

$$0 \leq P_k(0) \lesssim \sum_{\ell > k} \int_{\mathbb{R}^d} |J * \varphi_{\ell,k}|^4 \times \sum_{\ell'} |J * \varphi_{\ell',k}|^{2m-2} \lesssim \sum_{\ell > k} \|J * \varphi_{\ell,k}\|_{L^{2m+2}}^{2m+2}.$$

In view of the embedding  $\dot{H}^{s_{\text{sob}}} \hookrightarrow L^{2m+2}$ , we infer, thanks to Lemma 2.2, and since the map  $z \mapsto M^{z^2} e^{-Mz}$  is integrable on  $[1, \infty)$  and decreasing for  $z \geq z_0 \gg 1$ ,

$$P_k(0) \lesssim \left( \frac{|\log(h_k)|}{|\log(h_{k+1})|} \right)^{2m+2} \left( \frac{h_{k+1}}{h_k} \right)^{(2m+2)s} |\log(h_k)|.$$

Choosing  $M > 1$  sufficiently large, we have in particular  $P_k(0) = \mathcal{O}(\varepsilon_k^2)$ .

**Proposition 4.1** (Modulated energy estimate). *Let  $s < s_{\text{sob}}$  with  $s \leq 2$ . Then for every  $t \in [0, T]$ , where  $T$  is given by Lemma 3.4, there holds*

$$H_k(t) \lesssim \varepsilon_k^2 + h_k^{2(m+1)(s_{\text{sob}}-s)}.$$

*Proof.* We estimate the time derivative of  $H_k$ .

We follow line by line the proof of [1, Theorem 4.1], taking into account the fact that the  $L^2$ -norm of  $u_k$  has the upper bound

$$\|u_k\|_{L^2} = \|u_{0,k}\|_{L^2} \lesssim h_k^{-s},$$

hence it is not necessarily bounded as  $k \rightarrow \infty$ . Similarly, low order Sobolev norms of  $\tilde{V}_k$  may grow to infinity as  $k \rightarrow \infty$ .

Since we only consider weak solutions  $u_k$ , some integrations by part may not make sense. For simplicity, the following proof will hence be formal only, but can be fully justified by working on a sequence  $u_k^{(n)} \in \mathcal{C}(\mathbb{R}, H^2)$  of global strong solutions to the equation

$$i\varepsilon_k \partial_t u_k^{(n)} + \frac{\varepsilon_k^2}{2} \Delta u_k^{(n)} = f_n \left( |u_k^{(n)}|^2 \right) \quad ; \quad u_k^{(n)}|_{t=0} = u_{0,k},$$

$$f_n(y) = \frac{y^m}{1 + (\delta_n y)^m}, \quad \delta_n \rightarrow 0^+.$$

Indeed, as  $n \rightarrow \infty$ , the sequence  $(u_k^{(n)})_n$  will converge to a weak solution to (2.3) with initial data  $u_{0,k}$ . In this case, one should replace  $F$  by  $F_n(y) = \int_0^y f_n(z) dz$  in the formula for the modulated energy  $H_k^{(n)}$ , and  $G(y) = \int_0^y z f'(z) dz$  by  $G_n(y) = \int_0^y z f'_n(z) dz$ .

In order to estimate  $H_k(t)$ , we use Madelung transform and switch to the hydrodynamic variables

$$\rho = |u_k|^2, \quad J = \text{Im}(\varepsilon_k \overline{u_k} \nabla u_k),$$

satisfying the equation

$$\begin{cases} \partial_t \rho + \text{div}(J) = 0 \\ \partial_t J_j + \frac{\varepsilon_k^2}{4} \sum_{p=1}^d \partial_i (4 \text{Re}(\partial_j \overline{u_k} \partial_p u_k) - \partial_{pj} \rho) + \partial_j G(\rho) = 0. \end{cases}$$

As in [1], we write the time derivative of the kinetic energy using the hydrodynamic variables, then proceed by integration by parts. We get the formula

$$\frac{d}{dt}H_k = -\frac{1}{4}I - I' - \int (G(\rho) - G(\tilde{\rho}_k) - (\rho - \tilde{\rho}_k)G'(\tilde{\rho}_k) \operatorname{div} \tilde{V}_k),$$

where

$$I = \varepsilon_k^2 \int \nabla \left( \operatorname{div} \tilde{V}_k \right) \cdot \nabla |u_k|^2,$$

$$I' = \operatorname{Re} \sum_{p,j} \int \partial_j (\tilde{V}_k)_p (\varepsilon_k \partial_j u_k - i(\tilde{V}_k)_j u_k) \overline{(\varepsilon_k \partial_p u_k - i(\tilde{V}_k)_p u_k)}.$$

We note that  $\|\nabla \tilde{V}_k\|_{L^\infty}$  is uniformly bounded, hence  $I' = \mathcal{O}(K_k)$ .

The only new difficulty, compared to [1], is to show that  $I = \mathcal{O}(K_k + \varepsilon_k^2)$ . We have

$$I = \varepsilon_k \int \nabla \left( \operatorname{div} \tilde{V}_k \right) \cdot \left( \overline{u_k} (\varepsilon_k \nabla - i\tilde{V}_k) u_k + u_k \overline{(\varepsilon_k \nabla - i\tilde{V}_k) u_k} \right).$$

We note that if we proceed like in [1], we invoke Cauchy-Schwarz then Young inequalities to get the upper bound

$$|I| \leq \|(\varepsilon_k \nabla - i\tilde{V}_k) u_k\|_{L^2}^2 + \varepsilon_k^2 \|u_k\|_{L^2}^2,$$

which may go to infinity as  $k \rightarrow \infty$  since we only know that  $\|u_k\|_{L^2} \lesssim h_k^{-s}$ .

Instead, we decompose

$$|I| \leq \varepsilon_k \int \left| \nabla \left( \operatorname{div} \tilde{V}_k \right) \right| \times |u_k| \times \left| (\varepsilon_k \nabla - i\tilde{V}_k) u_k \right| = II + III$$

where

$$II = \varepsilon_k \int \left| \nabla \left( \operatorname{div} \tilde{V}_k \right) \right| \times \left( |u_k| - \sqrt{\tilde{\rho}_k} \right) \times \left| (\varepsilon_k \nabla - i\tilde{V}_k) u_k \right|,$$

$$III = \varepsilon_k \int \left| \nabla \left( \operatorname{div} \tilde{V}_k \right) \right| \times \sqrt{\tilde{\rho}_k} \times \left| (\varepsilon_k \nabla - i\tilde{V}_k) u_k \right|.$$

Then using Hölder inequality,

$$|II| \leq \varepsilon_k \left\| \nabla \operatorname{div} \tilde{V}_k \right\|_{L^{2+\frac{2}{m}}} \left\| |u_k| - \sqrt{\tilde{\rho}_k} \right\|_{L^{2m+2}} \|(\varepsilon_k \nabla - i\tilde{V}_k) u_k\|_{L^2}.$$

We know thanks to Lemma 3.4 and Sobolev embedding, that for  $N$  sufficiently large,

$$\left\| \nabla \operatorname{div} \tilde{V}_k \right\|_{L^{2+\frac{2}{m}}} \lesssim \left\| \nabla \operatorname{div} \tilde{V}_k \right\|_{H^N} \lesssim 1 + h_k^{3+m(s_c-s)-\frac{d}{2}}.$$

Rewriting

$$3 + m(s_c - s) - \frac{d}{2} = (m - 1) \left( \frac{d}{2} - s \right) + 2 - s,$$

we see that this power is nonnegative as soon as  $s \leq 2$ . Moreover, the last two factors are estimated respectively by

$$\begin{aligned} \left\| |u_k| - \sqrt{\tilde{\rho}_k} \right\|_{L^{2m+2}}^{2m+2} &= \int \left| |u_k| - \sqrt{\tilde{\rho}_k} \right|^{2m+2} \\ &\lesssim \int \left| |u_k|^2 - \tilde{\rho}_k \right|^2 (|u_k|^{2m} + (\tilde{\rho}_k)^m) \lesssim P_k, \end{aligned}$$

and

$$\|(\varepsilon_k \nabla - i\tilde{V}_k)u_k\|_{L^2}^2 = 2K_k.$$

Therefore,

$$|II| \lesssim \varepsilon_k P_k^{\frac{1}{2m+2}} \sqrt{K_k} \lesssim K_k + \varepsilon_k^2 P_k^{\frac{1}{m+1}} \lesssim K_k + P_k + \varepsilon_k^{\frac{2m+1}{m}},$$

where we have used Young inequality twice. Finally, using a similar strategy, we obtain the estimate

$$|III| \leq \varepsilon_k \left\| \nabla \operatorname{div} \tilde{V}_k \right\|_{L^2} \left\| \sqrt{\tilde{\rho}_k} \right\|_{L^\infty} \|(\varepsilon_k \nabla - i\tilde{V}_k)u_k\|_{L^2}.$$

In view of Lemma 3.1, (3.7), Lemma 3.4, and Sobolev embedding, we have

$$\|\tilde{\rho}_k\|_{L^\infty([0,T];L^\infty)} \lesssim 1.$$

To estimate  $\nabla \operatorname{div} \tilde{V}_k$ , that is  $\nabla^3 \tilde{\phi}_k$ , in  $L^2$ , we invoke Lemma 3.4 like above, to have, since  $s \leq 2$ ,

$$\left\| \nabla \operatorname{div} \tilde{V}_k \right\|_{L^\infty([0,T];L^2)} \lesssim 1.$$

Therefore,

$$|III| \lesssim \varepsilon_k \sqrt{K_k} \lesssim \varepsilon_k^2 + K_k.$$

We then conclude as in the proof of [1, Theorem 4.1] that

$$\frac{dH_k}{dt} \lesssim H_k + \varepsilon_k^2,$$

and the proposition follows from a Gronwall argument.  $\square$

## 5. RENORMALIZED MODULATED ENERGY ESTIMATE

When  $s \geq s_{\text{sob}}$ , the approach from Proposition 4.1 is not satisfying since the modulated energy functional is large even at time  $t = 0$ , due to the kinetic part. It turns out that this initial value is the main responsible for the failure of the approach: we renormalize the modulated energy functional by removing the initial bubbles  $\ell < k$  (those which have large lower-order Sobolev norms). More precisely, we introduce

$$\tilde{H}_k(t) = \tilde{K}_k(t) + P_k(t),$$

where we denote the renormalized kinetic part by

$$\tilde{K}_k(t) = \frac{1}{2} \|(\varepsilon_k \nabla - i\tilde{V}_k)u_k - \varepsilon_k \nabla \varphi\|_{L^2}^2, \quad \varphi = \sum_{\ell < k} J^* \varphi_{\ell,k},$$

and we leave the potential part unchanged. With this choice, at  $t = 0$ ,

$$\tilde{H}_k(0) \lesssim \varepsilon_k^2.$$

Note that this strategy somehow meets the approach followed in the proof of [12, Proposition 2.6], as noted in Remark 3.3.

**Proposition 5.1** (Renormalized modulated energy). *Let  $0 < s < s_c$ , with  $s \leq 2$ . For every  $t \in [0, T]$ , there holds*

$$\tilde{H}_k(t) \lesssim \varepsilon_k^2.$$

The rest of this section is devoted to the proof of Proposition 5.1. To emphasize the new terms compared to Section 4, we develop

$$\tilde{K}_k(t) = K_k(t) - L_k(t) + \|\varepsilon_k \nabla \varphi\|_{L^2}^2,$$

$$L_k(t) = 2 \operatorname{Re} \langle (\varepsilon_k \nabla - i \tilde{V}_k) u_k, \varepsilon_k \nabla \varphi \rangle,$$

then we evaluate the time derivative of the two components  $K_k(t)$  and  $L_k(t)$  separately ( $\nabla \varphi$  is obviously time-independent).

**5.1. Localized Sobolev norms of the WKB ansatz.** Let  $\chi_k \in C_c^\infty(\mathbb{R}^d)$  such that  $\chi_k$  localizes in space around the  $k$ -th bubble  $x \approx \frac{x_k}{h_k}$ :

$$\begin{aligned} \chi_k &\equiv 1 && \text{on } \operatorname{supp}(j * \varphi_{k,k}) = \operatorname{supp}(j * \alpha_k), \\ \chi_k &\equiv 0 && \text{on } \operatorname{supp}(j * \varphi_{\ell,k}) \quad \text{for } \ell \neq k. \end{aligned}$$

On the support of  $(1 - \chi_k)$ , we will use the fact that the Sobolev norms of  $(\tilde{V}_k, \tilde{A}_k)$  are proportional to the restriction of the Sobolev norms of its initial data  $(0, (\tilde{\rho}_k)^m)$  to the support of  $(1 - \chi_k)$ , hence the higher order Sobolev norms are decaying in  $k$ . More precisely we establish the following lemma.

**Lemma 5.2** (Localized Sobolev norms of the approximate phase). *For every  $n \geq 0$ , there holds*

$$\|(1 - \chi_k) |\nabla|^n \tilde{V}_k\|_{L^\infty} \lesssim \varepsilon_k^2 h_k^{3+n}.$$

*Proof.* We note that at time  $t = 0$ , we have  $|\nabla|^n \tilde{V}_k|_{t=0} = 0$ . Hence we use the equation (3.9) satisfied by  $\tilde{V}_k$ :

$$\frac{d}{dt} |\nabla|^n \tilde{V}_k = -|\nabla|^n \left( \tilde{V}_k \cdot \nabla \tilde{V}_k - \nabla(|\tilde{A}_k|^2) \right).$$

Then we note that on the support of  $(1 - \chi_k)$ , the Sobolev norms of  $|\tilde{A}_k|^2$  are proportional to the Sobolev norms of the restriction of its initial data  $(\tilde{\rho}_k)^m$  according to Lemma 3.4. Therefore the equality right below Lemma 3.4 taking into account the localization implies the estimate

$$\|(1 - \chi_k) |\nabla|^n \nabla(|\tilde{A}_k|^2)\|_{L^\infty} \lesssim h_k^{1+n+2m(\frac{d}{2}-s)} = h_k^{3+n} \varepsilon_k^2.$$

Let us now treat the convective part. Similarly, this term vanishes at time  $t = 0$  hence we compute one more time derivative:

$$\begin{aligned} \frac{d}{dt} |\nabla|^n \left( \tilde{V}_k \cdot \nabla \tilde{V}_k \right) &= -|\nabla|^n \left( \left( \tilde{V}_k \cdot \nabla \tilde{V}_k - \nabla(|\tilde{A}_k|^2) \right) \cdot \nabla \tilde{V}_k \right) \\ &\quad - |\nabla|^n \left( \tilde{V}_k \cdot \nabla \left( \tilde{V}_k \cdot \nabla \tilde{V}_k - \nabla(|\tilde{A}_k|^2) \right) \right). \end{aligned}$$

The terms involving  $\tilde{A}_k$  are small thanks to the same argument as before. Regarding the terms involving only  $\tilde{V}_k$ , the terms are of the form

$$\| |\nabla|^n ((\tilde{V}_k \cdot \nabla \tilde{V}_k) \cdot \nabla \tilde{V}_k) \|_{L^\infty} \lesssim h_k^{2+n} h_k^{3m(\frac{d}{2}-s)} \lesssim h_k^{5+n} \varepsilon_k^3,$$

hence the lemma after integration in time.  $\square$

**5.2. Linear part.** We compute

$$\begin{aligned} \frac{d}{dt} L_k(t) &= 2 \operatorname{Re} \langle (\varepsilon_k \nabla - i \tilde{V}_k) \partial_t u_k, \varepsilon_k \nabla \varphi \rangle + 2 \operatorname{Re} \langle -i \partial_t \tilde{V}_k u_k, \varepsilon_k \nabla \varphi \rangle \\ &= - \operatorname{Re} \langle i \varepsilon_k \Delta u_k, (\varepsilon_k \nabla - i \tilde{V}_k) \varepsilon_k \nabla \varphi \rangle + 2 \operatorname{Re} \langle i |u_k|^{2m} u_k, (\varepsilon_k \nabla - i \tilde{V}_k) \cdot \nabla \varphi \rangle \\ &\quad - 2 \operatorname{Re} \langle i \partial_t \tilde{V}_k u_k, \varepsilon_k \nabla \varphi \rangle. \end{aligned}$$

In the subsequent estimates, we leave out the dependence of  $\varepsilon_k$  upon  $\log(h_k)$  (see (2.2)) to lighten the notations, since, as pointed out before, the logarithmic correction is irrelevant when we deal with open algebraic conditions.

- First, we note that

$$\left| \langle i \varepsilon_k \Delta u_k, \varepsilon_k^2 \Delta \varphi \rangle \right| \leq \| \varepsilon_k \nabla u_k \|_{L^2} \| \varepsilon_k^2 \nabla \Delta \varphi \|_{L^2} \lesssim \varepsilon_k^3 h_k^{4-2s},$$

where we have used (2.7) to estimate  $\varepsilon_k \nabla u_k$ , and the first part of Lemma 2.2 with  $s' = 3$  to estimate  $\nabla \Delta \varphi$ .

- We now estimate  $\langle i |u_k|^{2m} u_k, \varepsilon_k \Delta \varphi \rangle$ . First, we decompose

$$\langle i |u_k|^{2m} u_k, \varepsilon_k \Delta \varphi \rangle = \langle i (|u_k|^{2m} - |\tilde{a}_k|^{2m}) u_k, \varepsilon_k \Delta \varphi \rangle + \langle i |\tilde{a}_k|^{2m} u_k, \varepsilon_k \Delta \varphi \rangle.$$

The first term on the right hand side has the upper bound

$$\left| \langle i (|u_k|^{2m} - |\tilde{a}_k|^{2m}) u_k, \varepsilon_k \Delta \varphi \rangle \right| \lesssim \| |u_k|^{2m} - |\tilde{a}_k|^{2m} \|_{L^{\frac{2m+2}{2m}}} \| u_k \|_{L^{2m+2}} \| \varepsilon_k \Delta \varphi \|_{L^{2m+2}}.$$

This implies, in view of (2.7), the embedding  $\dot{H}^{s_{\text{sob}}} \hookrightarrow L^{2m+2}$ , Lemma 2.2, and Young inequality,

$$\begin{aligned} \left| \langle i (|u_k|^{2m} - |\tilde{a}_k|^{2m}) u_k, \varepsilon_k \Delta \varphi \rangle \right| &\lesssim P_k^{\frac{2m}{2m+2}} h_k^{\frac{d}{2}-s-\frac{d}{2m+2}} \varepsilon_k h_k^{2+\frac{d}{2}-s-\frac{d}{2m+2}} \\ &\lesssim P_k + \varepsilon_k^{m+1} h_k^{2(m+1)+2(m+1)(\frac{d}{2}-s)-d} \\ &\lesssim P_k + \varepsilon_k^{m+1} h_k^{2(m+1)+2m(\frac{d}{2}-s)-2s}. \end{aligned}$$



We note that  $2m(\frac{d}{2} - s) - 2s = 2 + 2m(s_c - s)$ , so  $h_k^{2m(\frac{d}{2}-s)-2s} = \varepsilon_k^2 h_k^2$ . Let us now investigate the second term  $\langle i|\tilde{a}_k|^{2m}u_k, \varepsilon_k \Delta \varphi \rangle$ :

$$|\langle i|\tilde{a}_k|^{2m}u_k, \varepsilon_k \Delta \varphi \rangle| \lesssim \varepsilon_k \|\tilde{a}_k\|_{L^\infty}^{2m} \|u_k\|_{L^2} \|\Delta \varphi\|_{L^2} \lesssim \varepsilon_k h_k^{2m(\frac{d}{2}-s)+2-2s} = \varepsilon_k^3 h_k^{4-2s}.$$

We conclude that when  $t \lesssim 1$ ,

$$|\langle i|u_k|^{2m}u_k, \varepsilon_k \Delta \varphi \rangle| \lesssim P_k + \varepsilon_k^3 h_k^{4-2s}.$$

- Then we note that

$$\left| \langle \varepsilon_k \Delta u_k, \tilde{V}_k \cdot \varepsilon_k \nabla \varphi \rangle \right| = \varepsilon_k^2 \left| \langle u_k, \Delta(\tilde{V}_k \cdot \nabla \varphi) \rangle \right|.$$

As a consequence, since  $\nabla \varphi = (1 - \chi_k)\nabla \varphi$ , using the conservation of  $L^2$  norm and Lemma 5.2,

$$\left| \langle \varepsilon_k \Delta u_k, \tilde{V}_k \cdot \varepsilon_k \nabla \varphi \rangle \right| \lesssim \varepsilon_k^2 h_k^{3-2s} \varepsilon_k^2 h_k^3.$$

- Moreover, (2.7) and Lemma 5.2 yield

$$\begin{aligned} \left| \langle i|u_k|^{2m}u_k, i\tilde{V}_k \cdot \nabla \varphi \rangle \right| &\lesssim \|u_k\|_{L^{2m+2}}^{2m+1} \|(1 - \chi_k)\tilde{V}_k\|_{L^\infty} \|\nabla \varphi\|_{L^{2m+2}} \\ &\lesssim \varepsilon_k^2 h_k^{2-2s+1} \varepsilon_k^2 h_k^3. \end{aligned}$$

- Finally, we estimate  $\langle i\partial_t \tilde{V}_k u_k, \varepsilon_k \nabla \varphi \rangle$  on the support of  $\varphi$ .

Using the equation (3.9) satisfied by  $\tilde{V}_k$  and Lemma 5.2, we have the estimate

$$\|\partial_t \tilde{V}_k\|_{L^\infty} \lesssim \varepsilon_k^4 h_k^7,$$

and so

$$\left| \langle i\partial_t \tilde{V}_k u_k, \varepsilon_k \nabla \varphi \rangle \right| \lesssim \varepsilon_k^5 h_k^{8-2s}.$$

- In conclusion,

$$\left| \frac{d}{dt} L_k(t) \right| \lesssim P_k(t) + \varepsilon_k^3 h_k^{4-2s}.$$

**5.3. Nonlinear part.** We now also replace  $K_k$  by  $\tilde{K}_k$  in the upper bounds for estimating  $\frac{dK_k}{dt}$  that appear in the proof of [1, Theorem 4.1].

• First, we treat the following problematic term evidenced in the proof of Proposition 4.1,

$$I = \varepsilon_k^2 \int \nabla \left( \operatorname{div} \tilde{V}_k \right) \cdot \nabla (|u_k|^2).$$

The same argument as in Section 4 would lead to the inequalities

$$\begin{aligned} \left| \varepsilon_k \int \nabla \left( \operatorname{div} \tilde{V}_k \right) \cdot \left( \bar{u}_k (\varepsilon_k \nabla u_k - i\tilde{V}_k u_k - \varepsilon_k \nabla \varphi) \right) \right| \\ \lesssim \varepsilon_k (1 + h_k^{2-s}) \left( P_k^{\frac{1}{2m+2}} + 1 \right) \sqrt{\tilde{K}_k}, \\ \left| \varepsilon_k^2 \int \nabla \left( \operatorname{div} \tilde{V}_k \right) \cdot (\bar{u}_k \nabla \varphi) \right| \lesssim \varepsilon_k^2 h_k^{3-2s} \left( P_k^{\frac{1}{2m+2}} + 1 \right). \end{aligned}$$

However, since we want to tackle exponents  $s$  that may be larger than  $\frac{3}{2}$ , we refine slightly the argument in order to improve the estimate. Indeed, as we wish  $s$  to be arbitrarily close to  $s_c$ , the power of  $\varepsilon_k$  is essentially useless, and we need the remaining power of  $h_k$  to be nonnegative.

Lemma 5.2 taken with two derivatives leads to

$$\|(1 - \chi_k)\nabla \operatorname{div} \tilde{V}_k\|_{L^\infty} \lesssim \varepsilon_k^2 h_k^5,$$

and applying this estimate in the formula for

$$I = \varepsilon_k \int \nabla \left( \operatorname{div} \tilde{V}_k \right) \cdot \left( \overline{u_k}(\varepsilon_k \nabla - i\tilde{V}_k)u_k + u_k \overline{(\varepsilon_k \nabla - i\tilde{V}_k)u_k} \right).$$

we get

$$|I| \lesssim \tilde{H}_k + \varepsilon_k^2 h_k^{4-2s}.$$

• We also need to estimate the second problematic term from the proof of Proposition 5.1

$$I' := -\operatorname{Re} \sum_{i,j} \int \partial_j(\tilde{V}_k)_i (\varepsilon_k \partial_j u_k - i(\tilde{V}_k)_j u_k) \overline{(\varepsilon_k \partial_i u_k - i(\tilde{V}_k)_i u_k)}.$$

We decompose again  $(\varepsilon_k \nabla - i\tilde{V}_k)u_k = (\varepsilon_k \nabla - i\tilde{V}_k)u_k - \varepsilon_k \nabla \varphi + \varepsilon_k \nabla \varphi$  to get

$$\begin{aligned} |I'| \lesssim \tilde{K}_k + 2 \sum_{i,j} \int |\partial_j(\tilde{V}_k)_i| |\varepsilon_k \partial_j \varphi| |\varepsilon_k \partial_i u_k - i(\tilde{V}_k)_i u_k| \\ + \sum_{i,j} \int |\partial_j(\tilde{V}_k)_i| |\varepsilon_k \partial_j \varphi| |\varepsilon_k \partial_i \varphi|. \end{aligned}$$

The second term on the right hand side can be estimated from the first and third terms on the right hand side. Finally, Lemma 5.2 implies

$$\|(1 - \chi_k)\partial_j \tilde{V}_k\|_{L^\infty} \lesssim \varepsilon_k^2 h_k^4,$$

so that, since  $(1 - \chi_k) = 1$  on the support of  $\varphi$ ,

$$\int |\partial_j(\tilde{V}_k)_i| |\varepsilon_k \partial_j \varphi| |\varepsilon_k \partial_i \varphi| \lesssim \varepsilon_k^2 h_k^{6-2s}.$$

This leads to

$$|I'| \lesssim \tilde{K}_k + \varepsilon_k^2 h_k^{6-2s}.$$

• In conclusion, we get

$$\left| \frac{d\tilde{H}_k}{dt} \right| \lesssim \tilde{H}_k + \varepsilon_k^2 h_k^{4-2s},$$

hence Proposition 5.1 by integration.

## 6. LOCALIZED ESTIMATES AND CONCLUSION

**6.1. Localized mass estimate.** Like in Section 5, let  $\chi_k \in C_c^\infty(\mathbb{R}^d)$  such that  $\chi_k$  localizes in space around the  $k$ -th bubble  $x \approx \frac{x_k}{h_k}$ :

$$\begin{aligned} \chi_k &\equiv 1 && \text{on } \text{supp}(j * \varphi_{k,k}) = \text{supp}(j * \alpha_k), \\ \chi_k &\equiv 0 && \text{on } \text{supp}(j * \varphi_{\ell,k}) \text{ for } \ell \neq k. \end{aligned}$$

More precisely, we choose a cutoff function  $\chi$  independent of  $k$ , and a scaling parameter  $R_k \gtrsim 1$  (which will be crucial in the alternative argument presented in appendix), and set

$$\chi_k(x) = \chi\left(\frac{x - x_k}{R_k}\right).$$

We recall that in view of Lemma 3.1, for  $\ell \leq k$  and  $t \in [0, T]$ ,

$$\text{supp } \nabla \phi_{\ell,k}(t, \cdot) \cup \text{supp } \rho_{\ell,k}(t, \cdot) \subset \text{supp } j * \varphi_{\ell,k}.$$

We consider the mass localized near the bubble living at scale  $k$ ,

$$M_k(t) := \|\chi_k u_k(t)\|_{L^2}^2,$$

and show that is bounded.

**Lemma 6.1** (Localized mass estimate). *There exists  $C > 0$  such that for every  $t \in [0, T]$  and  $k \geq 1$ ,*

$$M_k(t) \leq CM_k(0) \lesssim 1.$$

*Proof.* At  $t = 0$ , we have

$$M_k(0) = \|j * \alpha_k\|_{L^2} = \|j * \alpha\|_{L^2}.$$

Let us now estimate the time derivative of the localized mass. Using the equation satisfied by  $u_k$ , (2.3), we get

$$\frac{dM_k}{dt} = 2 \operatorname{Re} \int \chi_k^2 \bar{u}_k \partial_t u_k = \varepsilon_k \operatorname{Re} \int \chi_k^2 \bar{u}_k i \Delta u_k = 2\varepsilon_k \operatorname{Im} \int \chi_k \bar{u}_k \nabla \chi_k \cdot \nabla u_k.$$

Given that  $\nabla \chi_k = 0$  on the support of  $\tilde{\phi}_k$  and of  $\varphi$ , we have

$$\frac{dM_k}{dt} = 2 \operatorname{Im} \int \chi_k \bar{u}_k \nabla \chi_k \cdot \left( (\varepsilon_k \nabla u_k - i \nabla \tilde{\phi}_k) u_k - \varepsilon_k \nabla \varphi \right).$$

Cauchy-Schwarz and Young inequalities yield

$$\frac{dM_k}{dt} \lesssim \|\nabla \chi_k\|_{L^\infty} \left( \tilde{H}_k + M_k \right),$$

where  $\tilde{H}_k$  is small, from Proposition 5.1. Gronwall lemma implies that for  $t \in [0, T]$ ,

$$M_k(t) \lesssim M_k(0) + o_k(1) \lesssim M_k(0). \quad \square$$

## 6.2. Lower and upper bounds on the $\dot{H}^1$ norm.

**Lemma 6.2** (Bounds on the local energy). *There exist  $C > 0$  and  $\tau \in [0, T]$  such that for every  $k \geq 1$ ,*

$$\frac{1}{C} \leq \|(\varepsilon_k \nabla)(\chi_k u_k)(\tau)\|_{L^2} \leq C.$$

*Proof.* We develop

$$(\varepsilon_k \nabla)(\chi_k u_k) = \varepsilon_k u_k \nabla \chi_k + \chi_k \varepsilon_k \nabla u_k.$$

Let  $\tilde{\chi} \in C_c^\infty$  such that  $\tilde{\chi} \geq |\nabla \chi|$  on  $\text{supp}(\chi)$ , and such that

$$\tilde{\chi}_k = \tilde{\chi} \left( \frac{x - x_k}{R_k} \right)$$

also satisfies

$$\begin{aligned} \tilde{\chi}_k &\equiv 1 && \text{on } \text{supp}(J * \varphi_{k,k}), \\ \tilde{\chi}_k &\equiv 0 && \text{on } \text{supp}(J * \varphi_{\ell,k}), \quad \ell \neq k. \end{aligned}$$

Then Lemma 6.1 applied with  $\tilde{\chi}_k$  instead of  $\chi_k$  yields

$$\|\nabla \chi_k u_k(t)\|_{L^2} \lesssim \|\tilde{\chi}_k u_k(t)\|_{L^2} \lesssim 1.$$

Moreover, since  $\varphi$  and  $\chi$  have disjoint supports, we have the inequality

$$\|\chi_k \varepsilon_k \nabla u_k\|_{L^2} \gtrsim \|\chi_k \tilde{V}_k u_k\|_{L^2} - \|\chi_k ((\varepsilon_k \nabla - i \tilde{V}_k) u_k - \varepsilon_k \nabla \varphi)\|_{L^2}.$$

Now we argue like in [1, Lemma 5.3]: in view of the coupling in (3.2), there exists  $\tau \in [0, T]$  such that

$$\|a(\tau) \nabla \phi(\tau)\|_{L^2} \gtrsim 1,$$

hence, for every  $k$ ,

$$\|\chi_k \tilde{V}_k(\tau) \tilde{a}_k(\tau)\|_{L^2} = \|a_k(\tau) \nabla \phi_k(\tau)\|_{L^2} \gtrsim 1.$$

Using that  $|\tilde{a}_k|^2 - |u_k|^2$  is small in  $L^{m+1}$  thanks to the renormalized modulated energy estimate from Proposition 5.1, we deduce that

$$\|\chi_k \tilde{V}_k u_k\|_{L^2} \gtrsim 1.$$

Using Proposition 5.1 to estimate the term  $\|\chi_k ((\varepsilon_k \nabla - i \tilde{V}_k) u_k - \varepsilon_k \nabla \varphi)\|_{L^2}$  (which is controlled by the renormalized kinetic term), we deduce that

$$\|\chi_k \varepsilon_k \nabla u_k(\tau)\|_{L^2} \gtrsim 1.$$

Note that there also holds

$$\|\chi_k \tilde{V}_k(t) \tilde{a}_k(t)\|_{L^2} \lesssim 1, \quad \forall t \in [0, T],$$

hence we also know that there is also an upper bound with the same order:

$$\|\chi_k \varepsilon_k \nabla u_k(t)\|_{L^2} \lesssim 1, \quad \forall t \in [0, T],$$

hence the lemma.  $\square$

**6.3. Higher-order Sobolev norms.** In this section, we fix  $0 < \sigma < 2$ , and prove that the homogeneous Sobolev norm  $\dot{H}^\sigma$  of the solution  $u_k$  at time  $\tau$ , provided by Lemma 6.2, grows like  $\varepsilon_k^{-\sigma}$  as  $k \rightarrow +\infty$ . First, in view of Lemmas 6.1 and 6.2, we have, by interpolation, for  $\sigma > 1$ ,

$$\begin{aligned} 1 &\lesssim \|(\varepsilon_k \nabla)(\chi_k u_k(\tau))\|_{L^2} \leq \|\chi_k u_k(\tau)\|_{L^2}^{1-1/\sigma} \| |\varepsilon_k \nabla|^\sigma (\chi_k u_k(\tau)) \|_{L^2}^{1/\sigma} \\ &\lesssim \| |\varepsilon_k \nabla|^\sigma (\chi_k u_k(\tau)) \|_{L^2}^{1/\sigma}. \end{aligned}$$

For the case  $0 < \sigma < 1$ , we invoke the following result:

**Lemma 6.3** (Lemma 5.1 from [1]). *There exists a constant  $K$  such that, for all  $\varepsilon \in ]0, 1]$ , for all  $\sigma \in [0, 1]$ , for all  $u \in H^1(\mathbb{R}^n)$  and for all  $v \in W^{1,\infty}(\mathbb{R}^n)$ ,*

$$\| |v|^\sigma u \|_{L^2} \leq \| |\varepsilon D_x|^\sigma u \|_{L^2} + \| (\varepsilon \nabla - iv) u \|_{L^2}^\sigma \| u \|_{L^2}^{1-\sigma} + \varepsilon^{\sigma/2} K (1 + \|\nabla v\|_{L^\infty}) \| u \|_{L^2}.$$

Applying this lemma to  $u = \chi_k u_k$ ,  $v = \nabla \phi_k$ , and noticing that  $\chi_k \nabla \phi_k \equiv 0$  so we may invoke Proposition 5.1, we infer, thanks to Lemma 6.1:

$$(6.1) \quad \| |\varepsilon_k \nabla|^\sigma (\chi_k u_k(\tau)) \|_{L^2} \gtrsim 1, \quad \forall \sigma > 0.$$

**Proposition 6.4** (Norm inflation). *Let  $0 < \sigma \leq 2$ , then, with  $\tau \in [0, T]$  as in Lemma 6.2,*

$$\| |\varepsilon_k \nabla|^\sigma u_k(\tau) \|_{L^2} \gtrsim 1.$$

Roughly speaking, the above result consists in getting rid of the cutoff function in (6.1). In the case  $\sigma = 2$ , this is direct from Leibniz formula:

$$\varepsilon_k^2 \Delta (\chi_k u_k) = \varepsilon_k^2 \chi_k \Delta u_k + 2\varepsilon_k^2 \nabla \chi_k \cdot \nabla u_k + \varepsilon_k^2 u_k \Delta \chi_k.$$

The  $L^2$ -norm of the second term is  $\mathcal{O}(\varepsilon_k)$  from Lemma 6.2, and the last term is  $\mathcal{O}(\varepsilon_k^2)$  from Lemma 6.1, hence, in view of (6.1),

$$\| \varepsilon_k^2 \Delta u_k(\tau) \|_{L^2} \geq \| \varepsilon_k^2 \chi_k \Delta u_k(\tau) \|_{L^2} + \mathcal{O}(\varepsilon_k) \gtrsim 1.$$

To prove Proposition 6.4 in the case  $0 < \sigma < 2$ , we first recall a characterization of the homogeneous Sobolev norms, based on the seminal work [5], which then makes it possible to easily extend the above Leibniz formula to the case of fractional derivative.

**Lemma 6.5.** *Let  $\sigma \in (0, 2)$ ,  $\sigma < d/2$ . The following equivalence holds:*

$$\| u \|_{\dot{H}^\sigma}^2 \approx \iint_{\mathbb{R}^{2d}} |u(x+y) + u(x-y) - 2u(x)|^2 \frac{dx dy}{|y|^{d+2\sigma}}.$$

*Proof.* From Plancherel equality in  $x$ , the quantity on the right hand side is equal to

$$4 \iint_{\mathbb{R}^{2d}} |\cos(y \cdot \xi) - 1|^2 |\hat{u}(\xi)|^2 \frac{d\xi dy}{|y|^{d+2\sigma}}.$$

By an homogeneous change of variable and a rotation, the integral in  $y$  is equal to

$$\begin{aligned} \int_{\mathbb{R}^d} |\cos(y \cdot \xi) - 1|^2 \frac{dy}{|y|^{d+2\sigma}} &= |\xi|^{2\sigma} \int_{\mathbb{R}^d} \left| \cos \left( z \cdot \frac{\xi}{|\xi|} \right) - 1 \right|^2 \frac{dz}{|z|^{d+2\sigma}} \\ &= |\xi|^{2\sigma} \int_{\mathbb{R}^d} |\cos(z_1) - 1|^2 \frac{dz}{|z|^{d+2\sigma}}. \end{aligned}$$

This quantity is finite as soon as  $\sigma \in (0, 2)$ .  $\square$

Note that for  $\delta > 0$ , the integral analyzed in the proof of the lemma, when restricted to the region  $\{|y| > \delta\}$ , is controlled by

$$\int_{|y|>\delta} |\cos(y \cdot \xi) - 1|^2 \frac{dy}{|y|^{d+2\sigma}} \leq 4 \int_{|y|>\delta} \frac{dy}{|y|^{d+2\sigma}} \lesssim \delta^{-2\sigma},$$

and so

$$\iint_{|y|>\delta} |u(x+y) + u(x-y) - 2u(x)|^2 \frac{dx dy}{|y|^{d+2\sigma}} \lesssim \delta^{-2\sigma} \|u\|_{L^2}^2.$$

We apply these properties to the function  $\chi_k u_k$ : for  $\delta > 0$  to be fixed later, we have

$$\begin{aligned} \varepsilon_k^{2\sigma} \|\chi_k u_k\|_{\dot{H}^\sigma}^2 &\lesssim \left(\frac{\varepsilon_k}{\delta}\right)^{2\sigma} \|\chi_k u_k\|_{L^2}^2 \\ &+ \varepsilon_k^{2\sigma} \iint_{|y|<\delta} |(\chi_k u_k)(x+y) + (\chi_k u_k)(x-y) - 2(\chi_k u_k)(x)|^2 \frac{dx dy}{|y|^{d+2\sigma}}. \end{aligned}$$

We leave out the index  $k$  in order to lighten notations. For the last integral, we use a discrete form of Leibniz formula:

$$\begin{aligned} (\chi u)(x+y) + (\chi u)(x-y) - 2(\chi u)(x) &= \\ \chi(x) (u(x+y) + u(x-y) - 2u(x)) &+ \\ + (\chi(x+y) - \chi(x)) (u(x+y) - u(x)) &+ \\ + (\chi(x) - \chi(x-y)) (u(x) - u(x-y)) &+ \\ + u(x) (\chi(x+y) + \chi(x-y) - 2\chi(x)). & \end{aligned}$$

The integral corresponding to the first term on the right hand side is obviously estimated by

$$\|\chi\|_{L^\infty}^2 \|u\|_{\dot{H}^\sigma}^2.$$

The second and third terms are similar, and the corresponding integrals are actually equal, through the change of variable  $y \mapsto -y$ . We choose  $\delta > 0$  (independent of  $k$ ) such that

$$\forall \ell \neq k, \quad (\text{supp } \chi + B(0, 3\delta)) \cap \text{supp } a_{\ell,k} = \emptyset,$$

and we pick another cut-off function  $\chi_1 \in C_0^\infty(\mathbb{R}^d; [0, 1])$  such that  $\chi_1 \equiv 1$  on  $\text{supp } \chi + B(0, \delta)$ , and

$$\text{supp } \chi_1 \subset \text{supp } \chi + B(0, 3\delta).$$

We thus have

$$\begin{aligned} & (\chi(x+y) - \chi(x))(u(x+y) - u(x)) \\ &= (\chi(x+y) - \chi(x))((\chi_1 u)(x+y) - (\chi_1 u)(x)). \end{aligned}$$

We infer

$$\begin{aligned} & \iint_{|y|<\delta} |(\chi(x+y) - \chi(x))(u(x+y) - u(x))|^2 \frac{dx dy}{|y|^{d+2\sigma}} \\ & \lesssim \|\nabla \chi\|_{L^\infty}^2 \iint_{|y|<\delta} |(\chi_1 u)(x+y) - (\chi_1 u)(x)|^2 \frac{dx dy}{|y|^{d+2\sigma-2}} \\ & \lesssim \|\nabla \chi\|_{L^\infty}^2 \|\chi_1 u\|_{\dot{H}^{\max(0, \sigma-1)}}^2, \end{aligned}$$

where we have used the more standard characterization of the  $\dot{H}^{\sigma-1}$ -norm (note that  $\sigma-1 < 1$ ) analogous to the one given in Lemma 6.5.

Finally, the last integral is equal to

$$\iint_{|y|<\delta} |(\chi_1 u)(x)|^2 |\chi(x+y) + \chi(x-y) - 2\chi(x)|^2 \frac{dx dy}{|y|^{d+2\sigma}} \lesssim \|\chi\|_{W^{2,\infty}}^2 \|\chi_1 u\|_{L^2}^2,$$

since, for  $\delta \leq 1$ ,

$$\int_{|y|<\delta} \frac{dy}{|y|^{d+2\sigma}} \lesssim \int_0^1 \frac{r^{d-1}}{r^{d-2\sigma}} dr < \infty.$$

We conclude:

$$1 \lesssim \varepsilon^{2\sigma} \|\chi u(\tau)\|_{\dot{H}^\sigma}^2 \lesssim \varepsilon^{2\sigma} \|u(\tau)\|_{\dot{H}^\sigma}^2 + \underbrace{\varepsilon^{2\sigma} \left( \|\chi_1 u(\tau)\|_{L^2}^2 + \|\chi_1 u(\tau)\|_{\dot{H}^{\max(0, \sigma-1)}}^2 \right)}_{=\mathcal{O}(\varepsilon^{2\sigma})},$$

hence

$$\varepsilon^{2\sigma} \|u\|_{\dot{H}^\sigma}^2 \gtrsim 1, \quad \forall \sigma \in (0, 2).$$

**6.4. Conclusion.** We can now go back to the original function

$$\psi_k(t, x) = h_k^{s-\frac{d}{2}} \frac{1}{|\log(h_k)|} u_k \left( \frac{t}{\varepsilon_k h_k^2}, \frac{x}{h_k} \right).$$

This function satisfies

$$\|\nabla^\sigma \psi_k(\varepsilon_k h_k^2 t)\|_{L^2} = h_k^{s-\sigma} |\log(h_k)|^{-1} \|\nabla^\sigma u_k(t)\|_{L^2}.$$

Let  $t_k = \varepsilon_k h_k^2 \tau$ , where  $\tau$  stems from Lemma 6.2:  $t_k \rightarrow 0$  as  $k \rightarrow +\infty$ . In view of Proposition 6.4, we know that when  $0 < \sigma < 2$ ,

$$\|\nabla^\sigma \psi_k(t_k)\|_{L^2} \gtrsim h_k^{s-\sigma} \varepsilon_k^{-\sigma} |\log(h_k)|^{-1}.$$

Given the choice  $\varepsilon_k = h_k^{m(s_c-s)} |\log(h_k)|^m$ , the lower bound goes to infinity as  $k$  goes to infinity as soon as

$$s < \sigma(1 + m(s_c - s)).$$

Finally, the density of initial data  $f_0$  in the pathological set is a direct consequence of [12, Proposition 2.10].

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#### APPENDIX A. ALTERNATIVE PROOF OF LOCALIZED ESTIMATES

In this appendix, we provide an alternative proof of Proposition 6.4. It has the drawback of being longer than in Section 6.3, but the advantage of being more flexible, and easily adapted to the case of geometries different from  $\mathbb{R}^d$ , typically  $\mathbb{T}^d$ .

**A.1. Tuning the size of cutoff functions.** We provide a proof that relies on the sizes of the cutoff  $R_k$  around the bubble  $k$ , as introduced in Section 6. We first show that up to some conditions on  $R_k$ , norm inflation occurs. In a second step, we prove that such conditions on  $R_k$  can be met even on  $\mathbb{T}^d$ .

**Lemma A.1** (Size of the cutoff functions). *Let  $0 < \sigma \leq 2$ . There exists  $C, C' > 0$  such that for every  $t \lesssim 1$  and  $k \geq 1$ , assuming that*

$$\begin{cases} R_k^\sigma \geq C' h_k^{-s} \varepsilon_k^\sigma & \text{if } 0 < \sigma < 1, \\ R_k^{\sigma-1} \geq C' h_k^{1-s} \varepsilon_k^\sigma h_{k-1}^{(m+1)(s_{\text{sob}}-s)} & \text{if } 1 < \sigma < 2, \end{cases}$$

then there holds

$$\|\varepsilon_k |\nabla|^\sigma u_k\|_{L^2} \gtrsim 1.$$

The conclusion of the above lemma corresponds to that of Proposition 6.4, and from that the proof of norm inflation is inferred like in Section 6.4.

*Proof.* Recall that in view of (6.1),

$$\|\varepsilon_k |\nabla|^\sigma (\chi_k u_k(\tau))\|_{L^2} \gtrsim 1, \quad \forall \sigma > 0.$$

We first treat the case  $0 < \sigma < 1$ , and write

$$|\nabla|^\sigma (\chi_k u_k) = [|\nabla|^\sigma, \chi_k] u_k + \chi_k |\nabla|^\sigma u_k.$$

Using the commutator estimate recalled in Lemma A.3 below,

$$\|[|\nabla|^\sigma, \chi_k] u_k\|_{L^2} \lesssim \frac{\|u_k\|_{L^2}}{R_k^\sigma}.$$

Given the non-localized estimate (2.6) on the  $L^2$ -norm of  $u_k$ , the upper bound is less than  $\frac{\varepsilon_k^{-\sigma}}{2C}$  as soon as for some  $C' > 0$ , we have

$$R_k^\sigma \geq C' h_k^{-s} \varepsilon_k^\sigma.$$

In this case we conclude that

$$\|\chi_k |\nabla|^\sigma u_k(\tau)\|_{L^2} \gtrsim \varepsilon_k^{-\sigma}.$$



In the case  $1 < \sigma < 2$ , we expand

$$\begin{aligned} |\nabla|^\sigma(\chi_k u_k) &= |\nabla|^{\sigma-1}(\nabla\chi_k u_k + \chi_k \nabla u_k) \\ &= |\nabla|^{\sigma-1}(\nabla\chi_k u_k) + [|\nabla|^{\sigma-1}, \chi_k] \nabla u_k + \chi_k |\nabla|^\sigma u_k. \end{aligned}$$

Using interpolation, we have

$$\| |\nabla|^{\sigma-1}(\nabla\chi_k u_k) \|_{L^2} \lesssim \| \nabla\chi_k u_k \|_{L^2}^{2-\sigma} \| \nabla(\nabla\chi_k u_k) \|_{L^2}^{\sigma-1}.$$

Thanks to Lemmas 6.1 and 6.2 applied to the cutoff function  $\nabla\chi_k$ , this term is uniformly bounded in  $k$  when  $t \in [0, T]$ . Concerning the second term in the expansion, we apply the commutator estimate from Lemma A.3 with  $\alpha = \sigma - 1$  and get that

$$\| [|\nabla|^{\sigma-1}, \nabla\chi_k] \nabla u_k \|_{L^2} \lesssim \frac{\| \nabla u_k \|_{L^2}}{R_k^{\sigma-1}}.$$

As a consequence of the energy estimate (2.7), if

$$R_k^{\sigma-1} \geq C' h_k^{1-s} \varepsilon_k^\sigma h_{k-1}^{(m+1)(s_{\text{sob}}-s)},$$

for some  $C' > 0$  large enough, we get that

$$\| \chi_k |\nabla|^\sigma u_k(\tau) \|_{L^2} \gtrsim \varepsilon_k^{-\sigma}.$$

In the case  $\sigma = 2$ , the argument presented in Section 6.3, based on Leibniz formula and localized estimates in  $L^2$  and  $\dot{H}^1$ , respectively, needs no modification.  $\square$

We now check that the condition on the size of  $R_k$  from the above lemma can be realized with a suitable choice of positions  $\frac{x_k}{h_k}$  for the bubbles.

**Lemma A.2** (Fitting the bubbles on the torus). *One can fix  $x_k$  such that there exists  $R_k$  satisfying  $\overline{B}(\frac{x_k}{h_k}, R_k) \cap \text{supp}(j * \varphi_{\ell,k}) = \emptyset$  for  $\ell \neq k$  and*

$$\begin{cases} R_k^\sigma \geq C' h_k^{-s} \varepsilon_k^\sigma & \text{if } 0 < \sigma < 1, \\ R_k^{\sigma-1} \geq C' h_k^{1-s} \varepsilon_k^\sigma h_{k-1}^{(m+1)(s_{\text{sob}}-s)} & \text{if } 1 < \sigma < 2. \end{cases}$$

Under these conditions, it is possible to construct a cutoff  $\chi_k$  of radius  $R_k$  around the  $k$ -th bubble located around position  $\frac{x_k}{h_k}$  in the rescaled variables for  $u_k$ .

*Proof.* We recall that in the original variables, we have

$$\psi_k(t, x) = h_k^{s-\frac{d}{2}} |\log(h_k)|^{-1} u\left(\frac{t}{\varepsilon_k h_k^2}, \frac{x}{h_k}\right).$$

In the original variables, the cutoff  $\chi_k$  corresponds to a cutoff of size  $h_k R_k$  around position  $x_k$ . Moreover,  $h_k = e^{-M^k}$  for some parameter  $M > 1$ . As a consequence, it is possible to fit all the bubbles in the torus if there exists  $\delta > 0$  such that

$$h_k R_k \lesssim h_k^\delta.$$

In the case  $0 < \sigma < 1$ , we combine this condition with the lower bound and  $R_k$  and we deduce that this is possible if

$$h_k^{\sigma(\delta-1)} \gtrsim c\varepsilon_k^\sigma h_k^{-s}.$$

Given the formula  $\varepsilon_k = h_k^{m(s_c-s)} |\log(h_k)|^m$ , it is enough that

$$\sigma(\delta - 1) < \sigma m(s_c - s) - s,$$

that is,

$$\sigma(1 + m(s_c - s) - \delta) > s.$$

We check that when

$$\sigma(1 + m(s_c - s)) > s,$$

then it is always possible to chose  $\delta > 0$  small enough so that this condition is satisfied.

In the case  $1 < \sigma \leq 2$ , this condition is compatible with the lower bound on  $R_k$  if

$$h_k^{(\sigma-1)(\delta-1)} \gtrsim c\varepsilon_k^\sigma h_k^{1-s} h_{k-1}^{(m+1)(s_{\text{sob}}-s)}.$$

Given the formula for  $\varepsilon_k$ , it is enough that

$$(\sigma - 1)(\delta - 1) < \sigma m(s_c - s) + 1 - s,$$

that is

$$\sigma(1 + m(s_c - s) - \delta) > s - \delta.$$

We check that when

$$\sigma(1 + m(s_c - s)) > s,$$

then it is always possible to chose  $\delta > 0$  small enough so that this condition is satisfied.  $\square$

## A.2. Commutator estimate.

**Lemma A.3** (Commutator estimate). *For every  $0 < \alpha < 1$ , there holds*

$$\| [|\nabla|^\alpha, \chi_k] f \|_{L^2} \lesssim \frac{\|\chi\|_{W^{1,\infty}}}{R_k^\alpha} \|f\|_{L^2}.$$

We give an elementary proof of this result, which is adapted from [17, Lemma D.1].

*Proof.* The operator  $|\nabla|^\alpha$  is the convolution operator with the tempered distribution  $\kappa = \mathcal{F}^{-1}(|\xi|^\alpha)$ , which is homogeneous of degree  $-\alpha - d$  and even. We deduce that there exists a universal constant  $c$  such that

$$|\nabla|^\alpha f(x) = \kappa * f(x) = c \int_{\mathbb{R}^d} \frac{f(y) - f(x)}{|y - x|^{\alpha+d}} dy.$$

As a consequence,

$$[|\nabla|^\alpha, \chi_k] f = c \int_{\mathbb{R}^d} \frac{\chi_k(y) - \chi_k(x)}{|y - x|^{\alpha+d}} f(y) dy.$$

We split the integral between the parts  $|y-x| \leq R_k$  and  $|y-x| > R_k$ . First, using the fact that  $\chi_k$  is Lipschitz continuous,  $\frac{|\chi_k(y) - \chi_k(x)|}{|y-x|^{\alpha+d}} \leq \frac{\|\nabla \chi_k\|_{L^\infty}}{|y-x|^{\alpha+d-1}}$  so that

$$\begin{aligned} \left\| \int_{|y-x| \leq R_k} \frac{\chi_k(y) - \chi_k(x)}{|y-x|^{\alpha+d}} f(y) dy \right\|_{L_x^2} &\lesssim \|\nabla \chi_k\|_{L^\infty} \left\| \frac{\mathbf{1}_{|x| \leq R_k}}{|x|^{\alpha+d-1}} * f \right\|_{L^2} \\ &\lesssim \frac{\|\nabla \chi\|_{L^\infty}}{R_k} \left\| \frac{\mathbf{1}_{|x| \leq R_k}}{|x|^{\alpha+d-1}} \right\|_{L^1} \|f\|_{L^2} \\ &\lesssim \frac{\|\nabla \chi\|_{L^\infty}}{R_k^\alpha} \left\| \frac{\mathbf{1}_{|x| \leq 1}}{|x|^{\alpha+d-1}} \right\|_{L^1} \|f\|_{L^2}. \end{aligned}$$

The term  $\left\| \frac{\mathbf{1}_{|x| \leq 1}}{|x|^{\alpha+d-1}} \right\|_{L^1}$  is finite since  $\alpha + d - 1 < d$ . Then, we have

$$\begin{aligned} \left\| \int_{|y-x| > R_k} \frac{\chi_k(y) - \chi_k(x)}{|y-x|^{\alpha+d}} f(y) dy \right\|_{L_x^2} &\lesssim \|\chi_k\|_{L^\infty} \left\| \frac{\mathbf{1}_{|x| > R_k}}{|x|^{\alpha+d}} * f \right\|_{L^2} \\ &\lesssim \|\chi\|_{L^\infty} \left\| \frac{\mathbf{1}_{|x| > R_k}}{|x|^{\alpha+d}} \right\|_{L^1} \|f\|_{L^2} \\ &\lesssim \frac{\|\chi\|_{L^\infty}}{R_k^\alpha} \left\| \frac{\mathbf{1}_{|x| > 1}}{|x|^{\alpha+d}} \right\|_{L^1} \|f\|_{L^2}. \end{aligned}$$

The  $L^1$ -norm is finite since  $\alpha + d > d$ . □

#### APPENDIX B. PROOF OF THEOREM 1.1

As mentioned in the introduction, the proof of Theorem 1.2 is readily adapted in order to prove Theorem 1.1. Let  $f_0 \in H^s(\mathbb{R}^d)$ : first, there exists a sequence  $g_{0,k} \in \mathcal{C}_c^\infty(\mathbb{R}^d)$  such that

$$\|f_0 - g_{0,k}\|_{H^s} \xrightarrow[k \rightarrow \infty]{} 0.$$

We then complement the initial datum  $g_{0,k}$  with a single bubble,

$$f_{0,k} = g_{0,k} + \varphi_k,$$

where  $\varphi_k$  is like in the rest of the paper, as introduced in Section 2.1, with the requirement that for any  $k$ , the supports of  $g_{0,k}$  and  $\varphi_k$  are disjoint. In view of the logarithmic factor  $|\log(h_k)|^{-1}$  in (2.1),

$$\|f_0 - f_{0,k}\|_{H^s} \leq \|f_0 - g_{0,k}\|_{H^s} + \|\varphi_k\|_{H^k} \xrightarrow[k \rightarrow \infty]{} 0.$$

The proof of Theorem 1.2 can then be repeated, by rescaling the unknown function as in Section 2.2: the initial datum  $u_{0,k}$  is the sum of the profile  $\alpha$  (possibly shifted in space), and a unique ‘‘low mode’’ stemming from  $g_{0,k}$ . The modulated energy estimate from Section 5 remains valid (note that the low mode stemming from  $g_{0,k}$  must be incorporated into the renormalized modulated energy, in the spirit of the proof of [31, Theorem 1.33], and as in [28, 12]), and we conclude like in Section 6.

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