



SHORT TIME DIFFUSION PROPERTIES OF INHOMOGENEOUS KINETIC EQUATIONS WITH FRACTIONAL COLLISION KERNEL

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SHORT TIME DIFFUSION PROPERTIES OF INHOMOGENEOUS KINETIC EQUATIONS WITH FRACTIONAL COLLISION KERNEL

FRÉDÉRIC HÉRAU, DANIELA TONON, AND ISABELLE TRISTANI

ABSTRACT. We prove regularization properties in short time for inhomogeneous kinetic equations whose collision kernel behaves like a fractional power of the Laplacian in velocity. We treat a fractional Kolmogorov equation and the linearized Boltzmann equation without cutoff (for hard potentials).

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1. INTRODUCTION AND RESULTS

1.1. Models and notations. In this paper, we consider two kinetic inhomogeneous equations on $\mathbb{R}^+ \times \mathbb{T}_x^d \times \mathbb{R}_v^d$ (\mathbb{T}^d being the d -dimensional torus) with collision kernel having the behavior of a fractional Laplacian in velocity:

$$(1) \quad \begin{cases} \partial_t f + v \cdot \nabla_x f = Lf \\ f|_{t=0} = f_0, \end{cases}$$

where $f = f(t, x, v)$ is the distribution of particles, and L is the collision kernel, roughly behaving like a fractional power of the Laplacian in velocity, and acting only in velocity.

Fractional Kolmogorov equation. The simplest model entering in this family is the fractional Kolmogorov equation: for $s \in (0, 1]$, the corresponding collision kernel is given by

$$(2) \quad L := -(1 - \Delta_v)^s.$$

Linearized Boltzmann equation. We also deal with a more complicated model associated to the linearized Boltzmann operator without cutoff for hard potentials in dimension $d = 3$. Let us describe it more precisely. The Boltzmann collision operator is defined as

$$(3) \quad Q(g, f) := \int_{\mathbb{R}^3 \times \mathbb{S}^2} B(v - v_*, \sigma) [g'_* f' - g_* f] \, d\sigma \, dv_*.$$

Here and below, we are using the shorthand notations $f = f(v)$, $g_* = g(v_*)$, $f' = f(v')$ and $g'_* = g(v'_*)$. In this expression, v , v_* and v' , v'_* are the velocities of a pair of particles before and after collision. We make a choice of parametrization of the set of solutions to the conservation of momentum and energy (physical laws of elastic collisions):

$$v + v_* = v' + v'_*,$$

$$|v|^2 + |v_*|^2 = |v'|^2 + |v'_*|^2,$$

so that the post-collisional velocities are given by:

$$v' = \frac{v + v_*}{2} + \frac{|v - v_*|}{2} \sigma, \quad v'_* = \frac{v + v_*}{2} - \frac{|v - v_*|}{2} \sigma, \quad \sigma \in \mathbb{S}^2.$$

The Boltzmann collision kernel $B(v - v_*, \sigma)$ only depends on the relative velocity $|v - v_*|$ and on the deviation angle θ through $\cos \theta = \langle \kappa, \sigma \rangle$ where $\kappa = (v - v_*)/|v - v_*|$ and $\langle \cdot, \cdot \rangle$ is the usual scalar product in \mathbb{R}^3 . By a symmetry argument, one can always reduce to the case where $B(v - v_*, \sigma)$ is supported on $\langle \kappa, \sigma \rangle \geq 0$ i.e. $0 \leq \theta \leq \pi/2$. So, without loss of generality, we make this assumption. In the sequel, we shall be concerned with the case when the kernel B satisfies the following conditions (which include the physical case of the so-called hard potentials):

- it takes product form in its arguments as

$$(4) \quad B(v - v_*, \sigma) = \Phi(|v - v_*|) b(\cos \theta);$$

- the angular function b is locally smooth, and has a nonintegrable singularity for $\theta \rightarrow 0$, it satisfies for some $c_b > 0$ and $s \in (0, 1/2)$

$$(5) \quad \forall \theta \in (0, \pi/2], \quad \frac{c_b}{\theta^{1+2s}} \leq \sin \theta \, b(\cos \theta) \leq \frac{1}{c_b \theta^{1+2s}};$$

- the kinetic factor Φ satisfies

$$(6) \quad \Phi(|v - v_*|) = |v - v_*|^\gamma \quad \text{with} \quad \gamma > 0,$$

this assumption could be relaxed to assuming only that Φ satisfies $\Phi(\cdot) = C_\Phi |\cdot|^\gamma$ for some $C_\Phi > 0$.

We will consider μ the only global Maxwellian equilibrium of the equation with mass 1, vanishing momentum and energy 3:

$$\mu(v) := (2\pi)^{-3/2} e^{-|v|^2/2}.$$

We are interesting in the linearized operator around the equilibrium μ (not the whole nonlinear Boltzmann operator) which is defined at first order through

$$\Lambda f := Q(\mu, f) + Q(f, \mu) - v \cdot \nabla_x f$$

and we thus consider the evolution equation (1) with L given by

$$(7) \quad Lf := -(Q(\mu, f) + Q(f, \mu))$$

with the collision operator Q defined through (3) and satisfying the conditions (4), (5), (6).

Notations. We will denote $\langle w \rangle = (1 + |w|^2)^{1/2}$ for any $w \in \mathbb{R}^d$. For convenience, we introduce the following strictly positive operators

$$\Lambda_v^2 = 1 - \Delta_v, \quad \Lambda_x^2 = 1 - \Delta_x$$

and the associated family of Fourier multipliers

$$\Lambda_x^\alpha = (1 - \Delta_x)^{\alpha/2}, \quad \Lambda_v^\beta = (1 - \Delta_v)^{\beta/2}, \quad \alpha, \beta \in \mathbb{R}$$

which act on a function in $\mathcal{S}(\mathbb{T}^d \times \mathbb{R}^d)$ in the following way

$$\widehat{\Lambda_x^\alpha f}(\xi, \eta) = \langle \xi \rangle^\alpha \widehat{f}(\xi, \eta), \quad \widehat{\Lambda_v^\beta f}(\xi, \eta) = \langle \eta \rangle^\beta \widehat{f}(\xi, \eta)$$

where the hat corresponds to the Fourier transform in both x and v variables. We also introduce the corresponding Sobolev spaces

$$H_{x,v}^{\alpha,\beta} = \left\{ f \in \mathcal{S}', \Lambda_x^\alpha \Lambda_v^\beta f \in L^2 \right\},$$

and we denote by $\|\cdot\|_{\alpha,\beta}$ the corresponding norm. Similarly, we introduce the weighted Sobolev spaces $H_{x,v}^{\alpha,\beta}(m)$ for m a weight function (the typical example in the sequel will be $m(v) = \langle v \rangle^k$ for some $k \geq 0$):

$$H_{x,v}^{\alpha,\beta}(m) = \left\{ f \in \mathcal{S}', \Lambda_x^\alpha \Lambda_v^\beta (fm) \in L^2 \right\},$$

and we denote by $\|\cdot\|_{H_{x,v}^{\alpha,\beta}(m)}$ the corresponding norm.

1.2. Main results and known results.

Fractional Kolmogorov equation. With the notations introduced above, the fractional Kolmogorov equation reads

$$\partial_t f + v \cdot \nabla_x f + \Lambda_v^{2s} f = 0$$

and a natural question is whether f benefits from some regularization induced by the elliptic properties of Λ_v^{2s} . The main result concerning the fractional Kolmogorov equation is the following:

Theorem 1.1. *Let $r \in \mathbb{R}$ and f be a solution of (1) with L given by (2) with initial data $f_0 \in H_{x,v}^{r,0}$. Then, there exists a constant $C_r > 0$ independent of f_0 such that for all $t \in (0, 1]$, we have*

$$\|f(t)\|_{r,s} \leq \frac{C_r}{t^{1/2}} \|f_0\|_{r,0} \quad \text{and} \quad \|f(t)\|_{r+s,0} \leq \frac{C_r}{t^{1/2+s}} \|f_0\|_{r,0}.$$

This result has already been proved in the case $s = 1$ in [8] by the first author and we give here a result concerning the cases $s \in (0, 1)$ following essentially the same core of the method as there: we introduce a functional which is a Lyapunov functional for our equation for small times (see also [15] by Villani for this type of methods). From this property, we are then able to recover some regularization estimates quantified in time. Let us emphasize that the main difficulty for the fractional case is to find a good entropy function (it is of course not the same as in the non fractional case $s = 1$). This type of result is of great use in the proof of the return to equilibrium in large functional spaces of solutions of inhomogeneous kinetic equations as in [13] by Mischler and Mouhot in the Fokker-Planck case ($s = 1$) following a general method also presented in [13]. The homogeneous fractional Fokker-Planck case has been studied by the third author in [14] where regularization properties in velocity (concerning the integrability of the solution) are investigated thanks to a fractional Nash inequality. In Section 2, devoted to the fractional Kolmogorov equation, we pay attention to give a proof for Theorem 1.1 *without* using any kind of pseudodifferential tool (only Fourier multiplier).

Linearized Boltzmann equation without cutoff. In Section 3, what we aim to do is to prove some similar regularization properties for the linearized inhomogeneous Boltzmann equation without cutoff as we do for the fractional Kolmogorov equation (Theorem 1.1). We recall that the Boltzmann equation is of type (1) in dimension 3 with L given by (7). Here is the main result that we obtain on this model:

Theorem 1.2. *Let $r \in \mathbb{N}$, $k > \gamma/2 + 3 + 2(r + 1)s$, $k' > k + \gamma + 5/2$ and f be a solution of (1) with L given by (7) with initial data $f_0 \in H_{x,v}^{r,0}(\langle v \rangle^k)$. Then, there exists a constant $C_r > 0$ independent of f_0 such that we have the following regularization estimates:*

$$\|f(t)\|_{H_{x,v}^{r,0}(\langle v \rangle^k)} \leq \frac{C_r}{t^{1/2}} \|f_0\|_{(H_{x,v}^{r,s}(\langle v \rangle^{k'}))'}, \quad \forall t \in (0, 1],$$

where $(H_{x,v}^{r,s}(\langle v \rangle^{k'}))'$ is the dual space of $H_{x,v}^{r,s}(\langle v \rangle^{k'})$ with respect to $H_{x,v}^{r,0}(\langle v \rangle^{k'})$. We also have:

$$\|f(t)\|_{H_{x,v}^{r,0}(\langle v \rangle^k)} \leq \frac{C_r}{t^{1/2+s}} \|f_0\|_{(H_{x,v}^{r+s,0}(\langle v \rangle^{k'}))'}, \quad \forall t \in (0, 1],$$

where $(H_{x,v}^{r+s,0}(\langle v \rangle^{k'}))'$ is the dual space of $H_{x,v}^{r+s,0}(\langle v \rangle^{k'})$ with respect to $H_{x,v}^{r,0}(\langle v \rangle^{k'})$.

First, we have to underline that it is the first result of regularization quantified in time on the Boltzmann equation without cutoff and that it is a key point for the development of the Cauchy theory of perturbative solutions in [9] by the same three authors for the nonlinear Boltzmann equation without cutoff.

The singularity of the Boltzmann kernel in the non cutoff case implies that the Boltzmann operator without cutoff (that we will describe later on) behaves as a fractional Laplacian in velocity:

$$Q(g, f) \approx -C_g(-\Delta_v)^s f + \text{lower order terms}$$

with C_g depending only on the physical properties of g . This type of result has already been studied in the homogeneous and non-homogeneous cases. The gain in velocity is quite obvious to observe even if it is complicated to understand it precisely: up to now, the most common way to understand it is through an anisotropic norm (see [7] by Gressman and Strain and [4] by Alexandre et al.). It is then natural to expect that the transport term allows to transfer the gain in velocity to the space variable. We refer to the references quoted in [2] for a review of this type of properties. Let us mention that the paper [2] by Alexandre et al. is the first one in which the hypoellipticity features of the operator have been deeply analyzed.

Our strategy here is to use the same method as for Kolmogorov type equations introduced in [8] by the first author. In short, except from the fact that the use of pseudo-differential tools is required and thus there are many additional technical difficulties, the method is the same as for the fractional Kolmogorov equation. For purposes of comparison, we can also mention that this kind of strategy has also been applied successfully to the Landau equation in [6] by Carrapatoso et al.. However, the study of this kind of properties is much harder in the case of the Boltzmann equation without cutoff since the gain in regularity is less clear and consists in an anisotropic gain of fractional derivatives: we have to exploit the fact that one can write a part the Boltzmann linearized operator as a pseudo-differential operator, in the spirit of what has been done in [2].

Indeed, we adapt here some ideas from there allowing to do computations for operators - including the Boltzmann one - whose symbols are in an adapted class called here S_K , where K is a large parameter. Let us point out that those classes are complicated partly because the order of the symbols does not decrease with derivation, which induces some great technical difficulties. The computations are done using the Wick quantization, widely studied in particular by Lerner (see [11] and [12]), which has very nice positivity properties. This allows to adapt to the Boltzmann case the Lyapunov strategy already introduced in [8] for the Kolmogorov case and in the second section of this article for the fractional Fokker-Planck case.

It is also important to underline the fact that this pseudo-differential study is not done on the whole linearized operator but only on a well-chosen part of it (this is the object of Subsection 3.3). Indeed, thanks to Duhamel formula, we will then be able to recover an estimate on the whole semigroup, the one associated to Λ (see Lemma 3.4).

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1.3. Outline of the paper. In Section 2, we prove Theorem 1.1 on the fractional Kolmogorov equation. In Section 3, we focus on the linearized Boltzmann equation and more precisely on Theorem 1.2 and most of its proof. The remainder of which contains pseudo-differential arguments and will be found in Section 4. Finally, in the Appendix, we present the pseudo-differential tools that we shall use in full generality.

2. THE FRACTIONAL KOLMOGOROV EQUATION

This section is devoted to the proof of Theorem 1.1. Following [8], we shall show below that this entropy functional is decreasing with time, and this will imply the result in the last subsection.

2.1. A Lyapunov functional. Let f be a solution of (1) with L given by (2) and with initial data f_0 . We first deal with the case $r = 0$. We follow the lines of the proof given in [8] and introduce an adapted entropy functional defined for all $t \geq 0$ by

$$\mathcal{H}(t) = C \|f\|^2 + Dt \|\Lambda_v^{s-1} \nabla_v f\|^2 + Et^{1+s} \operatorname{Re} (\Lambda_v^{s-1} \nabla_v f, \Lambda_x^{s-1} \nabla_x f) + t^{1+2s} \|\Lambda_x^{s-1} \nabla_x f\|^2$$

for large constants C, D, E to be chosen later, where $\|\cdot\|$ is the usual L^2 norm, (\cdot, \cdot) is the usual (complex) L^2 scalar product, we also have denoted

$$\|\Lambda_w^{s-1} \nabla_w f\|^2 = \sum_{k=1}^d \|\Lambda_w^{s-1} \partial_{w_k} f\|^2 \quad \text{for } w = x, v$$

and

$$(\Lambda_v^{s-1} \nabla_v f, \Lambda_x^{s-1} \nabla_x f) = \sum_{k=1}^d (\Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f).$$

The first step in the study is to show that \mathcal{H} is indeed non-negative. The lemma below shows in addition that for all $t > 0$, $\mathcal{H}(t)$ controls the H^s norm (where $H^s := H^{0,s} \cap H^{s,0}$).

Lemma 2.1. *If $E \leq \sqrt{D}$ then for all $t \geq 0$ we have $\mathcal{H}(t) \geq 0$. Precisely we have*

$$0 \leq C \|f\|^2 + \frac{D}{2} t \|\Lambda_v^{s-1} \nabla_v f\|^2 + \frac{1}{2} t^{1+2s} \|\Lambda_x^{s-1} \nabla_x f\|^2 \leq \mathcal{H}(t).$$

Proof. The proof is direct using the time-dependant Cauchy-Schwarz inequality

$$Et^s |(\Lambda_v^{s-1} \nabla_v f, \Lambda_x^{s-1} \nabla_x f)| \leq \frac{E^2}{2} \|\Lambda_v^{s-1} \nabla_v f\|^2 + \frac{1}{2} t^{2s} \|\Lambda_x^{s-1} \nabla_x f\|^2.$$

□

The main ingredient in the proof of Theorem 1.1 is the following commutation equality: for $j \in \llbracket 1, d \rrbracket$,

$$[\partial_{v_j}, v_j \partial_{x_j}] = \partial_{x_j}.$$

In the same spirit, we shall need later the following lemma giving formulas for slightly modified commutators. We denote from now on $X := v \cdot \nabla_x$ the Vlasov operator and $X_j := v_j \partial_{x_j}$, so that $X = \sum_{j=1}^d X_j$ and the previous fundamental equality reads $[\partial_{v_j}, X_j] = \partial_{x_j}$.

Lemma 2.2. *For $k \in \llbracket 1, d \rrbracket$, we have*

$$[\Lambda_v^{s-1} \partial_{v_k}, X] = \Lambda_v^{s-1} \partial_{x_k} + (1-s) \partial_{v_k} \sum_{j=1}^d \partial_{v_j} \Lambda_v^{s-3} \partial_{x_j}$$

and

$$[\Lambda_v^{s-1} \partial_{v_k}, \Lambda_v^{2s}] = [\Lambda_x^{s-1} \partial_{x_k}, \Lambda_v^{2s}] = [\Lambda_x^{s-1} \partial_{x_k}, X] = 0.$$

Proof. For the three last equalities, the result is immediate since differentiation in velocity and spatial direction commute. Let us deal with the first one. Let $j, k \in \llbracket 1, d \rrbracket$. We check that the commutator $[\Lambda_v^{s-1} \partial_{v_k}, X_j]$ is in fact a Fourier multiplier whose symbol reads

$$\sigma([\Lambda_v^{s-1} \partial_{v_k}, X_j]) = \frac{1}{i} \left\{ \langle \eta \rangle^{s-1} i \eta_k, i v_j \xi_j \right\}$$

where we denote by $\{\cdot, \cdot\}$ the Poisson bracket of two functions. Let us mention that in the Fourier formalism, we have that for $\alpha \in \mathbb{R}$,

$$\sigma(\partial_{v_k}) = i \eta_k, \quad \sigma(\partial_{x_j}) = i \xi_j, \quad \sigma(X_j) = i v_j \xi_j, \quad \sigma(\Lambda_v^\alpha) = \langle \eta \rangle^\alpha, \quad \sigma(-\Delta_v) = |\eta|^2.$$

We have then

$$\sigma([\Lambda_v^{s-1} \partial_{v_k}, X_j]) = i \xi_j \left\{ \langle \eta \rangle^{s-1} \eta_k, v_j \right\} = i \xi_j \left((s-1) \eta_j \eta_k \langle \eta \rangle^{s-3} + \langle \eta \rangle^{s-1} \delta_{kj} \right)$$

where δ_{kj} is the Kronecker delta of (k, j) . Then, summing on j , we get:

$$\begin{aligned} \sigma([\Lambda_v^{s-1} \partial_{v_k}, X]) &= i \sum_{j=1}^d \xi_j \left((s-1) \eta_j \eta_k \langle \eta \rangle^{s-3} + \langle \eta \rangle^{s-1} \delta_{kj} \right) \\ &= i \langle \eta \rangle^{s-3} \left(\xi_k (1 + s \eta_k^2) + \sum_{j \neq k} \eta_j ((s-1) \xi_j \eta_k + \xi_k \eta_j) \right). \end{aligned}$$

Coming back on the non-Fourier side, we obtain:

$$\begin{aligned}
[\Lambda_v^{s-1} \partial_{v_k}, X] &= (1 - s \partial_{v_k}^2) \Lambda_v^{s-3} \partial_{x_k} + (1 - s) \partial_{v_k} \sum_{j \neq k} \partial_{v_j} \Lambda_v^{s-3} \partial_{x_j} - \sum_{j \neq k} \partial_{v_j}^2 \Lambda_v^{s-3} \partial_{x_k} \\
&= (1 - \Delta_v) \Lambda_v^{s-3} \partial_{x_k} + (1 - s) \partial_{v_k}^2 \Lambda_v^{s-3} \partial_{x_k} + (1 - s) \partial_{v_k} \sum_{j \neq k} \partial_{v_j} \Lambda_v^{s-3} \partial_{x_j} \\
&= \Lambda_v^{s-1} \partial_{x_k} + (1 - s) \partial_{v_k} \sum_{j=1}^d \partial_{v_j} \Lambda_v^{s-3} \partial_{x_j}
\end{aligned}$$

which is the required result. \square

We now show that \mathcal{H} is indeed a Lyapunov function (entropy functional).

Lemma 2.3. *For well chosen (arbitrarily large) constants C , D and E we have*

$$\frac{d}{dt} \mathcal{H}(t) \leq 0, \quad \forall t \in (0, 1].$$

Proof. Using the previous lemma, we shall compute the time derivative of each terms appearing in the definition of \mathcal{H} . For convenience we introduce the operator associated the the Kolmogorov equation

$$P = X + \Lambda_v^{2s}.$$

so that f satisfies $\partial_t f + P f = 0$. We do below all the computations in (the complex) L^2 .

We first notice that

$$\frac{d}{dt} \|f\|^2 = -2 \operatorname{Re} (P f, f) = -2 \operatorname{Re} ((X + \Lambda_v^{2s}) f, f) = -2 (\Lambda_v^{2s} f, f)$$

since X is skew-adjoint. Using Parseval formula on the right-hand side we get that the first term in the derivative of \mathcal{H} is

$$(8) \quad \frac{d}{dt} C \|f\|^2 = - \underbrace{(2C \langle \eta \rangle^{2s})}_I \widehat{f}, \widehat{f}.$$

Note that this term is non-positive.

For the second term in the derivative of \mathcal{H} , we have

$$\frac{d}{dt} \left(t \|\Lambda_v^{s-1} \nabla_v f\|^2 \right) = \sum_{k=1}^d \left(\|\Lambda_v^{s-1} \partial_{v_k} f\|^2 + t \frac{d}{dt} (\Lambda_v^{s-1} \partial_{v_k} f, \Lambda_v^{s-1} \partial_{v_k} f) \right).$$

Let us fix $k \in \llbracket 1, d \rrbracket$. The derivative of the k -th term in the last term writes

$$\begin{aligned}
\frac{d}{dt} \|\Lambda_v^{s-1} \partial_{v_k} f\|^2 &= -2\operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} P f, \Lambda_v^{s-1} \partial_{v_k} f) \\
&= -2\operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} \Lambda_v^{2s} f, \Lambda_v^{s-1} \partial_{v_k} f) - 2\operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} X f, \Lambda_v^{s-1} \partial_{v_k} f) \\
&= -2\operatorname{Re}(\Lambda_v^{2s} \Lambda_v^{s-1} \partial_{v_k} f, \Lambda_v^{s-1} \partial_{v_k} f) - 2\operatorname{Re}(X \Lambda_v^{s-1} \partial_{v_k} f, \Lambda_v^{s-1} \partial_{v_k} f) \\
&\quad - 2\operatorname{Re}([\Lambda_v^{s-1} \partial_{v_k}, \Lambda_v^{2s}] f, \Lambda_v^{s-1} \partial_{v_k} f) - 2\operatorname{Re}([\Lambda_v^{s-1} \partial_{v_k}, X] f, \Lambda_v^{s-1} \partial_{v_k} f) \\
&= -2\operatorname{Re}(\Lambda_v^{2s} \Lambda_v^{s-1} \partial_{v_k} f, \Lambda_v^{s-1} \partial_{v_k} f) \\
&\quad - 2\operatorname{Re}(\Lambda_v^{s-1} \partial_{x_k} f + (1-s) \partial_{v_k} \sum_{j=1}^d \partial_{v_j} \Lambda_v^{s-3} \partial_{x_j} f, \Lambda_v^{s-1} \partial_{v_k} f) \\
&= 2\operatorname{Re}(\Lambda_v^{4s-2} \partial_{v_k}^2 f, f) + 2\operatorname{Re}(\Lambda_v^{2s-2} \partial_{x_k} \partial_{v_k} f, f) \\
&\quad + 2\operatorname{Re}((1-s) \partial_{v_k}^2 \sum_{j=1}^d \partial_{v_j} \Lambda_v^{2s-4} \partial_{x_j} f, f)
\end{aligned}$$

where we used that X is skew adjoint and the commutation expressions in Lemma 2.2. Writing the right-hand side on the Fourier side, summing over k and using Cauchy-Schwarz inequality gives us:

$$\begin{aligned}
\frac{d}{dt} \|\Lambda_v^{s-1} \nabla_v f\|^2 &\leq -2(\langle \eta \rangle^{4s-2} |\eta|^2 \widehat{f}, \widehat{f}) + 2(2-s)(\langle \eta \rangle^{2s-1} \langle \xi \rangle \widehat{f}, \widehat{f}) \\
&\leq -2(\langle \eta \rangle^{4s} \widehat{f}, \widehat{f}) + 2(\langle \eta \rangle^{4s-2} \widehat{f}, \widehat{f}) + 2(2-s)(\langle \eta \rangle^{2s-1} \langle \xi \rangle \widehat{f}, \widehat{f}).
\end{aligned}$$

The second term in \mathcal{H} therefore satisfies

$$\begin{aligned}
(9) \quad \frac{d}{dt} \left(Dt \|\Lambda_v^{s-1} \nabla_v f\|^2 \right) \\
\leq \left(\underbrace{(D \langle \eta \rangle^{2s})}_i - \underbrace{2Dt \langle \eta \rangle^{4s}}_{II} + \underbrace{2Dt \langle \eta \rangle^{4s-2}}_{ii} + \underbrace{2(2-s)Dt \langle \eta \rangle^{2s-1} \langle \xi \rangle}_{iii} \right) \widehat{f}, \widehat{f}.
\end{aligned}$$

We note that the term corresponding to II is non-positive, and that the three other ones are non-negative. Now we deal with the third term in the derivative of \mathcal{H} :

$$\begin{aligned}
&\frac{d}{dt} \left(t^{1+s} \operatorname{Re}(\Lambda_v^{s-1} \partial_v f, \Lambda_x^{s-1} \partial_x f) \right) \\
&= (1+s)t^s \operatorname{Re}(\Lambda_v^{s-1} \nabla_v f, \Lambda_x^{s-1} \nabla_x f) + t^{1+s} \frac{d}{dt} \operatorname{Re}(\Lambda_v^{s-1} \nabla_v f, \Lambda_x^{s-1} \nabla_x f) \\
&= (1+s)t^s \operatorname{Re}(\Lambda_v^{s-1} \nabla_v f, \Lambda_x^{s-1} \nabla_x f) + t^{1+s} \sum_{k=1}^d \frac{d}{dt} \operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f).
\end{aligned}$$

The k -th derivative in the last term writes

$$\begin{aligned}
&\frac{d}{dt} \operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f) \\
&= -\operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} P f, \Lambda_x^{s-1} \partial_{x_k} f) - \operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} P f) \\
&= -2\operatorname{Re}(\Lambda_v^{2s} \Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f) \\
&\quad - \operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} X f, \Lambda_x^{s-1} \partial_{x_k} f) - \operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} X f) \\
&= -2\operatorname{Re}(\Lambda_v^{2s} \Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f) \\
&\quad - \operatorname{Re}([\Lambda_v^{s-1} \partial_{v_k}, X] f, \Lambda_x^{s-1} \partial_{x_k} f) - \operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} f, [\Lambda_x^{s-1} \partial_{x_k}, X] f) \\
&\quad - \operatorname{Re}(X \Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f) - \operatorname{Re}(\Lambda_v^{s-1} \partial_{v_k} f, X \Lambda_x^{s-1} \partial_{x_k} f).
\end{aligned}$$

Now we use again that X is skew-adjoint and observe that it implies that the sum of the last two terms is zero by compensation. The previous term is also zero since the commutator inside is zero. Now with Lemma 2.2 we obtain

$$\begin{aligned} \frac{d}{dt} \operatorname{Re} (\Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f) &= -2 \operatorname{Re} (\Lambda_v^{2s} \Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f) \\ &\quad - \operatorname{Re} (\Lambda_v^{s-1} \partial_{x_k} f + (1-s) \partial_{v_k} \sum_{j=1}^d \partial_{v_j} \Lambda_v^{s-3} \partial_{x_j} f, \Lambda_x^{s-1} \partial_{x_k} f). \end{aligned}$$

Writing the right-hand side on the Fourier side then gives

$$\begin{aligned} \frac{d}{dt} \operatorname{Re} (\Lambda_v^{s-1} \partial_{v_k} f, \Lambda_x^{s-1} \partial_{x_k} f) &= -(\langle \eta \rangle^{3s-1} \langle \xi \rangle^{s-1} \eta_k \xi_k \widehat{f}, \widehat{f}) - (\langle \eta \rangle^{s-1} \xi_k^2 \langle \xi \rangle^{s-1} \widehat{f}, \widehat{f}) \\ &\quad + (1-s) \sum_{j=1}^d (\eta_k \langle \eta \rangle^{s-3} \xi_k \langle \xi \rangle^{s-1} \eta_j \xi_j \widehat{f}, \widehat{f}). \end{aligned}$$

Then, taking the sum over k gives us (using Cauchy-Schwarz inequality):

$$\begin{aligned} \frac{d}{dt} \operatorname{Re} (\Lambda_v^{s-1} \nabla_v f, \Lambda_x^{s-1} \nabla_x f) &\leq d(\langle \eta \rangle^{3s} \langle \xi \rangle^s \widehat{f}, \widehat{f}) - (\langle \eta \rangle^{s-1} |\xi|^2 \langle \xi \rangle^{s-1} \widehat{f}, \widehat{f}) \\ &\quad + (1-s) \left(\left(\sum_{j=1}^d \eta_j \xi_j \right)^2 \langle \eta \rangle^{s-3} \langle \xi \rangle^{s-1} \widehat{f}, \widehat{f} \right) \\ &\leq d(\langle \eta \rangle^{3s} \langle \xi \rangle^s \widehat{f}, \widehat{f}) - (\langle \eta \rangle^{s-1} |\xi|^2 \langle \xi \rangle^{s-1} \widehat{f}, \widehat{f}) \\ &\quad + (1-s)(|\eta|^2 |\xi|^2 \langle \eta \rangle^{s-3} \langle \xi \rangle^{s-1} \widehat{f}, \widehat{f}) \\ &\leq d(\langle \eta \rangle^{3s} \langle \xi \rangle^s \widehat{f}, \widehat{f}) - s(\langle \eta \rangle^{s-1} \langle \xi \rangle^{s+1} \widehat{f}, \widehat{f}) + (\langle \eta \rangle^{s-1} \langle \xi \rangle^{s-1} \widehat{f}, \widehat{f}). \end{aligned}$$

We therefore get that the third term in \mathcal{H} satisfies:

$$\begin{aligned} (10) \quad \frac{d}{dt} \left(Et^{1+s} \operatorname{Re} (\Lambda_v^{s-1} \nabla_v f, \Lambda_x^{s-1} \nabla_x f) \right) &\leq \left(\underbrace{E(s+1)t^s \langle \eta \rangle^s \langle \xi \rangle^s}_{iv} + \underbrace{dEt^{1+s} \langle \eta \rangle^{3s} \langle \xi \rangle^s}_v \right. \\ &\quad \left. - \underbrace{Est^{1+s} \langle \eta \rangle^{s-1} \langle \xi \rangle^{s+1}}_{III} + \underbrace{Et^{1+s} \langle \eta \rangle^{s-1} \langle \xi \rangle^{s-1}}_{vi} \right) \widehat{f}, \widehat{f}. \end{aligned}$$

We note that the term corresponding to III is non-positive, and that the three other ones are non-negative.

We can now deal with the last term in the derivative of \mathcal{H} . We write

$$\begin{aligned} \frac{d}{dt} \left(t^{1+2s} \|\Lambda_x^{s-1} \nabla_x f\|^2 \right) &= (1+2s)t^{2s} \|\Lambda_x^{s-1} \nabla_x f\|^2 + t^{1+2s} \frac{d}{dt} \|\Lambda_x^{s-1} \nabla_x f\|^2 \\ &= (1+2s)t^{2s} \sum_{k=1}^d \|\Lambda_x^{s-1} \partial_{x_k} f\|^2 + t^{1+2s} \sum_{k=1}^d \frac{d}{dt} \|\Lambda_x^{s-1} \partial_{x_k} f\|^2. \end{aligned}$$

The k -th derivative of the last term writes

$$\begin{aligned} \frac{d}{dt} \|\Lambda_x^{s-1} \partial_{x_k} f\|^2 &= -2 \operatorname{Re} (\Lambda_x^{s-1} \partial_{x_k} P f, \Lambda_x^{s-1} \partial_{x_k} f) \\ &= -2 \operatorname{Re} (\Lambda_v^{2s} \Lambda_x^{s-1} \partial_{x_k} f, \Lambda_x^{s-1} \partial_{x_k} f) - 2 \operatorname{Re} (X \Lambda_x^{s-1} \partial_{x_k} f, \Lambda_x^{s-1} \partial_{x_k} f) \\ &= -2 \operatorname{Re} (\Lambda_v^{2s} \Lambda_x^{s-1} \partial_{x_k} f, \Lambda_x^{s-1} \partial_{x_k} f). \end{aligned}$$

We used here the last commutations properties in Lemma 2.2 and again that X is skew-adjoint. Writing the right-hand side on the Fourier side and summing on k gives

$$\begin{aligned} \frac{d}{dt} \|\Lambda_x^{s-1} \nabla_x f\|^2 &= -2(\langle \eta \rangle^{2s} \langle \xi \rangle^{2s-2} |\xi|^2 \widehat{f}, \widehat{f}) \\ &= -2(\langle \eta \rangle^{2s} \langle \xi \rangle^{2s} \widehat{f}, \widehat{f}) + 2(\langle \eta \rangle^{2s} \langle \xi \rangle^{2s-2} \widehat{f}, \widehat{f}). \end{aligned}$$

The fourth term in the derivative of \mathcal{H} therefore satisfies:

$$(11) \quad \frac{d}{dt} \left(t^{1+2s} \|\Lambda_x^{s-1} \nabla_x f\|^2 \right) \leq \left(\underbrace{((1+2s)t^{2s} \langle \xi \rangle^{2s})}_{vii} - \underbrace{2t^{1+2s} \langle \eta \rangle^{2s} \langle \xi \rangle^{2s}}_{IV} + \underbrace{2t^{1+2s} \langle \eta \rangle^{2s} \langle \xi \rangle^{2s-2}}_{viii} \right) \widehat{f}, \widehat{f} \Bigg).$$

We note that the term corresponding to IV is non-positive, and that the other ones are non-negative.

Now we look at the different terms appearing in formulas (8-11). We want to show that with a good choice of constants C , D and E , the corresponding sum is non-positive, and therefore \mathcal{H} is indeed a Lyapunov functional. We shall study each non-negative term (small letters (i) to $(viii)$) and show that they can be controlled by combinations of terms I to IV , using essentially the Hölder inequality in \mathbb{R}^2 . We restrict the study to $t \in [0, 1]$.

The terms (i) and (ii) are immediately bounded by $I/10$ if

$$(12) \quad 2D \leq 2C/10.$$

since $s \leq 1$. The term (iii) is a little bit trickier. We check that for any $\varepsilon_{iii} > 0$

$$t \langle \eta \rangle^{2s-1} \langle \xi \rangle \leq \varepsilon_{iii}^{-1} \langle \eta \rangle^{2s} + \varepsilon_{iii}^s t^{1+s} \langle \eta \rangle^{s-1} \langle \xi \rangle^{s+1}.$$

Multiplying this inequality by $2D$ implies that $(iii) \leq I/10 + III/10$ if the following conditions are satisfied

$$(13) \quad \varepsilon_{iii}^{-1} 2(2-s)D \leq 2C/10, \quad \varepsilon_{iii}^s 2(2-s)D \leq Es/10.$$

Now we deal with the term (iv) . We first check that for any $\varepsilon_{iv} > 0$

$$t^s \langle \eta \rangle^s \langle \xi \rangle^s \leq \varepsilon_{iv}^{-1} \langle \eta \rangle^{2s} + \varepsilon_{iv}^{1/s} t^{1+s} \langle \eta \rangle^{s-1} \langle \xi \rangle^{s+1}.$$

Multiplying this inequality by $E(s+1)$ implies that $(iv) \leq I/10 + III/10$ if the following conditions are satisfied

$$(14) \quad \varepsilon_{iv}^{-1} E(s+1) \leq 2C/10, \quad \varepsilon_{iv}^{1/s} E(s+1) \leq Es/10.$$

For the term (v) we also have to give a refined estimate. We first check that for any $\varepsilon_v > 0$

$$t^{1+s} \langle \eta \rangle^{3s} \langle \xi \rangle^s \leq \varepsilon_v^{-1} t \langle \eta \rangle^{4s} + \varepsilon_v t^{1+2s} \langle \eta \rangle^{2s} \langle \xi \rangle^{2s}.$$

Multiplying this inequality by dE implies that $(v) \leq II/10 + IV/10$ if the following conditions are satisfied

$$(15) \quad \varepsilon_v^{-1} dE \leq 2D/10, \quad \varepsilon_v dE \leq 2/10.$$

The term (vi) is easily handled since $s \leq 1$, and we directly get that $(vi) \leq I/10$ if

$$(16) \quad E \leq 2C/10.$$

Now we study the term (vii) . We first notice that for any $\varepsilon_{vii} > 0$

$$t^{2s} \langle \xi \rangle^{2s} \leq \varepsilon_{vii}^{-1} \langle \eta \rangle^{2s} + \varepsilon_{vii}^{\frac{1-s}{2s}} t^{1+s} \langle \eta \rangle^{s-1} \langle \xi \rangle^{s+1}.$$

Multiplying this inequality by $(1 + 2s)$ implies that $(vii) \leq I/10 + III/10$ if the following conditions are satisfied

$$(17) \quad \varepsilon_{vii}^{-1}(1 + 2s) \leq 2C/10, \quad \varepsilon_{vii}^{\frac{1-s}{2s}}(1 + 2s) \leq Es/10.$$

To finish, the term $(viii)$ is also easily handled since $s \leq 1$, and we directly get that $(viii) \leq I/10$ if

$$(18) \quad 2 \leq 2C/10.$$

Now we can do the synthesis and check that we can choose (in order of reverse appearance) the constants C , D , E and the small constants ε_{iii} , ε_{iv} , ε_v and ε_{vii} such that conditions (12-18) are satisfied. Note that D and after that C can be taken arbitrarily large at the end of this procedure. We obtain therefore that

$$(19) \quad \frac{d}{dt} \mathcal{H}(t) \leq -\frac{1}{10} \left((I + II + III + IV) \hat{f}, \hat{f} \right) \leq 0$$

and the proof is complete. \square

Then we are able to conclude the proof of the main result Theorem 1.1 concerning the fractional Kolmogorov equation.

2.2. Proof of Theorem 1.1. We first prove the result for $r = 0$. Let C , D and E be constants given by Lemmas 2.1 and 2.3 and let us take $f_0 \in \mathcal{S}$. From Lemma 2.3 we first get that for all $t \in [0, 1]$

$$\mathcal{H}(t) \leq \mathcal{H}(0) = C \|f_0\|^2.$$

Now using Lemma 2.1, we get in particular

$$\frac{D}{2} t \|\Lambda_v^s f\|^2 \leq C \|f\|^2 + \frac{D}{2} t \|\Lambda_v^{s-1} \partial_v f\|^2 \leq \mathcal{H}(t) \leq C \|f_0\|^2$$

and this implies the result for the velocity regularization. Similarly, using again Lemma 2.1, we have

$$\frac{1}{2} t^{1+2s} \|\Lambda_x^s f\|^2 \leq C \|f\|^2 + \frac{1}{2} t^{1+2s} \|\Lambda_x^{s-1} \partial_x f\|^2 \leq \mathcal{H}(t) \leq C \|f_0\|^2$$

and this gives the regularization result for $r = 0$ in the spatial direction.

Now for $r \in \mathbb{R}$, we just use the fact that P commutes with Λ_x^r which implies that for f solution of $\partial_t f + Pf = 0$ with initial data f_0 , $\Lambda_x^r f$ is the solution of $\partial_t \Lambda_x^r f + P \Lambda_x^r f = 0$ with initial data $\Lambda_x^r f_0$. We can therefore apply the result on L^2 to $\Lambda_x^r f$ and this directly gives that

$$\frac{D}{2} t \|\Lambda_v^s \Lambda_x^r f\|^2 \leq C \|\Lambda_x^r f_0\|^2 \text{ and } \frac{1}{2} t^{1+2s} \|\Lambda_x^{s+r} f\|^2 \leq C \|\Lambda_x^r f_0\|^2.$$

This provides us the estimates for any $r \in \mathbb{R}$ and $f_0 \in \mathcal{S}$. The general result for initial data in the corresponding spaces follows by density of \mathcal{S} . The proof is complete. \square

3. THE INHOMOGENEOUS BOLTZMANN WITHOUT CUTOFF CASE

This section is devoted to the study of the Boltzmann equation without cutoff case and more precisely, to the proof of Theorem 1.2 (we recall that in this section, the dimension d equals 3). We start by making a few comments on this theorem:

- Notice that it is part of the results of [9] that Λ generates a semigroup in a large class of Lebesgue and Sobolev spaces and in particular in $H_{x,v}^{r,0}(\langle v \rangle^k)$ for $r \in \mathbb{N}$ and $k > \gamma/2 + 3 + 2(r+1)s$, so that f introduced in Theorem 1.2 is well-defined (we have $f(t) = S_\Lambda(t) f_0$ for any $t \in \mathbb{R}^+$ where $S_\Lambda(t)$ is the semigroup generated by Λ).

- Let us mention that this result is not optimal in the sense that there is a loss in weight in our estimates. But we strongly believe that one could obtain a better estimate (concerning the weights) carrying out a more careful study of the operator Λ . Indeed, in our proof, we perform a rough splitting of it and we use Duhamel formula to recover an estimate on the whole semigroup $S_\Lambda(t)$. We could have not split the operator and study it completely, that would certainly provides us a better result. However, the proof would be much more complicated and we are here interested in the gain of regularity in terms of derivatives (not in terms of weights). Furthermore, the result that we obtain is enough to develop our perturbative Cauchy theory in [9] because we have some leeway in the weights in our proof.
- Another important fact is that Theorem 1.2 provides a “dual” result of regularization, roughly speaking, from H^{-s} into L^2 . This is directly related to the use of this theorem that we make in [9]. We do not go into details here but a similar analysis could be carried out to obtain a regularization result from L^2 into H^s . The method would be the same, except from the fact that the analysis could be made easier taking another splitting of Λ .

3.1. Splitting of the operator. As already mentioned above, we are going to study the regularization properties only of a part of Λ , we thus start by exhibiting a splitting of it. There are two types of splittings that one can consider to separate grazing and non-grazing collisions, depending on the adopted truncature function: one can cut the small θ or the small $|v' - v|$. For our purpose, we will work with the second option which is more adapted to the study of hypoelliptic properties of the Boltzmann collision operator. To do that we introduce the truncation function $\chi \in \mathcal{D}(\mathbb{R})$ which satisfies $\mathbb{1}_{[-1,1]} \leq \chi \leq \mathbb{1}_{[-2,2]}$ and $\chi_\delta(\cdot) := \chi(\cdot/\delta)$ for $\delta > 0$ and consider the truncature function $\chi_\delta(|v' - v|)$. We denote Q_δ the operator associated to the kernel:

$$B_\delta(v - v_*, \sigma) := \chi_\delta(|v' - v|) b(\cos \theta) |v - v_*|^\gamma$$

and Q_δ^c the one associated to the remainder part of the kernel:

$$B_\delta^c(v - v_*, \sigma) := (1 - \chi_\delta(|v' - v|)) b(\cos \theta) |v - v_*|^\gamma.$$

We then have:

$$\begin{aligned} \Lambda f &= -v \cdot \nabla_x f + Q_\delta(\mu, f) + Q_\delta^c(\mu, f) + Q(f, \mu) \\ &= \left(-K \langle v \rangle^{\gamma+2s} f - v \cdot \nabla_x f + \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) (\mu_* f' - \mu'_* f) d\sigma dv_* \right) \\ &\quad + \left(K \langle v \rangle^{\gamma+2s} f + \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) (\mu'_* - \mu_*) (f' + f) d\sigma dv_* \right. \\ &\quad \left. + \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta^c(v - v_*, \sigma) (\mu'_* f' - \mu_* f) d\sigma dv_* + Q(f, \mu) \right) \\ &=: \Lambda_1 f + \Lambda_2 f \end{aligned}$$

where K is a large positive parameter to be fixed later. Notice that in Λ_1 , we have a term which is going to provide us some regularization

$$\int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) (\mu_* f' - \mu'_* f) d\sigma dv_*$$

and another one which provides us some dissipativity:

$$-K \langle v \rangle^{\gamma+2s} f.$$

3.2. Study of the controlled part Λ_2 . We first study the “nice” part of our splitting, namely Λ_2 which is “almost bounded” in the sense that it does not induce a loss of regularity but only a loss in weight.

Lemma 3.1. *Let $m := \langle v \rangle^k$ with $k \geq 0$. For any $K > 0$ and for any $\ell > 3/2$, we have the following estimate:*

$$(20) \quad \|\Lambda_2 f\|_{L_{x,v}^2(m)} \lesssim \|f\|_{L_{x,v}^2(\langle v \rangle^{\gamma+1+\ell} m)}.$$

Proof. We have

$$\begin{aligned} \Lambda_2 f &= K \langle v \rangle^{\gamma+2s} f + \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) (\mu'_* - \mu_*) f' d\sigma dv_* \\ &\quad + \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) (\mu'_* - \mu_*) d\sigma dv_* f + \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta^c(v - v_*, \sigma) \mu'_* f' d\sigma dv_* \\ &\quad - \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta^c(v - v_*, \sigma) \mu_* d\sigma dv_* f + Q(f, \mu) \\ &=: \Lambda_{21} f + \Lambda_{22} f + \Lambda_{23} f + \Lambda_{24} f + \Lambda_{25} f + \Lambda_{26} f. \end{aligned}$$

The estimate on Λ_{21} is obvious:

$$\|\Lambda_{21} f\|_{L_{x,v}^2(m)} \lesssim \|f\|_{L_{x,v}^2(\langle v \rangle^{\gamma+2s} m)}.$$

The analysis of Λ_{23} is also easy to perform using the cancellation lemma from [1], we have:

$$\Lambda_{23} f = (S * \mu) f$$

with S satisfying the estimate $|S(z)| \lesssim |z|^\gamma$. We deduce that $|S * \mu|(v) \lesssim \langle v \rangle^\gamma$ and thus

$$\|\Lambda_{23} f\|_{L_{x,v}^2(m)} \lesssim \|f\|_{L_{x,v}^2(\langle v \rangle^\gamma m)}.$$

To treat Λ_{24} and Λ_{25} , we use the fact that the kernel B_δ^c is not singular since the grazing collisions are removed. Since $|v' - v| \sim |v - v_*| \sin(\theta/2)$, we have:

$$|B_\delta^c(v - v_*, \sigma)| \leq b(\cos \theta) |v - v_*|^\gamma \mathbb{1}_{|v' - v| \geq \delta} \lesssim b(\cos \theta) |v - v_*|^{\gamma+1} \sin(\theta/2).$$

Consequently, we obtain using that $m \lesssim m' m'_*$ that for $\ell > 3/2$:

$$\begin{aligned} \|\Lambda_{24} f\|_{L_{x,v}^2(m)}^2 &\lesssim \int_{\mathbb{T}^3 \times \mathbb{R}^3} \left(\int_{\mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) |v - v_*|^{\gamma+1} \mu'_* f' d\sigma dv_* \right)^2 m^2 dv dx \\ &\lesssim \int_{\mathbb{T}^3 \times \mathbb{R}^3 \times \mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) |v - v_*|^{2(\gamma+1)} (\mu'_* m'_*)^2 (f' m')^2 \langle v_* \rangle^{2\ell} d\sigma dv_* dv dx \end{aligned}$$

where we have used Jensen inequality with the finite measure $b(\cos \theta) \sin(\theta/2) d\sigma$ and Cauchy-Schwarz inequality with the measure $\langle v_* \rangle^\ell dv_*$. Then, using the basic inequality $\langle v_* \rangle \lesssim \langle v' \rangle \langle v'_* \rangle$ and the pre-post collisional change of variable, we get:

$$\begin{aligned} &\|\Lambda_{24} f\|_{L_{x,v}^2(m)}^2 \\ &\lesssim \int_{\mathbb{T}^3 \times \mathbb{R}^3 \times \mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) |v - v_*|^{2(\gamma+1)} (\mu_* m_*)^2 (f m)^2 \langle v \rangle^{2\ell} \langle v_* \rangle^{2\ell} d\sigma dv_* dv dx \\ &\lesssim \|f\|_{L_{x,v}^2(\langle v \rangle^{\gamma+1+\ell} m)}^2 \quad \text{with } \ell > 3/2. \end{aligned}$$

The treatment of Λ_{25} is easier and we directly obtain:

$$\|\Lambda_{25} f\|_{L_{x,v}^2(m)} \lesssim \|f\|_{L_{x,v}^2(\langle v \rangle^{\gamma+1} m)}.$$

Concerning Λ_{26} , we have for any $\ell > 3/2$:

$$\|Q(f, \mu)\|_{L_v^2(m)} \lesssim \|f\|_{L_v^2(m \langle v \rangle^{\gamma+2s+\ell})}$$

where we used [3, Theorem 2.1]. We deduce that

$$\|\Lambda_{26}f\|_{L^2_{x,v}(m)} \lesssim \|f\|_{L^2_{x,v}(\langle v \rangle^{\gamma+2s+\ell}m)}, \quad \ell > 3/2.$$

It now remains to deal with Λ_{22} . Denoting $M := \sqrt{\mu}$, we have:

$$\begin{aligned} |\Lambda_{22}f| &\leq \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) |M'_* - M_*| (M'_* + M_*) |f'| d\sigma dv_* \\ &\lesssim \int_{\mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) |v - v_*|^{\gamma+1} (M'_* + M_*) |f'| d\sigma dv_* \end{aligned}$$

where we used that the gradient of M is bounded on \mathbb{R}^d . Then we use that $m \lesssim m'm'_*$ and $m \lesssim \langle v - v_* \rangle^k m_*$ to get:

$$\begin{aligned} \|\Lambda_{22}f\|_{L^2_{x,v}(m)}^2 &\lesssim \int_{\mathbb{T}^3 \times \mathbb{R}^3} \left(\int_{\mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) |v - v_*|^{\gamma+1} M'_* |f'| d\sigma dv_* \right)^2 m^2 dv dx \\ &\quad + \int_{\mathbb{T}^3 \times \mathbb{R}^3} \left(\int_{\mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) |v - v_*|^{\gamma+1} M_* |f'| d\sigma dv_* \right)^2 m^2 dv dx \\ &\lesssim \int_{\mathbb{T}^3 \times \mathbb{R}^3} \left(\int_{\mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) |v - v_*|^{\gamma+1} M'_* m'_* |f'| m' d\sigma dv_* \right)^2 dv dx \\ &\quad + \int_{\mathbb{T}^3 \times \mathbb{R}^3} \left(\int_{\mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) \langle v - v_* \rangle^{\gamma+1+k} M_* m_* |f'| d\sigma dv_* \right)^2 dv dx \\ &=: I_1 + I_2. \end{aligned}$$

Using Jensen inequality and Hölder inequality as previously, we obtain for $\ell > 3/2$:

$$\begin{aligned} \|\Lambda_{22}f\|_{L^2_{x,v}(m)}^2 &\lesssim \int_{\mathbb{T}^3 \times \mathbb{R}^3 \times \mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) |v - v_*|^{2(\gamma+1)} \mu'_*(m'_*)^2 |f'|^2 (m')^2 \langle v_* \rangle^{2\ell} d\sigma dv_* dv dx \\ &\quad + \int_{\mathbb{T}^3 \times \mathbb{R}^3 \times \mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) \langle v - v_* \rangle^{2(\gamma+1+k)} \mu_* m_*^2 |f'|^2 \langle v_* \rangle^{2\ell} d\sigma dv_* dv dx \\ &=: I_1 + I_2. \end{aligned}$$

The first term I_1 is treated as Λ_{24} and we thus have:

$$I_1 \lesssim \|f\|_{L^2_{x,v}(\langle v \rangle^{\gamma+1+\ell}m)}^2.$$

Concerning I_2 , we first look at the integral

$$J := \int_{\mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) \sin(\theta/2) \langle v - v_* \rangle^{2(\gamma+1+k)} |f'|^2 d\sigma dv.$$

Then, for each σ , with v_* still fixed, we perform the change of variables $v \rightarrow v'$. This change of variables is well-defined on the set $\{\cos \theta > 0\}$. Its Jacobian determinant is

$$\left| \frac{dv'}{dv} \right| = \frac{1}{8} (1 + \kappa \cdot \sigma) = \frac{(\kappa' \cdot \sigma)^2}{4},$$

where $\kappa = (v - v_*)/|v - v_*|$ and $\kappa' = (v' - v_*)/|v' - v_*|$. We have $\kappa' \cdot \sigma = \cos(\theta/2) \geq 1/\sqrt{2}$. The inverse transformation $v' \rightarrow \psi_\sigma(v') = v$ is then defined accordingly. We have

$$\cos \theta = \kappa \cdot \sigma = 2(\kappa' \cdot \sigma)^2 - 1 \quad \text{and} \quad \sin(\theta/2) = \sqrt{1 - \cos^2(\theta/2)} = \sqrt{1 - (\kappa' \cdot \sigma)^2},$$

and also

$$|\psi_\sigma(v) - v_*| = |v - v_*|/\kappa \cdot \sigma.$$

As a result, we get:

$$\begin{aligned}
J &= \int_{\mathbb{R}^3 \times \mathbb{S}^2} b(2(\kappa' \cdot \sigma)^2 - 1) \sqrt{1 - (\kappa' \cdot \sigma)^2} \langle \psi_\sigma(v') - v_* \rangle^{2(\gamma+1+k)} |f'|^2 d\sigma dv \\
&= \int_{\kappa' \cdot \sigma \geq 1/\sqrt{2}} b(2(\kappa' \cdot \sigma)^2 - 1) \sqrt{1 - (\kappa' \cdot \sigma)^2} \langle \psi_\sigma(v') - v_* \rangle^{2(\gamma+1+k)} |f'|^2 d\sigma \frac{4 dv'}{(\kappa' \cdot \sigma)^2} \\
&= \int_{\kappa \cdot \sigma \geq 1/\sqrt{2}} b(2(\kappa \cdot \sigma)^2 - 1) \sqrt{1 - (\kappa \cdot \sigma)^2} \langle \psi_\sigma(v) - v_* \rangle^{2(\gamma+1+k)} |f|^2 d\sigma \frac{4 dv}{(\kappa \cdot \sigma)^2} \\
&\lesssim \int_{\kappa \cdot \sigma \geq 1/\sqrt{2}} b(2(\kappa \cdot \sigma)^2 - 1) \sqrt{1 - (\kappa \cdot \sigma)^2} \langle v - v_* \rangle^{2(\gamma+1+k)} |f|^2 d\sigma dv \\
&\lesssim \int_{\mathbb{S}^2} b(\cos(2\theta)) \sin(\theta) d\sigma \int_{\mathbb{R}^3} f^2 m^2 \langle v \rangle^{2(\gamma+1)} dv \langle v_* \rangle^{2(\gamma+1)} m_*^2.
\end{aligned}$$

From this, we deduce that

$$I_2 \lesssim \|f\|_{L_{x,v}^2(\langle v \rangle^{\gamma+1} m)}^2$$

and this concludes the proof. \square

3.3. Regularization properties of Λ_1 . The main result of this Subsection is Proposition 3.2 and is about the regularization features of the semigroup associated to Λ_1 . Here, we just state the result and we postpone its proof to Section 4 in which we develop pseudo-differential arguments.

Functional spaces. In the remainder part of this section, we consider three weights:

$$\begin{cases} m(v) = \langle v \rangle^k \text{ with } k \geq 0, \\ m_0(v) = \langle v \rangle^{k_0} \text{ with } k_0 > \gamma/2 + 3 + 2s \\ m_1(v) = \langle v \rangle^{k_1} \text{ with } k_1 = k_0 + \gamma + 1 + \ell \text{ and } \ell > 3/2. \end{cases}$$

We then denote for $i = \emptyset, 0, 1$:

$$\begin{cases} X_i = L_{x,v}^2(m_i) \\ Y_i = H_{x,v}^{s,0}(\langle v \rangle^{\gamma/2} m_i) \\ Z_i = H_{x,v}^{0,s}(\langle v \rangle^{\gamma/2} m_i) \cap L_{x,v}^2(\langle v \rangle^{(\gamma+2s)/2} m_i) \\ Y'_i \text{ the dual of } Y_i \text{ w.r.t. } X_i \\ Z'_i \text{ the dual of } Z_i \text{ w.r.t. } X_i. \end{cases}$$

We also introduce the (almost) flat spaces:

$$\begin{cases} F = L_{x,v}^2 \\ G = H_{x,v}^{s,0}(\langle v \rangle^{\gamma/2}) \\ H = H_{x,v}^{0,s}(\langle v \rangle^{\gamma/2}) \cap L_{x,v}^2(\langle v \rangle^{(\gamma+2s)/2}) \\ G' \text{ the dual of } G \text{ w.r.t. } F \\ H' \text{ the dual of } H \text{ w.r.t. } F. \end{cases}$$

Remark on the dual embeddings. First, we notice that

$$(21) \quad \forall k_1 \leq k_2, \varsigma \in \mathbb{R}^+, \quad H_v^\varsigma(\langle v \rangle^{k_2}) \hookrightarrow H_v^\varsigma(\langle v \rangle^{k_1}).$$

This property is clear in the case $\varsigma \in \mathbb{N}$. It is less evident in the case $\varsigma \in \mathbb{R}^+ \setminus \mathbb{N}$. This case can be shown using a pseudo-differential argument or even more simply, using real interpolation. Indeed, since the weighted space $H_v^\varsigma(\langle v \rangle^{k_i})$ is defined through

$$h \in H_v^\varsigma(\langle v \rangle^{k_i}) \Leftrightarrow h \langle v \rangle^{k_i} \in H_v^\varsigma$$

and that we have, using the standard real interpolation notations (see for example [5]):

$$H_v^\varsigma = \left[H_v^{E(\varsigma)}, H_v^{E(\varsigma)+1} \right]_{\varsigma-E(\varsigma), 2}$$

one can prove that

$$H_v^\varsigma(\langle v \rangle^{k_i}) = \left[H_v^{E(\varsigma)}(\langle v \rangle^{k_i}), H_v^{E(\varsigma)+1}(\langle v \rangle^{k_i}) \right]_{\varsigma-E(\varsigma), 2}, \quad i = 1, 2.$$

From this, since $H_v^\ell(\langle v \rangle^{k_2}) \hookrightarrow H_v^\ell(\langle v \rangle^{k_1})$ for $\ell \in \mathbb{N}$, we deduce the desired embedding result: $H_v^\varsigma(\langle v \rangle^{k_2}) \hookrightarrow H_v^\varsigma(\langle v \rangle^{k_1})$.

We can now prove that the standard inclusions for dual spaces do not hold here. Indeed, we have for example $Y_1 \subset Y_0$ and also $Y'_1 \subset Y'_0$ (the same for “Z-spaces” hold). This is due to the fact that the pivot spaces are X_i and not $L_{x,v}^2$ as usually. Indeed, using that $m_1 \geq m_0$ and (21), we have

$$\begin{aligned} \|f\|_{Y'_0} &= \sup_{\|\varphi\|_{Y_0} \leq 1} \langle f, \varphi \rangle_{X_0} \\ &= \sup_{\|\varphi m_0\|_G \leq 1} \left\langle f m_1, \varphi \frac{m_0^2}{m_1} \right\rangle_F \\ &= \sup_{\|\psi m_1^2/m_0\|_G \leq 1} \langle f m_1, \psi m_1 \rangle_F \\ &\leq \sup_{\|\psi m_1\|_G \leq 1} \langle f m_1, \psi m_1 \rangle_F = \sup_{\|\varphi\|_{Y_1} \leq 1} \langle f, \varphi \rangle_{X_1} = \|f\|_{Y'_1}. \end{aligned}$$

Reduction of the problem to a “simpler” framework. We start by explaining how to avoid some difficulties coming from the spaces in which we are working. First, in order to simplify the problem, since we work in weighted spaces, we are going to “include” the weight in our operator. For this purpose, we define the operator Λ_1^m by

$$\Lambda_1^m f := m \Lambda_1(m^{-1} f).$$

We notice that if f satisfies $\partial_t f = \Lambda_1 f$, then $h := m f$ satisfies $\partial_t h = \Lambda_1^m h$ and we thus have $S_{\Lambda_1^m}(t)h = m S_{\Lambda_1}(t)f$. Then, in order to avoid having to work in dual spaces, we introduce formal dual operators for which we prove regularization properties in “positive” Sobolev spaces. To this end, we introduce the (formal) adjoint operator (w.r.t. the scalar product of $L_{x,v}^2$) of Λ_1^m that we denote $\Lambda_1^{m,*}$ and which is defined by:

$$\Lambda_1^{m,*} \varphi := \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) \mu'_*(\varphi' m' - \varphi m) d\sigma dv_* m^{-1} - K \langle v \rangle^{\gamma+2s} \varphi + v \cdot \nabla_x \varphi.$$

The advantage of working with this operator is that we can work in flat and positive Sobolev spaces. We now write our main regularization estimate:

Proposition 3.2. *For K large enough, we have the following estimates:*

$$(22) \quad \forall t \in (0, 1], \quad \|S_{\Lambda_1^{m,*}}(t)\varphi\|_H \lesssim \frac{1}{\sqrt{t}} \|\varphi\|_F \quad \text{and} \quad \|S_{\Lambda_1^{m,*}}(t)\varphi\|_G \lesssim \frac{1}{t^{1/2+s}} \|\varphi\|_F.$$

The proof of Proposition 3.2 is to be compared with the one of Theorem 1.1. Indeed, it is the same proof strategy, we introduce a functional which is going to be an entropy for our equation for small times. However, it is much more complicated in this case and our approach requires refined pseudo-differential tools, Section 4 is dedicated to its proof.

3.4. Proof of Theorem 1.2. The goal is now to prove Theorem 1.2 in the case $r = 0$. As already mentioned in the case of the fractional Kolmogorov equation, the proof will be exactly the same for other values of r since the operator Λ_x^r commutes with the Boltzmann operator. We can thus apply the result obtained for $r = 0$ to $\Lambda_x^r f_0$ to recover the result for $r \neq 0$.

From Proposition 3.2, we can deduce an estimate on the semigroup associated to Λ_1 in the “original” (non flat) spaces:

Corollary 3.3. *For K large enough, the following estimates hold:*

$$(23) \quad \forall t \in (0, 1], \quad \|S_{\Lambda_1}(t)f\|_X \lesssim \frac{1}{\sqrt{t}}\|f\|_{Z'} \quad \text{and} \quad \|S_{\Lambda_1}(t)f\|_X \lesssim \frac{1}{t^{1/2+s}}\|f\|_{Y'}.$$

Proof. Let us consider K large enough so that the conclusion of Proposition 3.2 holds. Using (22), we have for any $t \in (0, 1]$:

$$\begin{aligned} \|S_{\Lambda_1}(t)f\|_X &\lesssim \|S_{\Lambda_1^m}(t)h\|_F = \sup_{\|\varphi\|_F \leq 1} \langle S_{\Lambda_1^m}(t)h, \varphi \rangle = \sup_{\|\varphi\|_F \leq 1} \langle h, S_{\Lambda_1^{m,*}}(t)\varphi \rangle \\ &\lesssim \sup_{\|\varphi\|_F \leq 1} \|h\|_{H'} \|S_{\Lambda_1^{m,*}}(t)\varphi\|_H \lesssim \frac{1}{\sqrt{t}}\|h\|_{H'} \lesssim \frac{1}{\sqrt{t}}\|f\|_{Z'} \end{aligned}$$

which is exactly the first part of (23). The second one is proven in the same way. \square

Let us finally prove that the regularization properties of Λ_1 are enough to conclude that the whole operator Λ has some good regularization properties: even if we have a loss of weight in the final estimate, Λ inherits regularization properties from Λ_1 in terms of fractional Sobolev norms.

Lemma 3.4. *We have:*

$$(24) \quad \forall t \in (0, 1], \quad \|S_{\Lambda}(t)f\|_{X_0} \lesssim \frac{1}{\sqrt{t}}\|f\|_{Z'_1} \quad \text{and} \quad \|S_{\Lambda}(t)f\|_{X_0} \lesssim \frac{1}{t^{1/2+s}}\|f\|_{Y'_1}.$$

Proof. We recall that from [9], we have that Λ generates a semigroup in X_0 and thus we have the estimate

$$(25) \quad \forall t \in (0, 1], \quad \|S_{\Lambda}(t)f\|_{X_0} \lesssim \|f\|_{X_0}.$$

Then, we write Duhamel formula:

$$S_{\Lambda}(t) = S_{\Lambda_1}(t) + \int_0^t S_{\Lambda}(s)\Lambda_2 S_{\Lambda_1}(t-s) ds$$

from which we deduce, combining (25), (23) and (20) applied with the appropriate weights, that for $t \in (0, 1]$,

$$\begin{aligned}
\|S_\Lambda(t)h\|_{X_0} &\lesssim \|S_{\Lambda_1}(t)f\|_{X_0} + \int_0^t \|S_\Lambda(s)\Lambda_2 S_{\Lambda_1}(t-s)f\|_{X_0} ds \\
&\lesssim \frac{1}{\sqrt{t}}\|f\|_{Z'_0} + \int_0^t \|\Lambda_2 S_{\Lambda_1}(t-s)f\|_{X_0} ds \\
&\lesssim \frac{1}{\sqrt{t}}\|f\|_{Z'_0} + \int_0^t \|S_{\Lambda_1}(t-s)f\|_{X_1} ds \\
&\lesssim \frac{1}{\sqrt{t}}\|f\|_{Z'_0} + \int_0^t \frac{1}{\sqrt{t-s}}\|f\|_{Z'_1} ds \\
&\lesssim \frac{1}{\sqrt{t}}\|f\|_{Z'_0} + \int_0^1 \frac{1}{\sqrt{s}}\|f\|_{Z'_1} ds \lesssim \frac{1}{\sqrt{t}}\|f\|_{Z'_1}.
\end{aligned}$$

This concludes the proof of the first part of (24). Concerning the second one, we proceed as before using that $1/2 + s < 1$ since $s < 1/2$ and we obtain for any $t \in (0, 1]$:

$$\|S_\Lambda(t)h\|_{X_0} \lesssim \frac{1}{t^{1/2+s}}\|f\|_{Y'_1}.$$

□

4. PROOF OF PROPOSITION 3.2

The aim of this section is the proof of Proposition 3.2 about the regularization properties of the operator

$$\Lambda_1^{m,*}\varphi = \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) \mu'_*(\varphi' m' - \varphi m) d\sigma dv_* m^{-1} - K\langle v \rangle^{\gamma+2s} \varphi + v \cdot \nabla_x \varphi.$$

This will be done with a pseudodifferential version of the Lyapunov trick developed in the Fokker-Planck case and special classes of symbols that we recall in the Appendix.

4.1. Pseudodifferential formulation of the operator $\Lambda_1^{m,*}$. The operator $\Lambda_1^{m,*}$ is very similar to the operator $\mathcal{L}_{1,2,\delta}$ defined in [2, Proposition 3.1]. We shall thus take advantage of the analysis of the pseudo-differential operator $\mathcal{L}_{1,2,\delta}$ and its symbol in [2]. If we extract the collision part of the operator $\Lambda_1^{m,*}$ (forgetting the transport one and the addition of the multiplicative term), we obtain

$$\Lambda_1^{m,*,\text{collision}}\varphi := \int_{\mathbb{R}^3 \times \mathbb{S}^2} B_\delta(v - v_*, \sigma) \mu'_*(\varphi' m' - \varphi m) d\sigma dv_* m^{-1}$$

In the case $m = 1$, this operator is actually the main one studied in [2]:

$$\Lambda_1^{1,*,\text{collision}} \stackrel{\text{def}}{=} -\tilde{a}_0(v, D_v) = \mathcal{L}_{1,2,\delta},$$

where \tilde{a}_0 is a real symbol in (v, η) defined through

$$\tilde{a}_0(v, \eta) := \int_{\mathbb{R}_h^3} \frac{dh}{|h|^{3+2s}} \int_{E_{0,h}} d\alpha \tilde{b}(\alpha, h) \mathbf{1}_{|\alpha| \geq |h|} \chi_\delta(h) \mu(\alpha + v) |\alpha + h|^{\gamma+1+2s} (1 - \cos(\eta \cdot h))$$

thanks to Carleman representation (see Lemma A.1). We recall here the main result from [2] concerning the symbol \tilde{a}_0 (be careful, this symbol is denoted without tilde there):

Proposition 4.1 (Propositions 3.1 and 3.4 in [2]). *The symbol \tilde{a}_0 satisfies the following properties:*

- i) $\tilde{a}_0 \in S(\langle v \rangle^\gamma (1 + |\eta|^2 + |v \wedge \eta|^2)^s, \Gamma),$
- ii) $\forall \varepsilon > 0, \nabla_\eta \tilde{a}_0 \in S(\varepsilon \langle v \rangle^\gamma (1 + |\eta|^2 + |v \wedge \eta|^2)^s + \varepsilon^{-1} \langle v \rangle^{\gamma+2s}),$
- iii) $\exists c > 0, -c \langle v \rangle^{\gamma+2s} + \langle v \rangle^\gamma (1 + |\eta|^2 + |v \wedge \eta|^2)^s \lesssim \tilde{a}_0 \lesssim \langle v \rangle^\gamma (1 + |\eta|^2 + |v \wedge \eta|^2)^s,$

where $\Gamma := |dv|^2 + |d\eta|^2$ is the flat metric.

For convenience we denote by a_0 the Weyl symbol of operator $\tilde{a}_0(v, D_v)$, so that

$$a_0^w = \tilde{a}_0(v, D_v).$$

Everywhere in what follows, any symbol with a tilde will refer to a classical quantization, and when no tilde is present, the symbol will refer to the Weyl quantization. Both quantizations are recalled in the beginning of Section A.2 in the appendix. Note that a_0 is not real anymore, anyway we shall see later that it conserves good ellipticity properties. Denoting then

$$a(v, \eta) := (m^{-1} \sharp a_0 \sharp m)(v, \eta) + K \langle v \rangle^{\gamma+2s},$$

where \sharp denotes the usual Weyl composition and we omit the dependency of a with respect to K in our notation, we have:

$$\Lambda_1^{m,*} = -a^w + v \cdot \nabla_x.$$

For sake of simplicity, we introduce the following notation

$$A := a^w,$$

so that the collision part of operator $\Lambda_1^{m,*}$ writes

$$\Lambda_1^{m,*} = -A + v \cdot \nabla_x$$

(recall that they depend on K). In order to study the symbolic properties of a , we now introduce the main weights. We pose for $(v, \eta) \in \mathbb{R}^6$

$$\lambda_v^2(v, \eta) := \langle \eta \rangle^2 + \langle v \wedge \eta \rangle^2 + \langle v \rangle^2$$

and for given $s \in (0, 1/2)$ and $\gamma \in (0, 1)$ we pose

$$p(v, \eta) := \langle v \rangle^\gamma \lambda_v^{2s} + K \langle v \rangle^{\gamma+2s}$$

which will be the main reference symbol of our study (note that this symbol is denoted \tilde{a}_K in [2]). Although p depends on K , we will omit in the following any subscript or reference to this dependence. It will be shown in the next subsection that p is a good weight in the sense of the Appendix. The following Lemma shows that a has good properties in the class $S_K(p)$, the main class of symbols whose definition is recalled in full generality in the Appendix.

Lemma 4.2. *Let $m = \langle v \rangle^k$ for $k \in \mathbb{R}$. Then uniformly in K sufficiently large, we have that $\operatorname{Re} a \geq 0$, $a \in S_K(p)$ and $\operatorname{Re} a$ is elliptic positive in this class.*

Proof. We shall take profit of the estimates from [2] recalled above in Proposition 4.1. We first note that because of the symbolic estimates on \tilde{a}_0 we can take $\varepsilon = K^{-1/2}$ in ii) and, using Lemma A.5, we get that

$$\tilde{a}_0 \in S_K(p) \text{ and then } a_0 \in S_K(p).$$

Adding $K \langle v \rangle^{\gamma+2s}$ does not change the computation and we also get that

$$a_0 + K \langle v \rangle^{\gamma+2s} \in S_K(p).$$

Now we can do the conjugation with m . We first note that clearly, with the same notations as before, we have $m \in S_K(m)$ and $m^{-1} \in S_K(m^{-1})$. This can be checked directly by noticing that the derivatives of m in η are zero. The stability of the class S_K from Lemma A.4 implies then that

$$a = m^{-1} \sharp a_0 \sharp m + K \langle v \rangle^{\gamma+2s} = m^{-1} \sharp \left(a_0 + K \langle v \rangle^{\gamma+2s} \right) \sharp m \in S_K(p).$$

We can also notice that looking at the main terms in the asymptotic development of the \sharp product (see in particular Lemma A.5 and its proof), we have

$$a = a_0 + K \langle v \rangle^{\gamma+2s} + r = \tilde{a}_0 + K \langle v \rangle^{\gamma+2s} + r'$$

with r and $r' \in K^{-1/2}S(p)$ (note that r is exactly the Weyl symbol of $m^{-1}[a_0^w, m]$). Since from Proposition 4.1. iii) we have $\tilde{a}_0 + K \langle v \rangle^{\gamma+2s} \gtrsim p$ (uniformly in K), we get that

$$\operatorname{Re} a \gtrsim p$$

so that $\operatorname{Re} a$ is non-negative and elliptic for K large (note that this proof is very close to the one of Lemma A.5 in the appendix) The proof is complete. \square

4.2. Reference weights. We introduce the following weights, where K is a large constant to be defined later. Formally $1/\sqrt{K}$ plays the role of a small semiclassical parameter. We recall that for $(v, \eta) \in \mathbb{R}^6$

$$\lambda_v^2(v, \eta) = \langle \eta \rangle^2 + \langle v \wedge \eta \rangle^2 + \langle v \rangle^2$$

and for given $s \in (0, 1/2)$ and $\gamma \in (0, 1)$.

$$p(v, \eta) = \langle v \rangle^\gamma \lambda_v^{2s} + K \langle v \rangle^{\gamma+2s}.$$

We shall need their counterparts in the ξ variable (considered as a parameter) instead of η and thus also introduce

$$\lambda_x^2(v, \eta) := \langle \xi \rangle^2 + \langle v \wedge \xi \rangle^2 + \langle v \rangle^2$$

and

$$q(v, \eta) := \langle v \rangle^\gamma \lambda_x^{2s} + K \langle v \rangle^{\gamma+2s},$$

where we omit the dependance on K and ξ again in the notations. We eventually introduce a mixed symbol

$$\omega(v, \eta) := -\langle v \rangle^\gamma \lambda_x^{s-1} \lambda_v^{s-1} (\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi))$$

which will be crucial in the analysis.

Following the Appendix, we have in particular:

Lemma 4.3. *The symbols p , q and more generally $\langle v \rangle^\zeta p^\varrho q^\varsigma$ for ζ , ϱ and $\varsigma \in \mathbb{R}$ are temperate with respect to Γ uniformly w.r.t. K and ξ .*

Proof. These computations are done for e.g. in [2, Section 3.3]. \square

The symbols p , q , and ω are then good symbols w.r.t. these classes, as the following lemma shows.

Lemma 4.4. *We have $p \in S_K(p)$, $q \in S_K(q)$, $\omega \in S_K(\sqrt{pq})$ and more generally $\langle v \rangle^\zeta p^\varrho q^\varsigma \in S_K(\langle v \rangle^\zeta p^\varrho q^\varsigma)$ for ζ , ϱ and $\varsigma \in \mathbb{R}$, all this uniformly in K and ξ .*

Proof. We first do the job for p , the other being similar. We just have to differentiate the symbol p . We study first the gradient with respect to η (which corresponds to the case $|\beta| = 1$). We notice that

$$\nabla_\eta p = s \langle v \rangle^\gamma \lambda_v^{2s-2} \nabla_\eta (\lambda_v^2).$$

Now we have

$$|\nabla_\eta (\lambda_v^2)| \leq 2\lambda_v \langle v \rangle$$

from which we deduce that

$$\begin{aligned} |\nabla_\eta p| &\leq 2s \langle v \rangle^{\gamma+1} \lambda_v^{2s-1} \\ &= 2s K^{-1/2} \left(K^{1/2} \langle v \rangle^{\gamma/2+s} \right) \langle v \rangle^{\gamma/2+1-s} \lambda_v^{2s-1} \\ &\leq 2s K^{-1/2} p^{1/2} \langle v \rangle^{\gamma/2} \lambda_v^s \leq 2s K^{-1/2} p \end{aligned}$$

which is the desired result. We skip the other similar computations. \square

4.3. Technical lemmas. The main idea in the proof of the regularization result in Proposition 3.2 is to mimic the proof of the Fokker-Planck case, using deeply the positivity preserving property of the Wick quantization.

In what follows, we state a series of lemmas (from 4.5 to 4.9) which are crucial to be able to “compare” our operator A with quantizations of the simpler symbols p and q we introduced in the preceding subsection.

Lemma 4.5. *There exists $c_a > 0$ such that*

$$2\operatorname{Re} (Af, f) \geq c_a \left(p^{\operatorname{Wick}} f, f \right).$$

Proof. We first notice that

$$\operatorname{Re} (Af, f) = \operatorname{Re} (a^w f, f) = ((\operatorname{Re} a)^w f, f)$$

thanks to the properties of the Weyl quantization. Using (47) for $\operatorname{Re} a$, we therefore get that

$$\operatorname{Re} (Af, f) = ((\operatorname{Re} a)^w f, f) \simeq \left((\operatorname{Re} a)^{\operatorname{Wick}} f, f \right) = \operatorname{Re} \left(a^{\operatorname{Wick}} f, f \right).$$

Now $\operatorname{Re} a \simeq p$ uniformly in K from Lemma 4.2. This implies that there exists $c_a > 0$ such that $\operatorname{Re} a - c_a p \geq 0$. Using the positivity property of the Wick quantization gives $\operatorname{Re} (a)^{\operatorname{Wick}} - c_a p^{\operatorname{Wick}} \geq 0$ in the sense of operators. This proves the result. \square

Lemma 4.6. *There exists $c_p > 0$ such that*

$$\left(p^{\operatorname{Wick}} Af + A^* p^{\operatorname{Wick}} f, f \right) \geq c_p \left((p^2)^{\operatorname{Wick}} f, f \right)$$

Proof. We have from the definition of the Wick quantization (see (38))

$$p^{\operatorname{Wick}} A + A^* p^{\operatorname{Wick}} = ((p \star N) \sharp a + \bar{a} \sharp (p \star N))^w.$$

Now using Lemma A.5 we have that $p \in S_K(p)$ implies $p \star N \in S_K(p)$ and from the second point in Lemma A.4, we get that $(p \star N) \sharp a + \bar{a} \sharp (p \star N)$ is elliptic, real and positive (from selfadjointness) in $S_K(p^2)$. We therefore get from (47) that

$$(((p \star N) \sharp a + \bar{a} \sharp (p \star N))^w f, f) \simeq (((p \star N) \sharp a + \bar{a} \sharp (p \star N))^{\operatorname{Wick}} f, f)$$

Now since $(p \star N)\sharp a + \bar{a}\sharp(p \star N) \simeq p^2$ (uniformly in K), the positivity properties of the Wick quantization imply the result. \square

Lemma 4.7. *There exists $c_q > 0$ such that*

$$\left(q^{\text{Wick}} A f + A^* q^{\text{Wick}} f, f \right) \geq c_q \left((pq)^{\text{Wick}} f, f \right)$$

Proof. The proof is almost the same as the one of Lemma 4.6, the main difference being that the symbol q now depends on a parameter ξ , with respect to which all estimates have to be uniform. We write

$$q^{\text{Wick}} A + A^* q^{\text{Wick}} = ((q \star N)\sharp a + \bar{a}\sharp(q \star N))^w$$

where again a denotes the Weyl symbol of A . Now $q \in S_K(q)$ uniformly in K and ξ and this implies $q \star N \in S_K(q)$. From $a \in S_K(p)$ and the second point in Proposition A.4 we get that $(q \star N)\sharp a + \bar{a}\sharp(q \star N)$ is elliptic, real and positive in $S_K(pq)$. Together with (47), this implies that there exists $c_q > 0$ s.t.

$$(((q \star N)\sharp a + \bar{a}\sharp(q \star N))^w f, f) \simeq (((q \star N)\sharp a + \bar{a}\sharp(q \star N))^{\text{Wick}} f, f) \geq c_q ((pq)^{\text{Wick}} f, f)$$

where the last inequality comes from the positivity properties of the Wick quantization. \square

Lemma 4.8. *There exist $c_\omega > 0$ such that*

$$\left| \left(\omega^{\text{Wick}} A f + A^* \omega^{\text{Wick}} f, f \right) \right| \leq c_\omega \left((p^{3/2} q^{1/2})^{\text{Wick}} f, f \right).$$

Proof. We begin by denoting $\theta = p^{3/4} q^{1/4}$ so that $\theta^2 = p^{3/2} q^{1/2}$. Using Lemma 4.4 we get that θ is elliptic positive in $S_K(\theta)$. Note also that

$$\omega^{\text{Wick}} A + A^* \omega^{\text{Wick}} = ((\omega \star N)\sharp a + \bar{a}\sharp(\omega \star N))^w$$

using the definitions of the Wick quantization and still denoting again a the Weyl symbol of operator A . From Lemma 4.4, $\omega \in S_K(\sqrt{pq})$ so that $\omega \star N$ is also in $S_K(\sqrt{pq})$ by Lemma A.5. On the other hand, $a \in S_K(p)$ and using the stability Proposition A.4, we therefore get that

$$(26) \quad (\omega \star N)\sharp a + \bar{a}\sharp(\omega \star N) \in S_K(p^{3/2} q^{1/2}) = S_K(\theta^2).$$

We write then

$$\begin{aligned} & \left| \left(\omega^{\text{Wick}} A f + A^* \omega^{\text{Wick}} f, f \right) \right| \\ &= \left| \underbrace{\left((\theta^{-1})^{\text{Wick}} ((\omega \star N)\sharp a + \bar{a}\sharp(\omega \star N))^w (\theta^{-1})^{\text{Wick}} ((\theta^{-1})^{\text{Wick}})^{-1} f, ((\theta^{-1})^{\text{Wick}})^{-1} f \right)}_{\text{Operator } \Omega} \right| \end{aligned}$$

and prove now that operator Ω is bounded. For this, we first note that $(\theta^{-1})^{\text{Wick}} = (\theta^{-1} \star N)^w$ and recall that θ is elliptic positive. Lemma A.4 implies that θ^{-1} is positive elliptic in $S_K(\theta^{-1})$ too and from Lemma A.5 the same is true for $\theta^{-1} \star N$. Now the Weyl symbol of Ω can be written

$$\text{symb}(\Omega) = (\theta^{-1} \star N)\sharp ((\omega \star N)\sharp a + \bar{a}\sharp(\omega \star N))\sharp (\theta^{-1} \star N)$$

and from the stability Lemma A.4 and (26) this symbol is in $S_K(1)$. In particular, operator Ω is bounded on L^2 . Let us prove that

$$(27) \quad \begin{aligned} |(\Omega((\theta^{-1})^{\text{Wick}})^{-1}f, ((\theta^{-1})^{\text{Wick}})^{-1}f)| &\leq C \left\| ((\theta^{-1})^{\text{Wick}})^{-1}f \right\|^2 \\ &\leq C' \left\| \theta^{\text{Wick}} f \right\|^2 \leq C'' ((\theta^2)^{\text{Wick}} f, f). \end{aligned}$$

The first inequality comes from the fact that Ω is bounded. The last inequality is just a consequence of (46). Let us precise the arguments used for proving the second inequality: we have

$$(28) \quad \left\| ((\theta^{-1})^{\text{Wick}})^{-1}f \right\|^2 = \left\| ((\theta^{-1} \star N)^w)^{-1}f \right\|^2 \simeq \left\| ((\theta^{-1} \star N)^{-1})^w f \right\|^2$$

using the definition of the Wick quantization and (44). Now we check by direct computation that $(\theta^{-1} \star N)^{-1}$ is also elliptic positive in $S_K(\theta)$ using Lemmas A.5 (see also remark A.6) and A.4 b). This implies by (45) applied with $\tau = (\theta^{-1} \star N)^{-1}$ that

$$(29) \quad \left\| ((\theta^{-1} \star N)^{-1})^w f \right\|^2 \simeq \left\| \theta^w f \right\|^2,$$

and we get then by (46)

$$(30) \quad \left\| \theta^w f \right\|^2 \simeq ((\theta^2)^{\text{Wick}} f, f).$$

Using (28-30) yields the second inequality in (27). \square

To conclude this subsection, we state a lemma which will be useful in the sequel, and whose proof is direct using positivity properties of the Wick quantization.

Lemma 4.9. *We have the following estimates:*

$$\begin{aligned} \left((\langle v \rangle^{2\gamma} \lambda_v^{4s})^{\text{Wick}} f, f \right) &\leq \left((p^2)^{\text{Wick}} f, f \right) \leq 2(1 + K^2) \left((\langle v \rangle^{2\gamma} \lambda_v^{4s})^{\text{Wick}} f, f \right), \\ \left(p^{\text{Wick}} f, f \right) &= \left((\langle v \rangle^\gamma \lambda_v^{2s})^{\text{Wick}} f, f \right) + K \left((\langle v \rangle^{\gamma+2s})^{\text{Wick}} f, f \right), \\ \left((\langle v \rangle^{2\gamma} \lambda_v^{2s} \lambda_x^{2s})^{\text{Wick}} f, f \right) &\leq \left((pq)^{\text{Wick}} f, f \right) \leq (1 + K)^2 \left((\langle v \rangle^{2\gamma} \lambda_v^{2s} \lambda_x^{2s})^{\text{Wick}} f, f \right). \end{aligned}$$

4.4. The Lyapunov functional. From now on we fix once and for all the constant K so that Lemmas 4.5 to 4.9 are true. In the same spirit as in Subsection 2.1 in the Fokker-Planck case, we build below a Lyapunov functional corresponding to the following equation

$$\partial_t \varphi = v \cdot \nabla_x \varphi - A \varphi,$$

and we consider φ a solution. Then, since A acts only on the velocity variable, we can take the Fourier transform of our equation in $x \in \mathbb{T}^3$ and see the associated Fourier variable $\xi \in \mathbb{Z}^3$ as a parameter in our equation. We thus consider $\psi = \mathcal{F}_x \varphi$ to be a solution of

$$\partial_t \psi - i v \cdot \xi \psi + A \psi = 0$$

with initial data ψ_0 . We then follow the lines of the proof given in Section 2 and we introduce an adapted entropy functional defined for all $t \geq 0$ by

$$\mathcal{H}(t) = C \|\psi\|^2 + Dt \left(p^{\text{Wick}} \psi, \psi \right) + Et^{1+s} \left(\omega^{\text{Wick}} \psi, \psi \right) + t^{1+2s} \left(q^{\text{Wick}} \psi, \psi \right)$$

for large constants C, D, E to be chosen later, where $\|\cdot\|$ is the usual L^2 norm and (\cdot, \cdot) is the usual (complex) L^2 scalar product.

Lemma 4.10. *If $E \leq \sqrt{D}$ then for all $t \geq 0$ we have $\mathcal{H}(t) \geq 0$. Precisely, we have*

$$0 \leq C \|\psi\|^2 + \frac{D}{2} t \left(p^{\text{Wick}} \psi, \psi \right) + \frac{1}{2} t^{1+2s} \left(q^{\text{Wick}} \psi, \psi \right) \leq \mathcal{H}(t).$$

Proof. The first part of the inequality comes from the positivity property (39). For the bound on $\mathcal{H}(t)$, we start by noticing that using Cauchy-Schwarz inequality:

$$|\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi)| \leq \lambda_x \lambda_v.$$

Then, the time-dependent Cauchy-Schwarz inequality gives

$$-Et^s \langle v \rangle^\gamma \lambda_x^{s-1} \lambda_v^{s-1} (\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi)) \leq \frac{E^2}{2} \langle v \rangle^\gamma \lambda_v^{2s} + \frac{1}{2} t^{2s} \langle v \rangle^\gamma \lambda_x^{2s}.$$

The positivity of the Wick quantization and the fact that $E^2 \leq D$ imply that

$$Et^{1+s} \left(\omega^{\text{Wick}} \psi, \psi \right) \geq -\frac{D}{2} t \left(p^{\text{Wick}} \psi, \psi \right) - \frac{1}{2} t^{1+2s} \left(q^{\text{Wick}} \psi, \psi \right)$$

which proves the statement. \square

We now show that \mathcal{H} is indeed a Lyapunov function (entropy functional).

Lemma 4.11. *For well chosen (arbitrarily large) constants C , D and E we have*

$$\frac{d}{dt} \mathcal{H}(t) \leq 0, \quad \forall t \in (0, 1].$$

Proof.

Let us define

$$\mathcal{P} := p^{\text{Wick}} A + A^* p^{\text{Wick}}, \quad \Omega := \omega^{\text{Wick}} A + A^* \omega^{\text{Wick}}, \quad \mathcal{Q} := q^{\text{Wick}} A + A^* q^{\text{Wick}}.$$

Then, for each term in the sum, we have

$$(31) \quad \frac{d}{dt} C \|\psi\|^2 = -2C \operatorname{Re} (A\psi, \psi),$$

$$(32) \quad \frac{d}{dt} \left(Dt \left(p^{\text{Wick}} \psi, \psi \right) \right) = D \left(p^{\text{Wick}} \psi, \psi \right) - Dt \left(\mathcal{P} \psi, \psi \right) + Dt \left(\{p, v \cdot \xi\}^{\text{Wick}} \psi, \psi \right),$$

$$(33) \quad \begin{aligned} & \frac{d}{dt} \left(Et^{1+s} \left(\omega^{\text{Wick}} \psi, \psi \right) \right) \\ &= (1+s) Et^s \left(\omega^{\text{Wick}} \psi, \psi \right) - Et^{1+s} \left(\Omega \psi, \psi \right) + Et^{1+s} \left(\{\omega, v \cdot \xi\}^{\text{Wick}} \psi, \psi \right), \end{aligned}$$

$$(34) \quad \begin{aligned} & \frac{d}{dt} \left(t^{1+2s} \left(q^{\text{Wick}} \psi, \psi \right) \right) \\ &= (1+2s) t^{2s} \left(q^{\text{Wick}} \psi, \psi \right) - t^{1+2s} \left(\mathcal{Q} \psi, \psi \right) + t^{1+2s} \left(\{q, v \cdot \xi\}^{\text{Wick}} \psi, \psi \right), \end{aligned}$$

where, in the first term we used the skew-adjointness of the transport operator and in the last term of (32), (33), (34), we used (40).

The right hand side in (31) is non-positive (thanks to the property of positivity of the Wick quantization (39)) and using Lemma 4.5 and Lemma 4.9, it can be estimated as

$$\begin{aligned} -2C \operatorname{Re} (A\psi, \psi) &\leq -c_A C \left(p^{\text{Wick}} \psi, \psi \right) \\ &\leq \underbrace{-c_A C \left((\langle v \rangle^\gamma \lambda_v^{2s})^{\text{Wick}} \psi, \psi \right)}_I - \underbrace{c_A C K \left((\langle v \rangle^{\gamma+2s})^{\text{Wick}} \psi, \psi \right)}_{II}. \end{aligned}$$

Analogously, we can deduce a bound for the first term in (32). Indeed, we recover two non-negative terms

$$D \left(p^{\text{Wick}} \psi, \psi \right) \leq \underbrace{D \left((\langle v \rangle^\gamma \lambda_v^{2s})^{\text{Wick}} \psi, \psi \right)}_i + \underbrace{DK \left((\langle v \rangle^{\gamma+2s})^{\text{Wick}} \psi, \psi \right)}_{ii}.$$

Moreover, using the positivity of the Wick quantization (39), the second term in (32) is non-positive and, using Lemma 4.6 and Lemma 4.9, it can be estimated as

$$-Dt \left(\mathcal{P} \psi, \psi \right) \leq -c_p Dt \left((p^2)^{\text{Wick}} \psi, \psi \right) \leq -\underbrace{c_p Dt \left((\langle v \rangle^{2\gamma} \lambda_v^{4s})^{\text{Wick}} \psi, \psi \right)}_{III}.$$

Concerning the third term in (32), let us compute $\{p, v \cdot \xi\}$:

$$\begin{aligned} \{p, v \cdot \xi\} &= \nabla_\eta p \cdot \nabla_v (v \cdot \xi) - \nabla_v p \cdot \nabla_\eta (v \cdot \xi) = \langle v \rangle^\gamma (\nabla_\eta \lambda_v^{2s}) \cdot \xi \\ &= 2s \langle v \rangle^\gamma \lambda_v^{2s-2} (\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi)) \\ &\leq 2s \langle v \rangle^\gamma \lambda_x \lambda_v^{2s-1}, \end{aligned}$$

where we used the fact that $|\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi)| \leq \lambda_x \lambda_v$. Hence, for any $\varepsilon_1 > 0$, we obtain two non-negative terms

$$\begin{aligned} Dt \left(\{p, v \cdot \xi\}^{\text{Wick}} \psi, \psi \right) \\ \leq \underbrace{2s\varepsilon_1^{-1} D \left((\langle v \rangle^\gamma \lambda_v^{2s})^{\text{Wick}} \psi, \psi \right)}_{iii} + \underbrace{2s\varepsilon_1^s Dt^{1+s} \left((\langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1})^{\text{Wick}} \psi, \psi \right)}_{iv}. \end{aligned}$$

Let us now consider (33). Using the fact that $\omega \leq \langle v \rangle^\gamma \lambda_x^s \lambda_v^s$, we can bound the first term in (33), for any $\varepsilon_2 > 0$, with two non-negative terms

$$Et^s \left(\omega^{\text{Wick}} \psi, \psi \right) \leq \underbrace{\varepsilon_2^{-1} E \left((\langle v \rangle^\gamma \lambda_v^{2s})^{\text{Wick}} \psi, \psi \right)}_v + \underbrace{\varepsilon_2^{1/s} Et^{1+s} \left((\langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1})^{\text{Wick}} \psi, \psi \right)}_{vi}.$$

For the second term in (33), Lemma 4.8 implies

$$(\Omega \psi, \psi) \leq c_\omega \left((p^{3/2} q^{1/2})^{\text{Wick}} \psi, \psi \right).$$

and, for any $\varepsilon_3 > 0$, we have

$$t^{1+s} p^{3/2} q^{1/2} \leq \varepsilon_3^{-1} t p^2 + \varepsilon_3 t^{1+2s} p q.$$

Therefore, we can bound the second term in (33), using Lemma 4.9, for any $\varepsilon_3 > 0$, by

$$\begin{aligned} -Et^{s+1} (\Omega \psi, \psi) \\ \leq c_\omega \varepsilon_3^{-1} Et \left((p^2)^{\text{Wick}} \psi, \psi \right) + c_\omega \varepsilon_3 Et^{1+2s} \left((pq)^{\text{Wick}} \psi, \psi \right) \\ \leq \underbrace{2(1+K^2) c_\omega \varepsilon_3^{-1} Et \left((\langle v \rangle^{2\gamma} \lambda_v^{4s})^{\text{Wick}} \psi, \psi \right)}_{vii} \\ + \underbrace{(1+K)^2 c_\omega \varepsilon_3 Et^{1+2s} \left((\langle v \rangle^{2\gamma} \lambda_v^{2s} \lambda_x^{2s})^{\text{Wick}} \psi, \psi \right)}_{viii} \end{aligned}$$

where (vii) and (viii) are non-negative.

Let us now observe that

$$(\nabla_\eta \lambda_v^2) \cdot \xi = 2(\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi)),$$

and

$$\nabla_\eta(\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi)) \cdot \xi = \lambda_x^2 - \langle v \rangle^2.$$

We then compute

$$\begin{aligned} \{\omega, v \cdot \xi\} &= \nabla_\eta \omega \cdot \nabla_v (v \cdot \xi) - \nabla_v \omega \cdot \nabla_\eta (v \cdot \xi) = \nabla_\eta \omega \cdot \xi \\ &= -\langle v \rangle^\gamma \lambda_x^{s-1} \lambda_v^{s-1} \nabla_\eta (\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi)) \cdot \xi \\ &\quad - \langle v \rangle^\gamma \lambda_x^{s-1} (\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi)) (\nabla_\eta \lambda_v^{s-1}) \cdot \xi \\ &= -\langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1} + \langle v \rangle^{\gamma+2} \lambda_x^{s-1} \lambda_v^{s-1} - (s-1) \langle v \rangle^\gamma \lambda_x^{s-1} \lambda_v^{s-3} (\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi))^2. \end{aligned}$$

In the last expression of $\{\omega, v \cdot \xi\}$, we first notice that since $s-1 < 0$ and $\min(\lambda_x, \lambda_v) \geq \langle v \rangle$, the second term is bounded as follows:

$$\langle v \rangle^{\gamma+2} \lambda_x^{s-1} \lambda_v^{s-1} \leq \langle v \rangle^{\gamma+2s}.$$

Gathering the first and third terms, we use Cauchy-Schwarz inequality and $s < 1$ to find:

$$\begin{aligned} & -\langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1} - (s-1) \langle v \rangle^\gamma \lambda_x^{s-1} \lambda_v^{s-3} (\eta \cdot \xi + (v \wedge \eta) \cdot (v \wedge \xi))^2 \\ & \leq -\langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1} + (1-s) \langle v \rangle^\gamma \lambda_x^{s-1} \lambda_v^{s-3} (\lambda_x^2 - \langle v \rangle^2) (|\eta|^2 + |v \wedge \eta|^2) \\ & = -\langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1} + (1-s) \langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-3} (|\eta|^2 + |v \wedge \eta|^2) \\ & \quad - (1-s) \langle v \rangle^{\gamma+2} \lambda_x^{s-1} \lambda_v^{s-3} (|\eta|^2 + |v \wedge \eta|^2) \\ & \leq -\langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1} + (1-s) \langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1} - (1-s) \langle v \rangle^{\gamma+2} \lambda_x^{s+1} \lambda_v^{s-3} \\ & \leq -s \langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1}. \end{aligned}$$

Thus we have:

$$\{\omega, v \cdot \xi\} \leq -s \langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1} + \langle v \rangle^{\gamma+2s}.$$

Hence, the third term in (33) can be estimated as

$$\begin{aligned} Et^{s+1} \left(\{\omega, v \cdot \xi\}^{\text{Wick}} \psi, \psi \right) \\ \leq \underbrace{-sEt^{s+1} \left((\langle v \rangle^\gamma \lambda_x^{s+1} \lambda_v^{s-1})^{\text{Wick}} \psi, \psi \right)}_{IV} + \underbrace{Et^{s+1} \left((\langle v \rangle^{\gamma+2s})^{\text{Wick}} \psi, \psi \right)}_{ix}, \end{aligned}$$

where $(-IV)$ is non-positive and (ix) is non-negative.

It remains to consider (34). Observing that, for any $\varepsilon_4 > 0$,

$$t^{2s} \langle v \rangle^\gamma \lambda_x^{2s} \leq \varepsilon_4^{-1} \langle v \rangle^\gamma \lambda_v^{2s} + \varepsilon_4^{\frac{1-s}{2s}} t^{1+s} \langle v \rangle^\gamma \lambda_v^{s-1} \lambda_x^{s+1},$$

we have that the first term in (34) can be bounded for any $\varepsilon_4 > 0$, by

$$\begin{aligned} (1+2s)t^{2s} \left(q^{\text{Wick}} \psi, \psi \right) \\ \leq \underbrace{(1+2s)\varepsilon_4^{-1} \left((\langle v \rangle^\gamma \lambda_v^{2s})^{\text{Wick}} \psi, \psi \right)}_x + \underbrace{(1+2s)\varepsilon_4^{\frac{1-s}{2s}} t^{1+s} \left((\langle v \rangle^\gamma \lambda_v^{s-1} \lambda_x^{s+1})^{\text{Wick}} \psi, \psi \right)}_{xi} \\ + \underbrace{K(1+2s)t^{2s} \left((\langle v \rangle^{\gamma+2s})^{\text{Wick}} \psi, \psi \right)}_{xii} \end{aligned}$$

where $(x), (xi), (xii)$ are non-negative terms.

Moreover, using Lemma 4.7 and Lemma 4.9, the second term in (34) can be estimated as

$$-t^{1+2s}(\mathcal{Q}\psi, \psi) \leq -c_q t^{1+2s} \left((pq)^{\text{Wick}} \psi, \psi \right) \leq - \underbrace{c_q t^{1+2s} \left((\langle v \rangle^{2\gamma} \lambda_v^{2s} \lambda_x^{2s})^{\text{Wick}} \psi, \psi \right)}_V$$

where $(-V)$ is non-positive. Finally, since q does not depend on η , the Poisson bracket $\{q, v \cdot \xi\}$ vanishes, hence the third term in (34) is null.

We conclude the proof as we did for Theorem 1.1, checking that we can choose (in order of reverse appearance) the constants C, D, E and the small constants $\varepsilon_j, j = 1, \dots, 4$ such that for $t \in (0, 1]$,

$$\begin{aligned} -I + i + iii + v + x &\leq -\frac{1}{10}I, \\ -II + ii + ix + xii &\leq -\frac{1}{10}II, \\ -III + vii &\leq -\frac{1}{10}III, \\ -IV + iv + vi + xi &\leq -\frac{1}{10}IV, \\ -V + viii &\leq -\frac{1}{10}V. \end{aligned}$$

Note that D and C can be taken arbitrarily larger at the end of this procedure. This ends the proof. \square

4.5. Proof of Proposition 3.2. We can now prove Proposition 3.2. Consider φ the solution of

$$\partial_t \varphi = v \cdot \nabla_x \varphi - A\varphi,$$

with initial data φ_0 and $\psi = \mathcal{F}_x \varphi$ to be the solution of

$$\partial_t \psi - iv \cdot \xi \psi + A\psi = 0$$

with initial data $\psi_0 = \mathcal{F}_x \varphi_0$. From Lemma 4.11 we know that

$$\mathcal{H}(t) \leq \mathcal{H}(0) = C \|\psi_0\|^2,$$

and using Lemma 4.10, this gives for all $t \in (0, 1]$

$$(35) \quad \left(p^{\text{Wick}} \psi, \psi \right) \leq \frac{2C}{D} \frac{1}{t} \|\psi_0\|^2 \quad \text{and} \quad \left(q^{\text{Wick}} \psi, \psi \right) \leq \frac{2C}{t^{1+2s}} \|\psi_0\|^2,$$

where we used the fact that both left members are non-negative according to Proposition A.8. Working in the class $S_K(p)$ again, gives through Proposition A.8 and Lemma A.7 (see there the definition of H_R)

$$\begin{aligned} \left\| \langle v \rangle^{\gamma/2} \langle D_v \rangle^s \psi \right\|^2 &= \left\| \langle v \rangle^{\gamma/2} \langle D_v \rangle^s ((p^{1/2})^w)^{-1} (p^{1/2})^w \psi \right\|^2 \\ &= \left\| \underbrace{\langle v \rangle^{\gamma/2} \langle D_v \rangle^s ((p^{1/2})^{-1})^w}_{\text{bounded operator}} H_R (p^{1/2})^w \psi \right\|^2 \\ &\lesssim \left\| (p^{1/2})^w \psi \right\|^2, \end{aligned}$$

where we used that the operator $\langle v \rangle^{\gamma/2} \langle D_v \rangle^s$ has its Weyl symbol in $S_K(p^{1/2})$ (this Weyl symbol is $\langle v \rangle^{\gamma/2} \sharp \langle \eta \rangle^s$), and that $(p^{1/2})^{-1} \in S_K(p^{-1/2})$, so that $\langle v \rangle^{\gamma/2} \langle D_v \rangle^s ((p^{1/2})^{-1})^w$

is a bounded operator. Using then (46) and (35), we get

$$\left\| \langle v \rangle^{\gamma/2} \langle D_v \rangle^s \psi \right\|^2 \lesssim \left\| (p^{1/2})^w \psi \right\|^2 \simeq \left(p^{\text{Wick}} \psi, \psi \right) \lesssim \frac{1}{t} \|\psi_0\|^2.$$

Similarly,

$$\left\| \langle v \rangle^{\gamma/2+s} \psi \right\|^2 \lesssim \frac{1}{t} \|\psi_0\|^2,$$

and working in $S_K(q)$ gives, in the same way,

$$\left\| \langle v \rangle^{\gamma/2} \langle \xi \rangle^s \psi \right\|^2 \lesssim \frac{1}{t^{1+2s}} \|\psi_0\|^2.$$

Taking the inverse Fourier transform in the x variable yields finally

$$\begin{aligned} \left\| \langle v \rangle^{\gamma/2} \langle D_v \rangle^s \varphi \right\|^2 &\lesssim \frac{1}{t} \|\varphi_0\|^2, & \left\| \langle v \rangle^{\gamma/2+s} \varphi \right\|^2 &\lesssim \frac{1}{t} \|\varphi_0\|^2 \\ & & \text{and} & \left\| \langle v \rangle^{\gamma/2} \langle D_x \rangle^s \varphi \right\|^2 &\lesssim \frac{1}{t^{1+2s}} \|\varphi_0\|^2. \end{aligned}$$

This is exactly the statement of Proposition 3.2, the proof is thus complete. \square

APPENDIX A

A.1. Carleman representation. We state here a classical tool in the analysis of Boltzmann operator: the Carleman representation. We refer to [2] for more details on the version that we state here.

Lemma A.1 (Carleman representation). *Let F be a measurable function defined on $(\mathbb{R}^3)^4$. For any vector $h \in \mathbb{R}^3$, we denote by $E_{0,h}$ the (hyper)vector plane orthogonal to h . Then, when all sides are well defined, we have the following equality :*

$$\begin{aligned} &\int_{\mathbb{R}^3 \times \mathbb{S}^2} b(\cos \theta) |v - v_*|^\gamma F(v, v_*, v', v'_*) dv_* d\sigma \\ &= \int_{\mathbb{R}_k^3} dh \int_{E_{0,h}} d\alpha \tilde{b}(\alpha, h) \mathbf{1}_{|\alpha| \geq |h|} \frac{|\alpha + h|^{\gamma+1+2s}}{|h|^{3+2s}} F(v, v + \alpha - h, v - h, v + \alpha) \end{aligned}$$

where $\tilde{b}(\alpha, h)$ is bounded from above and below by positive constants and $\tilde{b}(\alpha, h) = \tilde{b}(\pm\alpha, \pm h)$.

A.2. Pseudodifferential calculus. We first recall the definitions of the quantizations we shall use in the following. Let us consider a temperate symbol $\sigma \in \mathcal{S}$, we define its standard quantization $\sigma(v, D_v)$ for $f \in L^2(\mathbb{R}^d)$ by

$$\sigma(v, D_v) f(v) = \frac{1}{(2\pi)^d} \int e^{iv \cdot \eta} \sigma(v, \eta) \hat{f}(\eta) d\eta.$$

The Weyl quantization is defined by

$$\sigma^w f(v) = \frac{1}{(2\pi)^d} \iint e^{i(v-w) \cdot \eta} \sigma\left(\frac{v+w}{2}, \eta\right) f(w) d\eta dw.$$

We recall that for two symbols σ and τ we have

$$(36) \quad \sigma^w \tau^w = (\sigma \sharp \tau)^w, \quad \sigma \sharp \tau = \sigma \tau + \int_0^1 (\partial_\eta \sigma \sharp_\theta \partial_v \tau - \partial_v \sigma \sharp_\theta \partial_\eta \tau) d\theta$$

where for $V = (v, \eta)$ we have $\sharp = \sharp_1$ and for $\theta \in (0, 1]$,

$$\sigma \sharp_\theta \tau(V) = \frac{1}{2i} \iint e^{-2i[V-V_1, V-V_2]/\theta} \sigma(V_1) \tau(V_2) dV_1 dV_2 / (\pi\theta)^d$$

with $[V_1, V_2] = v_2 \cdot \eta_1 - v_1 \cdot \eta_2$ the canonical symplectic form on \mathbb{R}^{2d} .

We shall also use the Wick quantization, which has very nice properties concerning positivity of operators (see [10, 11, 12] for more details on the subject). For this we first introduce the Gaussian in phase variables

$$(37) \quad N(v, \eta) = (2\pi)^{-d} e^{-(|v|^2 + |\eta|^2)/2}.$$

The Wick quantization is then defined by

$$(38) \quad \sigma^{\text{Wick}} f(v) = (\sigma \star N)^w f(v),$$

where \star denotes the usual convolution in (v, η) variables. Recall that one of the main property of Wick quantization is its positivity:

$$(39) \quad \forall (v, \eta) \in \mathbb{R}^6, \sigma(v, \eta) \geq 0 \Rightarrow \sigma^{\text{Wick}} \geq 0,$$

and that the following relation holds (see e.g. [10, Proposition 3.4]):

$$(40) \quad [g^{\text{Wick}}, iv \cdot \xi] = \{g, v \cdot \xi\}^{\text{Wick}}.$$

The previous definitions extend to symbols in \mathcal{S}' by duality.

A.3. The weak semiclassical class $S_K(g)$. Let $\Gamma := |dv|^2 + |d\eta|^2$ be the flat metric on $\mathbb{R}_{v,\eta}^6$. The first point is to verify that the introduced symbols and weights are indeed in a suitable symbolic calculus with large parameter K uniformly in parameter ξ . For this we first recall that a weight $1 \leq g$ is said to be temperate with respect to Γ if there exist $N \geq 1$ and C_N such that for all $(v, \eta), (v', \eta') \in \mathbb{R}^6$

$$g(v', \eta') \leq C_N g(v, \eta) (1 + |v' - v| + |\eta' - \eta|)^N$$

We introduce now adapted classes of symbols.

Definition A.2. Let g be a temperate weight. We denote by $S(g)$ the symbol class of all smooth functions $\sigma(v, \eta)$ (possibly depending on parameters K and ξ) such that

$$\left| \partial_v^\alpha \partial_\eta^\beta \sigma(v, \eta) \right| \leq C_{\alpha, \beta} g(v, \eta)$$

where for any multiindex α and β , $C_{\alpha, \beta}$ is uniform in K and ξ . We denote also $S_K(g)$ the symbol class of all smooth functions $\sigma(v, \eta)$ (possibly depending on K and ξ again) such that

$$|\sigma| \leq C_{0,0} g \quad \text{and} \quad \forall |\beta| \geq 1, \quad \left| \partial_v^\alpha \partial_\eta^\beta \sigma \right| \leq C_{\alpha, \beta} K^{-1/2} g$$

uniformly in K and ξ . Note that $S_K(g) \subset S(g)$ and that these definitions are with respect to the flat metric.

Eventually, we shall say that a symbol σ is elliptic positive in $S(g)$ or $S_K(g)$ if in addition $\sigma \geq 1$ and there exists a constant C uniform in parameters such that $C^{-1}g \leq \sigma \leq Cg$.

Before focusing on the class $S_K(g)$, we first recall one of the main results concerning the class without parameter (and without gain) $S(1)$:

Lemma A.3 (Calderon Vaillancourt Theorem). Let $\sigma \in S(1)$, then σ^w is a bounded operator with norm depending only on a finite number of semi-norms of σ in $S(1)$.

The classes S_K and S have standard internal properties:

Lemma A.4. For K sufficiently large, we have the following:

- a) Let g be a temperate weight and consider σ a elliptic positive symbol in $S_K(g)$ for all $v \in \mathbb{R}$, $\sigma^\nu \in S_K(g^\nu)$;
- b) Let g, h be temperate weights and consider σ in $S_K(g)$ and τ in $S_K(h)$, then $\sigma\tau$ is in $S_K(gh)$.

Proof. For point a), just notice that if σ is a elliptic positive symbol in $S_K(g)$, then $\sigma \simeq g$ so that $\sigma^\nu \simeq g^\nu$. We also have directly for β a multiindex of length 1

$$\left| \partial_\eta^\beta \sigma^\nu \right| = |\nu| \sigma^{\nu-1} \left| \partial_\eta^\beta \sigma \right| \leq C g^{\nu-1} K^{-1/2} g = C K^{-1/2} g^\nu$$

using $\sigma \simeq g$. Estimates on higher order derivatives are straightforward.

For point b), the computation is also straightforward using the Leibniz rule. \square

Now we can quantize the previously introduced symbols. The main *semiclassical* idea behind the introduction of the class S_K for K large is that invertibility and powers of operators associated to symbols are direct consequences of similar properties of symbols, essentially independently of the quantization.

We first check that the class S_K is essentially stable by change of quantization.

Lemma A.5. *Let g be a temperate weight and consider $\tilde{\sigma}$ a positive elliptic symbol in $S_K(g)$. We denote σ the Weyl symbol of the operator $\tilde{\sigma}(v, D_v)$ so that $\sigma^w = \tilde{\sigma}(v, D_v)$ and recall that the Weyl symbol of σ^{Wick} is $\sigma \star N$. Then σ and $\sigma \star N$ are both in $S_K(g)$. If in addition $\tilde{\sigma}$ is elliptic positive, then $\text{Re } \sigma$ and $\text{Re } \sigma \star N$ are elliptic positive.*

Proof. We first prove the result for σ supposing that $\tilde{\sigma}$ is elliptic positive. From for e.g. [12] and and adaptation of Lemma 4.4 in [2], we know that

$$(41) \quad \sigma - \tilde{\sigma} \in K^{-1/2} S(g).$$

Since $K^{-1/2} S(g) \subset S_K(g)$ this gives that $\sigma \in S_K(g)$. Now if in addition $\tilde{\sigma}$ is elliptic positive, then let us prove that $\text{Re } \sigma$ also is. There exist constants C, C' uniform in K large such that

$$C^{-1}g - C'K^{-1/2}g \leq \text{Re } \sigma \leq Cg + C'K^{-1/2}g$$

if $C^{-1}g \leq \sigma \leq Cg$. Taking K sufficiently large then gives the result.

Now we deal with $\sigma \star N$, supposing that σ is in $S_K(g)$. For $V = (v, \eta)$ we have

$$\sigma \star N(V) = \iint \sigma(V - W) N(W) dW$$

and using the temperance property of g , we get uniformly in all other possible parameters (including K)

$$|\sigma \star N(V)| \leq \iint Cg(V)(1 + |W|)^N N(W) dW \leq C'g(V).$$

For the derivatives we get similarly for multiindex α and β with $|\beta| \geq 1$

$$(42) \quad \begin{aligned} \left| \partial_v^\alpha \partial_\eta^\beta \sigma \star N(V) \right| &\leq \iint \left| \partial_v^\alpha \partial_\eta^\beta \sigma(V - W) \right| N(W) dW \\ &\leq CK^{-1/2} \iint g(V - W) N(W) dW \\ &\leq C'K^{-1/2} \iint g(V)(1 + |W|)^N N(W) dW \\ &\leq C''K^{-1/2}g(V). \end{aligned}$$

Now suppose that in addition $\tilde{\sigma}$ is elliptic positive, then $\text{Re } \sigma$ is elliptic positive and $C^{-1}g(V) \leq \text{Re } \sigma(V) \leq Cg(V)$ for a constant $C > 0$. Since $\text{Re } \sigma \star N$ is positive, this

implies with the temperance of g that

$$(43) \quad \begin{aligned} c'g(V) &\leq \iint C^{-1}C_N^{-1}g(V)(1+|W|)^{-N}N(W)dW \\ &\leq \operatorname{Re} \sigma \star N(V) \leq \iint CC_Ng(V)(1+|W|)^N N(W)dW = C'g(V) \end{aligned}$$

for some positive constants c' and C' , so that $\operatorname{Re} \sigma \star N$ is indeed elliptic positive. \square

Remark A.6 Note that using exactly the same argument as in the proof before, we also get that if τ is a given elliptic positive symbol in $S_K(g)$, with g temperate weight, then $\tau \star N$ is also an elliptic positive symbol in $S_K(g)$.

The next technical lemma is also proven in [2]:

Lemma A.7 (Lemma 4.2 in [2]). *Let g be a temperate weight and $\sigma \in S_K(g)$. Then for K sufficiently large (depending on a finite number of semi-norms of σ), the operator σ^w is invertible and there exists H_L and H_R bounded invertible operators that are close to identity as well as their inverse such that*

$$(\sigma^w)^{-1} = H_L(\sigma^{-1})^w = (\sigma^{-1})^w H_R.$$

The norms of operators H_L and H_R and their inverse can be bounded uniformly in parameters (including K).

Note that by “close to identity uniformly in parameters”, we mean that

$$\|H_L f\| \simeq \|H_R f\| \simeq \|f\|.$$

with constants uniform in parameters (including K sufficiently large).

Proof. The proof follows exactly the lines of the one given in [2, Lemma 4.2. i)]. \square

We now give the main Proposition that will be used in the proof of the technical Lemmas in Subsection 4.3.

Proposition A.8. *Let g be a temperate weight and consider σ an elliptic positive symbol in $S_K(g)$. Then for K sufficiently large, we have the following*

$$(44) \quad \left\| (\sigma^w)^{1/2} f \right\| \simeq \left\| (\sigma^{1/2})^w f \right\| \quad \text{and} \quad \left\| (\sigma^w)^{-1} f \right\| \simeq \left\| (\sigma^{-1})^w f \right\|.$$

In addition, suppose that τ is another elliptic positive symbol in $S_K(g)$ then

$$(45) \quad \left\| \sigma^w f \right\| \simeq \left\| \tau^w f \right\|.$$

In particular we have

$$(46) \quad \left\| \sigma^w f \right\|^2 \simeq \left\| \sigma^{\operatorname{Wick}} f \right\|^2 \simeq \left((\sigma^2)^{\operatorname{Wick}} f, f \right)$$

and

$$(47) \quad (\sigma^w f, f) \simeq \left(\sigma^{\operatorname{Wick}} f, f \right)$$

uniformly in parameters (in particular K).

Proof. We first prove (44). For the second almost equality, we just have to notice that from Lemma A.7, we have

$$\|(\sigma^w)^{-1}f\| = \|H_L(\sigma^{-1})^w f\| \simeq \|(\sigma^{-1})^w f\|$$

since H_L is close to identity (uniformly in parameters). For the first part of (44), we write that

$$(48) \quad \|\sigma^w f\|^2 = ((\sigma \sharp \sigma)^w f, f) = ((\sigma^2)^w f, f) + (r^w f, f)$$

where $r = \sigma \sharp \sigma - \sigma^2 \in K^{-1/2}S(g^2)$ by standard symbolic calculus: Precisely we can write from (36)

$$r = \int_0^1 (\partial_v \sigma \sharp_\theta \partial_\eta \sigma - \partial_\eta \sigma \sharp_\theta \partial_v \sigma) d\theta$$

and using that $\partial_v \sigma \in S(g)$ and $\partial_\eta \sigma \in K^{-1/2}S(g)$ gives the result by stability of the flat symbol class $S(g)$. We therefore get that

$$\begin{aligned} |(r^w f, f)| &= |((\sigma^w)^{-1} r^w (\sigma^w)^{-1} \sigma^w f, \sigma^w f)| \\ &= |(H_L(\sigma^{-1})^w r^w (\sigma^{-1})^w H_R \sigma^w f, \sigma^w f)|. \end{aligned}$$

Now $\sigma^{-1} \sharp r \sharp \sigma^{-1} \in K^{-1/2}S(1)$ since $\sigma^{-1} \in S(g)$, so that $(\sigma^{-1})^w r^w (\sigma^{-1})^w$ is a bounded operator with norm controlled by a constant times $K^{-1/2}$. Since H_L and H_R are bounded operators independently of K , there exists a constant such that

$$|(r^w f, f)| \leq CK^{-1/2} \|\sigma^w f\|^2.$$

This estimate and (48), gives that for K sufficiently large,

$$(49) \quad \frac{1}{2} \|\sigma^w f\|^2 \leq ((\sigma^2)^w f, f) \leq 2 \|\sigma^w f\|^2.$$

Taking $\sigma^{1/2} \in S_K(g^{1/2})$ (by Lemma A.4) instead of σ , we obtain

$$\left\| (\sigma^{1/2})^w f \right\|^2 \simeq (\sigma^w f, f) = \left\| (\sigma^w)^{1/2} \right\|^2$$

and the proof of (44) is complete.

Concerning (45), we just have to prove one inequality since the result is symmetric in τ and σ . For K sufficiently large, we have

$$\|\tau^w f\| = \|\tau^w (\sigma^w)^{-1} \sigma^w f\| = \|\tau^w (\sigma^{-1})^w H_R \sigma^w f\| = \|(\tau \sharp (\sigma^{-1}))^w H_R \sigma^w f\| \leq C \|\sigma^w f\|$$

since $\tau \sharp (\sigma^{-1}) \in S(1)$, so that $(\tau \sharp (\sigma^{-1}))^w$ is bounded (with bound independent of K). By symmetry this proves (45).

We then prove (46). We first recall that $\sigma^{\text{Wick}} = (\sigma \star N)^w$ and that $\sigma \star N$ is elliptic positive in $S_K(g)$ by Lemma A.5. From (45) this directly yields

$$\|\sigma^w f\| \simeq \|(\sigma \star N)^w f\| = \left\| \sigma^{\text{Wick}} f \right\|.$$

By direct computation $(\sigma^2 \star N)^{1/2}$ is also in $S_K(g)$ by point b) of Lemma A.4 with $\nu = 2$ and $\nu = 1/2$, respectively, and Lemma A.5. Using again (45) and (44), yields that

$$\|\sigma^w f\| \simeq \left\| ((\sigma^2 \star N)^{1/2})^w f \right\| \simeq \left\| ((\sigma^2 \star N)^w)^{1/2} f \right\| = ((\sigma^2 \star N)^w f, f) = ((\sigma^2)^{\text{Wick}} f, f).$$

The proof of the last point (47) follows exactly the same lines and we skip it. \square

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