Birkhoff normal form in low regularity for the nonlinear quantum harmonic oscillator

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Abstract

Given small initial solutions of the nonlinear quantum harmonic oscillator on \mathbb{R} , we are interested in their long time behavior in the energy space which is an adapted Sobolev space. We perturbate the linear part by V taken as multiplicative potentials, in a way that the linear frequencies satisfy a non-resonance condition. More precisely, we prove that for almost all potentials V, the low modes of the solution are almost preserved for very long times.

Key words: Nonlinear PDEs, quantum harmonic oscillator, Birkhoff normal form, low regularity, non-resonance, stability of solutions, Hilbertian basis

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1 Introduction

For half a century, the theory of partial differential equations has mainly focused on the study of the local or global existence of solutions, in well-chosen functional spaces. Nevertheless, the advances of this theory made it possible to consider other types of questions, in particular that of the qualitative behavior of solutions once their existence has been established. In other words, given a small initial datum as well as a non-resonant¹ Hamiltonian partial differential equation on a bounded domain,

$$i\partial_t u = \partial_{\bar{u}} H(u)$$

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¹The eigenvalues $(\Lambda_j)_{j\geq 1}$ of the linearized vector field enjoy a Diophantine condition, in particular rational independency. The precise definition is given later in Section 2.2.

with H a smooth Hamiltonian having 0 as elliptic equilibrium, what can be said about the solution in a Sobolev space H^s over long periods of time? Stability results of such solutions over long periods have been proved. For instance [2] and [6] proved stability results for Klein-Gordon and NLS on the tori: Given $r \gg 1$ arbitrarily large, there exists $s_0(r) \gg 1$ such that given small enough initial data $||u(0)||_{H^s} := \varepsilon$ with $s > s_0(r)$, no significant exchange of energy is possible before very long times $|t| \le \varepsilon^{-r}$, and we have the modulus of the Fourrier modes is almost preserved, i.e. $|u_n(t)|^2 \simeq |u_n(0)|^2$. The main flaw of their results lies in the constraint $s \ge s_0(r)$, which seemed to be essential in their proofs (mainly to deal with problems of small divisors) and in other similar results for dispersive Hamiltonian partial differential equations found for example in [3-5,7,10,16-18,26].

On the other hand, some numerical experiments strongly suggest that this restriction of smoothness condition is irrelevant and that $s_0(r)$ does not have to be very large (see for example [14]). Consequently, it makes sense to generate effective methods in order to lower the regularity and still obtain the stability result.

To this matter, the paper [8], recently done by Bernier and Grébert, deduced the almost global preservation of the low harmonic energies over very long times for Klein-Gordon equation and NLS with both Dirichlet and periodic boundary conditions in low regularity in the energy space. The crucial key point was developing a Birkhoff Normal Form Theorem in low regularity which is weaker than the classical version of the theorem, since it only concerns the low modes of the solutions. The idea is to design or construct a symplectic and close to the identity map τ which helps simplify the Hamiltonian system. More precisely, composing with τ , they pushed the non-normalized part of H to higher orders and thus killing the terms that influence the dynamics of the low modes. In [9] and along with Rivière, they extended this method to the sphere and worked with the Klein-Gordon equation.

My work was inspired by the later. I used similar techniques yet changed some notations, in order to obtain a suitable framework for the nonlinear quantum harmonic oscillator on an unbounded domain but with confined potentials (see (NLS) and (4)).

1.1 The model

In this paper, we study the long time behavior of small solutions of the perturbed quantum harmonic oscillator in one dimension in the adapted Sobolev spaces \widehat{H}^s (see (2)) with low regularity (s small). This equation is of great importance in quantum physics (refer for instance to [22]) and is defined for $(t,x) \in \mathbb{R} \times \mathbb{R}$ by the following Schrödinger equation

$$\begin{cases} i\partial_t u(t,x) = -\partial_{xx} u(t,x) + x^2 u(t,x) + V(x)u(t,x) \pm |u(t,x)|^{2p} u(t,x) \\ u_{|t=0} = u^{(0)} \in \widehat{H}^1(\mathbb{R}), \end{cases}$$
(NLS)

where $p \geq 1$ and V(x) is a real-valued potential. Moreover, \pm added to the nonlinearity term refers to the focusing and defocusing cases. For V = 0, the linear part of the equation simply describes a quantum harmonic oscillator on \mathbb{R} , denoted by $T := -\partial_{xx} + x^2$. Notice that (NLS) can be seen as a perturbation of the linear equation

$$i\partial_t u(t,x) = Tu(t,x). \tag{1}$$

It is well known that the spectrum of this operator is an increasing sequence $(\lambda_j)_{j\geq 1}$ given by $\lambda_j = 2j - 1$. More precisely, we have

$$Th_j = (2j - 1)h_j$$

with $(h_j)_{j\geq 1}$ being the Hermite functions and forming an orthonormal basis of $L^2(\mathbb{R})$ (we refer the reader to Chapter 6 in [13]). Moreover, these eigenvalues are completely resonant:

Since they are integers, they are not rationally independent. In this context, we define for $s \ge 0$ the Sobolev spaces

$$\widehat{H}^s := \{ u \in H^s(\mathbb{R}), \ \langle x \rangle^s u \in L^2(\mathbb{R}) \}$$
 (2)

and we endow them with the corresponding natural norms

$$||u||_{\widehat{H}^s}^2 := ||u||_{H^s}^2 + ||\langle x \rangle^s u||_{L^2}^2.$$

Notice that (II) can be written as a Hamiltonian system with a quadratic Hamiltonian

$$Z_2(u) = \frac{1}{2} \left(\|\partial_x u\|_{L^2}^2 + \|xu\|_{L^2}^2 \right) \simeq \|u\|_{\widehat{H}^1}^2.$$

On the other hand, the frequencies $(\lambda_j)_{j>1}$ appear in \mathbb{Z}_2 , and thus we also have

$$Z_2(u) = \frac{1}{2} \sum_{j>1} \lambda_j |u_j|^2 \simeq ||u||_{h^{1/2}}^2.$$

Here, we identify $u \in \hat{H}^1$ and its Hermite sequence $(u_j)_{j>1} \in h^{1/2}$ (see 1.4).

Our goal will be to adapt a suitable Birkhoff normal form theorem for the nonlinear quantum harmonic oscillator with a perturbation and establish its dynamical consequence in order to reach the main result presented in the next section.

To do so, we require a non-resonance condition² on the spectrum of operator T+V. We draw smooth potentials V to guarantee that, almost surely, the spectrum is strongly non-resonant (see Theorem 1.2). The spectral analysis and properties of the eigenvalues $(\Lambda_j)_{j\geq 1}$ and their associated eigenfunctions $(\psi_j)_{j\geq 1}$ will be explained rigorously in Section 2.

1.2 Main results and comments

We are interested in the actions for the nonlinear quantum harmonic oscillator describing the dynamics or the amplitudes of the modes of the solution and given as

$$I_j(u) = |u_j(t)|^2$$
 with $u_j(t) = \int_{\mathbb{R}} u(t, x)\psi_j(x) dx$

where we recall that $(\psi_j)_{j\geq 1}$ are the eigenfunctions of the operator T+V. Notice that the actions I_j are preserved by the linear part of the Schrödinger equation (refer to (NLS)). Nevertheless, once we turn on the nonlinear perturbation, we can expect some exchange of energy (see for example [15]), and the question of preservation of the actions then arises.

To state the main result, it is crucial to mention that equation (NLS) is globally well-posed for small solutions in \widehat{H}^1 (see Section 5). In the following theorem, we consider multiplicative potentials, and we specify the dynamics of the solution over very long times in low regularity.

Theorem 1.1. Let $N \ge 1$, $r \ge p+1$ arbitrarily large, $\nu > 0$ and let $V \in \widehat{H}^1 \cap \mathscr{C}^2$ such that the spectrum of T+V is strongly N,r non-resonant (refer to Definition [2.7]). Then, there exist $\epsilon_0 > 0$ depending on $\|V\|_{\widehat{H}^1}$ and a constant C > 0 depending on (N,r,V,ν) such that if we set $\varepsilon := \|u_0\|_{\widehat{H}^1} \le \epsilon_0$, the global solution of (NLS) satisfies

$$|t| < \varepsilon^{-2r}$$
 and $1 \le j \le N \implies \left| |u_j(t)|^2 - |u_j(0)|^2 \right| \le C\varepsilon^{2p+2-\nu}$ (3)

with 2p+2 being the order of the Hamiltonian non-linearity and $u_j(t) = \int_{\mathbb{R}} u(t,x)\psi_j(x) dx$.

²To get rid of resonances, we move the eigenvalues to obtain rational independency.

It is important to mention that in the above result, the set of potentials V is not empty. More precisely, for almost all V, the non-resonant assumption is satisfied. To see this, we present another main result as the following theorem:

Theorem 1.2. Let V be defined randomly on \mathbb{R} as

$$V(x) = \sum_{k>1} g_k h_k(x\sqrt{2}) P_k \tag{4}$$

where $g_k \sim \mathcal{N}(0,1)$ are some independent Gaussian variables and $P \in \widehat{H}^3$ is a given weight such that $P_k \in \mathbb{R}_+^*$. Then, for all $r \geq 1$ and $N \geq 1$, provided that $\|V\|_{\widehat{H}^1} \lesssim_r N^{-1/6}$, almost surely $V \in \widehat{H}^1 \cap \mathscr{C}^2$ and the frequencies of the operator T+V are strongly N, r non-resonant in the sense of Definition 2.7.

As a consequence, Theorem 1.1 applies.

Comments regarding the results.

- Theorem 1.2 makes sense because we prove that $\mathbb{P}(\|V\|_{\widehat{H}^1} < \lambda) > 0$ for all $\lambda > 0$ in Lemma A.1 of the Appendix.
- We prove the almost global preservation of the low actions over very long times $|t| < \varepsilon^{-2r}$ with r arbitrarily large.
- It seems interesting to mention that the term $\varepsilon^{-\nu}$ in the estimation of Theorem [1.1] is due to truncation and logarithmic loss. It could be removed with a little technicality and only serves to simplify the proofs.
- Note that (NLS) is locally well-posed in \widehat{H}^1 (for more details refer to Theorem 5.3), and the estimation (3) is trivial for time scales $|t| \leq \varepsilon^{-2p}$, even in the case of a vanishing potential. However, the conservation of the actions is not trivial on longer scales (for r taken arbitrarily large), which is the studied framework here.
- In the classical Birkhoff normal form theorem, a standard non-resonant argument is used (for instance, refer to [6]) in order to avoid³ the exchange of energy between modes and deduce the stability. However, since we are working with a non-smooth solution, we will use a stronger condition (Theorem 1.2) allowing us to remove much more terms from the original Hamiltonian.
- The passage to low regularity results in the loss of information concerning the high modes of the solution. Mainly, as mentioned before the Birkhoff normal form theorem developed by [8] concerns only the first N modes and so does our result. Furthermore, the strong N non-resonance condition stated in Theorem 1.2 clearly provides a relation between the potential V and N as well as indicates that the larger the number of modes N we would like to control, the smaller the potential V has to be. Unlike Theorem 1.10 in [8], the number of modes we control does not depend only on the size of the initial datum.
- Fortunately and without the additional smoothness constraint, we obtained a result of the same kind as in [18]. However, there seem to be two major differences. On one hand, here, in order to avoid the resonances, we perturbate the eigenvalues by adding multiplicative potentials instead of Hermite multipliers. Formally, if we had considered the operator T + M with M a Hermite multiplier given by $M\psi_j = m_j\psi_j$ for some

³On the contrary, for references regarding the exchange of energy in NLS see [20] and [21].

 $(m_j)_{j\geq 1}$, then we will be working with the frequencies $2j-1+m_j$ whose standard non-resonance condition was done⁴ in [18]. Thus, the work would have been much easier. On the other hand, in [18] thanks to the smoothness of the solutions, they were able to control and obtain stability for all modes and not only finitely many.

- The paper [23] generalises the result of [18] and proves a similar theorem for the operator T + V(x) + M where V belongs to the Schwartz class. A second result in [23] uses Chelkak-Kargaev-Korotyaev's results about the inverse spectral problem of harmonic oscillator and states that for M = 0, there exist some potentials V such that the spectrum of T + V(x) is non-resonant. Unfortunately, since these potentials live only in \widehat{H}^1 , the solution can be at most \widehat{H}^1 . Thus, the standard methods could not be applied.
- The authors in [19] worked with a similar nonlinear Schrödinger equation and constructed a class of potentials with the help of the dual basis of the finite family of Hermite polynomials $(h_j)_{1 \le j \le n}^2$. However, the new developed method we work with is simpler and applies to a larger class of potentials and initial data.
- Due to multiplicities, the generalization of our result to dimensions $d \geq 2$ is not clear since the spectral theory in higher dimensions becomes much more complicated. Therefore, it would certainly be necessary to work with Hermite multipliers.

1.3 Sketch of the proofs

I will formally explain the strategies of the proofs. Concerning Theorem $\boxed{1.1}$, the method of the proof requires the Birkhoff normal form process introduced in [8]. For the sake of simplicity, we do the case p = 1. Write (NLS) as a Hamiltonian system with

$$H = Z_2 + P + \mathcal{O}(\|u\|^6)$$

given explicitly in Section 5, where Z_2 is a quadratic Hamiltonian associated with the linear part of the equation and depends only on the actions $(I_j)_{j\geq 1}$. Also, P is a perturbation of order 4 belonging to a Hamiltonian class (refer to 3) and written as

$$P(u) = \sum_{j,l \in (\mathbb{N}^*)^2} P_{j,l} u_{j_1} u_{j_2} \overline{u_{l_1} u_{l_2}}.$$

We consider the flow $\phi_{\chi}^t(u)$ generated by χ , a polynomial of degree 4, solving the equation $-i\partial_t\phi_{\chi}=(\nabla\chi)\circ\phi_{\chi}$. The idea is to construct a symplectic⁵ close to the identity map τ such that, in the new variables, the Hamiltonian H is a function of the actions up to a remainder R of arbitrarily high order (we say that H is written in a Birkhoff normal form). More precisely, as a first step we compose by ϕ_{χ}^1 and use Taylor expansion in order to get

$$H \circ \phi_{\chi}^1 = Z_2 + \{\chi, Z_2\} + P + \mathcal{O}(\|u\|^6)$$

where $\{\cdot,\cdot\}$ denotes the Poisson brackets (refer to $\boxed{1.4}$). For the sake of normalisation and in order to eliminate the monomials $u_{j_1}u_{j_2}\overline{u_{l_1}u_{l_2}}$ that do not depend on the actions, we would like to solve the cohomological equation

$$\{\chi, Z_2\} + P = Q$$
 with $\{Q, I_j\} = 0$ for $j \le N$.

⁴It turns out that most of the time the strong non-resonance condition introduced in Section 2.2 holds when the standard one is satisfied.

⁵The symplectic transformations preserve the Hamiltonian structure.

However, during the process of solving this equation, small divisors in the form of

$$w_{i_1} + w_{i_2} - w_{l_1} - w_{l_2}$$

might appear in the denominator. As a result, we consider the strong non-resonance condition characterised by controlling these small divisors from below. The next step, would be to iterate this construction, and compose with a new symplectic map. At the end, we obtain a transformation pushing the non-normalized part of H to order 6, followed by a transformation pushing it to order 8 and so on. Consequently, we get

$$H \circ \tau = Z_2 + Q + R$$

where Q commutes with the low actions $I_j(u)$ for $j \leq N$ and R satisfies the estimate

$$||\nabla R(u)||_{h^{-1/2}} \lesssim_N ||u||_{h^{1/2}}^{2r+2}.$$

As a corollary of this result, introducing a new variable $v = \tau^{-1}(u)$, we notice that v is the solution of the equation

$$i\partial_t v = \nabla \tilde{H}(v)$$
 with $\tilde{H}(v) = H \circ \tau(v) = Z_2(v) + Q(v) + R(v)$.

Furthermore, we work with $\partial_t I_i(v(t))$ to get

$$\partial_t I_j(v) = (\nabla I_j(v), \partial_t v)_{\ell^2} = (i \nabla J_n(v), \nabla (Z_2 + Q + R)(v))_{\ell^2} = \{J_n, R\}(v).$$

Finally, we conclude by applying Cauchy-Schwarz and the Mean Value Inequality.

Now, we turn to the proof of Theorem 1.2. As explained above, in order to simplify the Hamiltonian system, we require a control of the frequencies of operator T + V. i.e. We face a problem of small divisors. To solve this, we follow the ideas of [8]. We seek a control of the first derivative of the small divisors in the simple case where V = 0 (refer to Lemma 2.13). In order to proceed, it seemed necessary to control the norm of V by $N^{-1/6}$. Thus, the relation between V and N appears and consequently, we estimate the first derivative with respect to V of the small divisors for $V \neq 0$. Finally, using probability arguments, we deduce a control of the small divisors by the smallest index involved. Further tools of spectral analysis are needed to obtain the main non-resonant condition (for details see Section 2.2).

Organization of the article. In section 2, we work with some spectral theory aspects and introduce the non-resonance condition satisfied by the corresponding spectrum. We provide some technical tools used to achieve this condition. Section 3 is devoted to defining a class of Hamiltonian functions suitable for the nonlinear quantum harmonic oscillator equation and satisfying nice properties. Then, we develop a normal form process in low regularity in Section 4 inspired by [8]. In the last section, we prove the main result which is a dynamical corollary of the Birkhoff normal form theorem, and we deduce the almost global preservation of the low actions over very long times.

1.4 Notations

We always consider the following set of notations:

- $2\partial_{\overline{z}} := \partial_{\Re z} + i\partial_{\Im z}$ and $2\partial_z := \partial_{\Re z} i\partial_{\Im z}$.
- For simplicity of notations, we write $x \lesssim_p y$ if there exists a constant C depending on p fixed such that $x \leq Cy$ for $(x, y) \in \mathbb{R}^2$.

- For $k \in \mathbb{Z}$, the Japanese bracket is denoted by $\langle k \rangle := (1 + |k|^2)^{1/2}$.
- For $s \in \mathbb{R}$ and M > 1, the discrete Sobolev space is written as

$$h^{s}([1,M]) = \left\{ u \in \mathbb{C}^{[1,M]}, \|u\|_{h^{s}}^{2} := \sum_{k \in [1,M]} \langle k \rangle^{2s} |u_{k}|^{2} < \infty \right\}.$$

• For $p \ge 1$ and M > 1, the Lebesgue space is written as

$$\ell^{p}([\![1,M]\!]) = \left\{ u \in \mathbb{C}^{[\![1,M]\!]}, \ \|u\|_{\ell^{p}}^{p} := \sum_{k \in [\![1,M]\!]} |u_{k}|^{p} < \infty \right\}.$$

$\mathbf{2}$ Non-resonance condition

In this section, we describe first the spectrum of the operator T+V for $V\in\mathscr{C}^2\cap\widehat{H}^1$ in order to deduce that, almost surely, this spectrum is strongly non-resonant according to the definition given in 2.2. For spectral aspects, we start by considering the potential V written in terms of the L²-basis $(h_k(\sqrt{2})2^{1/4})_{k>1}$ as

$$V(x) = \sum_{k>1} v_k h_k(x\sqrt{2}) 2^{1/4}.$$
 (5)

2.1Preliminaries on spectral analysis

In this part, we are interested in estimations on the Lebesgue norms of the eigenfunctions $(\psi_j)_{j>1}$ of the operator T+V. For $V\in L^\infty(\mathbb{R})$, we have that T+V is a self-adjoint operator of domain \hat{H}^2 (refer to Chapter 2 in [13]) and has a real, discrete spectrum (refer to [25]), consisting of simple eigenvalues $(\Lambda_j)_{j\geq 1}$ and satisfying

$$\Lambda_j = 2j - 1 + \mathcal{O}(1), \ j \to \infty.$$

As a consequence, similar to $(h_j)_{j>1}$, the eigenfunctions $(\psi_j)_{j>1}$ of the operator T+V form an orthonormal basis⁶ of $L^2(\mathbb{R})$, and we are able to ensure the spectral decomposition. We end up by estimating the corresponding eigenvalues $(\Lambda_j)_{j\geq 1}$ of the operator T+V. Using an important result of Koch-Tataru [24], we obtain the following lemma which is the key to our estimations:

Lemma 2.1. For all $j \geq 1$ and $V \in \mathcal{C}^2 \cap \widehat{H}^1$, there exists C > 0 such that

$$\|\psi_j\|_{L^4} \le Cj^{-1/12}.$$

Proof. Applying Hölder's inequality, we have the estimation

$$\|\psi_j\|_{L^4} \le \|\psi_j\|_{L^6}^{3/4} \|\psi_j\|_{L^2}^{1/4}. \tag{6}$$

Applying Corollary 3.2 from [24] for $W(x) = x^2 + V(x)$ and p = 6, we obtain ⁷

$$\|\psi_j\|_{L^6} \lesssim j^{-1/9} \|\psi_j\|_{L^2}.$$

Thus replacing in (6) and using that $(\psi_j)_{j>1}$ is an orthonormal basis, we get

$$\|\psi_j\|_{L^4} \lesssim \left(j^{-1/9} \|\psi_j\|_{L^2}\right)^{3/4} \|\psi_j\|_{L^2}^{1/4} \lesssim j^{-1/12}.$$

 $^{\|\}psi_j\|_{L^4} \lesssim \left(j^{-1/9} \|\psi_j\|_{L^2}\right)^{3/4} \|\psi_j\|_{L^2}^{1/4} \lesssim j^{-1/12}.$ ⁶In other words, the following are satisfied: The L^2 -normalisation property ($\|\psi_j\|_{L^2} = 1$) and the orthogonality property $((\psi_j, \psi_l)_{L^2} = \delta_{j,l})$.

⁷A personal communication by Herbert Koch regarding Theorem 4 in [24]: The proof can be modified in order to deal with $W \in \mathscr{C}^2$.

Remark 2.2. Note that for the case $W(x) = x^2$ (i.e. V = 0), the norm $||h_j||_{L^4}$ can be easily estimated by using Lemma 2.10 and Parseval–Bessel's equality.

Notations. In the following three results, we denote by $\Lambda_{j,V}$ (resp. $\psi_{j,V}$) the eigenvalues (resp. eigenfunctions) of the operator T+V. We adapt the proofs done in [19].

In this lemma, we can see that the eigenvalues are close to integer values.

Lemma 2.3. For all $j \geq 1$ and $V \in \widehat{H}^1$ small enough with respect to the norm $\|\cdot\|_{\widehat{H}^1}$, we have

$$|\Lambda_{j,V} - (2j-1)| \lesssim ||V||_{\widehat{H}^1} j^{-1/2}.$$

Proof. We refer the reader to Lemma 2.1 in [12].

The next lemma serves as a useful tool for Proposition 2.5.

Lemma 2.4. For $V_1, V_2 \in \widehat{H}^1 \cap \mathscr{C}^2$ small enough with respect to the norm $\|\cdot\|_{\widehat{H}^1}$, there exists C > 0 such that for all $j \geq 1$

$$\|\psi_{j,V_2} - (\psi_{j,V_1}, \psi_{j,V_2})_{L^2} \psi_{j,V_1}\|_{L^2} \le Cj^{-1/12} \|V_1 - V_2\|_{\widehat{H}^1}.$$

Proof. Since $(\psi_k)_{k\geq 1}$ is a Hilbertian basis of $L^2(\mathbb{R})$, then it is natural to decompose

$$\|\psi_{j,V_{2}} - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}} \psi_{j,V_{1}}\|_{L^{2}}^{2} = \sum_{k \geq 1} \left| (\psi_{j,V_{2}} - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}} \psi_{j,V_{1}}, \psi_{k,V_{1}})_{L^{2}} \right|^{2}$$

$$= \sum_{k \geq 1} \left| (\psi_{j,V_{2}}, \psi_{k,V_{1}})_{L^{2}} - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}} (\psi_{j,V_{1}}, \psi_{k,V_{1}})_{L^{2}} \right|^{2}$$

$$= \sum_{\substack{k \geq 1 \\ k \neq j}} \left| (\psi_{j,V_{2}}, \psi_{k,V_{1}})_{L^{2}} \right|^{2}$$

$$(7)$$

because $(\psi_{j,V_1}, \psi_{k,V_1})_{L^2} = \delta_{k,j}$. Similarly, since $T + V_1 - \Lambda_{j,V_2}$ is self-adjoint we write

$$\begin{split} \left\| (T + V_1 - \Lambda_{j,V_2}) \psi_{j,V_2} \right\|_{L^2}^2 &= \sum_{k \ge 1} \left| ((T + V_1 - \Lambda_{j,V_2}) \psi_{j,V_2}, \psi_{k,V_1})_{L^2} \right|^2 \\ &= \sum_{k \ge 1} \left| ((T + V_1 - \Lambda_{j,V_2}) \psi_{k,V_1}, \psi_{j,V_2})_{L^2} \right|^2 \\ &= \sum_{k \ge 1} \left| ((\Lambda_{k,V_1} - \Lambda_{j,V_2}) \psi_{k,V_1}, \psi_{j,V_2})_{L^2} \right|^2 \\ &= \sum_{k \ge 1} \left| \Lambda_{k,V_1} - \Lambda_{j,V_2} \right|^2 \left| (\psi_{k,V_1}, \psi_{j,V_2})_{L^2} \right|^2. \end{split}$$

Now from Lemma 2.3, we have that

$$|\Lambda_{k,V_1} - \Lambda_{j,V_2}| \gtrsim 1$$

for $k \neq j$ uniformly in V_1, V_2 small enough with respect to $\|\cdot\|_{\widehat{H}^1}$. This implies that

$$\|(T+V_1-\Lambda_{j,V_2})\psi_{j,V_2}\|_{L^2}^2 \gtrsim \sum_{\substack{k\geq 1\\k\neq j}} |(\psi_{k,V_1},\psi_{j,V_2})_{L^2}|^2.$$
 (8)

After this, applying (7) and (8) we deduce that

$$\|\psi_{j,V_2} - (\psi_{j,V_1}, \psi_{j,V_2})_{L^2} \psi_{j,V_1}\|_{L^2}^2 = \sum_{\substack{k \ge 1 \\ k \ne j}} \left| (\psi_{k,V_1}, \psi_{j,V_2})_{L^2} \right|^2 \lesssim \|(T + V_1 - \Lambda_{j,V_2}) \psi_{j,V_2}\|_{L^2}^2.$$

Notice that we can write

$$(T + V_1)\psi_{j,V_2}(x) = (-\partial_{xx} + x^2 + V_1)\psi_{j,V_2}(x) + (V_1 - V_2)\psi_{j,V_2}(x)$$

= $(-\partial_{xx} + x^2 + V_2)\psi_{j,V_2}(x) + (V_1 - V_2)\psi_{j,V_2}(x)$
= $\Lambda_{j,V_2}\psi_{j,V_2}(x) + (V_1 - V_2)\psi_{j,V_2}(x),$

and Hölder's inequality implies that

$$\|(T+V_1-\Lambda_{j,V_2})\psi_{j,V_2}\|_{L^2} = \|(V_1-V_2)\psi_{j,V_2}\|_{L^2} \le \|V_1-V_2\|_{L^4} \|\psi_{j,V_2}\|_{L^4}.$$

Next, using the Sobolev embedding $H^1 \hookrightarrow L^4$, the continuous inclusion $\widehat{H}^1 \subset H^1$ as well as Lemma [2.1], we get

$$\begin{aligned} \|(T+V_1-\Lambda_{j,V_2})\psi_{j,V_2}\|_{L^2} &\leq \|V_1-V_2\|_{H^1} \|\psi_{j,V_2}\|_{L^4} \\ &\leq \|V_1-V_2\|_{\widehat{H}^1} \|\psi_{j,V_2}\|_{L^4} \\ &\leq C\|V_1-V_2\|_{\widehat{H}^1} j^{-1/12}. \end{aligned}$$

We prove now that the eigenfunctions $(\psi_j)_{j\geq 1}$ are close to the Hermite functions.

Proposition 2.5. For all $j \geq 1$ and $V \in \widehat{H}^1 \cap \mathscr{C}^2$ small enough with respect to the norm $\|\cdot\|_{\widehat{H}^1}$, there exists C > 0 such that

$$\|\psi_j - h_j\|_{L^2} \le Cj^{-1/12} \|V\|_{\widehat{H}^1}.$$

Proof. Taking the scalar product of $\psi_{j,V_2} - (\psi_{j,V_1}, \psi_{j,V_2})_{L^2} \psi_{j,V_1}$ with ψ_{j,V_2} , we get

$$\left| \left(\psi_{j,V_2}, \psi_{j,V_2} - (\psi_{j,V_1}, \psi_{j,V_2})_{L^2} \psi_{j,V_1} \right)_{L^2} \right| = \left| 1 - (\psi_{j,V_1}, \psi_{j,V_2})_{L^2}^2 \right|.$$

Therefore, applying Cauchy–Schwarz inequality and Lemma 2.4 we have

$$\left|1 - (\psi_{j,V_1}, \psi_{j,V_2})_{L^2}^2\right| \le \|\psi_{j,V_2}\|_{L^2} \|\psi_{j,V_2} - (\psi_{j,V_1}, \psi_{j,V_2})_{L^2} \psi_{j,V_1}\|_{L^2} \lesssim j^{-1/12} \|V_1 - V_2\|_{\widehat{H}^1}.$$
 (9)

Finally, note that adding the terms $\pm (\psi_{j,V_1}, \psi_{j,V_2})_{I,2} \psi_{j,V_1}$ gives

$$\|\psi_{j,V_{1}} - \psi_{j,V_{2}}\|_{L^{2}}^{2} \leq 2\|\psi_{j,V_{2}} - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}}\psi_{j,V_{1}}\|_{L^{2}}^{2} + 2\|\psi_{j,V_{1}}\left(1 - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}}\right)\|_{L^{2}}^{2}$$

$$= 2\|\psi_{j,V_{2}} - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}}\psi_{j,V_{1}}\|_{L^{2}}^{2} + 2\left|1 - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}}\right|^{2} \underbrace{\|\psi_{j,V_{1}}\|_{L^{2}}^{2}}_{=1}.$$

Hence, using Lemma 2.4 and (9), we obtain

$$\|\psi_{j,V_{1}} - \psi_{j,V_{2}}\|_{L^{2}}^{2} \leq 2\|\psi_{j,V_{2}} - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}}\psi_{j,V_{1}}\|_{L^{2}}^{2} + 2\left|1 - (\psi_{j,V_{1}}, \psi_{j,V_{2}})_{L^{2}}^{2}\right|^{2}$$

$$\lesssim 2(j^{-1/12}\|V_{1} - V_{2}\|_{\widehat{H}^{1}})^{2} + 2(j^{-1/12}\|V_{1} - V_{2}\|_{\widehat{H}^{1}})^{2}$$

$$\lesssim (j^{-1/12}\|V_{1} - V_{2}\|_{\widehat{H}^{1}})^{2}.$$

In particular, for $V_2=0$ we have $\psi_{j,V_2}(x)=h_j(x)$ and thus the needed result. \square

Finally, using the expression of V and the expansion of h_j^2 , we get the following result:

Proposition 2.6. For $V \in \widehat{H}^1$, the gradient of the eigenvalues $\Lambda_j(V)$ with respect to v_{2k-1} (recall that v_k are the coefficients from the expansion of the potential V in (5)) is given by

$$\frac{\partial \Lambda_j(V)}{\partial v_{2k-1}} = \int_{\mathbb{R}} 2^{1/4} h_{2k-1}(x\sqrt{2}) \psi_j^2(x) \, \mathrm{d}x.$$

Proof. Note first that for all $j \geq 1$, each eigenvalue Λ_j and each eigenfunction ψ_j is \mathscr{C}^1 with respect to v_{2k-1} (we refer the reader to Lemma 2.4 in [12]). Now, we consider the equation

$$\underbrace{(-\partial_{xx} + x^2 + V(x))}_{T+V} \psi_j(x) = \Lambda_j \psi_j(x).$$

Differentiating the above with respect to v_{2k-1} for $k \geq 1$ we obtain

$$(T+V)\frac{\partial \psi_j}{\partial v_{2k-1}} + \frac{\partial (T+V)}{\partial v_{2k-1}}\psi_j = \frac{\partial \Lambda_j}{\partial v_{2k-1}}\psi_j + \Lambda_j \frac{\partial \psi_j}{\partial v_{2k-1}}.$$

Due to the expression of V given by (5), this implies that

$$(T+V-\Lambda_j)\frac{\partial \psi_j}{\partial v_{2k-1}} + 2^{1/4}h_{2k-1}(\cdot\sqrt{2})\psi_j = \frac{\partial \Lambda_j}{\partial v_{2k-1}}\psi_j.$$

Next, taking the scalar product with ψ_i we get

$$\left(T + V - \Lambda_j\right) \frac{\partial \psi_j}{\partial v_{2k-1}}, \psi_j \Big)_{L^2} + 2^{1/4} (h_{2k-1}(\sqrt{2})\psi_j, \psi_j)_{L^2} = \left(\frac{\partial \Lambda_j}{\partial v_{2k-1}}\psi_j, \psi_j\right)_{L^2}.$$
(10)

Using self-adjointness of T+V and the fact that $\psi_j \in \ker(T+V-\Lambda_j)$, we deduce

$$\left((T+V-\Lambda_j) \frac{\partial \psi_j}{\partial v_{2k-1}}, \psi_j \right)_{L^2} = \left(\frac{\partial \psi_j}{\partial v_{2k-1}}, (T+V-\Lambda_j) \psi_j \right)_{L^2} = 0.$$

Since $\frac{\partial \Lambda_j}{\partial v_{2k-1}}$ is independent of x and $\|\psi_j\|_{L^2} = 1$, then (10) gives

$$\frac{\partial \Lambda_j(V)}{\partial v_{2k-1}} = \int_{\mathbb{R}} 2^{1/4} h_{2k-1}(x\sqrt{2}) \psi_j^2(x) \, \mathrm{d}x. \tag{11}$$

2.2 Non-resonance condition

In the second part, we are interested in probabilistic aspects. For this, given a weight $P \in \widehat{H}^3$ such that $P_k \in \mathbb{R}_+^*$, we draw V randomly (recall (4)) as

$$V(x) = \sum_{k \ge 1} g_k h_k(x\sqrt{2}) P_k \tag{12}$$

where $g_k \sim \mathcal{N}(0,1)$ are some independent Gaussian variables. It is important to emphasize that adding such a weight ensures the following technical assumptions⁸ (for the proof of (13), refer to Lemma A.1) on V:

$$\begin{cases} V \in \widehat{H}^1 \cap \mathscr{C}^2 \text{ almost surely,} \\ \mathbb{P}(\|V\|_{\widehat{H}^1} < \lambda) > 0 \text{ for all } \lambda > 0. \end{cases}$$
 (13)

Roughly speaking, thanks to the parameters g_k , we will be able to perturbate each eigenvalue independently in order to obtain non-resonancy. This part will be dedicated to explaining this idea rigorously. We imitate the work done in [8] to prove that the frequencies of (NLS) (also known as the eigenvalues Λ_j of the operator T+V) obtained from the quadratic Hamiltonian are strongly N, r non-resonant in the following sense:

⁸These assumptions are used to prove Proposition 2.15

Definition 2.7. (Strong N, r non-resonance) Consider frequencies $w \in \mathbb{R}^{\mathbb{N}^*}$, $r \geq 1$ and $N \geq 1$. We say that w are strongly N, r non-resonant if there exists $\beta_{r,N} > 0$, such that for all $1 \leq r^* \leq r$, $\ell \in (\mathbb{Z}^*)^{r^*}$ and all $j \in (\mathbb{N}^*)^{r^*}$ with $j_1 < \cdots < j_{r^*}$, $j_1 \leq N$ and $|\ell_1| + \cdots + |\ell_{r^*}| \leq r$, we have

$$|\ell_1 w_{j_1} + \dots + \ell_{r^*} w_{j_{r^*}}| \ge \beta_{r,N}.$$

It is important to note that this definition does not deal with multiplicities (we are in the case of distinct frequencies). To prove this condition we use the following tool taken from [8]:

Proposition 2.8. Let $r \geq 1$, $N \geq 1$ and $w \in \mathbb{R}^{\mathbb{N}^*}$. Suppose that:

i) the frequencies are weakly non-resonant, i.e. there exist $\alpha_{r^*} > 0$ and $\gamma_{r,N} > 0$ such that for all $1 \leq r^* \leq r$, $\ell \in (\mathbb{Z}^*)^{r^*}$ and all $j \in (\mathbb{N}^*)^{r^*}$ with $j_1 < \cdots < j_{r^*}$, $j_1 \leq N$ and $|\ell_1| + \cdots + |\ell_{r^*}| \leq r$, we have

$$\forall k \in \mathbb{Z}, \quad |k + \ell_1 w_{j_1} + \dots + \ell_r w_{j_{r^*}}| \ge \gamma_{r,N} j_{r^*}^{-\alpha_{r^*}}, \tag{14}$$

ii) the frequencies accumulate polynomially fast on \mathbb{Z} , i.e. there exists C>0 and $\nu>0$ such that

$$\forall j \ge 1, \exists k \in \mathbb{Z}, \quad |w_j - k| \le Cj^{-\nu}. \tag{15}$$

Then w is strongly N, r non-resonant.

Remark 2.9. I would like to mention that the first assumption is satisfied by many interesting Hamiltonians, for instance Beam and Klein-Gordon equations. However, the localization assumption is easier to check but seems to be more restrictive.

Proof. The proof is done by induction on r^* and is found in Proposition 2.1 of [8].

Our goal now will be to apply Proposition 2.8 and obtain the main result of this section, Proposition 2.17. To do so, we are going to concentrate in what follows on proving that the frequencies $(\Lambda_j)_{j\geq 1}$ satisfy the weak non-resonance condition. We start with some useful lemmas. In the first one, we express h_j^2 in terms of the Hilbertian basis $(h_{2k-1}(\cdot\sqrt{2})2^{1/4})_{k\geq 1}$. The process was inspired by the decomposition of the product of the Hermite functions $h_j(x)h_l(x)$. In the case where j=l, we obtain the result given as Proposition 5.5 in [23]:

Lemma 2.10. For all $j \geq 1$, we can write

$$h_j^2(x) = \sum_{k=1}^j \mu_{k,j} h_{2k-1}(x\sqrt{2}) 2^{1/4}$$

with

$$\mu_{k,j} = (2\pi)^{-1/4} \sqrt{\alpha_k} \alpha_{j-k+1}$$
 and $\alpha_j = \frac{(2j-2)!}{(j-1)!^2 4^{j-1}} \sim \frac{1}{\sqrt{\pi j}}$.

It is easy to establish bounds for this explicit form.

Corollary 2.11. There exists C > 0 such that for all $j \ge 1$ and $k \le j$, we have

$$\mu_{k,j} \le Cj^{-1/4}.$$

Moreover, for j = k we also have the lower bound

$$\mu_{j,j} \ge C^{-1} j^{-1/4}.$$

Proof. We write for $j \geq 1$ and $k \leq j$, $\mu_{k,j} = (2\pi)^{-1/4} \sqrt{\alpha_k} \alpha_{j-k+1} \leq \frac{C}{k^{1/4} (j-k)^{1/2}}$.

- If $k \geq j/2$, then $\mu_{k,j} \leq 2^{1/4}Cj^{-1/4}$,
- If $k \le j/2$, then $\mu_{k,j} \le 2^{1/2}Cj^{-1/2} \le Cj^{-1/4}$.

Moreover, by definition of α_j , we naturally have $\mu_{j,j} = (2\pi)^{-1/4} \sqrt{\alpha_j} \sim \frac{1}{(\pi_j)^{1/4}}$.

We are interested now in deducing an estimation on the derivative for $V \neq 0$.

Lemma 2.12. For all $\rho > 0$, there exists C > 0 such that for all $j \geq 1$, $k \geq 1$ and $\|V\|_{\widehat{H}^1} \leq \rho$, we have

$$\left| \frac{\partial \Lambda_j(V)}{\partial v_{2k-1}} - \mu_{k,j} \right| \le C j^{-1/12} \|V\|_{\widehat{H}^1}.$$

Proof. From (11) we have

$$\frac{\partial \Lambda_j(V)}{\partial v_{2k-1}} = \int_{\mathbb{R}} 2^{1/4} h_{2k-1}(x\sqrt{2}) \psi_j^2(x) \, \mathrm{d}x$$

and in particular by the decomposition from Lemma 2.10

$$\frac{\partial \Lambda_j(0)}{\partial v_{2k-1}} = \int_{\mathbb{R}} 2^{1/4} h_{2k-1}(x\sqrt{2}) h_j^2(x) \, \mathrm{d}x = \mu_{k,j}.$$

Furthermore, using Propostion 2.5 we have

$$\left| \int_{\mathbb{R}} h_{2k-1} (\psi_j^2 - h_j^2) \, \mathrm{d}x \right| \le \|h_{2k-1}\|_{L^{\infty}} \|\psi_j - h_j\|_{L^2} \|\psi_j + h_j\|_{L^2}$$

$$\le \|h_{2k-1}\|_{\widehat{H}^1} \|\psi_j - h_j\|_{L^2} (\|\psi_j\|_{L^2} + \|h_j\|_{L^2})$$

$$\le C \|\psi_j - h_j\|_{L^2}$$

$$\le C j^{-1/12} \|V\|_{\widehat{H}^1}.$$

Consequently, we easily deduce the needed estimation

$$\left| \int_{\mathbb{R}} 2^{1/4} h_{2k-1}(x\sqrt{2}) \psi_j^2(x) \, \mathrm{d}x - \int_{\mathbb{R}} 2^{1/4} h_{2k-1}(x\sqrt{2}) h_j^2(x) \, \mathrm{d}x \right| \le C j^{-1/12} \|V\|_{\widehat{H}^1}. \qquad \Box$$

Notations. We denote the small divisors by $\Omega_{j,\ell}(V) = \sum_{n=1}^{r^*} \ell_n \Lambda_{j_n}$.

The last part of this section is inspired by the work done for NLS defined on \mathbb{T} in [8].

Lemma 2.13. For all $1 \leq r^* \leq r$, there exists $\gamma_r > 0$ such that for all $\ell \in (\mathbb{Z}^*)^{r^*}$ and $j \in (\mathbb{N}^*)^{r^*}$ with $j_1 < \cdots < j_{r^*}$ and $|\ell_1| + \cdots + |\ell_{r^*}| \leq r$, there exists $k \lesssim_r j_1$ such that

$$\left| \frac{\partial \Omega_{j,\ell}(0)}{\partial v_{2k-1}} \right| = \left| \sum_{n=1}^{r^*} \ell_n \mu_{k,j_n} \right| \ge \gamma_r j_1^{-1/4}. \tag{16}$$

Proof. Fix $r \geq 1$. We proceed with the proof by induction on r^* . Initial Step: If $r^* = 1$, then for all $j_1 \in \mathbb{N}^*$ we have by Corollary 2.11

$$\left| \frac{\partial \Omega_{j,\ell}(0)}{\partial v_{2j_1-1}} \right| = |\ell_1 \mu_{j_1,j_1}| \gtrsim \frac{|\ell_1|}{j_1^{1/4}} \gtrsim j_1^{-1/4}.$$

Induction Step: Assume that the result holds for all $1 \le r^* \le r$, and we prove it for $r^* + 1$. Let $\ell \in (\mathbb{Z}^*)^{r^*+1}$ and $j \in (\mathbb{N}^*)^{r^*+1}$ be some indices satisfying $|\ell_1| + \cdots + |\ell_{r^*+1}| \le r$ and $j_1 < \cdots < j_{r^*}$ and suppose that there exists $k \le C_r j_1$ such that (16) holds.

• By Corollary 2.11, induction hypothesis and the fact that $|\ell_{r^*+1}| \leq r$, we have

$$\begin{vmatrix} \sum_{n=1}^{r^*+1} \ell_n \mu_{k,j_n} \end{vmatrix} = \begin{vmatrix} \sum_{n=1}^{r^*} \ell_n \mu_{k,j_n} + \ell_{r^*+1} \mu_{k,j_{r^*+1}} \end{vmatrix} \ge \begin{vmatrix} \sum_{n=1}^{r^*} \ell_n \mu_{k,j_n} \end{vmatrix} - \left| \ell_{r^*+1} \mu_{k,j_{r^*+1}} \right|$$

$$\ge \gamma_r j_1^{-1/4} - rC j_{r^*+1}^{-1/4}.$$

Hence, if we take $j_{r^*+1} > (2rC\gamma_r^{-1})^4 j_1$ we directly conclude that

$$\left| \sum_{n=1}^{r^*+1} \ell_n \mu_{k,j_n} \right| \ge \frac{\gamma_r}{2} j_1^{-1/4}.$$

• Now if $j_{r^*+1} \leq (2rC\gamma_r^{-1})^4 j_1$, we consider $\frac{\partial \Omega_{j,\ell}(0)}{\partial v_{2j_{r^*+1}-1}} = \ell_{r^*+1} \mu_{j_{r^*+1},j_{r^*+1}}$. Consequently, we obtain by Corollary 2.11 the result for $k = j_{r^*+1}$ and $\tilde{\gamma}_r = \frac{\gamma_r}{2r}$

$$\left| \frac{\partial \Omega_{j,\ell}(0)}{\partial v_{2j_{r^*+1}-1}} \right| \ge Cj_{r^*+1}^{-1/4} \ge \tilde{\gamma}_r j_1^{-1/4}.$$

After this, we obtain a similar estimation for $V \neq 0$.

Corollary 2.14. For all $1 \leq r^* \leq r$ and all $\ell \in (\mathbb{Z}^*)^{r^*}$, $j \in (\mathbb{N}^*)^{r^*}$ and $V \in \widehat{H}^1$ satisfying $j_1 < \cdots < j_{r^*}$, $|\ell|_1 \leq r$ and $||V||_{\widehat{H}^1} \leq \frac{\gamma_r}{2r} j_1^{-1/6}$ where γ_r is given by Lemma 2.13, there exists $k \lesssim_r j_1$ such that

$$\left| \frac{\partial \Omega_{j,\ell}(V)}{\partial v_{2k-1}} \right| \ge \frac{\gamma_r}{2} j_1^{-1/4}.$$

Proof. From Lemma 2.12, we have that

$$\left| \frac{\partial \sum_{n=1}^{r^*} \ell_n \Lambda_{j_n}(V)}{\partial v_{2k-1}} - \frac{\partial \sum_{n=1}^{r^*} \ell_n \Lambda_{j_n}(0)}{\partial v_{2k-1}} \right| \lesssim \frac{\|V\|_{\widehat{H}^1}}{j_1^{1/12}} |\ell_1| + \dots + \frac{\|V\|_{\widehat{H}^1}}{j_{r^*}^{1/12}} |\ell_{r^*}| \lesssim \frac{r\|V\|_{\widehat{H}^1}}{j_1^{1/12}}.$$

Thus, using Lemma 2.13 and the assumption $||V||_{\widehat{H}^1} \leq \frac{\gamma_r}{2r} j_1^{-1/6}$, we establish

$$\left| \frac{\partial \Omega_{j,\ell}(V)}{\partial v_{2k-1}} \right| \ge \left| \frac{\partial \Omega_{j,\ell}(0)}{\partial v_{2k-1}} - \frac{r \|V\|_{\widehat{H}^1}}{j_1^{1/12}} \right| \ge \left| \frac{\partial \Omega_{j,\ell}(0)}{\partial v_{2k-1}} \right| - \frac{r \|V\|_{\widehat{H}^1}}{j_1^{1/12}} \ge \frac{\gamma_r}{j_1^{1/12}} - \frac{\gamma_r}{2j_1^{1/4}} - \frac{\gamma_r}{2j_1^{1/4}} \ge \frac{\gamma_r}{2j_1^{1/4}}. \quad \Box$$

As a result, we obtain the necessary weak non-resonance condition presented in the next Proposition. Recall that here we are considering V as random potentials given in (12).

Proposition 2.15. For all $1 \leq r^* \leq r$ and $N \geq 1$, provided that $\|V\|_{\widehat{H}^1} \leq \frac{\gamma_r}{2r} N^{-1/6}$ where γ_r is given by Lemma [2.13], almost surely, there exists $\gamma_{r,N} > 0$ such that for all $\ell \in (\mathbb{Z}^*)^{r^*}$ and $j \in (\mathbb{N}^*)^{r^*}$ satisfying $j_1 < \cdots < j_{r^*}$ with $j_1 \leq N$ and $|\ell|_1 \leq r$, we have

$$|\Omega_{j,\ell}(V)| \ge \gamma_{r,N} j_{r^*}^{-2r^*}.$$

Proof. Being given j satisfying the above assumptions, we consider the index k given by Corollary 2.14. We aim at estimating

$$\mathbb{P}(\;|\Omega_{j,\ell}(V)|<\gamma\quad \text{ and } \quad \|V\|_{\widehat{H}^1}\leq \frac{\gamma_r}{2r}N^{-1/6}\;)$$

for $\gamma > 0$. For this and following (12), we write $V = g_{2k-1}h_{2k-1}(x\sqrt{2})P_{2k-1} + V_{2k-1}$ with g_{2k-1} and V_{2k-1} independent. Then, we get

$$\mathbb{P}(|\Omega_{j,\ell}(V)| < \gamma \quad \text{and} \quad ||V||_{\widehat{H}^1} \le \frac{\gamma_r}{2r} N^{-1/6}) \\
= \mathbb{E} \left[\int_{G_{2k-1} \in \mathcal{I}} \mathbb{1}_{\left| \Omega_{j,\ell}(G_{2k-1}h_{2k-1}(x\sqrt{2})P_{2k-1} + V_{2k-1}) \right| < \gamma} f(G_{2k-1}) dG_{2k-1} \right]$$

where $f(x) = \frac{1}{\sqrt{2\pi}}e^{-x^2/2}$ denotes the probability density function and the interval

$$\mathcal{I} := \{ G_{2k-1} \in \mathbb{R}, \quad \| G_{2k-1} h_{2k-1} (\cdot \sqrt{2}) P_{2k-1} + V_{2k-1} \|_{\widehat{H}^1}^2 \le \left(\frac{\gamma_r}{2r} N^{-1/6} \right)^2 \}.$$

Next, for $G_{2k-1} \in \mathcal{I}$, we apply a change of variable $y_{2k-1} = G_{2k-1}P_{2k-1} \in \tilde{\mathcal{I}}$ to get

$$\mathbb{P}(|\Omega_{j,\ell}(V)| < \gamma \quad \text{and} \quad ||V||_{\widehat{H}^1} \le \frac{\gamma_r}{2r} N^{-1/6}) \\
\le \frac{P_{2k-1}^{-1}}{\sqrt{2\pi}} \, \mathbb{E} \big[\int_{y_{2k-1} \in \widetilde{\mathcal{I}}} \mathbb{1}_{ |\Omega_{j,\ell}(y_{2k-1}h_{2k-1}(x\sqrt{2}) + V_{2k-1})| < \gamma} \, \mathrm{d}y_{2k-1} \big].$$

Now, notice that for $j_1 \leq N$, Corollary 2.14 gives that

$$\left| \frac{\partial \Omega_{j,\ell}(y_{2k-1}h_{2k-1}(x\sqrt{2}) + V_{2k-1})}{\partial y_{2k-1}} \right| \ge \frac{\gamma_r}{2} j_1^{-1/4} \ge \frac{\gamma_r}{2} N^{-1/4}. \tag{17}$$

So, since $\tilde{\mathcal{I}}$ is a random interval, then the map

$$\Phi: \left\{ \begin{array}{ccc} \tilde{\mathcal{I}} & \to & \mathcal{J} \\ y_{2k-1} & \mapsto & \Omega_{j,\ell}(y_{2k-1}h_{2k-1}(x\sqrt{2}) + V_{2k-1}) \end{array} \right.$$

is a diffeomorphism from $\tilde{\mathcal{I}}$ onto its image \mathcal{J} . Moreover, due to the fact that the function $\mathbb{1}_{\left|\Omega_{j,\ell}(y_{2k-1}h_{2k-1}(x\sqrt{2})+V_{2k-1})\right|<\gamma}$ is integrable on $\tilde{\mathcal{I}}$, we deduce by using the change of variable theorem that the function $\mathbb{1}_{\left|y_{2k-1}\right|<\gamma}\left|\frac{\partial\Omega_{j,\ell}(y_{2k-1}h_{2k-1}(x\sqrt{2})+V_{2k-1})}{\partial y_{2k-1}}\right|^{-1}$ is integrable on \mathcal{J} and we have

$$\int_{y_{2k-1}\in\tilde{\mathcal{I}}} \mathbb{1}_{\left|\Omega_{j,\ell}(y_{2k-1}h_{2k-1}(x\sqrt{2})+V_{2k-1})\right|<\gamma} dy_{2k-1}
= \int_{y_{2k-1}\in\mathcal{J}} \mathbb{1}_{\left|y_{2k-1}\right|<\gamma} \left| \frac{\partial\Omega_{j,\ell}(y_{2k-1}h_{2k-1}(x\sqrt{2})+V_{2k-1})}{\partial y_{2k-1}} \right|^{-1} dy_{2k-1}.$$
(18)

Thus, making use of (17) and (18), we obtain the following estimation

$$\mathbb{P}(|\Omega_{j,\ell}(V)| < \gamma \text{ and } ||V||_{\widehat{H}^{1}} \leq \frac{\gamma_{r}}{2r} N^{-1/6})
\leq P_{2k-1}^{-1} \mathbb{E} \left[\int_{y_{2k-1} \in \mathcal{J}} \mathbb{1}_{|y_{2k-1}| < \gamma} \left| \frac{\partial \Omega_{j,\ell}(y_{2k-1}h_{2k-1}(x\sqrt{2}) + V_{2k-1})}{\partial y_{2k-1}} \right|^{-1} dy_{2k-1} \right]
\leq 2P_{2k-1}^{-1} \mathbb{E} \left[\gamma_{r}^{-1} N^{1/4} \underbrace{\int_{y_{2k-1} \in \mathcal{J}} \mathbb{1}_{|y_{2k-1}| < \gamma} dy_{2k-1}}_{\leq 2\gamma} \right]
\leq 4\gamma_{r}^{-1} P_{2k-1}^{-1} N^{1/4} \gamma.$$

Using (13) and the fact that $k \lesssim_r N$, it is possible to control P_{2k-1}^{-1} independently from j. As a consequence, we get

$$\begin{split} & \mathbb{P}(\ \exists (r^*,\ell,j), \ |\Omega_{j,\ell}(V)| < \gamma j_{r^*}^{-2r^*} \quad \text{ and } \quad \|V\|_{\widehat{H}^1} \leq \frac{\gamma_r}{2r} N^{-1/6} \) \\ & \leq \sum_{(r^*,\ell,j)} \mathbb{P}(\ |\Omega_{j,\ell}(V)| < \gamma j_{r^*}^{-2r^*} \quad \text{ and } \quad \|V\|_{\widehat{H}^1} \leq \frac{\gamma_r}{2r} N^{-1/6} \) \\ & \lesssim_{r,N} 4\gamma_r^{-1} \left(\sum_{(r^*,\ell,j)} j_{r^*}^{-2r^*} \right) \gamma. \end{split}$$

The convergence of this last sum is related to the fact that j_{r^*} is the largest index⁹. So,

$$\mathbb{P}(\exists (r^*, \ell, j), |\Omega_{j,\ell}(V)| < \gamma j_{r^*}^{-2r^*} \text{ and } \|V\|_{\widehat{H}^1} \le \frac{\gamma_r}{2r} N^{-1/6}) \lesssim_{r,N} \gamma \xrightarrow{\text{as } \gamma \to 0} 0.$$

It is natural to conclude that since the probability vanishes, almost surely there exists $\gamma > 0$ depending on r, N and V such that for all (r^*, ℓ, j) satisfying the given assumptions, we have

$$|\Omega_{j,\ell}(V)| \ge \gamma j_{r^*}^{-2r^*}.$$

Now, we have reached the proof of Theorem 1.2 which is the main result of this section. More precisely, we obtain the strong N, r non-resonance condition of the frequencies $(w_j)_{j \in \mathbb{N}^*}$ of the quantum harmonic oscillator with a perturbation.

Proof of Theorem 1.2 To start, we can directly see that the localization hypothesis (15) on the spectrum is obtained in Lemma 2.3. So, the frequencies are close to integer values, and we have that there exists a constant C > 0 such that

$$\sigma(T+V) \subset \bigcup_{j \geq 1} \mathcal{Z}_j \text{ with } \mathcal{Z}_j := [2j-1-Cj^{-1/2}, 2j-1+Cj^{-1/2}].$$

We just proved (14) in Proposition 2.15 where we obtained a control of the small divisors by the smallest index involved. Finally, our result is a direct consequence of Proposition 2.8.

Remark 2.16. The key point related to our model is that the Birkhoff normal form procedure described in Section 4 involves small divisors defined by

$$\Omega_{j,l}(V) = w_{j_1} + \dots + w_{j_r} - w_{l_1} - \dots - w_{l_r}$$
(19)

where we recall that w is the sequence of frequencies of the perturbed harmonic oscillator. Furthermore, a same term may appear both with a positive and a negative sign. Therefore, it would be sufficient to define the minimum index as follows:

$$\kappa(j,l) = \min\{ s_i := j_i \mid l_i, \ 1 \le i \le r \text{ and } \sum_{n=1}^r (\mathbb{1}_{j_n = s_i} - \mathbb{1}_{l_n = s_i}) \ne 0 \} \cup \{\infty\}.$$
 (20)

As a result, we establish a generalisation to Definition 2.7 and a suitable formalism for the Birkhoff normal form process by providing a uniform bound for the small divisors $\Omega_{j,l}(V)$ given in (19).

Proposition 2.17. Let V be given in (12). For all $r, N \geq 1$, provided that $||V||_{\widehat{H}^1} \lesssim_r N^{-1/6}$, there exists $\beta_{r,N} > 0$ such that for all $j,l \in (\mathbb{N}^*)^r$, if $\kappa(j,l) \leq N$, we either have

$$|\Omega_{j,l}(V)| \ge \beta_{r,N}$$

or the small divisor is trivial and we write, in this case, $\kappa(j,l) = \infty$.

Remark 2.18. We notice that this control rather than the control of the small divisors by the third largest index (standard non-resonance condition) will allow us to remove much more terms when solving the cohomological equations in the Birkhoff normal form process.

⁹Note that the sum with respect to r^* and ℓ is finite.

3 Hamiltonian formalism

We are going to introduce here a Hamiltonian class which plays an important role in classifying the Hamiltonian polynomials arising in the proof of the Birkhoff normal form theorem. Roughly speaking, the Hamiltonian polynomials in the normal form process are controlled by the \mathscr{H} -norm whereas the solutions to the cohomological equation are controlled by the \mathscr{H} -norm (see Definition 3.6).

3.1 Functional setting

We fix M>1, and we note that we are working in finite dimension. In other words, $h^{1/2}(\llbracket 1,M\rrbracket)\equiv \mathbb{C}^{\llbracket 1,M\rrbracket}$ is a finite dimensional vector space.

Definition 3.1. (Natural Scalar Product) We equip $\ell^2([1, M])$ with its natural real scalar product

$$(u,v)_{\ell^2} := \sum_{k \in \llbracket 1,M \rrbracket} \Re \, \overline{u_k} v_k = \sum_{k \in \llbracket 1,M \rrbracket} \Re \, u_k \Re \, v_k + \Im \, u_k \Im \, v_k \in \mathbb{R}.$$

Definition 3.2. (Poisson Bracket) Let $H, K : \mathbb{C}^{[\![1,M]\!]} \to \mathbb{R}$ be two smooth functions. Then the Poisson bracket of H and K is defined by:

$$\{H, K\}(u) := (i\nabla H(u), \nabla K(u))_{\ell^2}$$

where $\nabla H(u) = 2(\partial_{\overline{u_k}} H(u))_k$.

Lemma 3.3. We have the following identity

$$\{H,K\}(u) = 2i \sum_{k \in [1,M]} \partial_{\overline{u_k}} H(u) \partial_{u_k} K(u) - \partial_{u_k} H(u) \partial_{\overline{u_k}} K(u).$$

Proof. To see this, we write using the definition

$$\{H,K\}(u) = (i\nabla H(u), \nabla K(u))_{\ell^2} = 4\sum_{k \in \mathbb{I}_1.M\mathbb{I}} \Re i\partial_{\overline{u_k}} H(u) \overline{\partial_{\overline{u_k}} K(u)}.$$

By simple calculations, one can prove that

$$4\Re i\partial_{\overline{u_k}}H(u)\overline{\partial_{\overline{u_k}}K(u)} = 2i[\partial_{\overline{u_k}}H(u)\partial_{u_k}K(u) - \partial_{u_k}H(u)\partial_{\overline{u_k}}K(u)]. \qquad \Box$$

Definition 3.4. (Symplectic Map) Consider an open set \mathcal{C} of $\mathbb{C}^{[\![1,M]\!]}$ and a C^1 map $\tau:\mathcal{C}\to\mathbb{C}^{[\![1,M]\!]}$. We say that τ is a symplectic map if

$$\forall u \in \mathcal{C}, \forall v, w \in \mathbb{C}^{\llbracket 1, M \rrbracket}, \ (iv, w)_{\ell^2} = (i \mathrm{d}\tau(u)(v), \mathrm{d}\tau(u)(w))_{\ell^2}.$$

3.2 Class of Hamiltonian functions

Definition 3.5. (Class \mathscr{H}_{M}^{2r}) Being given M > 1 and $r \geq 1$, we denote by \mathscr{H}_{M}^{2r} the set of real valued homogeneous polynomials of degree 2r defined on $\mathbb{C}^{\llbracket 1,M\rrbracket}$ and commuting with the norm $\|\cdot\|_{\ell^{2}}^{2}$. These Hamiltonians are uniquely written as

$$H(u) = \sum_{j,l \in [1,M]^r} H_{j,l} u_{j_1} \cdots u_{j_r} \overline{u_{l_1}} \cdots \overline{u_{l_r}}$$

where $(H_{j,l})_{(j,l)\in [\![1,M]\!]^r\times [\![1,M]\!]^r}$ is a sequence of complex numbers satisfying:

• the reality condition

$$H_{j,l} = \overline{H_{l,j}}$$

• the symmetry condition

$$\forall (\phi, \psi) \in \mathscr{S}_r \times \mathscr{S}_r, \quad H_{j_1, \dots, j_r, l_1, \dots l_r} = H_{j_{\phi_1}, \dots, j_{\phi_r}, l_{\psi_1}, \dots l_{\psi_r}}$$

We endow this space of polynomials with the two following norms $\|\cdot\|_{\mathscr{H}}$ and $\|\cdot\|_{\mathscr{C}}$.

Definition 3.6. (Norms $\|\cdot\|_{\mathscr{H}}$ and $\|\cdot\|_{\mathscr{C}}$) Let $M>1, r\geq 1$ and $H,\chi\in\mathscr{H}_M^{2r}$. We introduce the norms

$$||H||_{\mathscr{H}} := \sup_{j,l \in \llbracket 1,M \rrbracket^r} |H_{j,l}|$$

and

$$\|\chi\|_{\mathscr{C}} := \sup_{j,l \in [1,M]^r} |\chi_{j,l}| \langle j_1 + \dots + j_r - l_1 - \dots - l_r \rangle.$$

We will show two essential lemmas needed to establish the continuity estimates enjoyed by the Hamiltonians. The first lemma states the following:

Lemma 3.7. For a Hamiltonian $H \in \mathscr{H}_{M}^{2r}$ and $u^{(1)}, \dots, u^{(2r)} \in \mathbb{C}^{[1,M]}$, we have

$$\sum_{j,l \in [\![1,M]\!]^r} \left| H_{j,l} u_{j_1}^{(1)} \cdots u_{j_r}^{(r)} \overline{u_{l_1}^{(r+1)}} \cdots \overline{u_{l_r}^{(2r)}} \right| \le (\log M)^r \|H\|_{\mathscr{H}} \prod_{i=1}^{2r} \|u^{(i)}\|_{h^{1/2}}.$$

Proof. Let $H \in \mathcal{H}_M^{2r}$ and $u^{(1)}, \dots, u^{(2r)} \in \mathbb{C}^{[\![1,M]\!]}$. We then write

$$\sum_{j,l \in [\![1,M]\!]^r} \left| H_{j,l} u_{j_1}^{(1)} \cdots u_{j_r}^{(r)} \overline{u_{l_1}^{(r+1)}} \cdots \overline{u_{l_r}^{(2r)}} \right| \leq \sum_{j,l \in [\![1,M]\!]^r} |\!| H |\!|_{\mathscr{H}} \left| u_{j_1}^{(1)} \right| \cdots \left| u_{j_r}^{(r)} \right| \left| \overline{u_{l_1}^{(r+1)}} \right| \cdots \left| \overline{u_{l_r}^{(2r)}} \right| \\
\leq |\!| H |\!|_{\mathscr{H}} \prod_{i=1}^{2r} \left(\sum_{k \in [\![1,M]\!]} \langle k \rangle^{1/2} \left| u_k^{(i)} \right| \frac{1}{\langle k \rangle^{1/2}} \right).$$

By Cauchy–Schwarz inequality and the fact that $\sum_{k \in [1,M]} \frac{1}{\langle k \rangle} \lesssim \log M$, we obtain

$$\sum_{j,l \in [\![1,M]\!]^r} \left| H_{j,l} u_{j_1}^{(1)} \cdots u_{j_r}^{(r)} \overline{u_{l_1}^{(r+1)}} \cdots \overline{u_{l_r}^{(2r)}} \right| \leq \|H\|_{\mathscr{H}} \left(\sum_{k \in [\![1,M]\!]} \frac{1}{\langle k \rangle} \right)^r \prod_{i=1}^{2r} \left(\sum_{k \in [\![1,M]\!]} \langle k \rangle \left| u_k^{(i)} \right|^2 \right)^{1/2} \\
\lesssim (\log M)^r \|H\|_{\mathscr{H}} \prod_{i=1}^{2r} \|u^{(i)}\|_{h^{1/2}}.$$

The second lemma seems a bit more complicated and writes as follows:

Lemma 3.8. For all $u^{(1)}, \dots, u^{(2r)} \in \mathbb{C}^{\llbracket 1, M \rrbracket}$, we have

$$\sum_{j,l \in [\![1,M]\!]^r} \frac{1}{\langle j_1 + \dots + j_r - l_1 - \dots - l_r \rangle} \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \left| u_{l_i}^{(r+i)} \right| \lesssim_r (\log M)^r \|u^{(2r)}\|_{h^{-1/2}} \prod_{i=1}^{2r-1} \|u^{(i)}\|_{h^{1/2}}.$$

Proof. Denote $v_k := \langle k \rangle^{-1/2} u_k^{(2r)}$ and $j_0 = -(j_1 + \dots + j_r - l_1 - \dots - l_r)$. We can easily notice that $||v||_{\ell^2} = ||u^{(2r)}||_{h^{-1/2}}$, and we write

$$\sum_{j,l \in [\![1,M]\!]^r} \frac{1}{\langle j_1 + \dots + j_r - l_1 - \dots - l_r \rangle} \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \left| u_{l_i}^{(r+i)} \right| \\
= \sum_{j,l \in [\![1,M]\!]^r} \frac{1}{\langle j_0 \rangle} \langle l_r \rangle^{1/2} \left| v_{l_r} \right| \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \prod_{i=1}^{r-1} \left| u_{l_i}^{(r+i)} \right|.$$

Now, in order to get rid of the term $\langle l_r \rangle^{1/2}$, we use Jensen's formula to obtain

$$\langle l_r \rangle^{1/2} = \langle j_0 + \dots + j_r - l_1 - \dots - l_{r-1} \rangle^{1/2} \le (\langle j_0 \rangle + \dots + \langle l_{r-1} \rangle)^{1/2} \le \sum_{n=0}^r \langle j_n \rangle^{1/2} + \sum_{n=1}^{r-1} \langle l_n \rangle^{1/2}.$$

Consequently, we get

$$\sum_{j,l \in [\![1,M]\!]^r} \frac{1}{\langle j_1 + \dots + j_r - l_1 - \dots - l_r \rangle} \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \left| u_{l_i}^{(r+i)} \right| \\
\leq \sum_{j,l \in [\![1,M]\!]^r} \frac{1}{\langle j_0 \rangle} \left(\sum_{n=0}^r \langle j_n \rangle^{1/2} + \sum_{n=1}^{r-1} \langle l_n \rangle^{1/2} \right) |v_{l_r}| \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \prod_{i=1}^{r-1} \left| u_{l_i}^{(r+i)} \right| \\
\leq \sum_{j,l \in [\![1,M]\!]^r} \left[\frac{1}{\langle j_0 \rangle^{1/2}} + \frac{1}{\langle j_0 \rangle} \left(\sum_{n=1}^r \langle j_n \rangle^{1/2} + \sum_{n=1}^{r-1} \langle l_n \rangle^{1/2} \right) \right] |v_{l_r}| \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \prod_{i=1}^{r-1} \left| u_{l_i}^{(r+i)} \right|.$$

Notice that

$$\left(\sum_{n=1}^{r} \langle j_n \rangle^{1/2}\right) \prod_{i=1}^{r} \left| u_{j_i}^{(i)} \right| \prod_{i=1}^{r-1} \left| u_{l_i}^{(r+i)} \right| = \left(\sum_{n=1}^{r} \langle j_n \rangle^{1/2} \left| u_{j_n}^{(n)} \right| \prod_{\substack{i=1 \ i \neq n}}^{r} \left| u_{j_i}^{(i)} \right| \right) \prod_{i=1}^{r-1} \left| u_{l_i}^{(r+i)} \right|$$

and similarly that

$$\left(\sum_{n=1}^{r-1} \langle l_n \rangle^{1/2}\right) \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \prod_{i=1}^{r-1} \left| u_{l_i}^{(r+i)} \right| = \left(\sum_{n=1}^{r-1} \langle l_n \rangle^{1/2} \left| u_{l_n}^{(r+n)} \right| \prod_{\substack{i=1\\i\neq n}}^{r-1} \left| u_{l_i}^{(r+i)} \right| \right) \prod_{i=1}^r \left| u_{j_i}^{(i)} \right|.$$

Thus, we obtain

$$\sum_{j,l \in [\![1,M]\!]^r} \frac{1}{\langle j_1 + \dots + j_r - l_1 - \dots - l_r \rangle} \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \left| u_{l_i}^{(r+i)} \right| \\
\leq \sum_{j,l \in [\![1,M]\!]^r} \frac{1}{\langle j_0 \rangle^{1/2}} \left| v_{l_r} \right| \prod_{i=1}^r \left| u_{j_i}^{(i)} \right| \prod_{i=1}^{r-1} \left| u_{l_i}^{(r+i)} \right| \\
+ \sum_{j,l \in [\![1,M]\!]^r} \left| v_{l_r} \right| \frac{1}{\langle j_0 \rangle} \left(\sum_{n=1}^r \langle j_n \rangle^{1/2} \left| u_{j_n}^{(n)} \right| \prod_{\substack{i=1\\i \neq n}}^r \left| u_{j_i}^{(i)} \right| \right) \prod_{i=1}^{r-1} \left| u_{l_i}^{(r+i)} \right| \\
+ \sum_{j,l \in [\![1,M]\!]^r} \left| v_{l_r} \right| \frac{1}{\langle j_0 \rangle} \left(\sum_{n=1}^{r-1} \langle l_n \rangle^{1/2} \left| u_{l_n}^{(r+n)} \right| \prod_{\substack{i=1\\i \neq n}}^r \left| u_{l_i}^{(r+i)} \right| \right) \prod_{i=1}^r \left| u_{j_i}^{(i)} \right|.$$

It turns out that the sum we aim at estimating writes as a convolution product, and the needed result is just a consequence of Young's convolution inequality

$$\ell^2 * \ell^2 * \ell^1 * \cdots * \ell^1 \hookrightarrow \ell^\infty$$
.

Therefore (21) can be expressed as

$$\left[|v| * \langle \cdot \rangle^{-1/2} * \left| u^{(1)} \right| * \cdots * \left| u^{(2r-1)} \right| \right]_{0}$$

$$+ \left[\sum_{n=1}^{r} |v| * \langle \cdot \rangle^{1/2} \left| u^{(n)} \right| * \langle \cdot \rangle^{-1} * \left(\bigwedge_{\substack{i=1 \ i \neq n}}^{r} \left| u_{j_{i}}^{(i)} \right| \right) * \left(\bigwedge_{i=1}^{r-1} \left| u_{l_{i}}^{(r+i)} \right| \right) \right]_{0}$$

$$+ \left[\sum_{n=1}^{r-1} |v| * \langle \cdot \rangle^{1/2} \left| u^{(r+n)} \right| * \langle \cdot \rangle^{-1} * \left(\bigwedge_{\substack{i=1 \ i \neq n}}^{r-1} \left| u_{l_{i}}^{(r+i)} \right| \right) * \left(\bigwedge_{\substack{i=1 \ i \neq n}}^{r} \left| u_{j_{i}}^{(i)} \right| \right) \right]_{0}$$

$$\leq \|v\|_{\ell^{2}} \|\langle \cdot \rangle^{-1/2} \|_{\ell^{2}} \prod_{i=1}^{2r-1} \|u^{(i)}\|_{\ell^{1}} + \sum_{n=1}^{r} \|v\|_{\ell^{2}} \|\langle \cdot \rangle^{1/2} u^{(n)} * \langle \cdot \rangle^{-1} \|_{\ell^{2}} \prod_{\substack{i=1 \ i \neq n}}^{r} \|u^{(i)}\|_{\ell^{1}} \prod_{i=1}^{r-1} \|u^{(r+i)}\|_{\ell^{1}}$$

$$+ \sum_{n=1}^{r-1} \|v\|_{\ell^{2}} \|\langle \cdot \rangle^{1/2} u^{(r+n)} * \langle \cdot \rangle^{-1} \|_{\ell^{2}} \prod_{\substack{i=1 \ i \neq n}}^{r-1} \|u^{(r+i)}\|_{\ell^{1}} \prod_{i=1}^{r} \|u^{(i)}\|_{\ell^{1}}.$$

We are left with proving the following estimates for the ℓ^1 -norm and the ℓ^2 -norm. Estimate of $||u^{(i)}||_{\ell^1}$: Using Cauchy–Schwarz inequality, we get

$$\|u^{(i)}\|_{\ell^1} = \left\|u^{(i)} \frac{\langle \cdot \rangle^{1/2}}{\langle \cdot \rangle^{1/2}}\right\|_{\ell^1} \le \|u^{(i)}\|_{h^{1/2}} \|\langle \cdot \rangle^{-1/2}\|_{\ell^2} \le (\log M)^{1/2} \|u^{(i)}\|_{h^{1/2}}.$$

Estimate of $\|\langle \cdot \rangle^{1/2} u^{(n)} * \langle \cdot \rangle^{-1} \|_{\ell^2}$: Apply Young's convolution inequality $\ell^2 * \ell^1 \hookrightarrow \ell^2$ to get

$$\|\langle \cdot \rangle^{1/2} u^{(n)} * \langle \cdot \rangle^{-1} \|_{\ell^2} \le \|\langle \cdot \rangle^{1/2} u^{(n)} \|_{\ell^2} \|\langle \cdot \rangle^{-1} \|_{\ell^1} \le (\log M) \|u^{(n)}\|_{h^{1/2}}.$$

Now we turn to the estimate on the gradient provided by the \mathcal{H} -norm and an even better estimate provided by the \mathcal{C} -norm.

Proposition 3.9. Let $M \geq 2$, $r \geq 1$. For all $H \in \mathcal{H}_M^{2r}$, the gradient of H is a smooth function enjoying the bound

$$\forall u \in \mathbb{C}^{[\![1,M]\!]}, \quad \|\nabla H(u)\|_{h^{-1/2}} \lesssim_r (\log M)^r \|H\|_{\mathscr{H}} \|u\|_{h^{1/2}}^{2r-1}.$$

Proof. The proof is obtained by duality. We fix $v \in \mathbb{C}^{[1,M]}$, and we write

$$\|\nabla H(u)\|_{h^{-1/2}} = \sup_{\|v\|_{h^{1/2}} \le 1} |(\nabla H(u), v)_{\ell^2}|.$$

Notice that since

$$(\nabla H(u), v)_{\ell^2} = 2r \sum_{j,l \in [1,M]^r} \Re \left[H_{j,l} u_{j_1} \cdots u_{j_r} \overline{u_{l_1}} \cdots \overline{v_{l_r}} \right],$$

then the needed result is a direct corollary of Lemma 3.7.

Proposition 3.10. Let $M \geq 2$, $r \geq 1$. For all $\chi \in \mathscr{H}_{M}^{2r}$ and all $u \in \mathbb{C}^{[1,M]}$, the gradient of χ enjoys the bounds

$$\|\nabla \chi(u)\|_{h^{1/2}} \lesssim_r (\log M)^r \|\chi\|_{\mathscr{C}} \|u\|_{h^{1/2}}^{2r-1}$$

and

$$\|\mathrm{d}\nabla\chi(u)\|_{\mathcal{L}(h^{1/2})} \lesssim_r (\log M)^r \|\chi\|_{\mathscr{C}} \|u\|_{h^{1/2}}^{2r-2}.$$

Proof. It is similar to the proof of Proposition 3.9, except that we use Lemma 3.8 instead of Lemma 3.7.

As a consequence, the second estimate of Proposition 3.10 can be written in the negative Sobolev space $h^{-1/2}$ as follows:

Corollary 3.11. Let $M \geq 2$, $r \geq 1$. For all $\chi \in \mathscr{H}_{M}^{2r}$ and all $u \in \mathbb{C}^{[1,M]}$, we have

$$\|d\nabla \chi(u)\|_{\mathcal{L}(h^{-1/2})} \lesssim_r (\log M)^r \|\chi\|_{\mathscr{C}} \|u\|_{h^{1/2}}^{2r-2}.$$

Proof. The proof uses a standard duality argument and is found in [9] Corollary 4.7.

Now, we introduce the flow generated by a Hamiltonian belonging to \mathscr{H}_{M}^{2r} .

Lemma 3.12. Let $M \geq 2$, $r \geq 2$ and $\chi \in \mathcal{H}_M^{2r}$. Then there exists

$$\varepsilon_1 = \left(K(\log M)^{(2r-1)/2} \|\chi\|_{\mathscr{C}}\right)^{-1/(2r-2)}$$

where K depends on r, and there exists a smooth map

$$\phi_{\chi} : \left\{ \begin{array}{ccc} [-1,1] \times B_{\mathbb{C}^{[1,M]}}(0,\varepsilon_{1}) & \to & \mathbb{C}^{[1,M]} \\ (t,u) & \mapsto & \phi_{\chi}^{t}(u) \end{array} \right.$$

solving the equation $-i\partial_t\phi_\chi=(\nabla\chi)\circ\phi_\chi$ and satisfying for all $t\in[-1,1]$ the following:

- $\text{1. close to the identity: } \forall u \in B_{\mathbb{C}^{[1,M]}}(0,\varepsilon_1), \ \|\phi_{\chi}^t(u) u\|_{h^{1/2}} \leq \left(\frac{\|u\|_{h^{1/2}}}{\varepsilon_1}\right)^{2r-2} \|u\|_{h^{1/2}},$
- $2. \ \ invertible: \ \|\phi_\chi^{-t}(u)\|_{h^{1/2}} < \varepsilon_1 \ \Longrightarrow \ \phi_\chi^t \circ \phi_\chi^{-t}(u) = u,$
- 3. symplectic: recall Definition 3.4.

Moreover, its differential is a continuous map and enjoys the bound:

$$\forall u \in B_{\mathbb{C}^{[1,M]}}(0,\varepsilon_1), \forall \sigma \in \{-1,1\}, \ \|\mathrm{d}\phi_\chi^t(u)\|_{\mathscr{L}(h^{\sigma/2})} \leq 2.$$

Proof. We refer the reader to the proof of Proposition 4.8 in [9].

We shall prove after this that the Hamiltonians are stable by the poisson brackets.

Proposition 3.13. Let $H \in \mathcal{H}_M^{2r}$ and $\chi \in \mathcal{H}_M^{2r'}$ with $r, r' \geq 1$. Then, there exists a Hamiltonian $N \in \mathcal{H}_M^{2r+2r'-2}$ such that

$$\forall u \in \mathbb{C}^{[1,M]}, \quad \{H,\chi\}(u) = N(u)$$

and

$$\|\{H,\chi\}\|_{\mathscr{H}} \lesssim_r \log M \|H\|_{\mathscr{H}} \|\chi\|_{\mathscr{C}}.$$

Proof. Let $u \in \mathbb{C}^{[1,M]}$. We express the Hamiltonians as

$$H(u) = \sum_{j,l \in \llbracket 1,M \rrbracket^r} H_{j,l} u_{j_1} \cdots u_{j_r} \overline{u_{l_1}} \cdots \overline{u_{l_r}} \quad \text{and} \quad \chi(u) = \sum_{j',l' \in \llbracket 1,M \rrbracket^{r'}} \chi_{j',l'} u_{j'_1} \cdots u_{j'_{r'}} \overline{u_{l'_1}} \cdots \overline{u_{l'_{r'}}}.$$

By Lemma 3.3, we have

$$\{H,\chi\}(u) = 2i \sum_{k \in [1,M]} \partial_{\overline{u_k}} H(u) \partial_{u_k} \chi(u) - \partial_{u_k} H(u) \partial_{\overline{u_k}} \chi(u).$$

Using the symmetry condition satisfied by the coefficients of H and χ , we get

$$\partial_{\overline{u_k}} H(u) \partial_{u_k} \chi(u) = rr' \sum_{\substack{j \in [\![1,M]\!]^r \\ l \in [\![1,M]\!]^{r-1} \\ j' \in [\![1,M]\!]^{r'-1} \\ l' \in [\![1,M]\!]^{r'}}} H_{j,l,k} u_{j_1} \cdots u_{j_r} \overline{u_{l_1}} \cdots \overline{u_{l_{r-1}}} \chi_{j',k,l'} u_{j'_1} \cdots u_{j'_{r'-1}} \overline{u_{l'_1}} \cdots \overline{u_{l'_{r'}}}.$$

Now, we set j'' := (j, j'), l'' := (l, l') and r'' := r + r' - 1. After reindexing, we can see that

$$\{H,\chi\}(u) = 2i \sum_{k \in [\![1,M]\!]^r} \left[rr' \sum_{\substack{j \in [\![1,M]\!]^{r-1} \\ l' \in [\![1,M]\!]^{r'-1} \\ l' \in [\![1,M]\!]^{r'}}} H_{j,l,k} u_{j_1} \cdots u_{j_r} \overline{u_{l_1}} \cdots \overline{u_{l_{r-1}}} \chi_{j',k,l'} u_{j'_1} \cdots u_{j'_{r'-1}} \overline{u_{l'_1}} \cdots \overline{u_{l'_{r'}}} \right]$$

$$- rr' \sum_{\substack{j \in [\![1,M]\!]^{r-1} \\ l \in [\![1,M]\!]^r \\ j' \in [\![1,M]\!]^{r'}}} H_{j,k,l} u_{j_1} \cdots u_{j_{r-1}} \overline{u_{l_1}} \cdots \overline{u_{l_r}} \chi_{j',l',k} u_{j'_1} \cdots u_{j'_{r'}} \overline{u_{l'_1}} \cdots \overline{u_{l'_{r'-1}}} \right]$$

$$= \sum_{\substack{j'',l'' \in [\![1,M]\!]^{r''} \\ l' \in [\![1,M]\!]^{r''}}} \underbrace{\left(2irr' \sum_{k \in [\![1,M]\!]} H_{j,l,k} \chi_{j',k,l'} - H_{j,k,l} \chi_{j',l',k}} \right) u_{j''_1} \cdots u_{j''_{r''}} \overline{u_{l''_1}} \cdots \overline{u_{l''_{r''}}}} .$$

Note that we can interchange the order of summation since we are dealing with finite sums. Moreover, we can obviously see that N(u) defines a homogeneous polynomial of degree 2r'' (i.e. $N \in \mathscr{H}_M^{2r''})^{10}$. On the other hand, we need to verify the upper bound on the \mathscr{H} -norm. For this, we write

$$\sum_{k \in [\![1,M]\!]} |H_{j,k,l} \chi_{j',l',k}| \le \sum_{k \in [\![1,M]\!]} ||H||_{\mathscr{H}} ||\chi||_{\mathscr{C}} \frac{1}{\langle j'_1 + \dots + j'_{r'} - l'_1 - \dots - k \rangle}.$$

By direct calculations, we have the estimation

$$\sum_{k \in \llbracket 1, M \rrbracket} \frac{1}{\langle j_1' + \dots + j_{r'}' - l_1' - \dots - k \rangle} \leq \sum_{k \in \llbracket 1, M \rrbracket} \frac{1}{\langle k \rangle} \lesssim \log M.$$

As a result, taking the norm of the poisson bracket we obtain

$$\|\{H,\chi\}\|_{\mathscr{H}} = \sup_{j'',l'' \in [1,M]^{r''}} |N_{j'',l''}| \lesssim_{r,r'} \log M \|H\|_{\mathscr{H}} \|\chi\|_{\mathscr{C}}.$$

¹⁰Both the symmetry and reality conditions of $N_{j'',l''}$ are a direct consequence of those satisfied by $H_{j,l}$ and $\chi_{j',l'}$.

4 Birkhoff normal form theorem

Now, we present Birkhoff normal form theorem in low regularity developed by Bernier and Grébert in [8] and provide a rigorous proof following the techniques from [9]. It plays an essential role to help us prove our main result. To start, consider $C_0 > 0$ and a polynomial Hamiltonian

$$H: \mathbb{C}^{[1,M]} \mapsto \mathbb{R}$$
 with $H = Z_2 + P$

where Z_2 is a quadratic Hamiltonian of the form $Z_2:\mathbb{C}^{[\![1,M]\!]}\to\mathbb{R}$ written as

$$Z_2(u) = \frac{1}{2} \sum_{j \in [1,M]} w_j |u_j|^2$$

with w_j being the frequencies of (NLS) satisfying the non-resonant condition (in the sense of Proposition 2.17). Moreover, P is a polynomial Hamiltonian of degree $2p + 2 \ge 4$ satisfying

$$P \in \mathscr{H}_{M}^{2p+2}$$
 and $\|P\|_{\mathscr{H}} \le C_0$.

Then the theorem writes:

Theorem 4.1. Let $r \geq 1$ and $N \geq 1$. There exist two positive constants C and b, such that for every $M \geq 2$ and every polynomial Hamiltonian H described above, we can find $\varepsilon_0 \geq 1/(C(\log M)^b)$ and two smooth symplectic maps $\tau^{(0)}$ and $\tau^{(1)}$ defined on $B_{\mathbb{C}^{[1,M]}}(0,\varepsilon_0)$ and $B_{\mathbb{C}^{[1,M]}}(0,2\varepsilon_0)$ respectively, satisfying the close to the identity property

$$\forall \sigma \in \{0, 1\}, \|u\|_{h^{1/2}} < 2^{\sigma} \varepsilon_0 \implies \|\tau^{(\sigma)}(u) - u\|_{h^{1/2}} \le \left(\frac{\|u\|_{h^{1/2}}}{2^{\sigma} \varepsilon_0}\right)^{2p} \|u\|_{h^{1/2}}$$
 (22)

and making the following diagram to commute

$$B_{\mathbb{C}^{[\![1,M]\!]}}(0,\varepsilon_0) \xrightarrow{\tau^{(0)}} B_{\mathbb{C}^{[\![1,M]\!]}}(0,2\varepsilon_0) \xrightarrow{\tau^{(1)}} \mathbb{C}^{[\![1,M]\!]}$$

such that $(Z_2 + P) \circ \tau^{(1)}$ admits on $B_{\mathbb{C}^{[1,M]}}(0,2\varepsilon_0)$ the following decomposition

$$(Z_2 + P) \circ \tau^{(1)} = Z_2 + \underbrace{Q^{(2p+2)} + \dots + Q^{(2r+2p)}}_{:=Q} + R$$
 (23)

where Q is a polynomial of degree 2(r+p) commuting with the low actions given by $I_{\ell}(u) = |u_{\ell}|^2$ with $\ell \leq N$. In other words, we have the property

$$\forall \ell \geq 1, \ \ell \leq N \implies \{I_{\ell}, Q\} = 0.$$

Besides, the remainder term R is a smooth function on $B_{\mathbb{C}[1,M]}(0,2\varepsilon_0)$ satisfying

$$\|\nabla R(u)\|_{h^{-1/2}} \le C(\log M)^b \|u\|_{h^{1/2}}^{2r+2p}.$$

Moreover, for $\sigma \in \{0,1\}$ and $u \in B_{\mathbb{C}[1,M]}(0,2^{\sigma}\varepsilon_0)$, $d\tau^{(\sigma)}(u)$ satisfies the bounds

$$\|d\tau^{(\sigma)}(u)\|_{\mathscr{L}(h^{1/2})} \le 4^r \quad and \quad \|d\tau^{(\sigma)}(u)\|_{\mathscr{L}(h^{-1/2})} \le 4^r.$$
 (24)

Proof. We proceed with the proof by induction on $r_* \in [p+1, r+p+1]$. Notice that for $r_* = p+1$, we have nothing to do and the proof is direct. Indeed, we can set

$$\tau^{(0)} = \tau^{(1)} = \mathrm{id}_{\mathbb{C}[1,M]}, \quad R = 0, \quad b = 0, \quad Q = P.$$

Now, we turn to the induction step. We assume that the result is true for r_* and prove it for r_*+1 . More precisely, we assume that there exists two positive constants C and b, such that for every $M \geq 2$ and every polynomial Hamiltonian H, we can find $\varepsilon_0 \geq 1/(C(\log M)^b)$ and two smooth symplectic close to the identity maps $\tau^{(0)}$ and $\tau^{(1)}$ making the above diagram commute such that $(Z_2 + P) \circ \tau^{(1)}$ admits on $B_{\mathbb{C}\mathbb{I}^{1,M}\mathbb{I}}(0, 2\varepsilon_0)$ the following decomposition

$$(Z_2 + P) \circ \tau^{(1)} = Z_2 + Q^{(2p+2)} + \dots + Q^{(2r+2p)} + R$$

where every $Q^{(n)} \in \mathscr{H}_M^n$ is a polynomial Hamiltonian of degree n satisfying $\|Q^{(n)}\|_{\mathscr{H}} \leq C(\log M)^b$ and commuting with the low actions, i.e.

$$\forall n < 2r_*, \forall \ell \ge 1, \ \ell \le N \implies \{J_\ell, Q^{(n)}\} = 0.$$

Besides, the remainder term R is a smooth function on $B_{\mathbb{C}[1,M]}(0,2\varepsilon_0)$ satisfying

$$\|\nabla R(u)\|_{h^{-1/2}} \le C(\log M)^b \|u\|_{h^{1/2}}^{2r+2p}.$$

Moreover, for $\sigma \in \{0,1\}$ and $u \in B_{\mathbb{CI}^{1,M}}(0,2^{\sigma}\varepsilon_{0}), d\tau^{(\sigma)}(u)$ satisfies the bounds

$$\|d\tau^{(\sigma)}(u)\|_{\mathscr{L}(h^{1/2})} \le 4^{r_*-p-1}$$
 and $\|d\tau^{(\sigma)}(u)\|_{\mathscr{L}(h^{-1/2})} \le 4^{r_*-p-1}$.

Note that in order to avoid confusion, we will distinguish between the terms associated to r_* and the ones associated to $r_* + 1$ by a symbol \sharp , and we begin with the work.

• First, we will start by decomposing $Q^{(2r_*)}$. Our goal is to write $Q^{(2r_*)}$ as L+U where $L,U\in\mathscr{H}_M^{2r_*}$ and U commutes with the low actions. For this, we recall (20) and define

$$L_{j,l} = \begin{cases} Q_{j,l}^{(2r_*)} & \text{if } \kappa(j,l) \le N, \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad U_{j,l} = \begin{cases} 0 & \text{if } \kappa(j,l) \le N, \\ Q_{j,l}^{(2r_*)} & \text{otherwise,} \end{cases}$$

and we check that U commutes with I_{ℓ} . Using direct calculations, we get

$$\{I_{\ell}, U\} = 2i \sum_{j,l \in [1,M]^{r_*}} \sum_{n=1}^{r_*} (\mathbb{1}_{j_n = \ell} - \mathbb{1}_{l_n = \ell}) U_{j,l} u_{j_1} \cdots u_{j_{r_*}} \overline{u_{l_1}} \cdots \overline{u_{l_{r_*}}}.$$

By definition of $U_{j,l}$ and $\kappa(j,l)$, it is obvious to see that for $\ell \leq N < \kappa(j,l)$, we must have

$$\sum_{n=1}^{r_*} (\mathbb{1}_{j_n=\ell} - \mathbb{1}_{l_n=\ell}) = 0.$$

• Second, we choose a Hamiltonian χ in such a way that L, the remaining terms of $Q^{(2r_*)}$, vanish by solving the following cohomological equation:

$$\{\chi, Z_2\} + L = 0. \tag{25}$$

To seek in, we recall $\Omega_{j,l}(V) := w_{j_1} + \cdots + w_{j_{r_*}} - w_{l_1} - \cdots - w_{l_{r_*}}$ and let $\chi \in \mathscr{H}_M^{2r_*}$ be the Hamiltonian defined by

$$\chi_{j,l} = \begin{cases} \frac{L_{j,l}}{i\Omega_{j,l}(V)} & \text{if } \kappa(j,l) \leq N, \\ 0 & \text{otherwise.} \end{cases}$$

Using direct computations, we can verify that χ satisfies (25). Moreover, we have a good control of its \mathscr{C} -norm. Indeed, since the frequencies are non-resonant (recall Proposition 2.17), there exists $\beta_{r_*,N} \in (0,1)$ and such that

$$\kappa(j,l) \leq N \implies \Omega_{j,l}(V) \geq \beta_{r_*,N} =: \delta.$$

Consequently, using Lemma A.2 we get

$$\frac{\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle}{|\Omega_{j,l}(V)|} \le \frac{C'(r_* + 1)}{|\Omega_{j,l}(V)|} + 1 \le C'(r_* + 1)\delta^{-1} + 1.$$

Thus, dividing by $\langle j_1 + \cdots + j_{r_*} - l_1 - \cdots - l_{r_*} \rangle$ and using the fact that $\delta < 1$ we get

$$\frac{1}{|\Omega_{j,l}(V)|} \le \frac{C'(r_* + 1)\delta^{-1}}{\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle} + \frac{\delta^{-1}}{\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle}$$

$$\le \frac{C'(r_* + 2)\delta^{-1}}{\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle}.$$

Therefore, we obtain

$$|\chi_{j,l}| = \left| \frac{L_{j,l}}{\Omega_{j,l}(V)} \right| \lesssim \frac{|L_{j,l}| (r_* + 2)\delta^{-1}}{\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle}.$$

By construction, we know that L satisfies the same norm estimate as $Q^{(2r_*)}$. So, taking the sup and using the induction hypothesis on $||Q^{(2r_*)}||_{\mathscr{H}}$ we establish that

$$\|\chi\|_{\mathscr{C}} = \sup_{j,l \in [1,M]^{r_*}} |\chi_{j,l}| \langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle \lesssim_{r_*} \delta^{-1} \underbrace{\sup_{j,l \in [1,M]^{r_*}} |L_{j,l}|}_{\|L\|_{\mathscr{L}}} \lesssim_{r_*} \delta^{-1} C(\log M)^b.$$

• Third, we define the new variables by composing $\tau^{(0)}$ and $\tau^{(1)}$ with the flow of the Hamiltonian χ . Applying Lemma 3.12, we get

$$\varepsilon_1' = \left(K_1'(\log M)^{(2r_*-1)/2} \|\chi\|_{\mathscr{C}}\right)^{-1/(2r_*-2)}$$

where $K'_1 > 0$ depends on r_* and a smooth symplectic invertible close to the identity map

$$\phi_{\chi}: \left\{ \begin{array}{ccc} [-1,1] \times B_{\mathbb{C}^{[\![1,M]\!]}}(0,\varepsilon_1') & \to & \mathbb{C}^{[\![1,M]\!]} \\ (t,u) & \mapsto & \phi_t^t(u) \end{array} \right.$$

solving the equation $-i\partial_t\phi_{\chi}=(\nabla\chi)\circ\phi_{\chi}$. Next, since $\|\chi\|_{\mathscr{C}}\lesssim_{r_*}\delta^{-1}C(\log M)^b$, we have

$$\varepsilon_1' \ge \left(K_2' C(\log M)^{(2r_* - 1)/2 + b} \right)^{-1/(2r_* - 2)} \ge 6(C_{\sharp} (\log M)^{b_{\sharp}})^{-1} =: 6\varepsilon_0^{\sharp}$$

where we set $C_{\sharp} \geq 6 \max \left((K_2'C)^{1/(2r_*-2)}, C \right)$ and $b_{\sharp} \geq \max \left(b, \frac{1}{2r_*-2} \left(\frac{2r_*-1}{2} + b \right) \right)$. As a consequence, it would make sense to define the maps 11 as mentioned above by

$$\tau_{\sharp}^{(1)} := \tau^{(1)} \circ \phi_{\chi}^1 \text{ on } B_{\mathbb{C}[\![1,M]\!]}(0,2\varepsilon_0^{\sharp}) \quad \text{and} \quad \tau_{\sharp}^{(0)} := \phi_{\chi}^{-1} \circ \tau^{(0)} \text{ on } B_{\mathbb{C}[\![1,M]\!]}(0,\varepsilon_0^{\sharp}).$$

¹¹The choice of ε_0^{\sharp} is dependent on the domains of definition of $\tau_{\sharp}^{(0)}$ and $\tau_{\sharp}^{(1)}$.

It is easy to see that the two maps are smooth and symplectic. To check that they are close to the identity, consider $u \in B_{\mathbb{C}^{[1,M]}}(0,2\varepsilon_0^{\sharp})$. Then, we have

$$\begin{split} \left\| \tau_{\sharp}^{(1)} u - u \right\|_{h^{1/2}} &= \left\| \tau^{(1)} \circ \phi_{\chi}^{1}(u) - u \right\|_{h^{1/2}} \\ &= \left\| \tau^{(1)} \circ \phi_{\chi}^{1}(u) - \phi_{\chi}^{1}(u) + \phi_{\chi}^{1}(u) - u \right\|_{h^{1/2}} \\ &\leq \underbrace{\left\| \tau^{(1)} \circ \phi_{\chi}^{1}(u) - \phi_{\chi}^{1}(u) \right\|_{h^{1/2}}}_{=:A_{1}} + \underbrace{\left\| \phi_{\chi}^{1}(u) - u \right\|_{h^{1/2}}}_{=:A_{2}}. \end{split}$$

Estimate of A_1 : We have that $||u||_{h^{1/2}} \leq 2\varepsilon_0^{\sharp} < 6\varepsilon_0^{\sharp} \leq \epsilon_1'$. Then, since ϕ_{χ}^1 is close to the identity, we get

$$\|\phi_{\chi}^{t}(u) - u\|_{h^{1/2}} \le \left(\frac{\|u\|_{h^{1/2}}}{\varepsilon_{1}'}\right)^{2r_{*}-2} \|u\|_{h^{1/2}} \le \|u\|_{h^{1/2}}.$$

Also, using the definitions of ε_0 and ε_0^{\sharp} we obtain that $3\varepsilon_0^{\sharp} \leq \varepsilon_0$, and we establish

$$\|\phi_{\chi}^t(u)\|_{h^{1/2}} \le 2\|u\|_{h^{1/2}} \le 4\varepsilon_0^{\sharp} < 6\varepsilon_0^{\sharp} \le 2\varepsilon_0.$$

By induction hypothesis, we know that $\tau^{(1)}$ is close to the identity (see (22)), thus

$$\|\tau^{(1)} \circ \phi_{\chi}^{1}(u) - \phi_{\chi}^{1}(u)\|_{h^{1/2}} \leq \left(\frac{\|\phi_{\chi}^{1}(u)\|_{h^{1/2}}}{2\varepsilon_{0}}\right)^{2p} \|\phi_{\chi}^{1}(u)\|_{h^{1/2}} \leq 2 \left(\frac{\|u\|_{h^{1/2}}}{6\varepsilon_{0}^{\sharp}}\right)^{2p} \|u\|_{h^{1/2}}$$

$$\leq \frac{2}{3} \left(\frac{\|u\|_{h^{1/2}}}{2\varepsilon_{0}^{\sharp}}\right)^{2p} \|u\|_{h^{1/2}}.$$

$$(26)$$

Estimate of A_2 : Similarly, we have $||u||_{h^{1/2}} \leq \epsilon'_1$. Then, we can write

$$\|\phi_{\chi}^{t}(u) - u\|_{h^{1/2}} \leq \left(\frac{\|u\|_{h^{1/2}}}{\varepsilon_{1}'}\right)^{2r_{*}-2} \|u\|_{h^{1/2}} \leq \left(\frac{\|u\|_{h^{1/2}}}{6\varepsilon_{0}^{\sharp}}\right)^{2r_{*}-2} \|u\|_{h^{1/2}}$$

$$\leq \frac{1}{3} \left(\frac{\|u\|_{h^{1/2}}}{2\varepsilon_{0}^{\sharp}}\right)^{2r_{*}-2} \|u\|_{h^{1/2}}.$$
(27)

Finally, replacing (26) and (27) back and noting that $2r_* - 2 > 2p$, we obtain

$$\|\tau_{\sharp}^{(1)}u-u\|_{h^{1/2}}\leq \left(\frac{2}{3}+\frac{1}{3}\right)\left(\frac{\|u\|_{h^{1/2}}}{2\varepsilon_{0}^{\sharp}}\right)^{2p}\|u\|_{h^{1/2}}\leq \left(\frac{\|u\|_{h^{1/2}}}{2\varepsilon_{0}^{\sharp}}\right)^{2p}\|u\|_{h^{1/2}}.$$

Same arguments and estimations can be used to prove this result for the map $\tau_{\sharp}^{(0)}$. It remains to prove that these two maps make the diagram commutative. For this, take $u \in B_{\mathbb{C}^{[1,M]}}(0,\varepsilon_0^{\sharp})$. Since $\tau_{\sharp}^{(0)}$ is close to the identity, then we have

$$\phi_{\chi}^{-1} \circ \tau^{(0)}(u) = \tau_{\sharp}^{(0)}(u) \in B_{\mathbb{C}^{[1,M]}}(0, 2\varepsilon_0^{\sharp}) \subset B_{\mathbb{C}^{[1,M]}}(0, \varepsilon_1').$$

Thus, since ϕ_{χ}^1 is invertible, we obtain

$$\tau_{\sharp}^{(1)} \circ \tau_{\sharp}^{(0)}(u) = \tau^{(1)} \circ \phi_{\chi}^{1} \circ \phi_{\chi}^{-1} \circ \tau^{(0)}(u) = \tau^{(1)} \circ \tau^{(0)}(u) = \mathrm{id}_{\mathbb{C}^{[\![1,M]\!]}}.$$

• Fourth, our goal now is to decompose $(Z_2 + P) \circ \tau_{\sharp}^{(1)}$ on $B_{\mathbb{C}^{[1,M]}}(0, 2\varepsilon_0^{\sharp})$. Notice that by definition of $\tau_{\sharp}^{(1)}$ and using induction hypothesis, we have

$$(Z_2 + P) \circ \tau_{\sharp}^{(1)} = (Z_2 + P) \circ \tau^{(1)} \circ \phi_{\chi}^1 = Z_2 \circ \phi_{\chi}^1 + \sum_{n=2n+2}^{2r+2p} Q^{(n)} \circ \phi_{\chi}^1 + R \circ \phi_{\chi}^1.$$

Now since ϕ_{χ}^{t} is a smooth function, applying Taylor expansion between 0 and 1 gives

$$(Z_{2} + P) \circ \tau_{\sharp}^{(1)}$$

$$= Z_{2} + \{\chi, Z_{2}\} + \sum_{k=2}^{m_{r_{*}}+1} \frac{1}{k!} \operatorname{ad}_{\chi}^{k} Z_{2} + \int_{0}^{1} \frac{(1-t)^{m_{r_{*}}+1}}{(m_{r_{*}}+1)!} \operatorname{ad}_{\chi}^{m_{r_{*}}+2} Z_{2} \circ \phi_{\chi}^{t} dt$$

$$+ \sum_{n=2p+2}^{2r+2p} \left[Q^{(n)} + \sum_{k=1}^{m_{n}} \frac{1}{k!} \operatorname{ad}_{\chi}^{k} Q^{(n)} + \int_{0}^{1} \frac{(1-t)^{m_{n}}}{m_{n}!} \operatorname{ad}_{\chi}^{m_{n}+1} Q^{(n)} \circ \phi_{\chi}^{t} dt \right] + R \circ \phi_{\chi}^{1}$$

with m_n the largest integer such that $n + m_n(2r_* - 2) < 2r + 2p + 2$. From (25) we have

$$\operatorname{ad}_{\chi}^{k+1} Z_2 = \underbrace{\{\chi, \{\chi, \dots, \{\chi, Z_2\} \dots\}\}}_{k+1 \text{ times}} = -\underbrace{\{\chi, \{\chi, \dots, \{\chi, L\} \dots\}\}}_{k \text{ times}} = -\operatorname{ad}_{\chi}^{k} L.$$

So, we write

$$\begin{split} &(Z_{2}+P)\circ\tau_{\sharp}^{(1)}\\ &=Z_{2}+\{\chi,Z_{2}\}-\sum_{k=1}^{m_{r_{*}}}\frac{1}{(k+1)!}\mathrm{ad}_{\chi}^{k}L-\int_{0}^{1}\frac{(1-t)^{m_{r_{*}}+1}}{(m_{r_{*}}+1)!}\mathrm{ad}_{\chi}^{m_{r_{*}}+1}L\circ\phi_{\chi}^{t}\,\mathrm{d}t\\ &+\sum_{n=2p+2}^{2r+2p}\left[Q^{(n)}+\sum_{k=1}^{m_{n}}\frac{1}{k!}\mathrm{ad}_{\chi}^{k}Q^{(n)}+\int_{0}^{1}\frac{(1-t)^{m_{n}}}{m_{n}!}\mathrm{ad}_{\chi}^{m_{n}+1}Q^{(n)}\circ\phi_{\chi}^{t}\,\mathrm{d}t\right]+R\circ\phi_{\chi}^{1}\\ &=Z_{2}+\sum_{n=2p+2}^{2r_{*}}Q^{(n)}+\{\chi,Z_{2}\}+\sum_{n=2r_{*}+1}^{2r+2p}Q^{(n)}+\sum_{n=2p+2}^{2r+2p}\sum_{k=1}^{m_{n}}\frac{1}{k!}\mathrm{ad}_{\chi}^{k}Q^{(n)}-\sum_{k=1}^{m_{r_{*}}}\frac{1}{(k+1)!}\mathrm{ad}_{\chi}^{k}L\\ &+R\circ\phi_{\chi}^{1}-\int_{0}^{1}\frac{(1-t)^{m_{r_{*}}+1}}{(m_{r_{*}}+1)!}\mathrm{ad}_{\chi}^{m_{r_{*}}+1}L\circ\phi_{\chi}^{t}\,\mathrm{d}t+\sum_{n=2p+2}^{2r+2p}\int_{0}^{1}\frac{(1-t)^{m_{n}}}{m_{n}!}\mathrm{ad}_{\chi}^{m_{n}+1}Q^{(n)}\circ\phi_{\chi}^{t}\,\mathrm{d}t. \end{split}$$

Using the induction hypothesis and Proposition 3.13, it is easy to see that $Q^{(n)}$ is of order n, $\{\chi, Z_2\}$ is of order $2r_*$, $\mathrm{ad}_\chi^k Q^{(n)}$ is of order $n+2k(r_*-1)>2r_*$ and $\mathrm{ad}_\chi^k L$ is of order $2r_*+2k(r_*-1)>2r_*$. As a result, after reordering it would make sense to set:

for
$$n < 2r_*$$
, $Q_{\sharp}^{(n)} = Q^{(n)}$,
for $n = 2r_*$, $Q_{\sharp}^{(n)} = Q^{(n)} + \{\chi, Z_2\}$,
for $n > 2r_*$, $Q_{\sharp}^{(n)} = \sum_{\substack{n_*, k \\ n_* + 2k(r_* - 1) = n}} \frac{1}{k!} \operatorname{ad}_{\chi}^k Q^{(n_*)} - \sum_{\substack{k \\ 2r_* + 2k(r_* - 1) = n}} \frac{1}{(k+1)!} \operatorname{ad}_{\chi}^k L$,

and

$$R_{\sharp} = R \circ \phi_{\chi}^{1} - \int_{0}^{1} \left(\frac{(1-t)^{m_{r_{*}}+1}}{(m_{r_{*}}+1)!} \operatorname{ad}_{\chi}^{m_{r_{*}}+1} L \circ \phi_{\chi}^{t} - \sum_{n=2p+2}^{2r+2p} \frac{(1-t)^{m_{n}}}{m_{n}!} \operatorname{ad}_{\chi}^{m_{n}+1} Q^{(n)} \circ \phi_{\chi}^{t} \right) dt.$$

Notice that $Q_{\sharp}^{(2r_*)} = Q^{(2r_*)} + \{\chi, Z_2\} = Q^{(2r_*)} - L = U$ which commutes with the low actions by construction (we already checked this property in the beginning of the proof). Hence, for $n \leq 2r_*$, $Q_{\sharp}^{(n)} \in \mathscr{H}_M^n$ commutes with the low actions and we have

$$n < 2(r_* + 1)$$
 and $\ell \le N \implies \{I_\ell, Q_{\sharp}^{(n)}\} = 0.$

Moreover, we have the bound

$$\|Q_{\sharp}^{(n)}\|_{\mathscr{H}} \le \|Q^{(n)}\|_{\mathscr{H}} \le C(\log M)^{b}.$$

For $n > 2r_*$, we use Proposition 3.13 and the estimate on $\|\chi\|_{\mathscr{C}}$ to obtain that

$$\|\operatorname{ad}_{\chi}^{k}Q^{(n_{*})}\|_{\mathscr{H}} \lesssim_{r} (\log M)^{k} \|\chi\|_{\mathscr{C}}^{k} \|Q^{(n_{*})}\|_{\mathscr{H}} \lesssim_{r} \beta_{r_{*},N}^{-k} C^{k+1} (\log M)^{k+b(k+1)}.$$

Since $\operatorname{ad}_{\chi}^{k}L$ and $\operatorname{ad}_{\chi}^{k}Q^{(n_{*})}$ enjoy the same estimate when $2r_{*}+2k(r_{*}-1)=n$ and since $k\leq 2r+2p+2$, we deduce that for $C_{\sharp}\gtrsim_{r}\beta_{r_{*},N}^{-2r-2p-2}C^{2r+2p+3}$ and $b_{\sharp}\geq (2r+2p+2)+b(2r+2p+3)$

$$\|Q_{\sharp}^{(n)}\|_{\mathscr{H}} \le C_{\sharp} (\log M)^{b_{\sharp}}.$$

• Fifth, we still have to control the remainder term. For this we fix $u \in B_{\mathbb{C}^{[1,M]}}(0,2\varepsilon_0^{\sharp})$ and start by checking that $\nabla(R \circ \phi_{\chi}^1) \in h^{-1/2}$. By composition, we have

$$\nabla (R \circ \phi_{\chi}^{1})(u) = (\mathrm{d}\phi_{\chi}^{1}(u))^{*}(\nabla R) \circ \phi_{\chi}^{1}(u).$$

We know from Lemma 3.12 that $\|(\mathrm{d}\phi_\chi^1(u))^*\|_{\mathscr{L}(h^{-1/2})} = \|\mathrm{d}\phi_\chi^1(u)\|_{\mathscr{L}(h^{1/2})} \leq 2$. Also, since $(\nabla R) \circ \phi_\chi^1 \in h^{-1/2}$, then $(\mathrm{d}\phi_\chi^1)^*(\nabla R) \circ \phi_\chi^1 \in h^{-1/2}$. Now we turn to controlling this term in $h^{-1/2}$. Using the induction hypothesis and $\|\phi_\chi^1(u)\|_{h^{1/2}} \leq 2\|u\|_{h^{1/2}}$, we get

$$\begin{split} \left\| \nabla (R \circ \phi_{\chi}^{1})(u) \right\|_{h^{-1/2}} &= \left\| (\mathrm{d} \phi_{\chi}^{1}(u))^{*} (\nabla R) \circ \phi_{\chi}^{1}(u) \right\|_{h^{-1/2}} \\ &\leq \left\| (\mathrm{d} \phi_{\chi}^{1}(u))^{*} \right\|_{\mathcal{L}(h^{-1/2})} \left\| (\nabla R) \circ \phi_{\chi}^{1}(u) \right\|_{h^{-1/2}} \\ &\leq 2 C (\log M)^{b} \|\phi_{\chi}^{1}(u)\|_{h^{1/2}}^{2r+2p} \\ &\leq 4^{r+p} C (\log M)^{b} \|u\|_{h^{1/2}}^{2r+2p}. \end{split}$$

Next, we estimate the terms of R_{\sharp} inside the integral. We denote $r_n := n + (m_n + 1)(2r_* - 2)$, and we notice that $\operatorname{ad}_{\chi}^{m_n+1}Q^{(n)}$ is a smooth function belonging to \mathscr{H}^{r_n} . Thus, arguing as above and using Proposition 3.9 and Proposition 3.13, we notice that we have for $2p + 2 \le n \le 2r + 2p$ and $t \in [0,1]$ we establish

$$\begin{split} &\|\nabla(\operatorname{ad}_{\chi}^{m_{n}+1}Q^{(n)}\circ\phi_{\chi}^{t})(u)\|_{h^{-1/2}} \\ &\leq 2\|\nabla(\operatorname{ad}_{\chi}^{m_{n}+1}Q^{(n)})\circ\phi_{\chi}^{t}(u)\|_{h^{-1/2}} \\ &\lesssim_{r} (\log M)^{r_{n}/2}\|\operatorname{ad}_{\chi}^{m_{n}+1}Q^{(n)})\|_{\mathscr{H}}\|\phi_{\chi}^{t}(u)\|_{h^{1/2}}^{r_{n}-1} \\ &\lesssim_{r} (\log M)^{r_{n}/2}(\log M)^{m_{n}+1}\|Q^{(n)}\|_{\mathscr{H}}\|\chi\|_{\mathscr{C}}^{m_{n}+1}\|\phi_{\chi}^{t}(u)\|_{h^{1/2}}^{r_{n}-1} \\ &\lesssim_{r} (\log M)^{r_{n}/2}(\delta^{-1}\log M)^{m_{n}+1}(C(\log M)^{b})^{m_{n}+2}\|\phi_{\chi}^{t}(u)\|_{h^{1/2}}^{r_{n}-1} \\ &\lesssim_{r} (\beta_{r_{*},N})^{-m_{n}-1}C^{m_{n}+2}(\log M)^{m_{n}+1}(\log M)^{r_{n}/2}(\log M)^{b(m_{n}+2)}\|\phi_{\chi}^{t}(u)\|_{h^{1/2}}^{r_{n}-1}. \end{split}$$

Using the fact that $m_n \leq 2r + 2p + 2$, $r_n \in [2(r+p+1), 4r + 4p + 2)]^{-12}$ and $||u||_{h^{1/2}} \leq 2$,

$$\|\nabla (\operatorname{ad}_{\chi}^{m_n+1} Q^{(n)} \circ \phi_{\chi}^t)(u)\|_{h^{-1/2}} \lesssim_r C_{\sharp} (\log M)^{b_{\sharp}} \|u\|_{h^{1/2}}^{2r+2p}$$

where $C_{\sharp} \gtrsim_r (\beta_{r_*,N})^{-2r-2p-3}C^{2r+2p+4}$ and $b_{\sharp} \geq 4(r+p+1)+2b(r+p+2)$. We can also check using similar calculations that $\|\nabla(\operatorname{ad}_{\chi}^{m_{r_*}+1}L\circ\phi_{\chi}^t)(u)\|_{h^{-1/2}}$ enjoys the same bound as $\|\nabla(\operatorname{ad}_{\chi}^{m_n+1}Q^{(n)}\circ\phi_{\chi}^t)(u)\|_{h^{-1/2}}$. Hence, putting the results together we conclude that

$$\|\nabla R_{\sharp}(u)\|_{h^{-1/2}} \leq \|\nabla (R \circ \phi_{\chi}^{1})(u)\|_{h^{-1/2}} + \int_{0}^{1} \left(\frac{1}{(m_{r_{*}}+1)!} \|\nabla (\operatorname{ad}_{\chi}^{m_{r_{*}}+1} L \circ \phi_{\chi}^{t})(u)\|_{h^{-1/2}} + \sum_{n=2p+2}^{2r+2p} \frac{1}{m_{n}!} \|\nabla (\operatorname{ad}_{\chi}^{m_{n}+1} Q^{(n)} \circ \phi_{\chi}^{t})(u)\|_{h^{-1/2}}\right) dt.$$

 $^{^{12}}$ By definition of m_n

Taking furthermore $C_{\sharp} \gtrsim_r C$ and $b_{\sharp} \geq b$ we get that

$$\|\nabla R_{\sharp}(u)\|_{h^{-1/2}} \lesssim_r C_{\sharp}(\log M)^{b_{\sharp}} \|u\|_{h^{1/2}}^{2r+2p}.$$

In order to end the proof, we choose the most optimal constants and thus we set

$$C_{\sharp} \simeq_r \max((K_2'C)^{1/(2r_*-2)}, (\beta_{r_*,N})^{-2r-2p-3}C^{2r+2p+4})$$
 and $b_{\sharp} = 4(r+p+1) + 2b(r+p+2)$.

5 Proof of the main result

The last part of this paper is dedicated to proving the main result known to be a dynamical corollary of Theorem 4.1. Before seeking into the details, I will briefly discuss the global well-posedness of our model (in the same spirit, see [11]) which is ensured thanks to the conservation of the Hamiltonian and the mass.

Lemma 5.1. For all $\rho > 0$, there exist $\varepsilon_{\rho} > 0$ and $C_{\rho} > 0$ such that provided $||V||_{L^{\infty}} \leq \rho$, we have for $u \in \widehat{H}^1$ satisfying $||u||_{\widehat{H}^1} \leq C_{\rho} \varepsilon_{\rho}$

$$C_{\rho}^{-1} \|u\|_{\widehat{H}^{1}}^{2} \le H(u) + \rho \|u\|_{L^{2}}^{2} \le C_{\rho} \|u\|_{\widehat{H}^{1}}^{2}.$$

Lemma 5.2. If $u \in \mathscr{C}^0((-T,T), \widehat{H}^1)$ solves (NLS), then its energy and mass are preserved

$$\forall t \in (-T, T), \quad H(u(t)) = H(u^{(0)}) \quad and \quad \|u(t)\|_{L^2}^2 = \|u^{(0)}\|_{L^2}^2.$$

The proofs of the above results use sobolev embeddings and the fact that \hat{H}^1 is an algebra¹³. Consequently, we obtain the global well-posedness of our Schrödinger equation:

Theorem 5.3. (Global Well-posedness) Let $\rho > 0$ and $\varepsilon_{\rho} > 0$ be given by Lemma [5.1]. Provided that $\varepsilon := \|u^{(0)}\|_{\widehat{H}^1} \leq \varepsilon_{\rho}$ and $\|V\|_{\widehat{H}^1} \leq \rho$, there exists a unique global solution $u \in \mathscr{C}_b^0(\mathbb{R}, \widehat{H}^1) \cap \mathscr{C}^1(\mathbb{R}, \widehat{H}^{-1})$ to (NLS).

Proof. The idea of the global well-posedness is quite standard: the local well-posedness is acheived by a fixed point argument. From this, we deduce Theorem 5.3 by extension using the boundedness of $||u(t)||_{\widehat{H}^1}$.

Note that Lemma 5.2 can now be extended for all $t \in \mathbb{R}$. As a corollary of Lemma 5.1 and the Hamiltonian and mass conservation, the norm of the solution is bounded for all $t \in \mathbb{R}$

$$||u(t)||_{\widehat{H}^1}^2 \le C_{\rho} \left(H(u(t)) + \rho ||u(t)||_{L^2}^2 \right) = C_{\rho} \left(H(u^{(0)}) + \rho ||u^{(0)}||_{L^2}^2 \right) \le C_{\rho}^2 ||u^{(0)}||_{\widehat{H}^1}^2 \le C_{\rho}^2 \varepsilon^2.$$

Proof of Theorem 1.1 To start, I would like to recall that we have $||u(t)||_{\widehat{H}^s} \simeq ||u(t)||_{h^{s/2}}$. Now, we consider $||u^{(0)}||_{\widehat{H}^1} \leq \varepsilon_{\rho}$ where ε_{ρ} is given in Lemma 5.1. We focus on the variations of the low modes. We fix $j_* \geq 1$ such that $j_* = N$ and we aim at estimating $|u_{j_*}(t)|^2$. To apply the Birkhoff Normal Form Theorem (see Theorem 4.1), we need to make a truncation up to a level M in order to restrict our work to the finite dimensional situation of the theorem. To this matter, we let

$$M = \varepsilon^{-4r+2}.$$

¹³This is due to Proposition 2.1.1 in [1] and the continuous inclusions $\widehat{H}^1(\mathbb{R}) \subset H^1(\mathbb{R}) \subset L^{\infty}(\mathbb{R})$.

Furthermore, we consider the eigenspaces of T+V

$$E_j = \ker(T + V - \Lambda_j) = \operatorname{Span}(\psi_j)$$
 where $L^2(\mathbb{R}) = \bigoplus_{j>1} E_j$,

and we introduce $\Pi_{\leq M}$ the orthogonal projection on $\bigoplus_{j\leq M} E_j$. In other words, we denote $\Pi_{\leq M}:=\sum_{j\leq M}\Pi_j$ where Π_j is the orthogonal projection on E_j . We set $\Pi_{>M}:=\mathrm{Id}_{L^2}-\Pi_{\leq M}$, $u^{\leq M}:=\Pi_{\leq M}u$ and $F^{>M}(t):=\pm\Pi_{\leq M}\left(-\left|u^{\leq M}\right|^{2p}u^{\leq M}+|u|^{2p}u\right)$. Notice that if u solves the Schrodinger equation (NLS), then $u^{\leq M}$ solves the equation

$$i\partial_{t}u^{\leq M} = \Pi_{\leq M}(i\partial_{t}u)$$

$$= \Pi_{\leq M}((T+V)u \pm |u|^{2p}u)$$

$$= (T+V)u^{\leq M} \pm \Pi_{\leq M}(|u|^{2p}u) \pm \Pi_{\leq M}\left(\left|u^{\leq M}\right|^{2p}u^{\leq M}\right) \mp \Pi_{\leq M}\left(\left|u^{\leq M}\right|^{2p}u^{\leq M}\right)$$

$$= (T+V)u^{\leq M} \pm \Pi_{\leq M}\left(\left|u^{\leq M}\right|^{2p}u^{\leq M}\right) + F^{>M}(t). \tag{28}$$

Our goal is to ensure that the remainder term $F^{>M}(t)$ is small in this reduction to finite dimension. Thus, we aim to prove that it is negligible provided that M is large enough (of order ε^{-4r+2}). For this, we write

$$||F^{>M}(t)||_{L^{2}} = \left\| \prod_{\leq M} \left(|u|^{2p} u - \left| u^{\leq M} \right|^{2p} u^{\leq M} \right) \right\|_{L^{2}} \leq \left\| |u|^{2p} u - \left| u^{\leq M} \right|^{2p} u^{\leq M} \right\|_{L^{2}}$$

with $|u|^{2p}u = \left|u - u^{\leq M} + u^{\leq M}\right|^{2p}(u - u^{\leq M} + u^{\leq M}) = \left|u^{\leq M} + u^{>M}\right|^{2p}(u^{\leq M} + u^{>M})$. Then, using the Mean Value Inequality, Holder's Inequality, the Sobolev embeddings $\hat{H}^1 \hookrightarrow H^1 \hookrightarrow L^{6p}$ and the fact that $H^{1/2}$ injects continuously in L^6 , we get

$$||F^{>M}(t)||_{L^{2}} \leq ||u^{\leq M} + u^{>M}|^{2p} (u^{\leq M} + u^{>M}) - |u^{\leq M}|^{2p} u^{\leq M}||_{L^{2}}$$

$$\lesssim ||u^{\leq M} + u^{>M} - u^{\leq M}) (|u^{\leq M} + u^{>M}|^{2p} + |u^{\leq M}|^{2p}) ||_{L^{2}}$$

$$\lesssim ||u^{>M}||_{L^{6}} (||u^{\leq M} + u^{>M}|^{2p} ||_{L^{3}} + ||u^{\leq M}|^{2p} ||_{L^{3}})$$

$$\lesssim ||u^{>M}||_{L^{6}} (||u^{\leq M} + u^{>M}||^{2p} ||_{L^{6p}} + ||u^{\leq M}||^{2p} ||_{L^{6p}})$$

$$\lesssim ||u^{>M}||_{\widehat{H}^{1/2}} ||u||^{2p} ||_{\widehat{H}^{1}}.$$

Since M > N, then $M > j_*$ and we have $|u_{j_*}|^2 = \left|u_{j_*}^{\leq M}\right|^2$. Moreover, we obtain

$$||u^{>M}||_{\widehat{H}^{1/2}} \lesssim M^{-1/2}||u-u^{\leq M}||_{h^{1/2}} \lesssim M^{-1/2}||u||_{\widehat{H}^1}.$$

Therefore, recalling that $M = \varepsilon^{-4r+2}$, we deduce that for all $t \in \mathbb{R}$ we get

$$||F^{>M}(t)||_{L^2} \lesssim M^{-1/2} ||u||_{\widehat{H}^1}^{2p+1} \lesssim \varepsilon^{2r+2p}.$$

We are now interested in writing (28) as a Hamiltonian system. Indeed, since $(\psi_j)_{j\geq 1}$ is a basis of L^2 , we can identify $\bigoplus_{j\leq M} E_j$ with $\mathbb{R}^{[\![1,M]\!]}$, and we can easily check that equation (28) can be written as

$$i\partial_t u^{\leq M} = \nabla H(u^{\leq M}) + F^{>M}(t)$$
 where $H = \underbrace{Z_2}_{\text{linear part}} + \underbrace{P}_{\text{perturbation}}$.

In particular, if we express u in terms of the eigenfunctions as $\sum_{j \in [1,M]} u_j \psi_j$, we obtain

$$H(u) = \frac{1}{2} \int_{\mathbb{R}} |\partial_x u|^2 + x^2 |u|^2 + V |u|^2 dx \pm \frac{1}{2p+2} \int_{\mathbb{R}} |u|^{2p+2} dx$$

$$= \frac{1}{2} \int_{\mathbb{R}} \overline{u}(T+V)u dx + \frac{1}{2p+2} \int_{\mathbb{R}} |u|^{2p+2} dx$$

$$= \frac{1}{2} \int_{\mathbb{R}} \left(\sum_{j \in [\![1,M]\!]} \overline{u_j} \psi_j \right) (T+V) \left(\sum_{j \in [\![1,M]\!]} u_j \psi_j \right) dx + \frac{1}{2p+2} \int_{\mathbb{R}} \left| \sum_{j \in [\![1,M]\!]} u_j \psi_j \right|^{2p+2} dx$$

$$= \frac{1}{2} \sum_{j \in [\![1,M]\!]} w_j u_j \overline{u_j} \int_{\mathbb{R}} \psi_j^2 dx$$

$$\pm \frac{1}{2p+2} \sum_{j \in [\![1,M]\!]^{2p+2}} \left(\int_{\mathbb{R}} \psi_{j_1} \cdots \psi_{j_{2p+2}} dx \right) u_{j_1} \cdots u_{j_{p+1}} \overline{u_{j_{p+2}}} \cdots \overline{u_{j_{2p+2}}}$$

$$= \underbrace{\frac{1}{2} \sum_{j \in [\![1,M]\!]} w_j |u_j|^2}_{Z_2(u)} \pm \underbrace{\frac{1}{2p+2} \sum_{j \in [\![1,M]\!]^{2p+2}} P_j u_{j_1} \cdots u_{j_{p+1}} \overline{u_{j_{p+2}}} \cdots \overline{u_{j_{2p+2}}}}_{P(u)}.$$

Clearly P is a Hamiltonian polynomial of degree 2p+2. Moreover, using Hölder's inequality and the fact that $\|\psi_j\|_{L^q} \lesssim 1$ for all $q \geq 2$, we get that 14

$$|P_j| = \|\psi_{j_1} \cdots \psi_{j_{2p+2}}\|_{L^1} \le \|\psi_{j_1}\|_{L^{2p+2}} \cdots \|\psi_{j_{2p+2}}\|_{L^{2p+2}} \lesssim 1.$$

At this stage, we are able to apply the Birkhoff Normal Form Theorem (recall Theorem 4.1). We obtain three positive constants C, b, and ε_0 as well as two symplectic maps $\tau^{(0)}$ and $\tau^{(1)}$ such that the theorem holds. Note that if $C_{\rho}\varepsilon \geq 1/(C(\log M)^b)$, then we obtain

$$\left| \left| u_{j_*}(t) \right|^2 - \left| u_{j_*}(0) \right|^2 \right| \le \left| u_{j_*}(t) \right|^2 + \left| u_{j_*}(0) \right|^2 \le \left\| u(t) \right\|_{h^{1/2}}^2 + \left\| u^{(0)} \right\|_{h^{1/2}}^2 \le (C_\rho^2 + 1)\varepsilon^2.$$

On the other hand, we have $\varepsilon^2 = \varepsilon^2 (C_\rho C(\log M)^b)^{2p} \frac{1}{(C_\rho C(\log M)^b)^{2p}} \le \varepsilon^2 (C_\rho C(\log M)^b)^{2p} \varepsilon^{2p}$, with $(\log M)^{2bp} \lesssim_{r,\nu} N^{2bp} \varepsilon^{-\nu}$ for $\nu > 0$. Thus, we conclude the result

$$||u_{j_*}(t)|^2 - |u_{j_*}(0)|^2| \lesssim_{\rho,r,N,\nu} \varepsilon^{2p+2-\nu}.$$

Consequently, we restrict the constants to the case $C_{\rho}\varepsilon < 1/(C(\log M)^b)$, and thus

$$\forall t \in \mathbb{R}, \quad \|u^{\leq M}(t)\|_{h^{1/2}} \leq C_{\rho}\varepsilon < \frac{1}{C(\log M)^b} < \varepsilon_0.$$

Therefore, it would make sense to consider the new variable given by $v := \tau^{(0)} \circ u^{\leq M}$. Now, we can see that by definition of the differential and by using Lemma A.3 we get

$$\partial_t v(t) = \frac{\mathrm{d}(\tau^{(0)} \circ u^{\leq M}(t))}{\mathrm{d}t} = \left(\nabla \tau^{(0)}(u^{\leq M}), \partial_t u^{\leq M}\right)_{\ell^2}$$

$$= \mathrm{d}\tau^{(0)}(u^{\leq M})(\partial_t u^{\leq M}) = \mathrm{d}\tau^{(0)}(u^{\leq M})(-i\nabla H(u^{\leq M}) - iF^{>M}(t))$$

$$= -i(\mathrm{d}\tau^{(1)} \circ \tau^{(0)}(u^{\leq M}))^* \nabla H(u^{\leq M}) - i\mathrm{d}\tau^{(0)}(u^{\leq M})(F^{>M}(t)).$$

Since the diagram commutes, $\tau^{(1)} \circ \tau^{(0)}(u^{\leq M}) = u^{\leq M}$, so we get $\tau^{(1)}(v) = u^{\leq M}$. Then

$$\begin{split} \partial_t v(t) &= -i (\mathrm{d} \tau^{(1)}(v))^* \, (\nabla H) \circ \tau^{(1)}(v) - i \mathrm{d} \tau^{(0)}(u^{\leq M}) (F^{>M}(t)) \\ &= -i \left(\nabla (H \circ \tau^{(1)})(v(t)) + \mathrm{d} \tau^{(0)}(u^{\leq M}) (F^{>M}(t)) \right). \end{split}$$

¹⁴The idea is that we need to control P_j in order to control the interaction between the modes via the nonlinear term.

Consequently, using (23) we obtain

$$\partial_t v(t) = -i \left(\nabla (Z_2 + Q + R)(v(t)) + d\tau^{(0)} (u^{\leq M})(F^{>M}(t)) \right). \tag{29}$$

Our goal is to estimate $\partial_t |v_{j_*}(t)|^2$ in order to apply the Mean Value Inequality. Since $|v_{j_*}|^2$ is smooth on $h^{-1/2}$, then by composition we have that $t \mapsto |v_{j_*}(t)|^2 \in \mathscr{C}^1(\mathbb{R}, \mathbb{R})$ using the chain rule. So, we differentiate with respect to t and use (29) to get

$$\begin{split} \partial_{t} \left| v_{j_{*}}(t) \right|^{2} &= \left(i \nabla \left| v_{j_{*}} \right|^{2}, i \partial_{t} v_{j_{*}} \right)_{\ell^{2}} \\ &= \left(i \nabla \left| v_{j_{*}} \right|^{2}, \nabla (Z_{2} + Q + R)(v) \right)_{\ell^{2}} + \left(i \nabla \left| v_{j_{*}} \right|^{2}, d\tau^{(0)}(u^{\leq M})(F^{>M}(t)) \right)_{\ell^{2}} \\ &= \left\{ \left| v_{j_{*}} \right|^{2}, Z_{2}(v) + Q(v) \right\} + \left(i \nabla \left| v_{j_{*}} \right|^{2}, \nabla R(v) \right)_{\ell^{2}} \\ &+ \left(i \nabla \left| v_{j_{*}} \right|^{2}, d\tau^{(0)}(u^{\leq M})(F^{>M}(t)) \right)_{\ell^{2}} \end{split}$$

From Birkhoff Normal Form Theorem and by direct calculations, we can see that since $j_* = N$, we have $\{|v_{j_*}|^2, Z_2(v) + Q(v)\} = 0$. Thus, using Cauchy–Schwarz, we estimate

$$\begin{split} \left| \partial_{t} \left| v_{j_{*}}(t) \right|^{2} \right| &\leq \left| \left(i \nabla \left| v_{j_{*}} \right|^{2}, \nabla R(v) \right)_{\ell^{2}} \right| + \left| \left(i \nabla \left| v_{j_{*}} \right|^{2}, \mathrm{d}\tau^{(0)}(u^{\leq M})(F^{>M}(t)) \right)_{\ell^{2}} \right| \\ &\leq \left\| \nabla \left| v_{j_{*}} \right|^{2} \left\|_{h^{1/2}} \left\| \nabla R(v) \right\|_{h^{-1/2}} + \left\| \nabla \left| v_{j_{*}} \right|^{2} \left\|_{h^{1/2}} \left\| \mathrm{d}\tau^{(0)}(u^{\leq M})(F^{>M}(t)) \right\|_{h^{-1/2}} \\ &\leq 2 \| v_{j_{*}} \|_{h^{1/2}} \left(\| \nabla R(v) \|_{h^{-1/2}} + \left\| \mathrm{d}\tau^{(0)}(u^{\leq M})(F^{>M}(t)) \right\|_{h^{-1/2}} \right). \end{split}$$

Estimate of $\|v_{j_*}\|_{h^{1/2}}$: Since $\tau^{(0)}$ is close to the identity, then

$$\|v\|_{h^{1/2}} \le \|u\|_{h^{1/2}} + \|\tau^{(0)}u - u\|_{h^{1/2}} \le \|u\|_{h^{1/2}} + \left(\frac{\|u\|_{h^{1/2}}}{C_{\rho\varepsilon}}\right)^{2p} \|u\|_{h^{1/2}} \le 2\|u\|_{h^{1/2}} \le 2\varepsilon_0.$$

Estimate of $\|\nabla R(v)\|_{h^{-1/2}}$: By Theorem 4.1, we have for $v \in B_{\mathbb{C}^{[1,M]}}(0,2\varepsilon_0)$

$$\|\nabla R(v)\|_{h^{-1/2}} \lesssim (\log M)^b \|v\|_{h^{1/2}}^{2r+2p} \lesssim (\log M)^b \varepsilon^{2r+2p}.$$

Estimate of $\|d\tau^{(0)}(u^{\leq M})(F^{>M}(t))\|_{h^{-1/2}}$: Again, by Theorem 4.1, we obtain

$$\|\mathrm{d}\tau^{(0)}(u^{\leq M})(F^{>M}(t))\|_{h^{-1/2}} \leq \|\mathrm{d}\tau^{(0)}(u^{\leq M})\|_{\mathscr{L}(h^{-1/2})} \|F^{>M}(t)\|_{h^{-1/2}} \lesssim 4^r \varepsilon^{2r+2p}.$$

As a consequence, combining all the above estimations we obtain

$$\left| \partial_t \left| v_{j_*}(t) \right|^2 \right| \lesssim_r \varepsilon((\log M)^b \varepsilon^{2r+2p} + \varepsilon^{2r+2p}) \lesssim_r (\log M)^b \varepsilon^{2r+2p+1}.$$

Now, we apply the Mean Value Inequality on [0, t]:

$$|t| < \varepsilon^{-2r+1} \implies \left| |v_{j_*}|^2 - |v_{j_*}(0)|^2 \right| \le |t| \left| \partial_t |v_{j_*}(t)|^2 \right| \lesssim_r \varepsilon^{-2r+1} (\log M)^b \varepsilon^{2r+2p+1} \lesssim_r (\log M)^b \varepsilon^{2p+2}.$$

In order to conclude, we need to obtain a similar result for $|u_{j_*}(t)|^2$. Notice that

$$\left| |u_{j_*}(t)|^2 - |u_{j_*}(0)|^2 \right| \le \left| |u_{j_*}(t)|^2 - |v_{j_*}(t)|^2 \right| + \left| |v_{j_*}(t)|^2 - |v_{j_*}(0)|^2 \right| + \left| |v_{j_*}(0)|^2 - |u_{j_*}(0)|^2 \right|.$$

$$(30)$$

In addition to this, we know that for all $t \in \mathbb{R}$ we have

$$\left| |u_{j_*}(t)|^2 - |v_{j_*}(t)|^2 \right| \le \|u^{\le M}(t) - v(t)\|_{\ell^2} (\|v(t)\|_{\ell^2} + \|u^{\le M}(t)\|_{\ell^2})$$

$$\le \|u^{\le M}(t) - v(t)\|_{h^{1/2}} (\|v(t)\|_{h^{1/2}} + \|u^{\le M}(t)\|_{h^{1/2}})$$

with

$$\|u^{\leq M}(t) - v(t)\|_{h^{1/2}} \leq \left(\frac{\|u^{\leq M}\|_{h^{1/2}}}{\varepsilon_0}\right)^{2p} \|u^{\leq M}\|_{h^{1/2}} \lesssim (\log M)^{2bp} \varepsilon^{2p+1}.$$

Finally, replacing in (80) and using that $(\log M)^{2bp} \lesssim_{r,\nu} N^{2bp} \varepsilon^{-\nu}$ for $\nu > 0$, we deduce

$$\left| |u_{j_*}(t)|^2 - |u_{j_*}(0)|^2 \right| \lesssim_r (\log M)^{2bp} \varepsilon^{2p+2} \lesssim_{r,N,\nu} \varepsilon^{2p+2-\nu}.$$

A Appendix

Here are few painless results.

Lemma A.1. For a given weight $P \in \widehat{H}^3$ with $P_k \in \mathbb{R}_+^*$, the assumptions (13) are satisfied.

Proof. We start by showing that almost surely $V \in \widehat{H}^1 \cap \mathcal{C}^2$. Indeed,

$$||V||_{\widehat{H}^3}^2 \simeq \sum_{j \ge 1} \langle j \rangle^3 \left(V, h_j(\cdot \sqrt{2}) \right)_{L^2}^2 = \sum_{j \ge 1} \langle j \rangle^3 \left(\sum_{k \ge 1} g_k h_k(\cdot \sqrt{2}) P_k, h_j(\cdot \sqrt{2}) \right)_{L^2}^2 = \sum_{k \ge 1} \langle k \rangle^3 P_k^2 g_k^2.$$

Setting $X = \sum_{k>1} \langle k \rangle^3 P_k^2 g_k^2$ and recalling that $g_k \sim \mathcal{N}(0,1)$, we notice that

$$\mathbb{E}[X] = \mathbb{E}\left[\sum_{k \geq 1} \langle k \rangle^3 P_k^2 g_k^2\right] = \sum_{k \geq 1} \mathbb{E}[\langle k \rangle^3 P_k^2 g_k^2] = \sum_{k \geq 1} \langle k \rangle^3 P_k^2 \underbrace{\mathbb{E}[(g_k - \mathbb{E}[g_k])^2]}_{\mathrm{Var}(g_k)} = \|P\|_{\widehat{H}^3}^2.$$

Since $P \in \hat{H}^3$, we deduce that almost surely, X is finite and V belongs to $\hat{H}^3 \subset \hat{H}^1$. Furthermore, using Sobolev embeddings we have $\hat{H}^3 \subset H^3 \subset \mathcal{C}^2$ and thus $V \in \mathcal{C}^2$. We turn next to proving the second assumption. For $P \in \hat{H}^3$, we denote by $\mathcal{K} > 0$ the sum of the convergent series $\sum_{k \geq 1} \langle k \rangle (\log(k+1))^2 P_k^2$. Then for a fixed $\lambda > 0$, we have

$$\begin{split} \mathbb{P}(\|V\|_{\widehat{H}^{1}} < \lambda) &\geq \mathbb{P}(\forall k \geq 1, \ |g_{k}| < \mathcal{K}^{-1/2} \lambda \log(k+1)) \\ &= \prod_{k \geq 1} \mathbb{P}(|g_{k}| < \mathcal{K}^{-1/2} \lambda \log(k+1)) \\ &= \prod_{k \geq 1} [1 - \mathbb{P}(|g_{k}| \geq \mathcal{K}^{-1/2} \lambda \log(k+1))] \\ &= \prod_{k \geq 1} \left[1 - \frac{2}{\sqrt{2\pi}} \int_{\mathcal{K}^{-1/2} \lambda \log(k+1)}^{+\infty} e^{-g_{k}^{2}/2} \, \mathrm{d}g_{k} \right] \\ &= \prod_{k \geq 1} \left[1 - \frac{2}{\sqrt{2\pi}} \int_{0}^{+\infty} e^{-(g_{k} + \mathcal{K}^{-1/2} \lambda \log(k+1))^{2}/2} \, \mathrm{d}g_{k} \right] \\ &\geq \prod_{k \geq 1} \left[1 - \frac{2}{\sqrt{2\pi}} e^{-\lambda^{2} (\log(k+1))^{2}/2\mathcal{K}} \int_{0}^{+\infty} e^{-g_{k}^{2}/2} \, \mathrm{d}g_{k} \right] \\ &\geq \prod_{k \geq 1} \left[1 - e^{-\lambda^{2} (\log(k+1))^{2}/2\mathcal{K}} \right] \end{split}$$

with

$$\sum_{k \geq 1} e^{-\lambda^2 (\log(k+1))^2/2\mathcal{K}} = \sum_{k \geq 1} (k+1)^{-\lambda^2 \log(k+1)/2\mathcal{K}} \lesssim_{\lambda} \sum_{k \geq 1} \langle k \rangle^{-2}$$

which converges. Finally, since $0 < e^{-\lambda^2(\log(k+1))^2/2\mathcal{K}} < 1$, we directly conclude that

$$\prod_{k\geq 1} \left[1 - \frac{2}{\sqrt{2\pi}} e^{-\lambda^2 (\log(k+1))^2/2\mathcal{K}} \right] > 0.$$

Lemma A.2. There exists K > 1 such that the following estimate holds

$$\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle \leq K(r_* + 1) + |\Omega_{j,l}(V)|.$$

Proof. From Lemma 2.3, we deduce that for all $j \geq 1$, there exists C > 0 such that

$$|w_j - j| \le Cj^{-1/12} \le C.$$

Now, consider the decomposition

$$\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle$$

$$= (w_{j_1} + \dots + w_{j_{r_*}} - w_{l_1} - \dots - w_{l_{r_*}})$$

$$+ [\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle - (j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*})]$$

$$+ [(j_1 - w_{j_1}) + \dots + (j_{r_*} - w_{j_{r_*}}) - (l_1 - w_{l_1}) - \dots - (l_{r_*} - w_{l_{r_*}})].$$

Using the fact that for all $y \ge 0$, we have $|\langle y \rangle - y| \le 1$, we directly establish that

$$\langle j_1 + \dots + j_{r_*} - l_1 - \dots - l_{r_*} \rangle \le 1 + \underbrace{\sum_{n=1}^{r_*} (|w_{j_n} - j_n| + |w_{l_n} - l_n|)}_{\le cr_*} + |\Omega_{j,l}(V)|$$

$$\le \max(1, c)(r_* + 1) + |\Omega_{j,l}(V)|.$$

Lemma A.3. If $(d\tau^{(1)} \circ \tau^{(0)})^*$ denotes the adjoint of $d\tau^{(1)} \circ \tau^{(0)}$, then we have

$$d\tau^{(0)}i = i(d\tau^{(1)} \circ \tau^{(0)})^*.$$

Proof. Let u, v and $w \in \mathbb{C}^{[1,M]}$. Since $\tau^{(1)}$ is symplectic (recall Definition 3.4), we have

$$\left((\mathrm{d}\tau^{(1)}(u))^* i (\mathrm{d}\tau^{(1)})(u)(v), w \right)_{\ell^2} = \left(i (\mathrm{d}\tau^{(1)})(u)(v), (\mathrm{d}\tau^{(1)})(u)(w) \right)_{\ell^2} = (iv, w)_{\ell^2}.$$

This implies that for all $u \in B_{\mathbb{C}^{[1,M]}}(0,\varepsilon_0)$, we get $(d\tau^{(1)}(u))^*i(d\tau^{(1)})(u) = i$. In particular for $u = \tau^{(0)}$. Now, since the diagram in Theorem 4.1 commutes, we obtain

$$((d\tau^{(1)}) \circ \tau^{(0)})d\tau^{(0)} = d(\tau^{(1)} \circ \tau^{(0)}) = d(id_{\mathbb{C}[1,M]}) = id_{\mathbb{C}[1,M]}.$$
(31)

Finally, multiplying $(d\tau^{(1)}(u))^*i(d\tau^{(1)})(u) = i$ by $d\tau^{(0)}$ and using (31), we deduce

$$i(\mathrm{d}\tau^{(0)}) = (\mathrm{d}\tau^{(1)} \circ \tau^{(0)})^* i((\mathrm{d}\tau^{(1)}) \circ \tau^{(0)}) \mathrm{d}\tau^{(0)} = (\mathrm{d}\tau^{(1)} \circ \tau^{(0)})^* i(\mathrm{id}_{\mathbb{C}^{[\![1,M]\!]}}) = (\mathrm{d}\tau^{(1)} \circ \tau^{(0)})^* i.$$

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